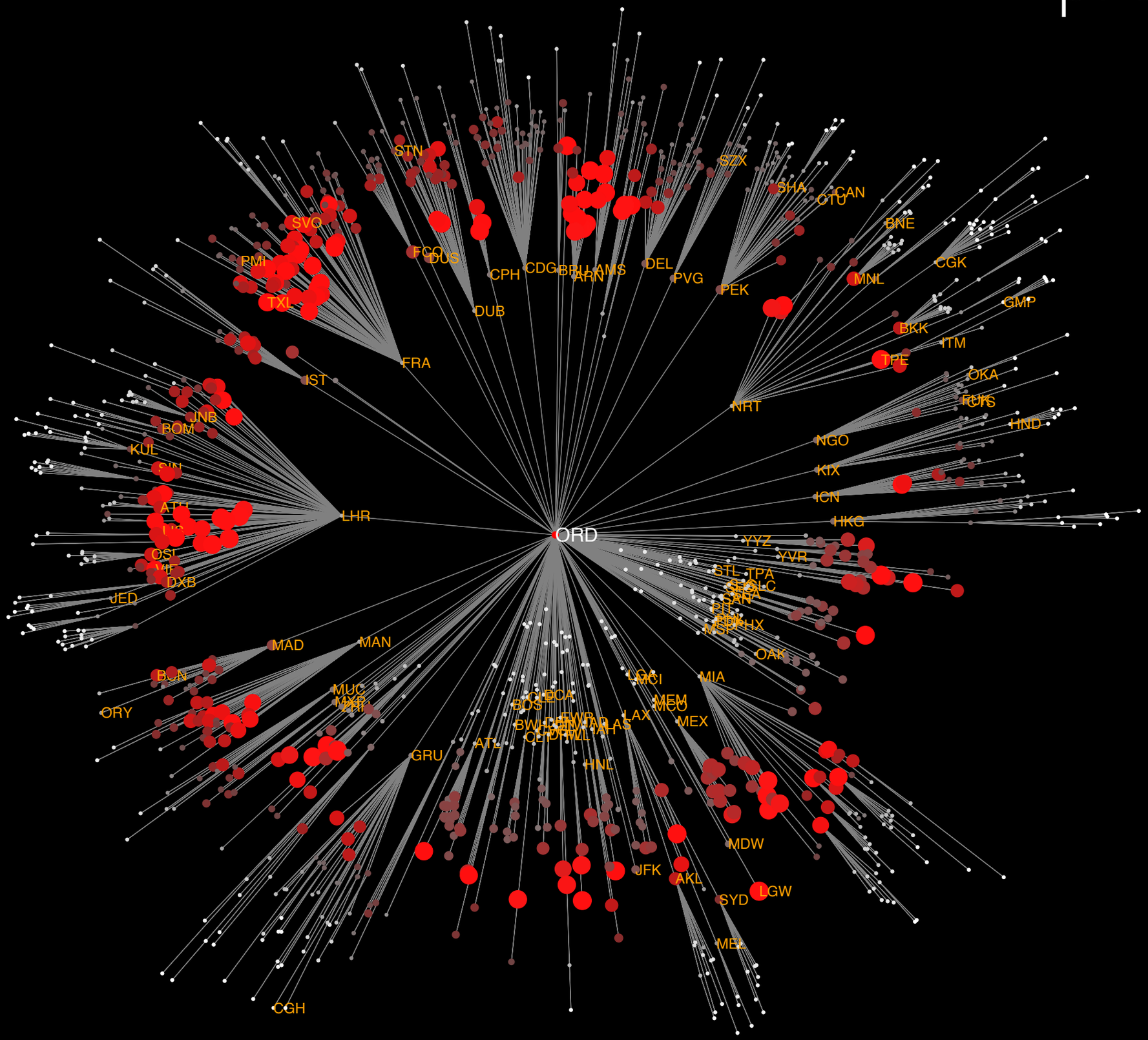
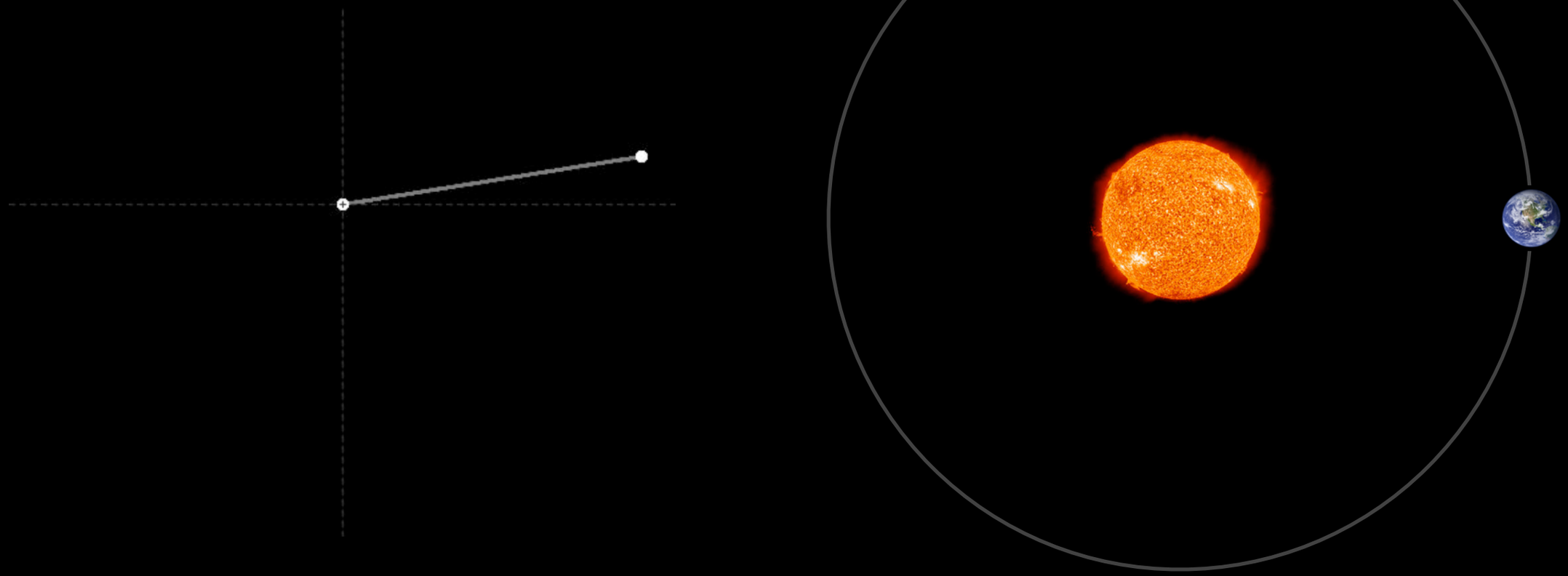
predictability and global disease dynamics

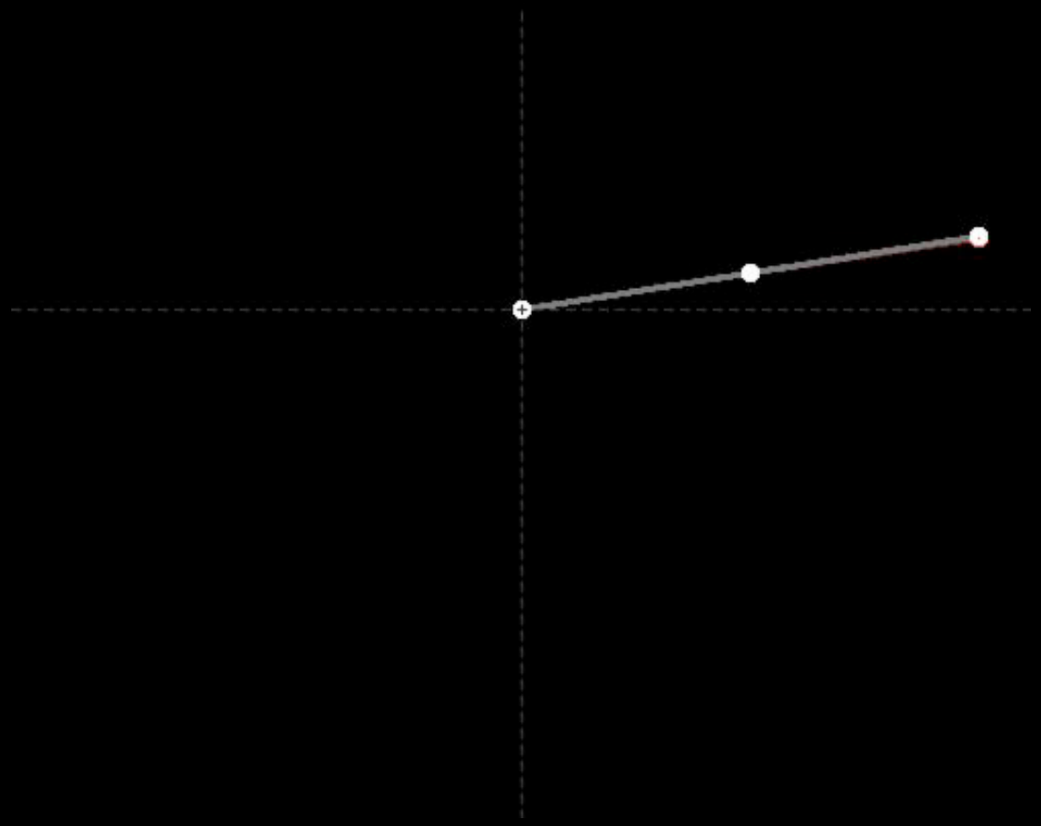


dirk brockmann
northwestern institute on complex systems

predictability

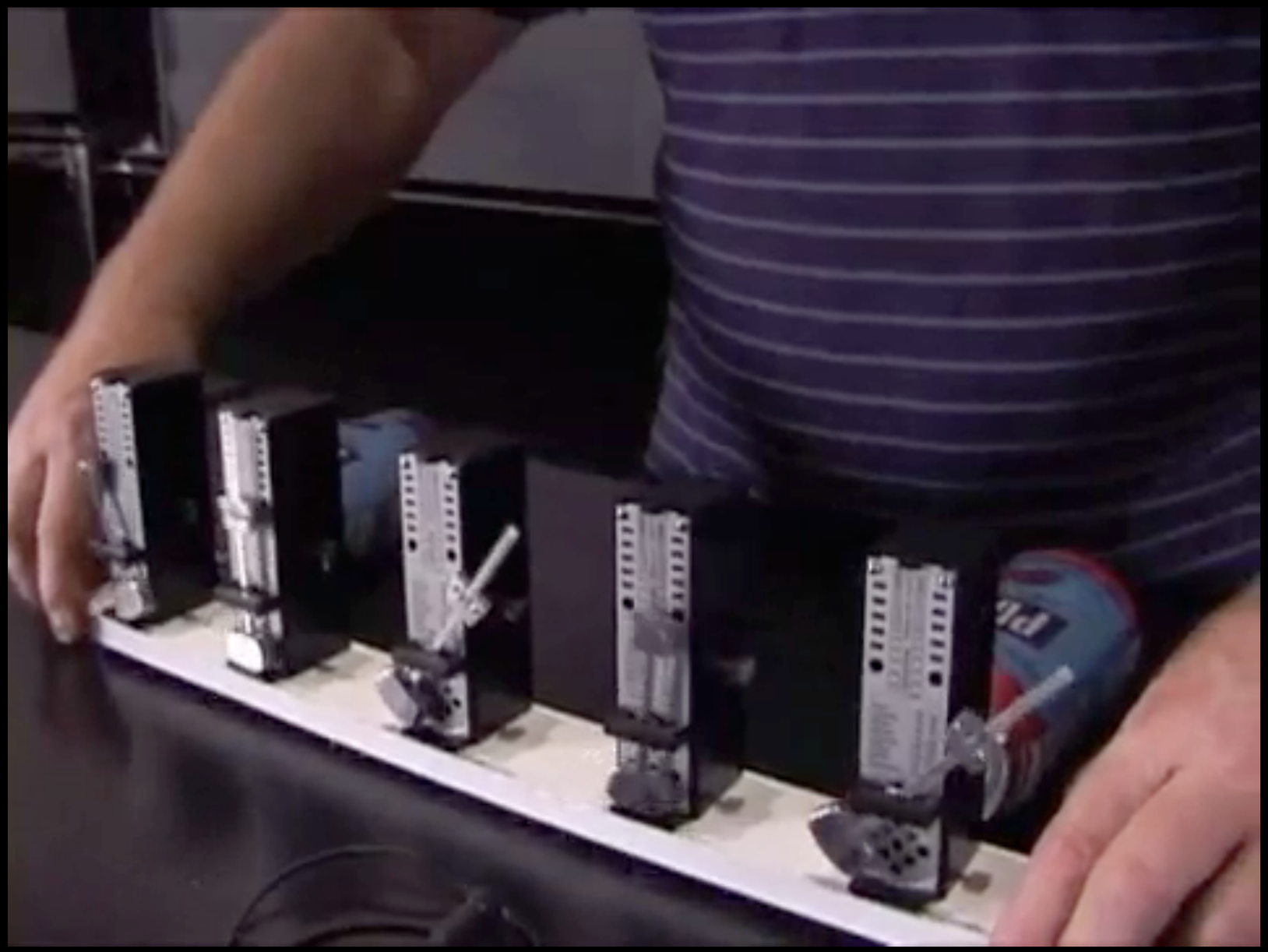


predictability



predictability = knowing initial conditions

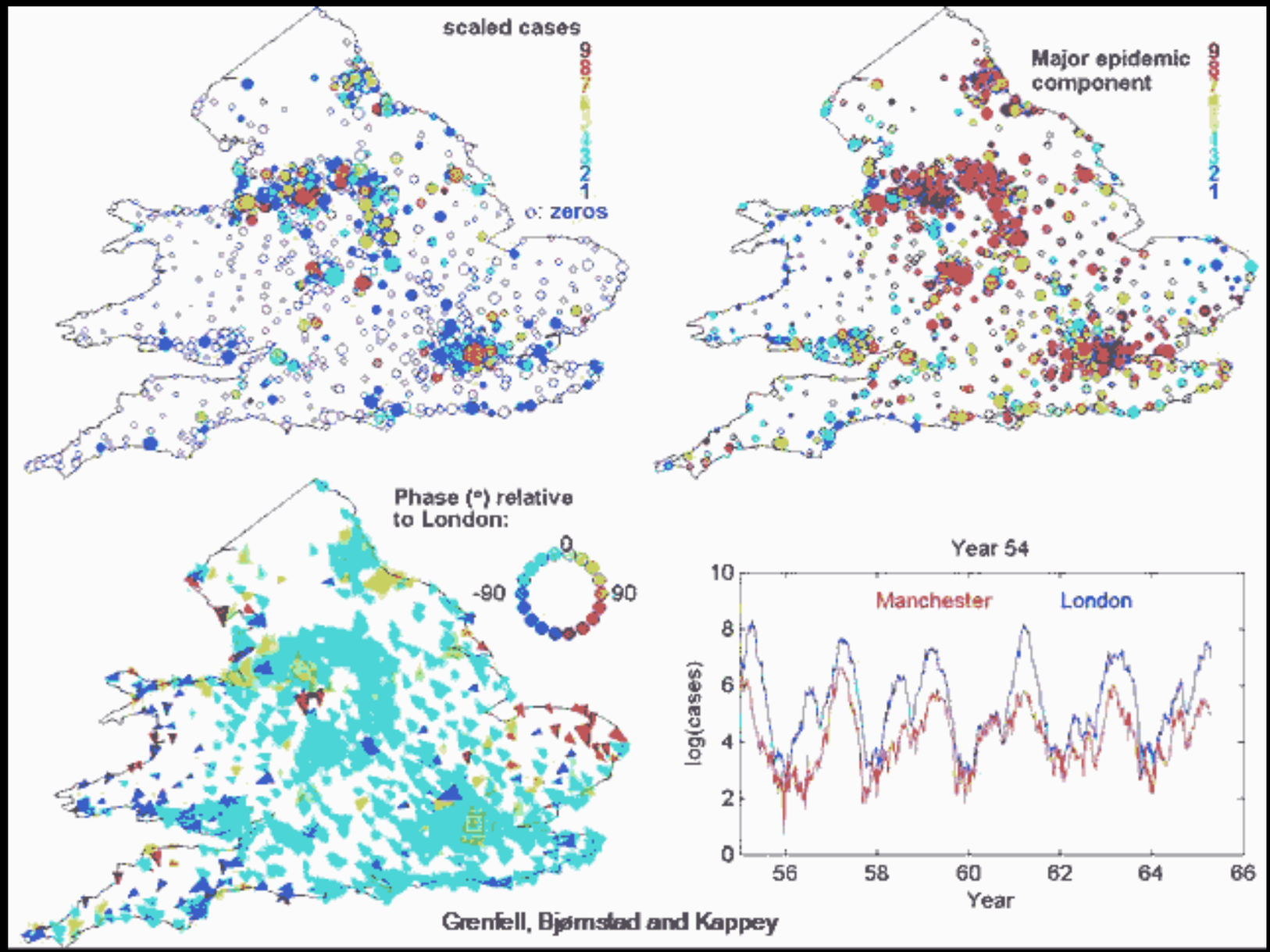
predictability



predictability = knowing parametric conditions

the millennium bridge, London

traveling waves in measles epidemic



Grenfell, B., et al., Nature 414, 716–723 (2001).

predictability in global disease dynamics

1760

MATHEMATICS IN EPIDEMIOLOGY

DANIEL BERNOULLI
(1700-1782)

- model for smallpox inoculation
- use of differential equations
- published in 1766
- the use of calculus, in particular differential equations was novel

'I simply wish that, in a matter which so closely concerns the wellbeing of the human race, no decision shall be made without all the knowledge which a little analysis and calculation can provide'

Daniel Bernoulli 1760.

Mem Math Phy Acad Roy Sci Paris 1766

inoculation debate

pro

Charles Marie de la Condamine
(1701–1774)

con

Pierre Louis Moreau de
Maupertuis (1698–1759)

- ☐ D'ALEMBERT WAS A MEMBER OF THE ROYAL SOCIETY
- ☐ KNEW OF BERNOULLI'S WORK SINCE 1760 PRESENTATION BY CONDAMINE
- ☐ GENERALIZED BERNOULLI'S MODEL AND PUBLISHED IT BEFORE HIM IN 1765
- ☐ D'ALEMBERT DID NOT LIKE LEONARD EULER, EULER WAS A GOOD FRIEND OF BERNOULLI HOWEVER.
- ☐ BERNOULLI WAS VERY ANGRY ABOUT D'ALEMBERT'S BEHAVIOUR

What do you say about the enormous platitudes of the great d'Alembert about the probabilities; as I find myself too frequently unjustly treated in his publications, I have decided already some time ago to read nothing anymore which comes from his pen; I have taken this decision on the occasion of a manuscript about inoculation which I sent to the Academy in Paris eight years ago and which was greatly appreciated because of the novelty of the analysis; it was, I dare say, like incorporating a new province into the body of mathematics; it seems that the success of this new analysis caused him pains of the heart;

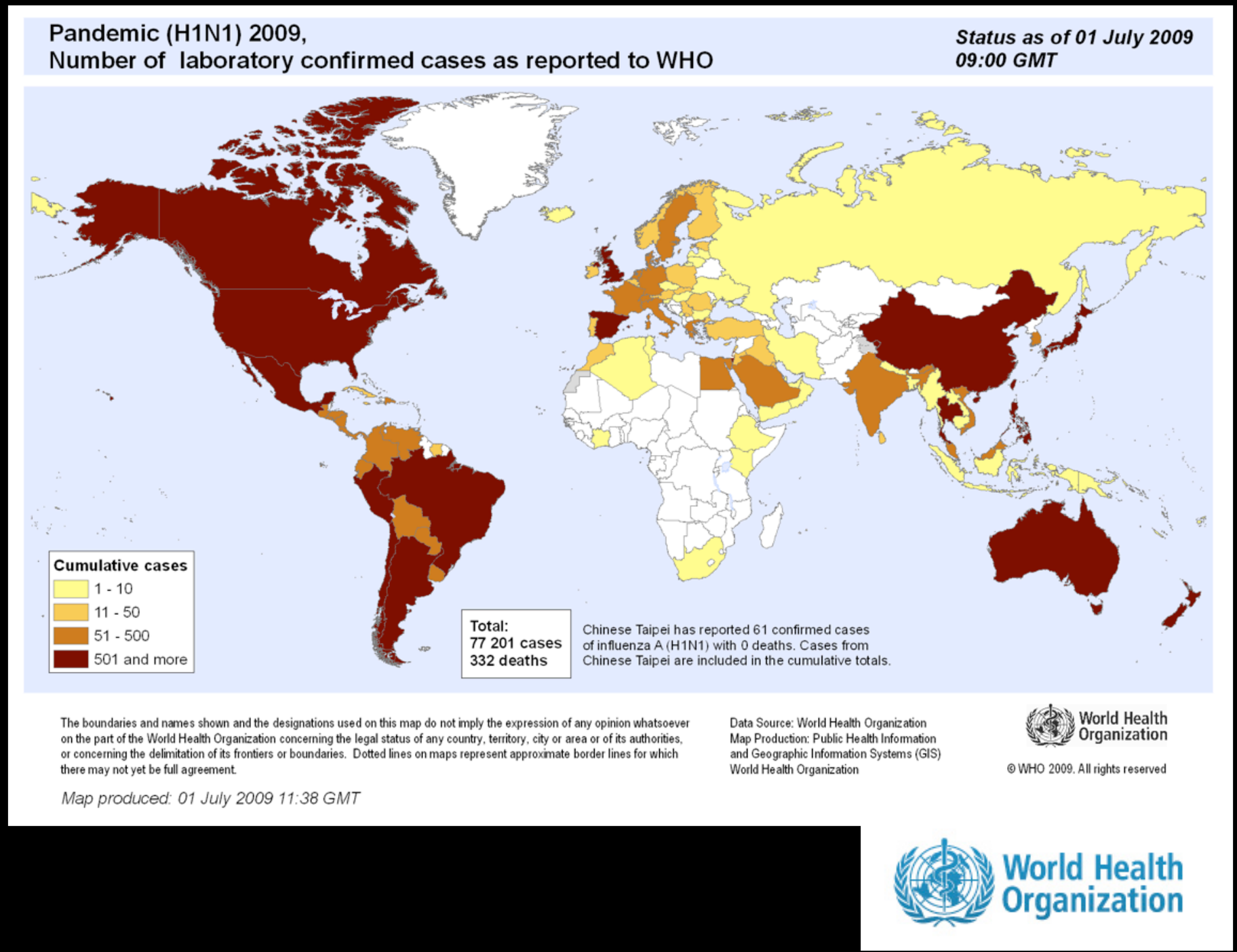
he has criticized it in a thousand ways all equally ridiculous, and after having it well criticized, he pretends to be the first author of a theory which he did not only hear mentioned. He, however, knew that my manuscript could only appear after some seven or eight years, and he could only have knowledge about it in his capacity as member of the Academy, and in this respect my manuscript should have stayed sacred until it was made public. Dolus an virtus quis in hoste requirat!

2013

global mobility and dense populations

- > 50 % urban population
- population > 7 billion
- 3 billion passengers / yr
- 5 trillion km / yr

H1N1 (swine flue) 2009



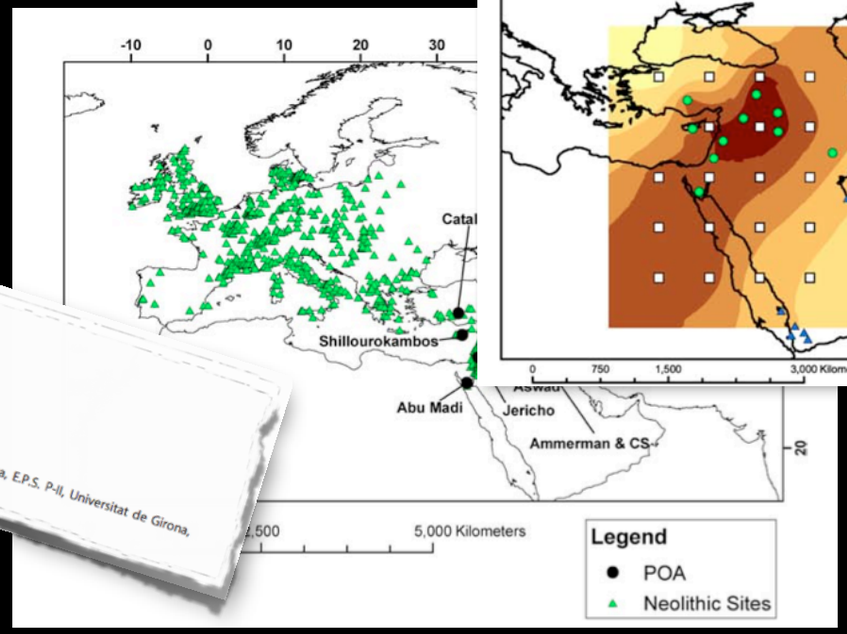
World Health Organization

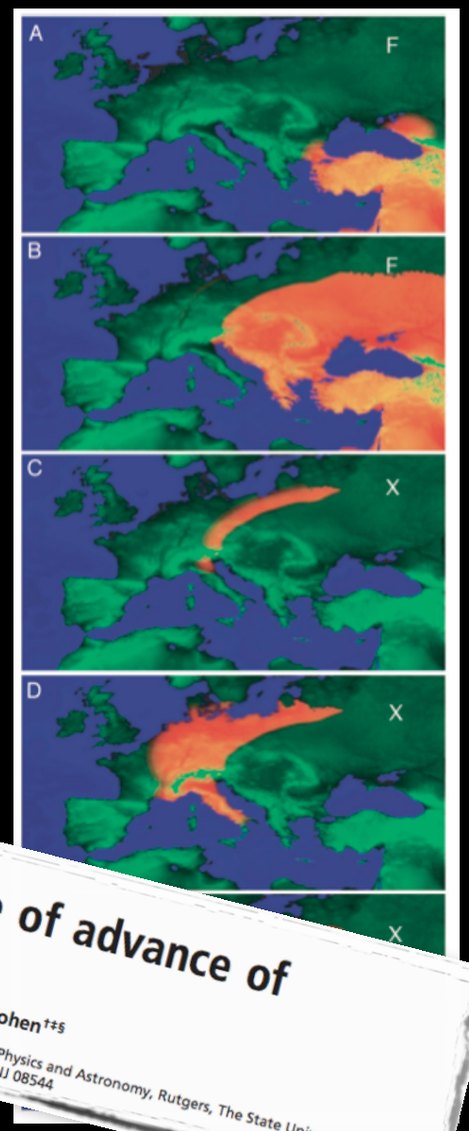
EHEC 2011

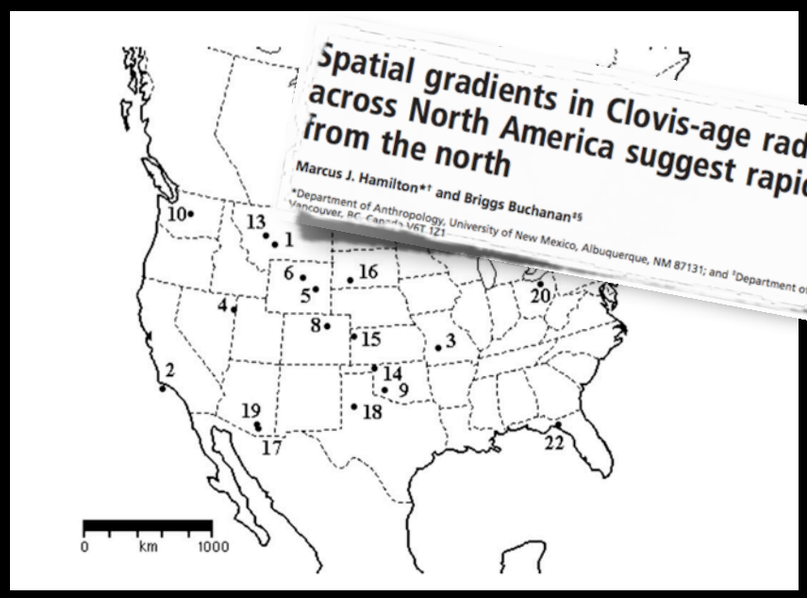
- foodborn disease
- E. Coli
- May - June 2011
- 4000 affected, 60 died

Frank, et al., New England Journal of Medicine (2011).

finding outbreaks







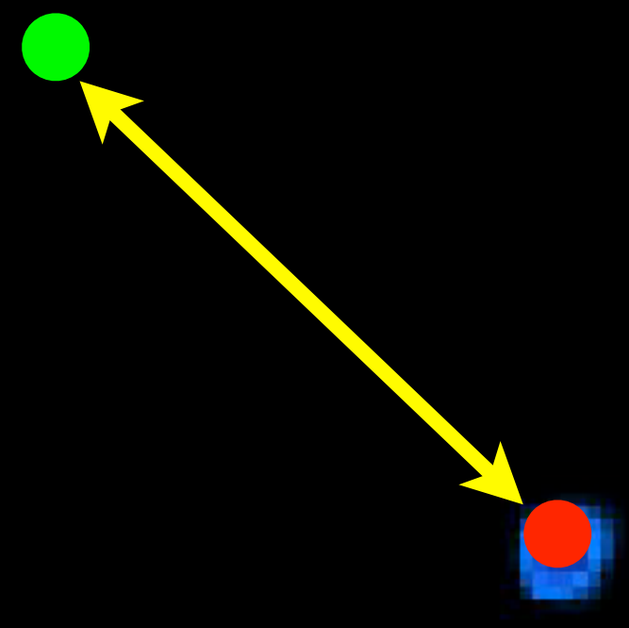
Ackland, G. J., Signitzer, M., Stratford, K. & Cohen, M. H. P PNAS (2007).
Pinhasi, R., Fort, J. & Ammerman, A., Plos Biol (2005)
Hamilton, M. J. & Buchanan, B., PNAS, (2007).

questions

Speed?

Arrival?

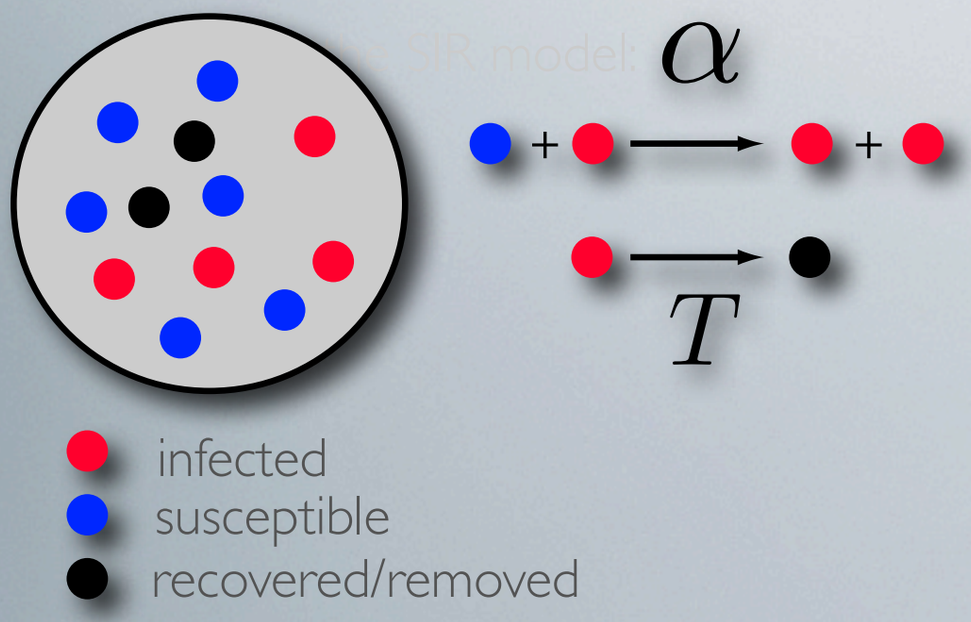
Origin?



$$T = \frac{D}{V}$$

Noble, Nature (1974) vol. 250 (5469) pp. 726-728
Fort, J. & Méndez, V.,. Phys Rev Lett (1999).

SIR DYNAMICS

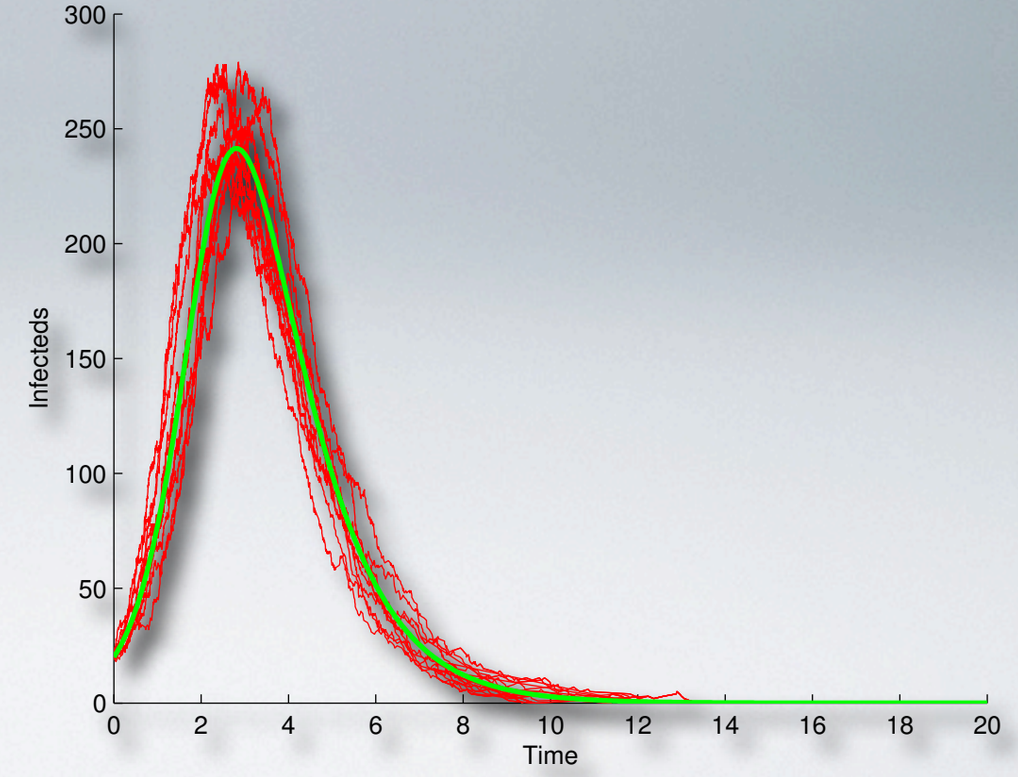


mean field dynamics:

$$\begin{aligned} \partial_t S &= -R_0 I S \\ \partial_t I &= R_0 I S - I \\ R &= 1 - S - I \end{aligned}$$

The basic reproduction number

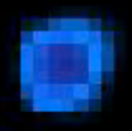
$$\alpha \times T = R_0 > 1$$



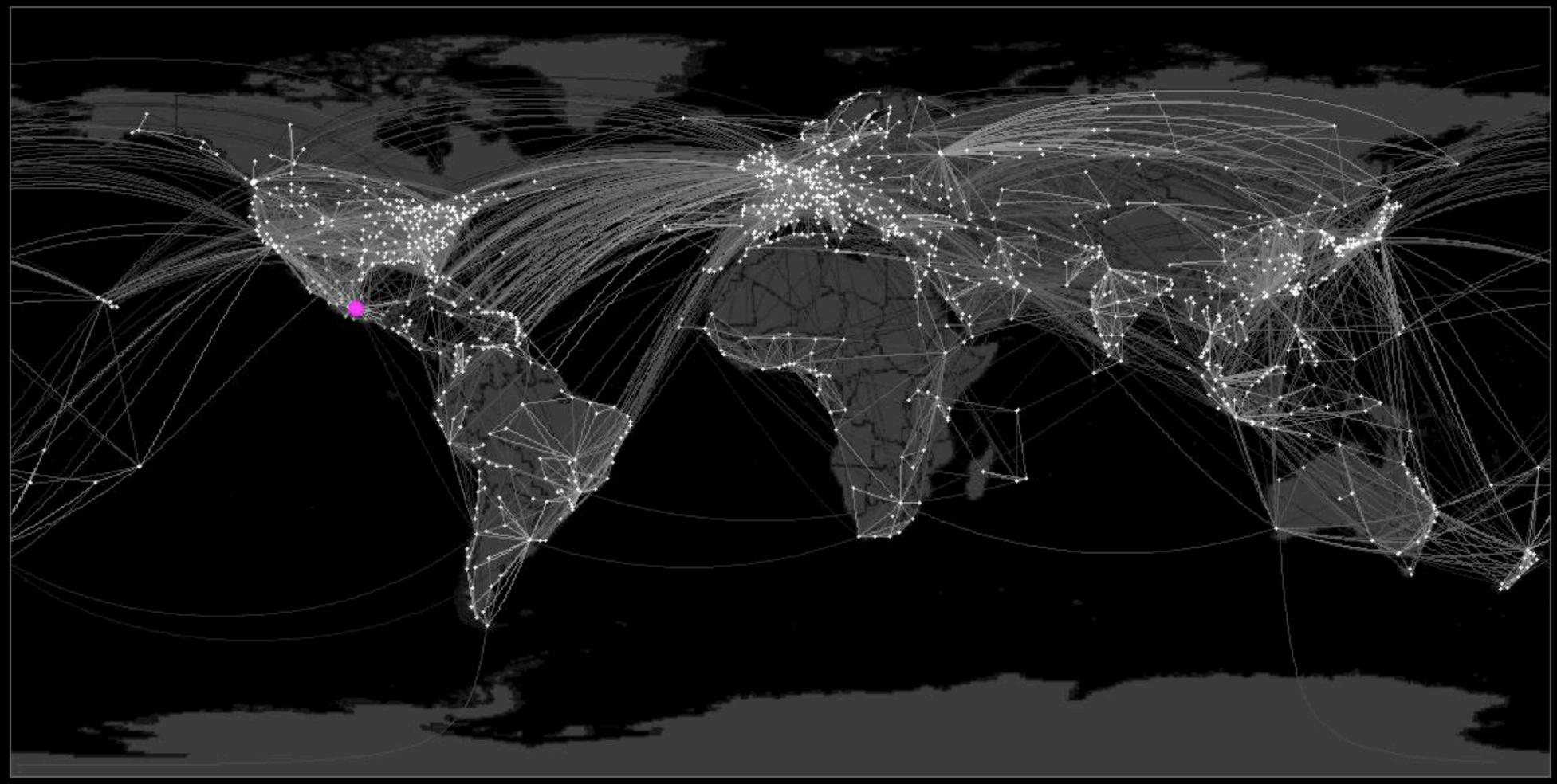
reaction diffusion models

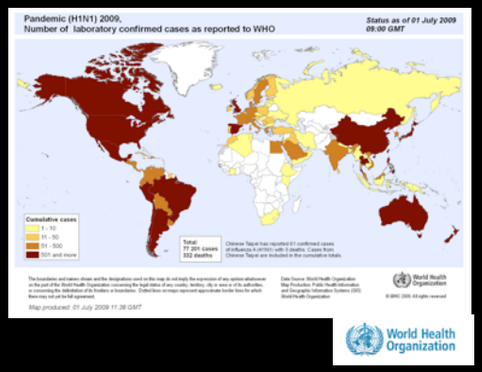
$$
\begin{aligned}
\partial_t I &= \alpha I S/N - \beta I + D\partial_x^2 I \\
\partial_t S &= -\alpha I S/N + D\partial_x^2 S
\end{aligned}
$$

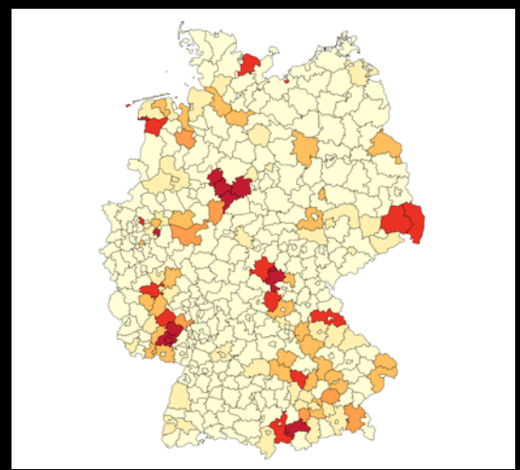
$$
v \propto \sqrt{(R_0 - 1)D}
$$



NICO - northwestern institute on complex systems



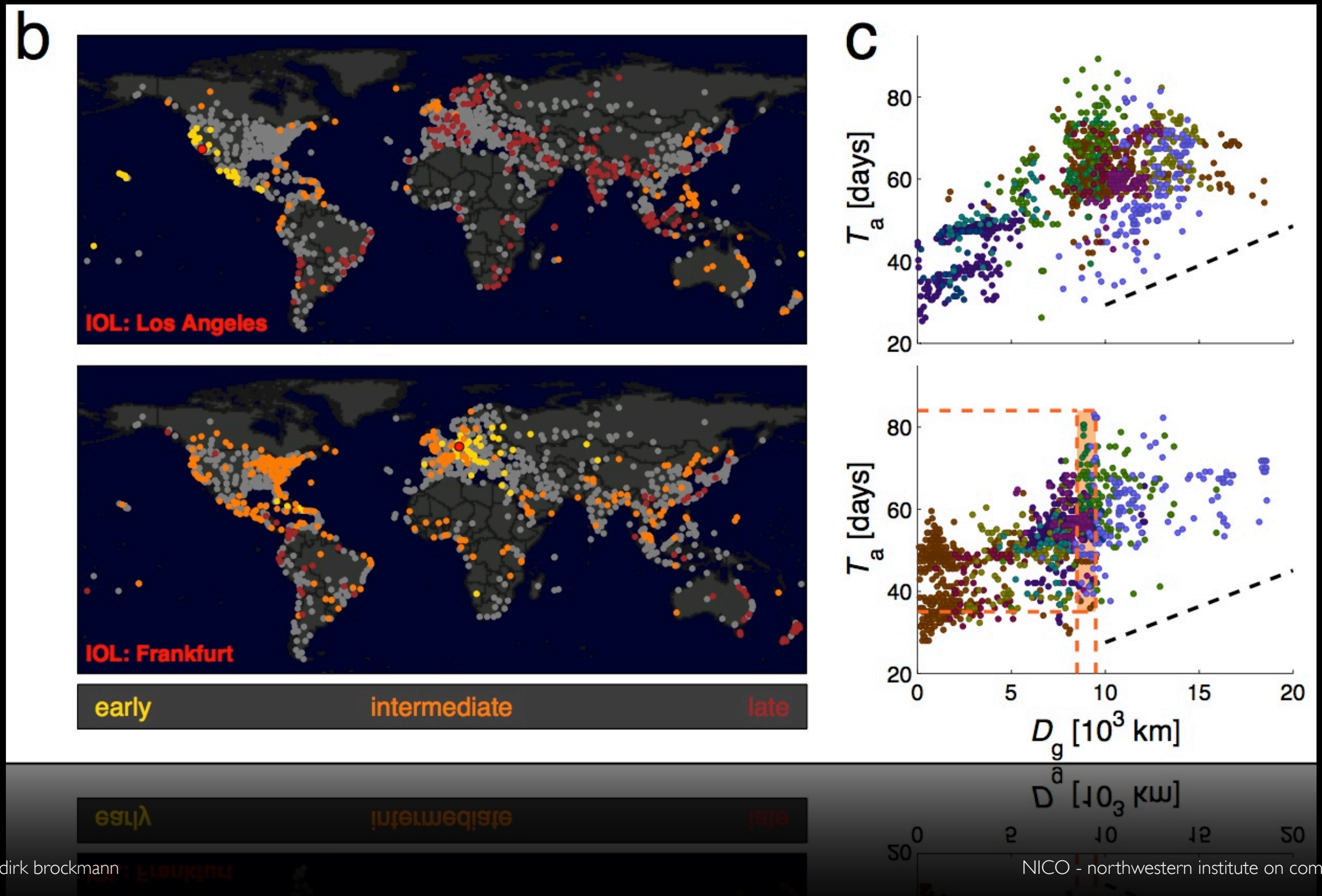


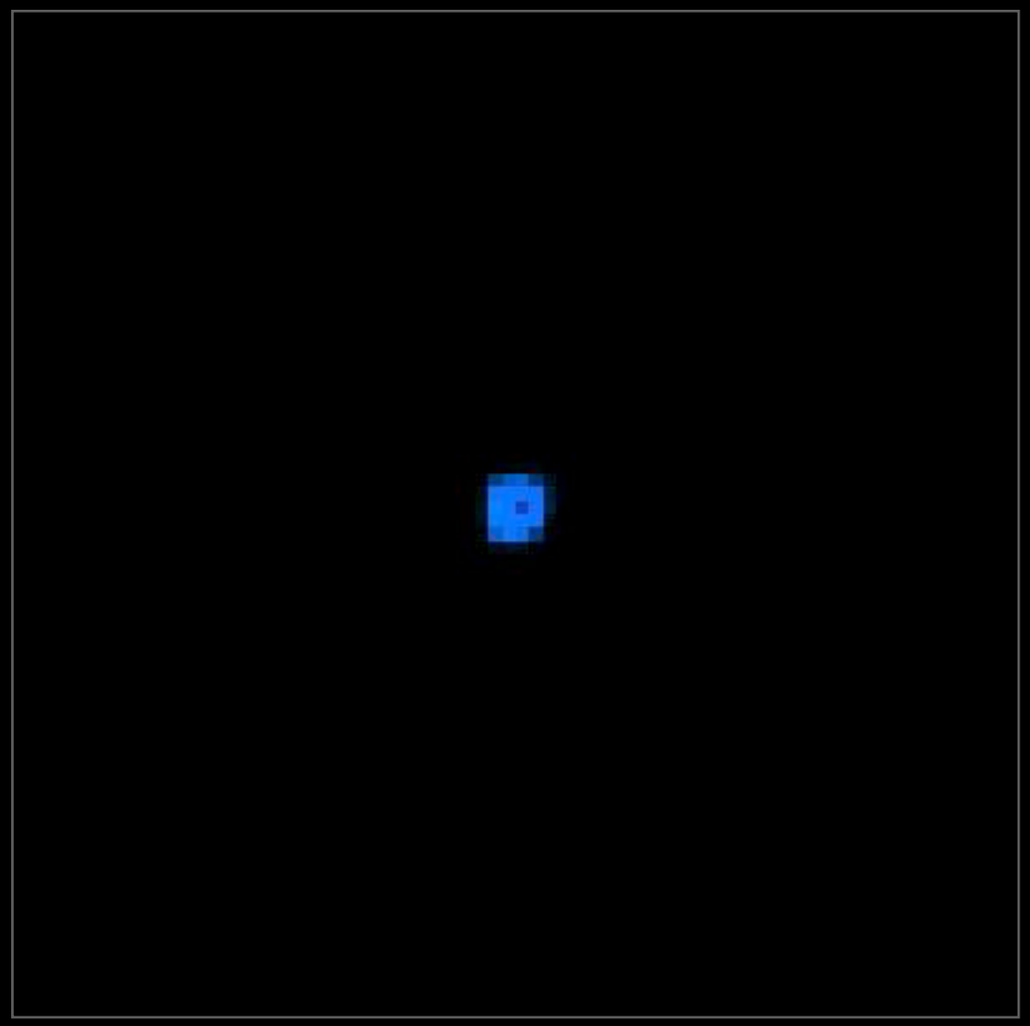


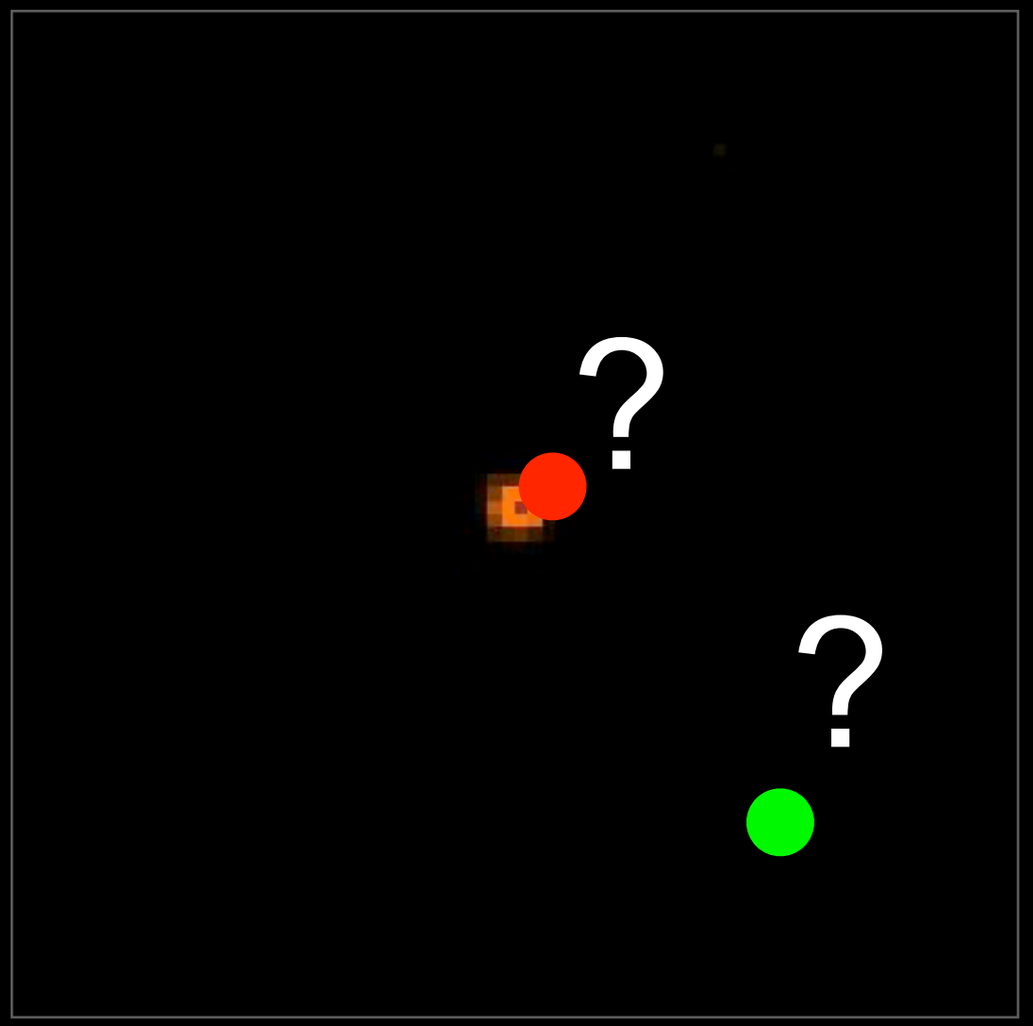
$$\partial_t j_n = \alpha s_n j_n - \beta j_n + \gamma \sum_{m \neq n} P_{nm} \left(j_m - j_n \right) .$$

$$\partial_t s_n = -\alpha s_n j_n + \gamma \sum_{m \neq n} P_{nm} \left(s_m - s_n \right) .$$

geographic distance and arrival times in a hypothetical pandemic







quantitative computational models

GLEaMviz

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)

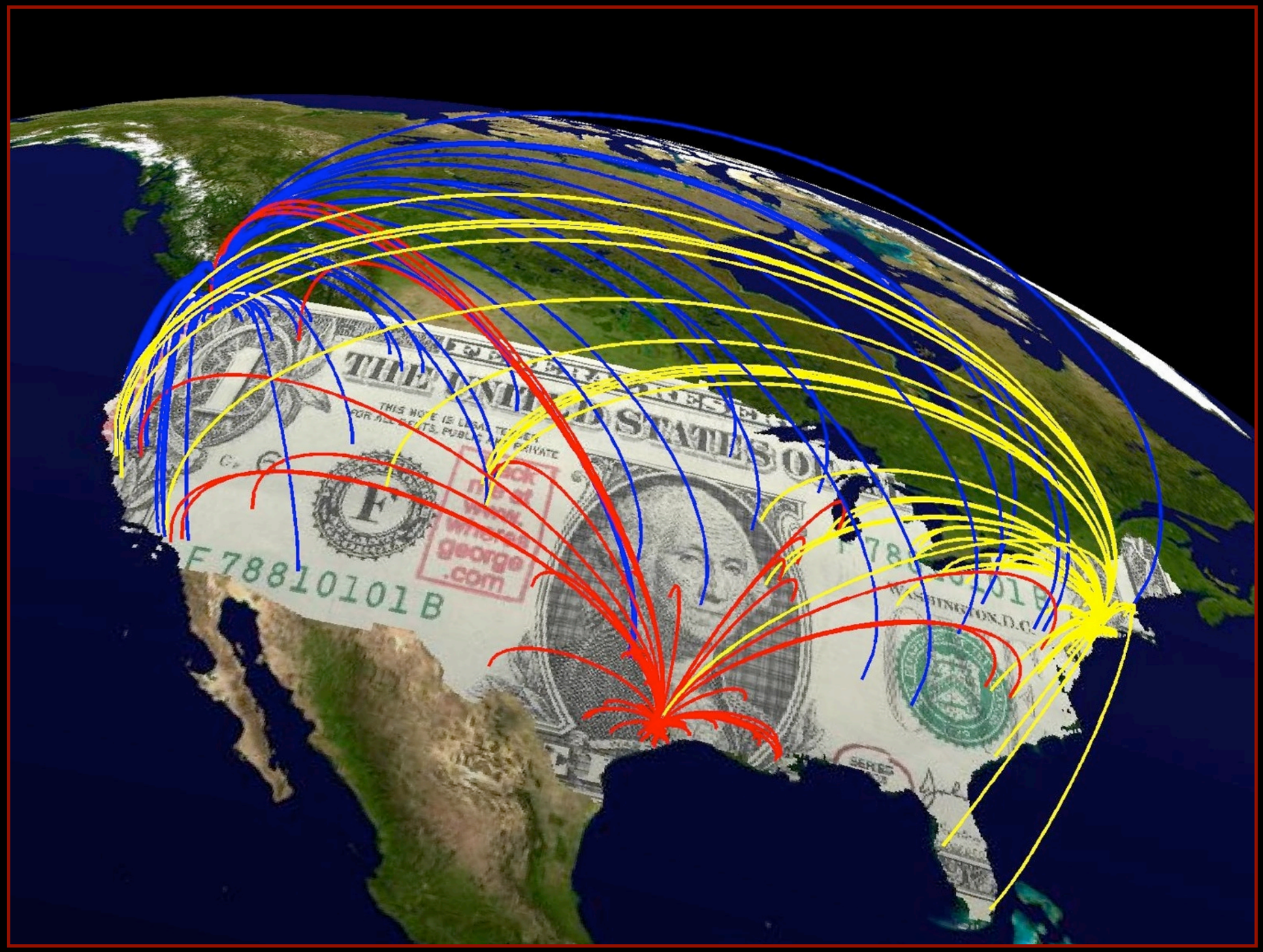
Colizza et al. Reaction-diffusion processes and metapopulation models in heterogeneous networks. Nat Phys (2007)

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

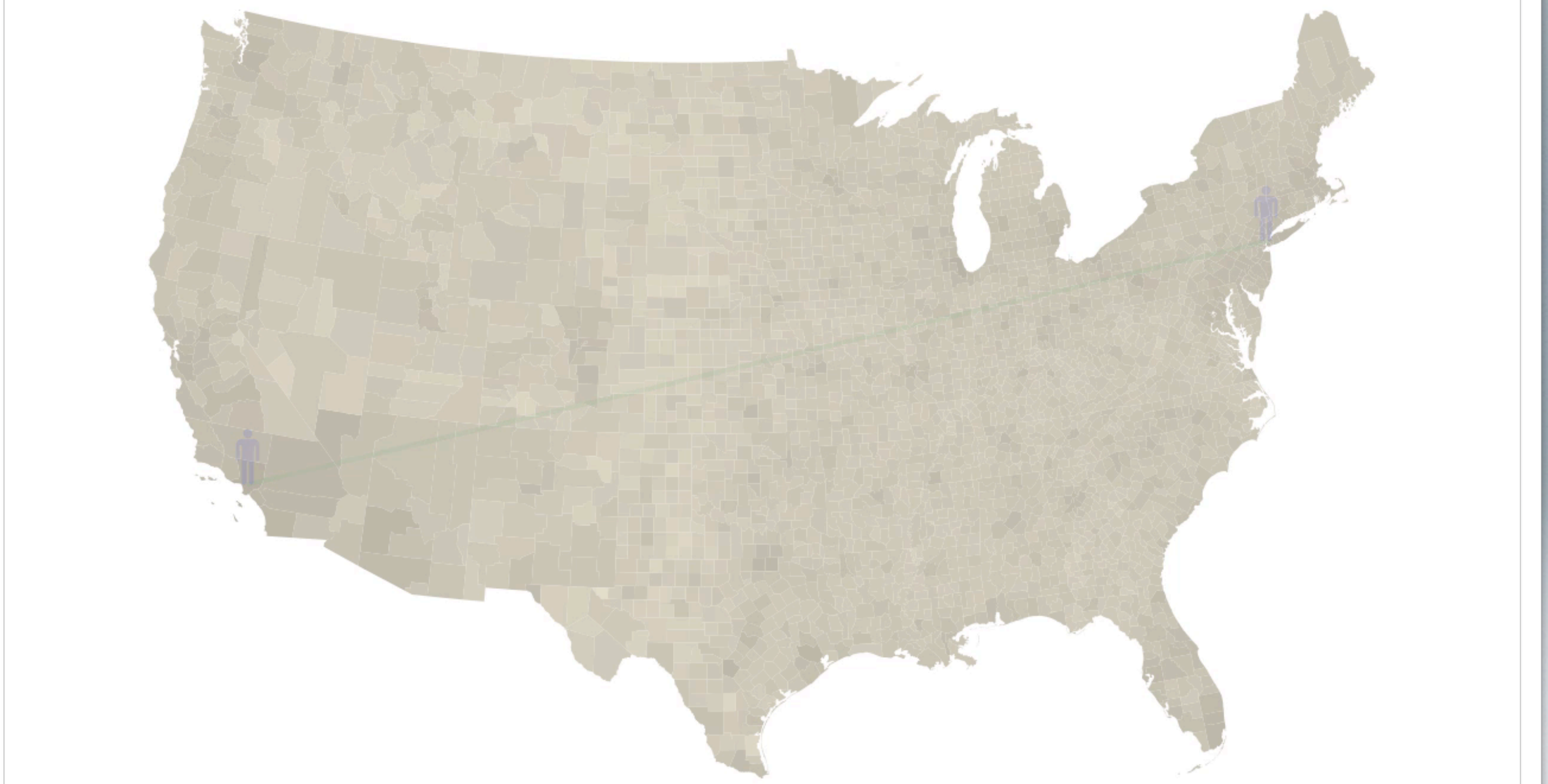
Riley. **Large-scale spatial-transmission** models of infectious disease. Science (2007)

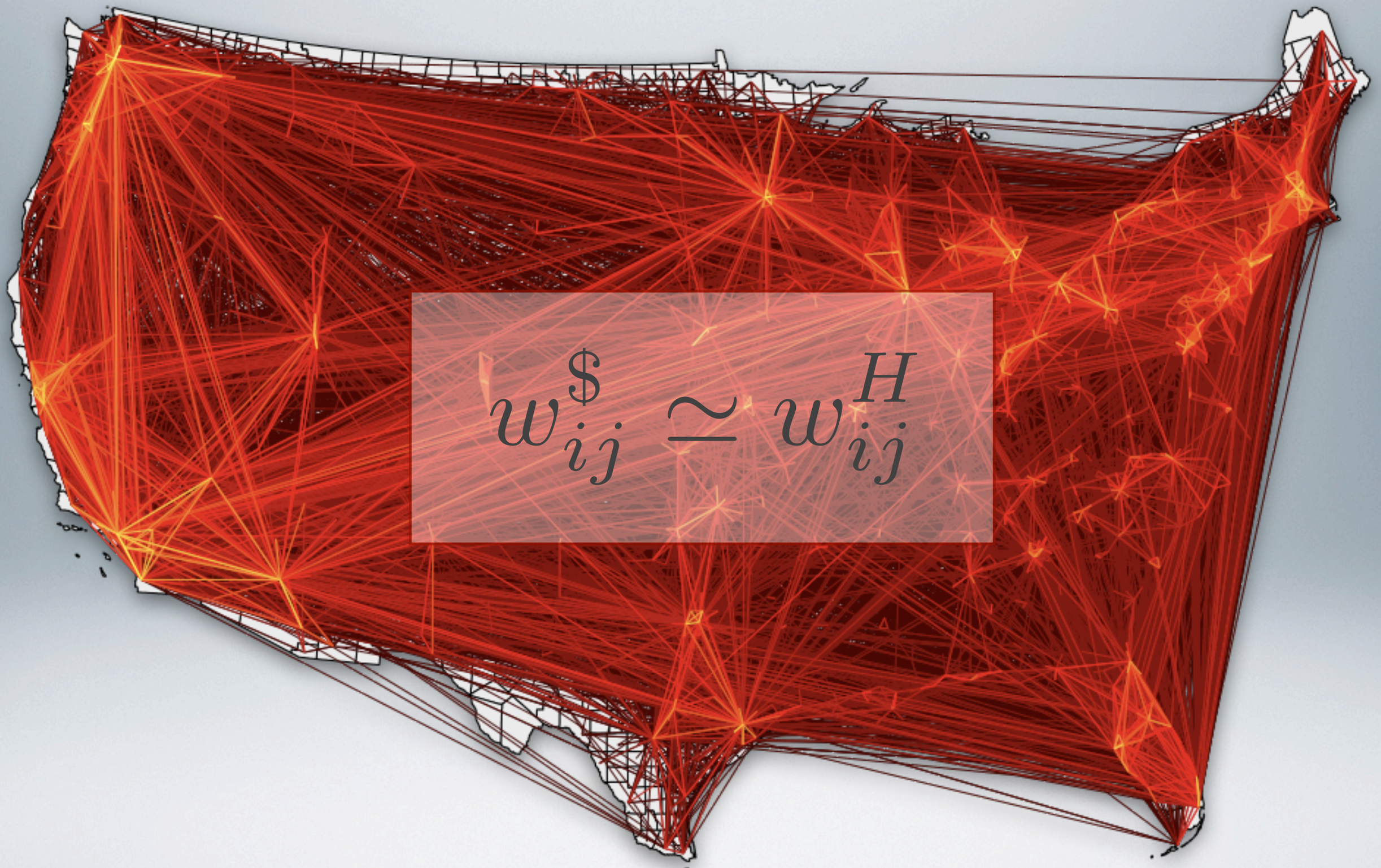
Colizza et al. Epidemic modeling in metapopulation systems with heterogeneous coupling pattern: Theory and simulations. J Theor Biol (2008)

measuring human mobility



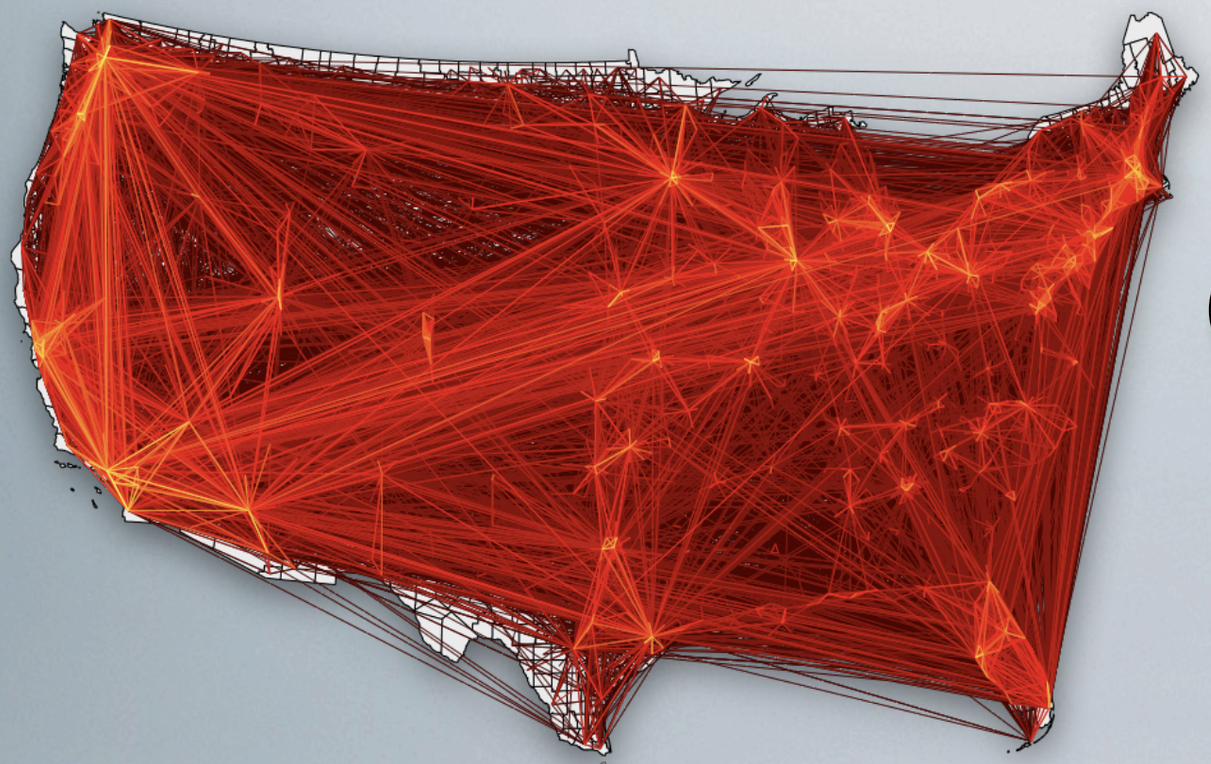
THE FLUX OF DOLLARS

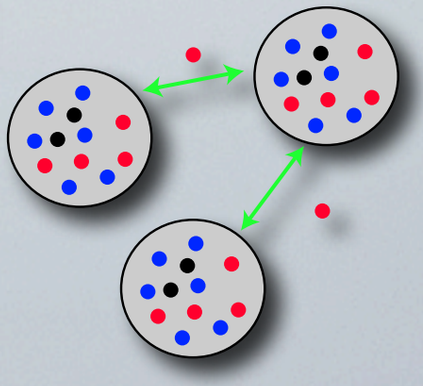




$$w_{ij}^{\$} \simeq w_{ij}^{H}$$

A MODEL FOR THE SPREAD OF H1N1 IN THE US





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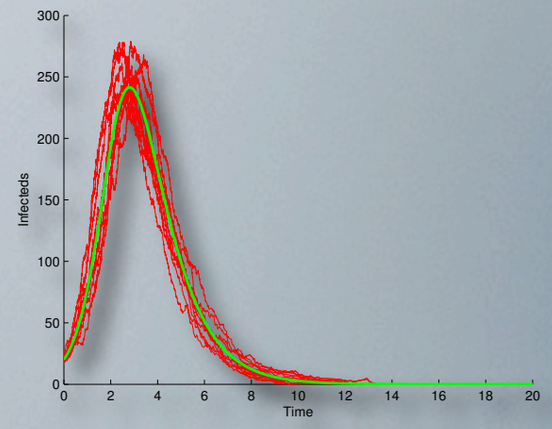
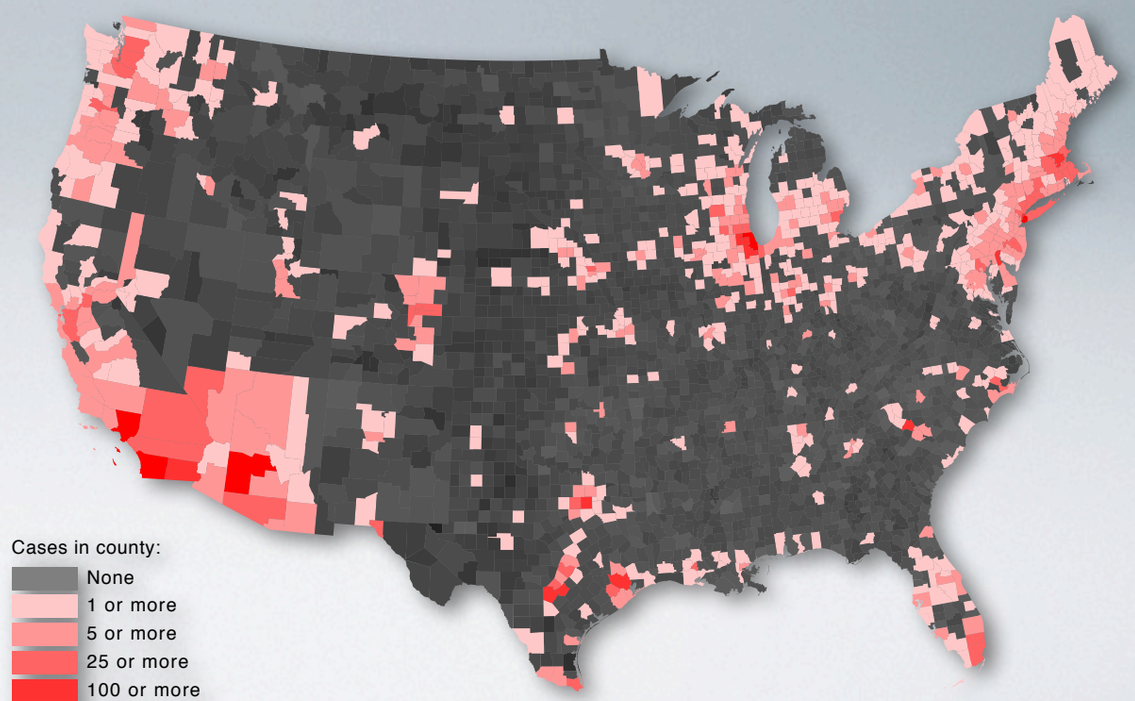
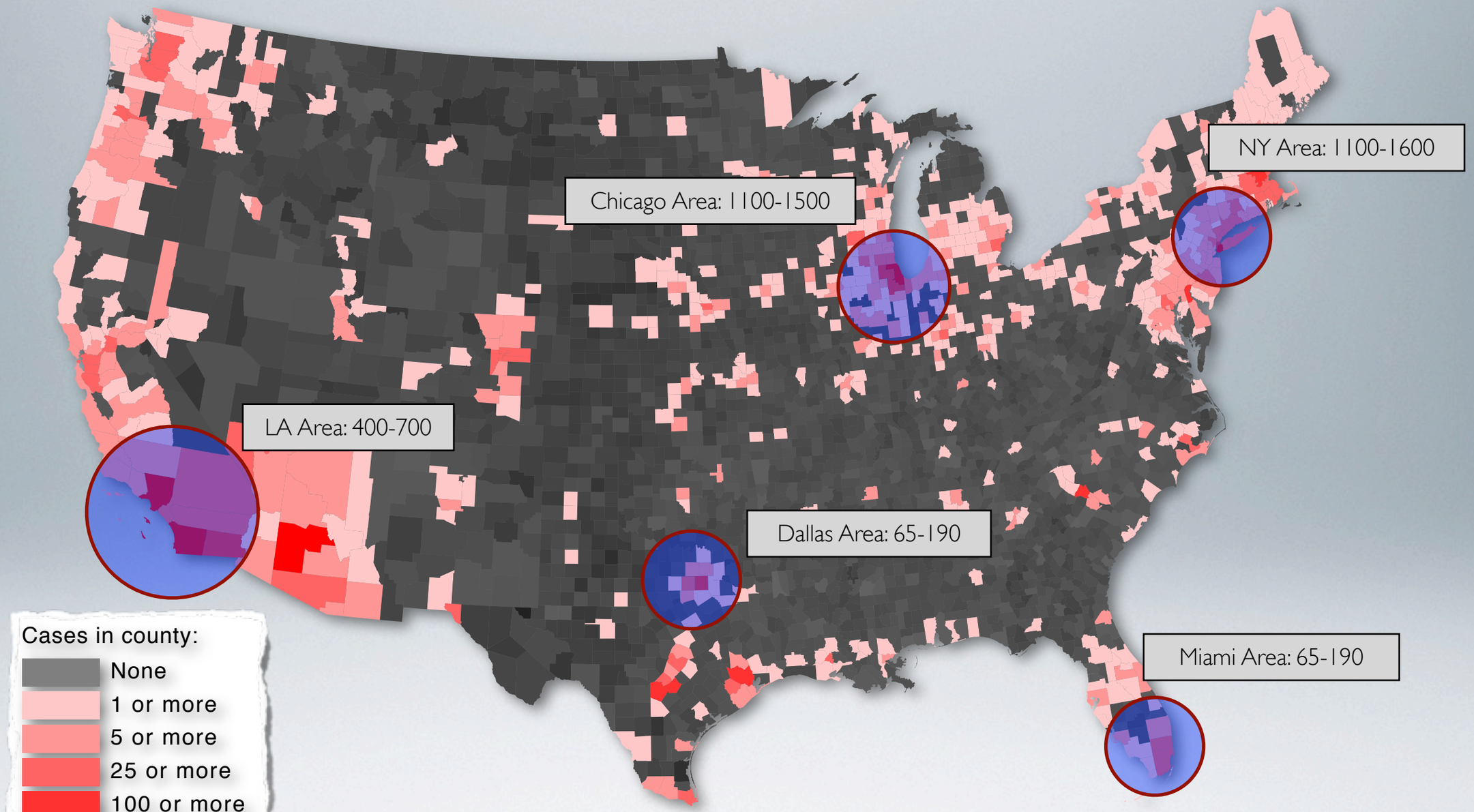




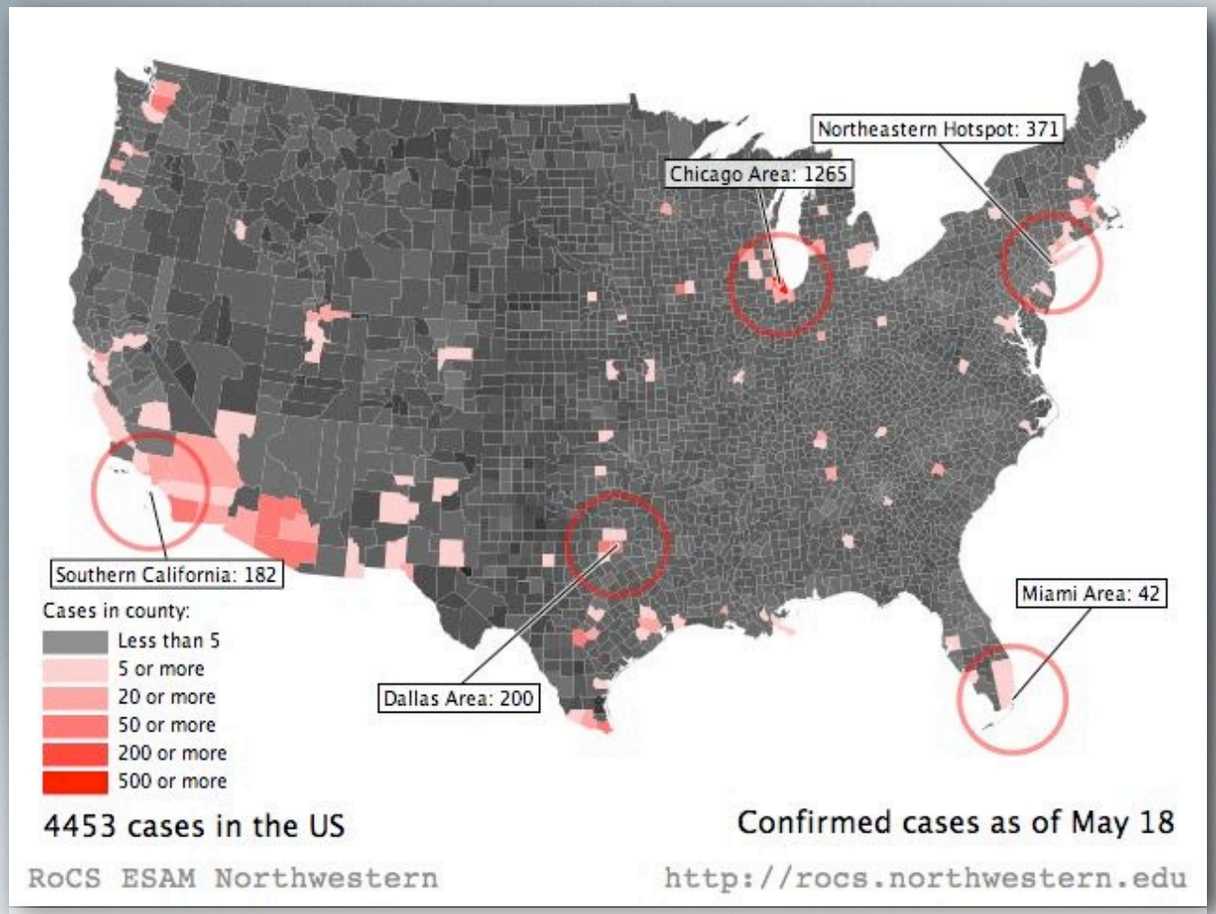
H1N1 PROJECTIONS US

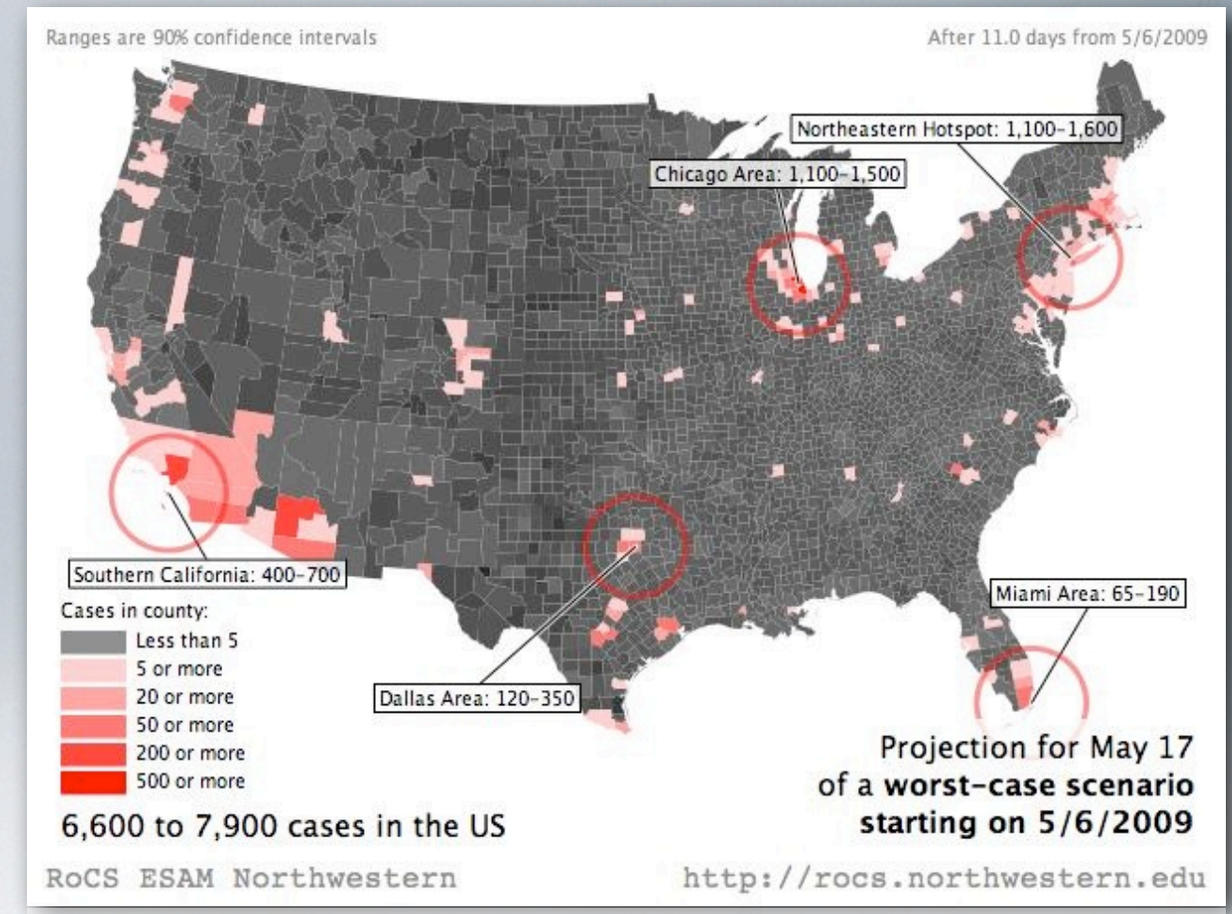


May 17th, 2009

projected May 2nd

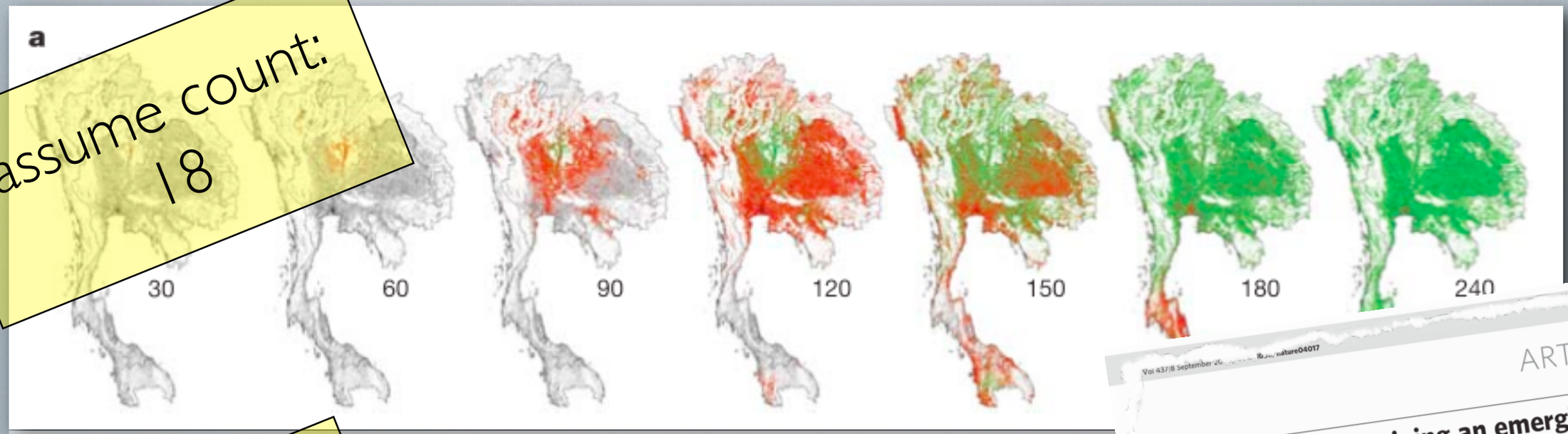
H1N1 PANDEMIC 2009





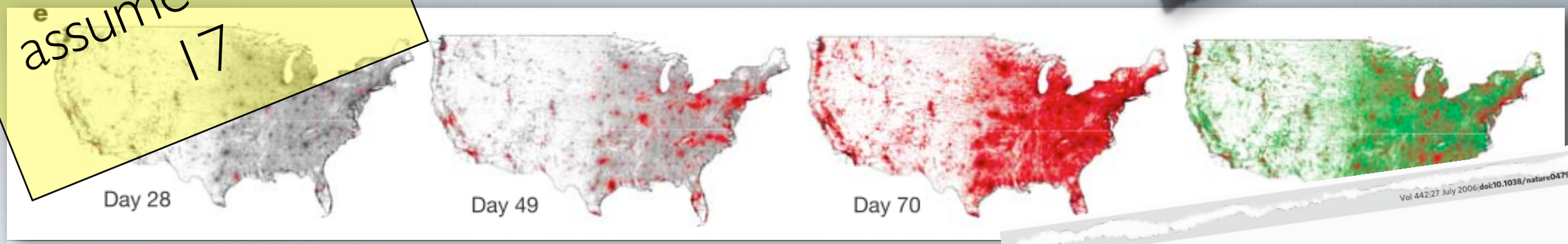
QUANTITATIVE MODELS

assume count: 18




ARTICLES
Strategies for containing an emerging influenza pandemic in Southeast Asia

assume count: 17




LETTERS
Strategies for mitigating an influenza pandemic
Neil M. Ferguson[1], Derek A. T. Cummings[2], Christophe Fraser[1], James C. Cajka[3], Philip C. Cooley[3] & Donald S. Burke[2]

ROBERT MAY

VIEWPOINT

Uses and Abuses of Mathematics in Biology

Robert M. May

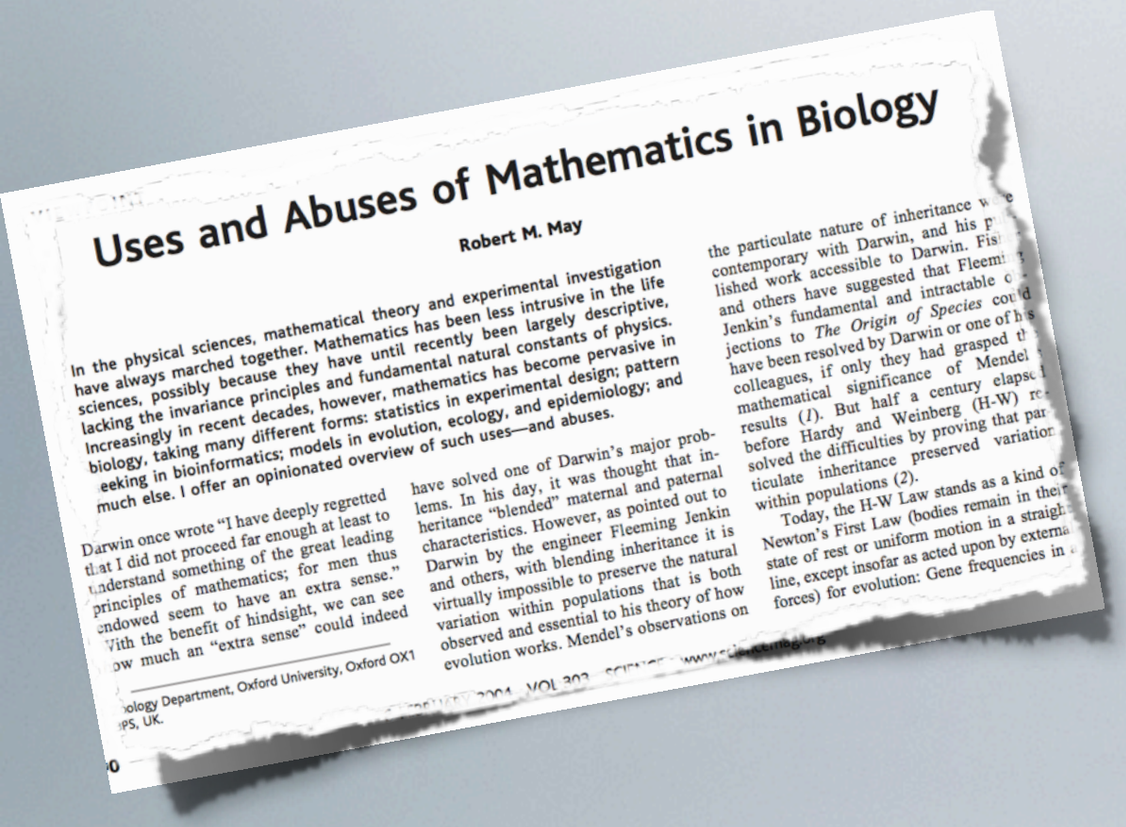
In the physical sciences, mathematical theory and experimental investigation have always marched together. Mathematics has been less intrusive in the life sciences, possibly because they have until recently been largely descriptive, lacking the invariance principles and fundamental natural constants of physics. Increasingly in recent decades, however, mathematics has become pervasive in biology, taking many different forms: statistics in experimental design; pattern seeking in bioinformatics; models in evolution, ecology, and epidemiology; and much else. I offer an opinionated overview of such uses—and abuses.

Darwin once wrote "I have deeply regretted that I did not proceed far enough at least to understand something of the great leading principles of mathematics; for men thus endowed seem to have an extra sense." With the benefit of hindsight, we can see how much an "extra sense" could indeed have solved one of Darwin's major problems. In his day, it was thought that inheritance "blended" maternal and paternal characteristics. However, as pointed out to Darwin by the engineer Fleeming Jenkin and others, with blending inheritance it is virtually impossible to preserve the natural variation within populations that is both observed and essential to his theory of how evolution works. Mendel's observations on the particulate nature of inheritance were contemporary with Darwin, and his published work accessible to Darwin. Fisher and others have suggested that Fleeming Jenkin's fundamental and intractable objections to *The Origin of Species* could have been resolved by Darwin or one of his colleagues, if only they had grasped the mathematical significance of Mendel's results (*1*). But half a century elapsed before Hardy and Weinberg (H-W) resolved the difficulties by proving that particulate inheritance preserved variation within populations (*2*).

Today, the H-W Law stands as a kind of Newton's First Law (bodies remain in their state of rest or uniform motion in a straight line, except insofar as acted upon by external forces) for evolution: Gene frequencies in a

Zoology Department, Oxford University, Oxford OX1 3PS, UK.

ROBERT MAY



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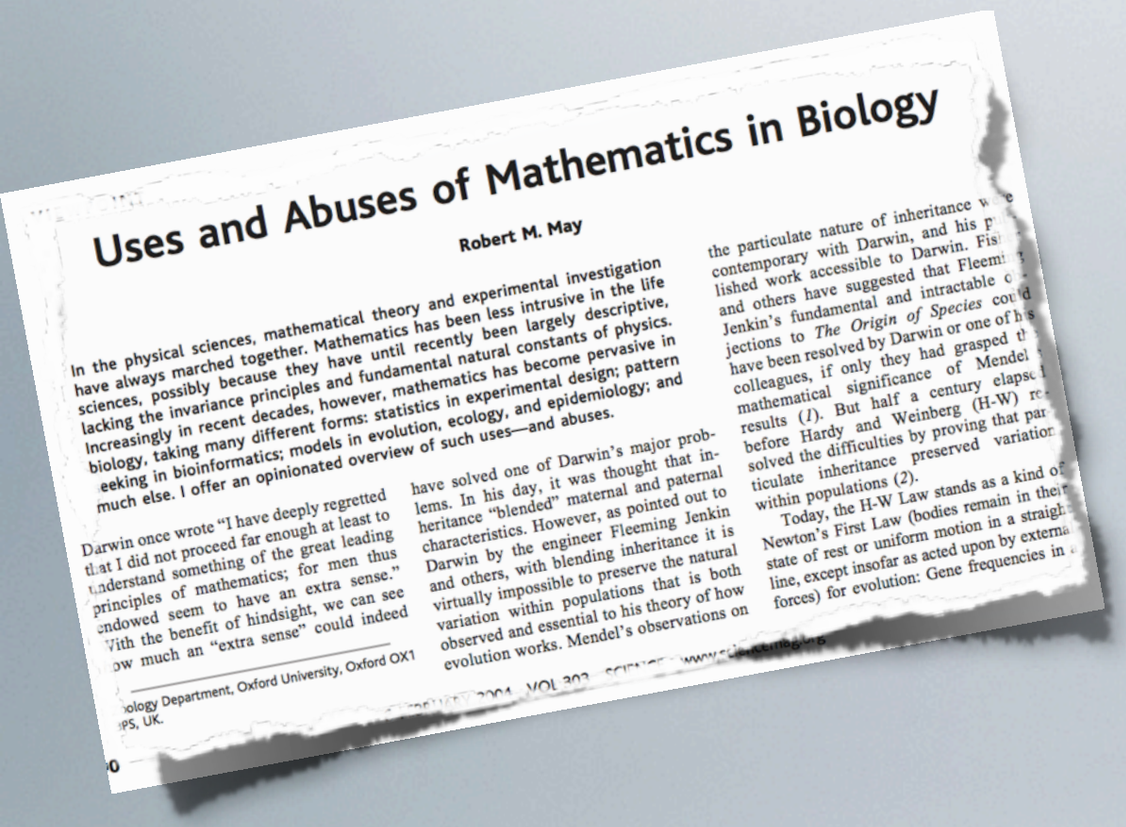
…2004 VOL 303 SCIENCE www.sciencemag.org

The increasing speed and sophistication and ease of use of computers enables an increasingly large number of life scientists who have no substantial background in mathematics to explore "mathematical models" and draw conclusions about them.

ROBERT MAY



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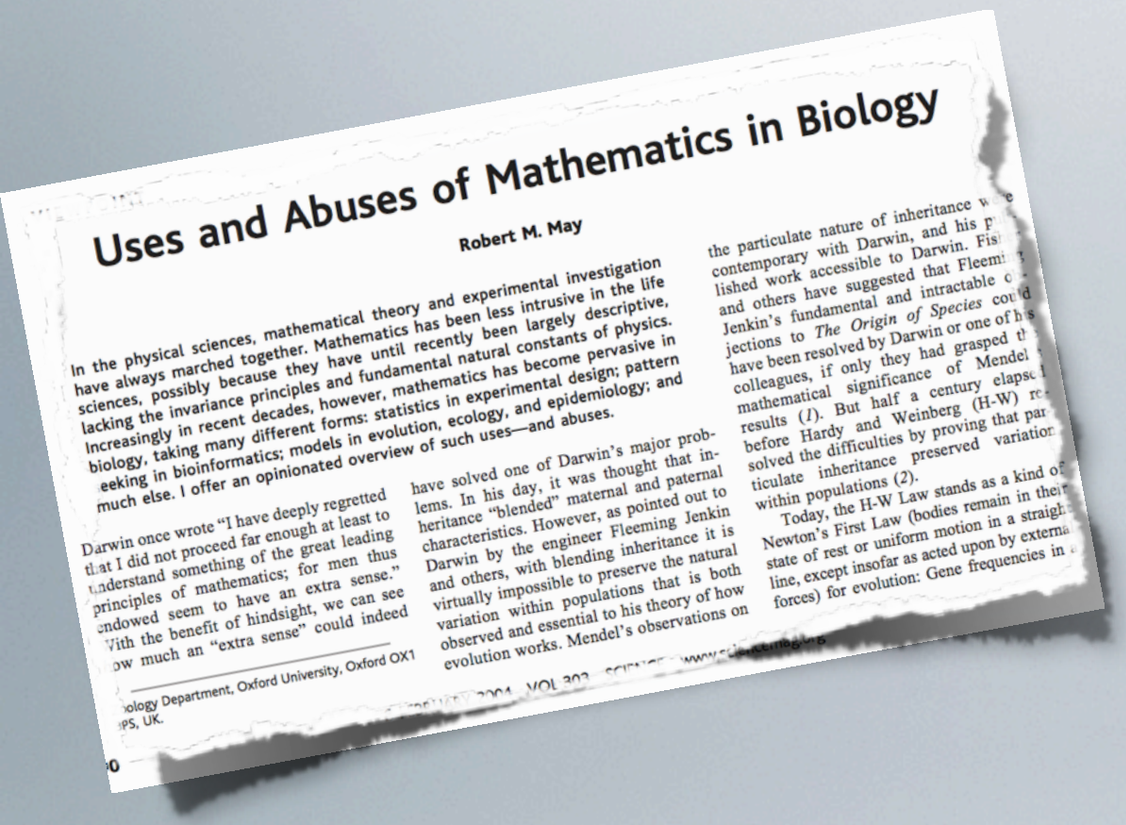
Such activity usually consists of representing sensible and evidence-based assumptions as the starting point for a complicated and usually nonlinear dynamical system, assigning particular parameters (often in an arbitrary way), and then letting this complicated system rip.

ROBERT MAY



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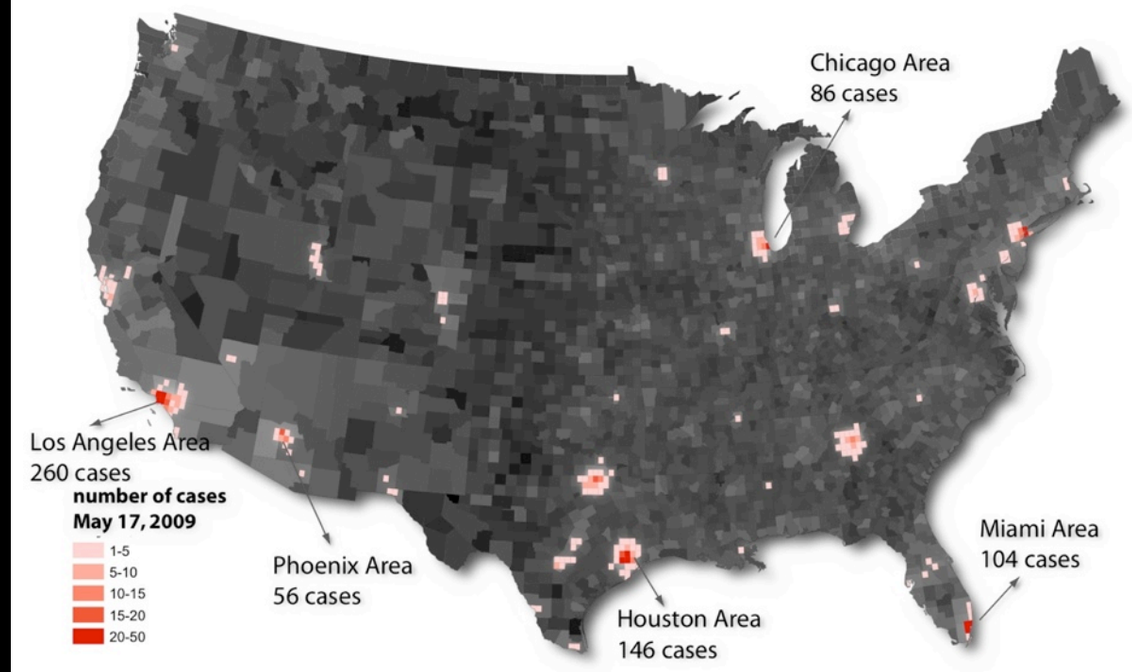
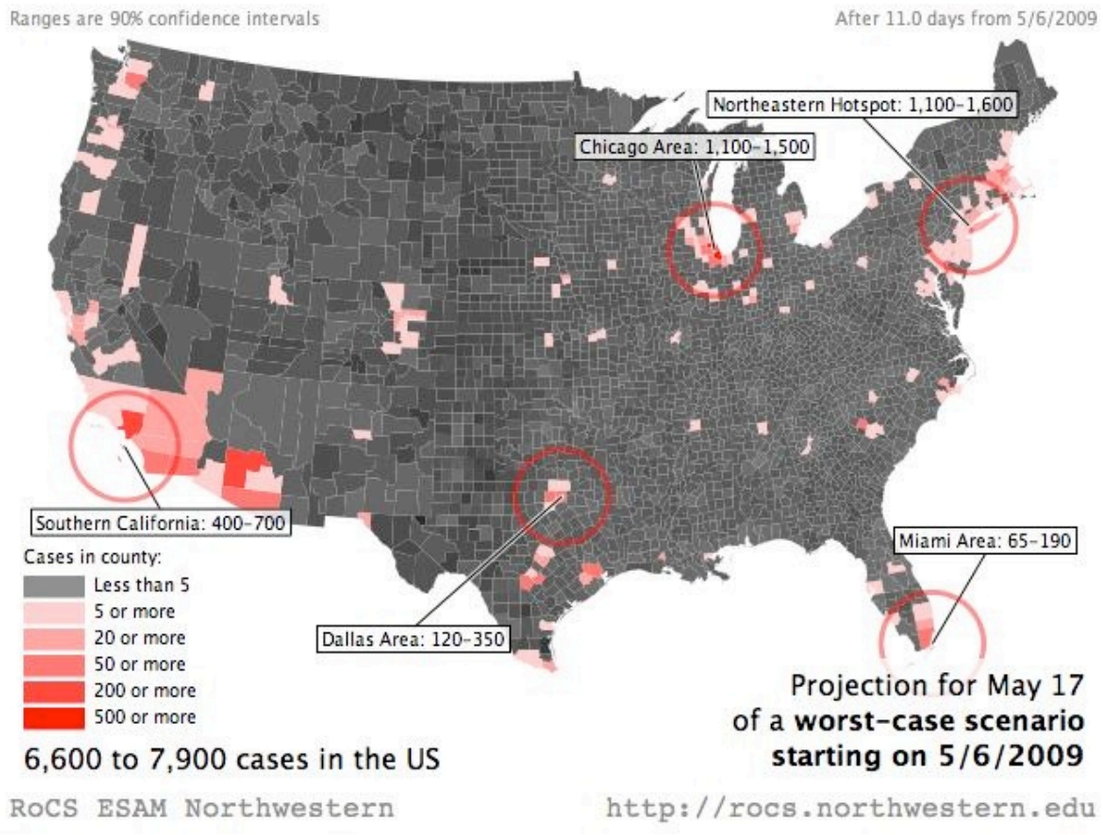
...2004, VOL 303 SCIENCE www.sciencemag.org

we arguably are seeing an increasingly large body of work in which sweeping conclusions - "emergent phenomena" - are drawn from the alleged working of a mathematical model, without clear understanding of what is actually going on. I think this can be worrying.



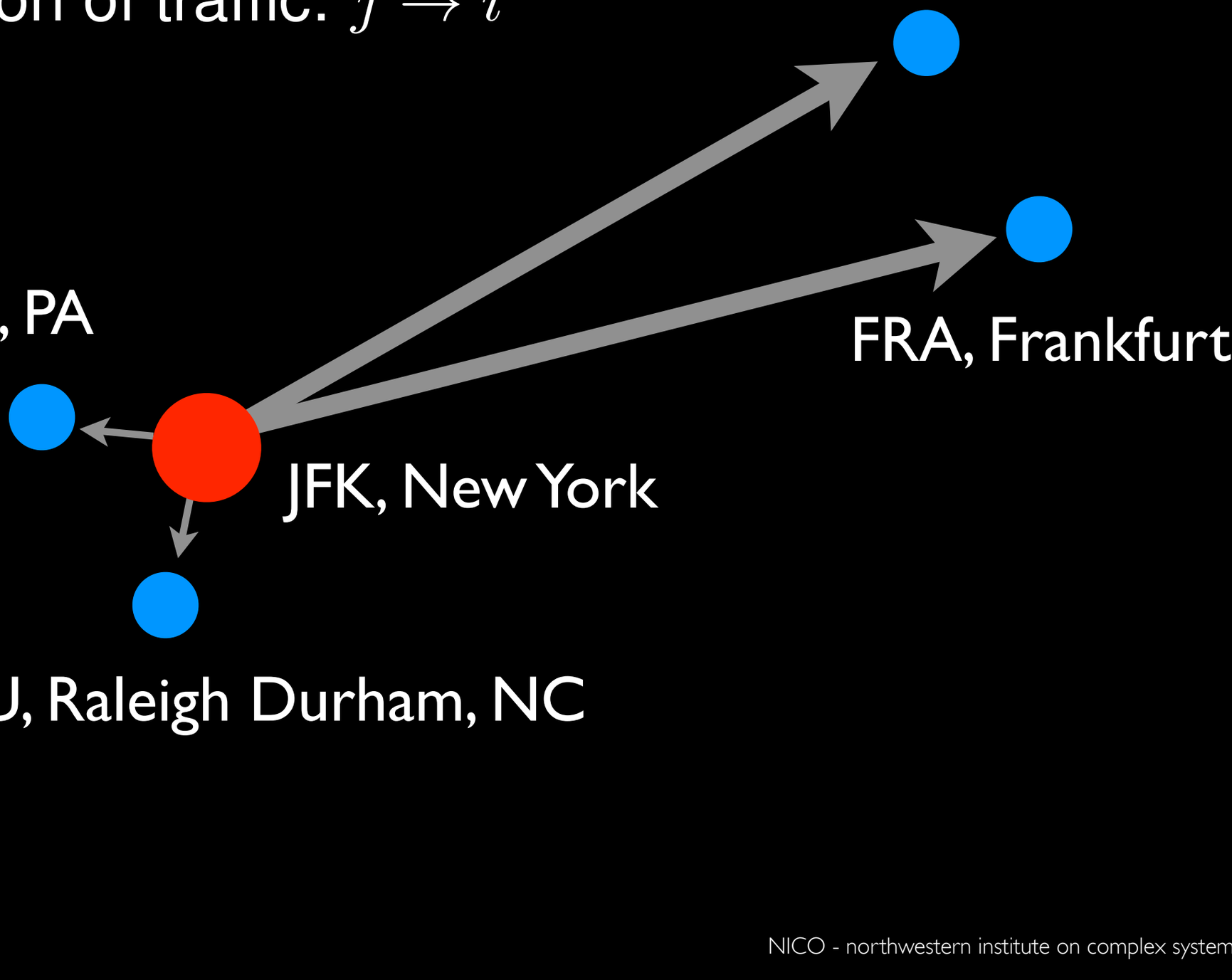


is something more fundamental going on?

redefining the notion of distance

simple idea: effective distance

$P(i|j)$: fraction of traffic: $j \to i$



a different notion of distance

PIT, Pittsburgh, PA

LHR, New York

JFK, New York

FRA, Frankfurt

RDU, Raleigh Durham, NC

$$d(i|j) = 1 - \log P(i|j)$$

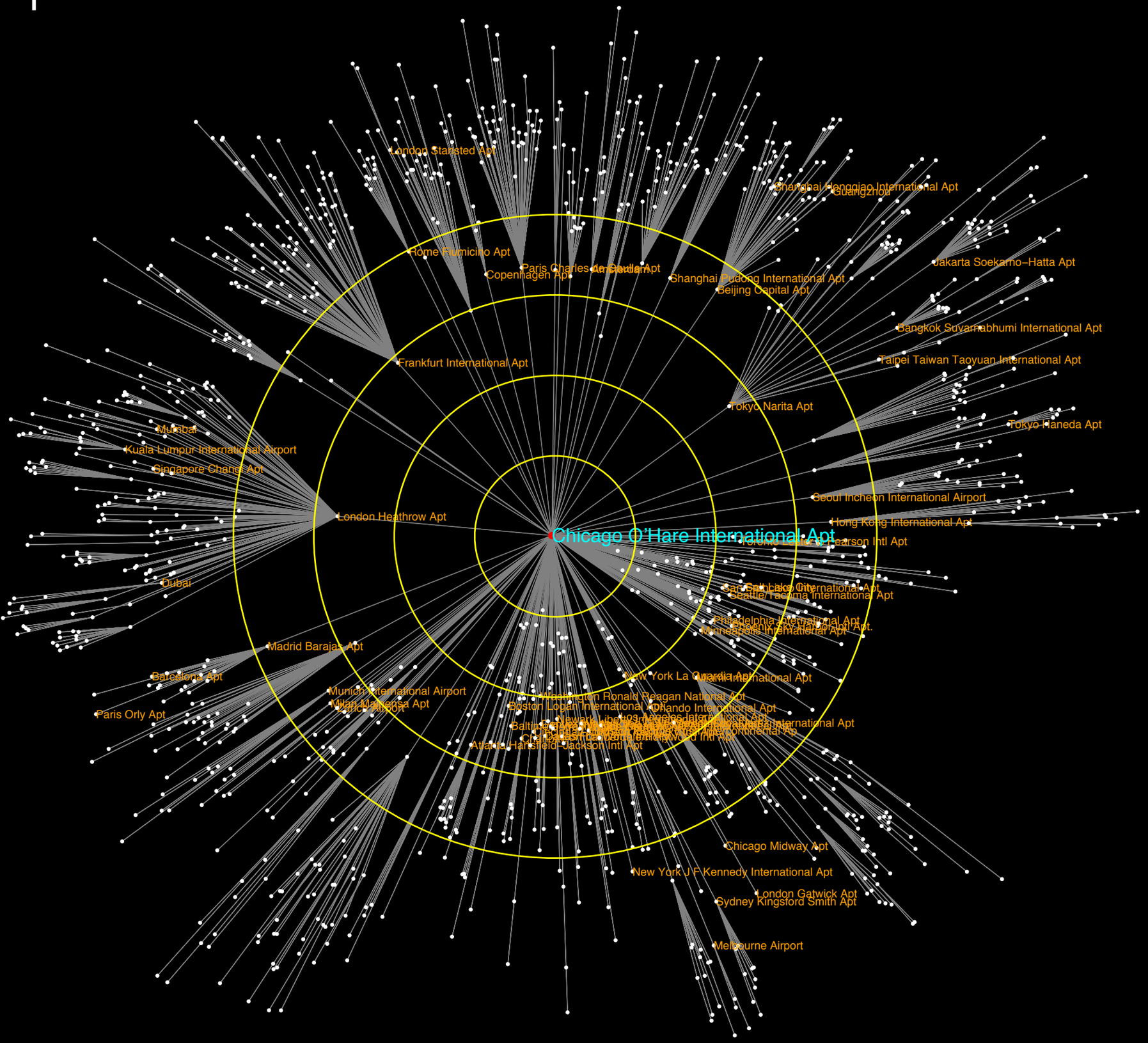
shortest path trees

$$d(i|j) = 1 - \log P(i|j) \qquad \lambda(\Gamma) = L - \sum_{i=1}^{L-1} \log P(i|j)$$

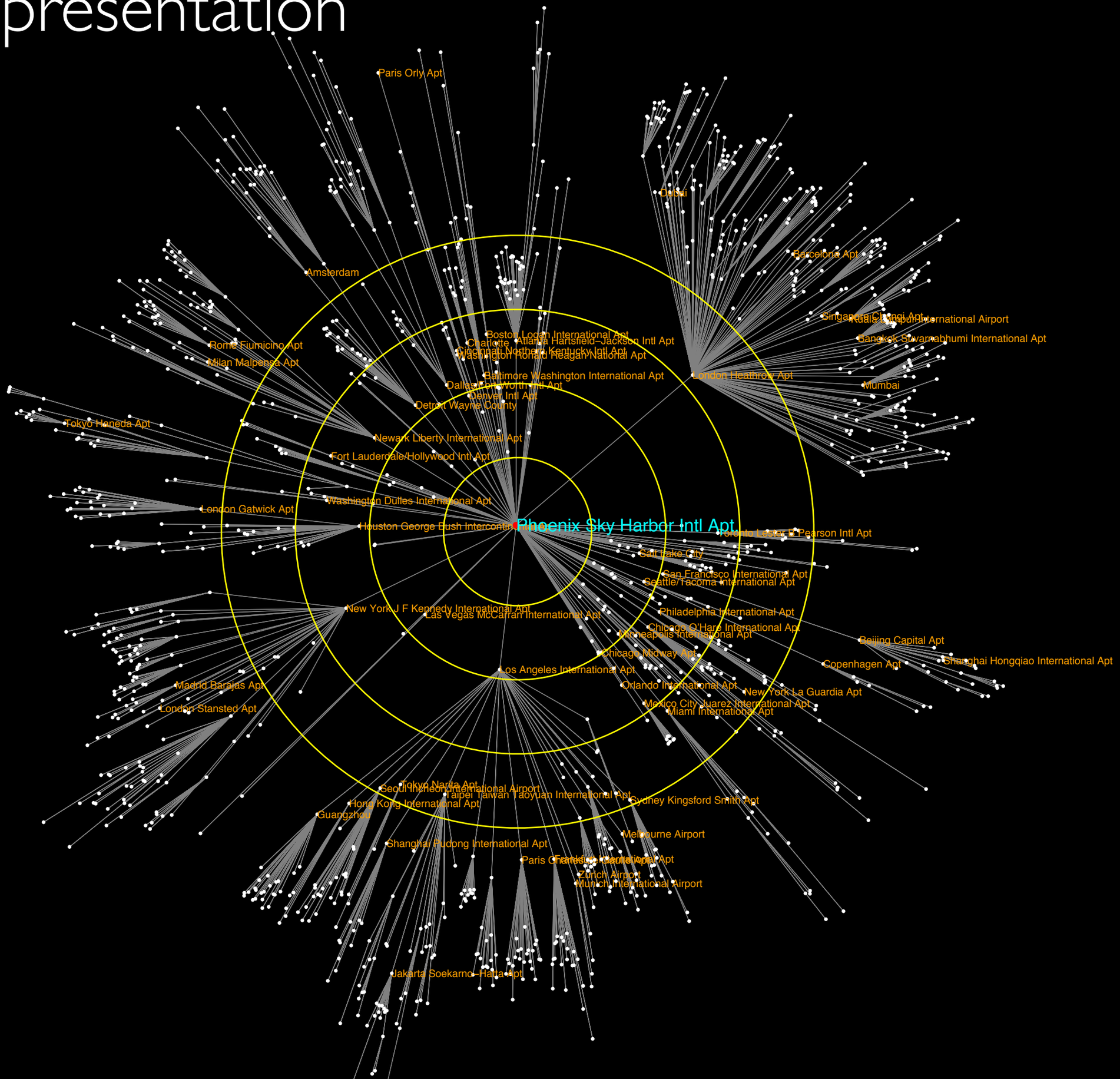
$$D(m|n) = \min_{\Gamma} \lambda(\Gamma)$$

Grady, Thiemann, Brockmann., Nat. Comm. (2012).

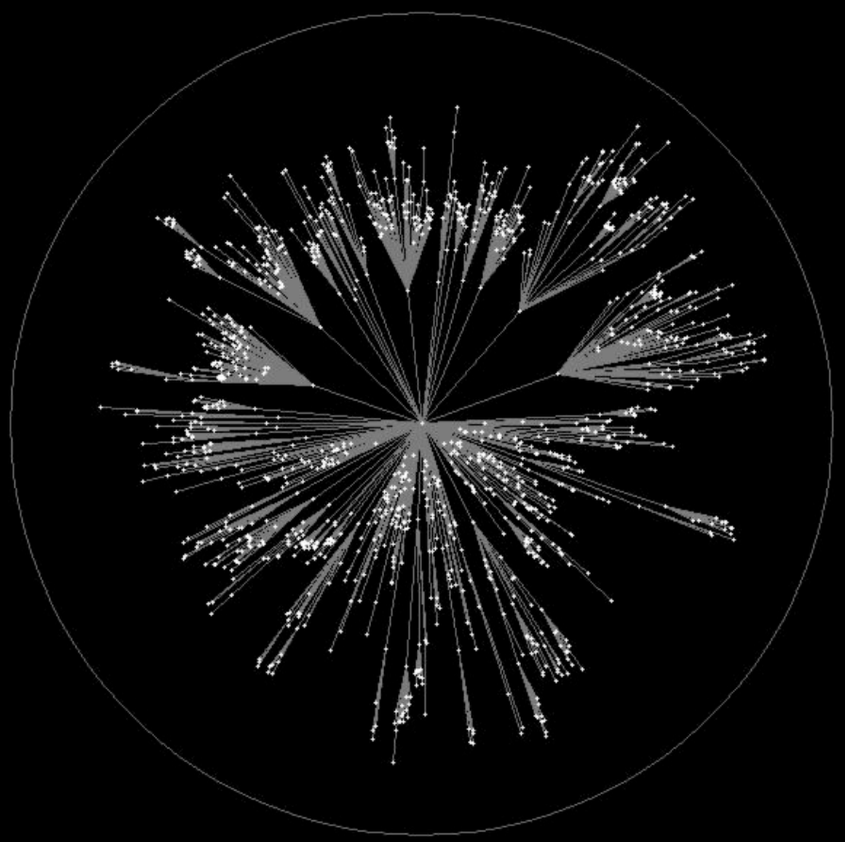
SPT representation

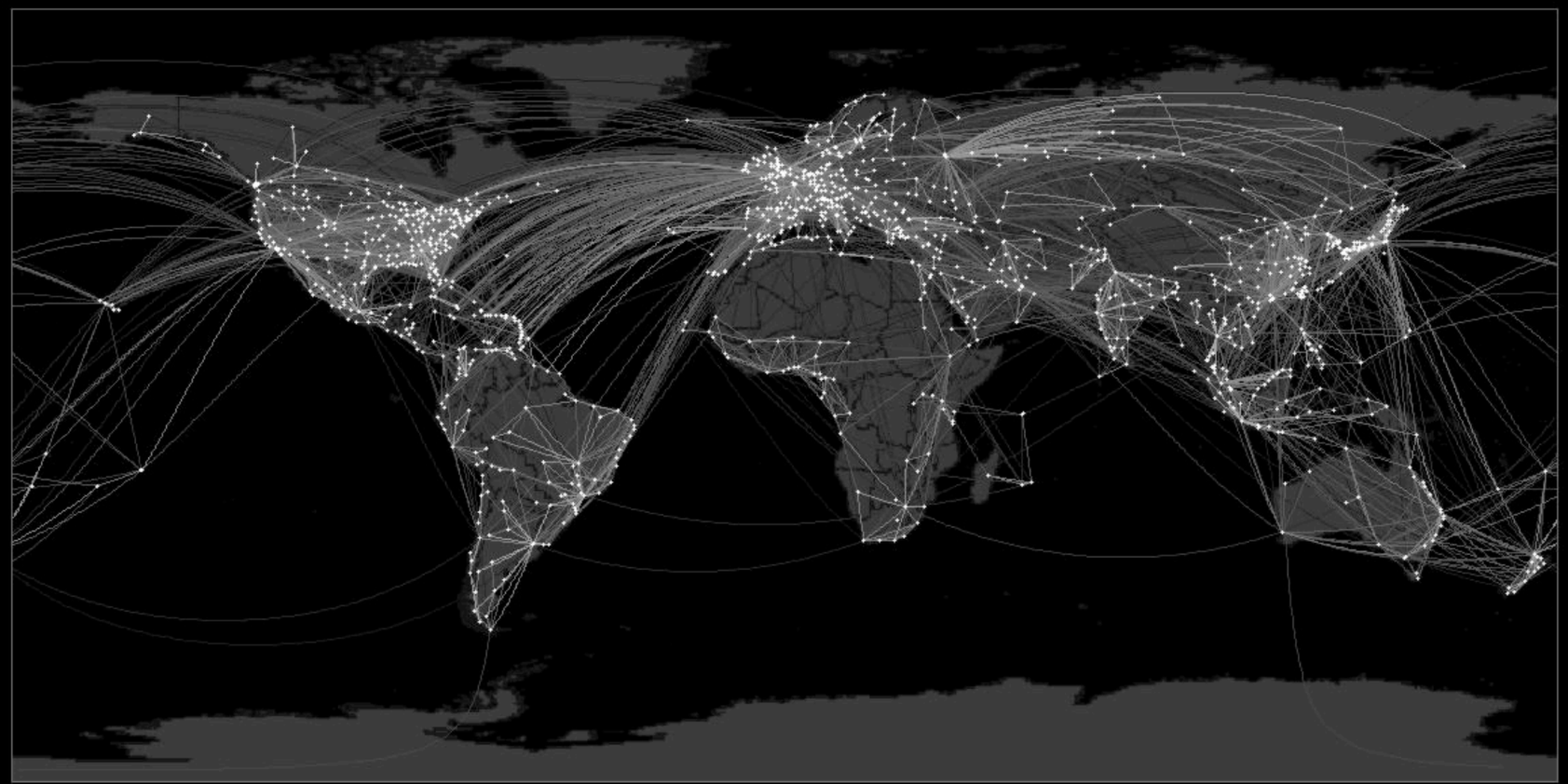


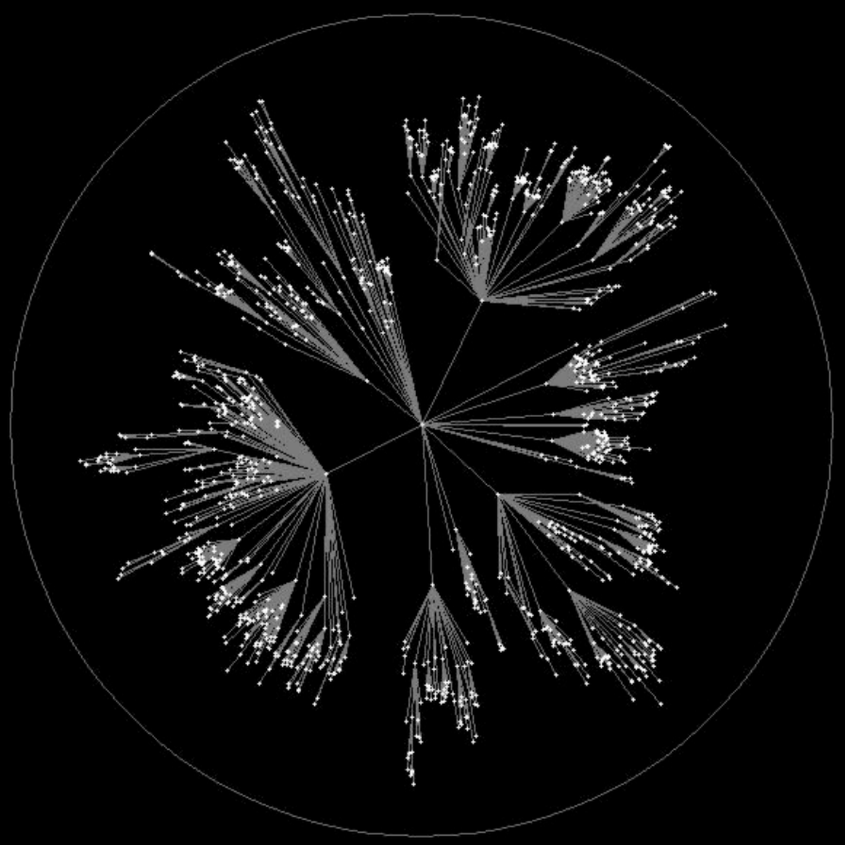
SPT representation

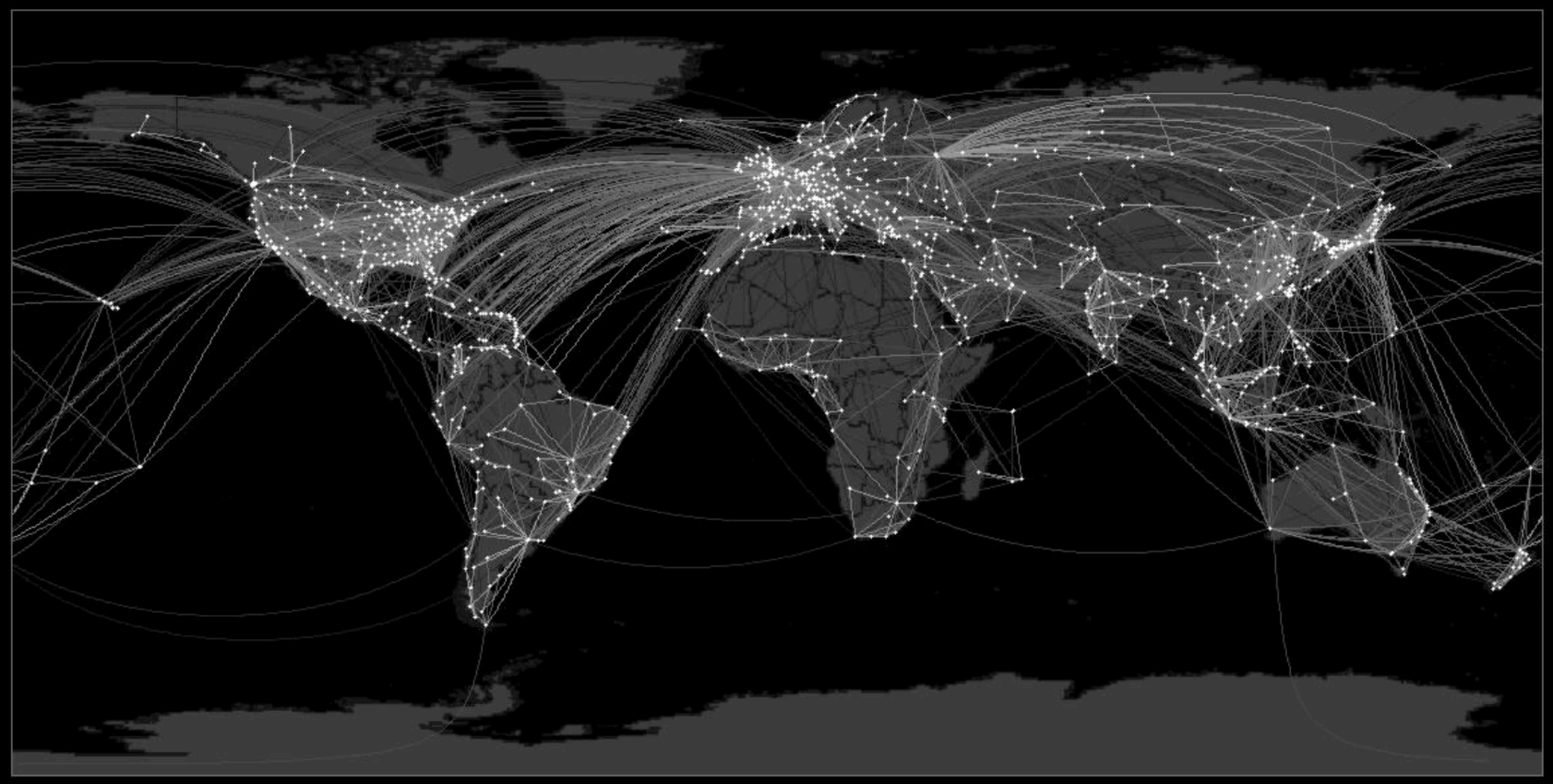


propagating waves

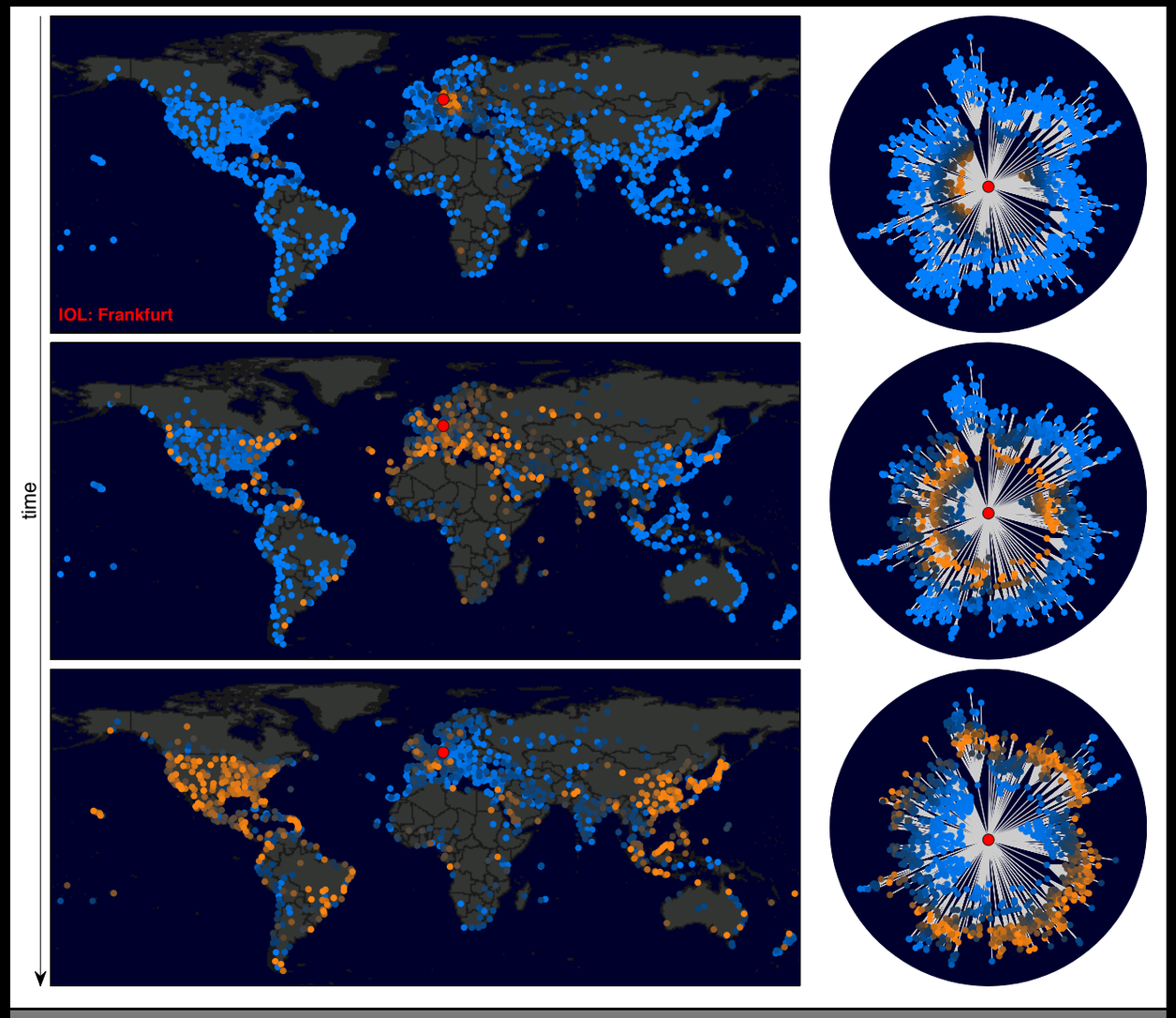


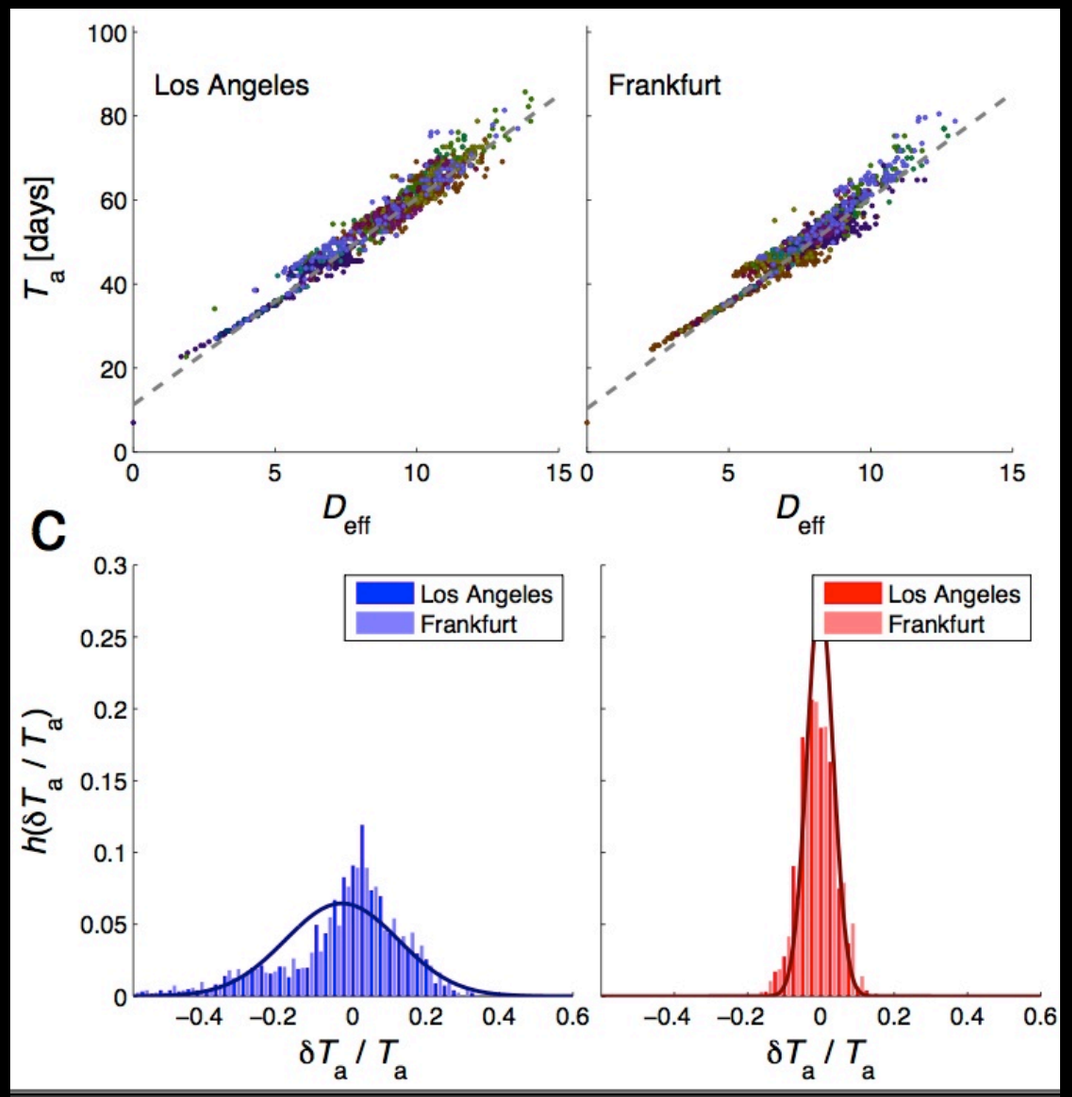




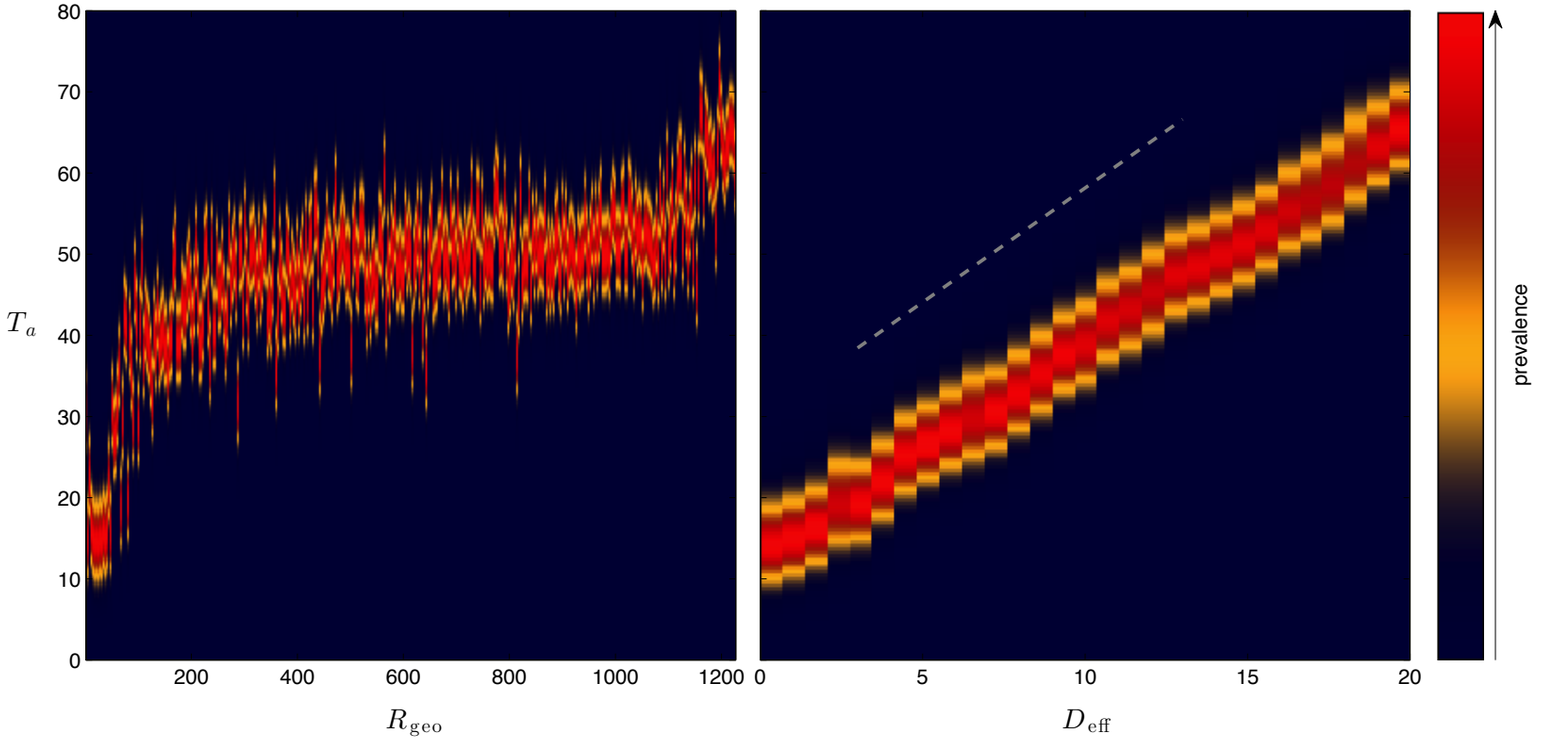


the spread in effective distance

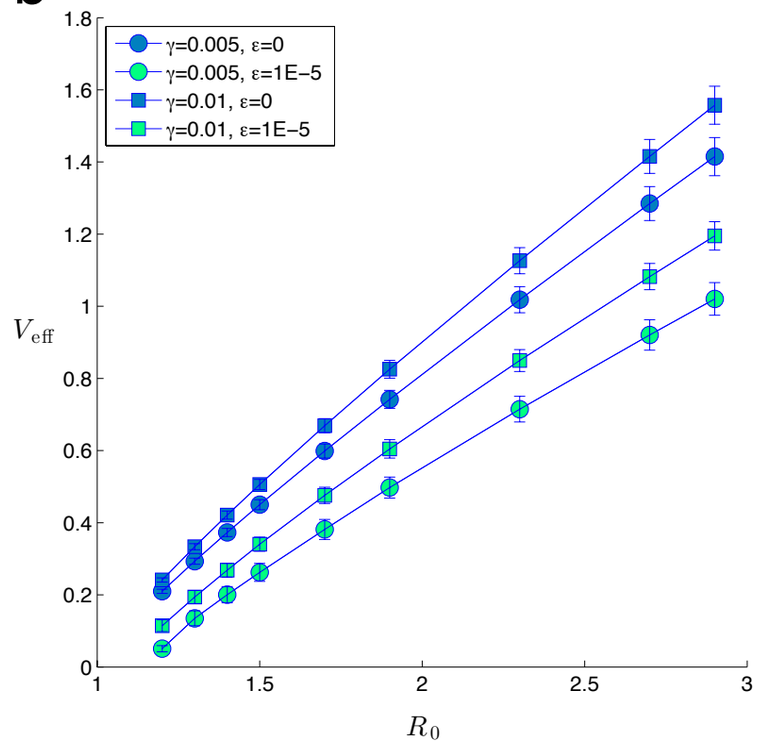




a

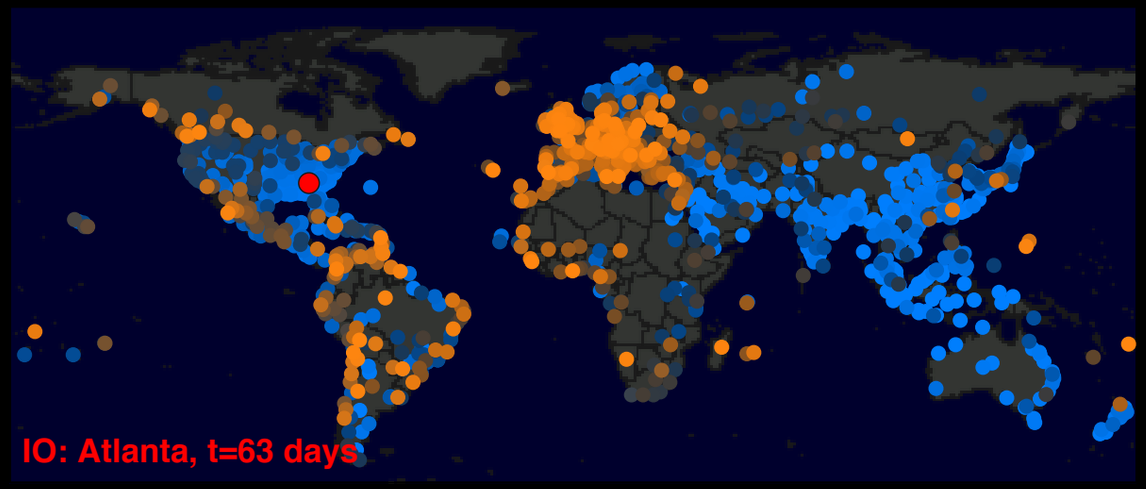


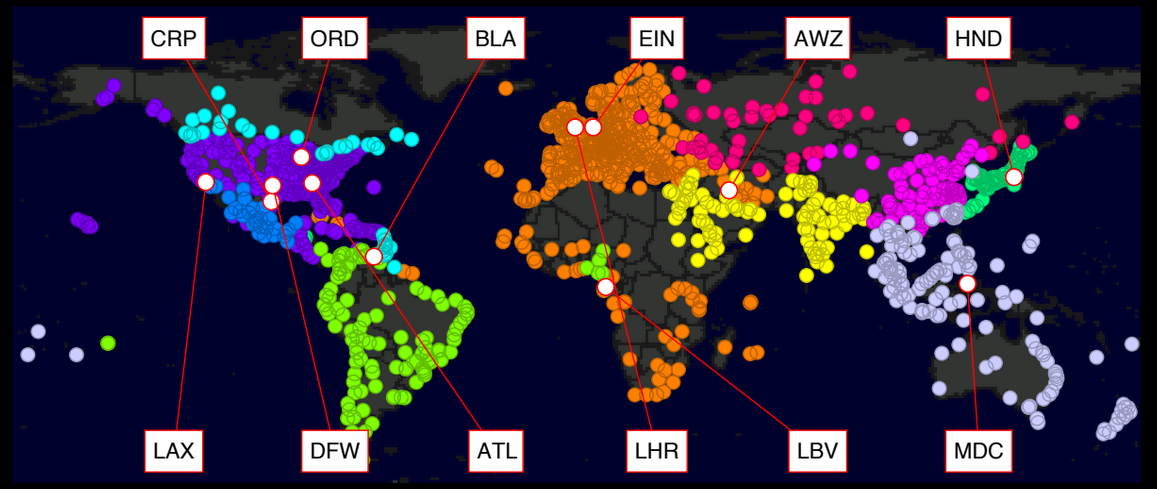
b

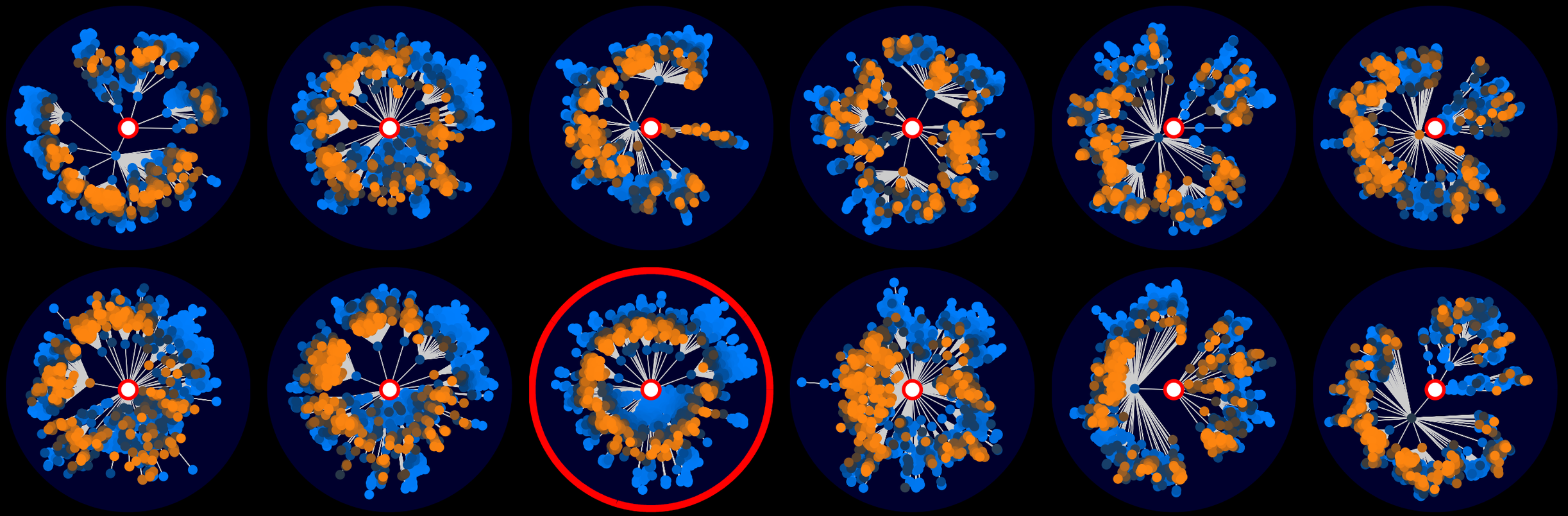


reconstructing an outbreak origin

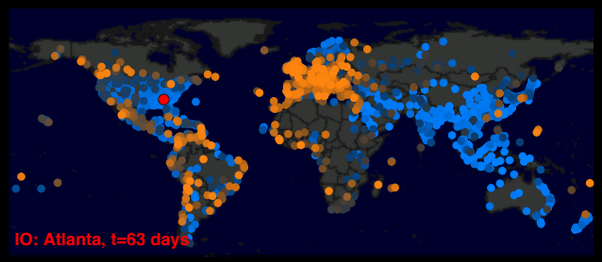
outbreak origin reconstruction

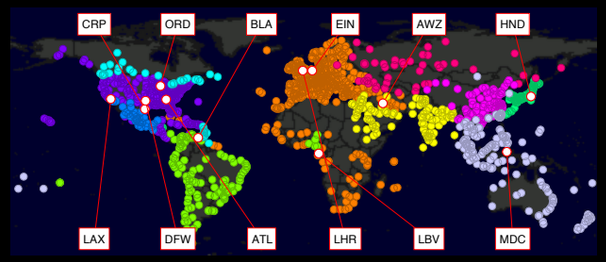


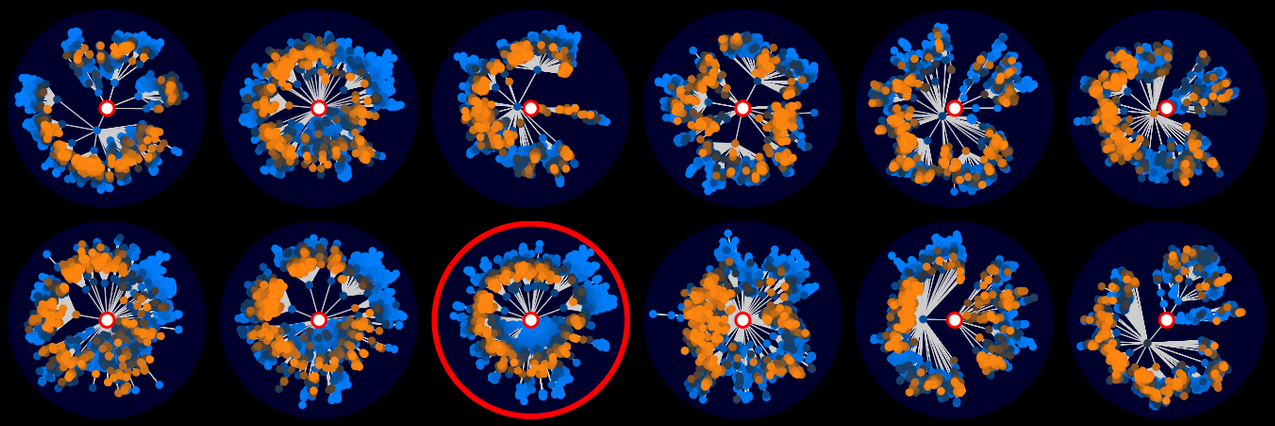


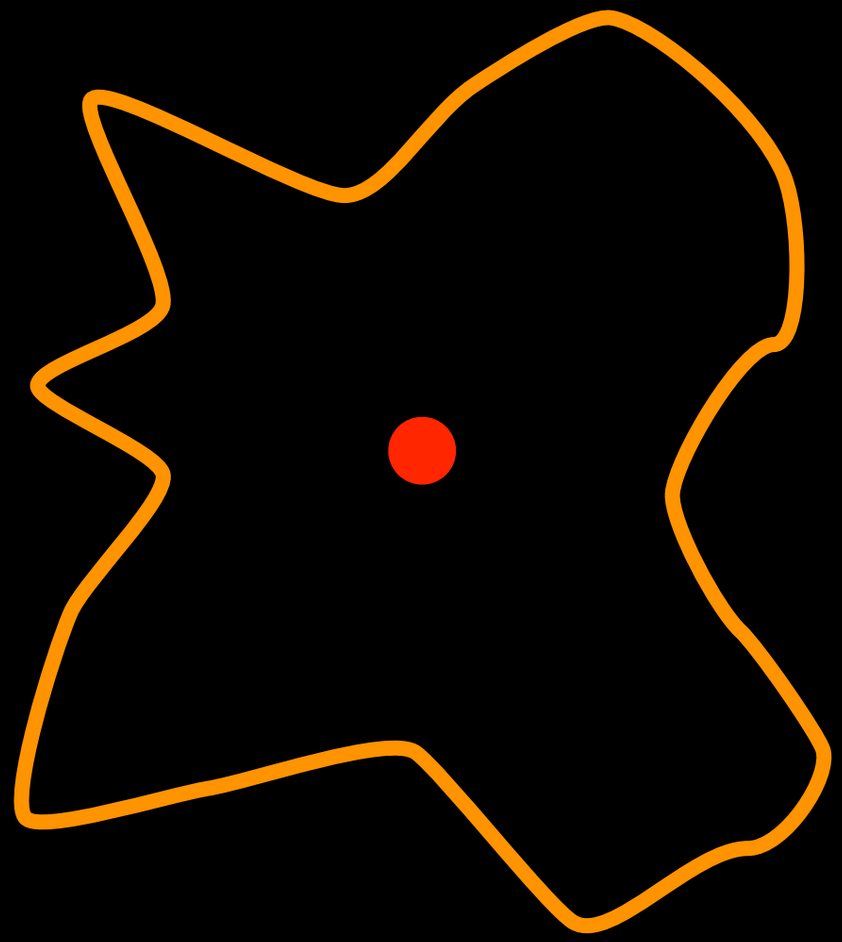


outbreak origin reconstruction

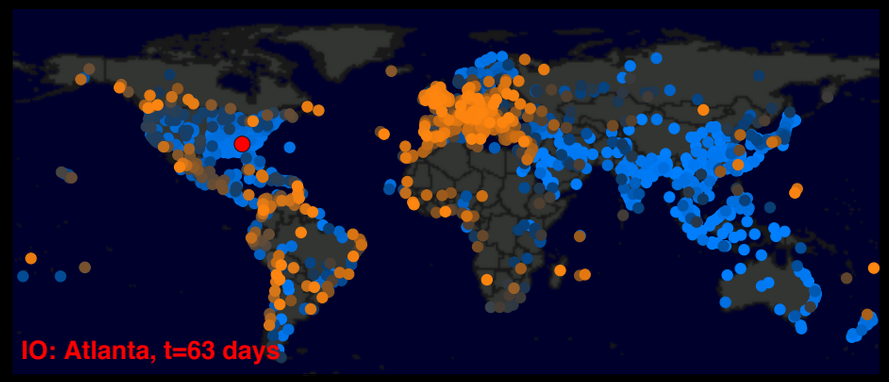


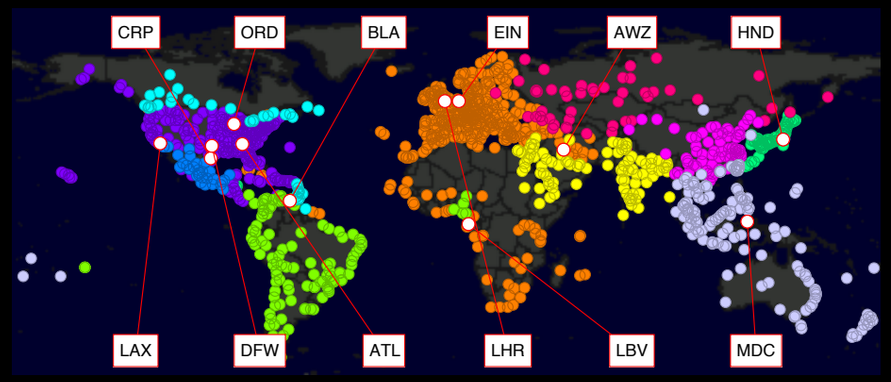


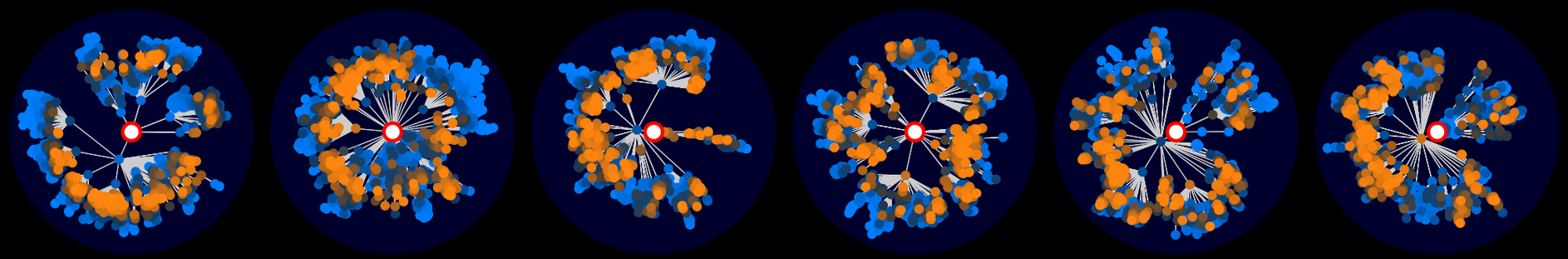


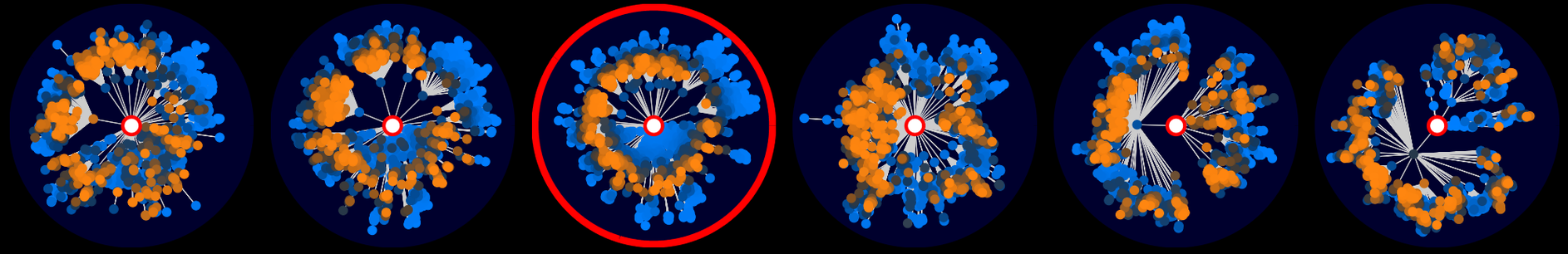


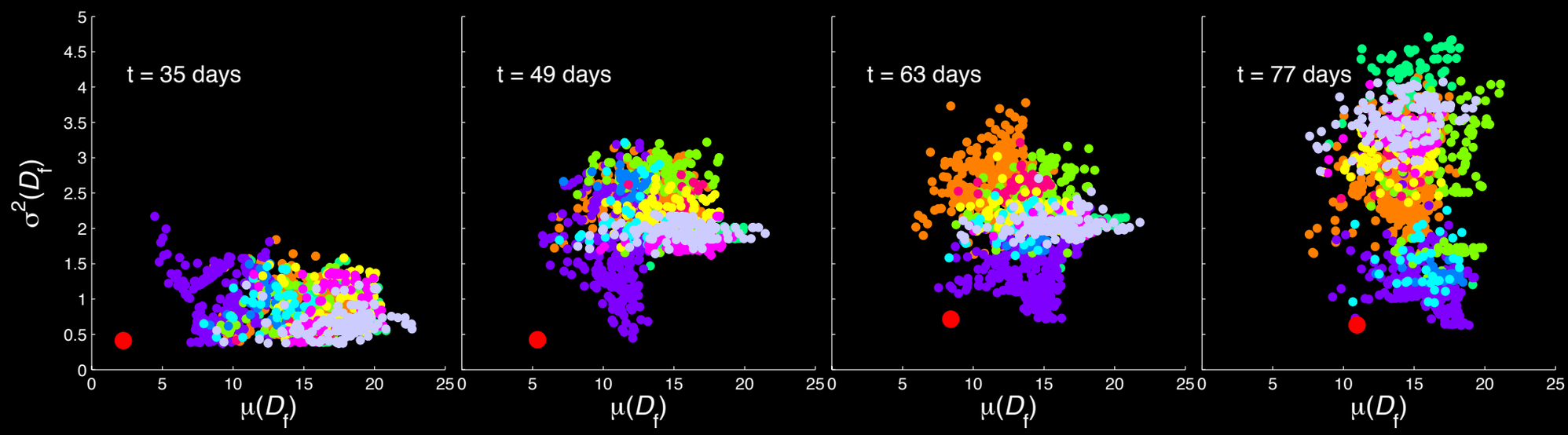
outbreak origin reconstruction





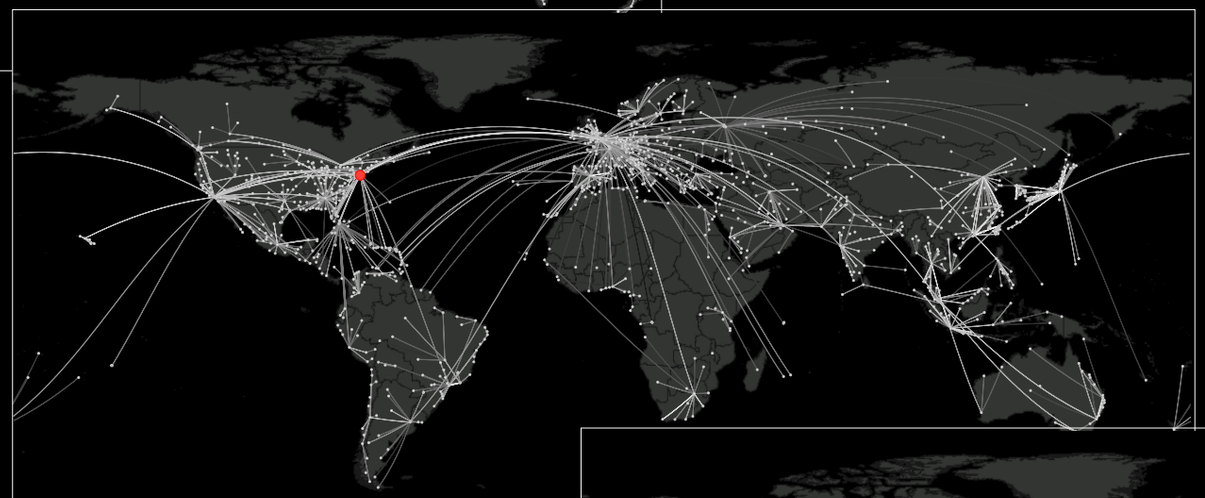






a key component of predictability

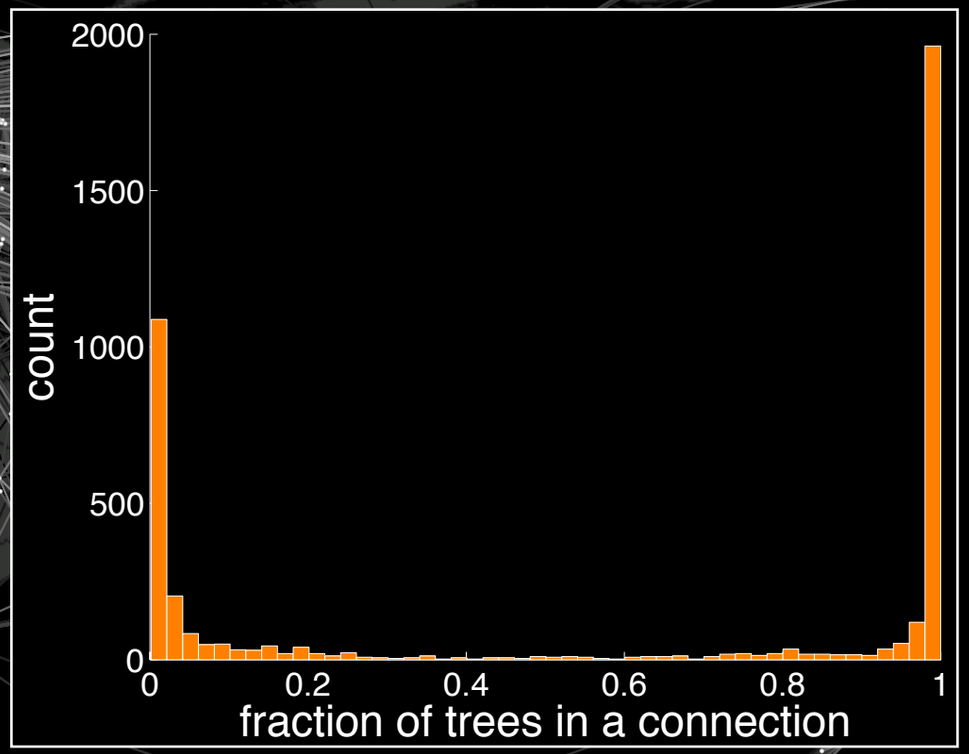
Madrid



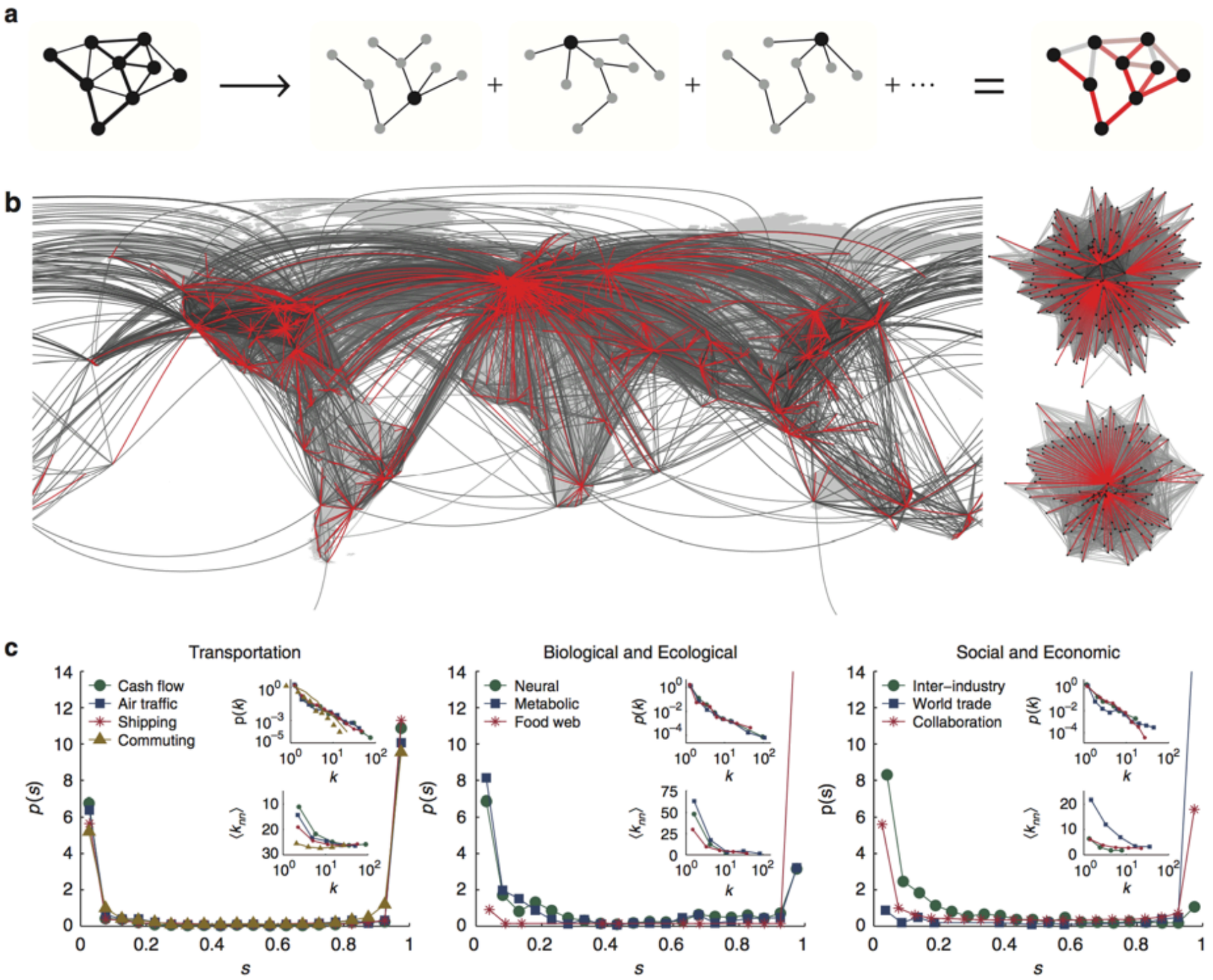
NY

Frankfurt

Grady, Thiemann, Brockmann., Nat. Comm. (2012).



Grady, Thiemann, Brockmann., Nat. Comm. (2012).


a
b
c
Transportation
Biological and Ecological
Social and Economic
Cash flow
Air traffic
Shipping
Commuting
Neural
Metabolic
Food web
Inter–industry
World trade
Collaboration
p(s)
s
p(k)
k
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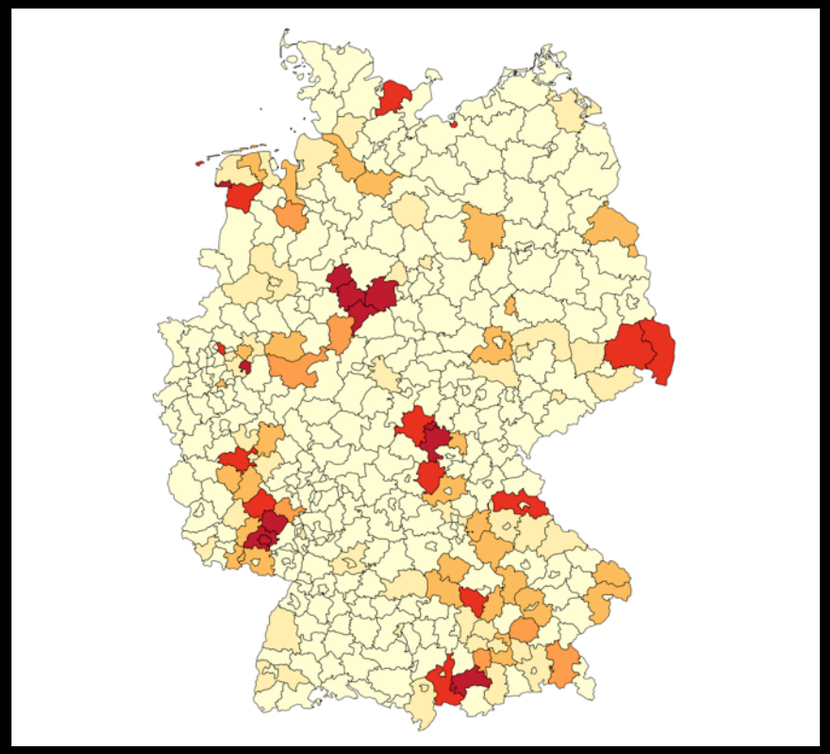
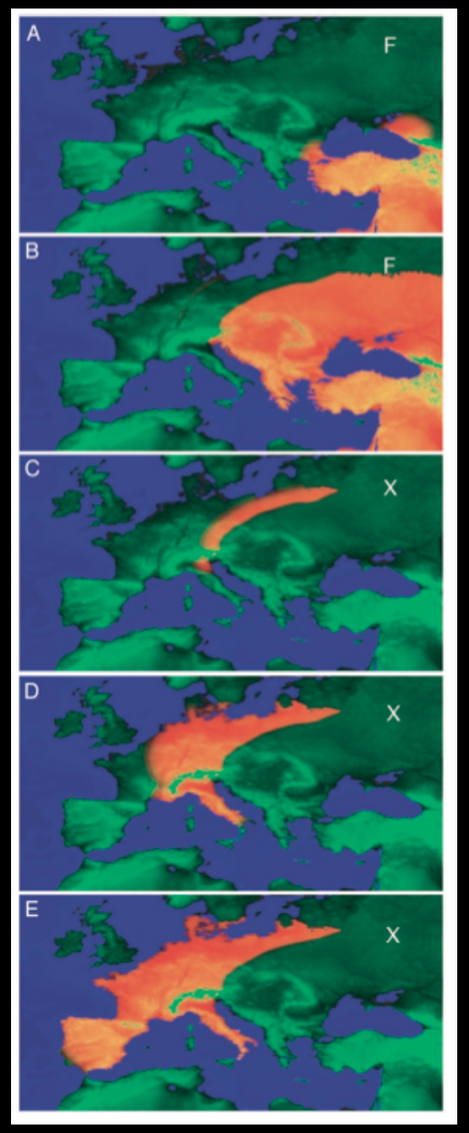
ongoing projects

HUS/EHEC 2011



neolithic spread of farming



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