Multiscale Modelling of Behaviour-induced Critical Regimes during Epidemics

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Connecting Micro to Macro in Epidemiological Models
Isaac Newton Institute for Mathematical Sciences (INI)
Newton Gateway to Mathematics, 18 October 2023

Part 1: Agent-based pandemic modelling

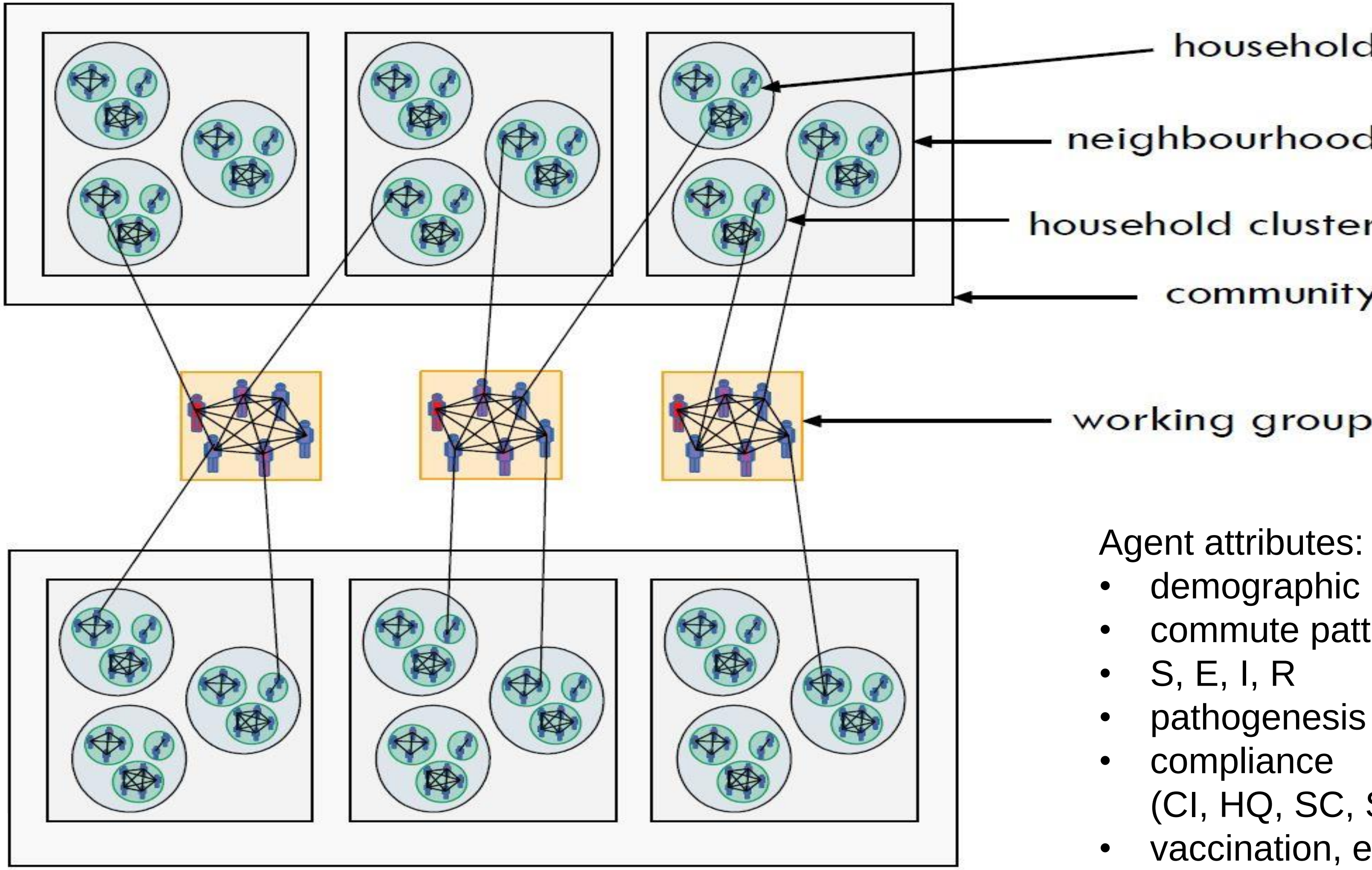
COVID-19 pandemic modelling using ABM

- Large-scale high-resolution agent-based models
  - *demographics*: from census based data to agents
  - *mobility*: travel patterns including long-distance
  - *infection*: epidemiology

- AMTraC-19: **A**gent-based **M**odel of **Tra**nsmission and **C**ontrol of the COVID-**19** pandemic in Australia (~ 24M agents)

- Model calibration and validation during COVID-19 pandemic
  - 1st stage, ancestral (March – June 2020)
  - 2nd stage, ancestral (July – September 2020)
  - 3rd stage, Delta (June – November 2021)
  - 4th stage, Omicron (December 2021 – November 2022)

“Same storm, different boats”



Agent attributes:
- demographic
- commute pattern
- S, E, I, R
- pathogenesis
- compliance (CI, HQ, SC, SD)
- vaccination, etc.

C. Zachreson, K. M. Fair, N. Harding, M. Prokopenko, Interfering with influenza: nonlinear coupling of reactive and static mitigation strategies, *Journal of Royal Society Interface*, 17(165): 20190728, 2020.

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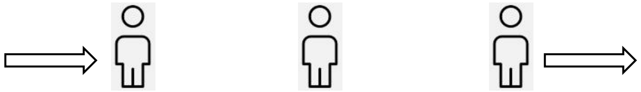
Features of AMTraC-19

- ~24M stochastically generated agents (Census, ABS & ACARA data)
- household size and composition vary across different local areas
- commuting patterns between residence and work / study
- flexible infection seeding scenarios
- transmission within mixing contexts
- different symptomatic ratios for children and adults
- vaccination rollout with two vaccines



- vaccine efficacy split across components (infection, symptoms, transmission)
- varying social distancing ("stay-at-home" restrictions)

S. L. Chang, N. Harding, C. Zachreson, O. M. Cliff, M. Prokopenko, Modelling transmission and control of the COVID-19 pandemic in Australia, *Nature Communications*, 11, 5710, 2020.

C. Zachreson, S. L. Chang, O. M. Cliff, M. Prokopenko, How will mass-vaccination change COVID-19 lockdown requirements in Australia? *The Lancet Regional Health – Western Pacific*, 14: 100224, 2021.

Population partitions: residential areas and destination zones

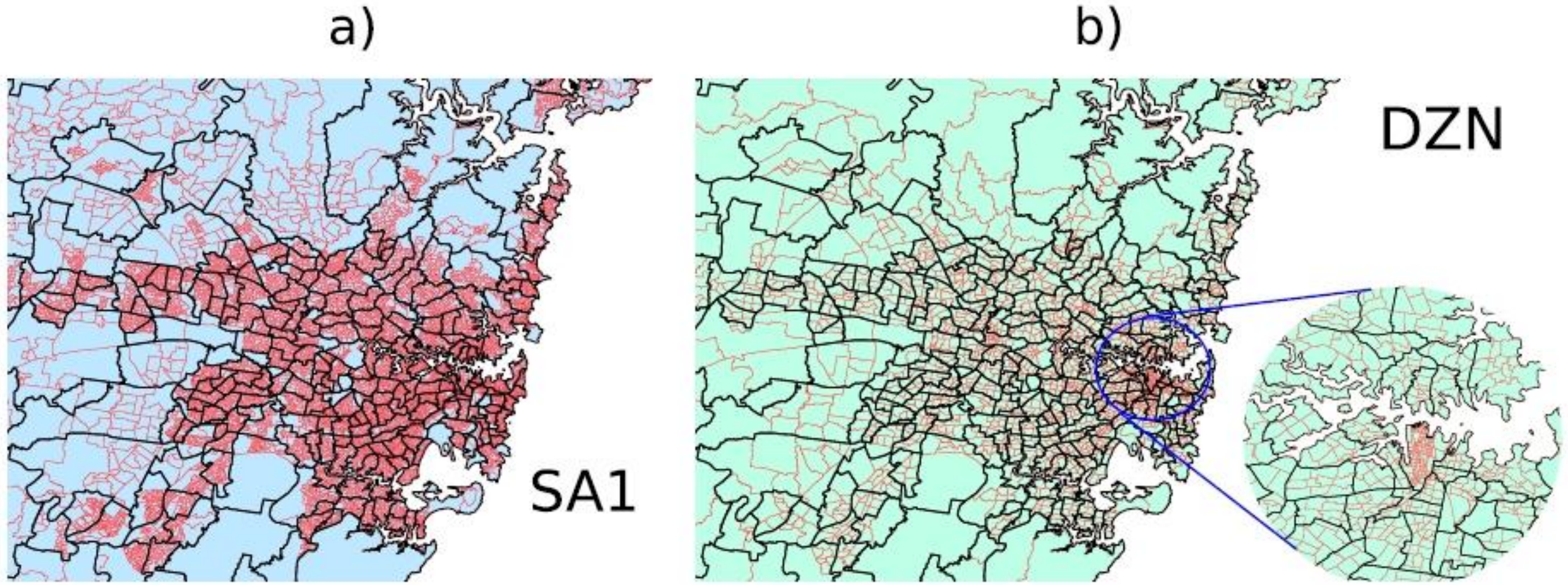


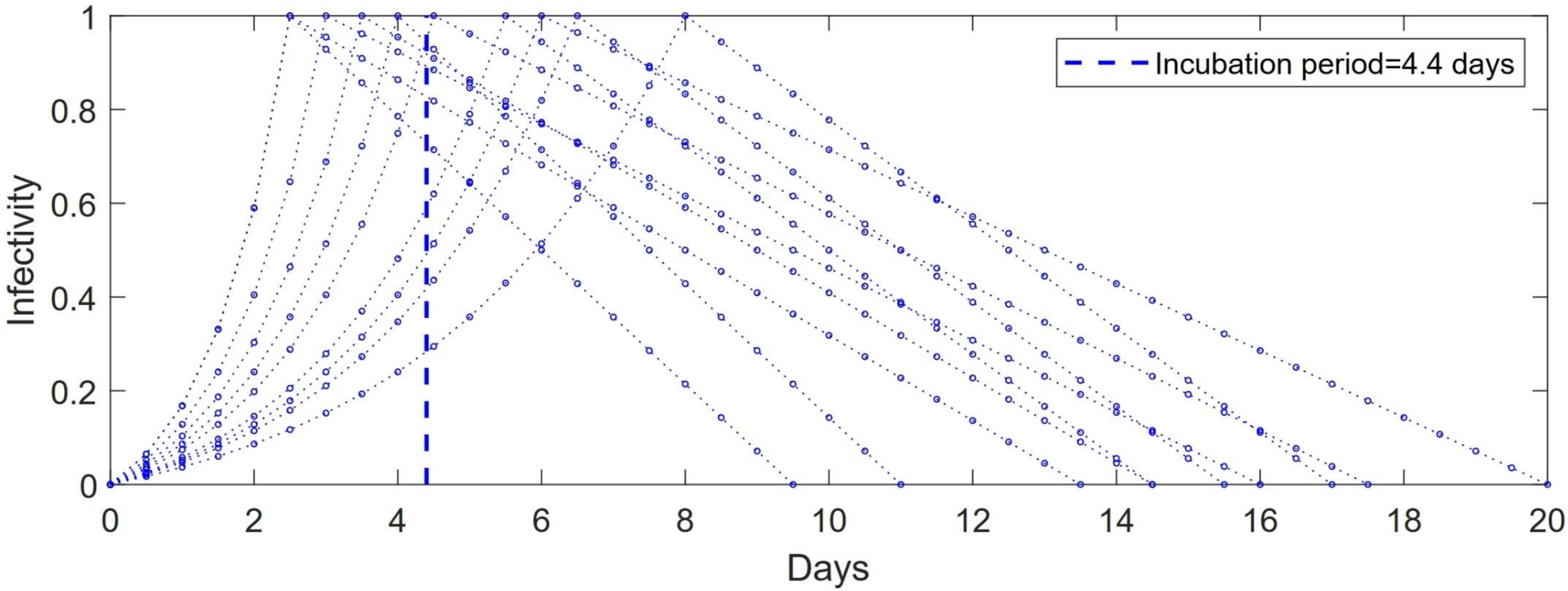
Fig. 1 Maps of the Greater Sydney region illustrating the distribution of population partitions. (**a**) A map of the Greater Sydney region showing SA2 (black) and SA1 (red) population partitions. (**b**) A map of the same area showing SA2 (black) and DZN (red) partitions. The inset in (**b**) zooms in on the Sydney central business district to illustrate the much denser packing of DZN partitions in that area.

K. M. Fair, C. Zachreson, M. Prokopenko, Creating a surrogate commuter network from Australian Bureau of Statistics census data, *Scientific Data*, 6, 150, 2019.

Transmission probabilities

Mixing context	Type of interaction	Daily transmission probability ($q^g_{j \to i}$)
Household (size 2)	Any to child (0 - 18)	0.09335
	Any to adult (19+)	0.02420
Household (size 3)	Any to child (0 - 18)	0.05847
	Any to adult (19+)	0.01495
Household (size 4)	Any to child (0 - 18)	0.04176
	Any to adult (19+)	0.01061
Household (size 5)	Any to child (0 - 18)	0.03211
	Any to adult (19+)	0.00813
Household (size 6)	Any to child (0 - 18)	0.02588
	Any to adult (19+)	0.00653
Household Cluster	Child (0 - 18) to child (0 - 18)	0.00400
	Child (0 - 18) to adult (19+)	0.00400
	Adult (19+) to child (0 - 18)	0.00400
	Adult (19+) to adult (19+)	0.00400
Working Group	Adult (19+) to adult (19+)	0.00400
School	Child (0 - 18) to child (0 - 18)	0.00029
Grade	Child (0 - 18) to child (0 - 18)	0.00158
Class	Child (0 - 18) to child (0 - 18)	0.00865
Neighborhood	Any to child (0 - 4)	0.035×10^{-5}
	Any to child (5 - 18)	1.044×10^{-5}
	Any to adult (19 - 64)	2.784×10^{-5}
	Any to adult (65+)	5.568×10^{-5}
Community	Any to child (0 - 4)	0.872×10^{-6}
	Any to child (5 - 18)	2.608×10^{-6}
	Any to adult (19 - 64)	6.960×10^{-6}
	Any to adult (65+)	13.92×10^{-6}

Natural history of the disease (the Delta variant)



	R_0	T_{gen} (days)	T_{inc} (days)	T_{rec} (days)
Mean	6.2	6.93	4.4	10
95% CI	6.16 – 6.23	6.87 – 6.99	3.9 – 5.0	range: 7 – 14 (uniform)

S. L. Chang, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating Transmission Scenarios of the Delta Variant of SARS-CoV-2 in Australia, *Frontiers in Public Health,* 10, 10.3389/fpubh.2022.823043, 2022.

Non-pharmaceutical interventions (NPIs)

NPI	Compliance (macro)	Interaction strength (micro)		
		Household	Community	Workplace
Case isolation	0.7 – 0.8	1.0	0.1 – 0.25	0.1 – 0.25
Home quarantine	0.5 – 0.7	2.0	0.1 – 0.25	0.1 – 0.25
School (students)	1.0	1.0	0.1 – 0.5	0.0
School (parents)	0.5	1.0	0.1 – 0.5	0.0
Social distancing	0.0 – 1.0	1.0	0.1 – 0.25	0.1

S. L. Chang, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating Transmission Scenarios of the Delta Variant of SARS-CoV-2 in Australia, *Frontiers in Public Health,* 10, 10.3389/fpubh.2022.823043, 2022.

Social Distancing (SD): “stay-at-home” restrictions

Table 2 The micro- and macro-distancing parameters: macro-compliance levels and context-dependent micro-distancing levels.

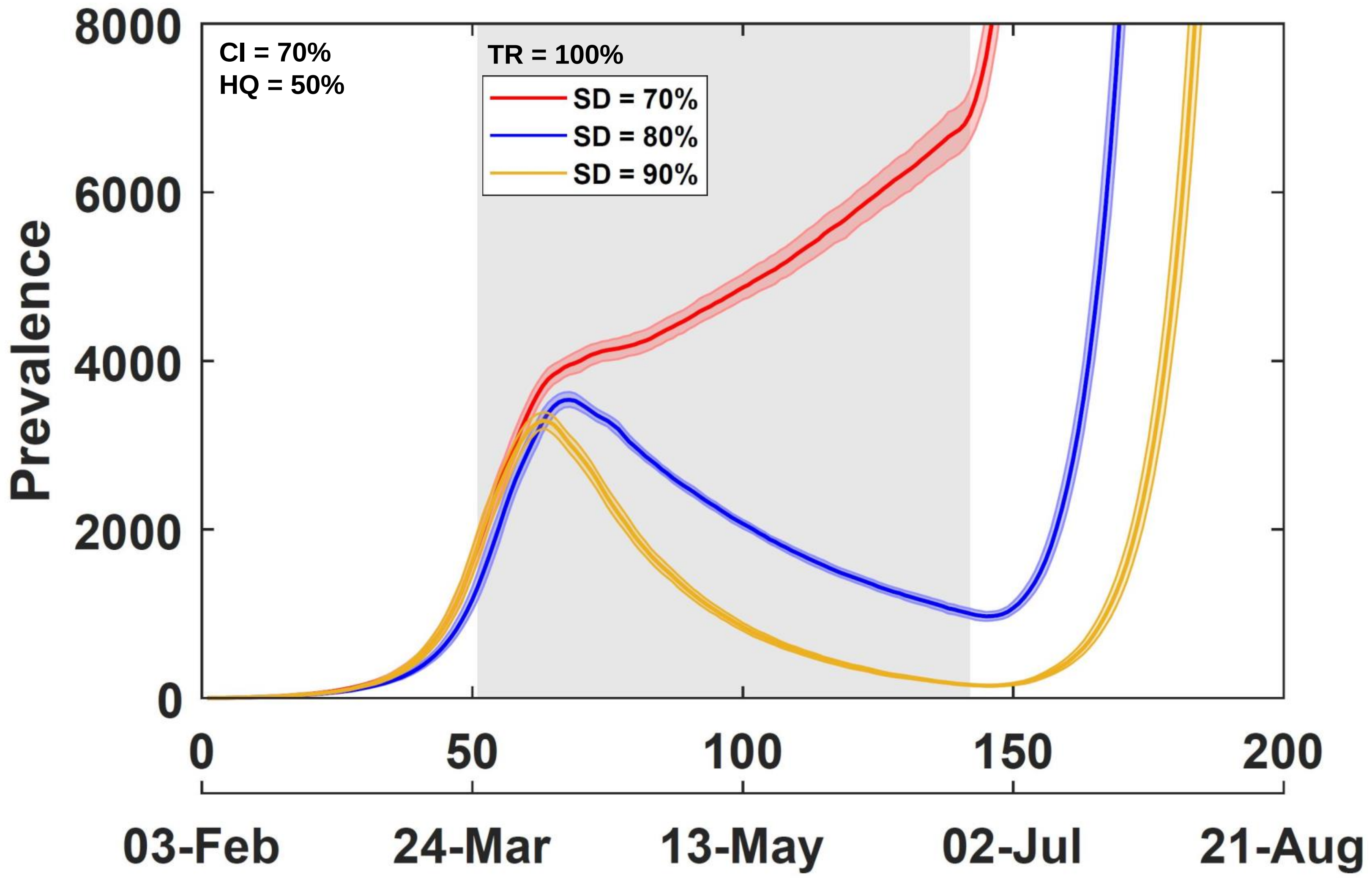
Strategy	Macro-distancing	Micro-distancing contacts		
	Compliance levels	Household	Community	Workplace/school
No intervention	100%	100%	100%	100%
Case isolation	70%	100%	25%	25%
Home quarantine	50%	200%	25%	25%
School closure (children)	100%	150%	150%	0%
School closure (parents)	25 or 50%	150%	150%	0%
Social distancing	0–100%	100%	50%	0%

$$p_i(n) = 1 - \prod_{g \in G_i(n)} \left[\prod_{j \in A_g \setminus i} \left(1 - p^g_{j \to i}(n)\right) \right]$$

$$p_i(n) = 1 - \prod_{g \in G_i(n)} \left[1 - F_g(i) \left(1 - \prod_{j \in A_g \setminus \{i\}} \left(1 - F_g(j)\, p^g_{j \to i}(n)\right) \right) \right]$$

S. L. Chang, N. Harding, C. Zachreson, O. M. Cliff, M. Prokopenko, Modelling transmission and control of the COVID-19 pandemic in Australia, *Nature Communications*, 11, 5710, 2020.

Tipping point in social distancing



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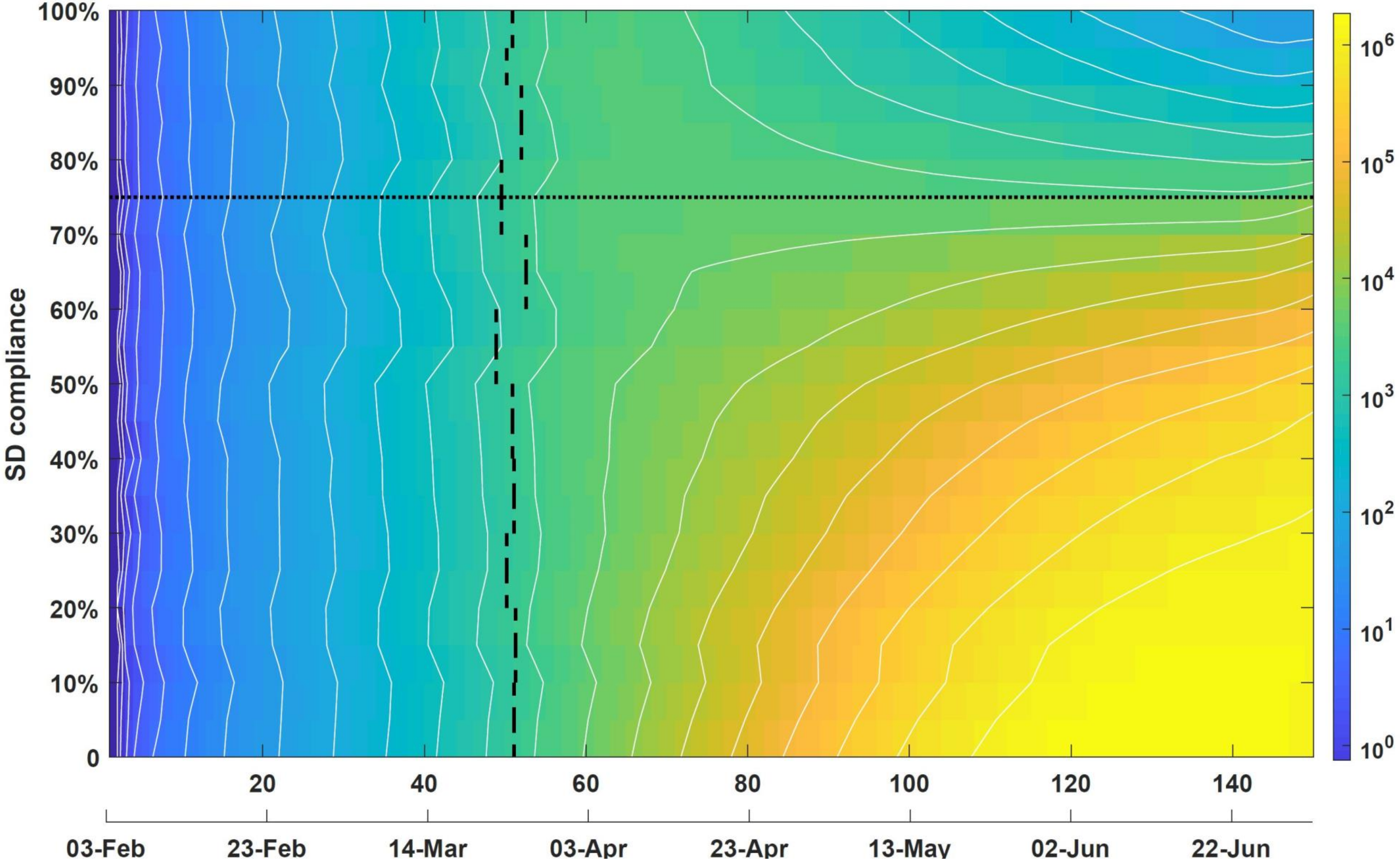
Tipping point (phase transition) in SD compliance



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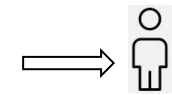
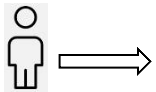
Modelling vaccination rollout

- Efficacy for susceptibility (VEs): impacts immunity in those susceptible to the virus (reduces the probability of becoming infected if exposed)



- Efficacy for disease (VEd): impacts the expression of illness in those who are vaccinated and subsequently become infected (reduces the probability of expressing symptoms if infected)

- Efficacy for infectiousness (VEi): impacts the potential for vaccinated individuals to transmit the virus if infected (reduces the force of infection produced by infected individuals who are vaccinated)



$$\mathrm{VE} = \mathrm{VEd} + \mathrm{VEs} - \mathrm{VEs} \times \mathrm{VEd} \qquad \mathrm{VEi} = \sim 0.5$$

for example:

$$0.91 = 0.7 + 0.7 - 0.7 \times 0.7$$
$$0.92 = 0.8 + 0.6 - 0.8 \times 0.6$$

$$0.75 = 0.5 + 0.5 - 0.5 \times 0.5$$
$$0.65 = 0.5 + 0.3 - 0.5 \times 0.3$$

C. Zachreson, S. L. Chang, O. M. Cliff, M. Prokopenko, How will mass-vaccination change COVID-19 lockdown requirements in Australia? *The Lancet Regional Health – Western Pacific*, 14: 100224, 2021.

Vaccination components

$$p_i(n) = 1 - \prod_{g\in G_i(n)} \left[\prod_{j\in A_g\setminus i} \left(1 - p^g_{j\to i}(n)\right) \right]$$

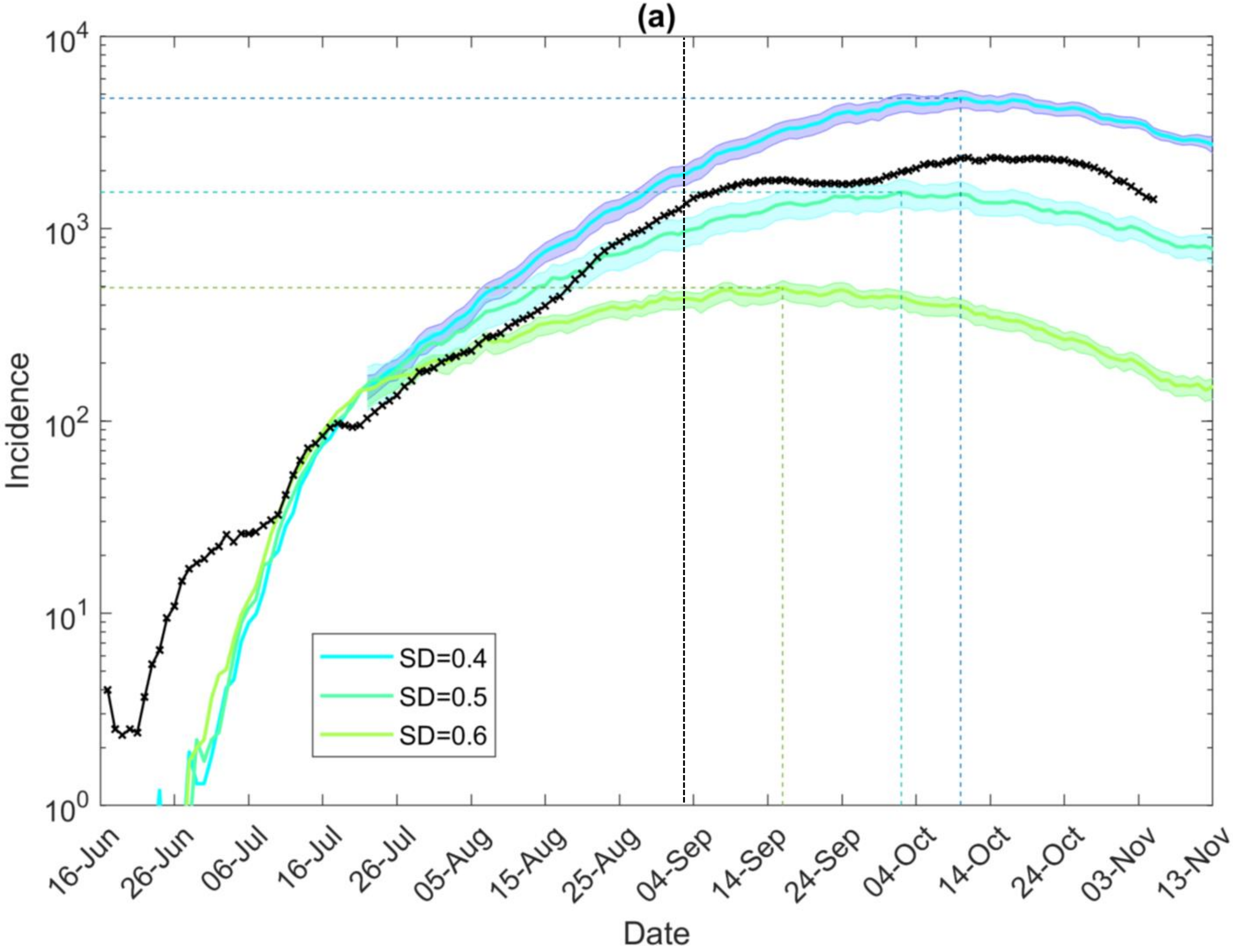
$$p_i(n) = 1 - \prod_{g\in G_i(n)} \left[1 - F_g(i) \left(1 - \prod_{j\in A_g\setminus\{i\}} \left(1 - F_g(j)\; p^g_{j\to i}(n)\right) \right) \right]$$

$$p_i(n) = 1 - \prod_{g\in G_i(n)} \left[1 - (1 - VE_i^s) F_g(i) \left(1 - \prod_{j\in A_g\setminus i} \left(1 - (1 - VE_j^t) F_g(j)\; p^g_{j\to i}(n)\right) \right) \right]$$

$$p_i^d(n) = (1 - VE_i^d)\; \sigma_{a|c}\; p_i(n)$$

The Delta variant: SD compliance scenarios (25 August → 5 November 2021)

$R_0 = 6.20$



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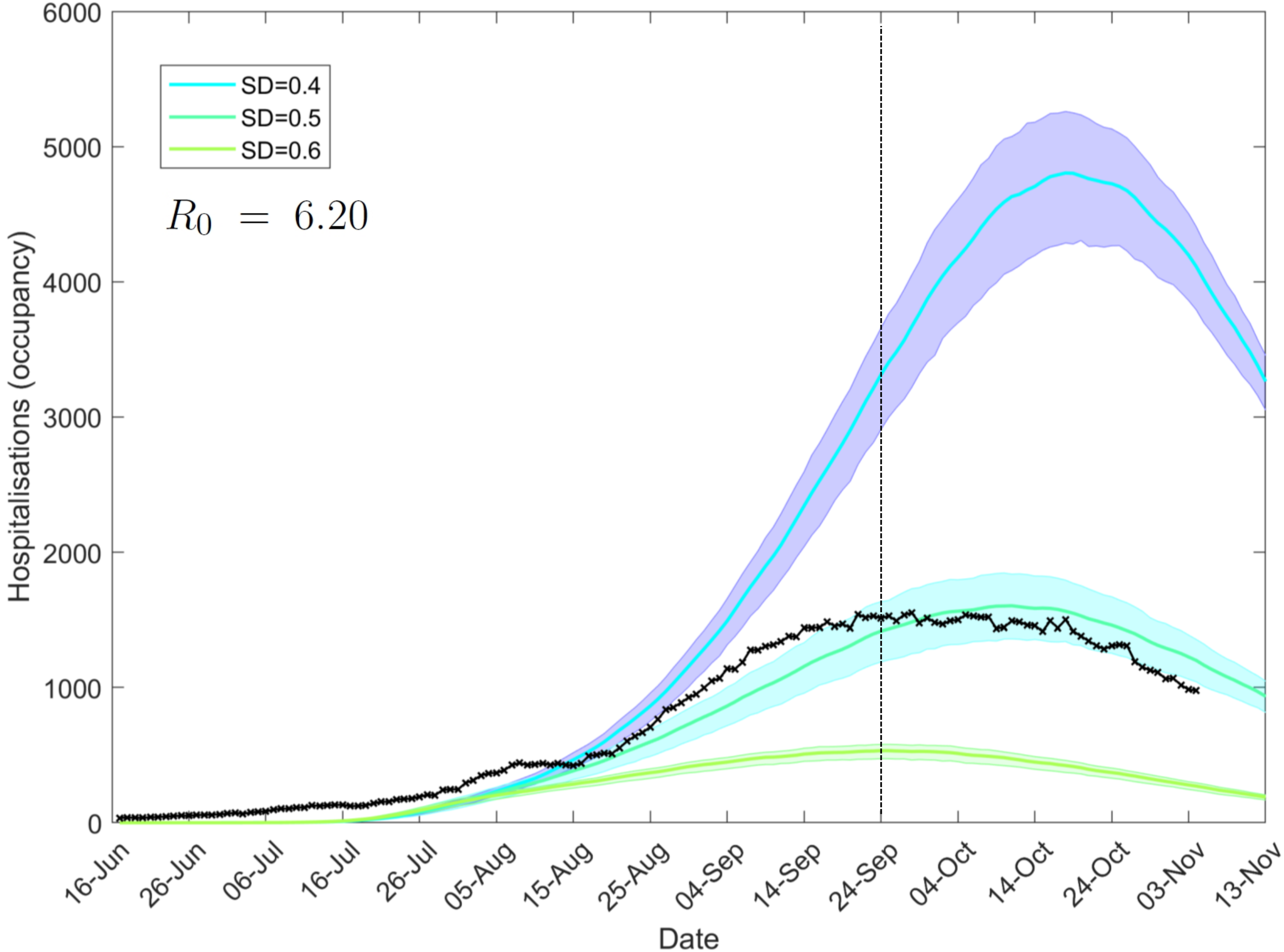
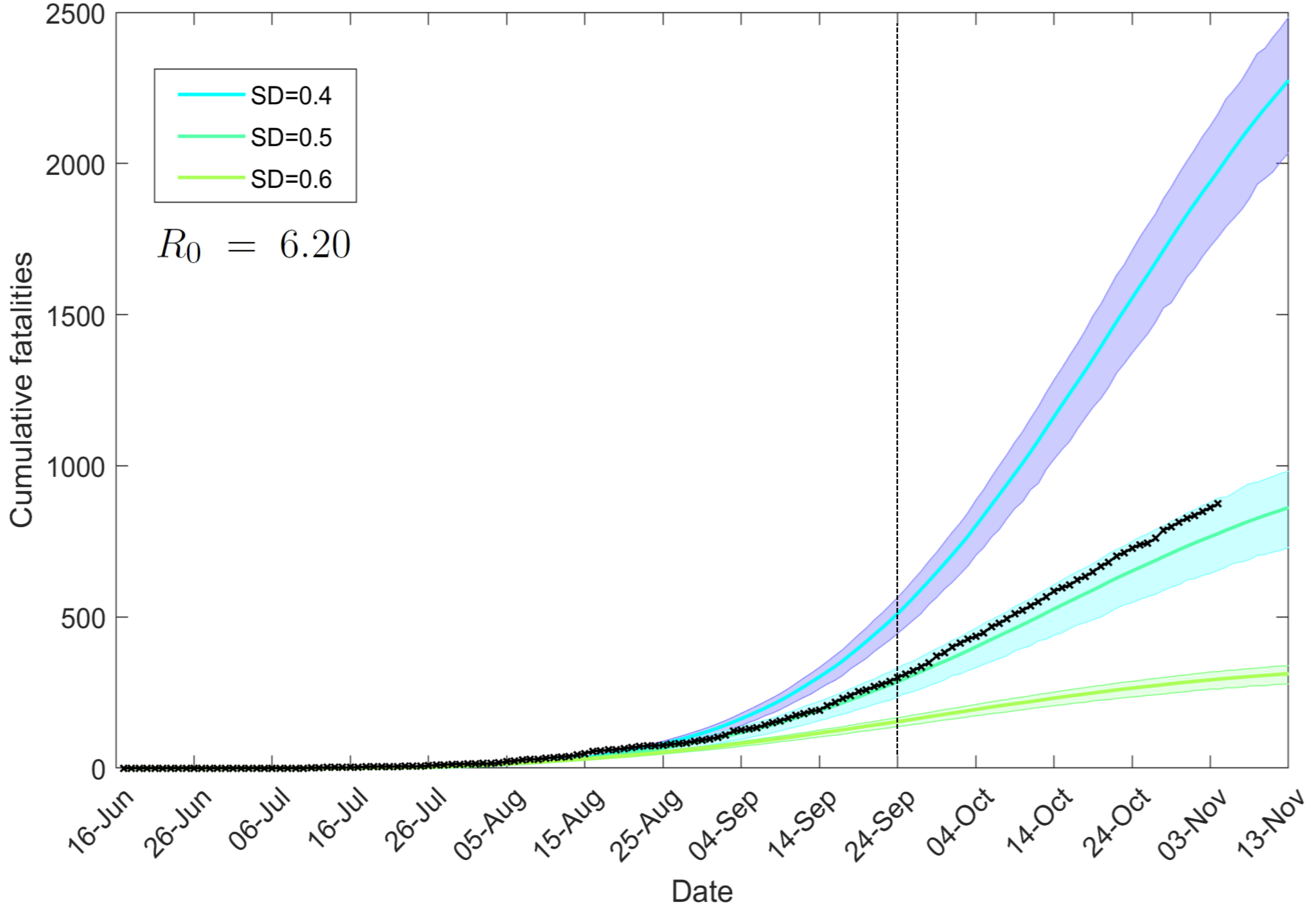
Hospitalisations (occupancy): a threefold reduction for 10% increase in SD

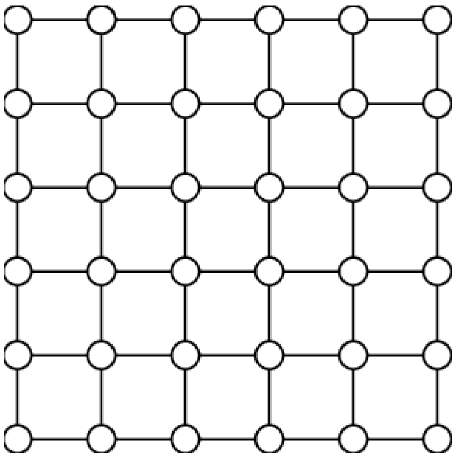


Mortality (cumulative deaths): a two-fold reduction for 10% increase in SD



Part 2: Spatial interaction pandemic modelling

Dynamic meta-population epidemic (SIS) model



$$\frac{dI_i}{dt} = -\gamma I_i + \beta \sum_{j,k} \phi_{ij}^{S}(\mathbf{I}, \mathbf{C}) \phi_{kj}^{I}(\mathbf{I}, \mathbf{C}) \frac{S_i I_k}{\hat{N}_j(\mathbf{I}, \mathbf{C})}$$

$$\hat{N}_j(\mathbf{I}, \mathbf{C}) = \sum_k S_k \phi_{kj}^{S}(\mathbf{I}, \mathbf{C}) + I_k \phi_{kj}^{I}(\mathbf{I}, \mathbf{C})$$

Benefit

$$b_j = N_j^{-1}(N_j - I_j)$$

N. Harding, R. E. Spinney, M. Prokopenko, Population mobility induced phase separation in SIS epidemic and social dynamics, *Scientific Reports*, 10: 7646, 2020.

Boltzmann-Lotka-Volterra spatial interaction

MaxEnt Principle

$$H_Y = -\sum_y p_Y(y) \ln p_Y(y)$$

$$B^I = \sum_{i,j} I_i \phi_{ij}^I(\mathbf{I}, \mathbf{C}) b_j / \sum_i I_i,$$

constraints

vs

control parameters

$$B^S = \sum_{i,j} S_i \phi_{ij}^S(\mathbf{I}, \mathbf{C}) b_j / \sum_i S_i$$

$$C = \sum_{i,j} (I_i \phi_{ij}^I(\mathbf{I}, \mathbf{C}) + S_i \phi_{ij}^S(\mathbf{I}, \mathbf{C})) c_{ij} / \sum_i (I_i + S_i)$$

N. Harding, R. E. Spinney, M. Prokopenko, Population mobility induced phase separation in SIS epidemic and social dynamics, *Scientific Reports*, 10: 7646, 2020.

Boltzmann-Lotka-Volterra spatial interaction

MaxEnt Principle

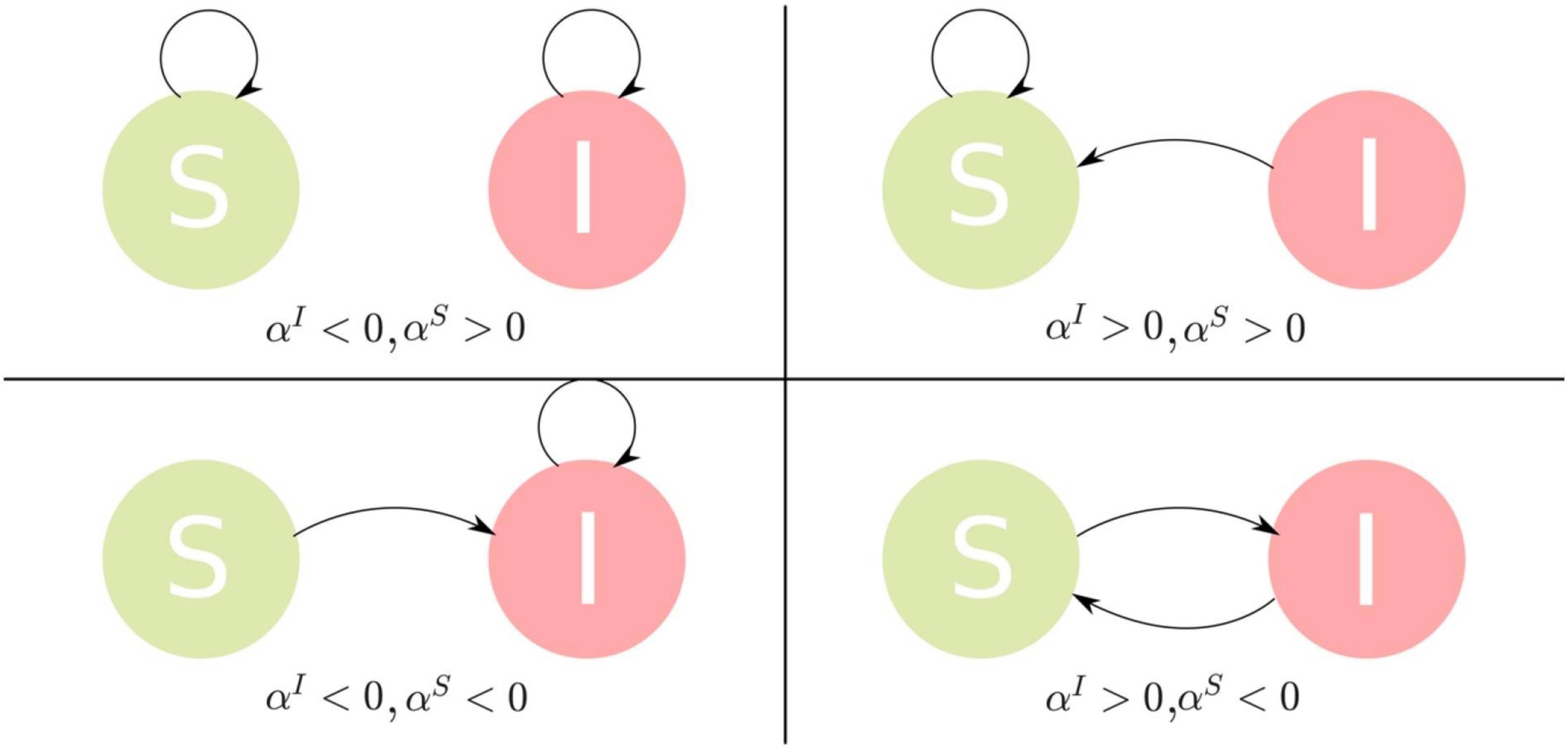
$$H_Y = -\sum_y p_Y(y) \ln p_Y(y)$$

$$\begin{pmatrix} \alpha^S \\ \alpha^I \\ \omega \end{pmatrix} \begin{array}{c} \text{Specify constraints: Infer model parameters} \\ \leftrightharpoons \\ \text{Specify parameters: Model generates quantities} \end{array} \begin{pmatrix} B^S \\ B^I \\ C \end{pmatrix}$$

N. Harding, R. E. Spinney, M. Prokopenko, Population mobility induced phase separation in SIS epidemic and social dynamics, *Scientific Reports*, 10: 7646, 2020.

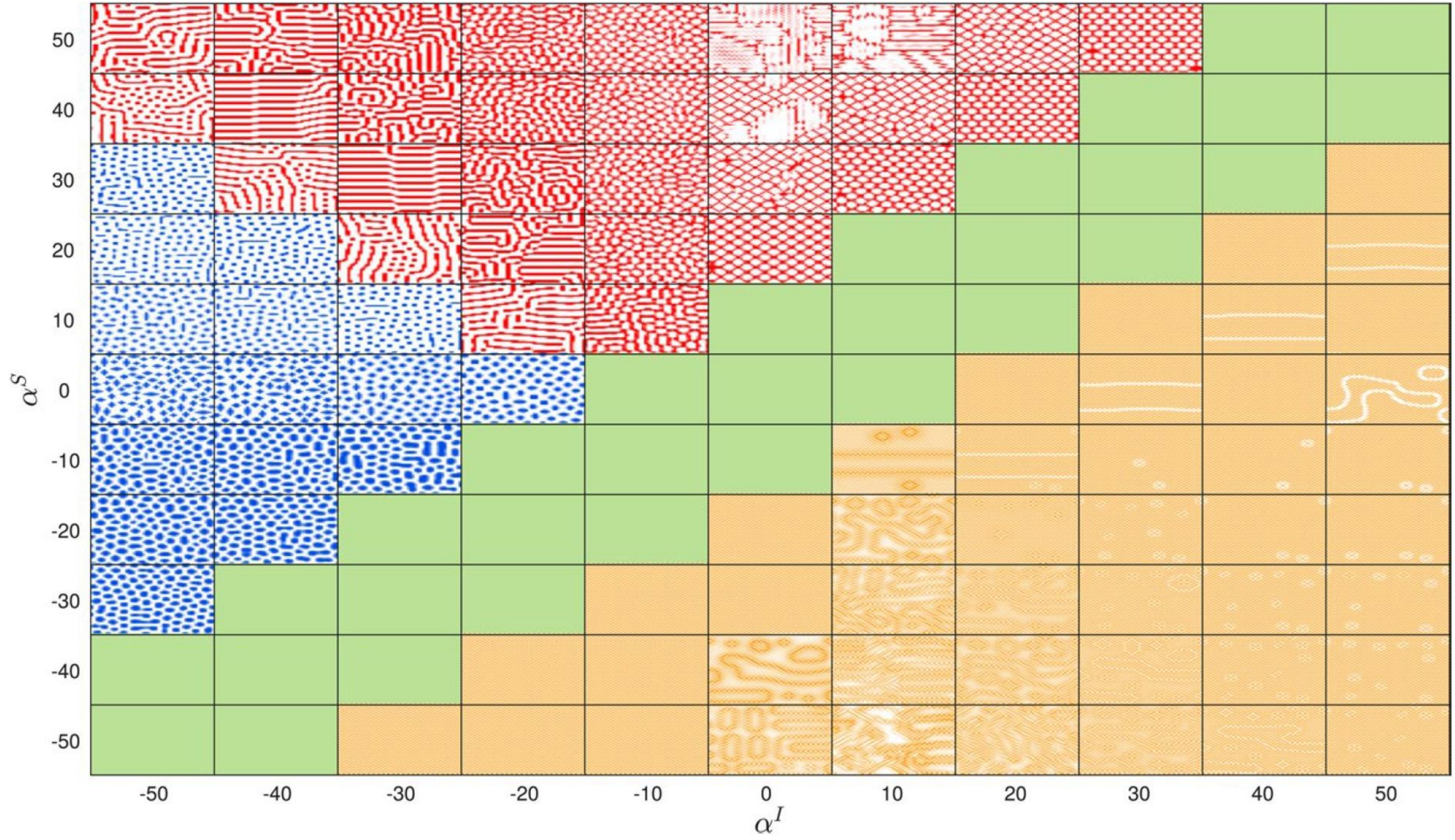
Bounded rationality: four types of dynamics

$$\phi_{ij}^{x}(\mathbf{I}, \mathbf{C}|\alpha^{x}, \omega) = Z_{x,i}^{-1}\exp\left(\alpha^{x}b_{j} - \omega c_{ij}\right)$$



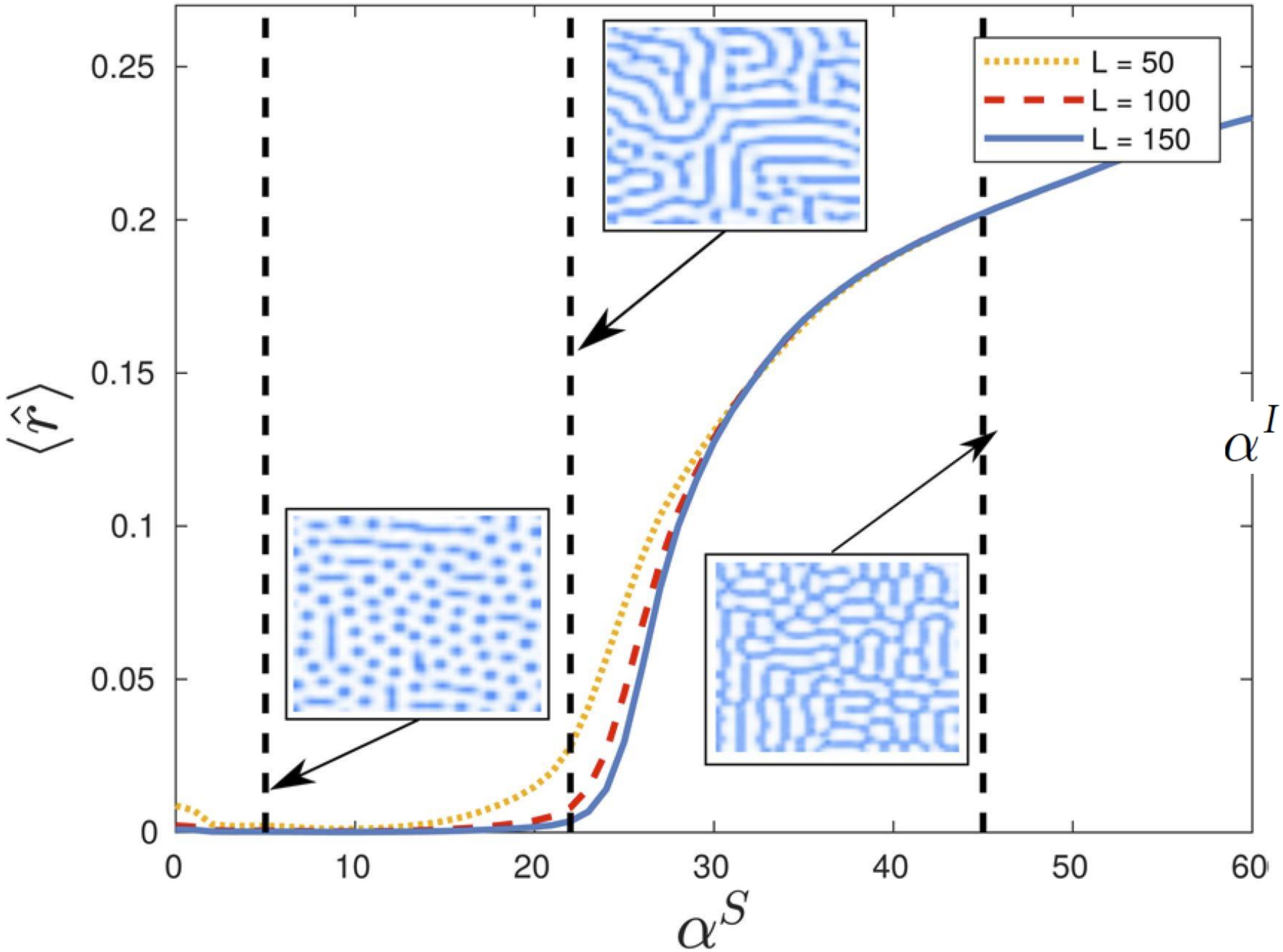
Behaviour-induced spatial morphology

$$\phi_{ij}^{x}(\mathbf{I}, \mathbf{C}|\alpha^{x}, \omega) = Z_{x,i}^{-1}\exp\left(\alpha^{x}b_{j} - \omega c_{ij}\right)$$



Spatial morphology: critical regimes

average cluster size

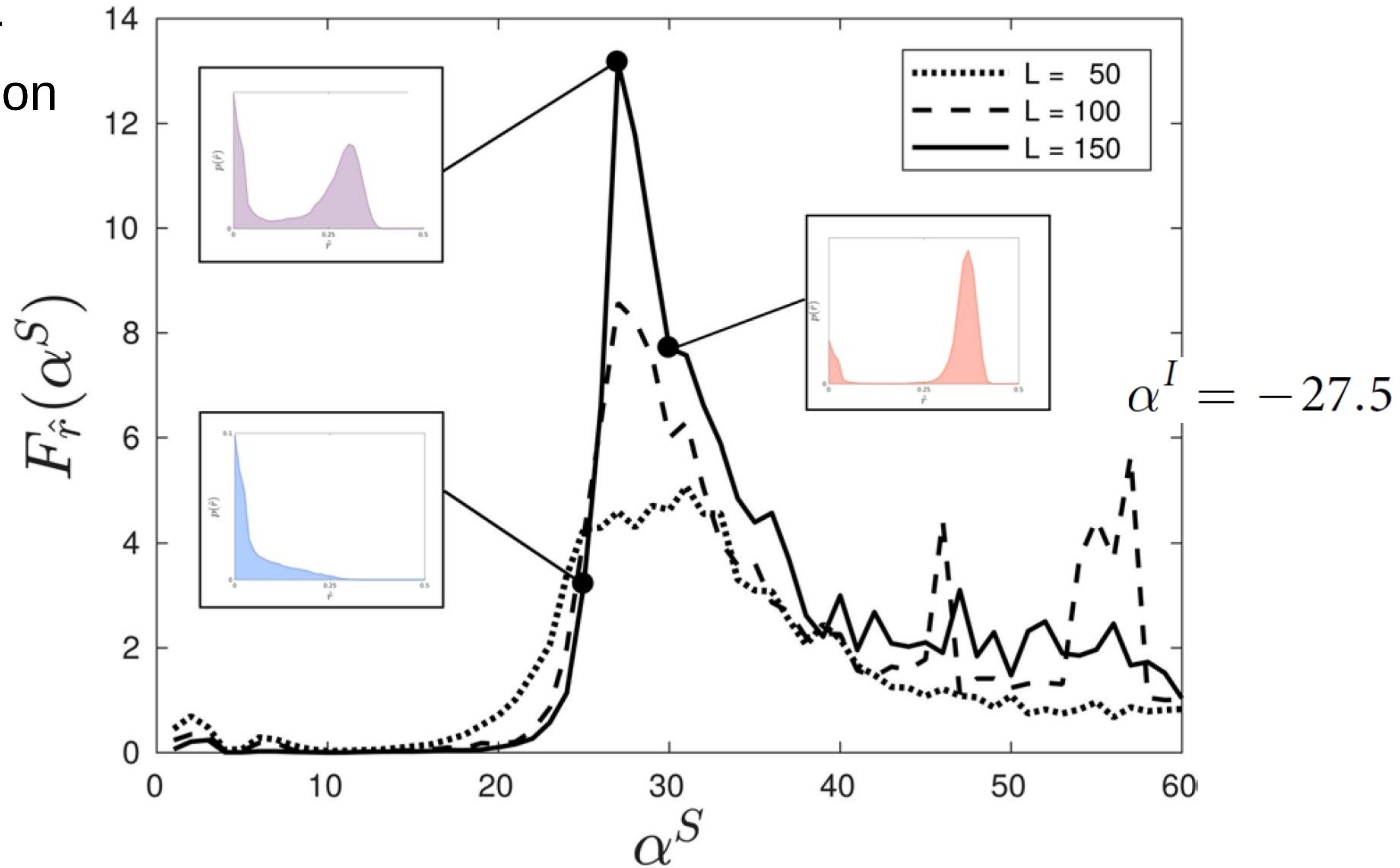


$\alpha^I = -27.5$

N. Harding, R. E. Spinney, M. Prokopenko, Population mobility induced phase separation in SIS epidemic and social dynamics, *Scientific Reports*, 10: 7646, 2020.

Spatial morphology: Fisher information

Fisher information



N. Harding, R. E. Spinney, M. Prokopenko, Population mobility induced phase separation in SIS epidemic and social dynamics, *Scientific Reports*, 10: 7646, 2020.

Behaviour-induced critical regimes

- tipping points in pandemic response:
  compliance with social distancing

- amplification effects of NPIs on disease burden:
  compliance with social distancing

- transitions in morphology (spots → labyrinth → gaps):
  bounded rationality

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References

- K. M. Fair, C. Zachreson, M. Prokopenko, Creating a surrogate commuter network from Australian Bureau of Statistics census data, *Scientific Data*, 6: 150, 2019.
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