Earthquake-earthquake Triggering in Natural Swarms and Fluid-induced Seismicity

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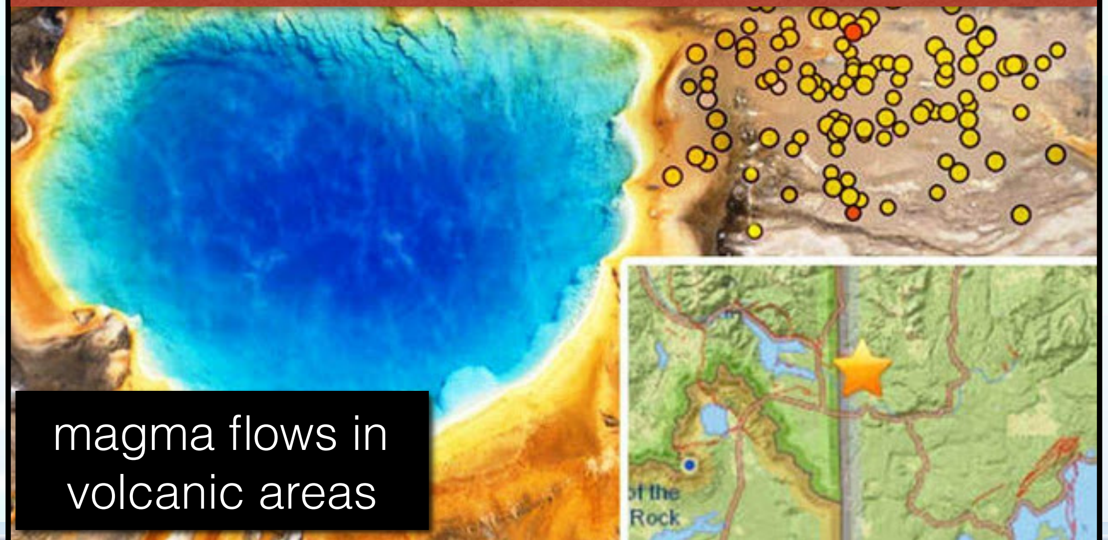
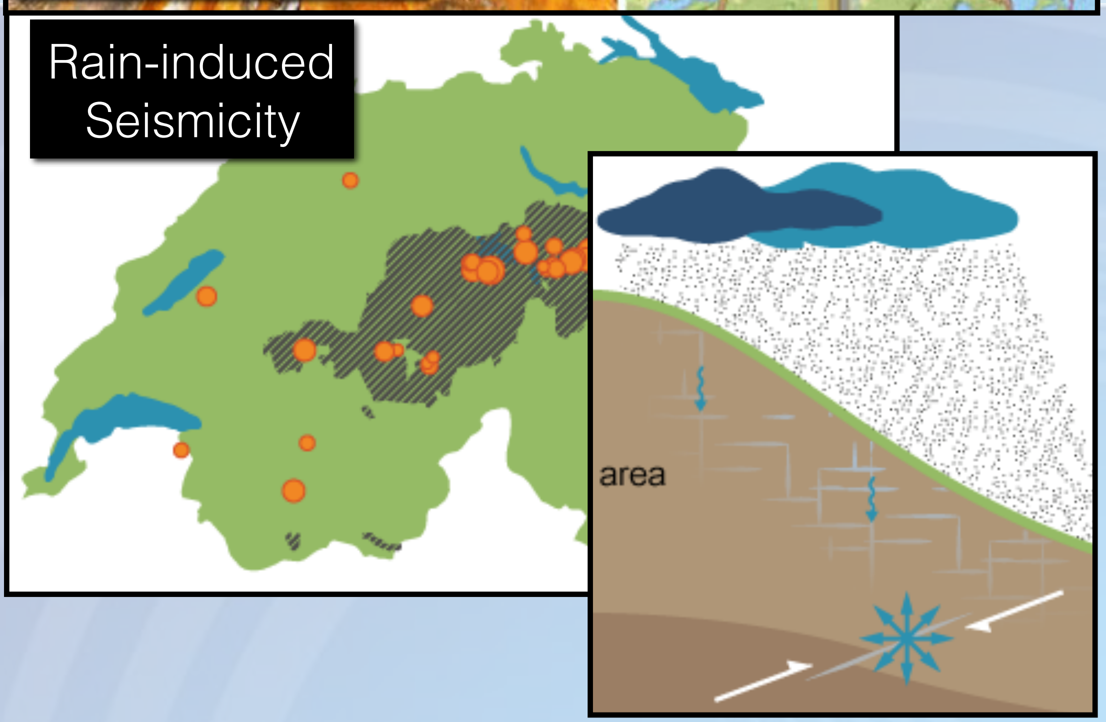
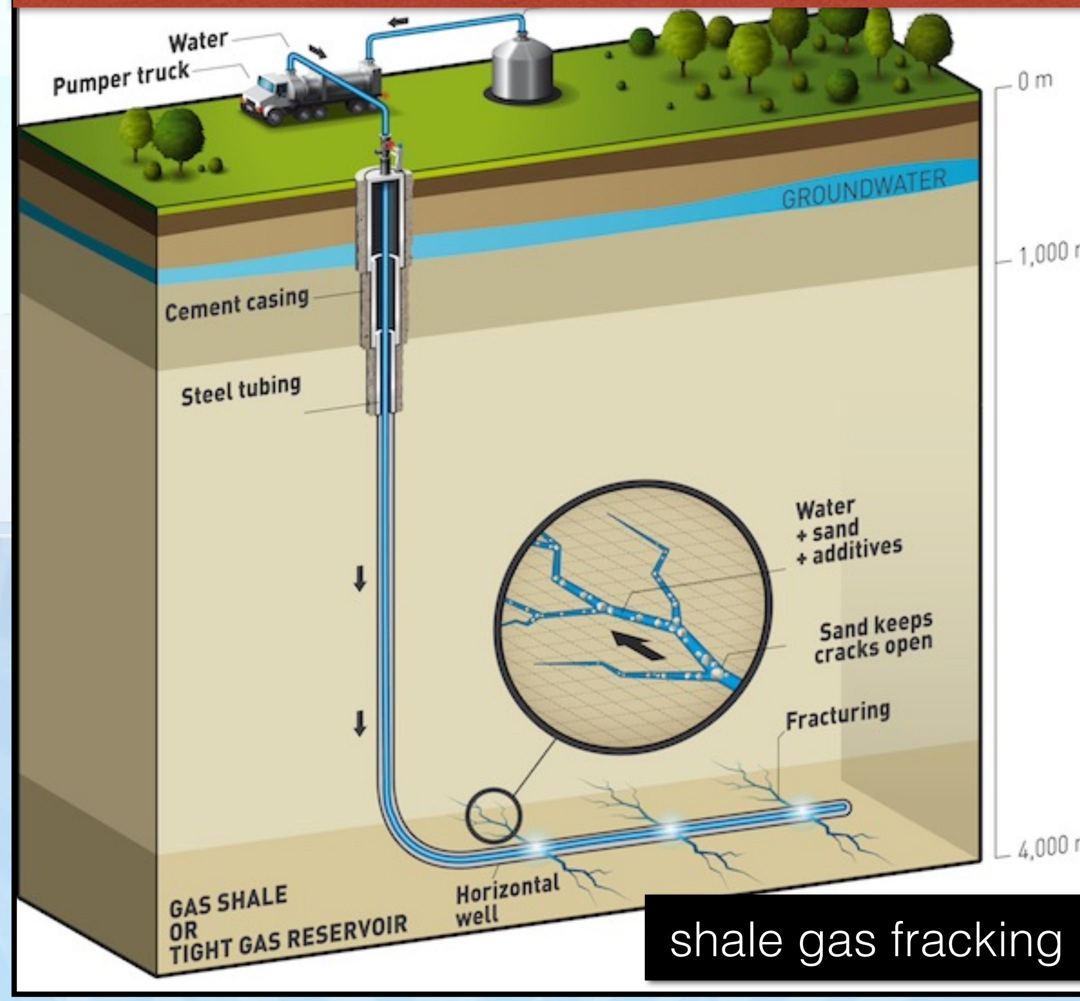
Fluid-Induced Seismicity

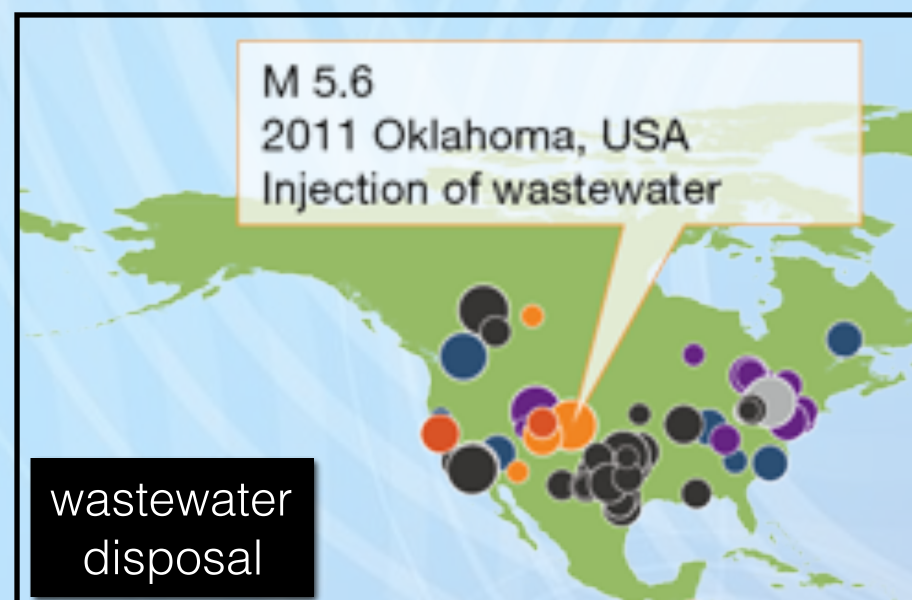
Natural Flows





Human-made





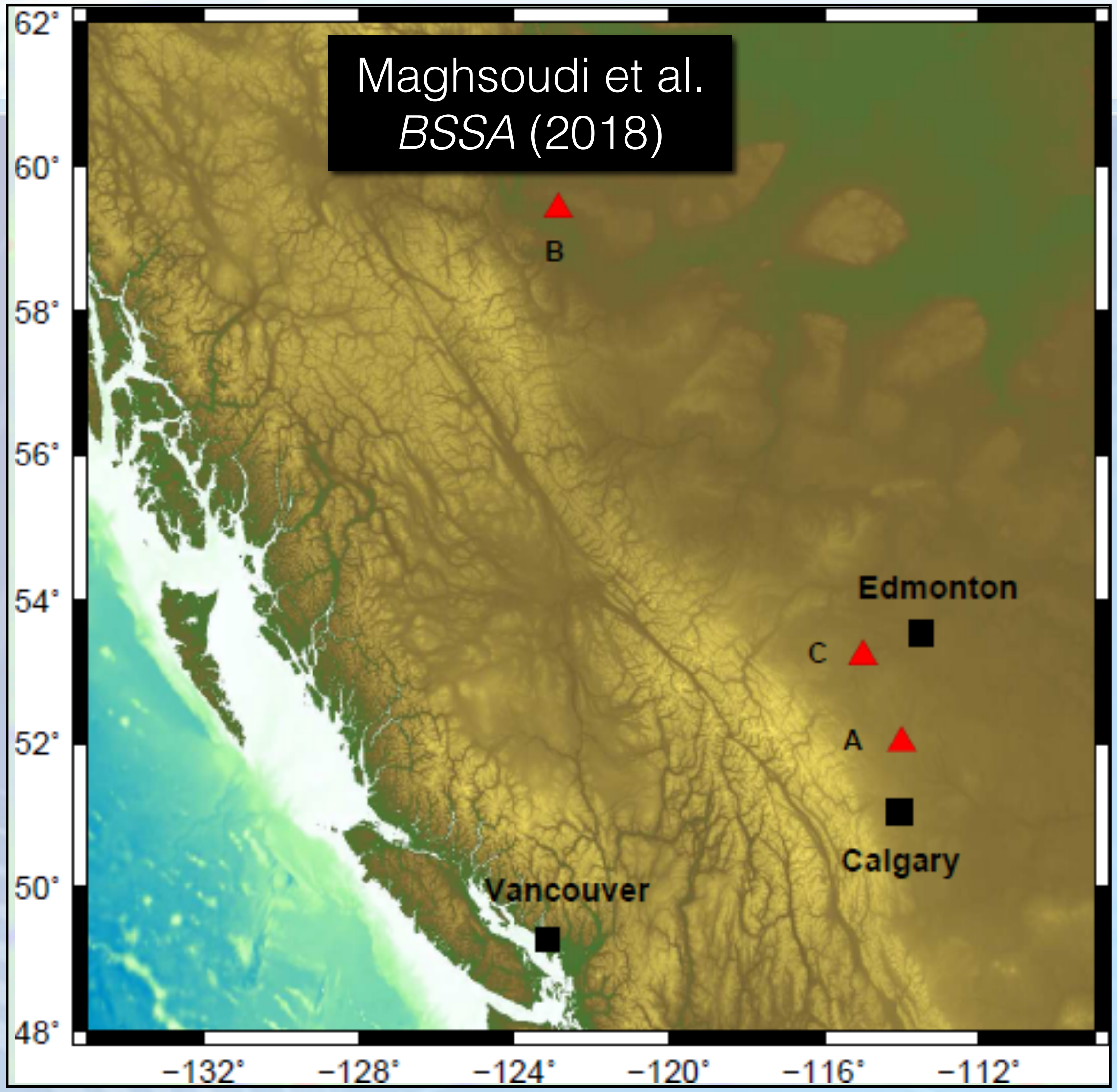
★ Natural Flows often lead to earthquake ***swarms***

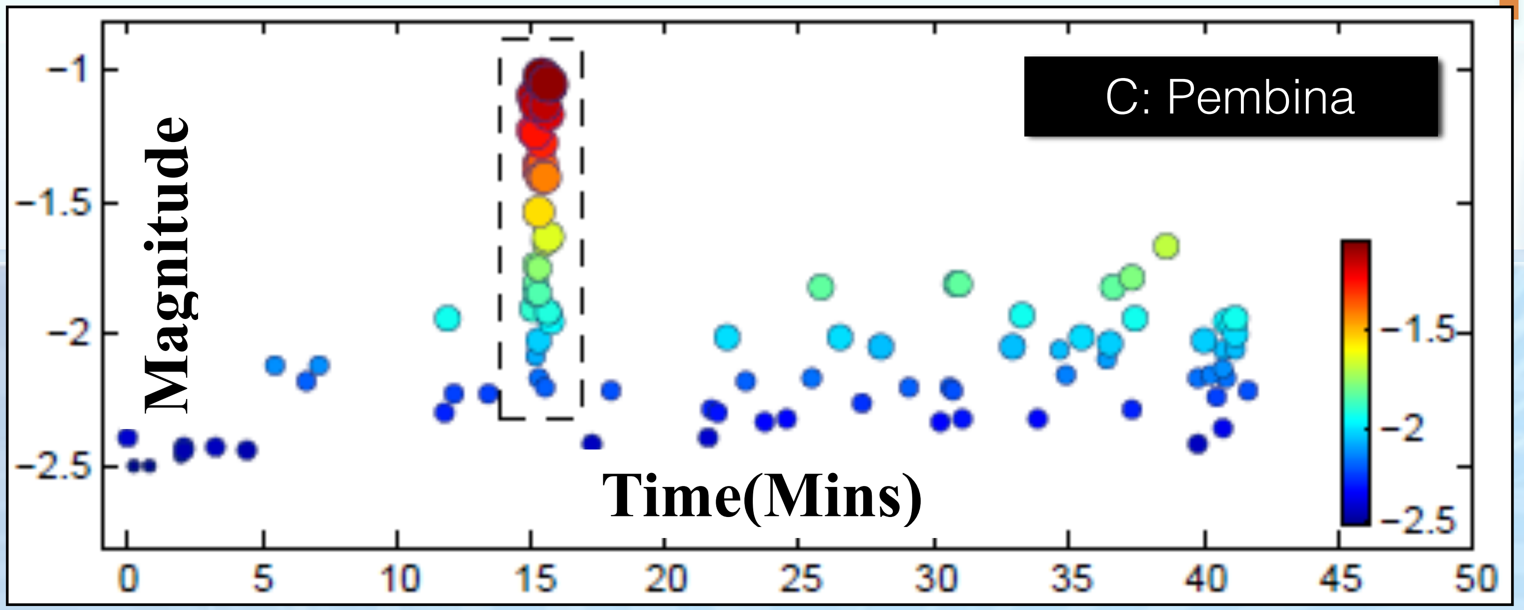
★ Are swarm-like features present in human-made fluid-driven earthquakes?

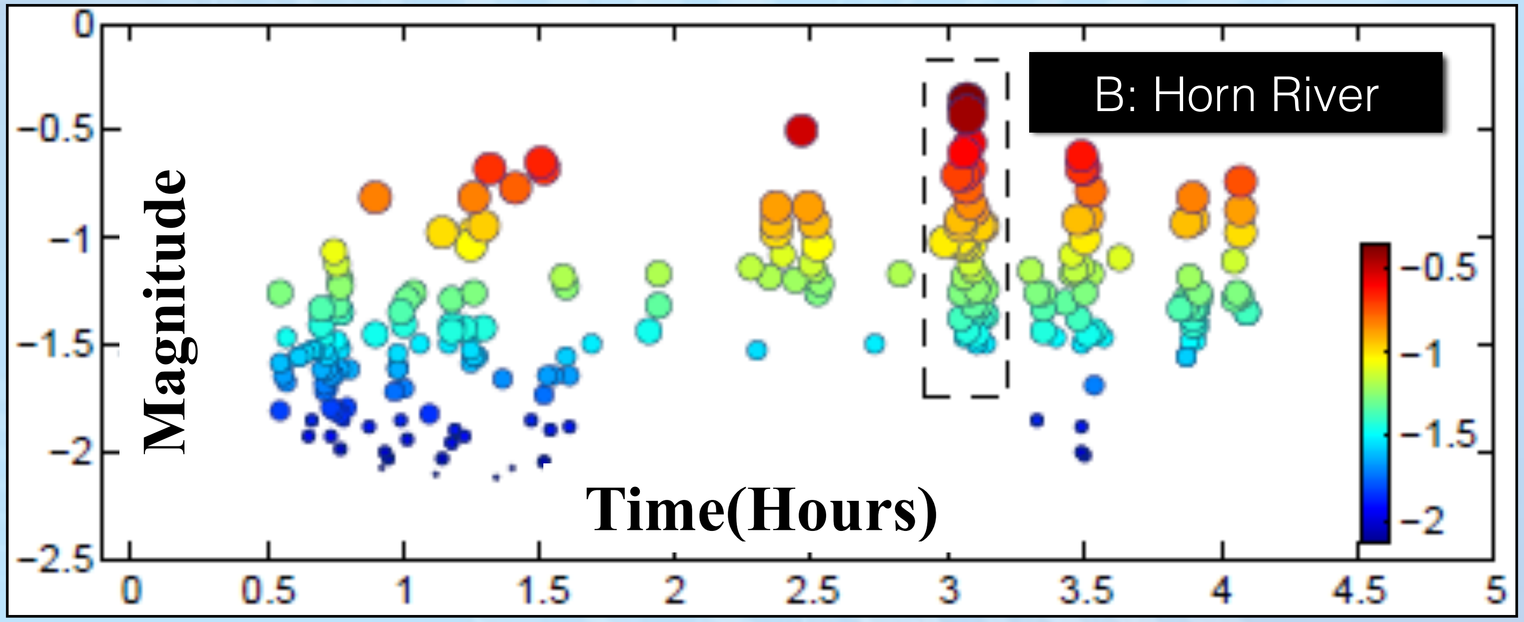
Hydraulic Fracturing

★ Temporal Evolution of ***Aftershocks***:

Swarm-like Features Have Been Observed.

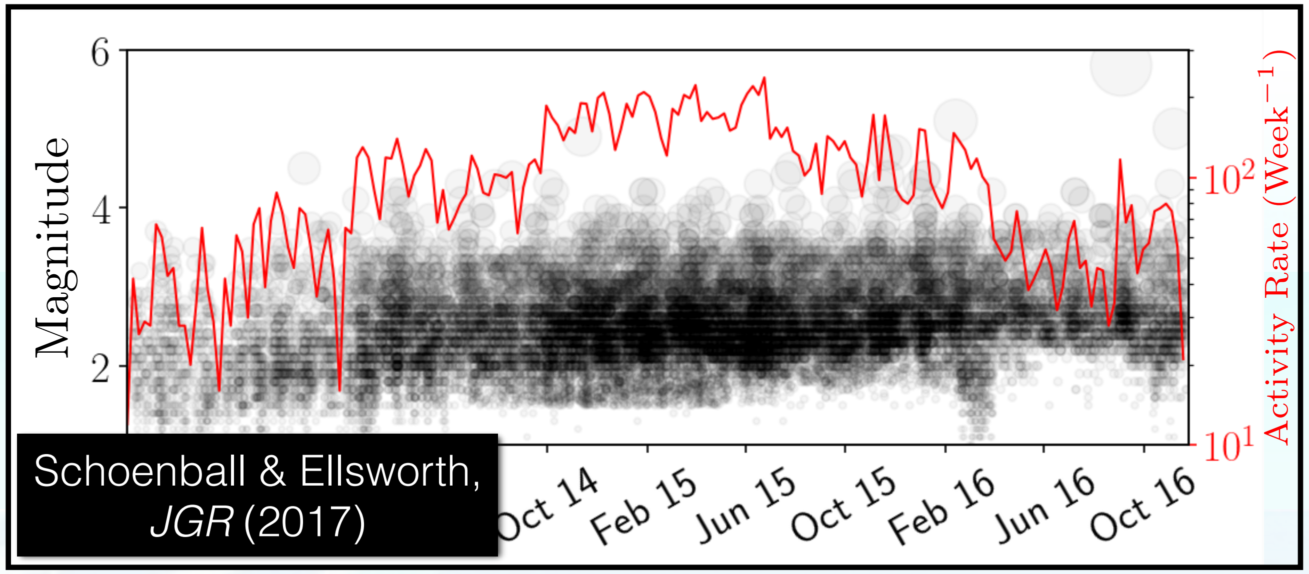






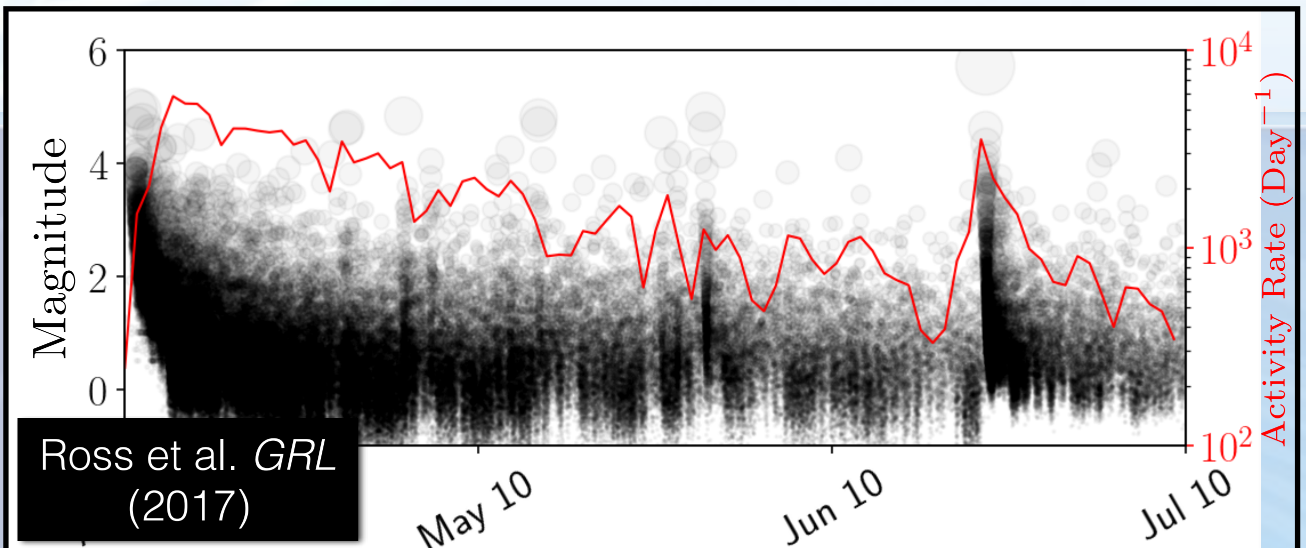
Case Studies

We Analyzed three High Resolution Catalogs



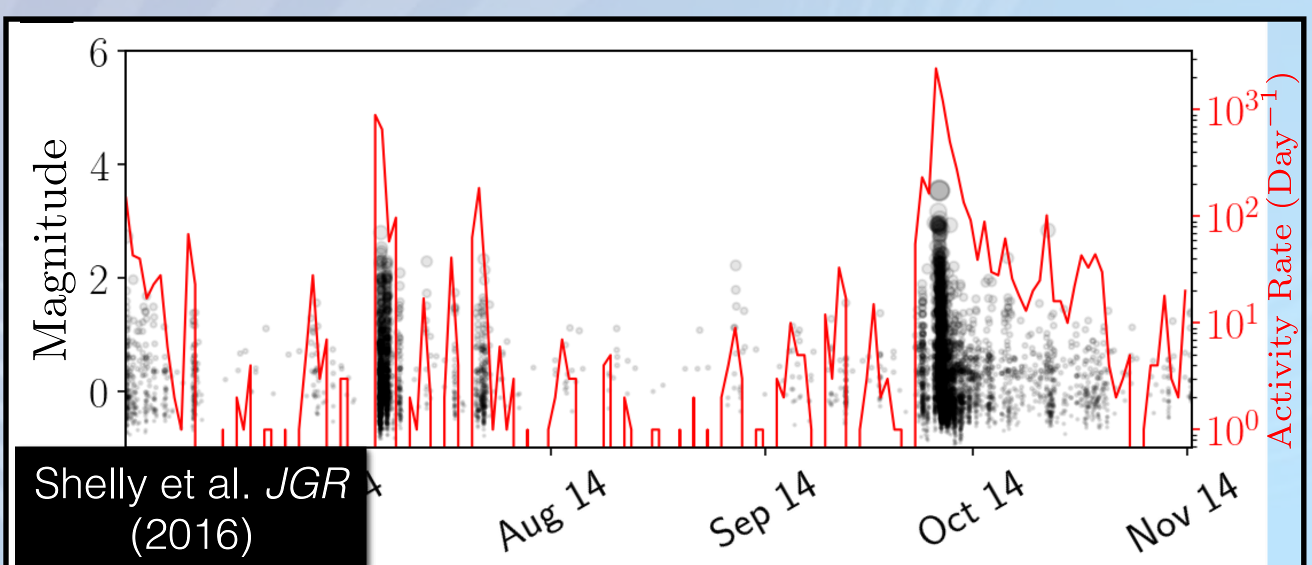
★ ***Induced*** Seismicity

Oklahoma & southern Kansas



★ (suspected) ***swarms***

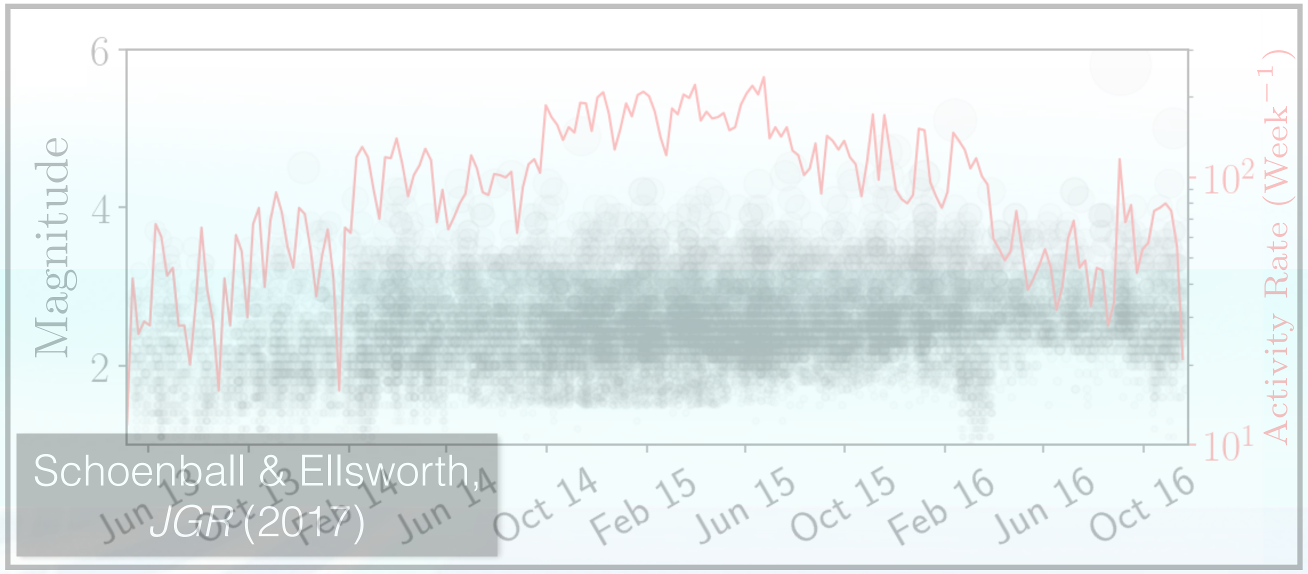
the Yuha Desert



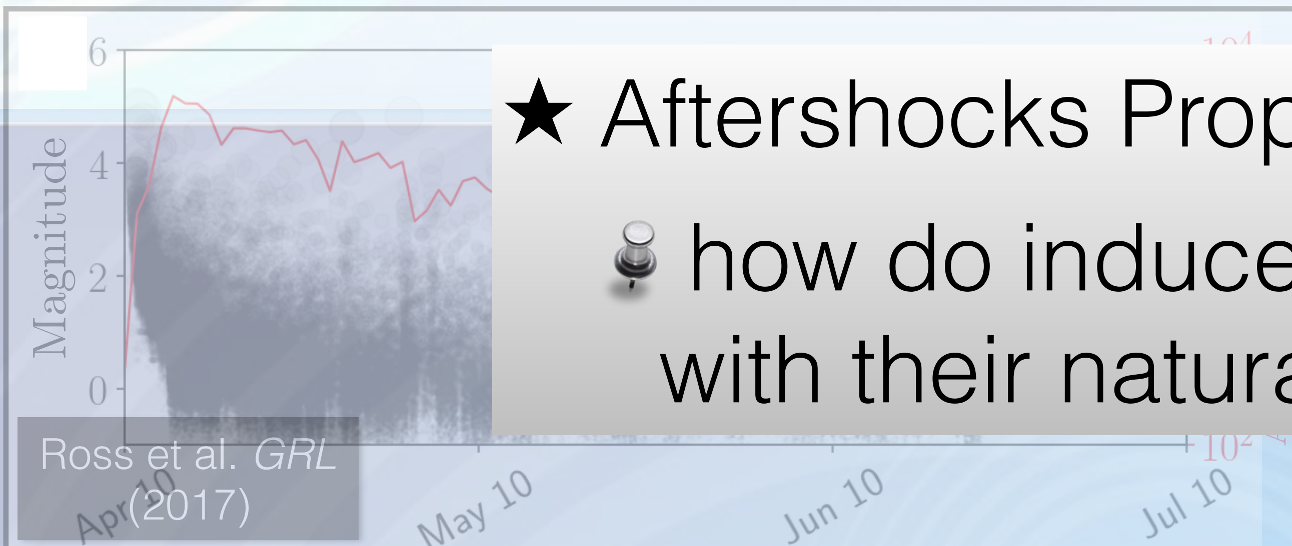
★ ***natural swarms***

the Long Valley, Caldera

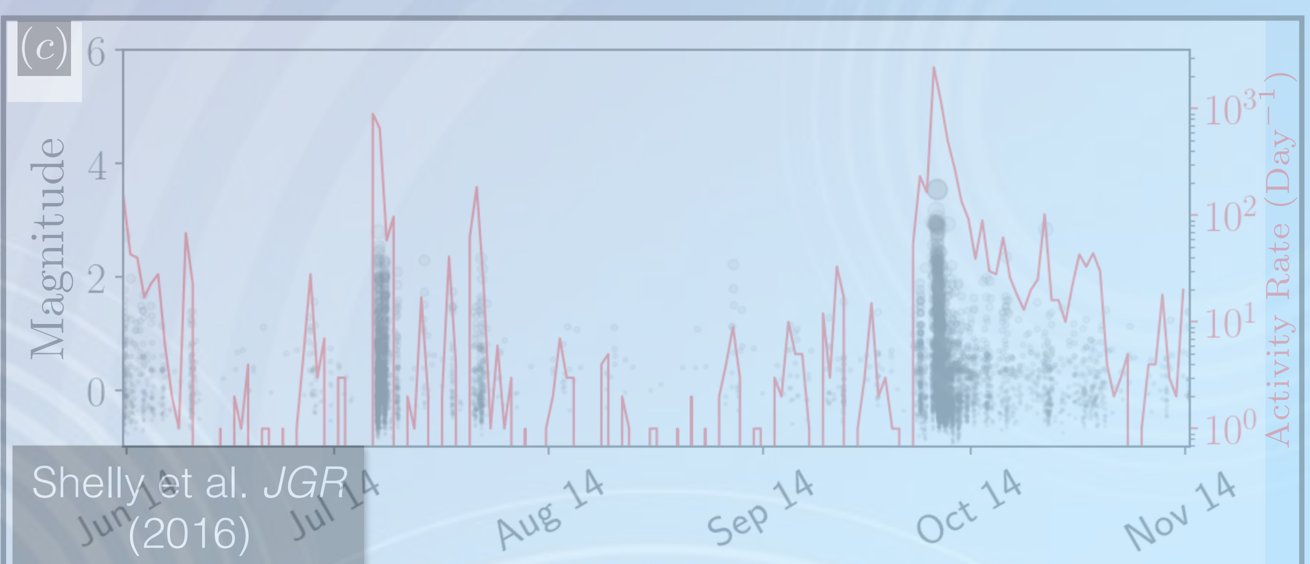
Case Studies



Schoenball & Ellsworth, *JGR* (2017)



Ross et al. *GRL* (2017)



Shelly et al. *JGR* (2016)

We Analyzed three High Resolution Catalogs

★ ***Induced*** Seismicity

Oklahoma & southern Kansas

★ Aftershocks Properties:

- how do induced events compare with their natural analogs?

…arms

the Yuha Desert

★ ***natural swarms***

the Long Valley, Caldera

Infer Aftershocks:
Declustering Method

Build A ***Null*** Model Of Uncorrelated Events: *Poisson* Process With Gutenburg-Richter Rate

$$\lambda \doteq c \times 10^{-bm_i}$$

Deviations From the Null Model Implies Aftershocks ***Triggering***

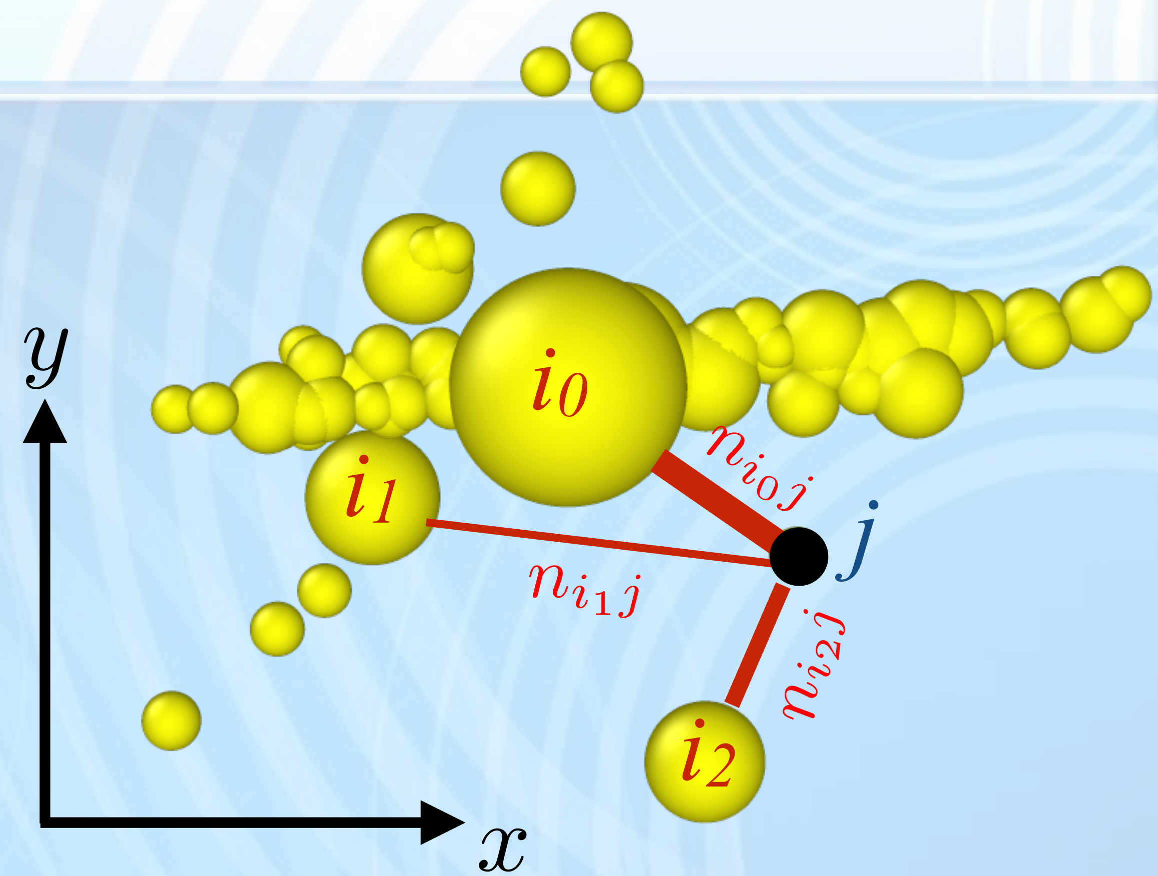
$$n_{ij} = \lambda \times |\vec{r}_i - \vec{r}_j|^{d_f} \times t_{ij}$$

$$n^*_{ij} = \min\{n_{ij}\}$$

c : Global Activity Rate

Fractal Dimension

$$d_f \simeq 2$$



Zaliapin *et al.* (2008), Zaliapin & Ben-Zion (2013), Gu *et al.* (2013)

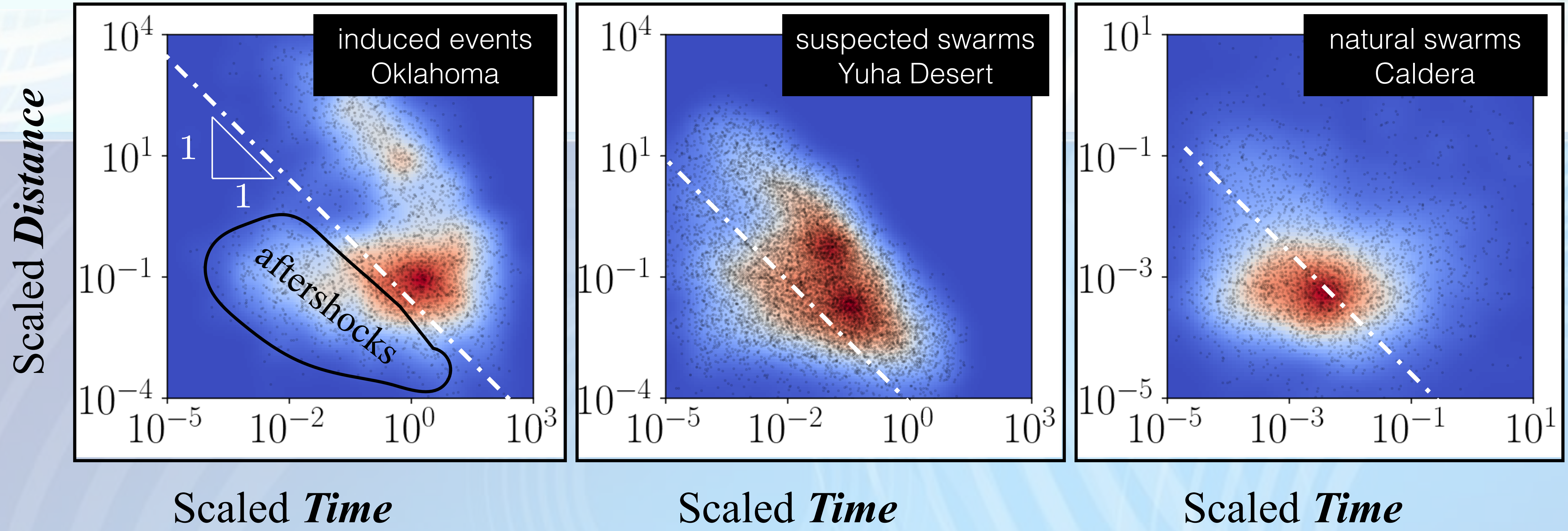
Infer Aftershocks:
Density Maps

Scaled ***Time***

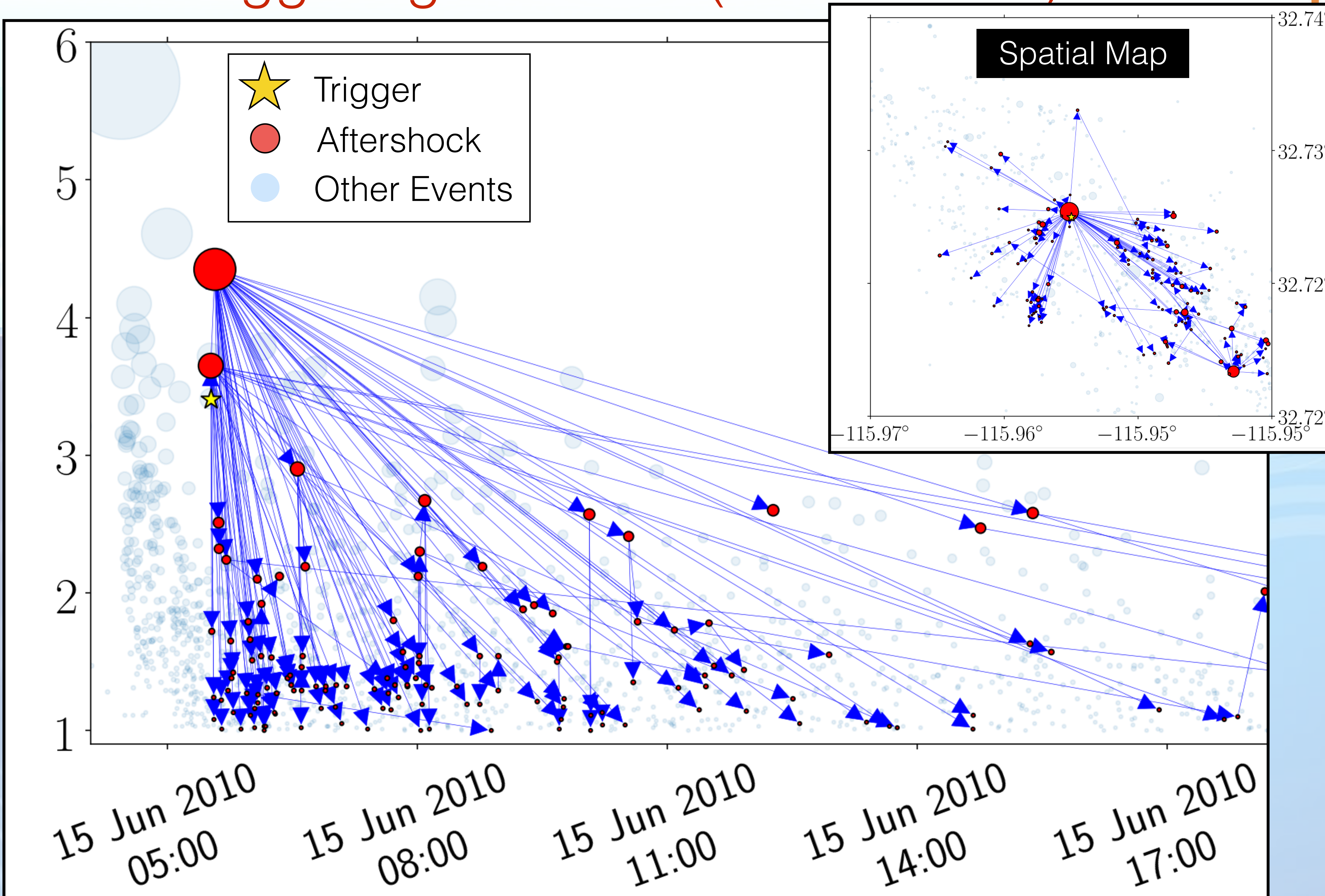
$$t_j^* \equiv t_{i^*j}\ 10^{-\frac{b}{2}m_{i^*}}$$

Scaled ***Distance***

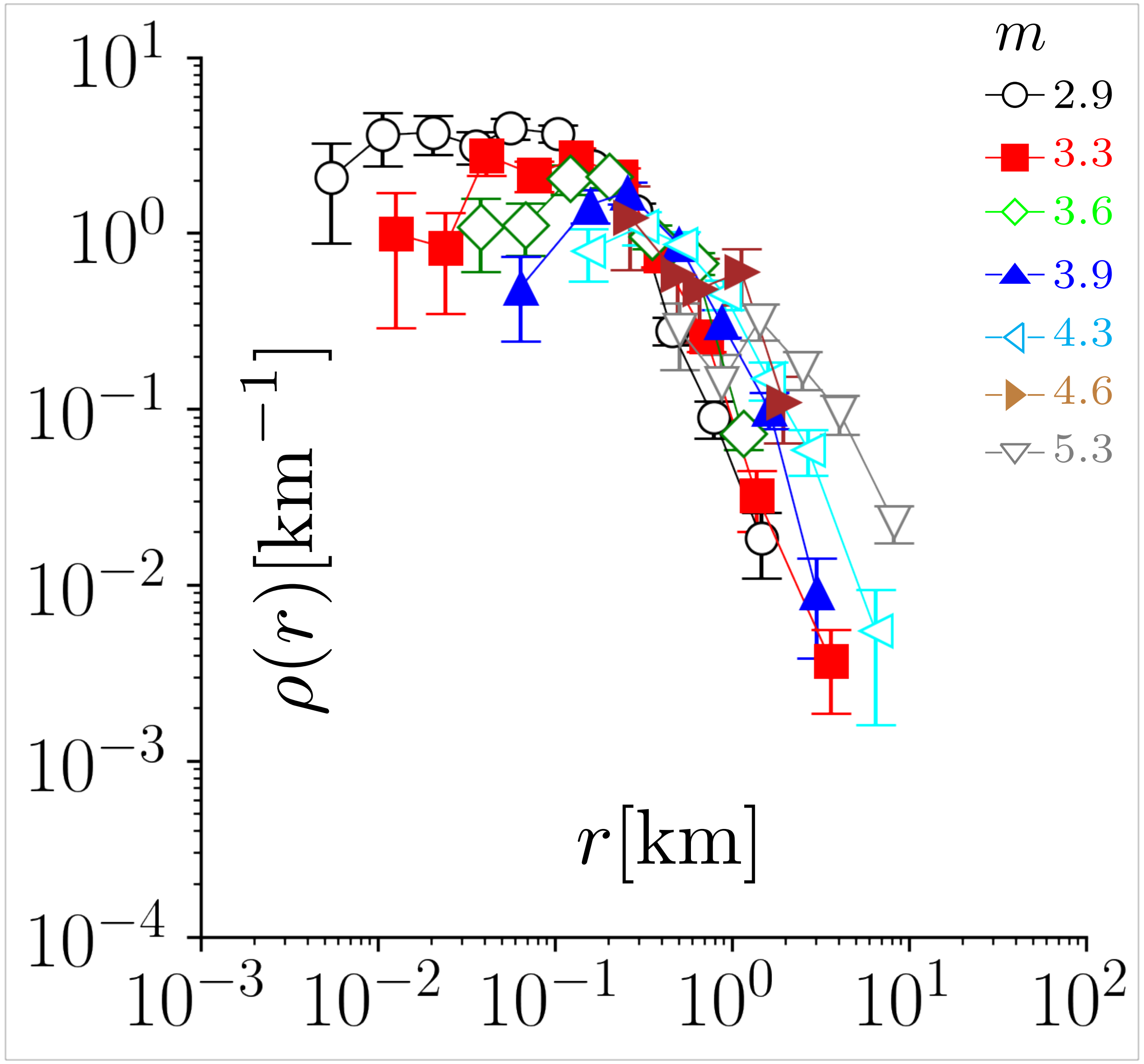
$$r_j^* \equiv r_{i^*j}^{d_f}\ 10^{-\frac{b}{2}m_{i^*}}$$

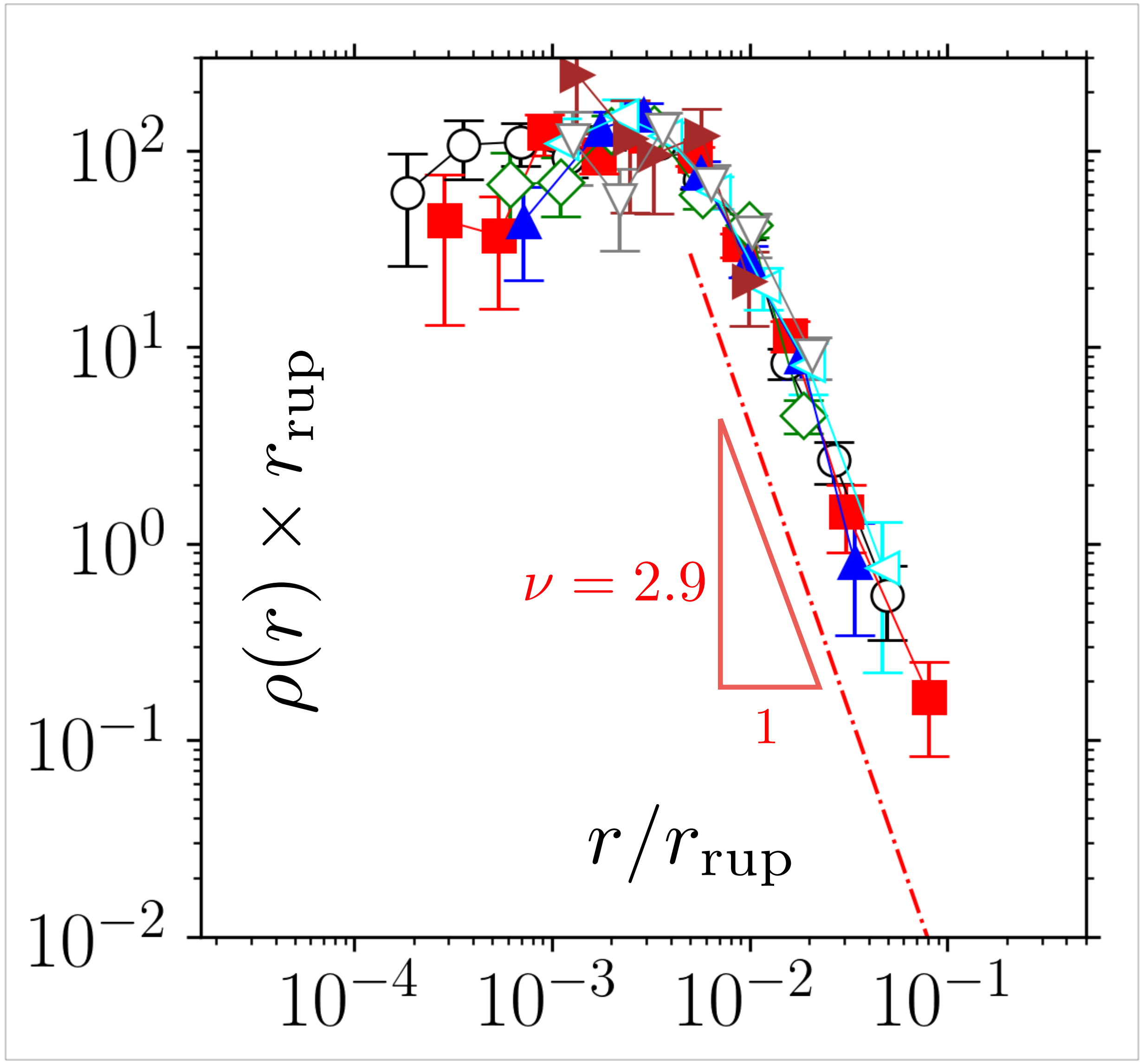


Infer Aftershocks:
Triggering Cascade (Yuha Desert)



Spatial Density of Aftershocks
Induced Case: **Oklahoma**





Peak interpreted as ***rupture*** length

$$r_{\mathrm{rup}} \propto 10^{\sigma \times m}$$

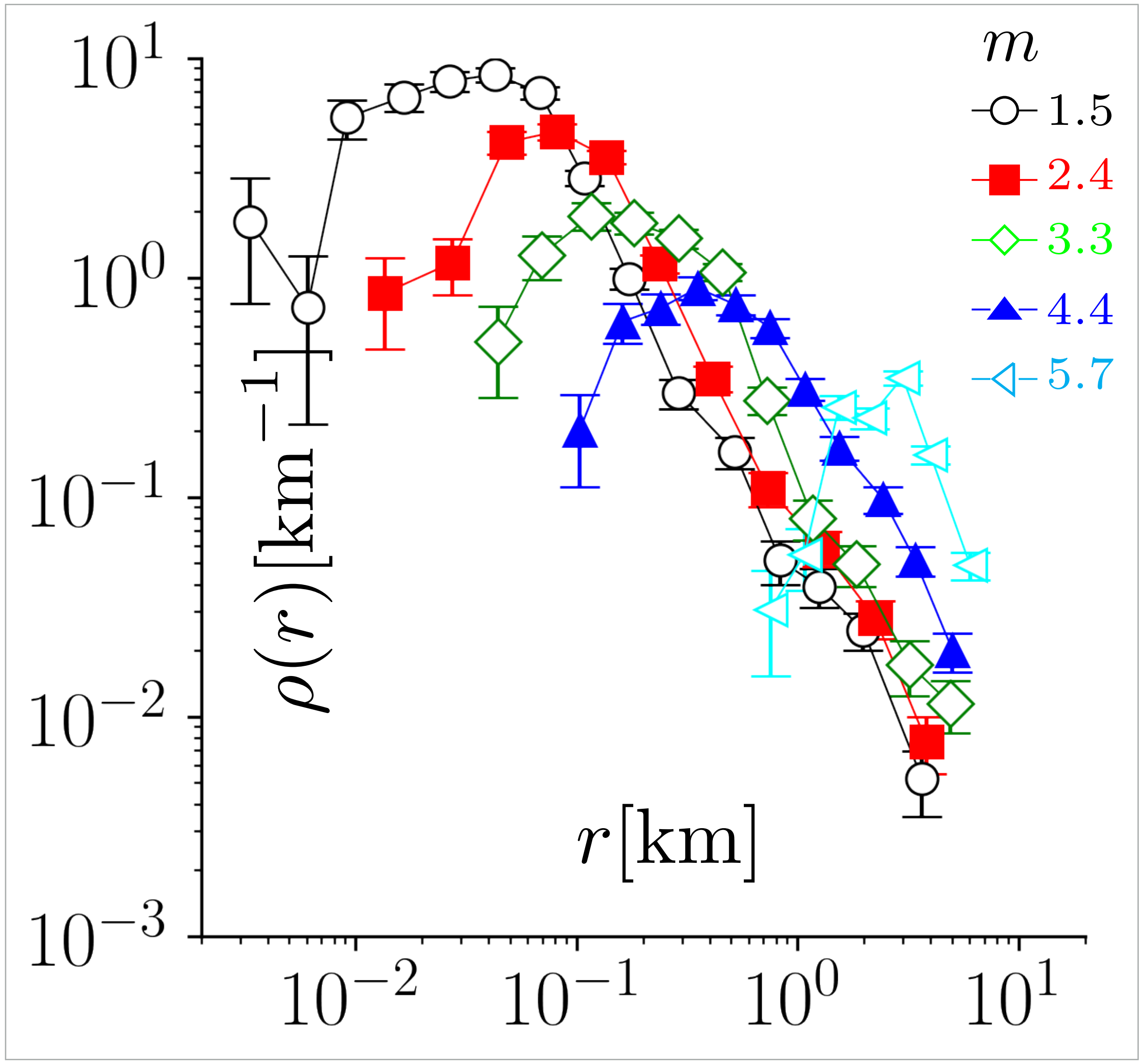
$$\sigma = 0.5$$

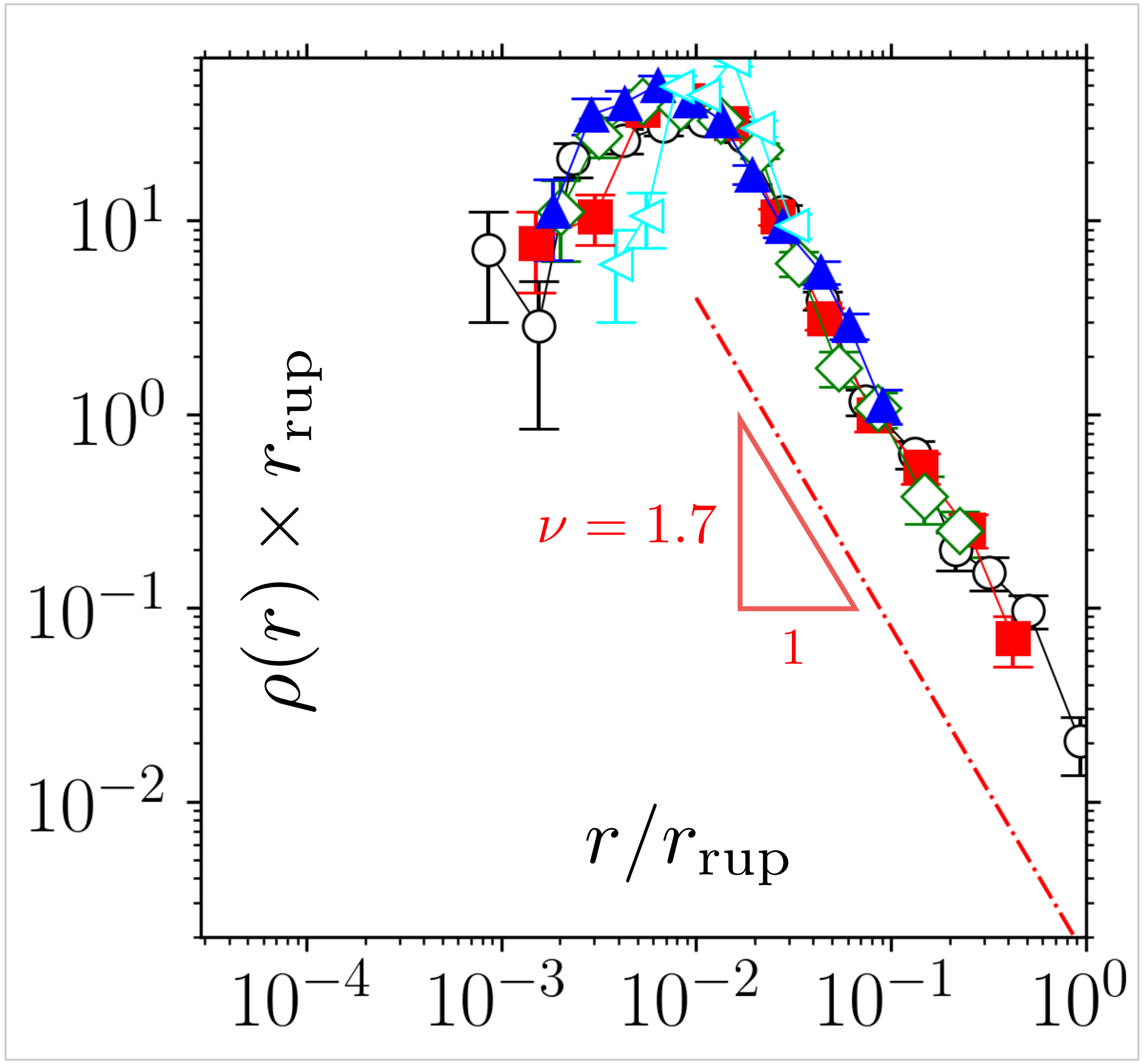
Power-law Decay

$$\rho(r) \propto r^{-\nu}$$

Spatial Density of Aftershocks

Suspected Swarms (**Yuha Desert**)





Peak interpreted as ***rupture*** length

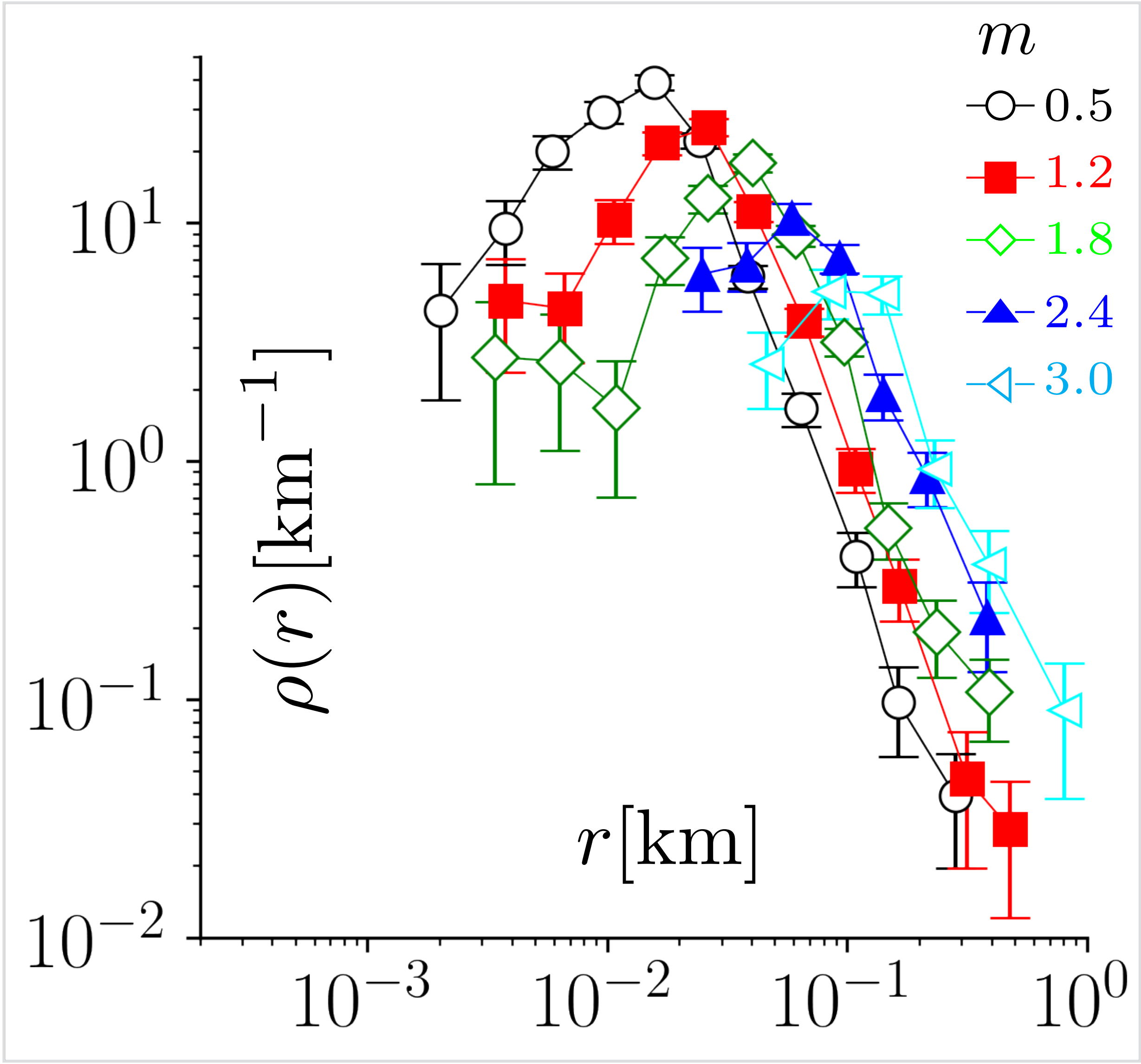
$$r_{\mathrm{rup}} \propto 10^{\sigma \times m}$$
$$\sigma = 0.4$$

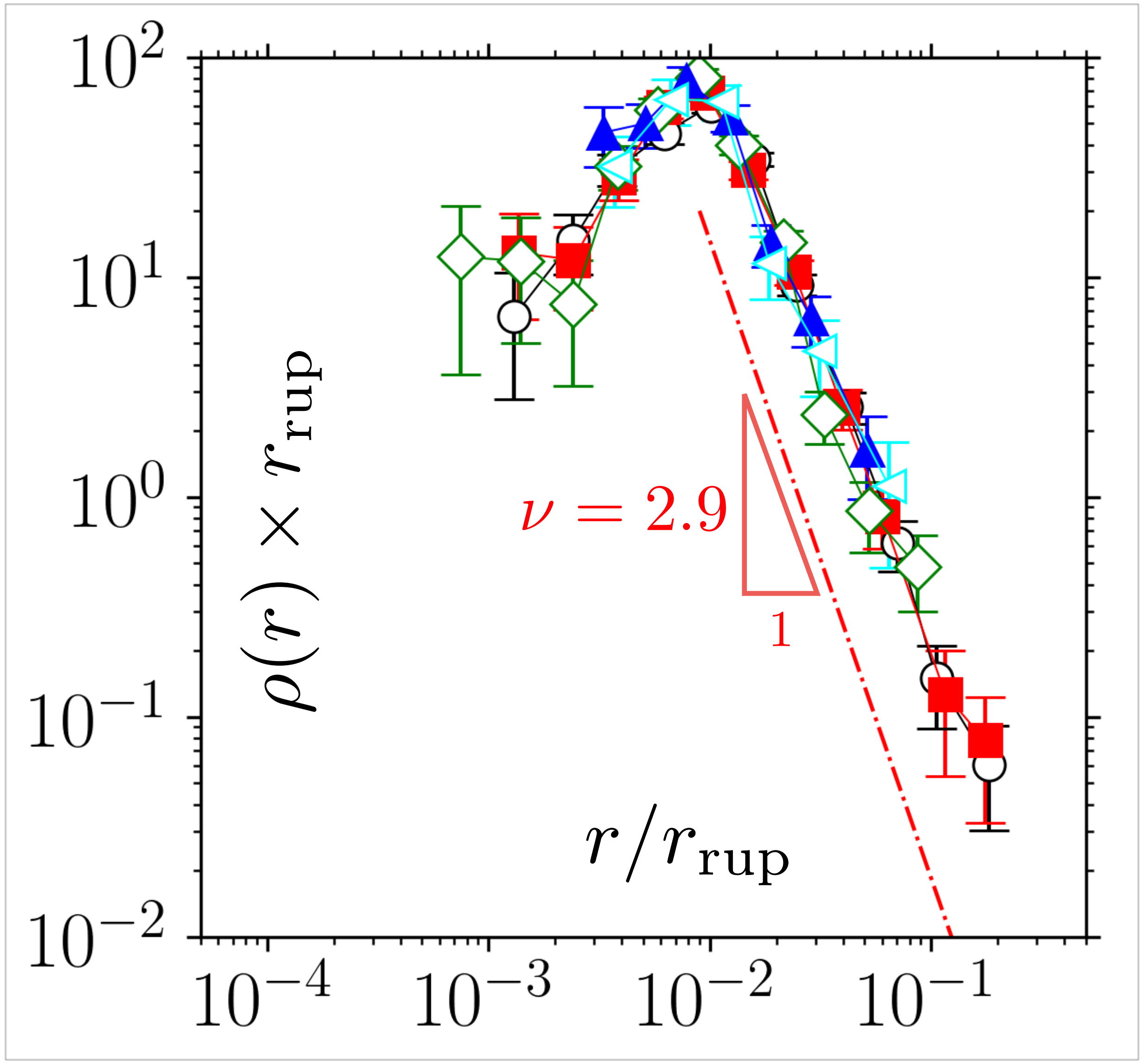
Power-law Decay

$$\rho(r) \propto r^{-\nu}$$

Spatial Density of Aftershocks

Natural Swarms (**Caldera**)





Peak interpreted as ***rupture*** length

$$r_{\mathrm{rup}} \propto 10^{\sigma \times m}$$
$$\sigma = 0.36$$

Power-law Decay

$$\rho(r) \propto r^{-\nu}$$

Aftershock Zones

Table of Exponents

Location (Year)	Type	Linear Density $\rho(r) \propto r^{-\nu}$ ν	Rupture Size $r_{\text{rup}} \propto 10^{\sigma m}$ σ
Oklahoma & southern Kansas (2014–2017)	Fluid Induced (Man-made)	2.9	0.5
Long Valley Caldera, California (2014 *a*)	Natural Swarm	2.9	0.36
Yuha Desert, California (2010)	Fluid Induced (Natural)	1.7	0.4

❖ Longer Ranged Trend (Typical of Tectonic Seismicity in California)

❖ Explained by Non-local Transfer of Static (Coulomb Stress)

❖ Steep Decay Indicating the Dominant Role of Fluid Migration

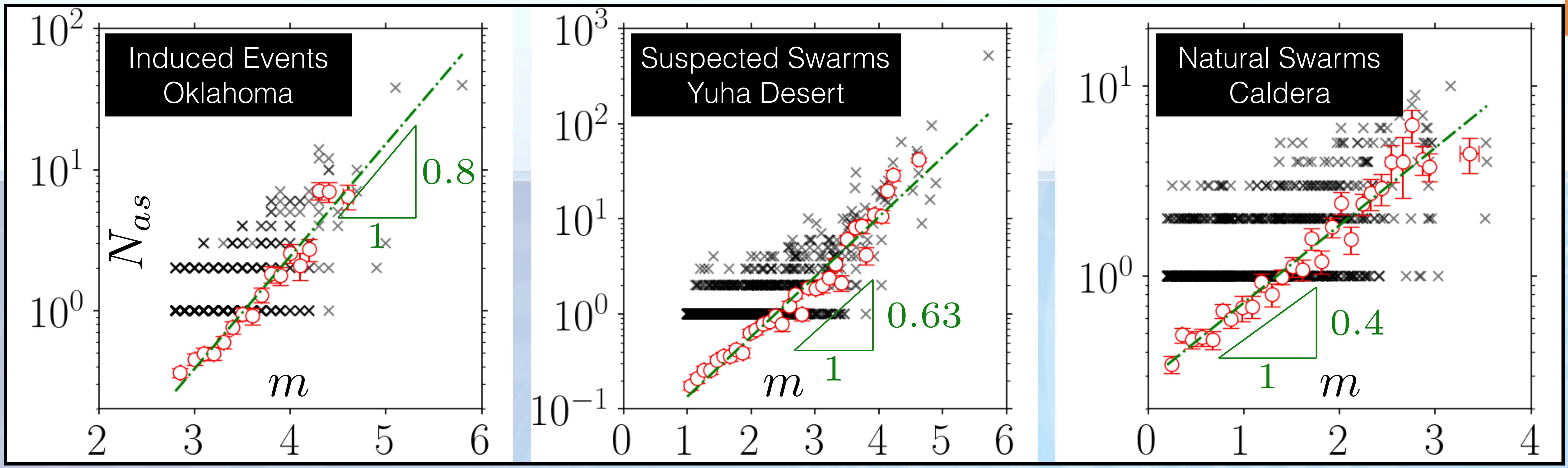
❖ Consistent with Diffusive Nature of the Swarm Propagation (Shelly et al. *JGR* 2016)

Aftershock Productivity

★Average Number of Aftershocks of an Earthquake Magnitude m

$$N_{as} \propto 10^{\alpha m}$$

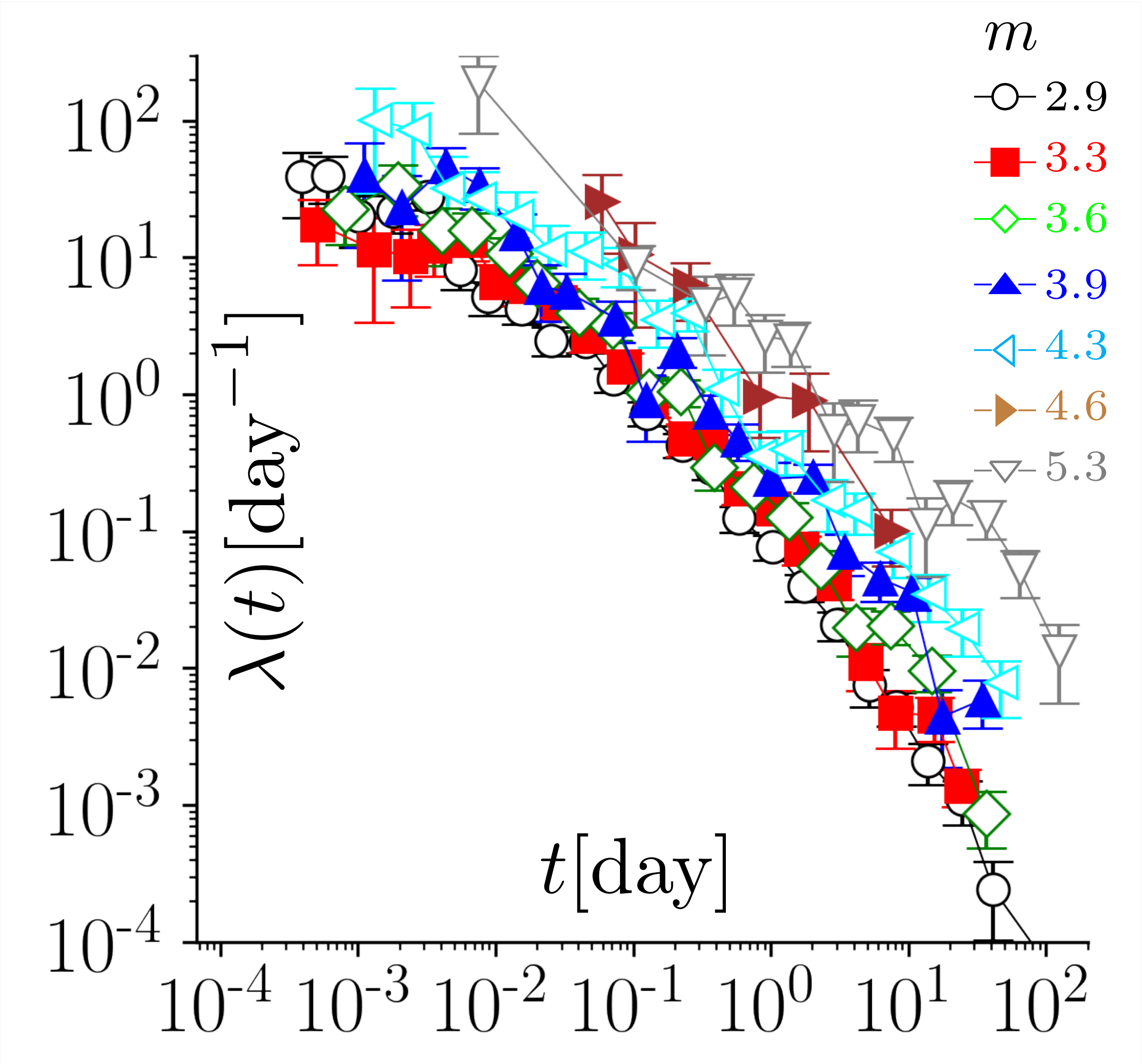
Productivity Exponent: α

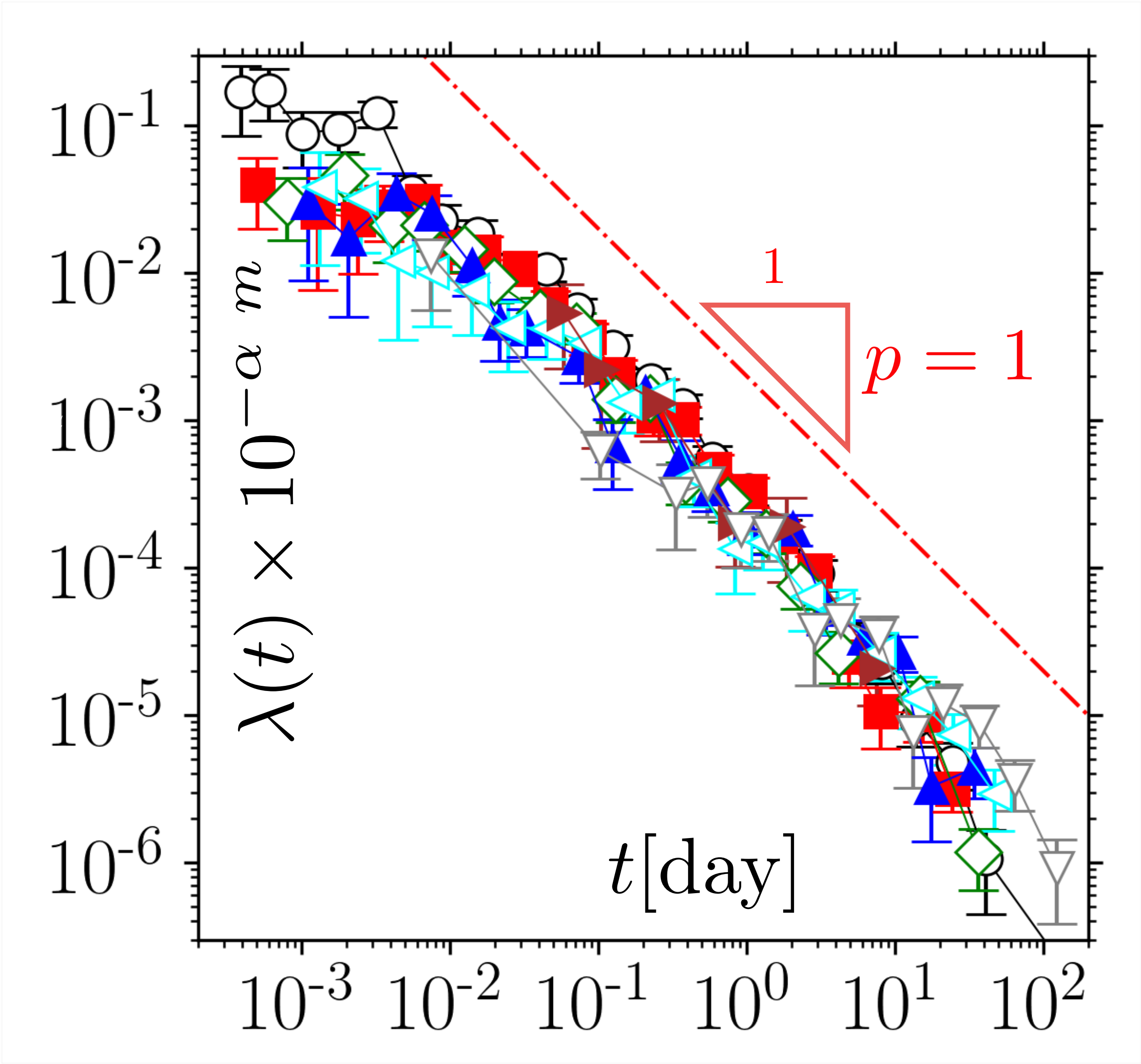


- High Aftershock Productivity In Oklahoma

- Low Productivity Associated With Natural Earthquake Swarms (Hainzl & Ogata, 2005)

Temporal Characteristics
Induced Case: **Oklahoma**





Omori-Utsu relation

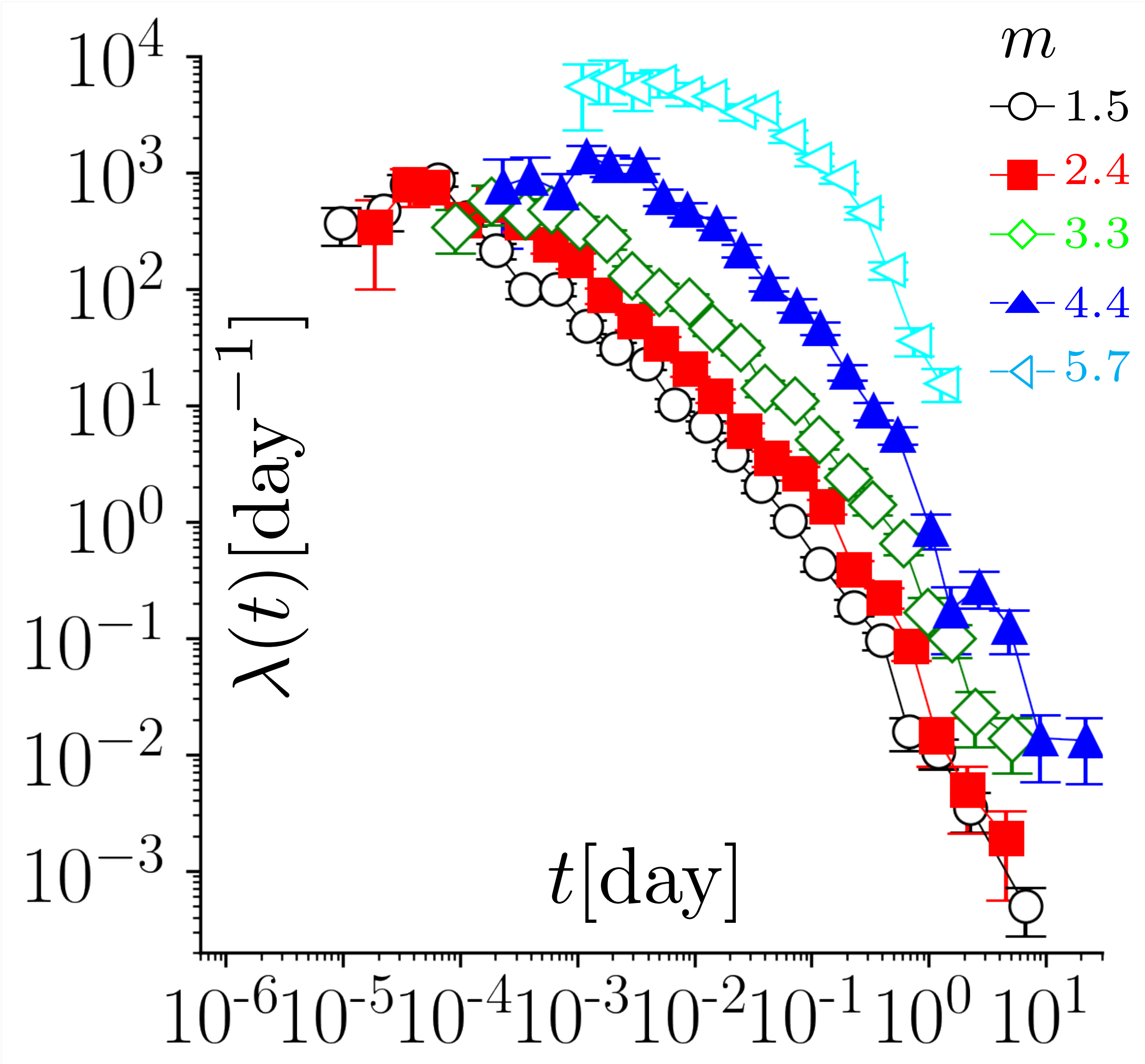
α: Productivity Exponent

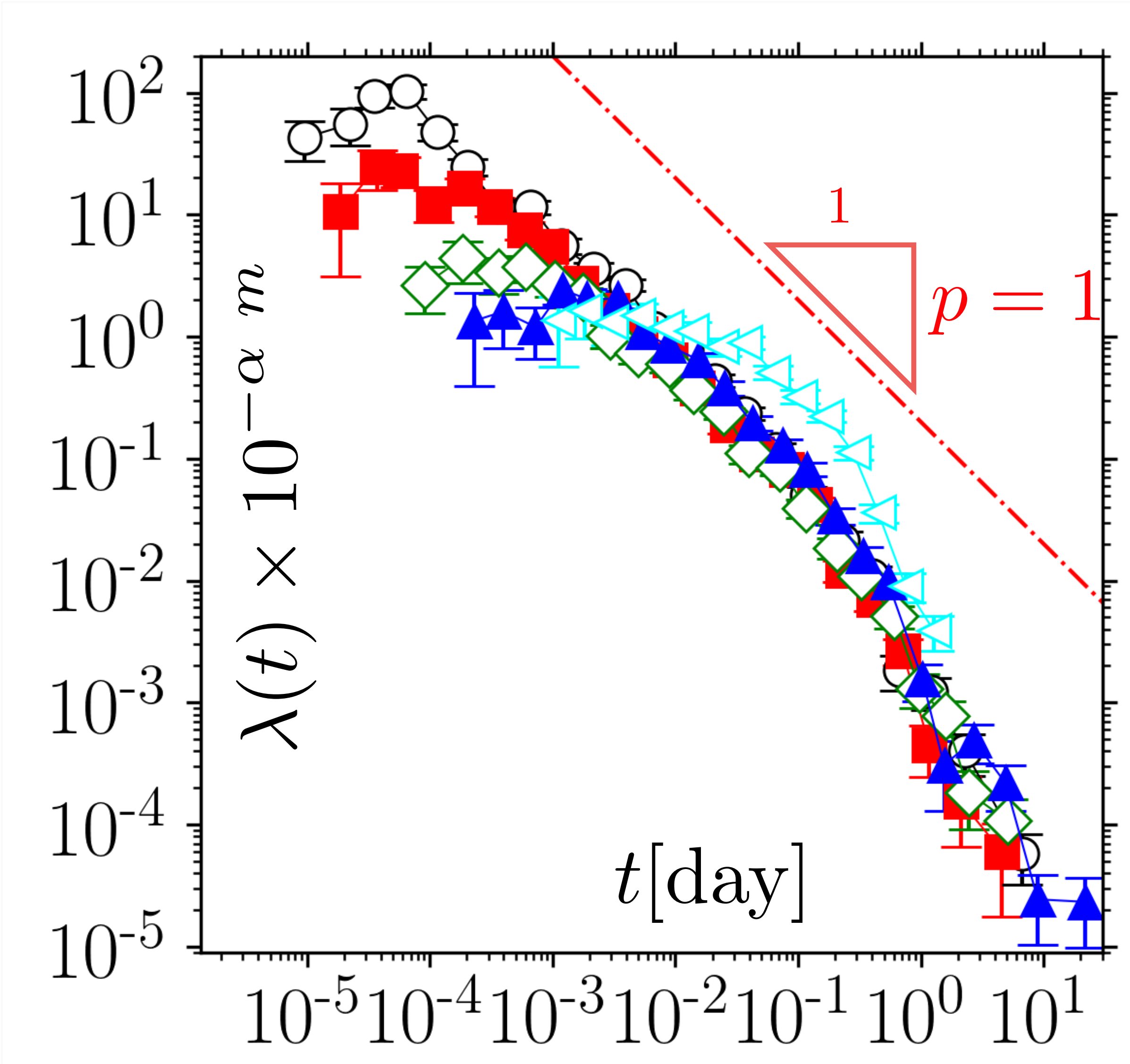
$$\lambda(t) = \frac{K}{(t+c)^p}$$

$$K \propto 10^{\alpha m}$$

Temporal Characteristics

Suspected Swarms (**Yuha Desert**)





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Temporal Characteristics
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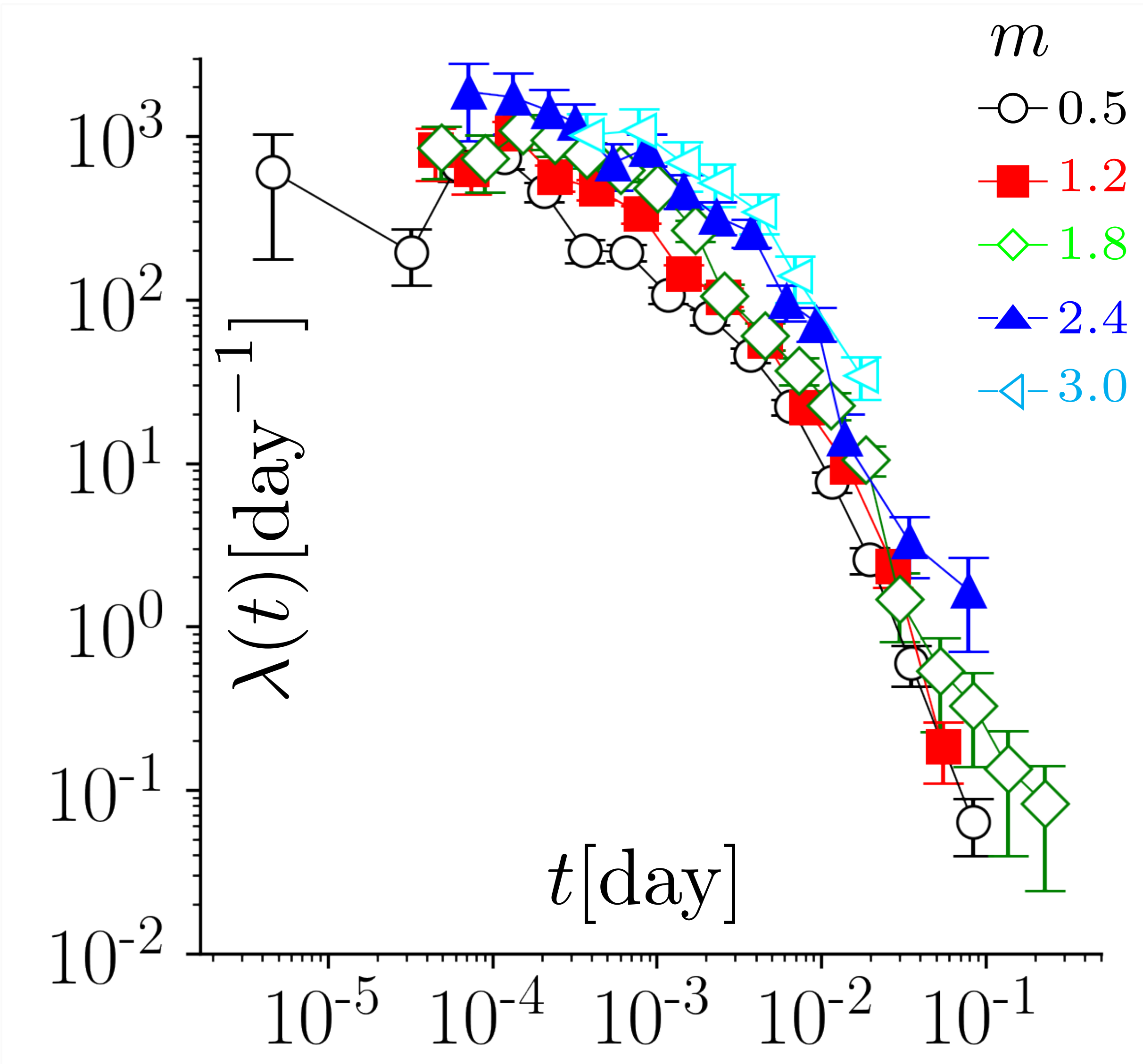

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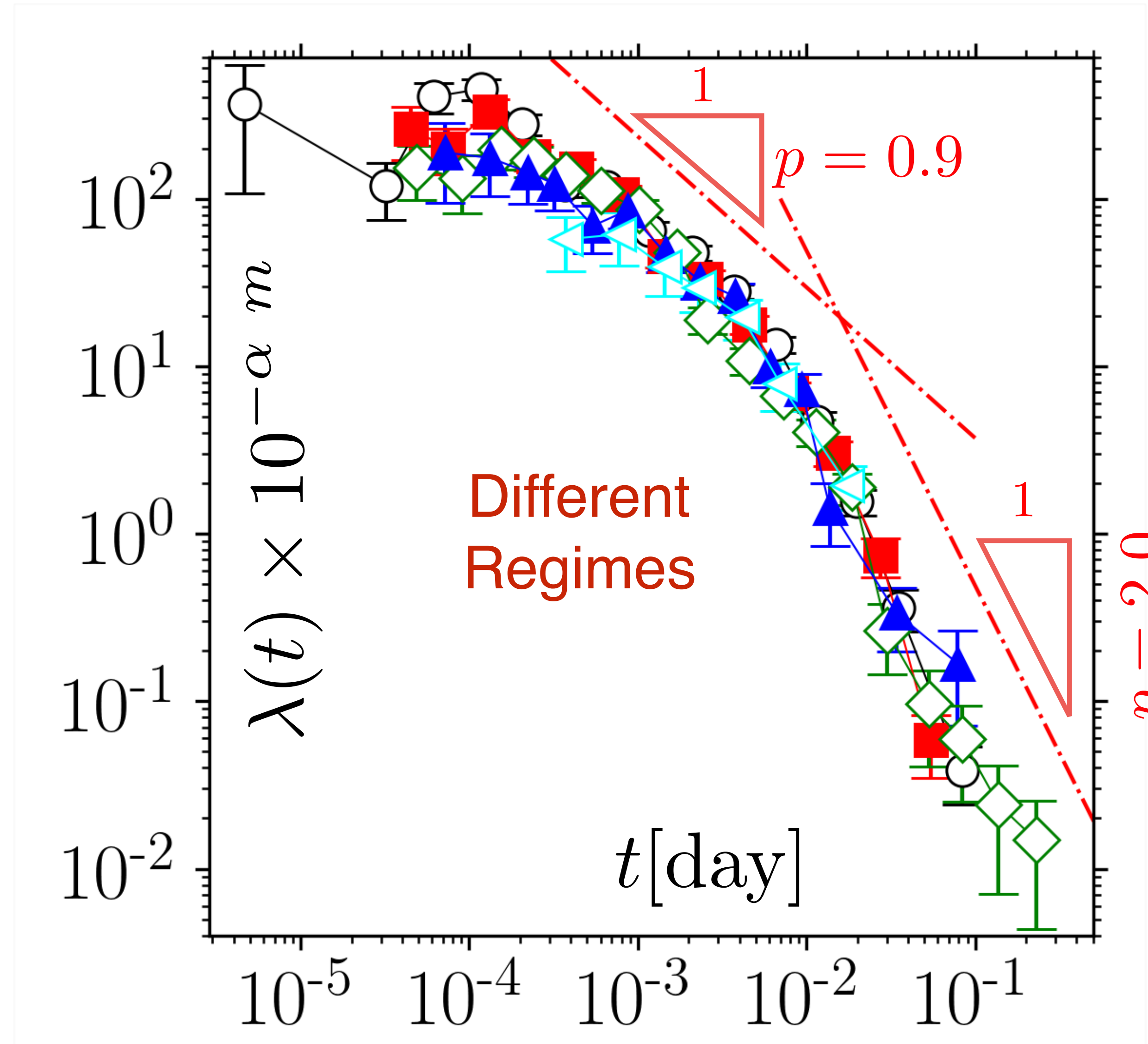
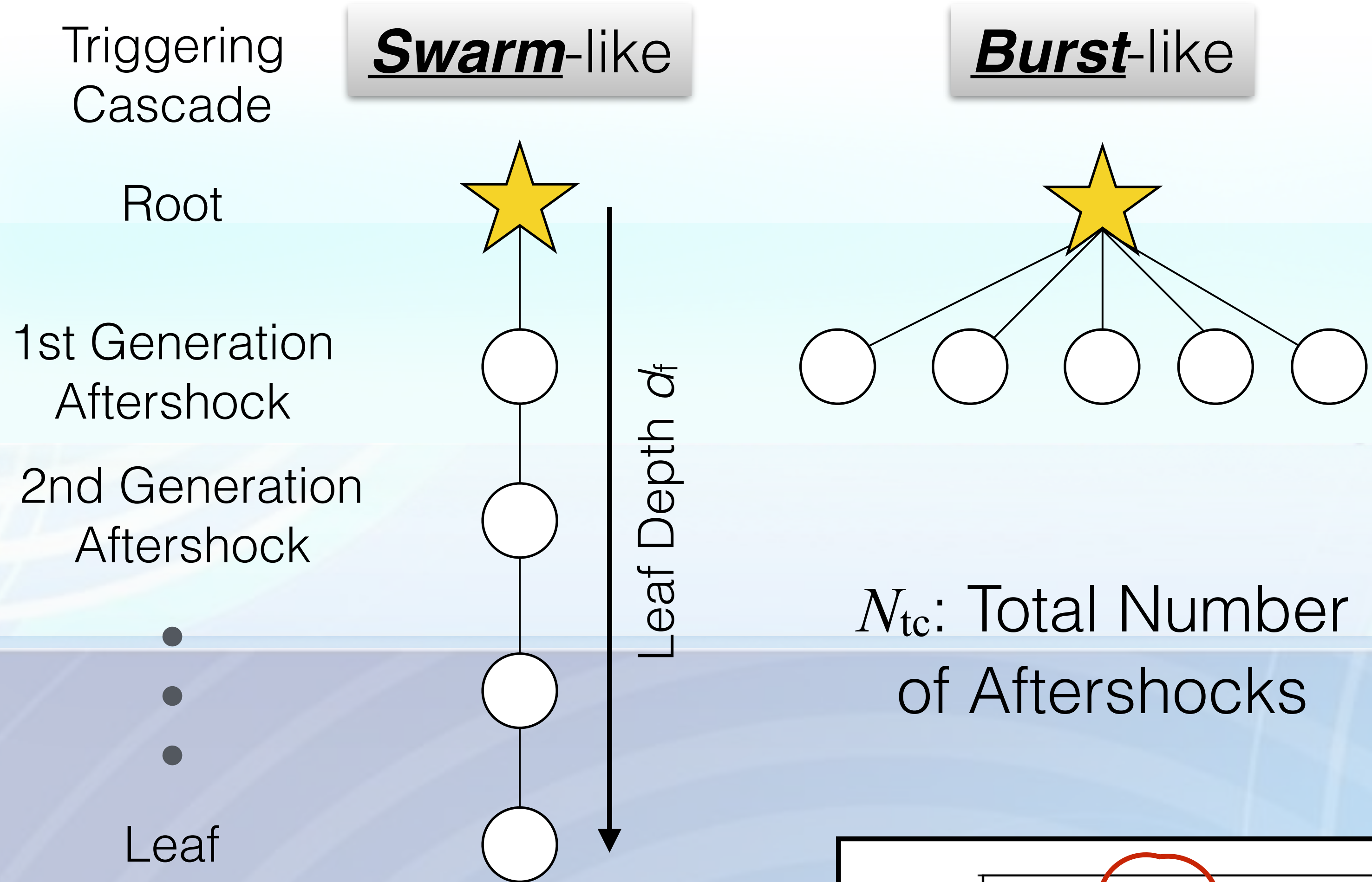


α: Productivity Exponent

Triggering Topology



N_{tc}: Total Number of Aftershocks

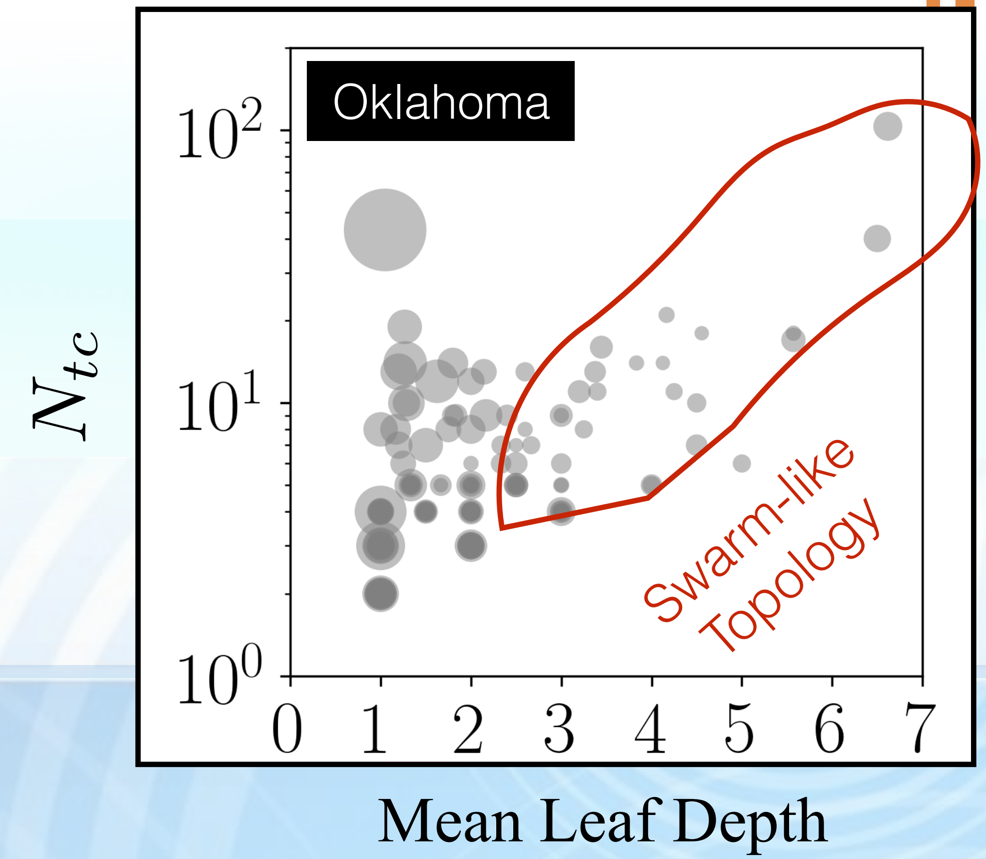
Zaliapin & Ben Zion, *JGR* (2013)

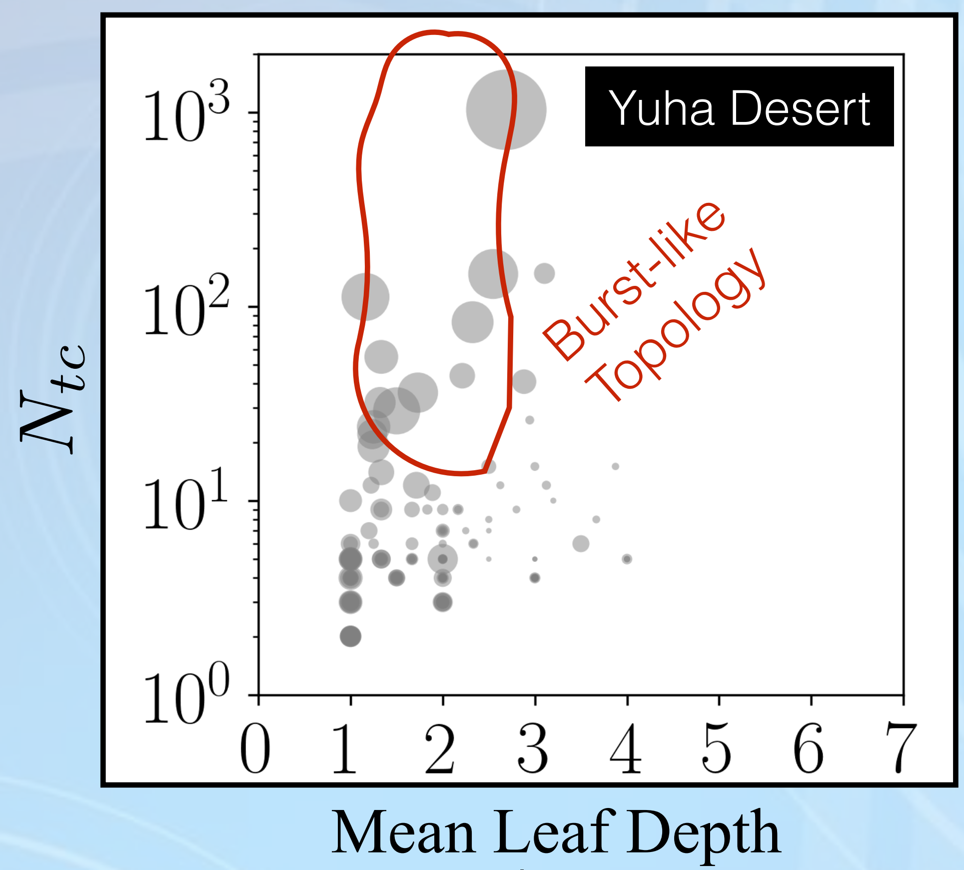
Burst-like:

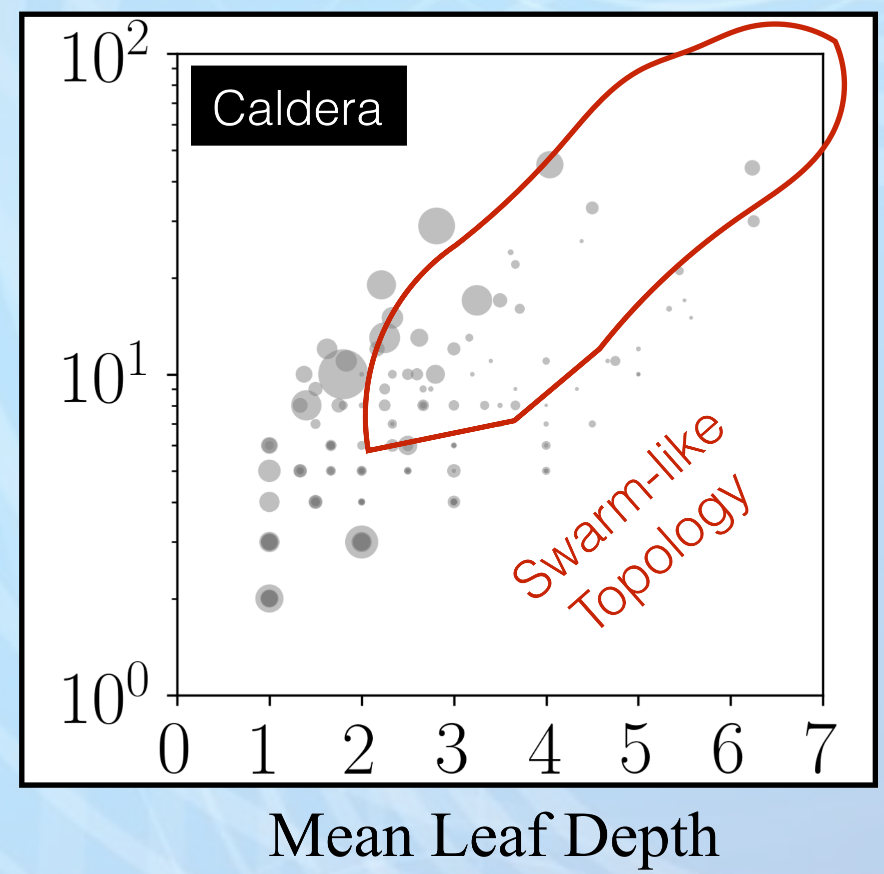
- Large N_{tc}
- Small d_f

Swarm-like:

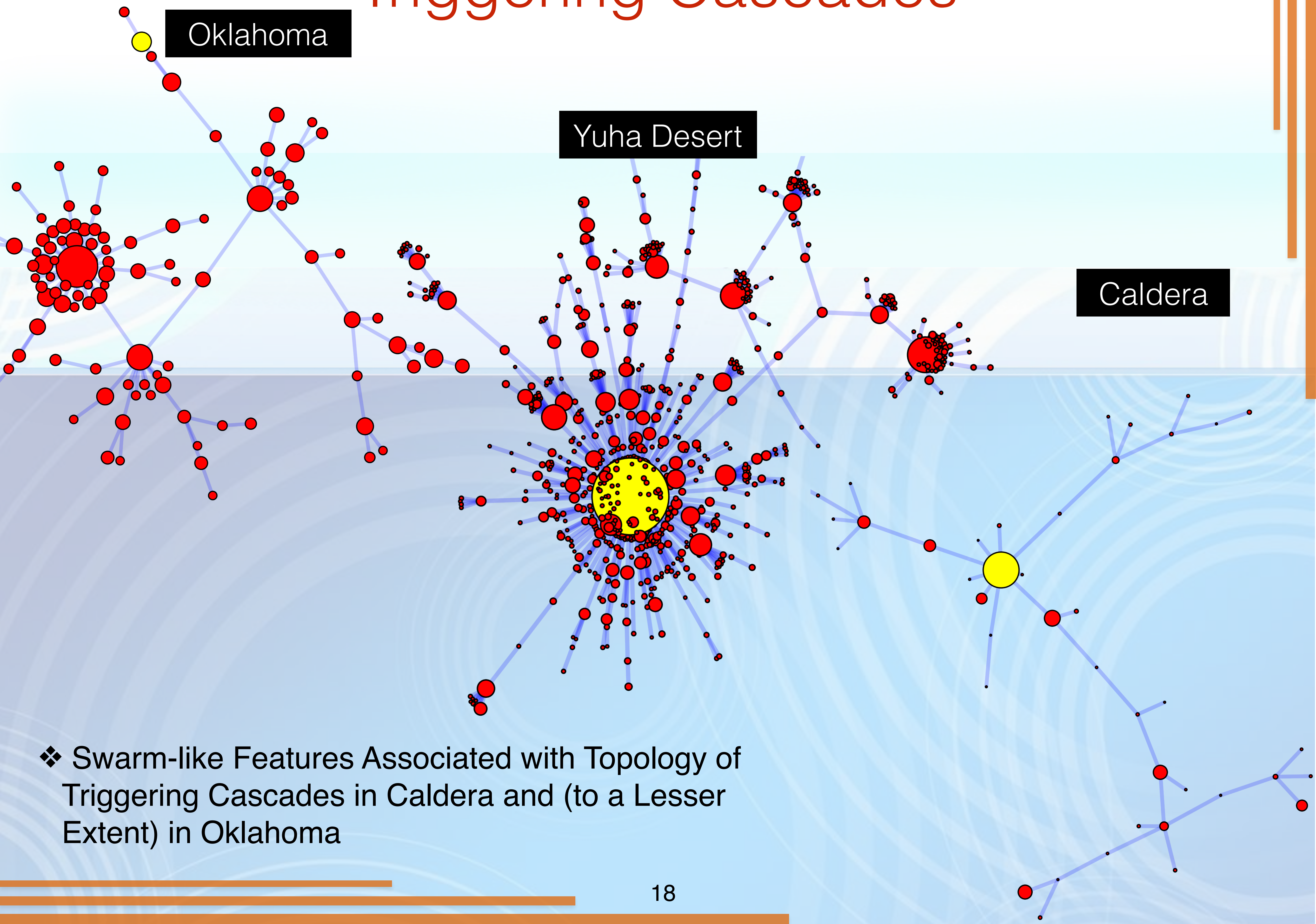
- Small N_{tc}
- Large d_f







Triggering Cascades



❖ Swarm-like Features Associated with Topology of Triggering Cascades in Caldera and (to a Lesser Extent) in Oklahoma

Take-home Messages

- Significant **<u>event-event triggering</u>** in both natural swarms & induced seismicity
- **<u>Narrow</u>** aftershock zones are not specific to induced seismicity but also occur in natural swarms
- Aftershock **<u>productivity</u>** might allow to distinguish between natural swarms and induced seismicity