Approaching Gutenberg–Richter through Damage and Defects

C. A. Serino

Preliminary Oral Examination
Boston University Department of Physics

8 September 2010

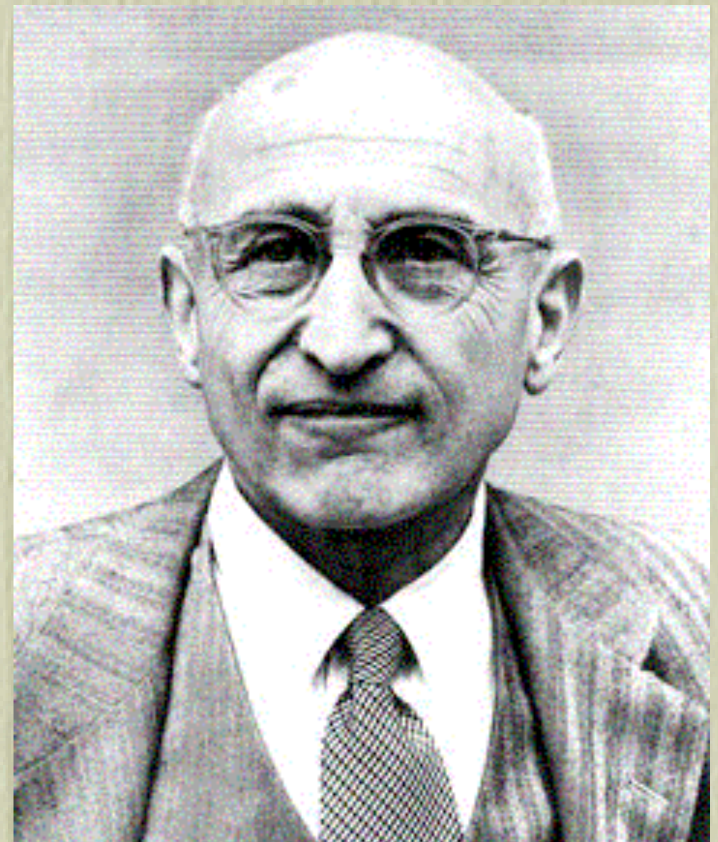
Outline

- Observations, Empirical Scaling & Motivation
- Early Models
- Model "Fault System"
- Simulations & Numerical Data
- Theoretical Description
- Future Work & Similar Physical Systems

Outline

- **Observations, Empirical Scaling & Motivation**
- Early Models
- Model "Fault System"
- Simulations & Numerical Data
- Theoretical Description
- Future Work & Similar Physical Systems

Gutenberg–Richter Distribution



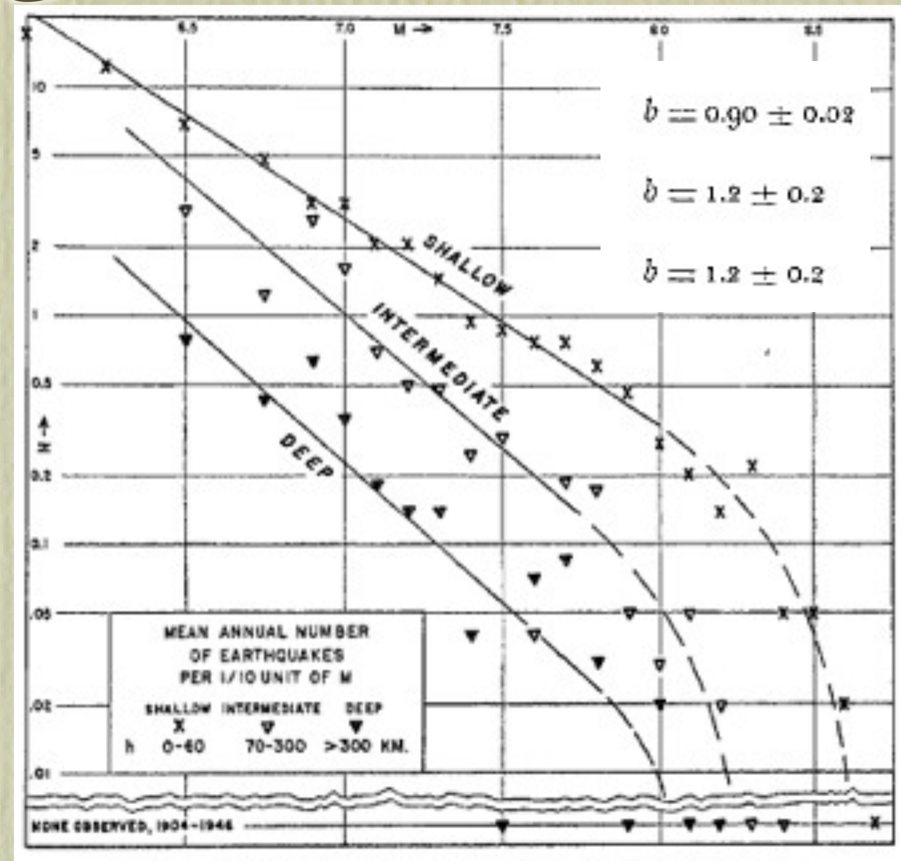
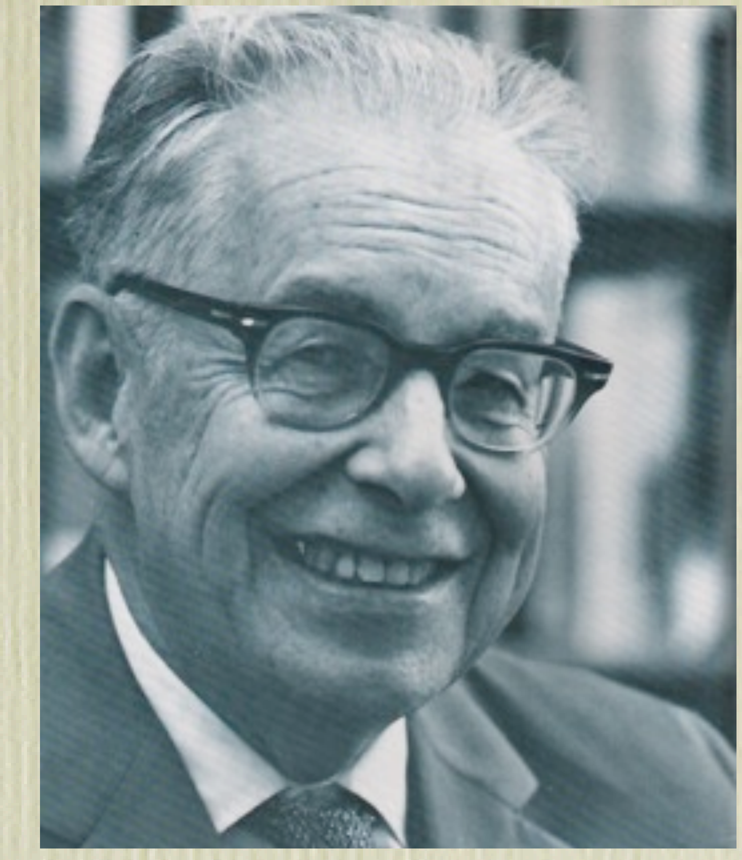


FIGURE 5. Mean annual number of earthquakes per 1/10 unit of magnitude.



- B. Gutenberg and C.F. Richter, Seismicity of the Earth and Associated Phenomena, 2nd ed. (Princeton, N.J.: Princeton University Press, 1954), p. 17

$$N\left(M \geq m\right) \sim \exp\left[-b\, m\right],\ b \approx 1$$

- G. Ekström and A. M. Dziewonski, *Nature* **332**, 319 (1988)

$$E(m) \sim \exp\left[d\, m\right],\ d \approx 3/2$$

Power–law Distribution

$$N(E_0 > E) \sim E^{-b/d} \approx E^{-2/3}$$

Power–law Distribution

$$N(E_0 > E) \sim E^{-b/d} \approx E^{-2/3}$$

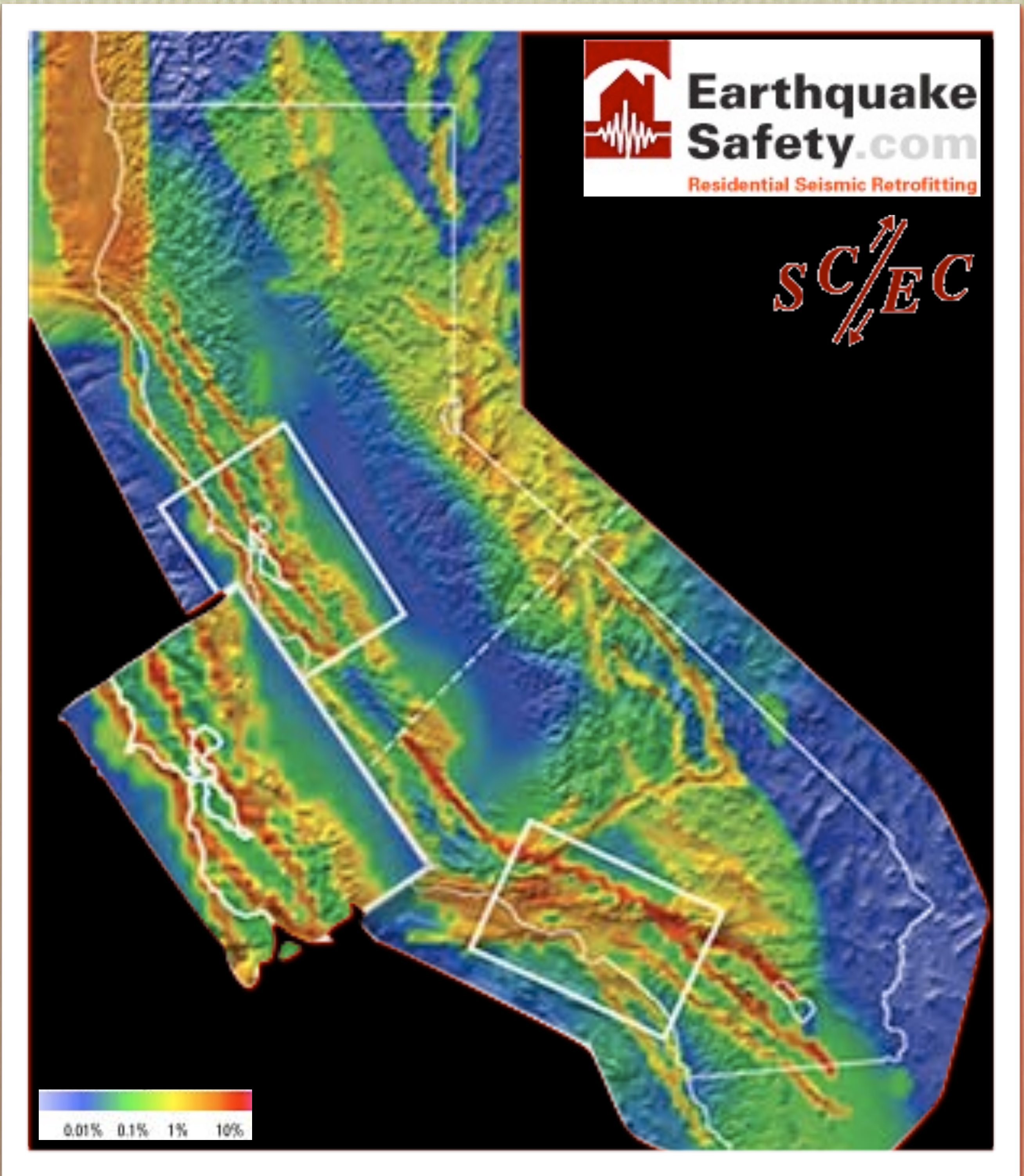
SO WHAT?

Power–law Distribution

$$N(E_0 > E) \sim E^{-b/d} \approx E^{-2/3}$$

What is the essential physics behind this distribution?

Prevention & Forecasting



- "More than **99%** probability in the next **30 years** for one or more **6.7 M** earthquakes"

  [Uniform California Earthquake Rupture Forecast (http://www.scec.org/ucerf/) SoCal Ethqk. Cntr. funded by NSF and USGS]

  - **99%** can't do much better
  - **30 years** can do better
  - **6.7 M** compare w/ Haiti 7, so about 64% as destructive.

- Black Magic / Data Massaging

  What is essential? What is detail?

Outline

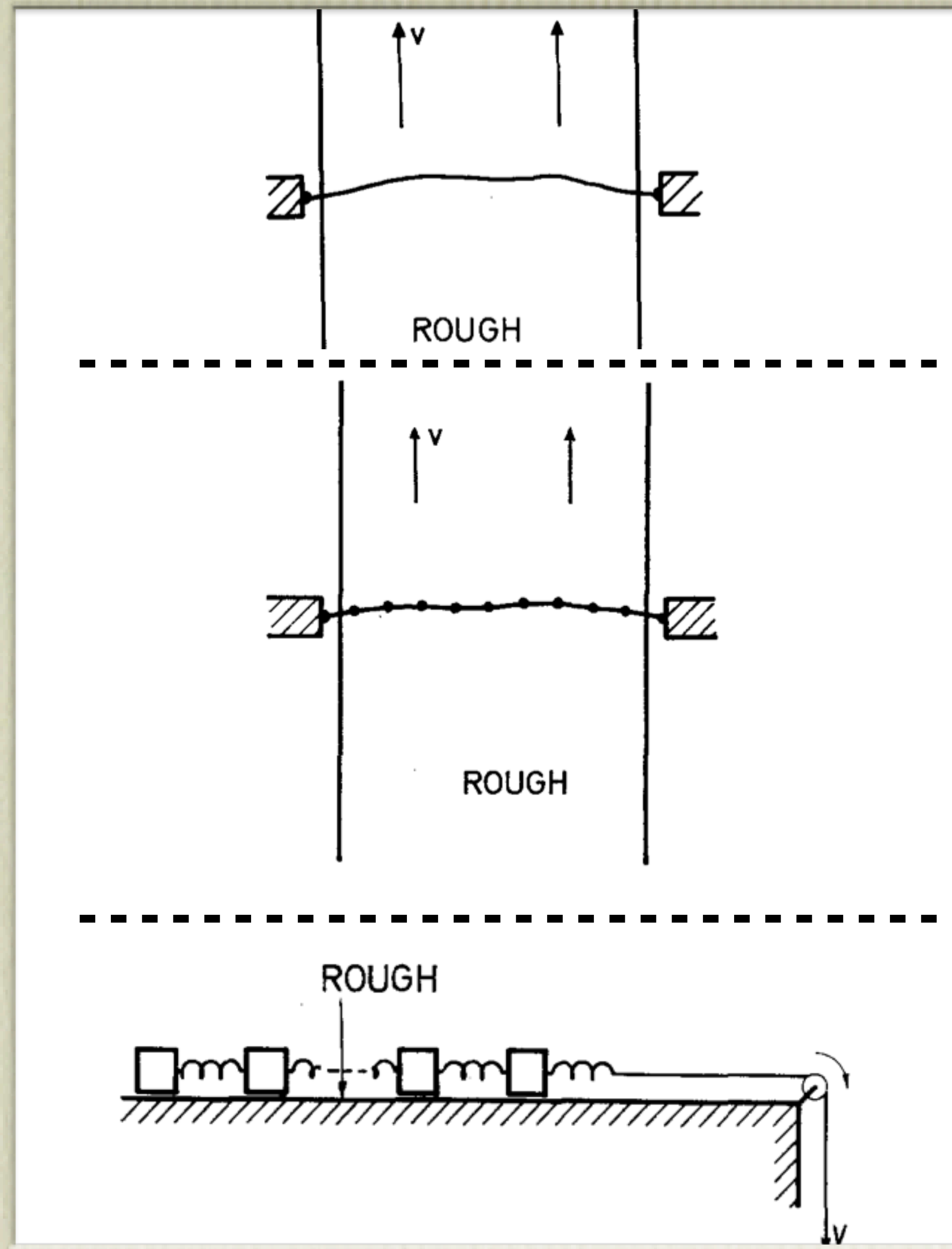
- Observations, Empirical Scaling & Motivation
- **Early Models**
- Model "Fault System"
- Simulations & Numerical Data
- Theoretical Description
- Future Work & Similar Physical Systems

Model and Theoretical Seismicity

R Burridge and L. Knopoff

Bulletin of the Seismological Society of America **57**, 341 (1967)

- Introduce four models
- Linear elastic media on rough, moving surfaces



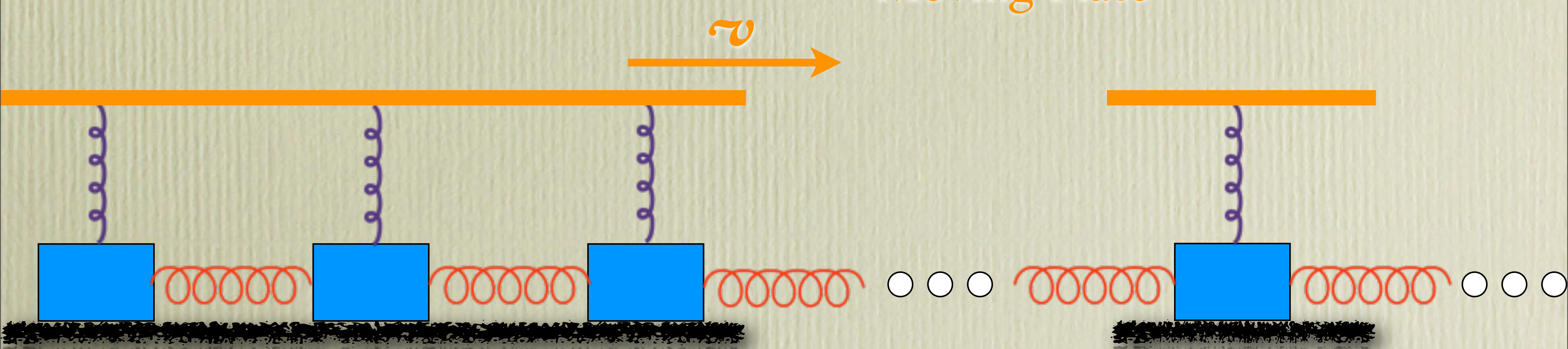
BOSTON UNIVERSITY

Model and Theoretical Seismicity

R Burridge and L. Knopoff
Bulletin of the Seismological Society of America **57**, 341 (1967)

- Introduce four models
- Linear elastic media on rough, moving surfaces
- Ultimately, it is the 4th that bears their names

- Rough surface
- Linear (Hooke's Law) springs
- Linear "Leaf" Springs
- Moving Plate



Continuum Model to Cellular Automata

Continuum Model to Cellular Automata

- The continuum model is computationally expensive
- The dissipation of energy associated with the frictional forces makes theoretical analysis difficult

Continuum Model to Cellular Automata

- The continuum model is computationally expensive
- The dissipation of energy associated with the frictional forces makes theoretical analysis difficult
- Introduce two simplifications on Burridge-Knopoff model:

{J. B. Rundle and D. D. Jackson Bull. Seis. Soc. Am. 67, 1363 (1977) &

Z. Olami, H. J. S. Feder and K. Christensen Phys. Rev. Lett. 68, 1244 (1988)}

Continuum Model to Cellular Automata

- The continuum model is computationally expensive
- The dissipation of energy associated with the frictional forces makes theoretical analysis difficult
- Introduce two simplifications on Burridge-Knopoff model:

  {J. B. Rundle and D. D. Jackson Bull. Seis. Soc. Am. 67, 1363 (1977) &

  Z. Olami, H. J. S. Feder and K. Christensen Phys. Rev. Lett. 68, 1244 (1988)}

  1. When a block slips, it moves to its equilibrium position before any other blocks can slip (massless limit)

Continuum Model to Cellular Automata

- The continuum model is computationally expensive
- The dissipation of energy associated with the frictional forces makes theoretical analysis difficult
- Introduce two simplifications on Burridge-Knopoff model:

  [J. B. Rundle and D. D. Jackson Bull. Seis. Soc. Am. 67, 1363 (1977) &

  Z. Olami, H. J. S. Feder and K. Christensen Phys. Rev. Lett. 68, 1244 (1988)]

  1. When a block slips, it moves to its equilibrium position before any other blocks can slip (massless limit)
  2. Loader plate always moves the same amount each time step

Continuum Model to Cellular Automata

- The continuum model is computationally expensive

- The dissipation of energy associated with the frictional forces makes theoretical analysis difficult

- Introduce two simplifications on Burridge-Knopoff model:

  [J. B. Rundle and D. D. Jackson Bull. Seis. Soc. Am. 67, 1363 (1977) &

  Z. Olami, H. J. S. Feder and K. Christensen Phys. Rev. Lett. 68, 1244 (1988)]

  1. When a block slips, it moves to its equilibrium position before any other blocks can slip (massless limit)

  2. Loader plate always moves the same amount each time step

- Rather than solving Newton's Equations for the $2dN$ phase-space variables, we can track N variables with simple update rules

What is a cellular automata?

What is a cellular automata?

- A lattice model in which each vertex is assigned a value at time *t*.

- The value at each vertex at time *t+1* is determined by the configuration at previous times.

What is a cellular automata?

- A lattice model in which each vertex is assigned a value at time *t*.
- The value at each vertex at time *t+1* is determined by the configuration at previous times.
- Example: Conway's Game of Life

What is a cellular automata?

- A lattice model in which each vertex is assigned a value at time *t*.
- The value at each vertex at time *t+1* is determined by the configuration at previous times.
- Example: Conway's Game of Life [Gardner, M. *Scientific American* (Oct. 1970)]
  1. Cell with fewer than 2 neighbors dies.
  2. Cell with more than 3 neighbors dies.
  3. A cell with 2 or 3 neighbors lives.
  4. An empty cell with 3 neighbors becomes live.

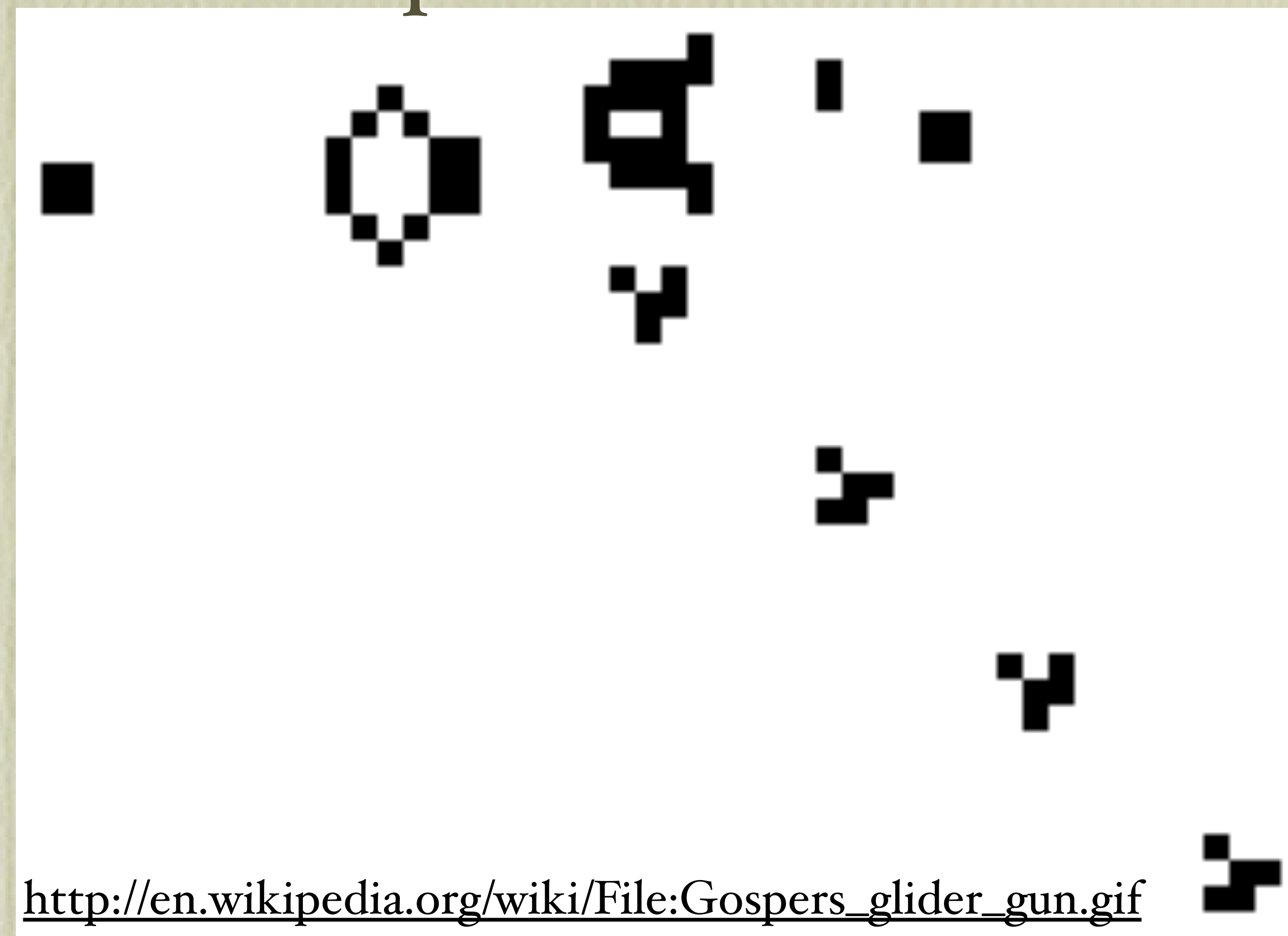
What is a cellular automata?

- A lattice model in which each vertex is assigned a value at time *t*.

- The value at each vertex at time *t+1* is determined by the configuration at previous times.

- Example: Conway's Game of Life [Gardner, M. *Scientific American* (Oct. 1970)]

"Gosper's Glider Gun"

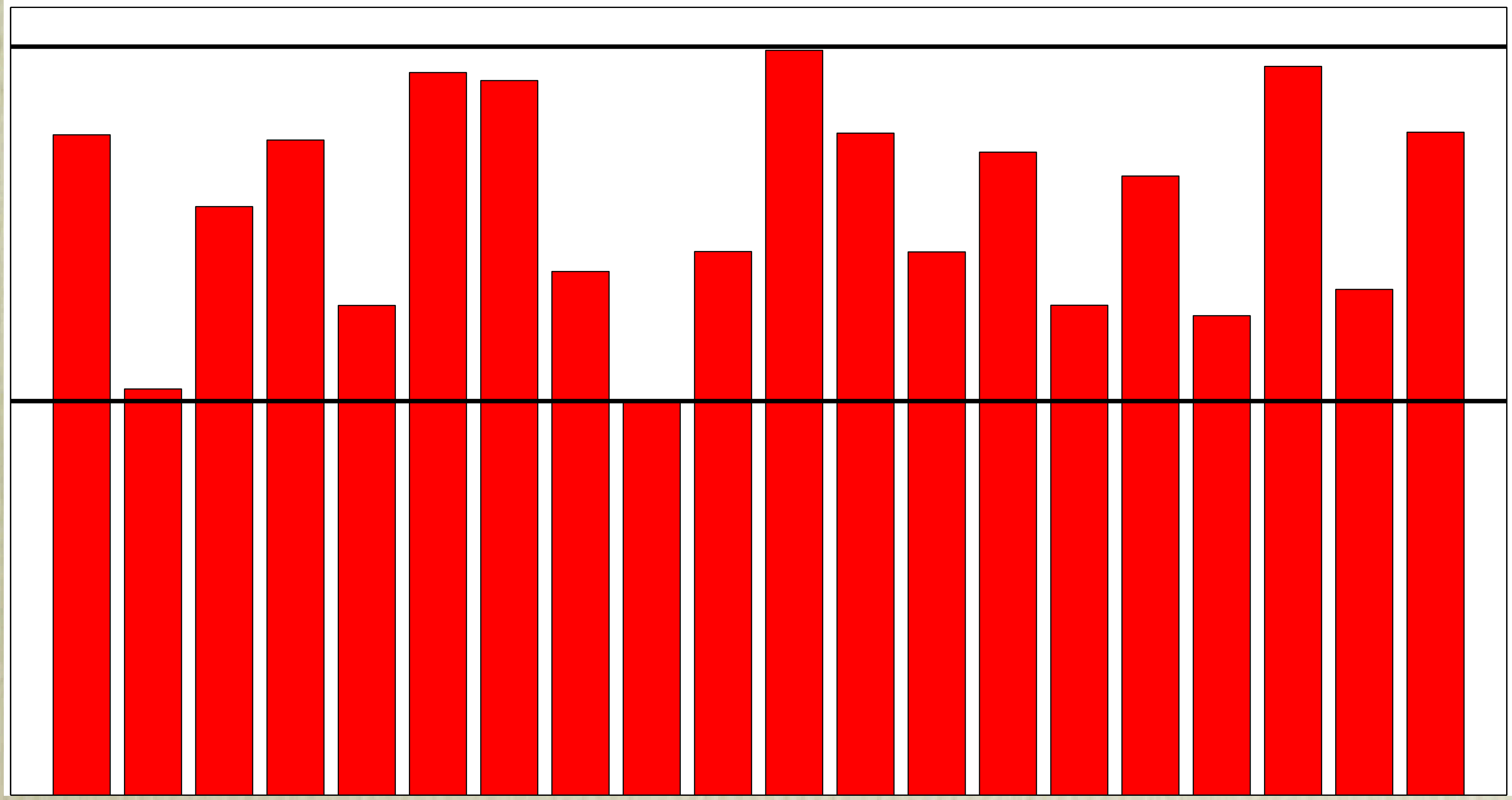


http://en.wikipedia.org/wiki/File:Gospers_glider_gun.gif

1. Cell with fewer than 2 neighbors dies.
2. Cell with more than 3 neighbors dies.
3. A cell with 2 or 3 neighbors lives.
4. An empty cell with 3 neighbors becomes live.

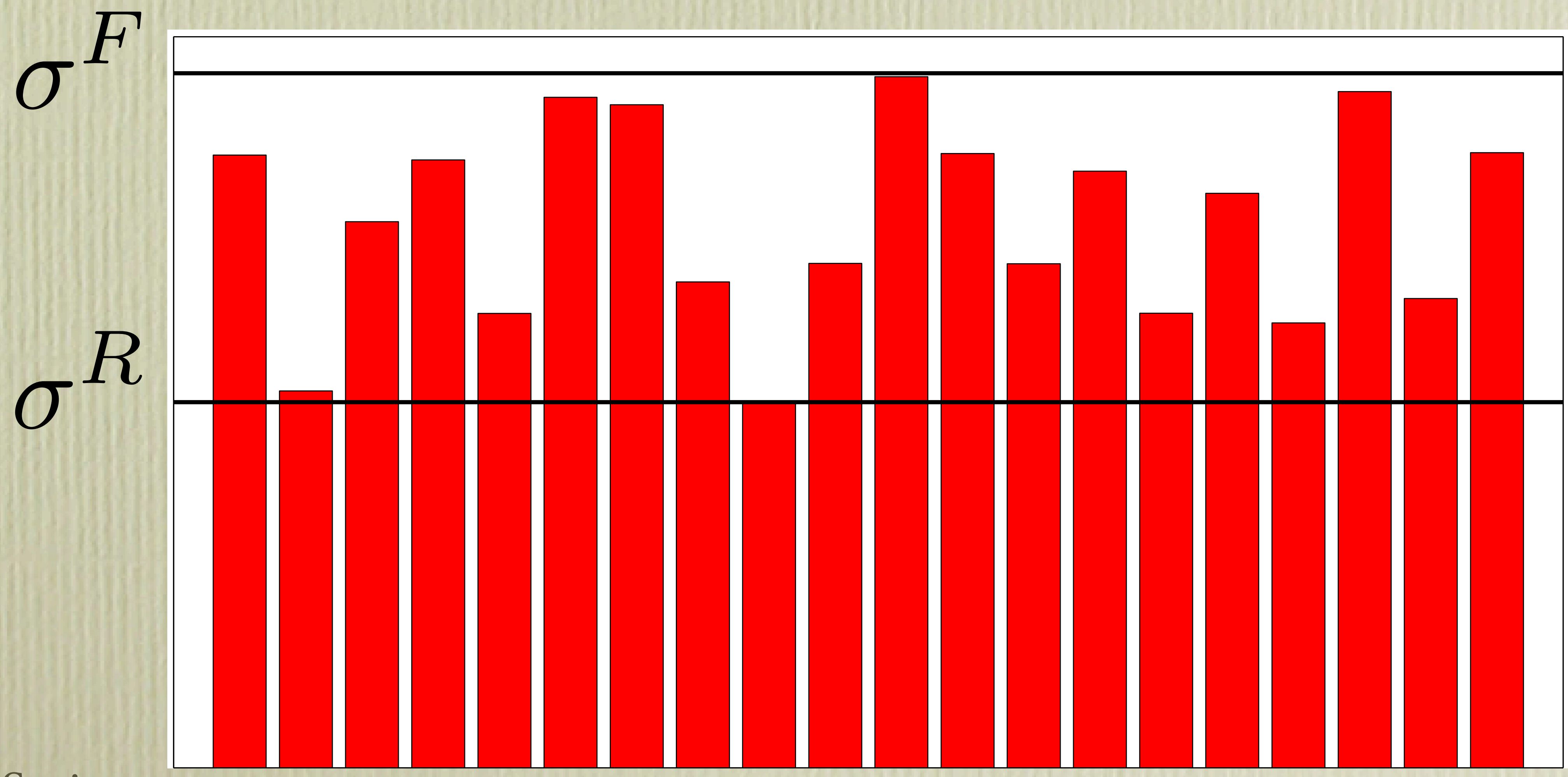
RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)



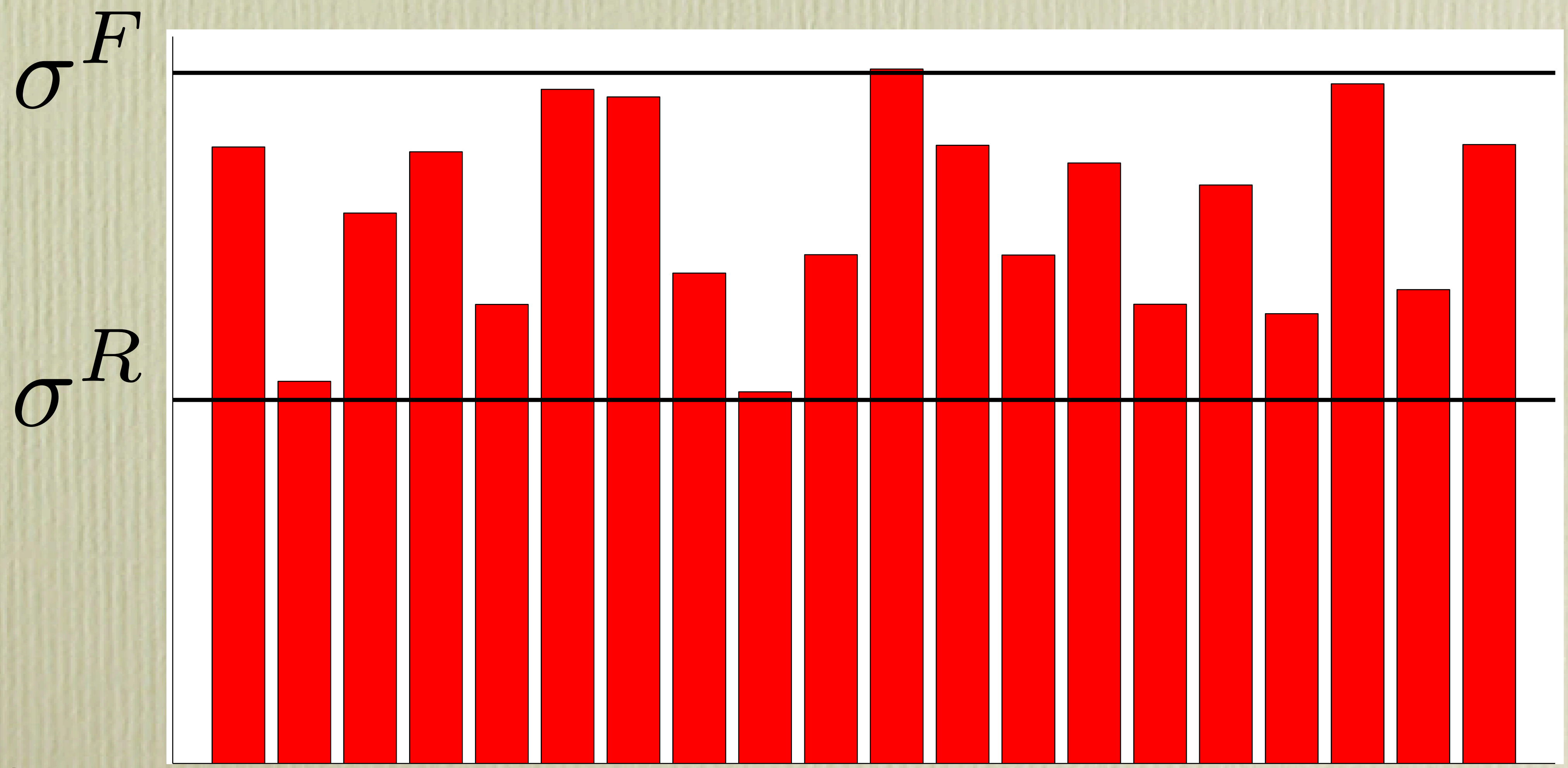
RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)



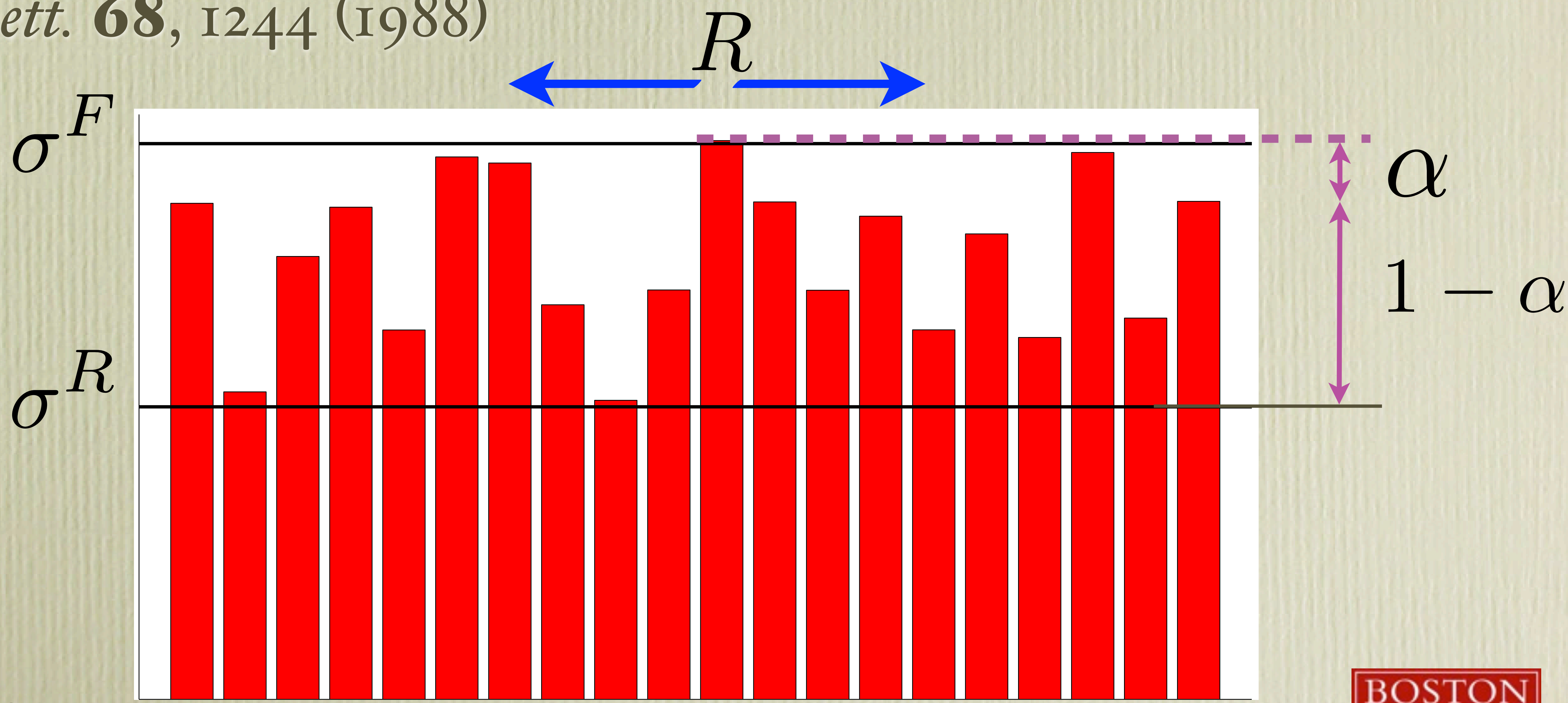
RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)



RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)

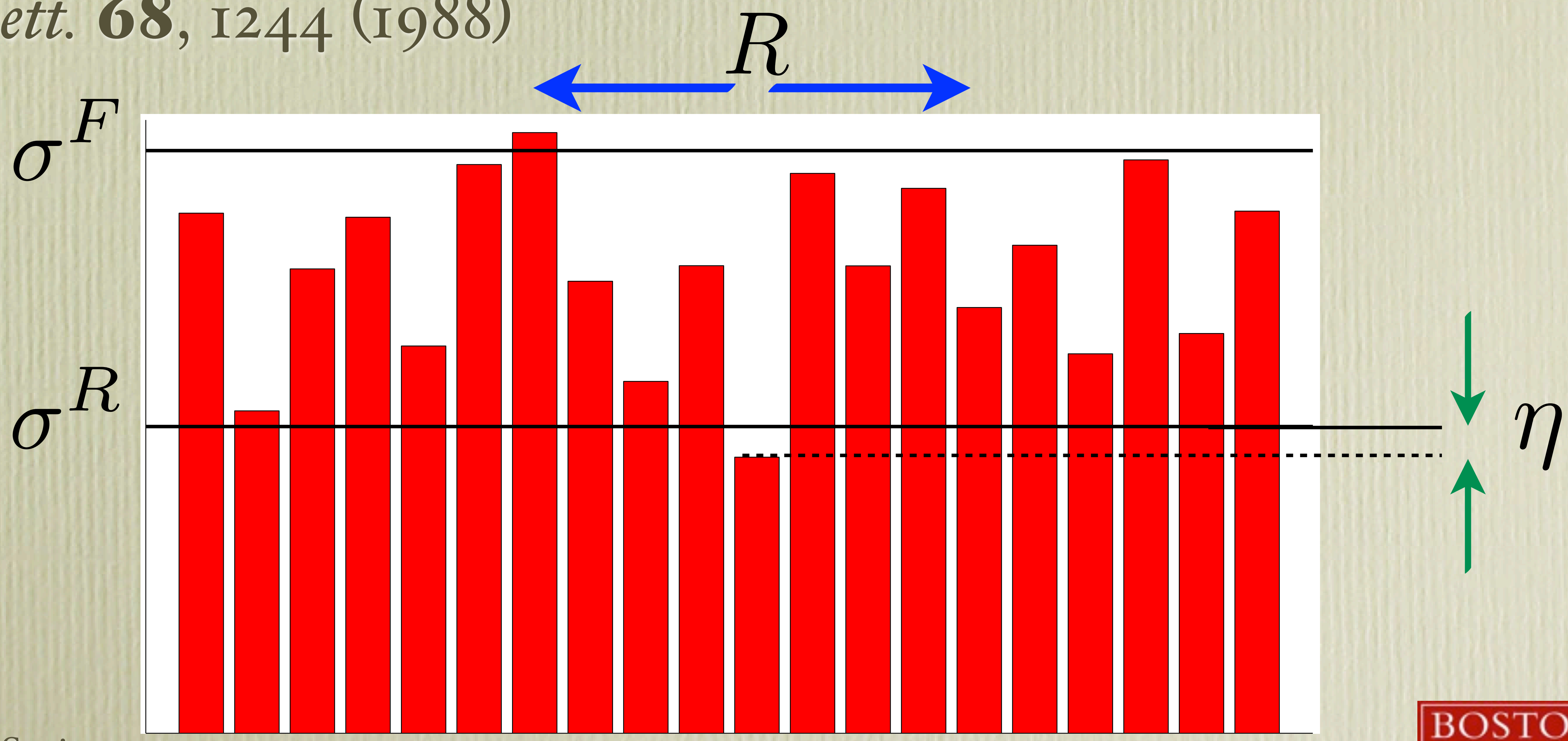


C. A. Serino

BOSTON UNIVERSITY

RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)



RJB & OFC Model

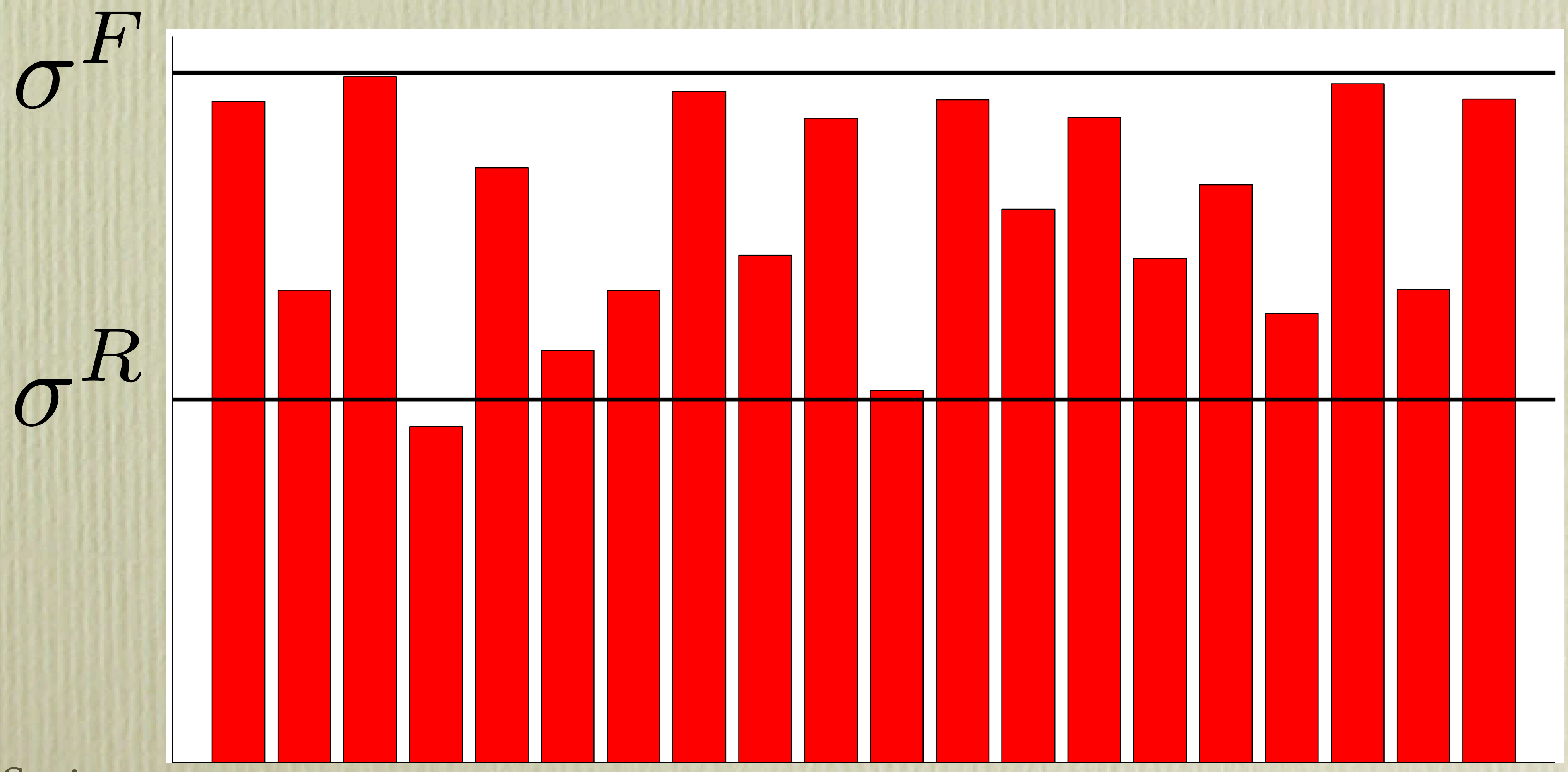
- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)

RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)

RJB & OFC Model

- J. B. **R**undle and D. D. **J**ackson *Bull. Seis. Soc. Am.* **67**, 1363 (1977)
- Z. **O**lami, H. J. S. **F**eder and K. **C**hristensen *Phys. Rev. Lett.* **68**, 1244 (1988)

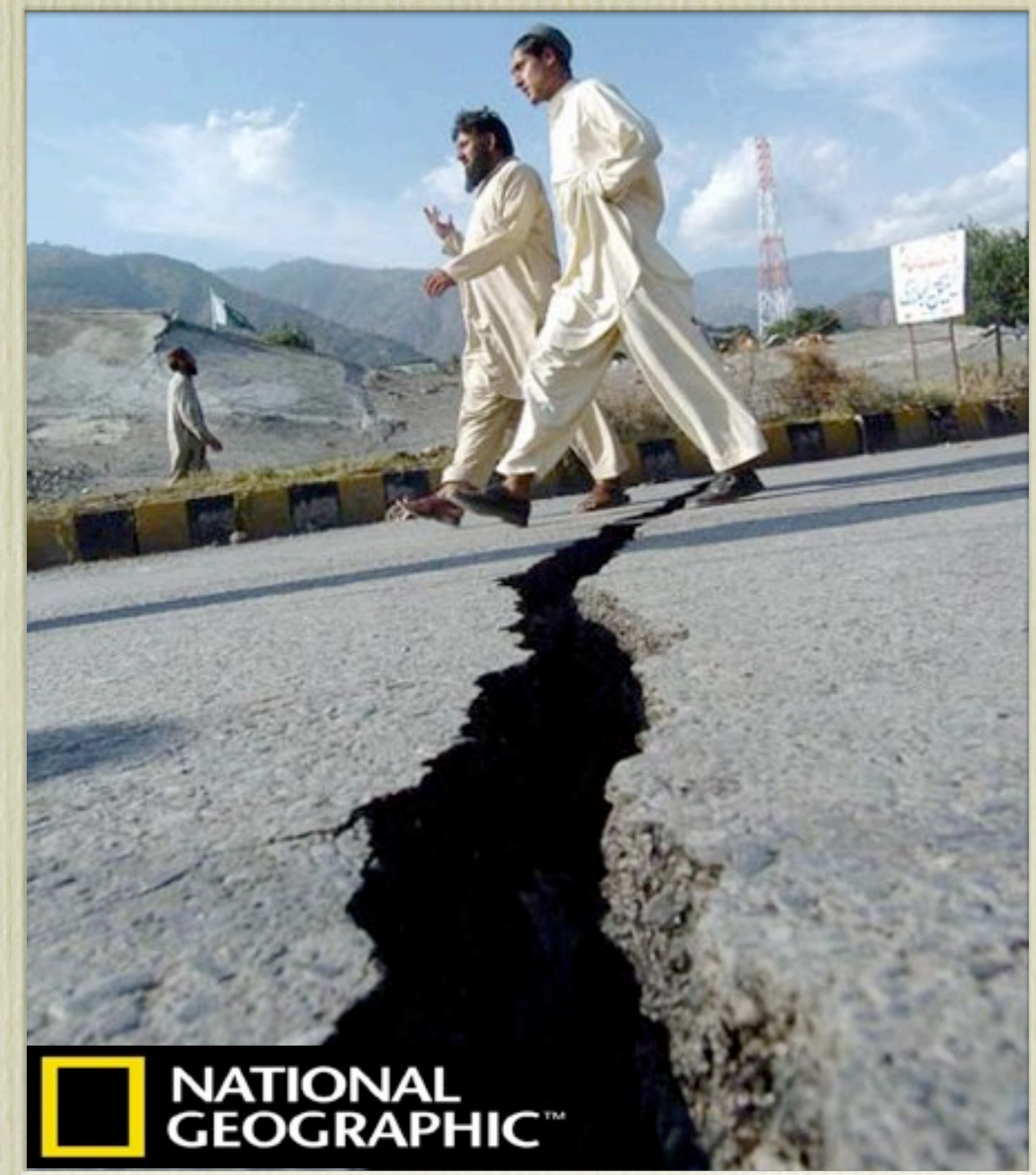


C. A. Serino

BOSTON UNIVERSITY

Outline

- Observations, Empirical Scaling & Motivation
- Early Models
- **Model "Fault System"**
- Simulations & Numerical Data
- Theoretical Description
- Future Work & Similar Physical Systems



Limitations of the Early Models

Limitations of the Early Models

- These models must run near a critical point to generate scaling.

Limitations of the Early Models

- These models must run near a critical point to generate scaling.

- The models are homogenous but faults vary drastically in size and composition throughout systems.

Limitations of the Early Models

- These models must run near a critical point to generate scaling.
- The models are homogenous but faults vary drastically in size and composition throughout systems.
- The models are best described as individual faults .

Limitations of the Early Models

- These models must run near a critical point to generate scaling.
- The models are homogenous but faults vary drastically in size and composition throughout systems.
- The models are best described as individual faults .
- Scaling is rarely observed in individual faults.

Improvements on the Early Models

- These models must run near a critical point to generate scaling.
- The models are homogenous but faults vary drastically in size and composition throughout systems.
- The models are best described as individual faults .
- Scaling is rarely observed in individual faults.

Improvements on the Early Models

- These models must run near a critical point to generate scaling.
- The models are homogenous but faults vary drastically in size and composition throughout systems.

} Introduce defects into the lattice

- The models are best described as individual faults .
- Scaling is rarely observed in individual faults.

Improvements on the Early Models

- These models must run near a critical point to generate scaling.
- The models are homogenous but faults vary drastically in size and composition throughout systems.

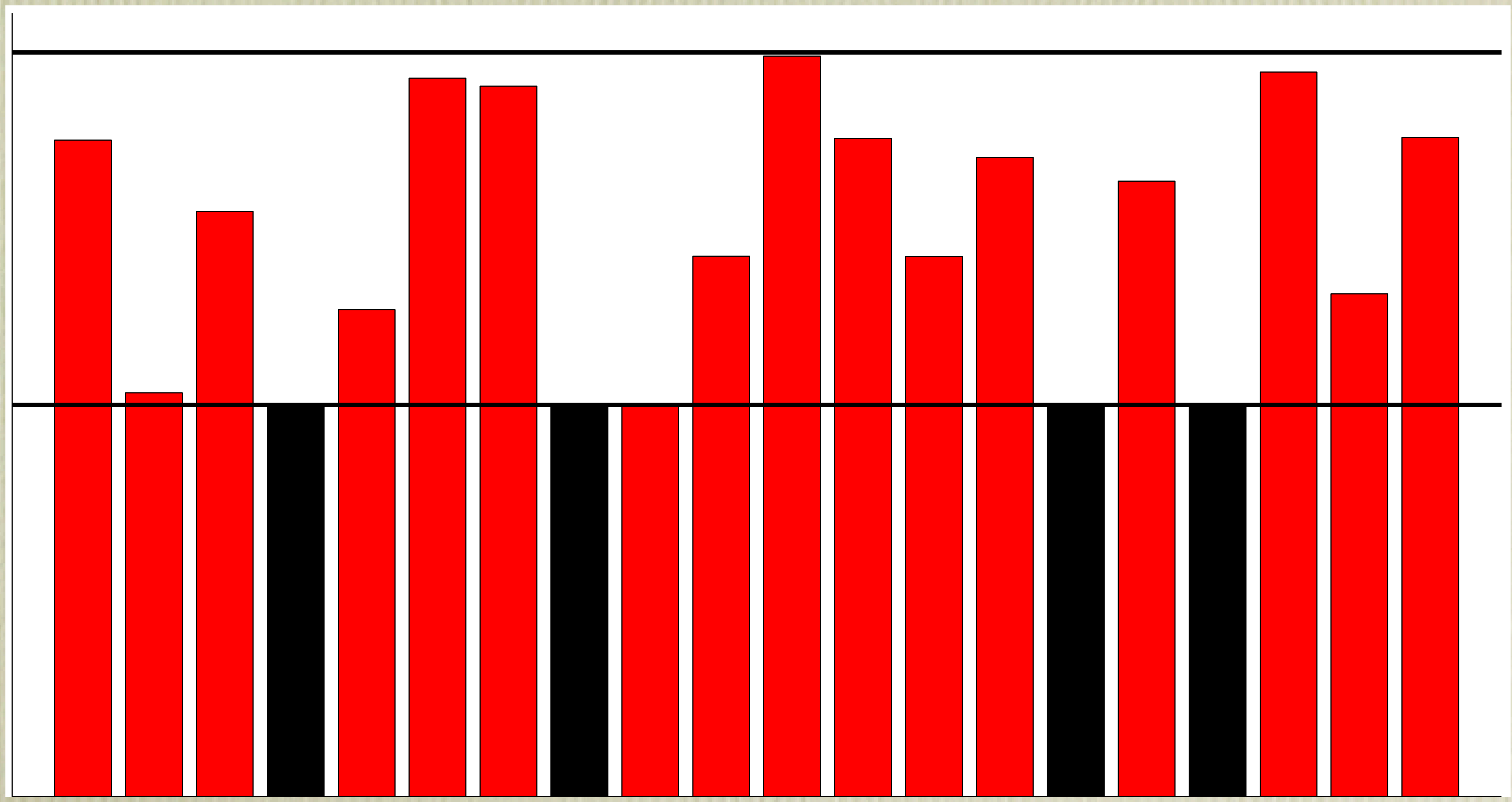
Introduce defects into the lattice

- The models are best described as individual faults .
- Scaling is rarely observed in individual faults.

"Sew" together these damaged or defected lattices (model faults) to create a fault system

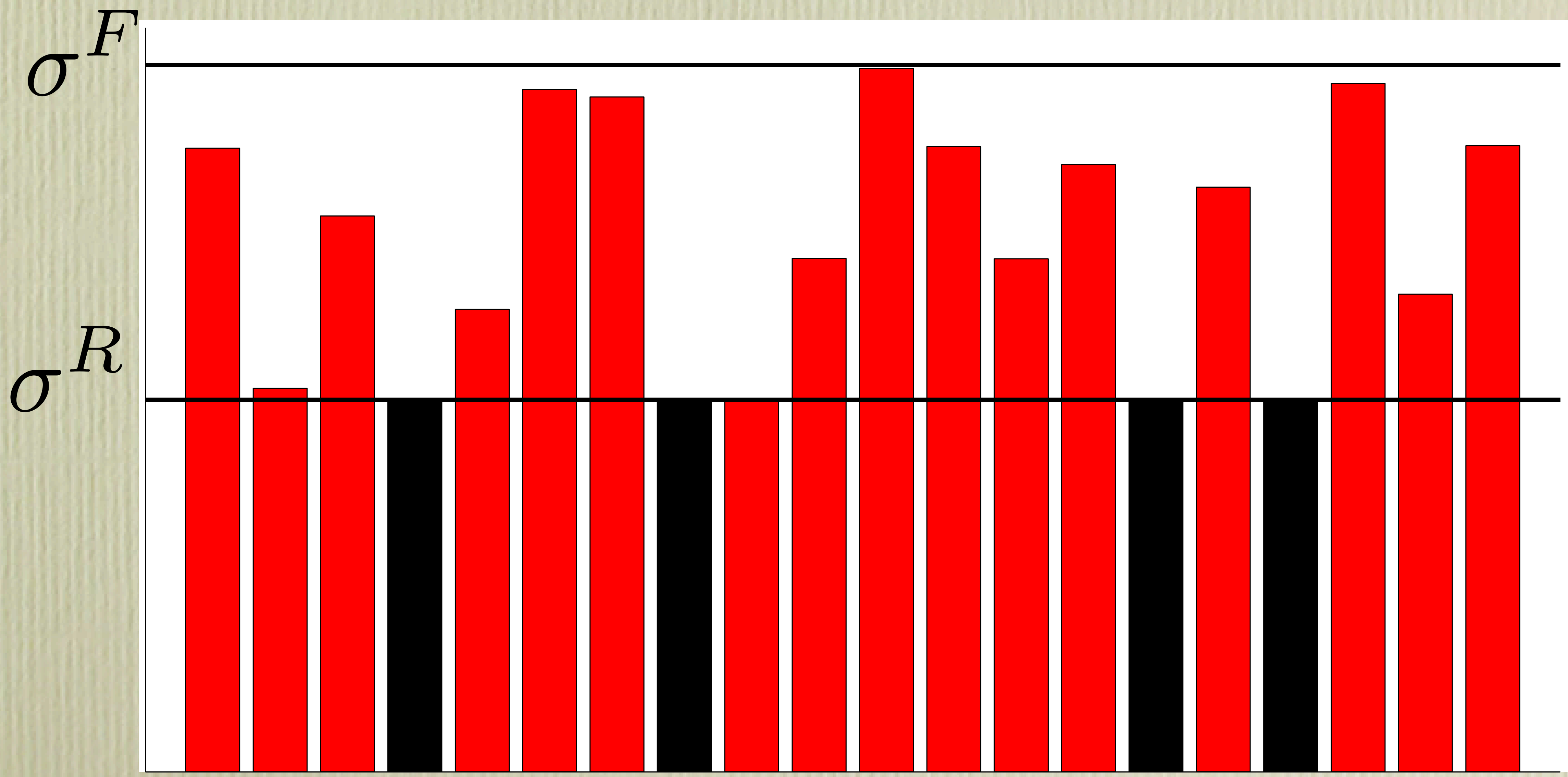
Damage Properties

- The damaged sites are dissipative in nature.
- They are distributed uniformly with concentration $1 - p$.
- The defects are quenched and are not to be treated as statistical variables.



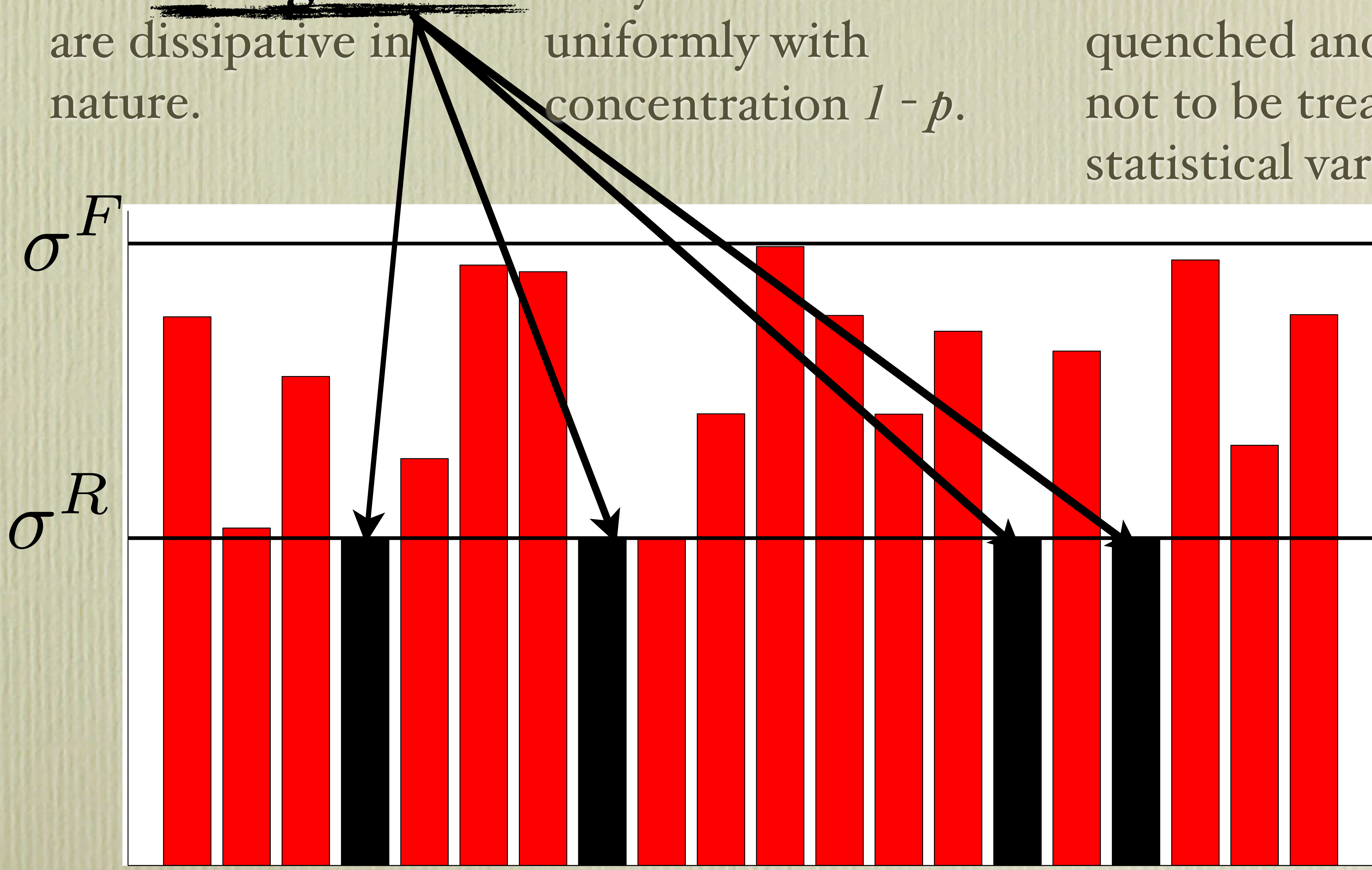
Damage Properties

- The damaged sites are dissipative in nature.
- They are distributed uniformly with concentration *1 - p*.
- The defects are quenched and are not to be treated as statistical variables.



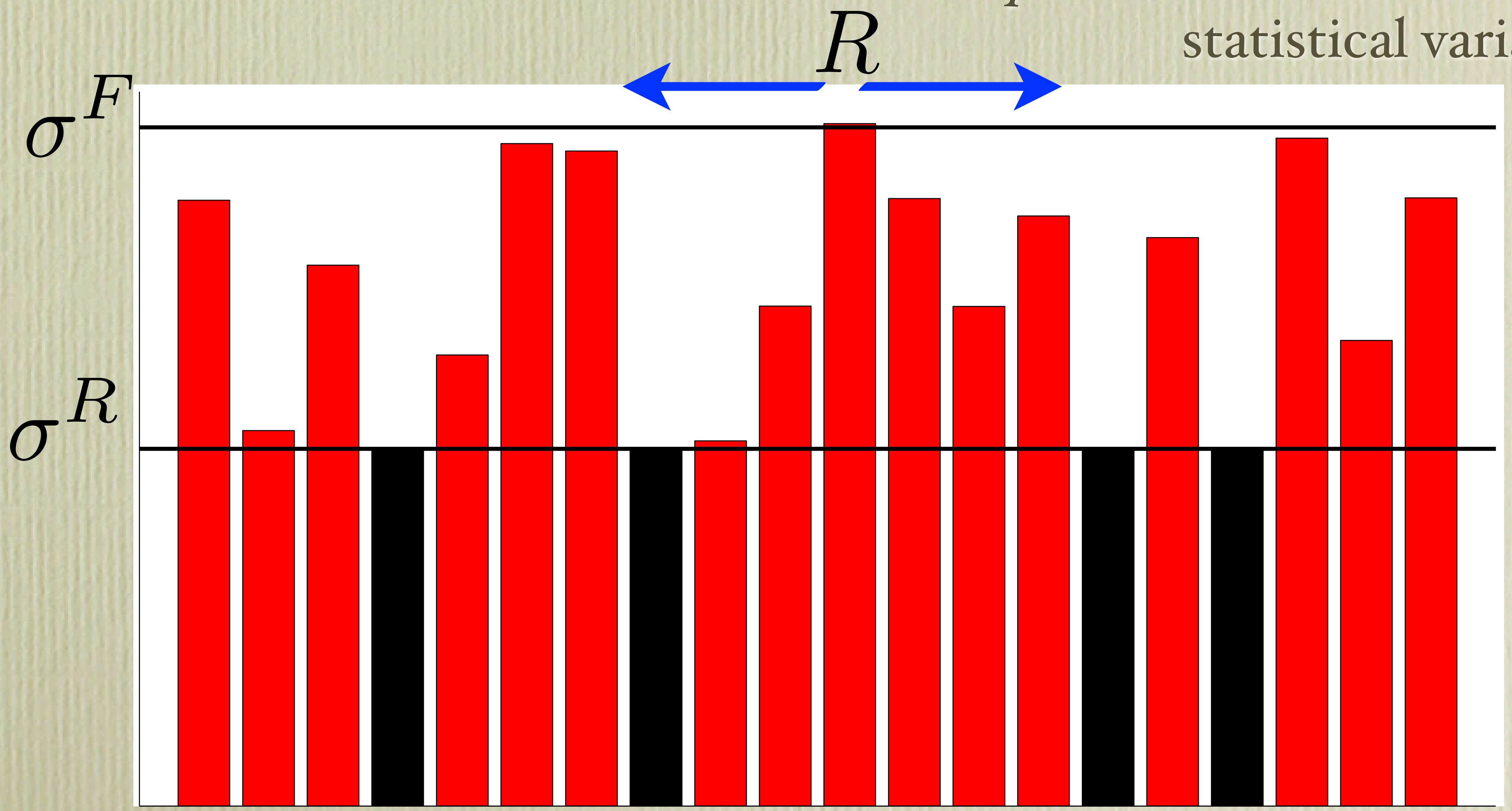
Damage Properties

- The **damaged sites** are dissipative in nature.
- They are distributed uniformly with concentration $1 - p$.
- The defects are quenched and are not to be treated as statistical variables.



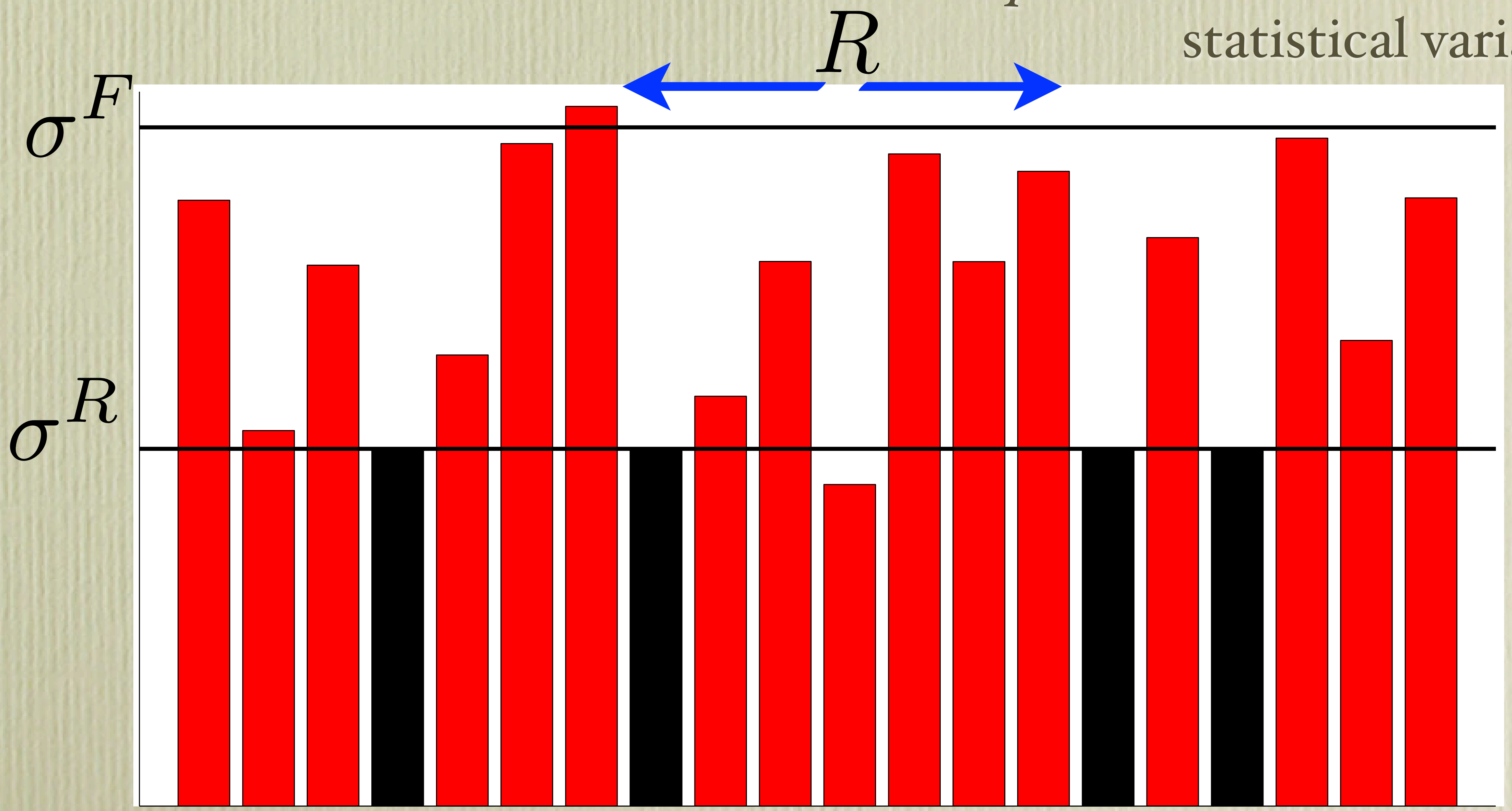
Damage Properties

- The damaged sites are dissipative in nature.
- They are distributed uniformly with concentration *1 - p*.
- The defects are quenched and are not to be treated as statistical variables.



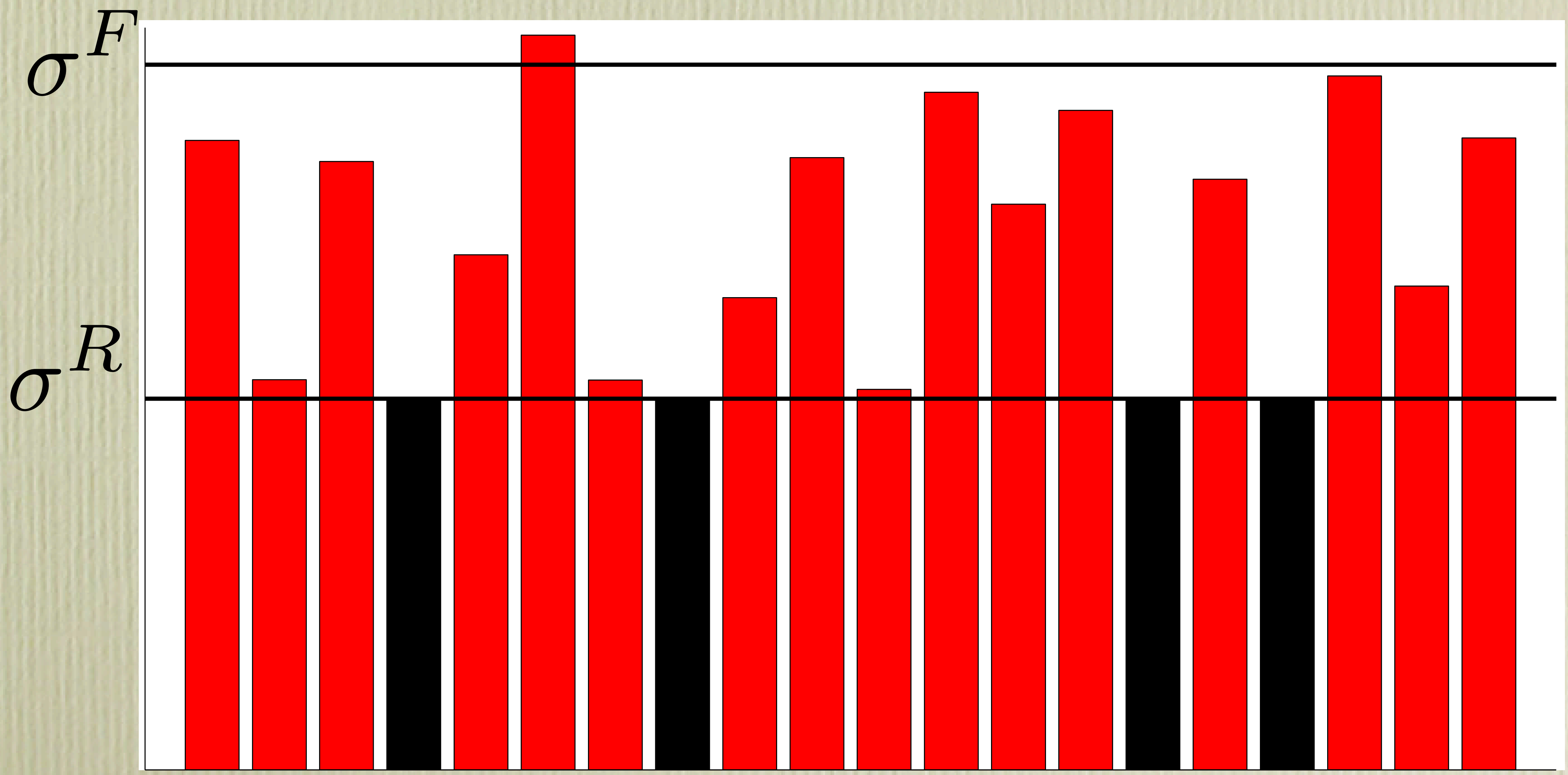
Damage Properties

- The damaged sites are dissipative in nature.
- They are distributed uniformly with concentration *1 - p*.
- The defects are quenched and are not to be treated as statistical variables.



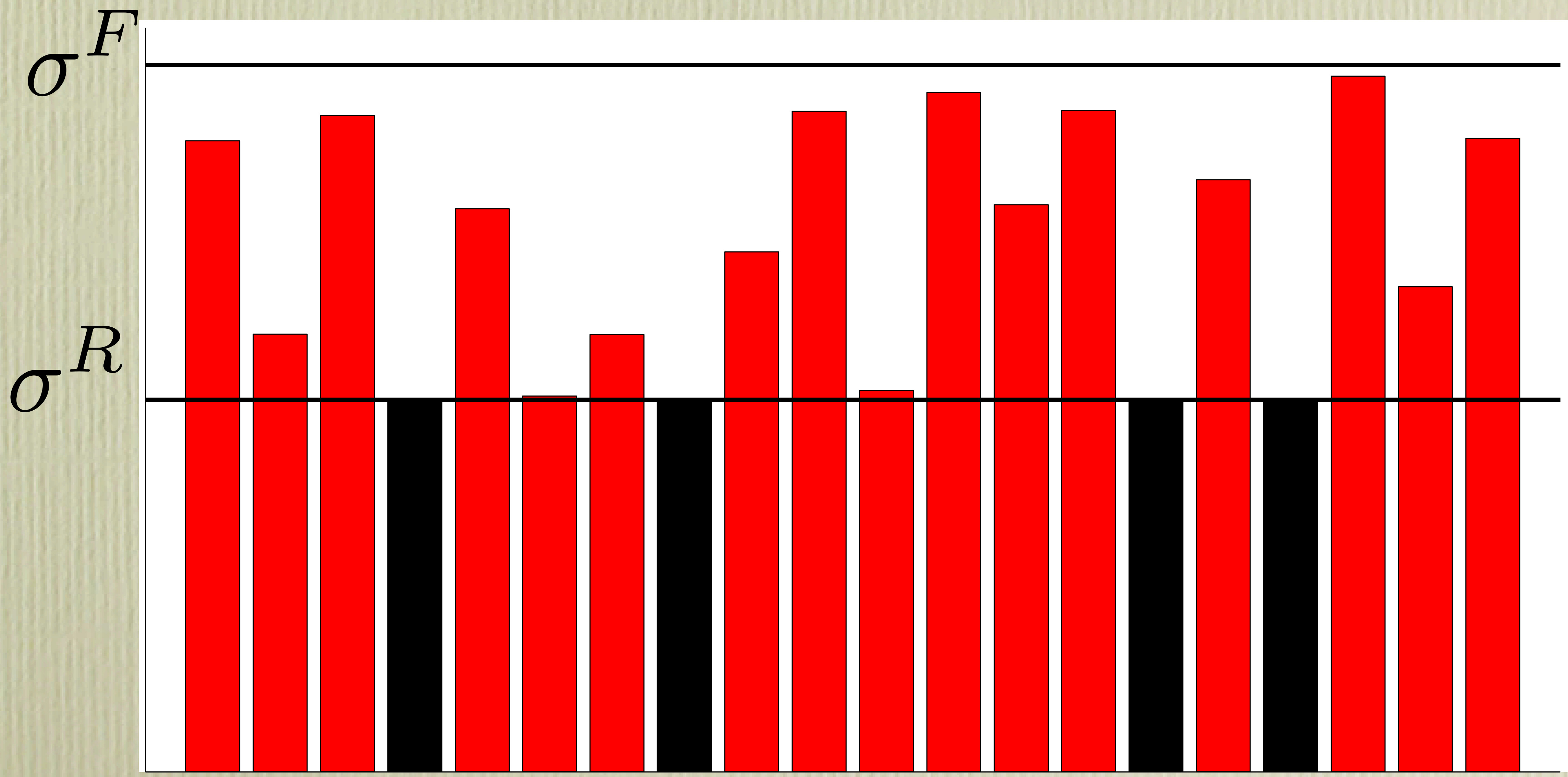
Damage Properties

- The damaged sites are dissipative in nature.
- They are distributed uniformly with concentration *1 - p*.
- The defects are quenched and are not to be treated as statistical variables.



Damage Properties

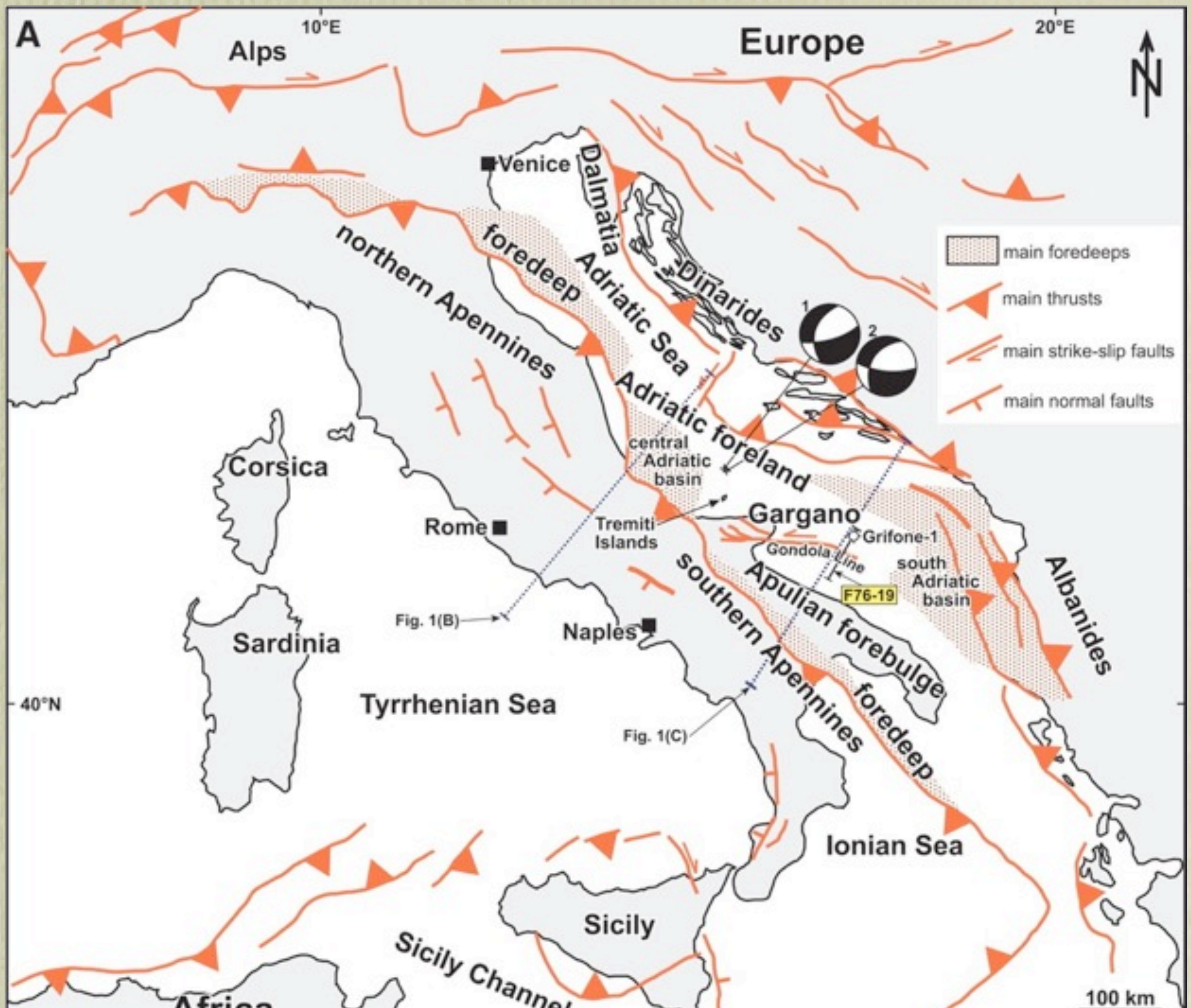
- The damaged sites are dissipative in nature.
- They are distributed uniformly with concentration *1 - p*.
- The defects are quenched and are not to be treated as statistical variables.



Fault System

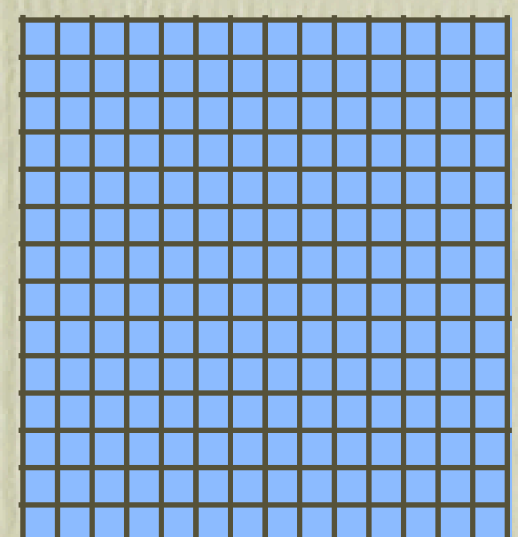
- Different elevation
- Different soils types
- Different geometries
- Irregular spacing
- In general, complicated

See, for example, Tiampo *et. al. Euro. Phys. Lett.* **60,** 481 (2002) & Tiampo *et. al. Phys. Rev. E* **75**, 066107 (2007)

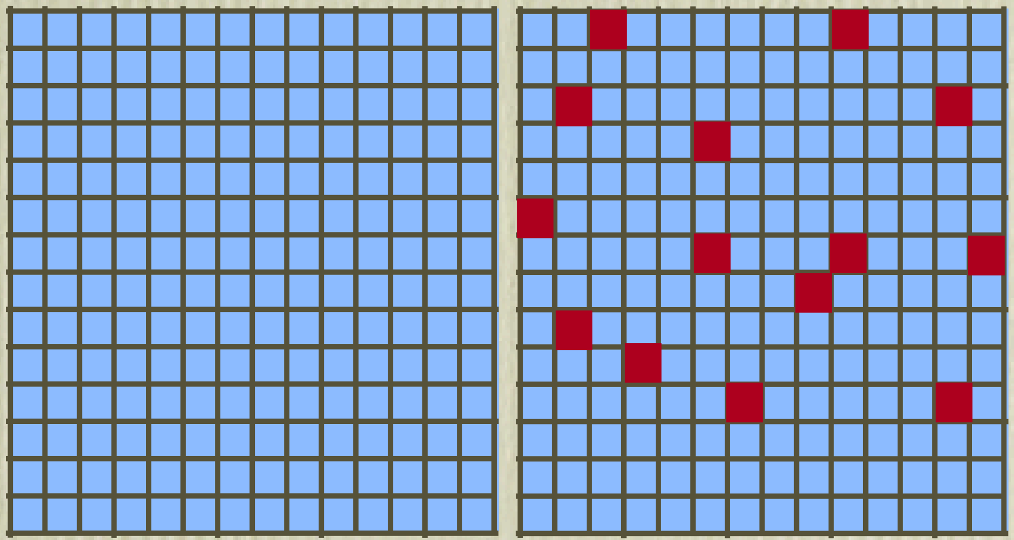


[A. Billi *et al. Geosphere* **3**, 1 (2007)]

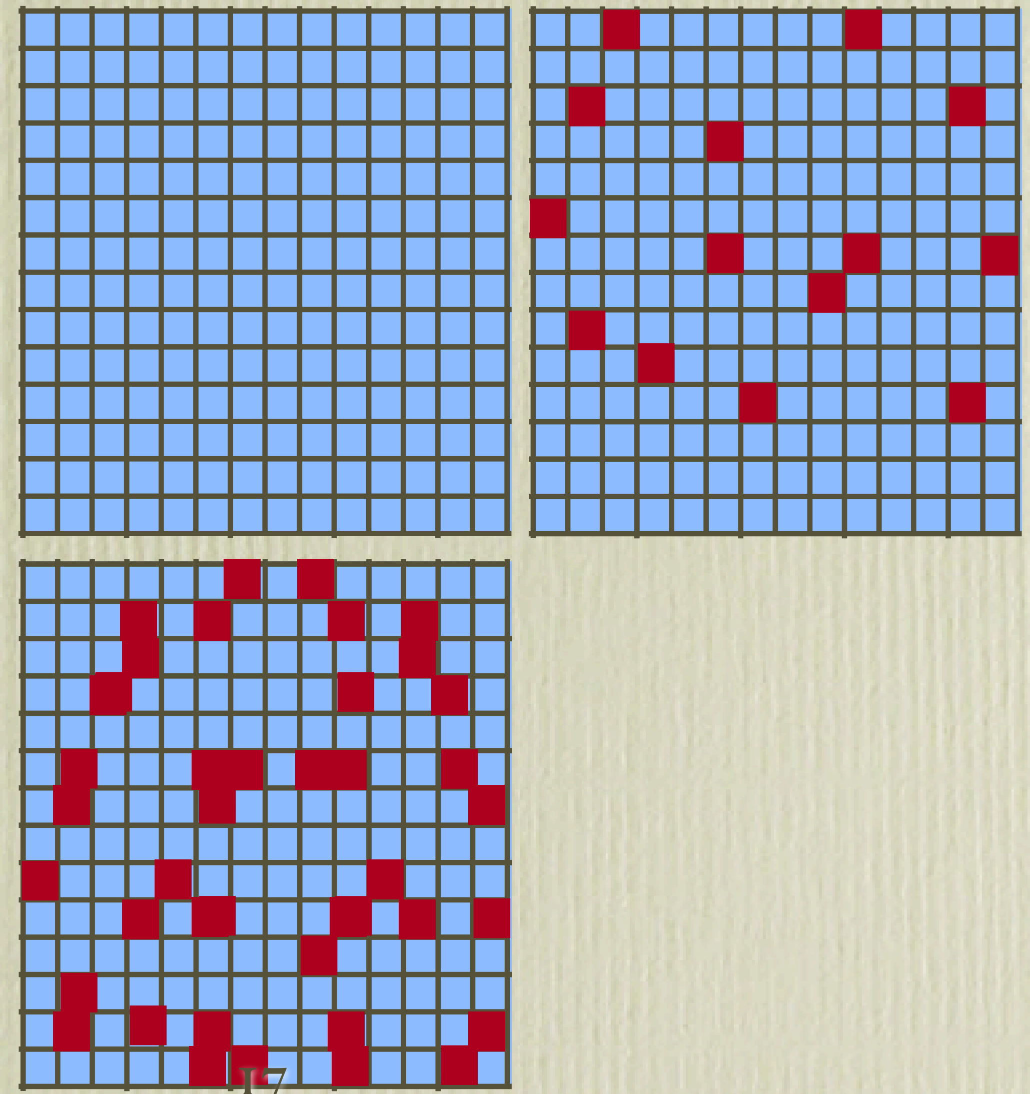
"Fault System"



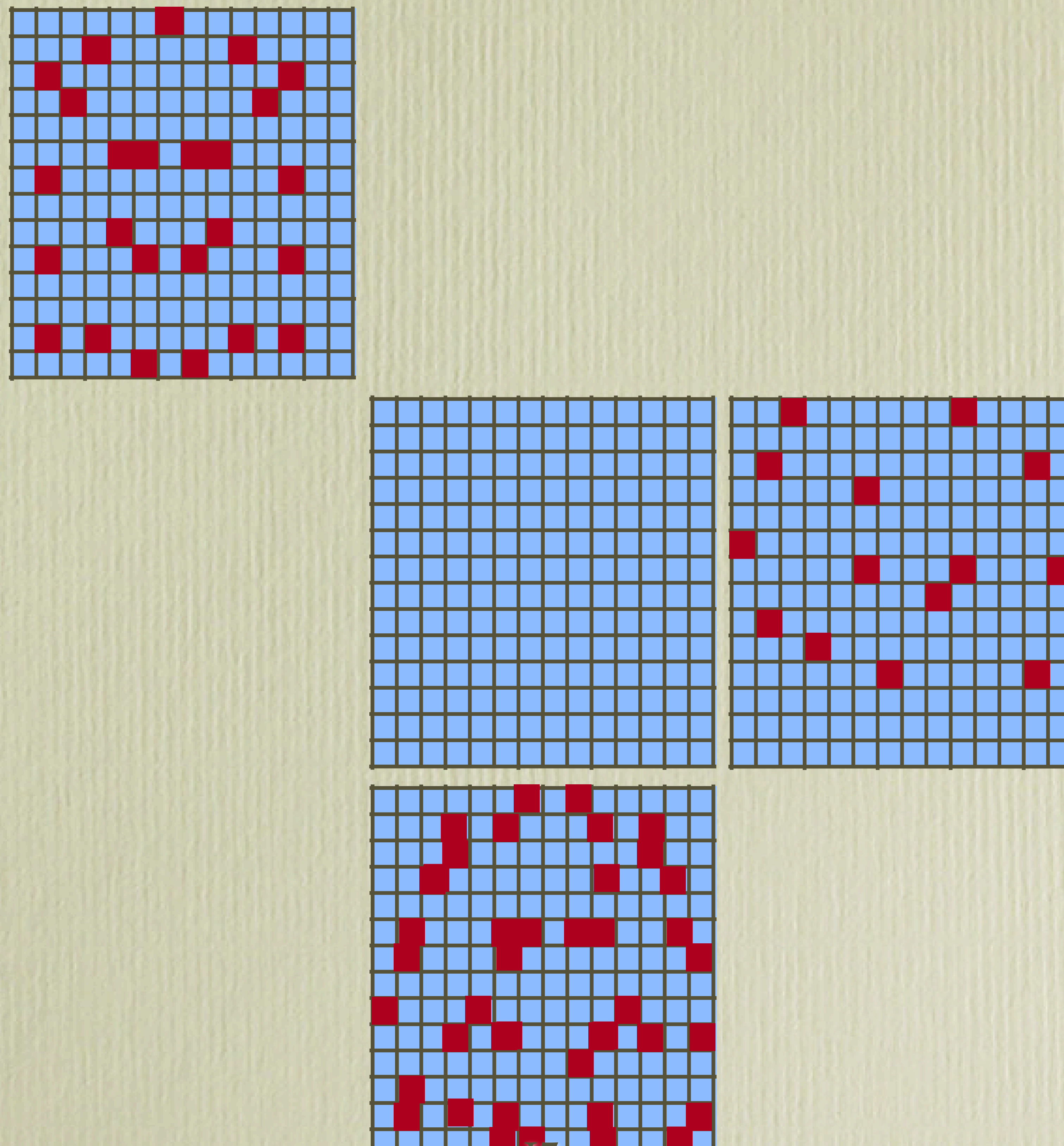
"Fault System"



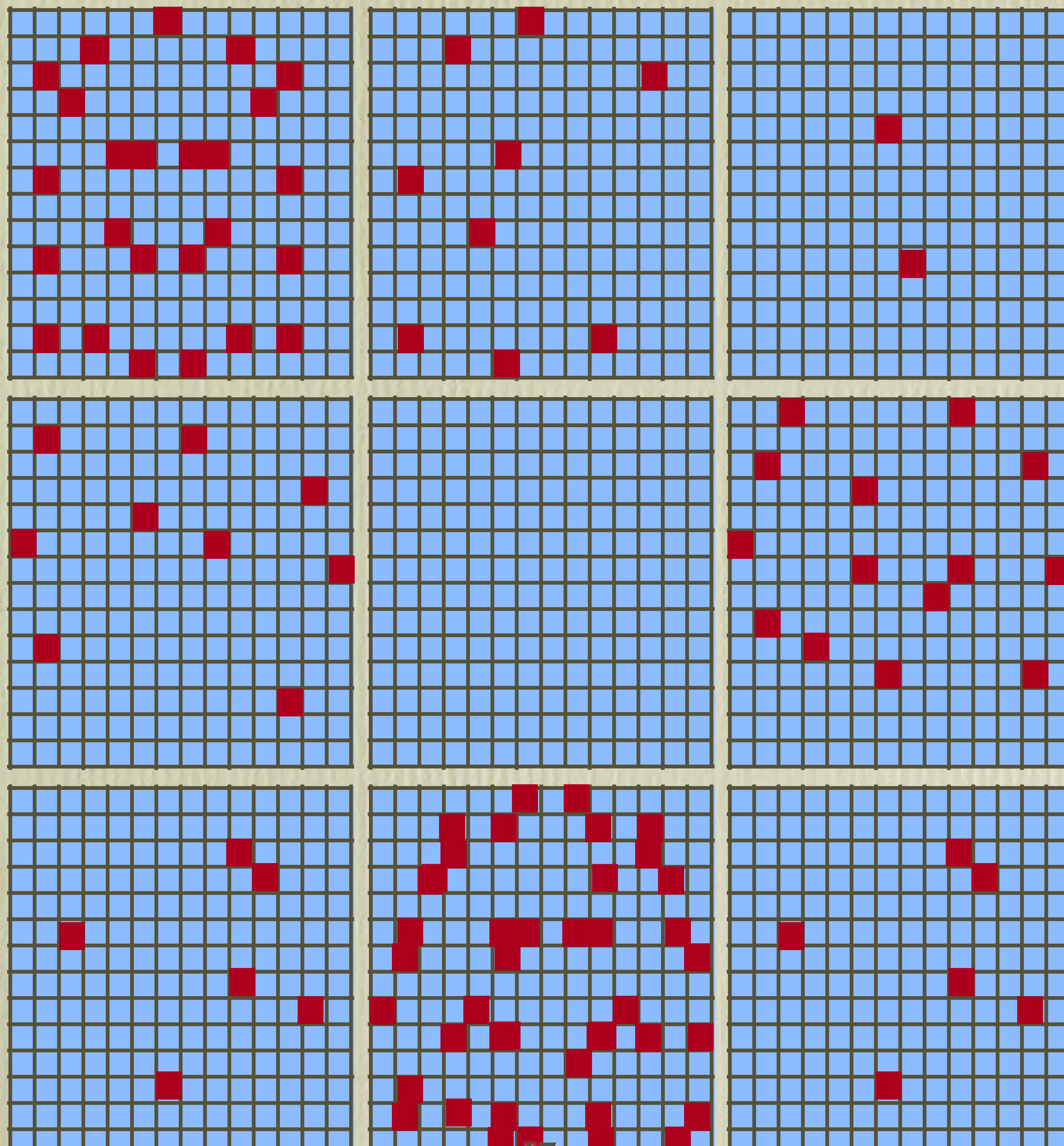
“Fault System”



"Fault System"



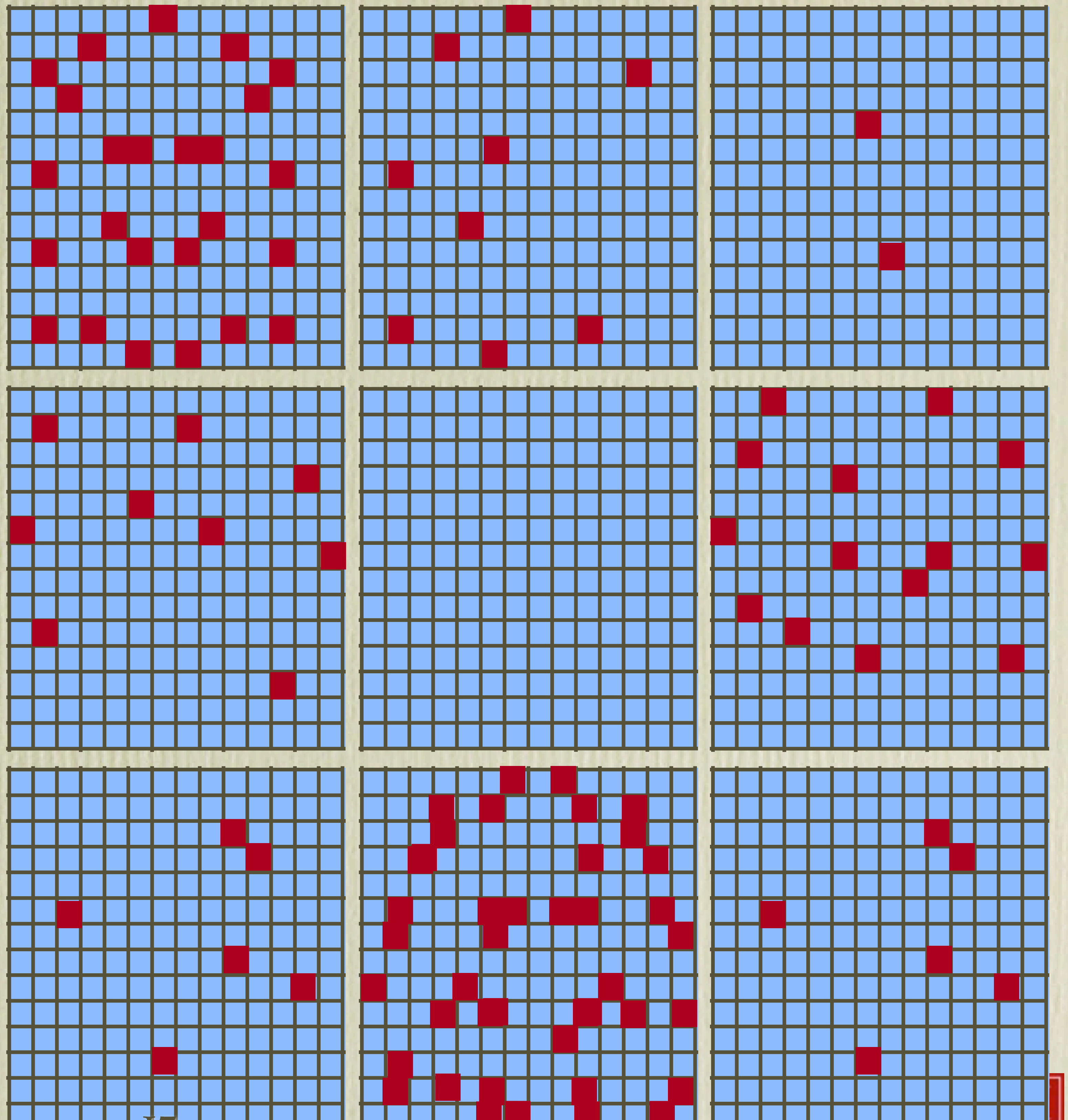
"Fault System"



C. A. Serino

"Fault System"

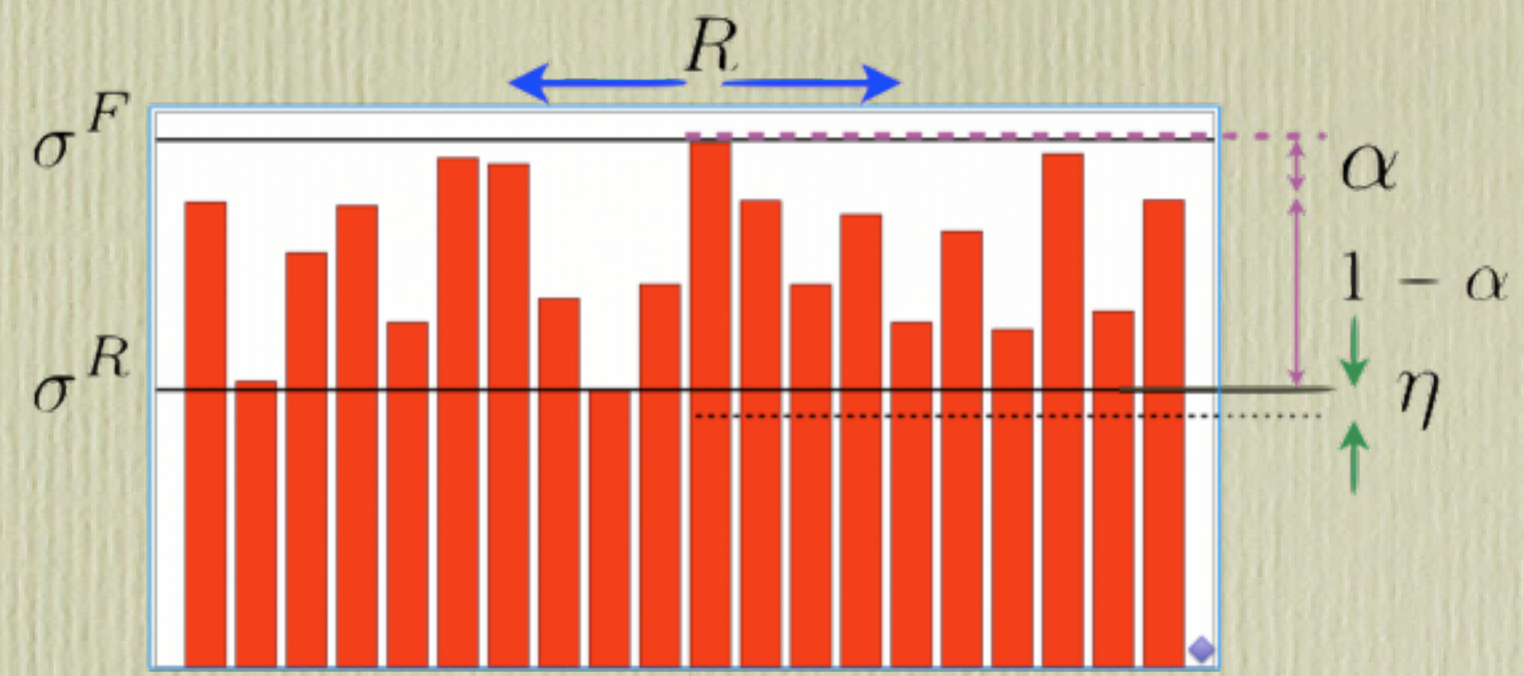
- To simulate a fault system, we include *many* faults.
- This is not computationally feasible.
- Instead we work in the limit where the linear size of the fault diverges and, thus, fault-fault interactions can be neglected.
- We can now simulate a single fault and average the data post-simulation.

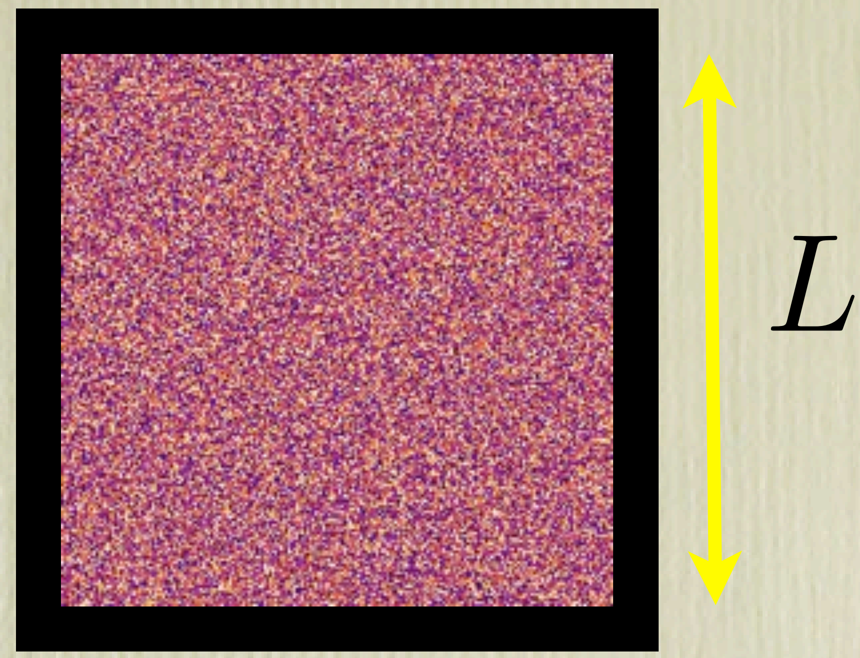


Outline

- Observations, Empirical Scaling & Motivation
- Early Models
- Model "Fault System"
- **Simulations & Numerical Data**
- Theoretical Description
- Future Work & Similar Physical Systems

Parameter Values



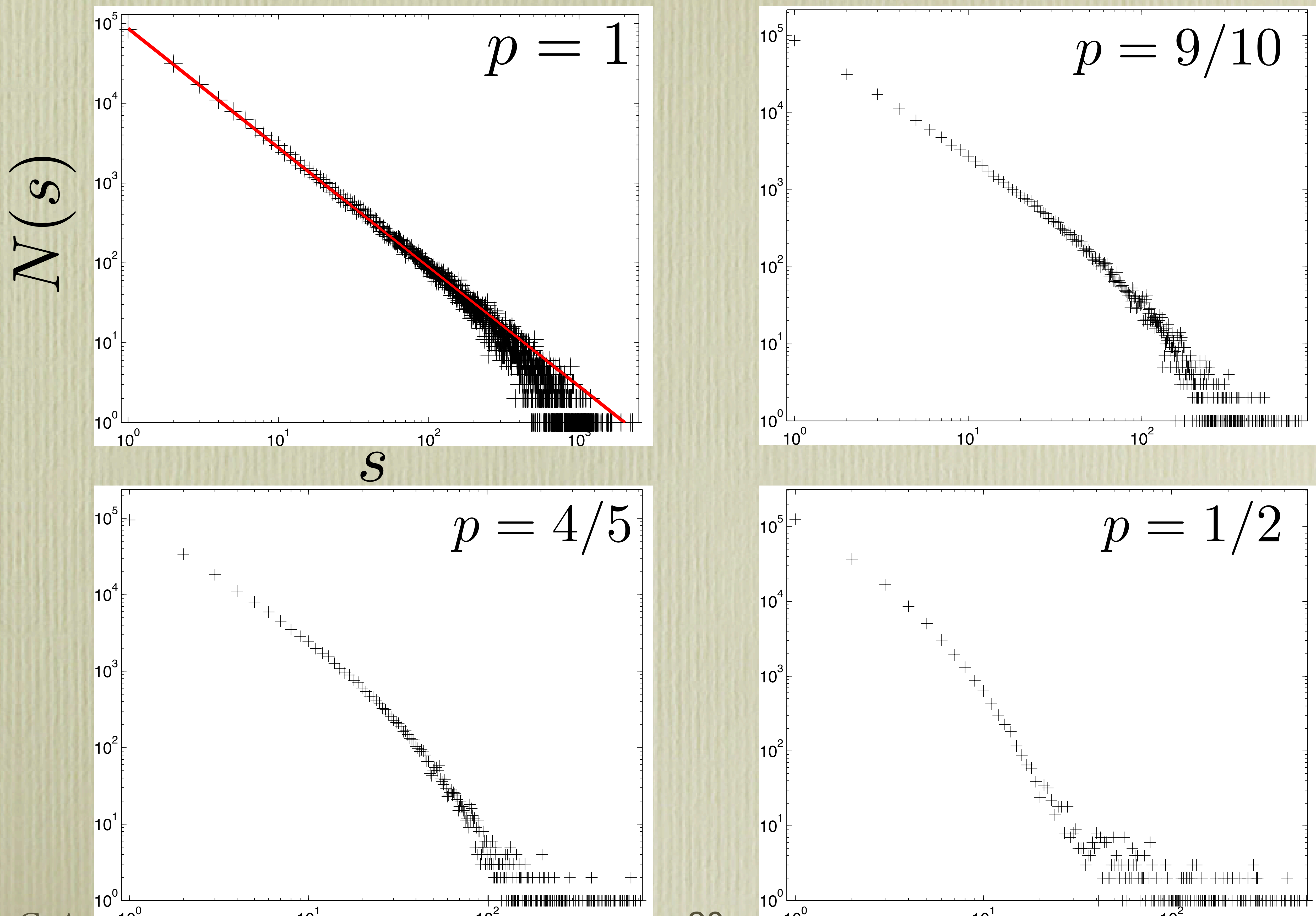


$\sigma^F = 2$	$\sigma^R = 1$	$R = 20$
$\alpha = 0.025$	$d = 2$	$L = 512$

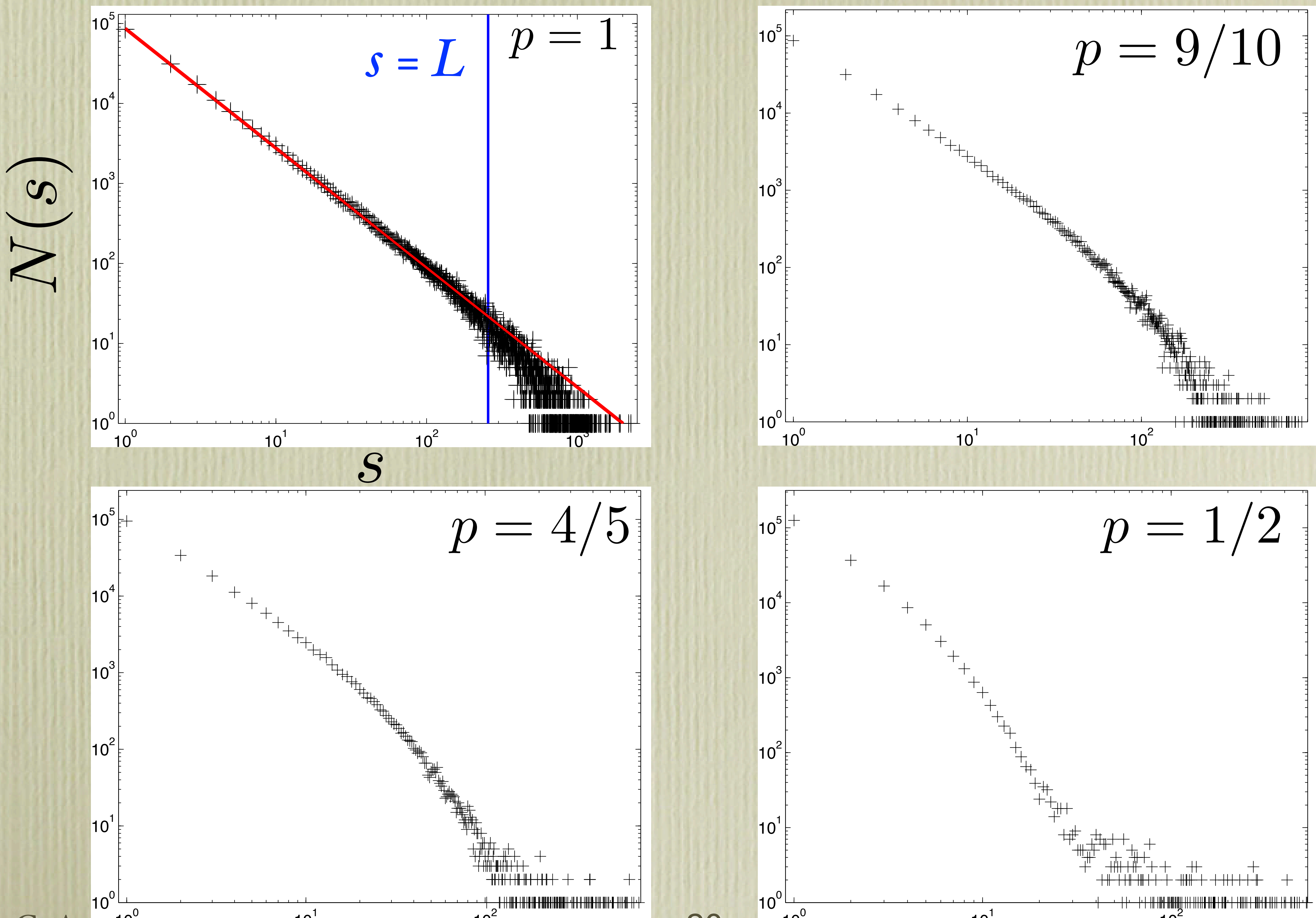
$$\rho(\eta) = \frac{1}{0.2}\,\Theta(1.1 - \eta)\Theta(\eta - 0.9)$$

(flat random on [0.9 , 1.1])

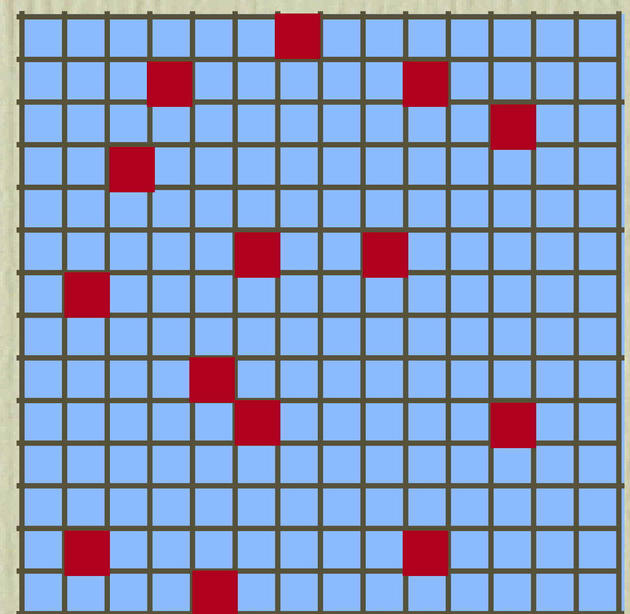
Scaling on Damaged Faults

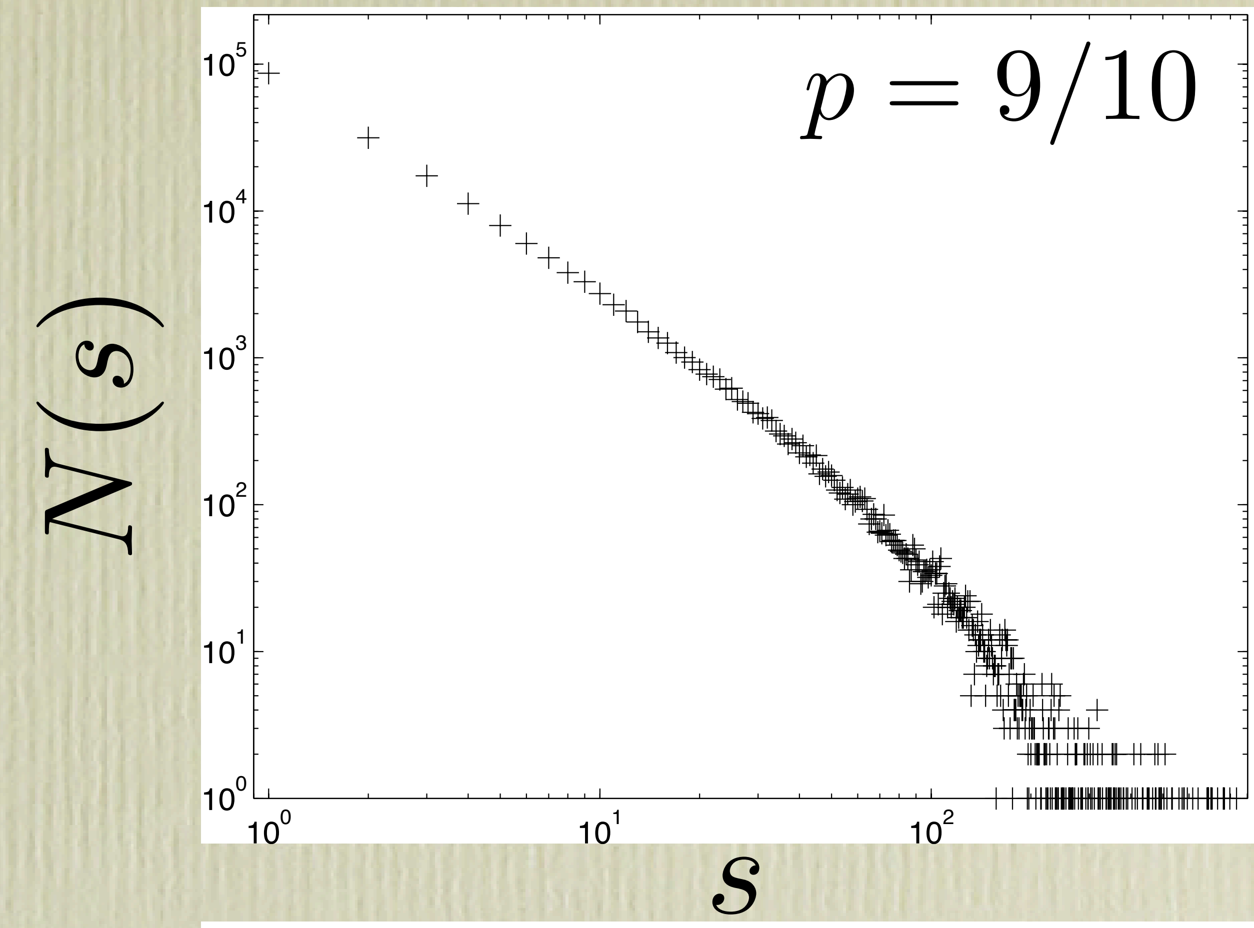


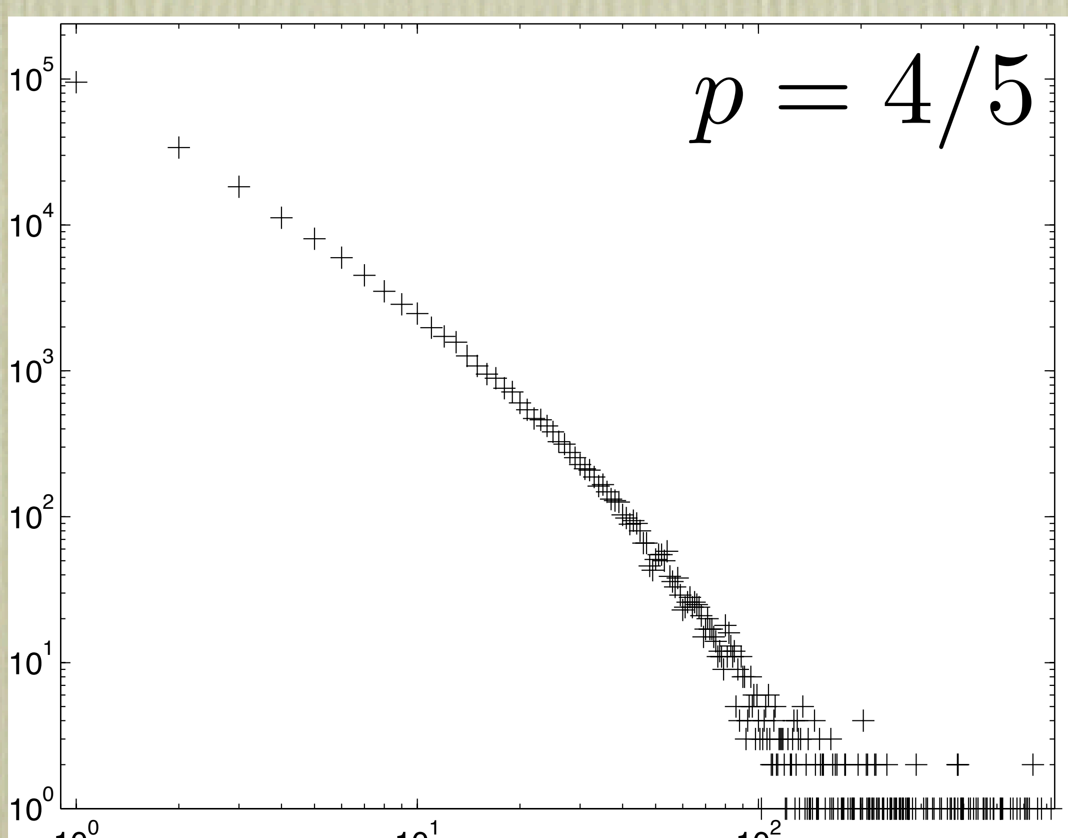
Scaling on Damaged Faults

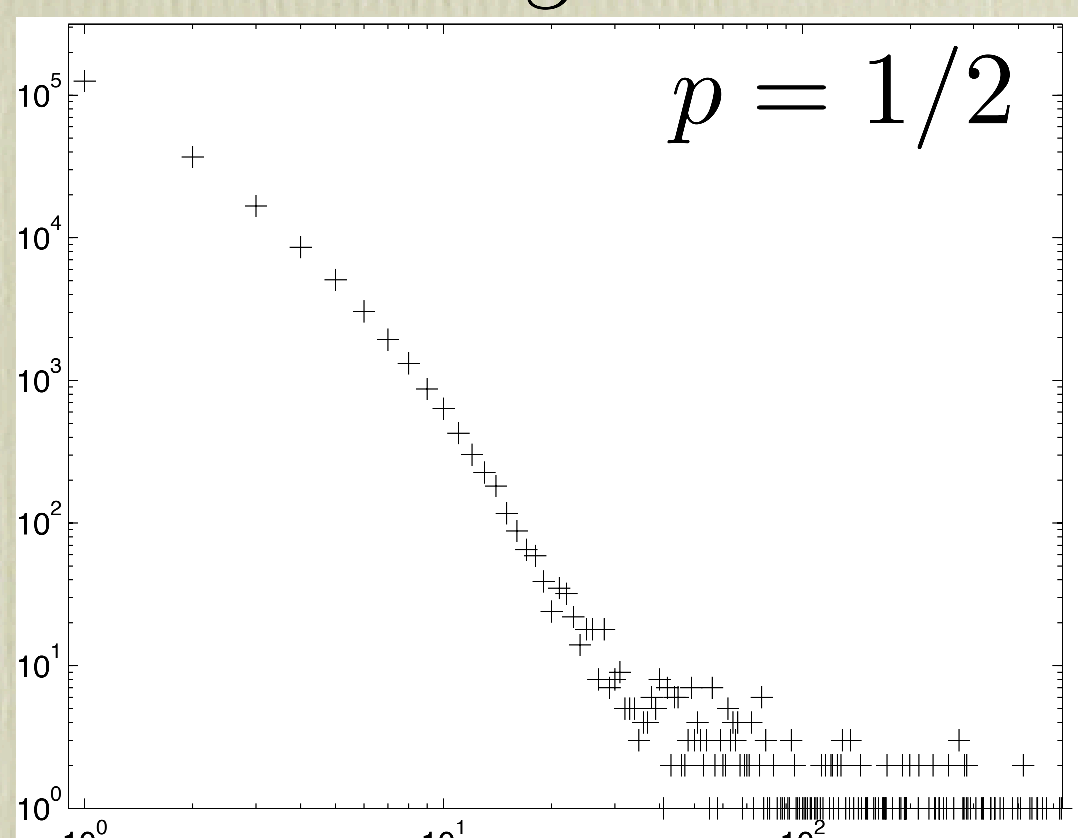


Scaling on Damaged Faults

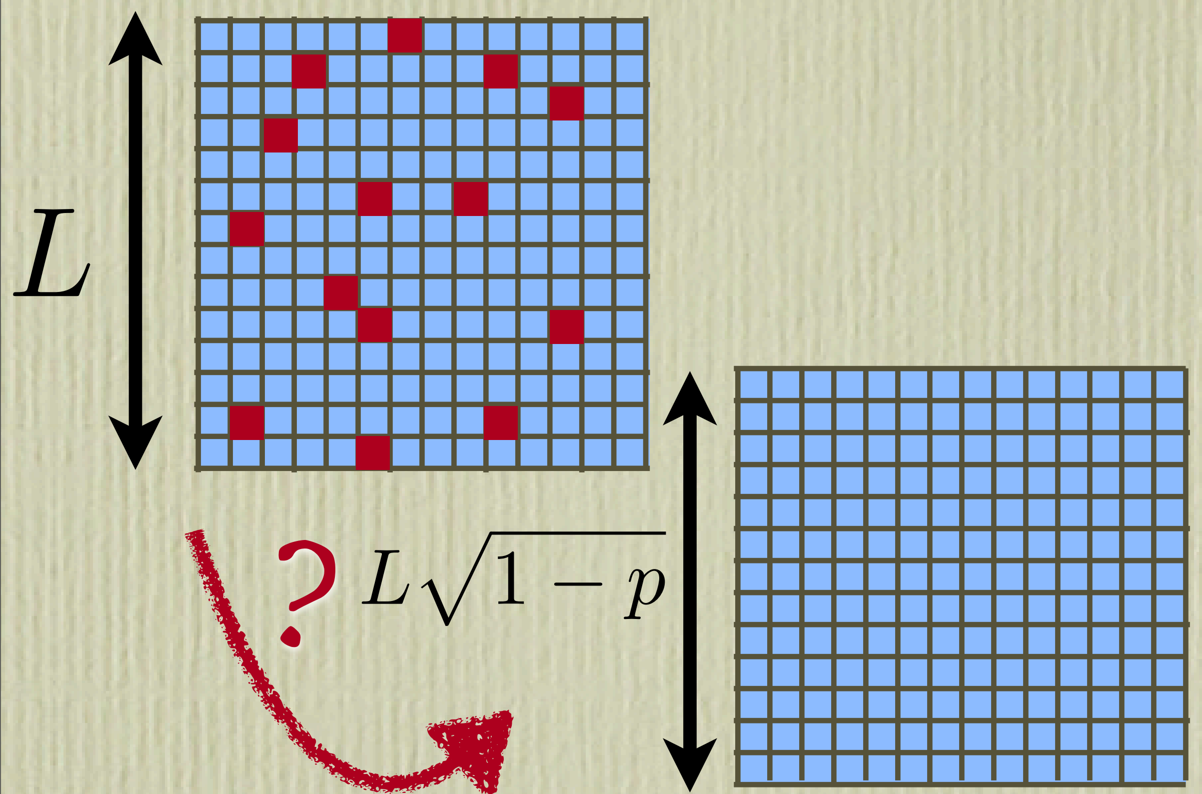


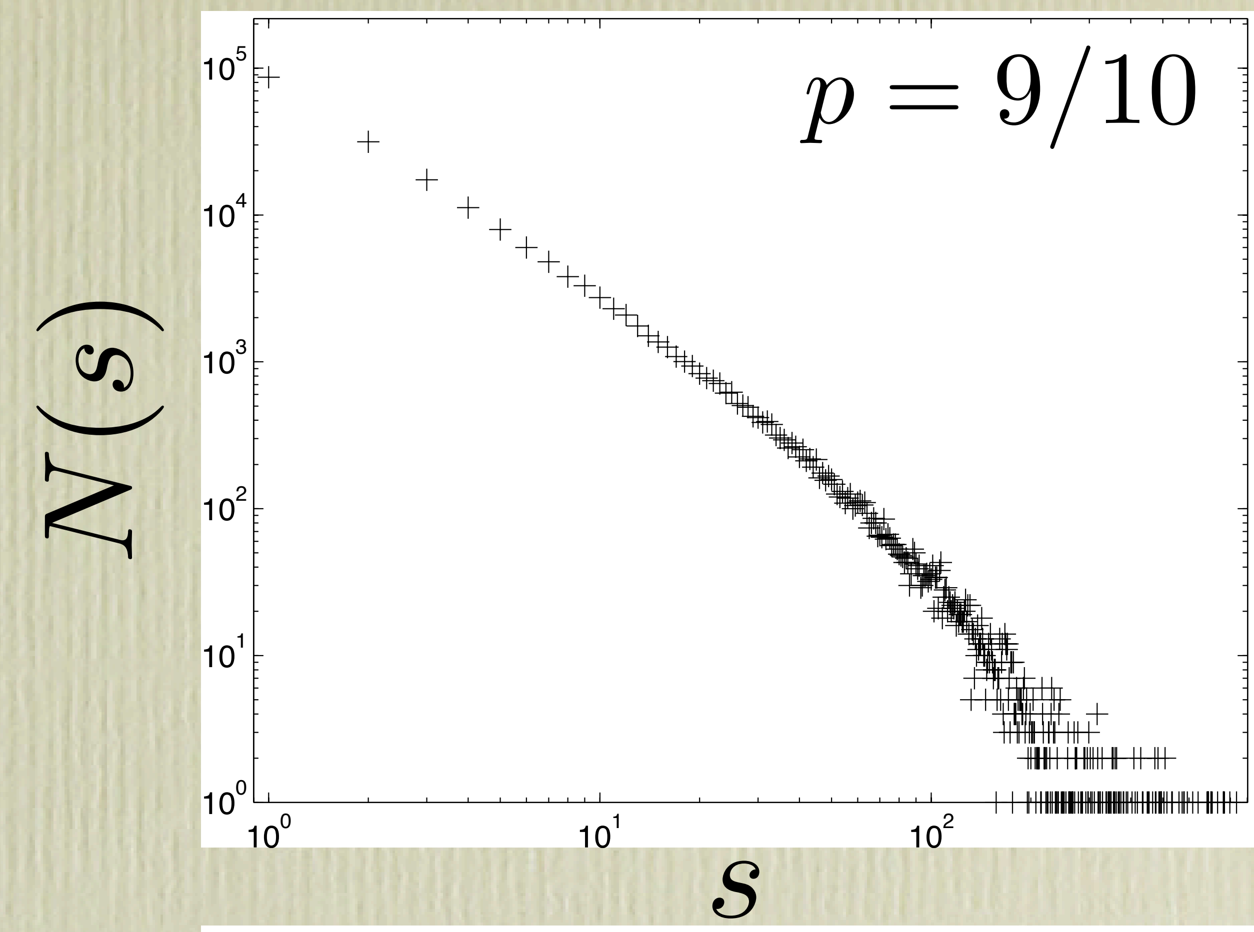


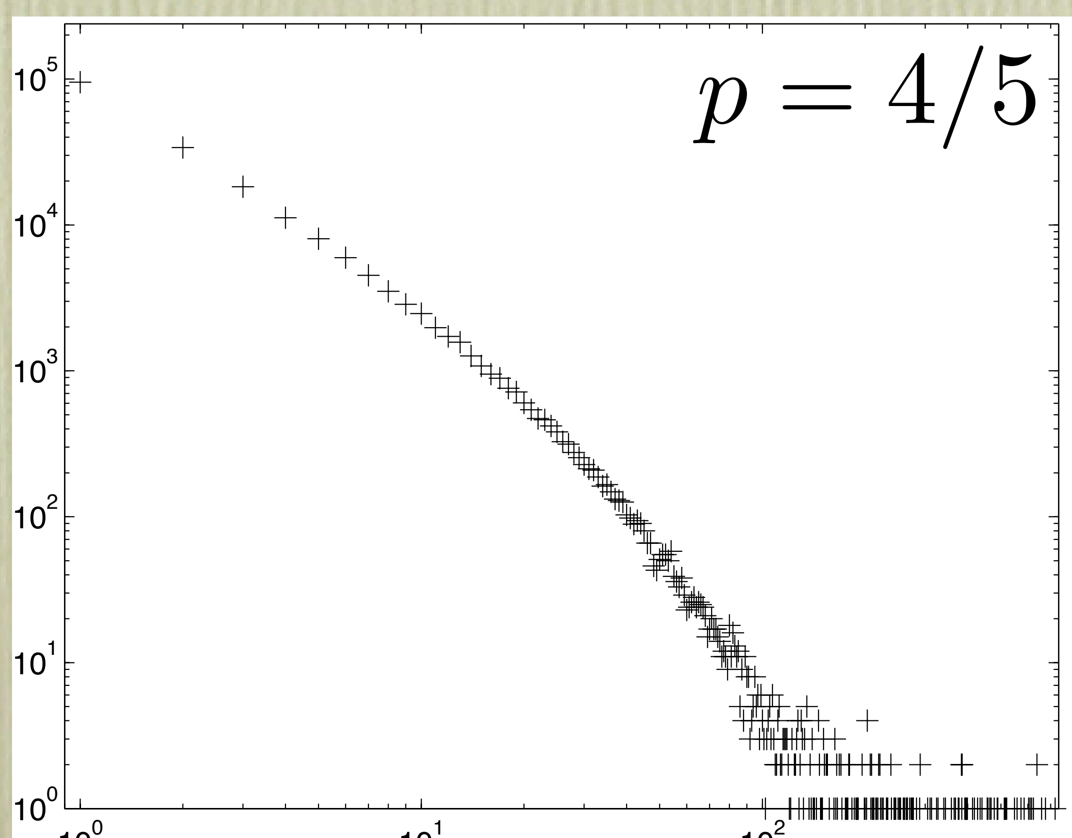


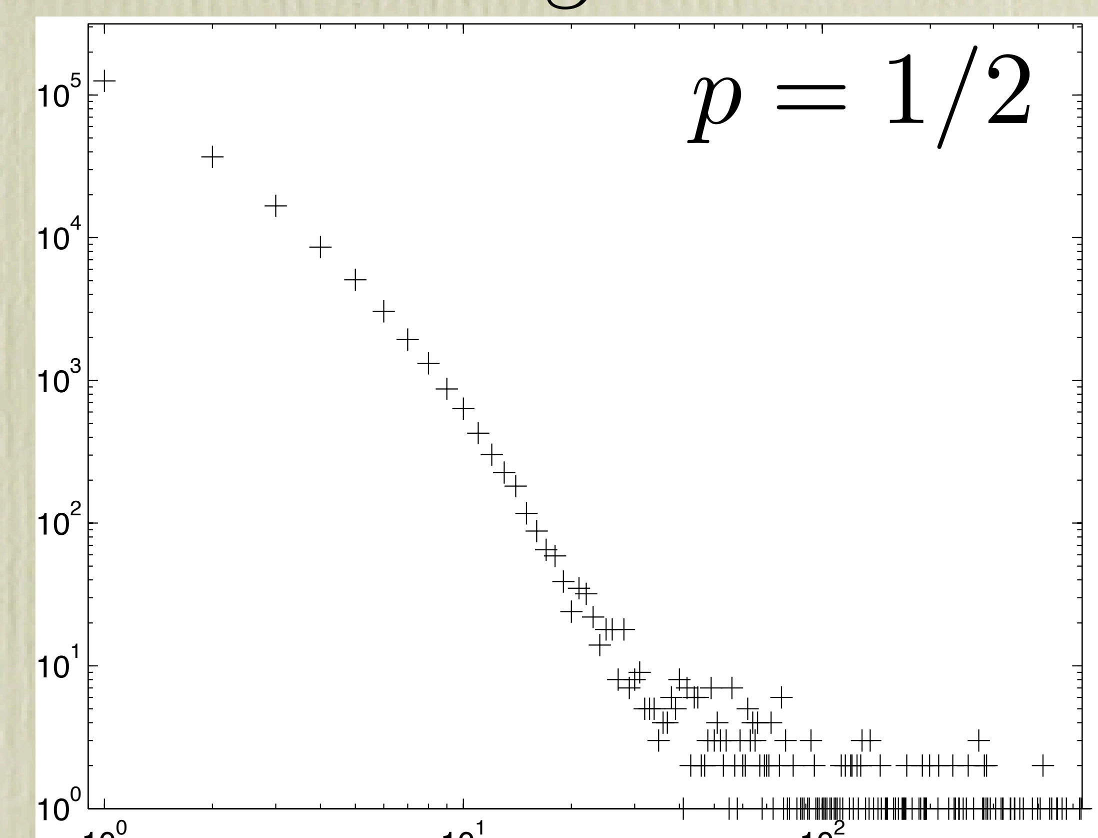


Reduced Size $\stackrel{?}{=}$ Damaged Lattice

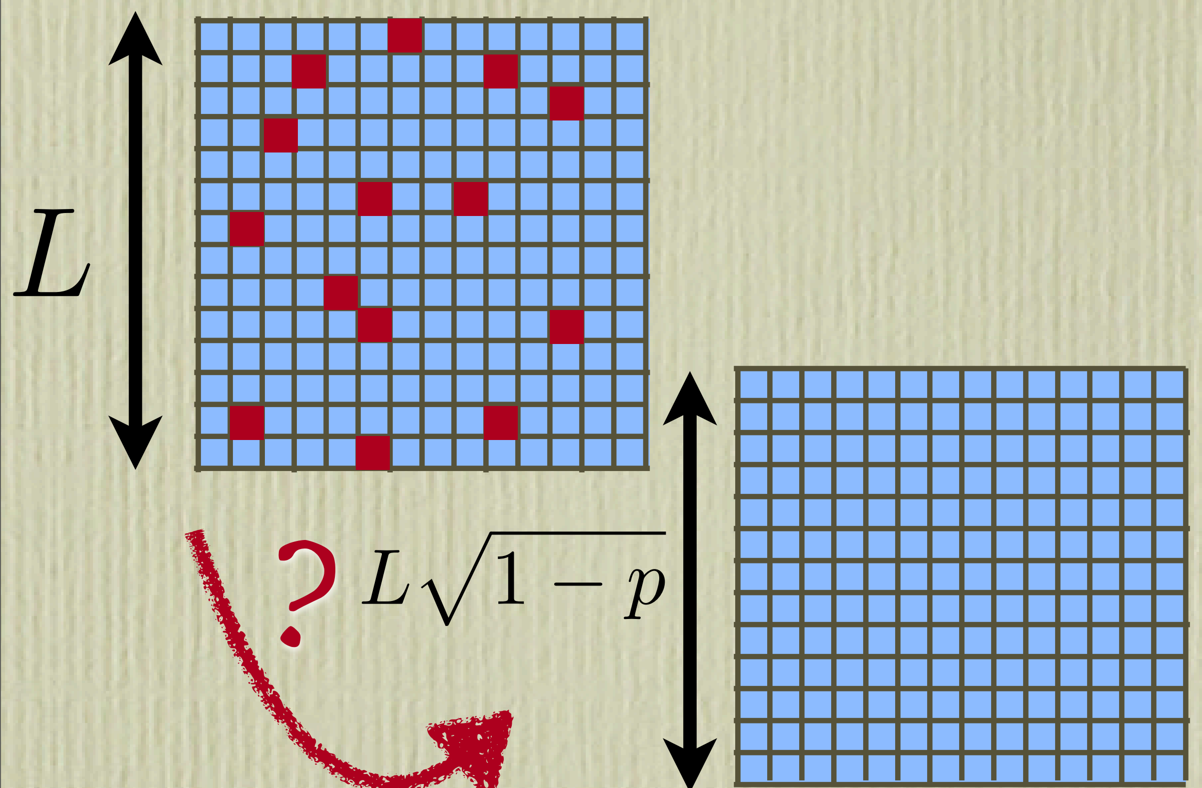


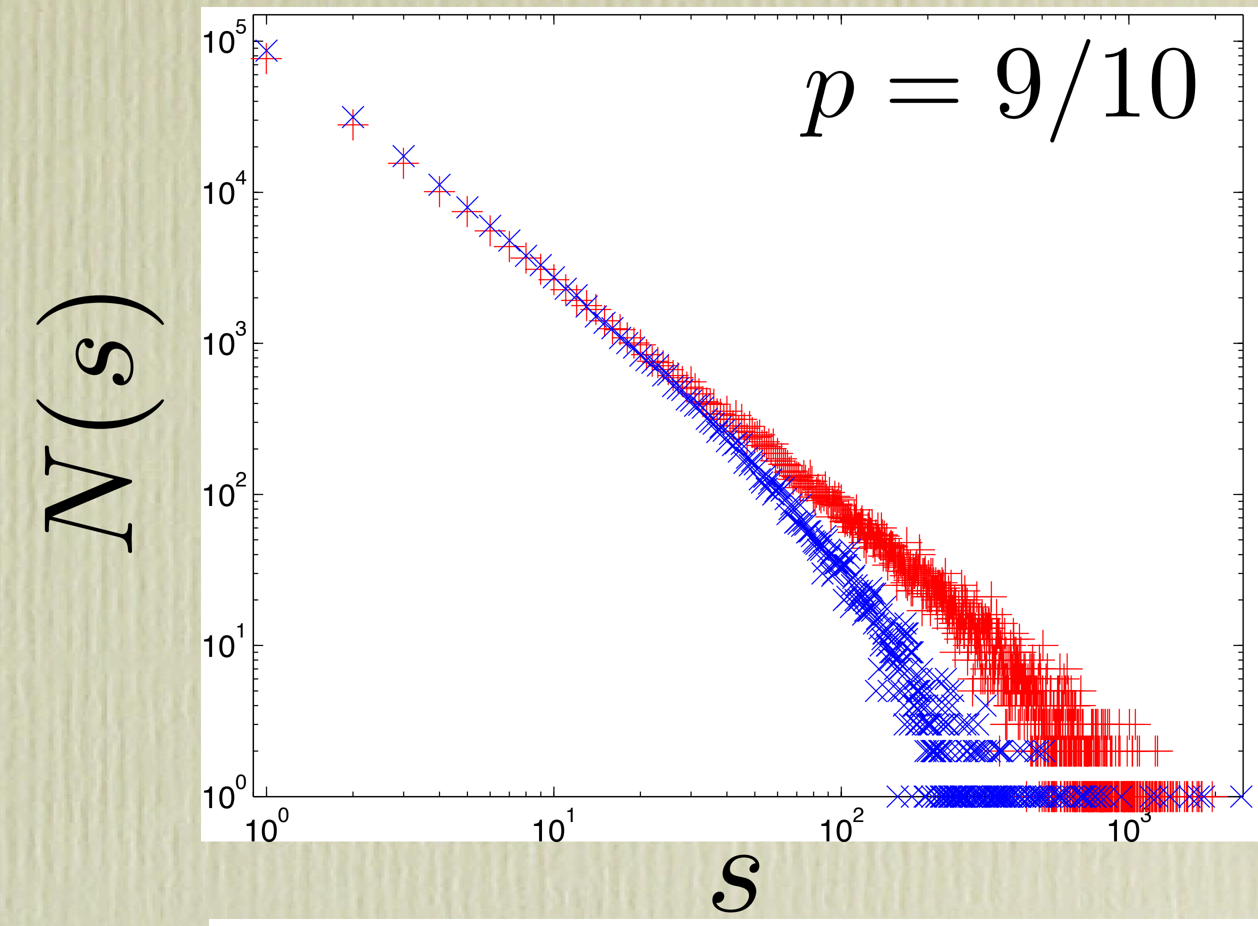


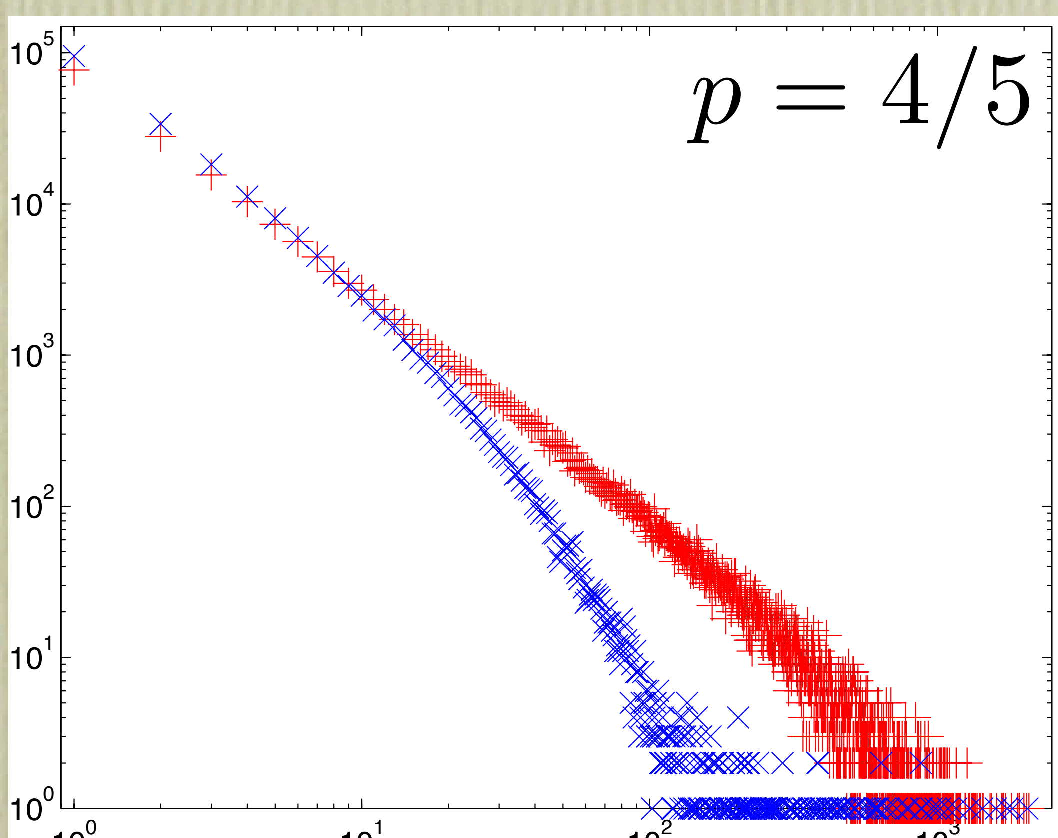


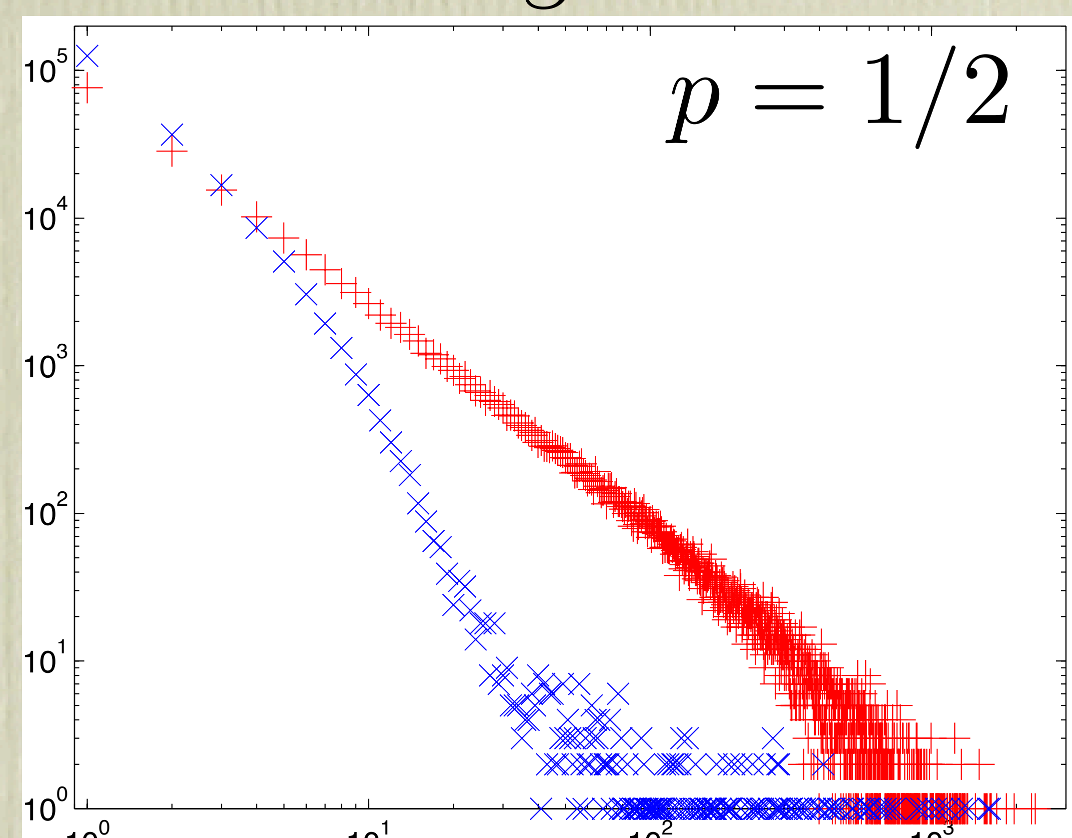


Reduced Size ≠ Damaged Lattice









Effectively Larger α

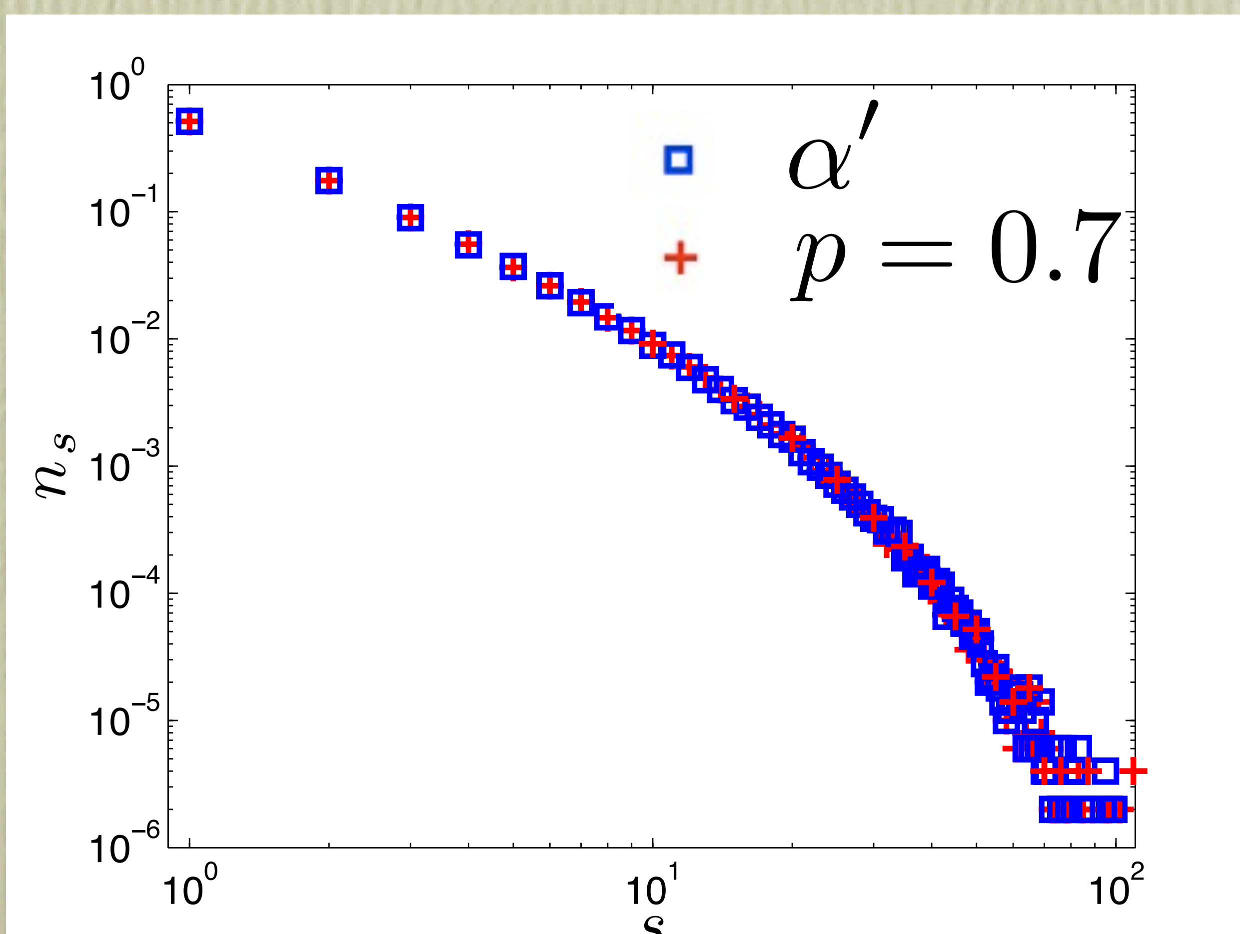
- In the damaged model, when a site fails and passes its stress to its neighbors, additional stress is dissipated by the dead sites.

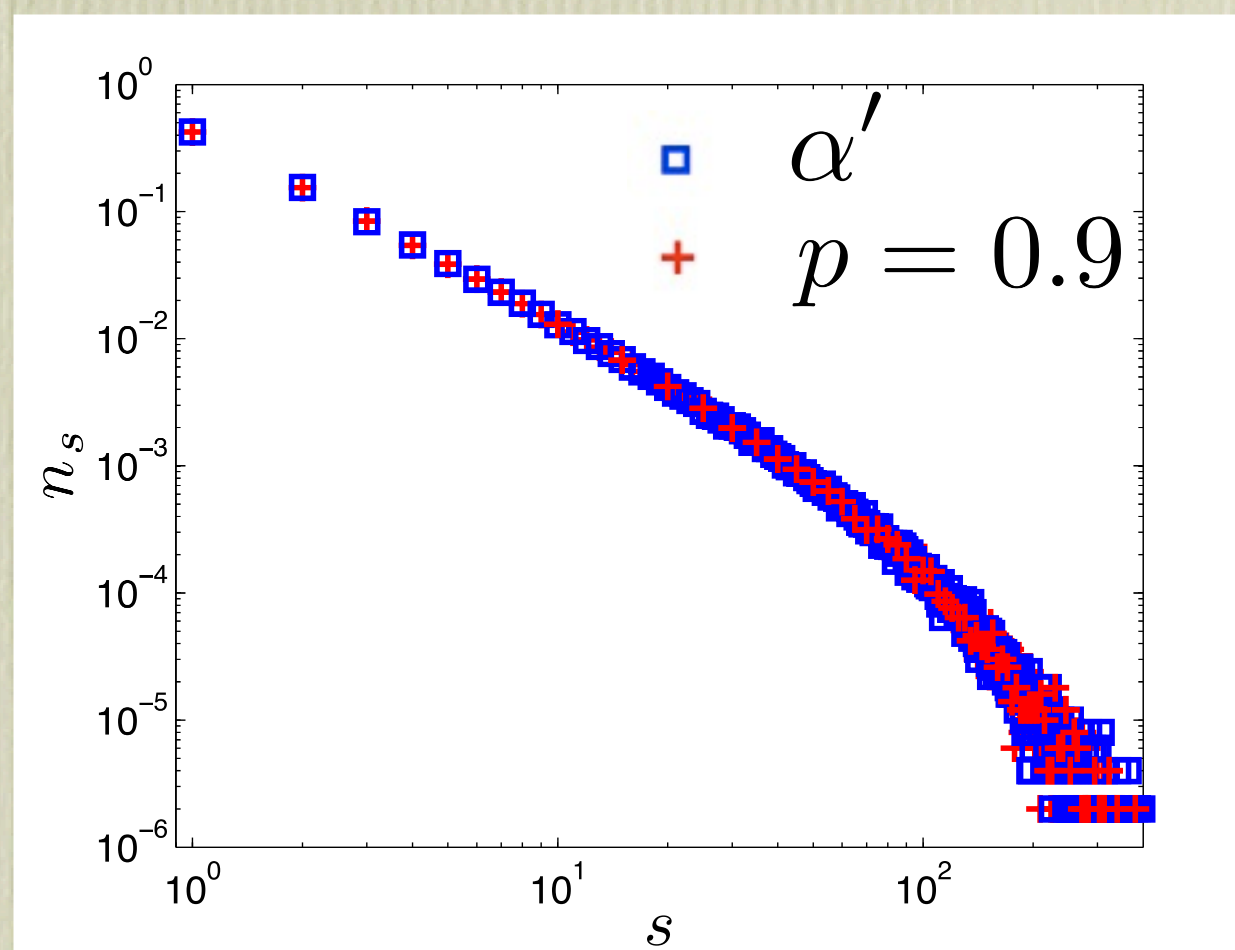
- On average (or exactly in the meanfield limit) the extra fraction of dissipated stress is simply the density of damaged sites, 1 - *p*.

- This suggests a model with damage *p* and dissipation a will produce the same frequency-size statistics as an undamaged model running with dissipation $\alpha' = 1 - p(1 - \alpha)$.

Effectively Larger α

- In the damaged model, when a site fails and passes its stress to its neighbors, additional stress is dissipated by the dead sites.
- On average (or exactly in the meanfield limit) the extra fraction of dissipated stress is simply the density of damaged sites, 1 - *p*.
- This suggests a model with damage *p* and dissipation a will produce the same frequency-size statistics as an undamaged model running with dissipation $\alpha' = 1 - p(1-\alpha)$.

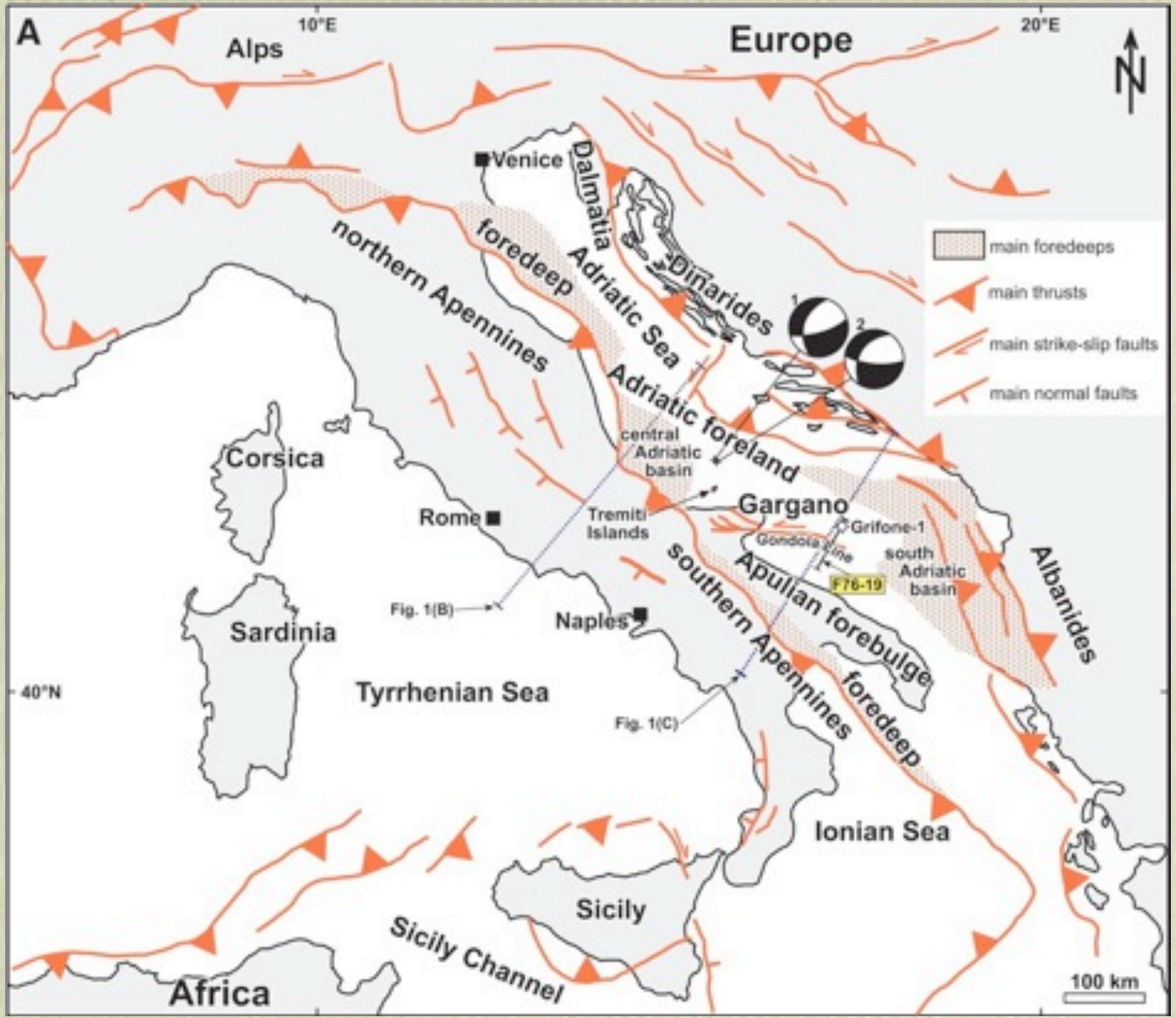




Seismologists, Geologists, and the Data they Collect

- Data is collected across *fault systems*, not just individual faults and thus, data is collected over regions with many inhomogeneities.

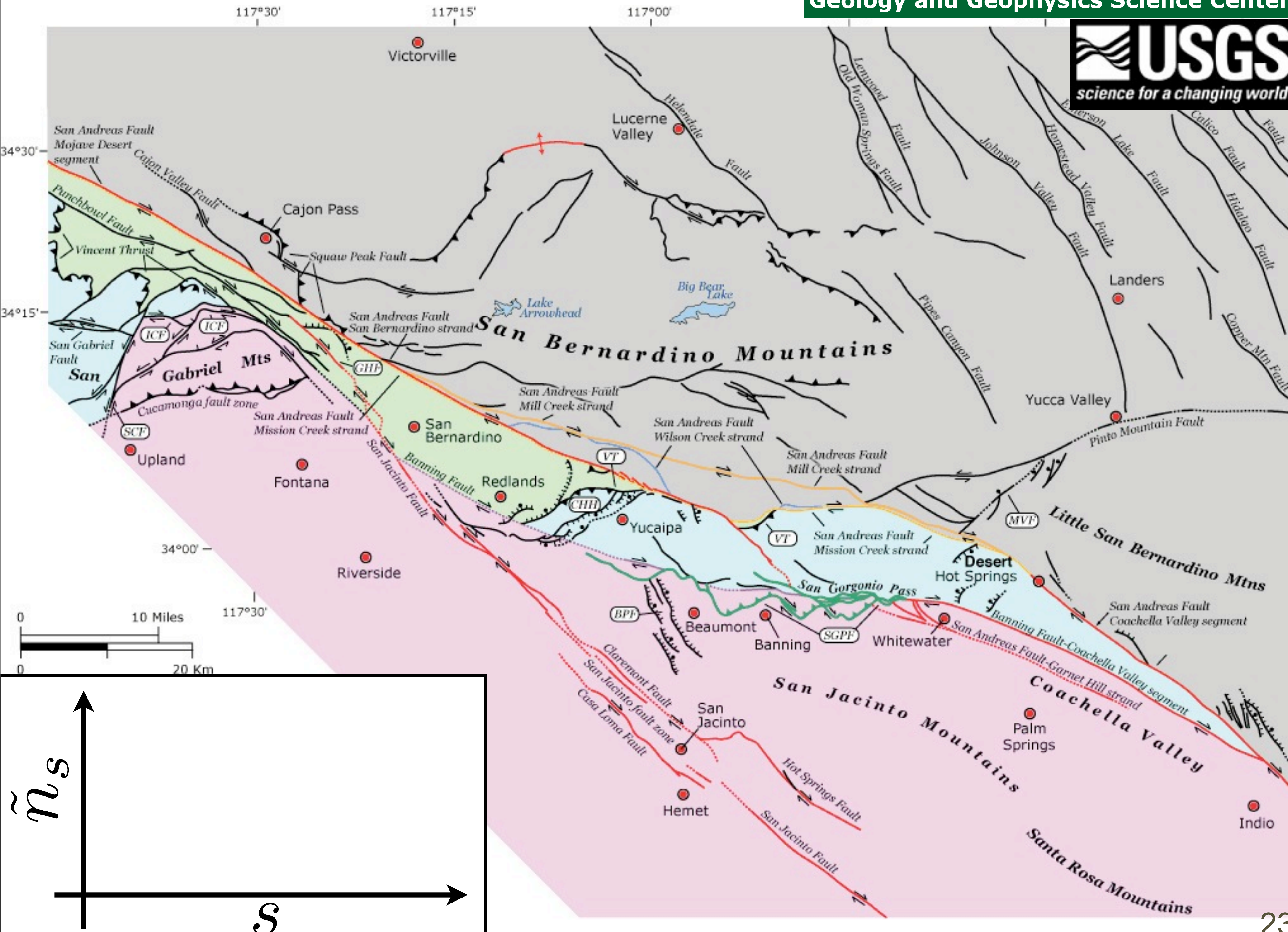
[E. R. Dominguez *et. al.* in preparation]

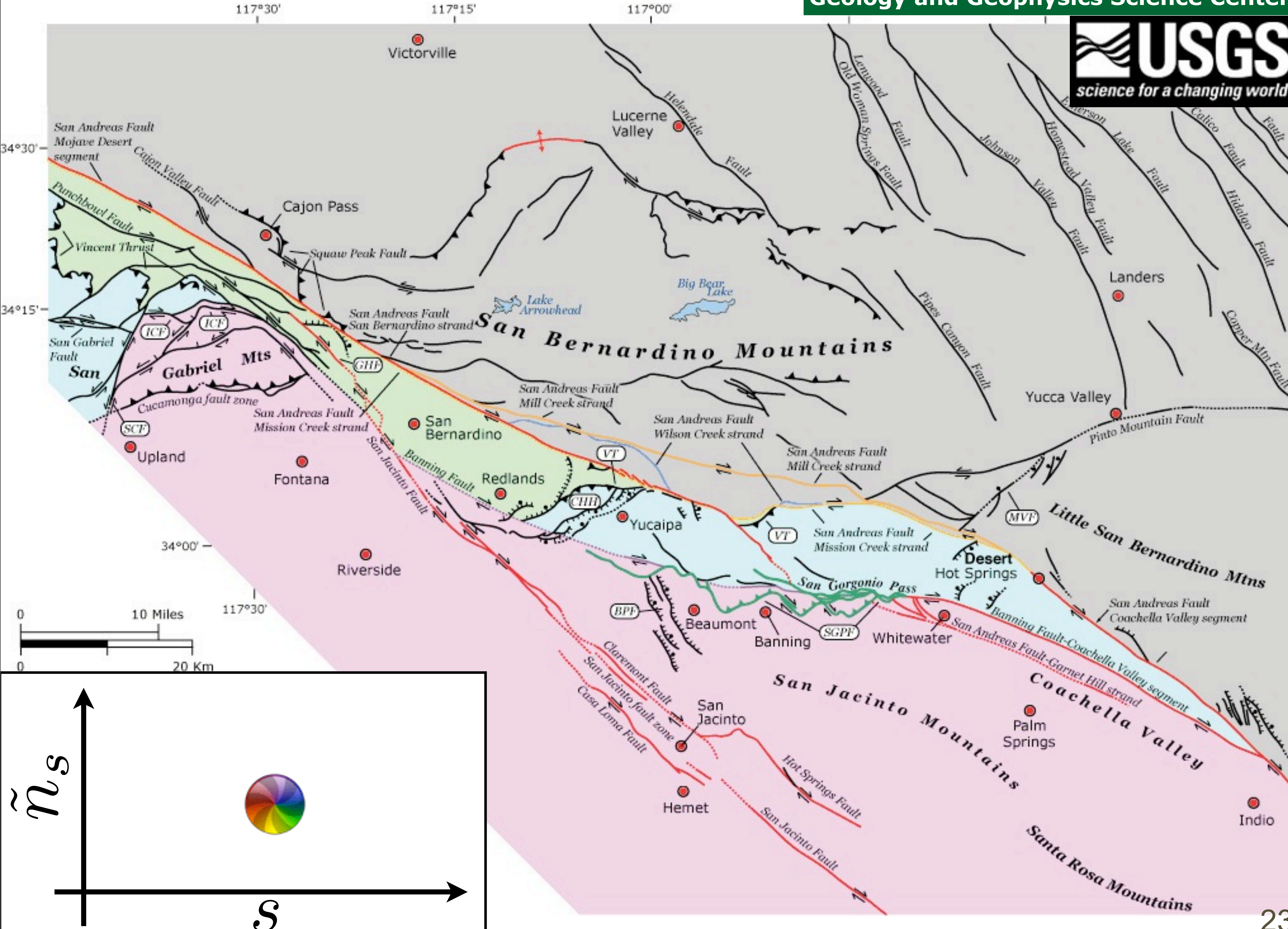


[A. Billi *et al.* *Geosphere* **3**, 1 (2007)]

BOSTON UNIVERSITY

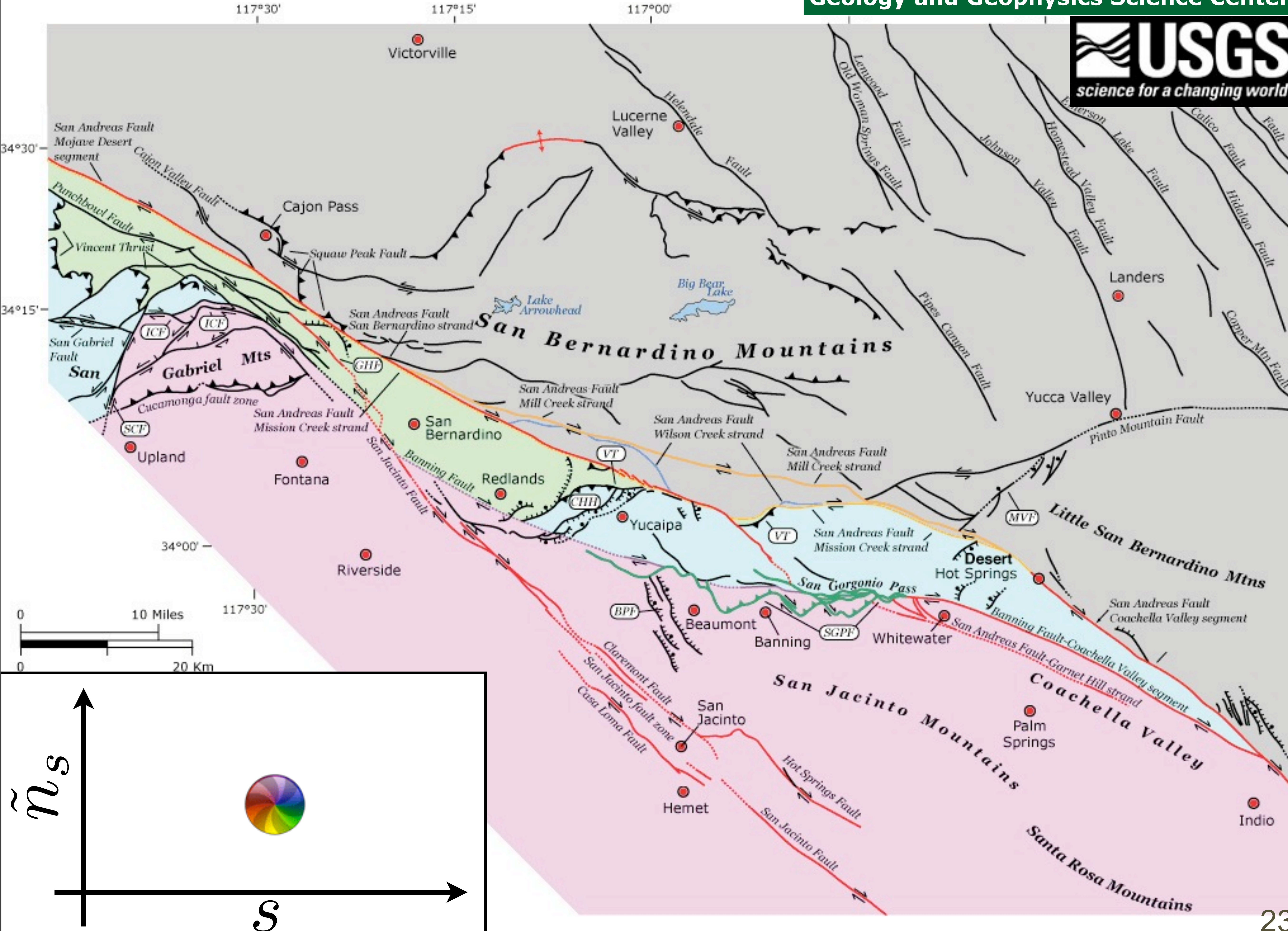
USGS science for a changing world



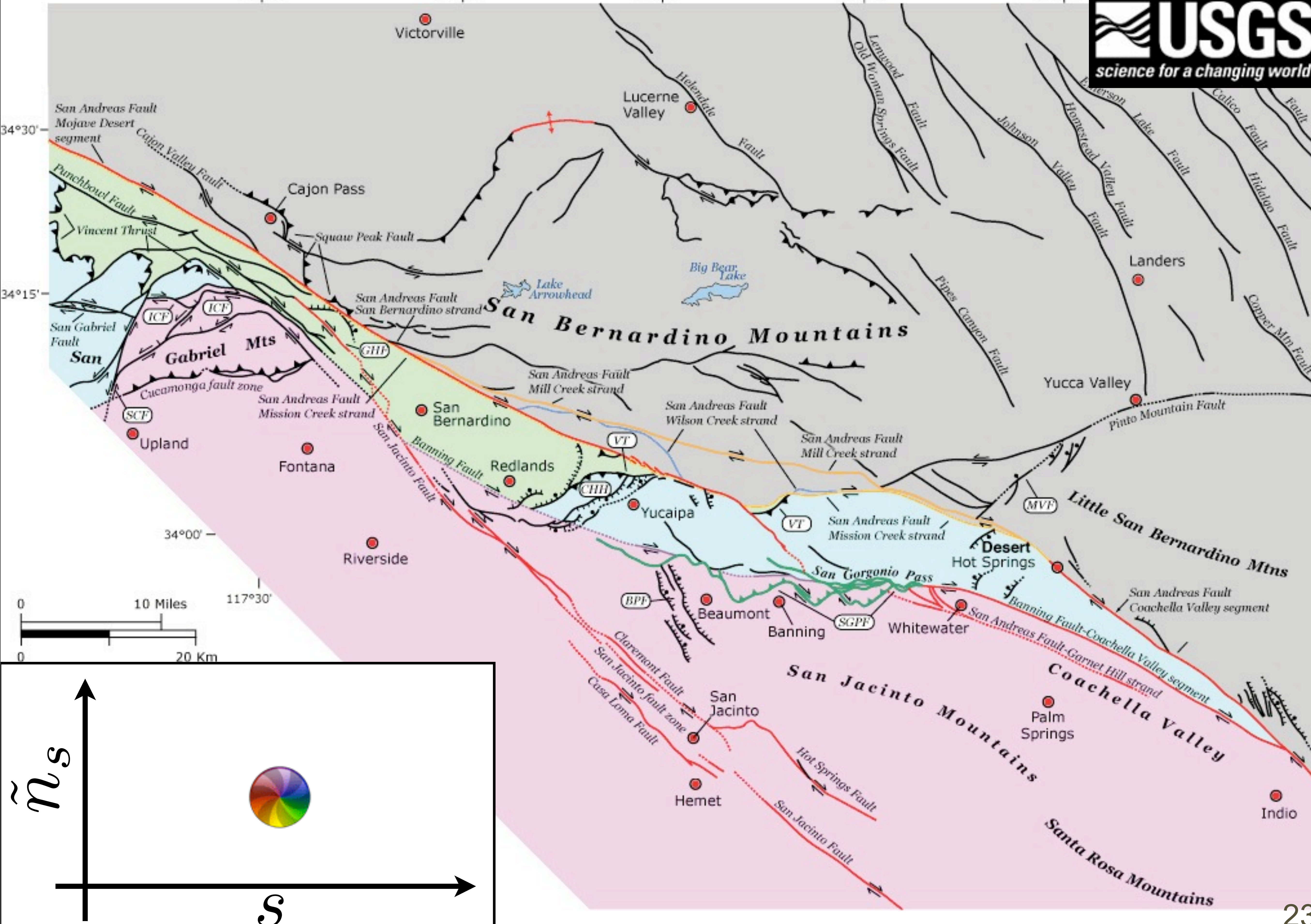

117°30'
117°15'
117°00'
34°30'
34°15'
34°00'
117°30'
Victorville
Lucerne Valley
Helendale Fault
Lenwood Fault
Old Woman Springs Fault
Johnson Valley Fault
Homestead Valley Fault
Emerson Lake Fault
Calico Fault
Hidalgo Fault
Camp Rock Fault
Landers
Pipes Canyon Fault
Copper Mtn Fault
Yucca Valley
Pinto Mountain Fault
San Andreas Fault Mojave Desert segment
Cajon Valley Fault
Punchbowl Fault
Vincent Thrust
Cajon Pass
Squaw Peak Fault
Lake Arrowhead
Big Bear Lake
San Andreas Fault San Bernardino strand
San Bernardino Mountains
San Gabriel Fault
San Gabriel Mts
ICF
GHF
Cucamonga fault zone
SCF
Upland
Fontana
San Andreas Fault Mission Creek strand
San Bernardino
San Andreas Fault Mill Creek strand
San Andreas Fault Wilson Creek strand
San Andreas Fault Mill Creek strand
VT
Banning Fault
San Jacinto Fault
Redlands
CHH
Yucaipa
San Andreas Fault Mission Creek strand
MVF
Little San Bernardino Mtns
Desert Hot Springs
Riverside
San Gorgonio Pass
BPF
Beaumont
Banning
SGPF
Whitewater
San Andreas Fault Coachella Valley segment
Banning Fault-Coachella Valley segment
San Andreas Fault-Garnet Hill strand
Claremont Fault
San Jacinto fault zone
Casa Loma Fault
San Jacinto
San Jacinto Mountains
Coachella Valley
Palm Springs
Hemet
Hot Springs Fault
San Jacinto Fault
Indio
Santa Rosa Mountains
0
10 Miles
0
20 Km
$\tilde{n}_S$
S

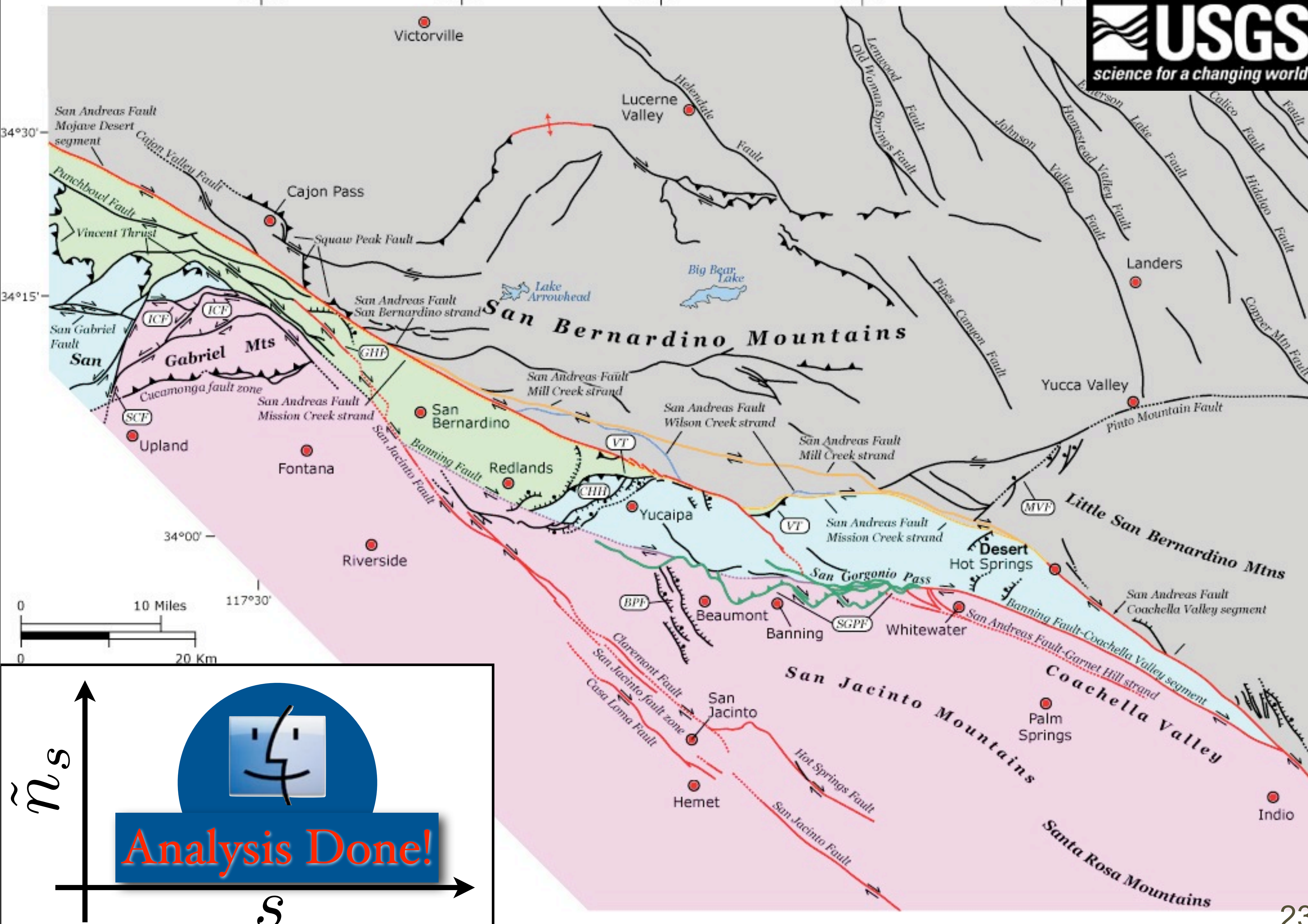
Geology and Geophysics Science Center

USGS science for a changing world

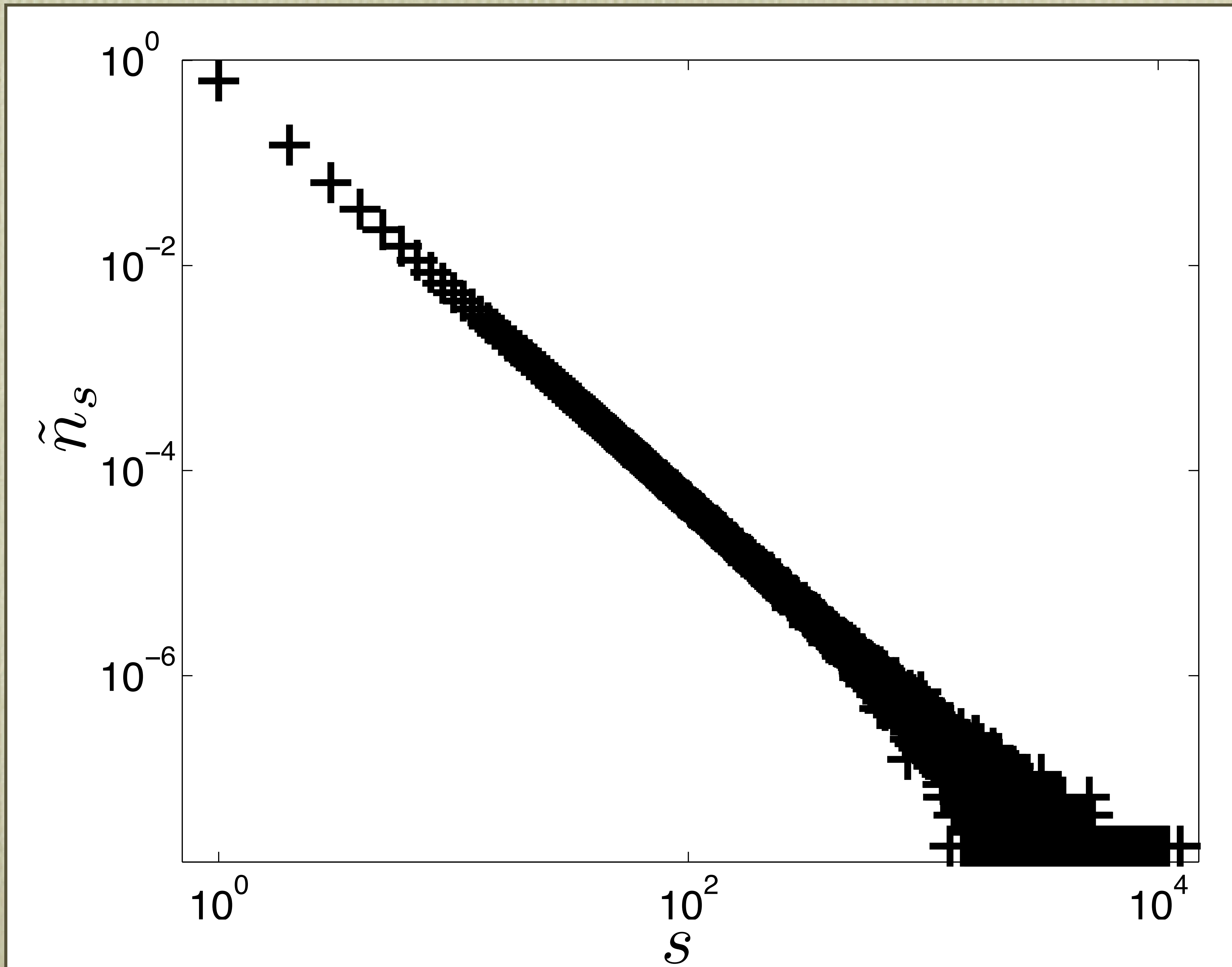


USGS science for a changing world

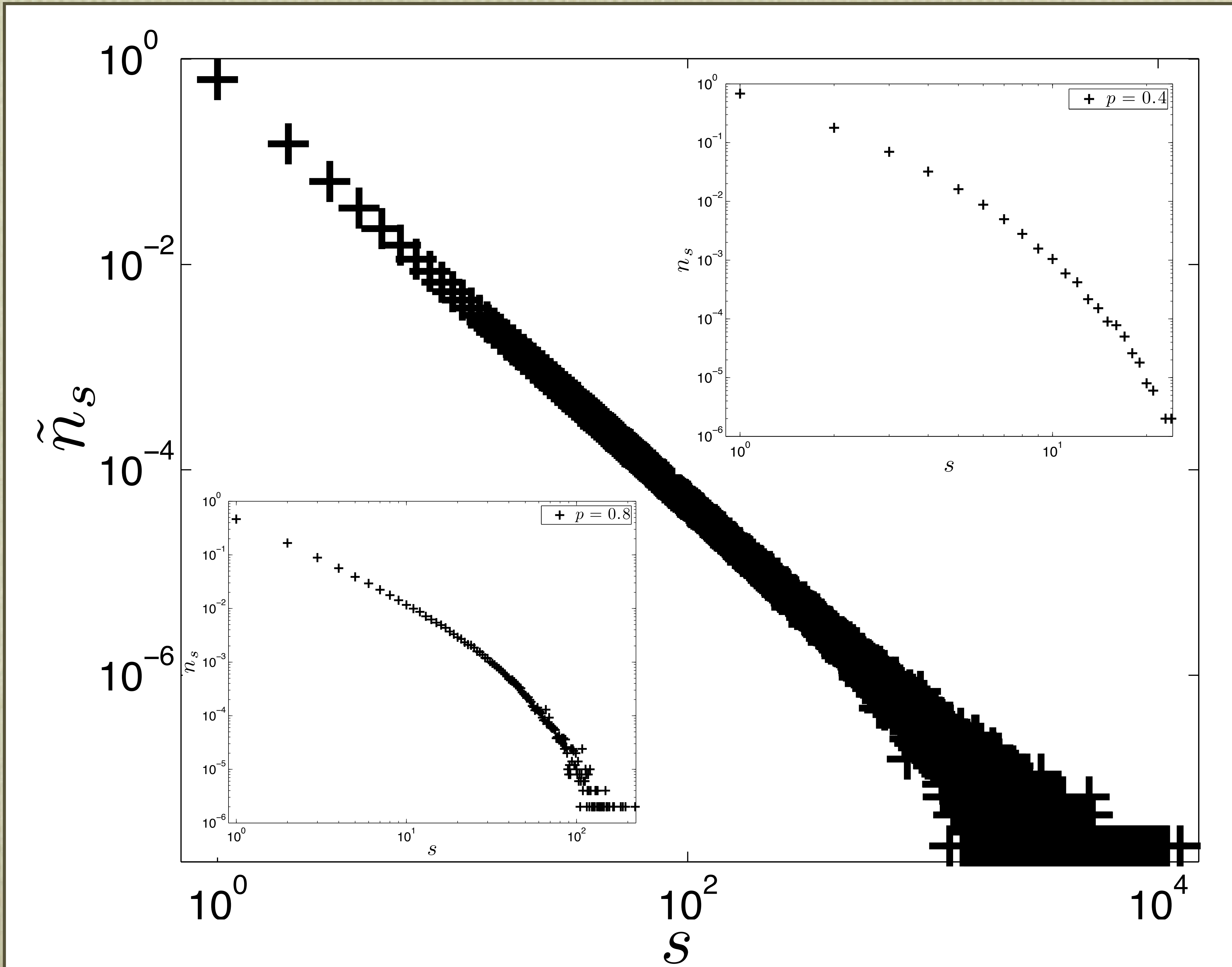



Victorville
Lucerne Valley
Cajon Pass
San Andreas Fault Mojave Desert segment
Cajon Valley Fault
Punchbowl Fault
Vincent Thrust
Squaw Peak Fault
Helendale Fault
Lenwood Fault
Old Woman Springs Fault
Johnson Valley Fault
Homestead Valley Fault
Emerson Lake Fault
Calico Fault
Hidalgo Fault
Landers
Big Bear Lake
Lake Arrowhead
San Andreas Fault San Bernardino strand
San Bernardino Mountains
Pipes Canyon Fault
Copper Mtn Fault
San Gabriel Fault
San Gabriel Mts
ICF
GHF
Cucamonga fault zone
SCF
Upland
Fontana
San Andreas Fault Mission Creek strand
San Bernardino
San Andreas Fault Mill Creek strand
Yucca Valley
Pinto Mountain Fault
San Andreas Fault Wilson Creek strand
VT
Redlands
Banning Fault
San Jacinto Fault
CHH
Yucaipa
MVF
Little San Bernardino Mtns
Desert Hot Springs
Riverside
San Gorgonio Pass
BPF
Beaumont
Banning
SGPF
Whitewater
San Andreas Fault Coachella Valley segment
Banning Fault-Coachella Valley segment
San Andreas Fault-Garnet Hill strand
Claremont Fault
San Jacinto fault zone
Casa Loma Fault
San Jacinto
Hemet
Hot Springs Fault
San Jacinto Mountains
Coachella Valley
Palm Springs
Indio
Santa Rosa Mountains
117°30'
117°15'
117°00'
34°30'
34°15'
34°00'
0
10 Miles
20 Km
$\tilde{n}_s$
s
Analysis Done!

Scaling in the Fault System

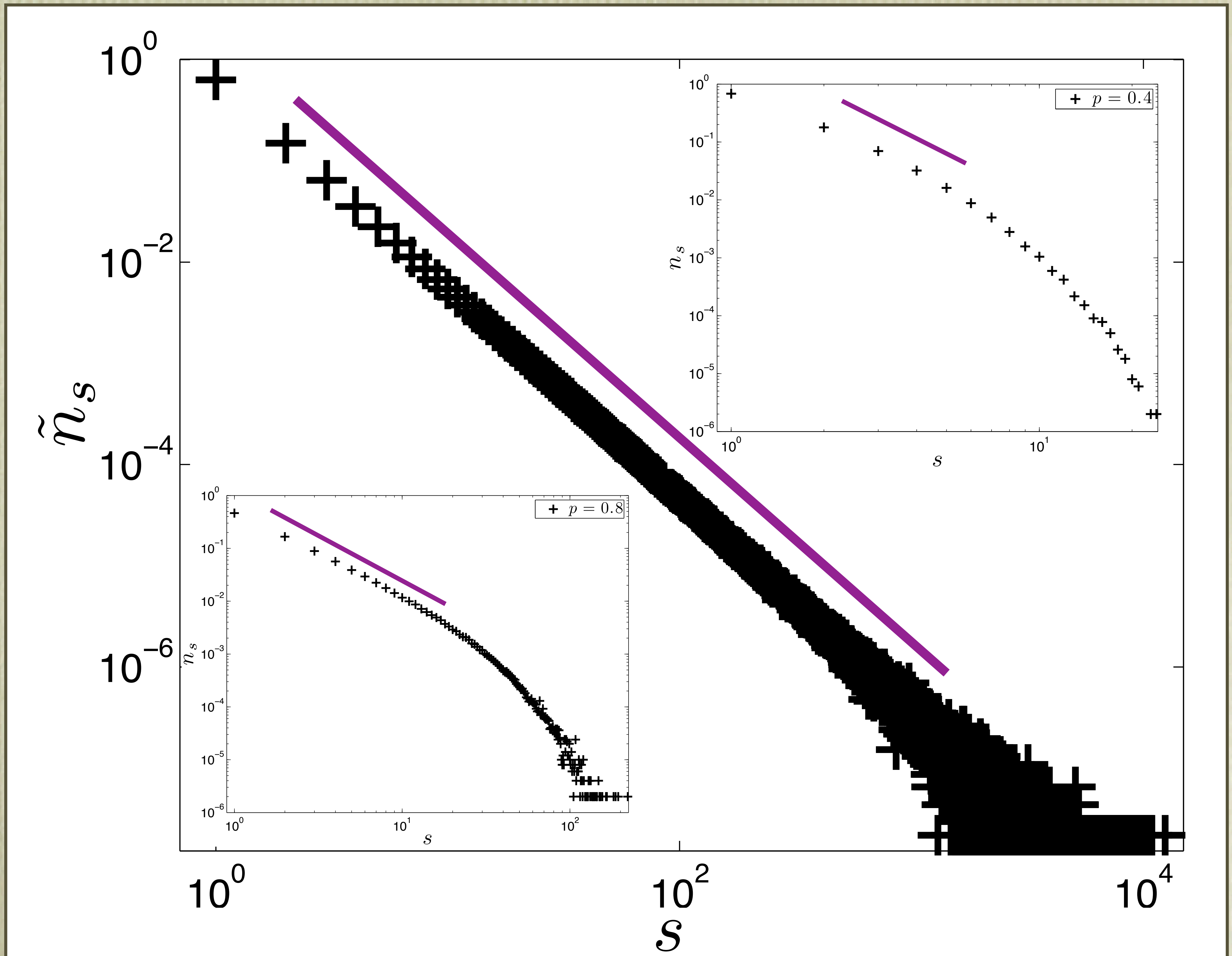


Scaling in the Fault System



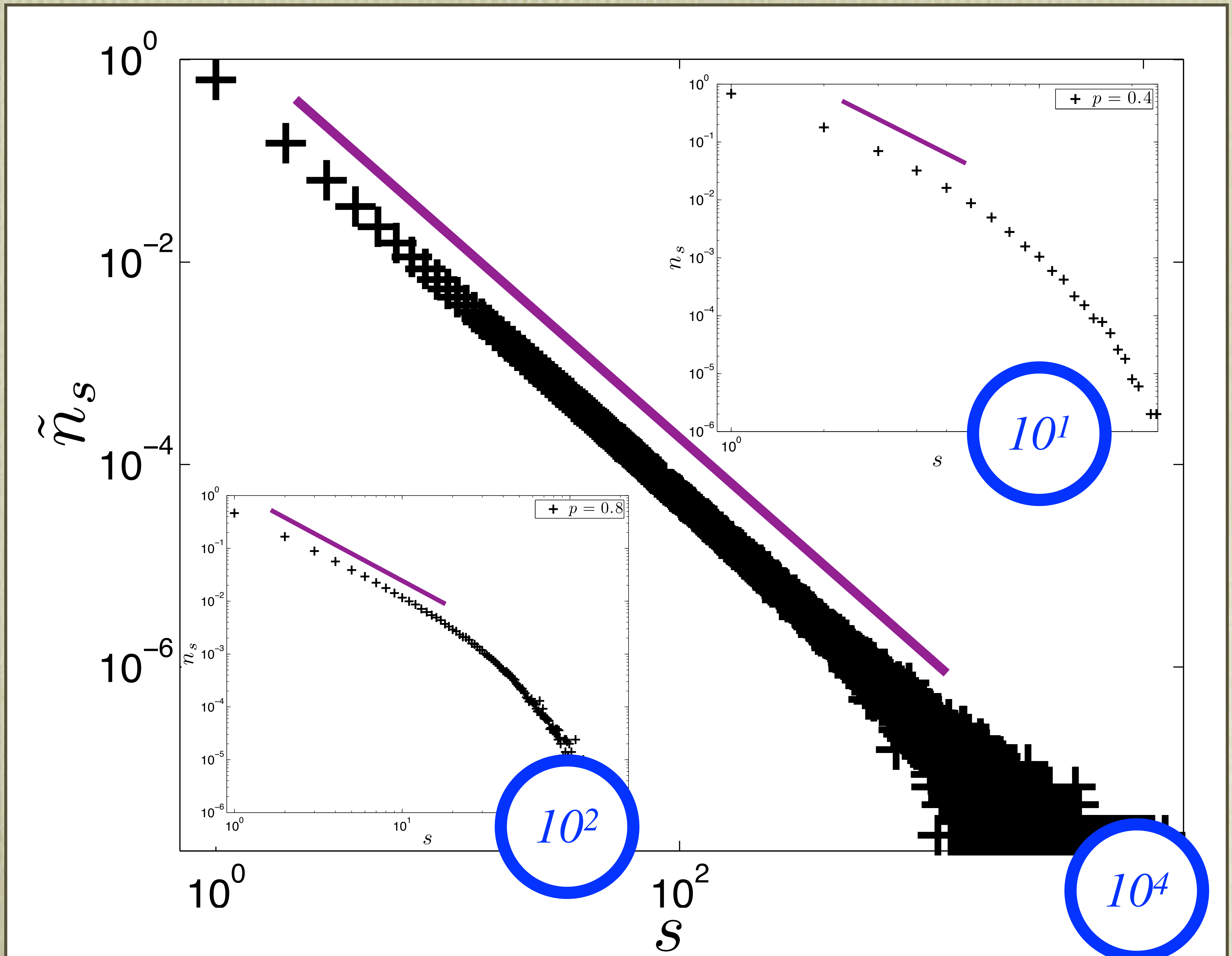
BOSTON UNIVERSITY

Scaling in the Fault System



BOSTON UNIVERSITY

Scaling in the Fault System



Friday, September 10, 2010

Outline

- Observations, Empirical Scaling & Motivation
- Early Models
- Model “Fault System”
- Simulations & Numerical Data
- **Theoretical Description**
- Future Work & Similar Physical Systems

Returning to the Continuum: A Meanfield Theoretic Description

- Klein *et al.* "Statistical Analysis of A Model for Earthquake Faults with Long-Range Stress Transfer." in GeoComplexity and the Physics of Earthquakes (2000) pp. 43 derive a Langevin equation for this model by coarse graining the equation of motion for the RJB formulation of the automata.

Returning to the Continuum: A Meanfield Theoretic Description

- Klein *et al.* "Statistical Analysis of A Model for Earthquake Faults with Long-Range Stress Transfer." in GeoComplexity and the Physics of Earthquakes (2000) pp. 43 derive a Langevin equation for this model by coarse graining the equation of motion for the RJB formulation of the automata.

- $$\frac{\partial \overline{\sigma}(\mathbf{x},\tau)}{\partial \tau} = \left(\frac{\sigma^F - \sigma^R}{2}\right)\left(\frac{qk_C\nabla^2 - k_L}{k_L + qk_C}\right)\left(\mathrm{erf}\left[-\sqrt{\beta}(\sigma^F - \overline{\sigma}(\mathbf{x},\tau))\right] - \mathrm{erf}\left[-\sqrt{\beta}(\sigma_0 - \overline{\sigma}(\mathbf{x},\tau)\right]\right) -$$
$$- \frac{\beta^2}{\pi^2(\sigma^F - \sigma^R)}\int_{\sigma^R}^{\sigma^F} \mathrm{d}\sigma \, \log\left(\frac{\sigma - \sigma^R}{\sigma^F - \sigma}\right)\exp\left[-\beta(\sigma - \overline{\sigma}(\mathbf{x},\tau))^2\right] -$$
$$- \frac{1}{\beta(\sigma^F - \sigma^R)}\log\left(\frac{\overline{\sigma}(\mathbf{x},\tau) - \sigma^R}{\sigma^F - \overline{\sigma}(\mathbf{x},\tau)}\right) + k_L V + \overline{\eta}(\mathbf{x},\tau)$$

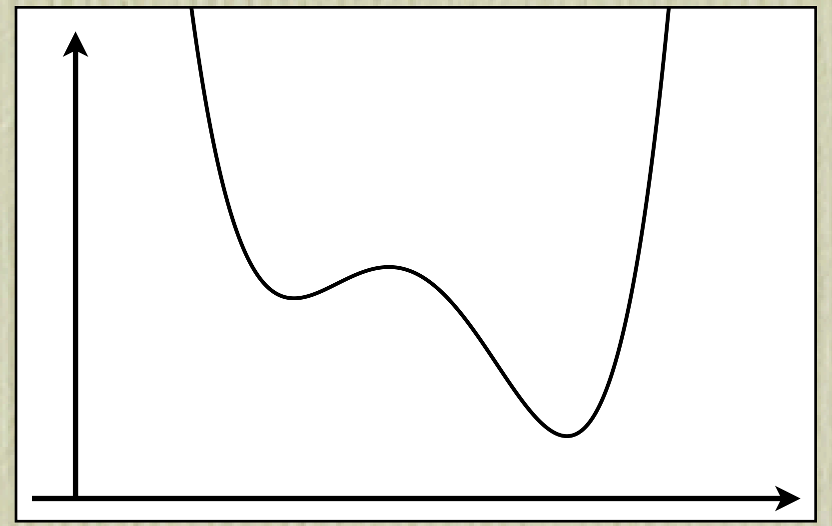
Returning to the Continuum: A Meanfield Theoretic Description

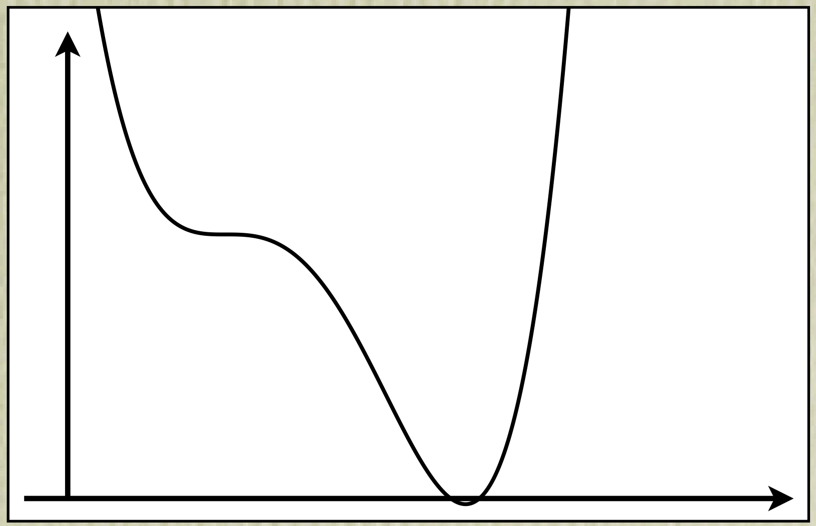
- Klein *et al.* "Statistical Analysis of A Model for Earthquake Faults with Long-Range Stress Transfer." in GeoComplexity and the Physics of Earthquakes (2000) pp. 43 derive a Langevin equation for this model by coarse graining the equation of motion for the RJB formulation of the automata.

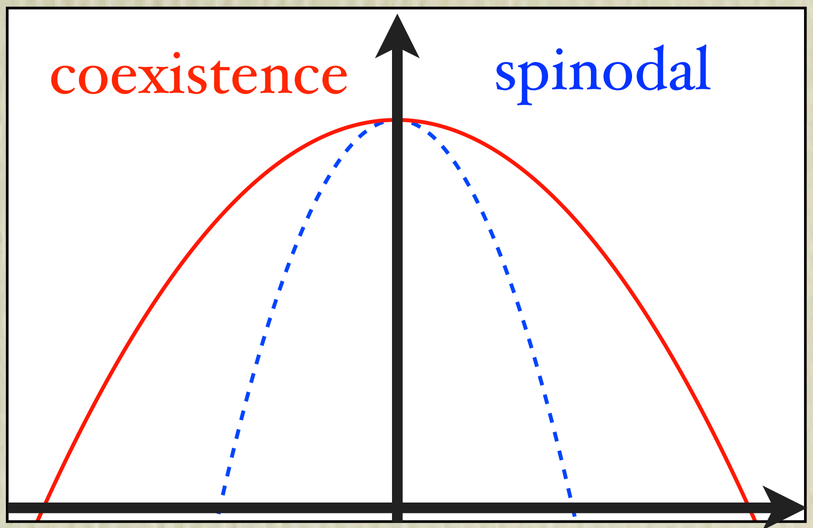
- $$\frac{\partial\overline{\sigma}(\mathbf{x},\tau)}{\partial\tau} = \left(\frac{\sigma^F-\sigma^R}{2}\right)\left(\frac{qk_C\nabla^2-k_L}{k_L+qk_C}\right)\left(\mathrm{erf}\left[-\sqrt{\beta}(\sigma^F-\overline{\sigma}(\mathbf{x},\tau))\right]-\mathrm{erf}\left[-\sqrt{\beta}(\sigma_0-\overline{\sigma}(\mathbf{x},\tau)\right]\right)- \\ -\frac{\beta^2}{\pi^2(\sigma^F-\sigma^R)}\int_{\sigma^R}^{\sigma^F}\mathrm{d}\sigma\ \log\left(\frac{\sigma-\sigma^R}{\sigma^F-\sigma}\right)\exp\left[-\beta(\sigma-\overline{\sigma}(\mathbf{x},\tau))^2\right]- \\ -\frac{1}{\beta(\sigma^F-\sigma^R)}\log\left(\frac{\overline{\sigma}(\mathbf{x},\tau)-\sigma^R}{\sigma^F-\overline{\sigma}(\mathbf{x},\tau)}\right)+k_LV+\overline{\eta}(\mathbf{x},\tau)$$

- By considering numerical solutions to the steady-state, spacially uniform equation, Klein *et al.* show there is a spinodal critical point in the meanfield limit of the RJB model.

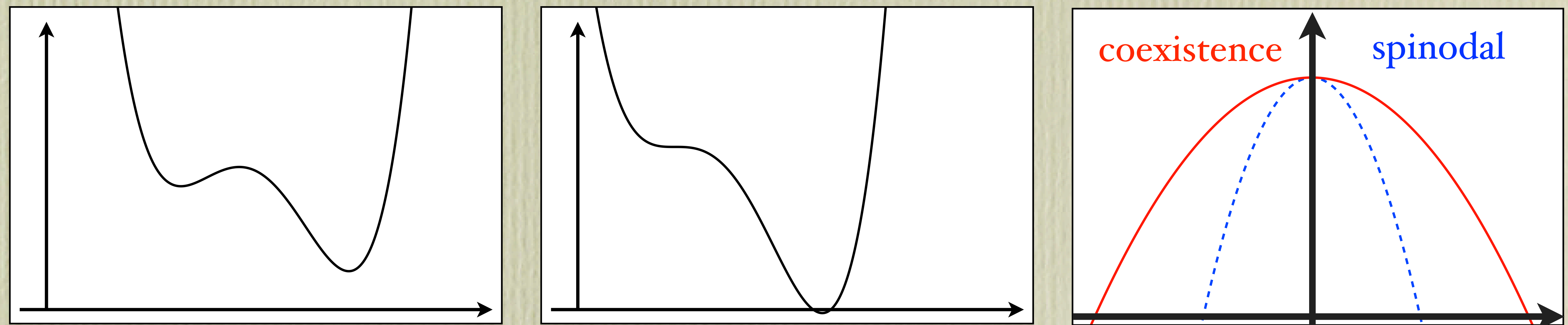
Returning to the Continuum: A Meanfield Theoretic Description





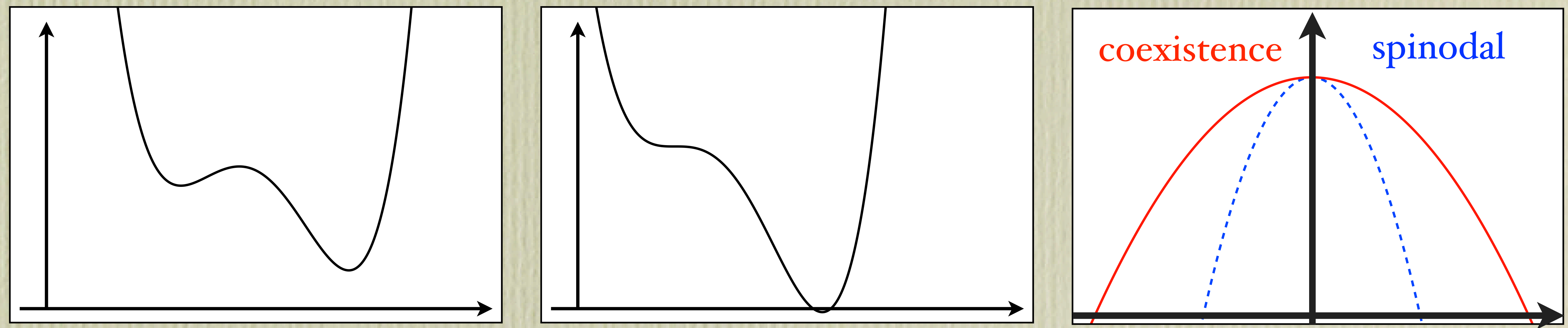


Returning to the Continuum: A Meanfield Theoretic Description



- Klein *et al.* identify the events (earthquakes) with arrested nucleation droplets (Ising $\Leftrightarrow$ RJB, $h \leftrightarrow k_L V$, $m \leftrightarrow \overline{\sigma}$).

Returning to the Continuum: A Meanfield Theoretic Description



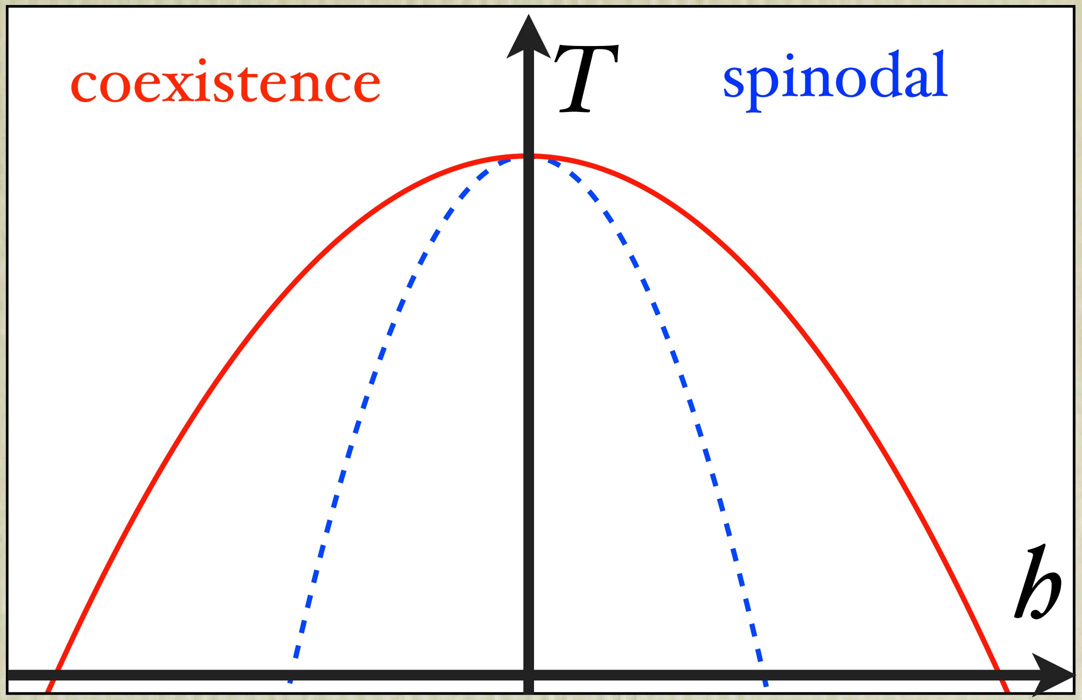
- Klein *et al.* identify the events (earthquakes) with arrested nucleation droplets (Ising ⇔ RJB, $h \leftrightarrow k_L V$, $m \leftrightarrow \overline{\sigma}$).

- Using the technology developed for spinodal nucleation, Klein *et al.* argue that the number of events, n_s, of size s scales as $n_s \sim s^{-3/2}$, that is $\tau = 3/2$.

Event Frequency and Damage

- Frequency-size statics obey

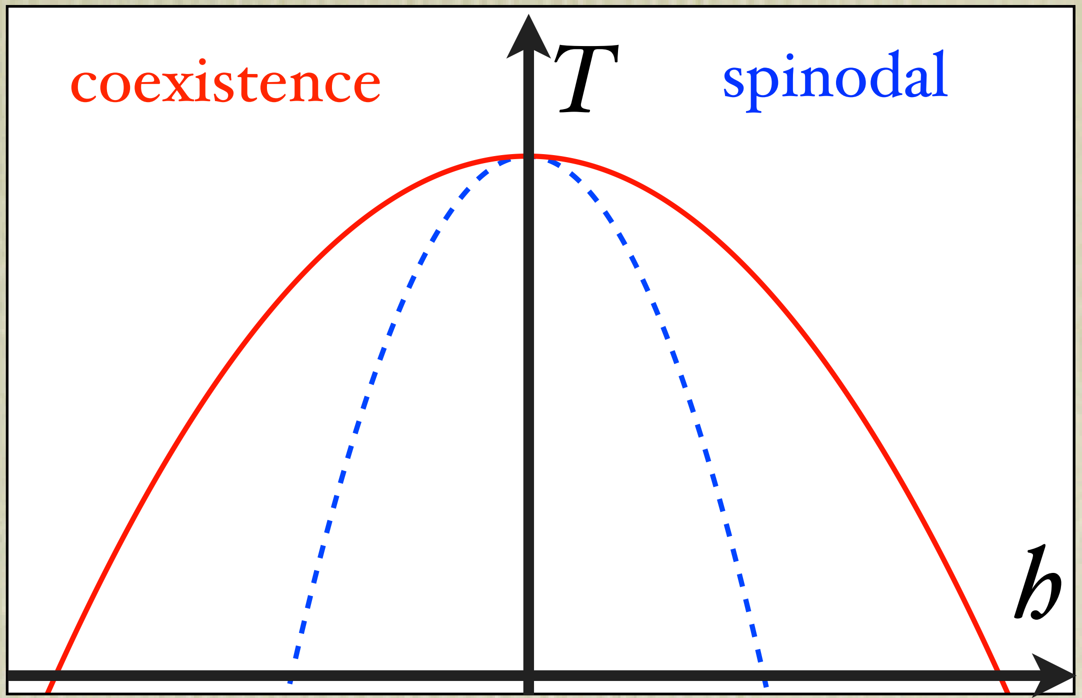
$$n_s \sim \frac{\exp[-\Delta h\ s]}{s^\tau}$$



Event Frequency and Damage

- Frequency-size statics obey

$$n_s \sim \frac{\exp[-\Delta h \; s]}{s^\tau}$$

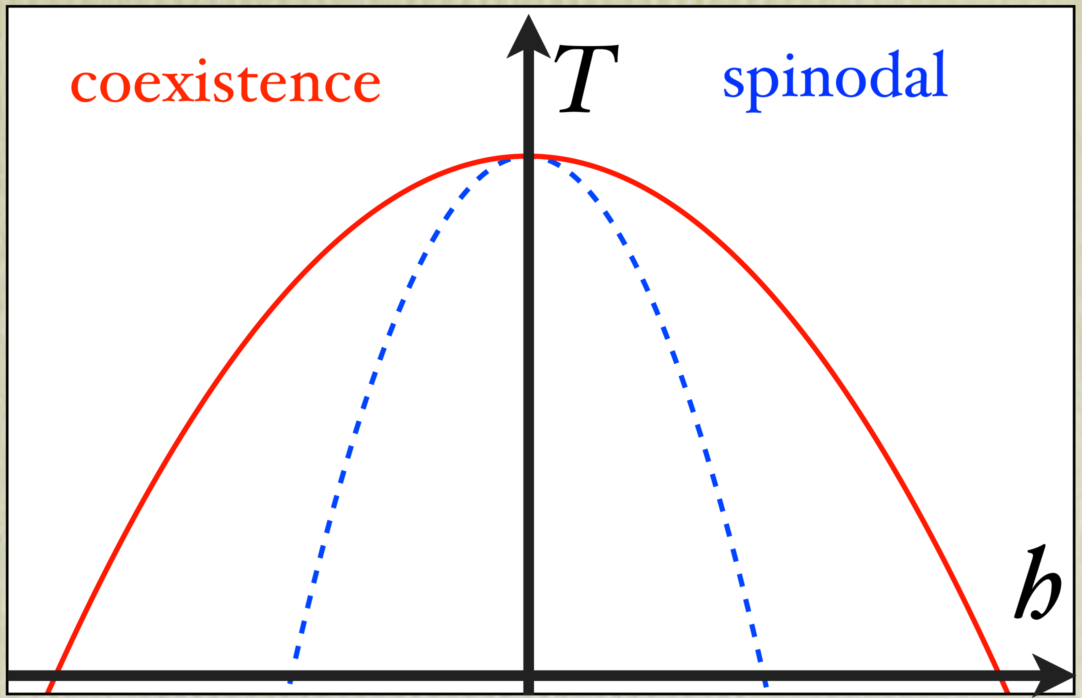


- Since we collect data over all values of *p*, the new distribution, $\tilde{n}_s$, is generated by summing , n_s , over all *p*.

Event Frequency and Damage

- Frequency-size statics obey

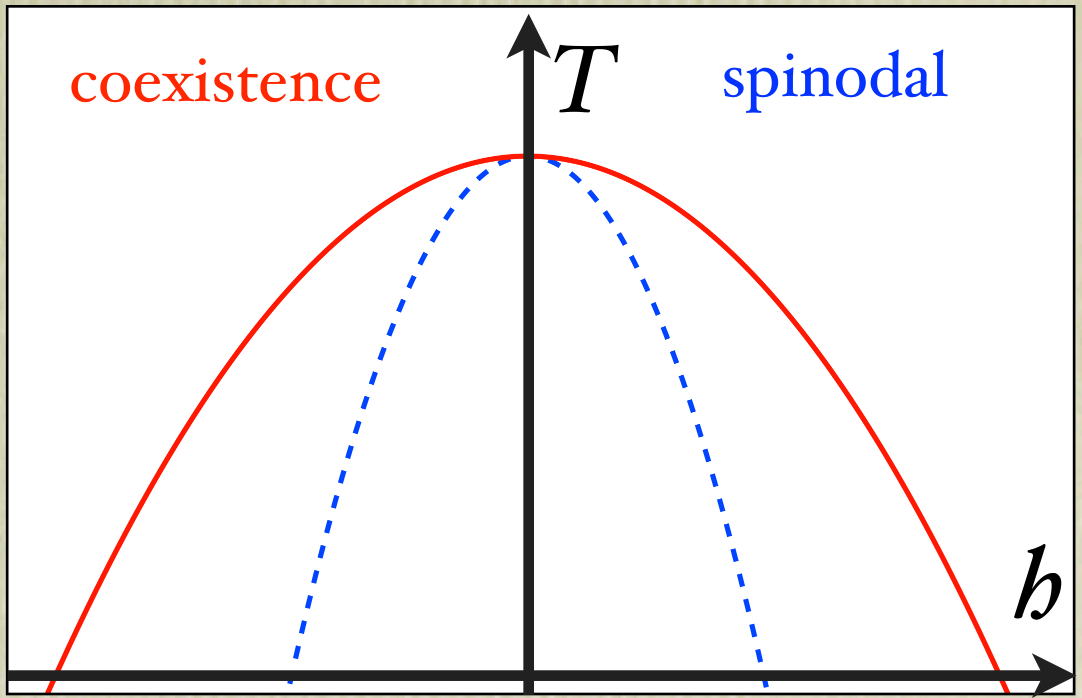
$$n_s \sim \frac{\exp[-\Delta h\ s]}{s^\tau}$$



- Since we collect data over all values of *p*, the new distribution, $\tilde{n}_s$, is generated by summing , n_s , over all *p*.

- This requires relating *p* to Δh.

Event Frequency and Damage



- Frequency-size statics obey

$$n_s \sim \frac{\exp[-\Delta h\, s]}{s^\tau}$$

- Since we collect data over all values of *p*, the new distribution, $\tilde{n}_s$, is generated by summing , n_s , over all *p*.

- This requires relating *p* to Δ*h*.

$$\Delta h \sim (1-p)^2 \qquad n_0 \sim p^{-1}$$

[CAS *et al.* in preparation]

Calculating the New Scaling Relations

$$\tilde{n}_s = \int_0^1 \mathrm{d}p\, n_s(p) \sim \int_0^1 \mathrm{d}p\, \frac{1}{p} \frac{\exp[-(1-p)^2 s]}{s^\tau} \quad \xrightarrow{s \gg 1} \quad \frac{1}{s^{\tau+1/2}}$$

Calculating the New Scaling Relations

$$\tilde{n}_s = \int_0^1 \mathrm{d}p \, n_s(p) \sim \int_0^1 \mathrm{d}p \, \frac{1}{p} \frac{\exp[-(1-p)^2 s]}{s^\tau} \xrightarrow{s \gg 1} \frac{1}{s^{\tau+1/2}}$$

- Two predictions

Calculating the New Scaling Relations

$$\tilde{n}_s = \int_0^1 \mathrm{d}p\, n_s(p) \sim \int_0^1 \mathrm{d}p\, \frac{1}{p} \frac{\exp[-(1-p)^2 s]}{s^\tau} \xrightarrow{s \gg 1} \frac{1}{s^{\tau+1/2}}$$

- Two predictions

  i. The new distribution scales as a power-law with exponent $\tilde{\tau} = \tau + 1/2 = 2$

Calculating the New Scaling Relations

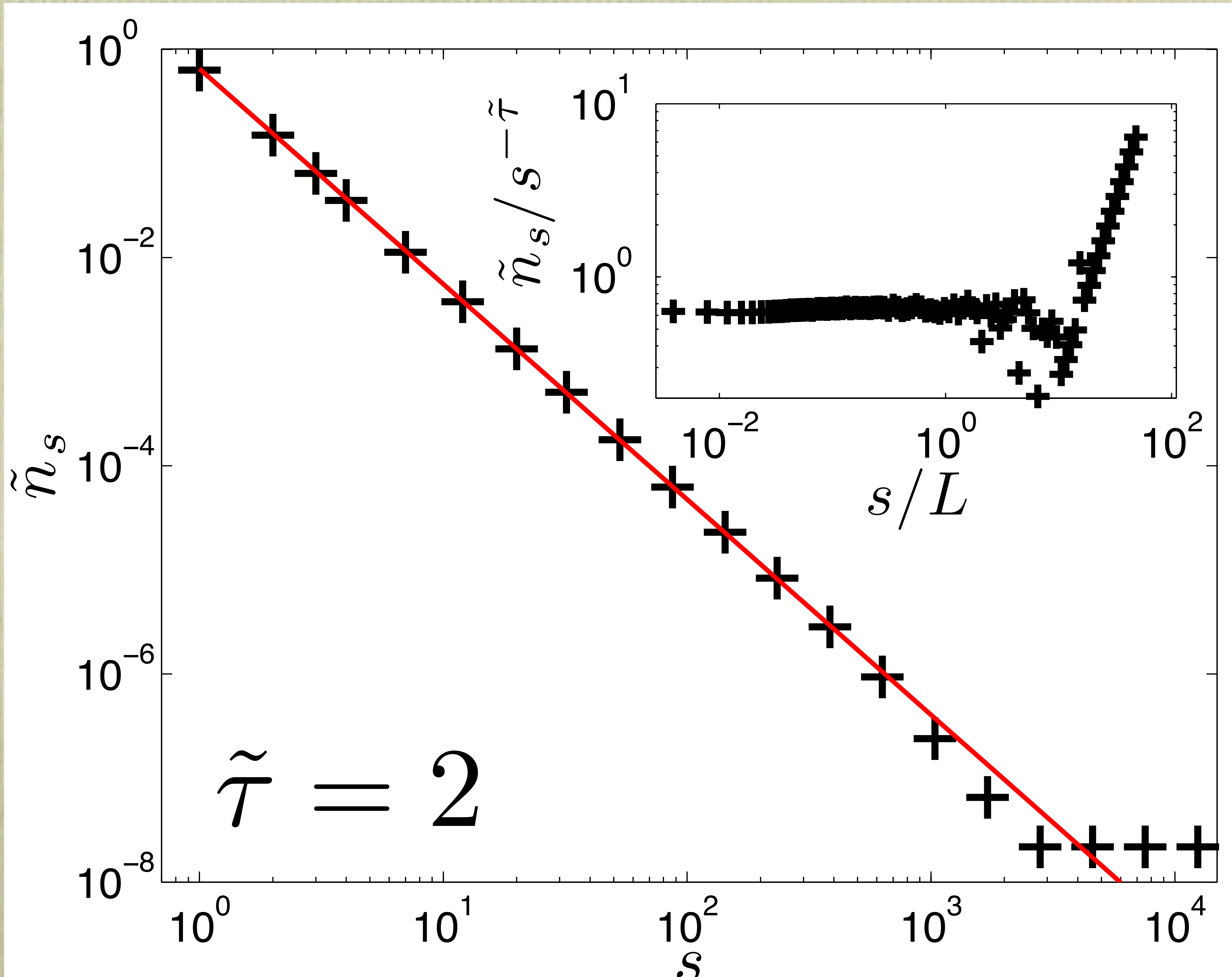
$$\tilde{n}_s = \int_0^1 \mathrm{d}p \, n_s(p) \sim \int_0^1 \mathrm{d}p \, \frac{1}{p} \frac{\exp[-(1-p)^2 s]}{s^\tau} \quad \xrightarrow{s \gg 1} \quad \frac{1}{s^{\tau+1/2}}$$

- Two predictions

  i. The new distribution scales as a power-law with exponent $\tilde{\tau} = \tau + 1/2 = 2$

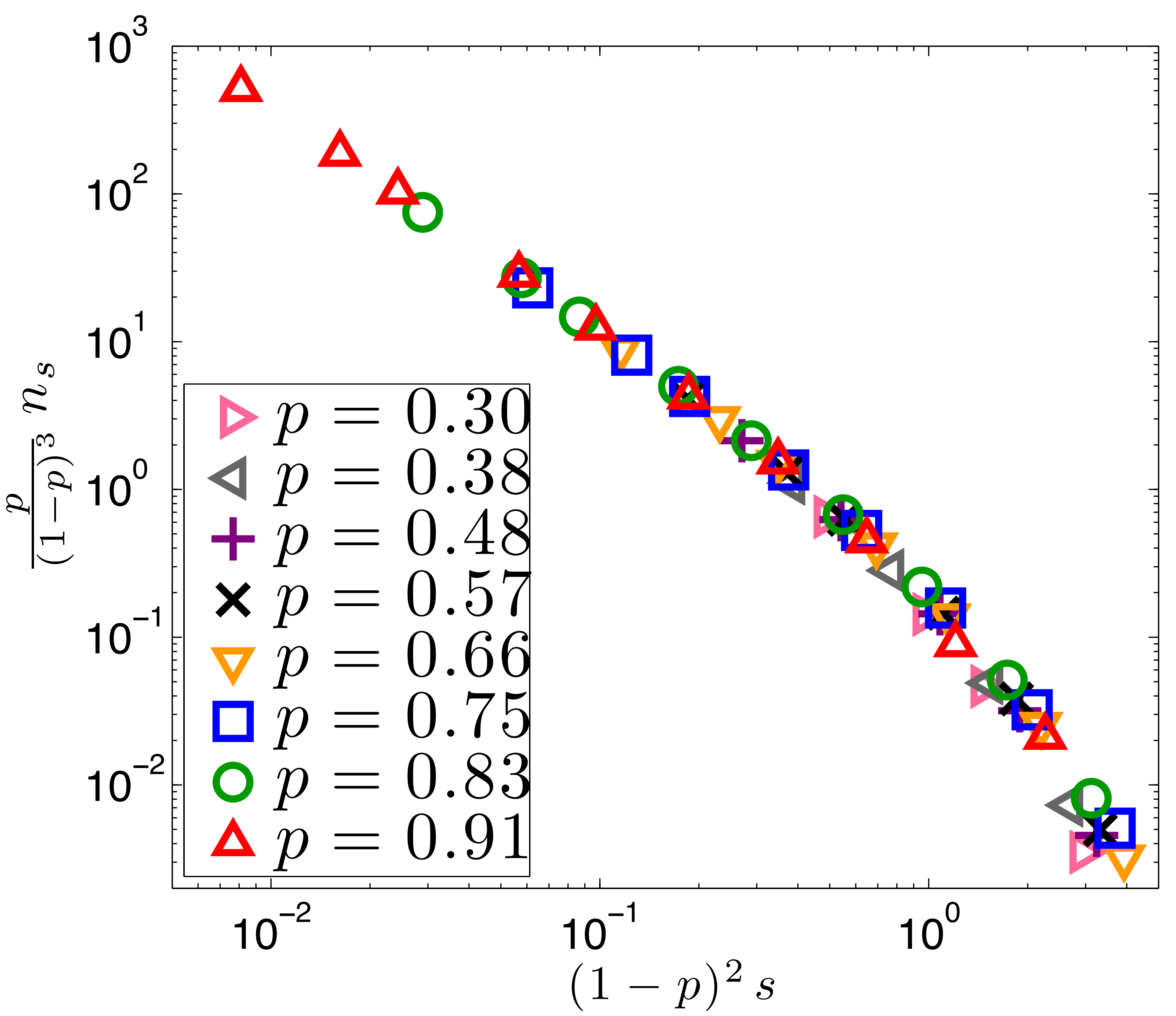
  ii. There exists a scaling variable $z \equiv (1-p)^2 s$ such that plots of $p/(1-p)^{2\tau} n(z)$ vs z will collapse to a single curve for all values of p.

Prediction 1: New Exponent



BOSTON UNIVERSITY

Prediction II: Data Collapse



Outline

- Observations, Empirical Scaling & Motivation
- Early Models
- Model "Fault System"
- Simulations & Numerical Data
- Theoretical Description
- **Future Work & Similar Physical Systems**

More with this Model

More with this Model

- How sensitive is the power-law (GR) distribution to the weights of the *p*'s in the combined data set?

More with this Model

- How sensitive is the power-law (GR) distribution to the weights of the *p*'s in the combined data set?

- Is there a (non-spinodal) critical point in this model?

More with this Model

- How sensitive is the power-law (GR) distribution to the weights of the *p*'s in the combined data set?

- Is there a (non-spinodal) critical point in this model?

- Must $\alpha = 0$ in for this model to be critical?

More with this Model

- How sensitive is the power-law (GR) distribution to the weights of the p's in the combined data set?
- Is there a (non-spinodal) critical point in this model?
- Must $\alpha = 0$ in for this model to be critical?
- Does this model contain enough of the "correct physics" so that we can use event "run-up" to forecast devastating events?

More with this Model

- How sensitive is the power-law (GR) distribution to the weights of the *p*'s in the combined data set?

- Is there a (non-spinodal) critical point in this model?

- Must $\alpha = 0$ in for this model to be critical?

- Does this model contain enough of the "correct physics" so that we can use event "run-up" to forecast devastating events?

- How about quiescence?

More with this Model

- How sensitive is the power-law (GR) distribution to the weights of the *p*'s in the combined data set?
- Is there a (non-spinodal) critical point in this model?
- Must $\alpha = 0$ in for this model to be critical?
- Does this model contain enough of the "correct physics" so that we can use event "run-up" to forecast devastating events?
- How about quiescence?
- After big events, are there aftershocks consistent with Omori's Law?

Other Systems

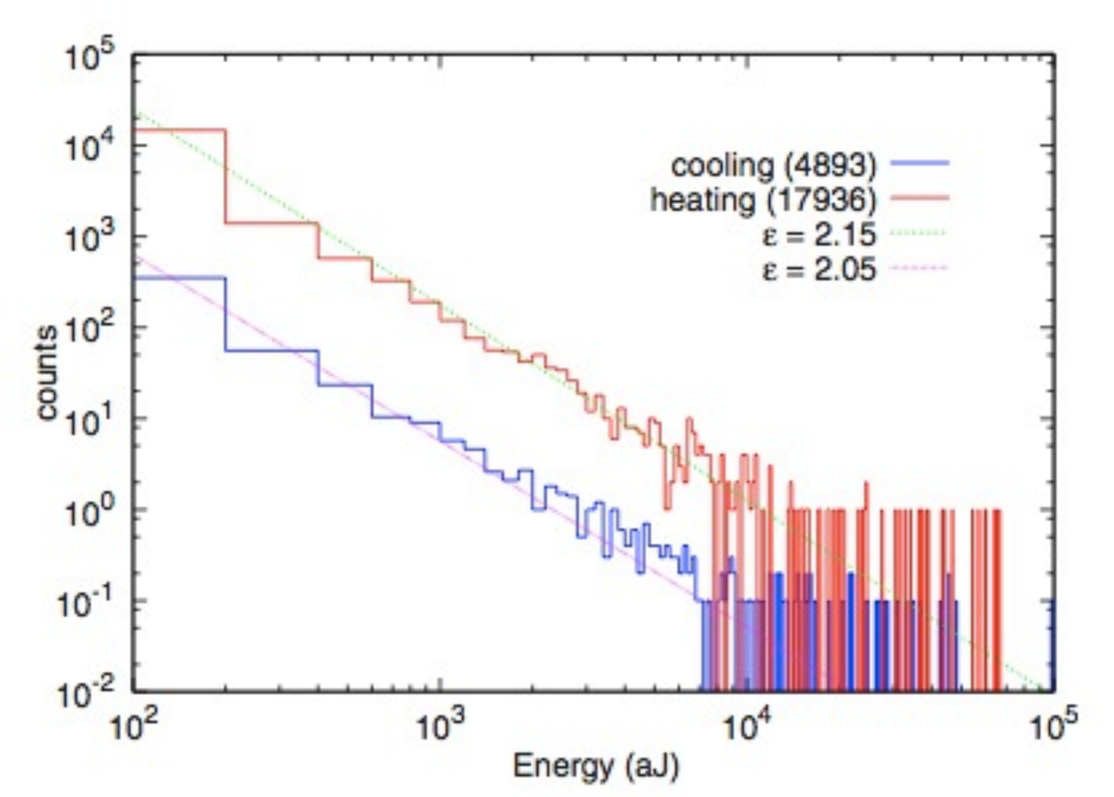
Other Systems

- Systems Under Stress

Other Systems

- Systems Under Stress

i. Martensitic Transition of $Cu_{76.64}Zn_{17.71}Al_{15.65}$



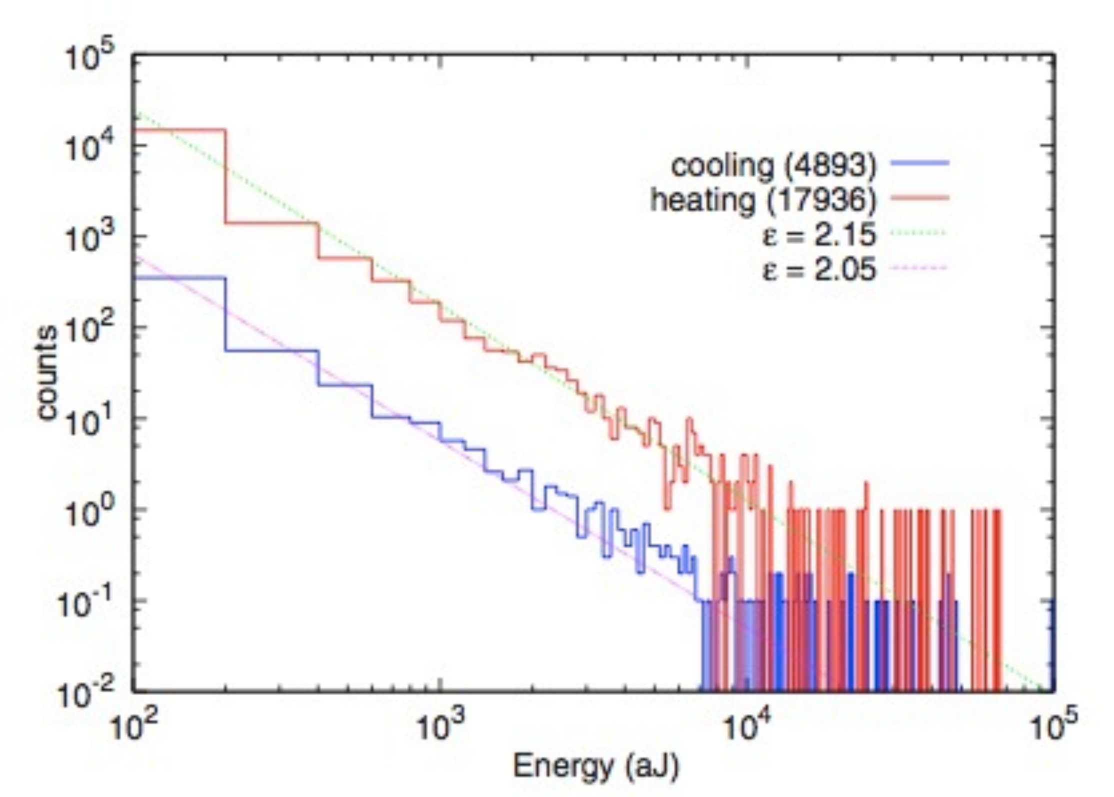
[Gallardo *et al. Phys. Rev. B.* **81**, 174102 (2010)]

Other Systems

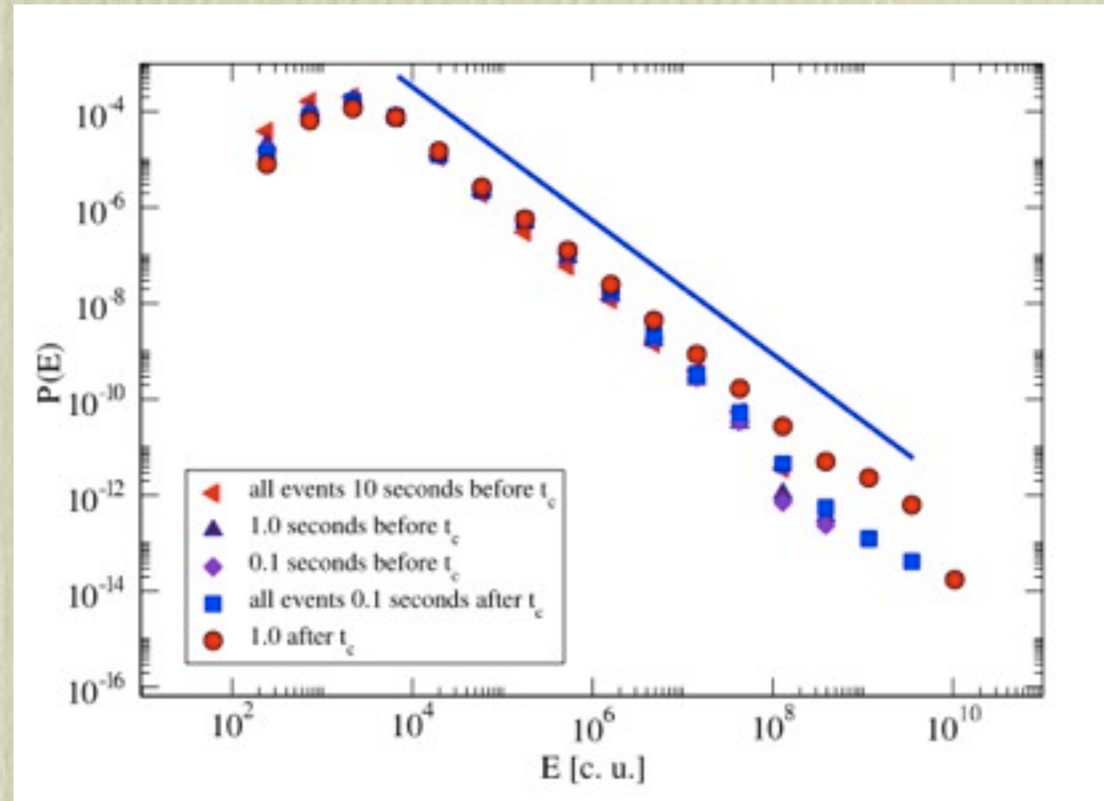
- Systems Under Stress

  i. Martensitic Transition of $Cu_{76.64}Zn_{17.71}Al_{15.65}$

  ii. Tensile Strain in Paper Sheets



[Gallardo *et al. Phys. Rev. B.* **81**, 174102 (2010)]



[J Rosti *et al. J. Stat. Mech.* (2010) P02016]

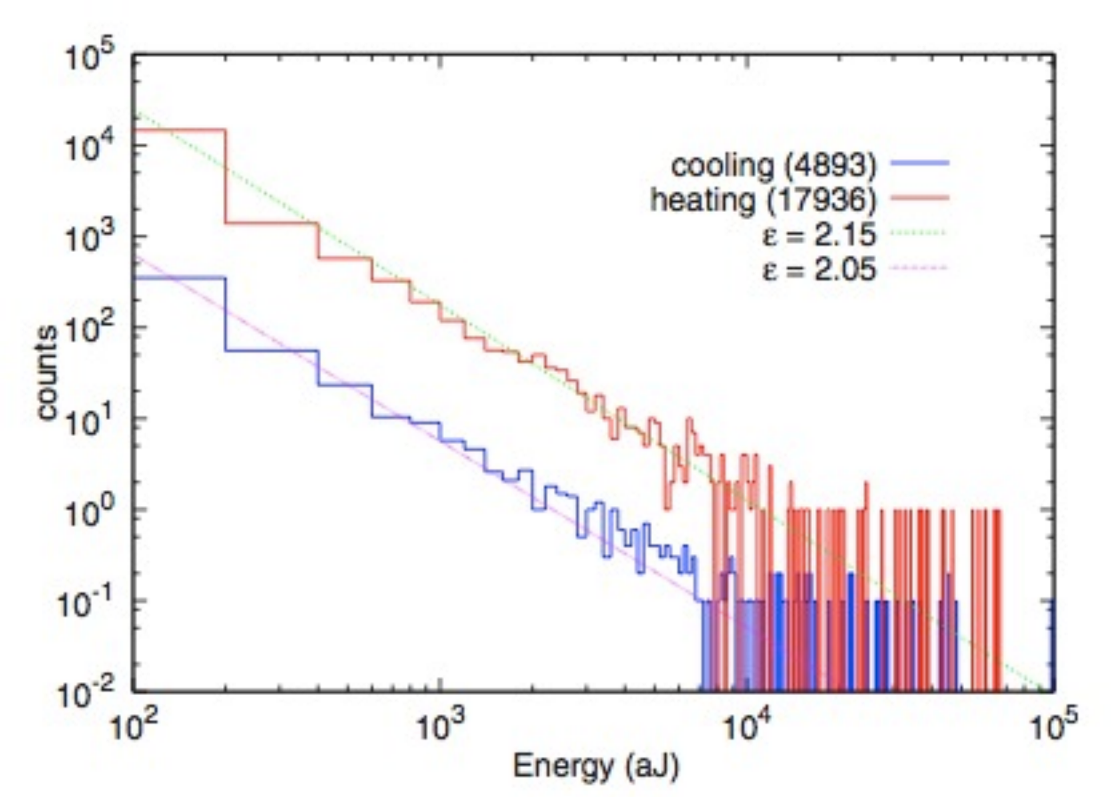
Other Systems

- Systems Under Stress

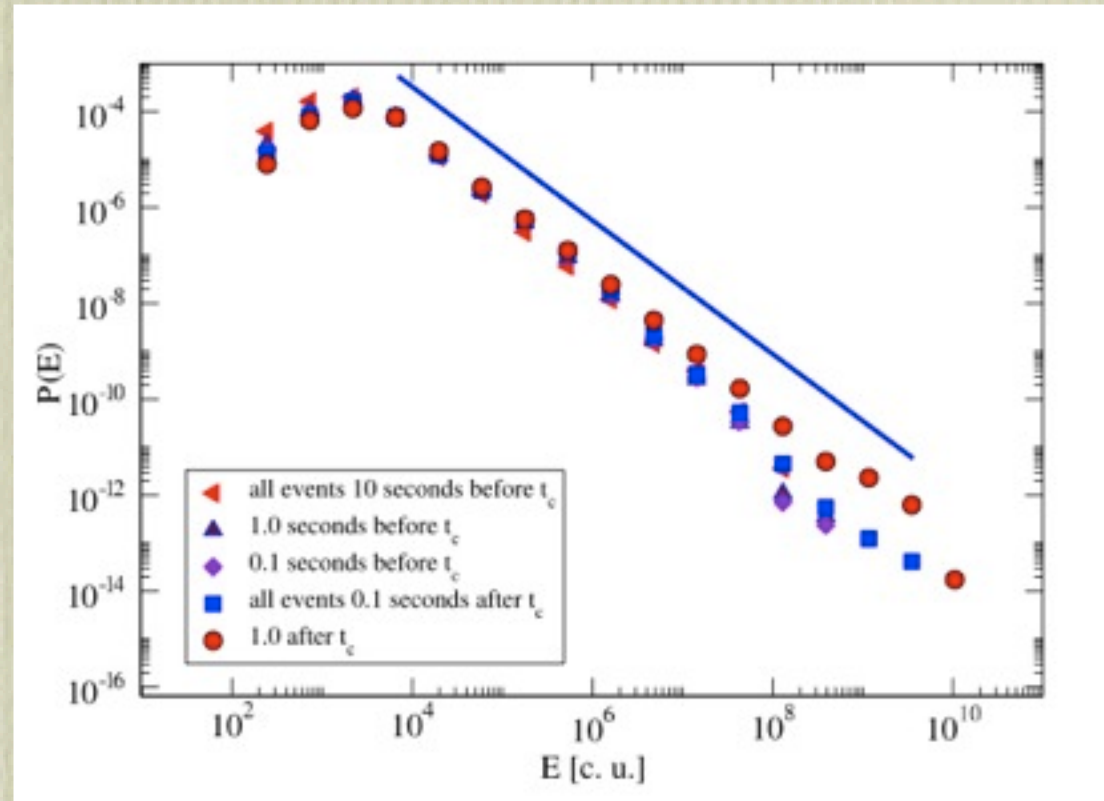
  i. Martensitic Transition of $Cu_{76.64}Zn_{17.71}Al_{15.65}$

  ii. Tensile Strain in Paper Sheets

  iii. Martensitic Transition in Co system (C. Sanborn *et al.*)



[Gallardo *et al.* *Phys. Rev. B.* **81**, 174102 (2010)]



[J Rosti *et al.* *J. Stat. Mech.* (2010) P02016]

Other Systems (cont.)

Other Systems (cont.)

- Magnetic Systems - Quenched Dilute Ising Model (K. Liu *et al.*)

  i. Can we locate the nucleating droplet?

Other Systems (cont.)

- Magnetic Systems - Quenched Dilute Ising Model (K. Liu *et al.*)

  i. Can we locate the nucleating droplet?

  ii. If so, how does the dilution (damage or defect) affect the nucleating droplet?

Other Systems (cont.)

- Magnetic Systems - Quenched Dilute Ising Model (K. Liu *et al.*)

  i. Can we locate the nucleating droplet?

  ii. If so, how does the dilution (damage or defect) affect the nucleating droplet?

     a. It's shape?

Other Systems (cont.)

- Magnetic Systems - Quenched Dilute Ising Model (K. Liu *et al.*)

    i. Can we locate the nucleating droplet?

    ii. If so, how does the dilution (damage or defect) affect the nucleating droplet?

        a. It's shape?

        b. It's location?

Other Systems (cont.)

- Magnetic Systems - Quenched Dilute Ising Model (K. Liu *et al.*)

  i. Can we locate the nucleating droplet?

  ii. If so, how does the dilution (damage or defect) affect the nucleating droplet?

     a. It's shape?

     b. It's location?

     c. It's growth dynamics?

Other Systems (cont.)

- Magnetic Systems - Quenched Dilute Ising Model (K. Liu *et al.*)

  i. Can we locate the nucleating droplet?

  ii. If so, how does the dilution (damage or defect) affect the nucleating droplet?

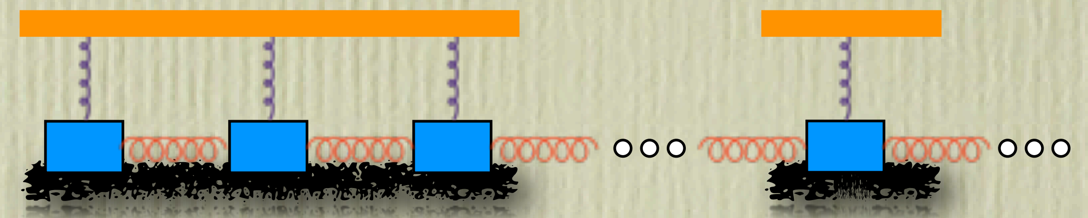
     a. It's shape?

     b. It's location?

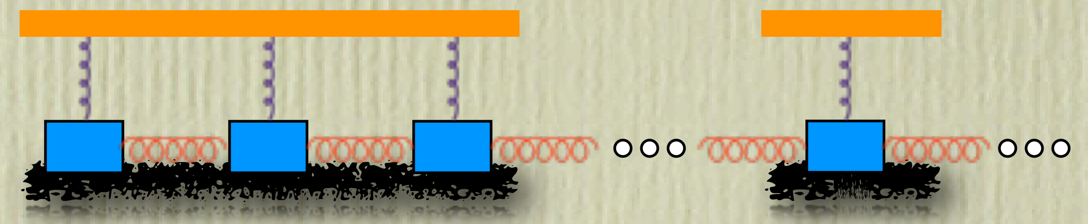
     c. It's growth dynamics?

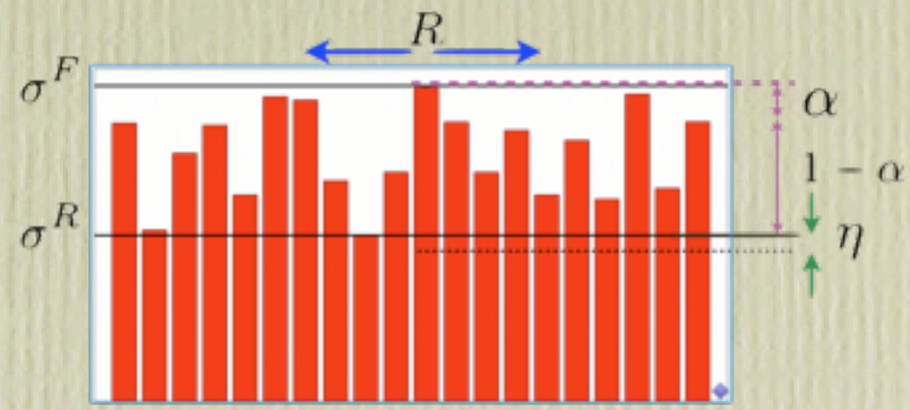
  iii. Can we make any theoretical progress with this model?

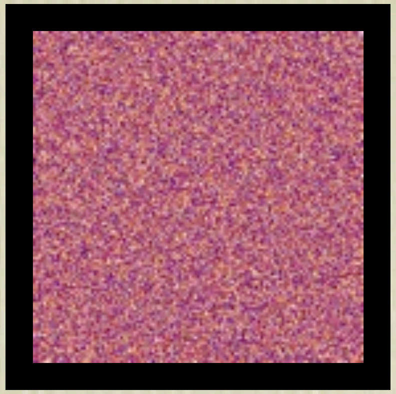
Picture Book



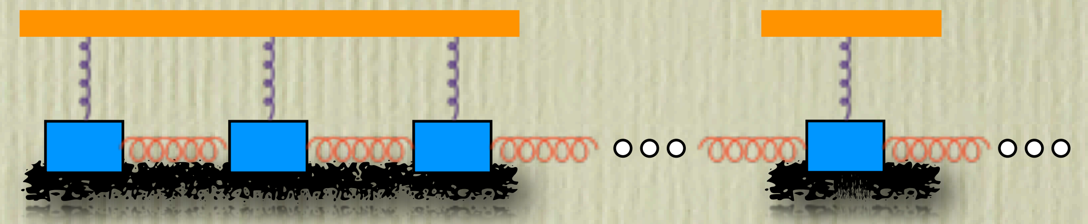
Picture Book

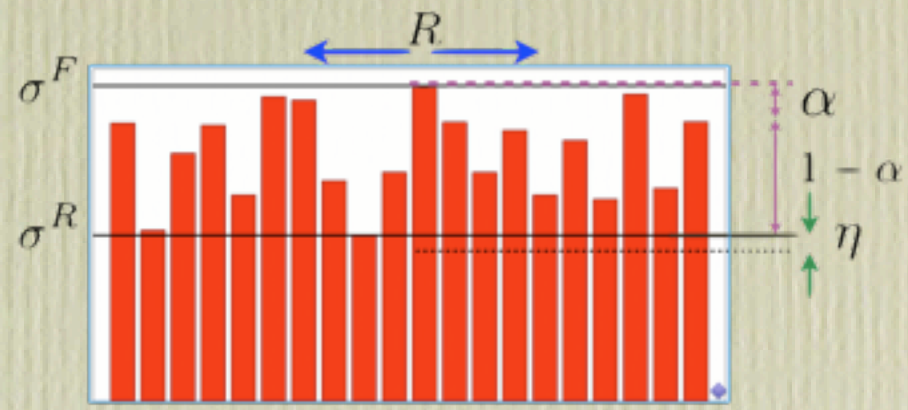


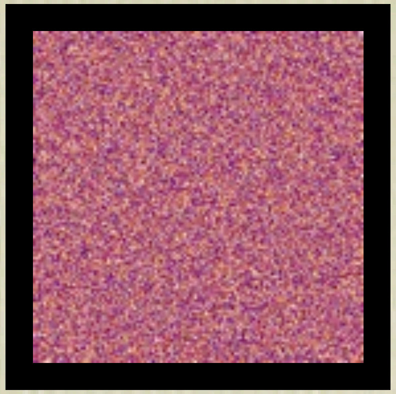


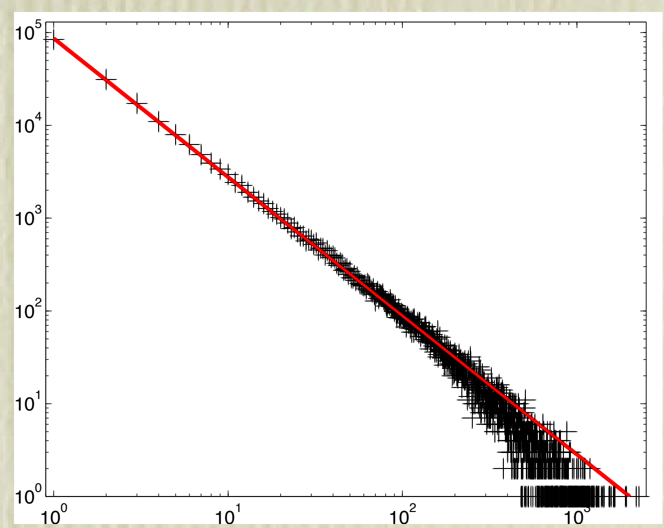


Picture Book

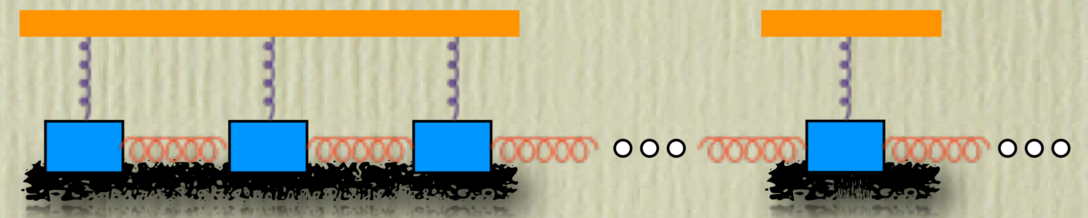


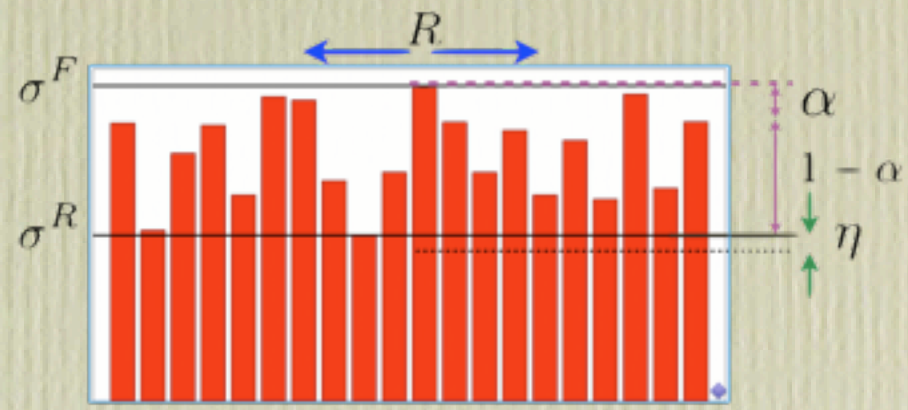


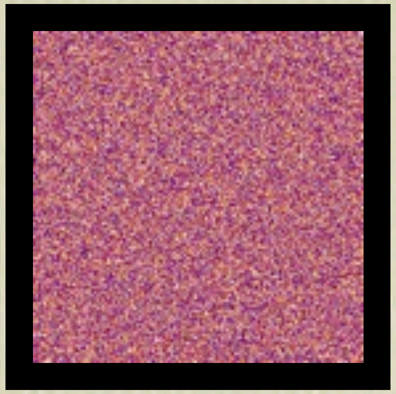


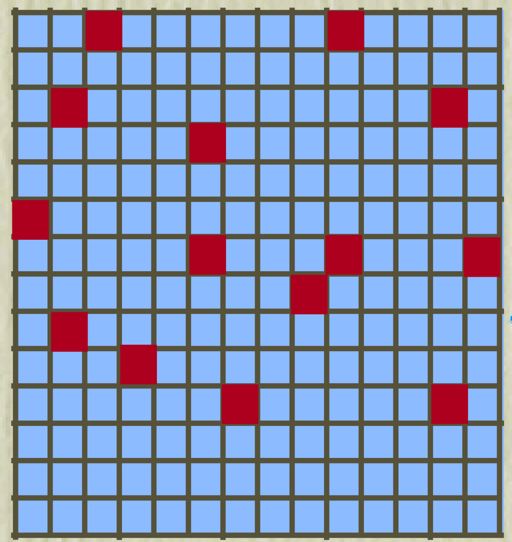


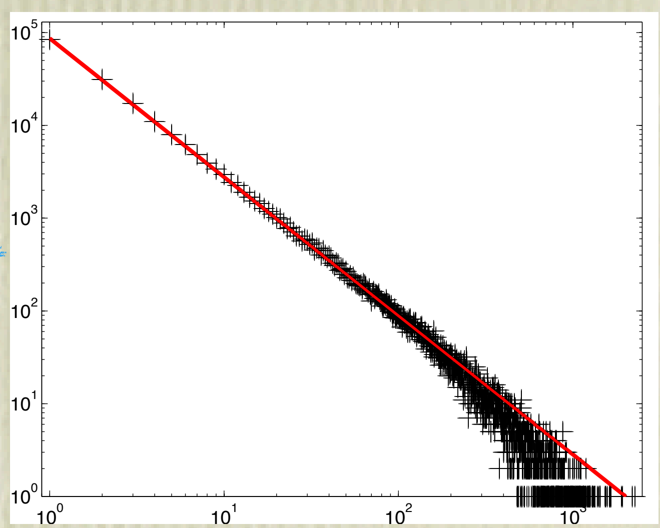
Picture Book



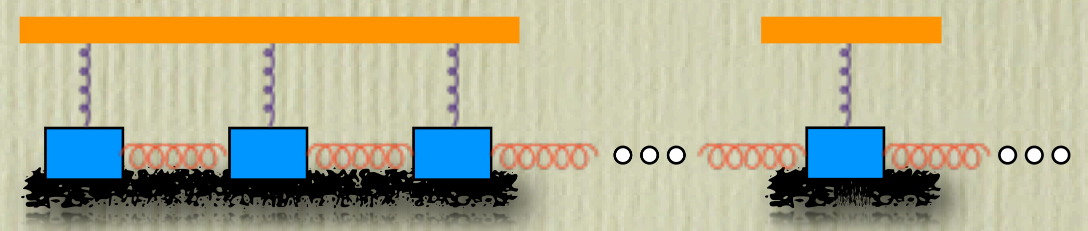


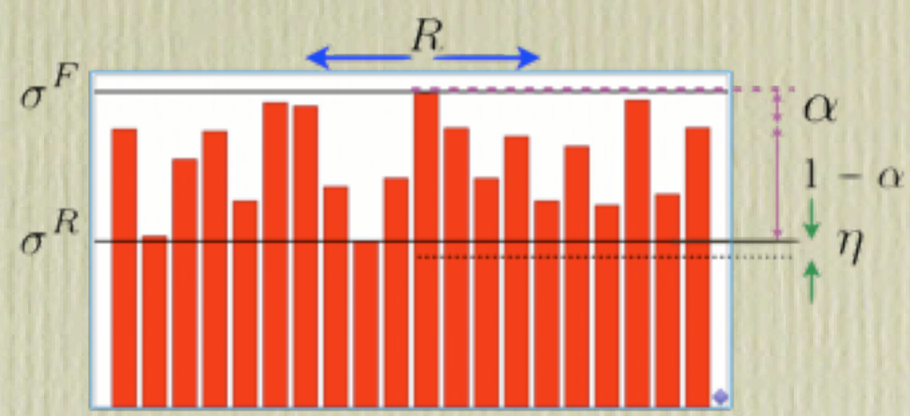


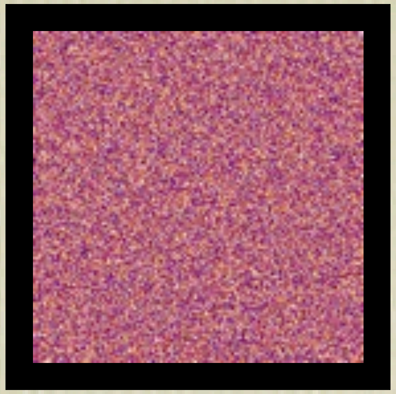


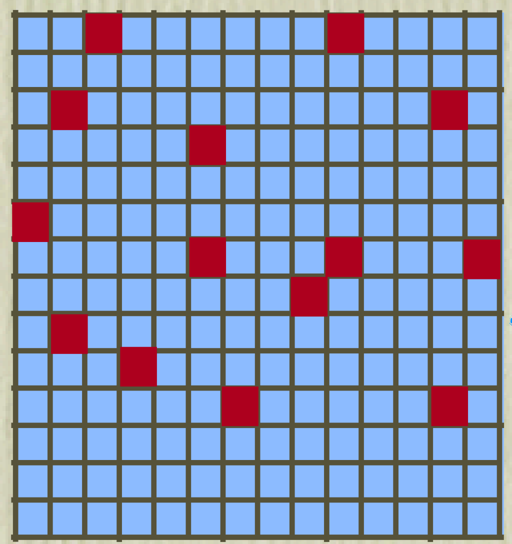


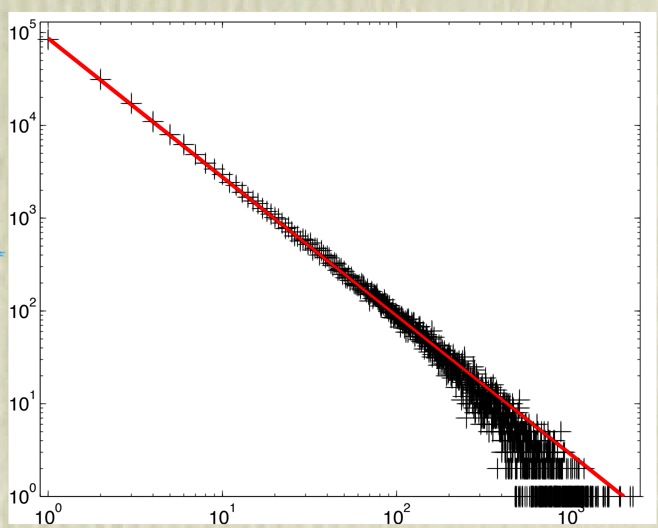
Picture Book

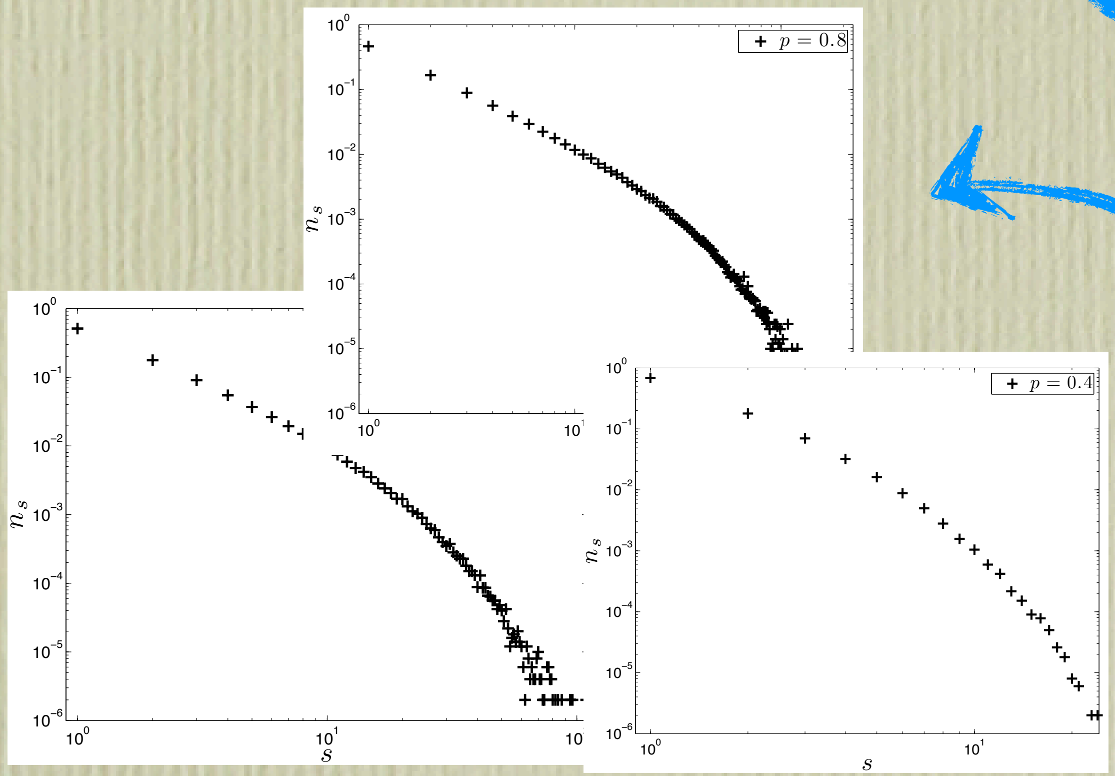






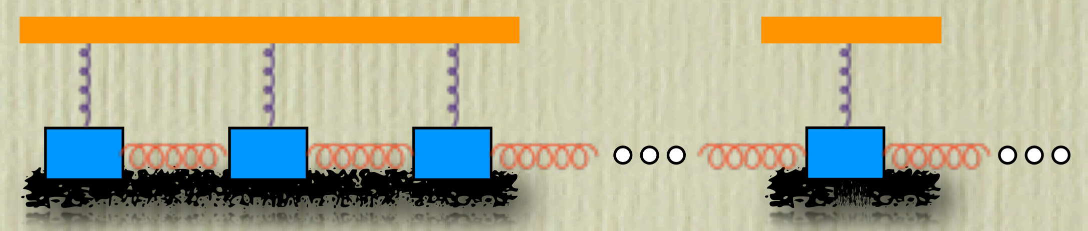


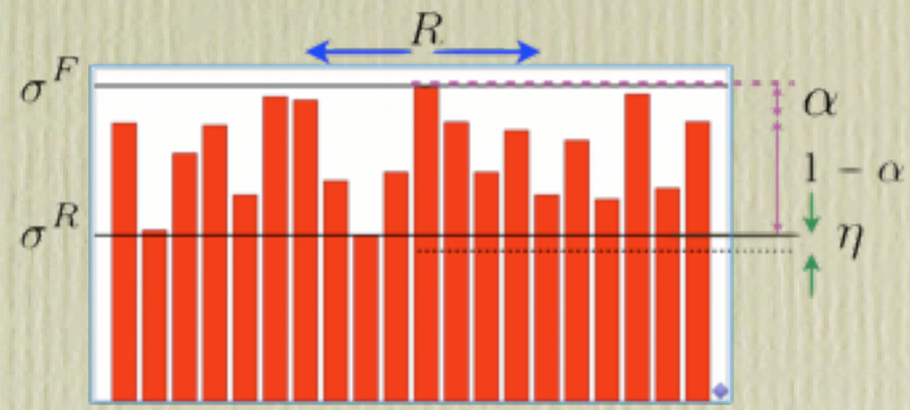


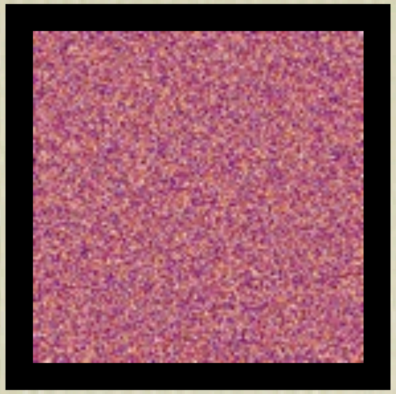


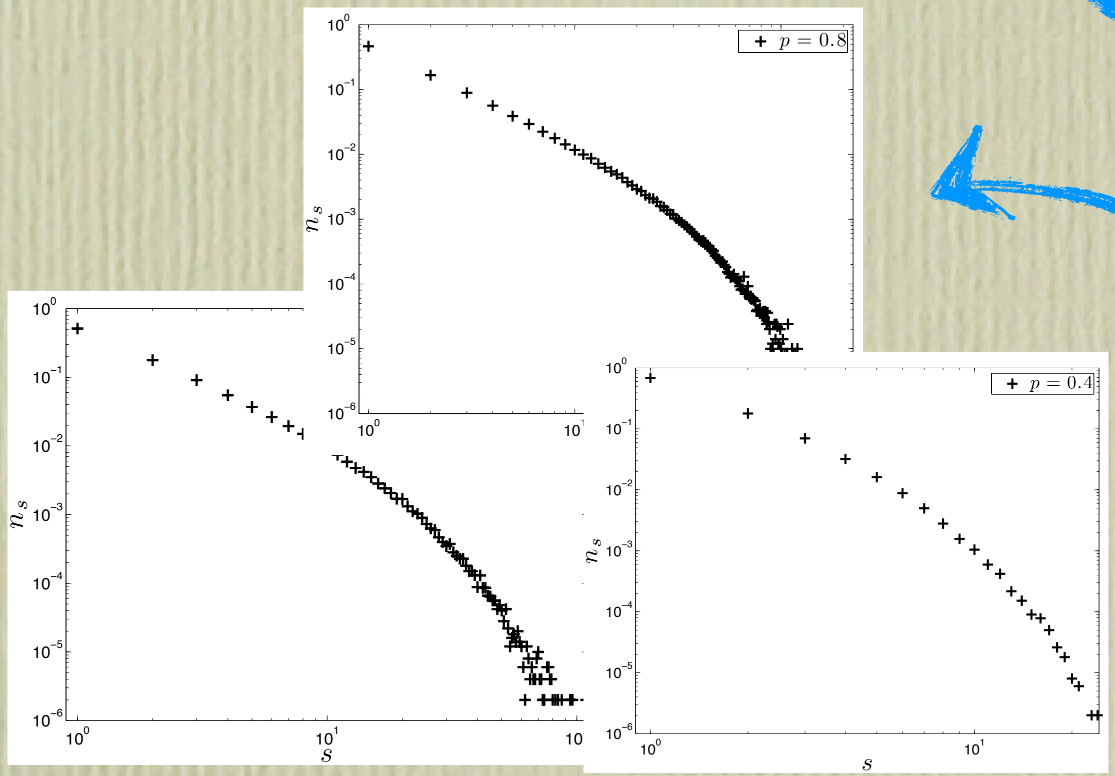
Friday, September 10, 2010

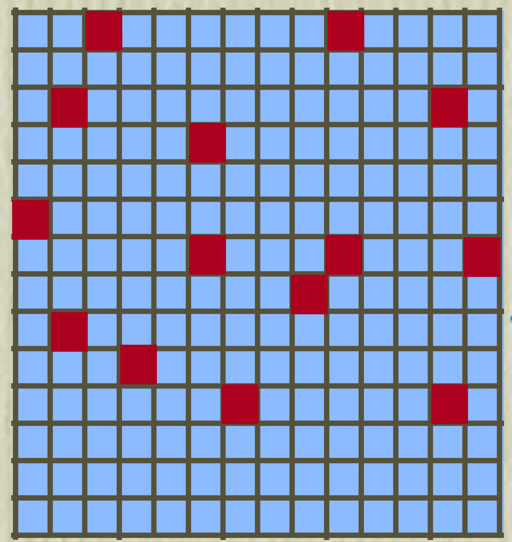
Picture Book

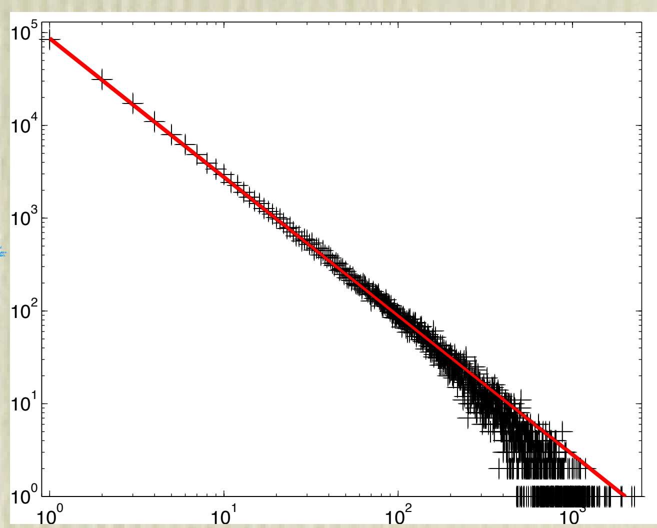


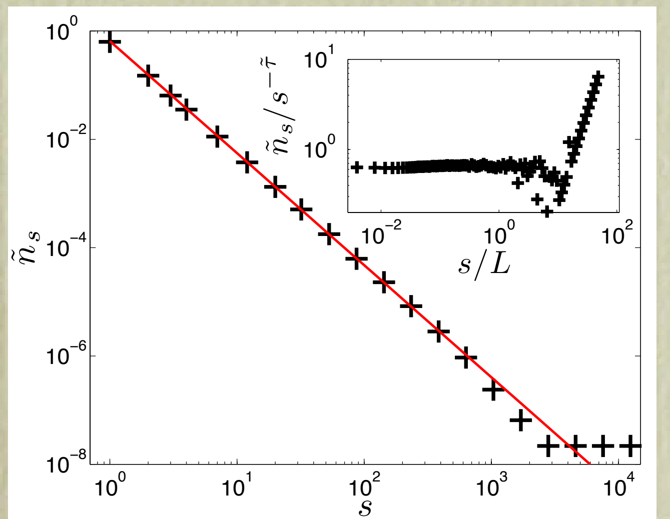






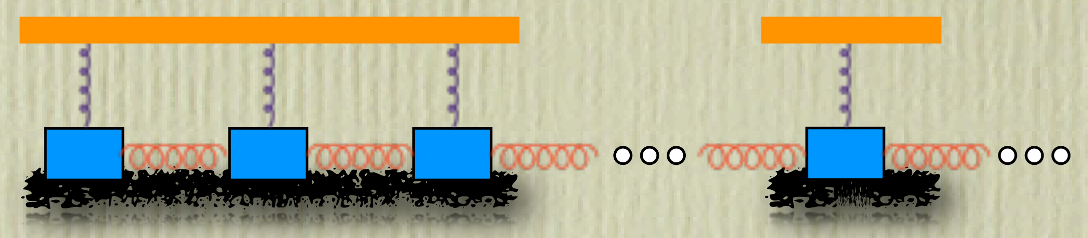


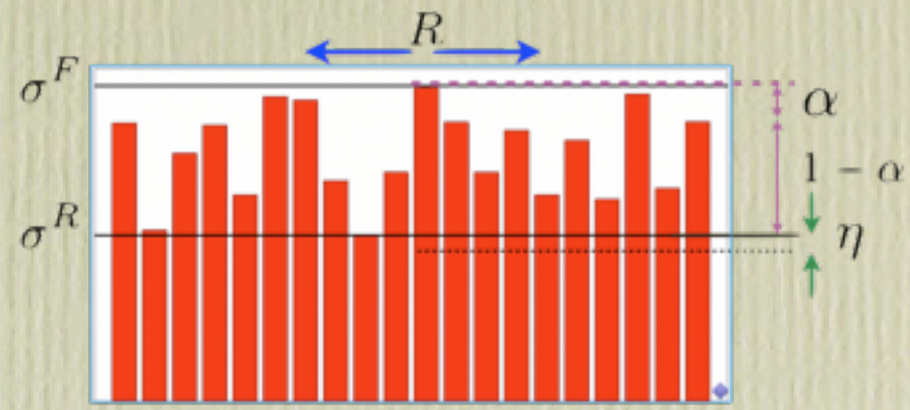


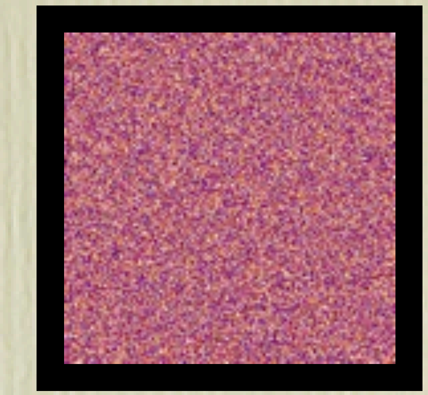


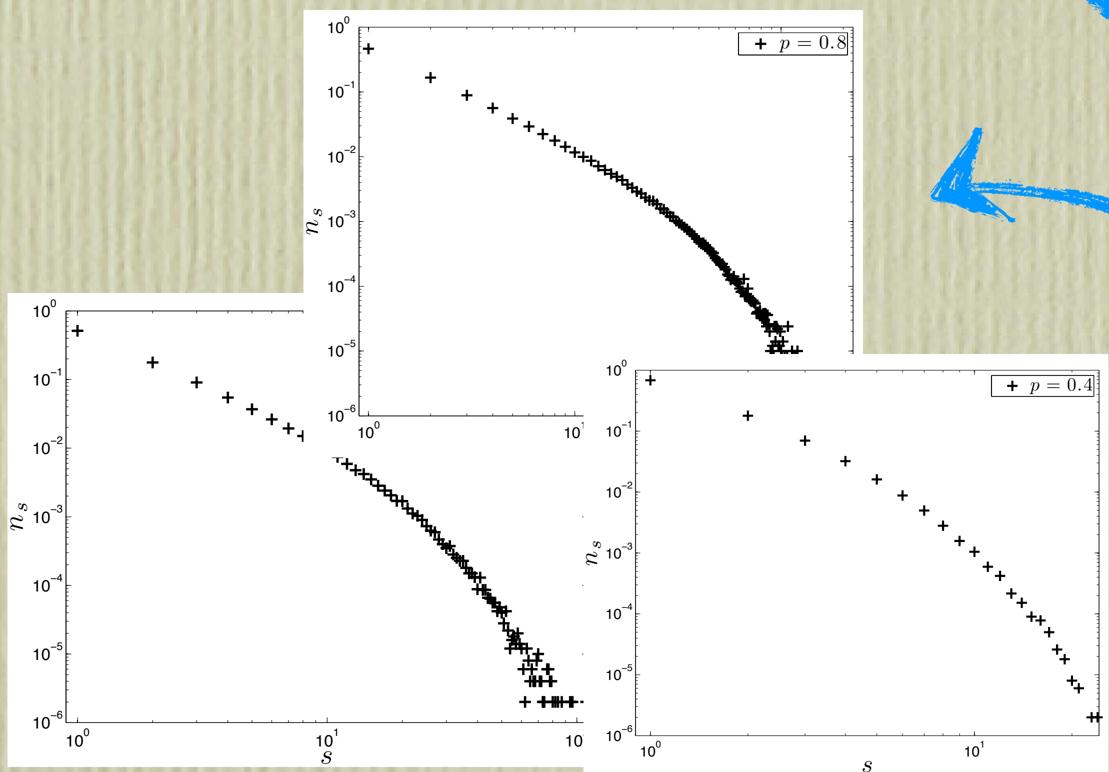
Friday, September 10, 2010

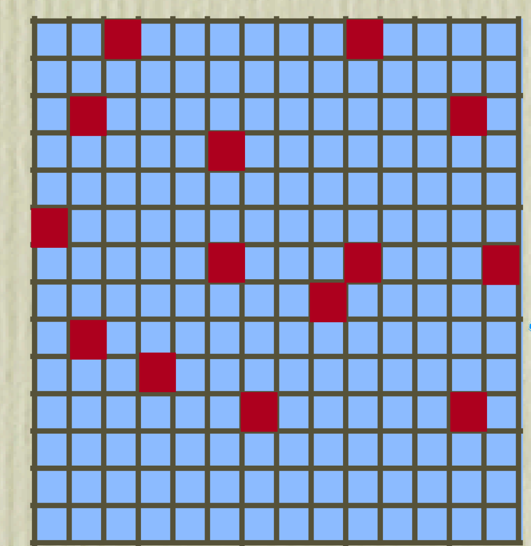
Picture Book

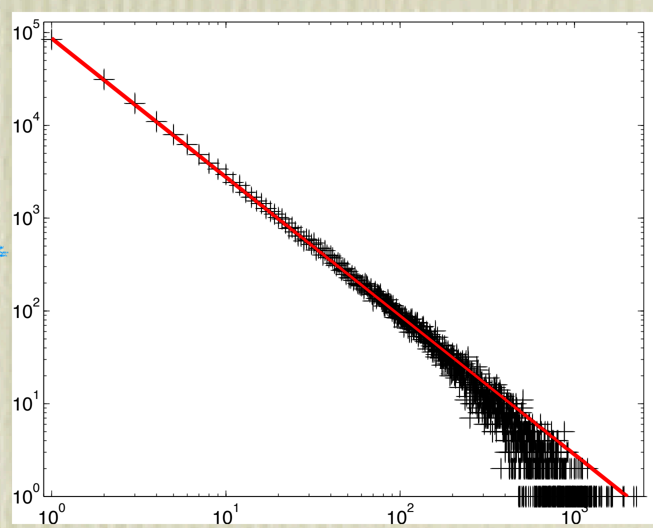


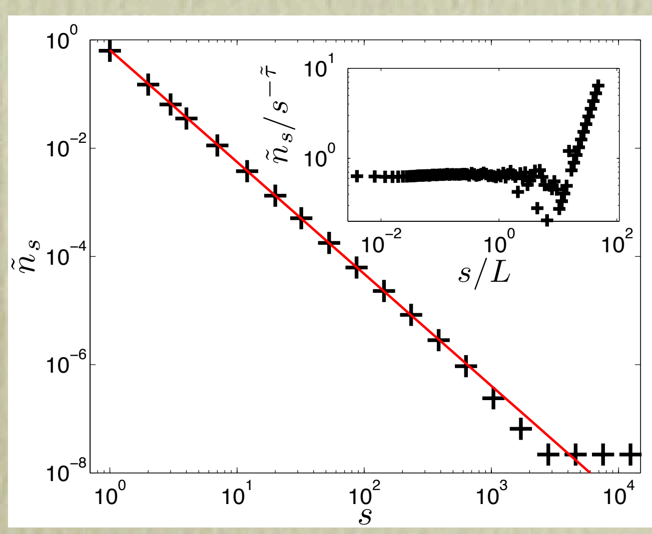


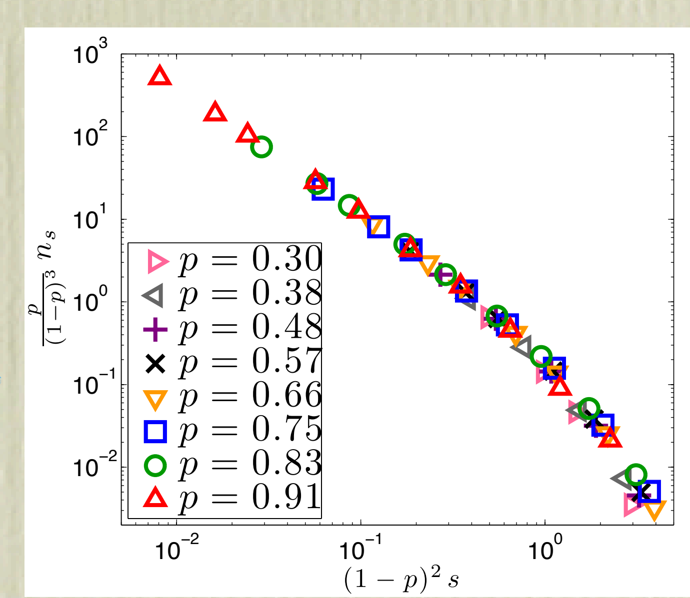












Moral of the Story

Moral of the Story

- Conventional thinking was / is that earthquake fault systems produce frequency-size statics that scale (Gutenberg–Richter) because:

  i. The system is critical (i.e. very near a critical point)

  ii. Inhomogeneities occur on length scales small compared to the interaction range and are thus negligible

Moral of the Story

- Conventional thinking was / is that earthquake fault systems produce frequency-size statics that scale (Gutenberg–Richter) because:

  i. The system is critical (i.e. very near a critical point)

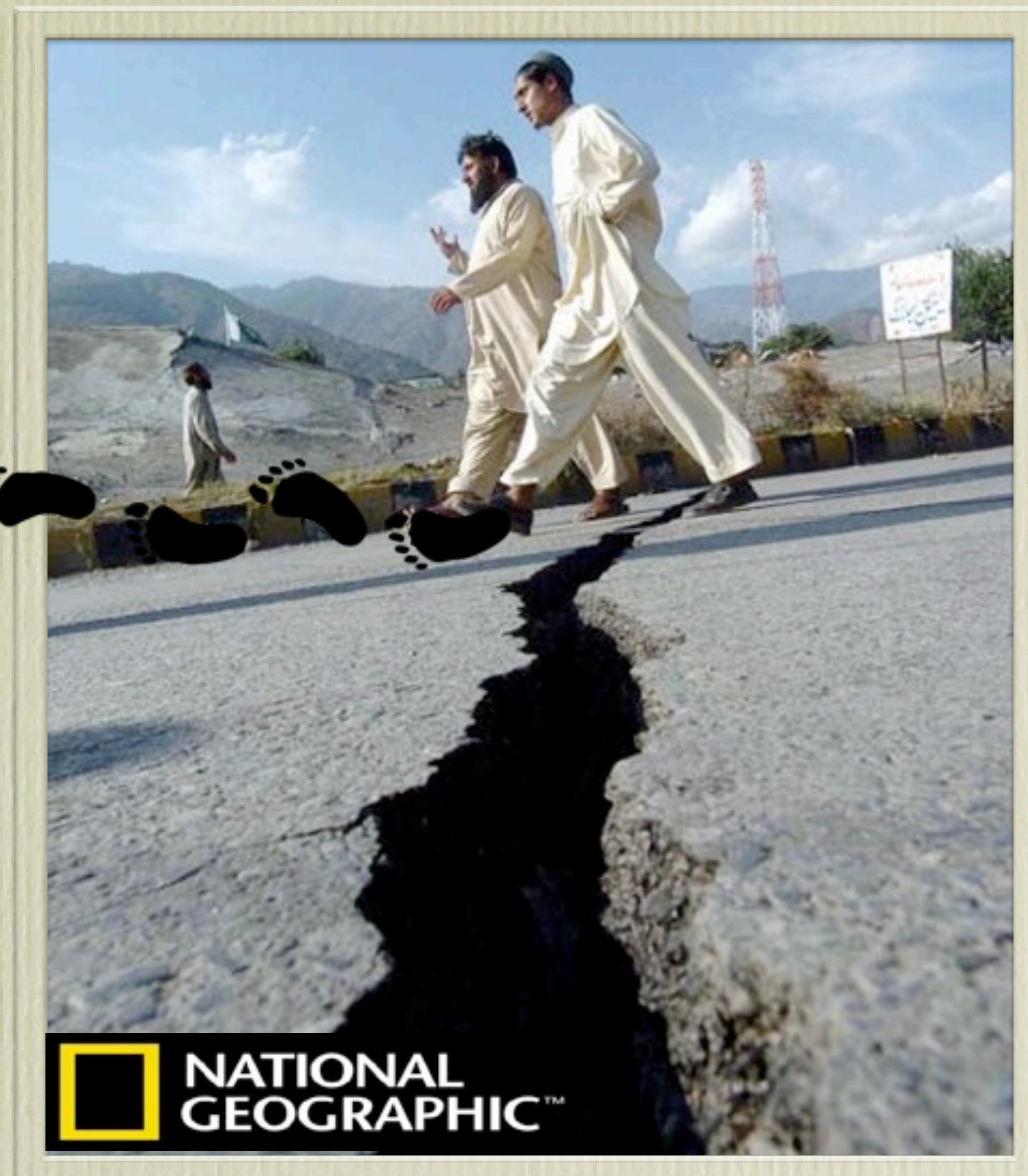
  ii. Inhomogeneities occur on length scales small compared to the interaction range and are thus negligible

- Our work shows:

  i. Fault systems need not be critical to generate GR statistics

  ii. Inhomogeneities are crucial in obtaining power-law distributed frequency-size statistics.

Thank You



Questions?