Stochastic Modeling of Infectious Diseases

The 34th Quality and Productivity Research Conference - 2017

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Agenda

- **Historical Example**
- Metabiota Overview
- Disease Spread Modeling
- Preparedness Index and Coronavirus Risk Model

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Outbreak Starts…

- On February 21st (2003), 64-year-old doctor who was treating "atypical pneumonia" in Guangdong province (China) arrived in Hong Kong to attend a wedding and stayed in Hotel Metropole

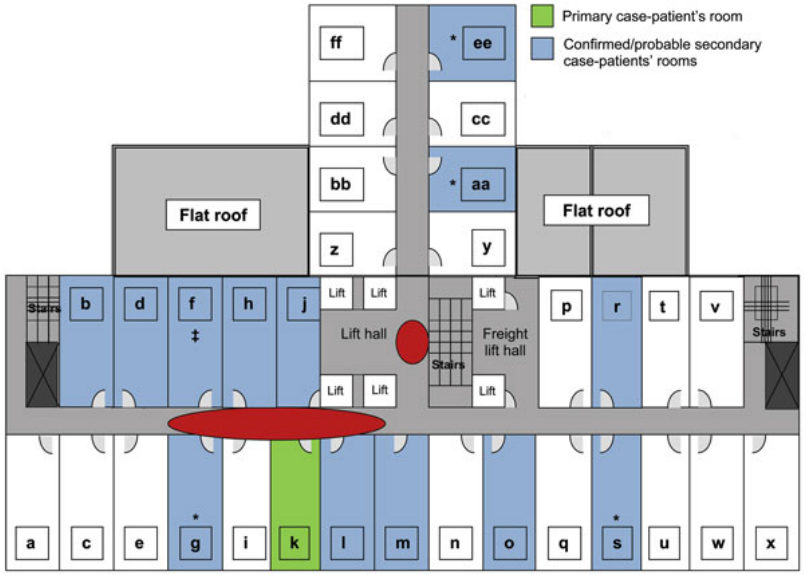
- **Next day** he felt ill and was admitted to the intensive care unit

- On March 4 he died from a mysterious respiratory disease of **unknown origin**

Outbreak Spreads…

- **20 cases** were associated with the transmission on 9th floor started from the index patient who spent only **one** night in the hotel

- 7 out of 20 cases were responsible for consequent large outbreaks in **Canada**, **Vietnam**, **Singapore**, and **Hong Kong** itself



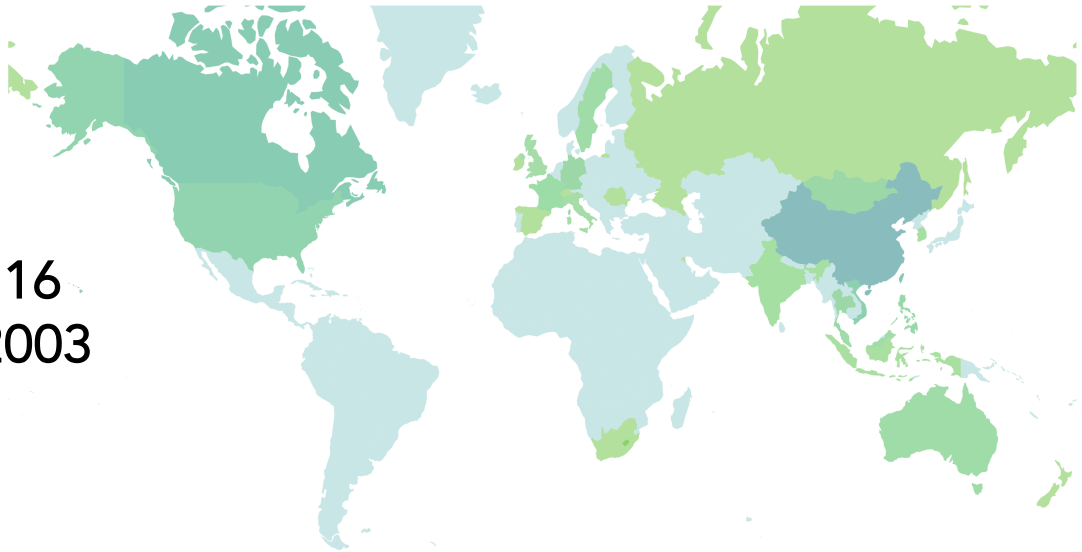
9th floor layout of the **Hotel Metropole** in Hong Kong

Source: Christopher R. Braden, Scott F. Dowell, Daniel B. Jernigan, and James M. Hughes - Emerging Infectious Diseases Journal, Volume 19, Number 6—June 2013

- In Vietnam, **Dr. Carlo Urbani**, a WHO physician, recognized a new and highly contagious disease. He later became infected and died, but his **early warning** started a massive response worldwide

Outbreak Aftermath…

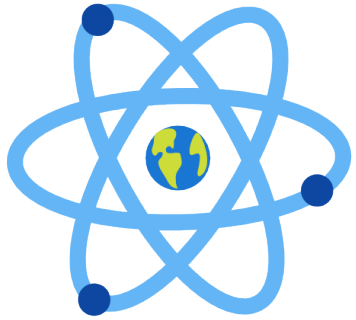
- Mysterious disease was eventually named as **Severe acute respiratory syndrome** (SARS)
- SARS outbreak started in Guangdong, China, on **16 November 2002** and ended in Taiwan on **5 July 2003** (spreading to **27 countries**)



Country	Cases	Fatal
China	5327	349
Hong Kong	1755	299
Taiwan	346	73
Canada	251	43
Singapore	238	33
Vietnam	63	5
USA	27	0
Philippines	14	2
Other	75	6
TOTAL	8096	810

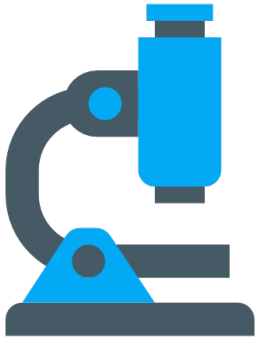
- Numerous **Super-Spreading Events**, like one in Metropolitan Hotel, had been recorded
- **SARS-CoV** spread to humans from wild **palm civet cats** that are valued for their meat and are sold in Chinese markets.
- It is also believed that **bats** are the **natural reservoirs** of SARS-like coronaviruses.

Lessons learned for modeling…



- We must be **flexible** to consider different **disease specific characteristics** like Super-Spreading Events, availability of vaccines, vaccination strategies (mass or ring), etc.

- **Global connectivity** and **travel** patterns play a crucial role in the spread and magnitude of the disease epidemic



- We must be prepared for **newly emerging** infectious diseases

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Metabiota Mission

In the last decade, there have been over **470** human disease outbreaks

$54B
SARS
(Global, 2003)

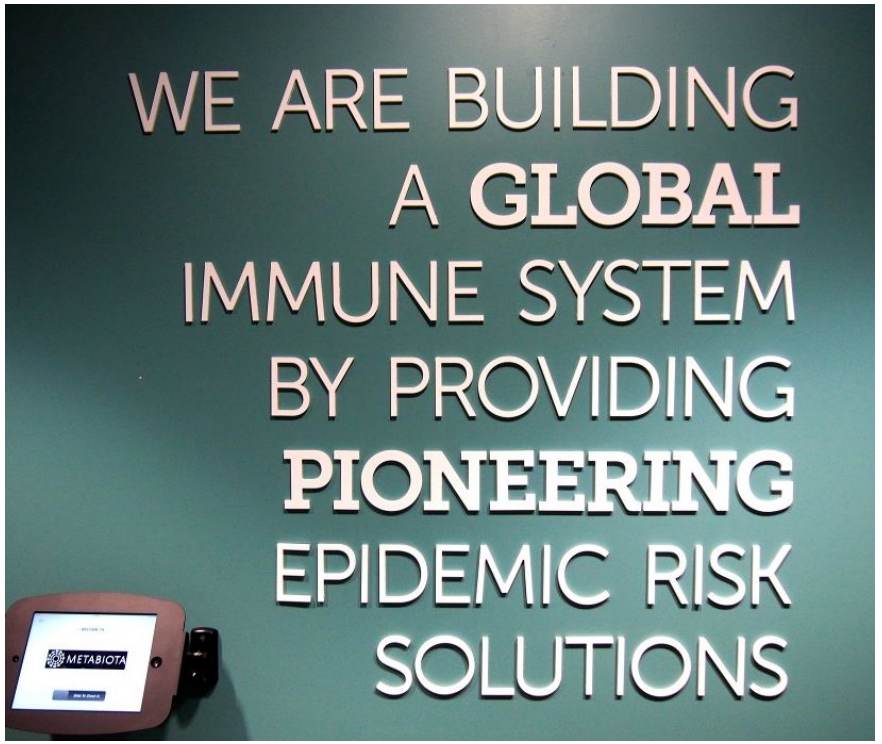
$23B
MERS
(Korea, 2015)

$11B
Foot & Mouth
(UK, 2001)

$3.3B
Avian Flu
(US Midwest, 2015)

$2B
Ebola
(W. Africa, 2015)

$900M
Dengue Fever
(Brazil, 2013)



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Where is Metabiota?

- Founded in 2008 with offices in San Francisco, Canada, Ukraine, Democratic Republic of Congo, and Cameroon and operations in 20 countries

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Metabiota Team

- Multidisciplinary team
- Collaboration with academic partners
- Perform epidemiological, statistical, and actuarial modeling

Cathine Lam
ACTUARIAL ASSOCIATE

Mike Gahan
ACTUARIAL ASSOCIATE

Mark Gallivan
MODELER

Ben Oppenheim
SENIOR SCIENTIFIC CONSU...

Kierste Miller
MODELER

Volodymyr Serhiyen...
DATA SCIENTIST/STATISTIC...

Nita Madhav
DIRECTOR, INFECTIOUS DI...

Nicole Stephenson
MODELER

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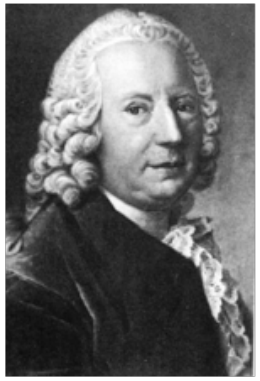
Milestones in Epidemic Modeling



Daniel Bernoulli

Model for change in life expectancy if smallpox were to be eradicated

1766

A Contribution to the Mathematical Theory of Epidemics.
By W. O. Kermack and A. G. McKendrick.
(Communicated by Sir Gilbert Walker, F.R.S.—Received May 13, 1927.)
(From the Laboratory of the Royal College of Physicians, Edinburgh.)

Kermack & McKendrick

SIR differential equation model for plague in Bombay

1927

A Mathematical Model for the Global Spread of Influenza

LEONID A. RVACHEV
Gamaleya Institute of Epidemiology and Microbiology, Academy of Medical Sciences, Moscow, U.S.S.R.

AND

IRA M. LONGINI, JR.*†
Department of Statistics and Biometry, Emory University, Uppergate House, Atlanta, Georgia 30322

Received 7 January 1985; revised 10 April 1985

Rvachev & Longini

Global metapopulation model for 1968 flu pandemic

1985

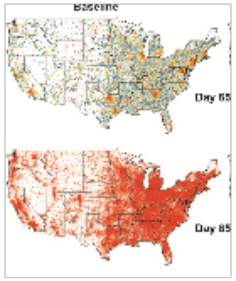
OXFORD SCIENCE PUBLICATIONS
INFECTIOUS DISEASES OF HUMANS
DYNAMICS AND CONTROL
ROY M. ANDERSON AND ROBERT M. MAY

Anderson & May

Lucid description of the mathematical theory of epidemics

1991

Modeling the Worldwide Spread of Pandemic Influenza: Baseline Case and Containment Interventions



Los Alamos

Agent-based flu model for US

2006

Vespignani & colleagues

Global multi-scale model with air travel and commuting

2007

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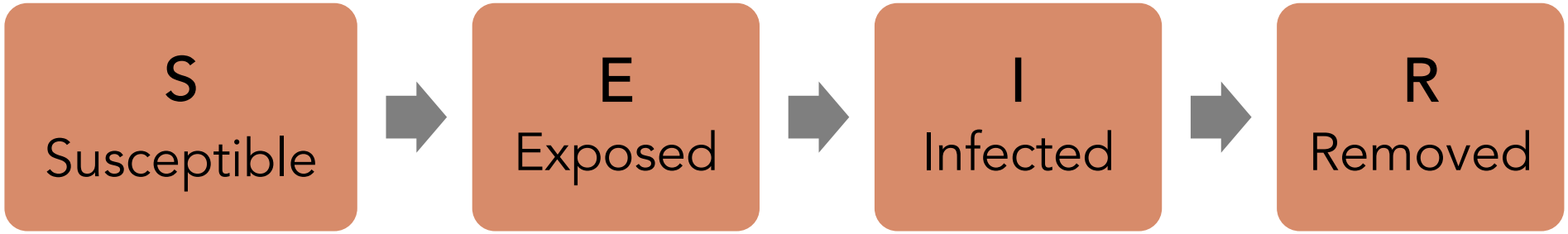
Modeling Cooperation

- **Metabiota** closely cooperates with **Alessandro Vespignani** and his colleagues from Northeastern University's Laboratory for the **Modeling of Biological and Socio-technical Systems**

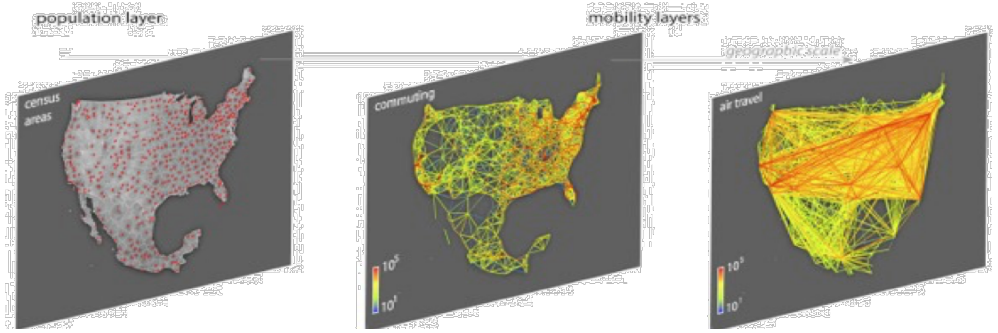
- Together we are developing disease spread models to realistically simulate disease spark, spread, and duration of epidemics

- Our main framework is Global Epidemic and Mobility model (GLEaM) that stochastically simulates the spread of epidemics at the worldwide scale

GLEaM framework



Underlying Compartmental Model



- Global population is divided into basins around transportation hubs (i.e. airports). The resulting network consists of 3,362 geographic subpopulations
  + Full **airline** transportation data
  + **Short-range** mobility network

Individual based model

- Model probabilistically progresses **individuals** through each compartment by **stochastically simulating** values from binomial and multinomial distributions

$$Multinomial\left(E_j(t), p_{E_j \to I_j^a}, p_{E_j \to I_j^t}, p_{E_j \to I_j^{nt}}\right)$$

$$Binomial\left(S_j(t), p_{S_j \to E_j}\right)$$

- More details can be found in:
  Balcan, D., Gonçalves, B., Hu, H., Ramasco, J. J., Colizza, V., & Vespignani, A. (2010). Modeling the spatial spread of infectious diseases: The GLobal Epidemic and Mobility computational model. *Journal of computational science*, 1(3), 132-145.

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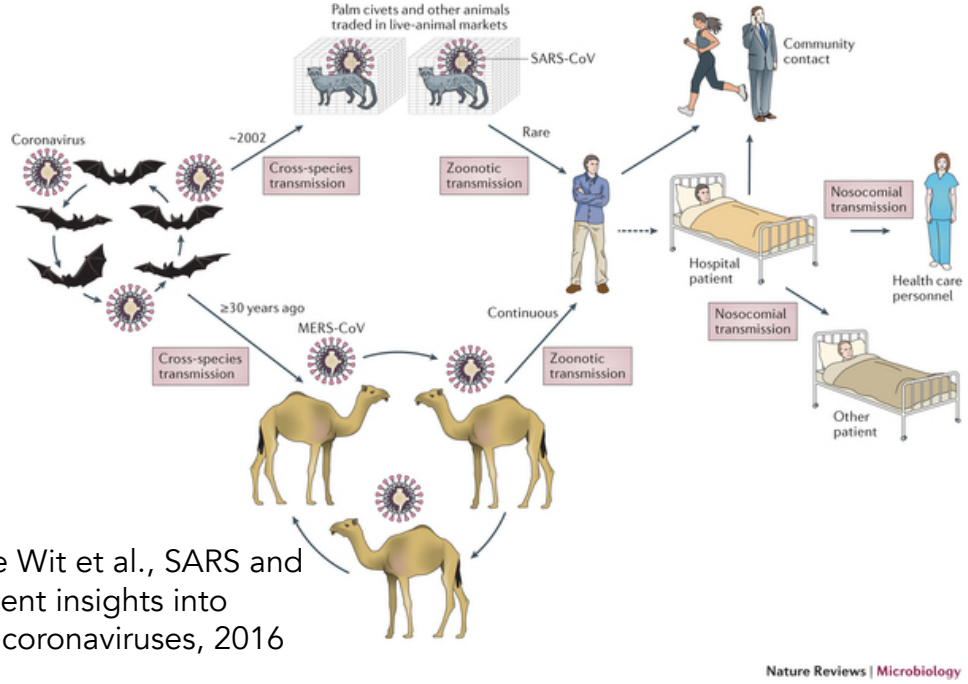
Coronavirus Outbreaks

- **SARS 2003** outbreak: 8096 cases, 810 deaths, 27 countries effected
- **Middle East Respiratory Syndrome** (MERS) 2013 outbreak: 1980 cases, 699 deaths, 15 countries effected (as of June 6, 2017) – cased by novel MERS-CoV



Source: de Wit et al., SARS and MERS: recent insights into emerging coronaviruses, 2016

- First case reported in Saudi Arabia April 2012, still on-going
- Saudi Arabia is the most affected country (80% of total cases)
- Notable event:
  South Korea 2015 MERS outbreak
  Caused by one index patient
  182 cases with 37 deaths

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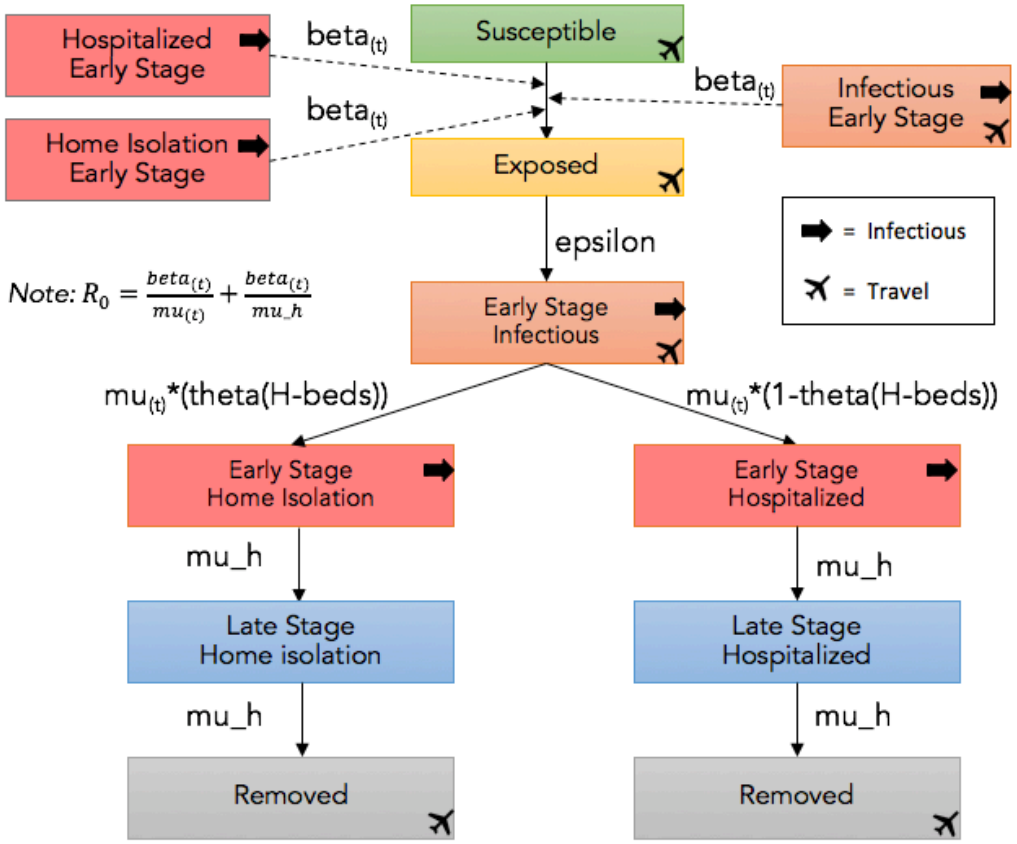
Model Design – Compartments



- Main model parameters:

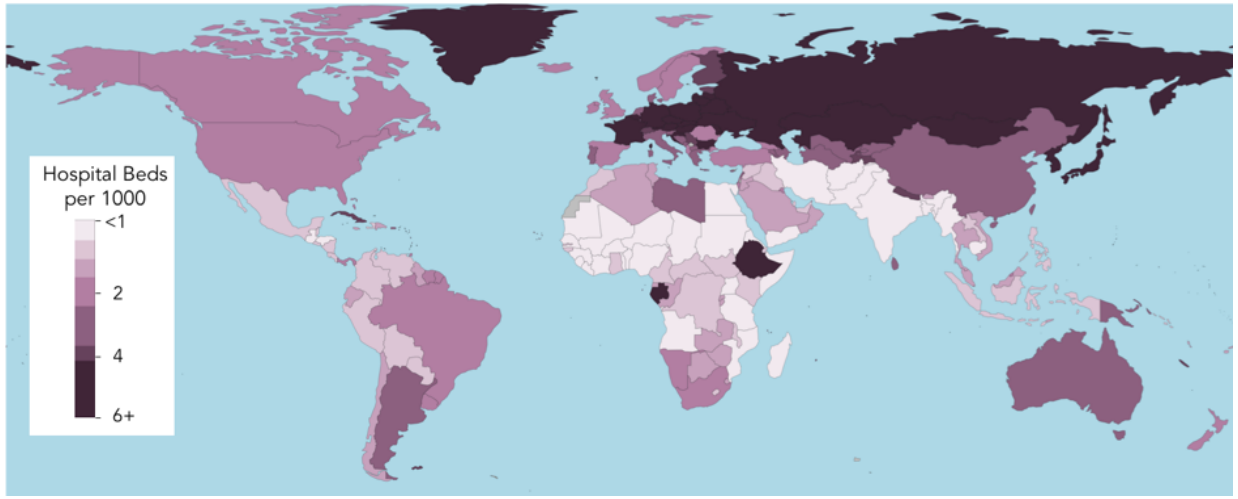
  R_0 - basic reproductive number (number of secondary infections)
  ϵ^{-1} - incubation period
  μ^{-1} - infectious period
  Travel Reduction (%)
  Transmissibility reduction time, etc.

- Super-Spreading Events:

$$\begin{matrix} Number \\ of\ secondary \\ cases \end{matrix} \sim NegBinomial(R_0, k)$$

Differences among countries

Hospital beds per capita



Source: World Bank

If outbreak starts in USA, is it going to be different from China or Sierra Leone outbreak of the same disease?

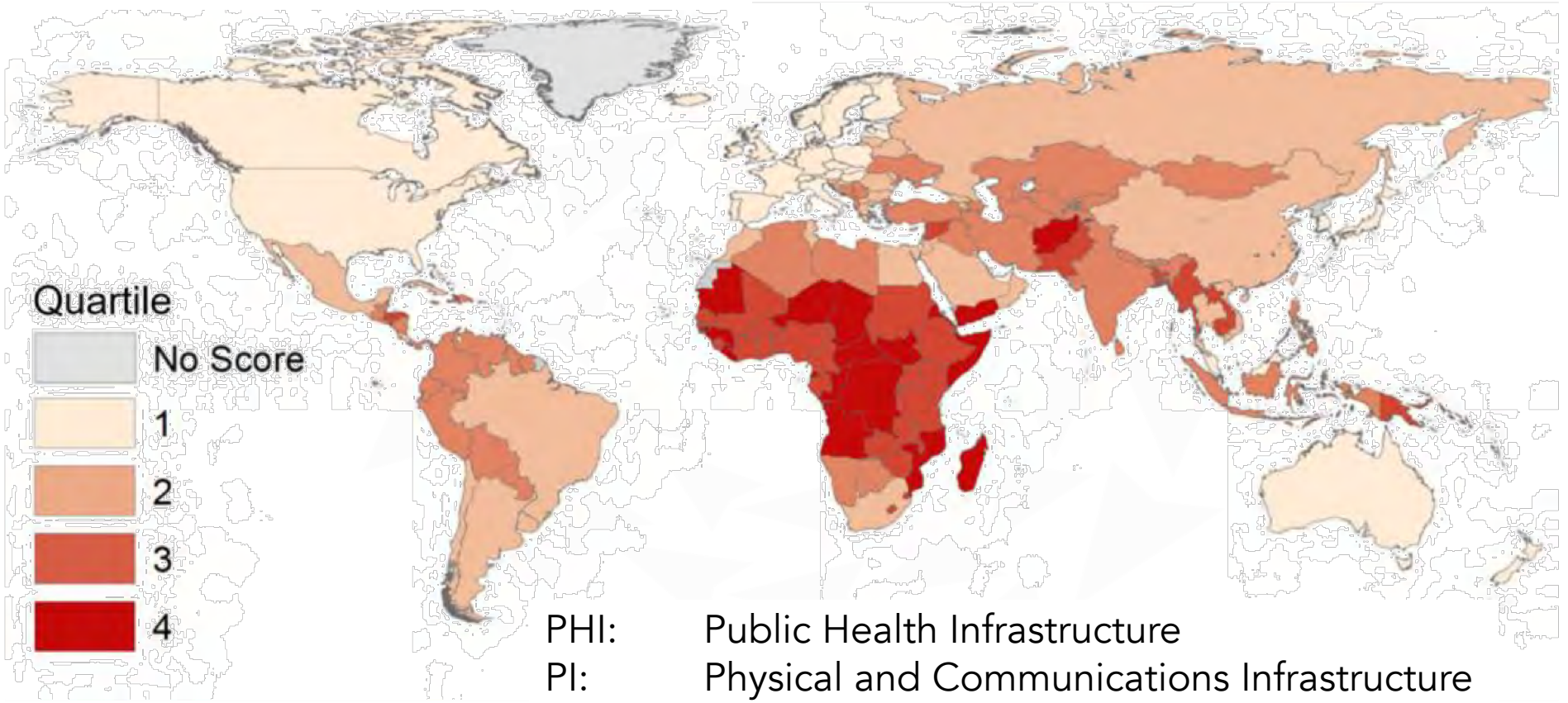
Country-level differences in

- Outbreak surveillance
- Outbreak reporting time
- Timing of intervention measures
- …

How do we capture these differences?

Epidemic Preparedness Index

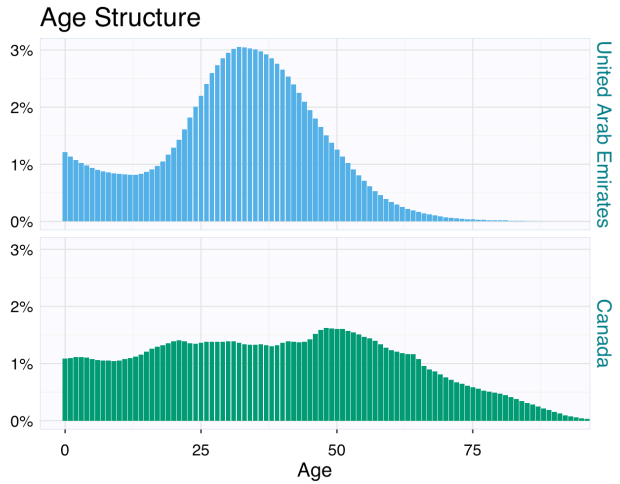
(1=most prepared, 4=least prepared)

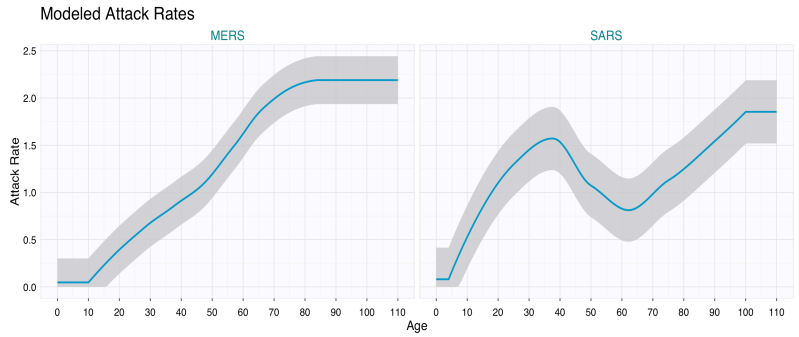


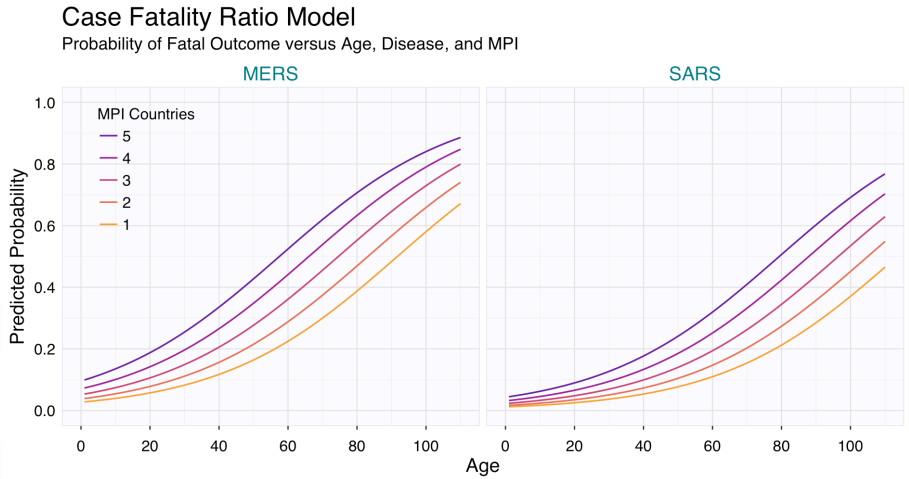
Source: Metabiota

PHI:	Public Health Infrastructure
PI:	Physical and Communications Infrastructure
IC:	Institutional Capacity
EF:	Economic Factors
PHC:	Public Health Communications

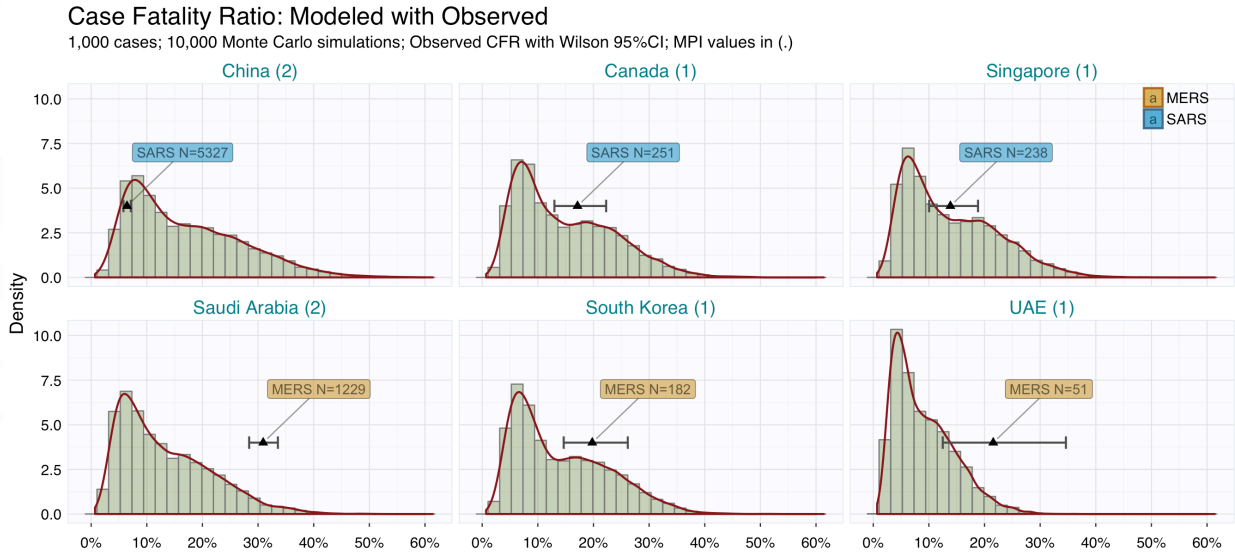
EPI influence on CFR







On average, improving country's Epidemic Preparedness by one unit is decreasing odds of dying by 28%



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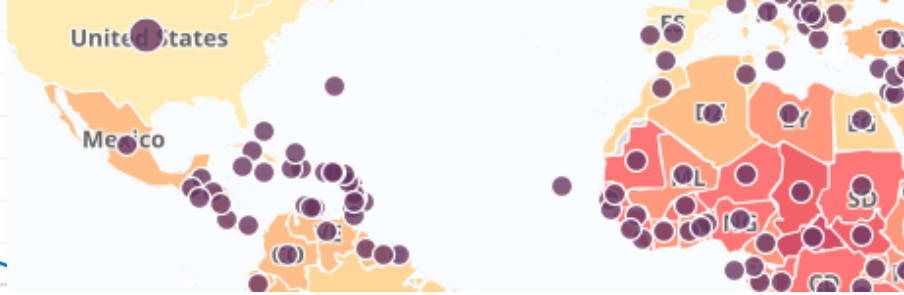
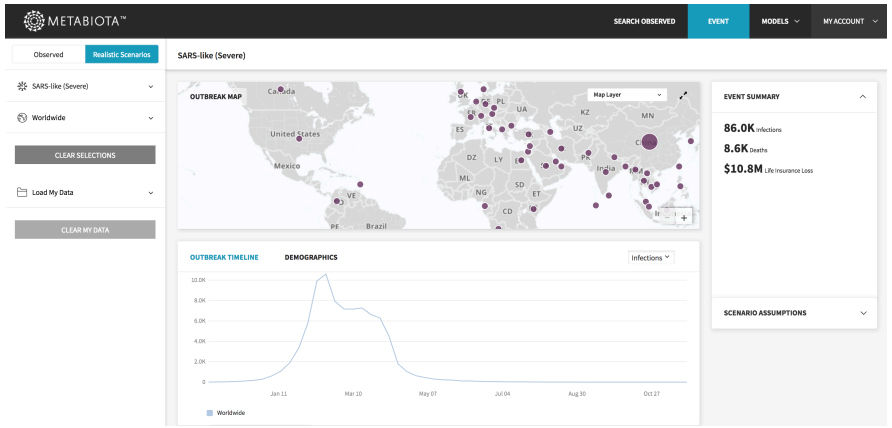
Be the Trusted Source for Best in Class Models





Proprietary Data Set

- 1,200+ Outbreaks
- 150+ Pathogens
- 240+ Data Sources
- 230+ Countries / Territories
- Over 48M Cases
- Over 6M Deaths
- Curated, cleansed, continuously updated

Disease Model Library

- 1M year stochastic event catalog
- 18M stochastic realizations with weekly resolution informed the event catalog
- 180K simulations evaluated
- 117K distinct demographic subpopulations
- 88K+ AWS Compute optimized hours to date
- 100+TB of data
- Largest in the industry

Thank you!

Questions?

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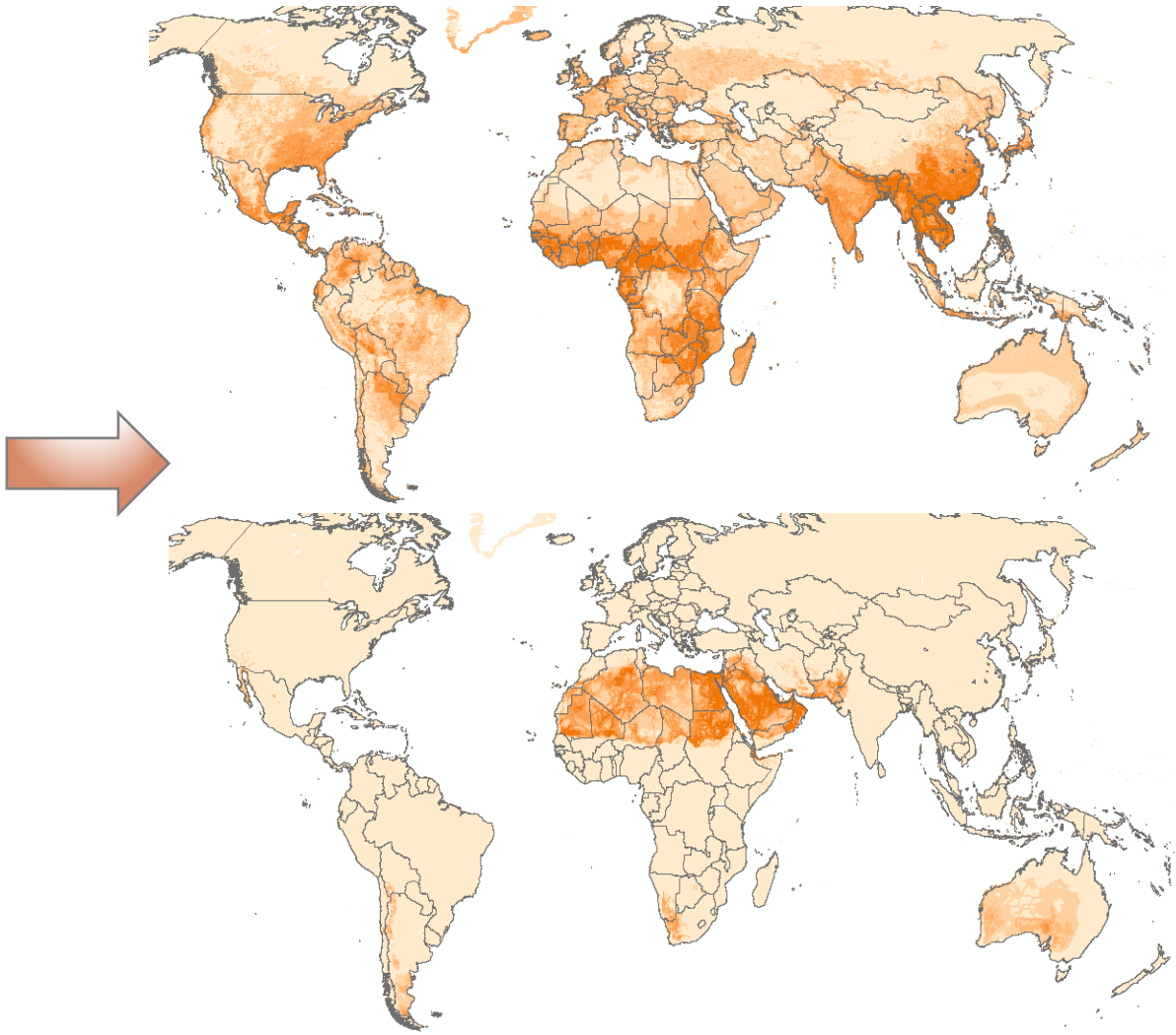
Model Design – Spark Map

Data Layers
Bioclimatic Data
Number of shared human-bat viruses
Zoonotic mammal species
Proximity to large cities
Human Density
Bat (Taphozous sp.)
Dromedary Camel abundance
PREDICT (Metabiota) data



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