HOT: Chaocritiplexity meets Robustness

Jean Carlson and John Doyle

Background

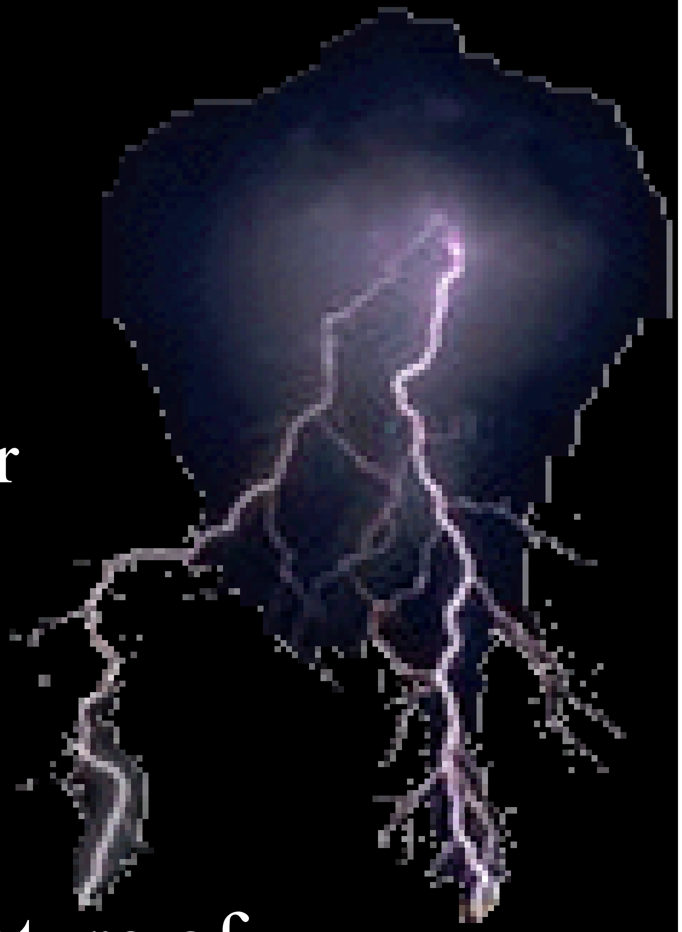
- Much attention has been given to "complex adaptive systems" in the last decade.
- Popularization of information, entropy, phase transitions, criticality, fractals, self-similarity, power laws, chaos, emergence, self-organization, etc.
- Physicists emphasize *emergent* complexity via *self-organization* of a homogeneous substrate near a critical or bifurcation point (SOC/EOC)

Good try, but not much progress in making connections with anything real!

Highly Optimized Tolerance (HOT)

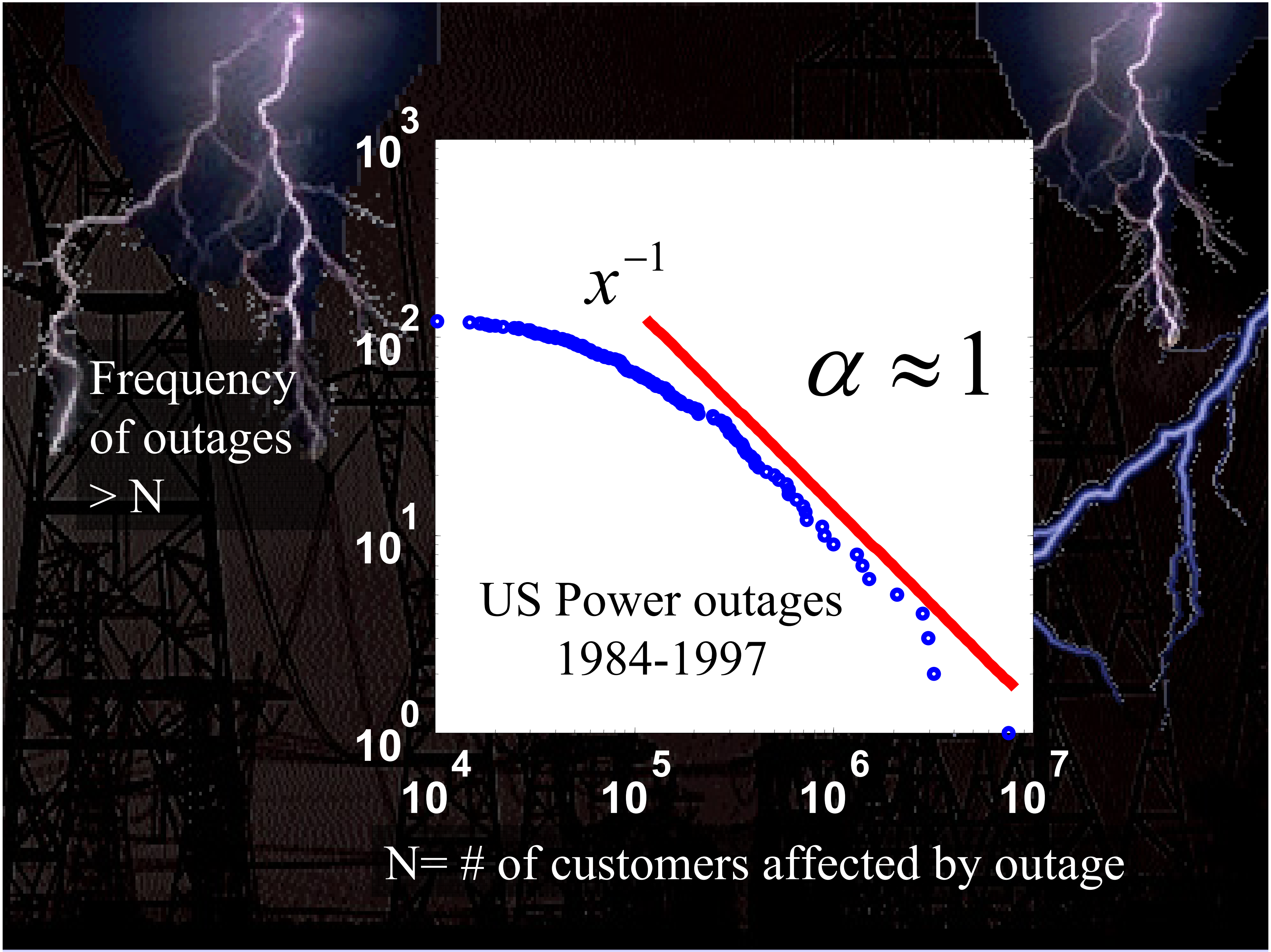
- Complex systems in biology, ecology, technology, sociology, economics, …
- are driven by design, evolution, or sorting to high-performance states which are also tolerant to uncertainty in the environment and components.
- This leads to specialized, modular, hierarchical structures, often with enormous “hidden” complexity,
- with new sensitivities to unknown or neglected perturbations and design flaws.
- “Robust, yet fragile!”

"Robust, yet fragile"

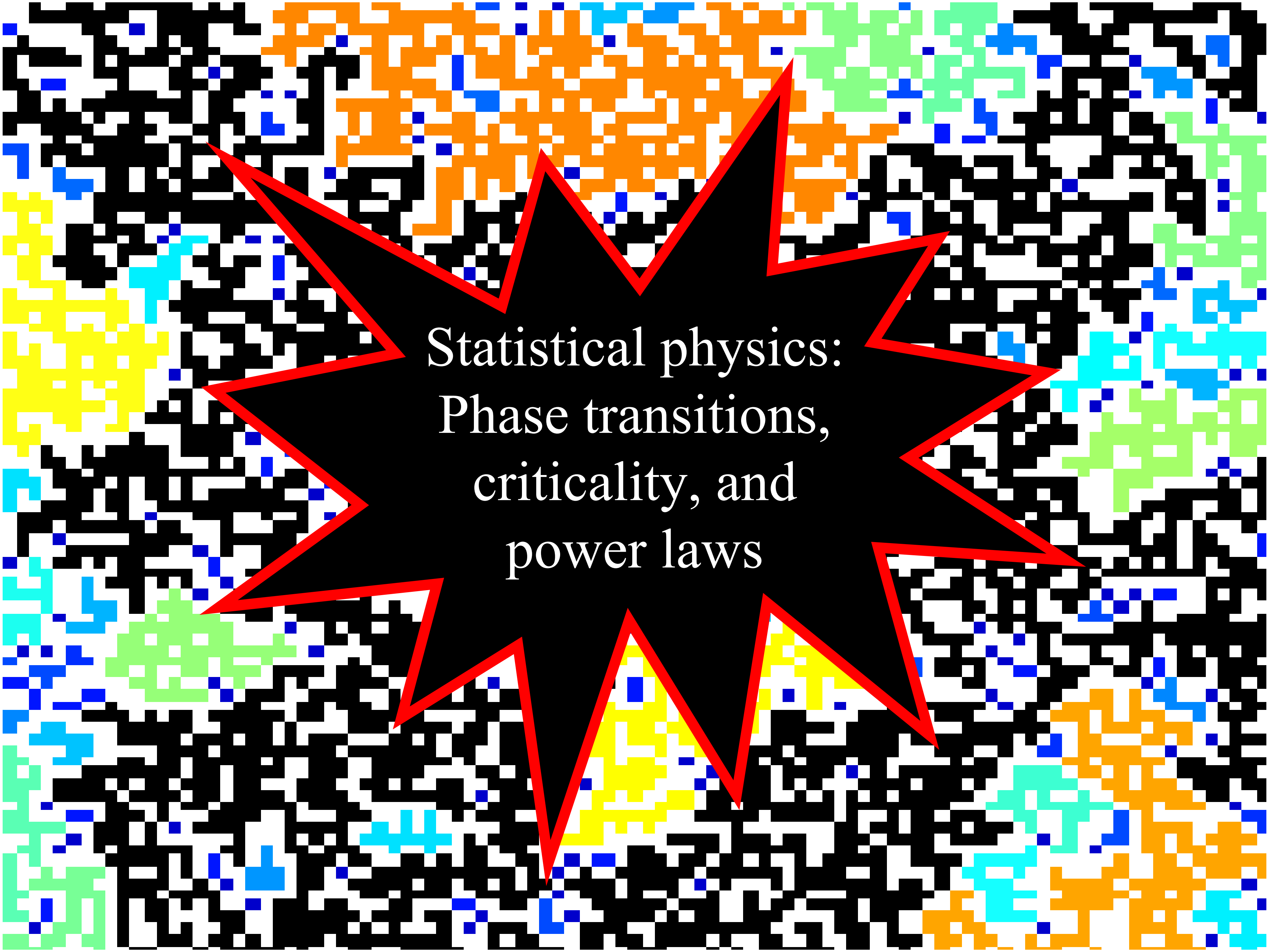


- **Robust** to uncertainties
  - that are common,
  - the system was designed for, or
  - has evolved to handle,
- **…yet fragile** otherwise

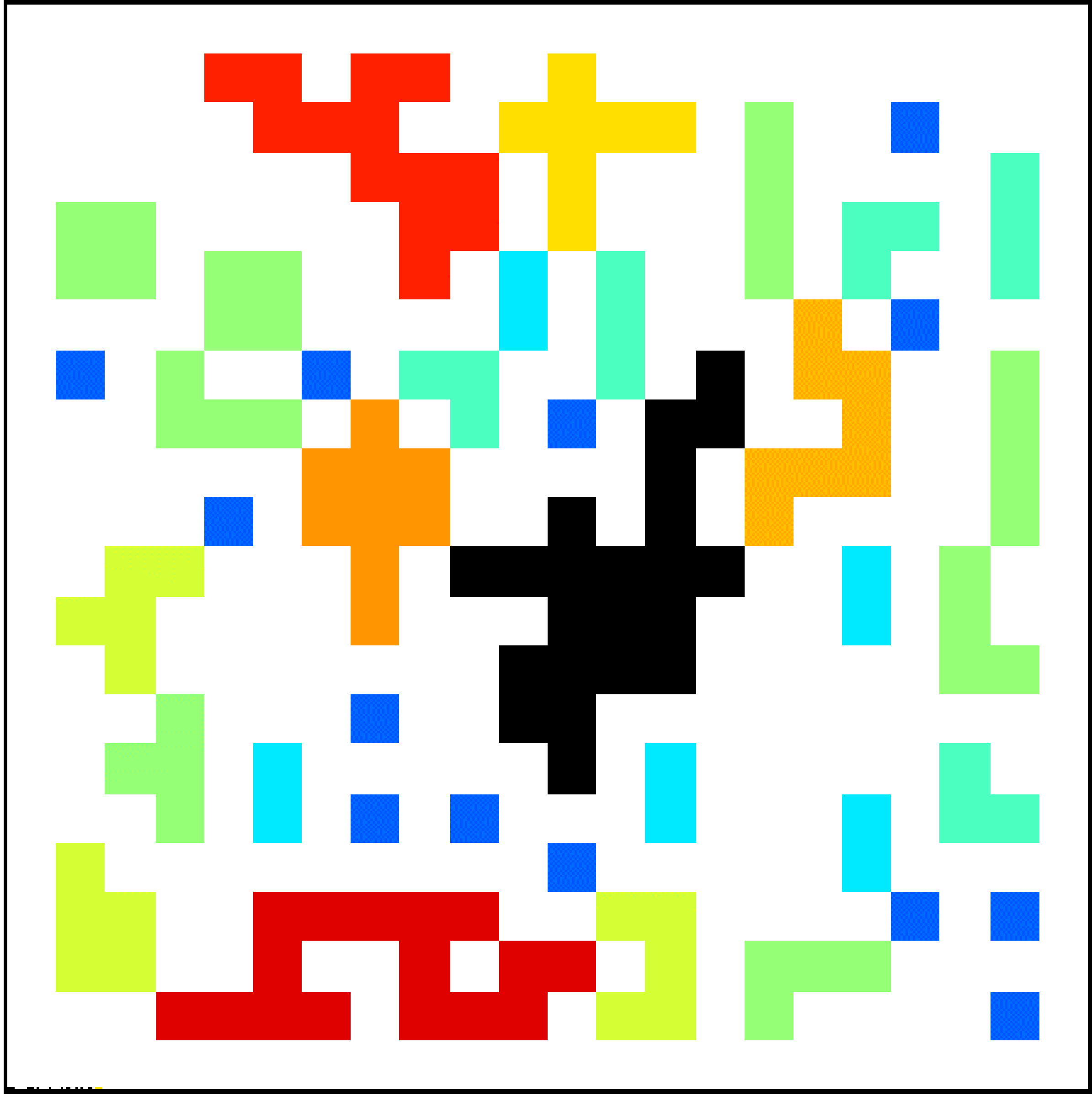
- This is *the* most important feature of complex systems (the essence of HOT).



10^3
10^2
10^1
10^0
Frequency of outages > N
x^{-1}
$\alpha \approx 1$
US Power outages 1984-1997
10^4
10^5
10^6
10^7
N= # of customers affected by outage


Statistical physics:
Phase transitions,
criticality, and
power laws

The simplest possible spatial model of HOT.

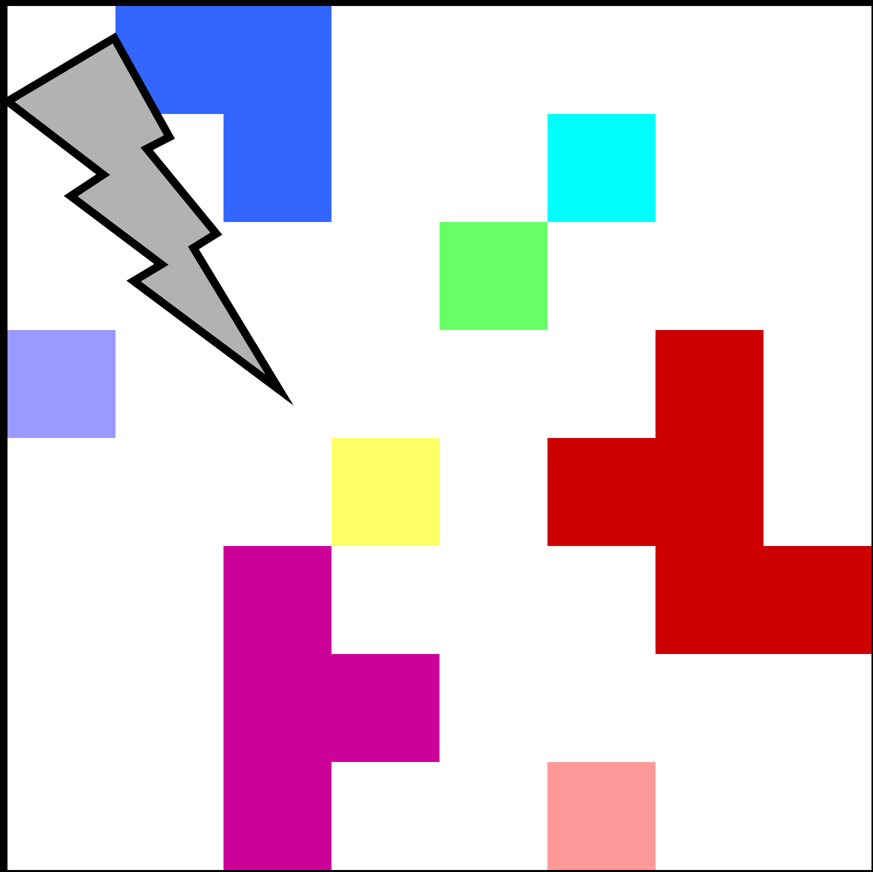


Square site percolation or simplified “forest fire” model.

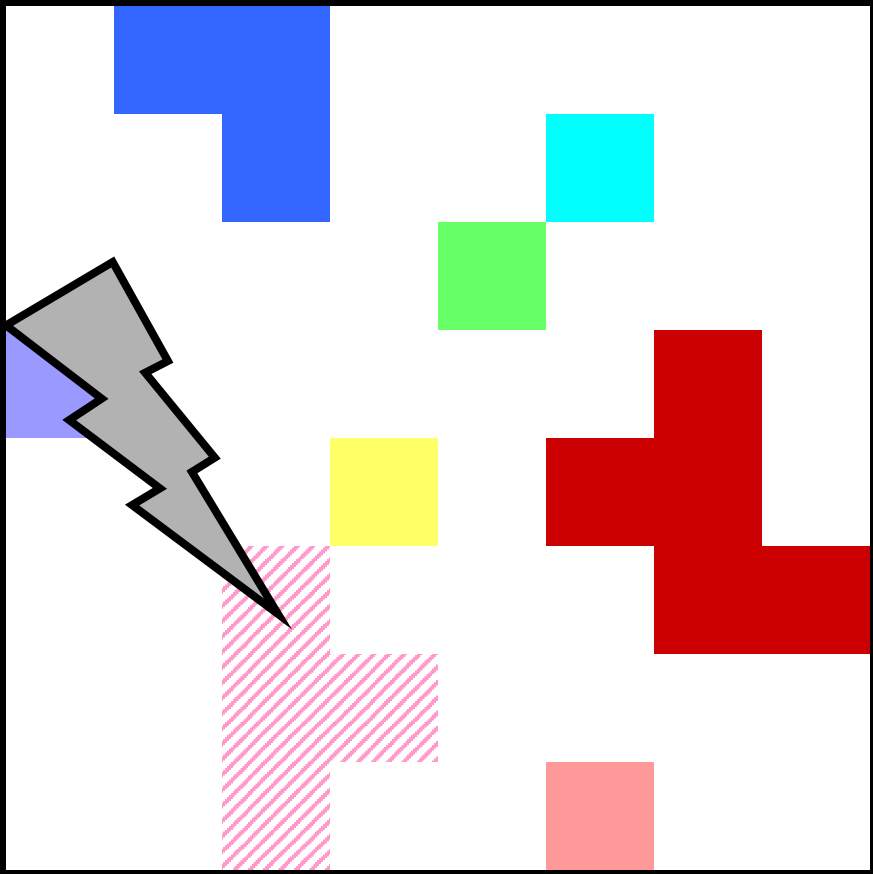
Carlson and Doyle, PRE, Aug. 1999

Assume one "spark" hits the lattice at a single site.

A "spark" that hits an empty site does nothing.

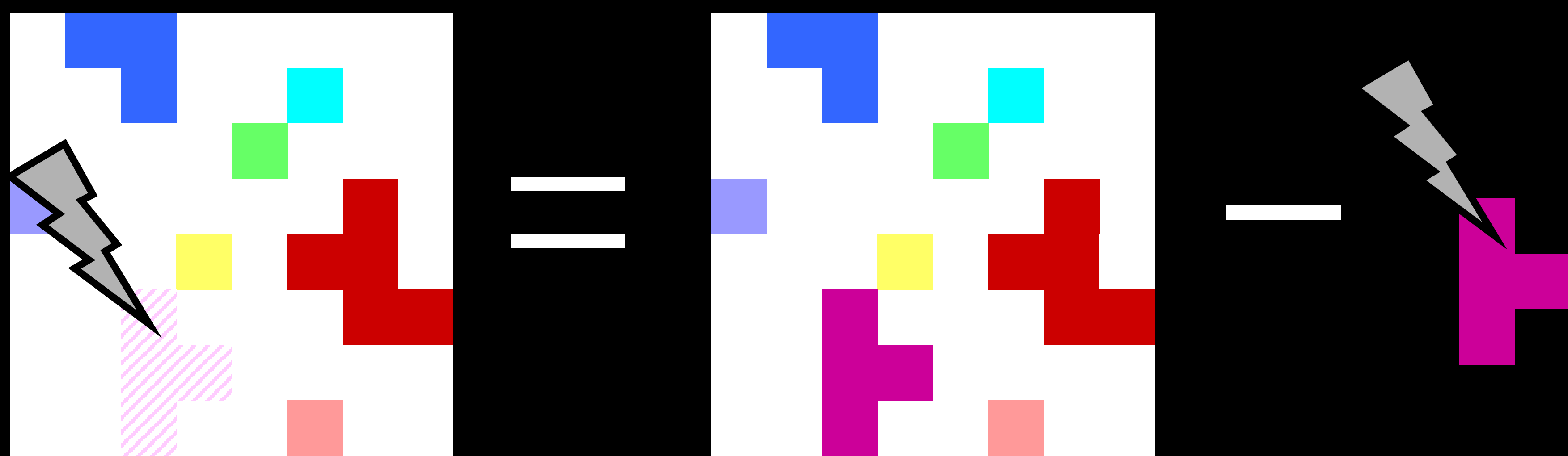


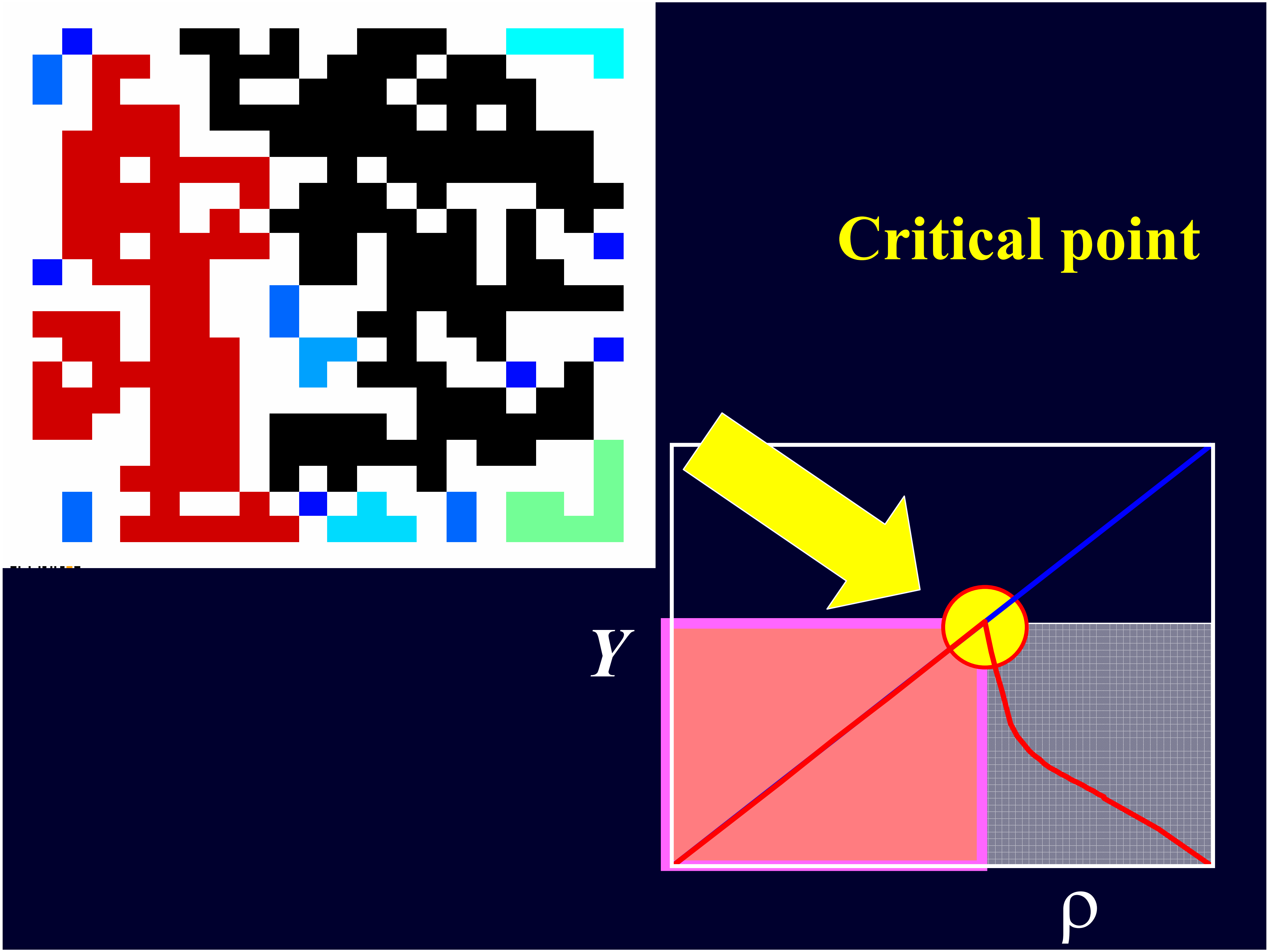
A “spark” that hits a cluster causes loss of that cluster.

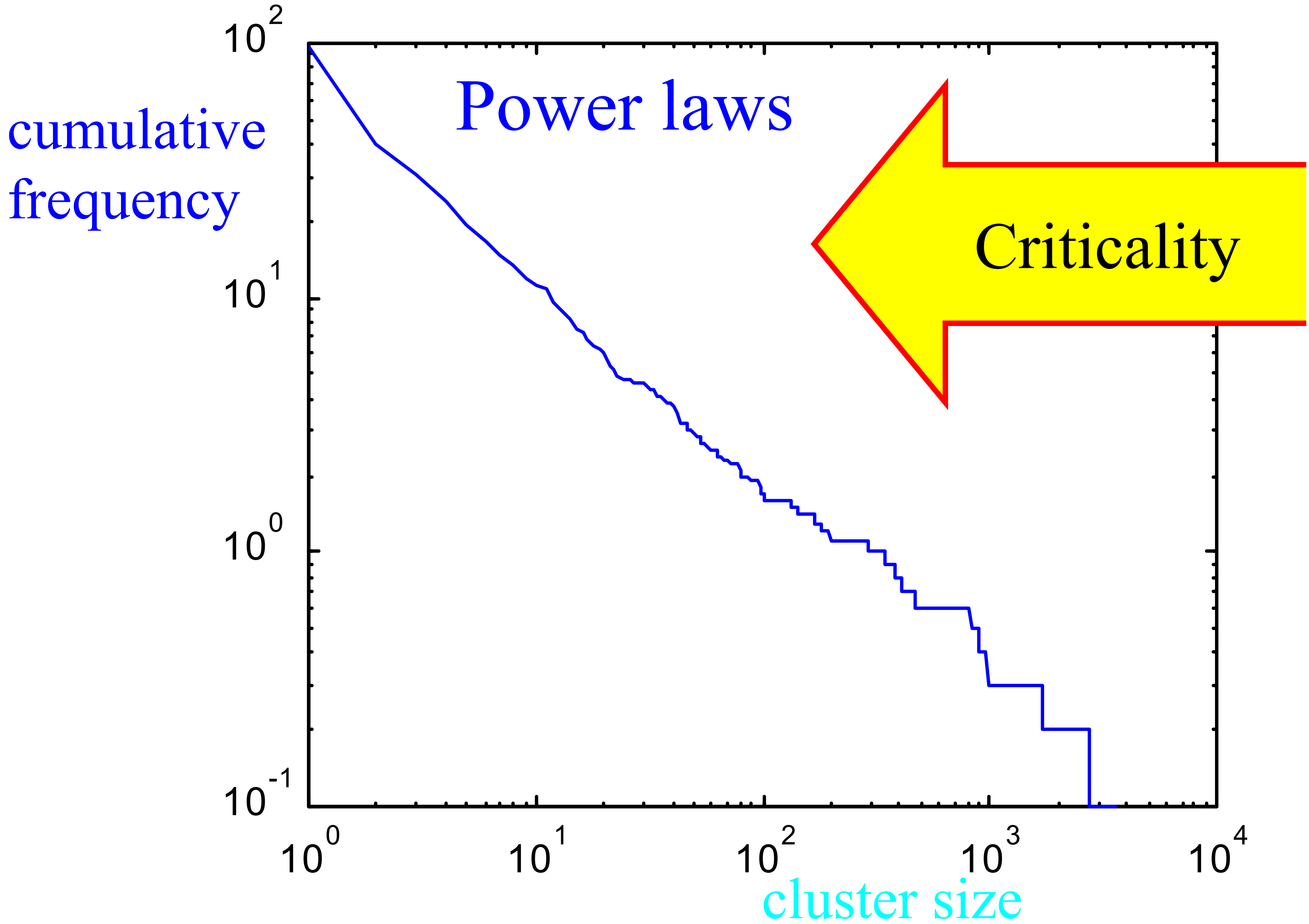


Yield = the density *after* one spark

yield = density − loss




Critical point
Y
ρ



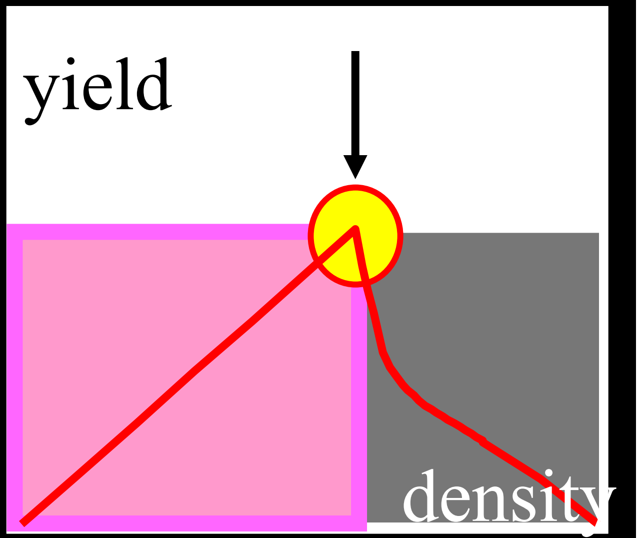
cumulative frequency
Power laws
Criticality
cluster size
10^2
10^1
10^0
10^-1
10^0
10^1
10^2
10^3
10^4

Edge-of-chaos, criticality, self-organized criticality (EOC/SOC)

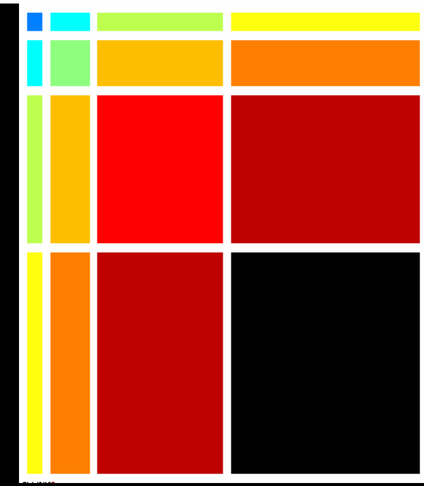
Essential claims:

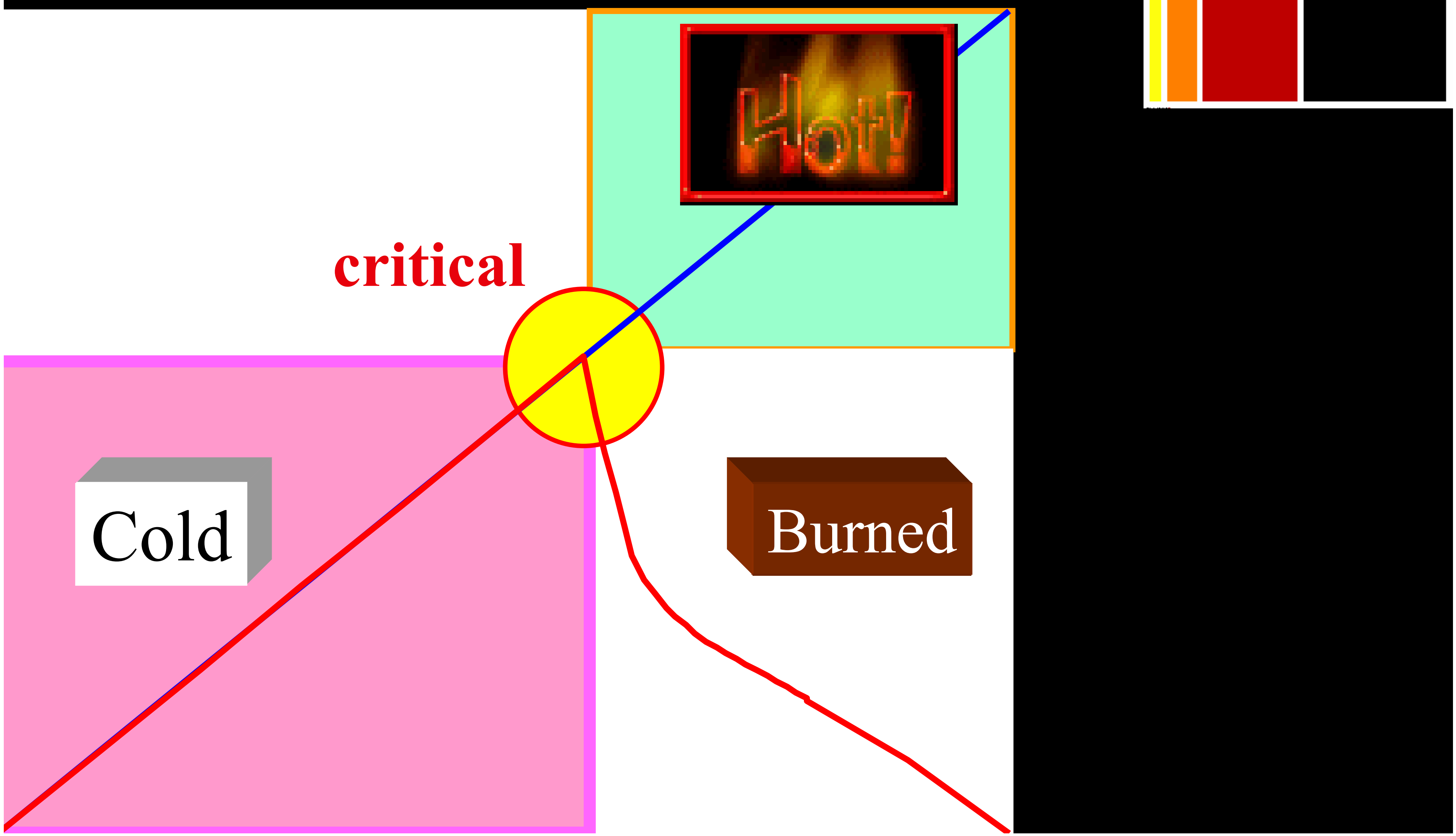
• Nature is adequately described by generic configurations (with generic sensitivity).

• Interesting phenomena is at criticality (or near a bifurcation).

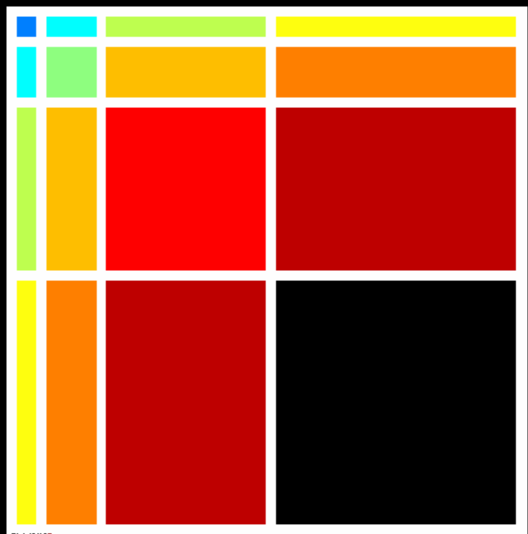


Highly Optimized Tolerance (HOT)



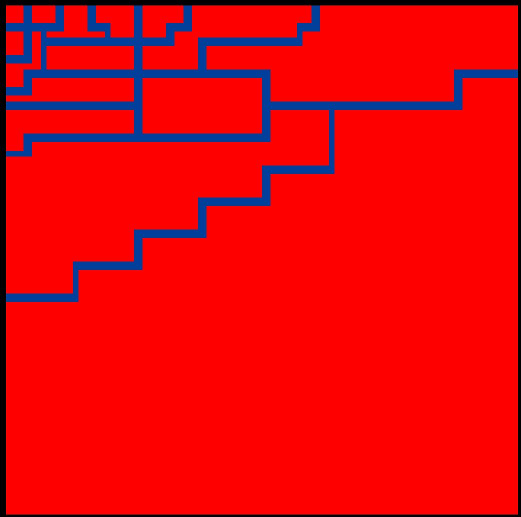


HOT: many mechanisms



grid

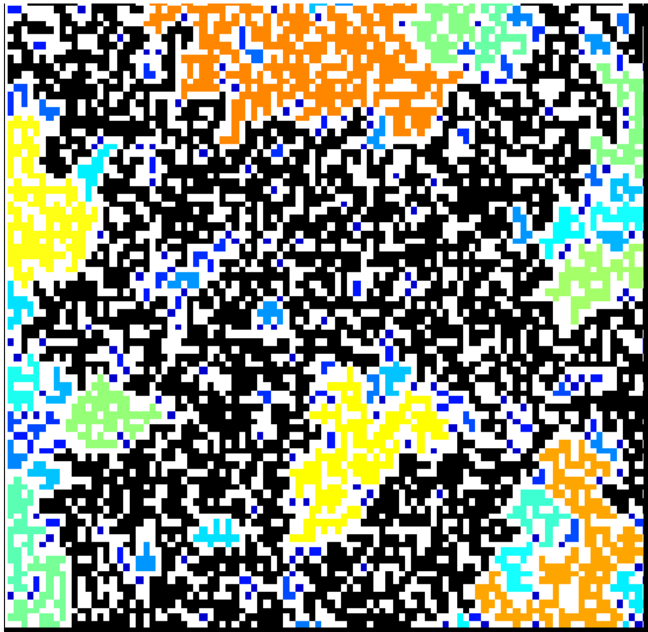
local incremental



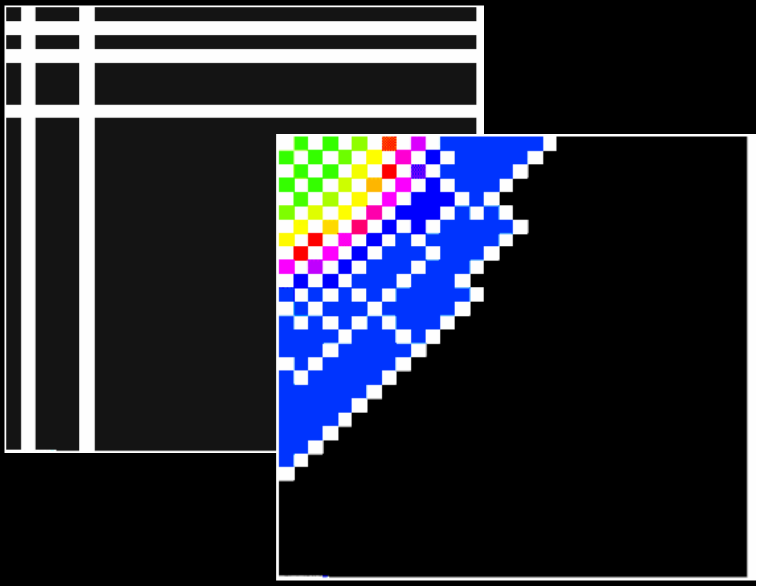
Design Degrees of Freedom

All produce:

- High densities
- Modular Structures reflecting external disturbance patterns
- Efficient barriers, limiting losses in cascading failure
- Power Laws



Optimized

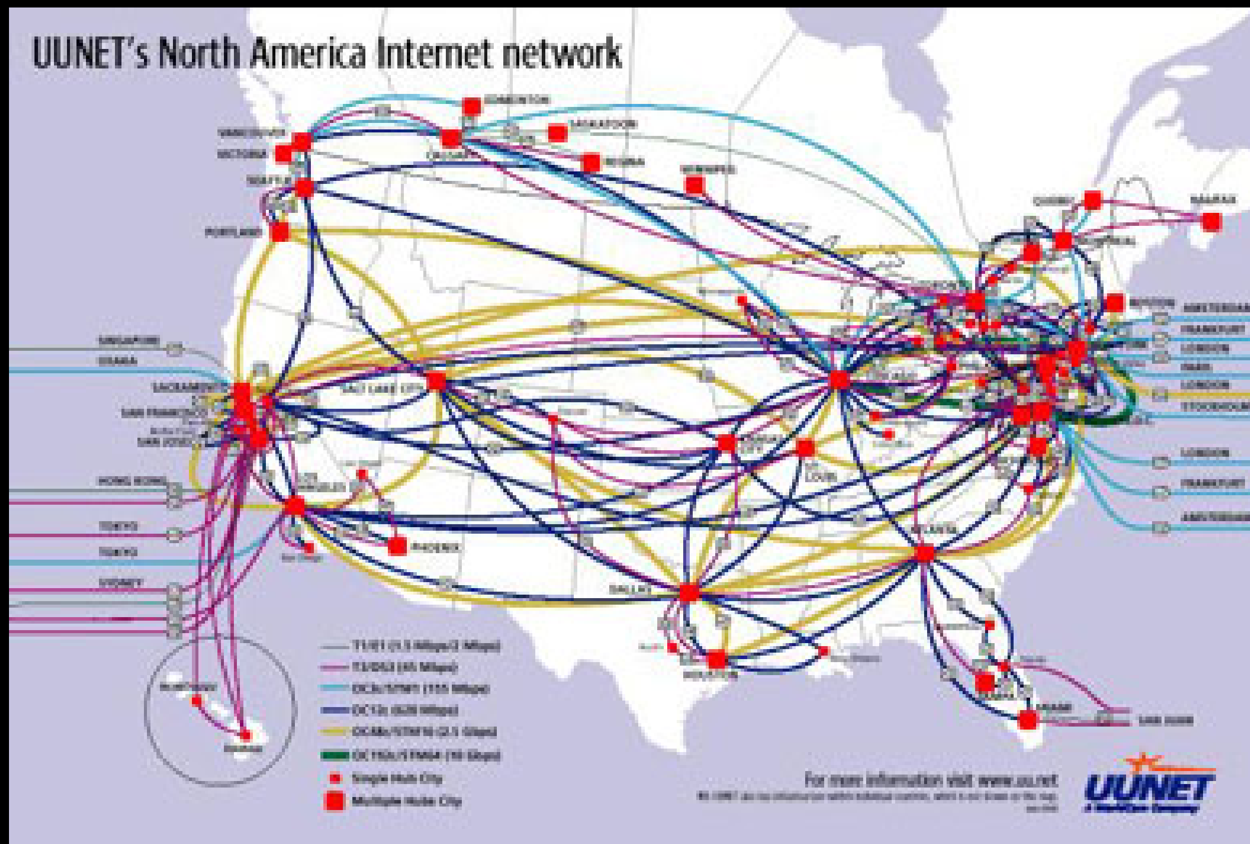


Critical percolation and SOC forest fire models

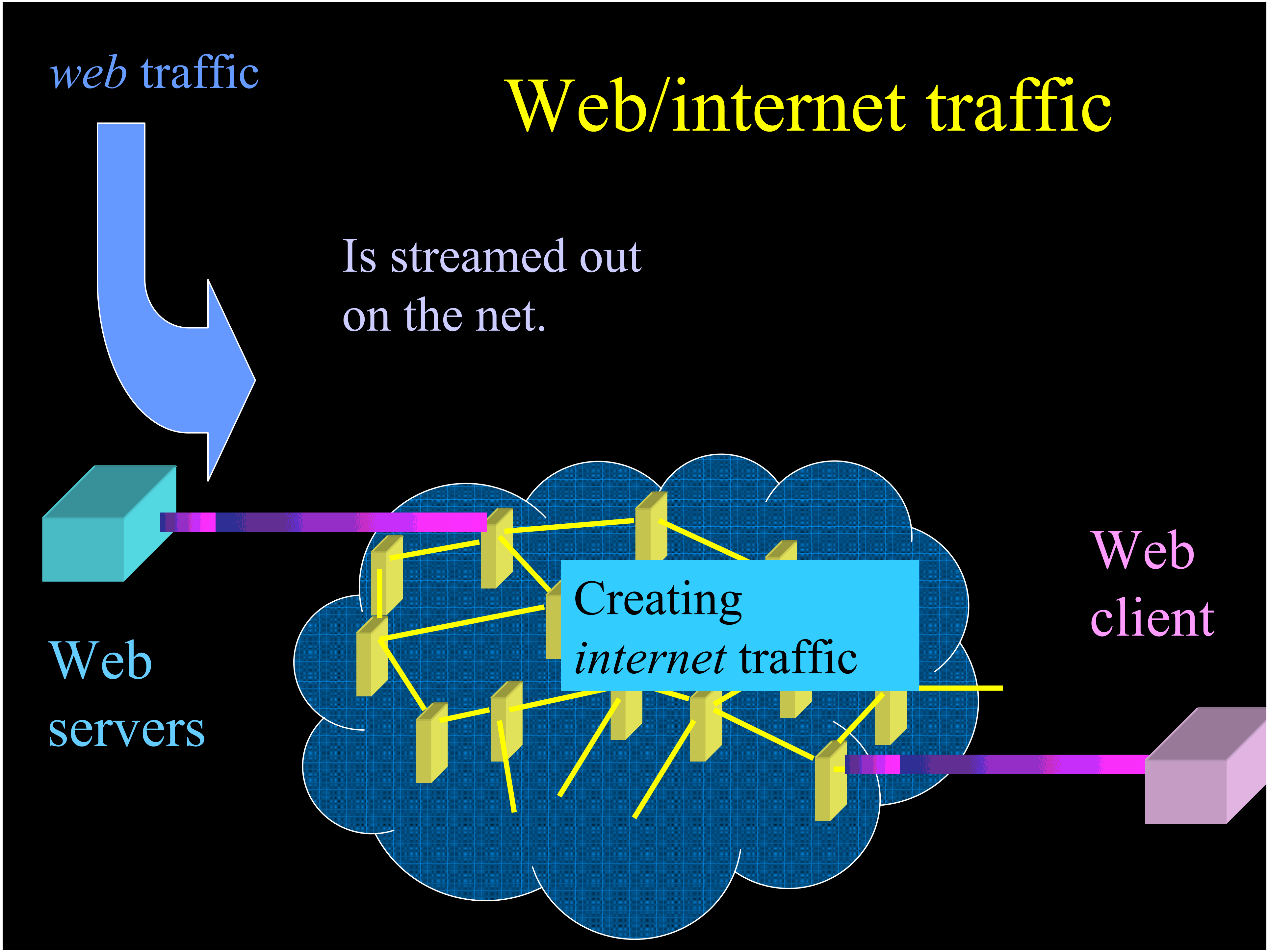
HOT forest fire models

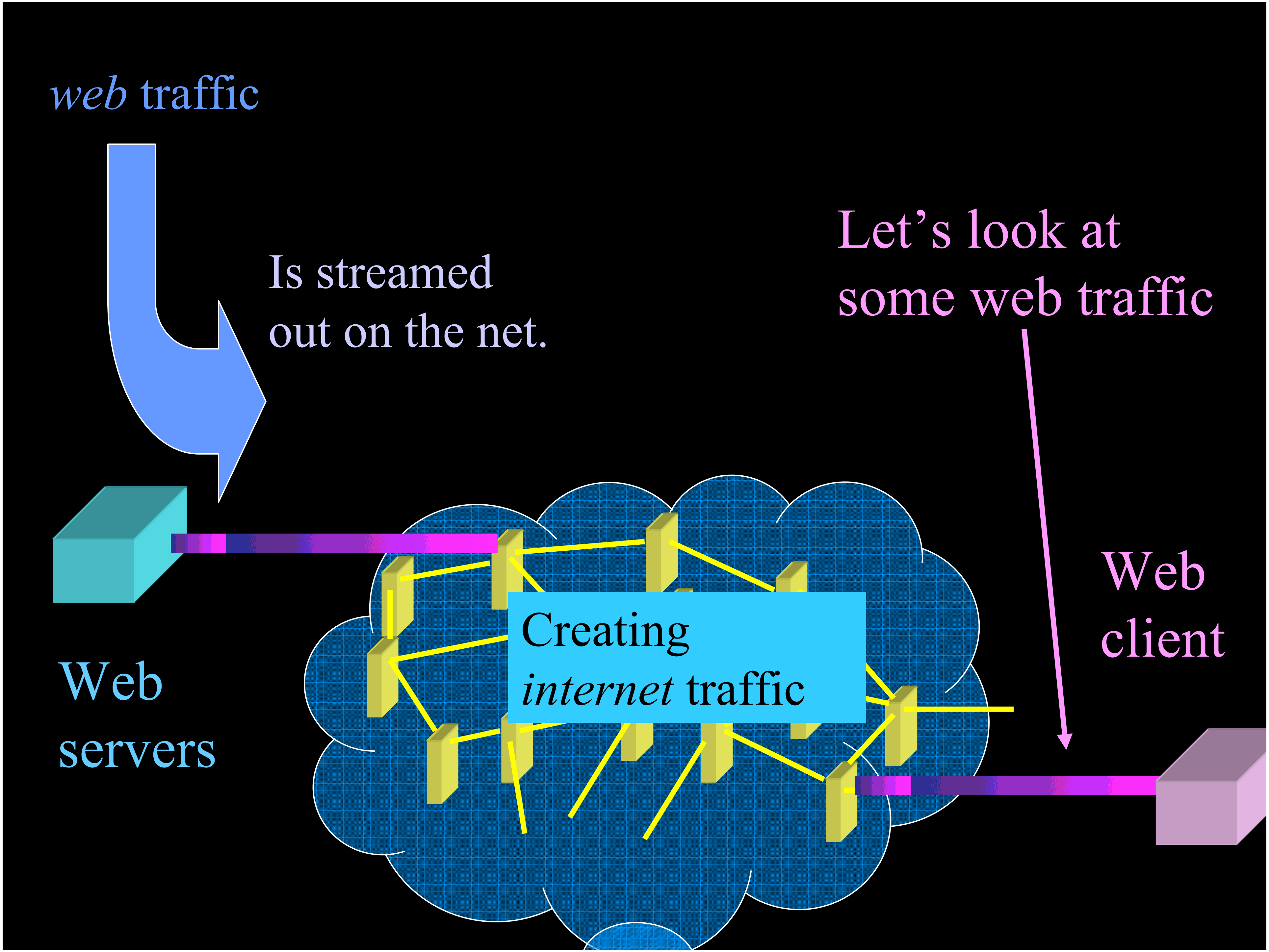
- SOC & HOT have completely different characteristics.
- SOC vs HOT story is consistent across different models.
- Focus on “generalized coding” abstraction for HOT

Is the Internet HOT?

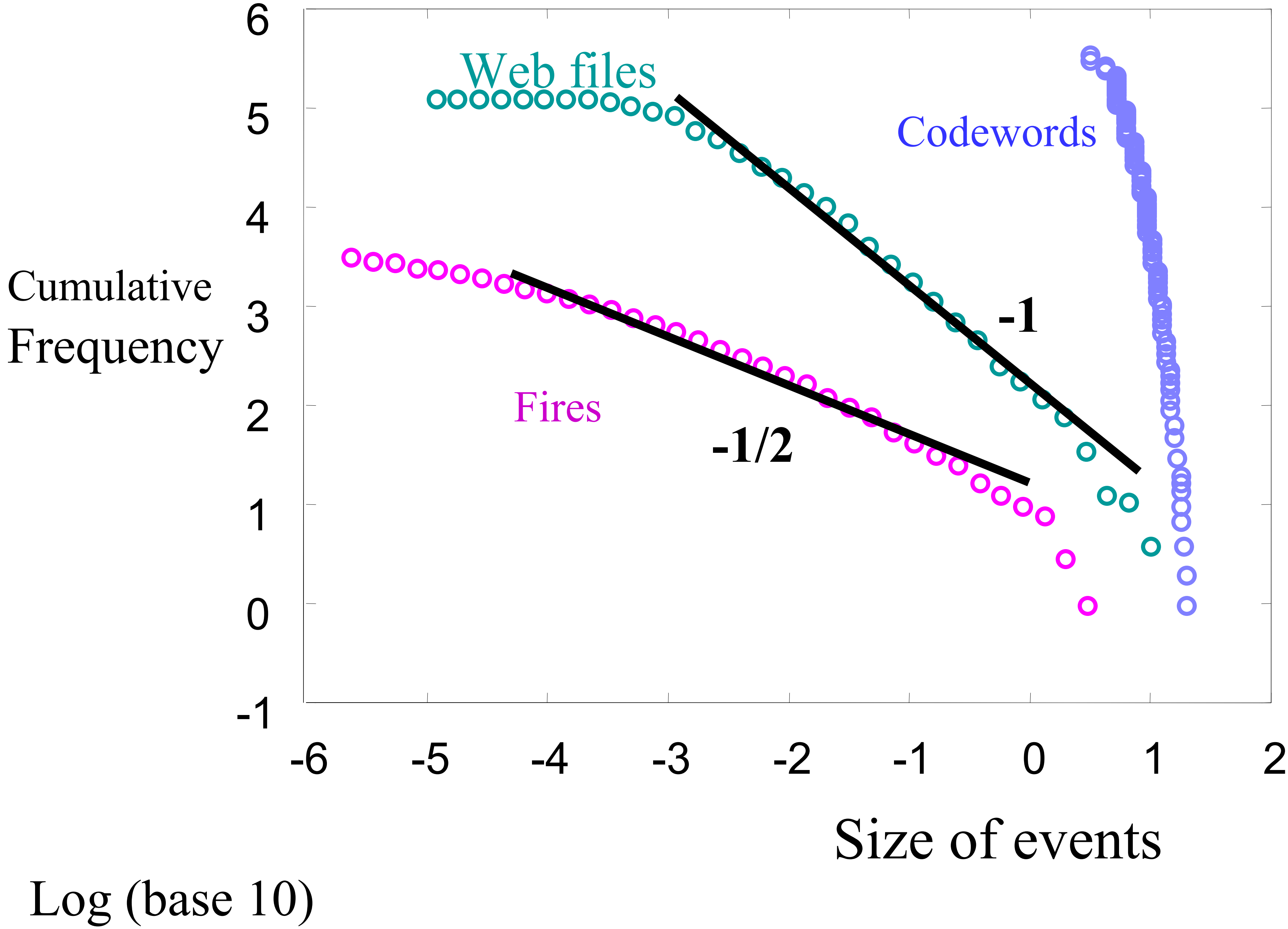


Design is clearly relevant for technological networks


Web/internet traffic
web traffic
Is streamed out
on the net.
Web
servers
Creating
internet traffic
Web
client



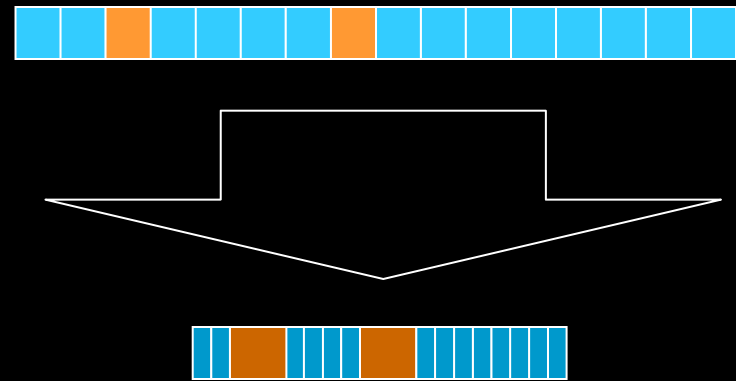
web traffic
Is streamed
out on the net.
Let's look at
some web traffic
Web
servers
Creating
internet traffic
Web
client



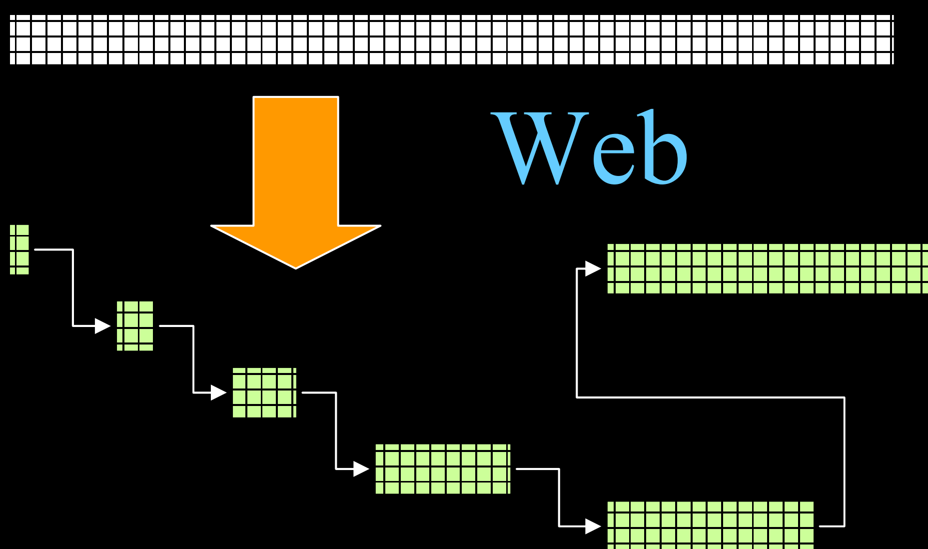
Web files
Codewords
Fires
-1
-1/2
Cumulative
Frequency
Size of events
Log (base 10)
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0
1
2

Generalized "coding" problems

Optimizing *d*-1 dimensional cuts in *d* dimensional spaces.



Data compression



PLR optimization

Minimize expected loss

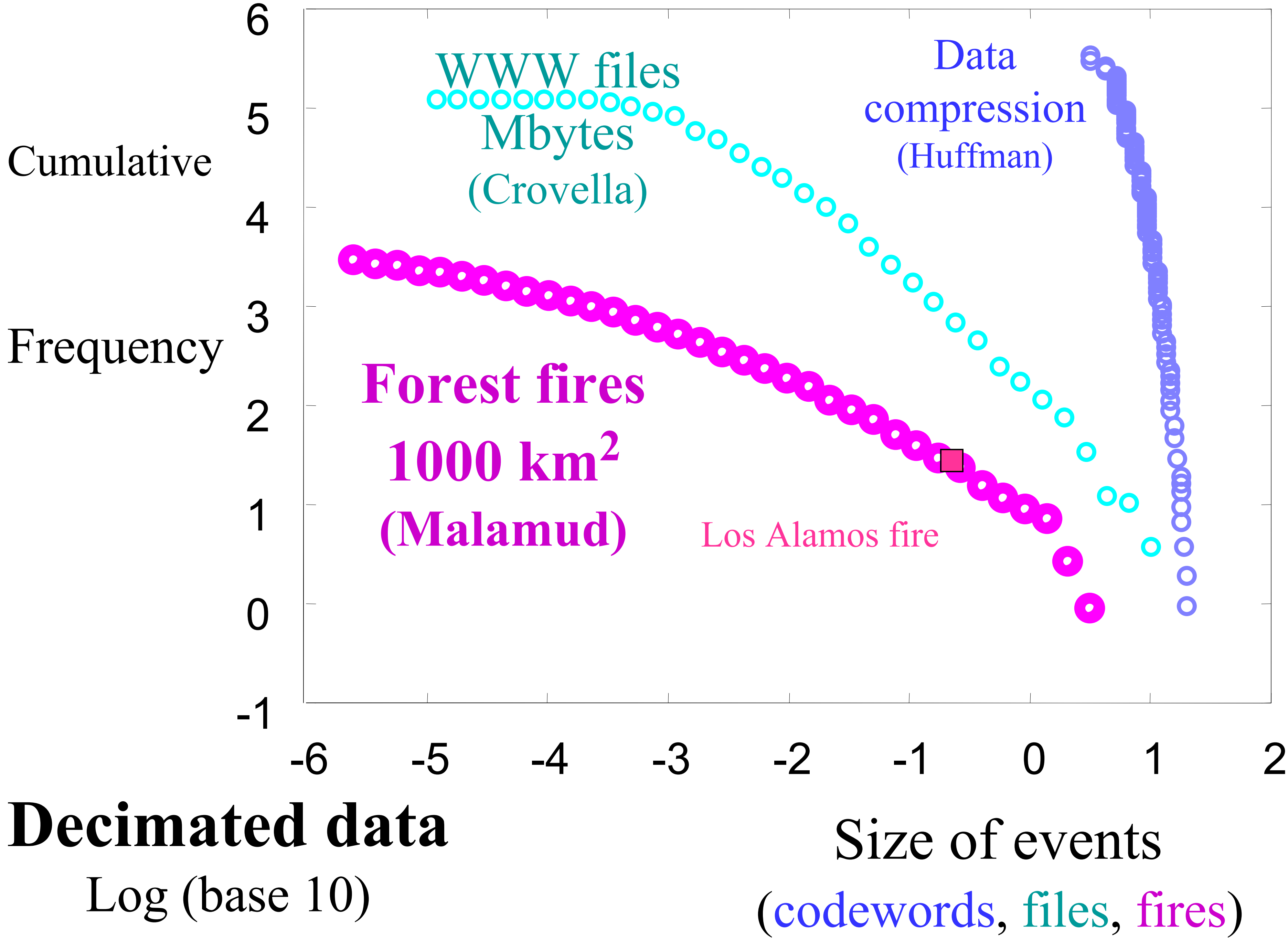
$$J = \left\{ \sum p_i l_i \;\middle|\; \sum r_i \le R \right\}$$

P: uncertain events with probabilities p_i

L: with loss l_i

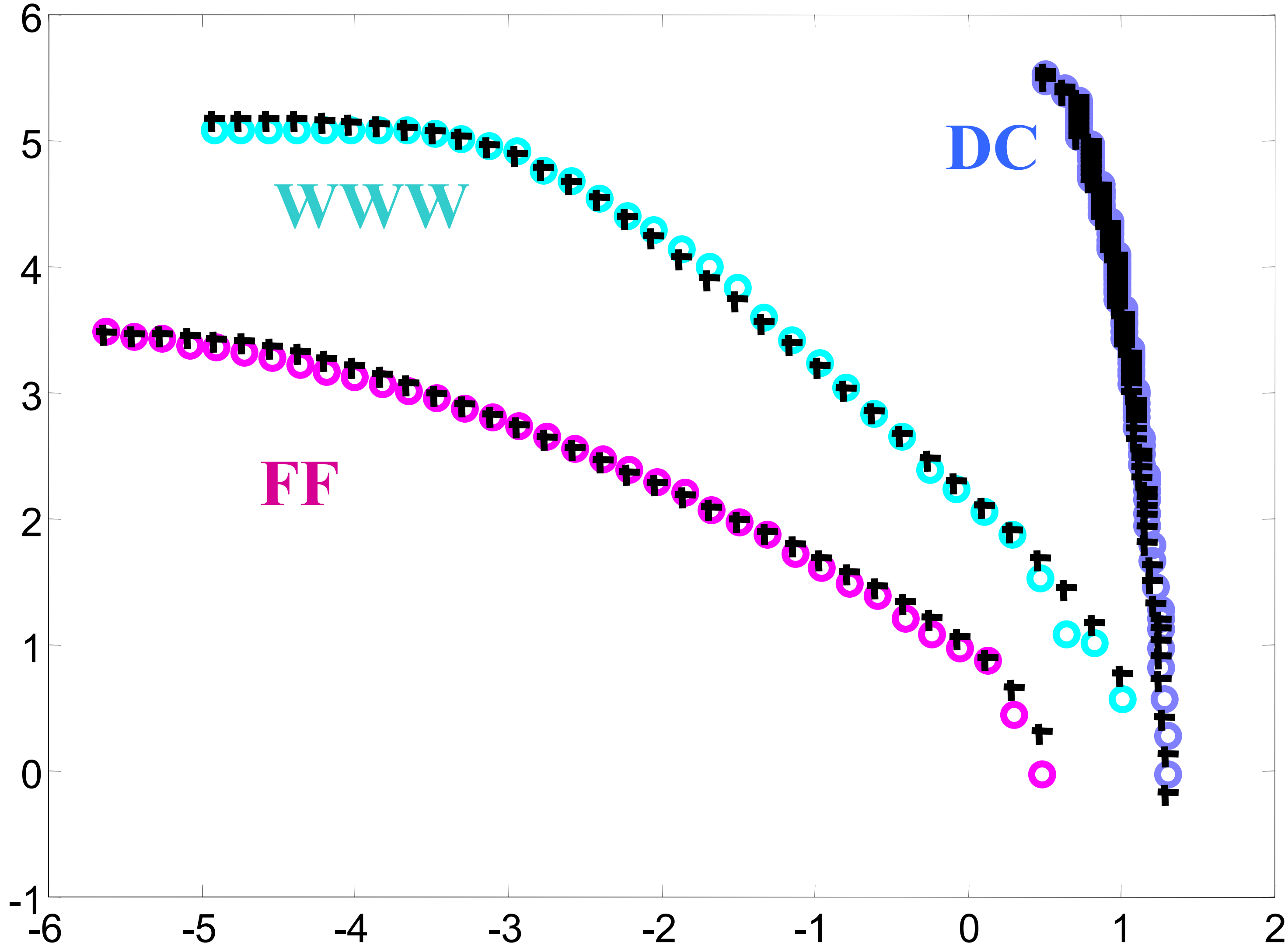
R: limited resources r_i

	P	L	R
DC	source	codewords	decodability
WWW	user access	files	web layout
FF	sparks	fires	firebreaks



Cumulative
Frequency
WWW files
Mbytes
(Crovella)
Data
compression
(Huffman)
Forest fires
1000 km2
(Malamud)
Los Alamos fire
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0
1
2
Decimated data
Log (base 10)
Size of events
(codewords, files, fires)

Data + Model



What can we learn from this simple model?

$$J = \left\{ \sum p_i l_i \;\middle|\; \sum r_i \le R \right\}$$

- P: uncertain events with probabilities p_i
- R: limited resources r_i to minimize…
- L: loss l_i due to event i

$$l(r) = \frac{c}{\beta}\left(r^{-\beta} - 1\right)$$

- Be cautious about simple theories that ignore design.
- Power laws arise easily in designed systems due to resource vs. loss tradeoffs.
- Exploiting *assumptions*, makes you sensitive to them.
- More robustness leads to sensitivities elsewhere.
- **Robust, yet fragile.**

Characteristic	Critical	HOT
Yield/density	Low	High
Robustness	Generic	Robust, yet fragile
Events/structure	Generic, fractal	Structured, modular
External behavior Internally	Complex Simple	Nominally simple Complex
Power laws	at criticality	everywhere
Details	Don't matter	Do matter

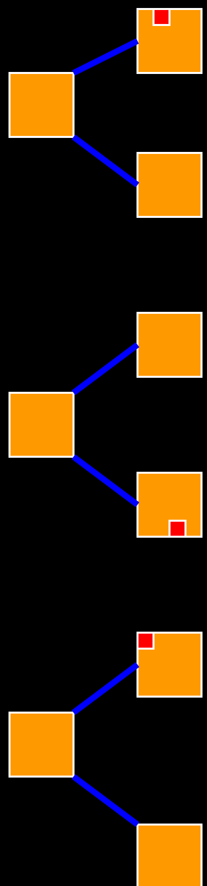
A wide range of systems share characteristic features associated with HOT. We are developing connections and detailed models for these applications.

- Power systems
- Computers
- Internet
- Software
- Ecosystems
- Extinction
- Turbulence

HOT features of ecosystems

- Organisms are constantly challenged by environmental uncertainties,
- And have evolved a diversity of mechanisms to minimize the consequences by exploiting the regularities in the uncertainty.
- The resulting specialization, modularity, structure, and redundancy leads to high densities and high throughputs,
- But increased sensitivity to novel perturbations not included in evolutionary history.
- Robust, yet fragile!
- But the role of design is subtle and controversial

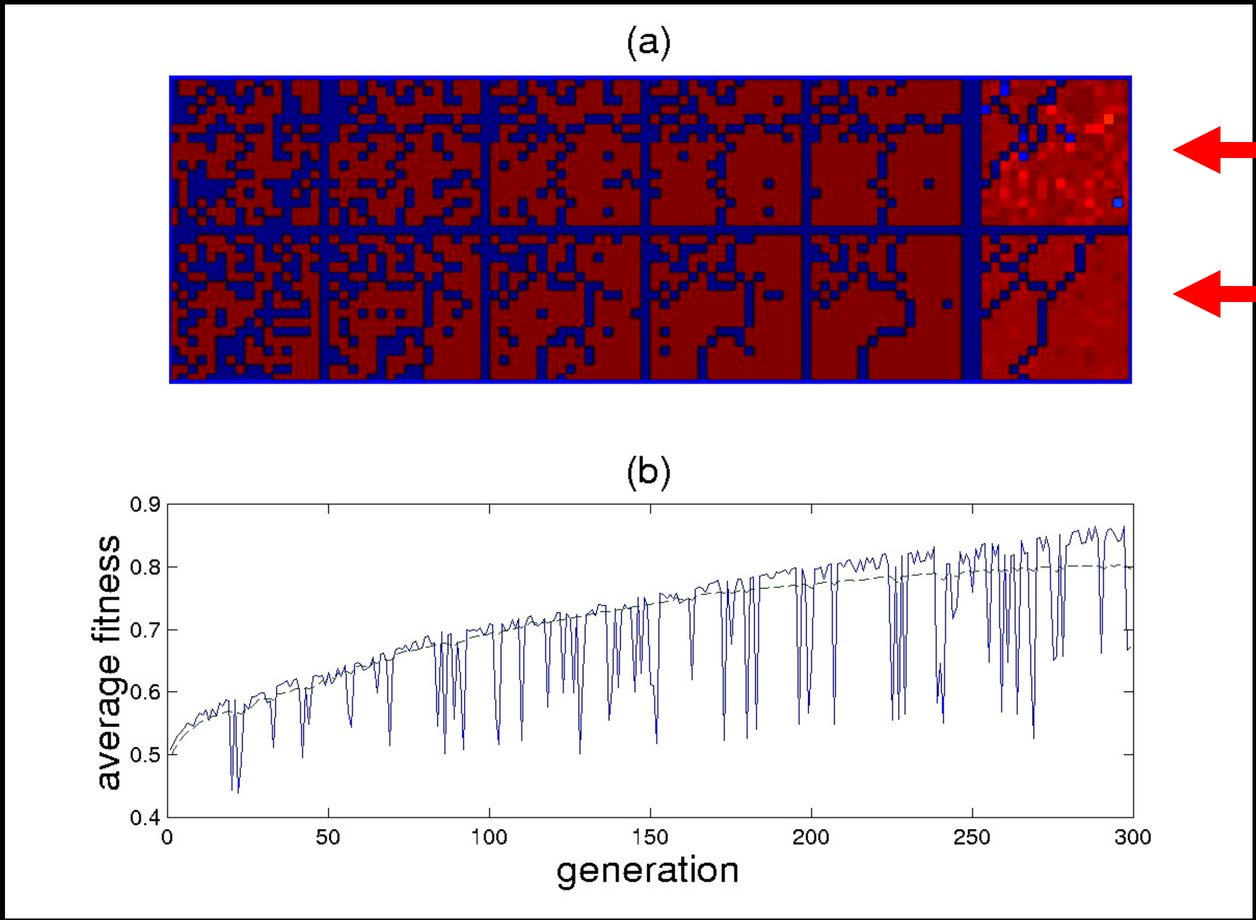
HOT and evolution : mutation and natural selection in a community



- Begin with 1000 random lattices, equally divided between tortoise and hare families
- Each parent gives rise to two offspring
- Small probability of mutation per site
- Sparks are drawn from P(i,j)
- Fitness= Yield (1 spark for hares, full P(i,j) for tortoises)
- Death if Fitness<0.4
- Natural Selection acts on remaining lattices
- Competition for space in a community of bounded size

Barriers to cascading failure: an abstraction of biological mechanisms for robustness

Tong Zhou



Fast mutators (hares)

Slow mutators (tortoises)

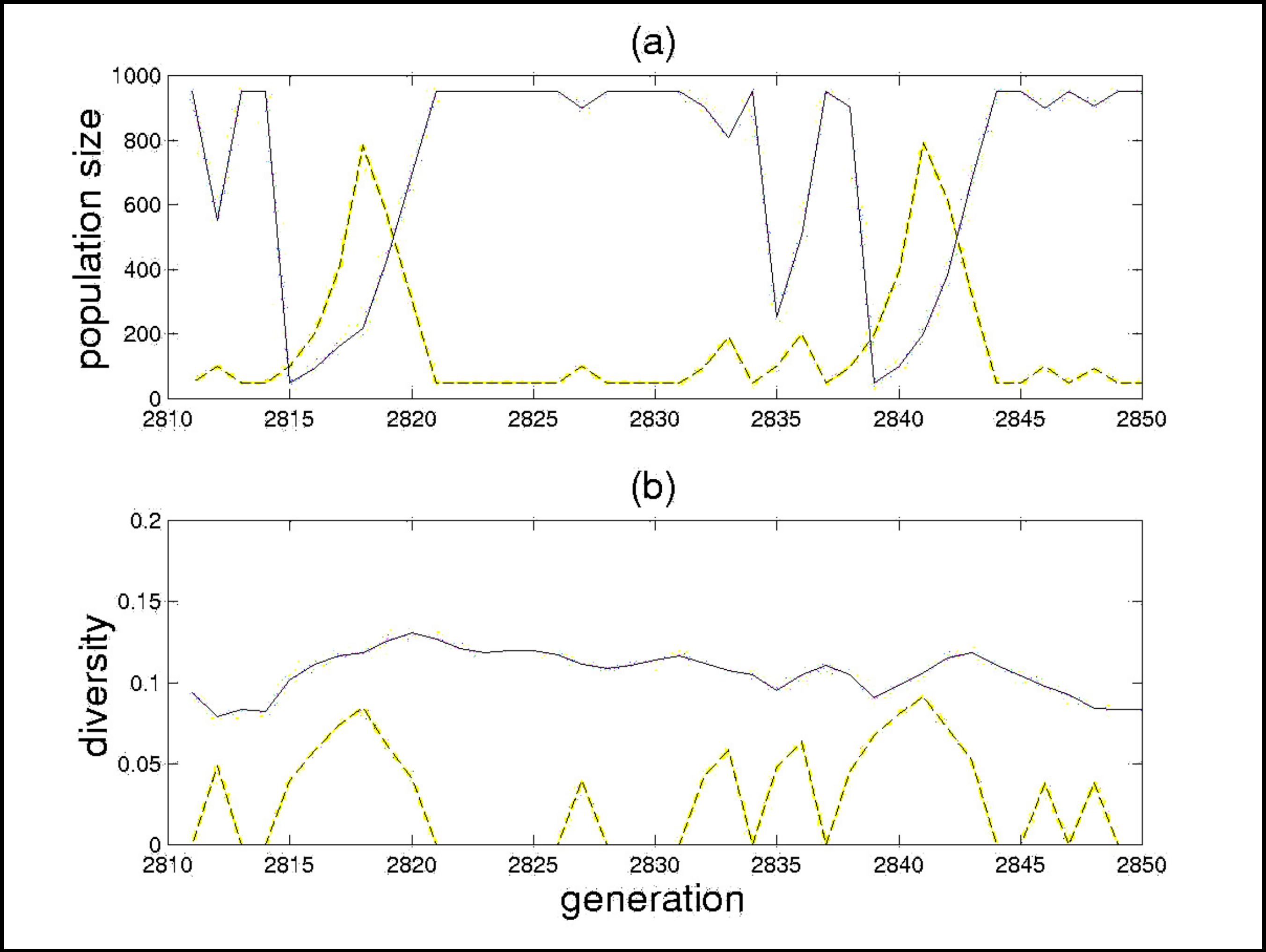
Hares:
-noisy patterns
-lack protection for rare events

Genotype (heritable traits): lattice layout

Phenotype (characteristics which can be observed in the environment): cell sizes and probabilities

Fitness (based on performance in the organisms lifetime): Yield

(Primitive) Punctuated Equilibrium:



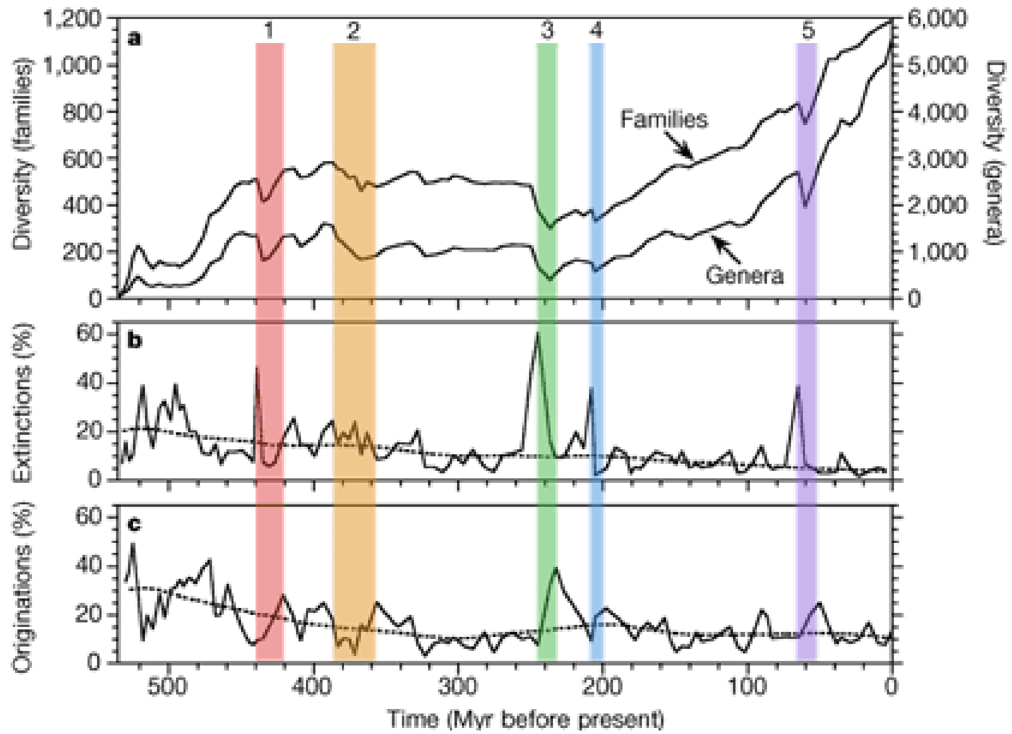
Hares win in the short run.

But face episodic extinction due to rare events (niche protects 50).

Tortoises take over, and diversity increases.

Until hares win again.

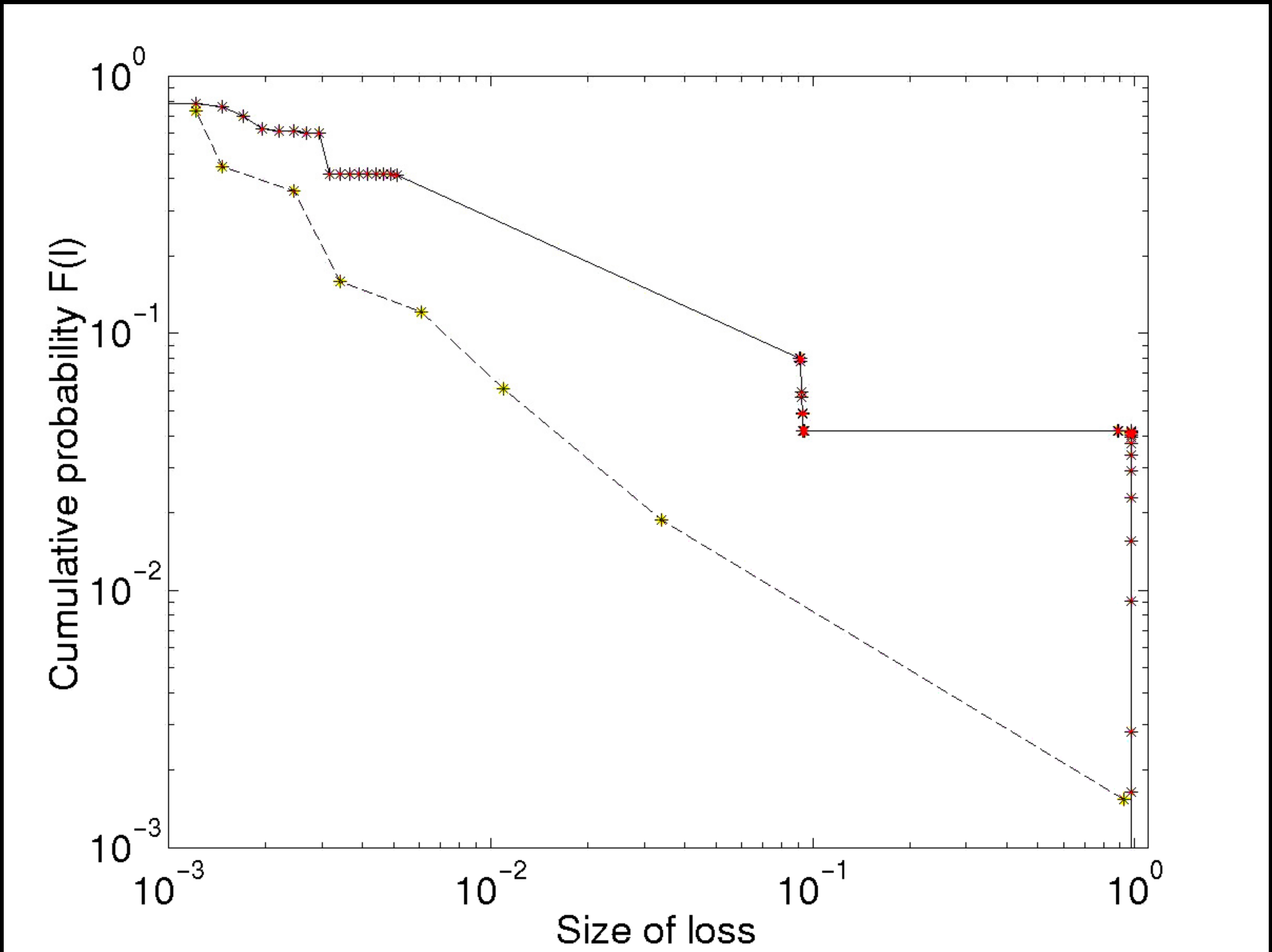
hares tortoises



The fossil record of marine animal biodiversity. Standing diversity of genera and families through the Phanerozoic (a), and corresponding percentages of extinction (b) and origination (c) of genera in each stratigraphic interval. Shaded bands highlight recovery intervals (between extinction rate peaks and subsequent origination rate peaks) for the 'Big Five' mass extinctions: end-Ordovician (1), late Devonian (2), end-Permian (3), end-Triassic (4) and Cretaceous–Tertiary (5). Dotted lines in b and c show the long-term trends (estimated using LOWESS, a robust curve-fitting technique19) that are subtracted from extinction and origination time series before calculating cross-correlations.

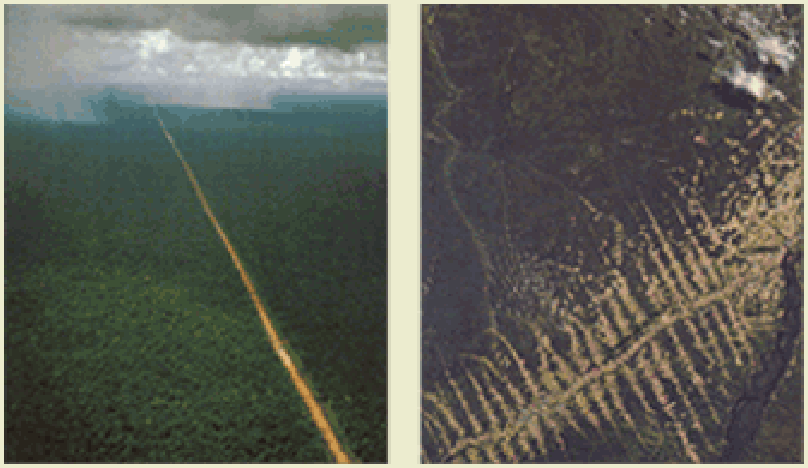
Large extinction events are typically followed by increased diversity. The recovery period is the time lapse between the peak extinction rate, and the maximum rate of origination of new species.

Our analogy: extinction of the hares is are followed by diversification of both families

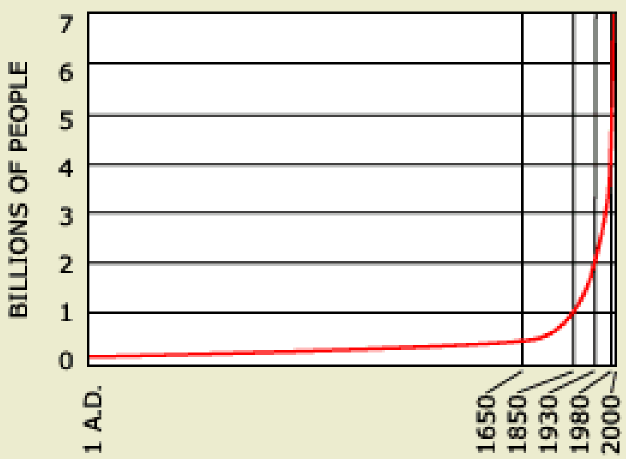


Tortoise population exhibits power laws
Hares have excess large events

The current mass extinction is frequently attributed to overpopulation and causes which can be attributed to humans, such as deforestation



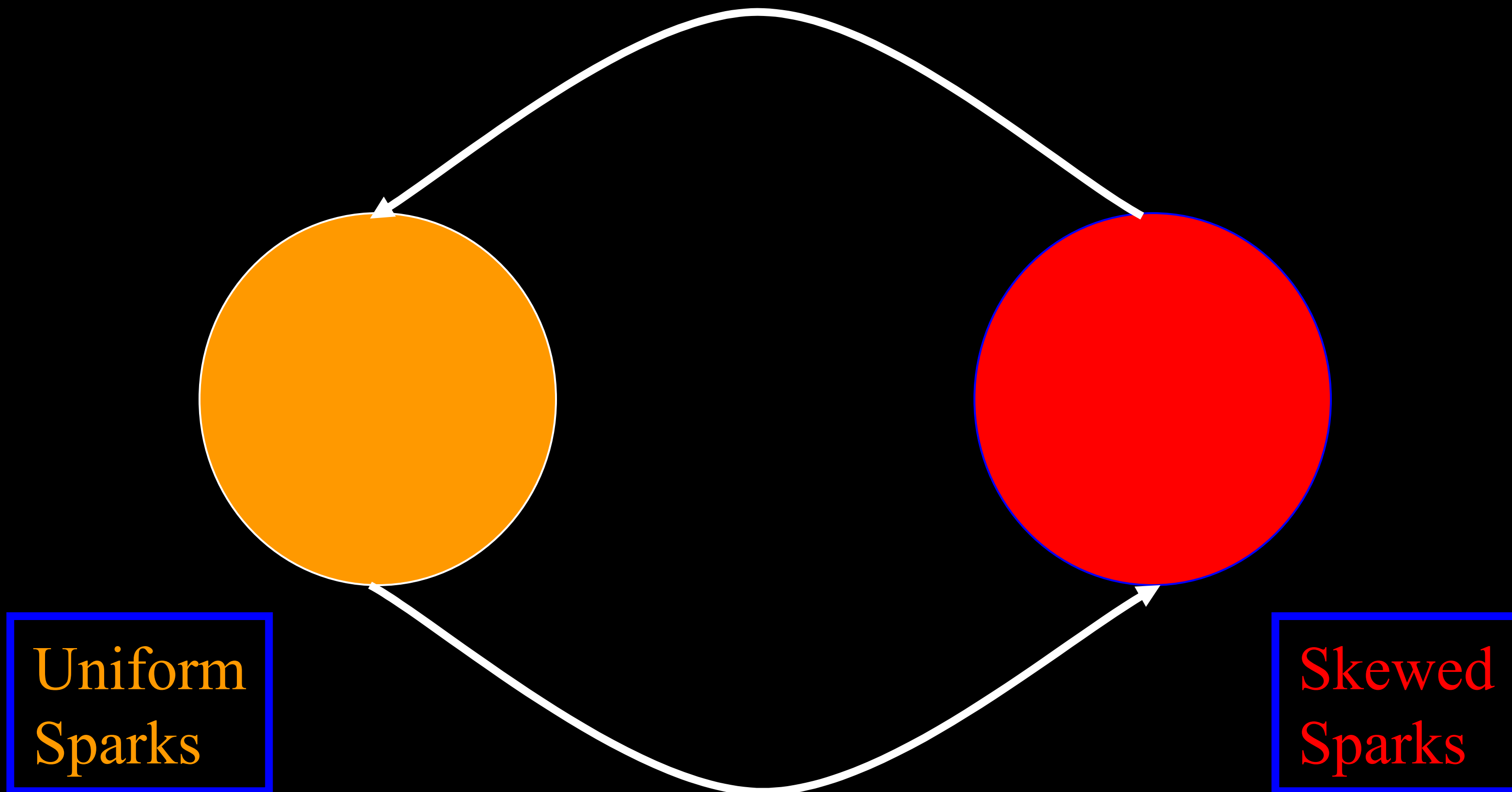
(*Left*) Shortly after construction was completed, the Transamazonian highway near Altimira, Brazil, stretches through virgin forest. (*Right*) A satellite view of the same area a few years later reveals an advancing wave of deforestation. Lots are parceled out to farmers along perpendicular access roads.



Our analogy: large events can be due to rare disturbances, especially If they are not not part of the evolutionary history of the (vulnerable) species.

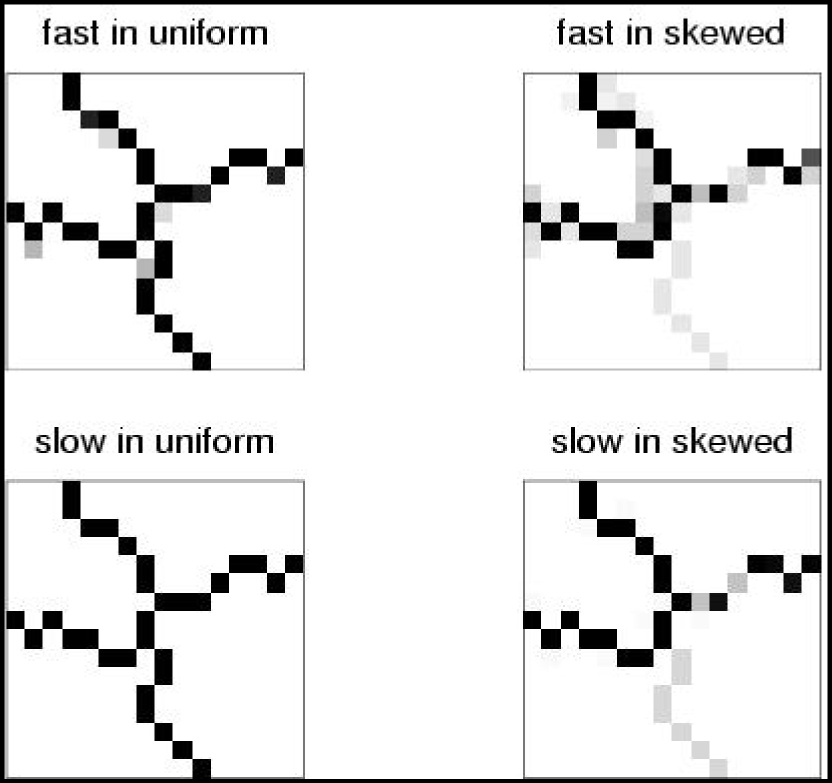
Robust, yet Fragile!

Evolution by Natural Selection in Coupled communities with different environments:



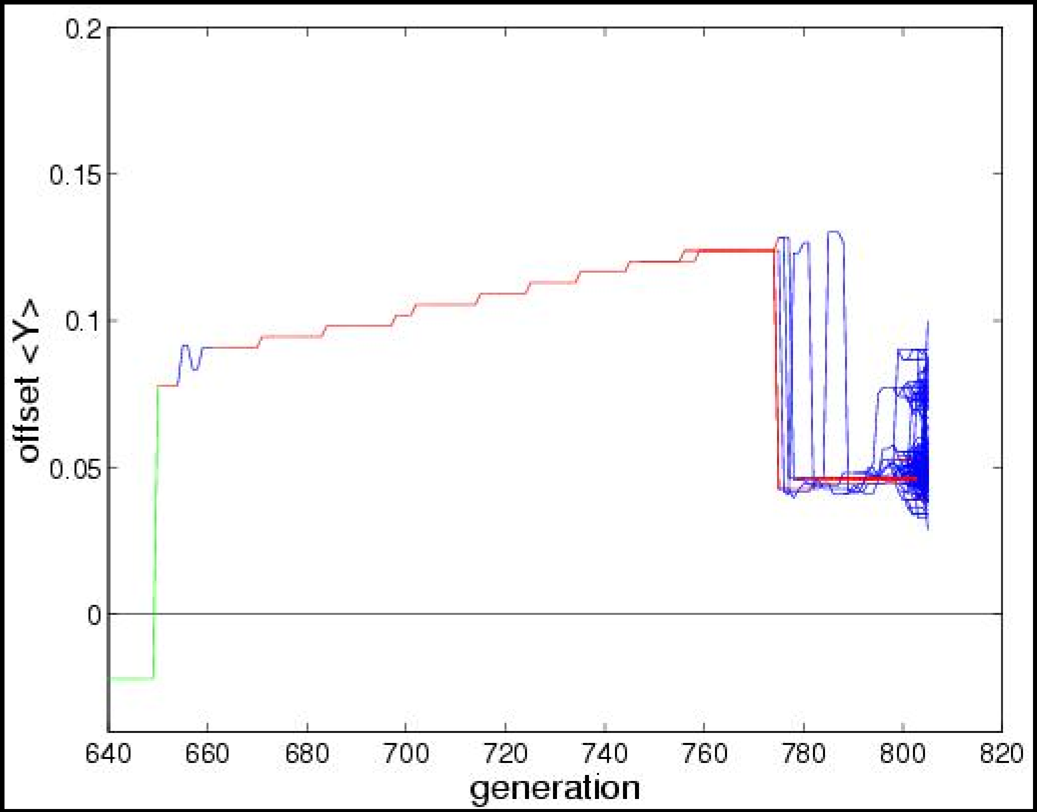
Fitness based on a single spark.
Eliminate protective niches.
Fixed maximum capacity for each habitat.
Fast and slow mutation rates (rate subject to mutation).

Coupled Habitats: Fast and slow mutators compete with each other in each habitat, with a small chance of migration from one habitat to the other.



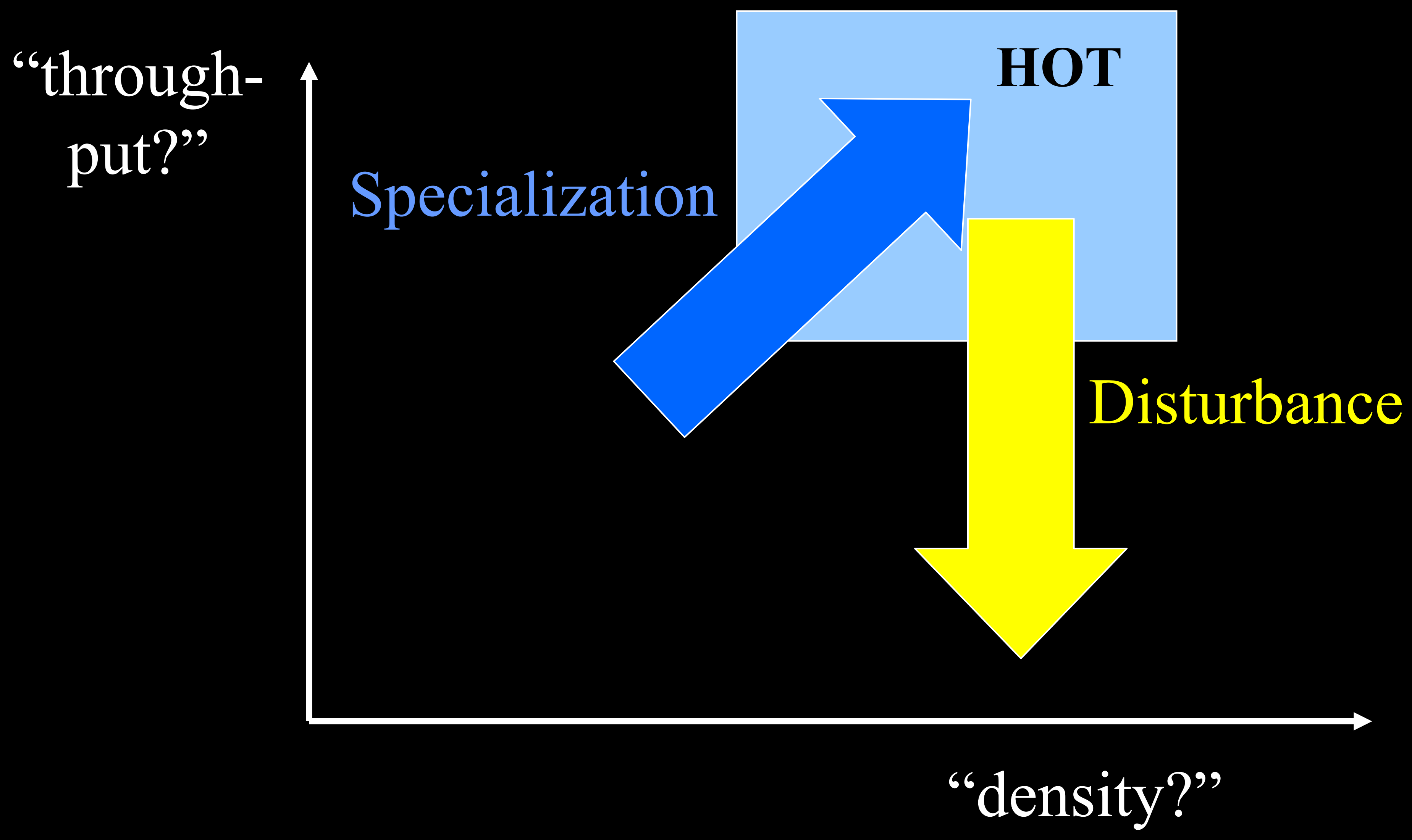
Efficient barrier patterns develop in the uniform habitat. After An extinction in the skewed habitat, uniform lattices invade, and Subsequently lose their lower right barriers: a successful strategy In the short term, but leads to vulnerability on longer time scales

Patterns of extinction, invasion, evolution



Over an extended time window, spanning the two previous extinctions, we see the long term fitness <Y> initially increases as the invading lattices adapt to their new environment. This is followed by a sudden decline when the lattices lose a barrier. This adaptation is beneficial for common events, but fatal for rare events.

Evolution and extinction



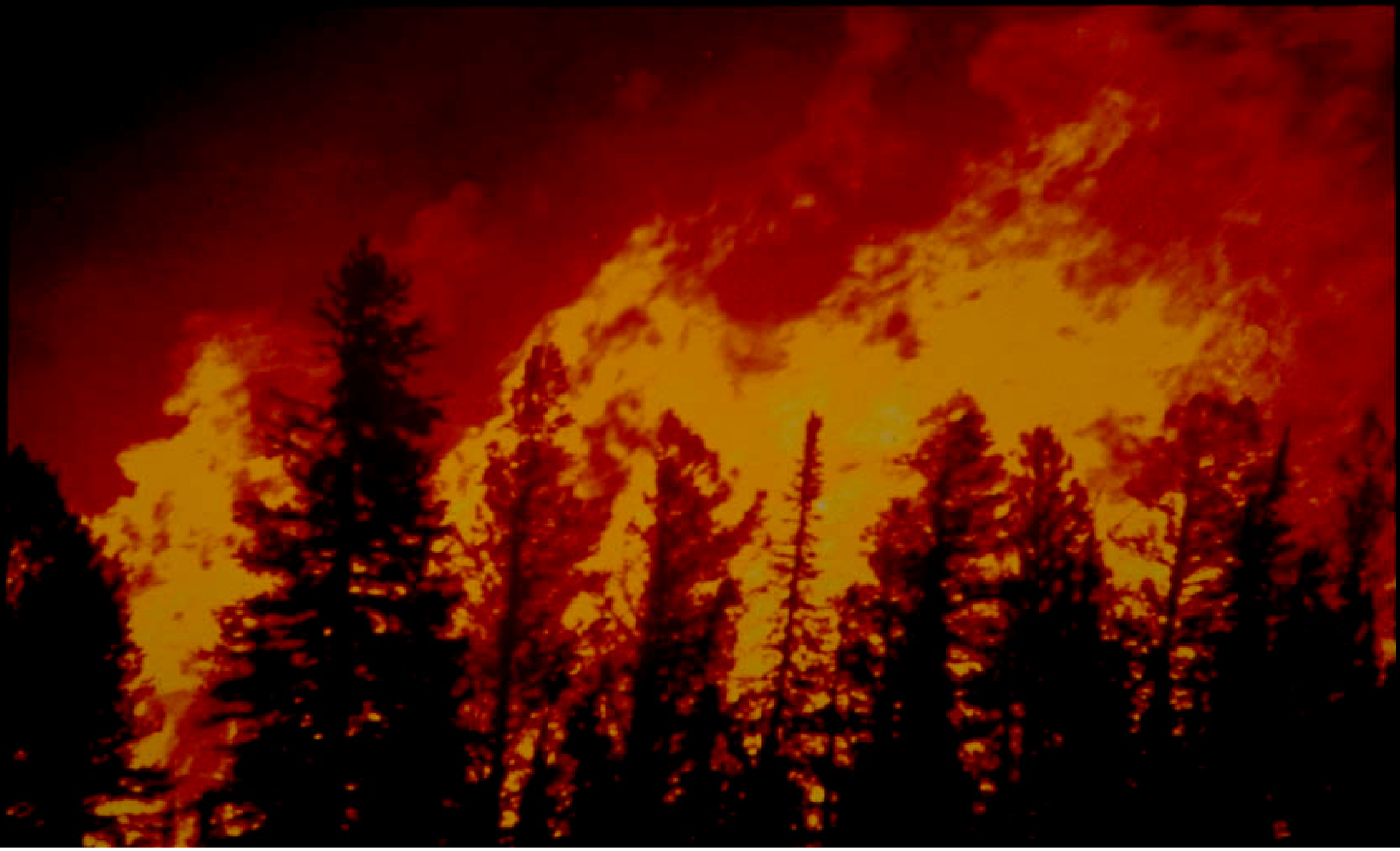
HOT and Evolution

- Robustness in an uncertain environment provides a mechanism which leads to a variety of phenomena consistent with observations in the fossil record (large extinctions associated with rare disturbance, punctuated equilibrium, genotypic divergence, phenotypic convergence).

- In a model which retains abstract notions of genotype, phenotype, and fitness, highly evolved lattices develop efficient barriers to cascading failure, similar to those obtained by deliberate design.

- Robustness barriers are central in natural and man made complex systems. They may be physical (skin) or in the state space (immune system) of a complex, interconnected system.

- Forest Fires: a case where a common disturbance type (fires)
- Acts over a broad range of scales (terrestrial ecosystems)
- Power law statistics describing the distribution of fire sizes.
- Exponents are consistent with the simplest low resolution HOT model involving optimal allocation of resources (suppress fires).
- Evolution and ecological sorting lead to organization.



Are Forest Fires HOT?

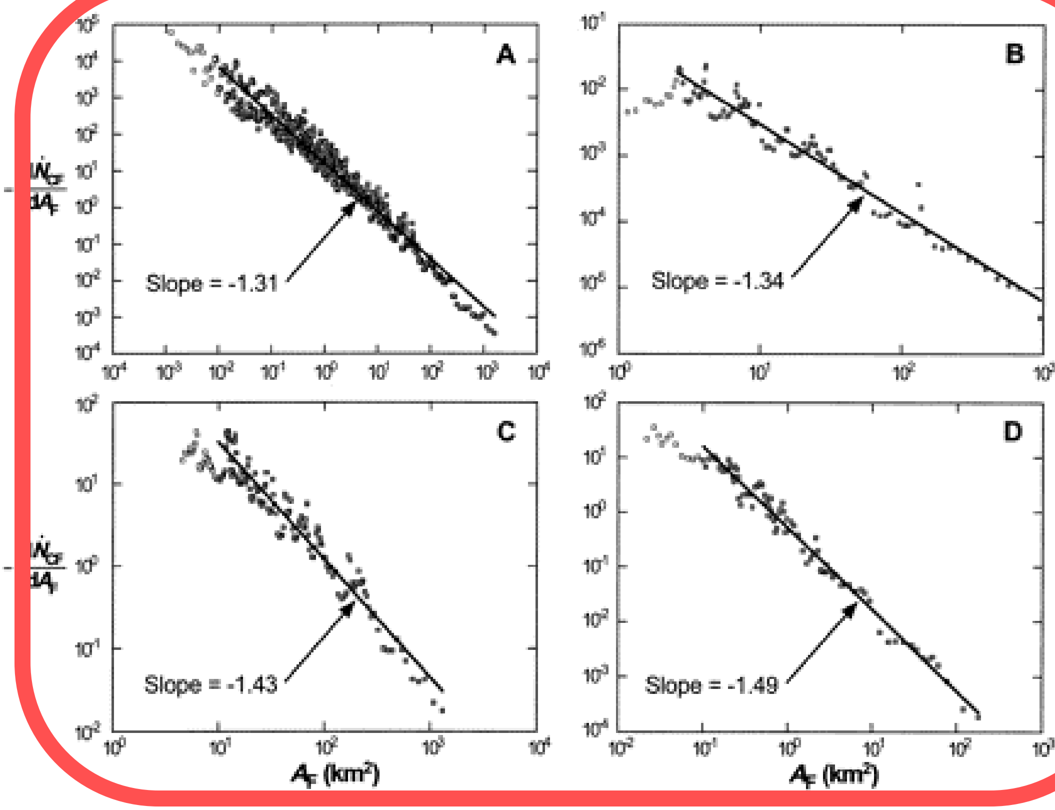
Jean Carlson,
Max Moritz,
John Doyle,
Marco Morias,
Lora Summerell

Science MAGAZINE

18 Sep 1998

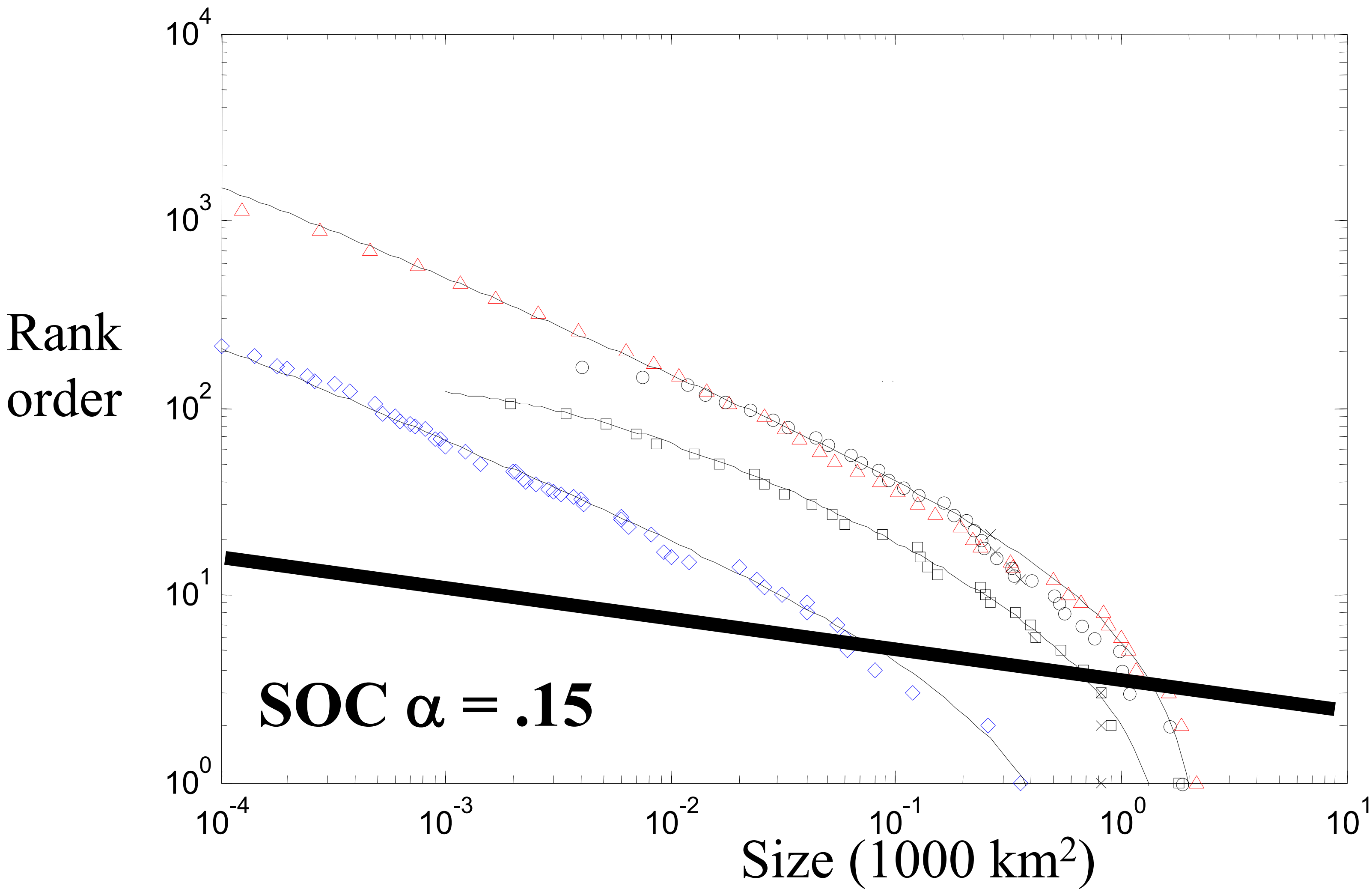
Forest Fires: An Example of Self-Organized Critical Behavior

Bruce D. Malamud, Gleb Morein, Donald L. Turcotte

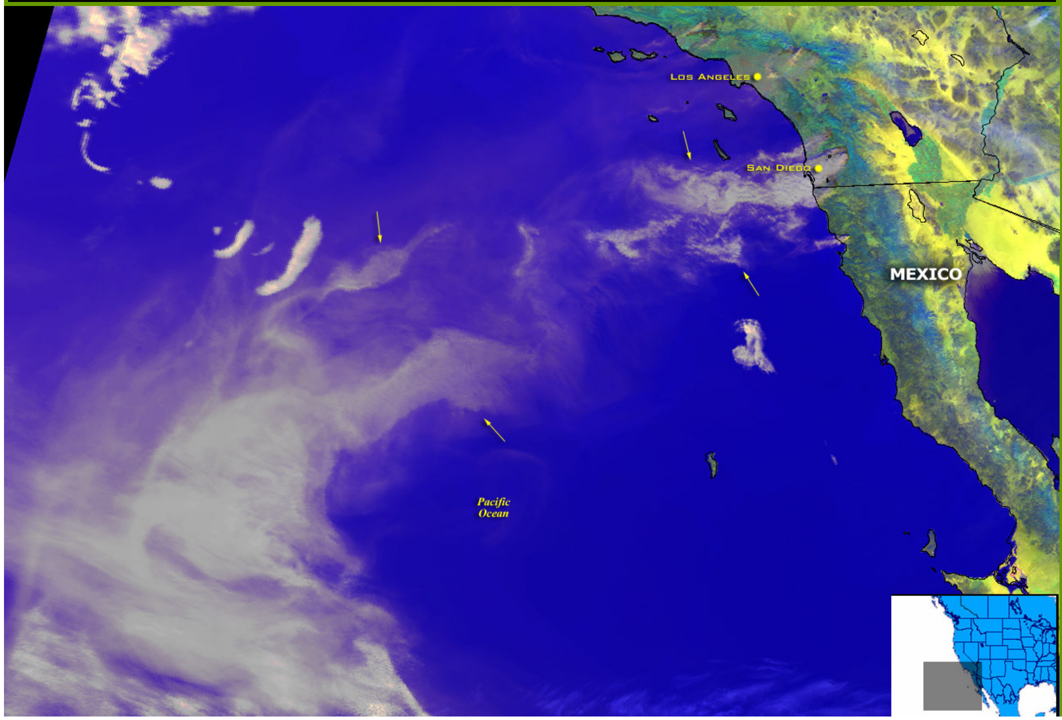


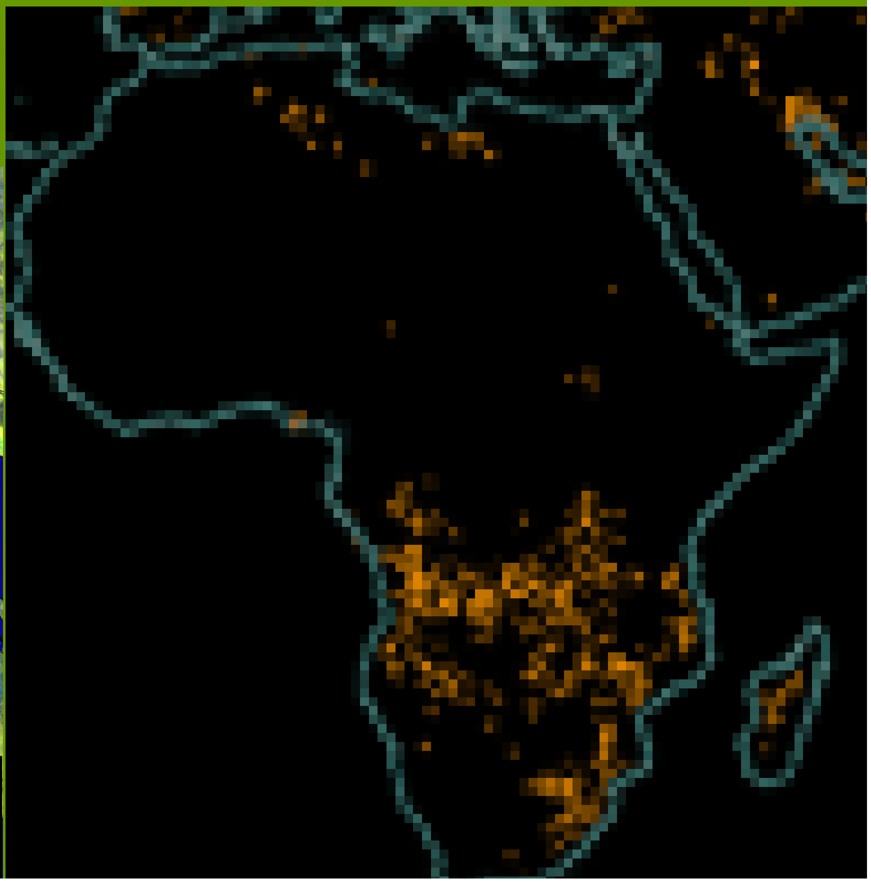
4 data sets

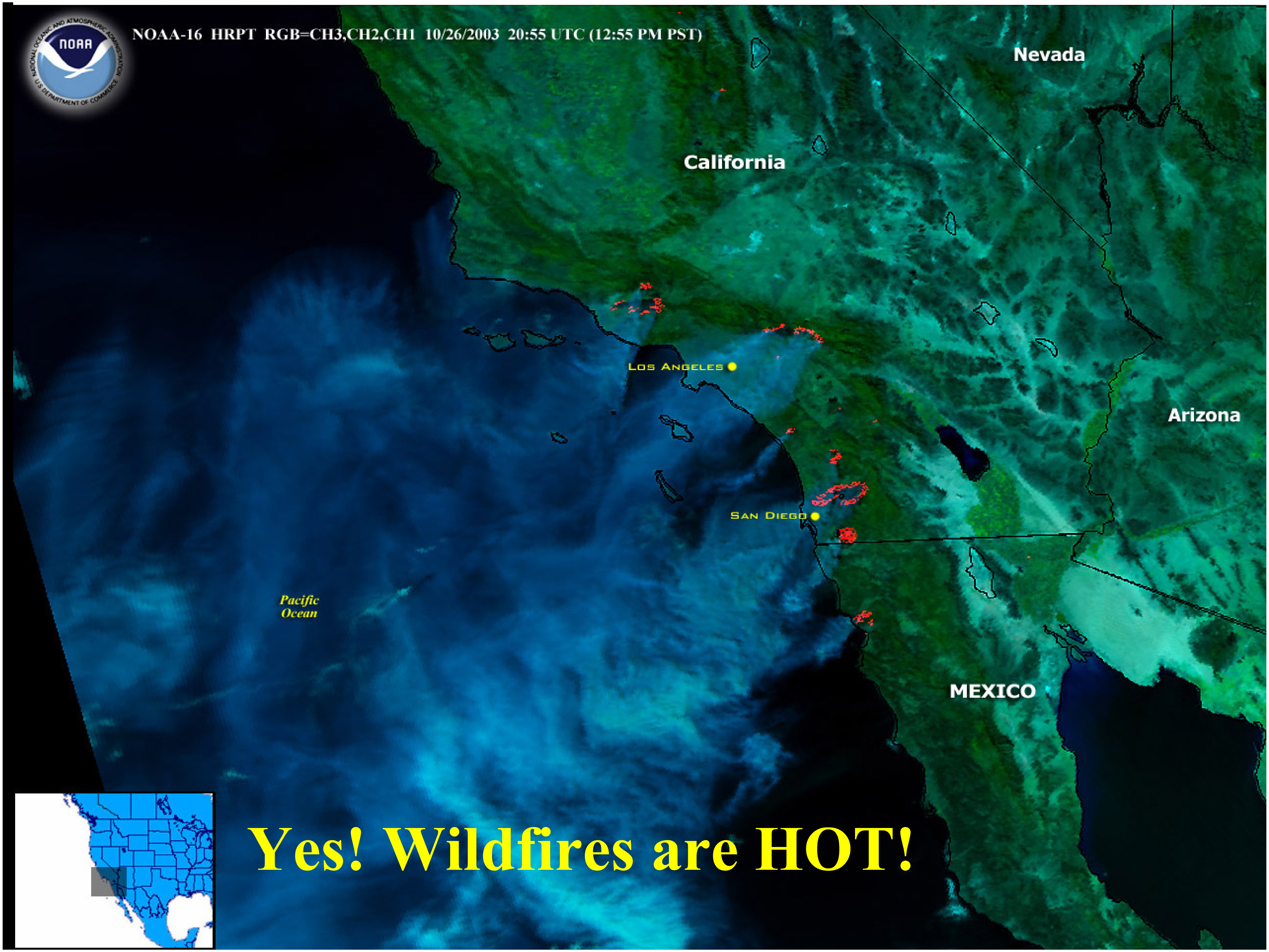
All four data sets are fit the PLR HOT model with α=1/2 and not the SOC forest fire model.



~~Self-si larity?~~



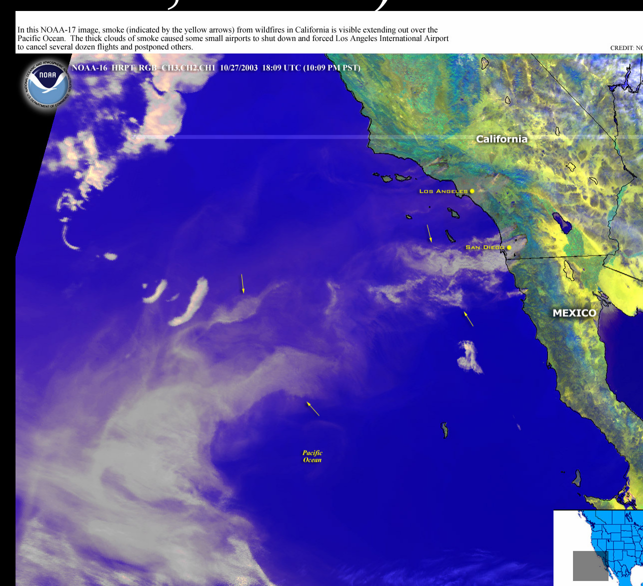



NOAA-16 HRPT RGB=CH3,CH2,CH1 10/26/2003 20:55 UTC (12:55 PM PST)
NOAA
Nevada
California
Arizona
Los Angeles
San Diego
MEXICO
Pacific Ocean
Yes! Wildfires are HOT!

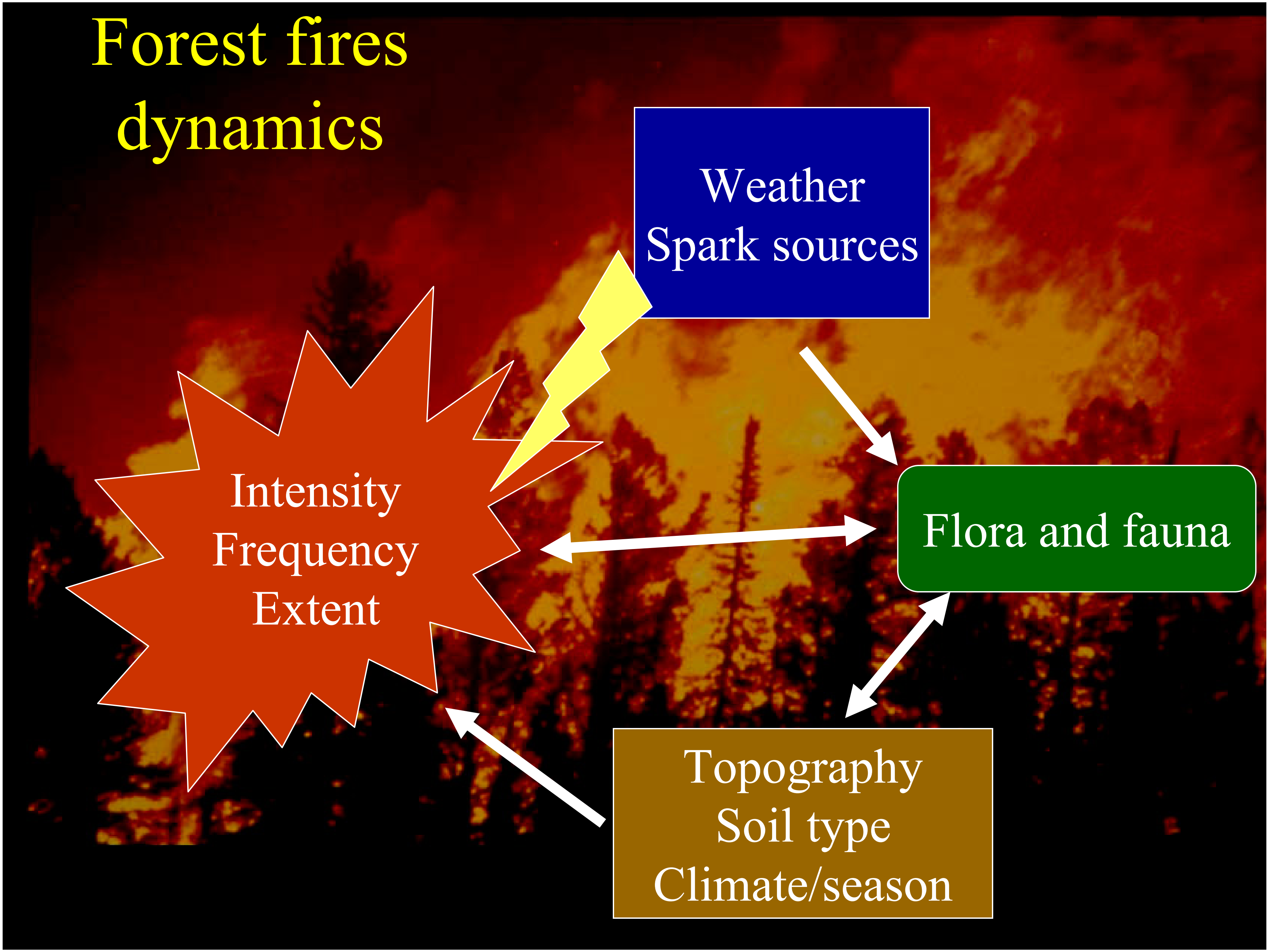
Hazard Factors:

Terrain (slope, aspect, roads, rivers)

Fuel conditions (type, density, age, moisture)



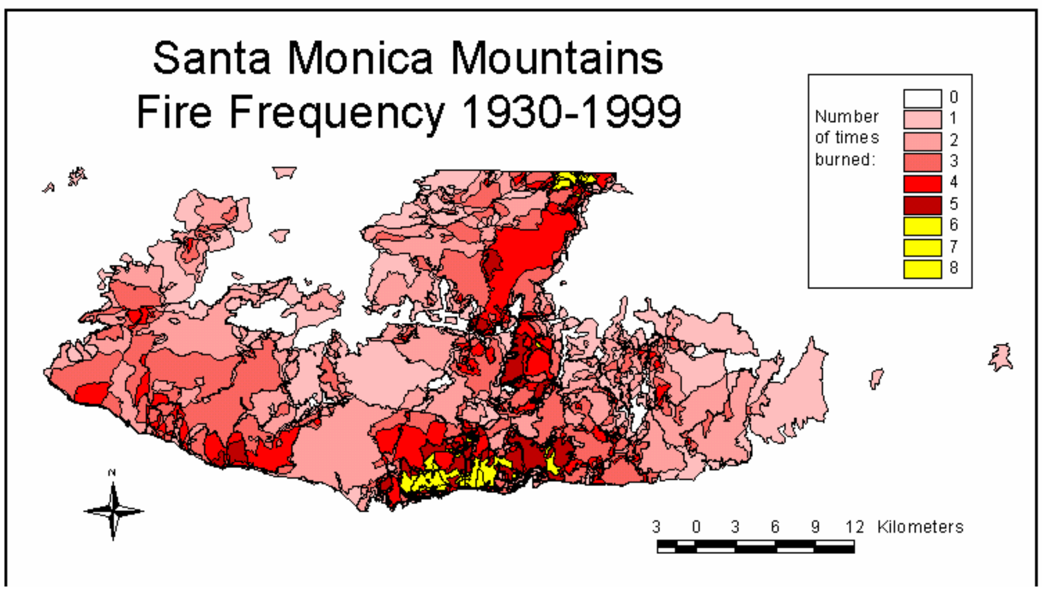
Weather (winds, temperature, humidity)

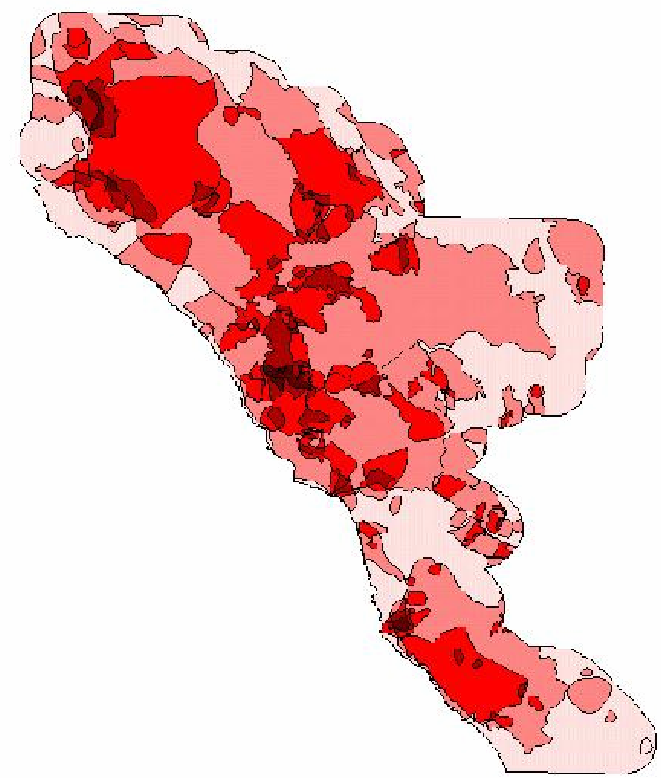

Forest fires
dynamics
Weather
Spark sources
Intensity
Frequency
Extent
Flora and fauna
Topography
Soil type
Climate/season

HFire: Detailed "designed" model

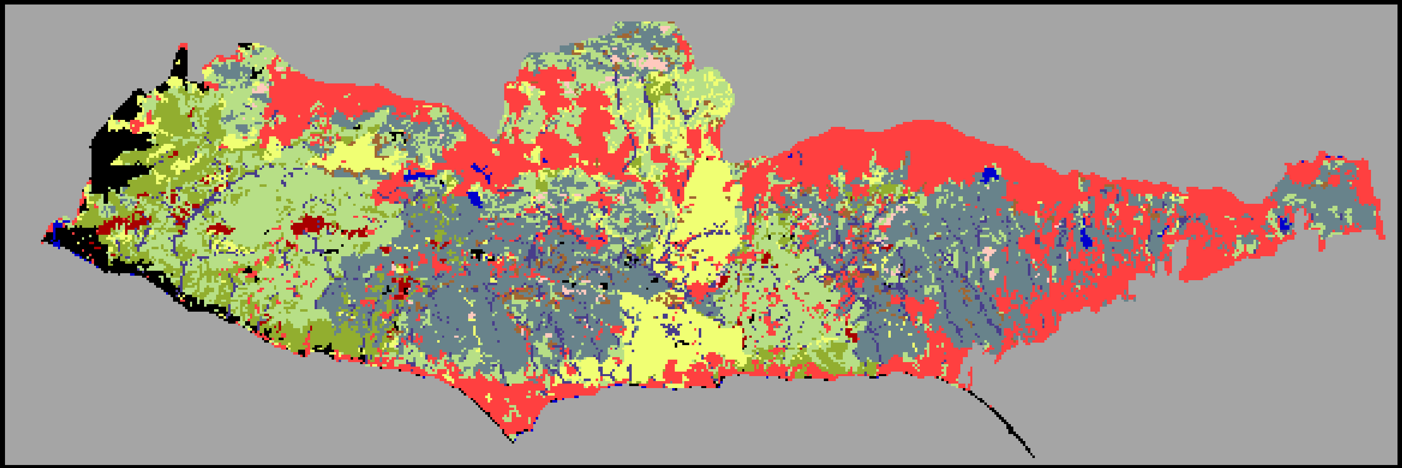
Focus on California Fires, with mapped perimeters and similar, well characterized, vegetation, relatively frequent fire return intervals.

Los Padres National Forest,
And Santa Monica Mountains National Recreation Area

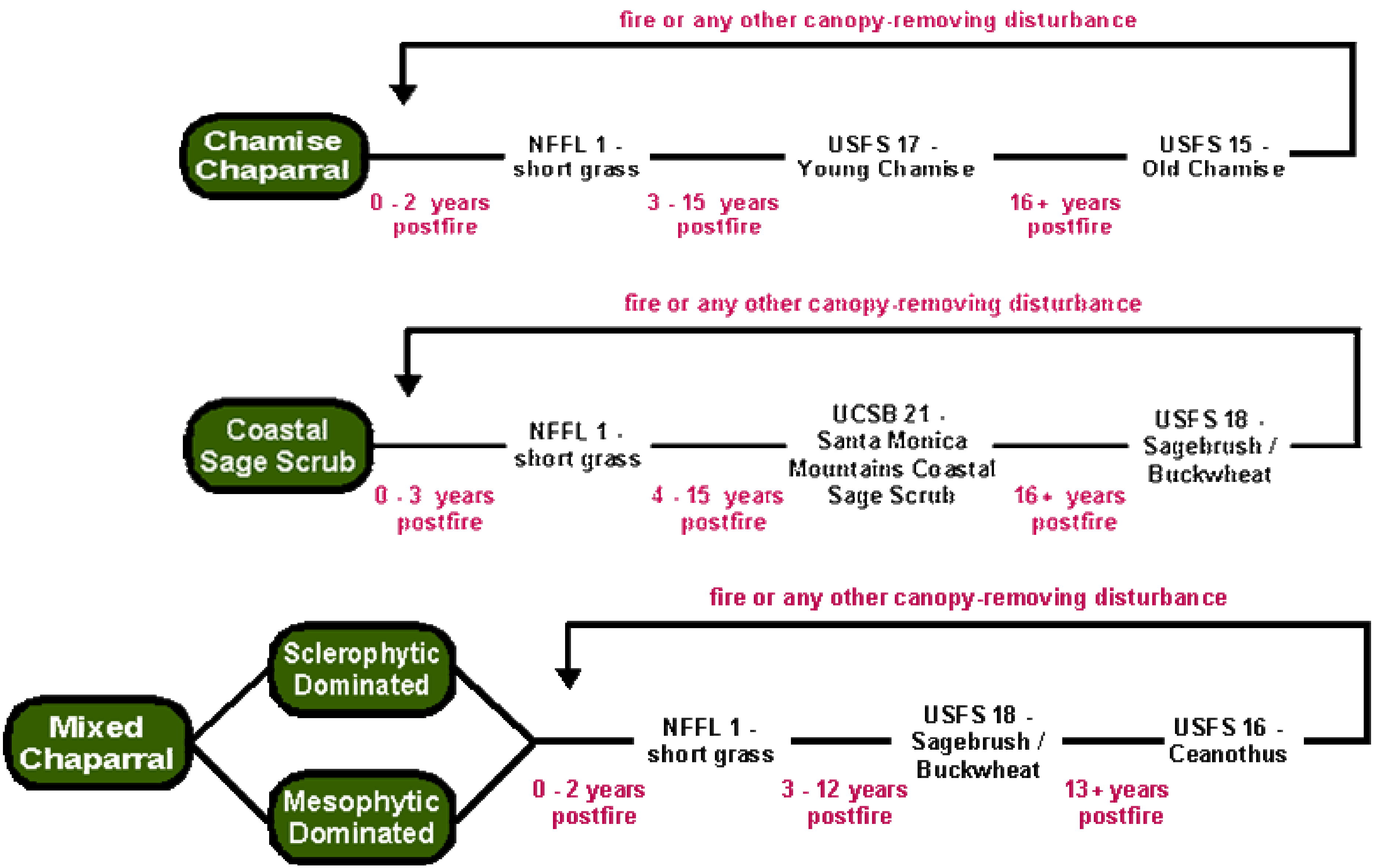




GIS data for landscape images



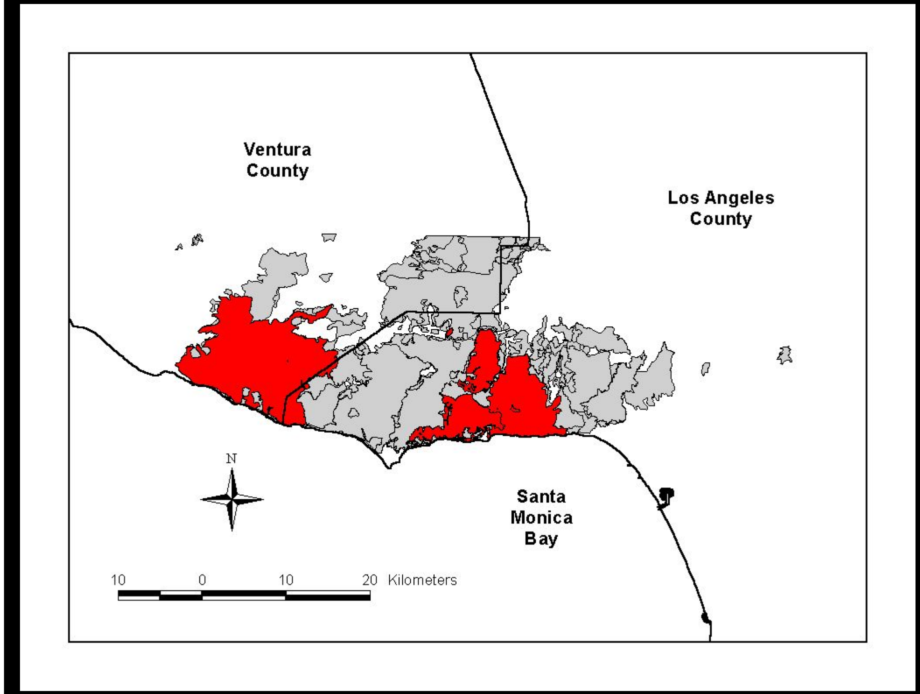
Regrowth modeled by vegetation succession models

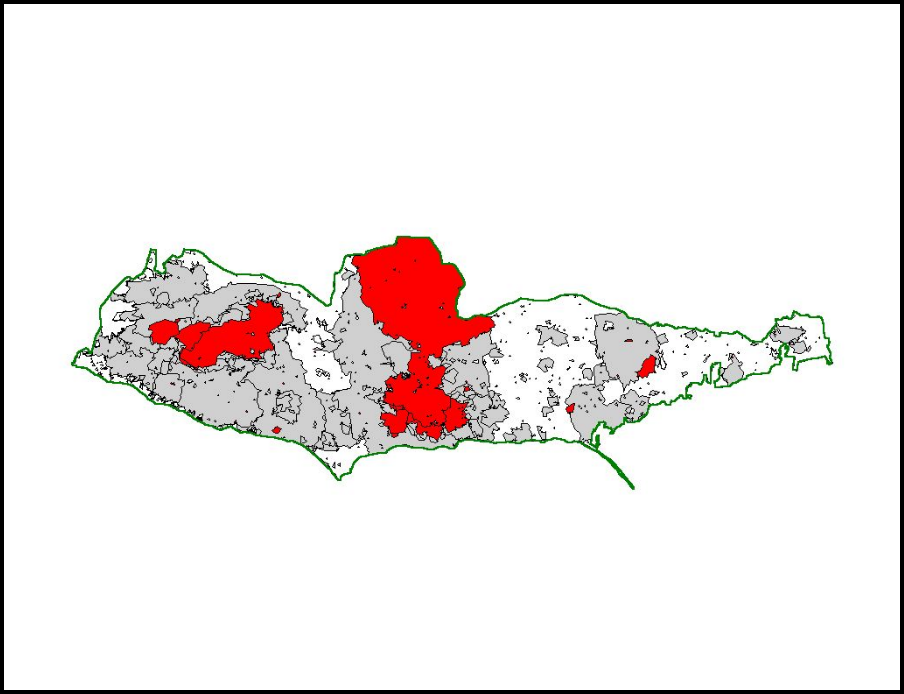


Results from the HFire simulations with suppression
(2 Santa Anas per year)

(we have generated many 600 year catalogs varying both extreme weather and suppression)

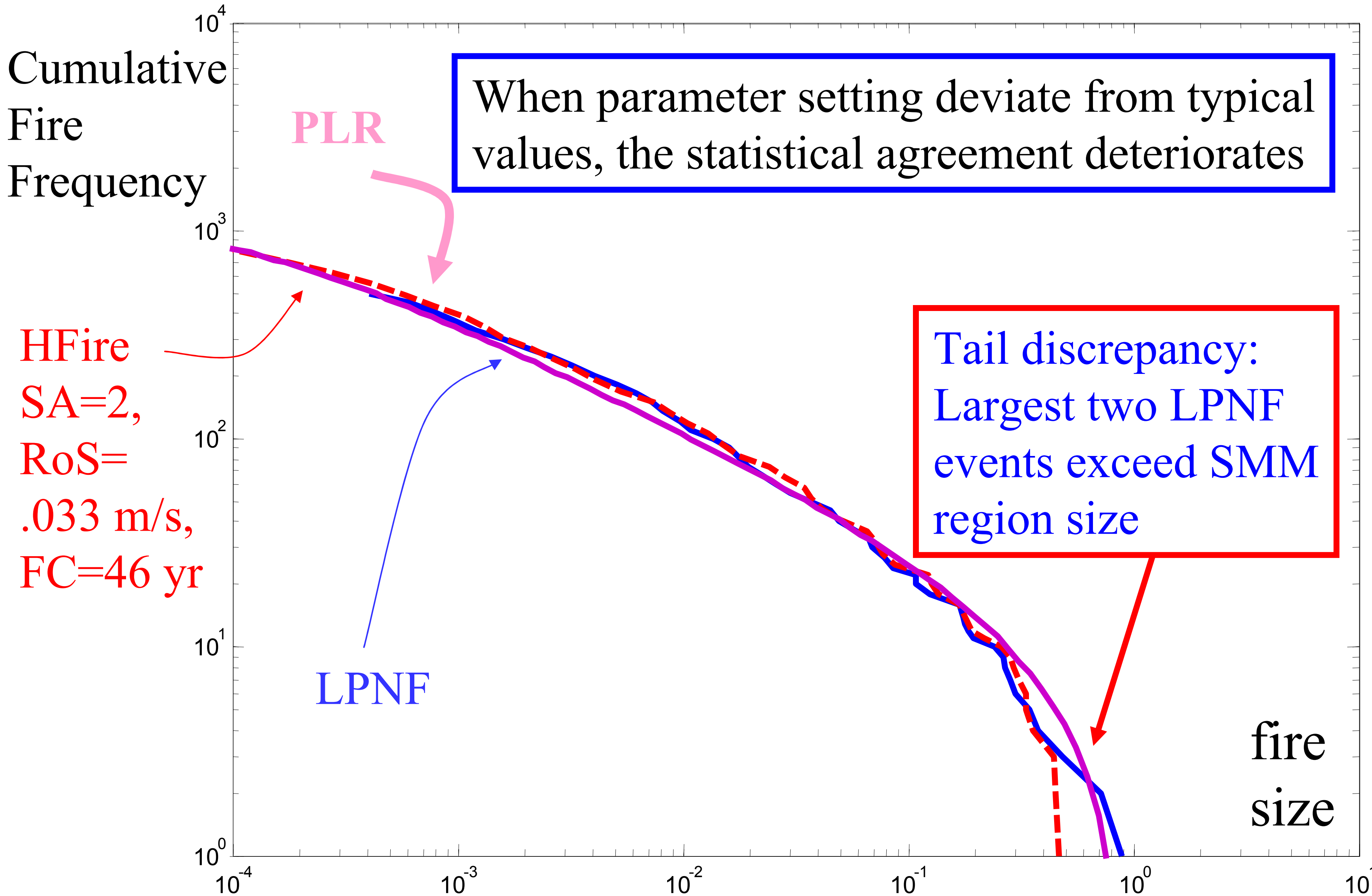
Fire scar shapes are compact





Data: typical five year period

HFire simulations: typical five year period



Excellent agreement between HFire, LPNF, and the PLR HOT model over a range of reasonable HFire parameter settings

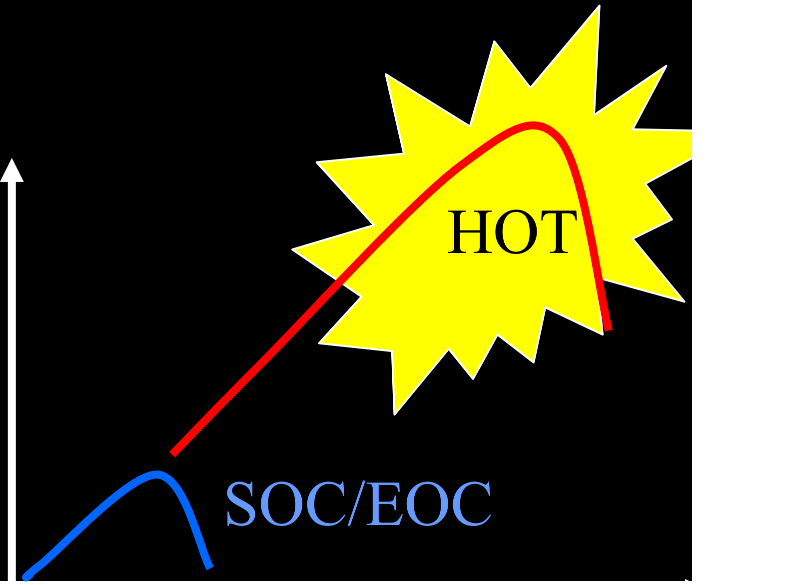
SOC and HOT are ***extremely*** different.

	SOC	**HOT & Data**
Max event size	Infinitesimal	**Large**
Large event shape	Fractal	**Compact**
Slope α	Small	**Large**
Dimension d	$\alpha \propto d-1$	$\boldsymbol{\alpha \propto 1/d}$

What's at stake?

If ecosystems are:

- EOC/SOC: Specie extinction, global warming, etc. are random fluctuations. Not to worry, nothing to do. Details don't matter.
- HOT: Robust, but fragile. Worry! Do something! Details do matter.

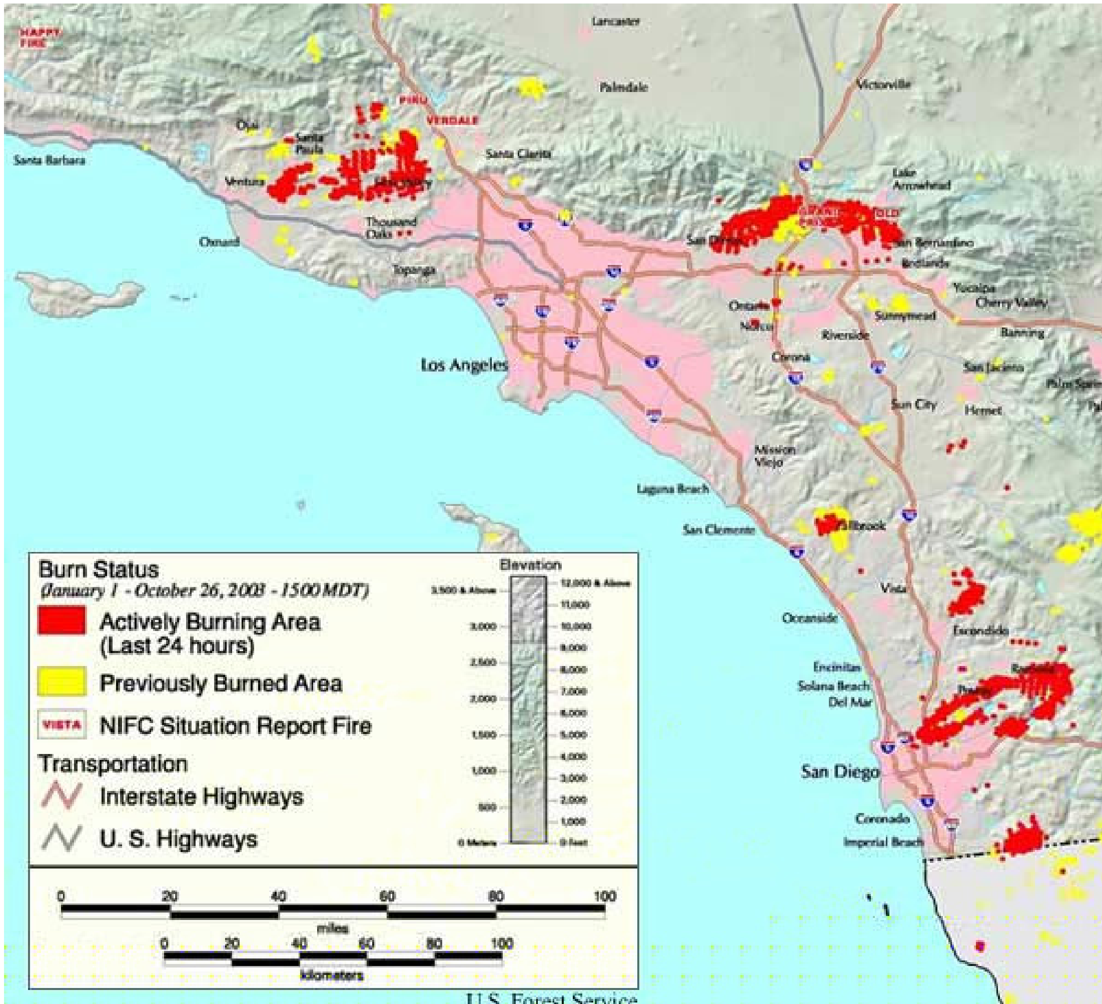


Are things getting worse?

US Fire Suppression policies over the last 100 years have greatly increased the national fire hazard because of the buildup of fuels.

Urbanization of fire prone areas increases economic losses, loss of life, ignition risk, and presence of exotic species, maladapted to the local fire regime.

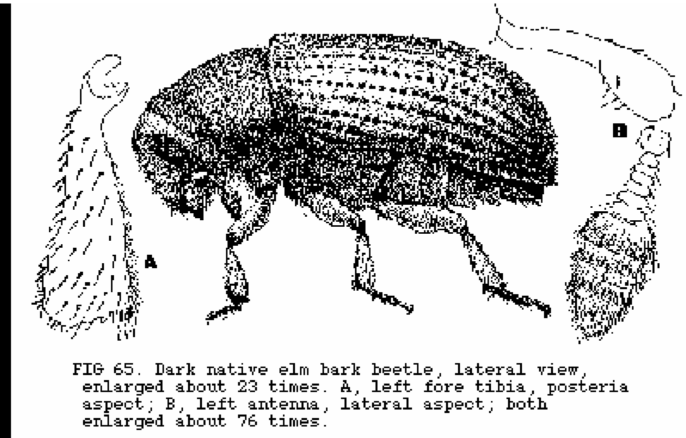
Climate change may have a long term impact on Fire hazard.

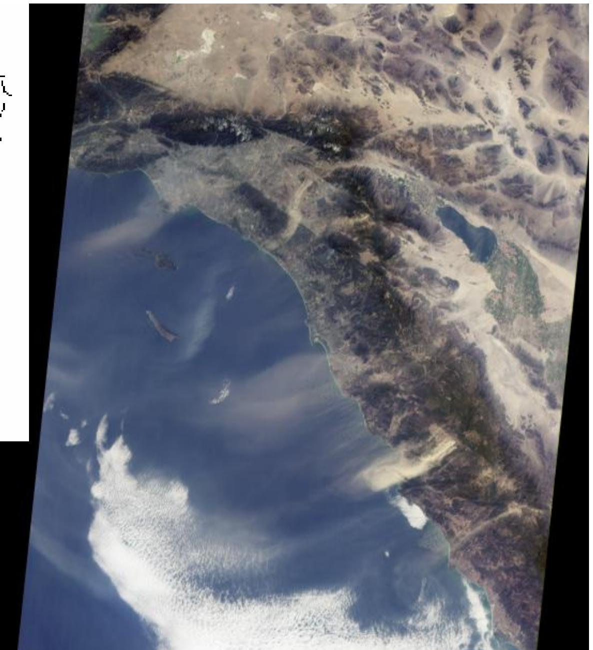


Burn status as of Sunday 10/26

- Over 500,000 acres burned
- 16 deaths
- 1600 homes burned
- 80,000+ evacuated
- School and business closures
- Flights canceled
- Estimated total costs reaching $2 billion

Perhaps California's worst economic disaster ever!





Urbanization and suppression interrupts the fire cycle in regions historically adapted to fire

Bark beetle infestation led to dead, dry, fuel accumulation

Santa Ana wind conditions lead to rapid fire spread

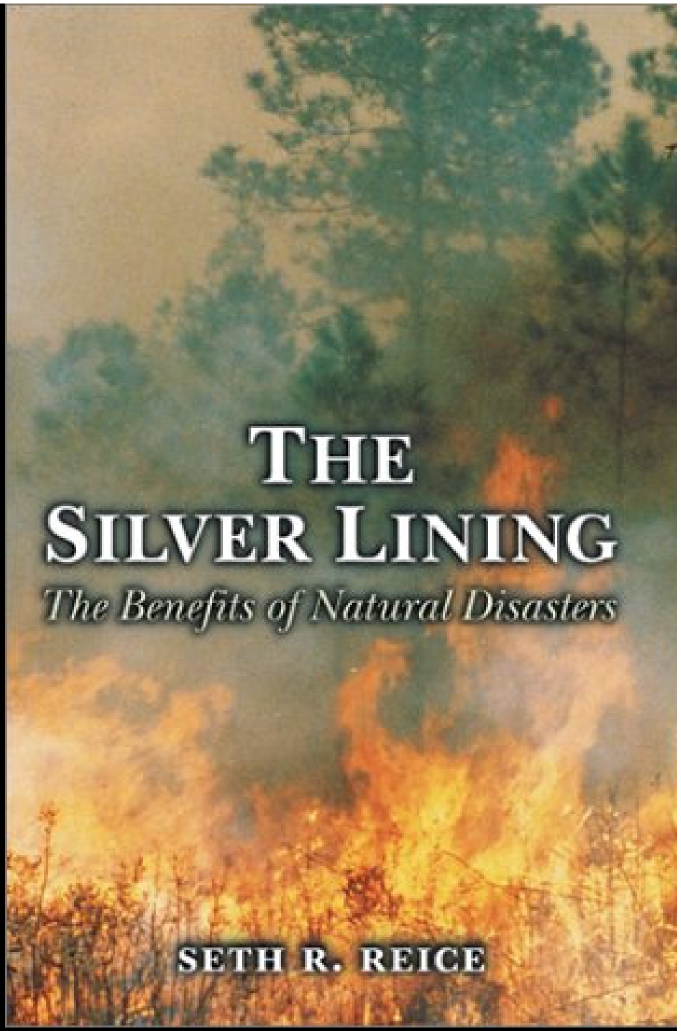
Such large wildfires in Southern California are not random, unexpected events!

Evidence: numerous fires, burn simultaneously from separate ignitions!

We continue to urbanize fire prone areas, repeatedly rebuilding homes after fires, and suppressing fires at the urban/wildland interface, leading to fuel accumulation– extreme fire hazard!

Regular burn cycles are intrinsic, and beneficial to many ecosystem types:

Exceptions:
The very dry (deserts)
The very wet (oceans)
The very urbanized (golf courses)



Otherwise:

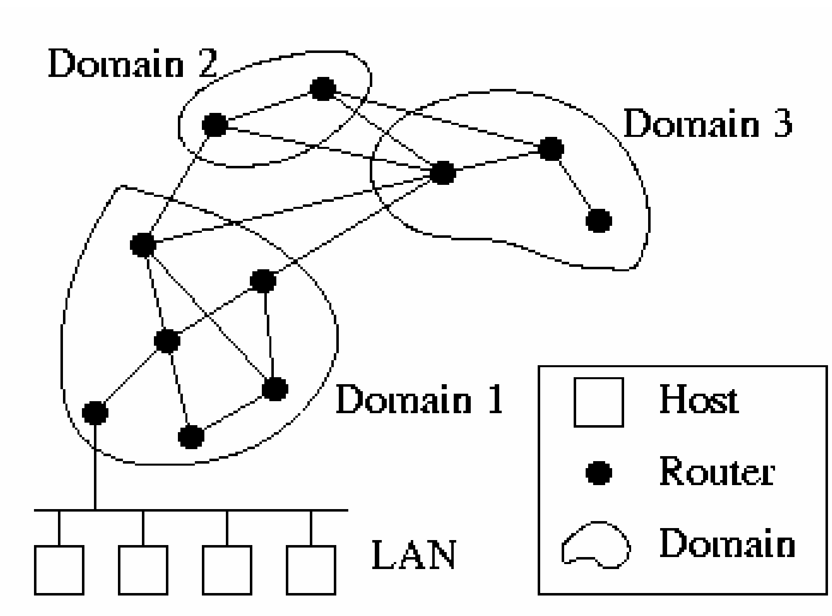
- Biodiversity increases in the recovery period that follows a fire
- Many native plants in fire prone regions depend on fire for seed germination

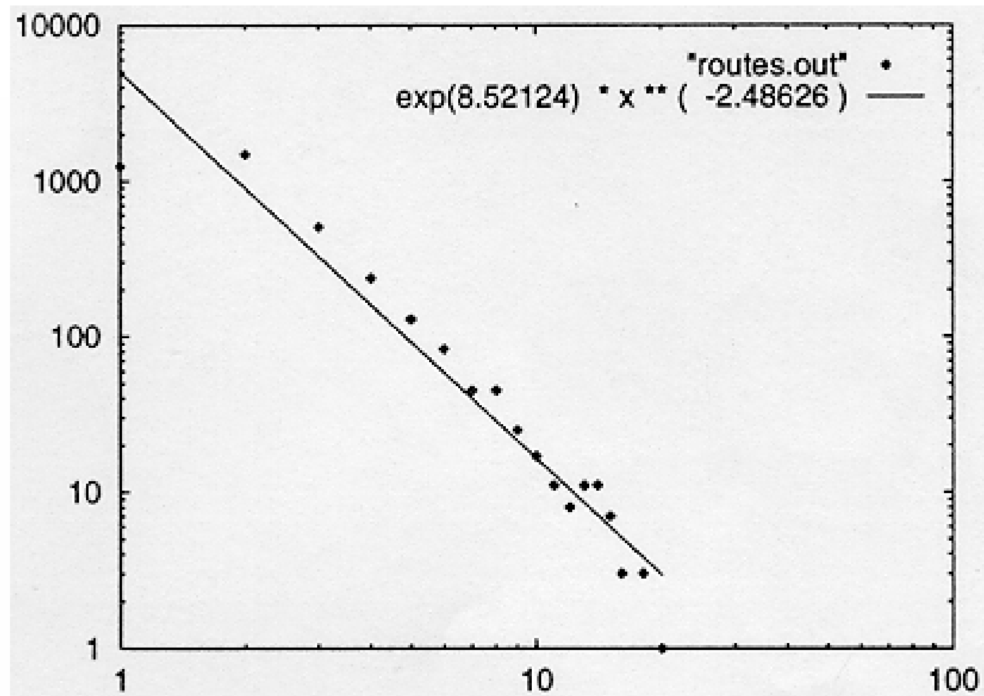
Wildfires are not the only problem

Technological networks are also becoming increasingly dense and heavily interconnected.

INTERNET BACKBONE

Nodes: computers, routers
Links: physical lines

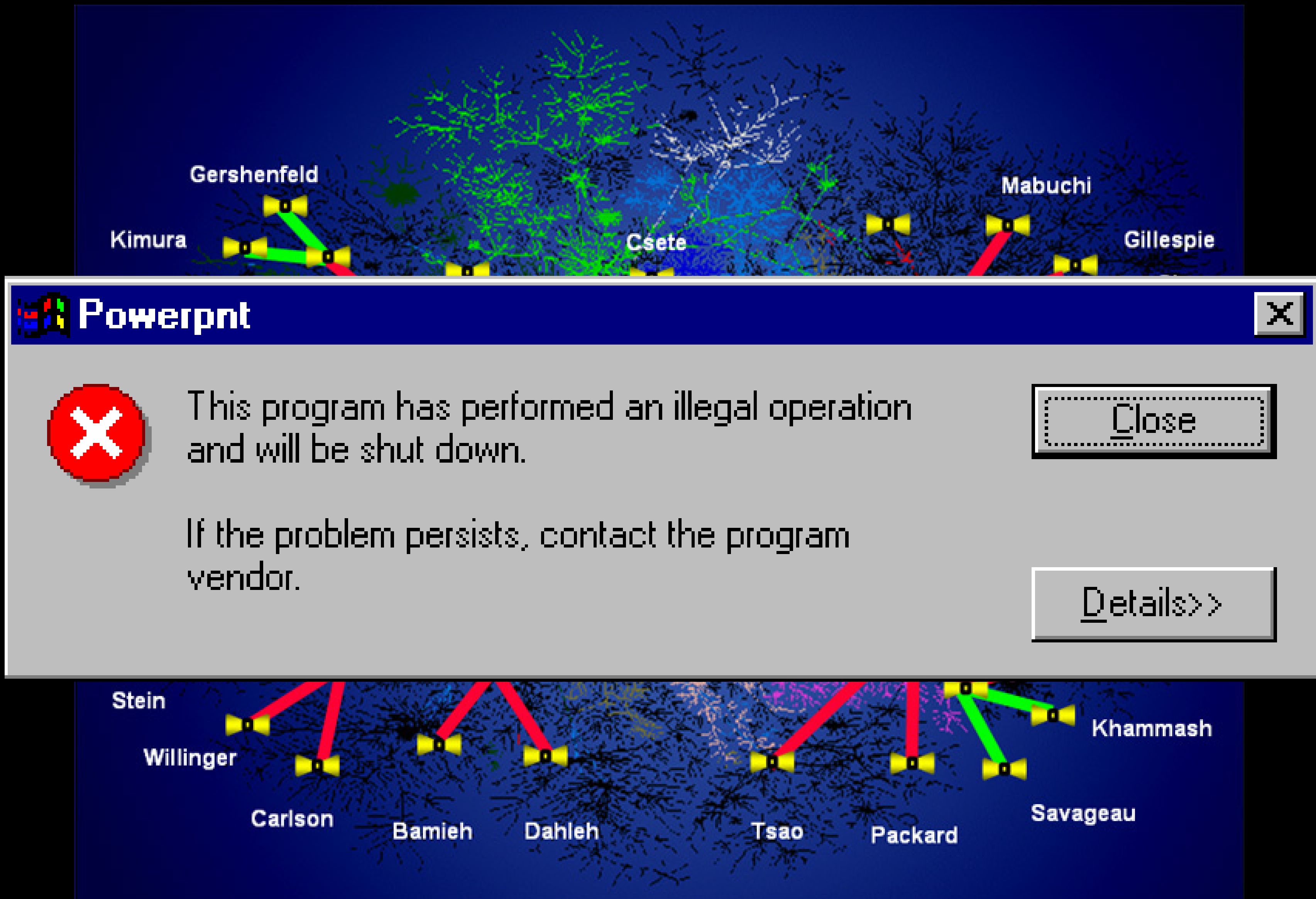




Physicists have suggested the Internet is a scale free network, with an "Achilles Heel."

Wrong again!

But the network has vulnerabilities



Happy Birthday John!