The spatio-temporal spread of infectious pathogens: lessons learned from COVID-19

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NSERC-PHAC Emerging Infectious Disease Modelling Consortium

Thank you

for receiving me in your homes/offices and to ..

- many people over the years, including most recently
  - Pierre-Yves Boëlle (IPLESP, Sorbonne Université, Paris)
  - Evan Milliken (University of Louisville)
  - Stéphanie Portet (U of M)
- based also on earlier work with Nicolas Bajeux, S. Portet and James Watmough
- PHAC external modelling group members for discussions

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Funding and logistical support: Public Health Agency of Canada (PHAC)

Pathogens have been mobile for a while

It first began, it is said, in the parts of Ethiopia above Egypt, and thence descended into Egypt and Libya and into most of the [Persian] King's country. Suddenly falling upon Athens, it first attacked the population in Piraeus [..] and afterwards appeared in the upper city, when the deaths became much more frequent.

Thucydides (c. 460 BCE - c. 395 BCE)
History of the Peloponnesian War

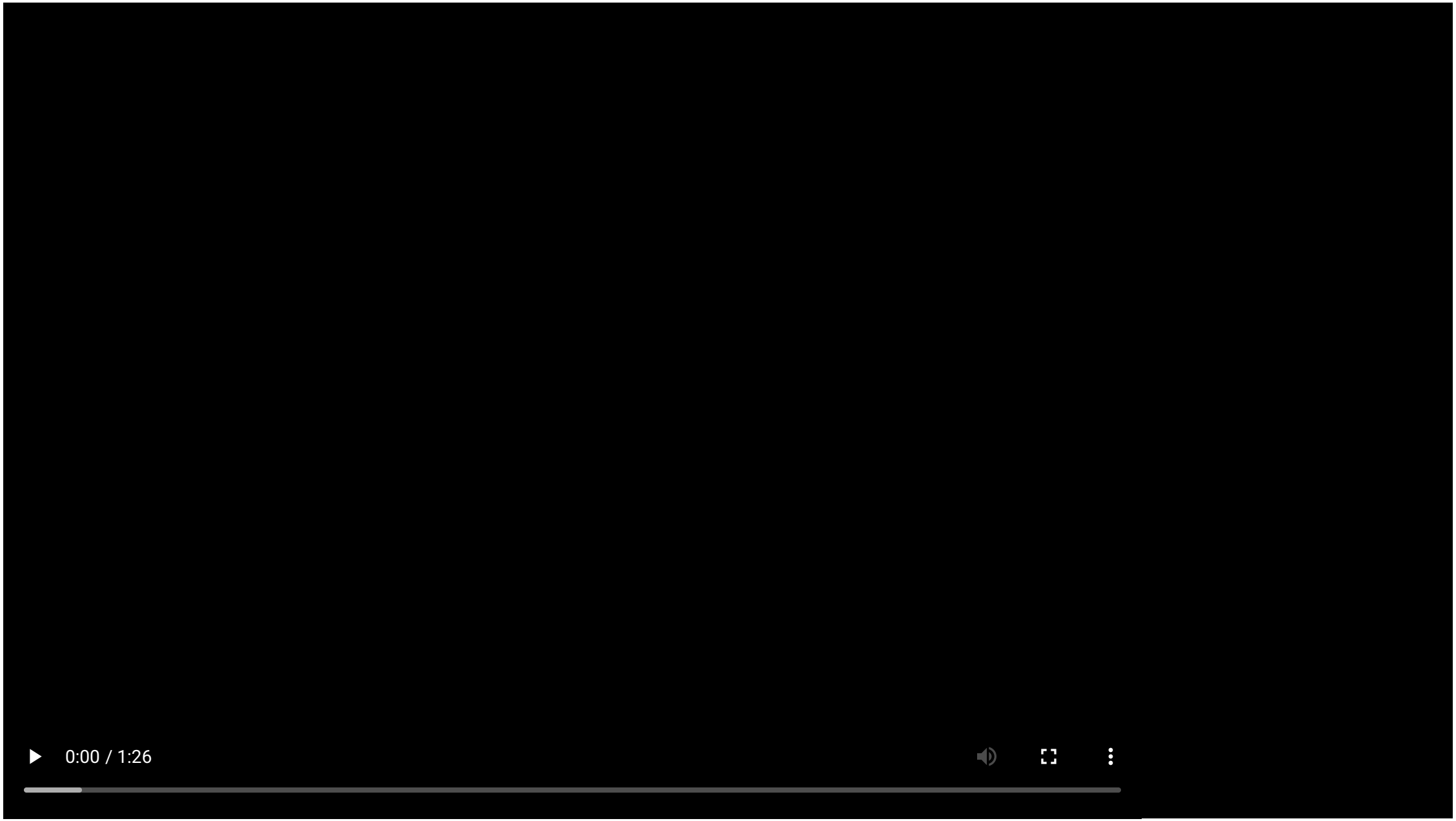
Outline

- Movement and the spatialisation of an epidemic
- The initial spread of COVID-19
- Role of transport restrictions
- Role of quarantine

Movement and the spatialisation of an epidemic

Following 2 slides

- S (blue), I (red), R (green) model
- Individuals spatially located
- Interaction radius to model local movement
- When contacts occur, each contact is infecting with indicated $\mathbb{P}$.. so binomial
- Infecting contact to an R is "lost"
  - First slide: fixed infectious period of 5 days
  - Second slide: infectious period in $\mathcal{U}(3, 10)$ days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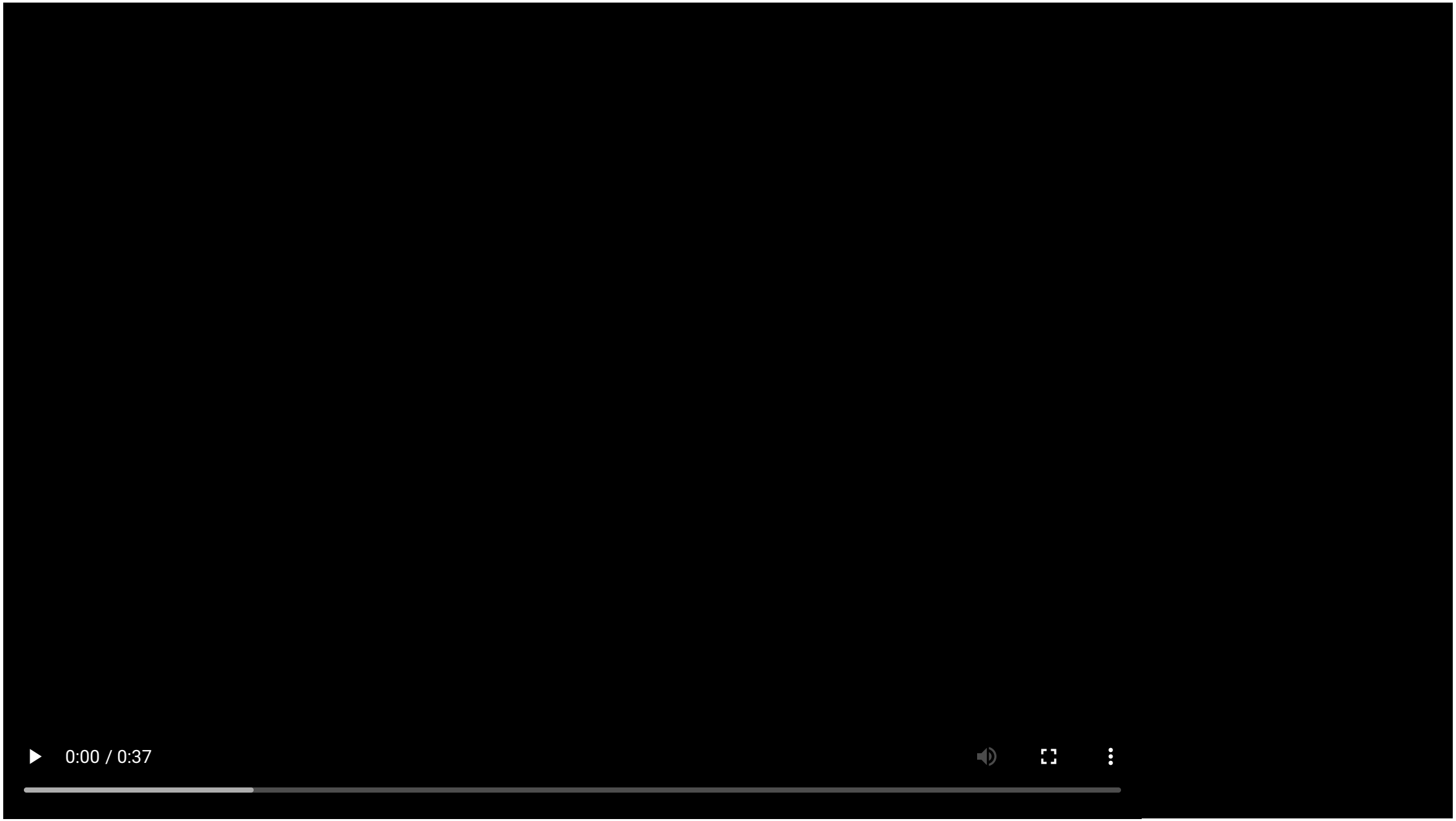
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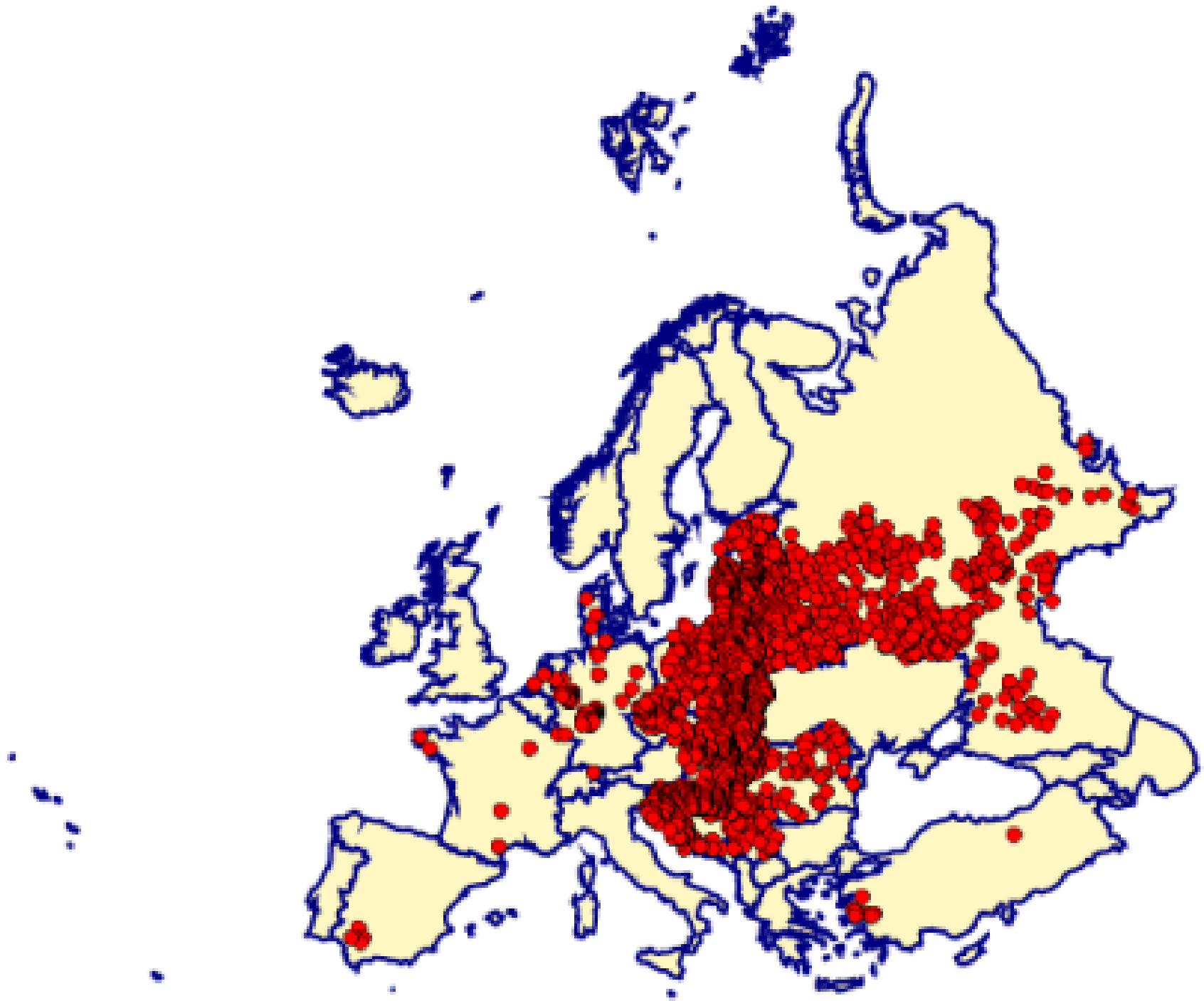
This is good for diseases of (not winged) animals

- Range is typically not huge
- Disease moving between species see patchiness of the support bridged by variety of ranges in the different species

1990

2000



2010

Model of Lopez, Coutinho, Buratini & Massad (1999)

$$\frac{\partial}{\partial t}S(x,t) = -\lambda(x,t)S(x,t) - \mu S(x,t) + \mu N(x) + \gamma_1 I(x,t)$$
$$\frac{\partial}{\partial t}I(x,t) = \lambda(x,t)S(x,t) - (\mu + \gamma_1 + \gamma_2)I(x,t)$$
$$\frac{\partial}{\partial t}R(x,t) = \gamma_2 I(x,t) - \mu R(x,t)$$

with force of infection

$$\lambda(x,t) = \frac{1}{N}\int_0^L dx' \beta(x,x')I(x',t)$$

and total population along the road

$$N = \int_0^L dx' N(x')$$

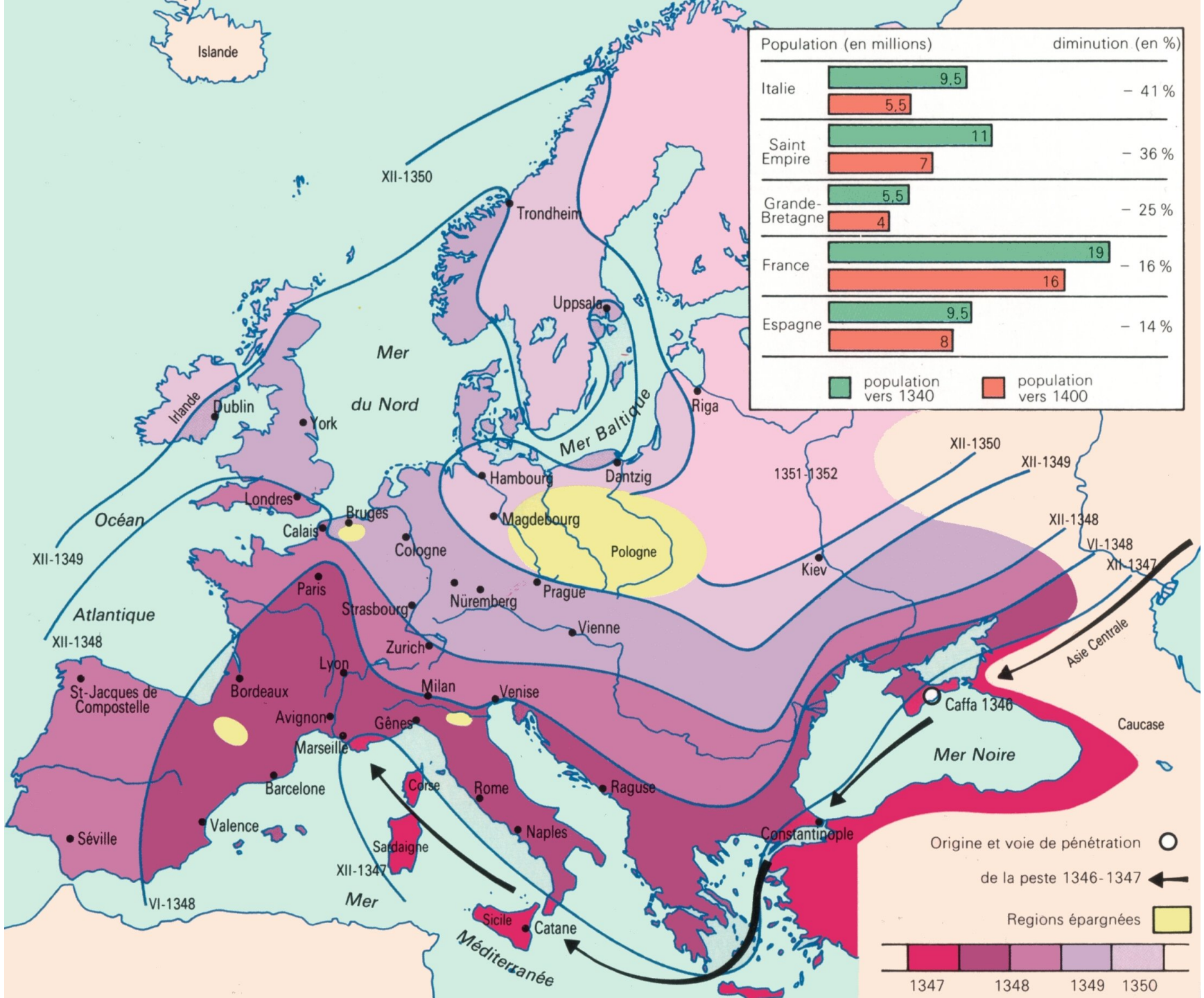
Why human diseases differ

- Pathogens of humans follow .. humans
- Not all humans are mobile, but some humans have for a very long time been more mobile (because of trade)
- Complex spatial patterns have been observed for a long time

First known epidemics (from Wikipedia)

Event	Date	Location	Disease	Death toll (estimate)
Plague of Megiddo	1350 BCE	Megiddo, land of Canaan	Unknown	Unknown
Plague of Athens	429–426 BCE	Greece, Libya, Egypt, Ethiopia	Possibly typhus, typhoid fever or VHF	75,000–100,000
412 BCE epidemic	412 BCE	Greece, Roman Republic	Possibly influenza	Unknown
Antonine Plague	165–180 CE (possibly up to 190 CE)	Roman Empire	Possibly smallpox	5–10 million
Jian'an Plague	217 CE	Han dynasty	Possibly typhoid fever or VHF	Unknown
Plague of Cyprian	250–266 CE	Europe	Possibly smallpox	Unknown
Plague of Justinian				15–100 million (25–60%


A.D.1212
FURS
TIMBER
TALLOW
IRON
COPPER
Novgorod
FISH
CORN
WOOL
TIN
Flemish routes
FISH
TIMBER
German Routes
SALT
AMBER
TALLOW
HONEY
WAX
IRON
Cologne
COPPER
LEAD
SILVER
BEER
WOOL
WINE
CORN
Paris
WINE
GOLD
HONEY
WAX
SILVER
SLAVES
SILVER
GOLD
MERCURY
IRON
COPPER
SLAVES
PAPER
Urganj
Bukhara
IRON SILVER
Milan
Venice
Genoa
TIMBER
CORN
SALT
Merv
Florence
Rome
Naples
Genoese
Routes
Venetian Routes
Salonika
Constantinople
SILVER
COPPER
TIN
Nishapur
Silk Route
Herat
WINE
MERCURY
SUGAR
Seville
Islamic Routes
Hamadan
Isfahan
Fez
Palermo
Mahdia
Antioch
Aleppo
Baghdad
SUGAR
FRUIT
COPPER
Damascus
SUGAR
MERCURY
IRON
SILVER
Shiraz
Siraf
Basra
Spice Route
Cairo
CORN
PAPER
Pilgrim routes to Mecca
GOLD
IVORY
SLAVES
GOLD IVORY SLAVES SPICES

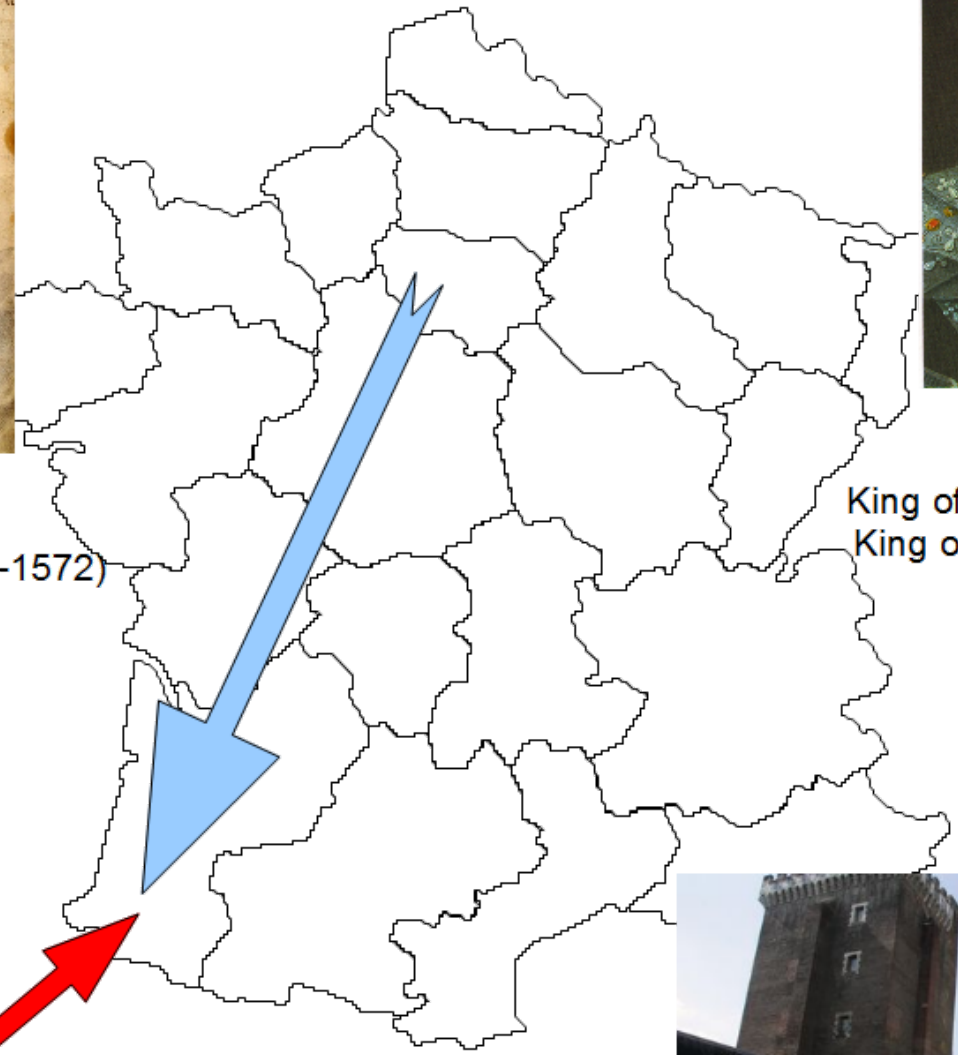

Population (en millions)
diminution (en %)
Italie
9,5
5,5
– 41 %
Saint Empire
11
7
– 36 %
Grande-Bretagne
5,5
4
– 25 %
France
19
16
– 16 %
Espagne
9,5
8
– 14 %
population vers 1340
population vers 1400
Islande
Irlande
Dublin
York
Londres
Océan
Atlantique
Mer du Nord
Mer Baltique
Trondheim
Uppsala
Riga
Hambourg
Dantzig
Magdebourg
Pologne
Bruges
Calais
Cologne
Paris
Strasbourg
Nüremberg
Prague
Vienne
Zurich
Lyon
Milan
Venise
Gênes
Avignon
Marseille
Bordeaux
St-Jacques de Compostelle
Barcelone
Valence
Séville
Corse
Sardaigne
Rome
Naples
Raguse
Sicile
Catane
Mer
Méditerranée
Kiev
Caffa 1346
Asie Centrale
Caucase
Mer Noire
Constantinople
XII-1350
XII-1349
XII-1348
VI-1348
XII-1347
VI-1348
1351-1352
Origine et voie de pénétration
de la peste 1346-1347
Regions épargnées
1347
1348
1349
1350

Human epidemics have evolved..

- because human mobility has changed a lot:
  - Range has vastly increased
  - Time to range has diminished
  - Duration of travel has decreased (on average)
  - Fraction of population able to undertake travel has increased

Jeanne d'Albret
(1528-1572)
Queen of Navarre (1555-1572)

Henri IV
(1553-1610)
King of Navarre (1572-1610)
King of France (1589-1610)



Cosy turtle shell crib in Pau
(then capital of Béarn & Navarre)

ONLY 15 DAYS

Liverpool to Winnipeg

PROVINCE OF MANITOBA.

MANITOBA offers the most easily accessible and the most promising and productive Lands of any Colonial Province in the world. Situated in a pure, healthy climate, under a free form of government, and within close proximity by direct rail communication to the great centres of the Continent, which afford ready markets for Live Stock, Grain, and other products.

THE LAND IS PRAIRIE

NOT BUSH LAND,

—IN—

MANITOBA

AND THE NORTHWEST TERRITORIES,

Total area of Lands fit for cultivation is estimated at 375,184,000 acres, of which 10,660,369 acres are already surveyed.

THE DOMINION HOMESTEAD LAW

Is one of the most liberal character. Every actual settler is entitled to enter one quarter section of 160 acres as a Homestead, for which a patent is given on proof of three years' residence and cultivation.

He may at the same time enter by PRE-EMPTION any adjacent quarter section, the patent for which will issue to him on payment of $1.00 per acre, and when he has completed his Homestead duties he may enter a quarter section for forest tree cultivation and obtain a patent for it at the expiration of six years, on proof of having planted eight acres of trees for four years subsequent to year of entry. The ordinary Dominion Lands are open for sale at the rate of One Dollar per acre, payable in Cash, Scrip, or Military Bounty Warrants.

THE

MOST DIRECT ROUTE

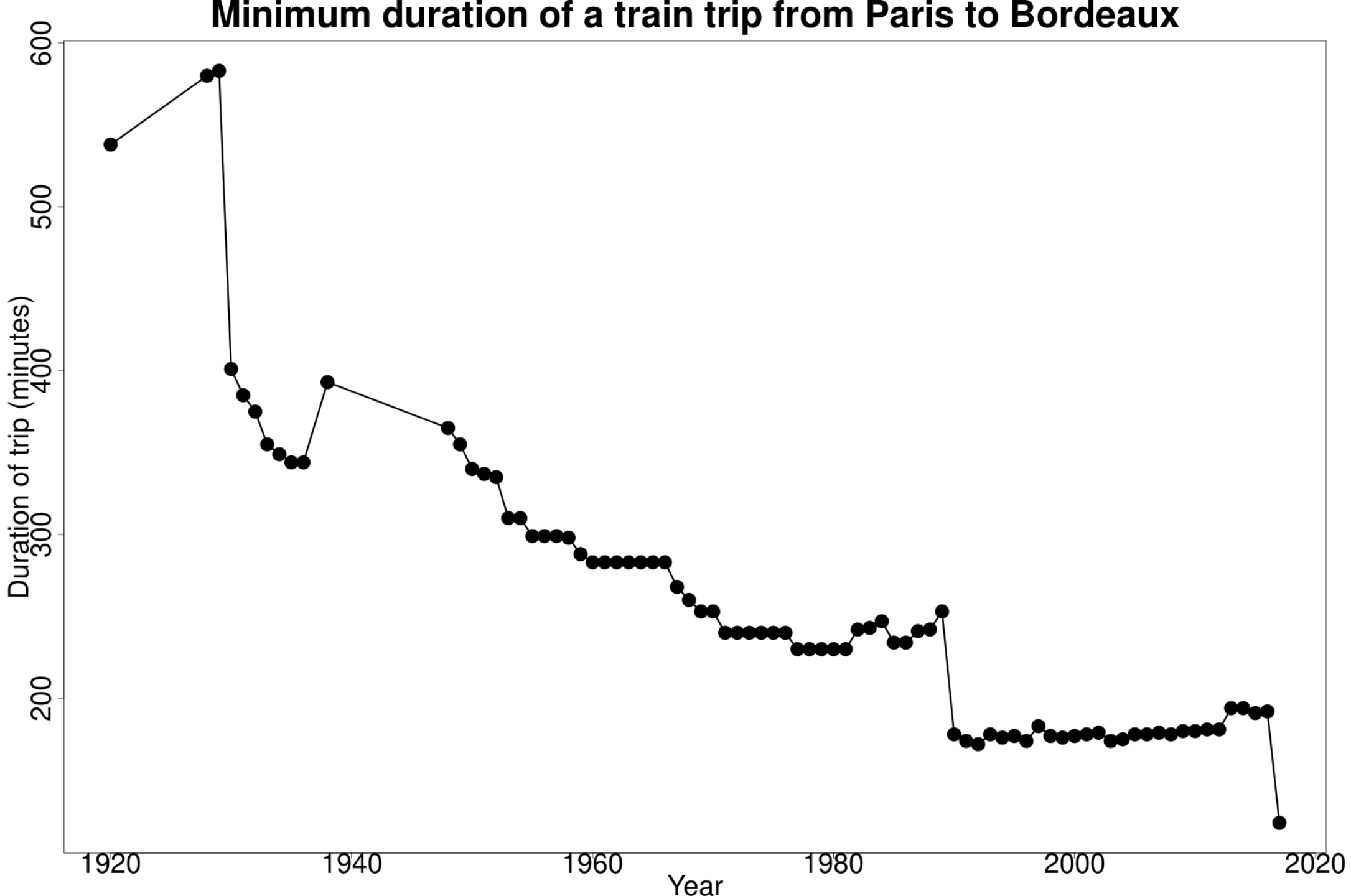
—FROM—

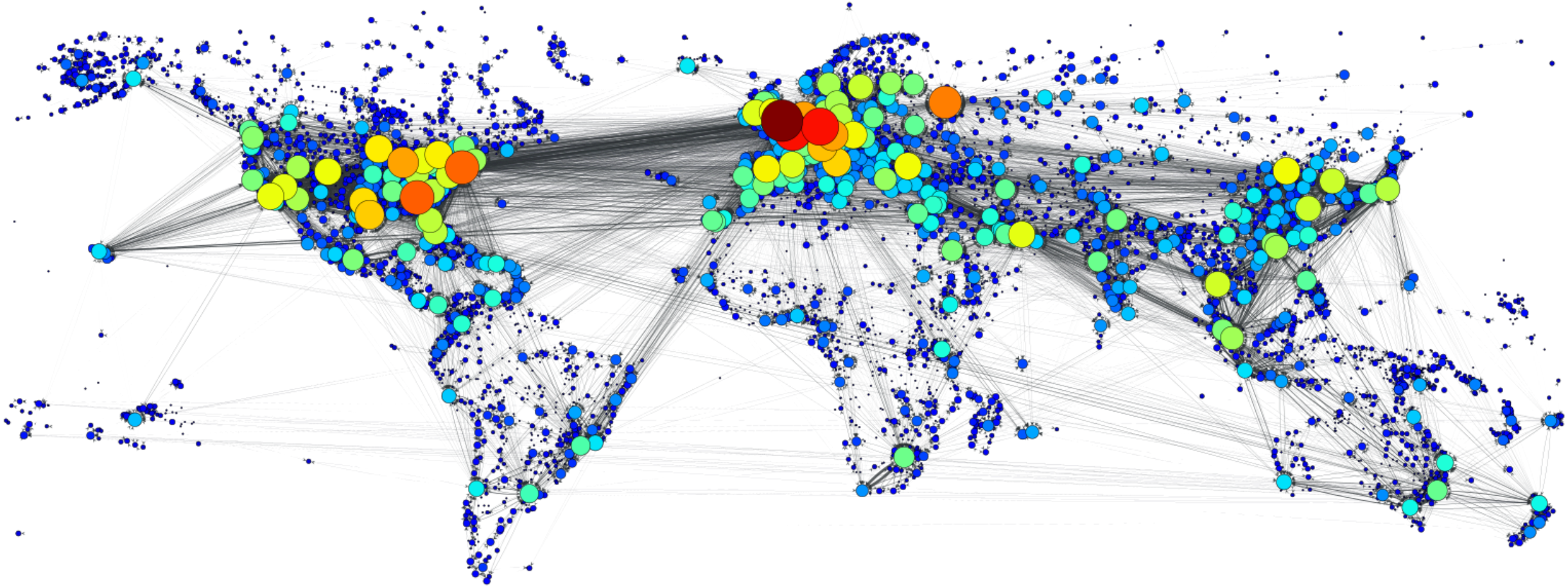
LIVERPOOL to the GREAT NORTHWEST,

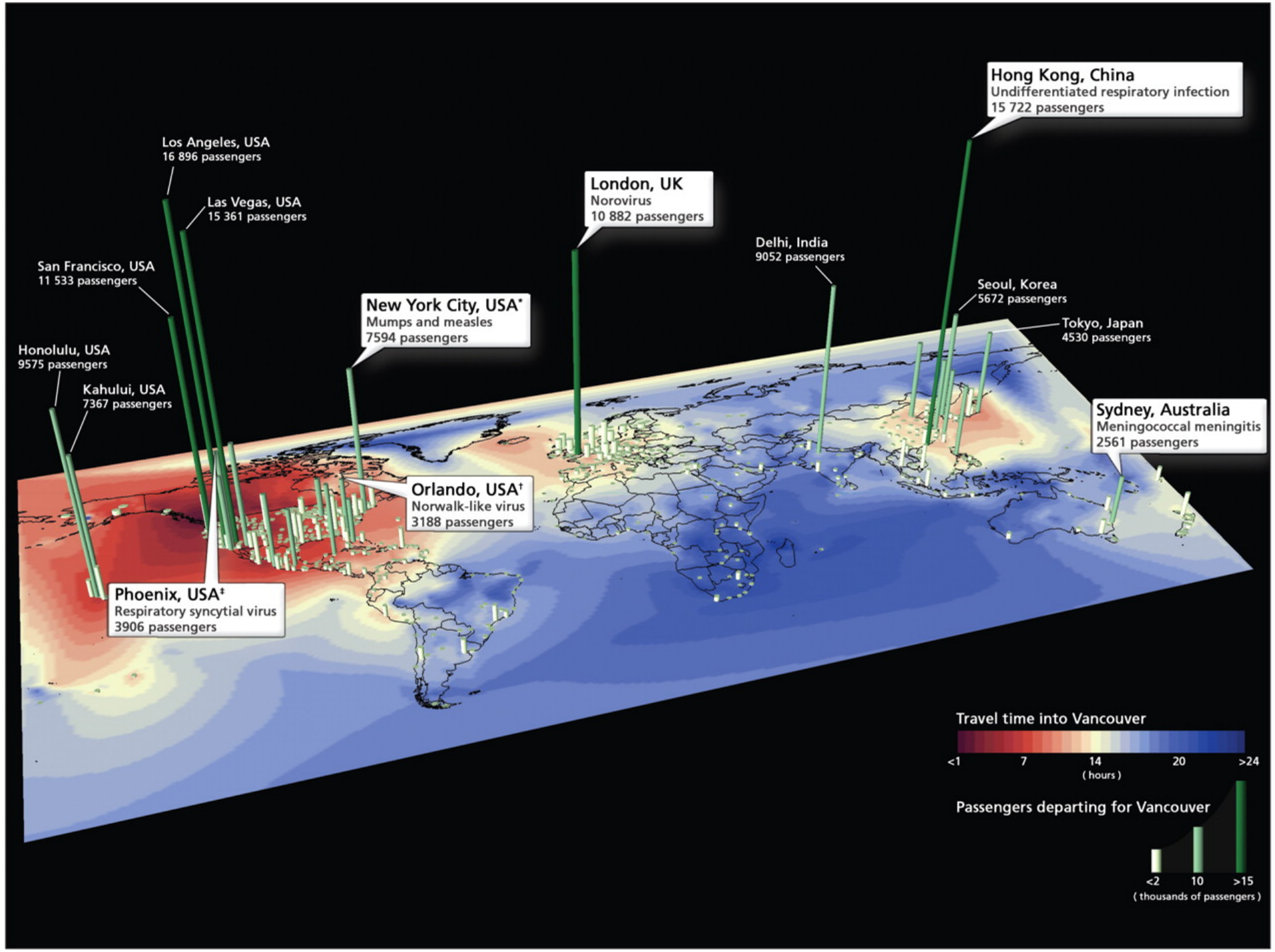
VIA **QUEBEC** AND THE

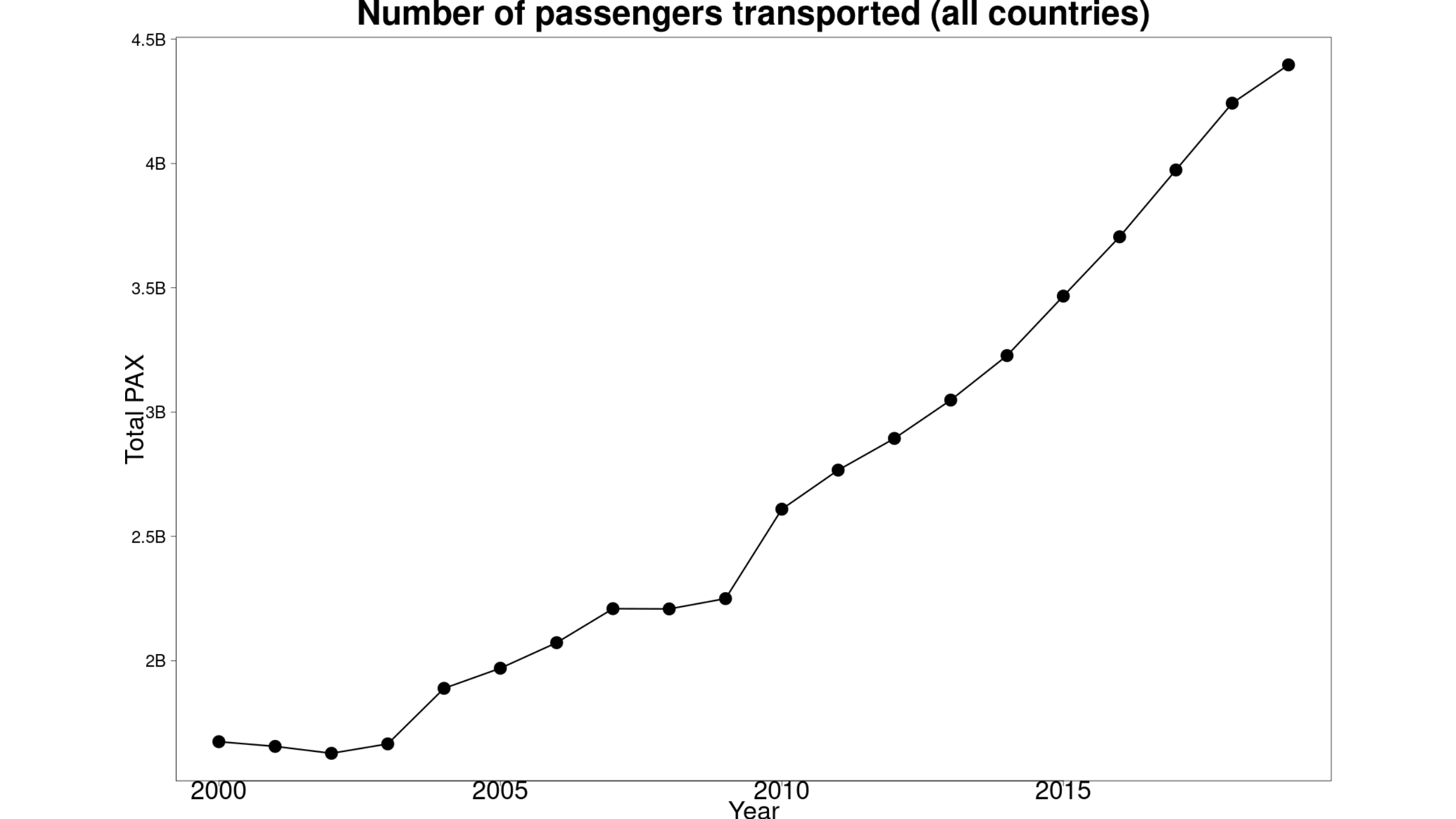
GRAND TRUNK RAILWAY

AND CONNECTIONS.


Minimum duration of a train trip from Paris to Bordeaux
Duration of trip (minutes)
600
500
400
300
200
1920
1940
1960
1980
2000
2020
Year

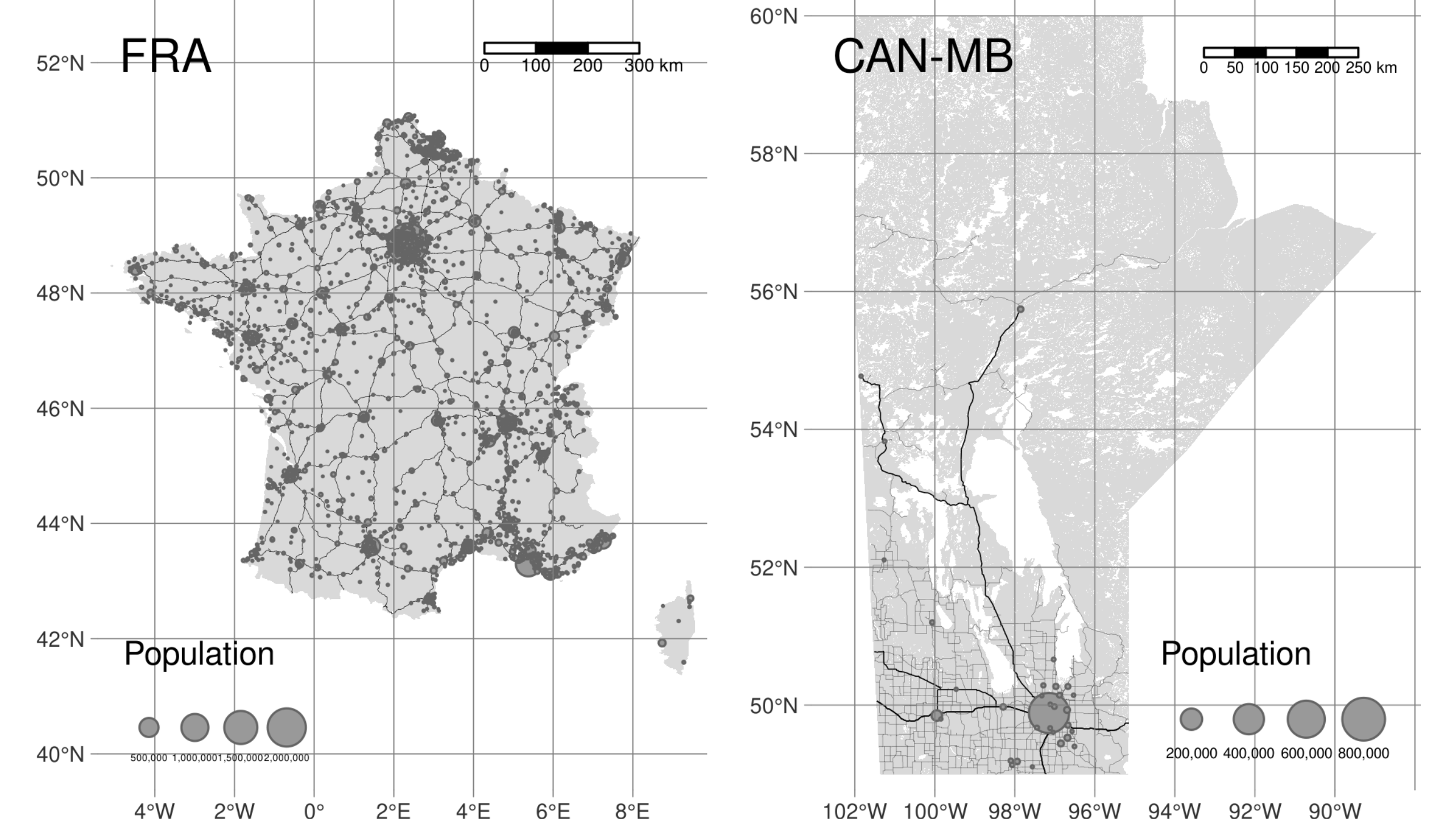


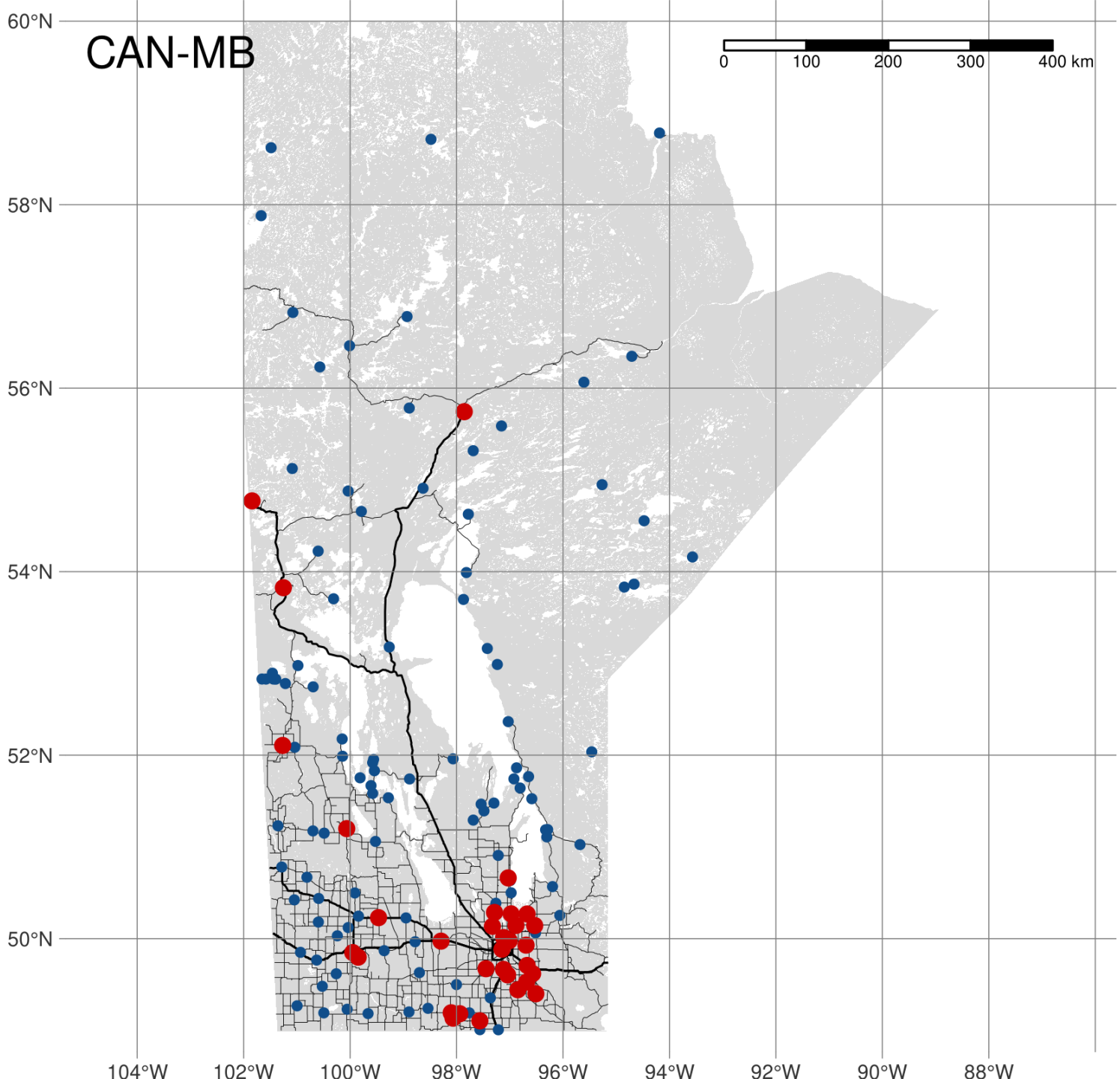

Hong Kong, China
Undifferentiated respiratory infection
15 722 passengers
Los Angeles, USA
16 896 passengers
Las Vegas, USA
15 361 passengers
London, UK
Norovirus
10 882 passengers
Delhi, India
9052 passengers
San Francisco, USA
11 533 passengers
New York City, USA*
Mumps and measles
7594 passengers
Seoul, Korea
5672 passengers
Tokyo, Japan
4530 passengers
Honolulu, USA
9575 passengers
Kahului, USA
7367 passengers
Sydney, Australia
Meningococcal meningitis
2561 passengers
Orlando, USA†
Norwalk-like virus
3188 passengers
Phoenix, USA‡
Respiratory syncytial virus
3906 passengers
Travel time into Vancouver
<1
7
14
20
>24
(hours)
Passengers departing for Vancouver
<2
10
>15
(thousands of passengers)

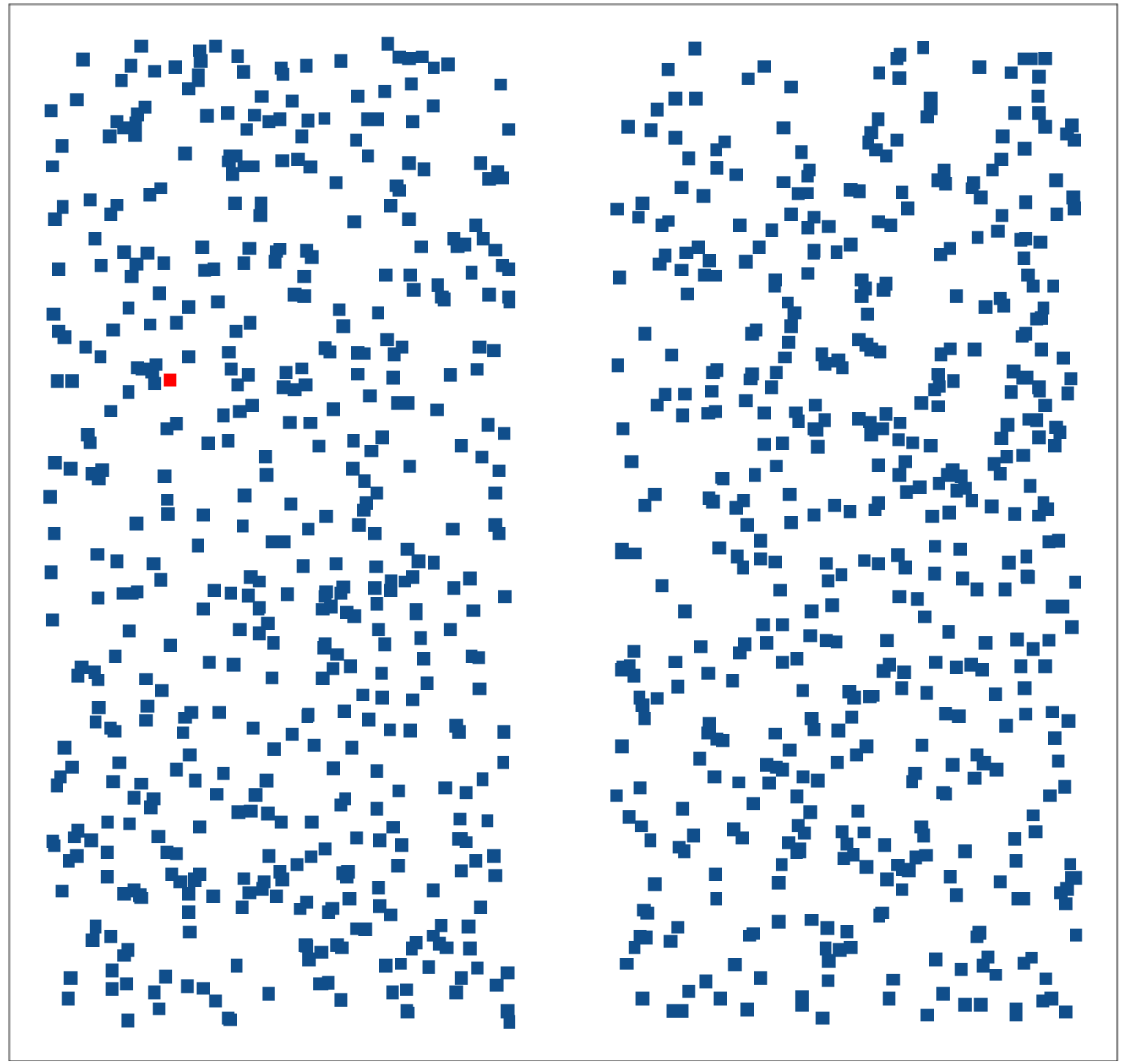

Number of passengers transported (all countries)
4.5B
4B
3.5B
3B
2.5B
2B
Total PAX
2000
2005
2010
2015
Year

The human world is fragmented

- Political divisions: nation groups (e.g., EU), nations, provinces/states, regions, counties, cities..
- With increasing administration, movement between jurisdictions might become more complicated
- Data is also integrated at the jurisdicional level
- Long range mobility is a bottom$\rightarrow$top$\rightarrow$top$\rightarrow$bottom process ("moving between cones")
- Mobility in bottom layer is on a more continuous support than higher levels
- Situation is highly variable even at the country level

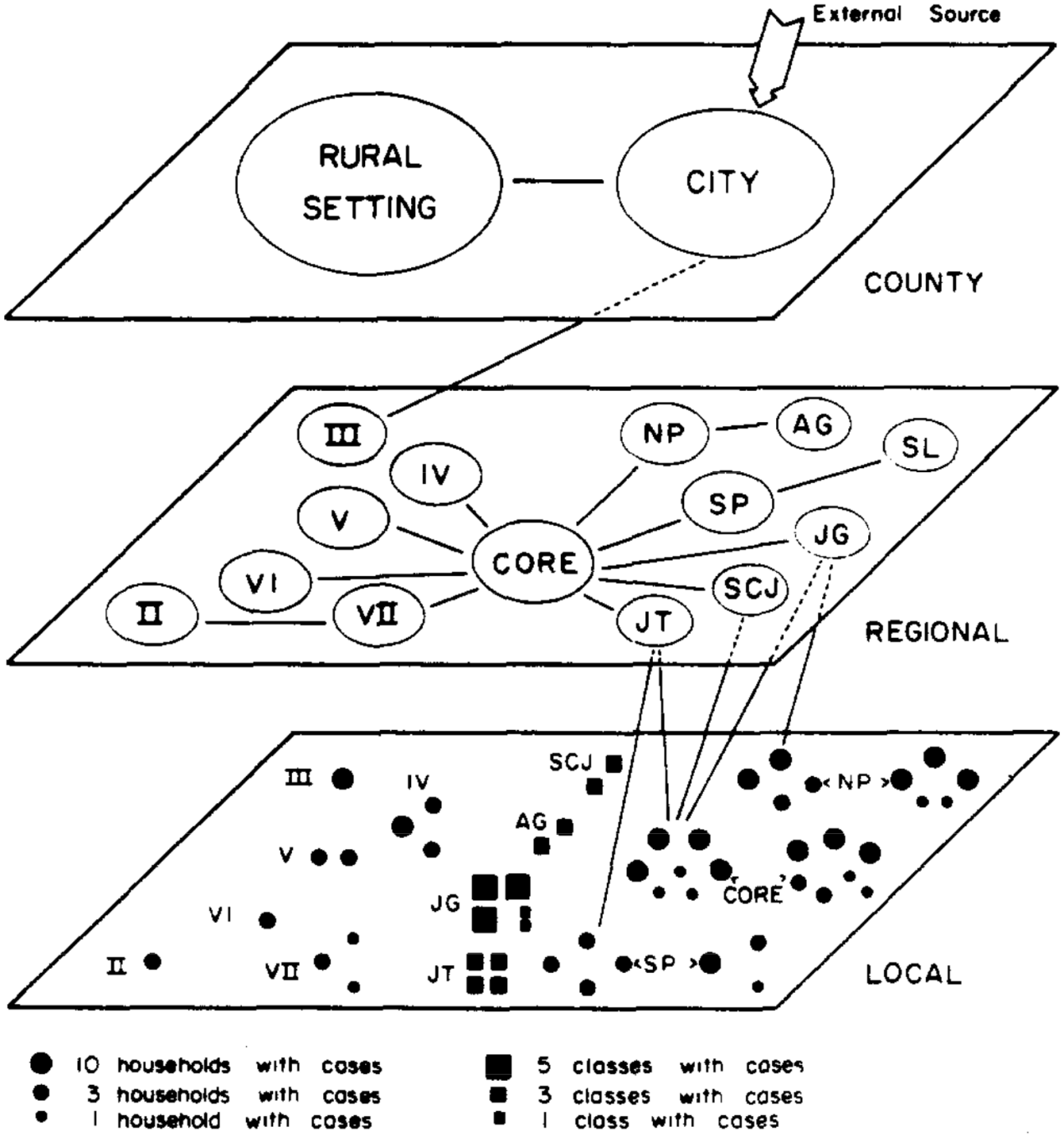

FRA
0 100 200 300 km
52°N
50°N
48°N
46°N
44°N
42°N
40°N
Population
500,000 1,000,000 1,500,000 2,000,000
4°W 2°W 0° 2°E 4°E 6°E 8°E
CAN-MB
0 50 100 150 200 250 km
60°N
58°N
56°N
54°N
52°N
50°N
Population
200,000 400,000 600,000 800,000
102°W 100°W 98°W 96°W 94°W 92°W 90°W

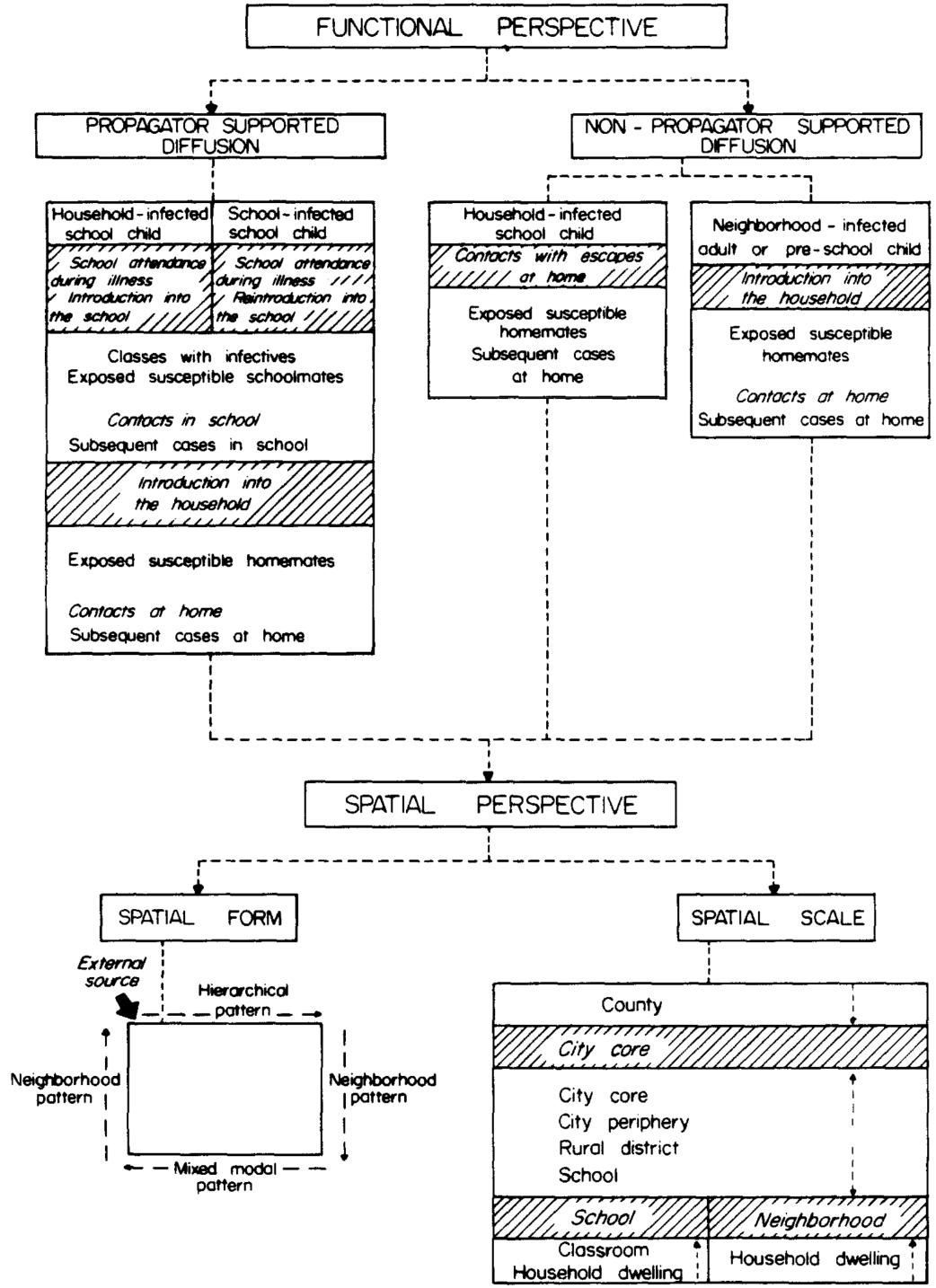

CAN-MB
0
100
200
300
400 km
60°N
58°N
56°N
54°N
52°N
50°N
104°W
102°W
100°W
98°W
96°W
94°W
92°W
90°W
88°W



Cones of resolution

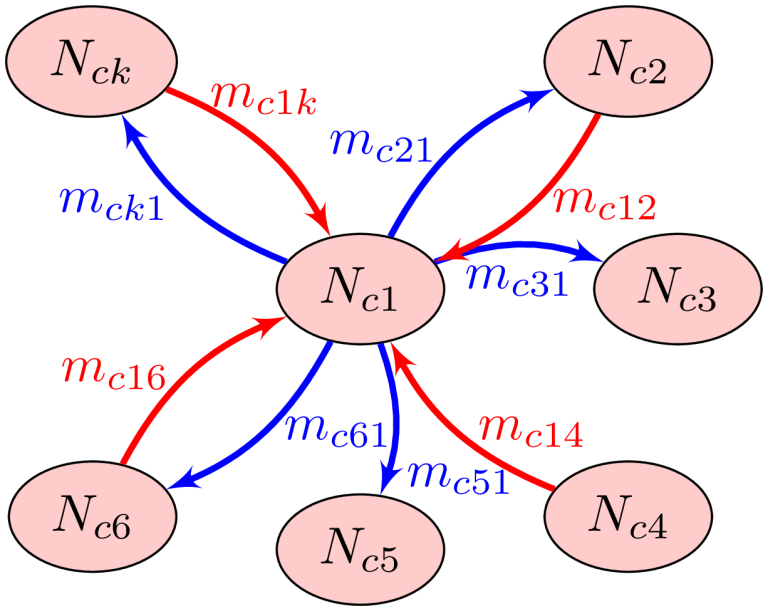
= various levels or scales of the functional or spatial aspects of a diffusion process. Scale (cone of resolution) takes on two dimensions: *functional* (decisions made by different groups of individuals) and *spatial* (manifestations of these decisions as observed in a spatial context)




FUNCTIONAL PERSPECTIVE
PROPAGATOR SUPPORTED DIFFUSION
NON - PROPAGATOR SUPPORTED DIFFUSION
Household - infected school child
School - infected school child
School attendance during illness
Introduction into the school
School attendance during illness
Reintroduction into the school
Classes with infectives
Exposed susceptible schoolmates
Contacts in school
Subsequent cases in school
Introduction into the household
Exposed susceptible homemates
Contacts at home
Subsequent cases at home
Household - infected school child
Contacts with escapes at home
Exposed susceptible homemates
Subsequent cases at home
Neighborhood - infected adult or pre-school child
Introduction into the household
Exposed susceptible homemates
Contacts at home
Subsequent cases at home
SPATIAL PERSPECTIVE
SPATIAL FORM
External source
Hierarchical pattern
Neighborhood pattern
Neighborhood pattern
Mixed modal pattern
SPATIAL SCALE
County
City core
City core
City periphery
Rural district
School
School
Neighborhood
Classroom
Household dwelling
Household dwelling

Modelling heterogeneity using metapopulations

J. Arino. Spatio-temporal spread of infectious pathogens of humans. Infectious Disease Modelling, 2017



Movement for compartment c in patch 1

$$N'_{c1} = \sum_{p \in \mathcal{L} \setminus \{1\}} m_{c1p} N_{cp} - N_{c1} \sum_{p \in \mathcal{L} \setminus \{1\}} m_{cp1}$$

or

$$N'_{c1} = \sum_{p \in \mathcal{L}} m_{c1p} N_{cp} \text{ assuming } m_{c11} = -\sum_{p \in \mathcal{L} \setminus \{1\}} m_{cp1}$$

In each patch, put a system describing the evolution of the number of individuals in each compartment present

Assume **uninfected** (s) and **infected** (i) compartments $\mathcal{U}$ and $\mathcal{I}$. For all $j \in \mathcal{U}$, $k \in \mathcal{I}$ and $\ell \in \mathcal{L}$

$$s'_{j\ell} = f_{j\ell}(S_\ell, I_\ell) + \sum_{q \in \mathcal{L}} m_{j\ell q} s_{jq}$$

$$i'_{k\ell} = g_{k\ell}(S_\ell, I_\ell) + \sum_{q \in \mathcal{L}} m_{k\ell q} i_{kq}$$

f and g describe interactions between compartments in a given location. Might involve more than S_ℓ, I_ℓ, but always local (ℓ)

Sums describe movement of (individuals from) compartments between locations

Describing movement - The movement matrix

Movement from location $q \in \mathcal{L}$ to location $p \in \mathcal{L}$ occurs at rate m_{Xpq} for individuals in compartment X

Movement matrix for compartment X:

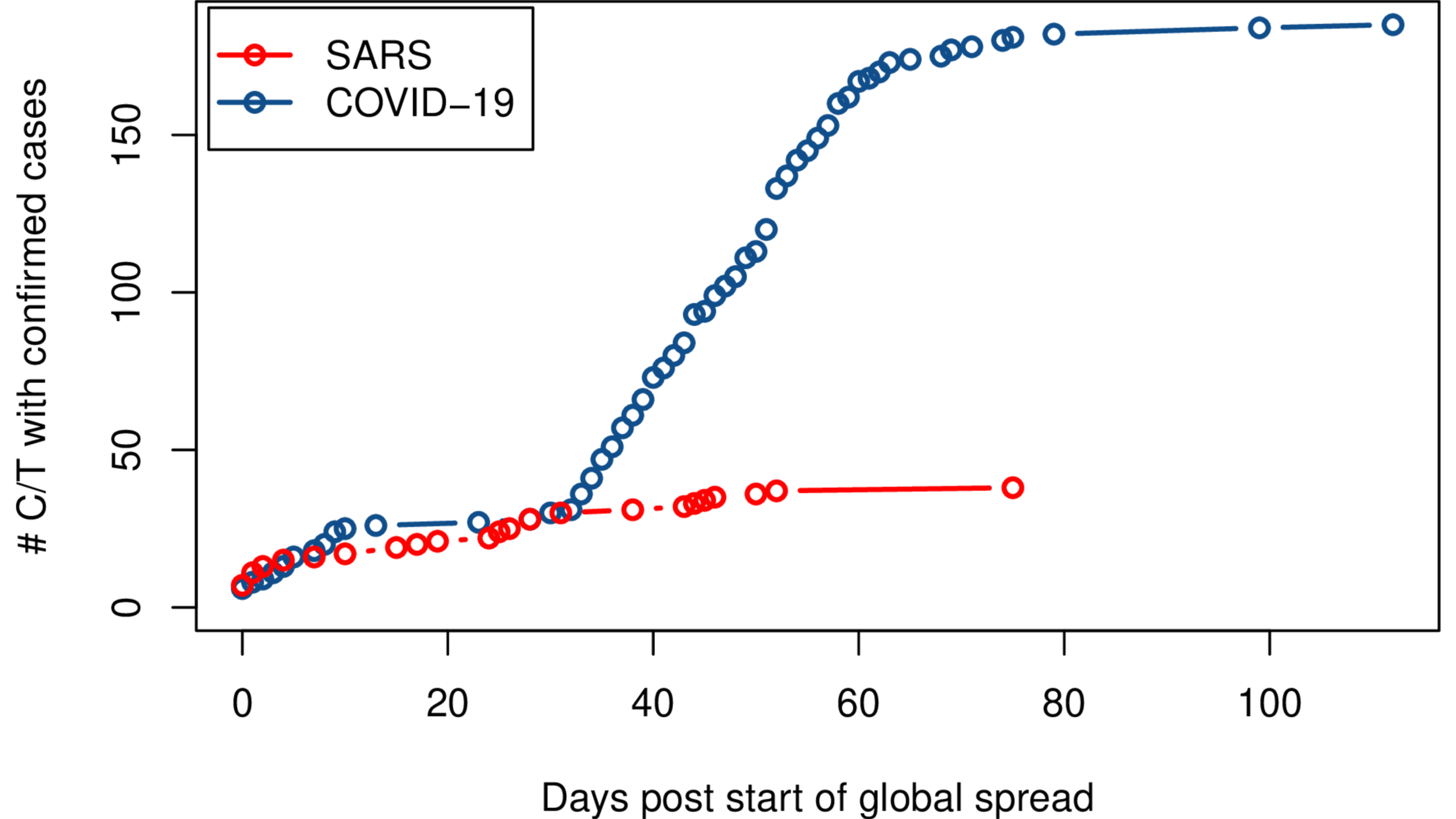
$$\mathcal{M}^X = \begin{pmatrix} -\sum_{q\in\mathcal{L},q\neq p} m_{Xq1} & m_{X12} & \cdots & m_{X1|\mathcal{L}|} \\ m_{X21} & -\sum_{q\in\mathcal{L},q\neq p} m_{Xq2} & & m_{X2|\mathcal{L}|} \\ & & & \\ m_{X|\mathcal{L}|1} & m_{X|\mathcal{L}|2} & & -\sum_{q\in\mathcal{L},q\neq p} m_{Xq|\mathcal{L}|} \end{pmatrix}$$

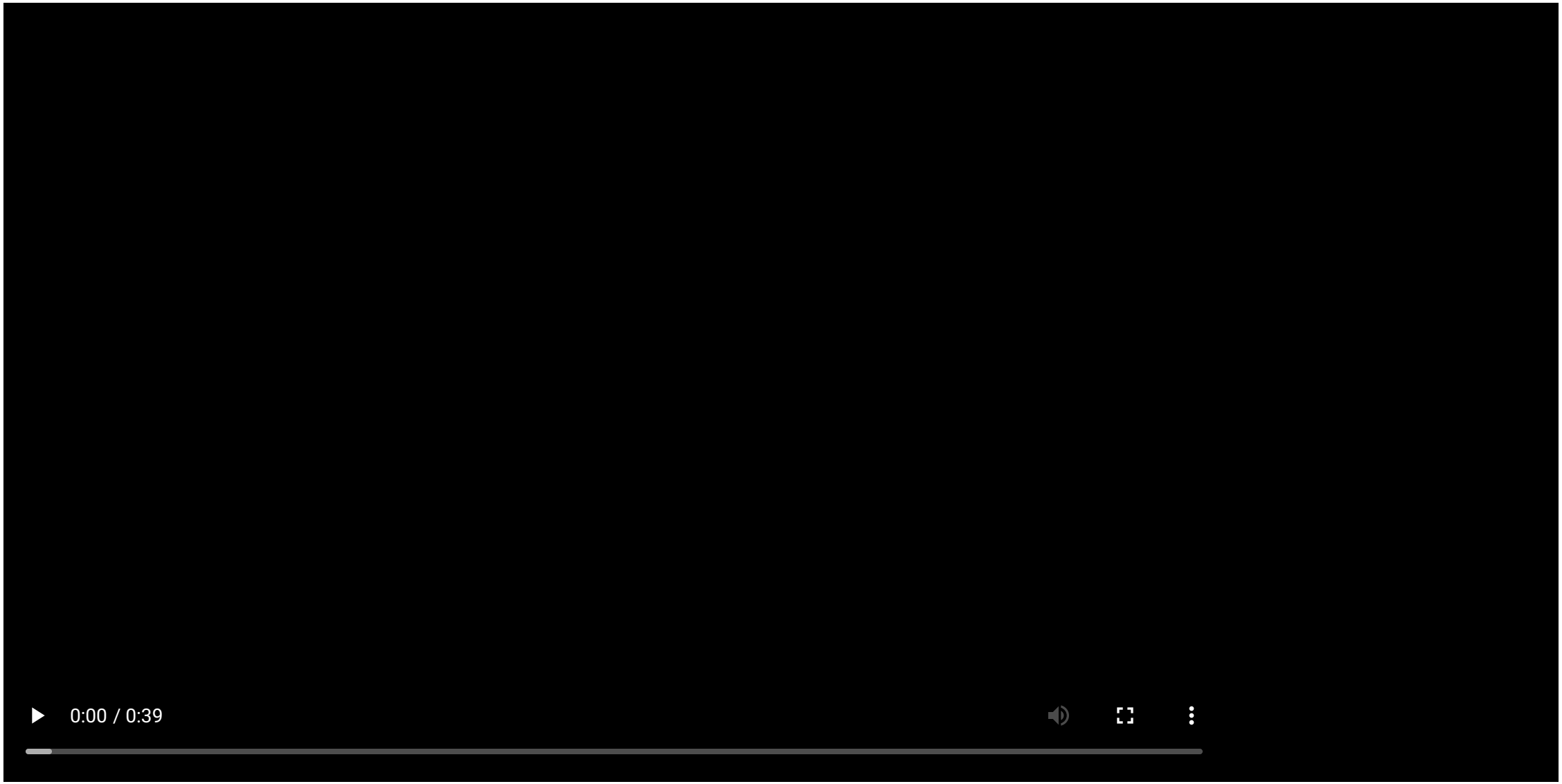
J. Arino, N. Bajeux & S. Kirkland. Number of source patches required for population persistence in a source-sink metapopulation with explicit movement. Bulletin of Mathematical Biology, 2019

The initial spread of COVID-19

First detections outside China

Date	Location	Note
13 Jan.	Thailand	Arrived 8 Jan.
16 Jan.	Japan	Arrived 6 Jan.
20 Jan.	Republic of Korea	Airport detected on 19 Jan.
20 Jan.	USA	Arrived Jan. 15
23 Jan.	Nepal	Arrived 13 Jan.
23 Jan.	Singapore	Arrived 20 Jan.
24 Jan.	France	Arrived 22 Jan.
24 Jan.	Vietnam	Arrived 13 Jan.
25 Jan.	Australia	Arrived 19 Jan.
25 Jan.	Malaysia	Arrived 24 Jan.


SARS
COVID−19
C/T with confirmed cases
0
50
100
150
0
20
40
60
80
100
Days post start of global spread


0:00 / 0:39

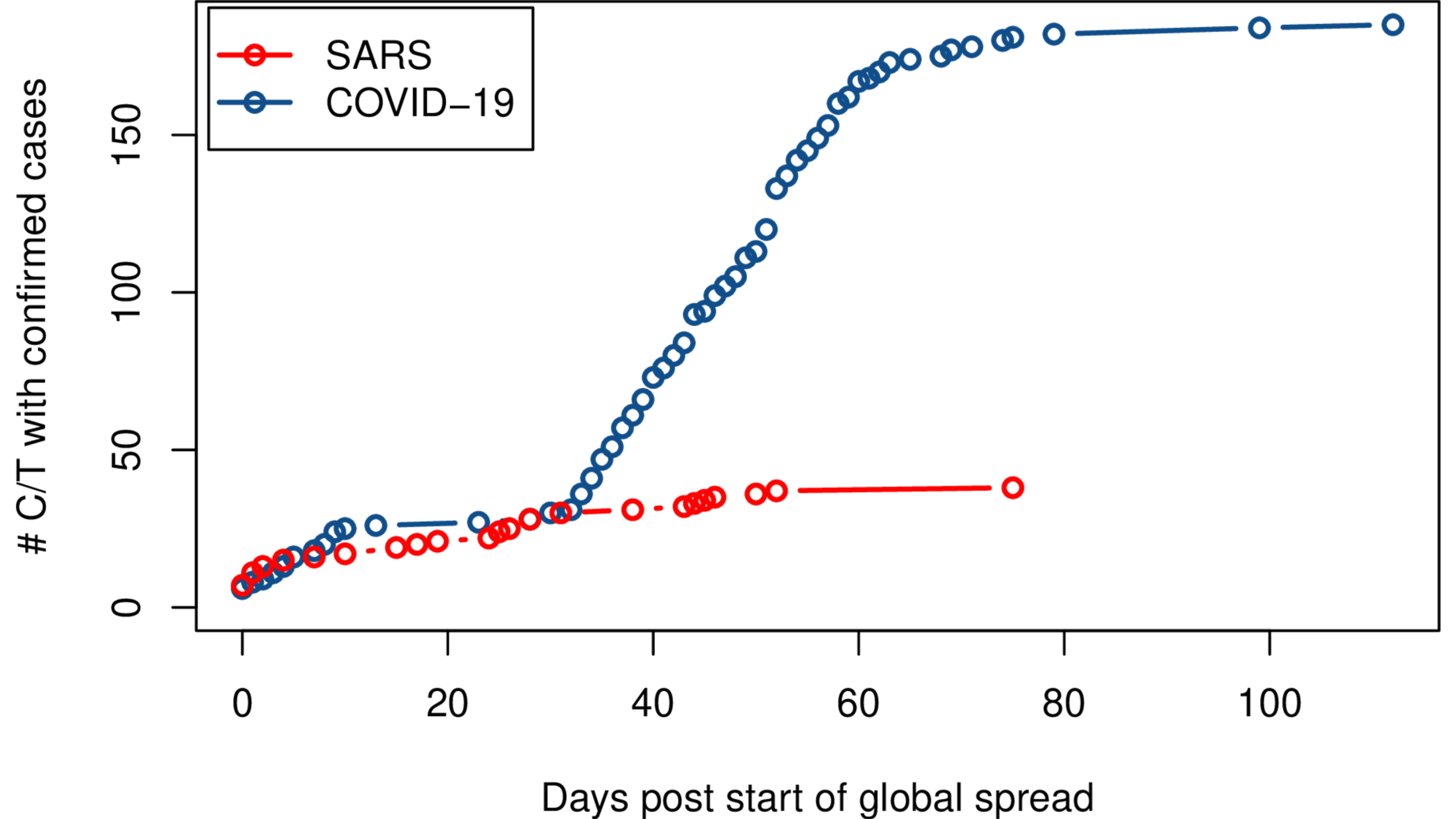
Case importations

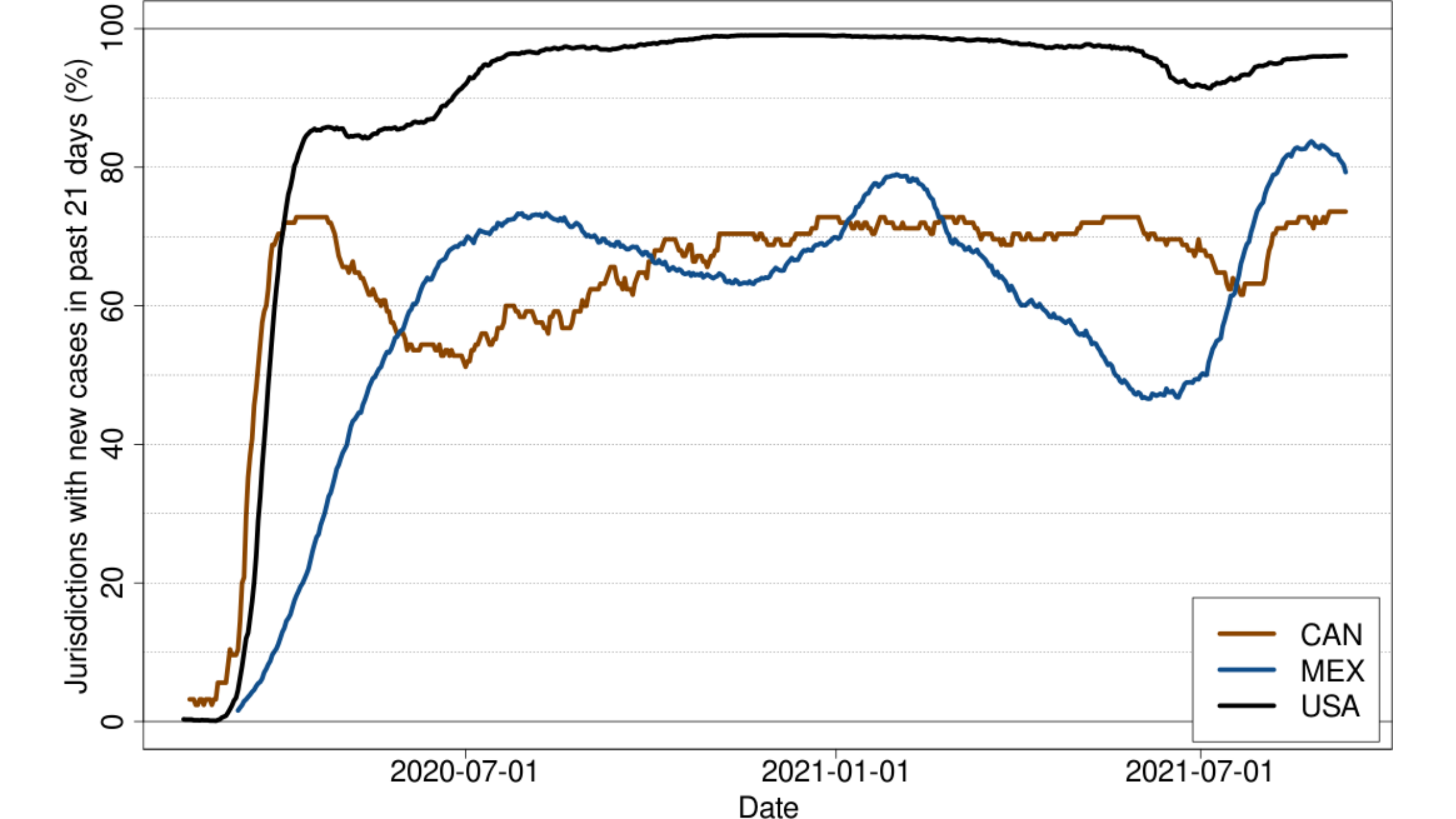
J. Arino & S. Portet. A simple model for COVID-19. Infectious Disease Modelling, 2020

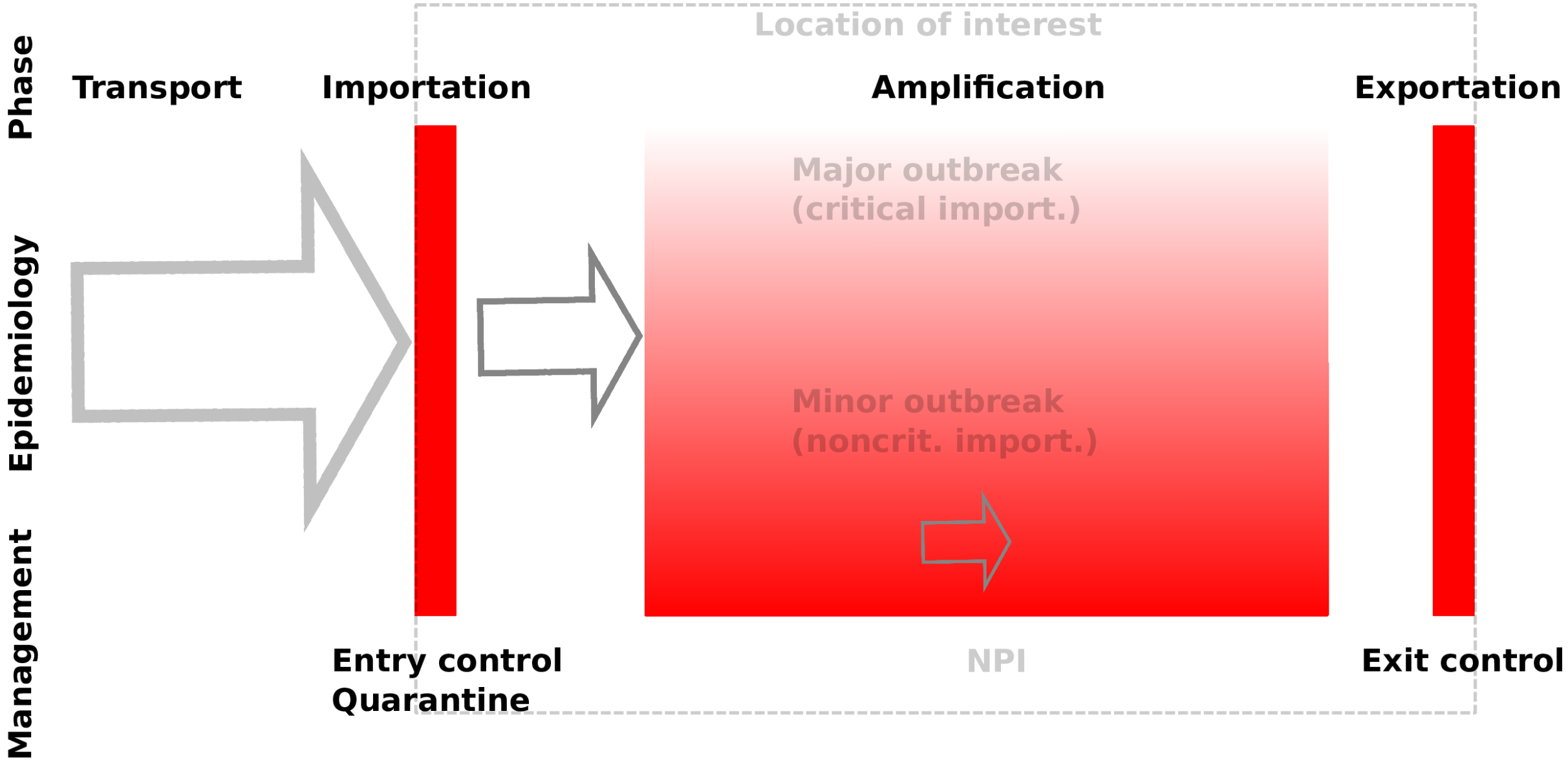
J. Arino, N. Bajeux, S. Portet & J. Watmough. Quarantine and the risk of COVID-19 importation. Epidemiology & Infection, 2020

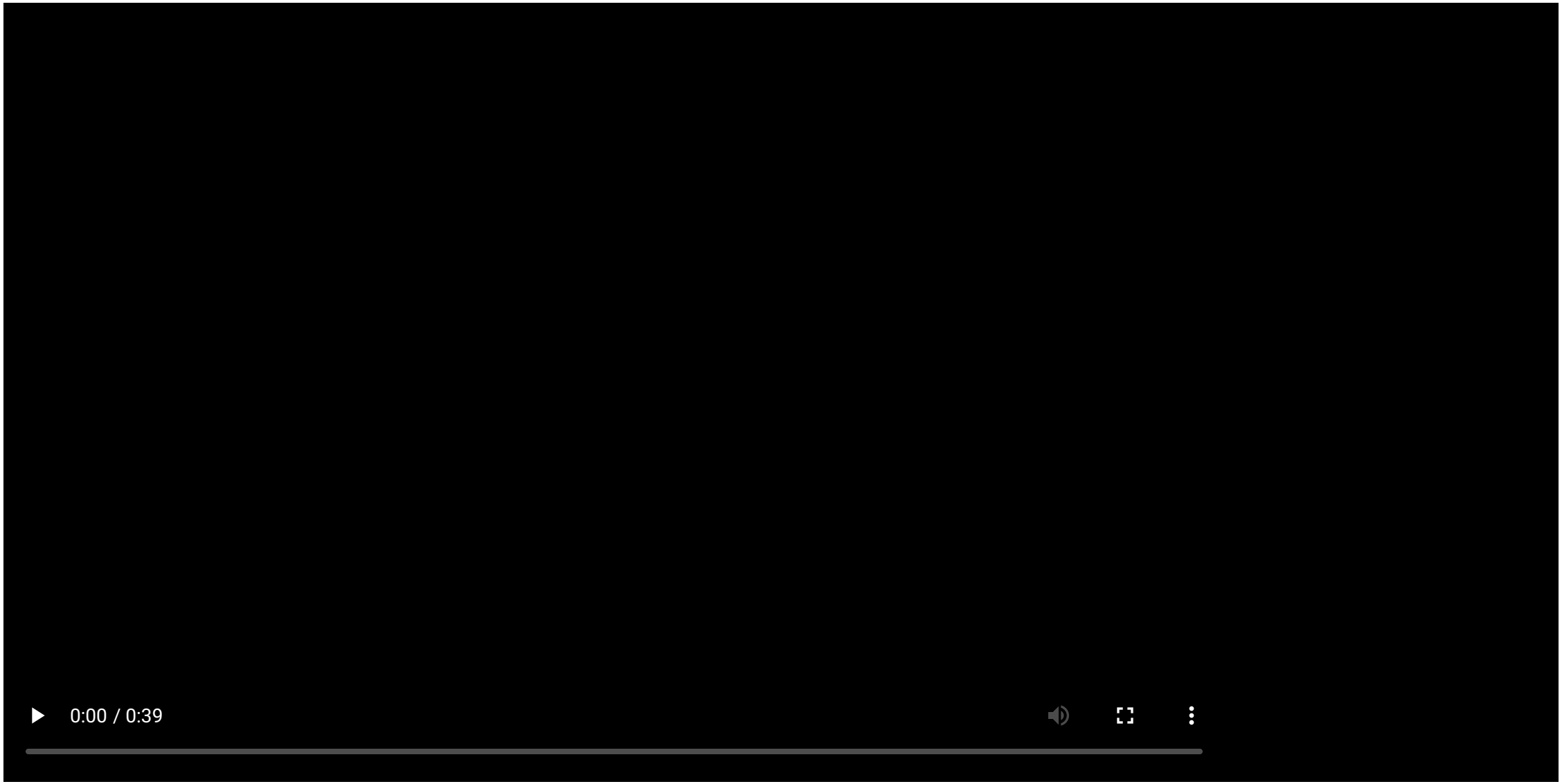
Importations

- In Ecology, importations are called *introductions* and have been studied for a while, because they are one of the drivers of evolution and, more recently, because of *invasive species*
- An importation occurs when an individual who acquired the infection in a jurisdiction makes their way to another jurisdiction while still infected with the disease
- Geographies greatly influence reasoning
    - At the country level, importations quickly become less relevant
    - Consider an isolated location of 500 people.. disease may become extinct then be reimported


SARS
COVID−19
C/T with confirmed cases
0
50
100
150
0
20
40
60
80
100
Days post start of global spread


Jurisdictions with new cases in past 21 days (%)
0
20
40
60
80
100
2020-07-01
2021-01-01
2021-07-01
Date
CAN
MEX
USA


Location of interest
Phase
Transport
Importation
Amplification
Exportation
Epidemiology
Major outbreak
(critical import.)
Minor outbreak
(noncrit. import.)
Management
Entry control
Quarantine
NPI
Exit control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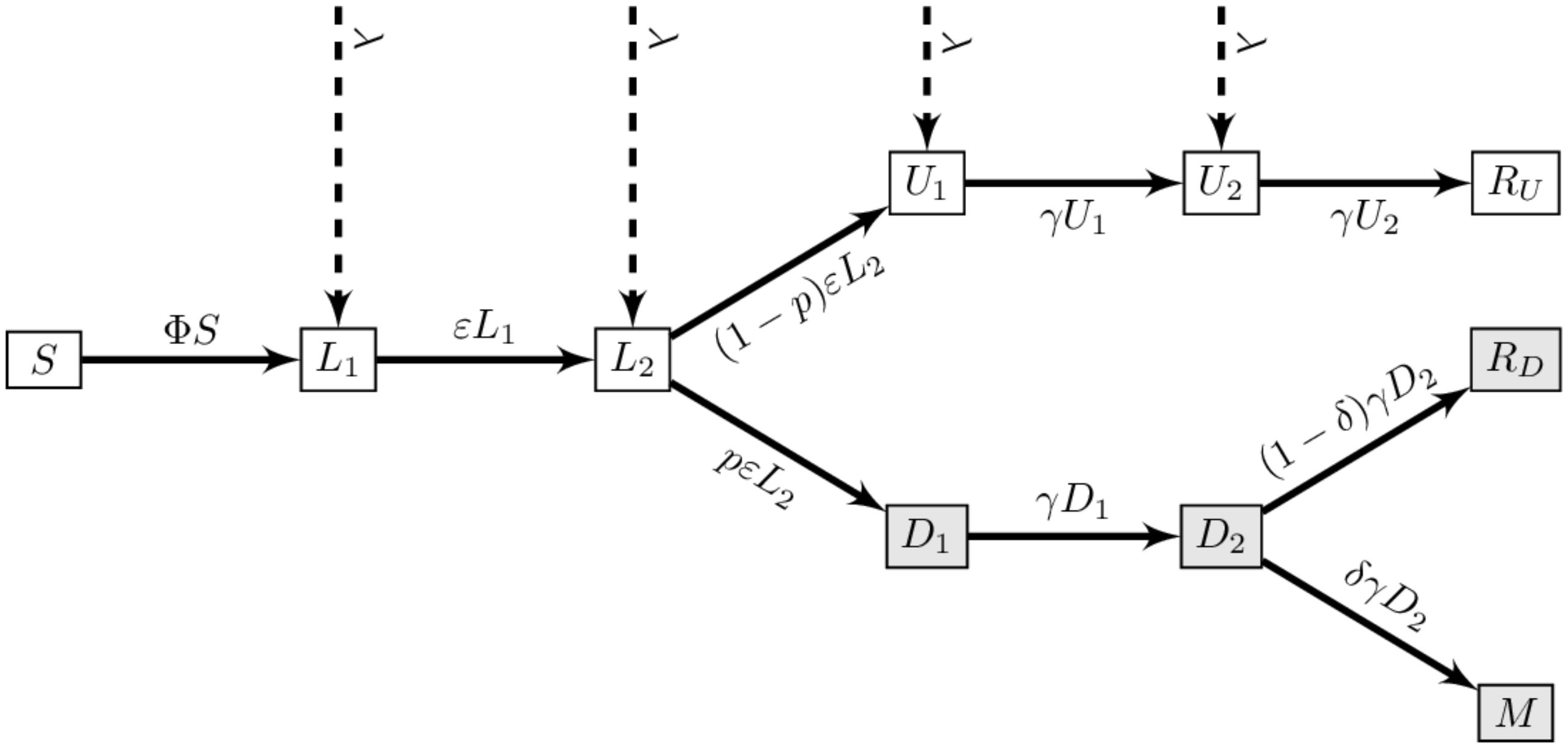
Our base model for considering COVID-19 uses detection-based compartments

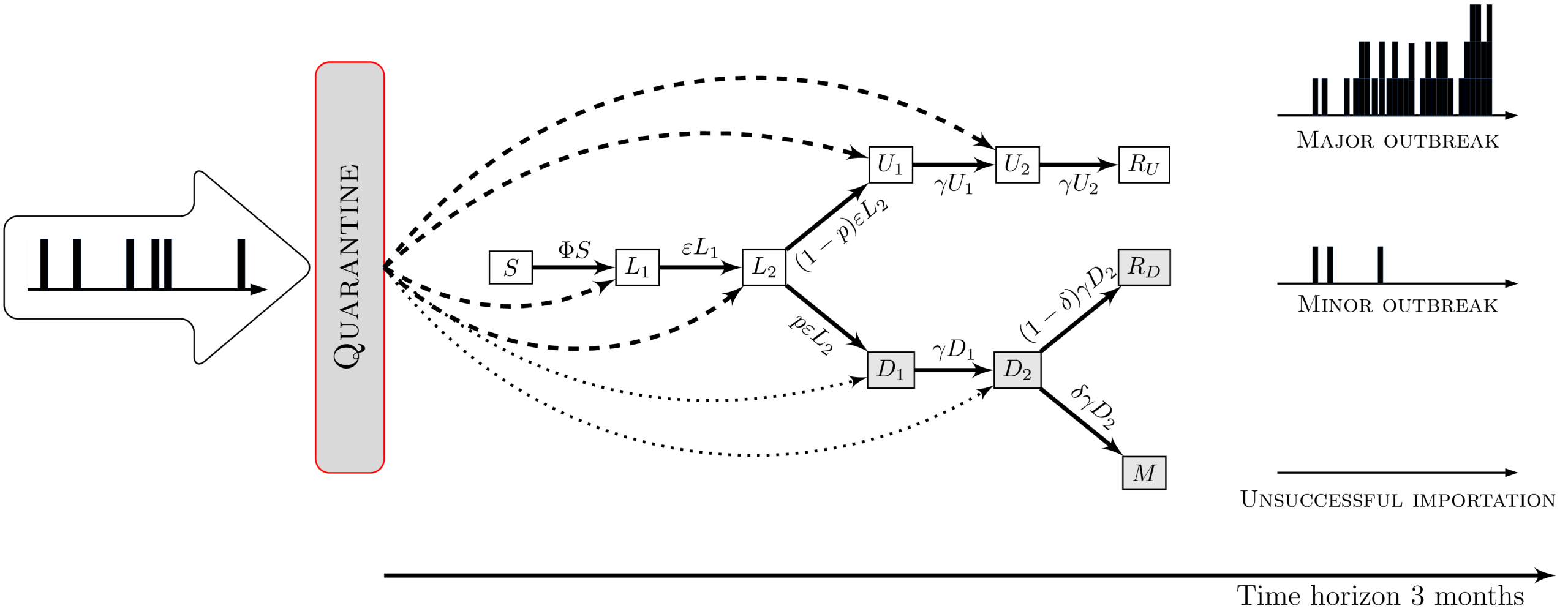
Modify the usual S (*susceptible*), L (*latent*), I (*infectious with symptoms*), A (*infectious without symptoms*) and R (*recovered*)

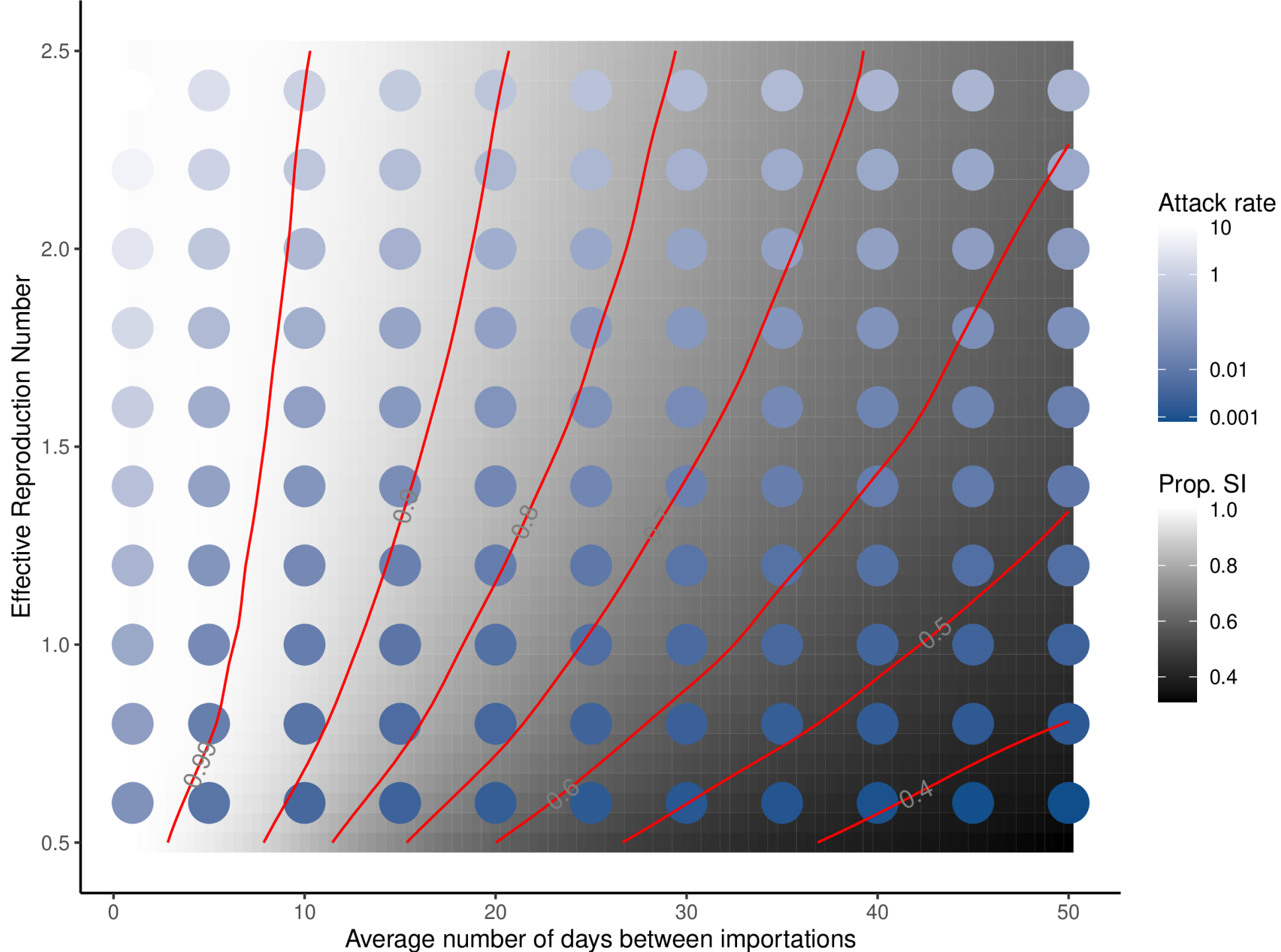
- D (instead of I) are **detected** (positive tests)
- U (instead of A) are **undetected** (even with symptoms)

p fraction of cases detected *a posteriori* (stricto sensu)

J. Arino & S. Portet. A simple model for COVID-19. Infectious Disease Modelling, 2020


γ
γ
γ
γ
S
ΦS
L_1
εL_1
L_2
$(1-p)\varepsilon L_2$
$p\varepsilon L_2$
U_1
γU_1
U_2
γU_2
R_U
D_1
γD_1
D_2
$(1-\delta)\gamma D_2$
$\delta\gamma D_2$
R_D
M


Quarantine
S
ΦS
L_1
εL_1
L_2
$(1-p)\varepsilon L_2$
$p\varepsilon L_2$
U_1
γU_1
U_2
γU_2
R_U
D_1
γD_1
D_2
$(1-\delta)\gamma D_2$
R_D
$\delta\gamma D_2$
M
Major outbreak
Minor outbreak
Unsuccessful importation
Time horizon 3 months


Effective Reproduction Number
2.5
2.0
1.5
1.0
0.5
0
10
20
30
40
50
Average number of days between importations
0.99
0.9
0.8
0.6
0.5
0.4
Attack rate
10
1
0.01
0.001
Prop. SI
1.0
0.8
0.6
0.4

Understanding variant dynamics and how to control it

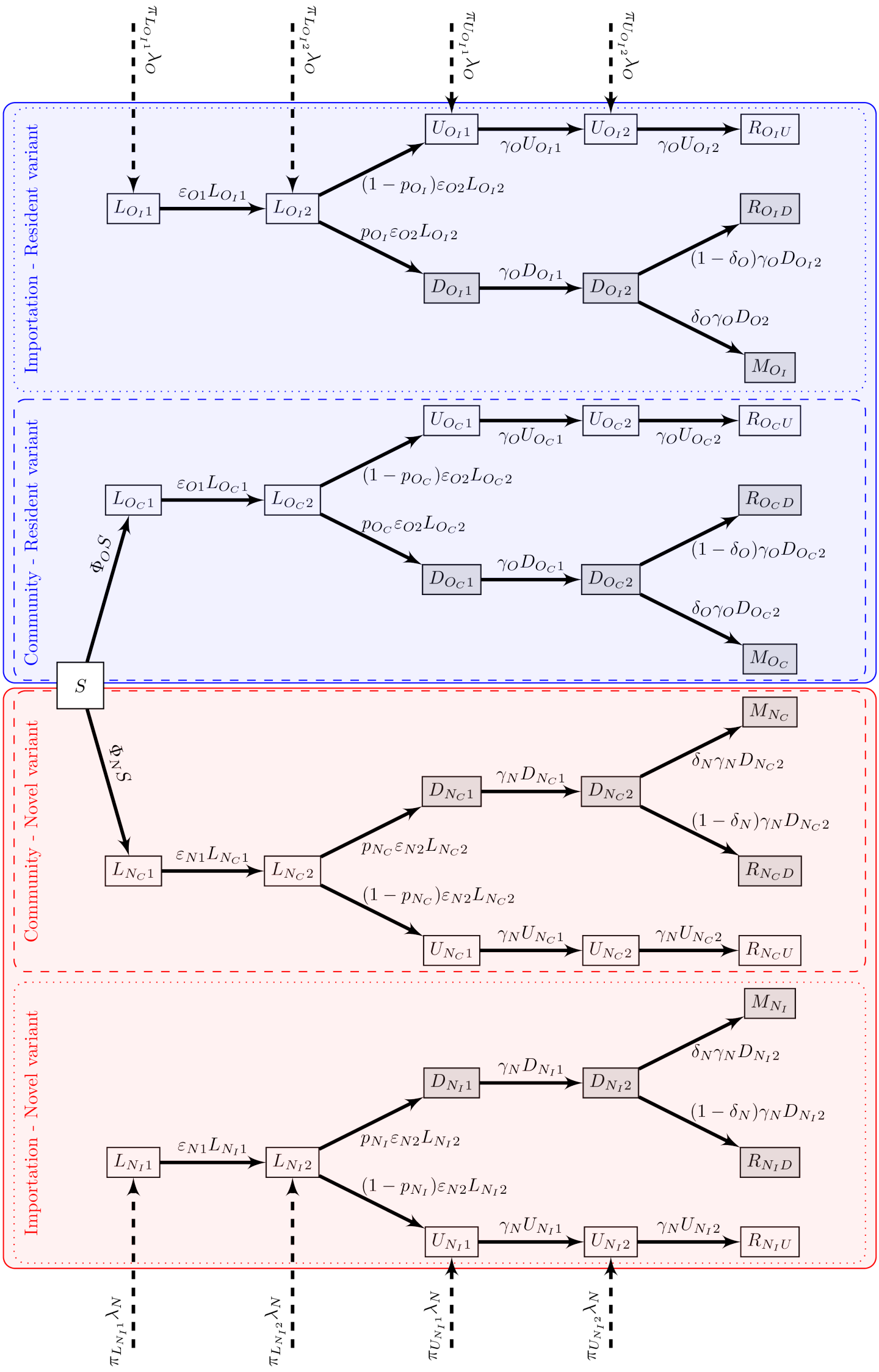
- Suppose a *resident variant* is propagating in a population, say, the original wild type or, now, B.1.1.7
- A *novel variant* comes along, say B.1.617.2 (SARS-CoV-2 Delta) that is more transmissible

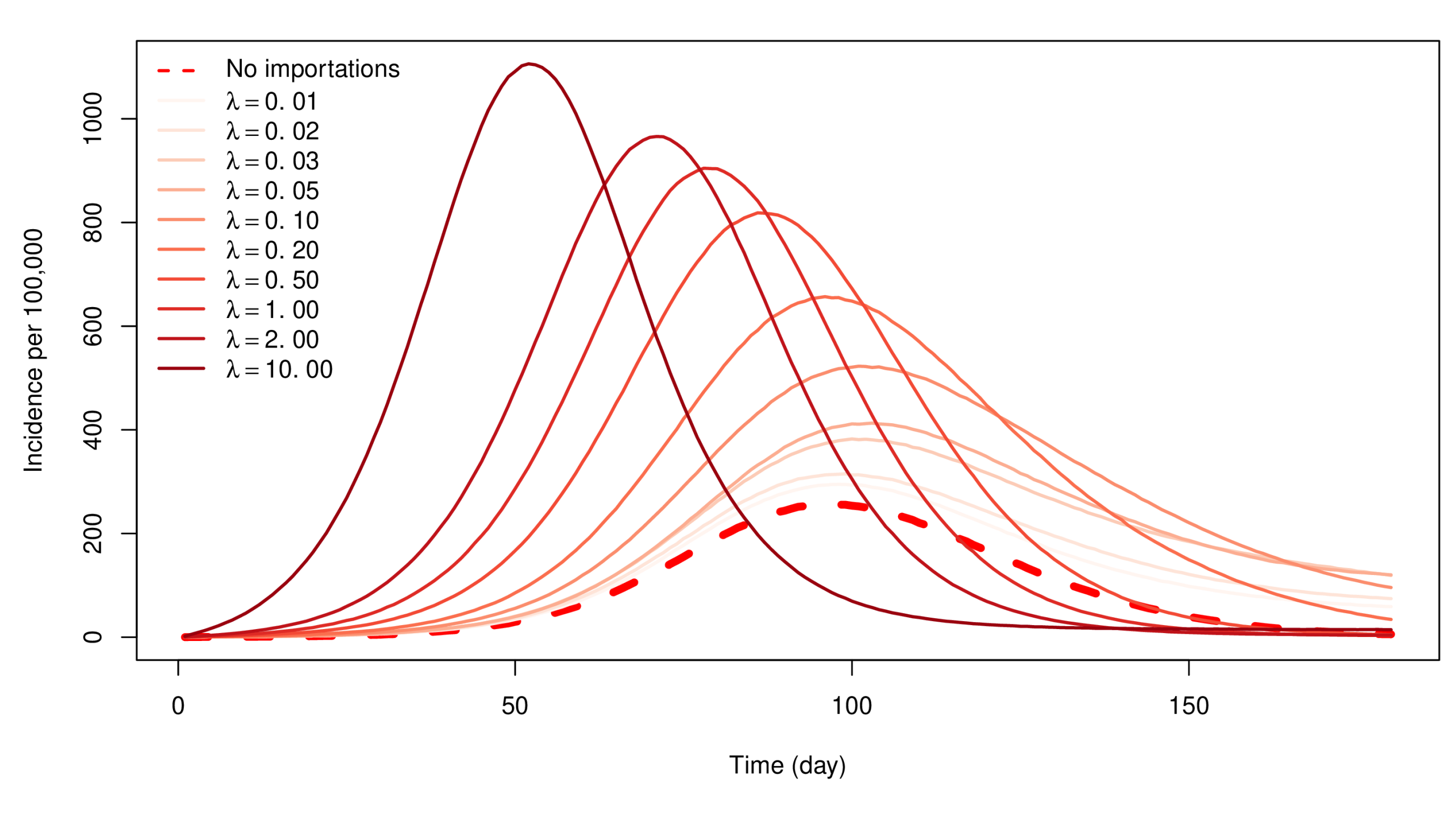
Q:

- How long until novel replaces resident variant in terms of propagation?
- What role do importations play in this?
- How does one diminish role of importations and how useful are measures used to do so?

J. Arino, P.-Y. Boëlle, E.M. Milliken & S. Portet. Risk of COVID-19 variant importation - How useful are travel control measures? Infectious Disease Modelling, 2021

S.P Otto, T. Day, J. Arino, C. Colijn *et al*. The origins and potential future of SARS-CoV-2 variants of concern in the evolving COVID-19 pandemic. Current Biology, 2021


Importation - Resident variant
Community - Resident variant
Community - Novel variant
Importation - Novel variant
$\pi_{L_{O_I1}}\lambda_O$
$\pi_{L_{O_I2}}\lambda_O$
$\pi_{U_{O_I1}}\lambda_O$
$\pi_{U_{O_I2}}\lambda_O$
L_{O_I1}
$\varepsilon_{O1}L_{O_I1}$
L_{O_I2}
$(1-p_{O_I})\varepsilon_{O2}L_{O_I2}$
$p_{O_I}\varepsilon_{O2}L_{O_I2}$
U_{O_I1}
$\gamma_O U_{O_I1}$
U_{O_I2}
$\gamma_O U_{O_I2}$
R_{O_IU}
D_{O_I1}
$\gamma_O D_{O_I1}$
D_{O_I2}
$(1-\delta_O)\gamma_O D_{O_I2}$
$\delta_O\gamma_O D_{O2}$
R_{O_ID}
M_{O_I}
S
$\Phi_O S$
L_{O_C1}
$\varepsilon_{O1}L_{O_C1}$
L_{O_C2}
$(1-p_{O_C})\varepsilon_{O2}L_{O_C2}$
$p_{O_C}\varepsilon_{O2}L_{O_C2}$
U_{O_C1}
$\gamma_O U_{O_C1}$
U_{O_C2}
$\gamma_O U_{O_C2}$
R_{O_CU}
D_{O_C1}
$\gamma_O D_{O_C1}$
D_{O_C2}
$(1-\delta_O)\gamma_O D_{O_C2}$
$\delta_O\gamma_O D_{O_C2}$
R_{O_CD}
M_{O_C}
$S\Phi_N$
L_{N_C1}
$\varepsilon_{N1}L_{N_C1}$
L_{N_C2}
$p_{N_C}\varepsilon_{N2}L_{N_C2}$
$(1-p_{N_C})\varepsilon_{N2}L_{N_C2}$
D_{N_C1}
$\gamma_N D_{N_C1}$
D_{N_C2}
$\delta_N\gamma_N D_{N_C2}$
$(1-\delta_N)\gamma_N D_{N_C2}$
M_{N_C}
R_{N_CD}
U_{N_C1}
$\gamma_N U_{N_C1}$
U_{N_C2}
$\gamma_N U_{N_C2}$
R_{N_CU}
L_{N_I1}
$\varepsilon_{N1}L_{N_I1}$
L_{N_I2}
$p_{N_I}\varepsilon_{N2}L_{N_I2}$
$(1-p_{N_I})\varepsilon_{N2}L_{N_I2}$
D_{N_I1}
$\gamma_N D_{N_I1}$
D_{N_I2}
$\delta_N\gamma_N D_{N_I2}$
$(1-\delta_N)\gamma_N D_{N_I2}$
M_{N_I}
R_{N_ID}
U_{N_I1}
$\gamma_N U_{N_I1}$
U_{N_I2}
$\gamma_N U_{N_I2}$
R_{N_IU}
$\pi_{L_{N_I1}}\lambda_N$
$\pi_{L_{N_I2}}\lambda_N$
$\pi_{U_{N_I1}}\lambda_N$
$\pi_{U_{N_I2}}\lambda_N$


No importations
λ = 0. 01
λ = 0. 02
λ = 0. 03
λ = 0. 05
λ = 0. 10
λ = 0. 20
λ = 0. 50
λ = 1. 00
λ = 2. 00
λ = 10. 00
Incidence per 100,000
0
200
400
600
800
1000
0
50
100
150
Time (day)

Travel interruptions

Mur de la Peste in Cabrières-d’Avignon

Progression de la peste

Foyer (juin 1720)

Espace contaminé

- En juin
- En août
- En septembre
- D'octobre à décembre
- Été 1721

7 août Date du début de l'épidémie

Axe de propagation

- Été 1720
- Automne 1720

Tentative d'endiguement

- Cordon sanitaire
- Mur de la peste

Mortalité

Nombre de morts :

50 000
15 000
5 000
1 000
500

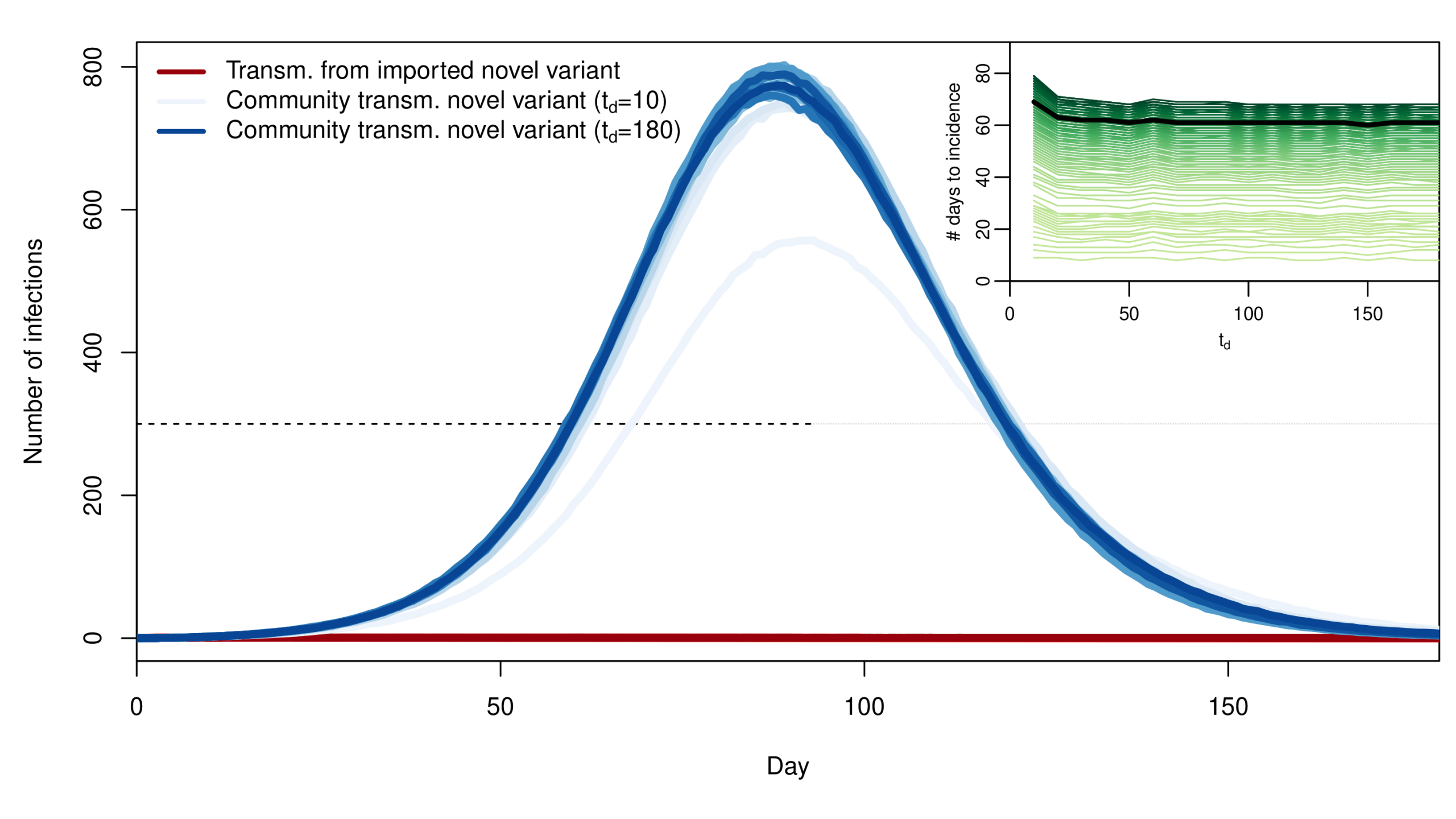
Taux de mortalité :

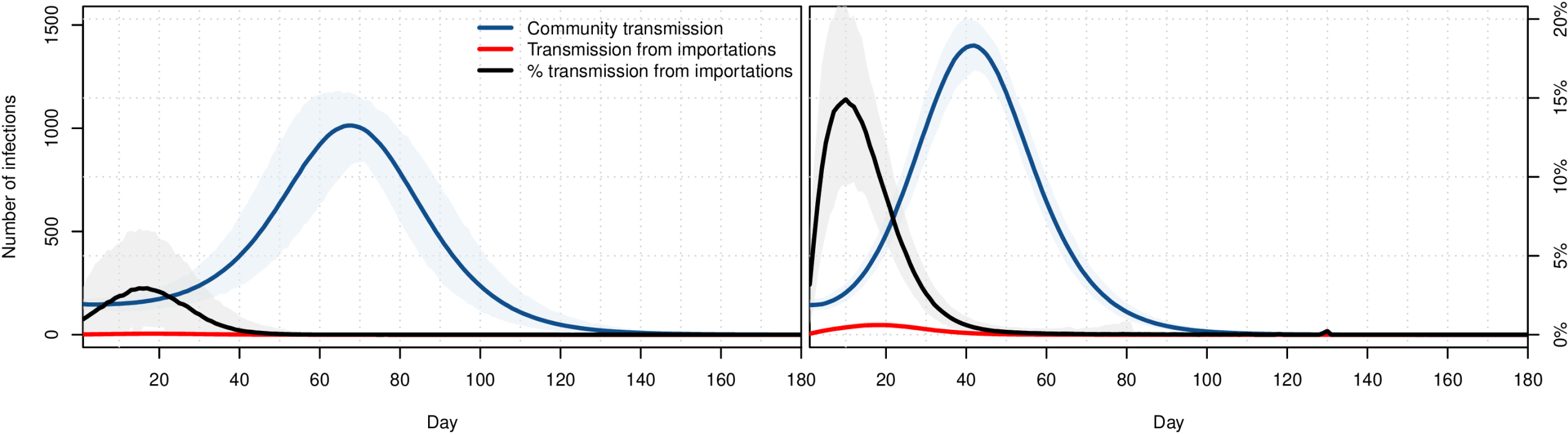
- Supérieur à 50 %
- De 10 à 50 %
- Moins de 10 %

20 km

D'après Jean-Noël Biraben, *Les Hommes et la peste*, Mouton, 1975

Légendes Cartographie


Transm. from imported novel variant
Community transm. novel variant (t_d=10)
Community transm. novel variant (t_d=180)
Number of infections
0
200
400
600
800
0
50
100
150
Day
days to incidence
0
20
40
60
80
0
50
100
150
t_d


Community transmission
Transmission from importations
% transmission from importations
Number of infections
0
500
1000
1500
0%
5%
10%
15%
20%
20
40
60
80
100
120
140
160
180
Day
Day

Interruption of travel during first wave

Country	Travel suspension	First_case
Seychelles	2020-03-03	2020-03-14
El Salvador	2020-03-17	2020-03-18
Cape Verde	2020-03-17	2020-03-20
Sudan	2020-03-17	2020-04-05
Marshall Islands	2020-04-22	2020-10-29
Vanuatu	2020-03-20	2020-11-11
North Korea	2020-01-21	Unreported
Turkmenistan	2020-03-20	Unreported
Tuvalu	2020-03-26	

Quarantine

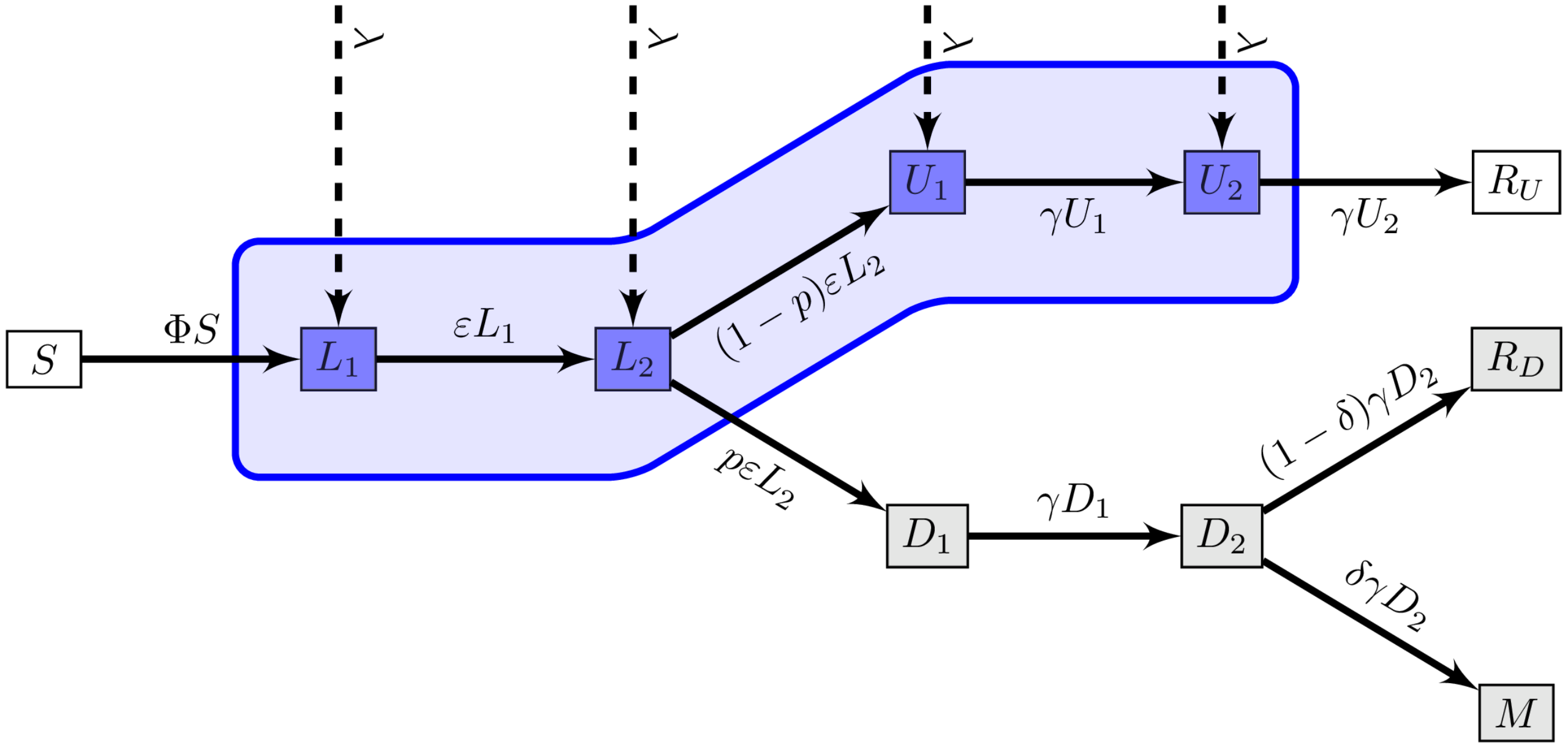
(Quarantaine)

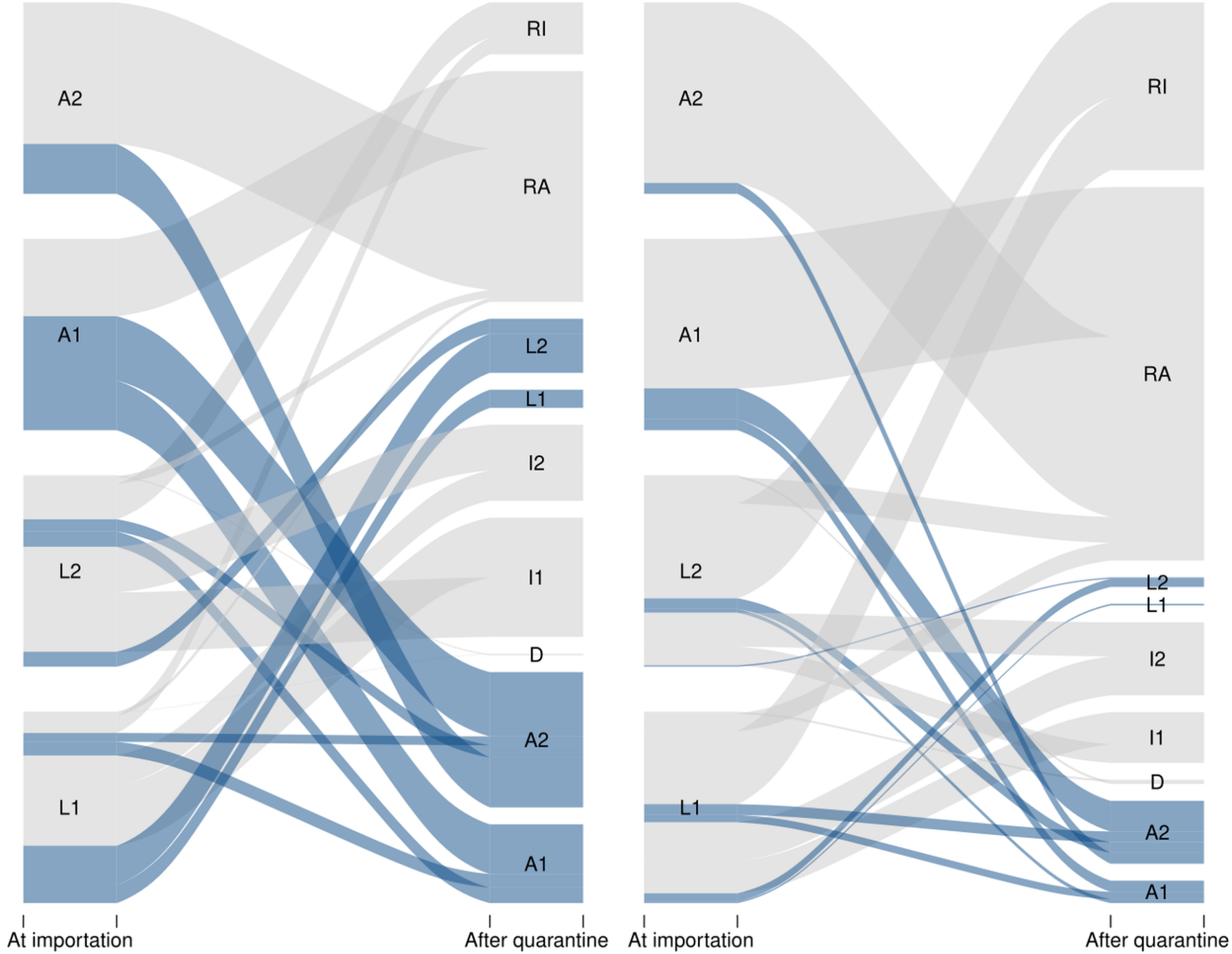
Quarantine ≠ Isolation

- *Quarantine* is indiscriminate and applies to all incoming flux
- *Isolation* is imposed to known or suspected cases and known contacts
- First used in (the lazzarettos of) Dubrovnik in 1377
- Name comes from Venitian *quarantena*

Lazzaretto vecchio


Lazzaretto nuovo


γ
γ
γ
γ
S
ΦS
L_1
εL_1
L_2
$(1-p)\varepsilon L_2$
$p\varepsilon L_2$
U_1
γU_1
U_2
γU_2
R_U
D_1
γD_1
D_2
$(1-\delta)\gamma D_2$
R_D
$\delta\gamma D_2$
M



(a) $t_q = 7$ days

(b) $t_q = 14$ days

Effect of quarantine on importation rates

$1/\lambda$ the mean time between case importations, $1/\lambda_q$ the mean quarantine-regulated time between case importations, c the efficacy of quarantine (in %). Then

$$\lambda_q = (100 - c) \times \lambda$$

Suppose $1/\lambda = 5$ days and efficacy of quarantine is 90% at 7 days and 98% at 14 days, respectively

Then $1/\lambda_q = 50$ and 250 days, respectively

Conclusion

- Case importations **will** occur no matter what
- Success of an importation depends on transmissibility of novel vs resident variant
- Travel interruptions are not efficacious at all on average
    - Need to be put in place very early on
- Quarantine is an efficacious tool to control case importations
    - It does not stop spread, but helps slow it down
    - Less stigmatising than travel interruptions
- Problem very quickly switches from input to local control

Emergency response during public health crises

- Get in there to help .. and for the adrenalin
- Get out of there burned out (19-20 hours a day 7 days a week the first two months, down to 80-100 hours/week now)
- Interesting and frustrating at the same time
- You are one of many being consulted. Don't expect anything you say to be used
- Expect wild goose chases, many aborted publications (*it's not relevant anymore!*)
- You sometimes get *insider* information and data but are often sworn to secrecy

Merci / Miigwech / Thank you / Xièxie