# Targeted Pandemic Containment Through Identifying Local Contact Network Bottlenecks

Shenghao Yang[1]

With Chris Bauch[1], Kimon Fountoulakis[1], Priyabrata Senapati[1], Di Wang[2]

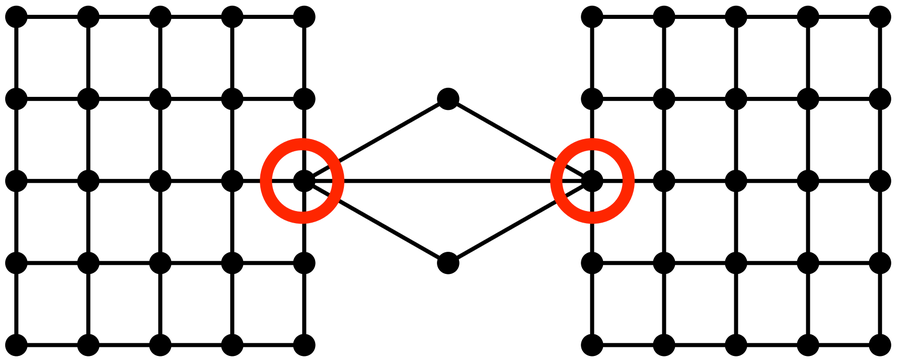
[1]University of Waterloo [2]Google Research


# Network epidemic modelling and control strategies

- Networks are a powerful tool for modelling epidemic dynamics
- Previous models of infection control mostly focused on node-level interventions, e.g., targeted vaccination

# Network epidemic modelling and control strategies

- Networks are a powerful tool for modelling epidemic dynamics
- Previous models of infection control mostly focused on node-level interventions, e.g., targeted vaccination



"… in networks with strong community structure, immunization interventions targeted at individuals bridging communities are more effective …" (Salathe and Jones, 2010)

# Network epidemic modelling and control strategies

- In this work we look at edge-level interventions, e.g., contact reduction, physical distancing, quarantine

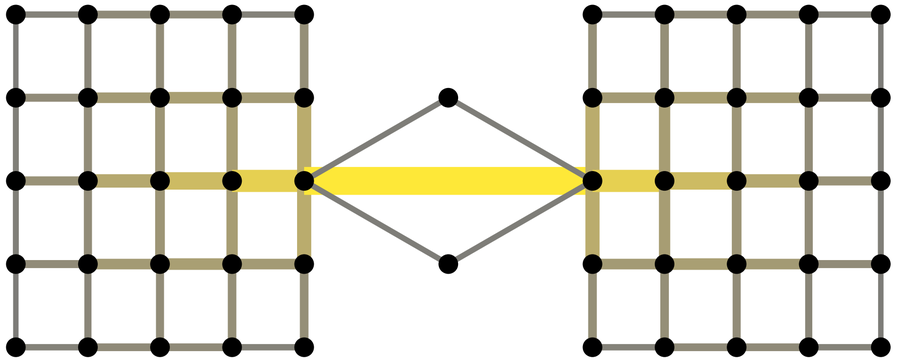
  - For **county-level** networks, selectively closing roads or quarantining towns and cities

  - For **individual-level** networks, enforce or encourage physical distancing by providing incentives

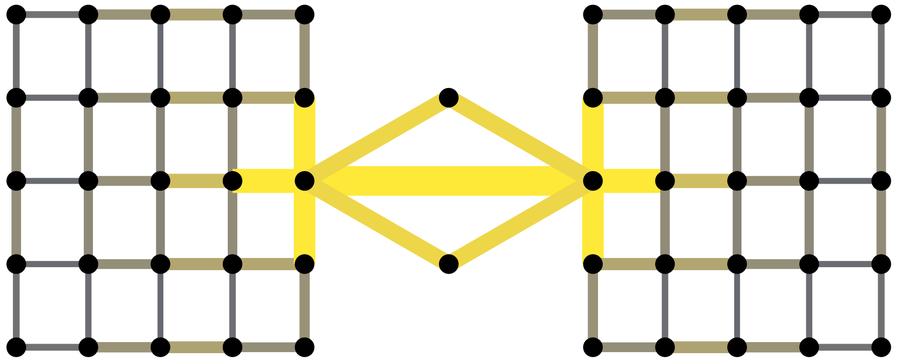
# Network epidemic modelling and control strategies

- In this work we look at edge-level interventions, e.g., contact reduction, physical distancing, quarantine

- How to identify important edges for intervention strategies?



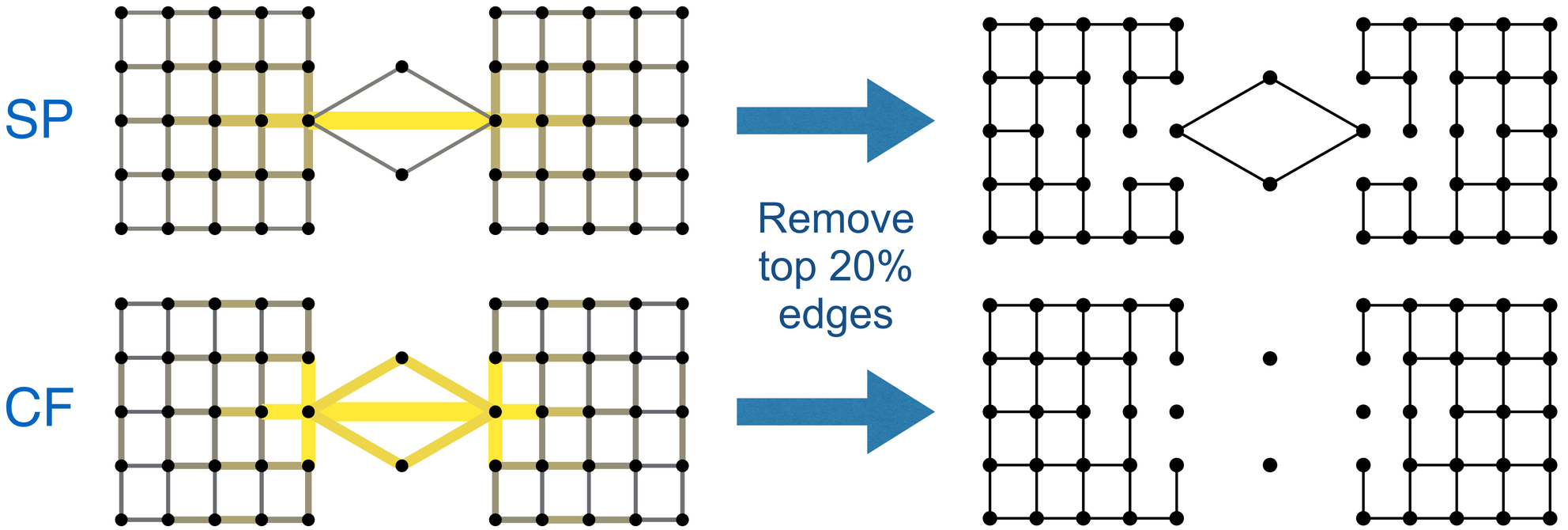
Shortest-path (SP) edge-betweenness



Current-flow (CF) edge-betweenness

# Network epidemic modelling and control strategies

- SP and CF may not work well
- Global “bottlenecks” do not block local transmission
- Less effective in the presence of community outbreak



# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks

# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks

- Electrical current flow

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s = \mathbf{1}_t \quad (P') \qquad \min \ x^T L x - x^T(\mathbf{1}_s - \mathbf{1}_t) \quad (D')$$

$f \in \mathbb{R}^{|E|}$

*incidence matrix*

*indicator vector of* $s \in V$

$x \in \mathbb{R}^{|V|}$

*Laplacian matrix*

# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks

- Electrical current flow

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s = \mathbf{1}_t \quad (P') \qquad \min \ x^T L x - x^T(\mathbf{1}_s - \mathbf{1}_t) \quad (D')$$

$f \in \mathbb{R}^{|E|}$

*incidence matrix*

*indicator vector of* $s \in V$

$x \in \mathbb{R}^{|V|}$

*Laplacian matrix*

*Global focus: All possible pairs* $(s,t) \in V \times V$ *are taken into account*

# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks
- $p$-norm flow diffusion (for brevity, $p = 2$ in this presentation)

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s \leq T \quad (P) \qquad \min_{x \geq 0} \ x^T L x - x^T(\mathbf{1}_s - T) \quad (D)$$

- Electrical current flow

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s = \mathbf{1}_t \quad (P') \qquad \min \ x^T L x - x^T(\mathbf{1}_s - \mathbf{1}_t) \quad (D')$$

$f \in \mathbb{R}^{|E|}$

*incidence matrix*

*indicator vector of* $s \in V$

$x \in \mathbb{R}^{|V|}$

*Laplacian matrix*

# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks
- $p$-norm flow diffusion (for brevity, $p = 2$ in this presentation)

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s \leq T \quad (P) \qquad \min_{x \geq 0} \ x^T L x - x^T(\mathbf{1}_s - T) \quad (D)$$

$T \in \mathbb{R}_+^{|V|}$ specifies node capacities

- Electrical current flow

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s = \mathbf{1}_t \quad (P') \qquad \min \ x^T L x - x^T(\mathbf{1}_s - \mathbf{1}_t) \quad (D')$$

$f \in \mathbb{R}^{|E|}$

*incidence matrix*

*indicator vector of* $s \in V$

$x \in \mathbb{R}^{|V|}$

*Laplacian matrix*

# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks
- $p$-norm flow diffusion (for brevity, $p = 2$ in this presentation)

$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s \leq T \quad (P) \qquad\qquad \min_{x \geq 0} \ x^T L x - x^T(\mathbf{1}_s - T) \quad (D)$$

- We set $T(v) = \deg(v)/(2\lambda|E|)$, where $\lambda \in (0,1]$ controls locality

# Quantifying edge importance locally

- We need a new edge-betweenness measure that detects local bottlenecks
- $p$-norm flow diffusion (for brevity, $p = 2$ in this presentation)

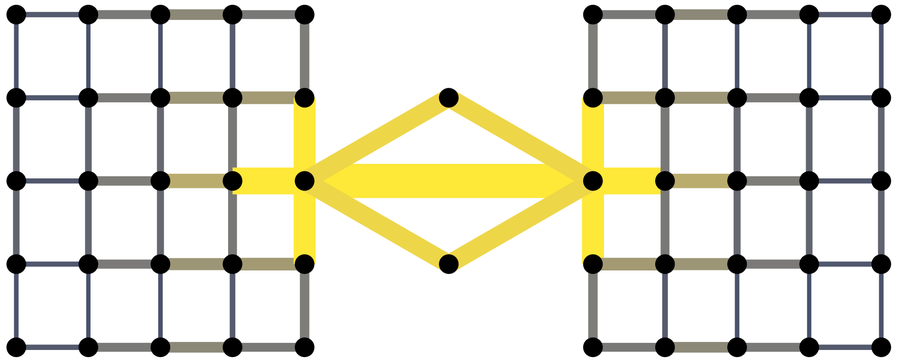
$$\min \ \|f\|_2^2 \ \text{ s.t. } B^T f + \mathbf{1}_s \leq T \quad (P) \qquad \min_{x \geq 0} \ x^T L x - x^T(\mathbf{1}_s - T) \quad (D)$$

- We set $T(v) = \deg(v)/(2\lambda|E|)$, where $\lambda \in (0,1]$ controls locality
- Denote $f_s^\lambda$ the optimal flow arising form source node $s$ with locality $\lambda$
- Local-flow (LF) betweenness of an edge $e \in E$ is

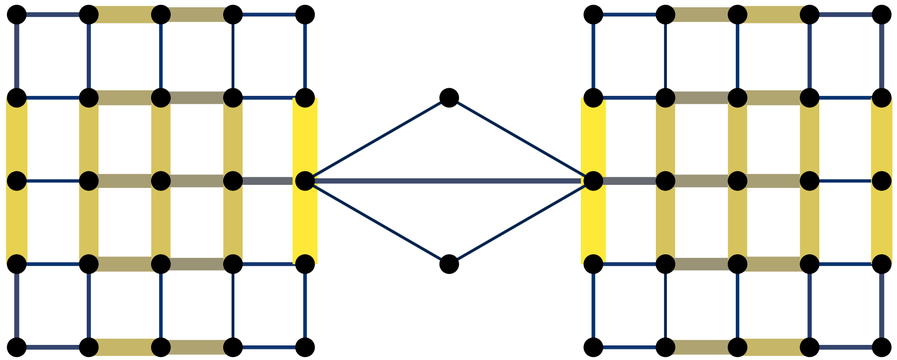
$$lb(e;\lambda) := \frac{1}{|V|} \sum_{s \in V} |f_s^\lambda(e)|$$

# Quantifying edge importance locally

- Local-flow (LF) betweenness
  - Colors and edge widths are chosen to reflect relative magnitude

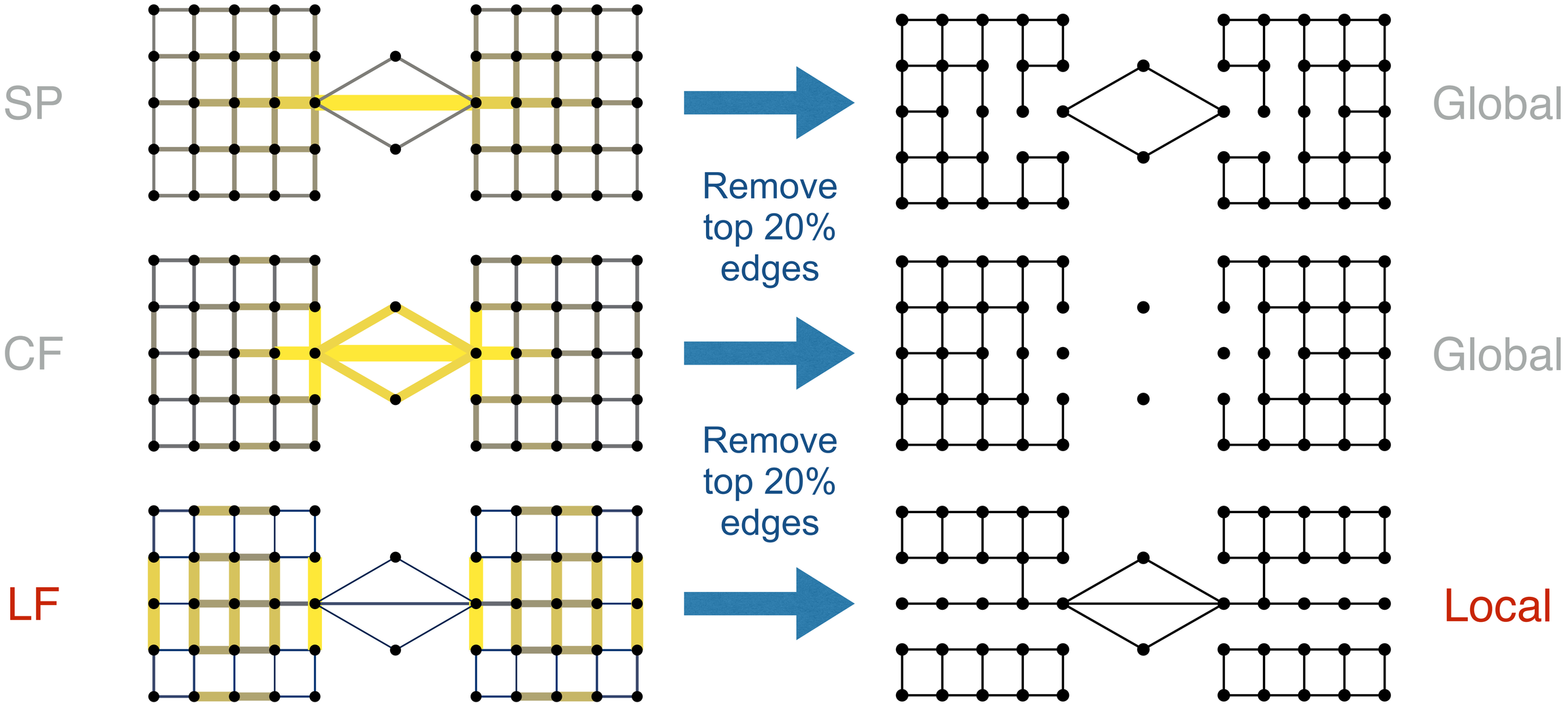


$\lambda = 1$



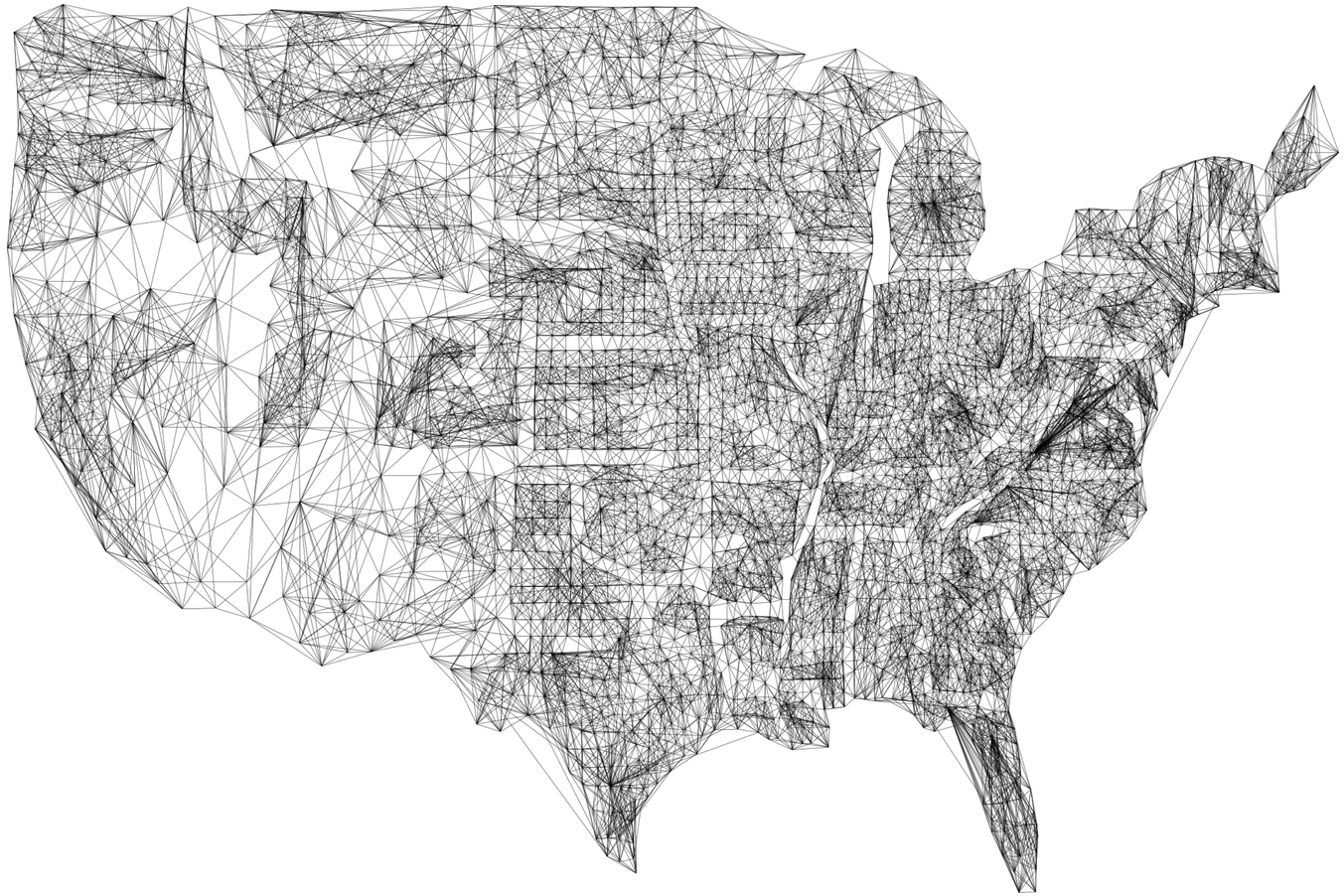
$\lambda = 0.4$

# Quantifying edge importance locally



# Facebook-county network

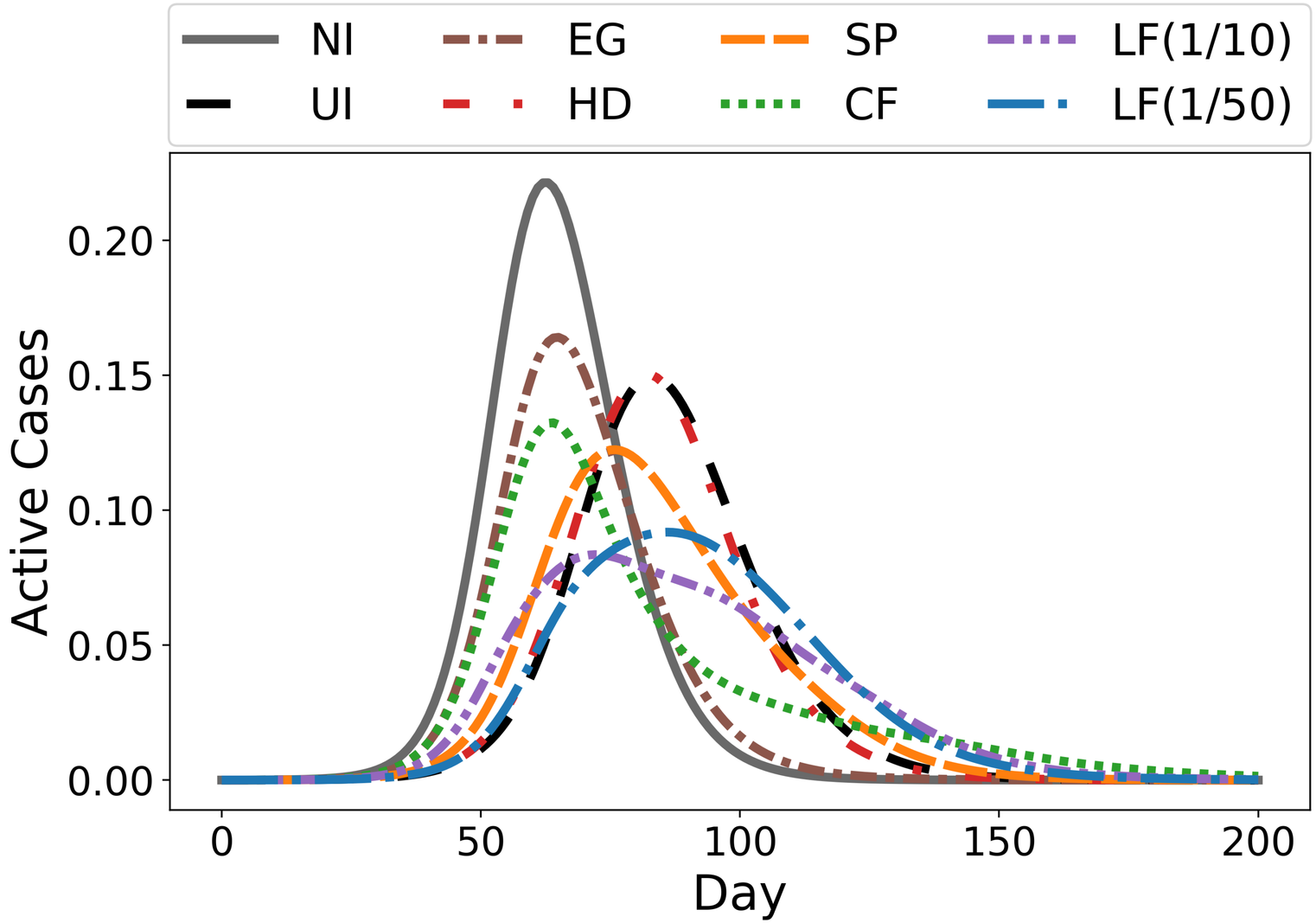
- 3100 counties
- Two counties are connected with an edge if there exists strong social interaction
- Social interaction tends to happen mostly among nearby counties



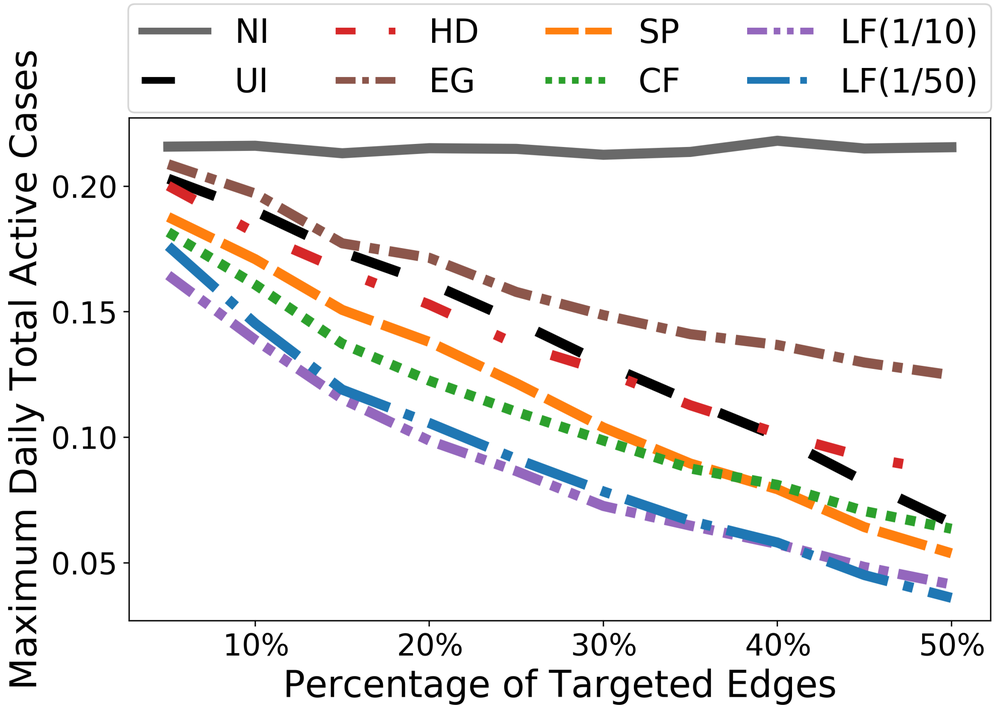
# Facebook-county network - simulated epidemic dynamics

- Network SEIR model
- Targeting top 25% edges

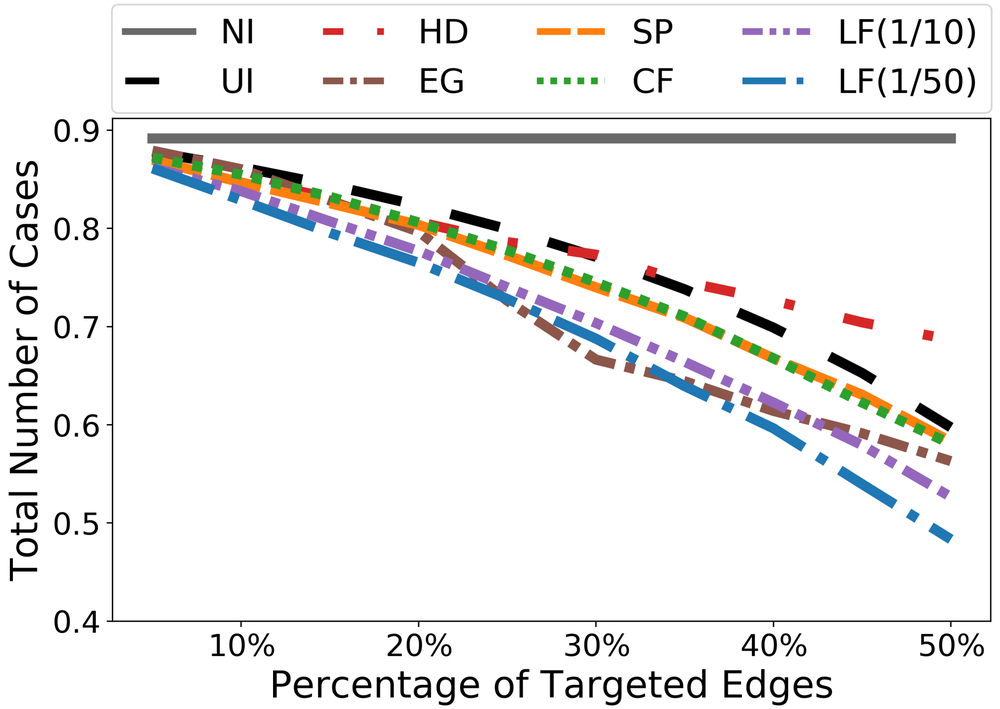
NI: No Intervention
UI: Uniform Intervention
EG: Eigenvector centrality
HD: Degree centrality
SP: Shortest-Path betweenness
CF: Current-Flow betweenness
LF: Local-Flow betweenness



# Facebook-county network - simulated epidemic dynamics



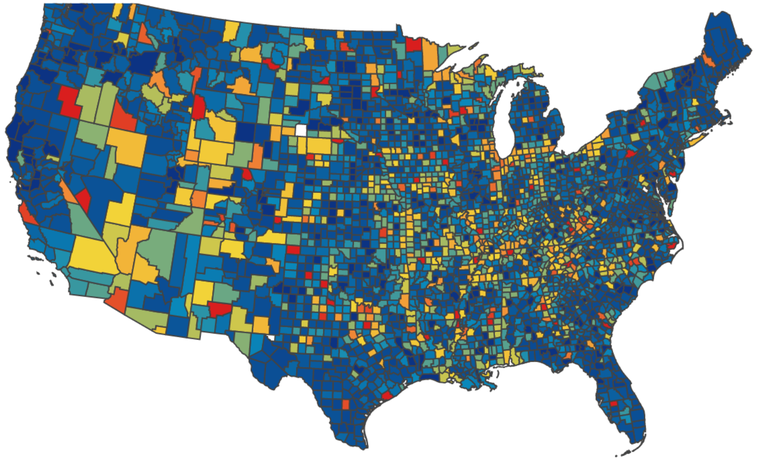

Epidemic peak



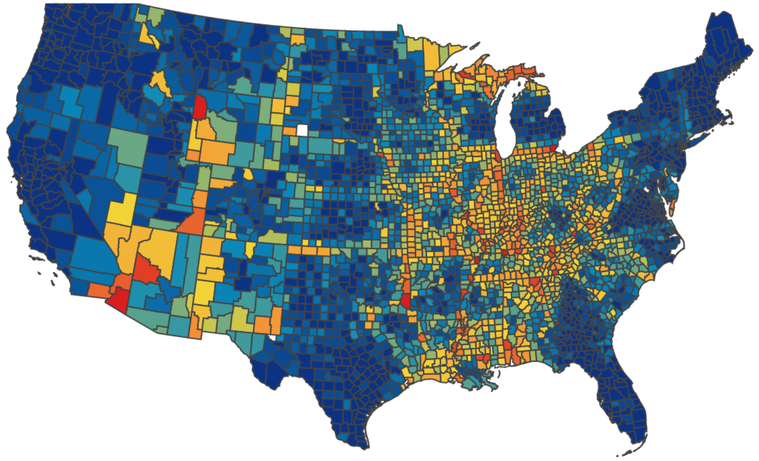

Outbreak size

NI: No Intervention UI: Uniform Intervention EG: Eigenvector centrality
HD: Degree centrality SP: Shortest-Path betweenness CF: Current-Flow betweenness
LF: Local-Flow betweenness

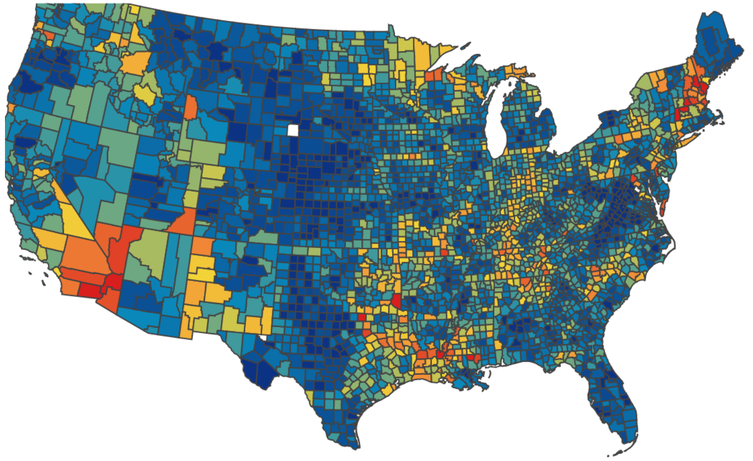
# Why is LF most effective?



SP



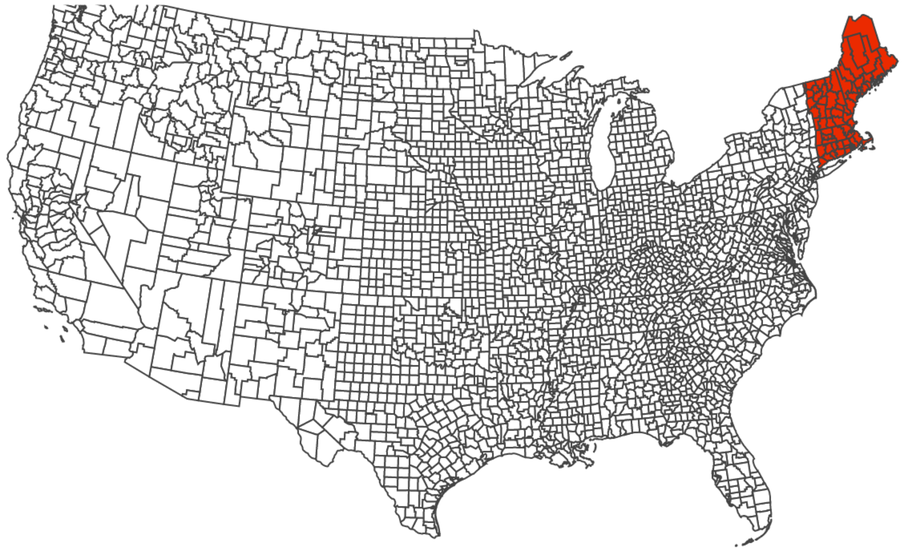
CF

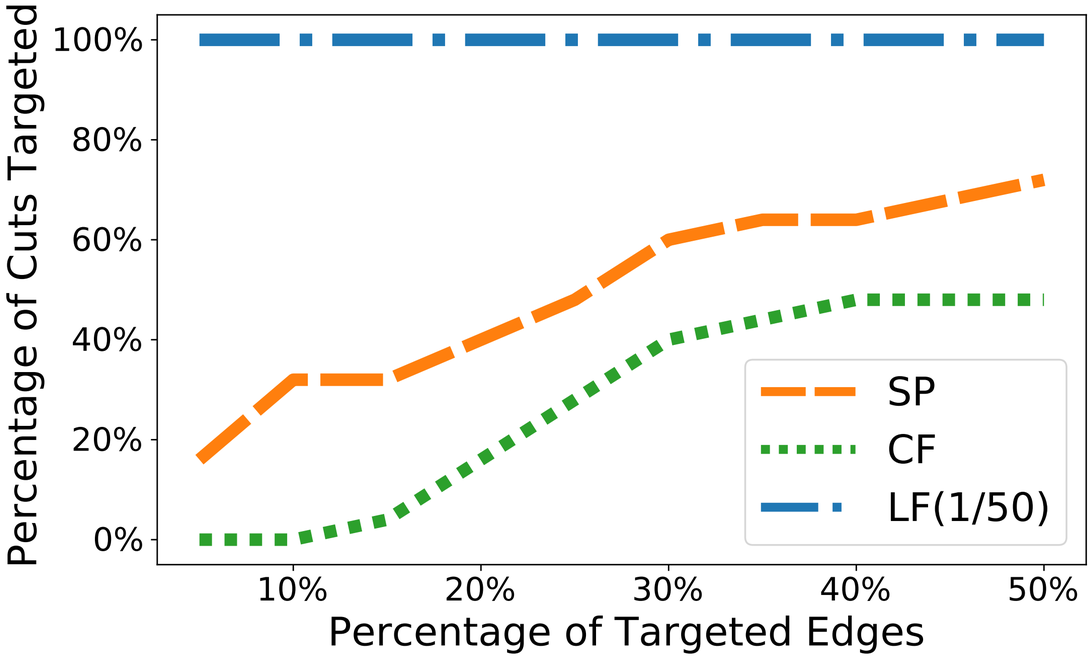


LF

- **Distribution of top 25% edges** reflected by county-level colors:
  - red means most incident edges are reduced (in edge weights)
  - dark blue means few incident edges are reduced (in edge weights)

# Why is LF most effective?






- Counties in red form a tightly-knit local cluster with few out-links
- 100% out-links are among top 5% edges identified by LF
- <20% out-links are identified by SP or CF

# Are the results robust?

- Estimated reproduction number for Covid-19 is $R_0 = 2.5$
- We tried **varying reproduction numbers** $R_0 \in \{1.5, 2.5, 3.5, 4.5\}$

- 3 very **different initializations** from where epidemic starts
  - randomly chosen 1% counties spread across the network
  - a tightly-knit cluster of counties
  - single cities: Chicago, New York, Los Angeles

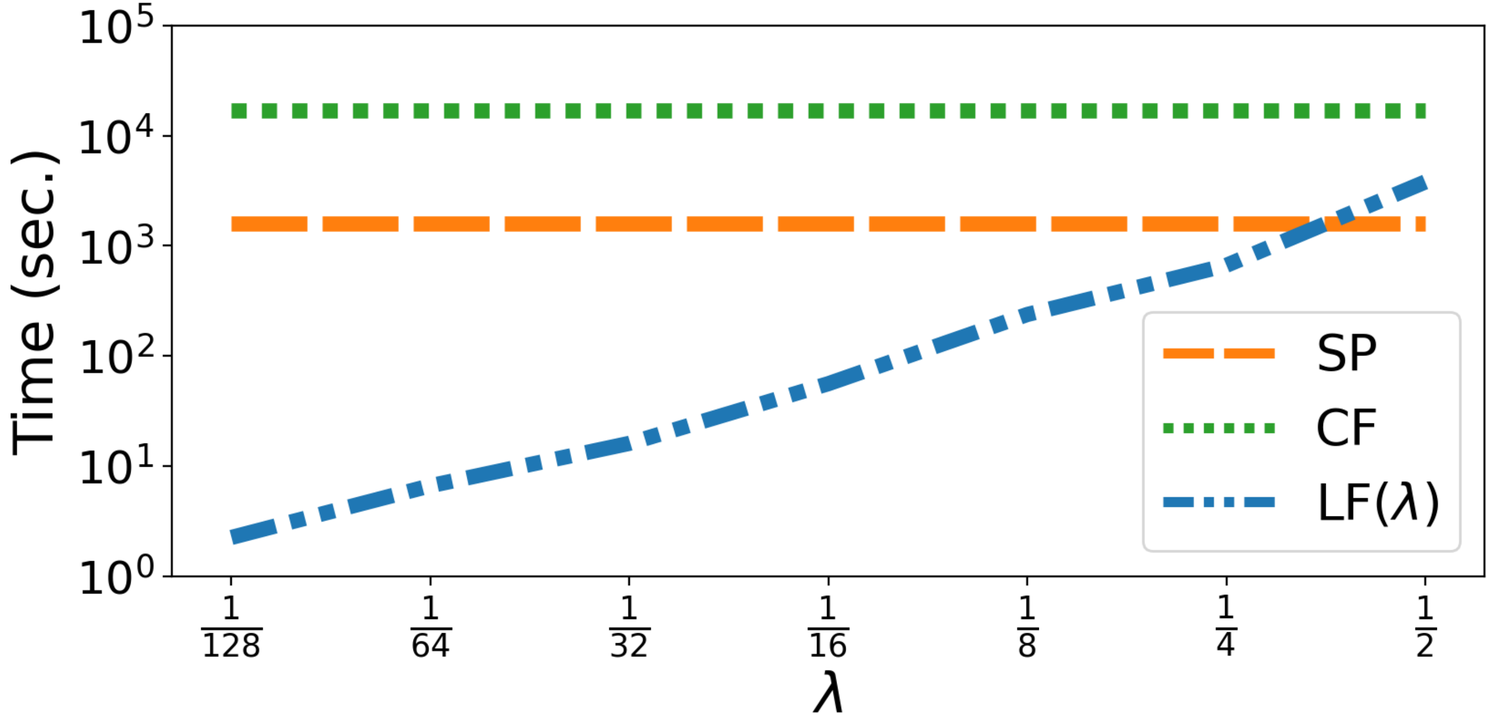
- **Delayed interventions** applied in the middle of the epidemic (not from the start)

- **All these different settings produce consistent results**

# Thank you!

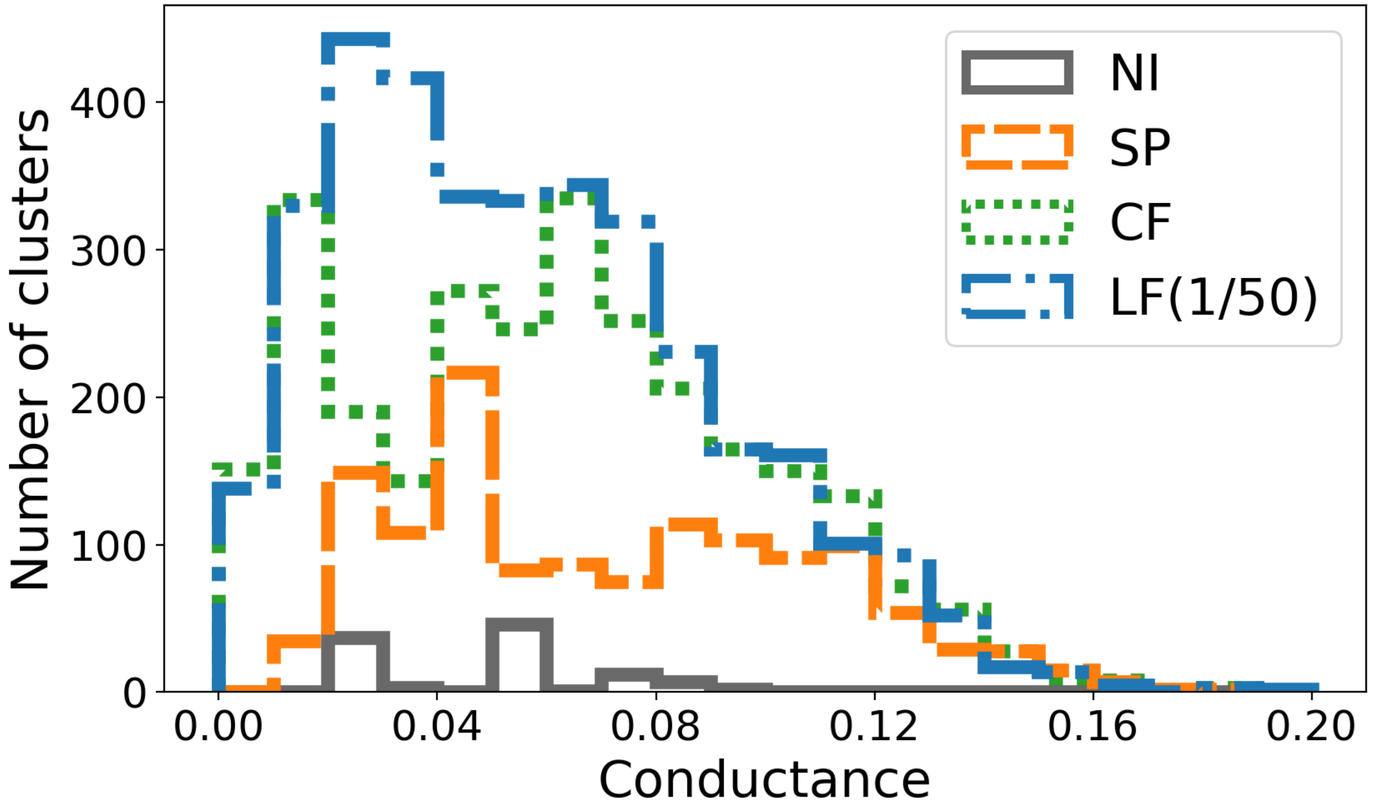
# Computation time

- Computing LF for all edges requires $O(\lambda |V||E|), \lambda \in (0,1]$




$$|V| = 10{,}000,\ |E| = 199{,}128$$

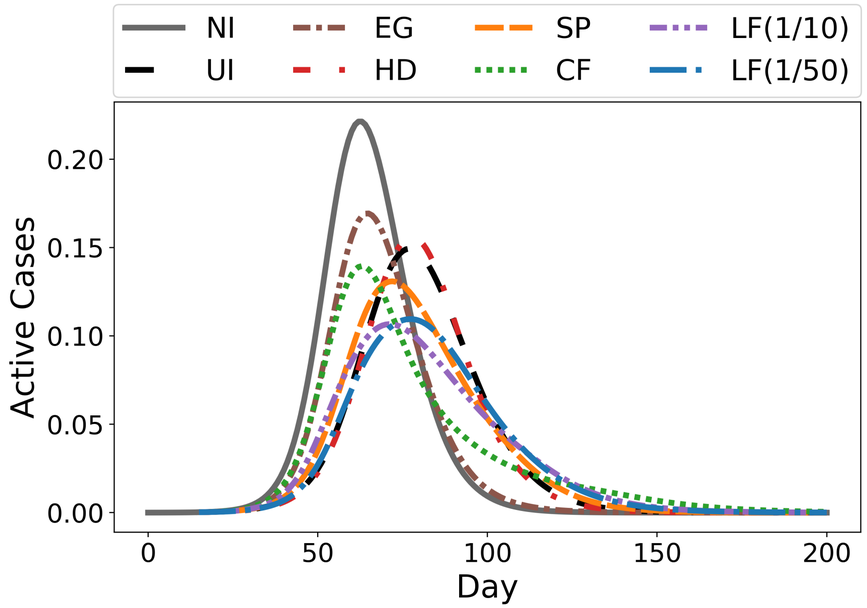
# Why is LF most effective?



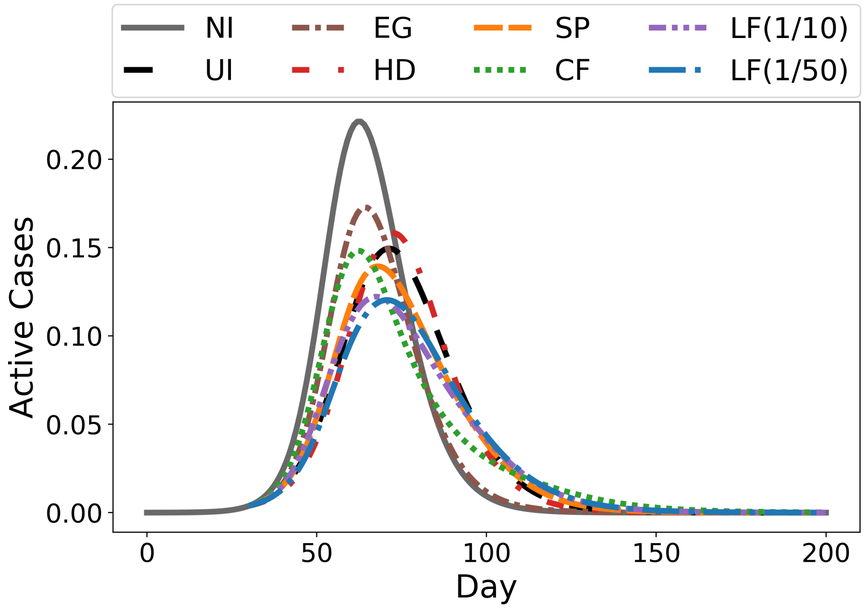

- **Distribution of small-size clusters** (consisting of $\leq 100$ counties) by conductance

# Facebook-county network - simulated epidemic dynamics

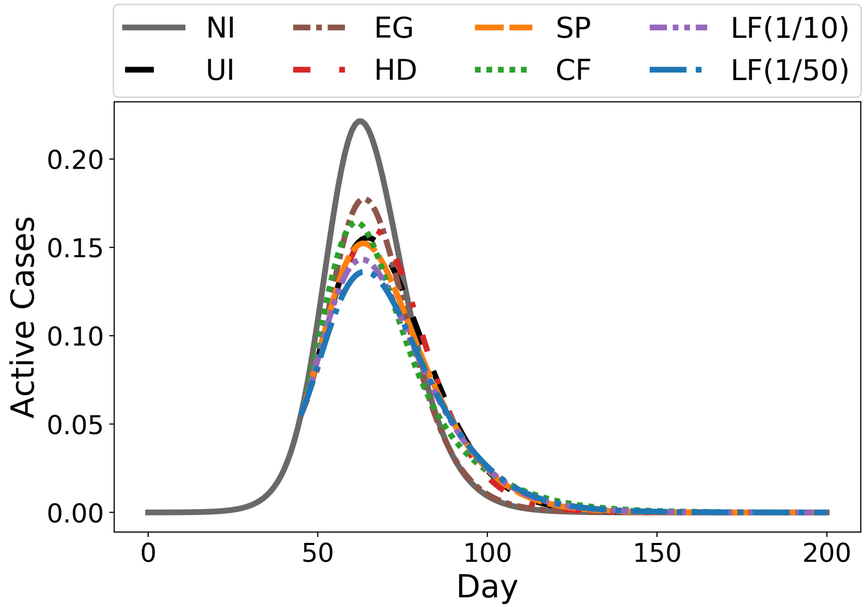
15-day delay



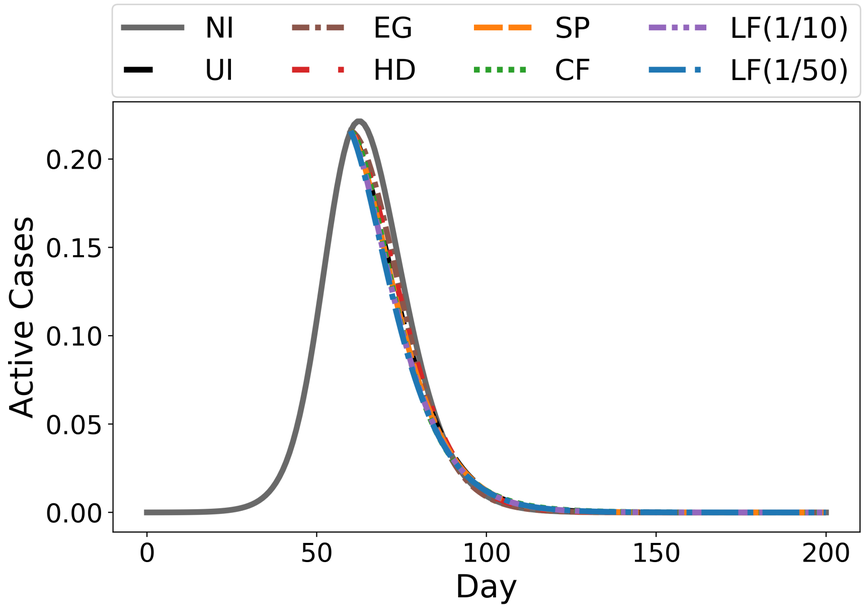

30-day delay




45-day delay

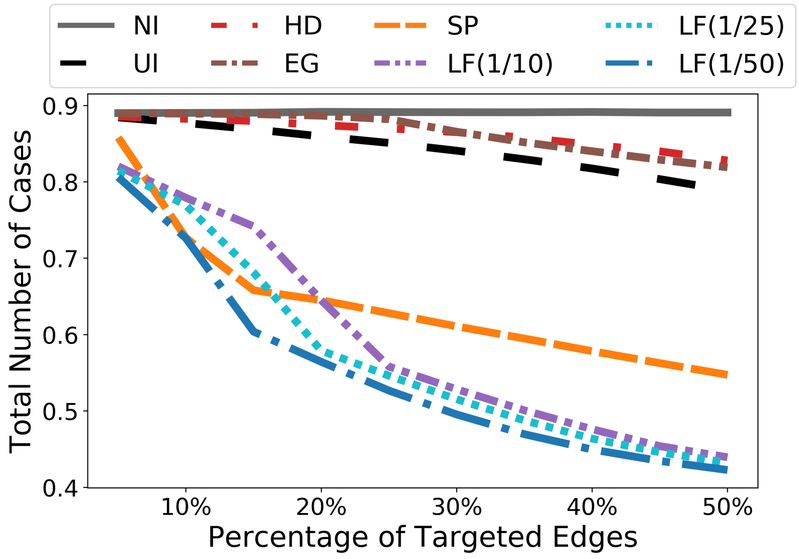



60-day delay

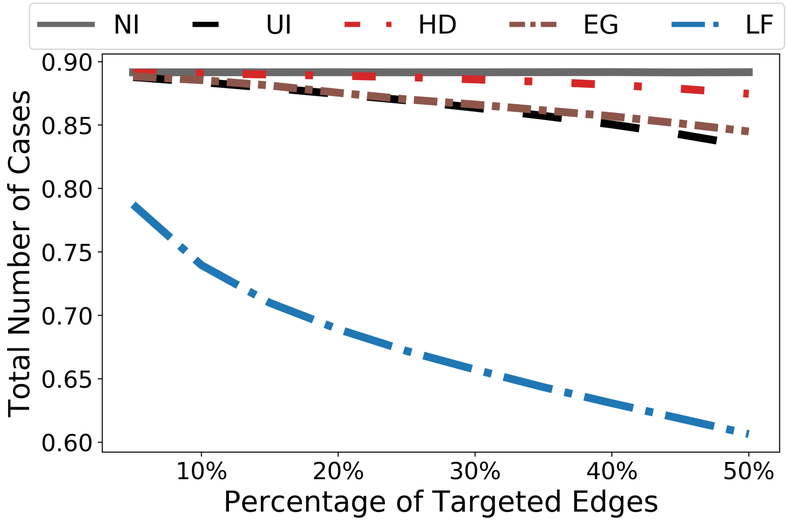


# More datasets

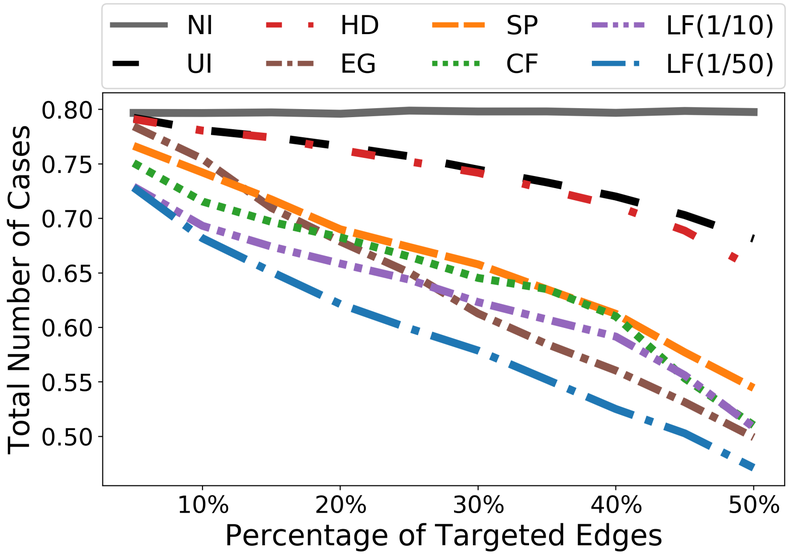
- *Wi-Fi hotspots Montreal* network, |V| = 103K, |E| = 631K
- *Portland, Oregon* network, |V| = 1.6M, |E| = 31M
- *Sub-sampled Portland, Oregon* network, |V| = 10K, |E| = 199K
- Agent-based SEIR network model




Wi-Fi Montreal




Portland




Portland Sub-sampled