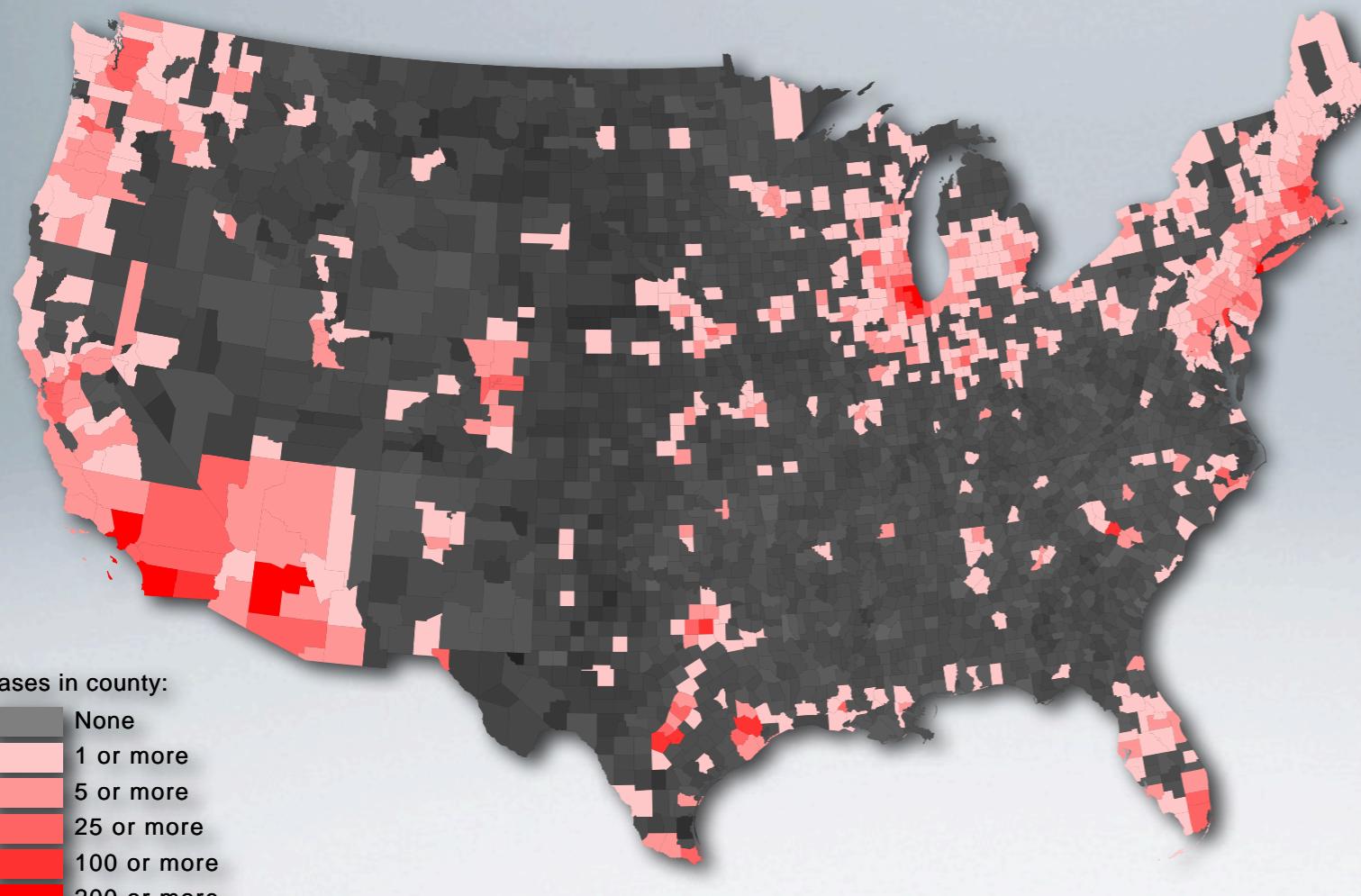


MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE



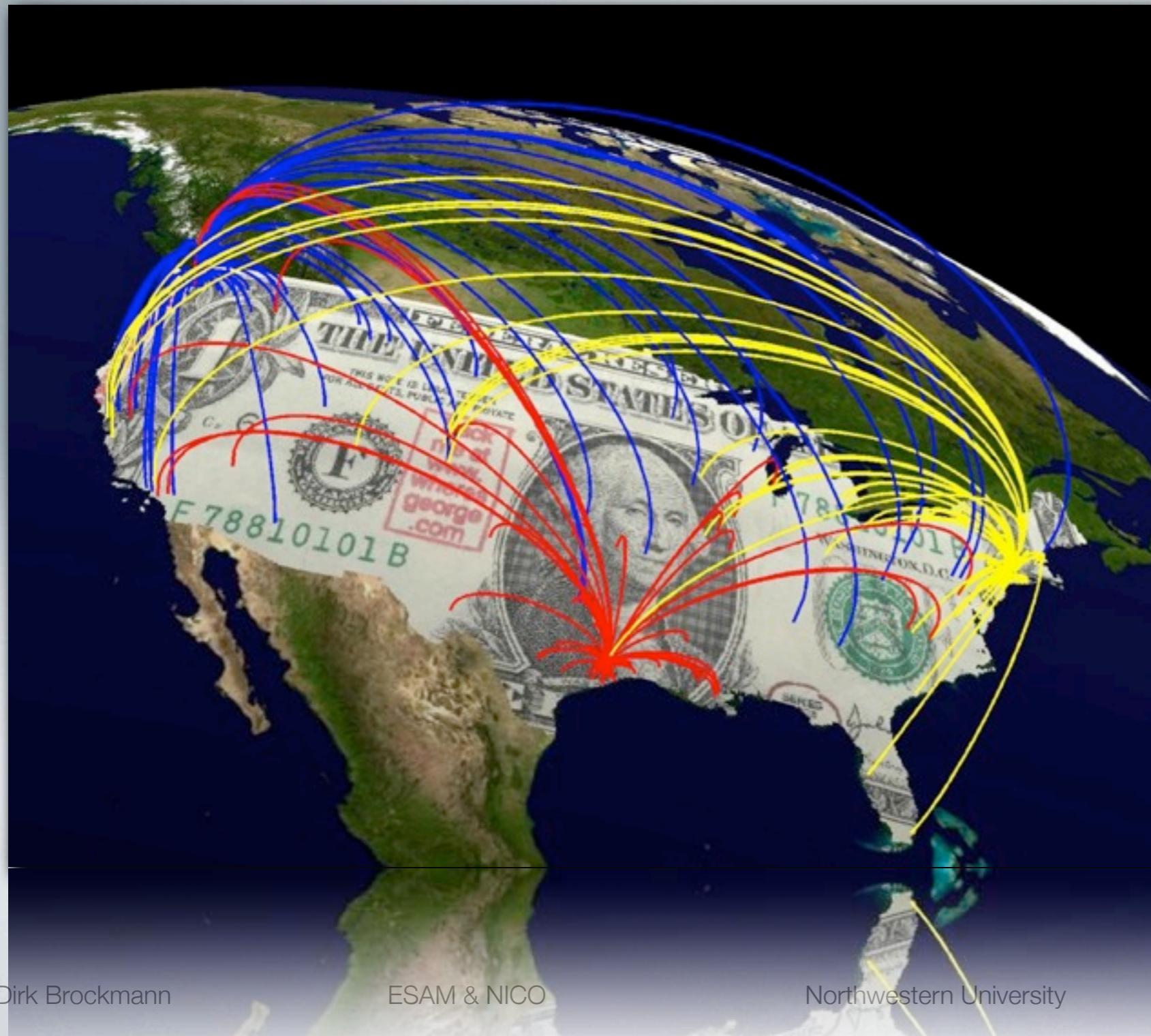
Dirk Brockmann
Northwestern University

MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE



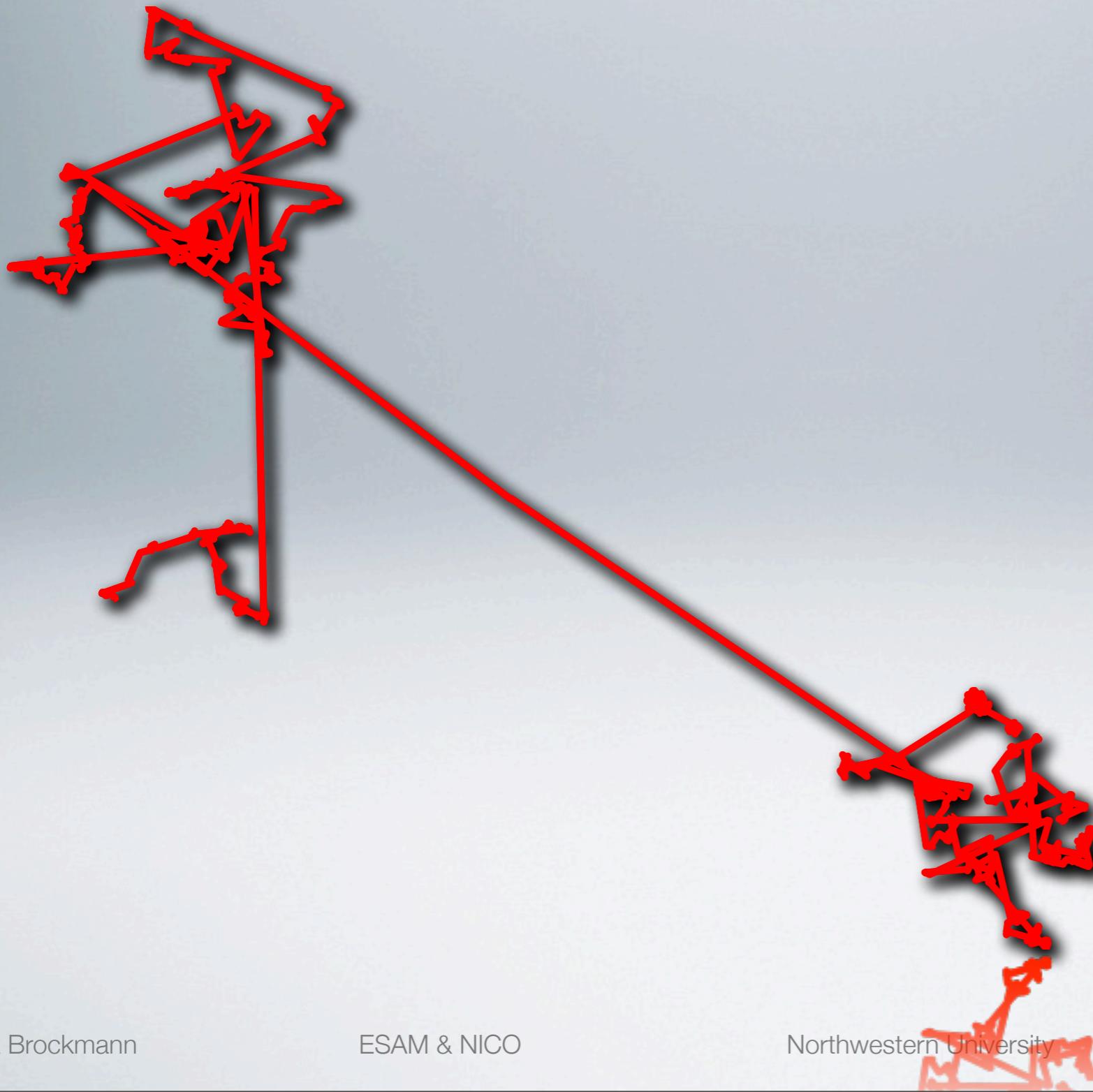
Dirk Brockmann
Northwestern University

MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE



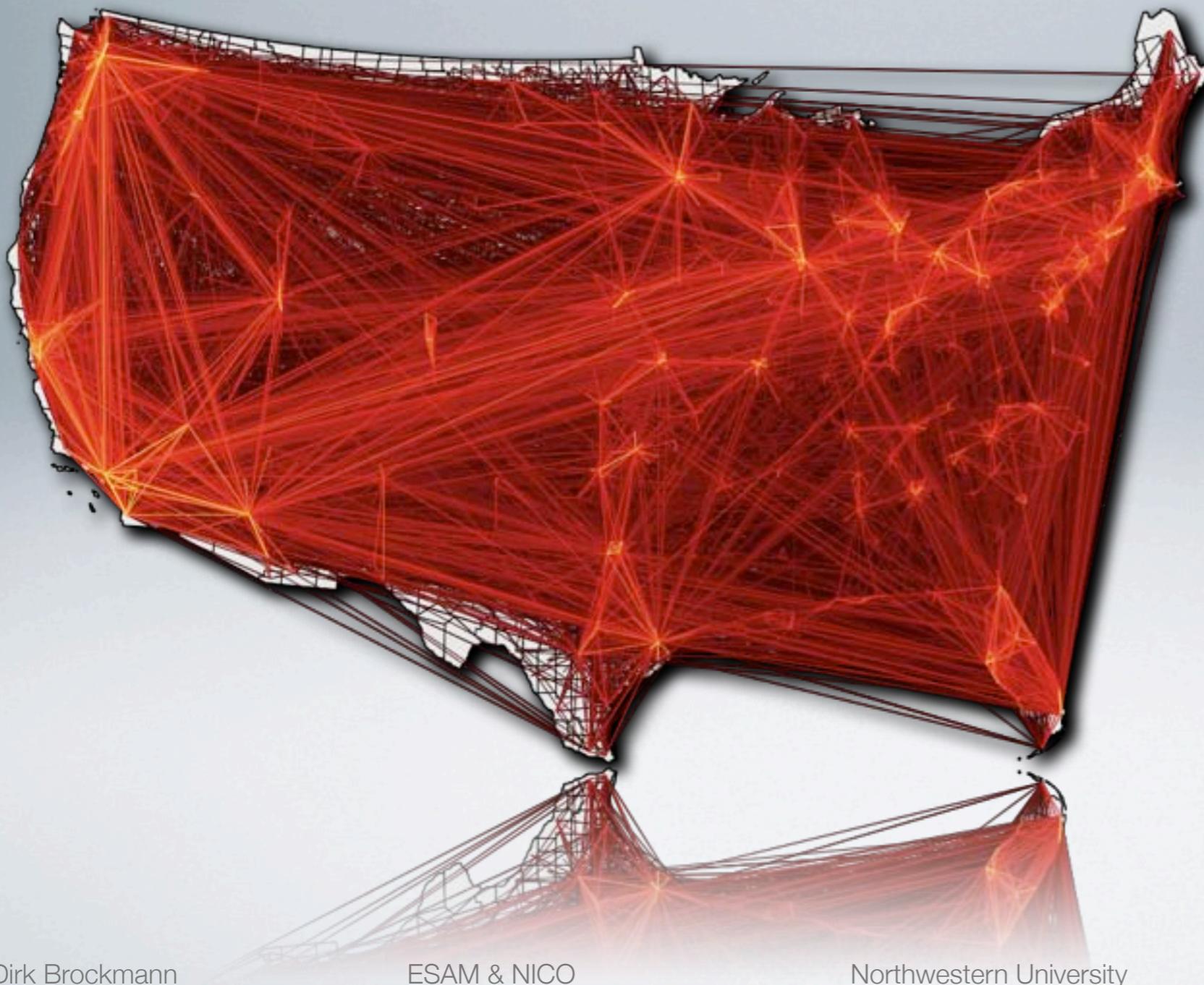
Dirk Brockmann
Northwestern University

MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE



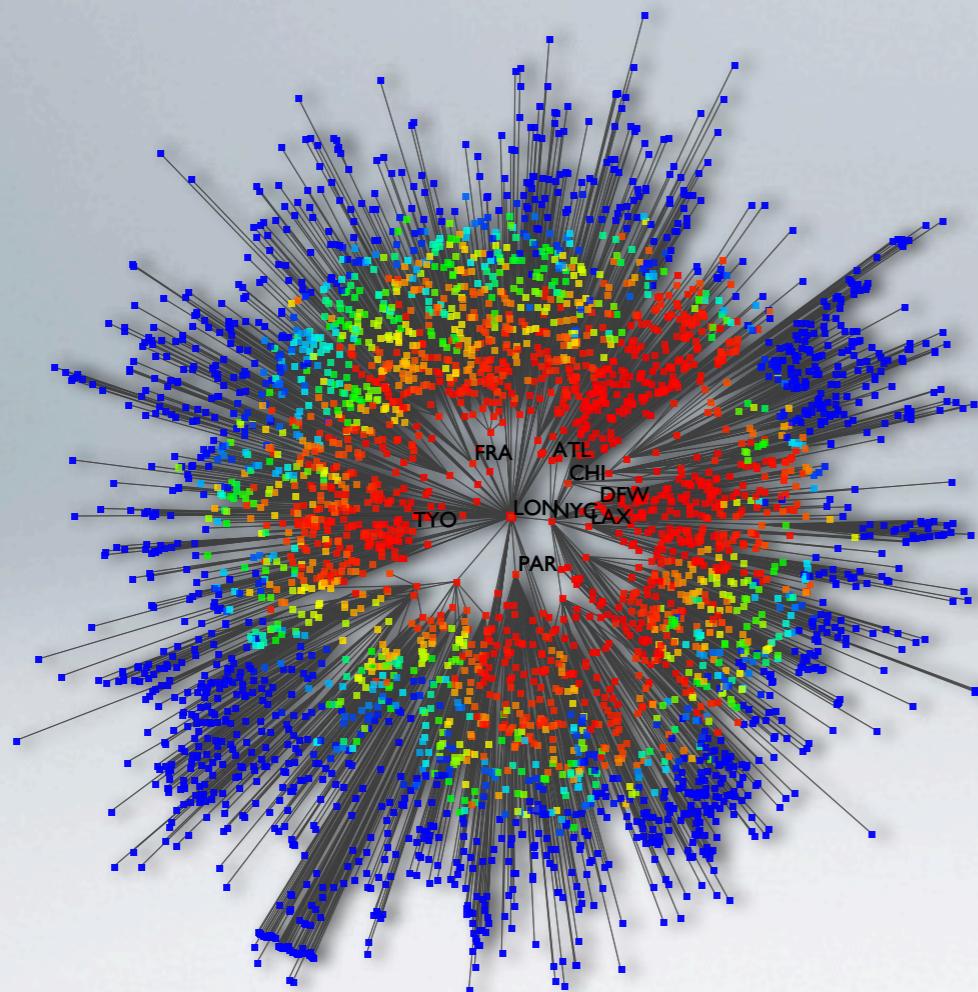
Dirk Brockmann
Northwestern University

MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE



Dirk Brockmann
Northwestern University

MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE



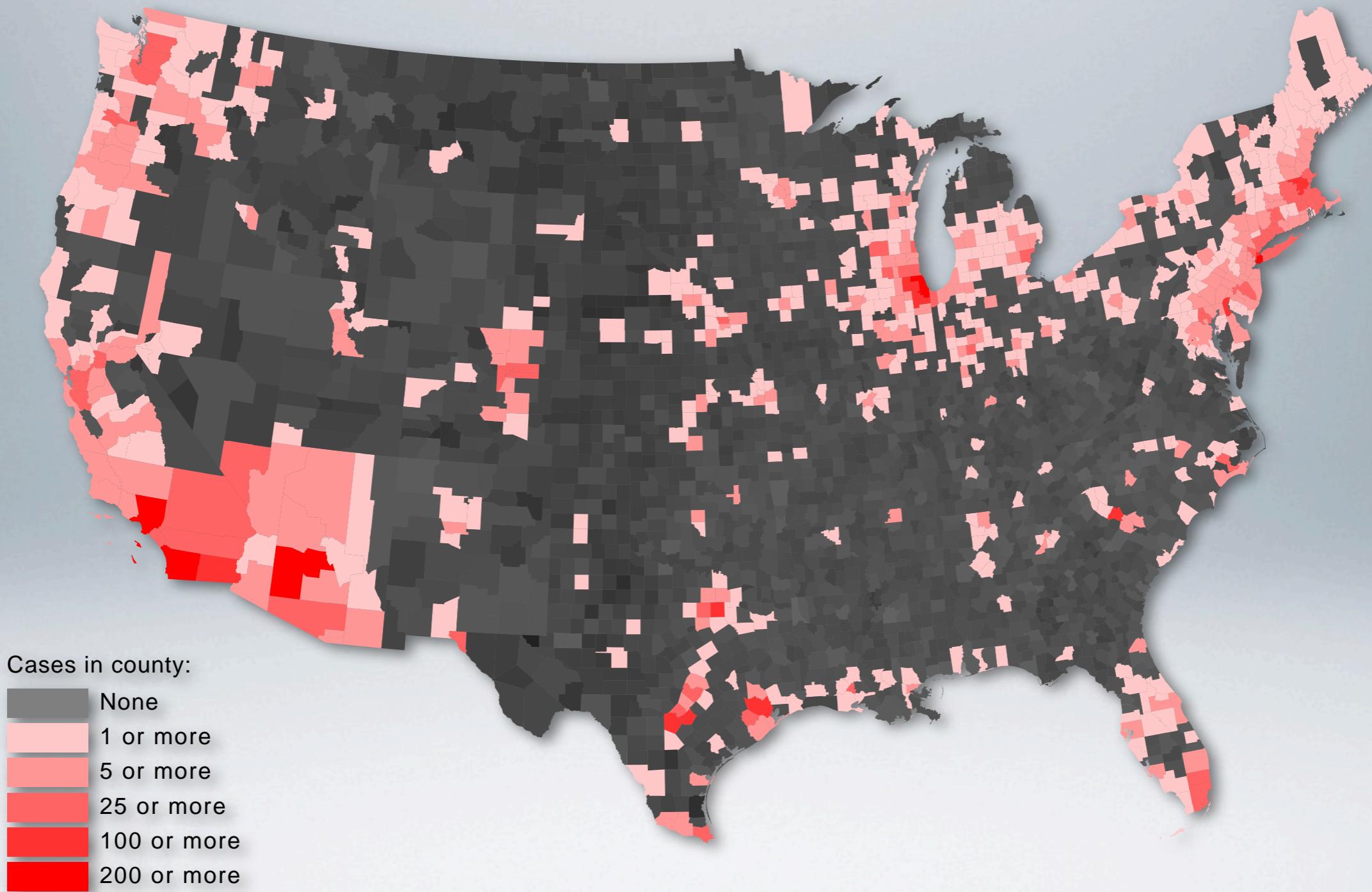
Dirk Brockmann
Northwestern University

MODELLING DISEASE DYNAMICS ON A GLOBAL SCALE

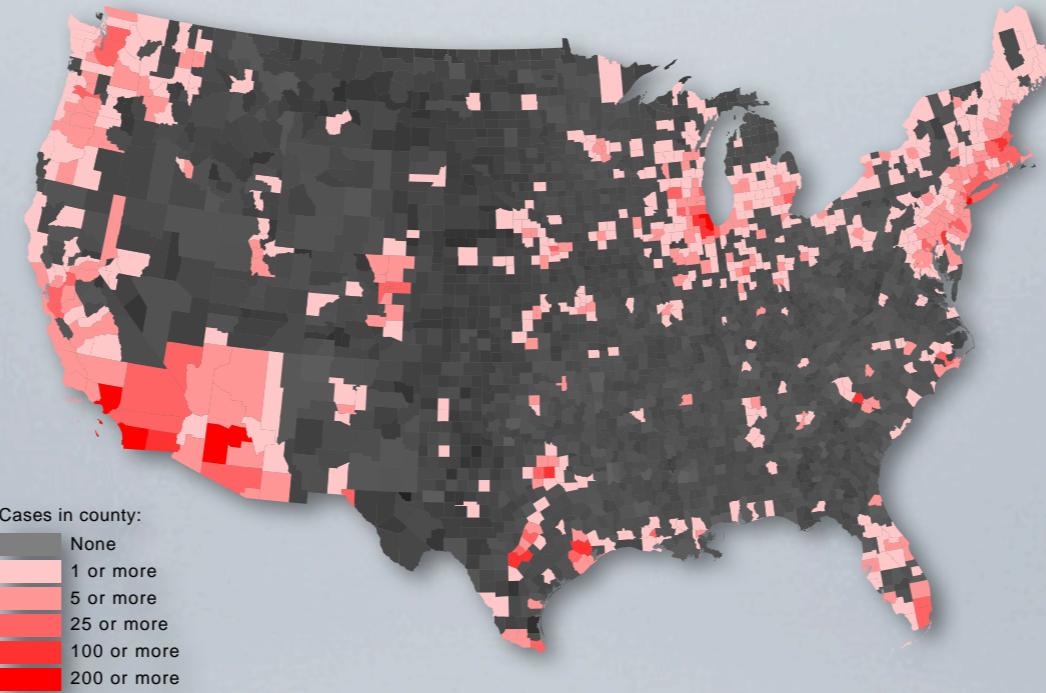


Dirk Brockmann Northwestern University

THE QUESTIONS



THE QUESTIONS

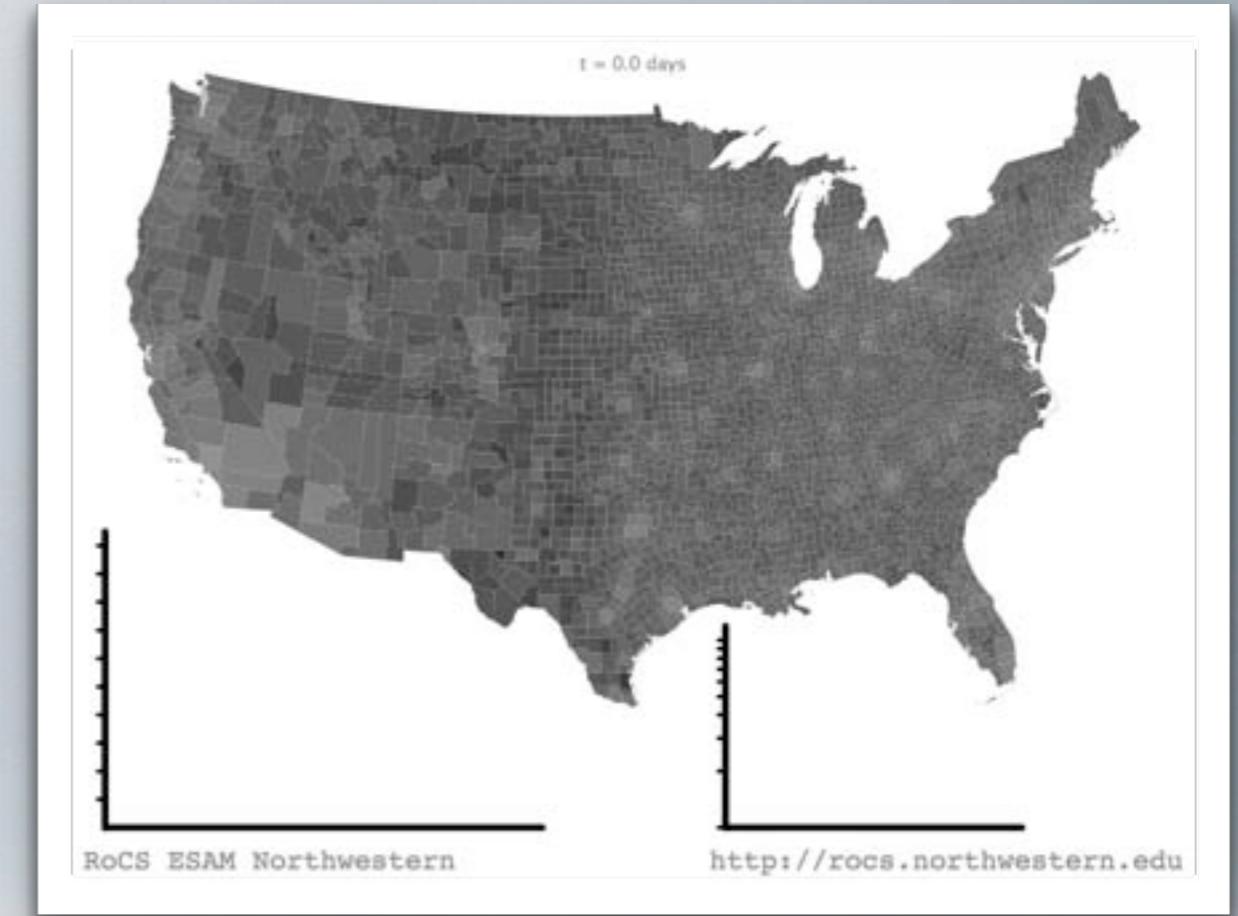


Where?

When?

How many?

MULTISCALE MOBILITY AND EPIDEMICS



what topological,
structural and
statistical features.....

ROCS ESAM Northwestern

http://rocs.northwestern.edu

...yield or induce
dynamic phenomena?

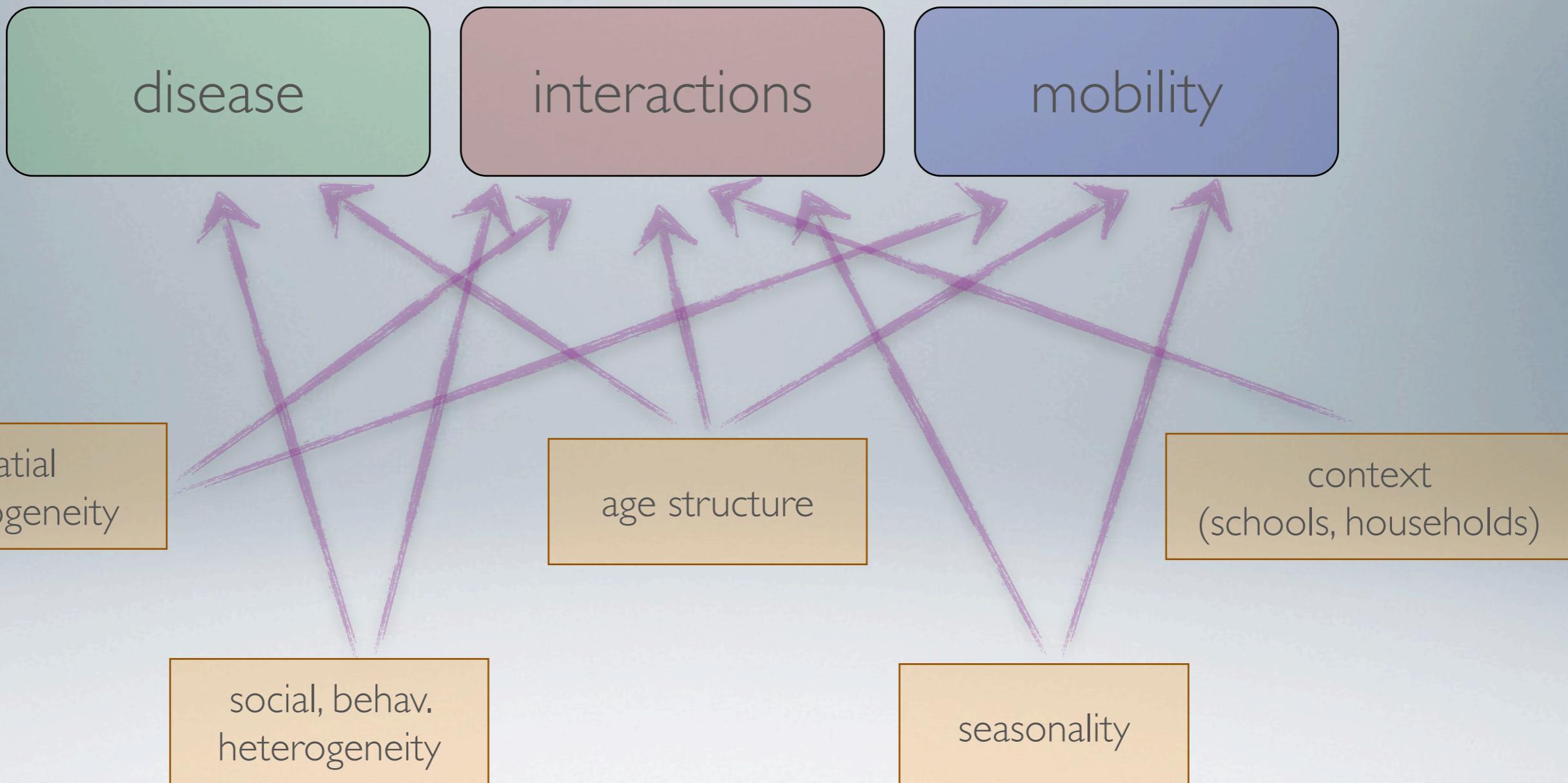
FACTORS

disease

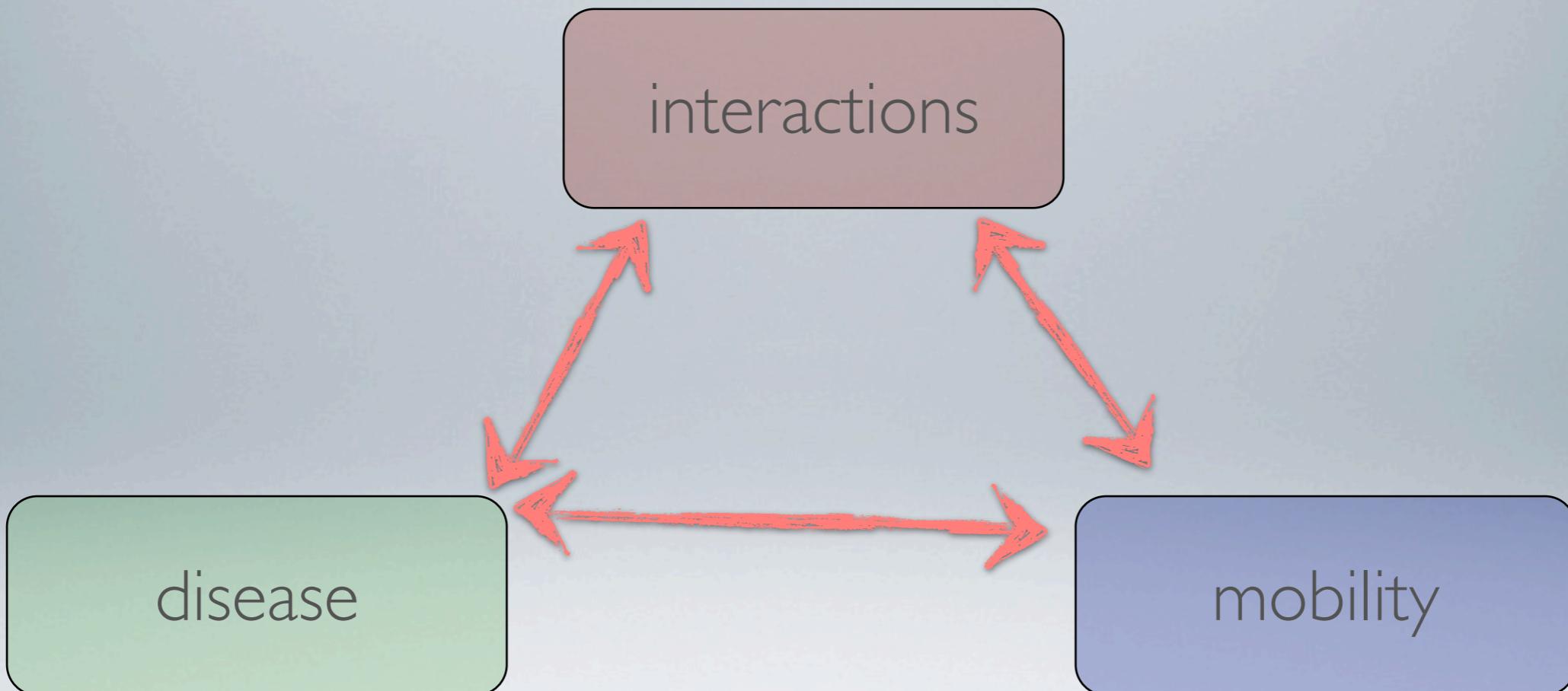
interactions

mobility

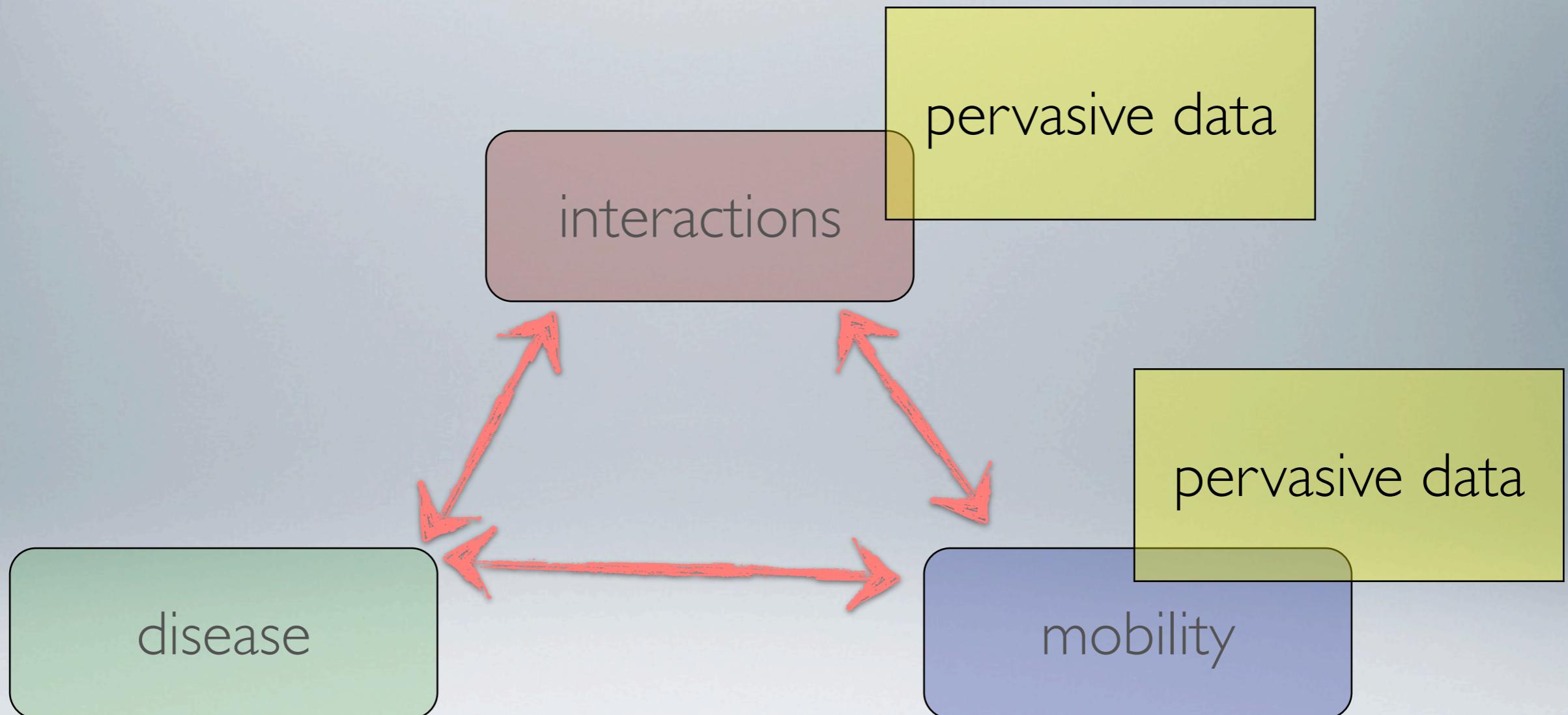
FACTORS



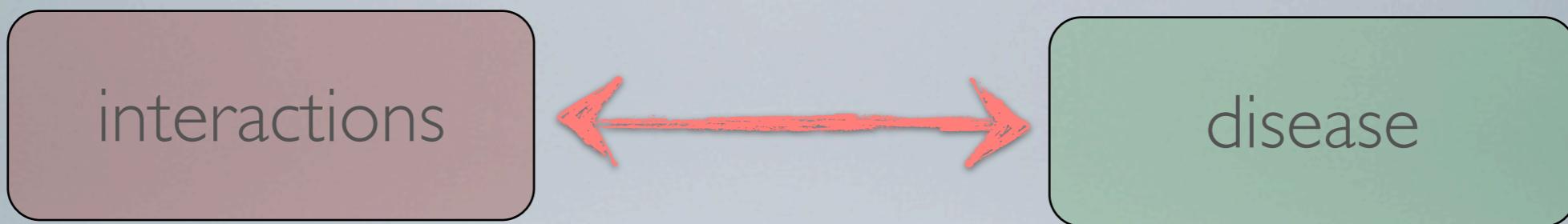
FACTORS



FACTORS

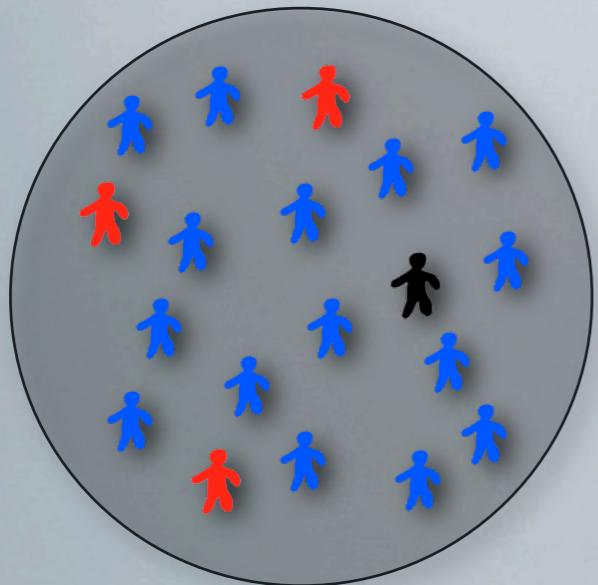


FACTORS

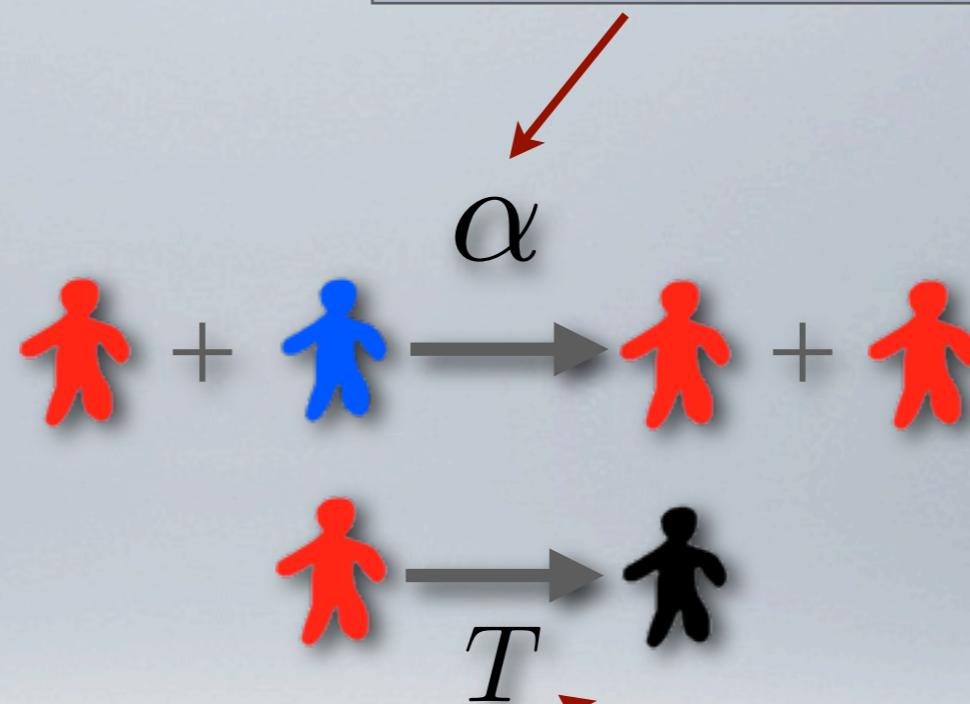


THE SIR MODEL

$N \leftarrow$ Population Size



infection rate:
e.g. 2 effective contacts/week

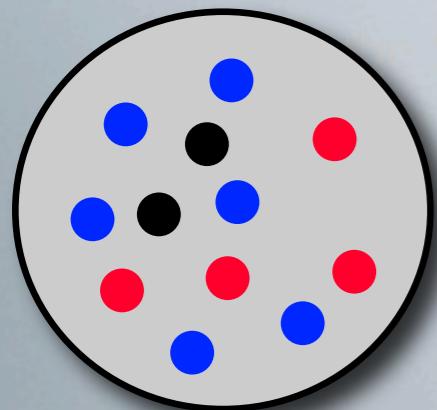


The basic reproduction number

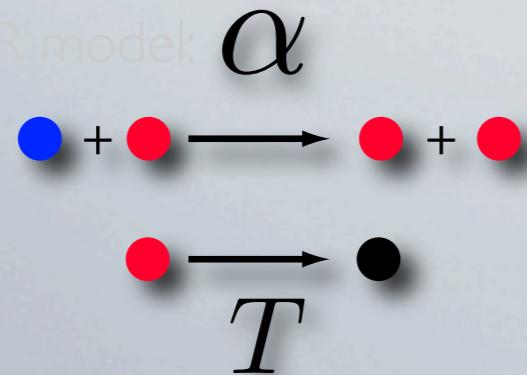
$$\alpha \times T = R_0 > 1$$

infectious period
e.g. 4 days.

SIR DYNAMICS



The SIR model:
• infected
• susceptible
• recovered/removed



mean field dynamics:

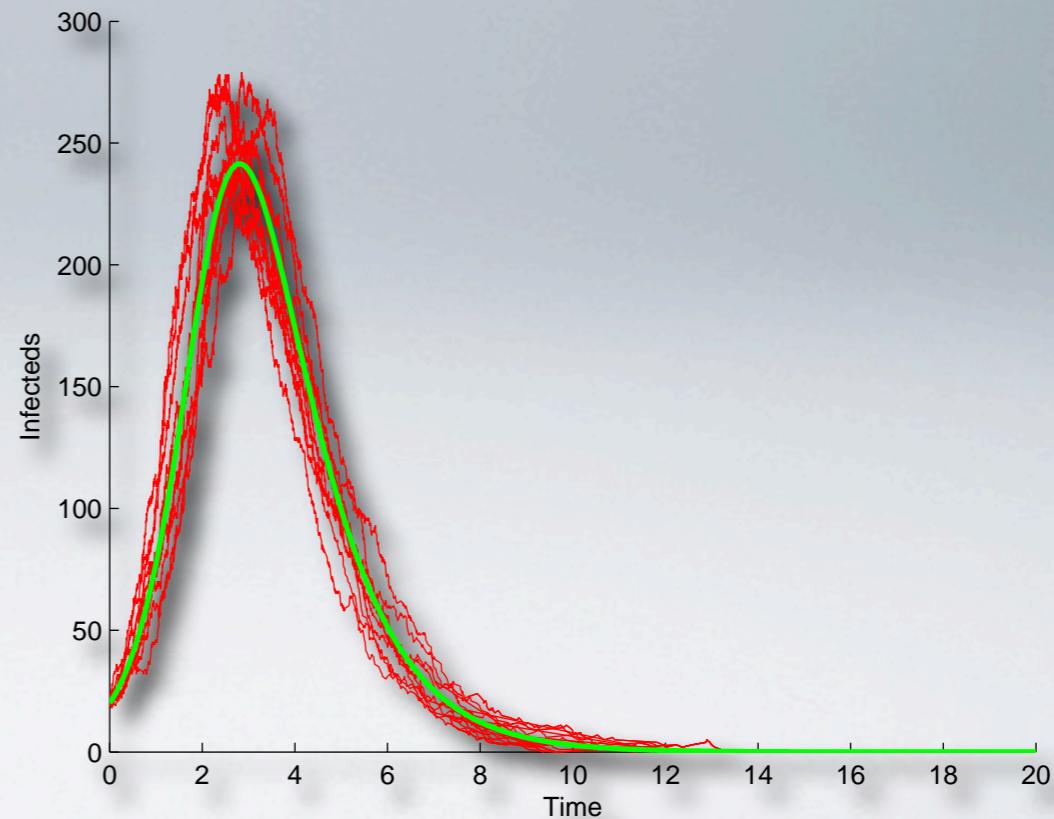
$$\partial_t S = -R_0 I S$$

$$\partial_t I = R_0 I S - I$$

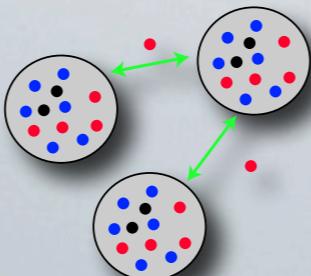
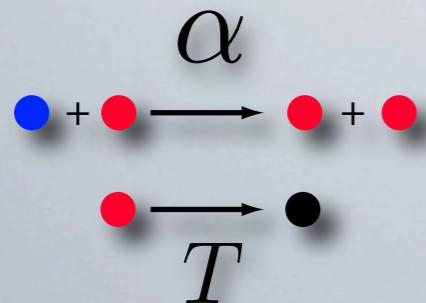
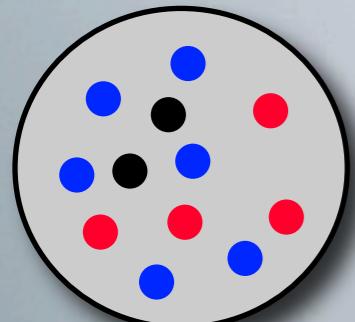
$$R = 1 - S - I$$

The basic reproduction number

$$\alpha \times T = R_0 > 1$$



SPATIAL DYNAMICS

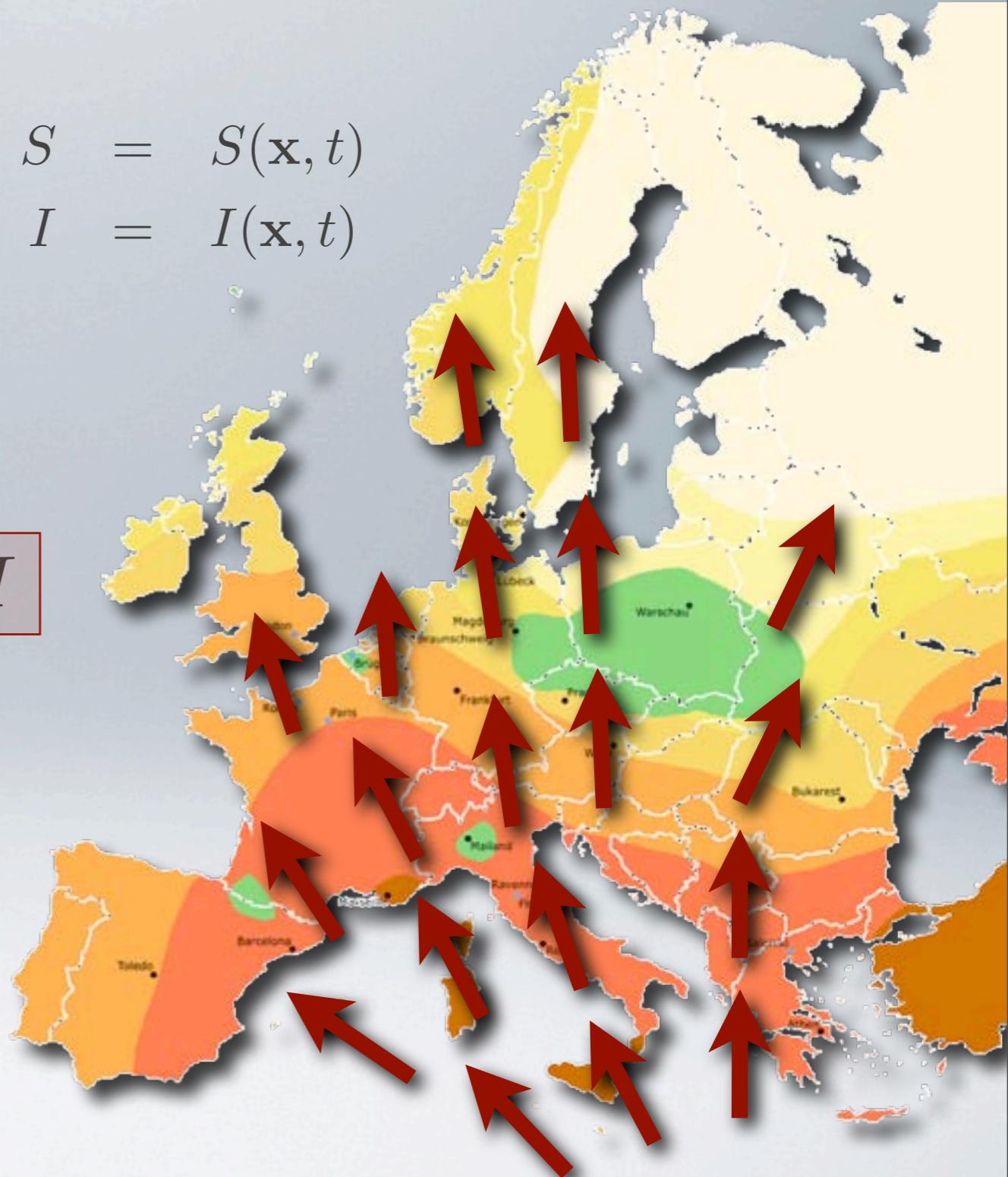


$$\begin{aligned} S &= S(\mathbf{x}, t) \\ I &= I(\mathbf{x}, t) \end{aligned}$$

- infected
- susceptible
- recovered/removed

$$\partial_t S = -R_0 SI + D \partial_x^2 S$$

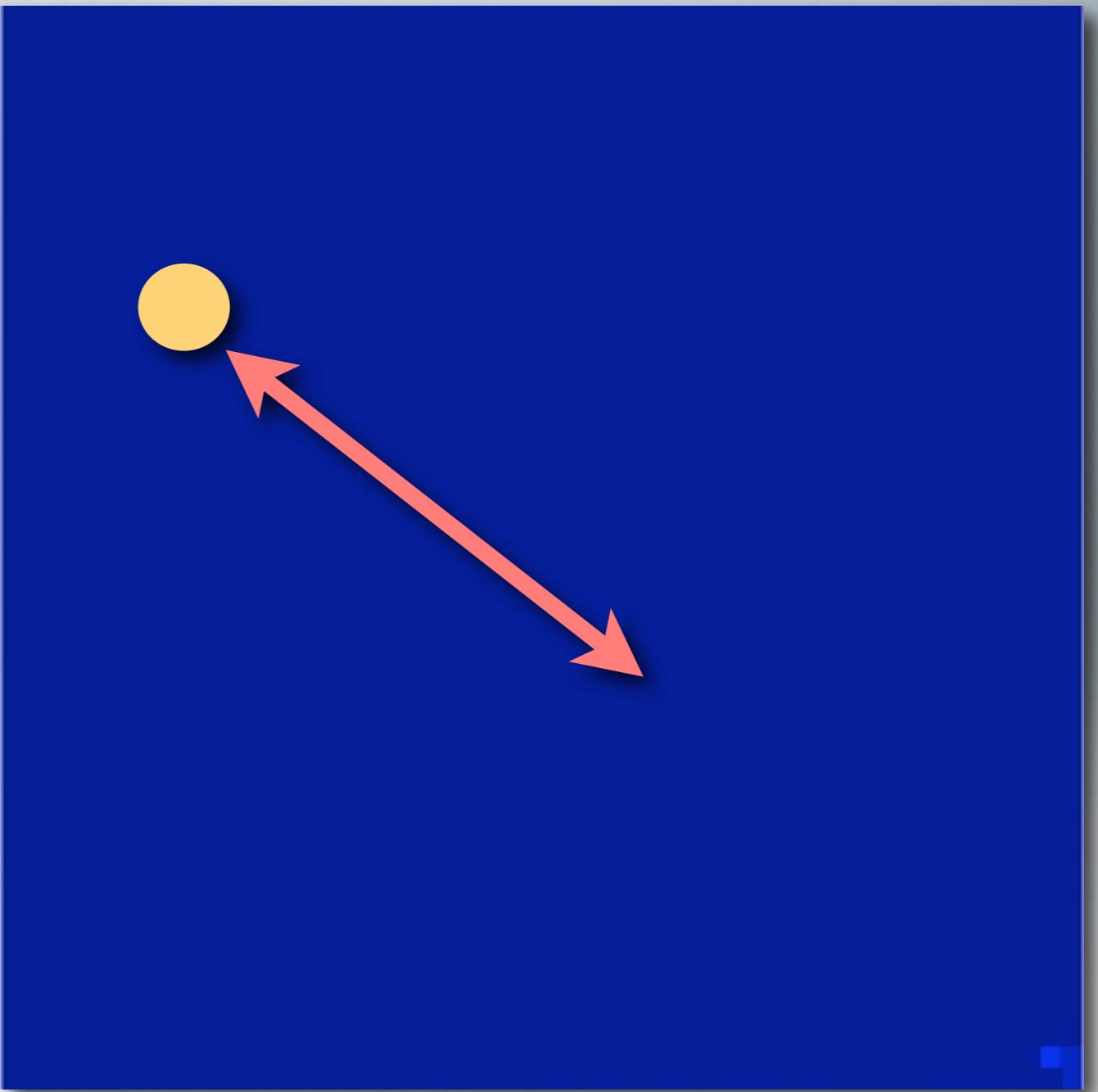
$$\partial_t I = R_0 SI - I + D \partial_x^2 I$$



WHEN?

WHEN?

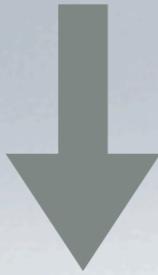
$$T = \frac{d}{v}$$



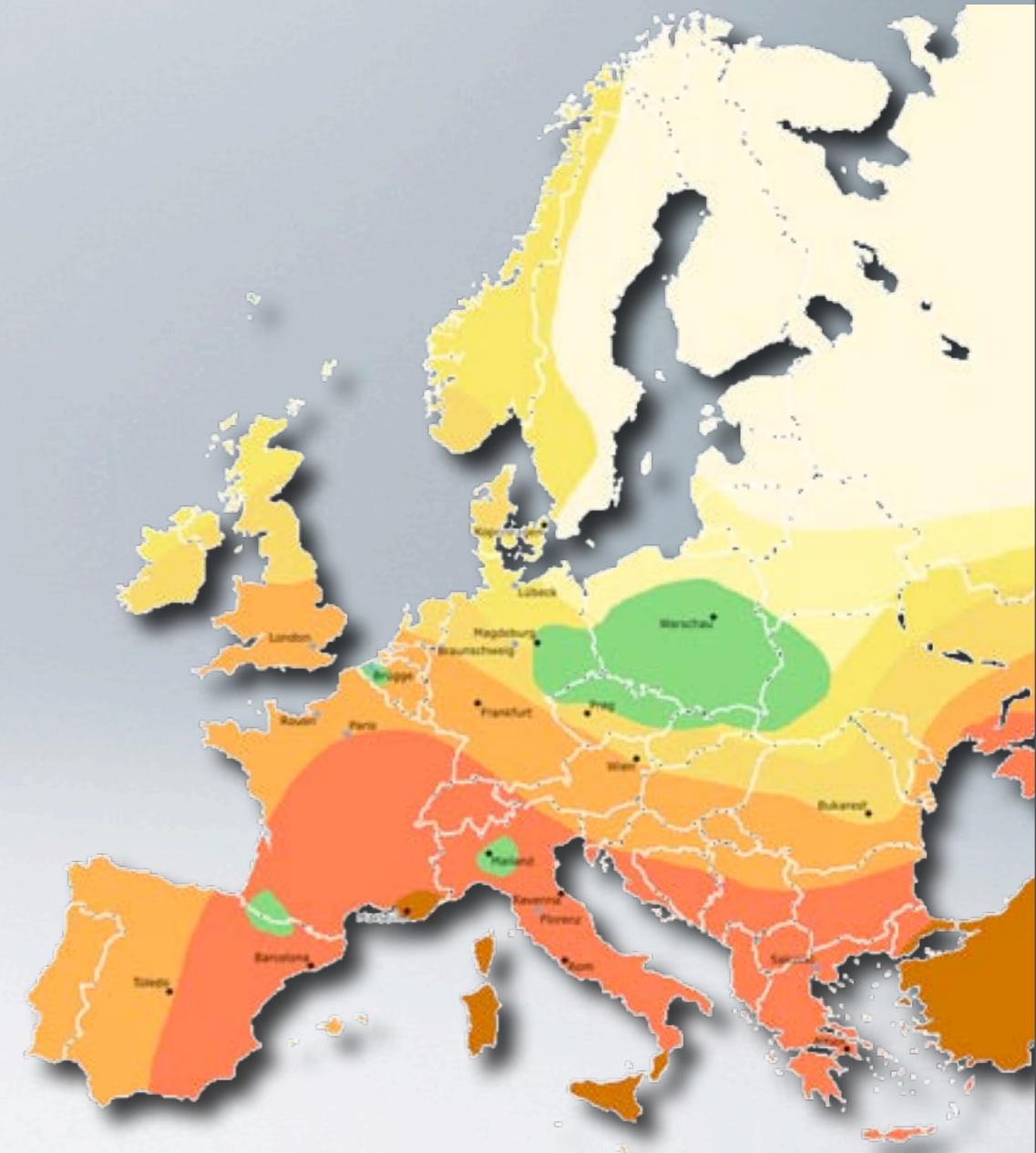
FRONT VELOCITY IN FISHER TYPE SYSTEMS

$$u = u(\mathbf{x}, t)$$

$$\partial_t u = \lambda u(1 - u) + D \partial_x^2 u$$



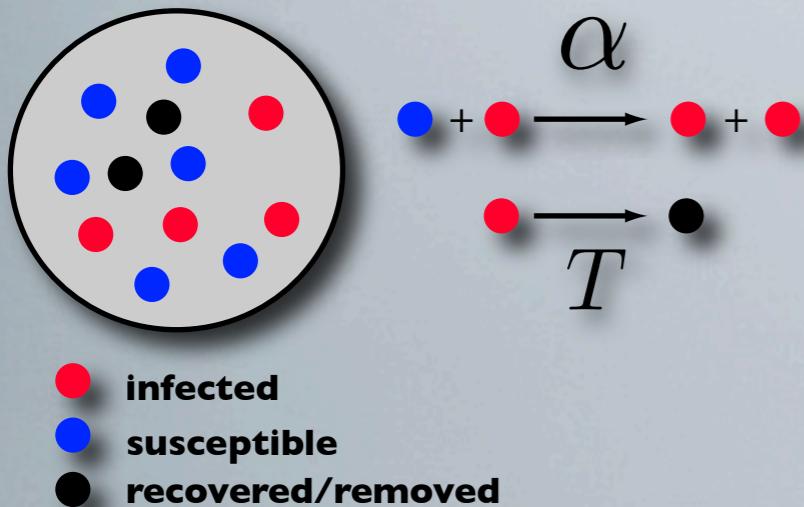
$$v \propto \sqrt{D\lambda}$$



Noble, Nature (1974) vol. 250 (5469) pp. 726-728

SINGLE POPULATION AND SPATIAL MODELS

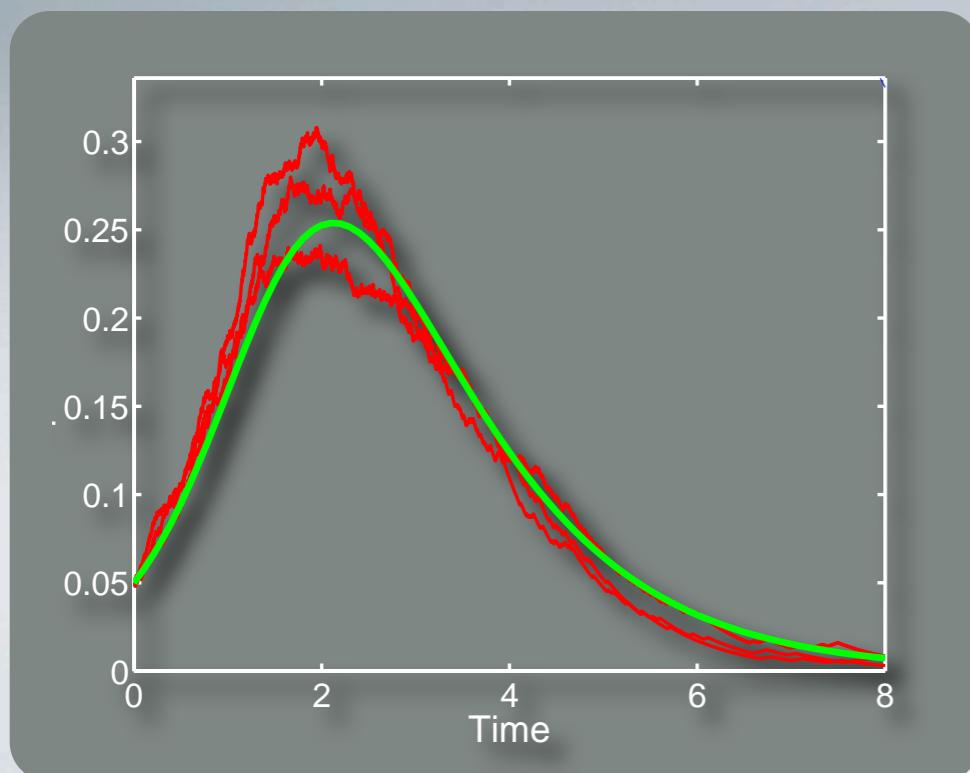
SIR dynamics



$$\partial_t I = \alpha IS/N - \beta I$$

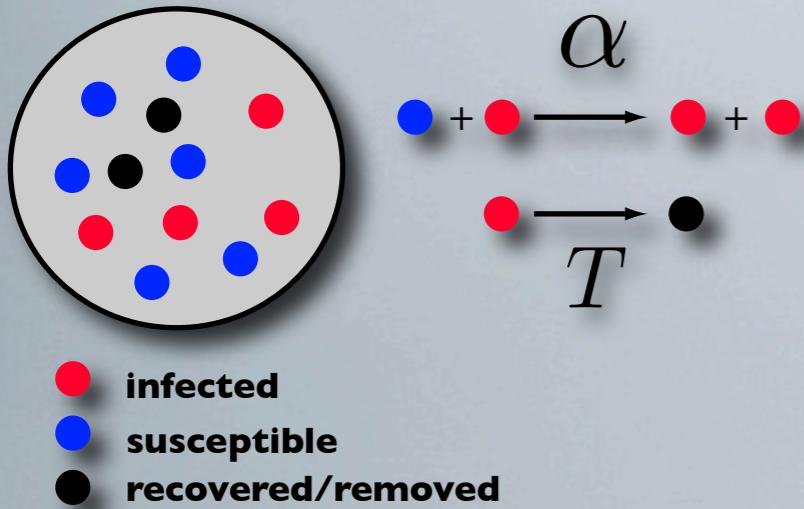
$$\partial_t S = -\alpha IS/N$$

$$R_0 = \alpha/\beta$$



SINGLE POPULATION AND SPATIAL MODELS

SIR dynamics

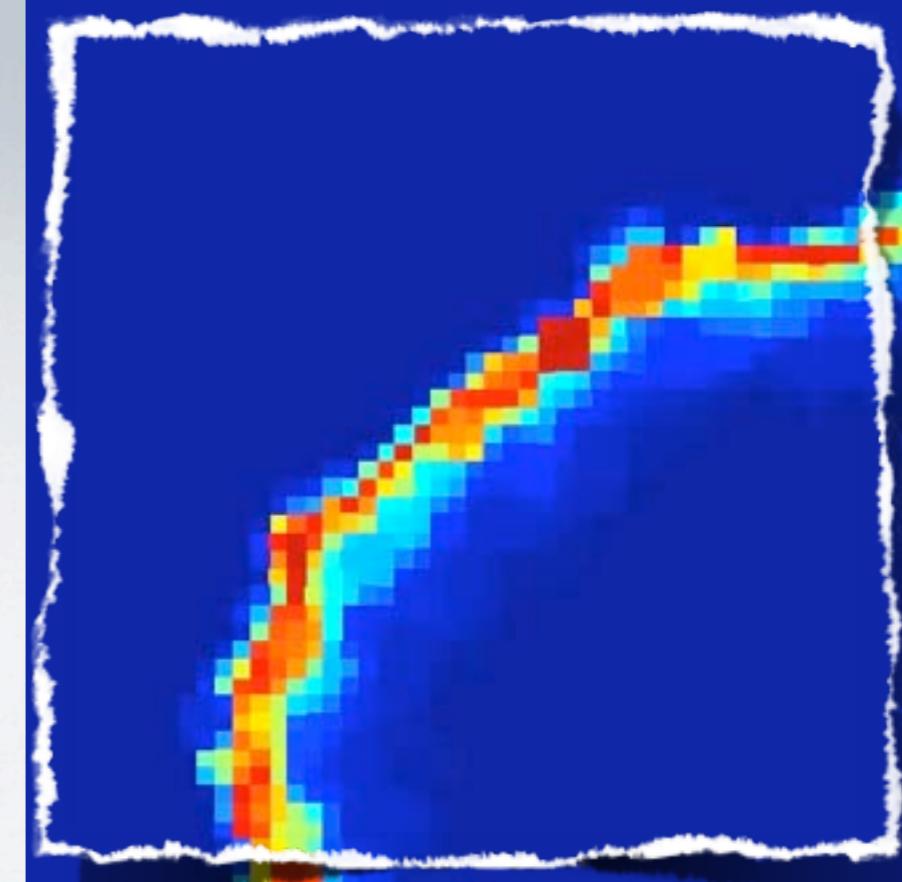
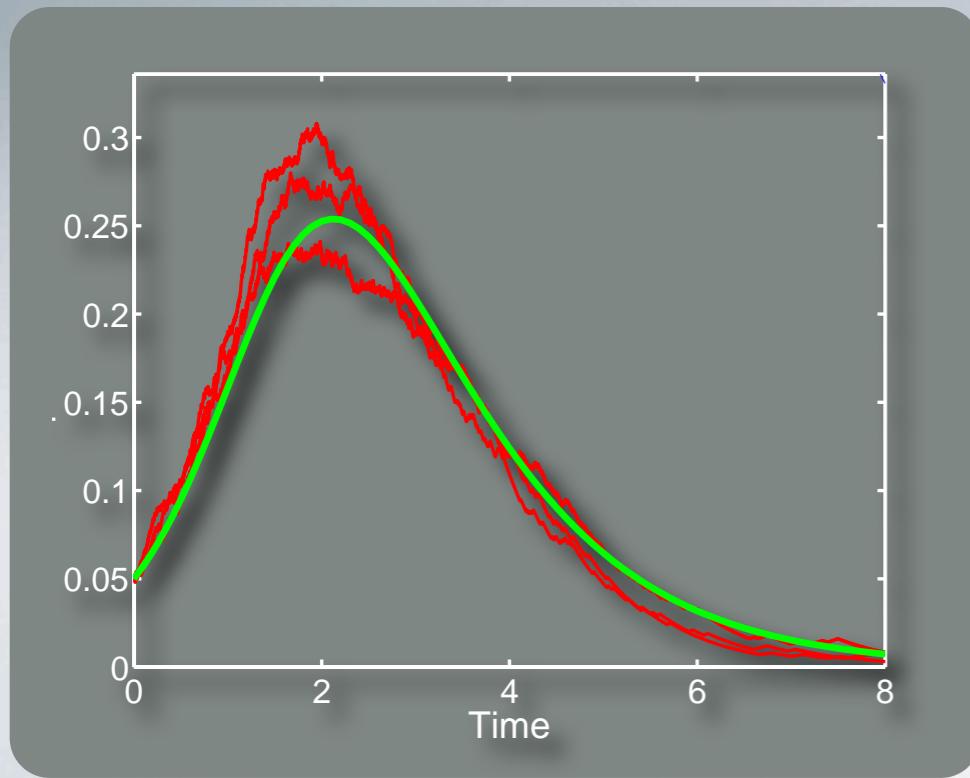


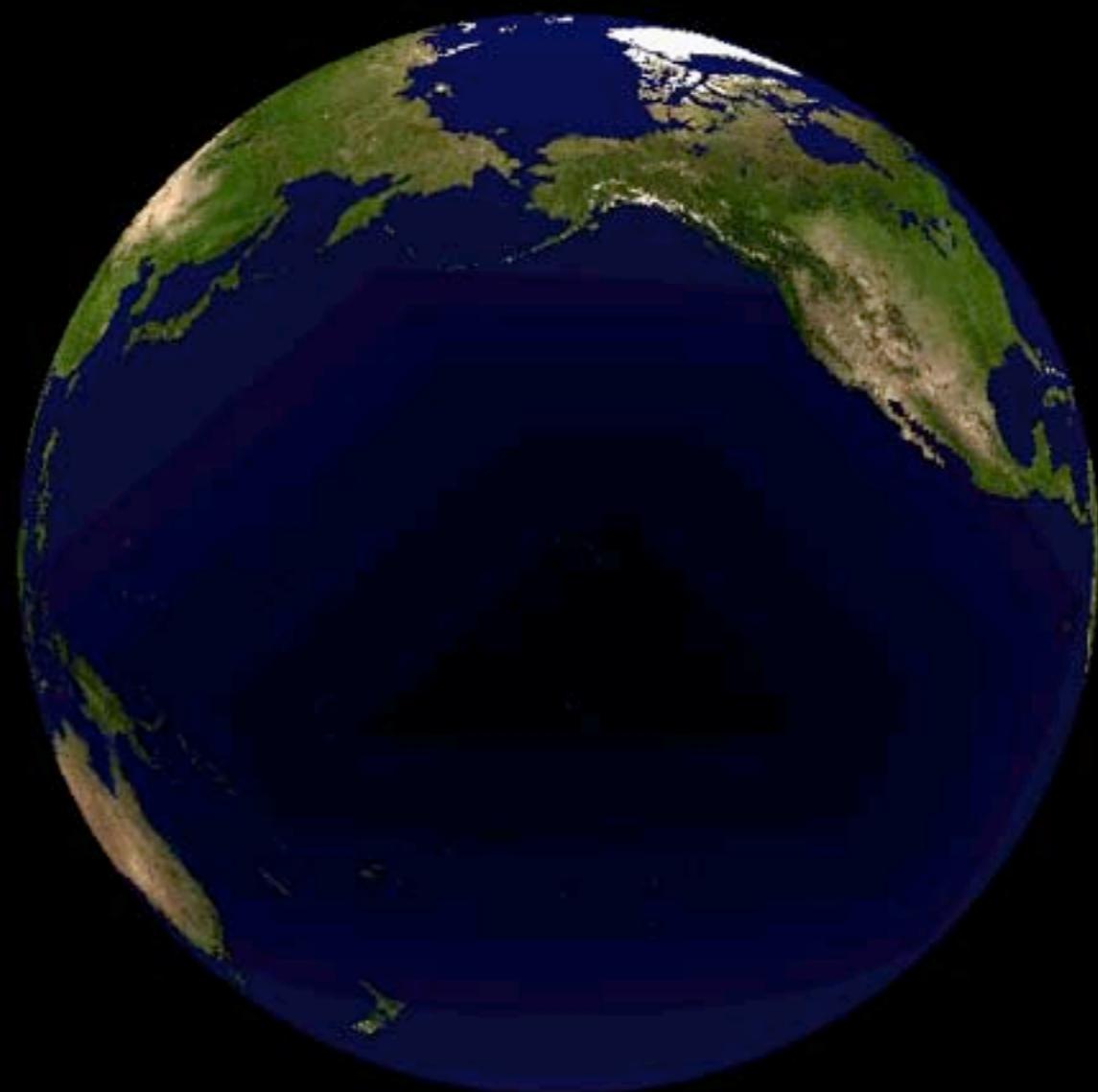
$$\partial_t I = \alpha IS/N - \beta I + D\partial_x^2 I$$

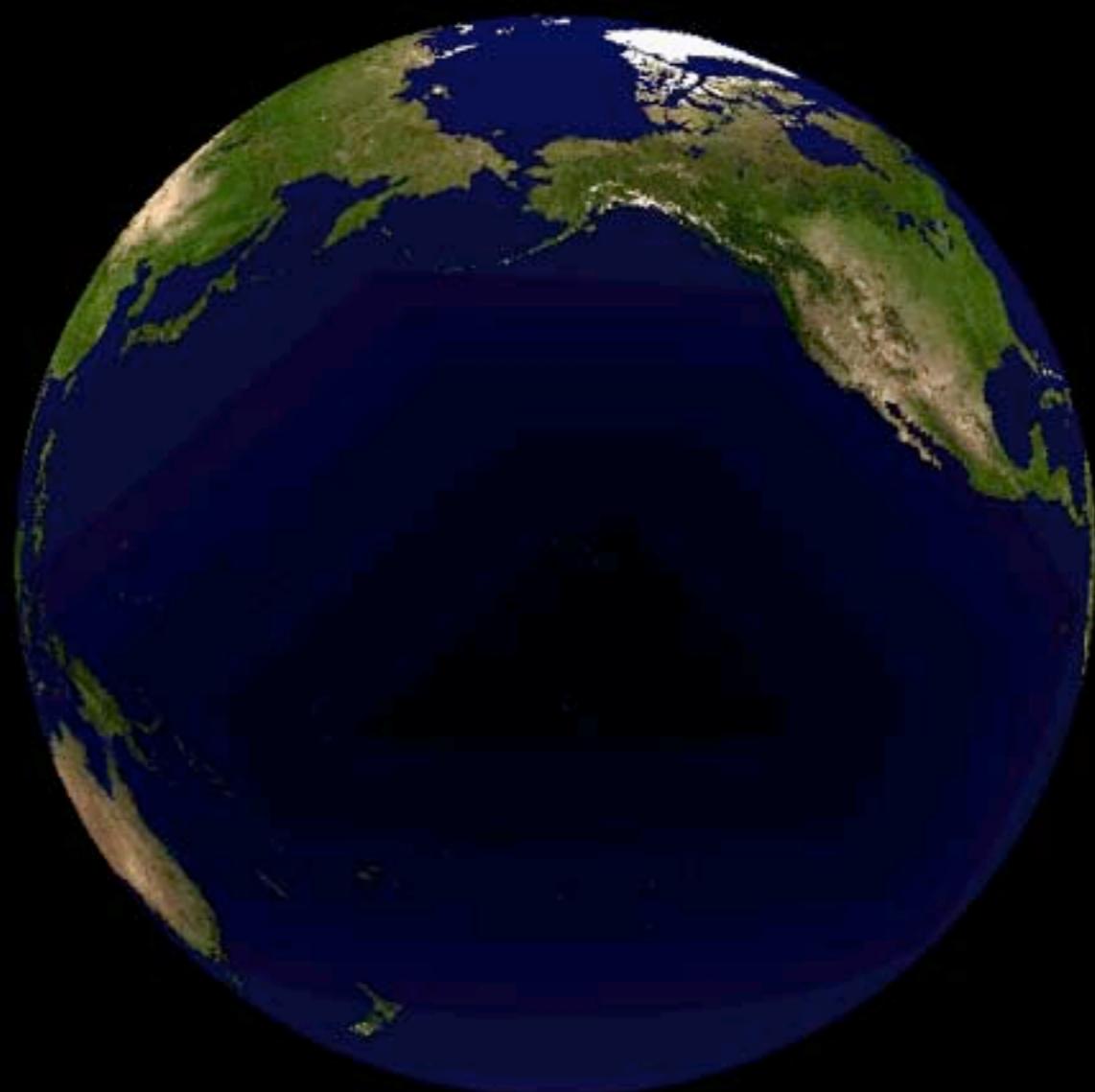
$$\partial_t S = -\alpha IS/N + D\partial_x^2 S$$

$$R_0 = \alpha/\beta$$

$$v \propto \sqrt{(R_0 - 1)D}$$

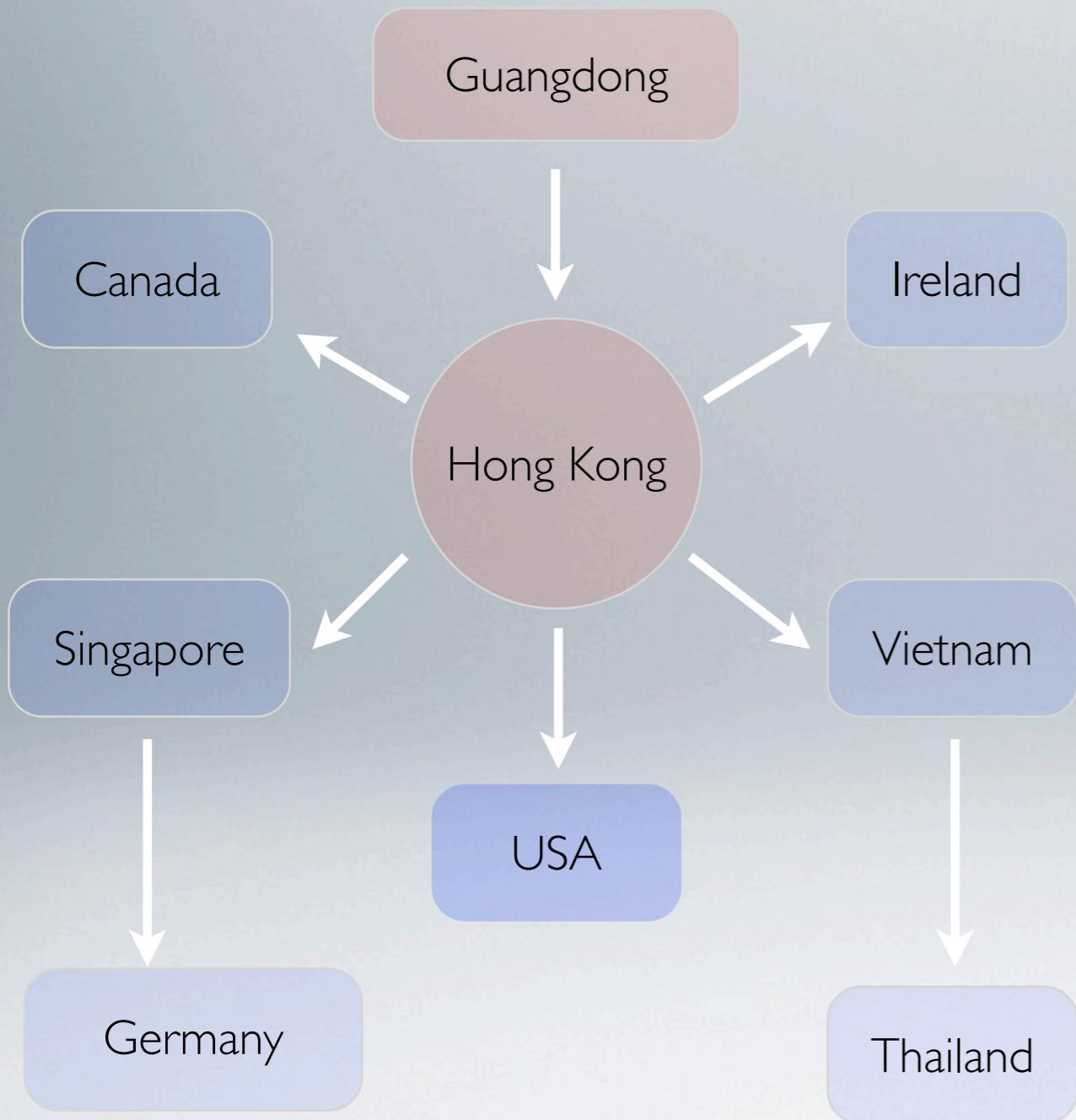




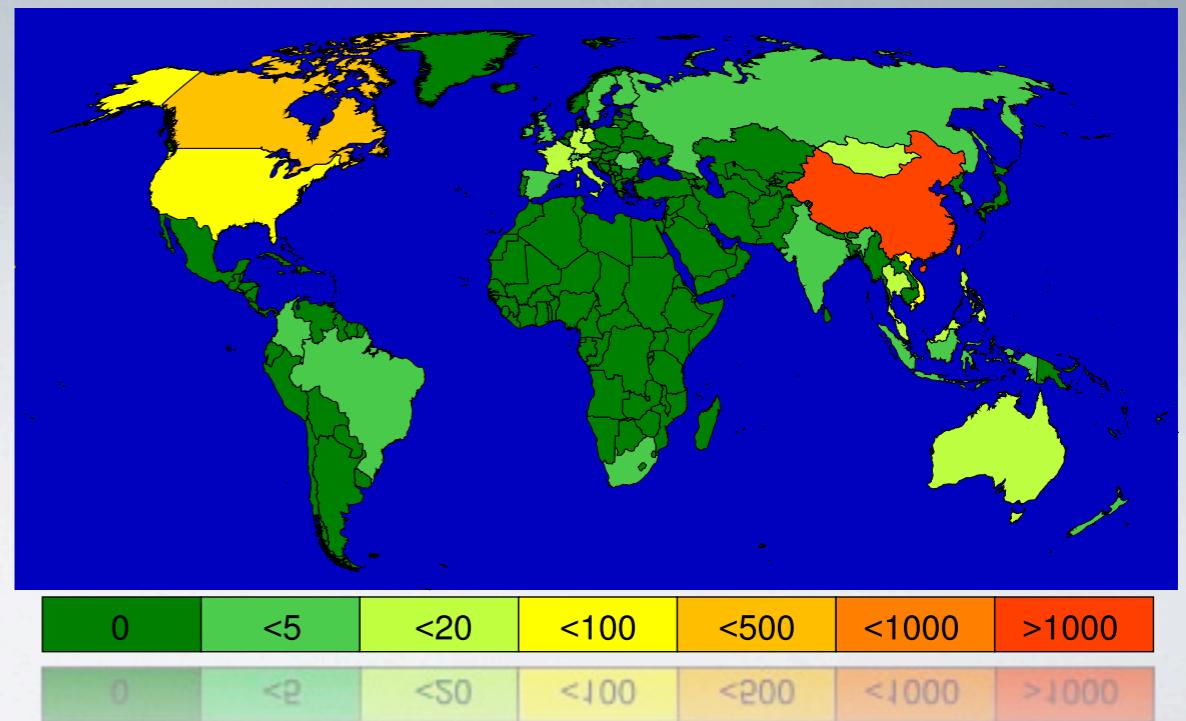


- 3 billion passengers/yr.
- 4095 airports
- 2 Mio. flights/week

THE „SEVERE ACUTE RESPIRATORY SYNDROME“ (SARS)



- caused by coronavirus
- first outbreak: China
- February 2003 in Hong Kong
- worldwide spread in over 30 countries
- approx 8000 infections
- 10% die

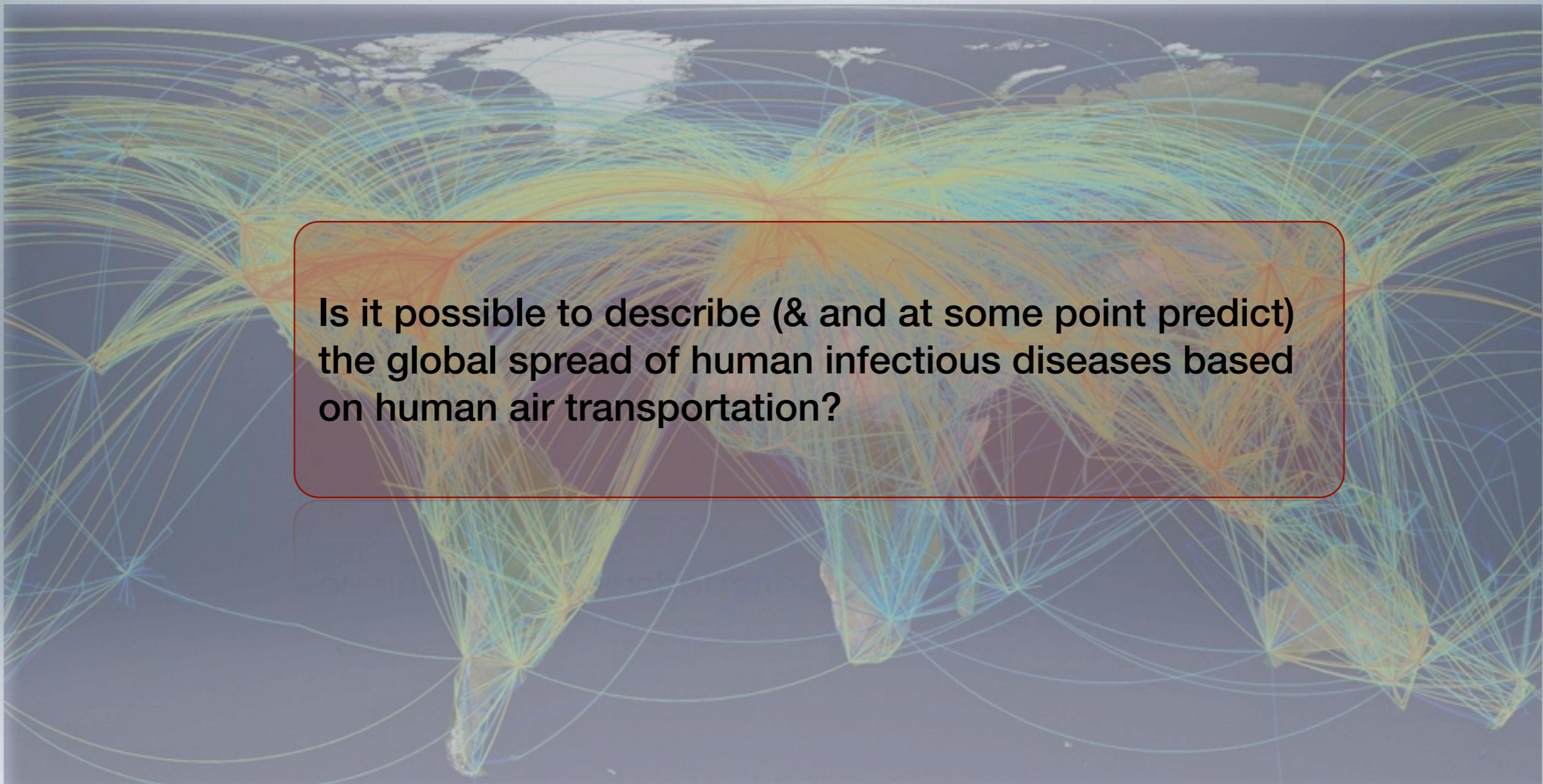


MODEL FOR THE WORLDWIDE SPREAD OF AN



Hufnagel, L., Brockmann, D. & Geisel, T., *PNAS*, 2004

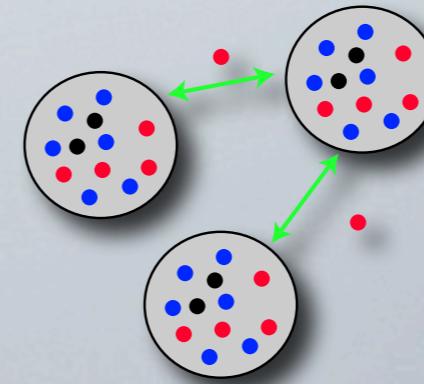
MODEL FOR THE WORLDWIDE SPREAD OF AN



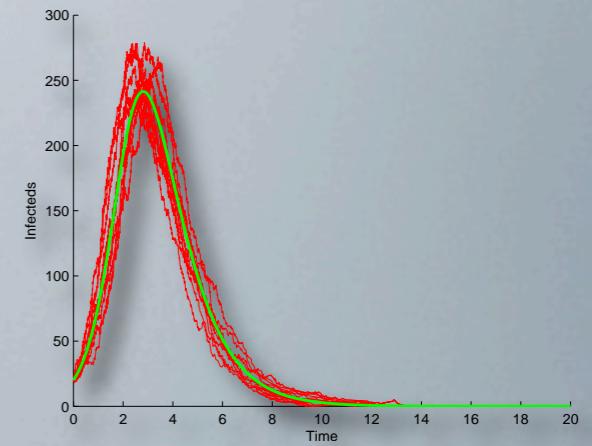
Is it possible to describe (& and at some point predict) the global spread of human infectious diseases based on human air transportation?

Hufnagel, L., Brockmann, D. & Geisel, T., *PNAS*, 2004

METAPOPULATION MODEL



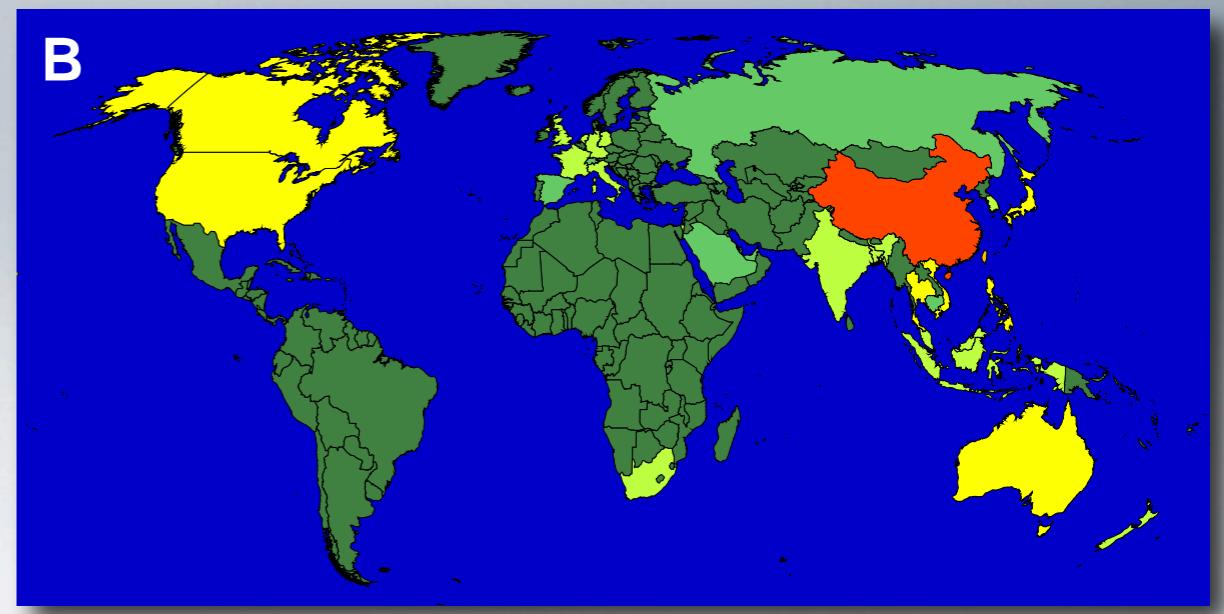
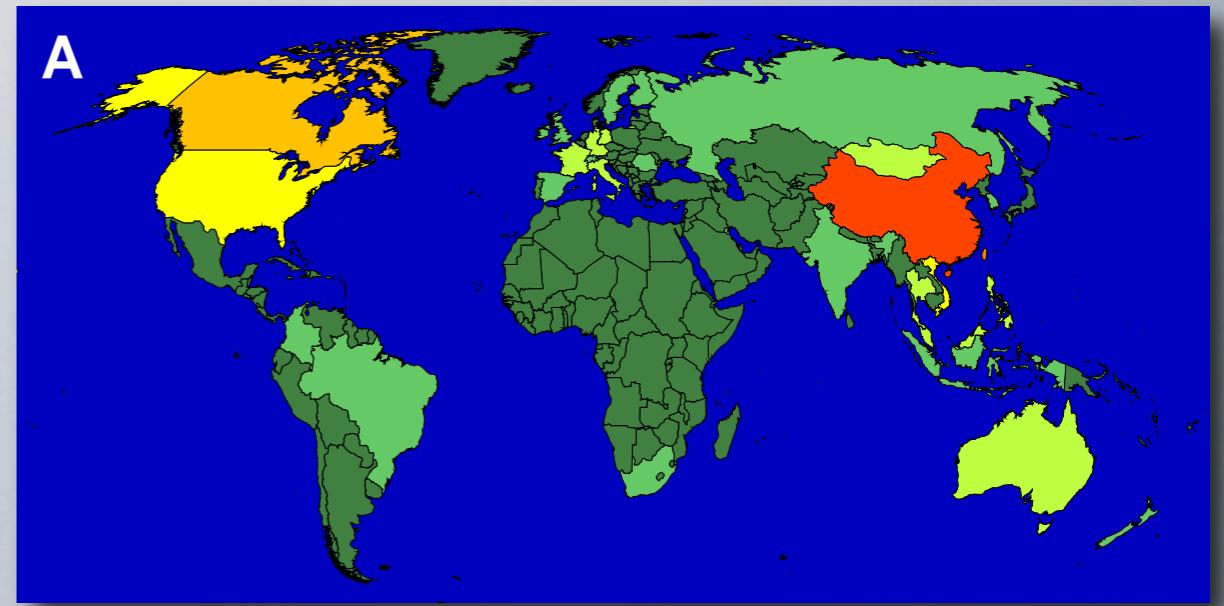
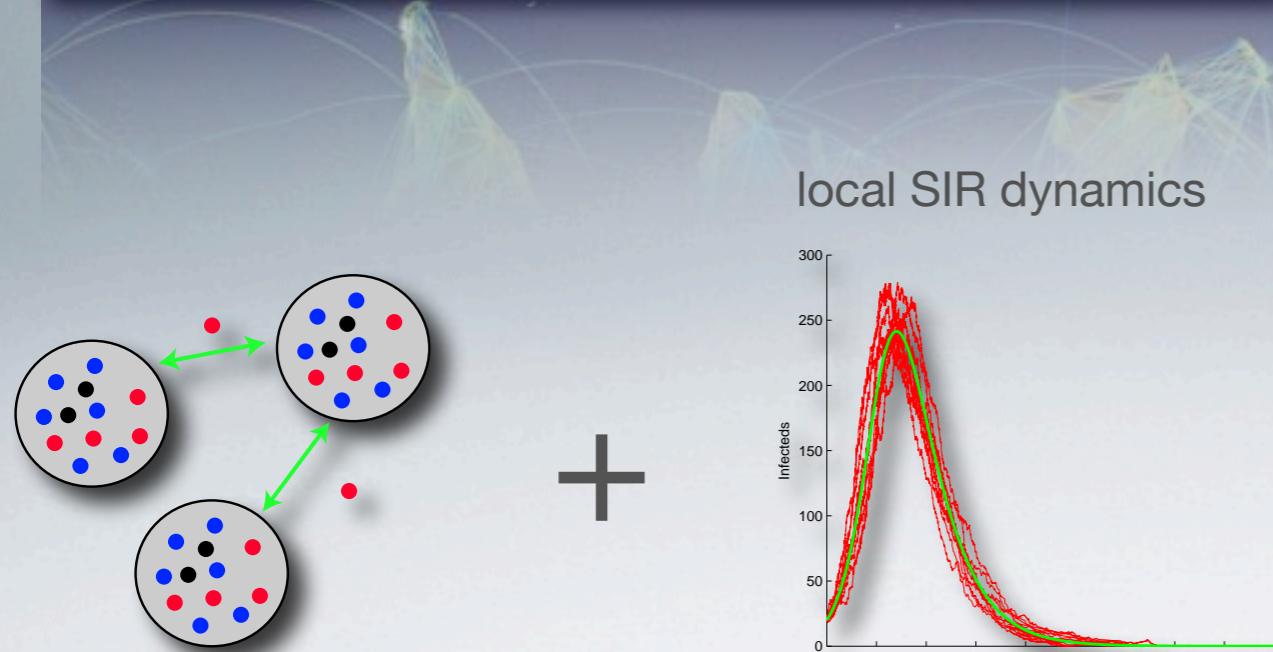
local SIR dynamics



$$\partial_t I_n = \alpha S_n I_n / N_n - \beta I_n + \sum_{m \neq n} (w_{nm} I_m - w_{mn} I_n)$$

$$\partial_t S_n = -\alpha S_n I_n / N_n + \sum_{m \neq n} (w_{nm} S_m - w_{mn} S_n)$$

A MODEL FOR THE GLOBAL SPREAD OF SARS



A: WHO B: model

Hufnagel, L., Brockmann, D. & Geisel, T., PNAS, 2004

global air transportation in epidemic contexts



Dirk Brockmann

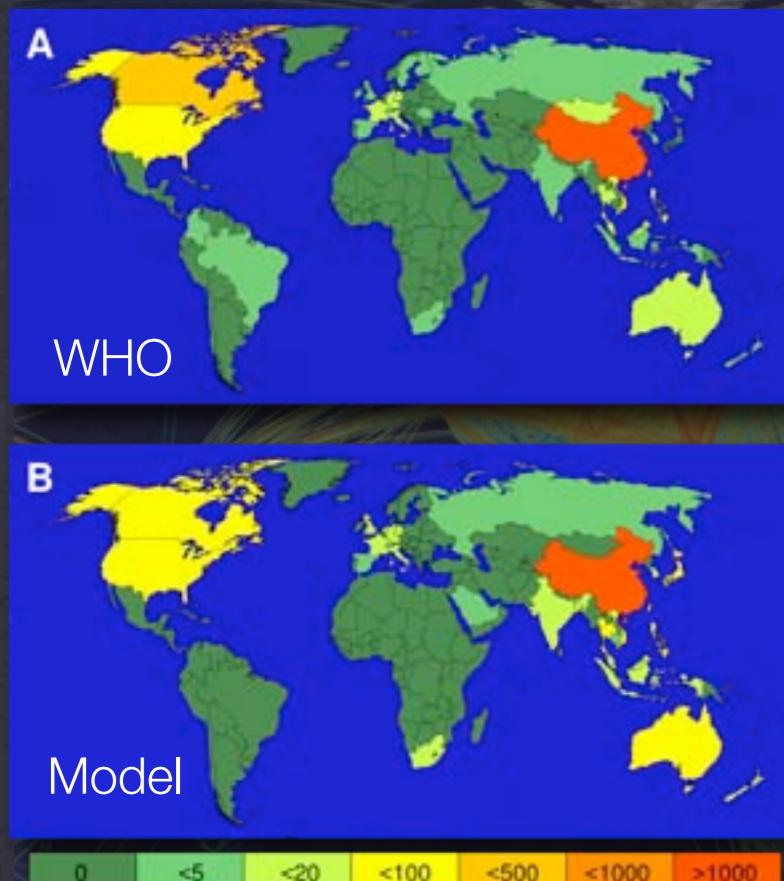
ESAM & NICO

Northwestern University

<http://rocs.northwestern.edu>

global air transportation in epidemic contexts

SARS 2003



Hufnagel et al. Forecast and control of epidemics in a **globalized** world. PNAS (2004)

Ferguson et al. Strategies for containing an emerging influenza **pandemic** in Southeast Asia. Nature (2005)

Hollingsworth et al. Will **travel restrictions** control the **international spread** of pandemic influenza?. Nat Med (2006)

Colizza et al. The role of the **airline transportation** network in the prediction and predictability of global epidemics. PNAS (2006)

Ferguson et al. Strategies for mitigating an influenza **pandemic**. Nature (2006)

Colizza et al. Modeling the **worldwide spread** of pandemic influenza: Baseline case and containment interventions. Plos Med (2007)

Colizza et al. Reaction-diffusion processes and metapopulation models in heterogeneous networks. Nat Phys (2007)

Colizza et al. Invasion threshold in heterogeneous metapopulation networks. Phys Rev Lett (2007) vol. 99 (14)

Riley. **Large-scale spatial-transmission** models of infectious disease. Science (2007)

Colizza et al. Epidemic modeling in metapopulation systems with heterogeneous coupling pattern: Theory and simulations. J Theor Biol (2008)



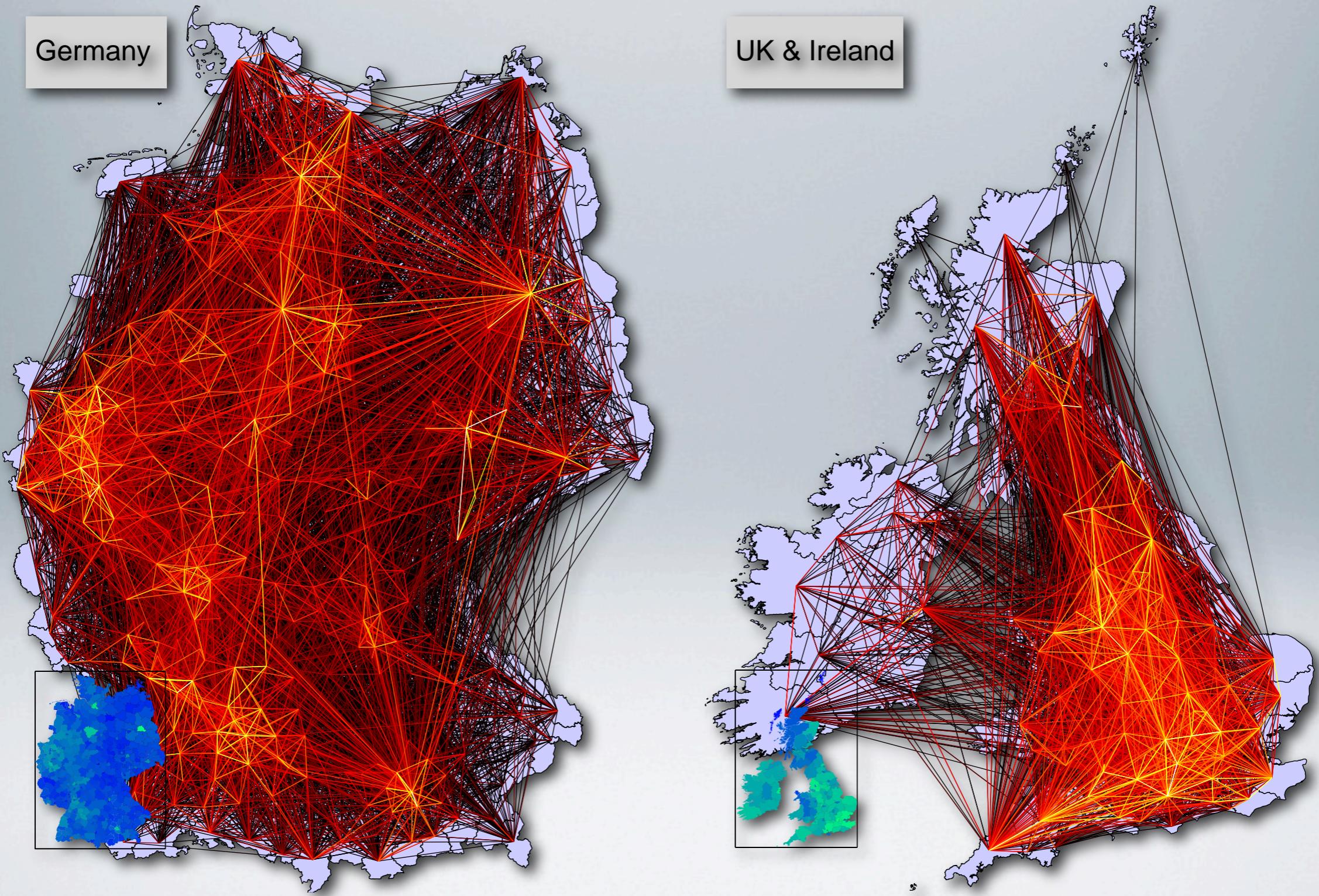
Dirk Brockmann

ESAM & NICO

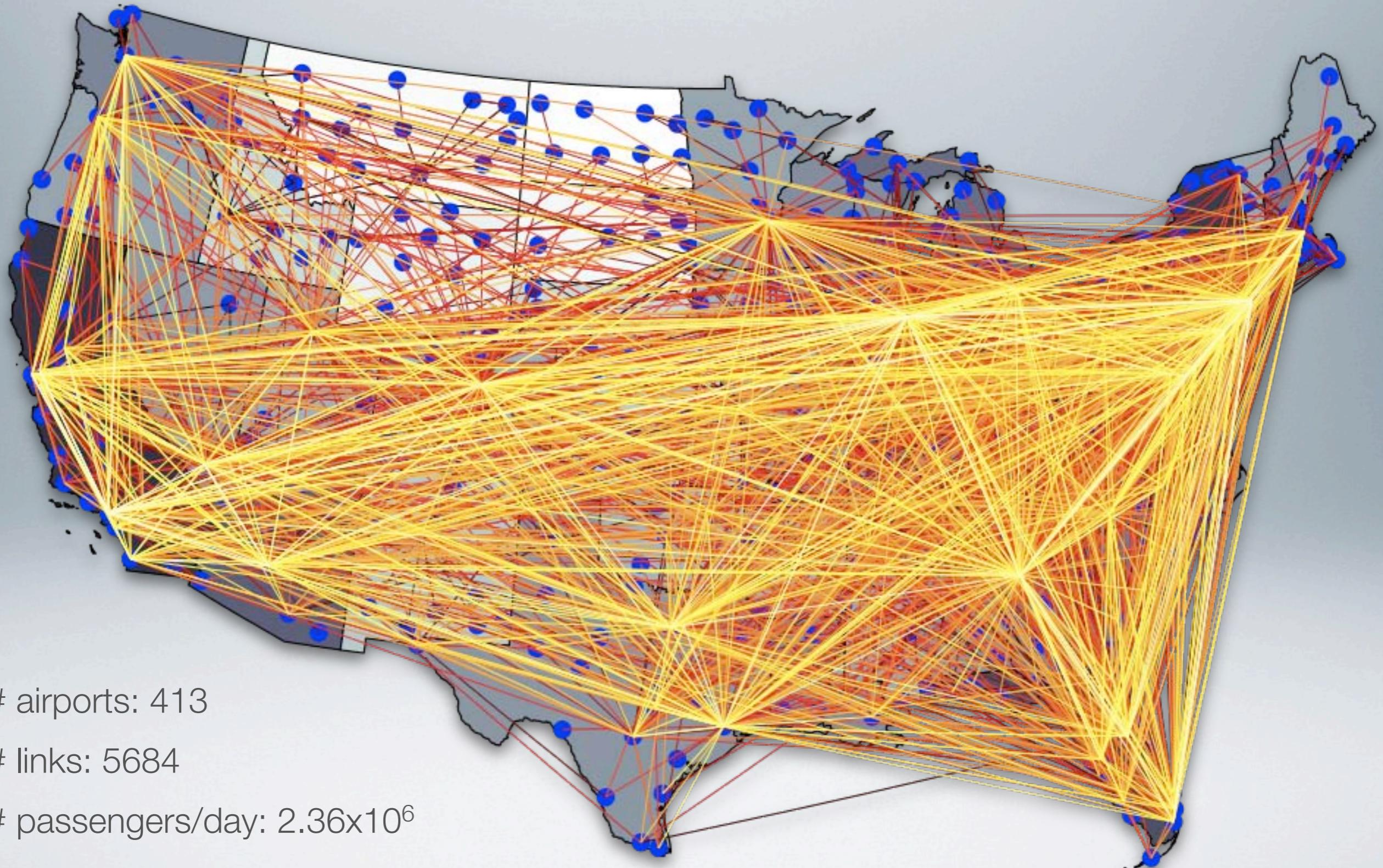
Northwestern University

<http://rocs.northwestern.edu>

MULTI-SCALE MOBILITY



US AIR TRANSPORTATION

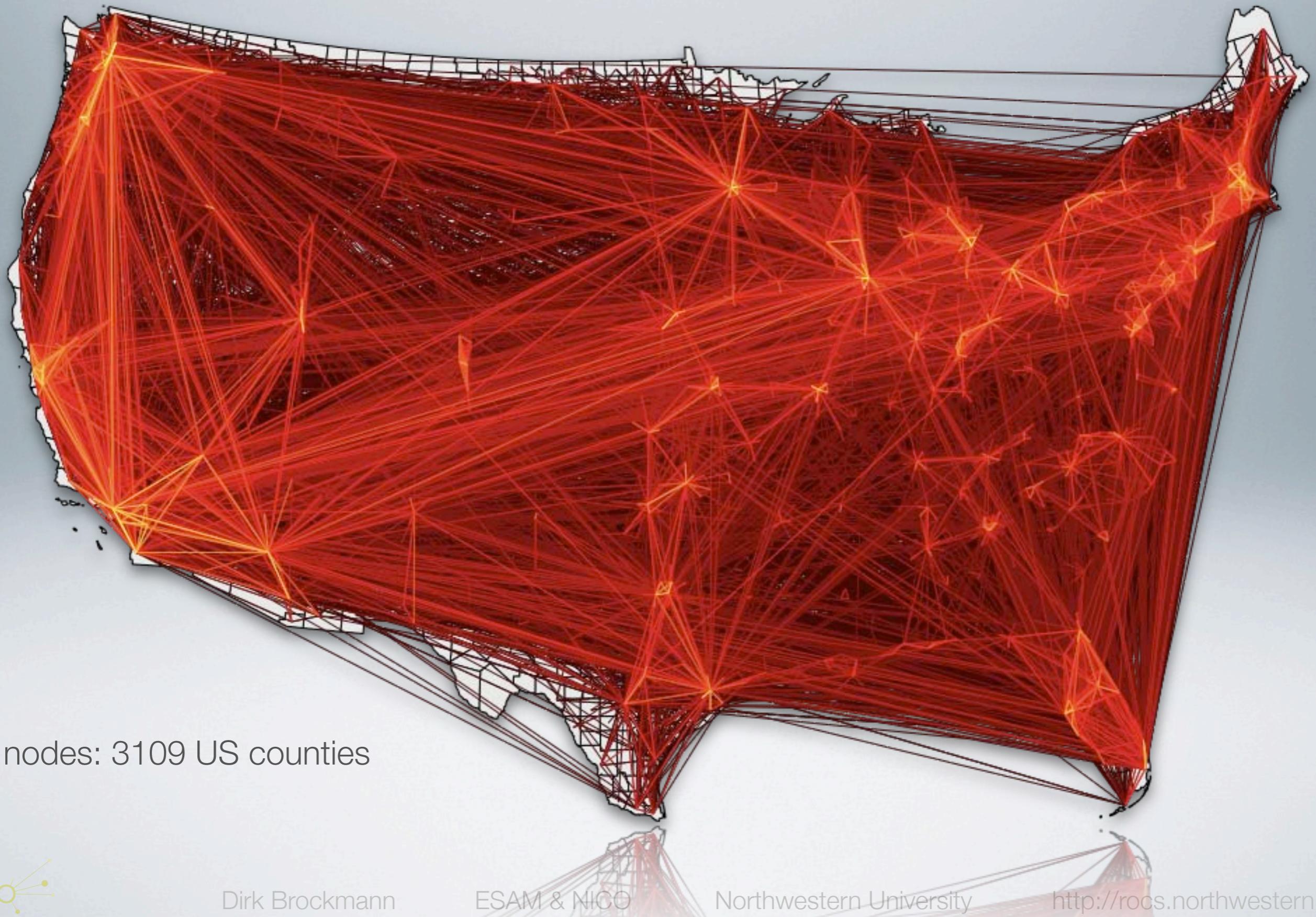


airports: 413

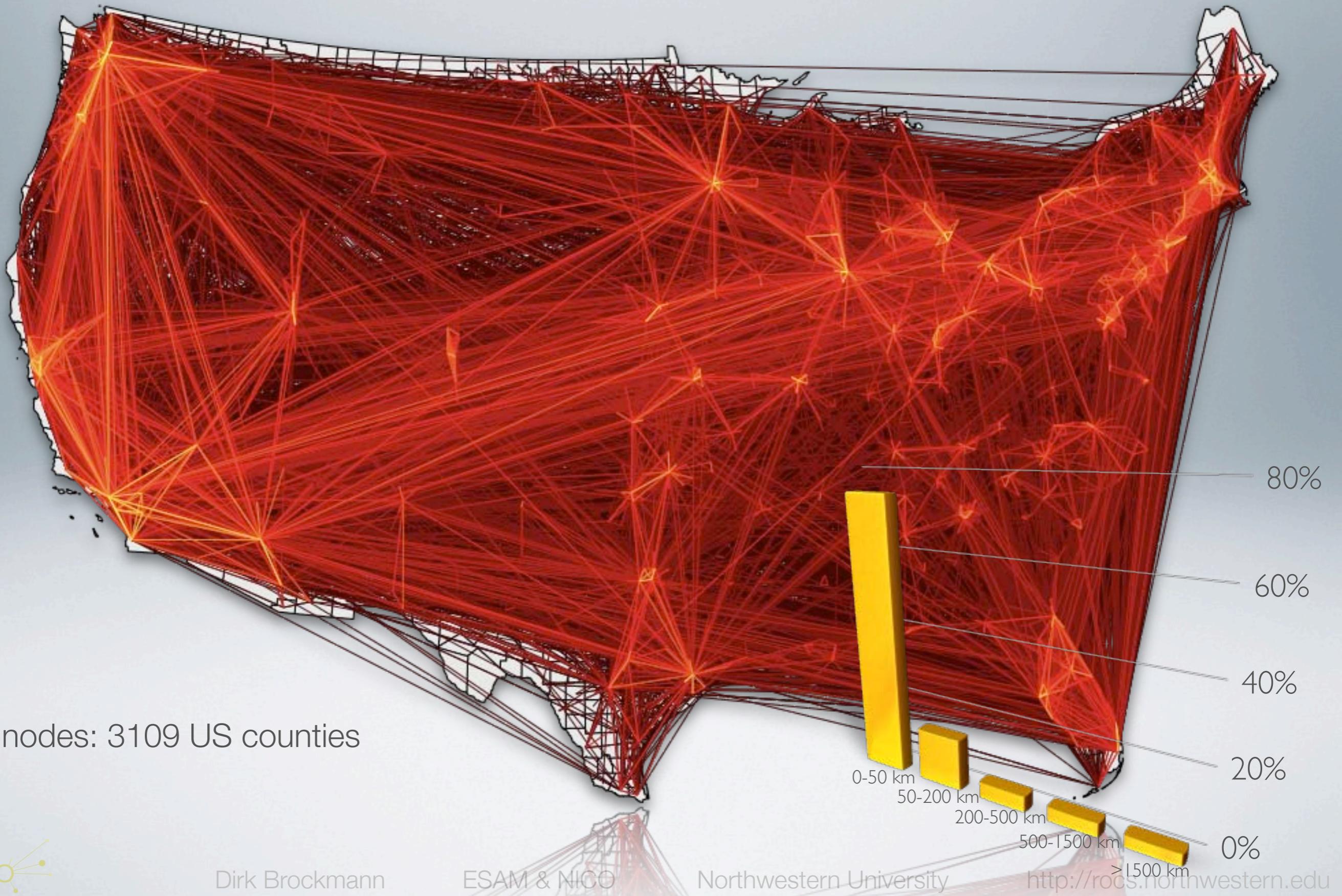
links: 5684

passengers/day: 2.36×10^6

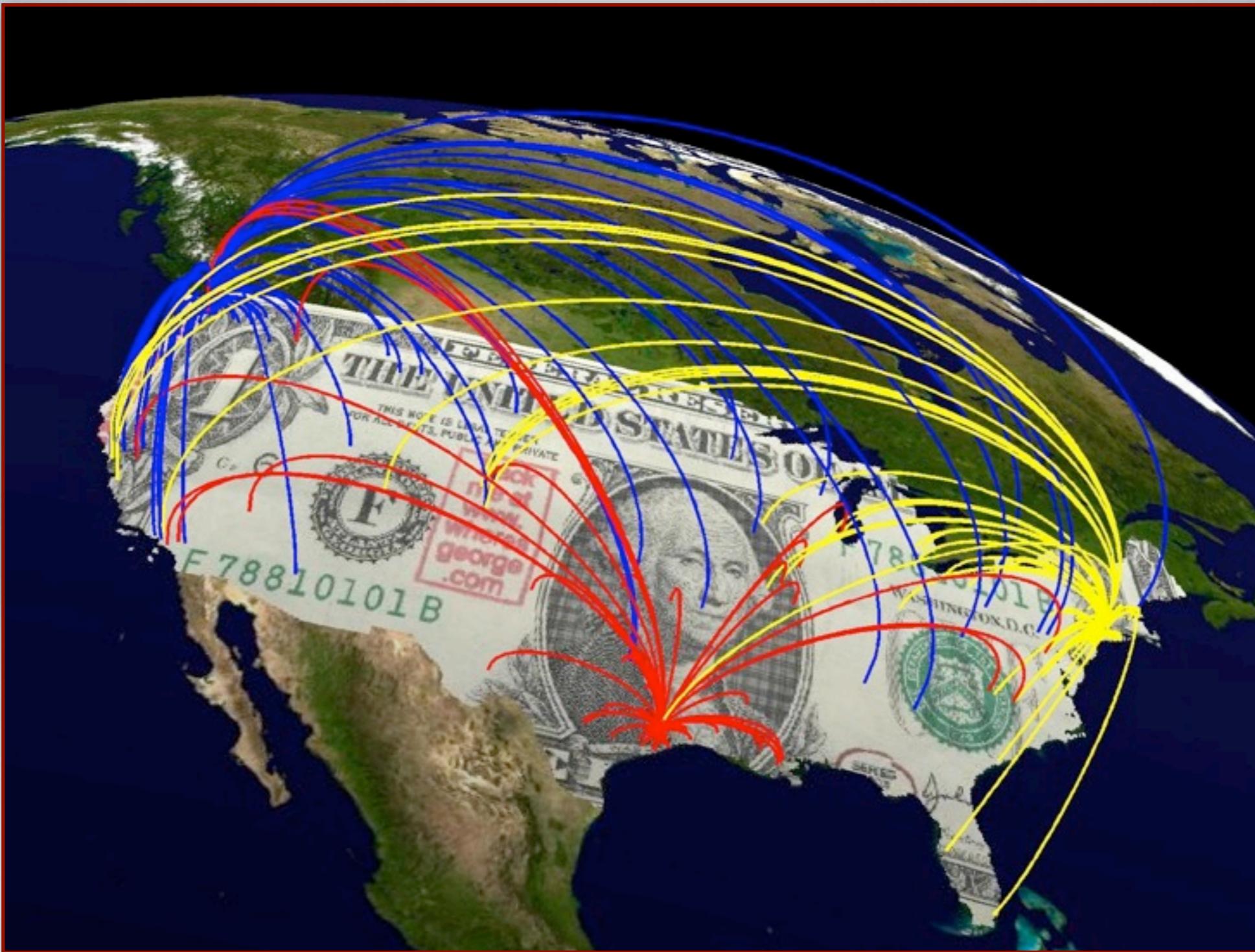
MULTI SCALE HUMAN MOBILITY



MULTI SCALE HUMAN MOBILITY



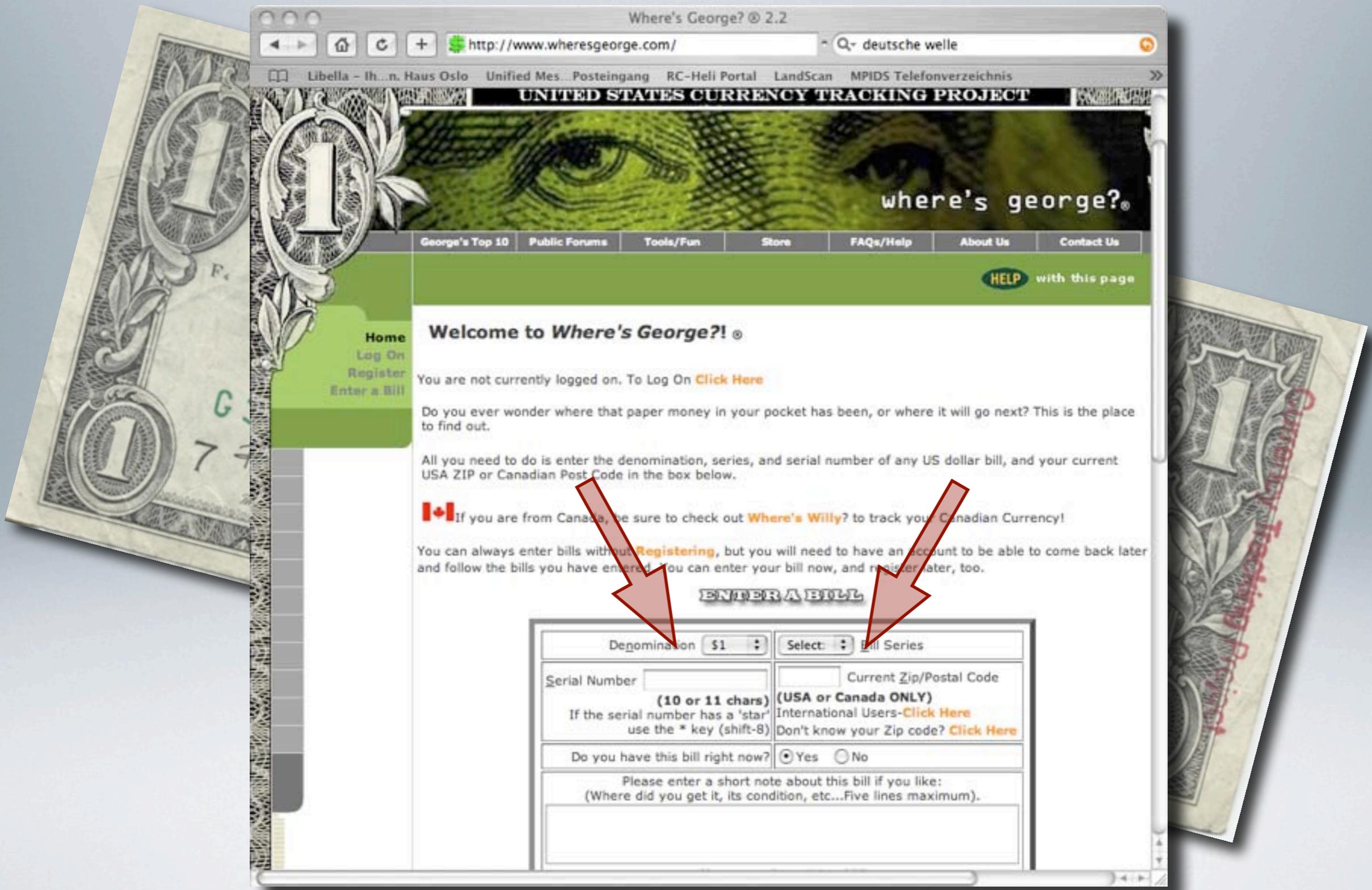
IDEA : „FOLLOW THE MONEY“



IDEA : „FOLLOW THE MONEY“



IDEA : „FOLLOW THE MONEY“



HOW WHERESGEORGE WORKS

The screenshot shows the homepage of the Where's George? website. At the top, there's a banner featuring a close-up of a US dollar bill with the text "where's george?". Below the banner, the main content area has a green header bar with links for "George's Bill ID", "Public Records", "Newest Bills", "More", "Help/FAQ", "About Us", and "Feedback". A "HELP with this page" link is also present. The main text area says "Welcome to Where's George?". It asks users if they've ever wondered where their paper money has been or where it will go next. It explains that users just need to enter the bill's denomination, series, serial number, and current location (USPS ZIP or Canadian Post Code). It also mentions that users can enter bills without logging in, but they'll need an account to come back later and follow the bills they've entered. There's a note for Canadian users and a link to "Where's WHOLE?" for Canadian currency tracking. A "SEARCH A BILL" button is at the bottom of the form. The form itself includes fields for "Denomination" (set to \$1), "Bill Series" (set to 2001), "Serial Number" (containing "G31552587D"), "Current Zip/Postal Code" (containing "60001-3300"), and "International Users" (with a link to "Click Here"). It also asks if the user has the bill now ("Do you have this bill right now?") with options "Yes" (checked) and "No". A note says "Please enter a short note about this bill if you like! (Where did you get it, its condition, etc... Five lines maximum.)".



HOW WHERE'S GEORGE WORKS



1. bills are registered
2. bills enter circulation
3. bills travel
4. bills are reported
5. bills reenter circulation
6. ...



HOW WHERE'S GEORGE WORKS

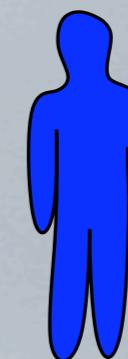


1. bills are registered
2. bills enter circulation
3. bills travel
4. bills are reported
5. bills reenter circulation
6. ...

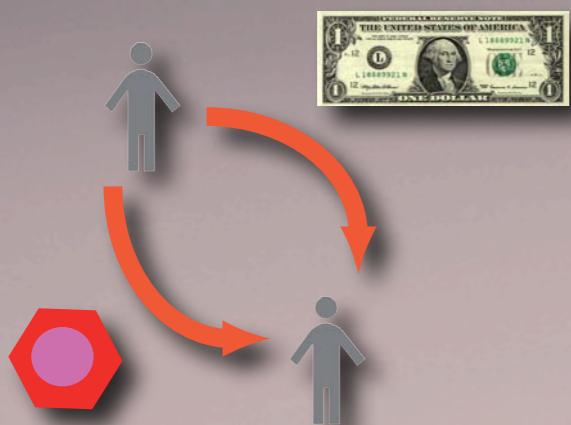


- initiated in 1998 by Hank Eskin
- high spatial and temporal resolution
- more than 100 million bills are registered
- more than 10 million bills with hits

HUMAN MOBILITY AND MONEY DISPERSAL



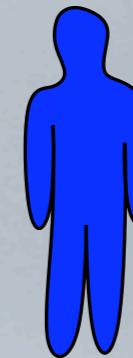
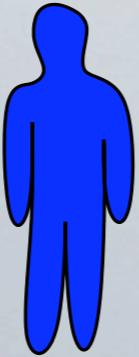
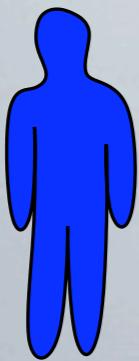
the idea



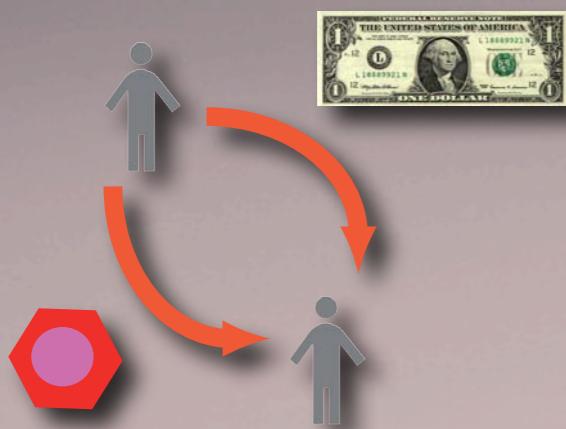
indirect measurement
of human travel
behavior

the immense size of
the dataset permits
reliable estimates of
the geostatistical
properties of human
travel.

HUMAN MOBILITY AND MONEY DISPERSAL



the idea



indirect measurement
of human travel
behavior

the immense size of
the dataset permits
reliable estimates of
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properties of human
travel.



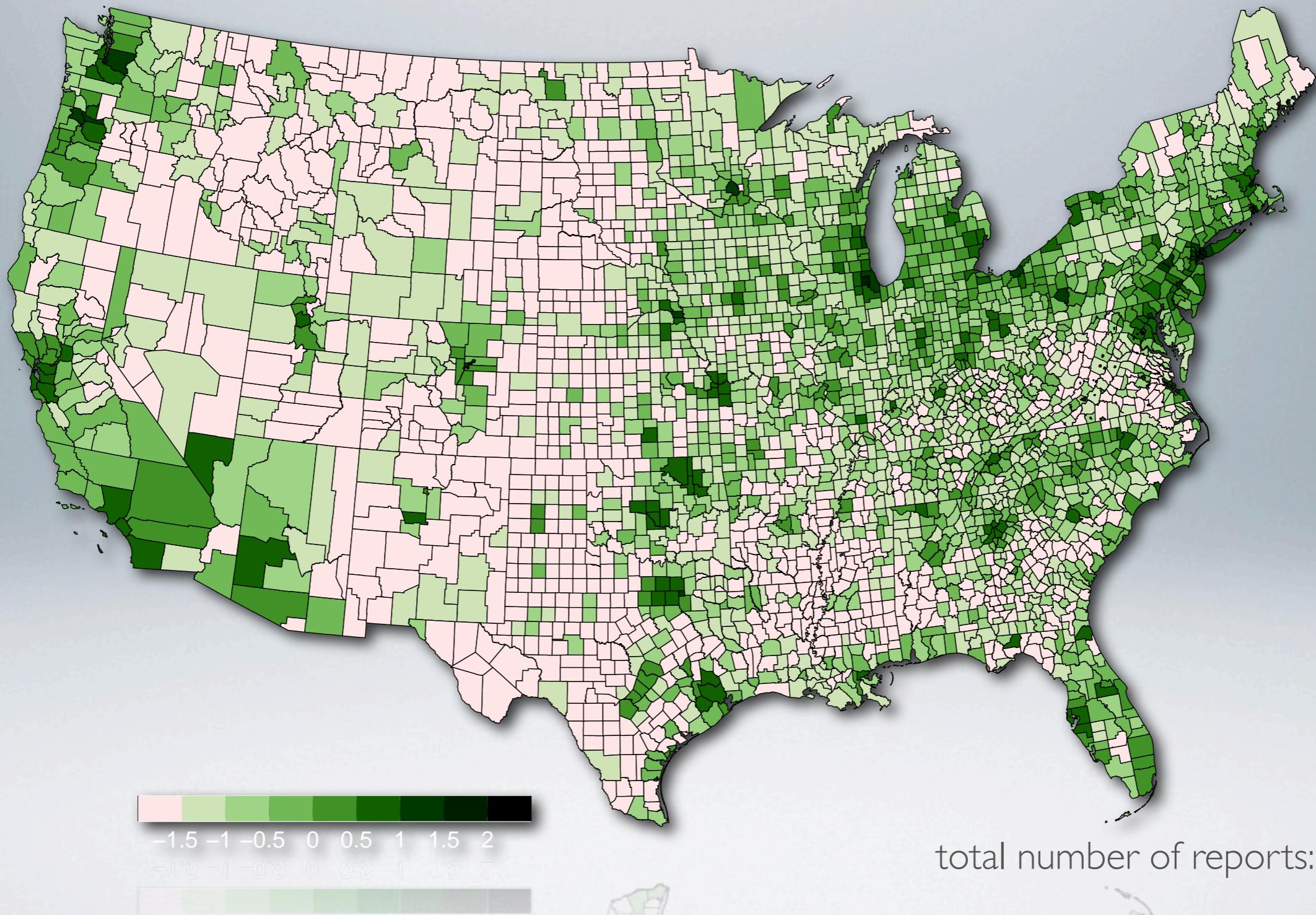
www.wheresgeorge.com

www.eurobilltracker.com

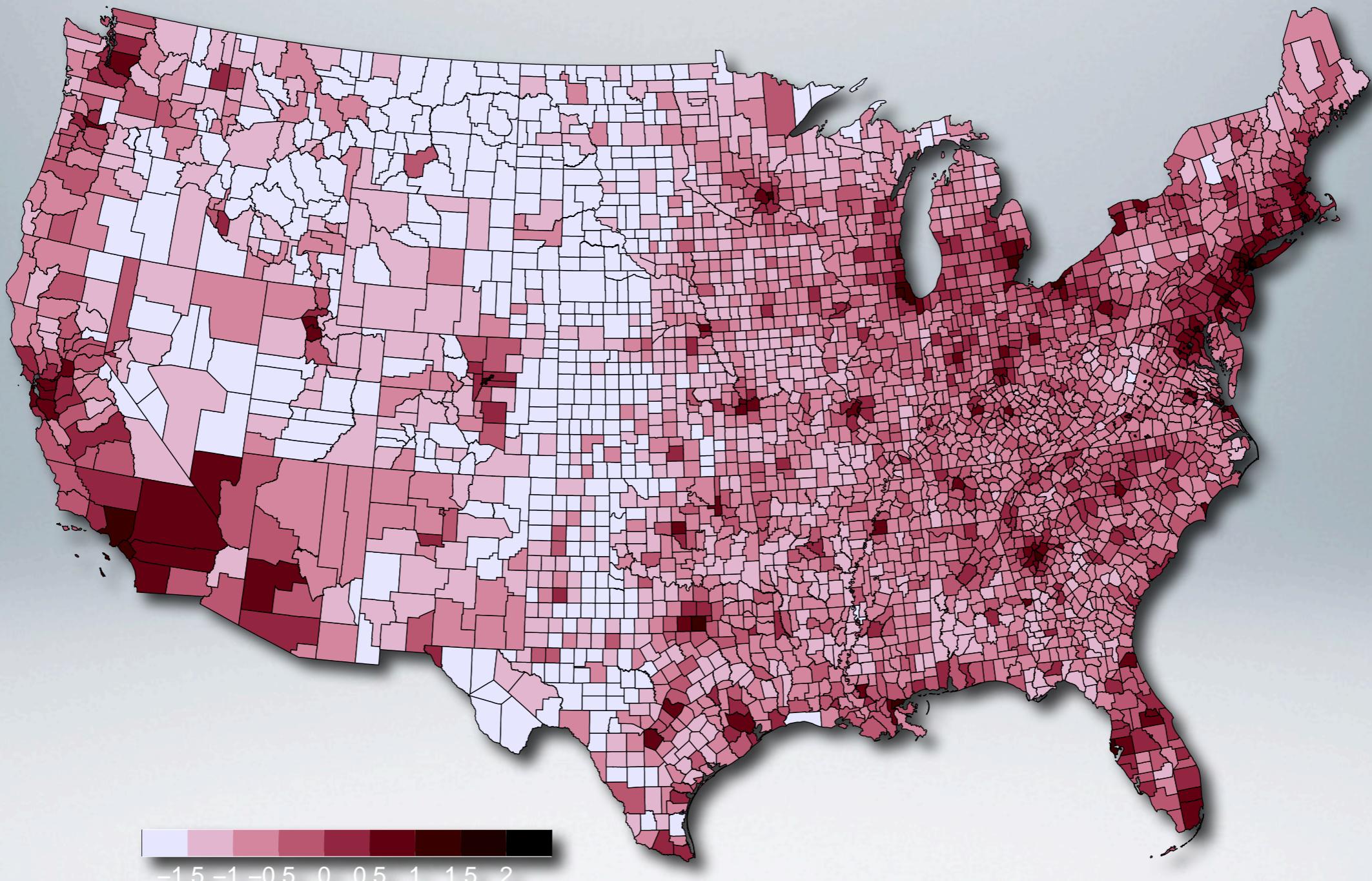
The screenshot shows the homepage of the Where's George? website. The header features a large image of a dollar bill with a green eye and the text "where's george?". Below the header, there are links for "George's Top 10", "Public Finance", "Tools/Van", "Home", "FAQs/Help", "About Us", and "Contact Us". A "HELP with this page" link is also present. The main content area is titled "Welcome to Where's George?!" and includes a message about logging in. It features a form for entering a bill's serial number, current zip/postal code, and a note about having the bill now. There is also a section for leaving a note about the bill.

The screenshot shows the homepage of the EuroBillTracker website. The header features a large image of a euro bill and the text "Begleiten Sie die Euro-Scheine auf ihrer Reise". Below the header, there are links for "Home", "Über diese Seite", "Links", "Presse", "Neu anmelden", "Durchmischung", "Statistiken", "News", "Fragen & Antworten (FAQ)", and "Forum". A "HELP with this page" link is also present. The main content area is titled "Der Zweck des Ganzen" and includes a message about the project's purpose. It features a list of tracked bills with details like value, user, series, and location. There is also a section for user statistics and a list of users who have tracked bills.

REPORT DENSITY

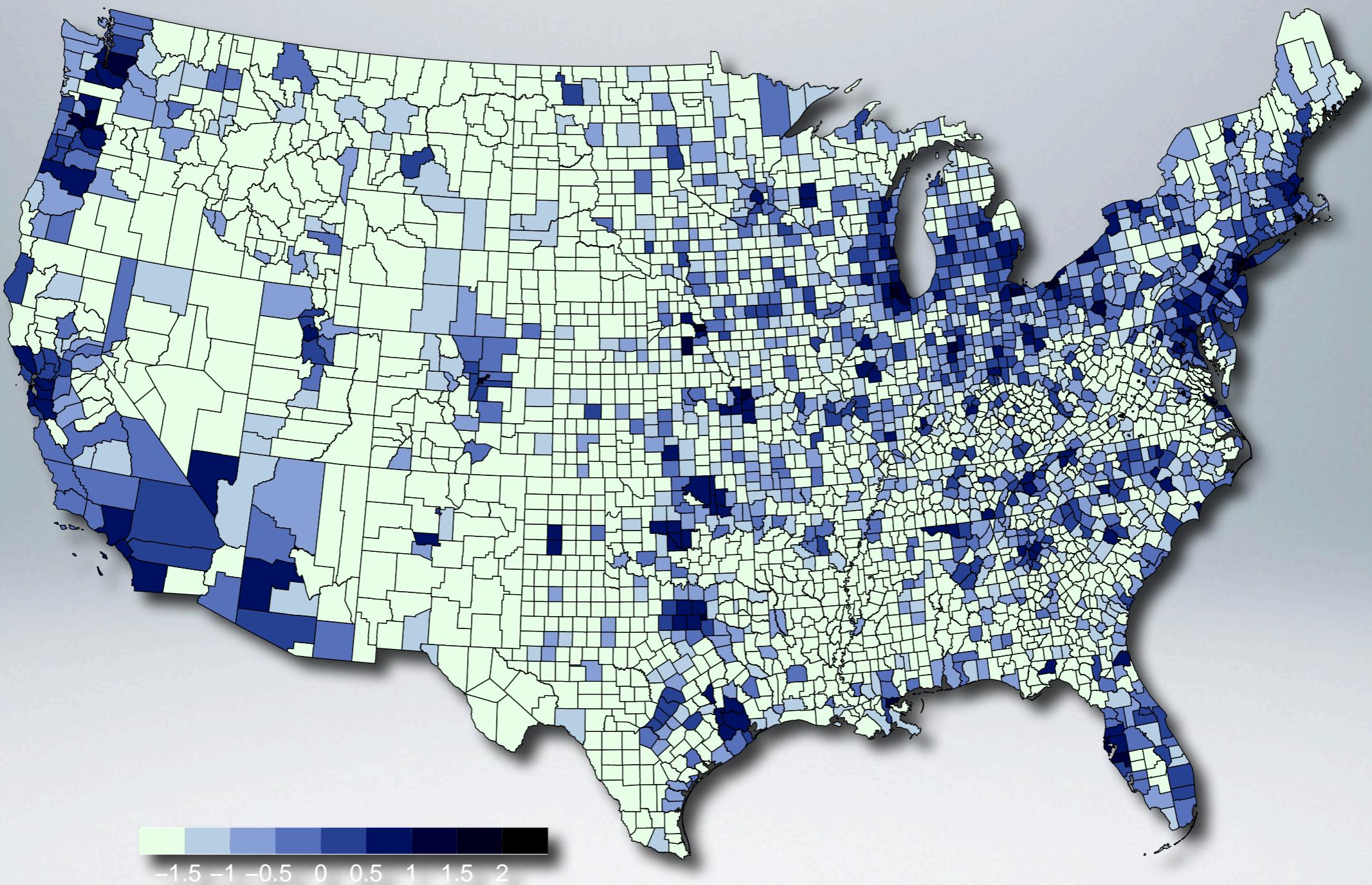


POPULATION DENSITY

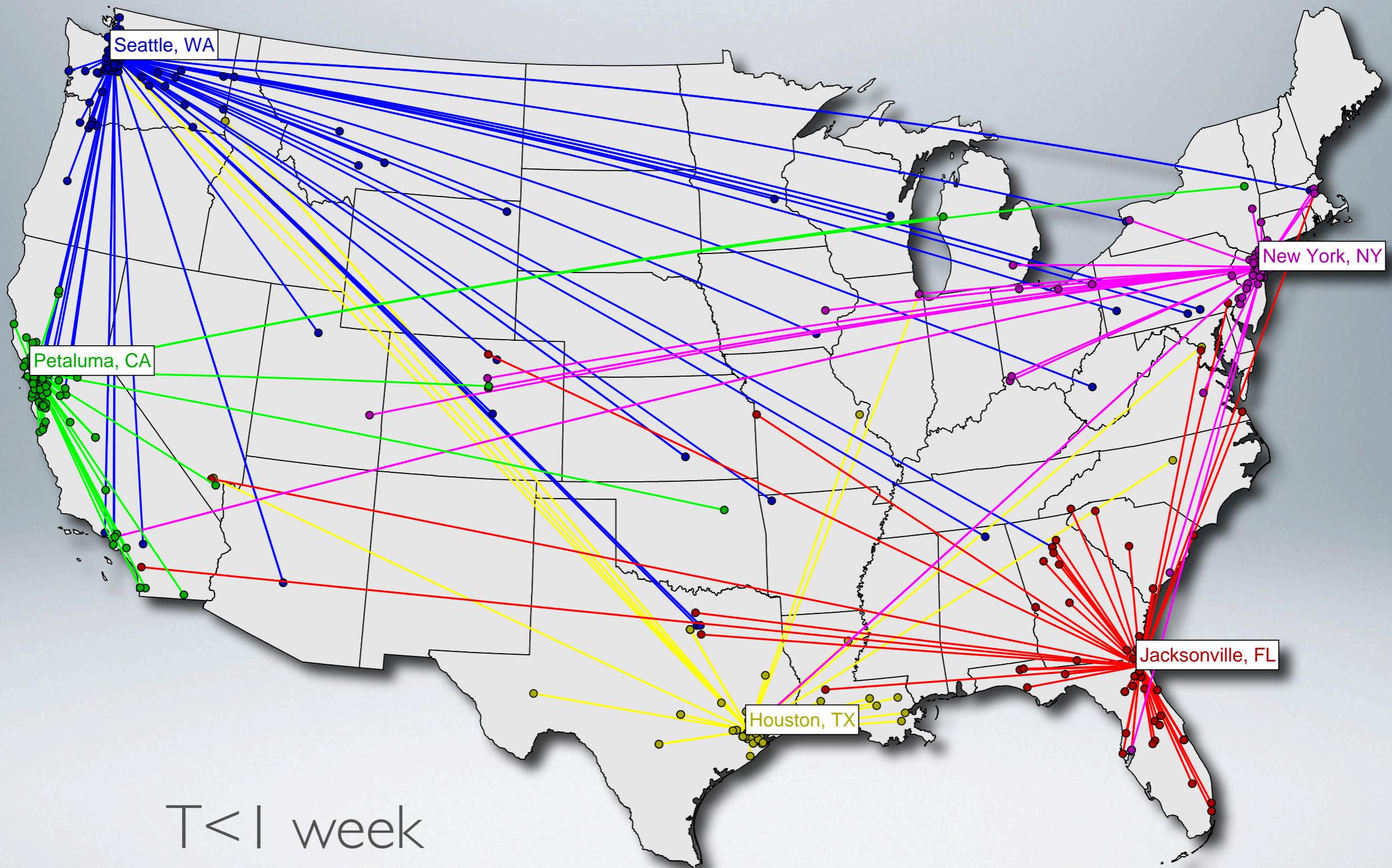


total population: 280 Mio.

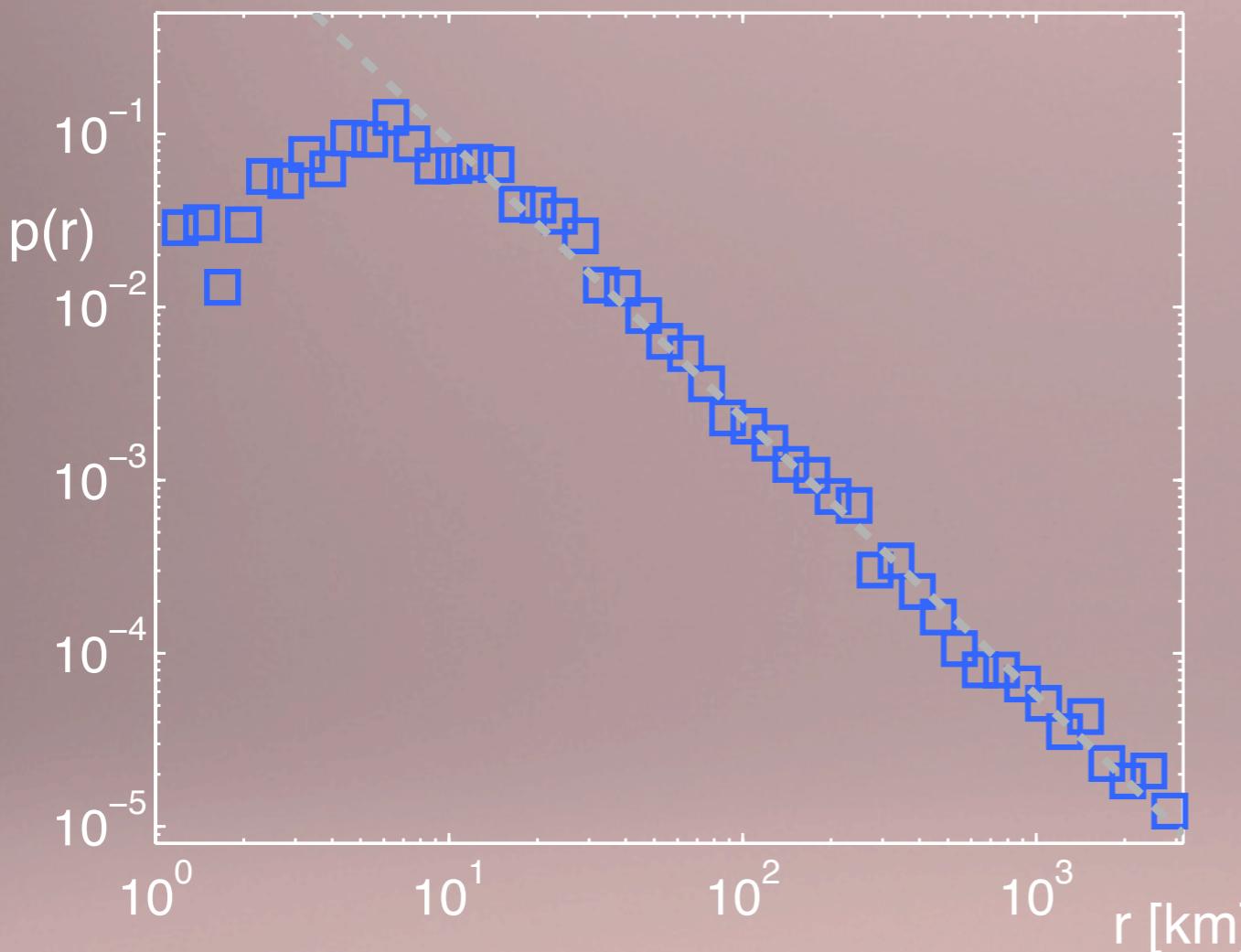
INITIAL ENTRY DENSITY



DYNAMICS AND SHORT TIME TRAJECTORIES



SHORT TIME TRAJECTORY STATISTICS

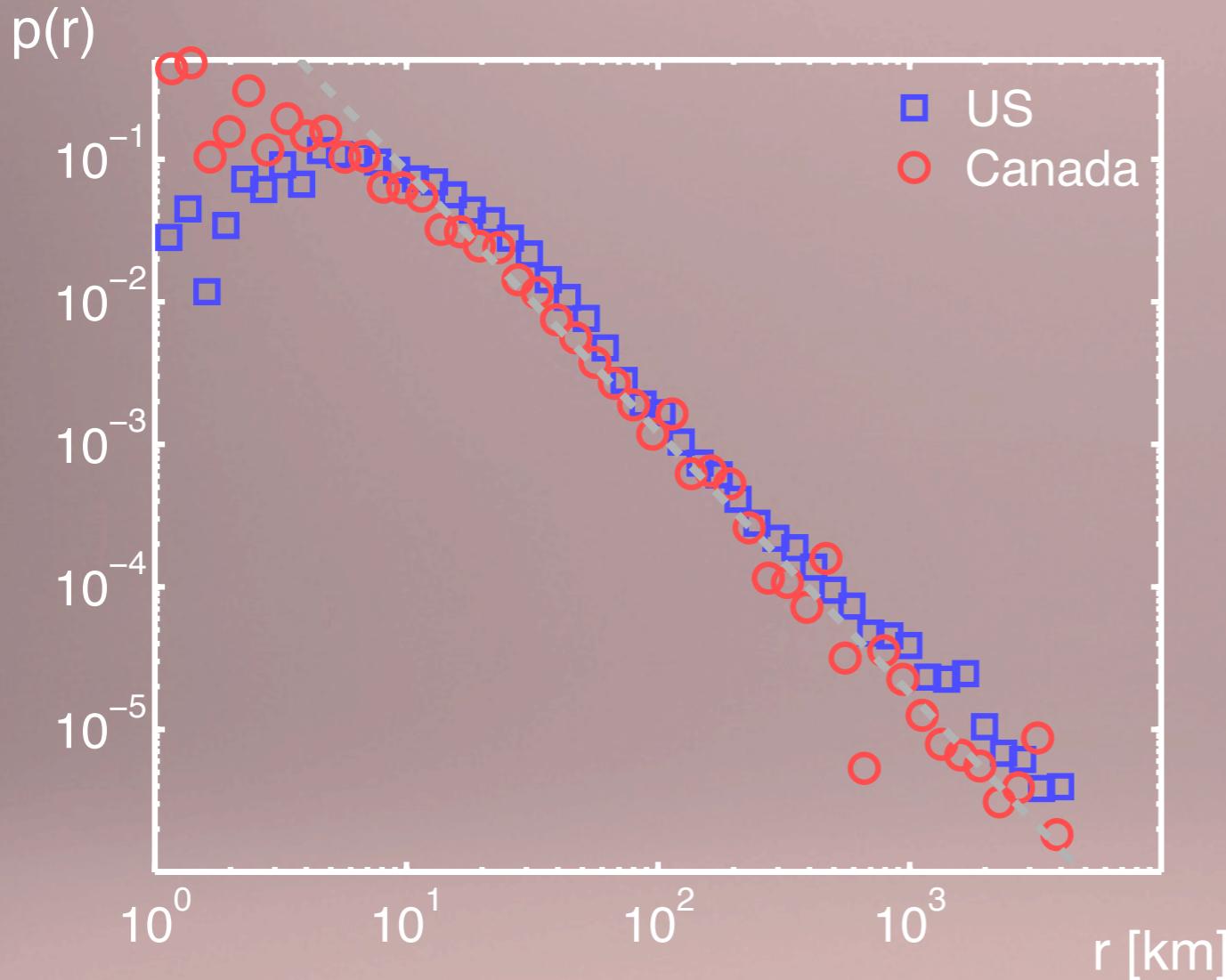


- power law (20-3500 km)
- travel lacks a scale
- trajectories of bills are reminiscent of lévy flights
- dispersal is superdiffusive

$$p(r) \sim \frac{1}{r^{1+\beta}}$$
$$\beta \approx 0.6$$

Brockmann,D., Hufnagel, L. & Geisel, T., Nature 2006

SHORT TIME TRAJECTORY STATISTICS



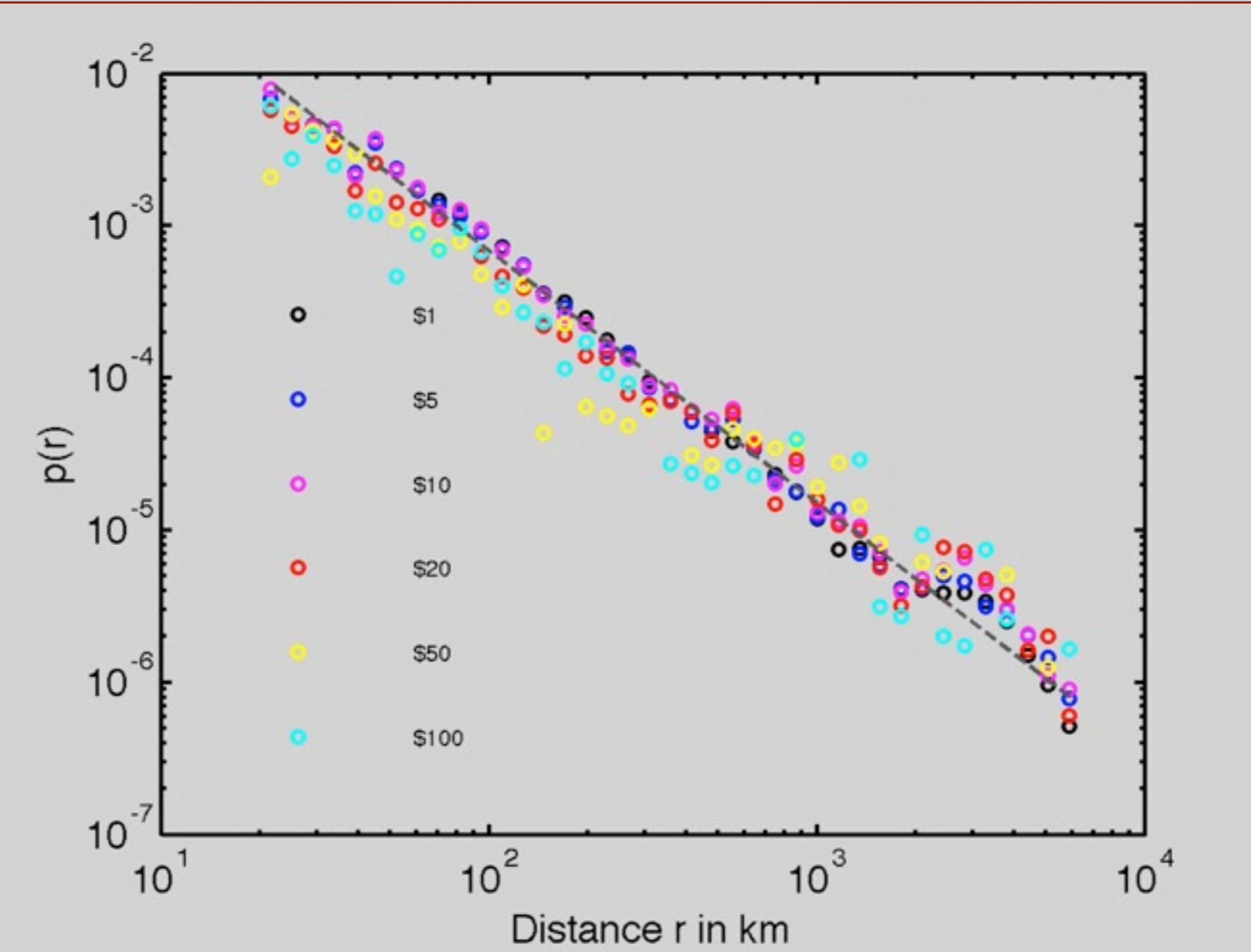
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$$p(r) \sim \frac{1}{r^{1+\beta}}$$
$$\beta \approx 0.6$$

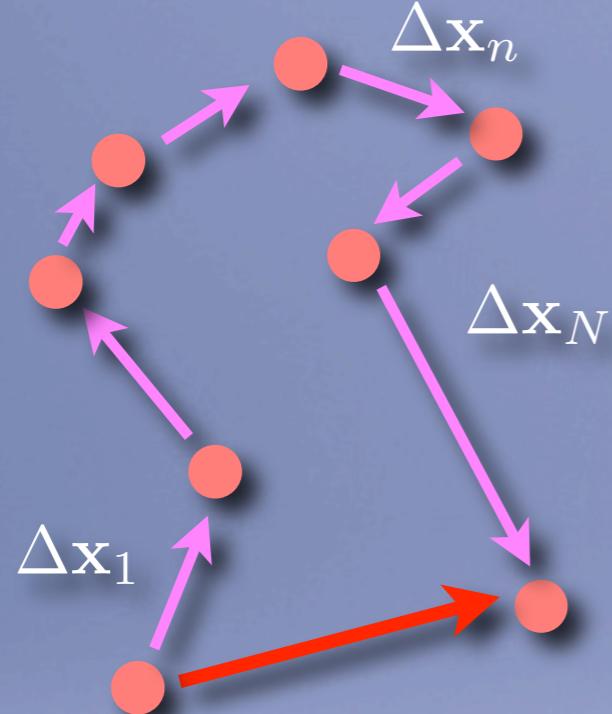
Brockmann,D., Hufnagel, L. & Geisel, T., Nature 2006

DENOMINATION ANALYSIS



RANDOM WALKS

2-d random walk



position after N steps

$$\mathbf{x}_N = \sum_{n=1}^N \Delta\mathbf{x}_n$$

$$p(\Delta\mathbf{x}) = p(|\Delta\mathbf{x}|) \quad \langle \Delta\mathbf{x}^2 \rangle = \sigma^2$$

$$p(\mathbf{x}, N) \sim N^{-1} G\left(\mathbf{x}/N^{1/2}\right)$$

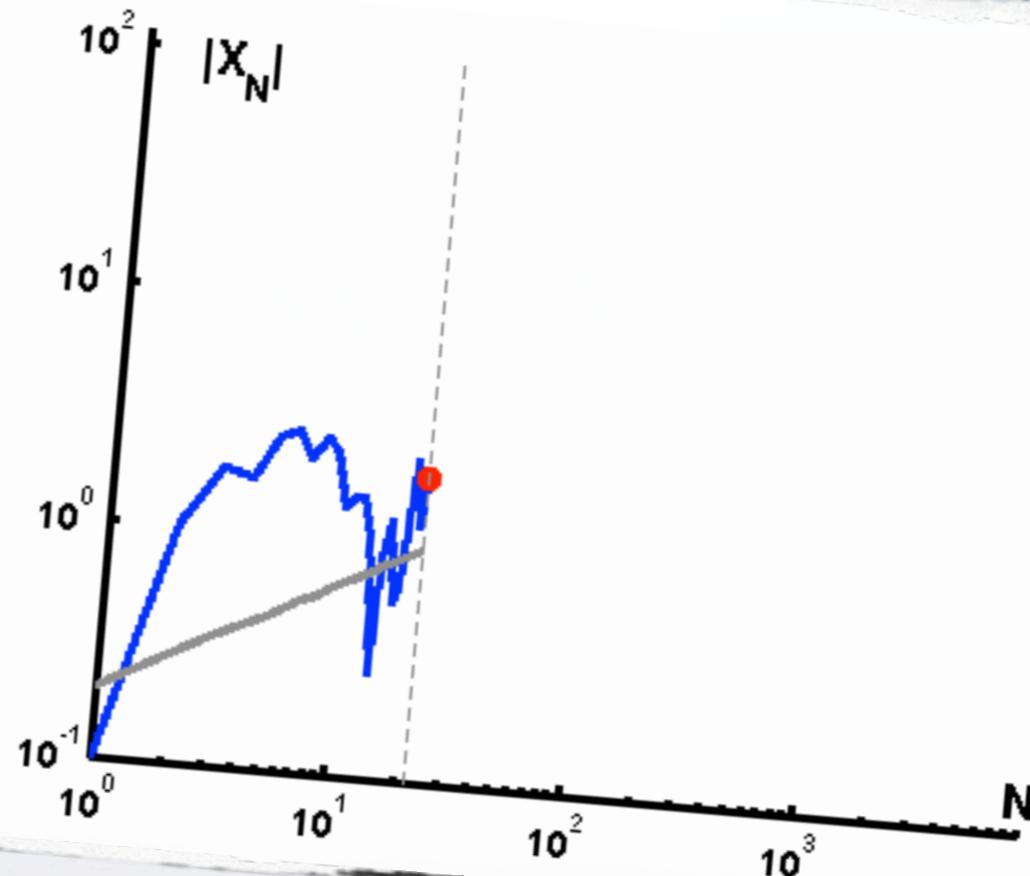
$|\mathbf{x}_N| \sim N^{1/2}$ gaussian

RANDOM WALKS

2-d random walk

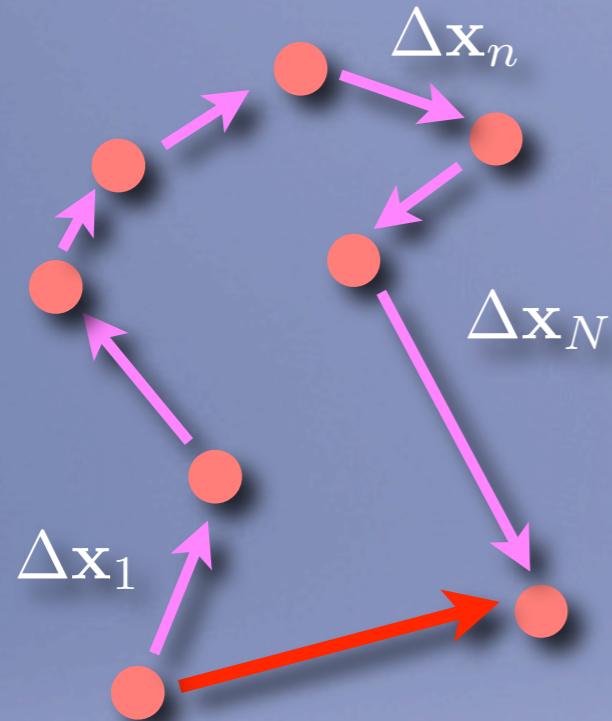
$$\mathbf{x}_N = \sum_{n=1}^N \Delta \mathbf{x}_n$$

$$p(\Delta \mathbf{x}) = p(|\Delta \mathbf{x}|) \quad \langle \Delta \mathbf{x}^2 \rangle = \sigma^2$$



LEVY FLIGHTS

2-d random walk



$$\mathbf{x}_N = \sum_{n=1}^N \Delta\mathbf{x}_n$$

$$p(\Delta\mathbf{x}) = \frac{1}{|\Delta\mathbf{x}|^{D+\beta}} \quad \beta < 2$$

$$p(\mathbf{x}, N) \sim N^{-2/\beta} L_\beta \left(\mathbf{x}/N^{1/\beta} \right)$$

$|\mathbf{x}_N| \sim N^{1/\beta}$

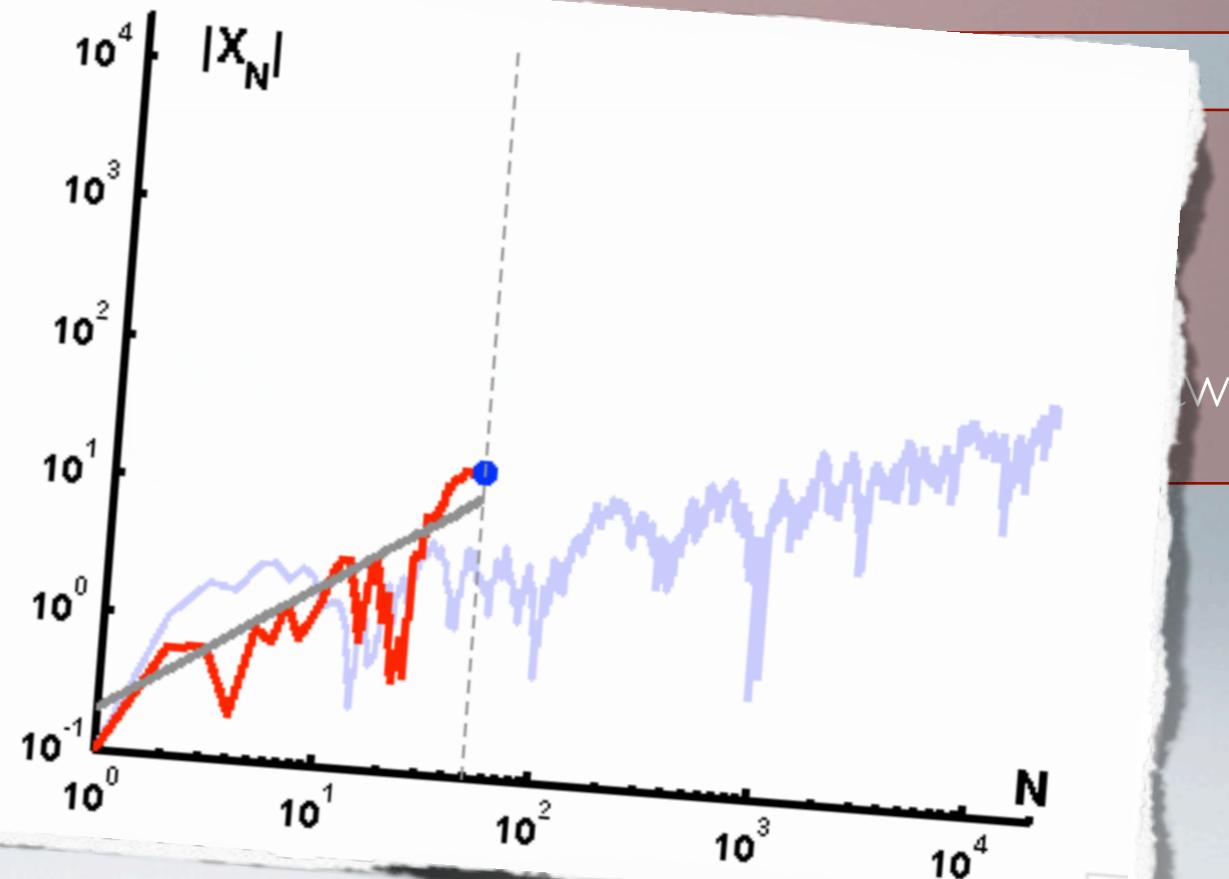
Lévy stable law

LEVY FLIGHTS

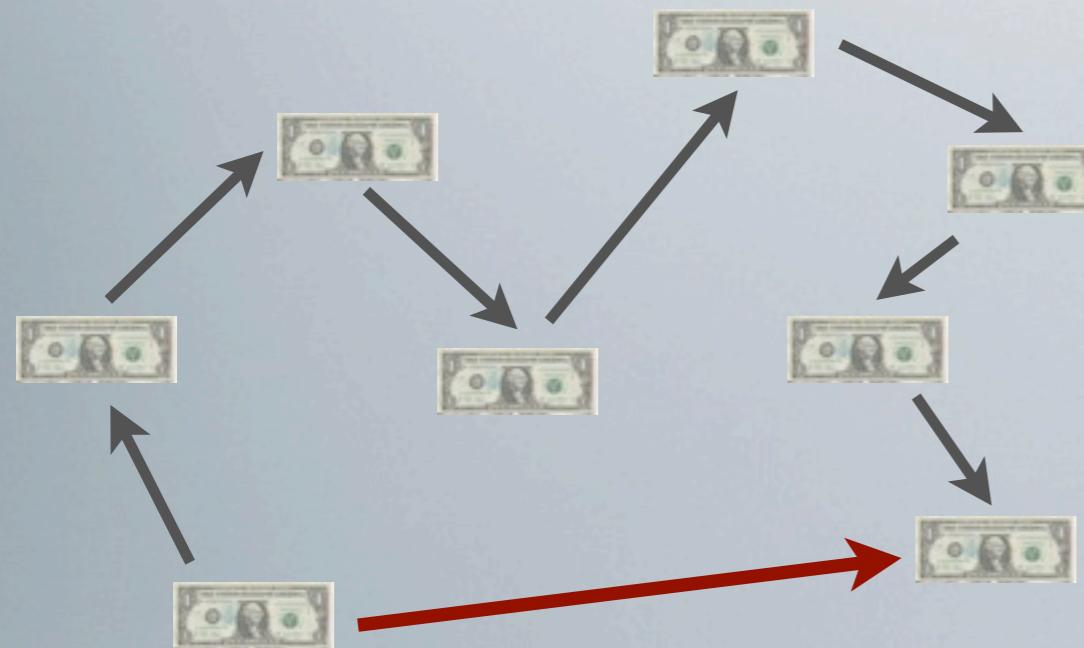
2-d random walk

$$p(\Delta \mathbf{x}) = \frac{1}{|\Delta \mathbf{x}|^{D+\beta}} \quad \beta < 2$$

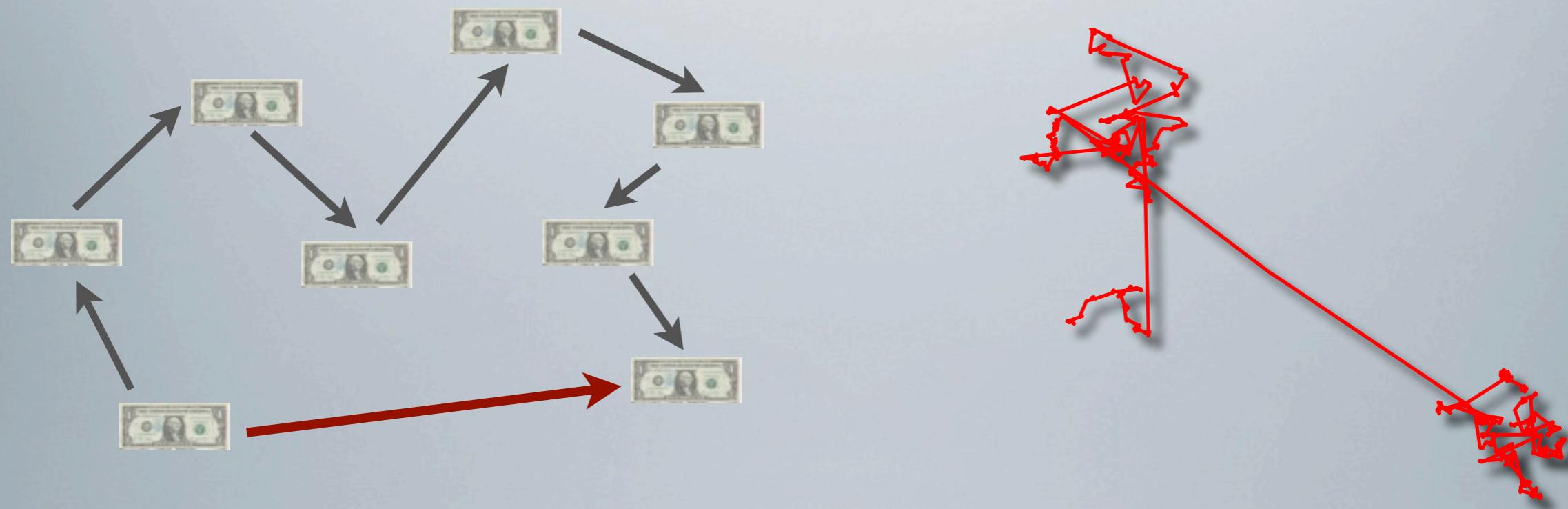
$$\mathbf{x}_N = \sum_{n=1}^N \Delta \mathbf{x}_n$$



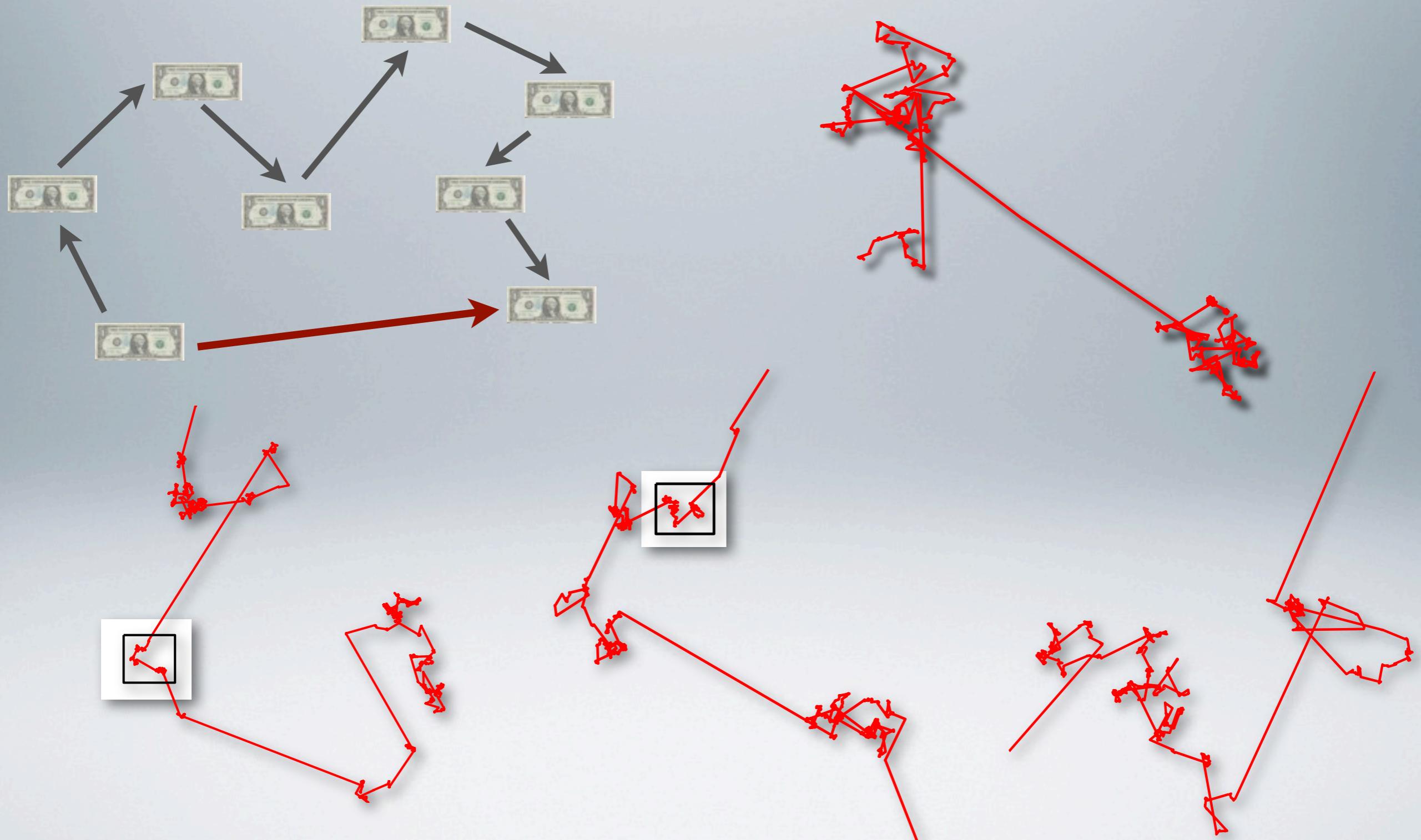
IMPLICATIONS FOR THE GEOMETRY OF MONEY CIRCULATION



IMPLICATIONS FOR THE GEOMETRY OF MONEY CIRCULATION

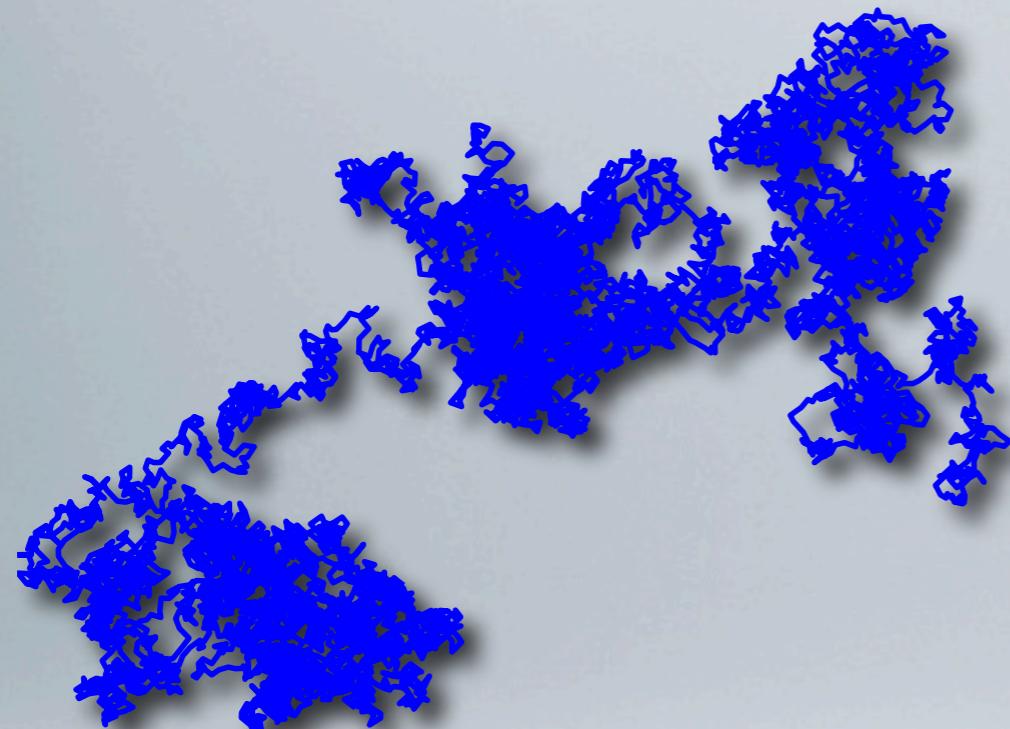


IMPLICATIONS FOR THE GEOMETRY OF MONEY CIRCULATION

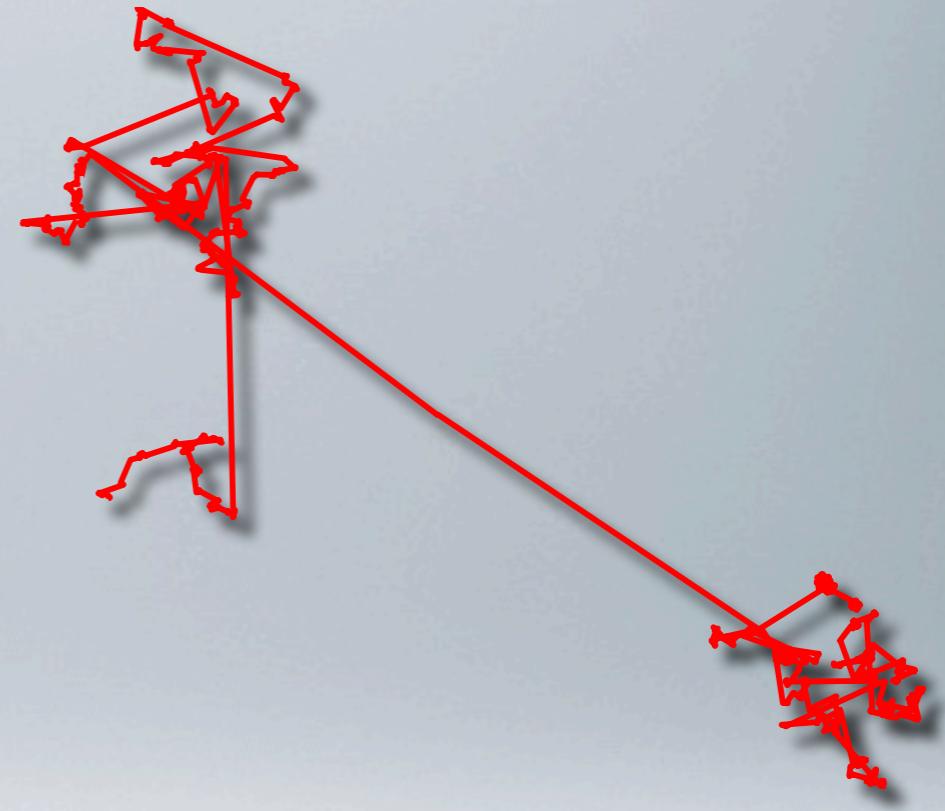


LÉVY FLIGHTS AND FRACTIONAL DISPERSAL

ordinary diffusion



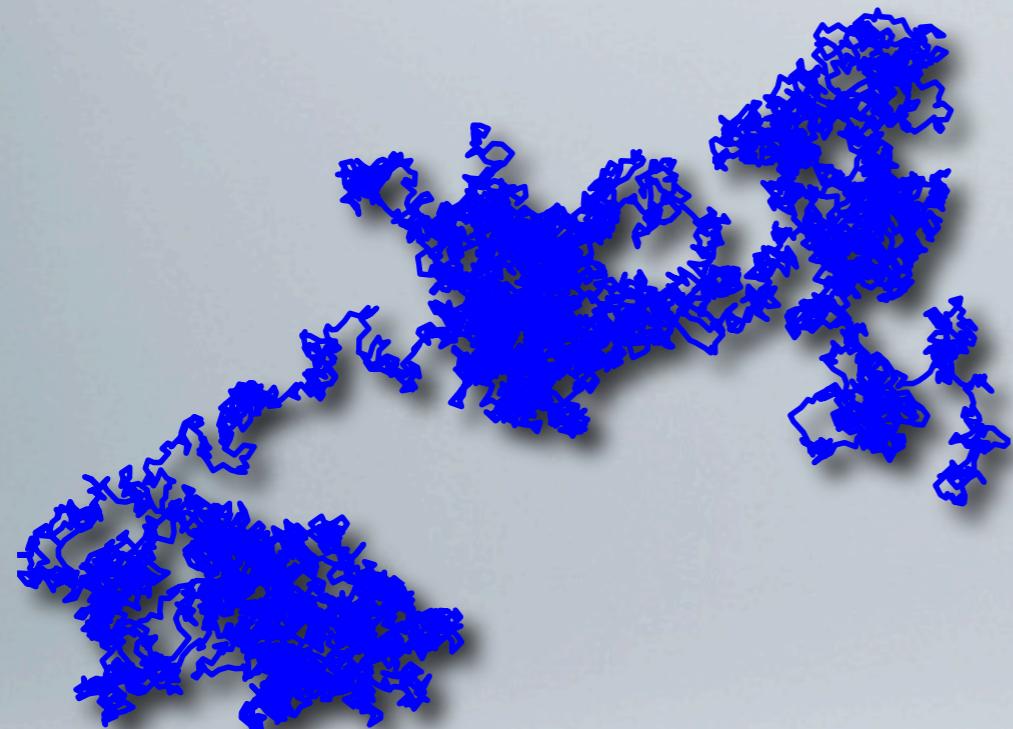
Lévy stable process



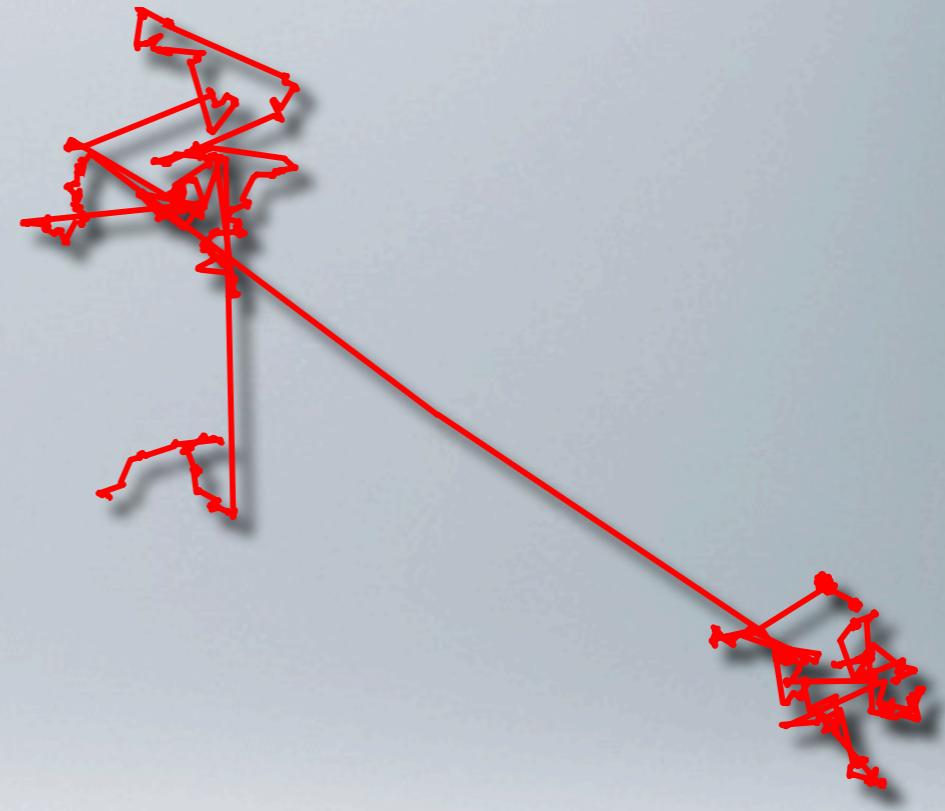
$$\partial_t p = D \nabla^2 p$$

LÉVY FLIGHTS AND FRACTIONAL DISPERSAL

ordinary diffusion



Lévy stable process



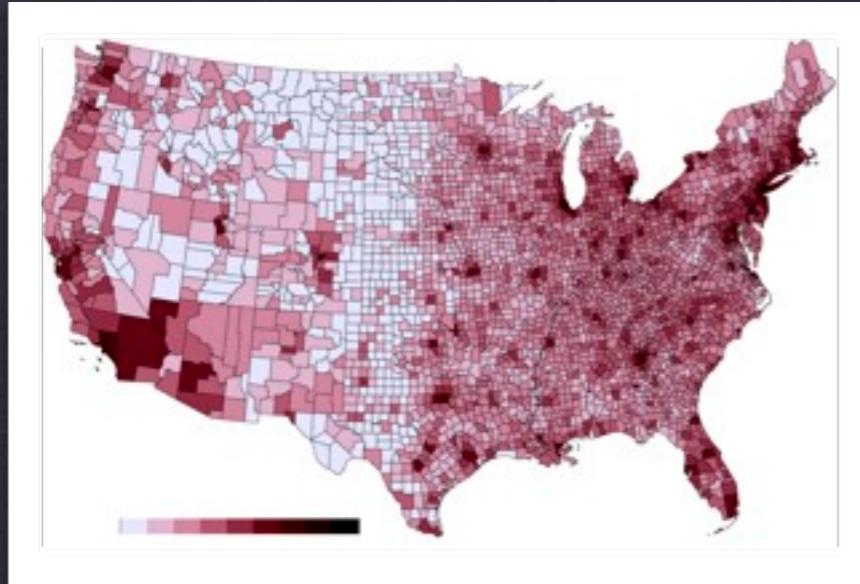
$$\partial_t p = D \nabla^2 p$$

$$\partial_t p = D_\beta |\nabla|^\beta p$$

fractional Laplacian

Lévy flights and heterogeneities

$n(\mathbf{x}) \neq \text{const}$

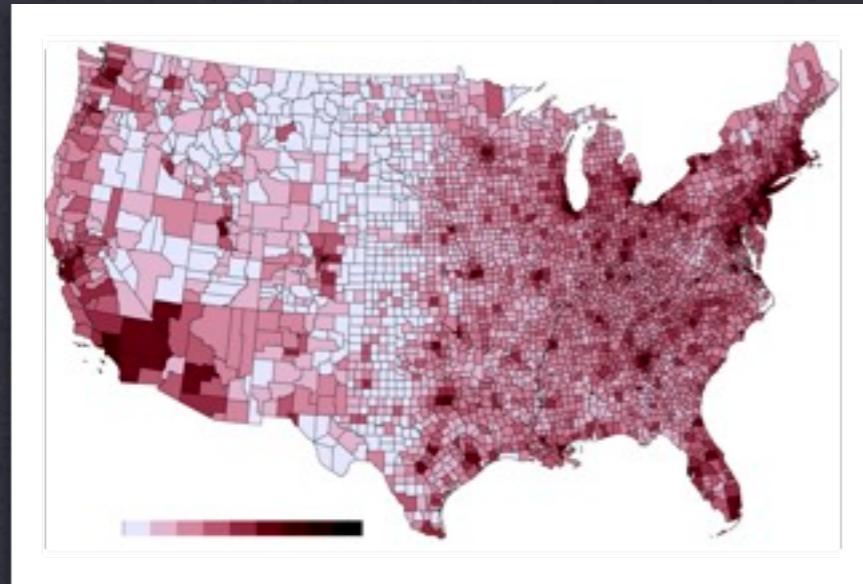


Lévy flights and heterogeneities

$n(\mathbf{x}) \neq \text{const}$

GRAVITY MODEL

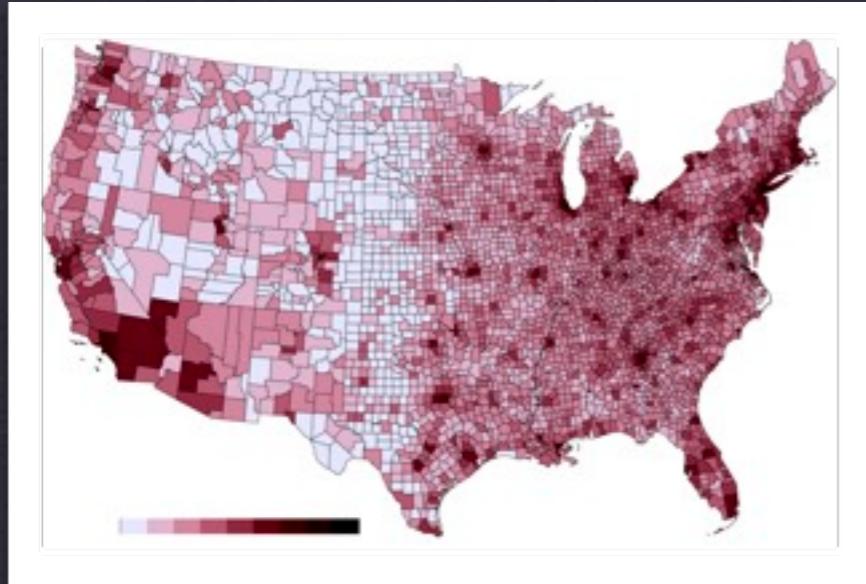
$$w(\mathbf{x}|\mathbf{y}) \propto \frac{n(\mathbf{x})^\xi n(\mathbf{y})^{\xi-1}}{|\mathbf{x} - \mathbf{y}|^{D+\beta}}$$
$$0 < \xi \leq 1$$



Lévy flights and heterogeneities

$n(\mathbf{x}) \neq \text{const}$

GRAVITY MODEL

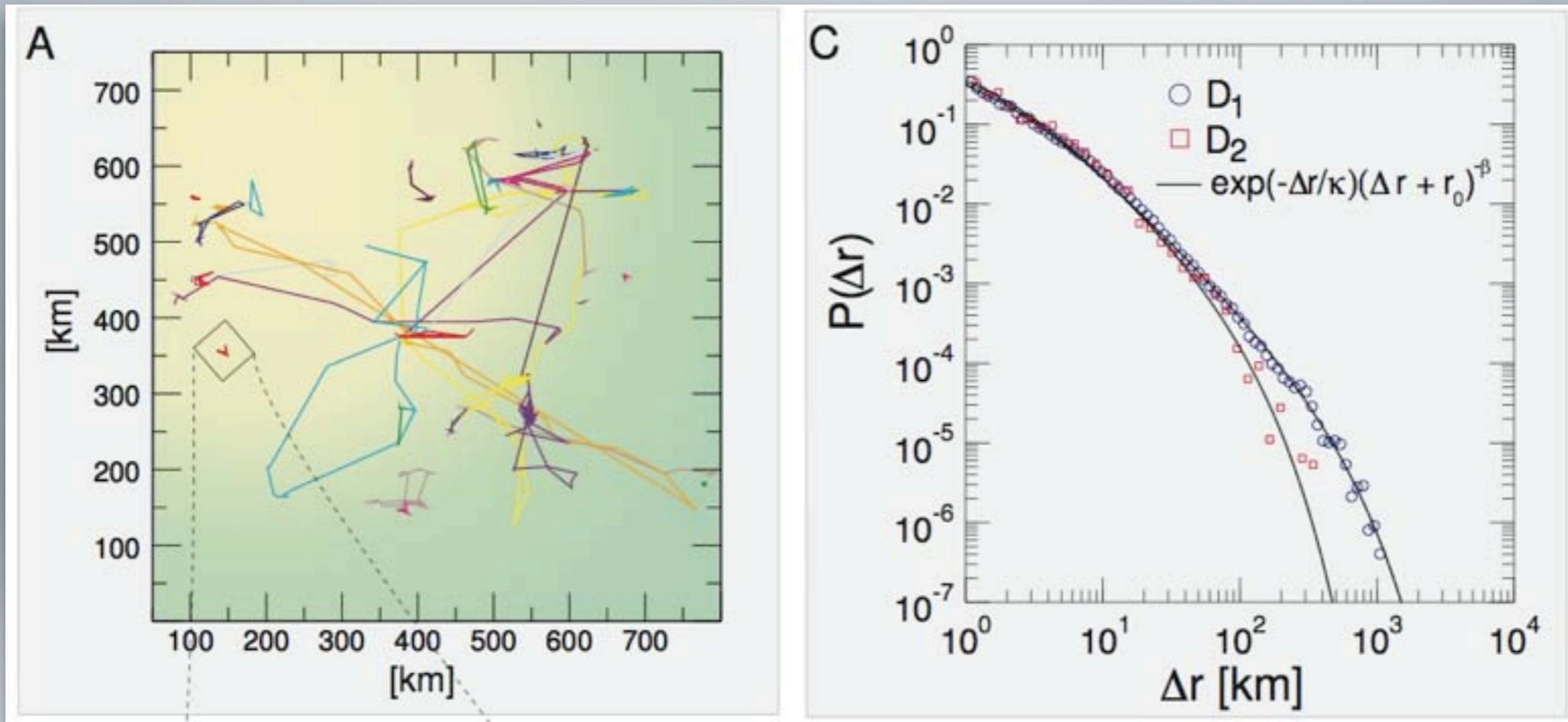


$$w(\mathbf{x}|\mathbf{y}) \propto \frac{n(\mathbf{x})^\xi n(\mathbf{y})^{\xi-1}}{|\mathbf{x} - \mathbf{y}|^{D+\beta}}$$
$$0 < \xi \leq 1$$



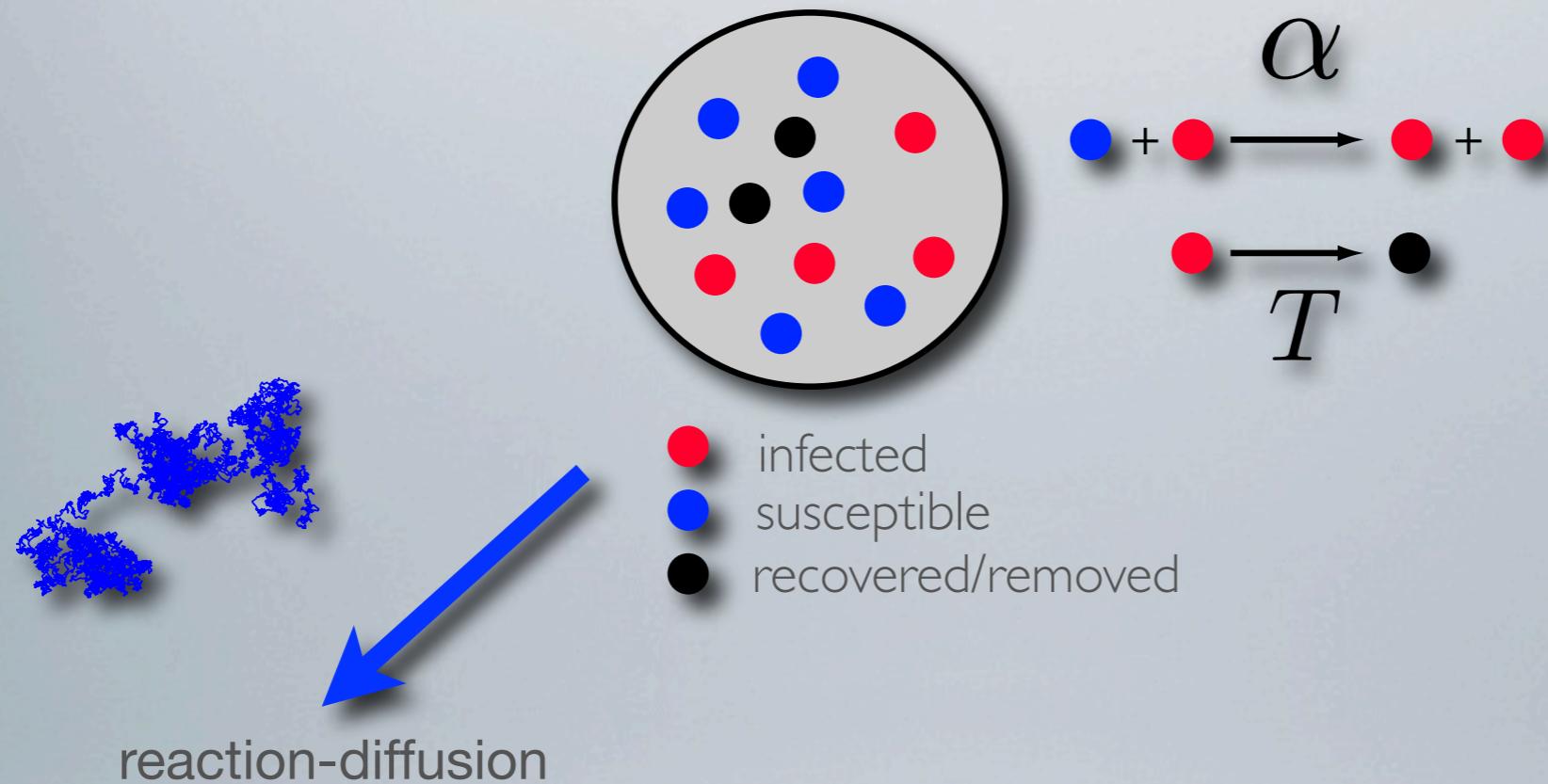
$$\partial_t p(\mathbf{x}, t) = n(\mathbf{x}) \Delta^{\beta/2} p(\mathbf{x}, t) - p(\mathbf{x}, t) \Delta^{\beta/2} n(\mathbf{x})$$

INDIVIDUAL MOBILITY PATTERNS

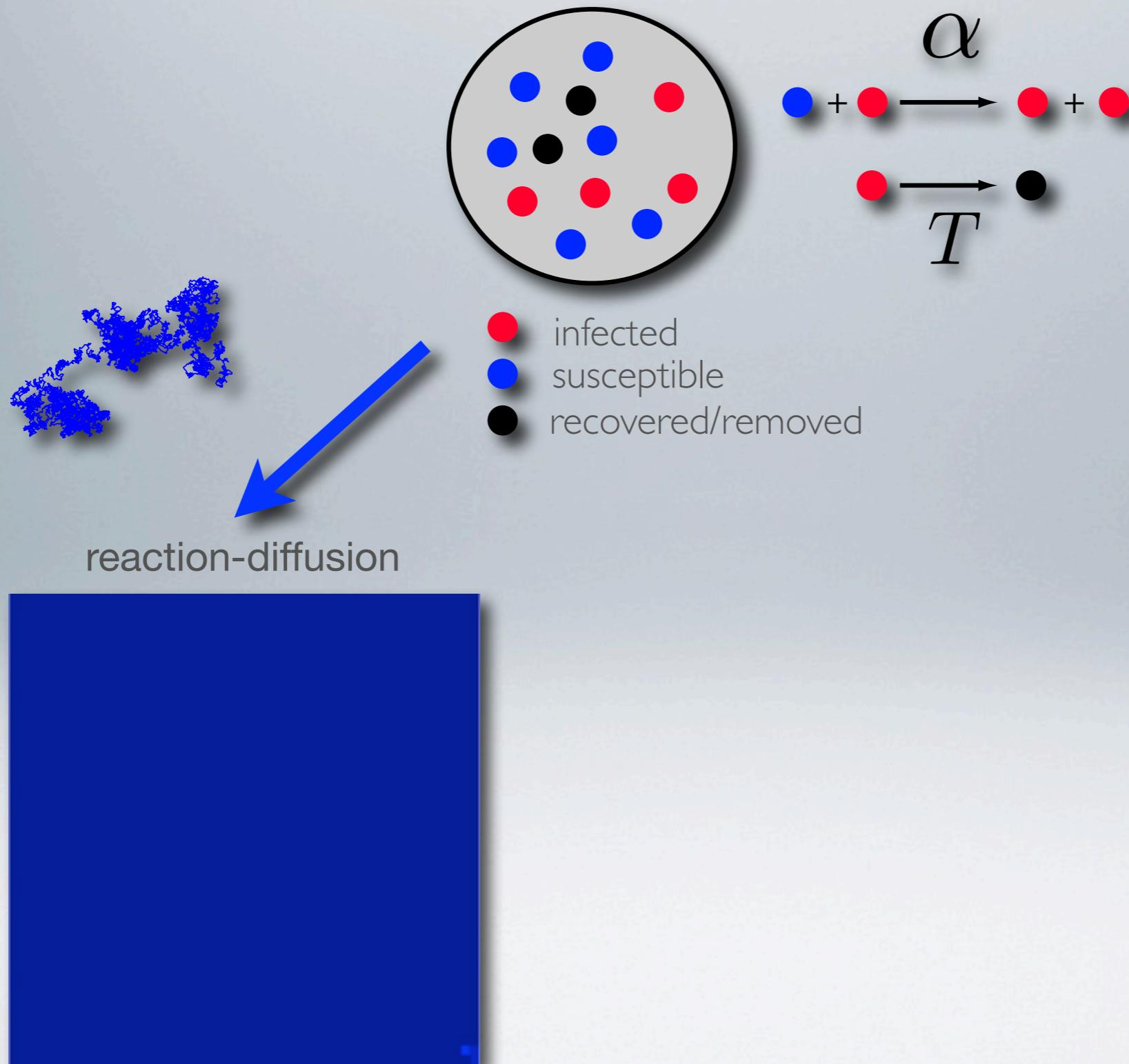


from Gonzalez et al. Nature (2008)

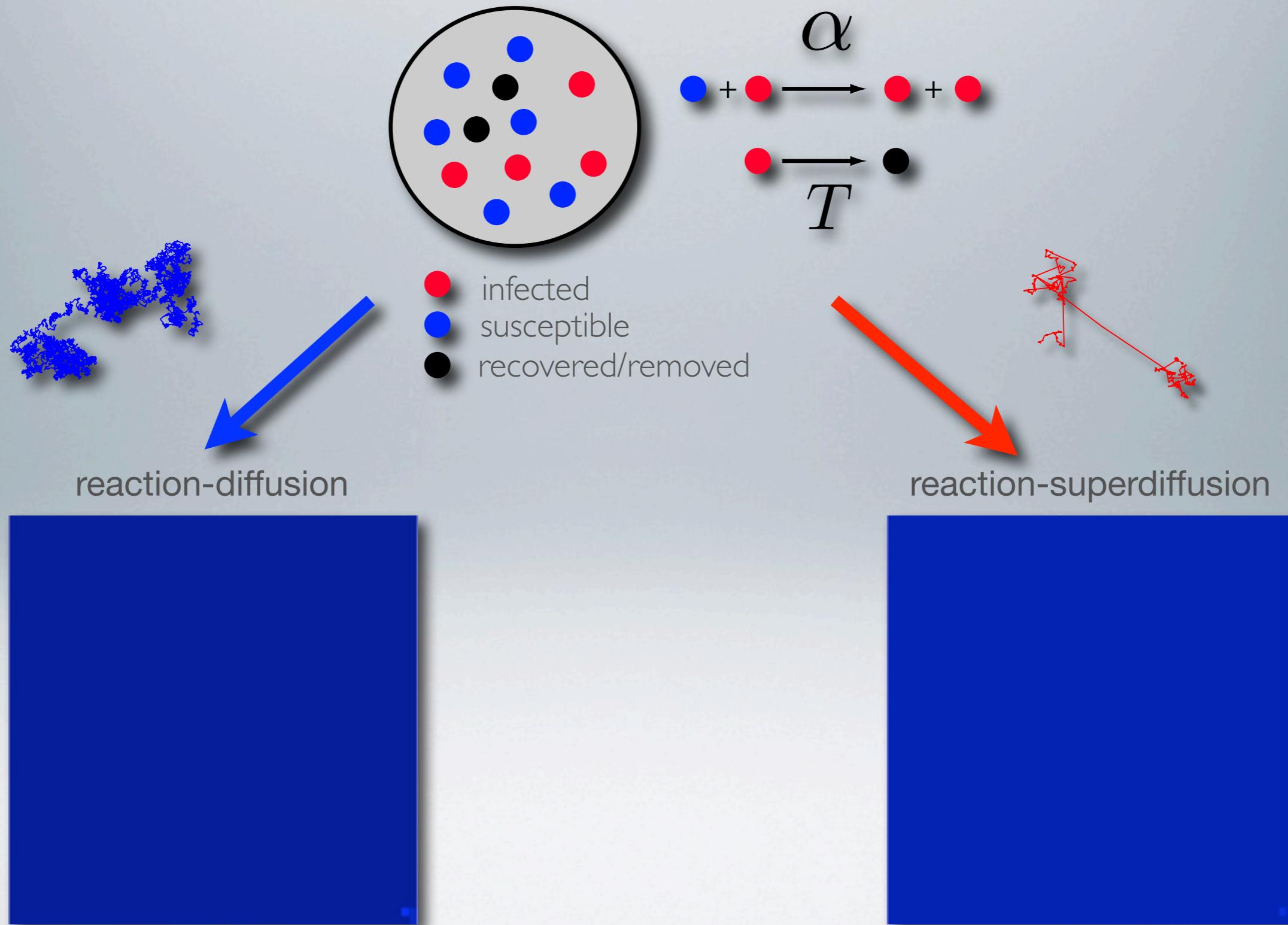
GENERIC PATTERNS



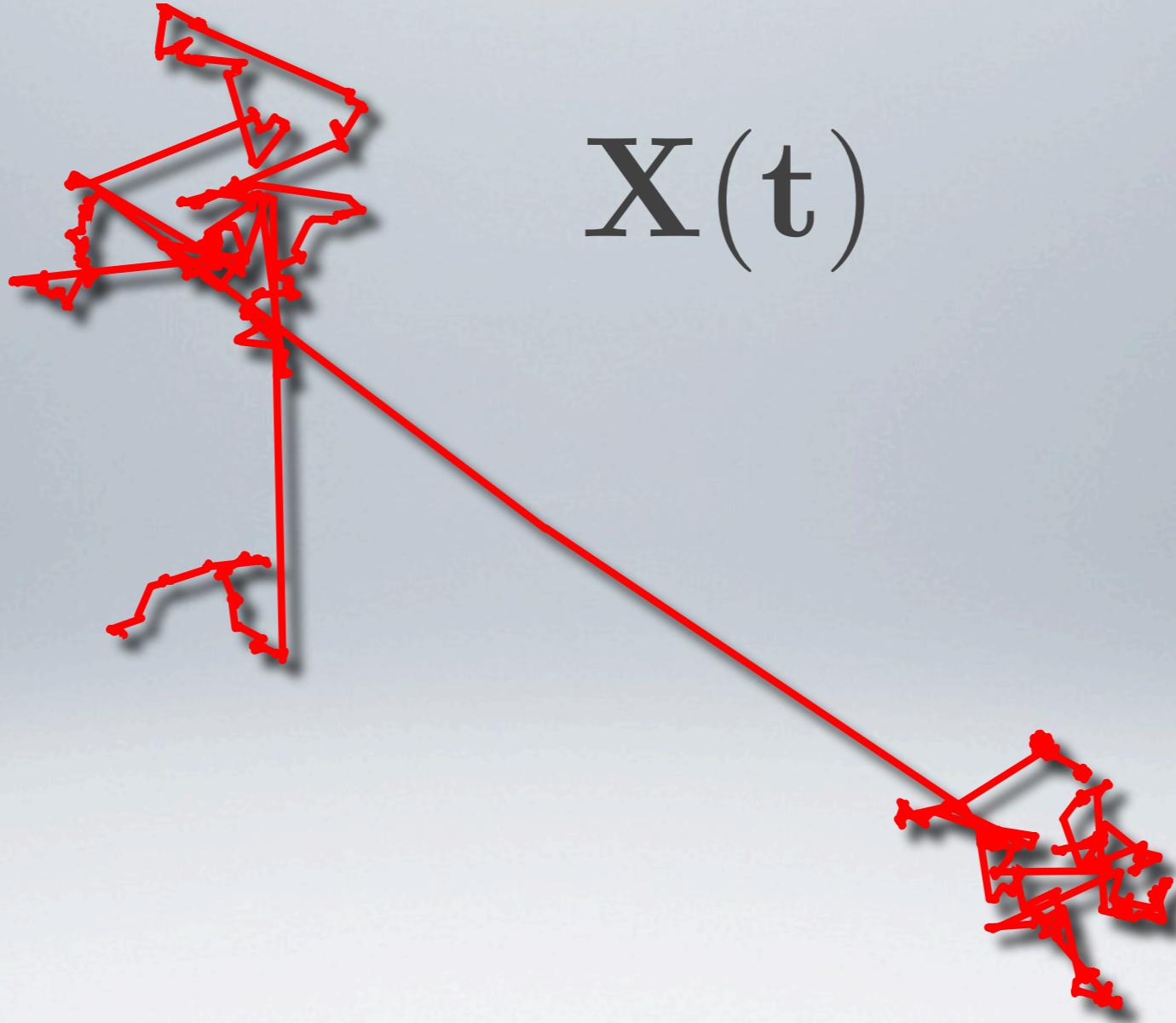
GENERIC PATTERNS



GENERIC PATTERNS

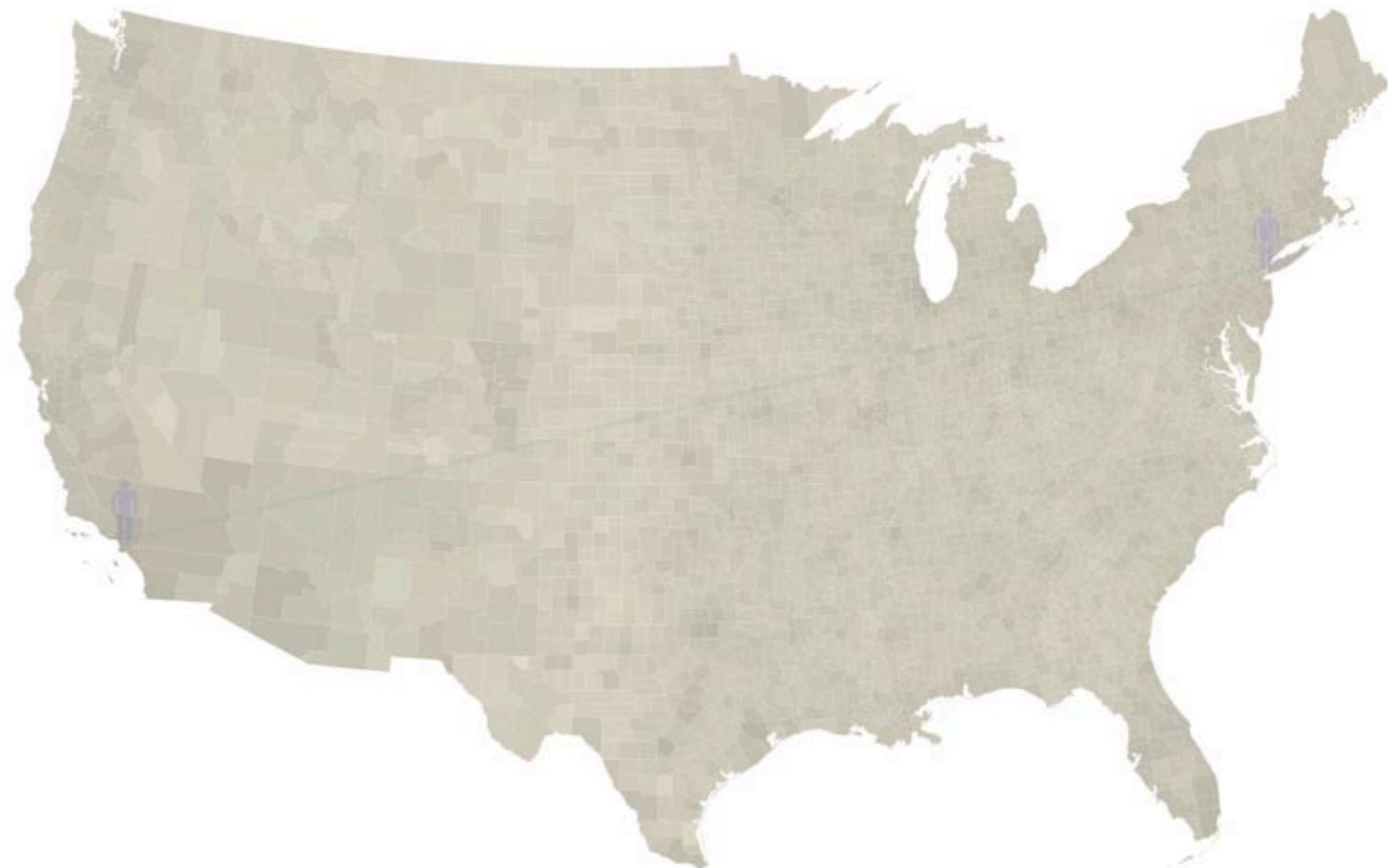


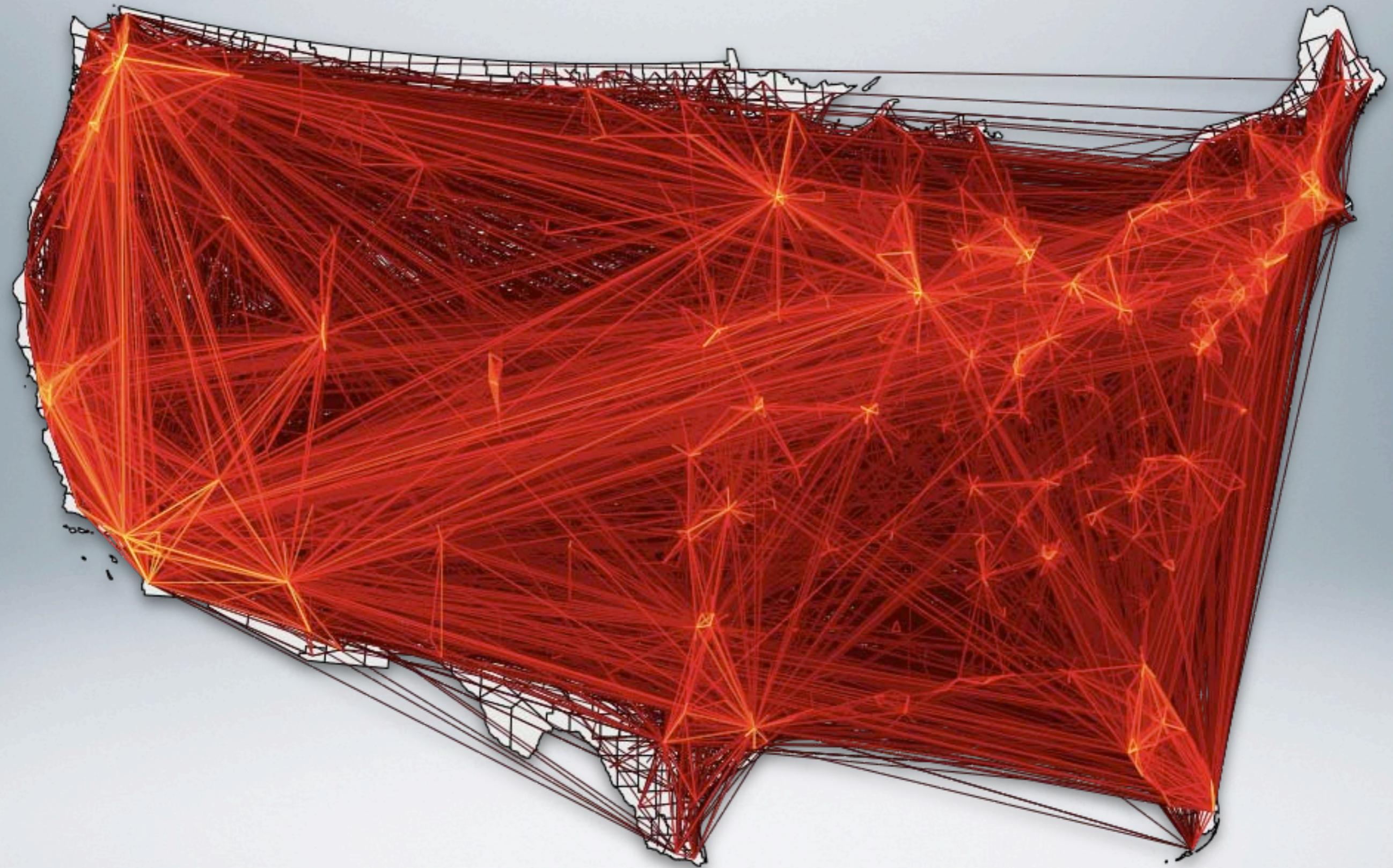
PATH AND NETWORKS

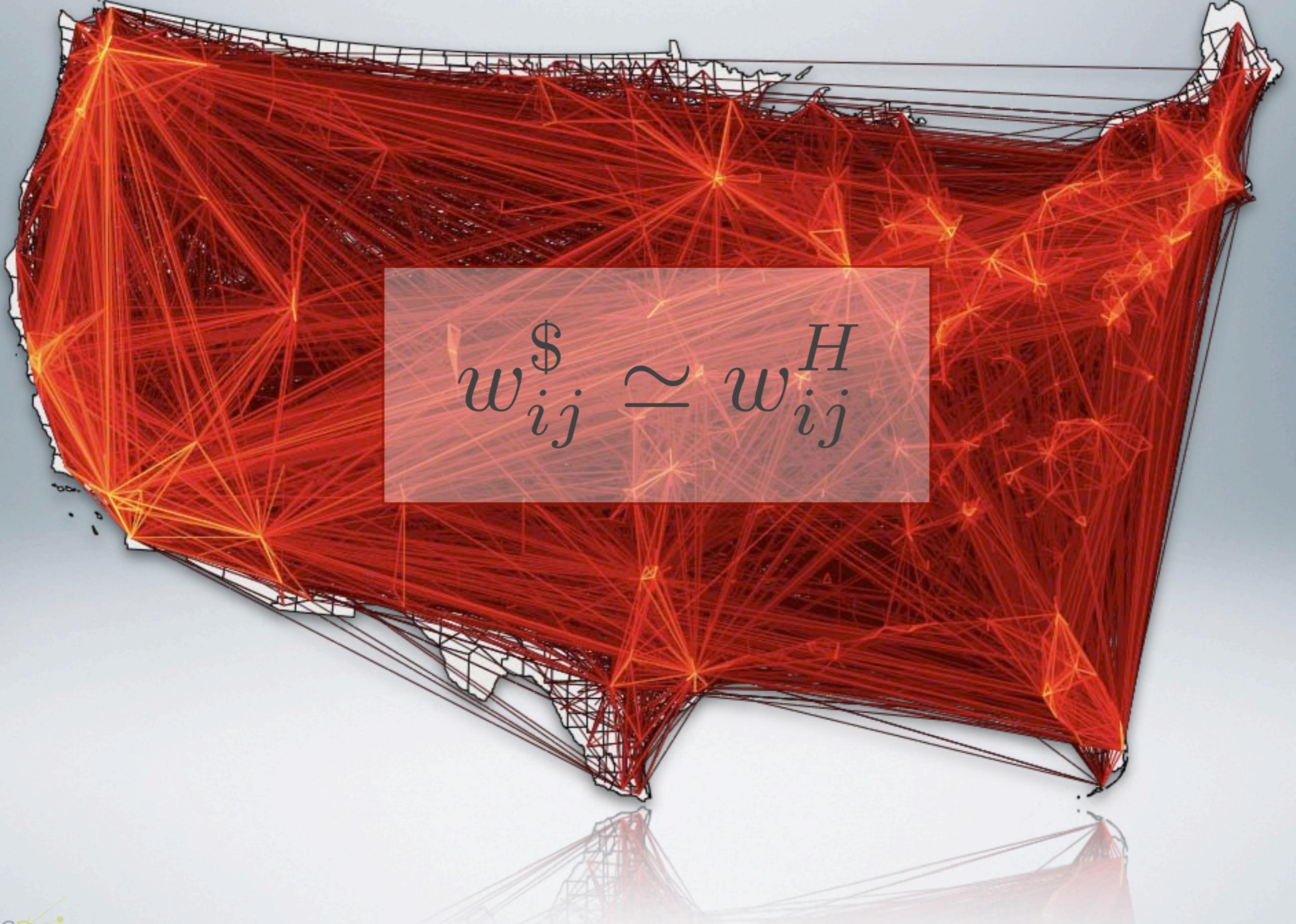


THE FLUX OF DOLLARS

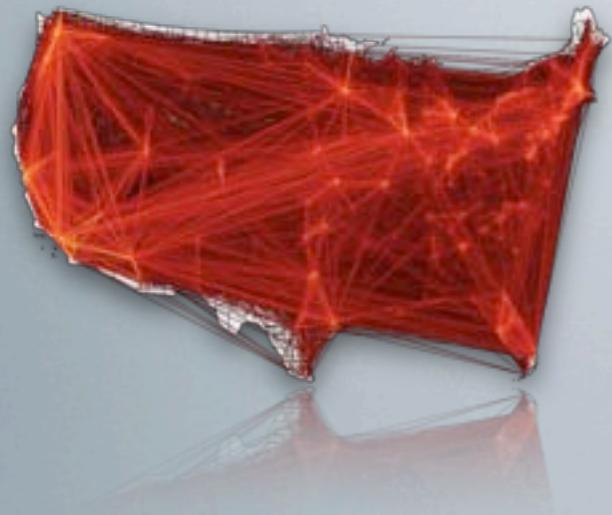
THE FLUX OF DOLLARS



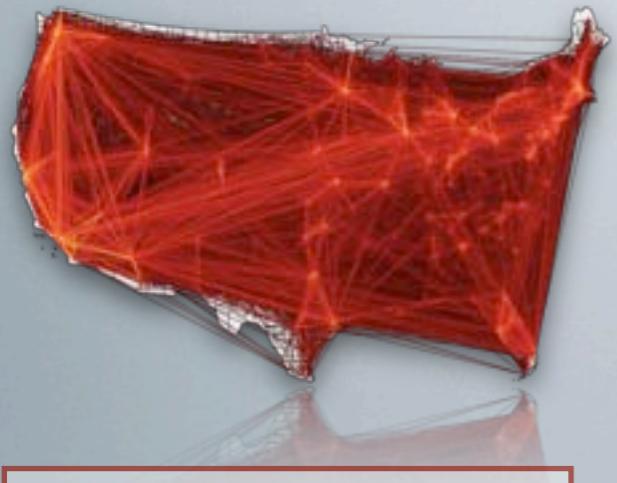



$$w_{ij}^{\$} \simeq w_{ij}^H$$

FLUX COMPARISON



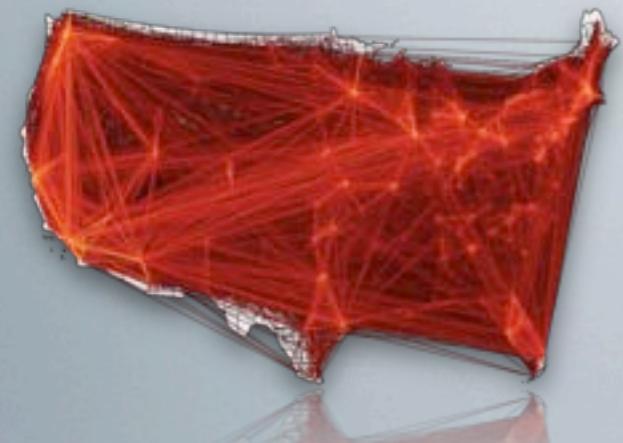
FLUX COMPARISON



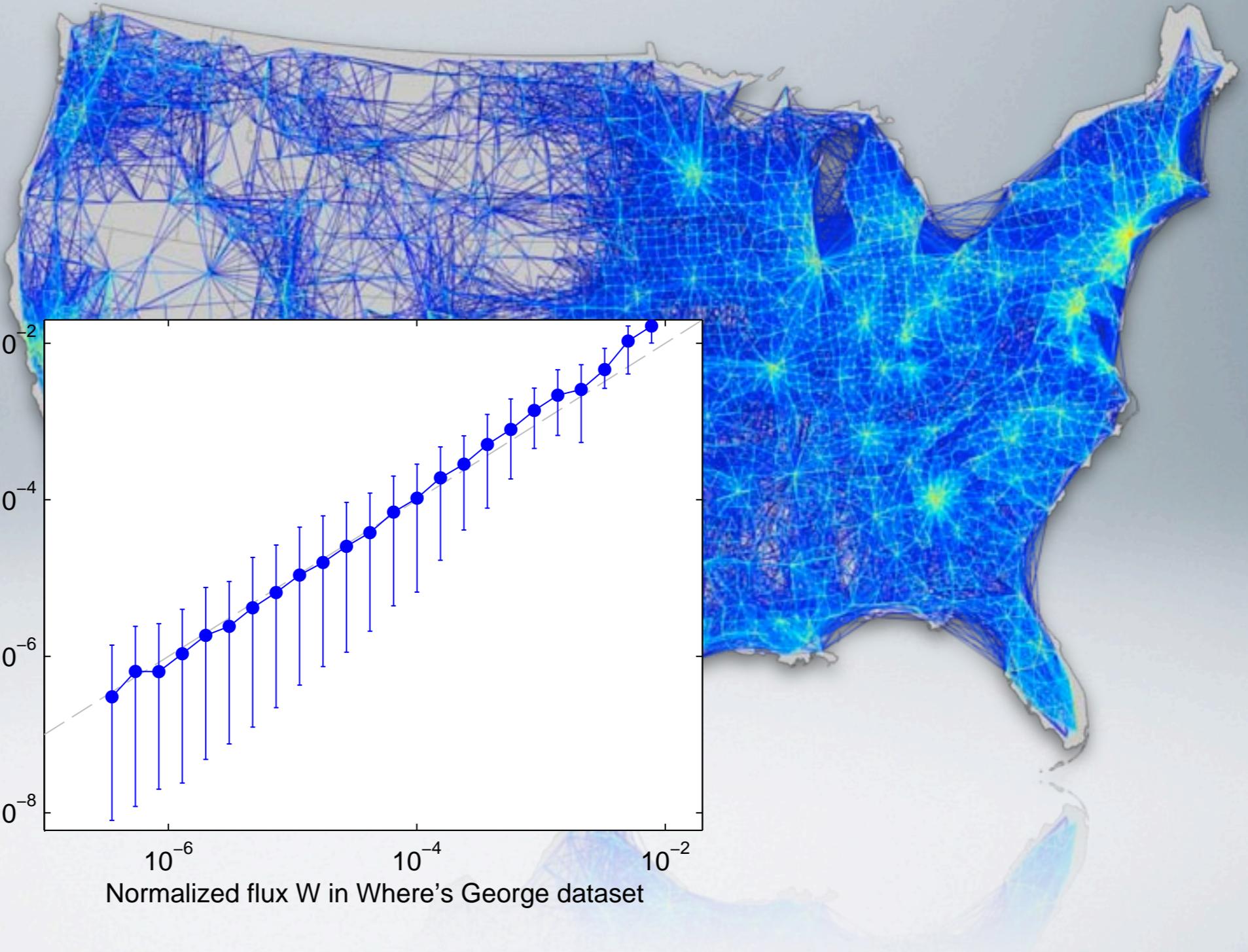
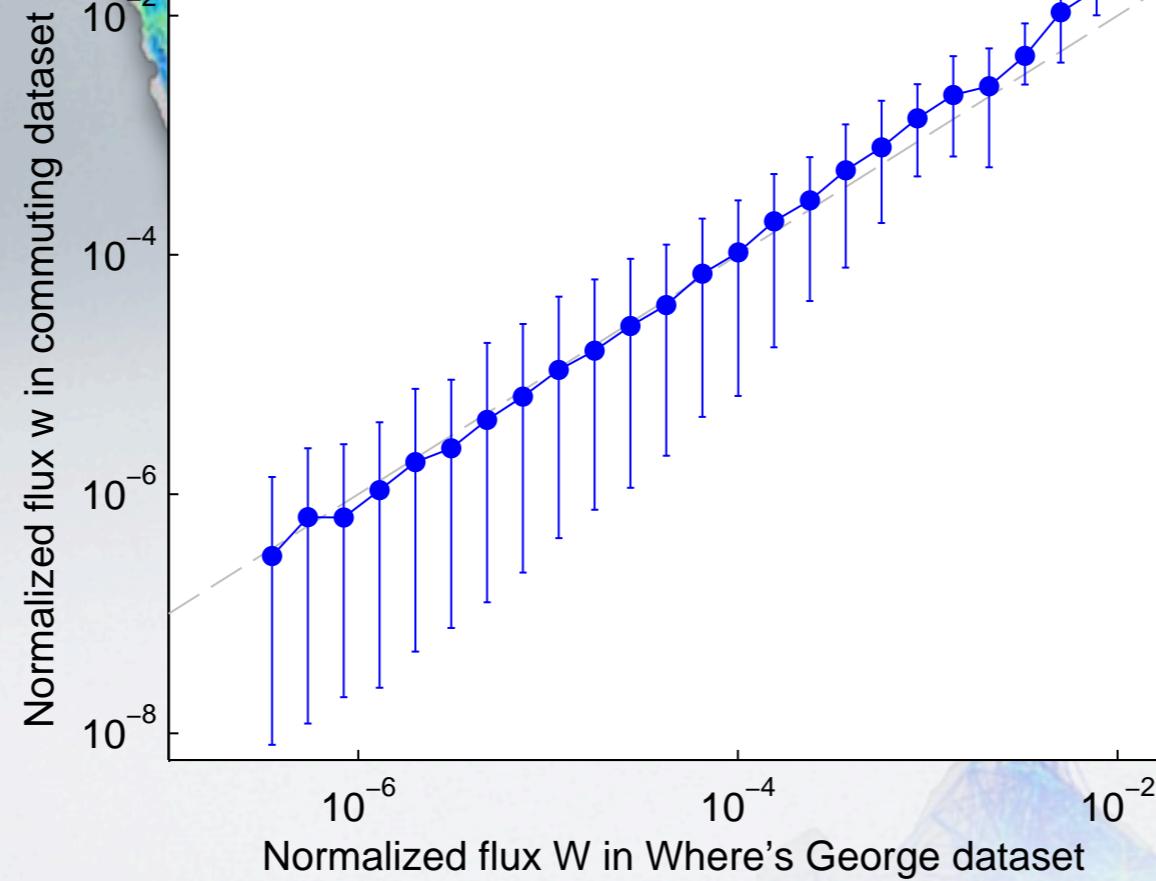
$$w_{ij}^{\$} \simeq w_{ij}^H$$



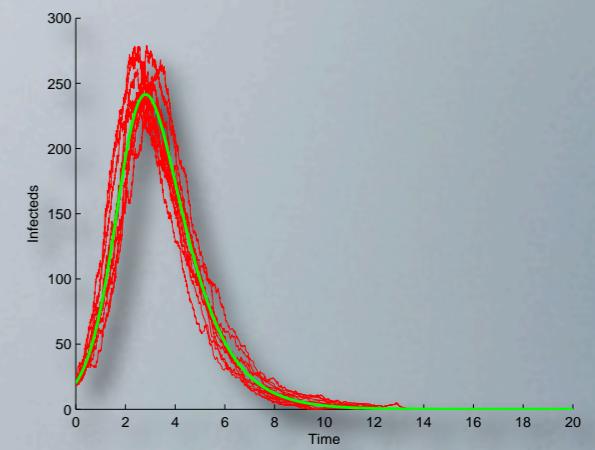
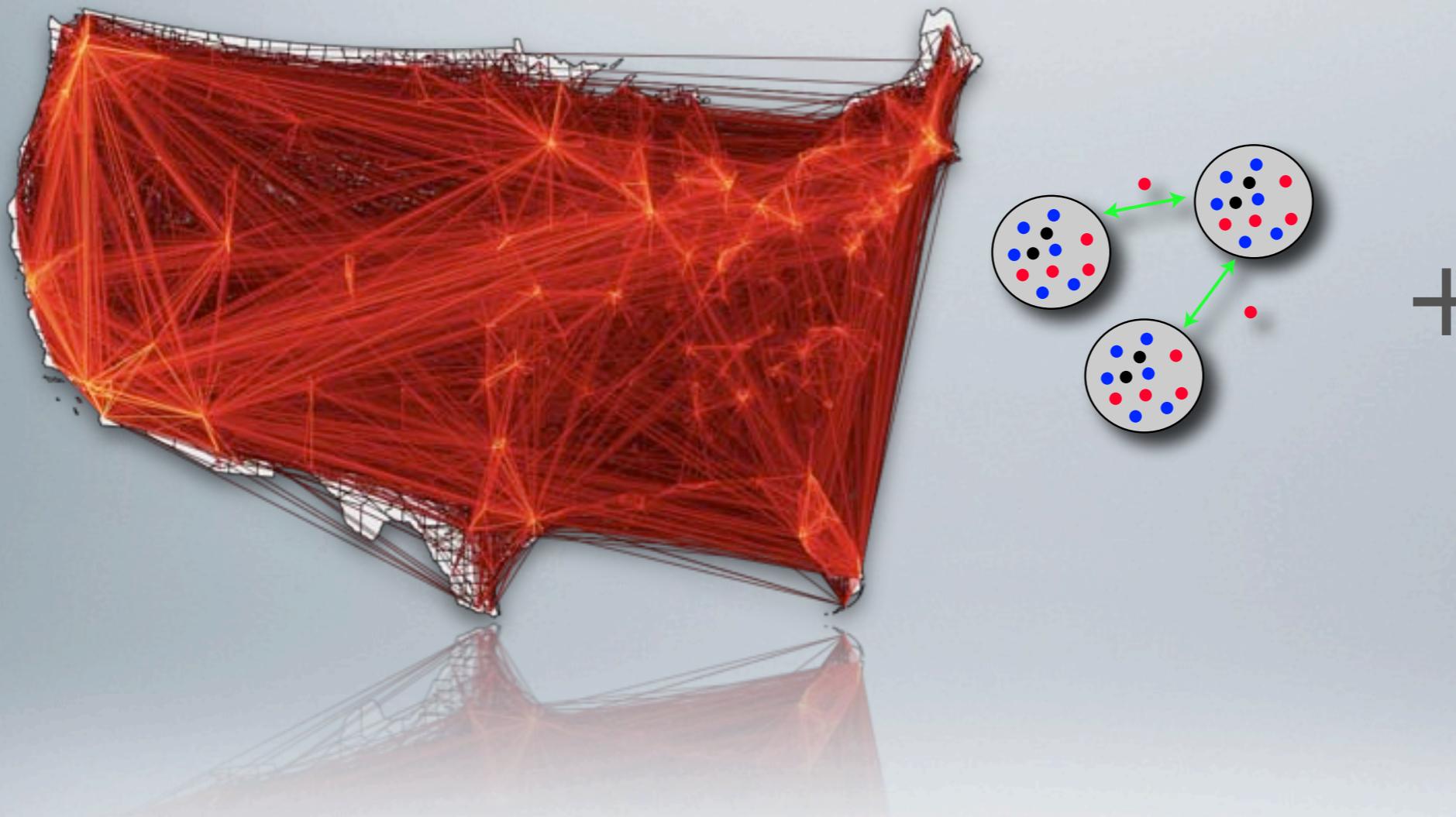
FLUX COMPARISON



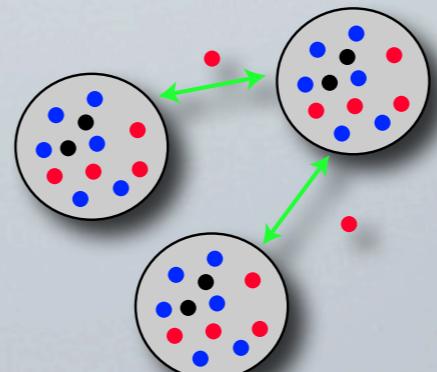
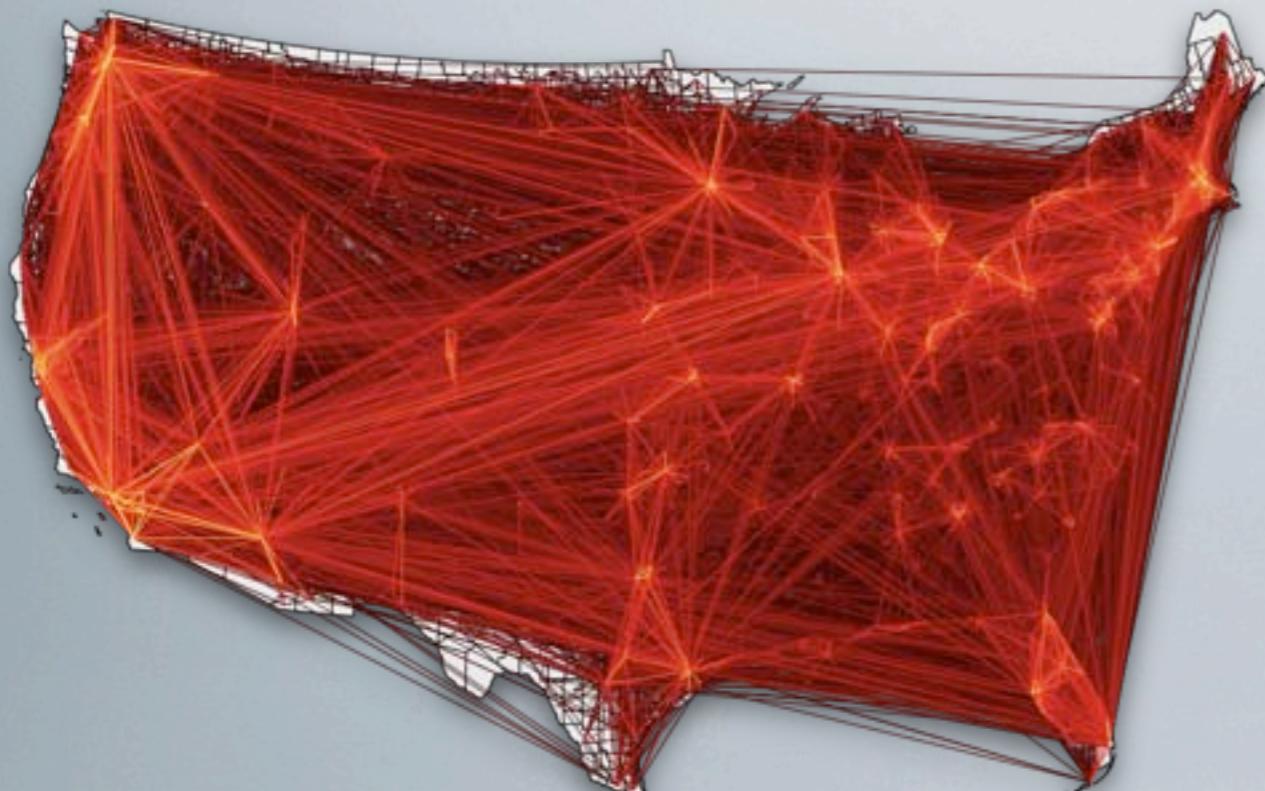
$$w_{ij}^{\$} \approx w_{ij}^H$$



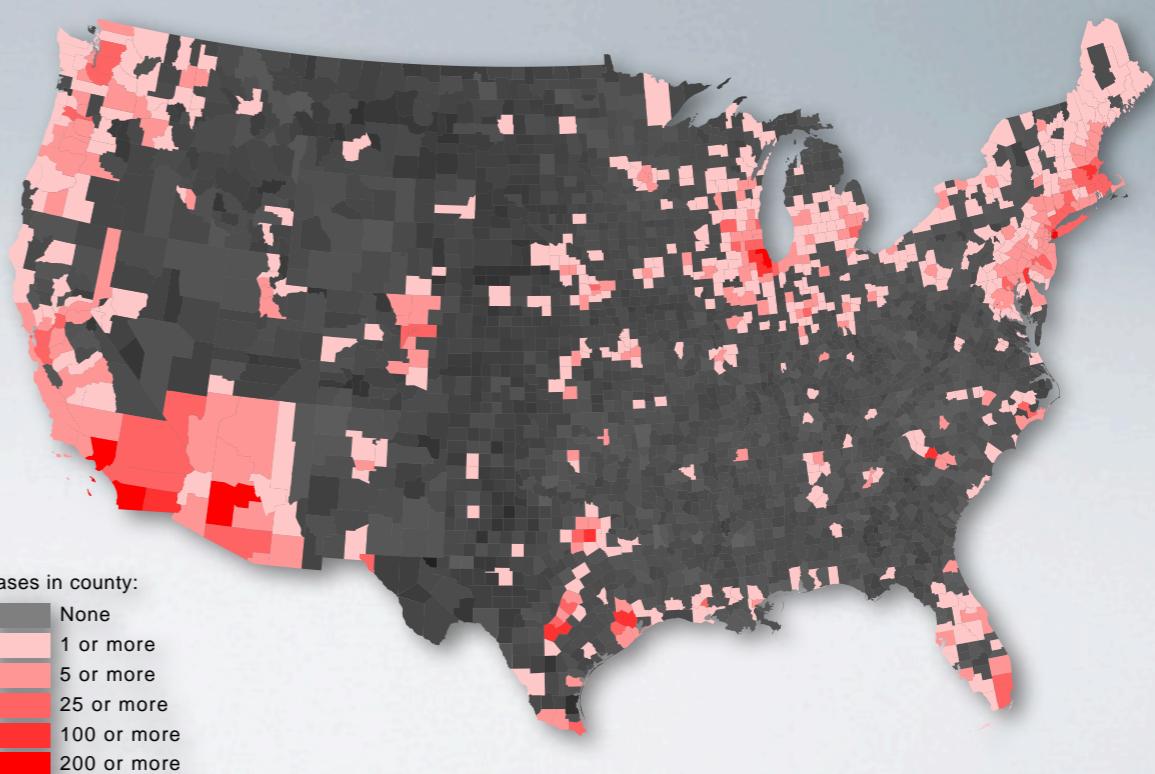
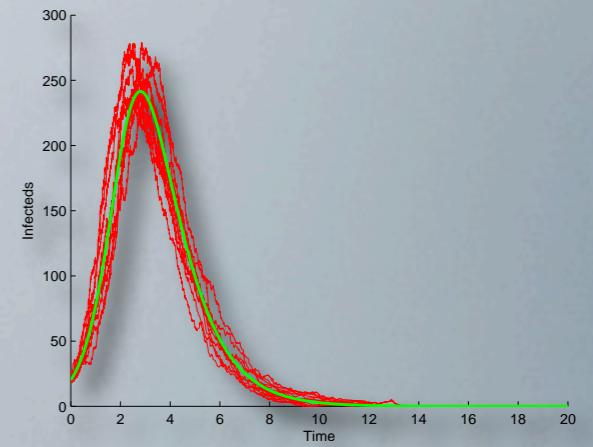
A MODEL FOR THE SPREAD OF HINI IN THE US



A MODEL FOR THE SPREAD OF HINI IN THE US

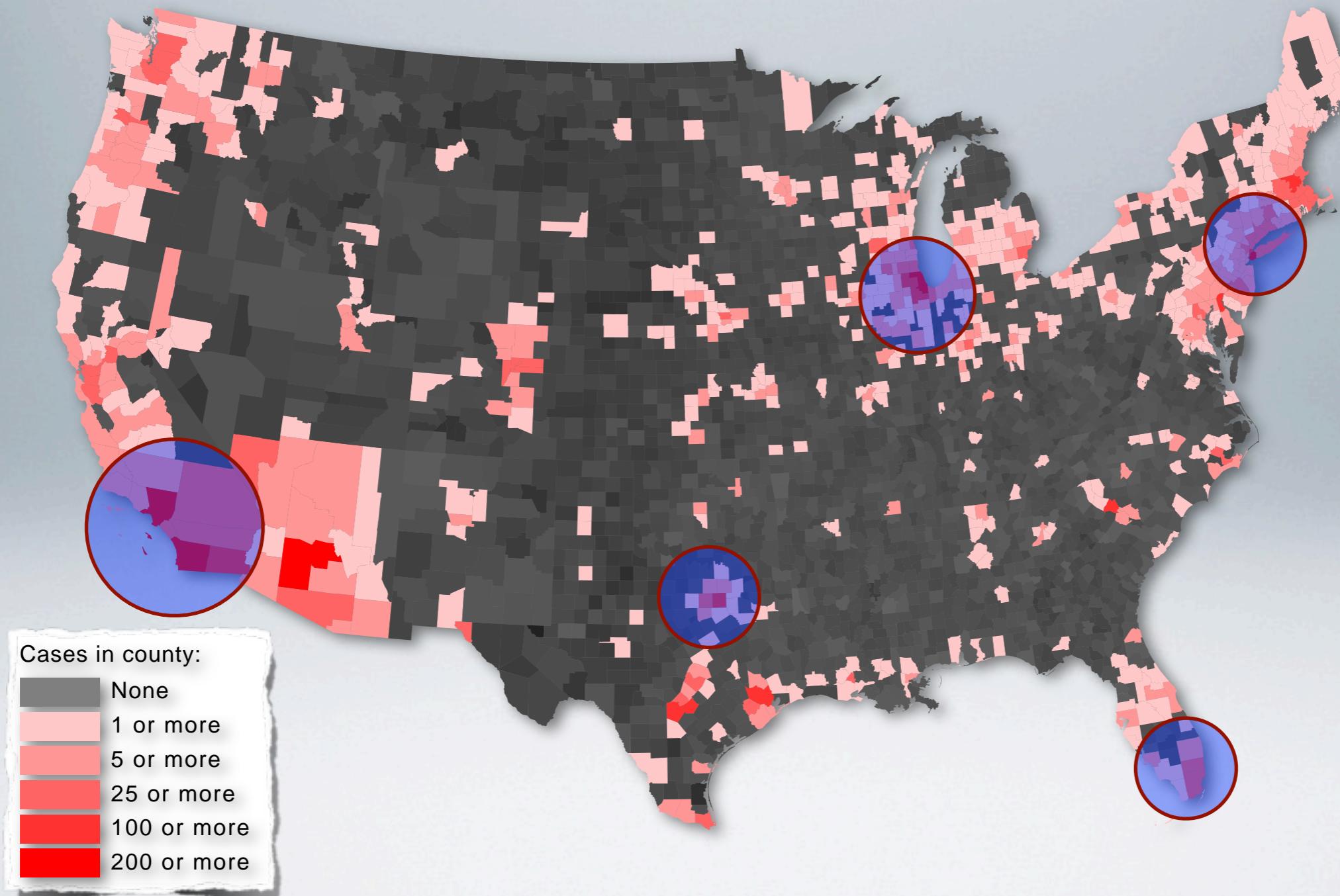


+



Cases in county:
None
1 or more
5 or more
25 or more
100 or more
200 or more

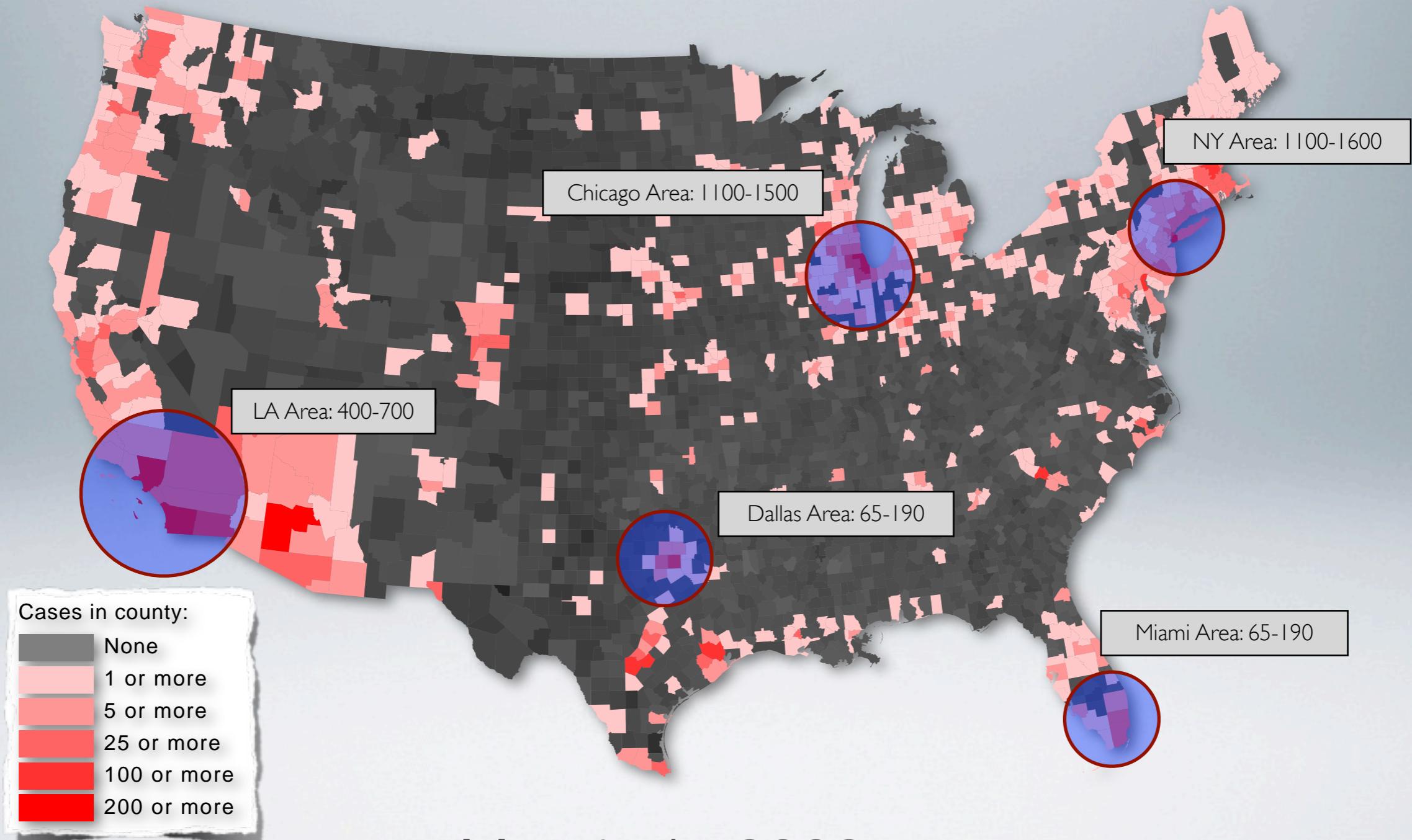
COMPUTATIONAL MODELS HINI PROJECTIONS, US 2009



May 17th, 2009

projected May 2nd

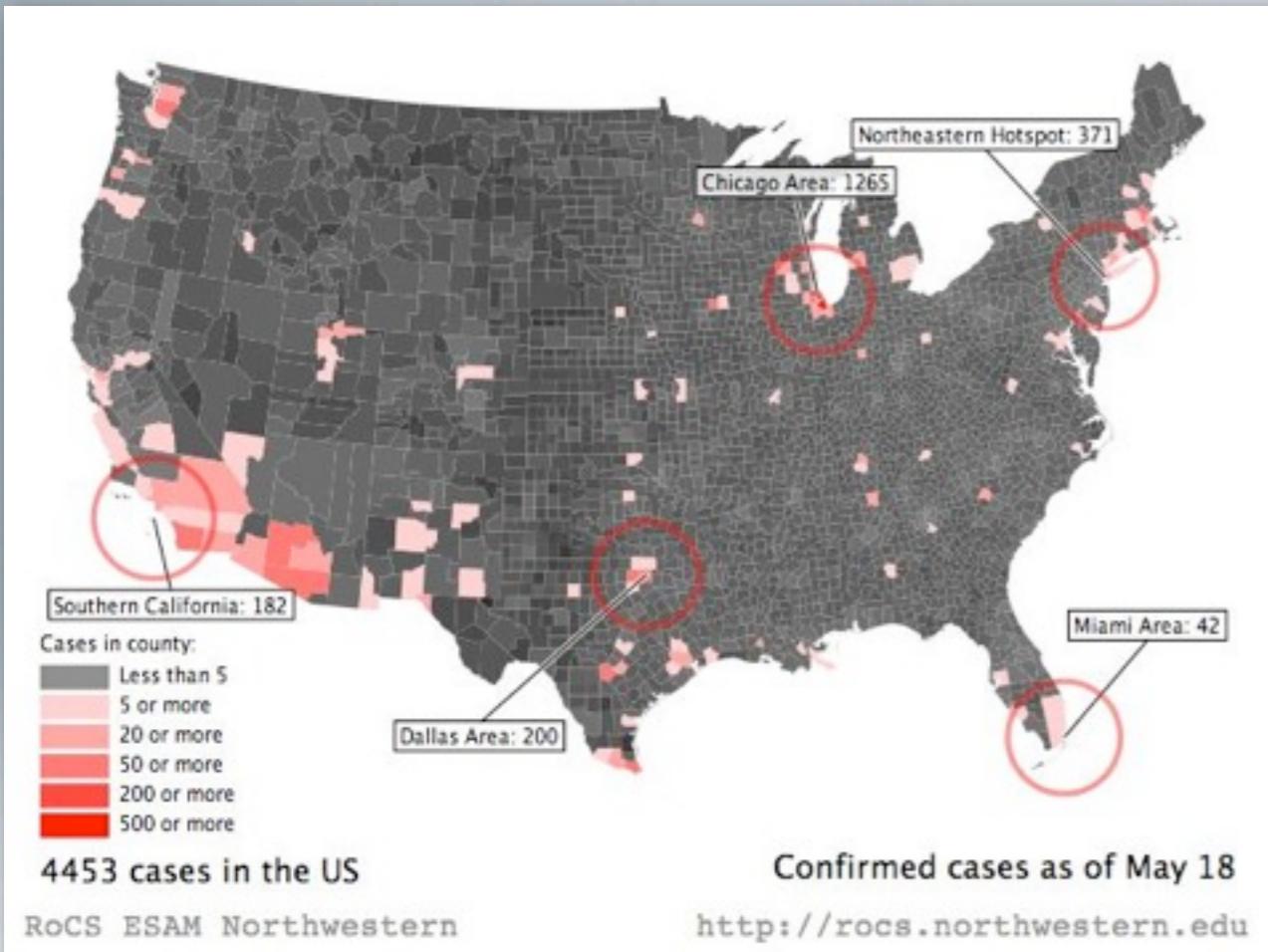
COMPUTATIONAL MODELS HINI PROJECTIONS, US 2009



May 17th, 2009

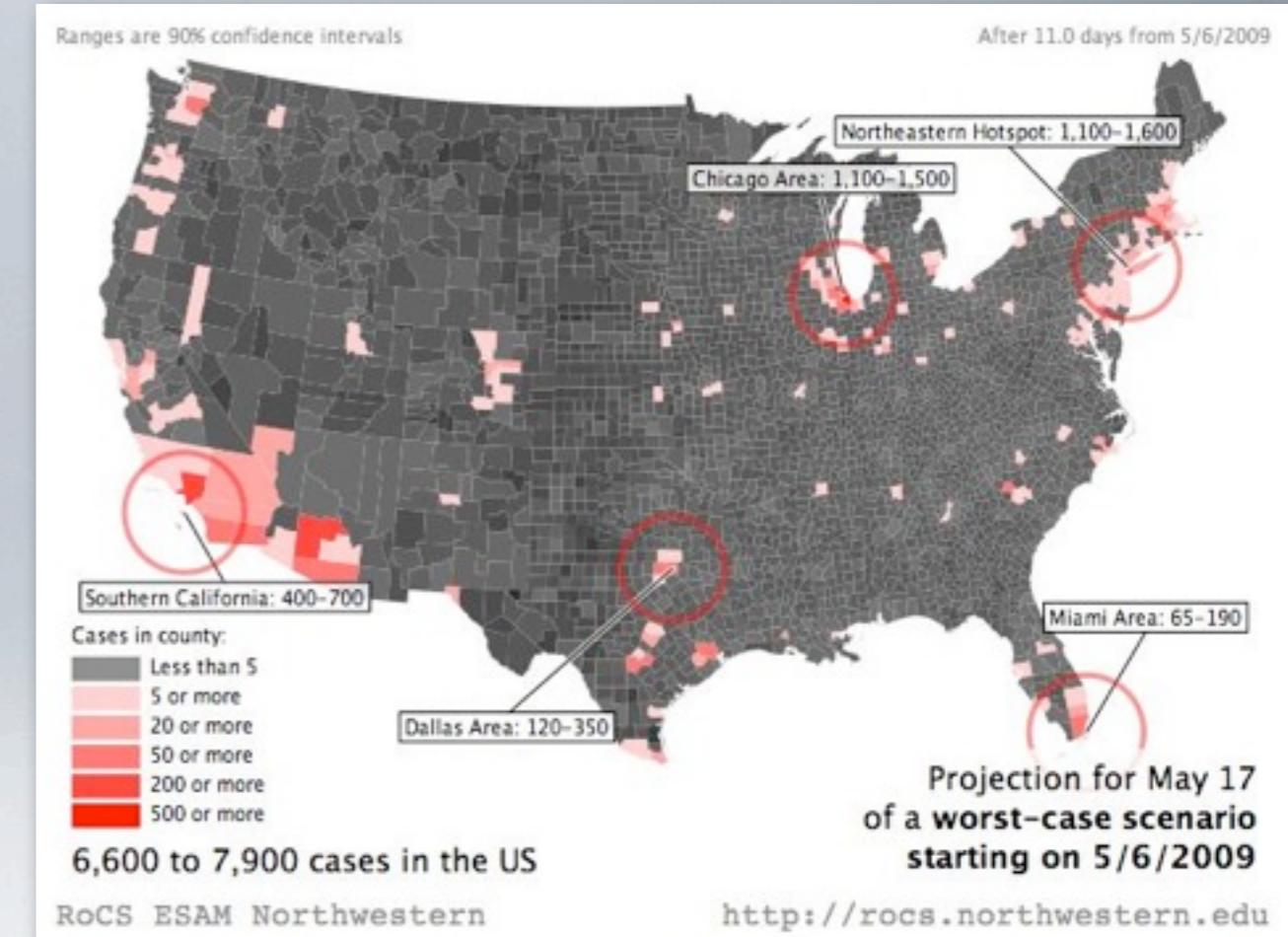
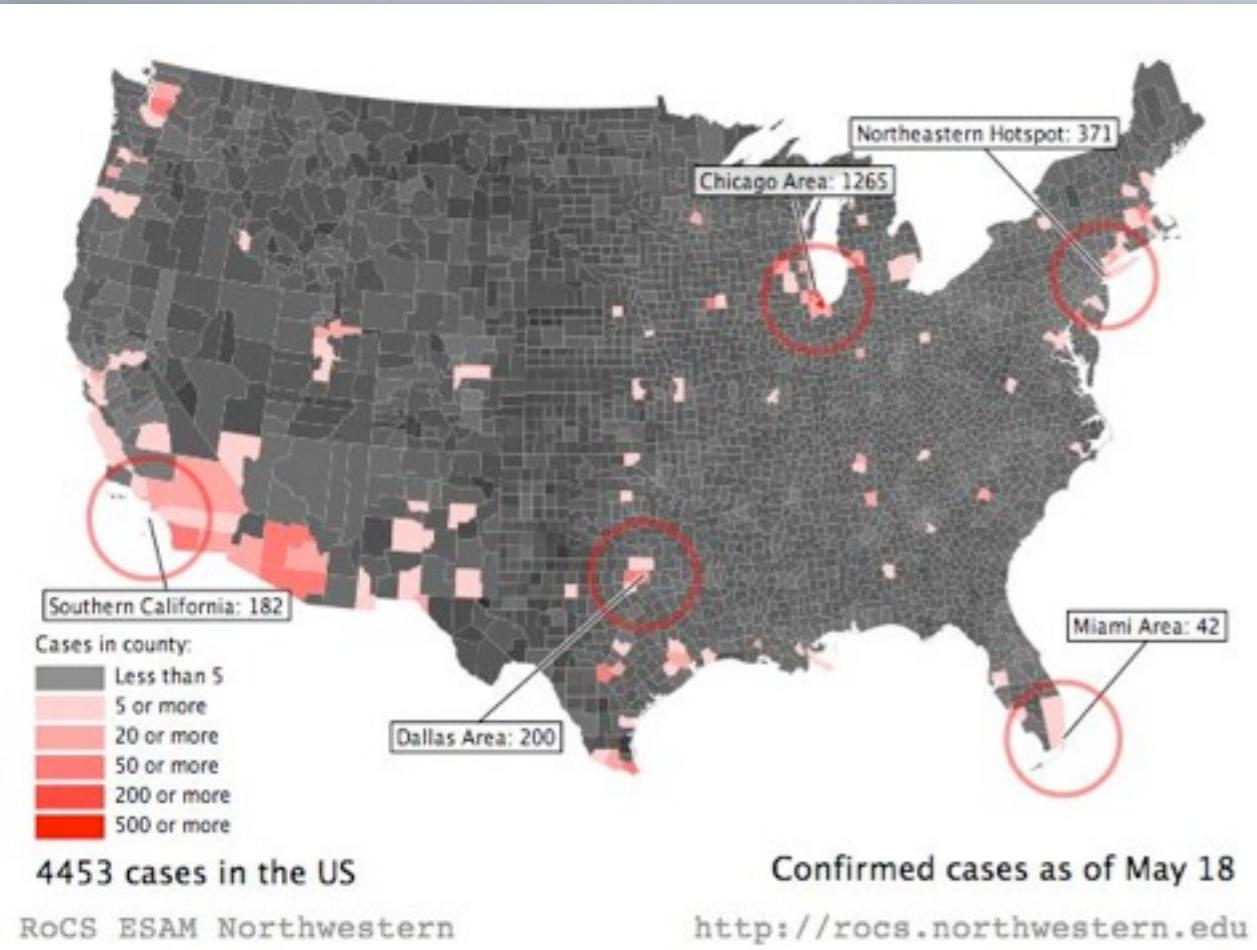
projected May 2nd

HINI PANDEMIC 2009



<http://rocs.northwestern.edu>

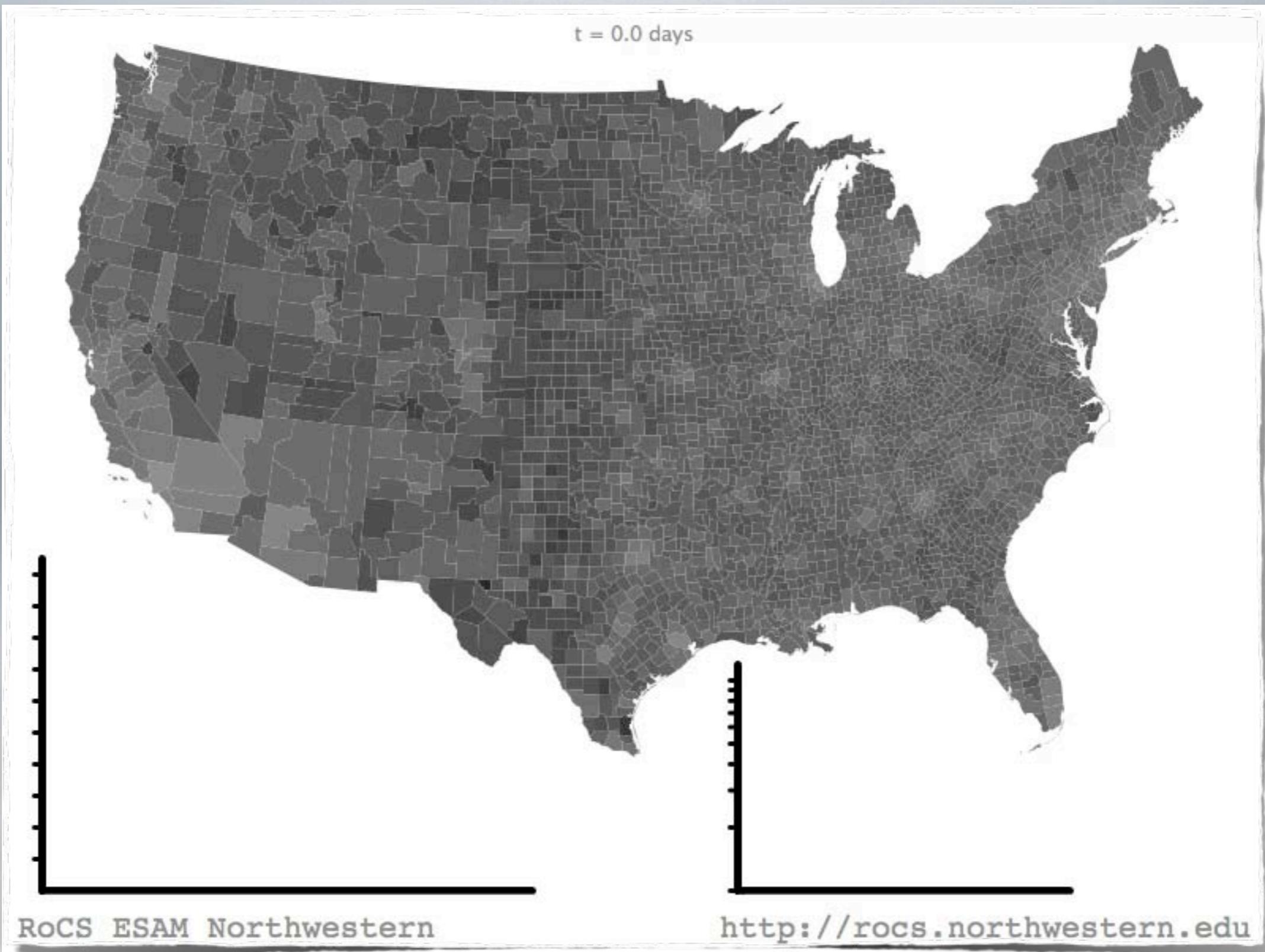
HINI PANDEMIC 2009



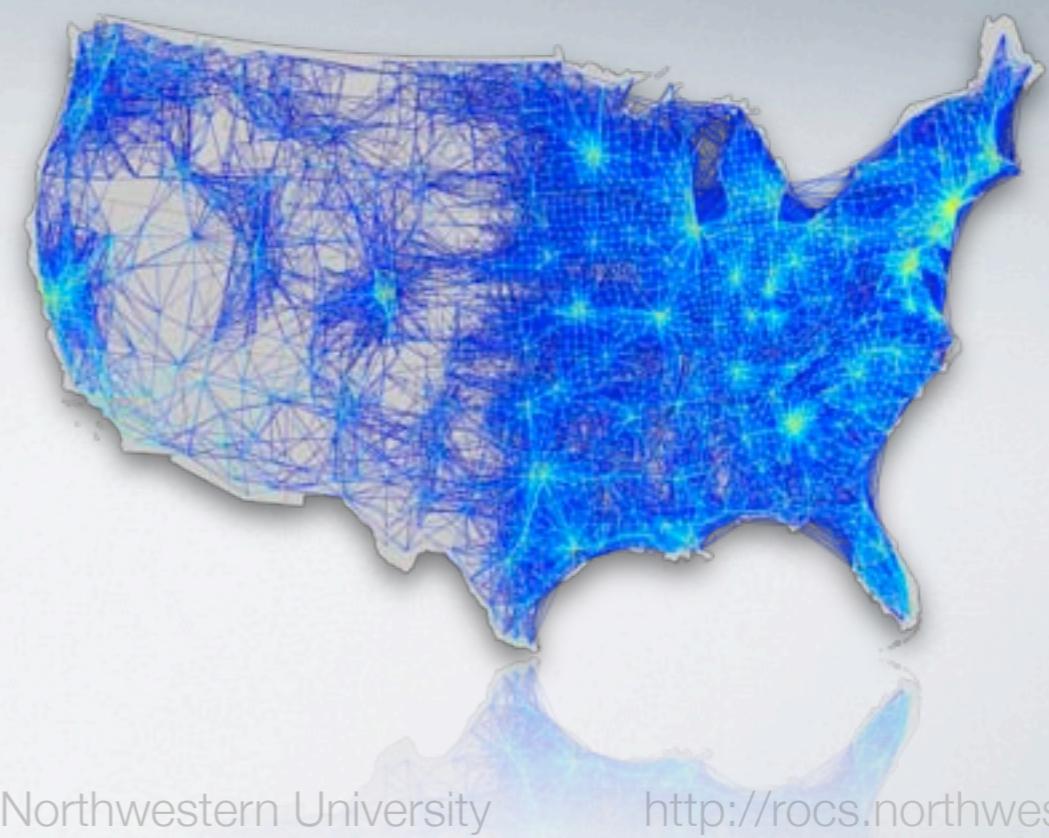
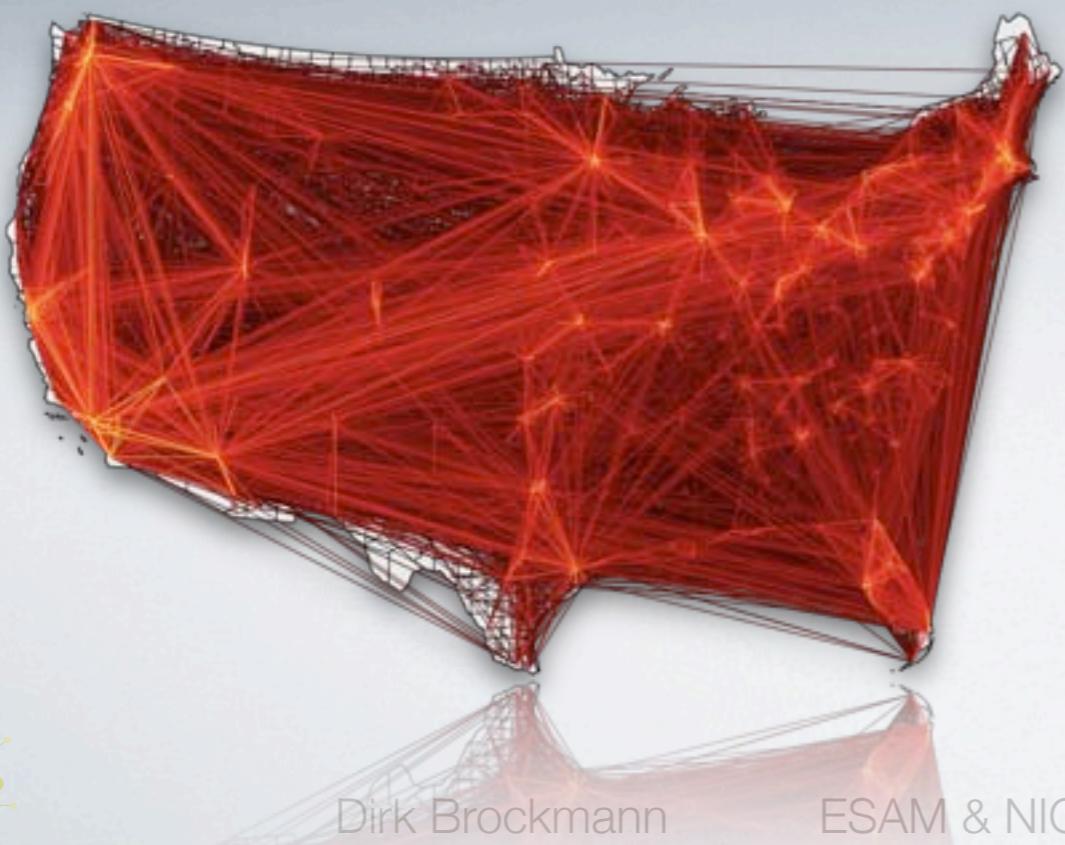
<http://rocs.northwestern.edu>

PANDEMIC SCENARIO

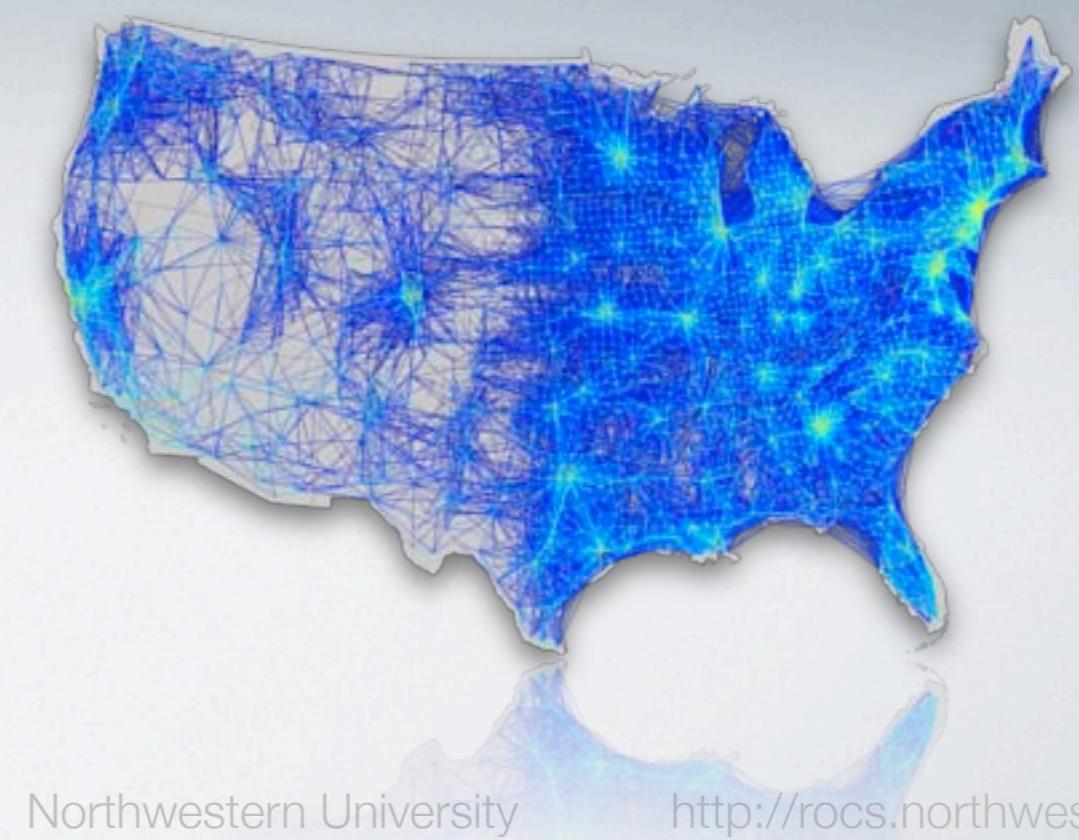
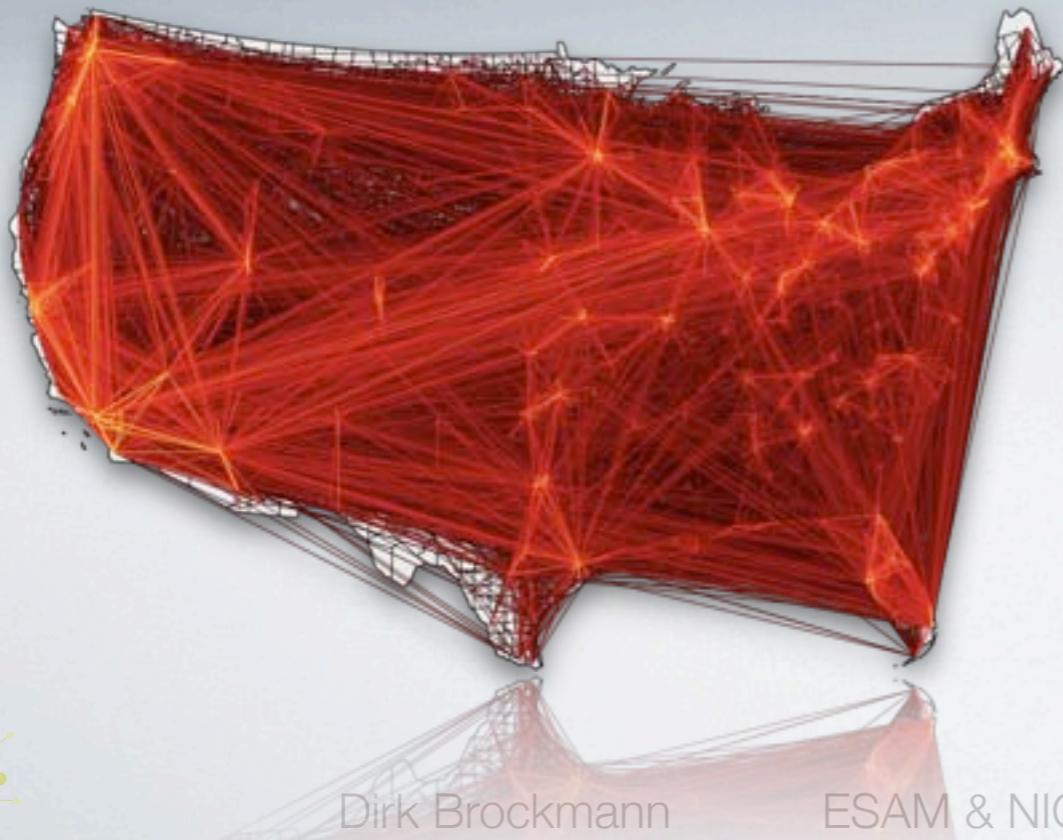
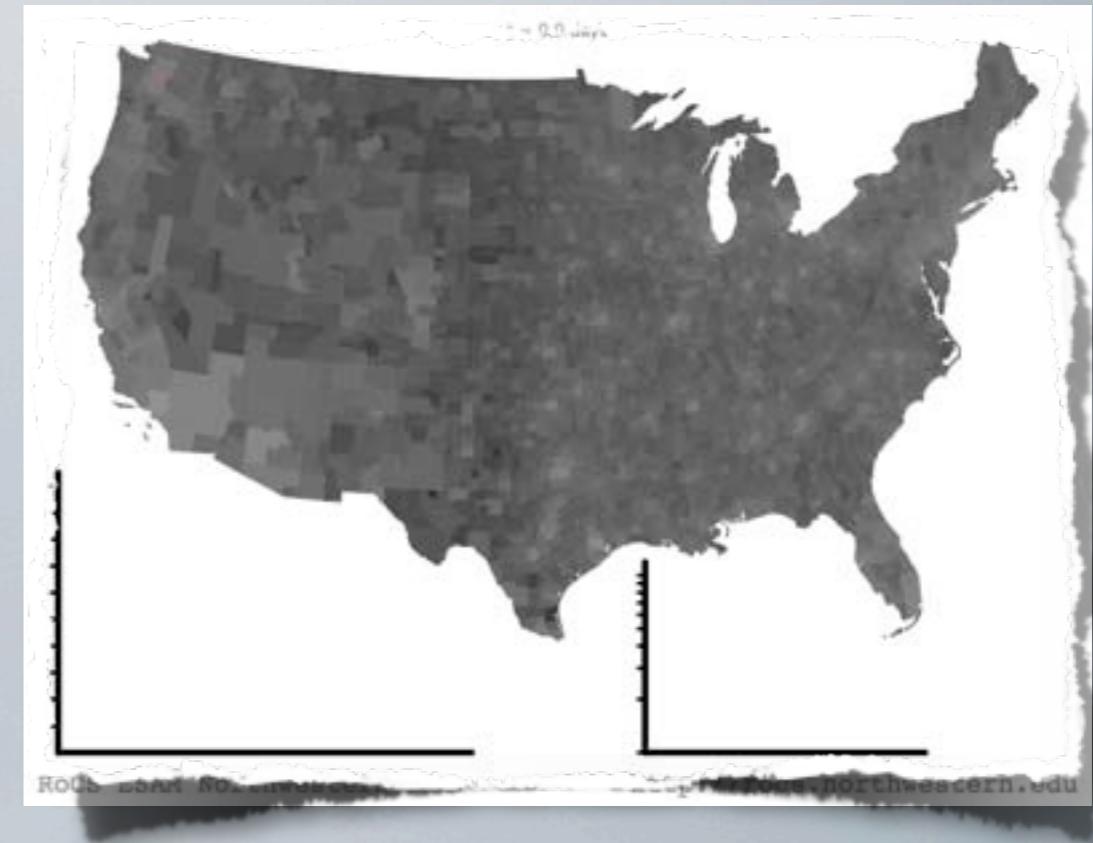
PANDEMIC SCENARIO



THE IMPACT OF LONG RANGE TRAFFIC



THE IMPACT OF LONG RANGE TRAFFIC



QUESTION

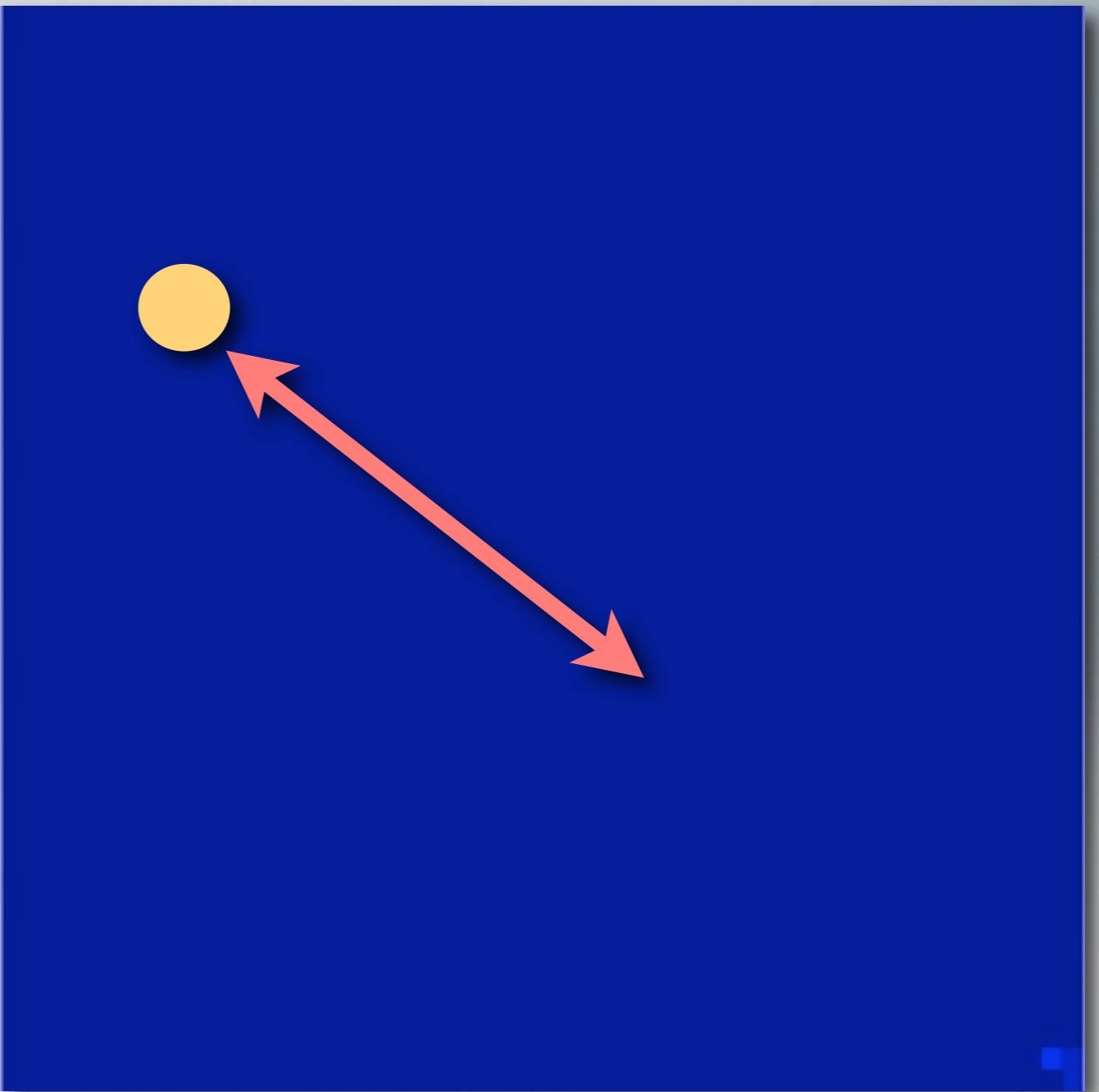
can we find simplify the picture?

can we compute effective “front” velocities?

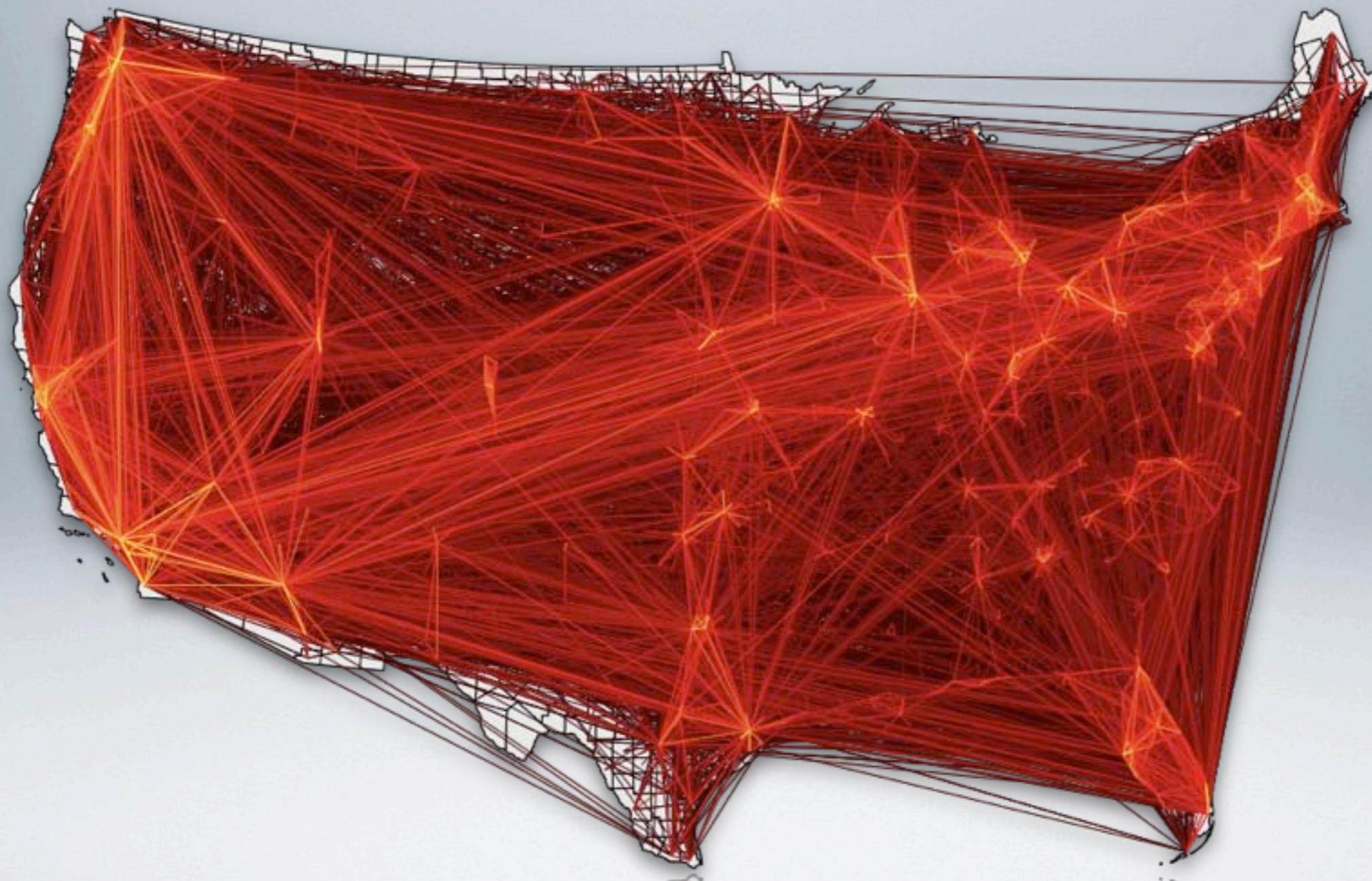
WHEN?

WHEN?

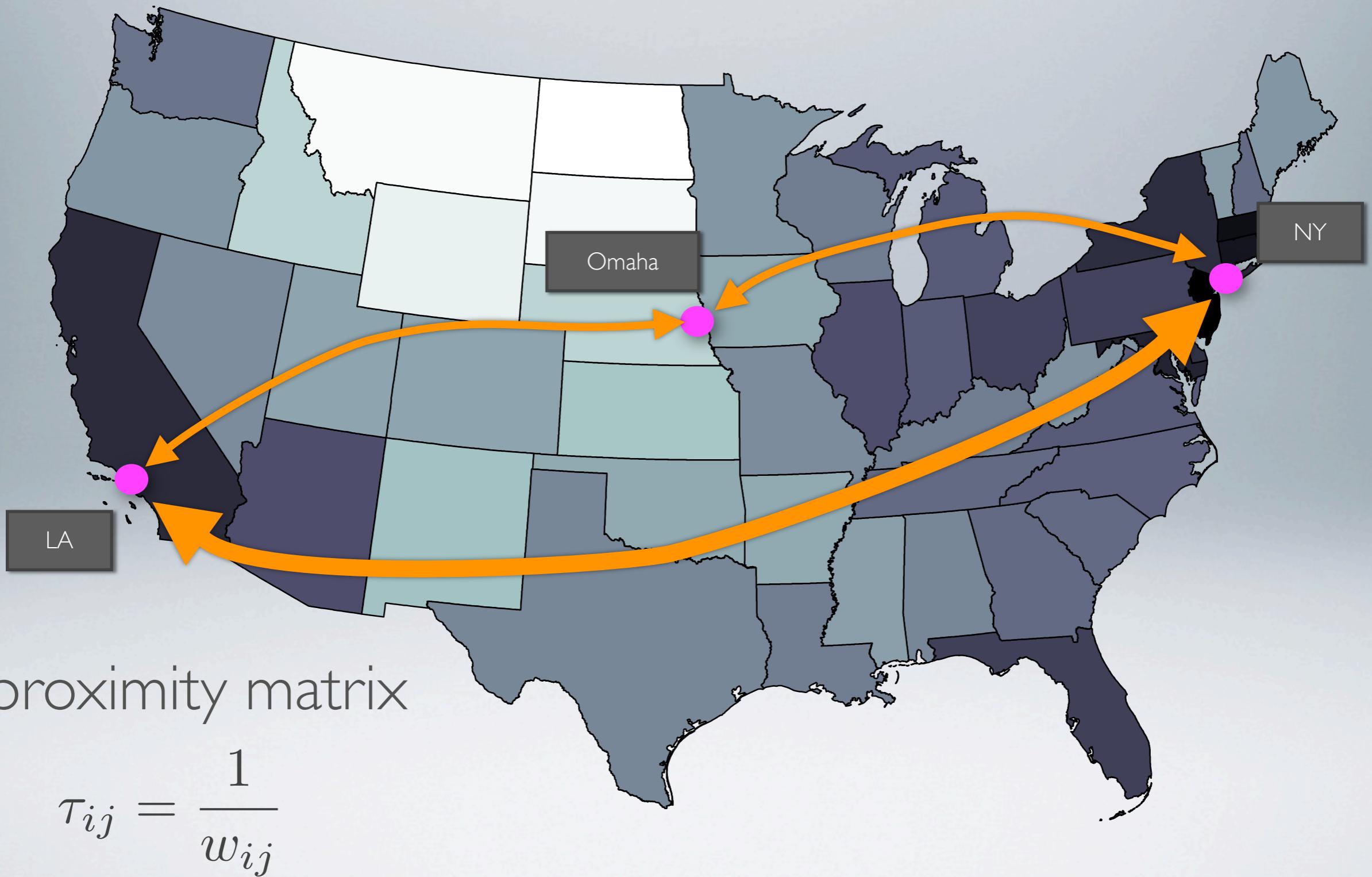
$$T = \frac{d}{v}$$



PROXIMITY, PATHS AND TREES



EFFECTIVE PROXIMITY



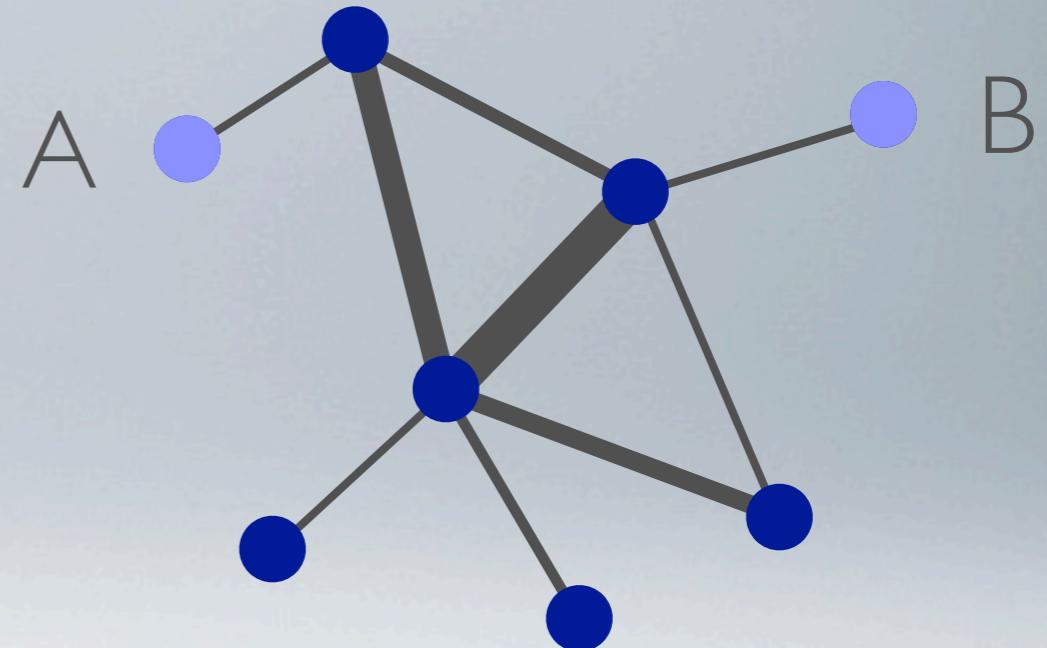
SHORTEST PATHS AND EFFECTIVE DISTANCE

proximity matrix

$$\tau_{ij} = \frac{1}{w_{ij}}$$

weighted shortest path
distance

$$d_{ij} = \sum_{\{k,l\} \in P_{ij}^*} \tau_{kl}$$



SHORTEST PATHS AND EFFECTIVE DISTANCE

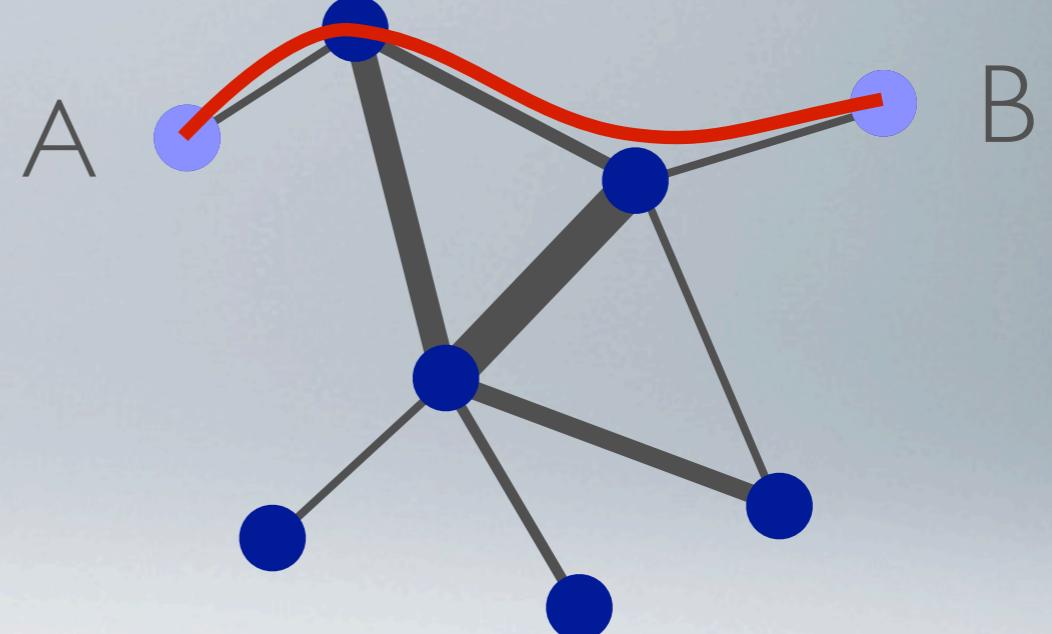
proximity matrix

$$\tau_{ij} = \frac{1}{w_{ij}}$$

weighted shortest path
distance

$$d_{ij} = \sum_{\{k,l\} \in P_{ij}^*} \tau_{kl}$$

through topology



SHORTEST PATHS AND EFFECTIVE DISTANCE

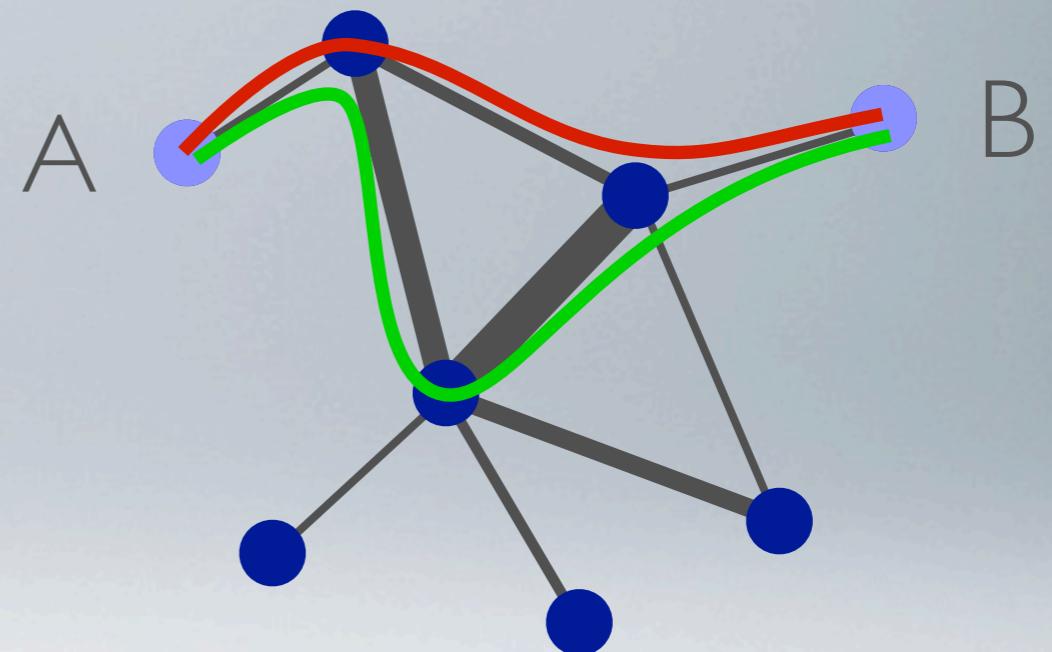
proximity matrix

$$\tau_{ij} = \frac{1}{w_{ij}}$$

weighted shortest path
distance

$$d_{ij} = \sum_{\{k,l\} \in P_{ij}^*} \tau_{kl}$$

through topology



through weighted network

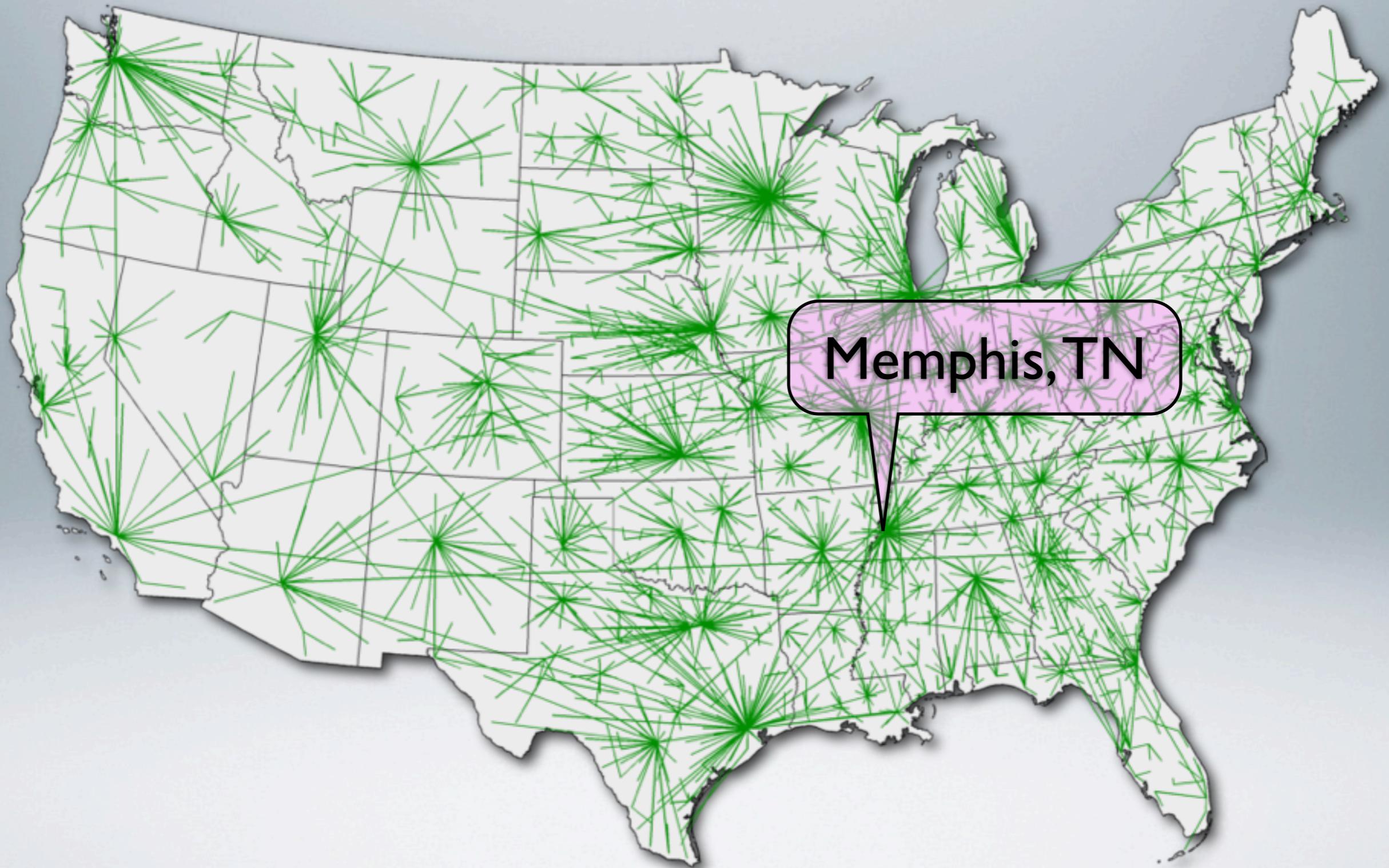
SHORTEST PATH TREES EXAMPLES



SHORTEST PATH TREES EXAMPLES



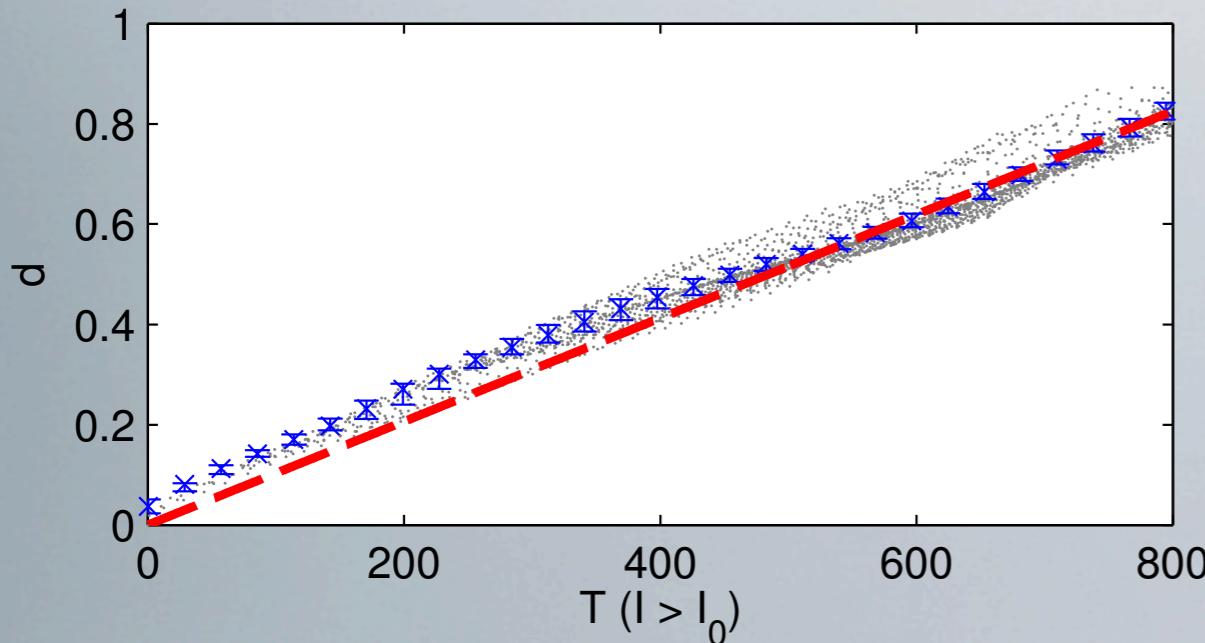
SHORTEST PATH TREES EXAMPLES



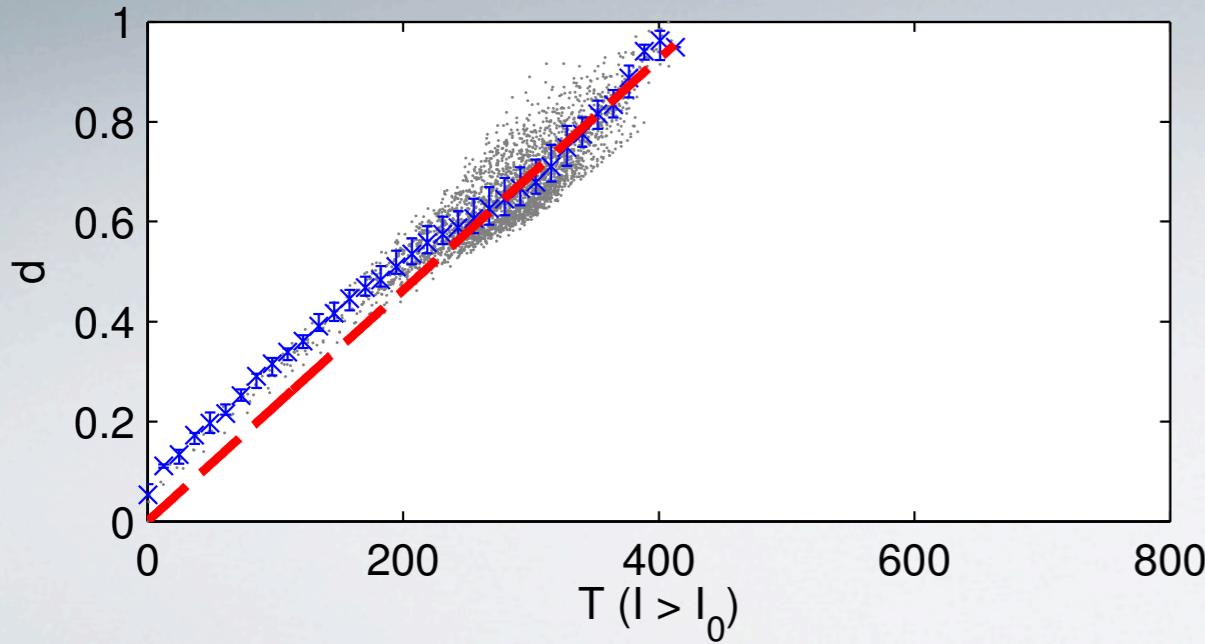
SPATO

EFFECTIVE VELOCITIES

d vs T Correlation – Lattice Noise

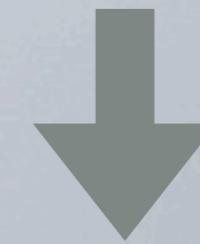


d vs T Correlation – Lattice Small World



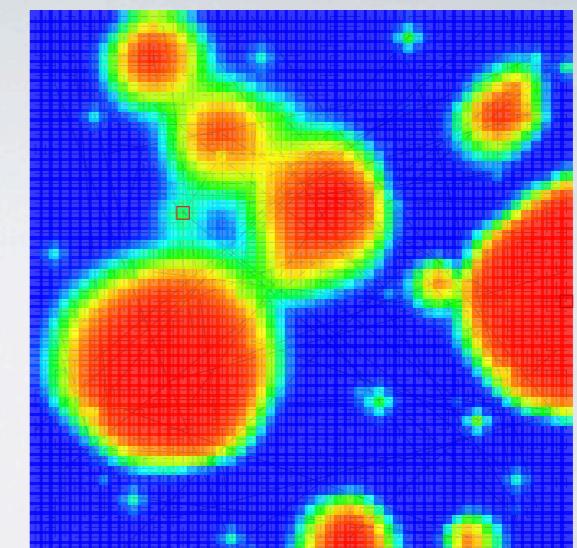
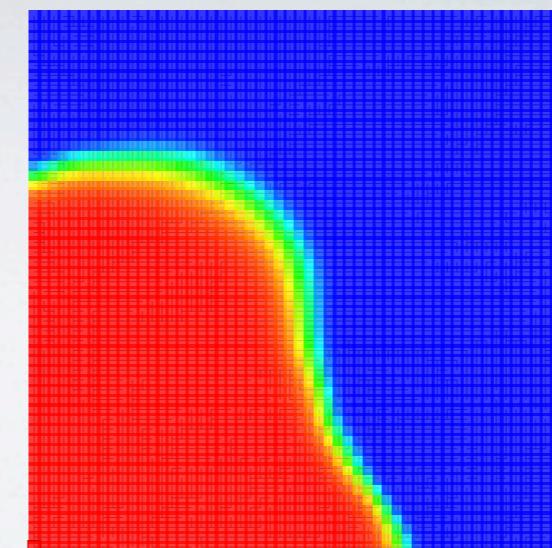
arrival time: $T(I > I_0)$

shortest path distance: d

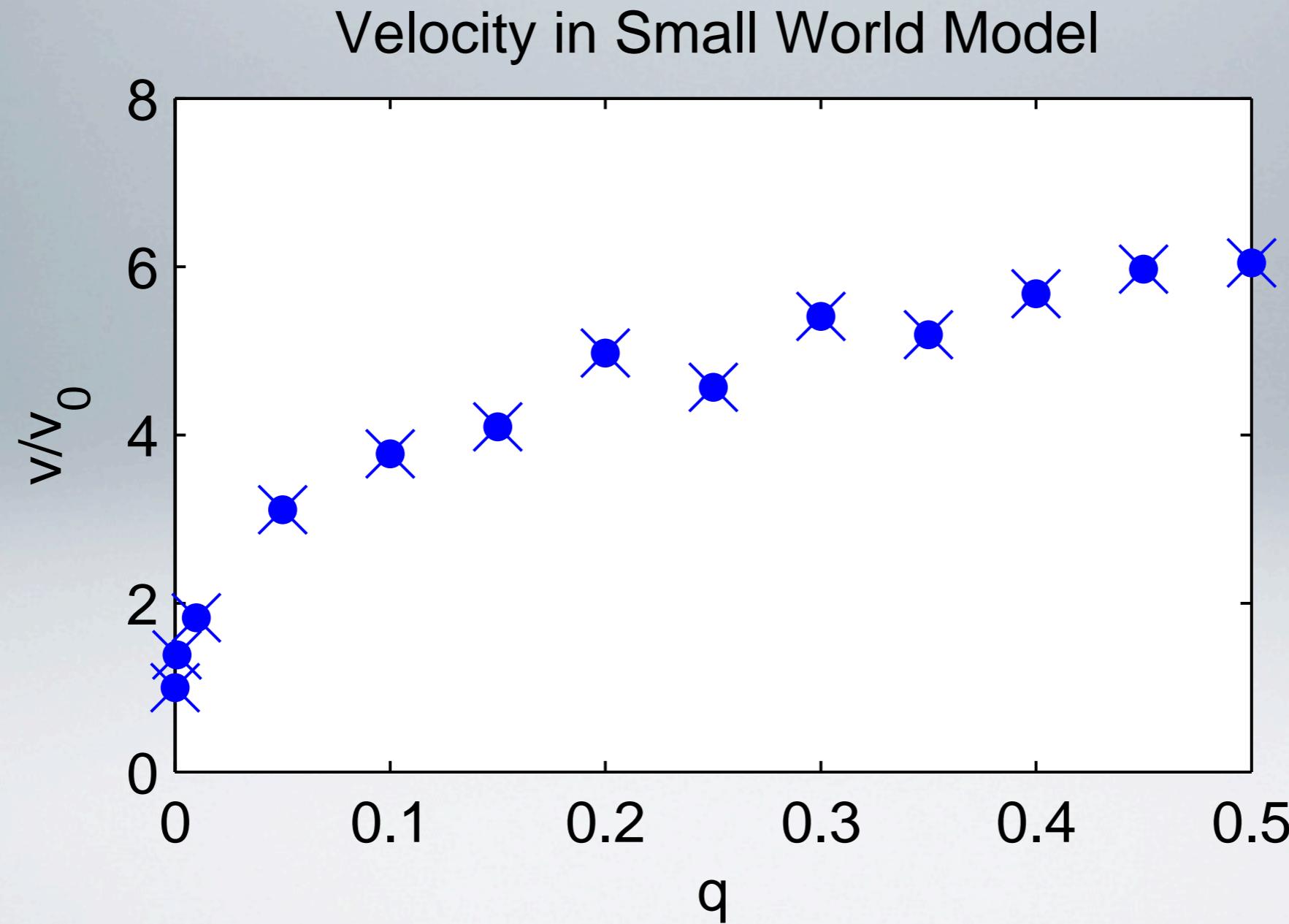


effective velocity

$$v = d/T$$



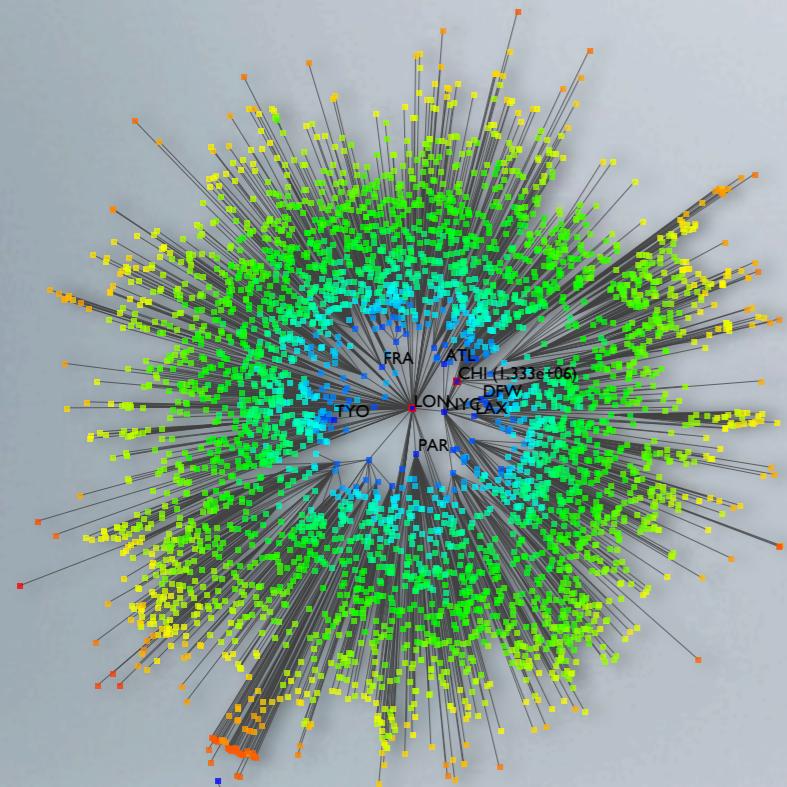
EFFECTIVE VELOCITY AS A FUNCTION OF LONG RANGE LINKS



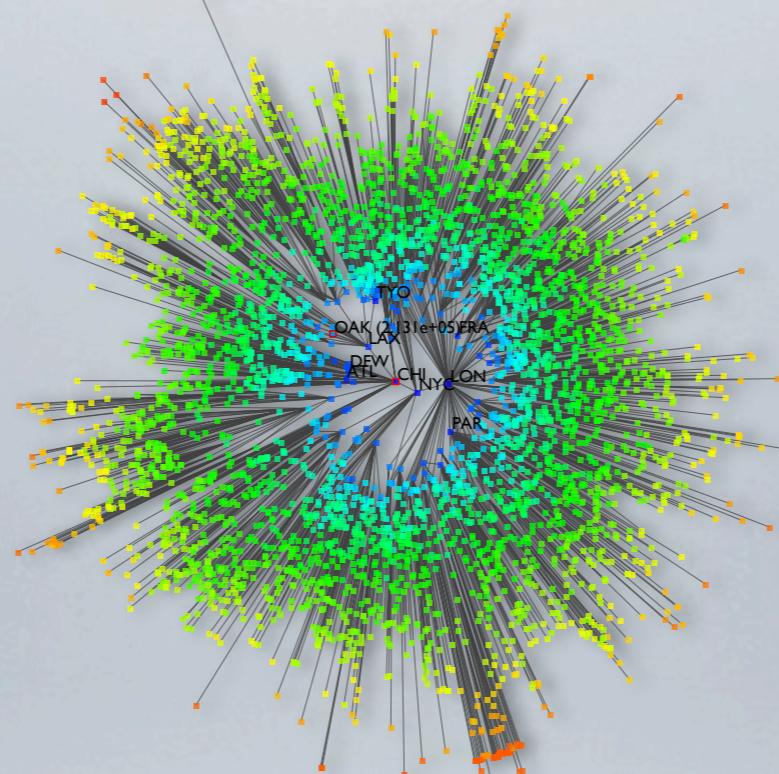
SPATO

WORLDWIDE AIR TRANSPORTATION NETWORK

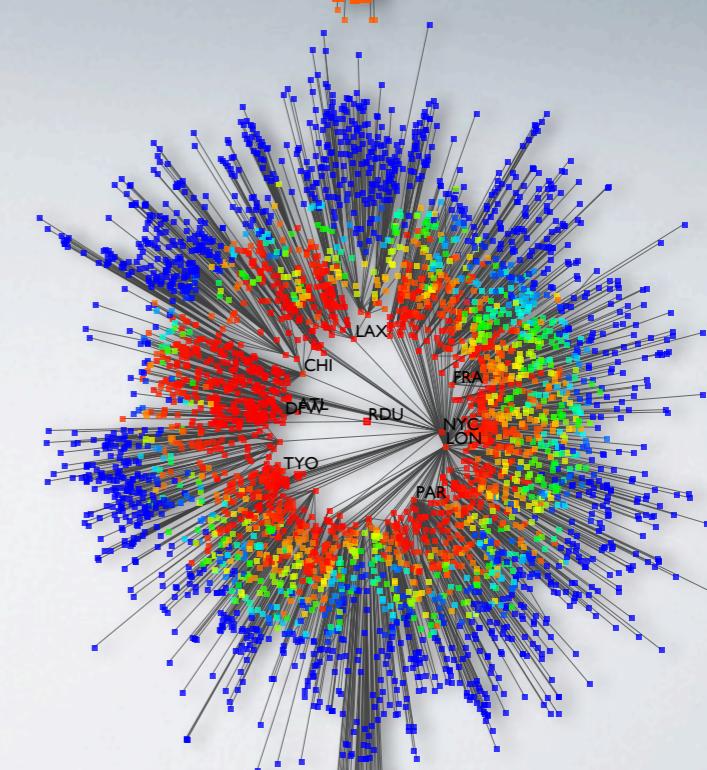
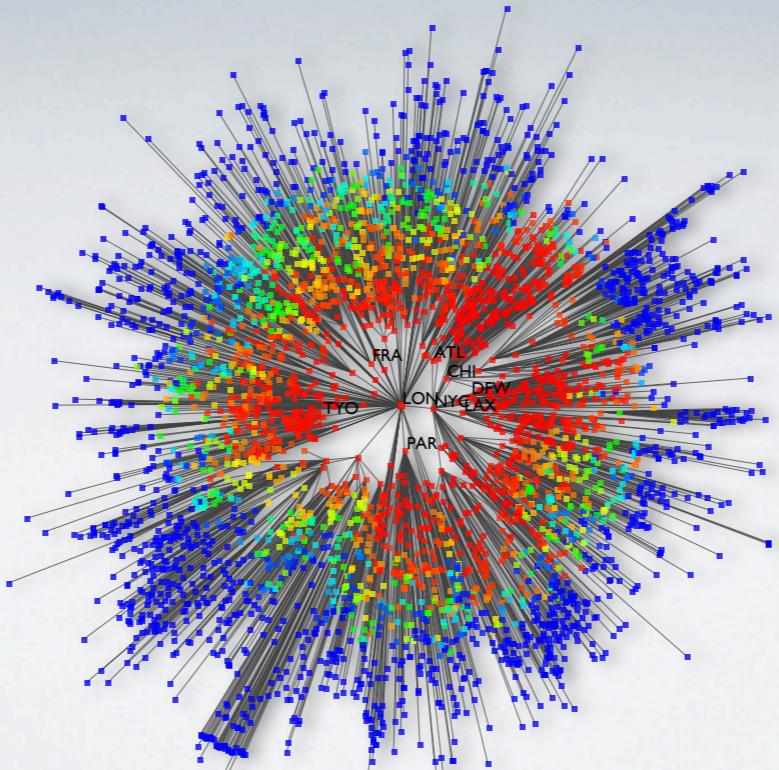
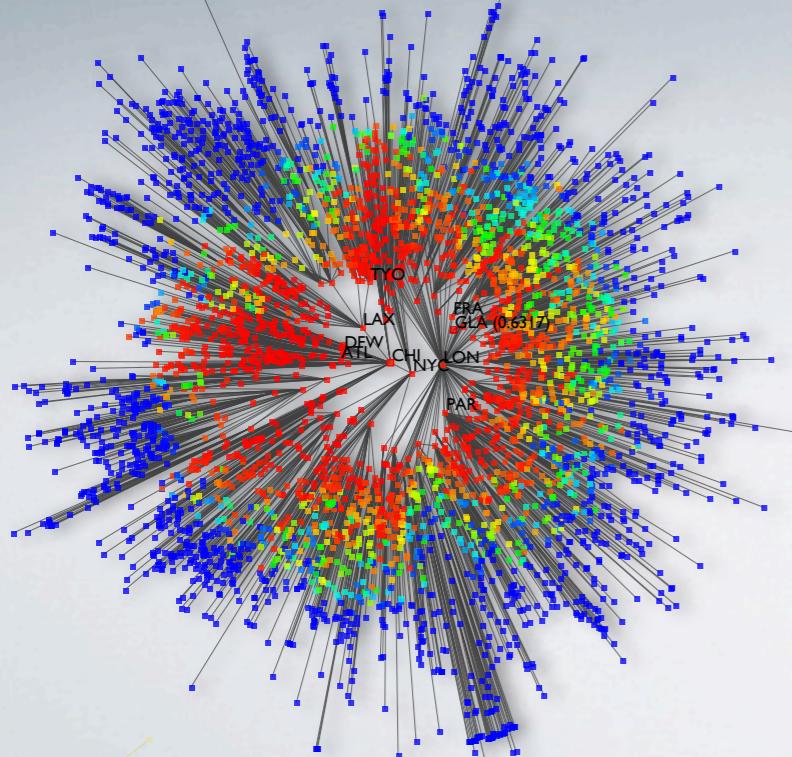
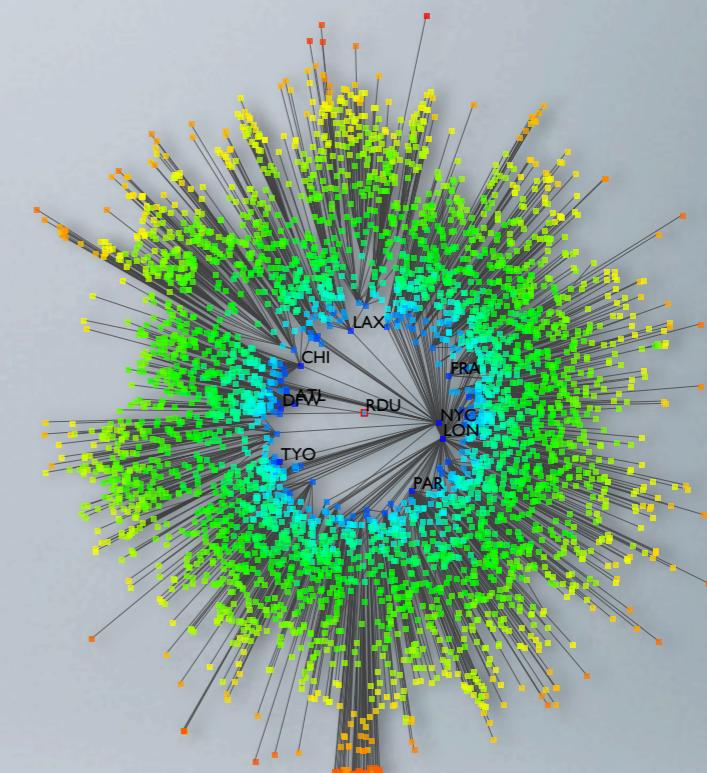
London



Chicago



durham, NC

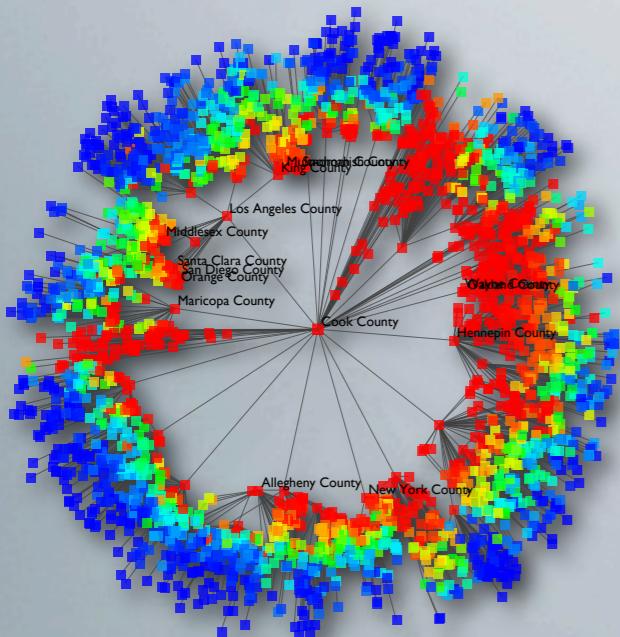


US MULTISCALE MOBILITY

US MULTISCALE MOBILITY



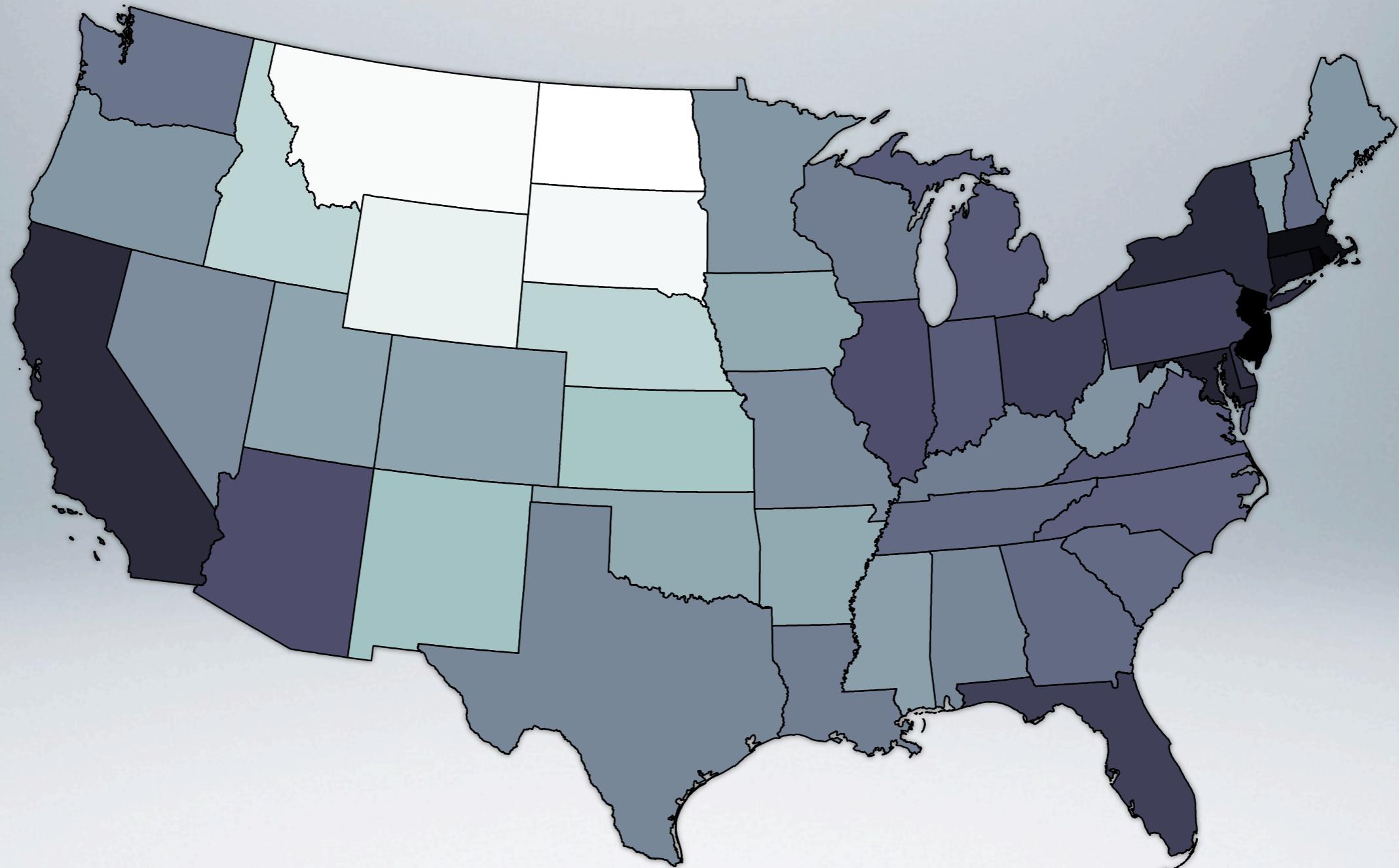
CONCLUSIONS



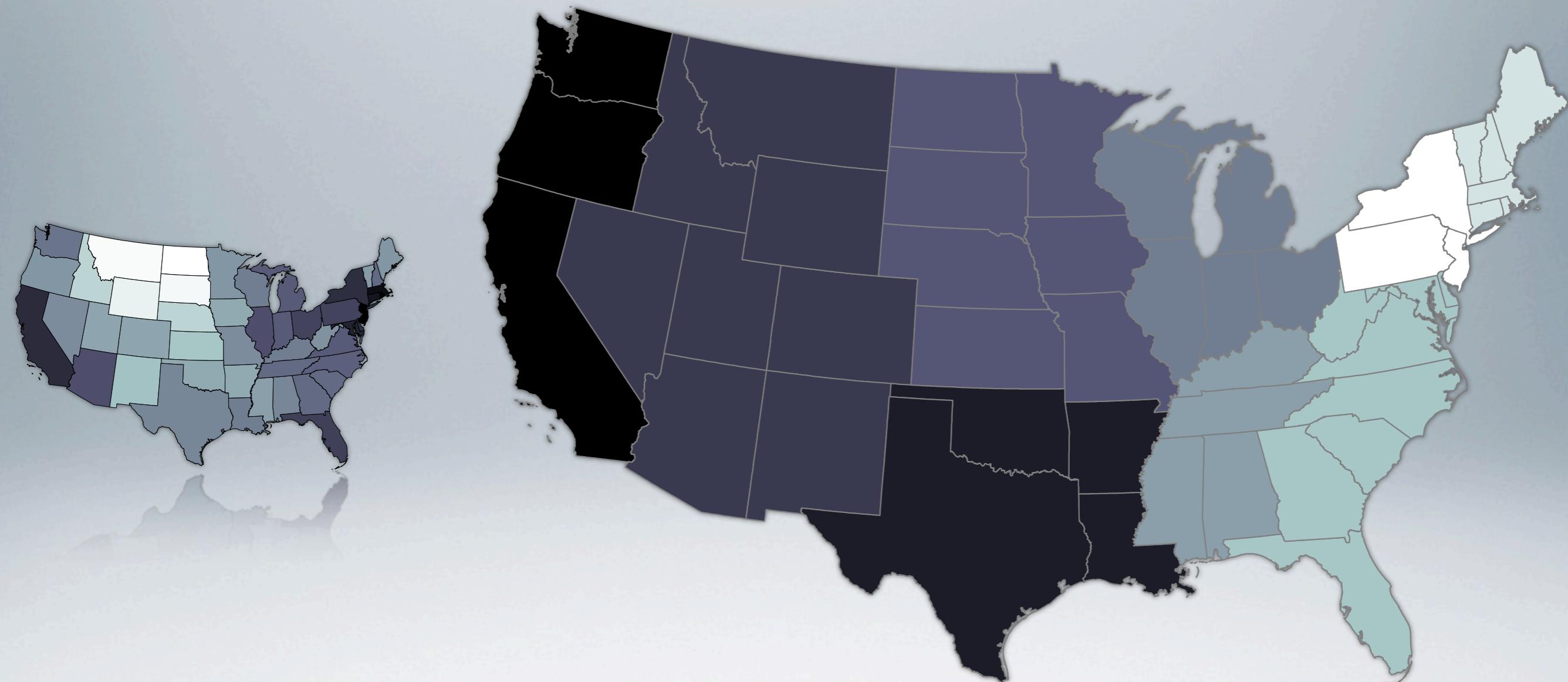
- Shortest paths and shortest path tree representations simplify the dynamics
- effective propagation speeds based on effective distance
- long links along imply constant velocity
- the combination of scale free traffic and weight heterogeneity yield exponential spread

THE BORDERS IN HUMAN MOBILITY

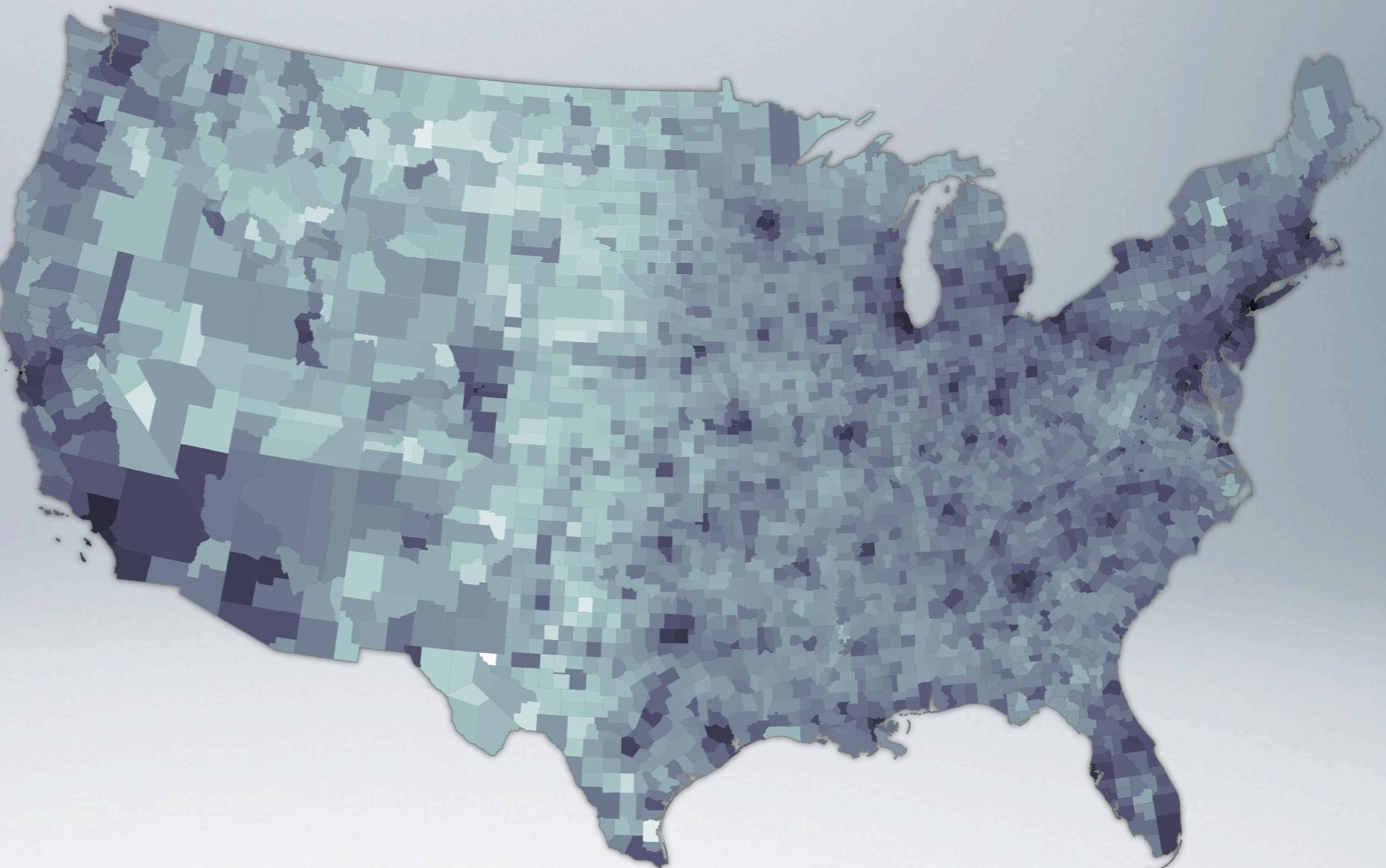
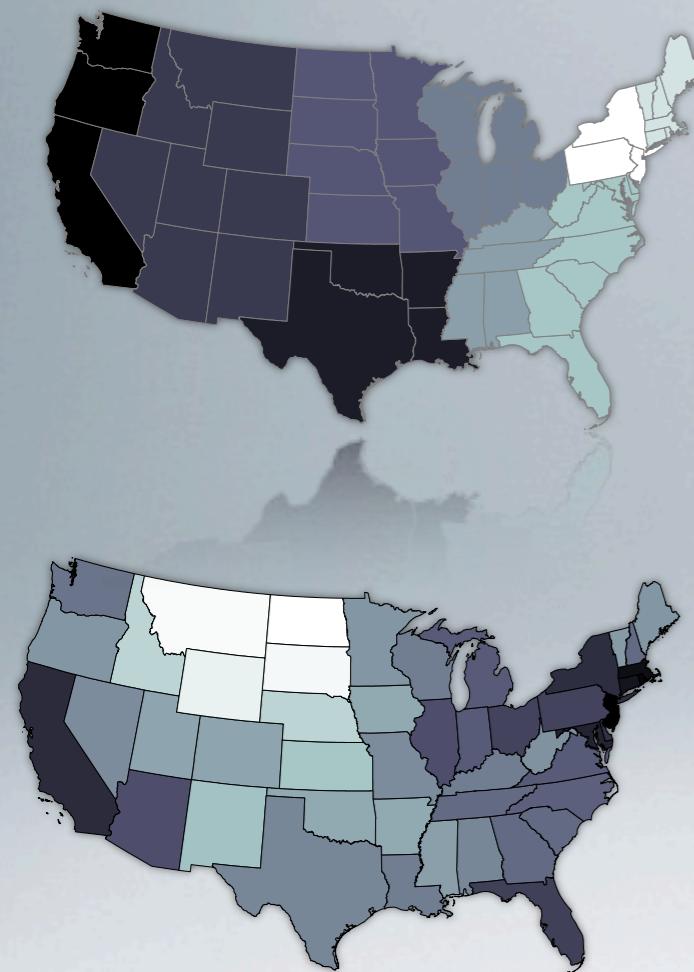
GEOGRAPHICAL SUBDIVISIONS



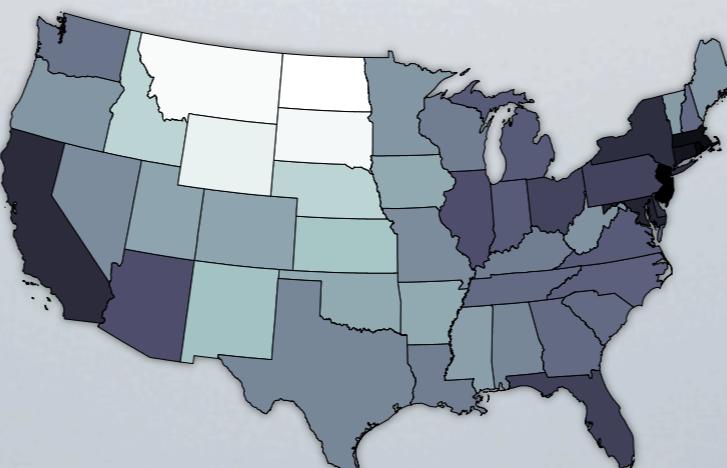
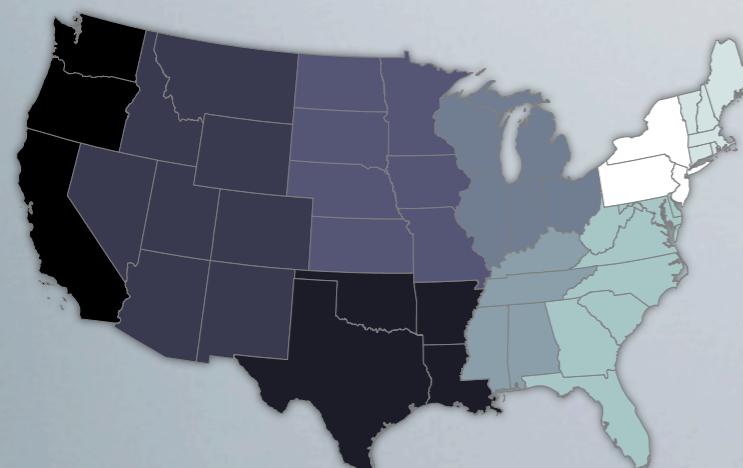
GEOGRAPHICAL SUBDIVISIONS



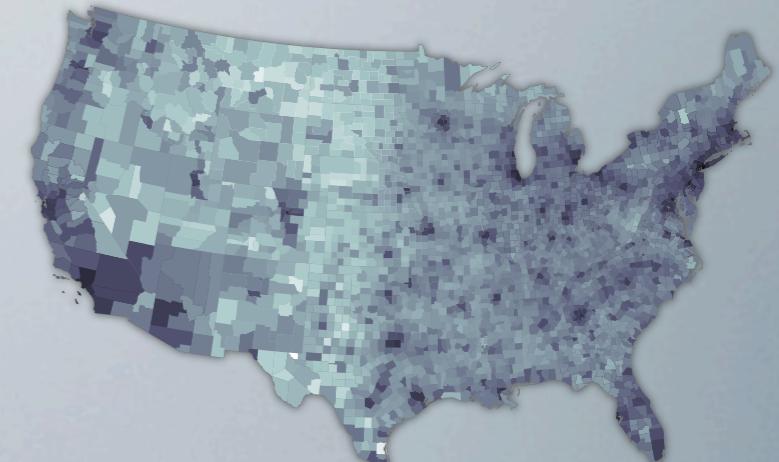
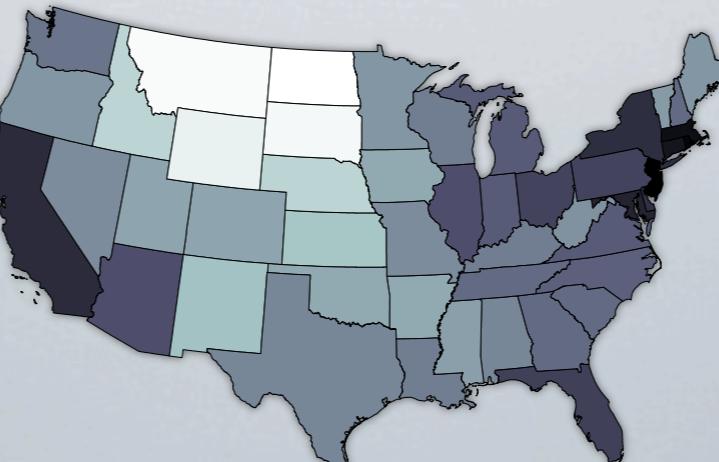
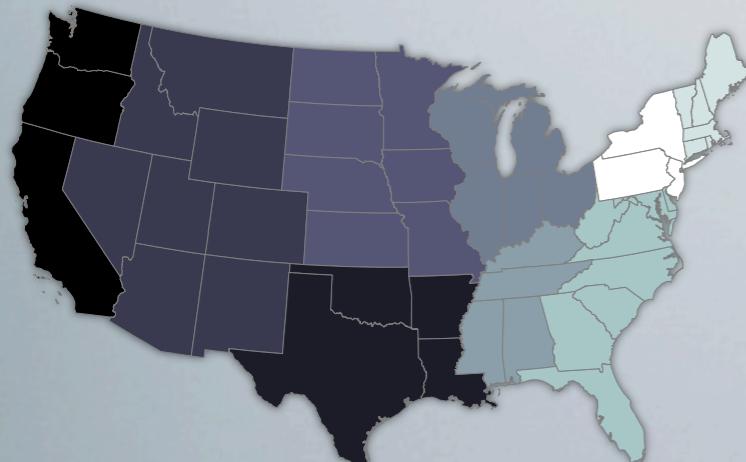
GEOGRAPHICAL SUBDIVISIONS



GEOGRAPHICAL SUBDIVISIONS

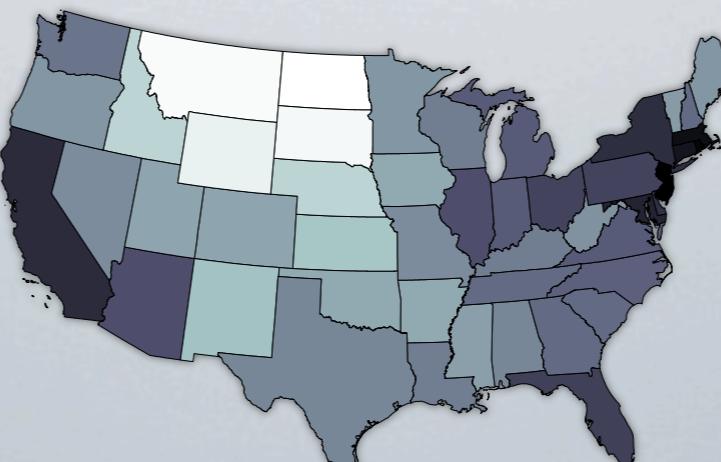
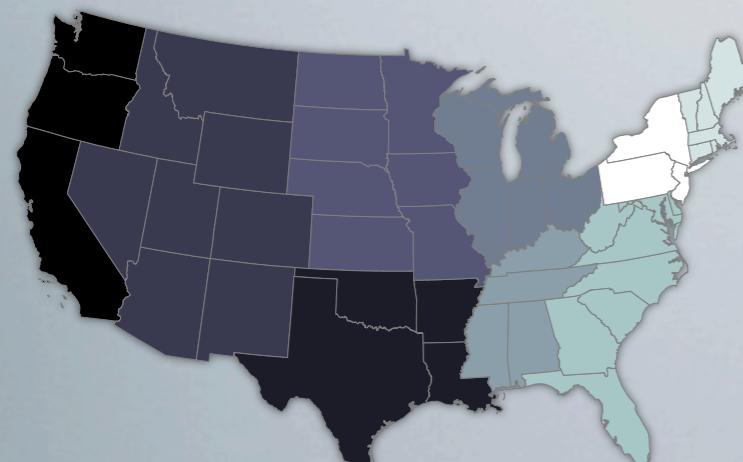


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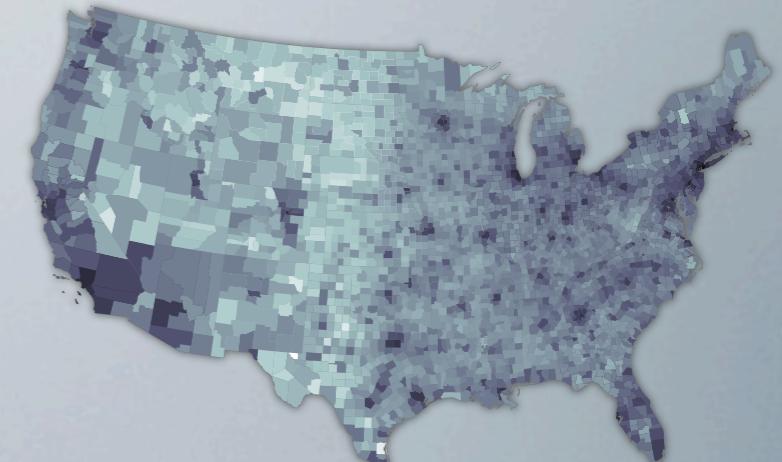
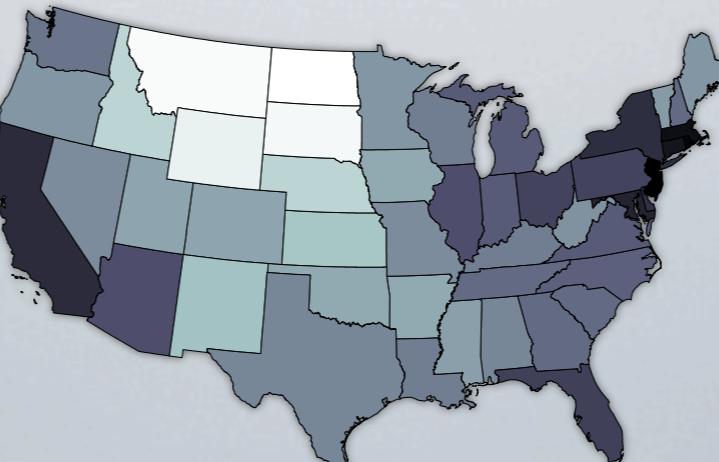
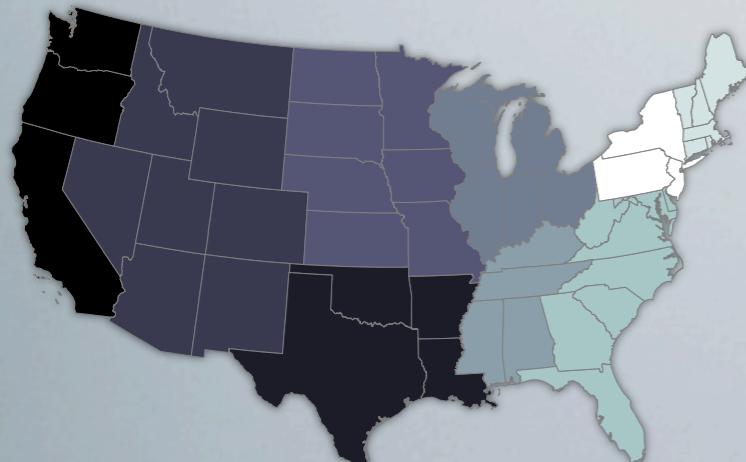


hierarchical structure
spatially compact
historically evolved
geographic determinants

GEOGRAPHICAL SUBDIVISIONS

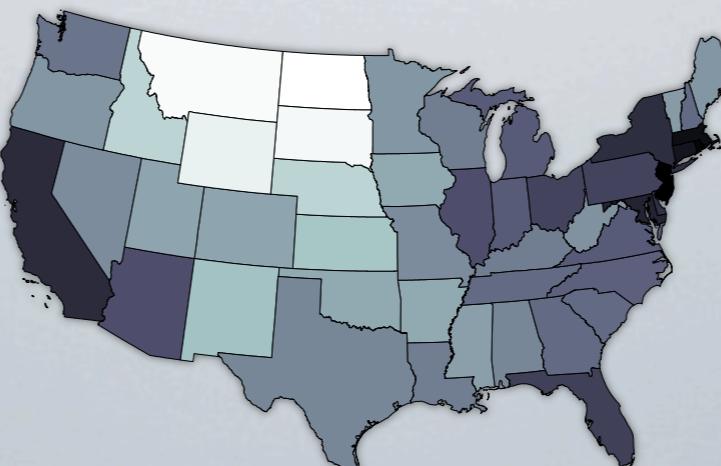
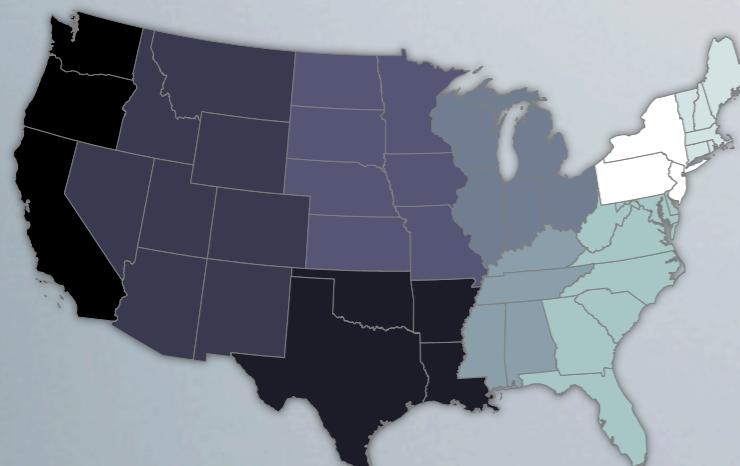


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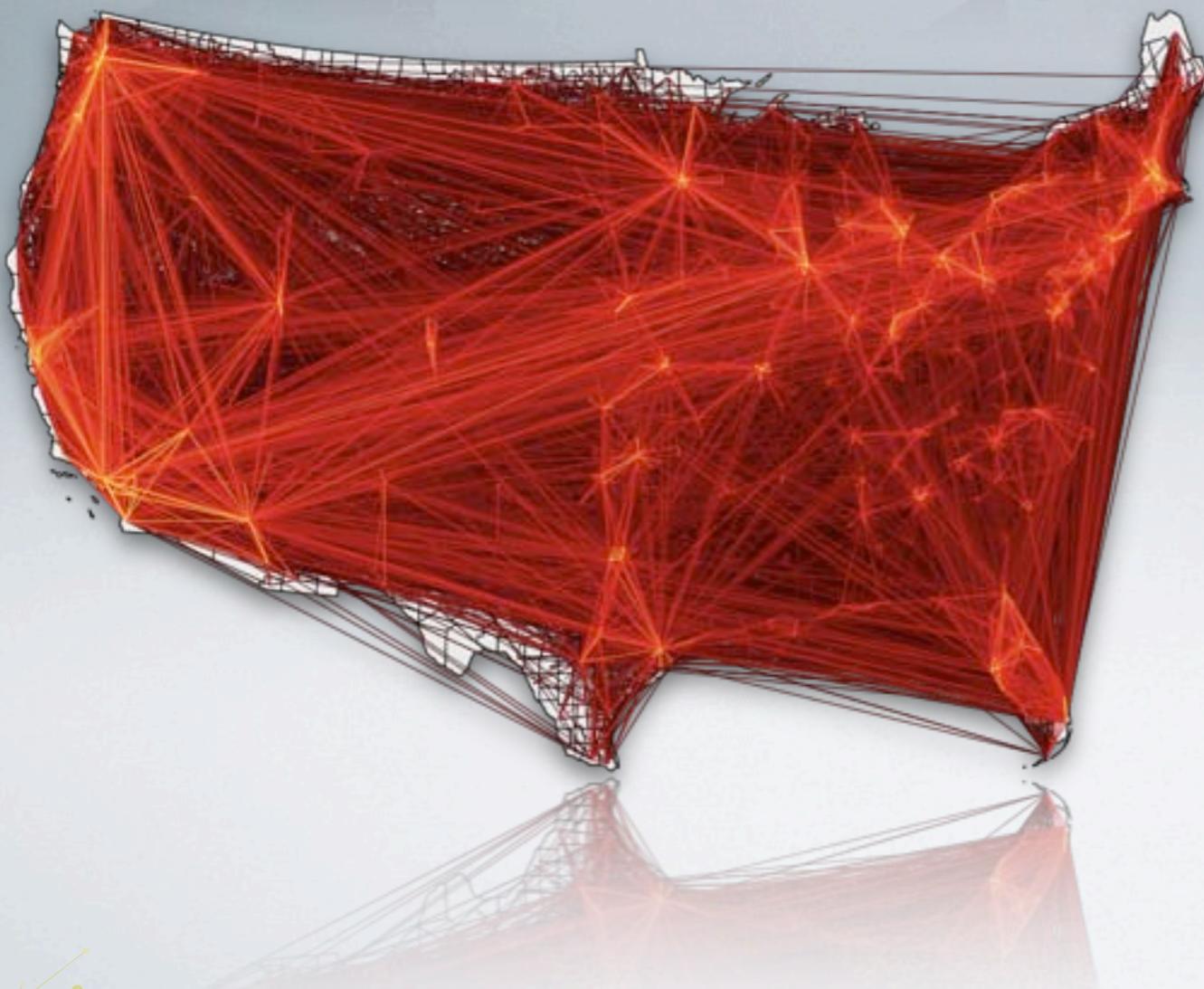
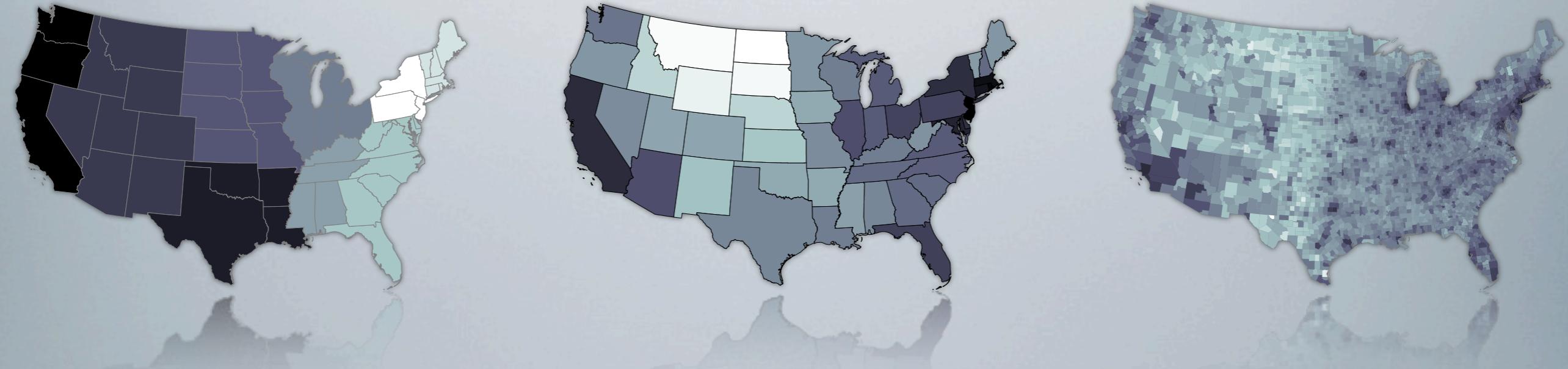


- What are the **effective** subdivisions of the United States?
- Where are **effective** borders?
- Are **effective** subdivisions spatially compact?

GEOGRAPHICAL SUBDIVISIONS

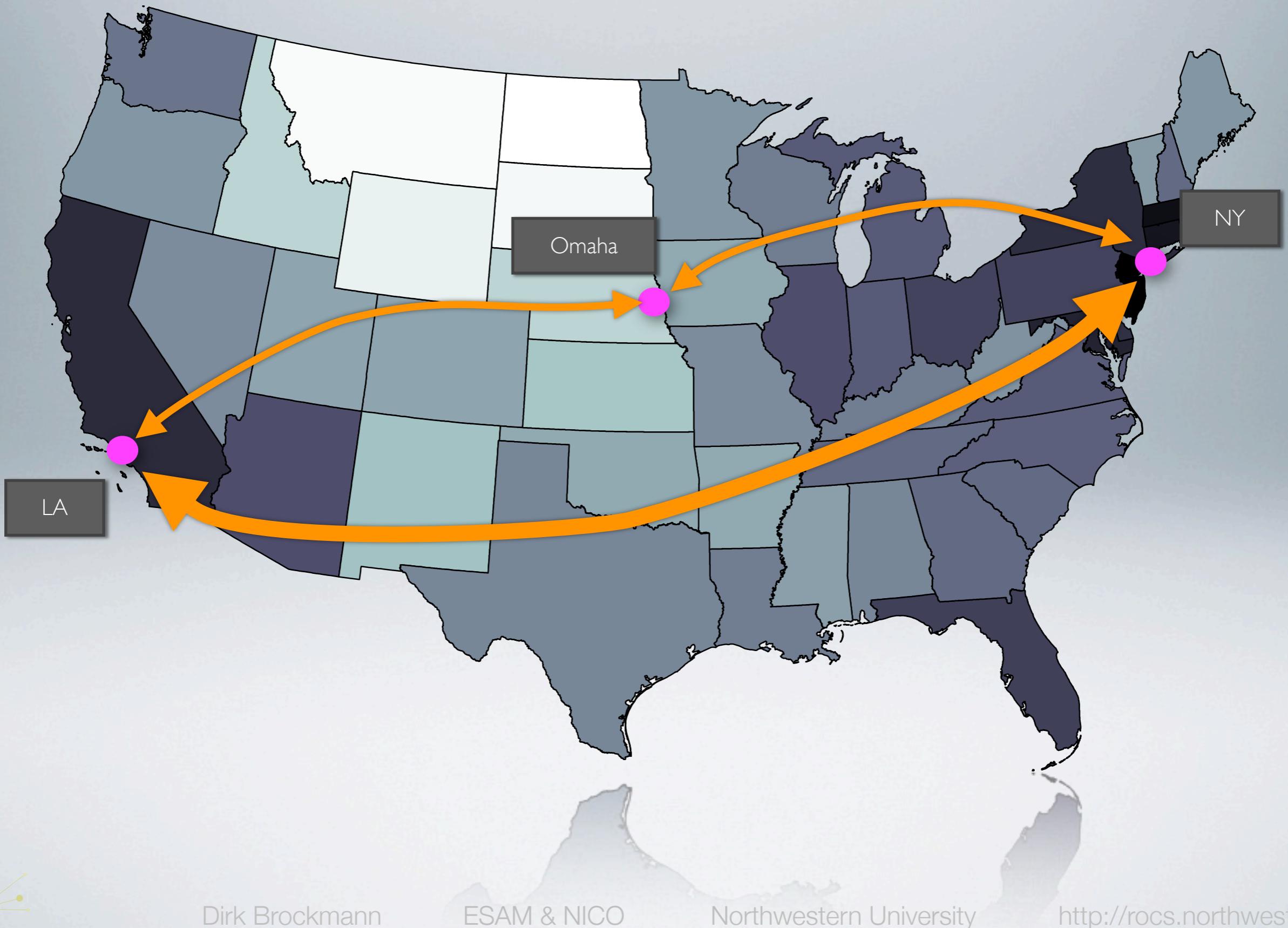


GEOGRAPHICAL SUBDIVISIONS

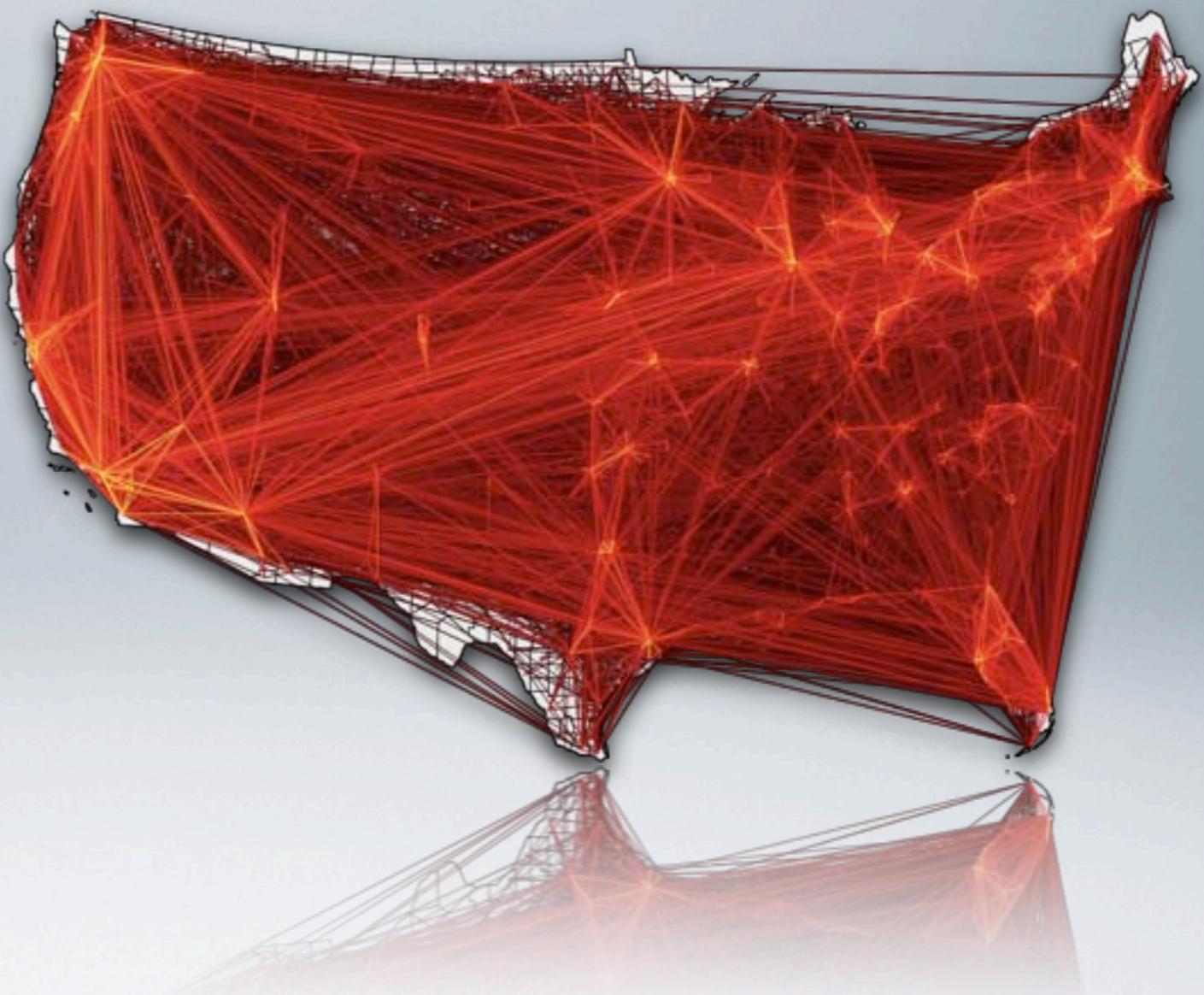
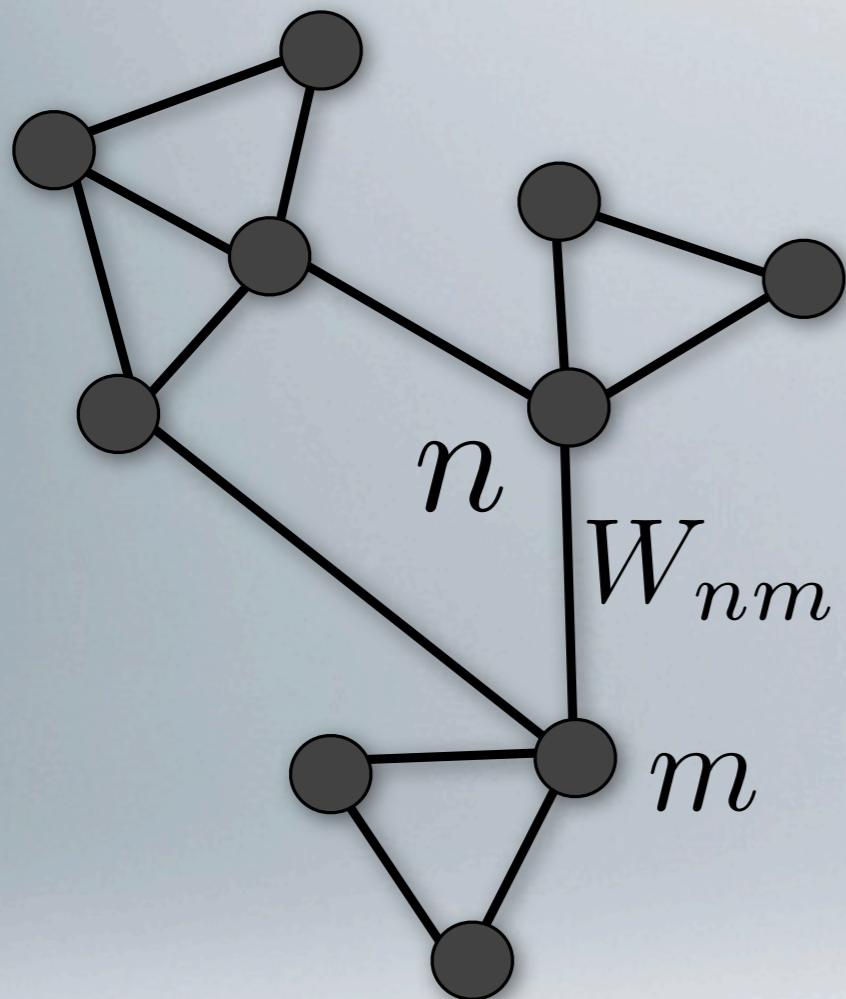


effective:
based on mobility

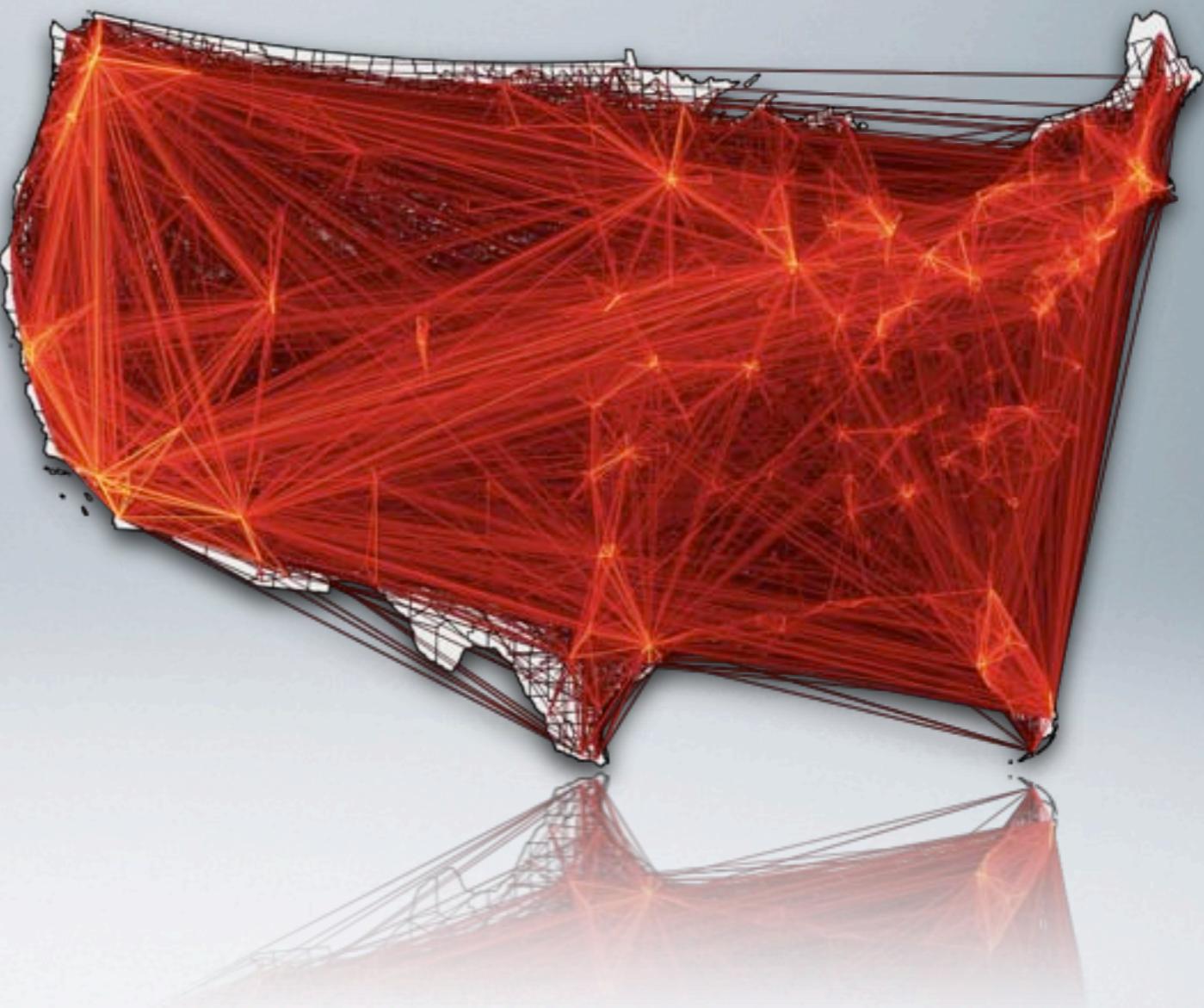
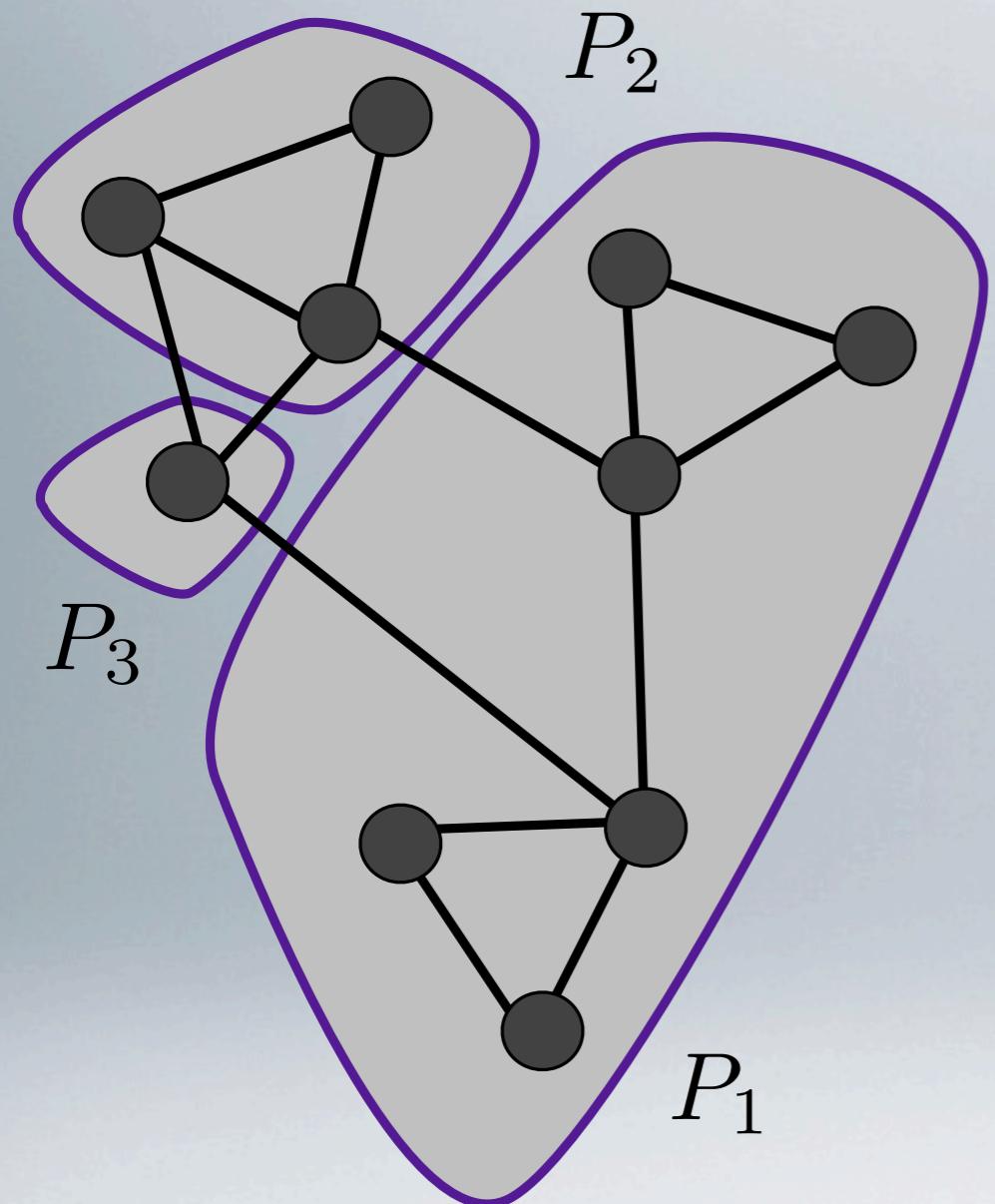
EFFECTIVE DISTANCE



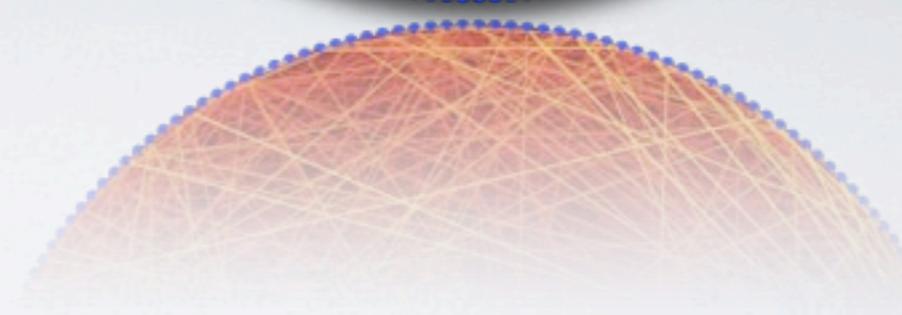
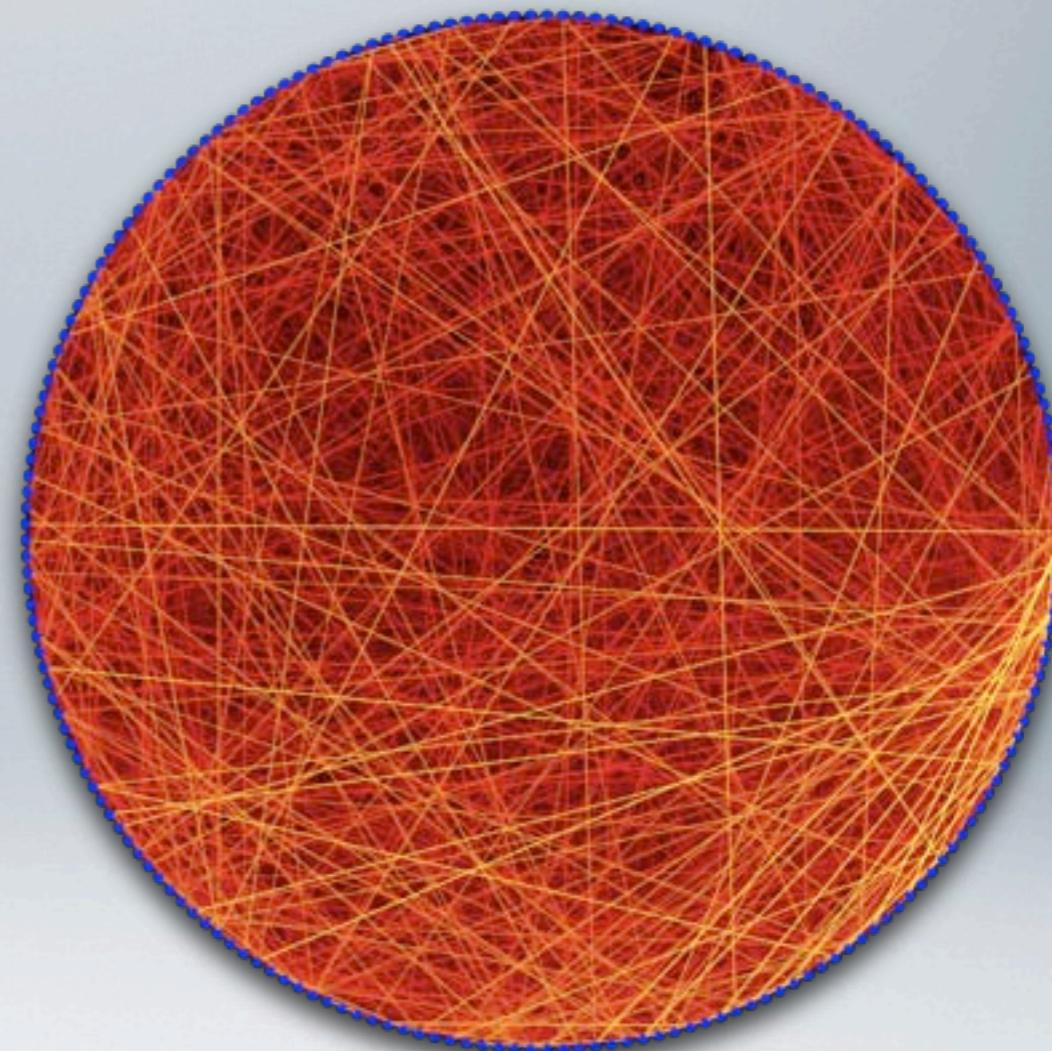
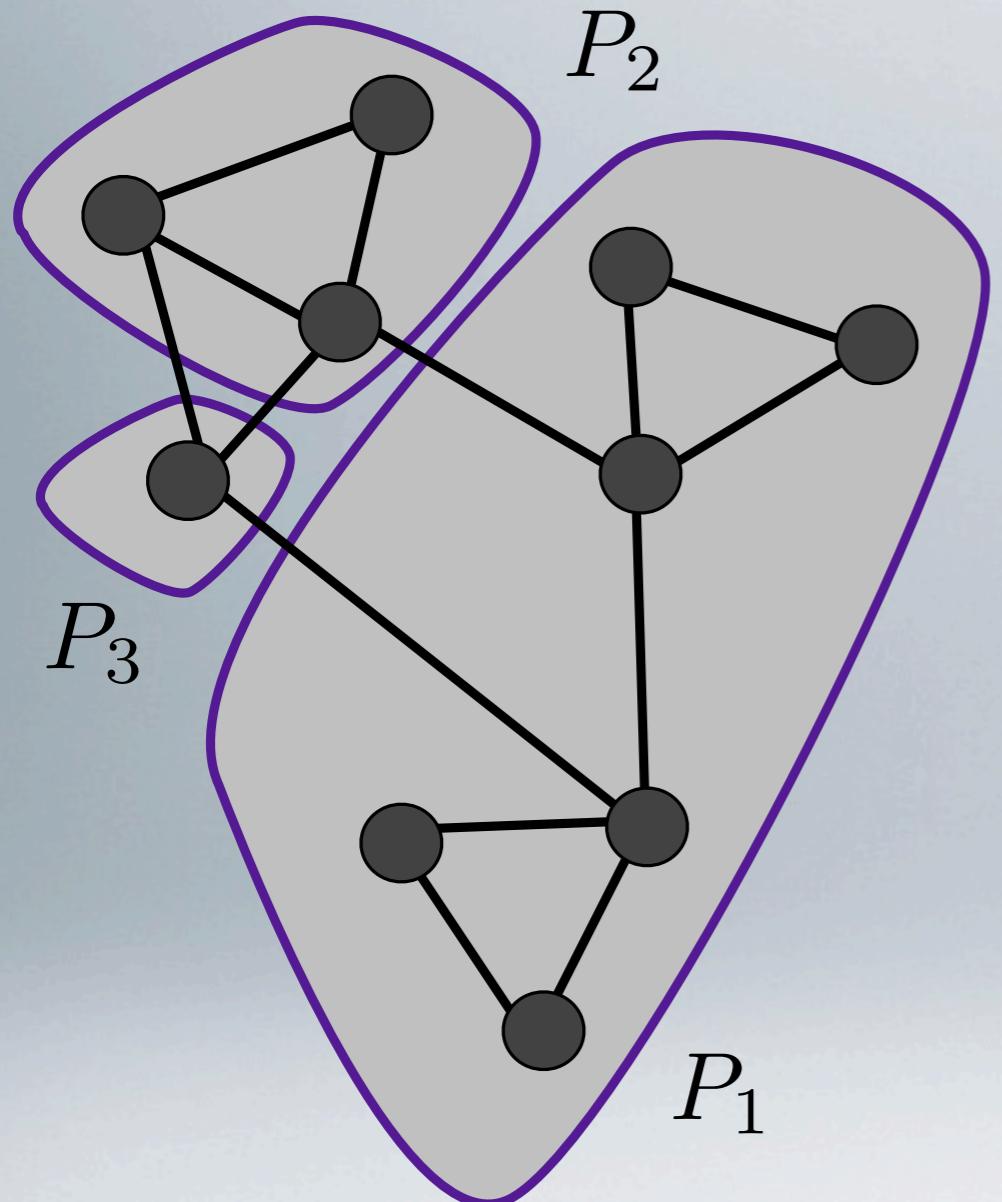
FINDING COMMUNITY STRUCTURE IN NETWORKS



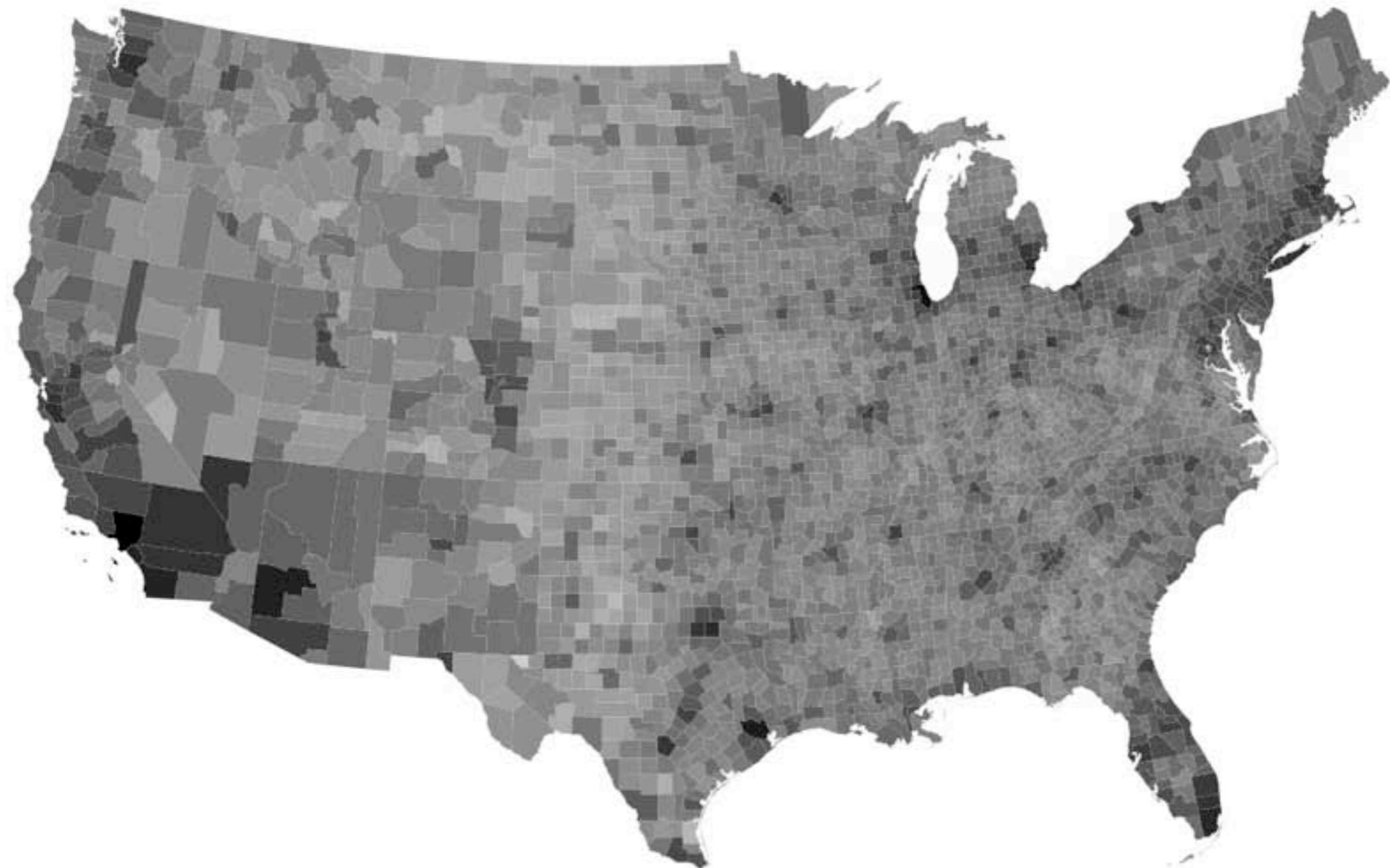
FINDING COMMUNITY STRUCTURE IN NETWORKS



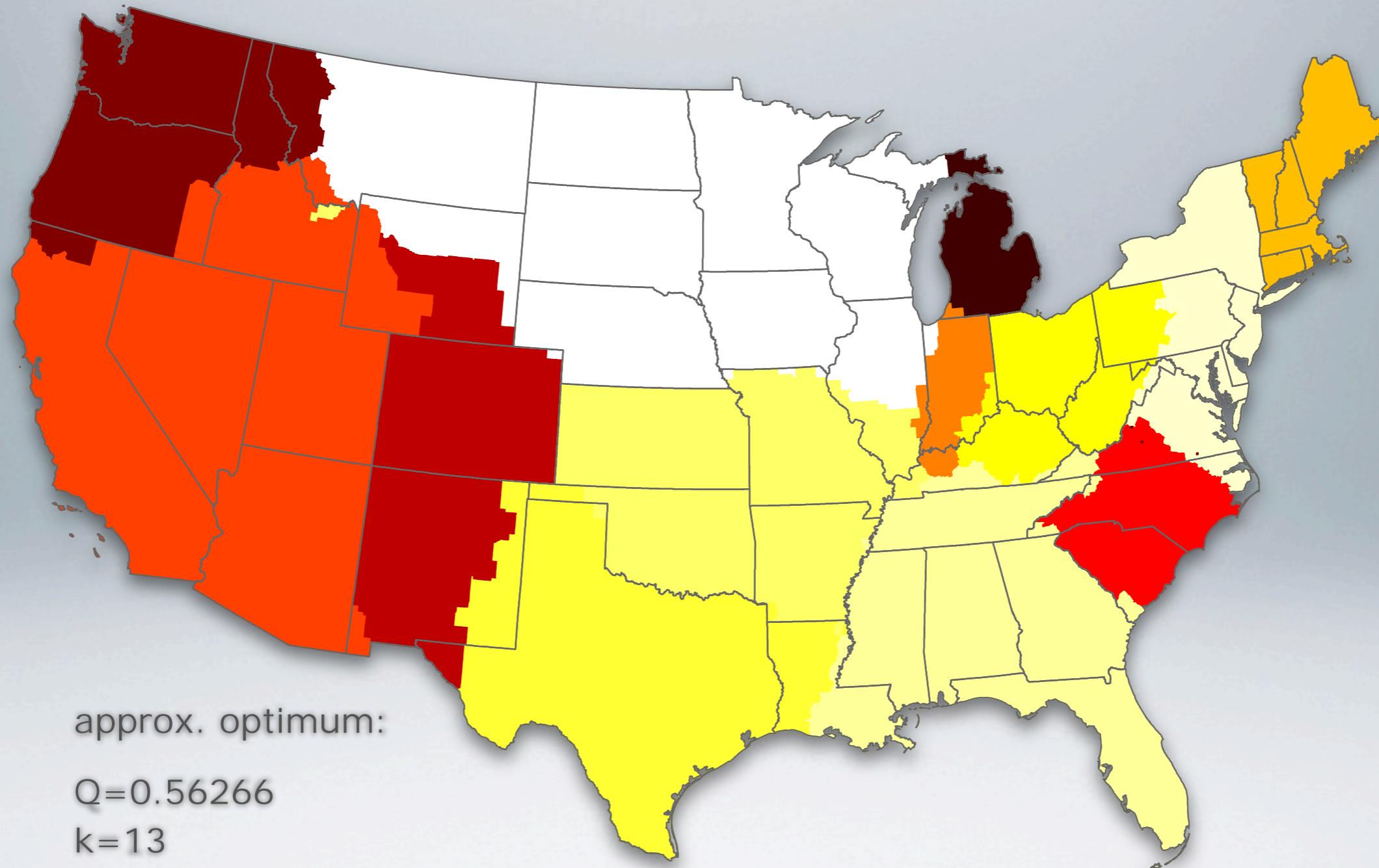
FINDING COMMUNITY STRUCTURE IN NETWORKS



OPTIMIZING MODULARITY

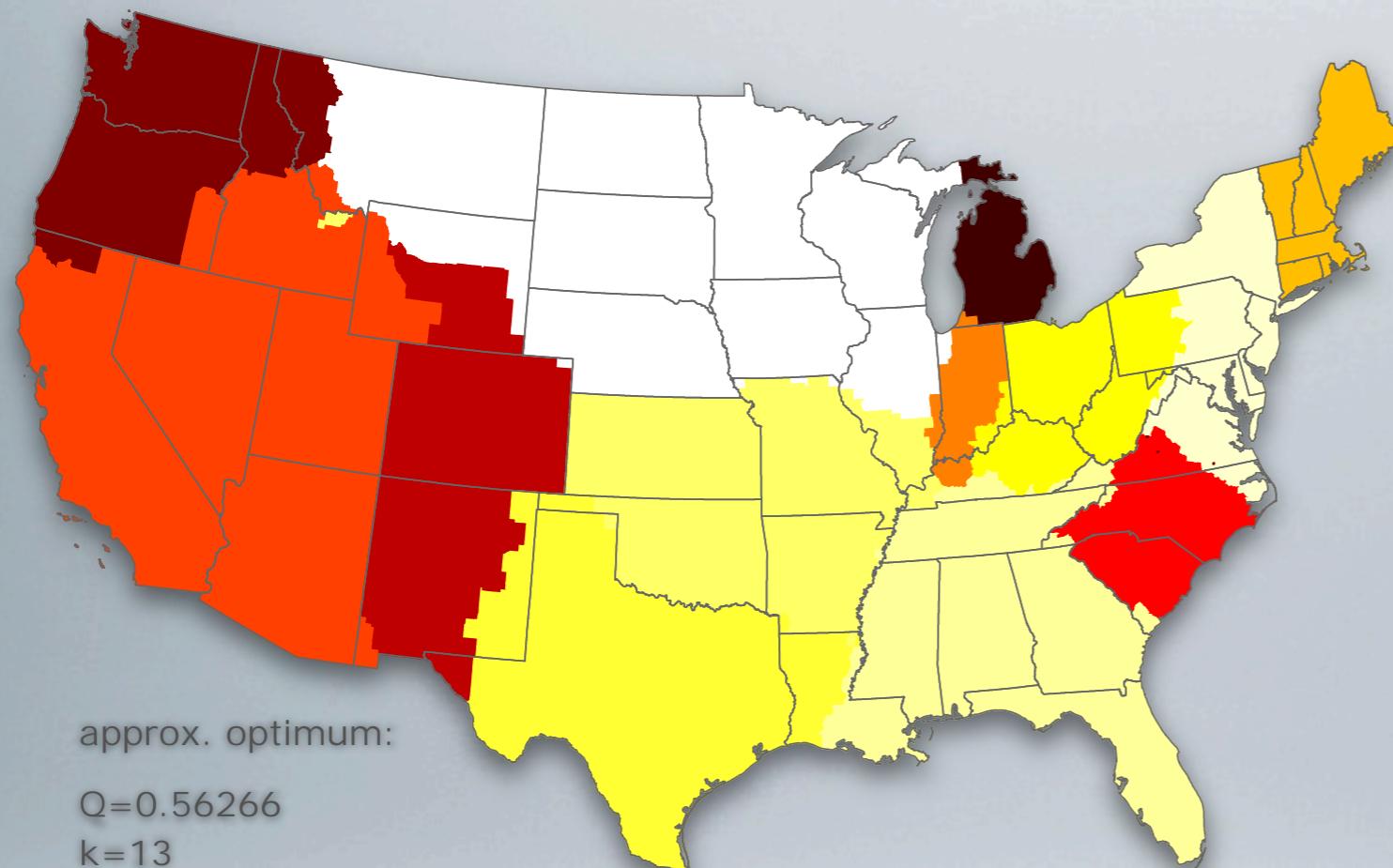


KEY FEATURES



F. J. Theis, P. Gruber and M. Vingron, *Soft Clustering finds hard partitioning*, (2008, submitted)

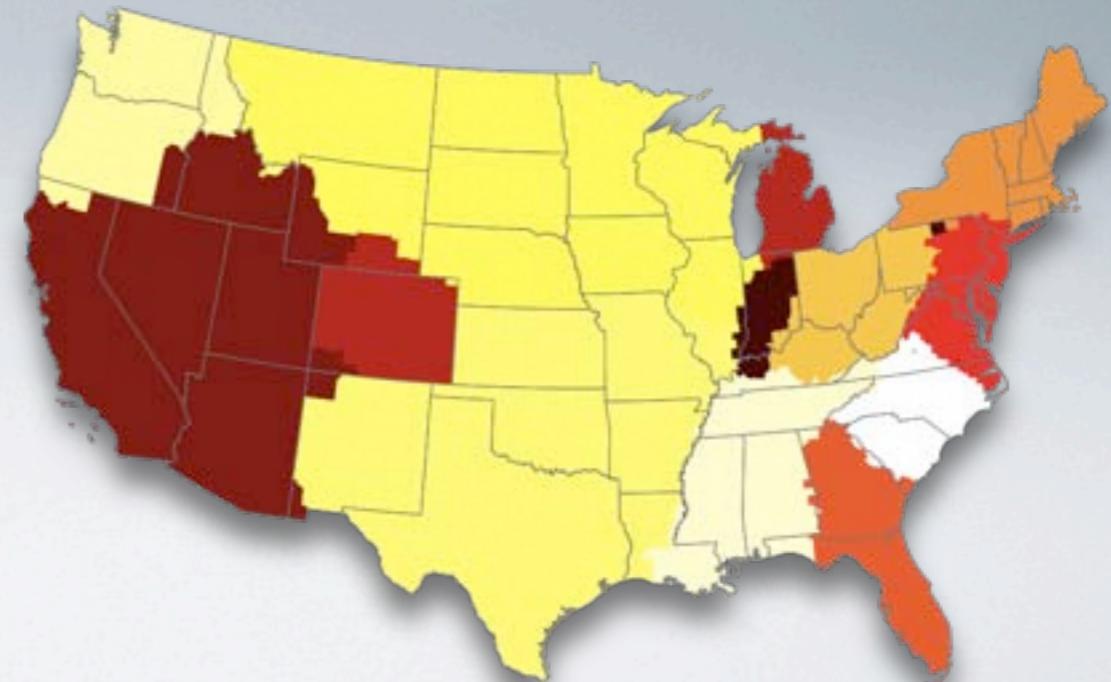
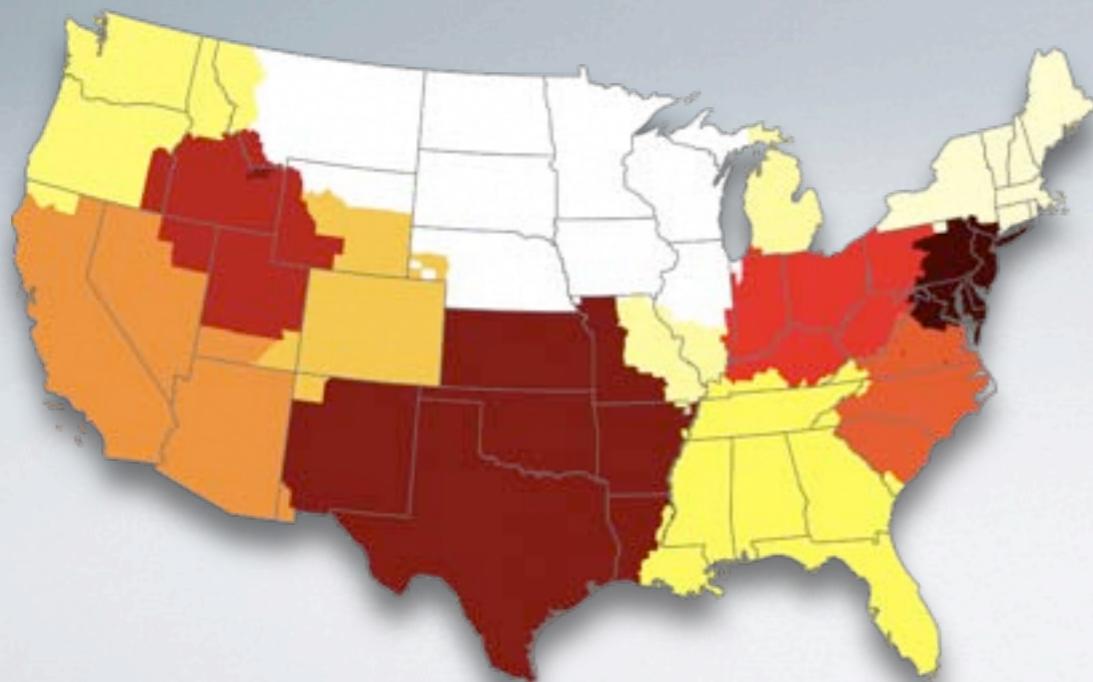
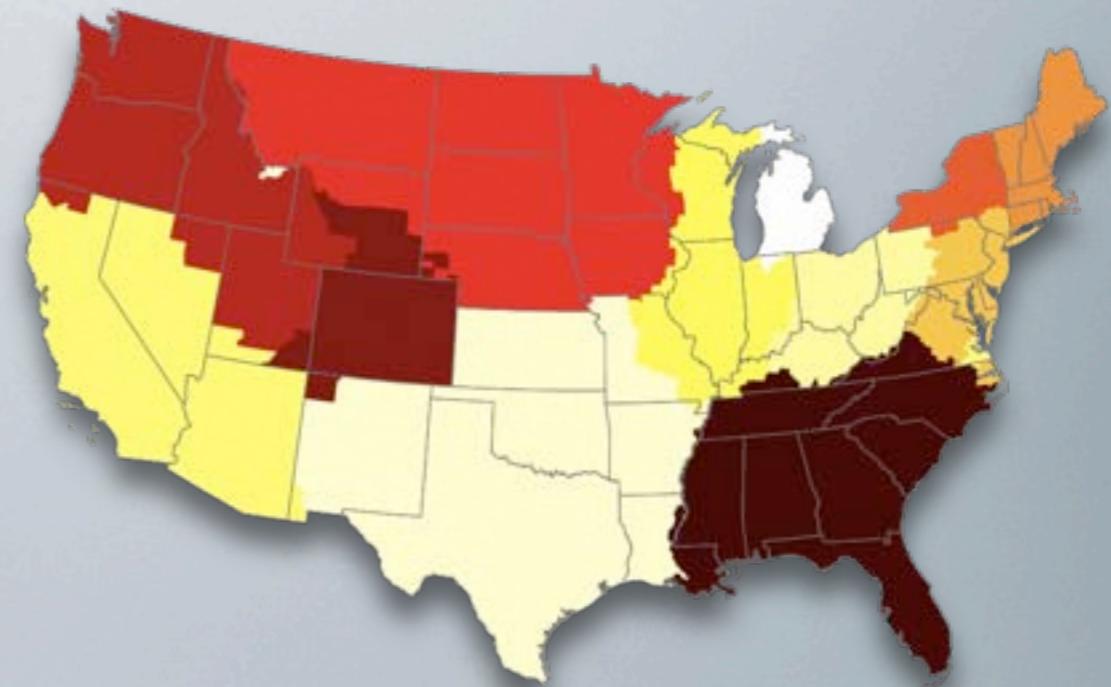
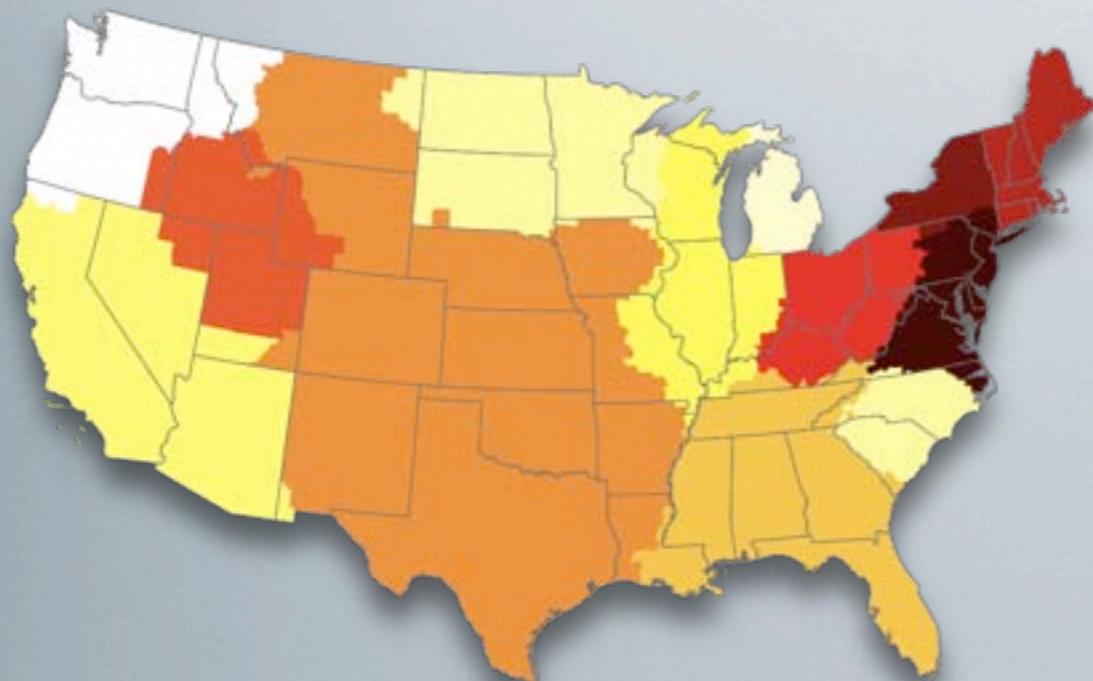
KEY FEATURES



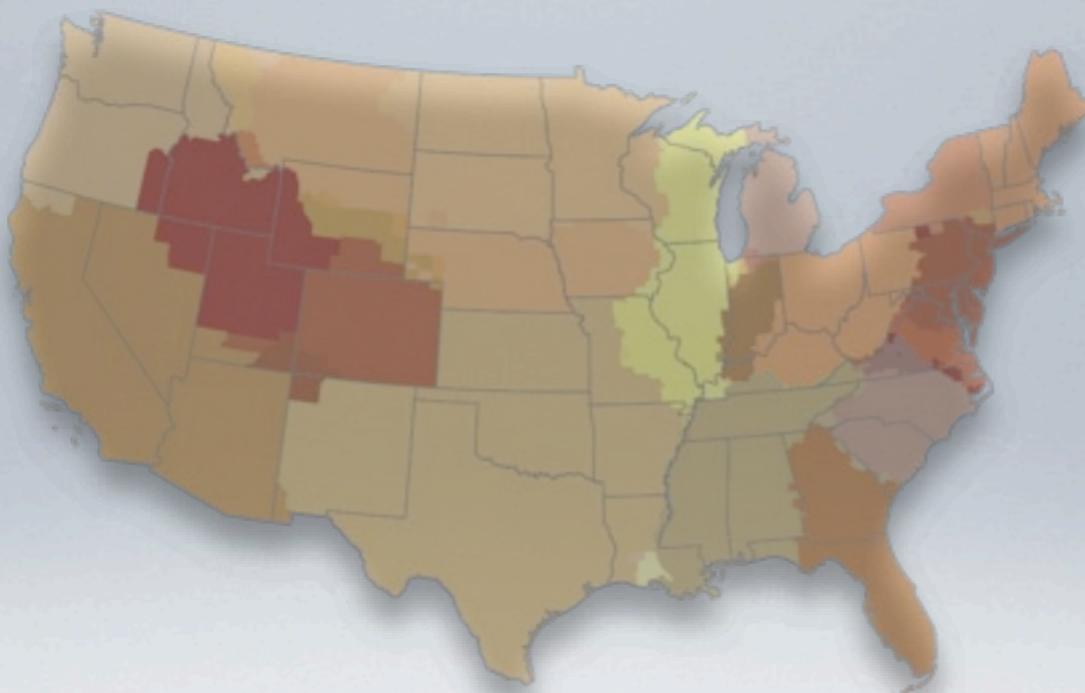
- global units are compact
- regional correlation with geographical features (rivers, mountains)
- regional correlation with state boundaries

F. J. Theis, P. Gruber and M. Vingron, *Soft Clustering finds hard partitioning*, (2008, submitted)

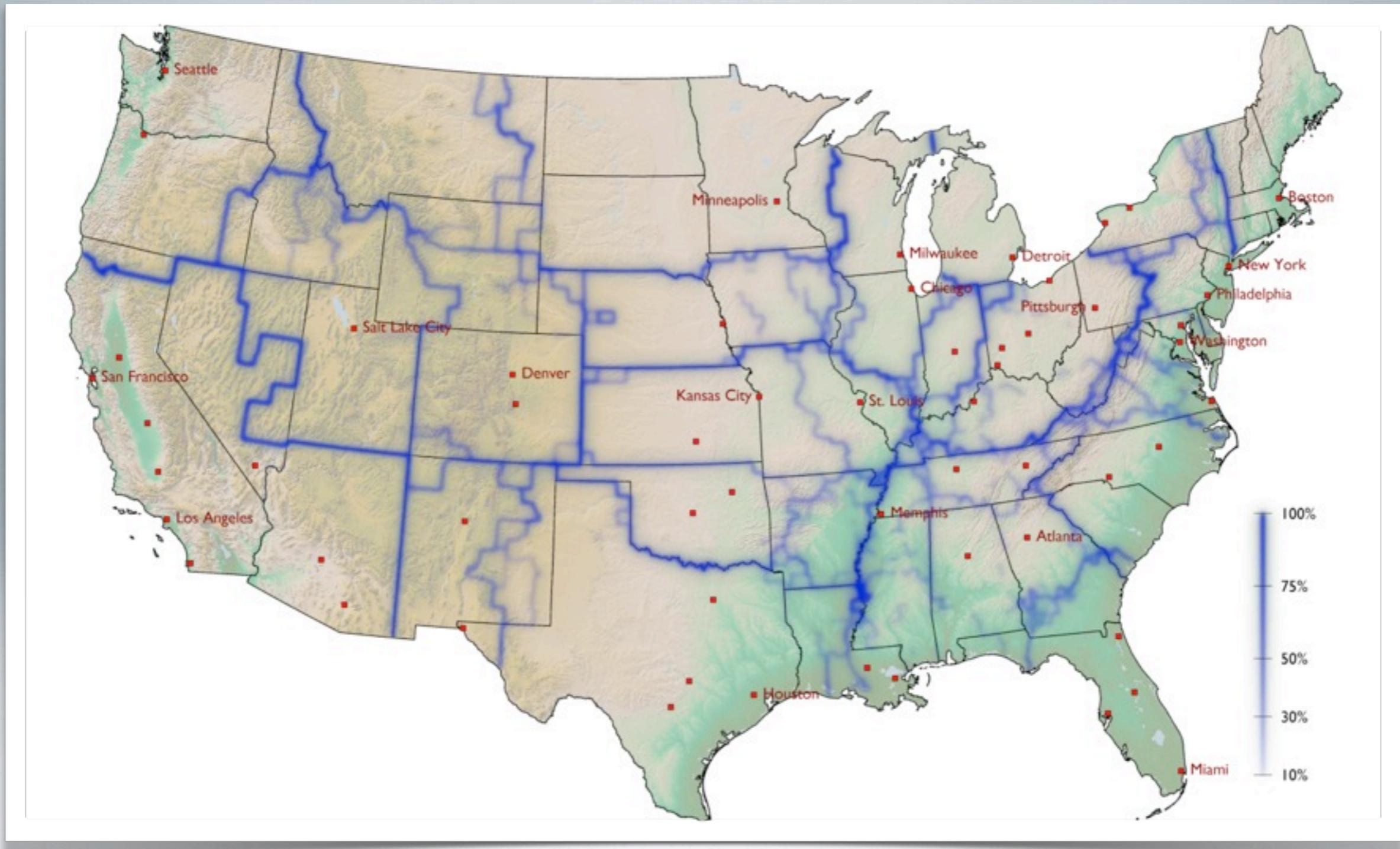
SUPERPOSITION



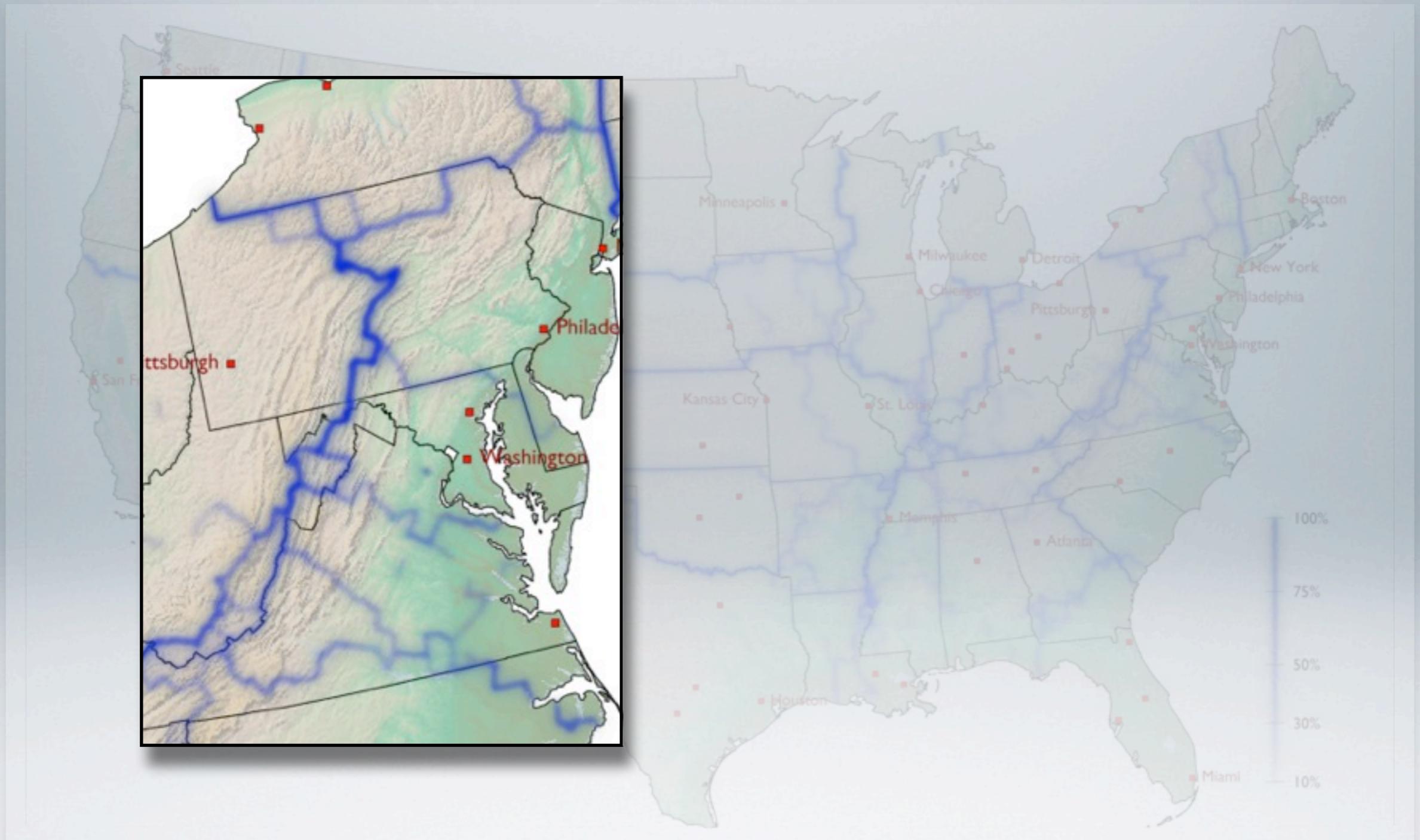
SUPERPOSITION



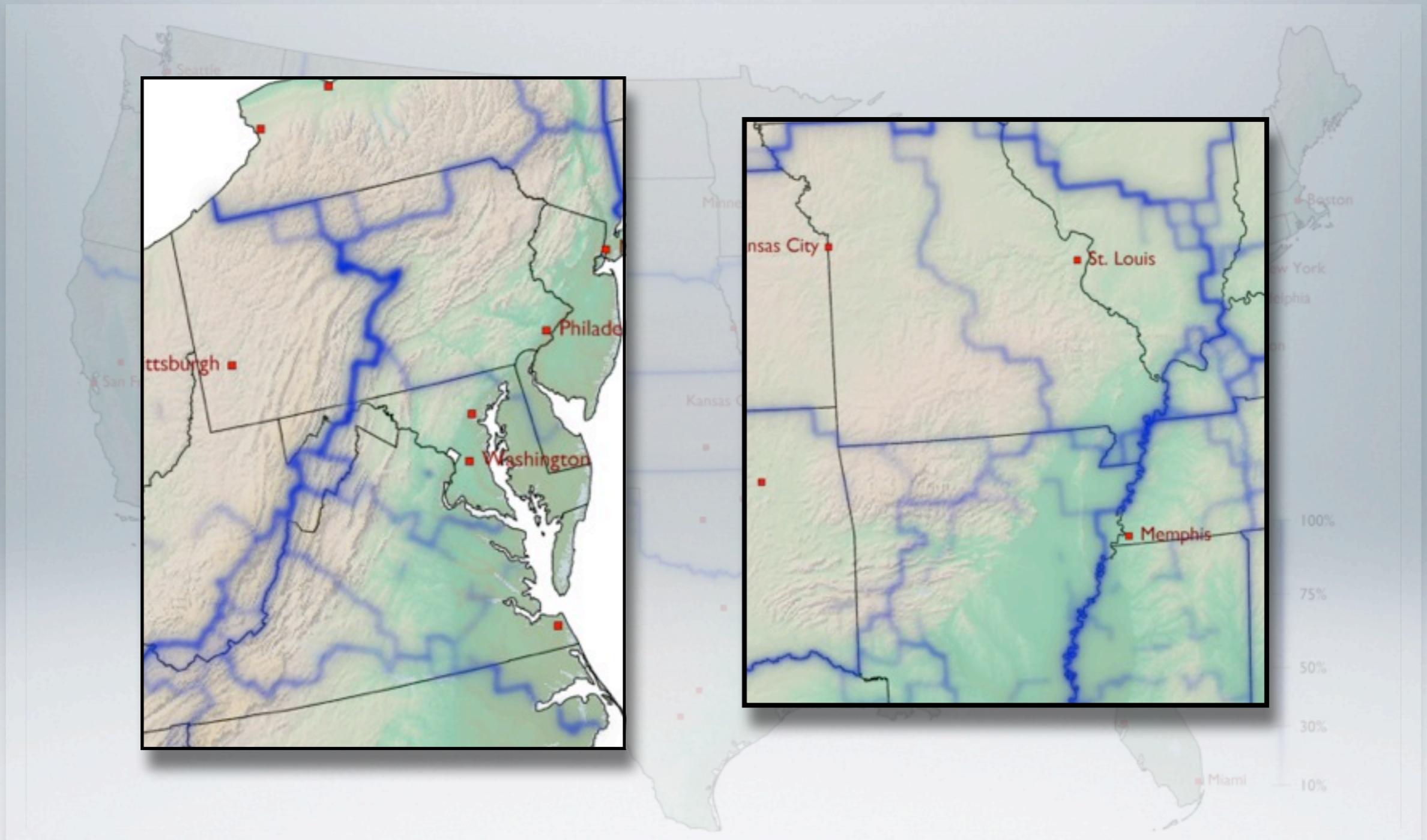
MOBILITY BORDERS



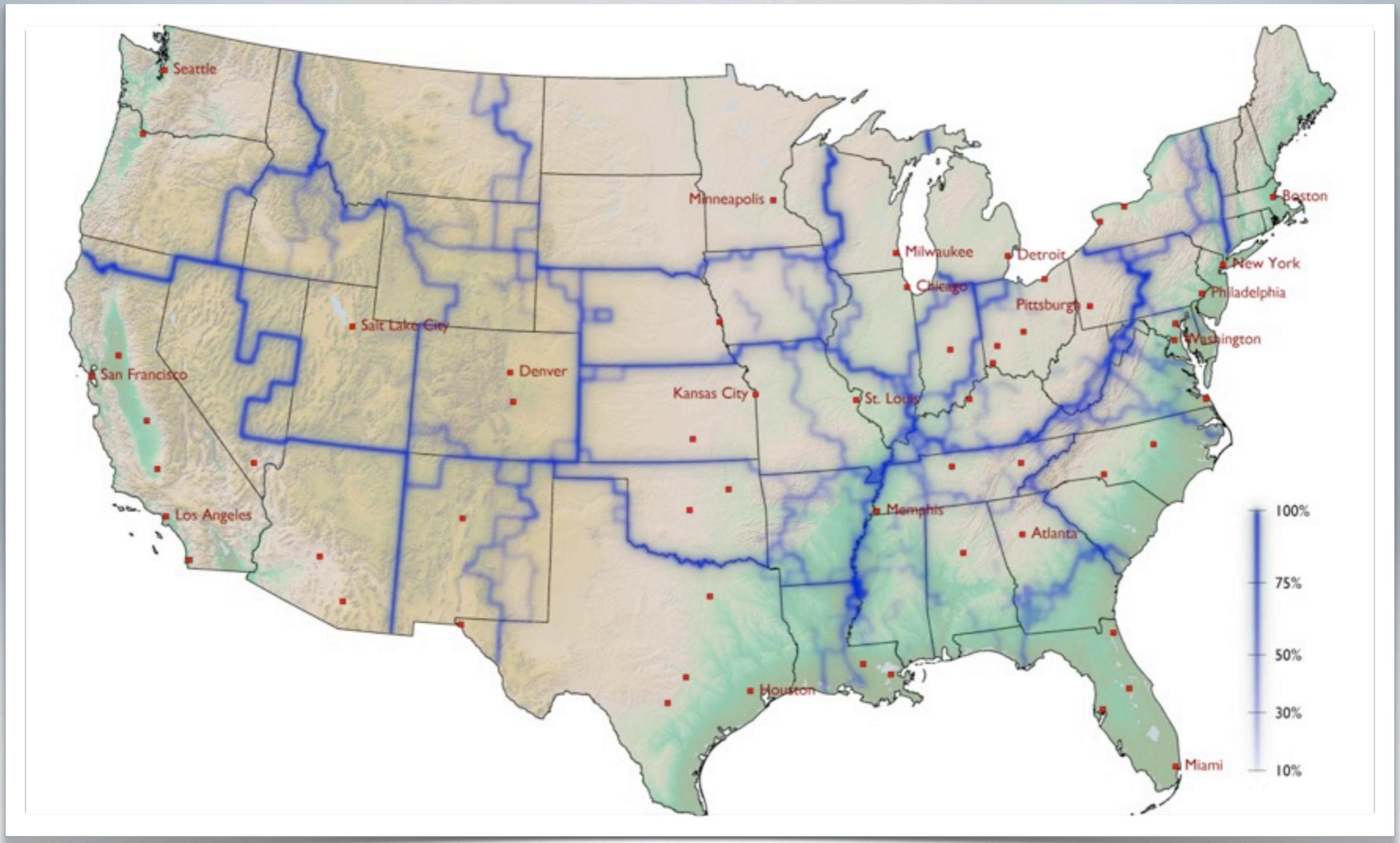
MOBILITY BORDERS



MOBILITY BORDERS



MOBILITY BORDERS



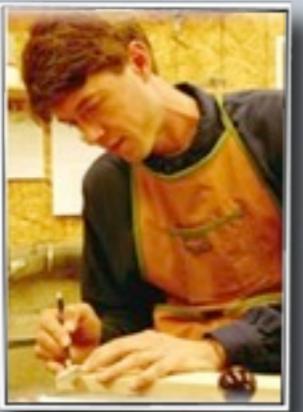
ACKNOWLEDGEMENTS

ACKNOWLEDGEMENTS

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Hank Eskin



Christian Thiemann



Fabian Theis



Daniel Grady



Rafael Brune



Alejandro
Morales Gallardo



Olivia Woolley

