Pattern formation during social contagions: epidemics, infodemics and civil unrest

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THE UNIVERSITY OF SYDNEY

Conference on “Dynamics of biological systems: emergent phenomena at different scales”
Jagiellonian University, 3 December 2023

Outline

- Epidemic modelling: preliminaries
- Pattern formation during social dynamics
- Phase transitions and Fisher information
- Tipping points during the COVID-19 pandemic

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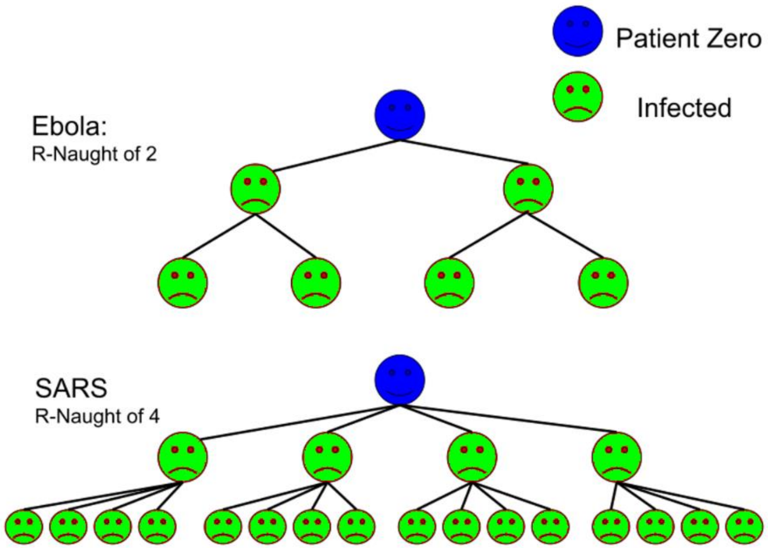
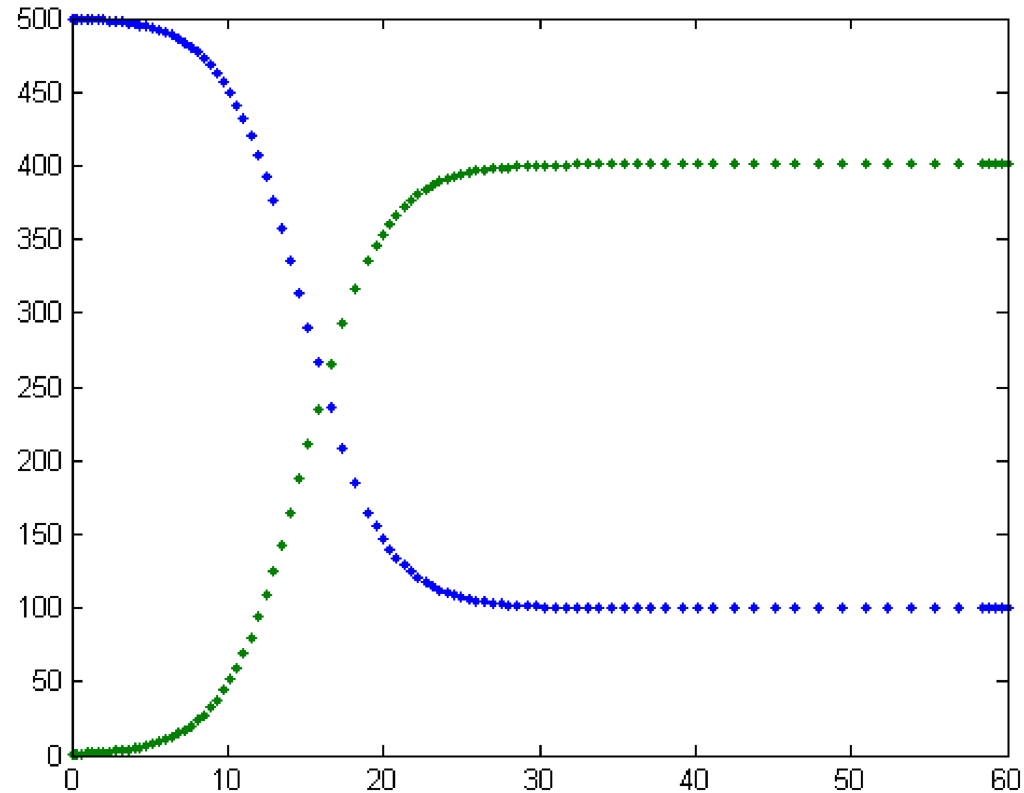
Epidemic modelling

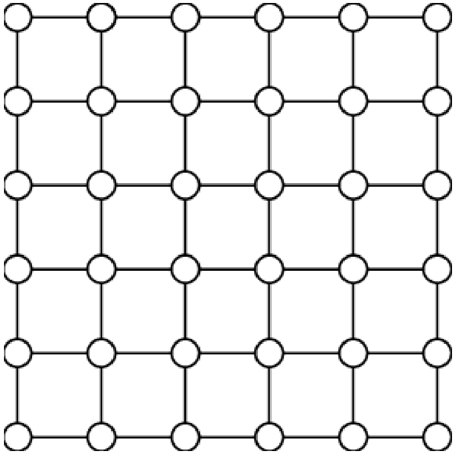


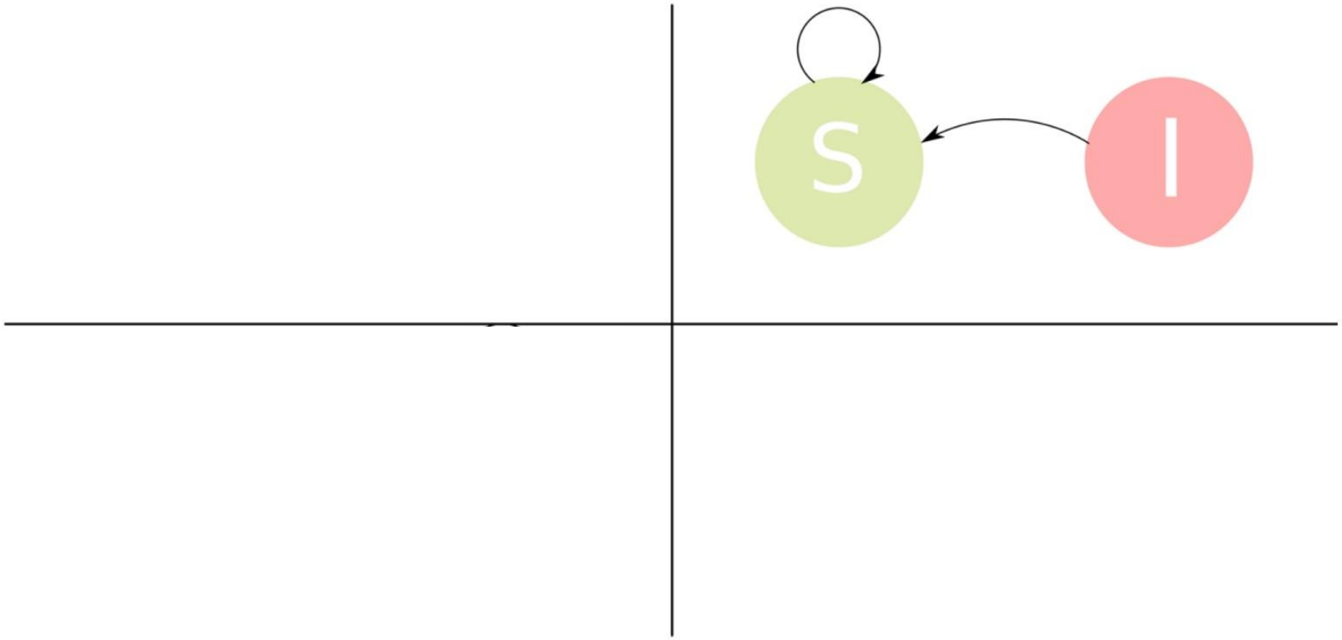
$$\left.\begin{aligned}\frac{\mathrm{d}S}{\mathrm{d}t} &= \gamma I - \beta I S \\[2em] \frac{\mathrm{d}I}{\mathrm{d}t} &= \beta I S - \gamma I,\end{aligned}\right\} \beta / \gamma = R_0$$

SIS: Susceptible - Infectious - Susceptible



Social contagions: four types of dynamics





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

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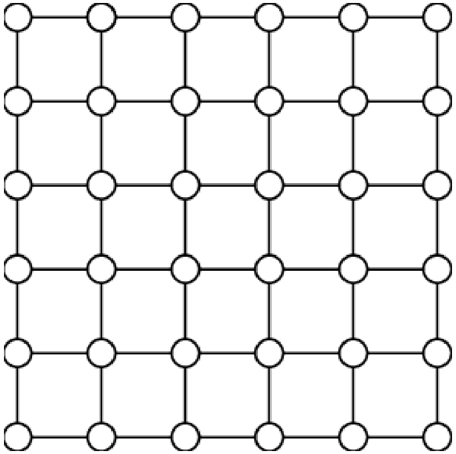

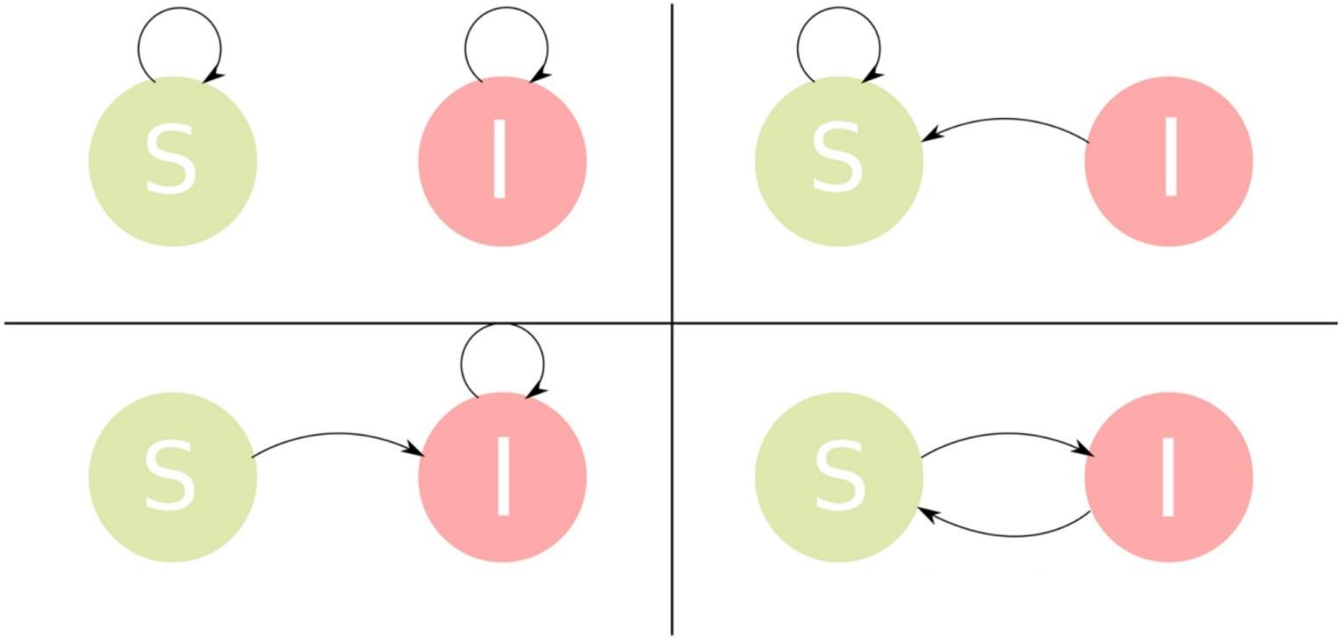

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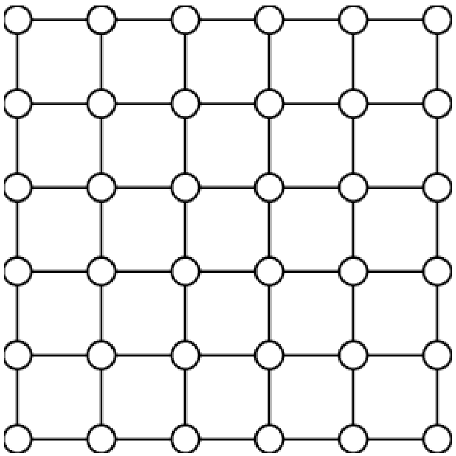
Dynamic meta-population epidemic (SIS) model



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

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

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

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

constraints

vs

control parameters

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

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

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

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

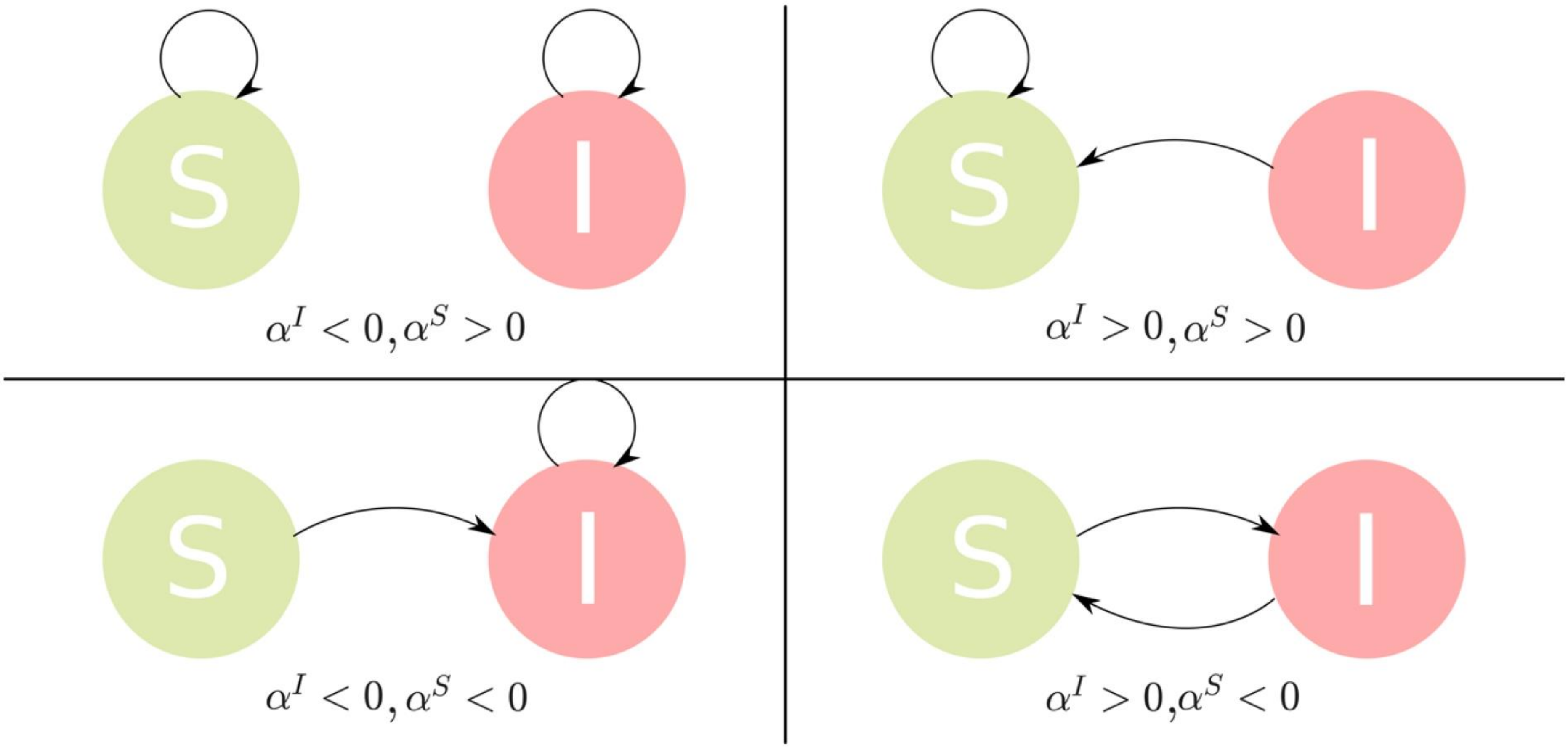
$$H_Y = -\sum_y p_Y(y) \ln p_Y(y)$$

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

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

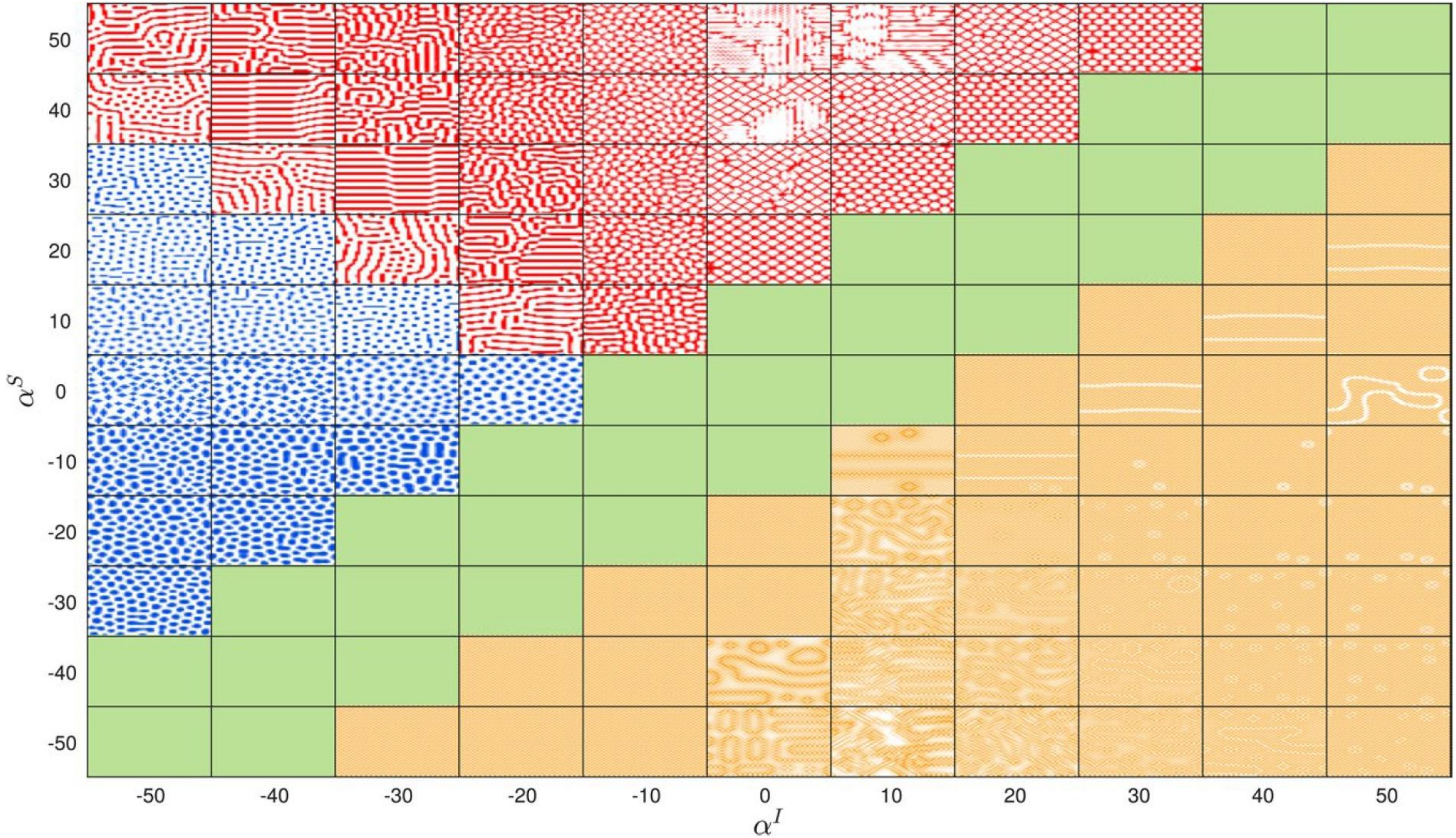
Bounded rationality: four types of dynamics

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

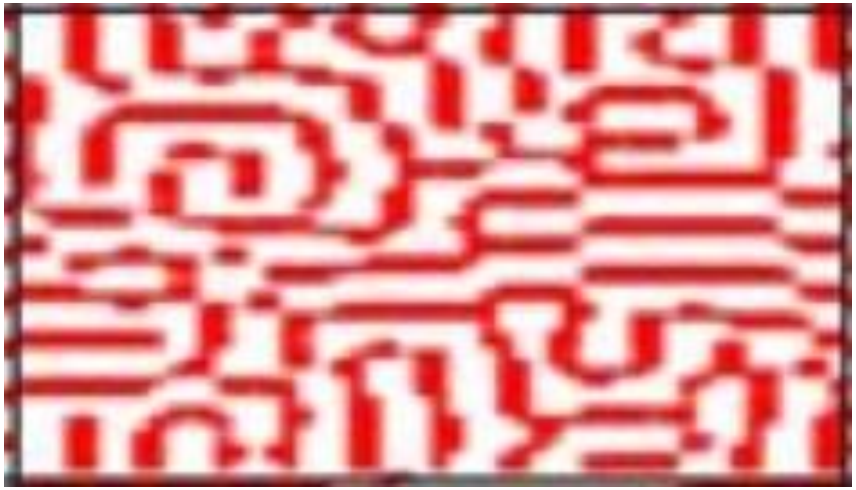


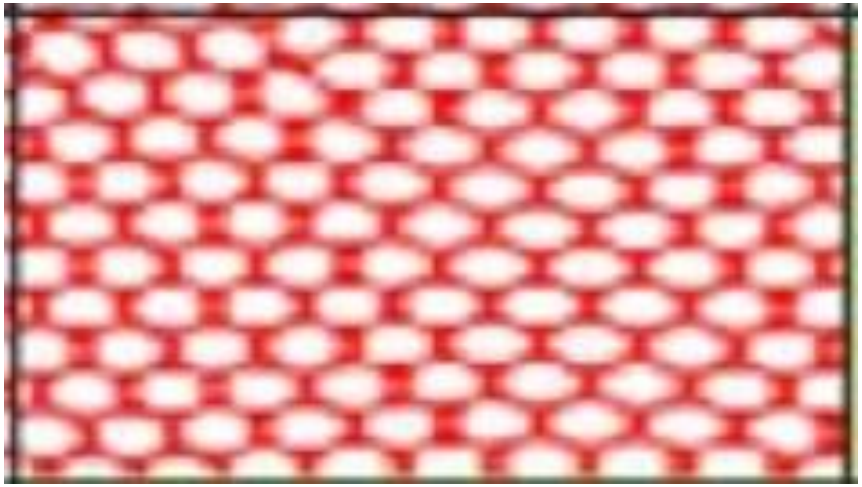
Behaviour-induced spatial morphology

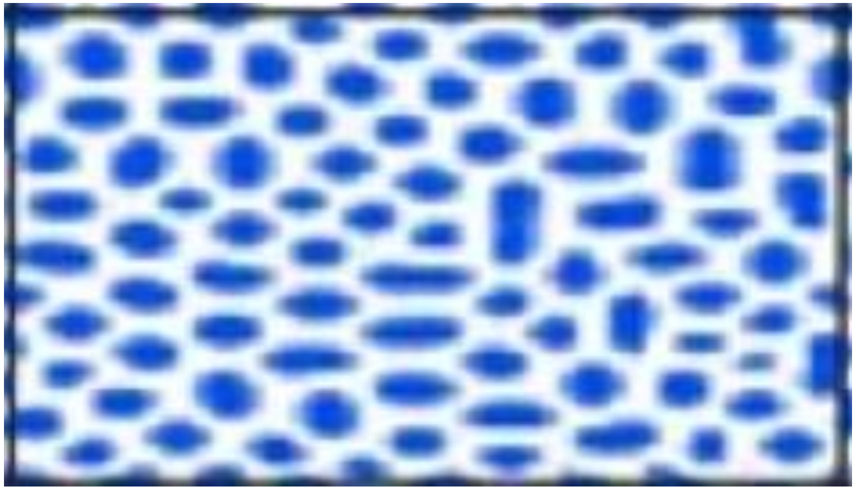
$$\phi_{ij}^{x}(\mathbf{I}, \mathbf{C}|\alpha^{x}, \omega) = Z_{x,i}^{-1}\exp\left(\alpha^{x} b_j - \omega c_{ij}\right)$$



Patterns: spots, labyrinth, gaps, checkerboard

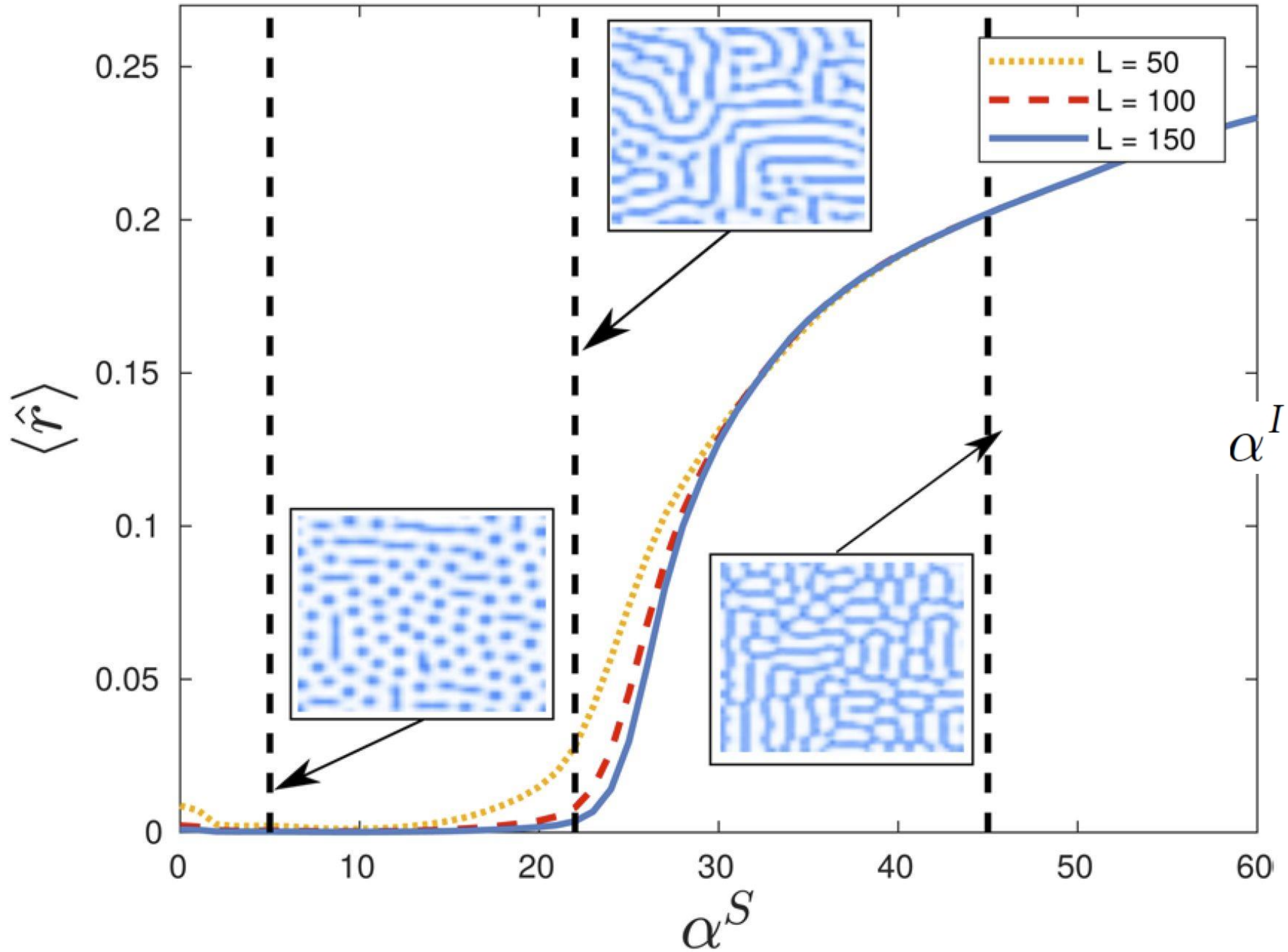






Spatial morphology: critical regimes

average cluster size



$\alpha^I = -27.5$

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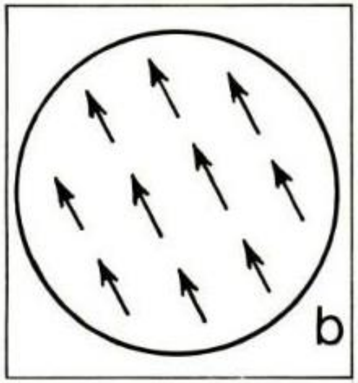
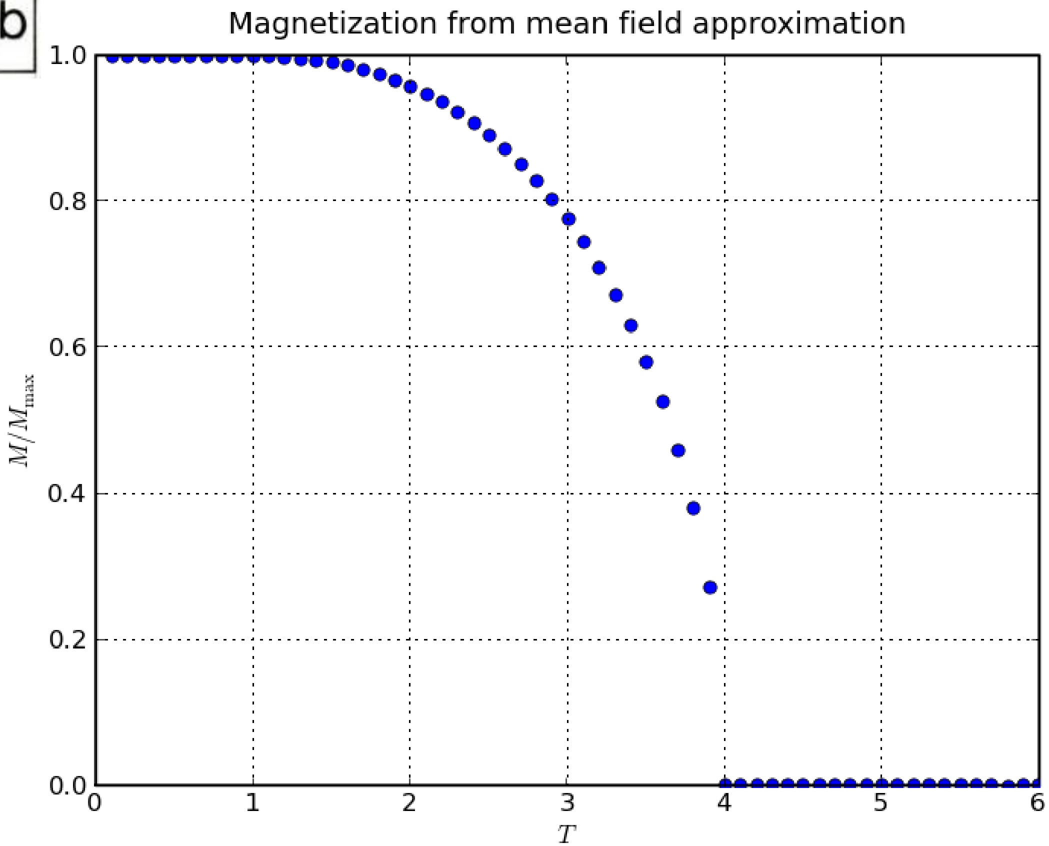
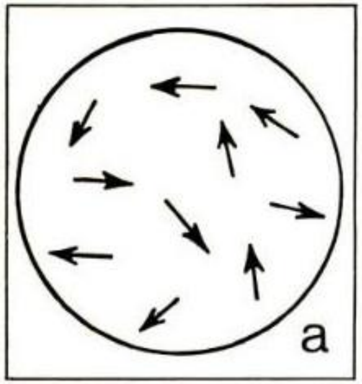
Phase transitions and order parameters



anisotropic
“coherent”

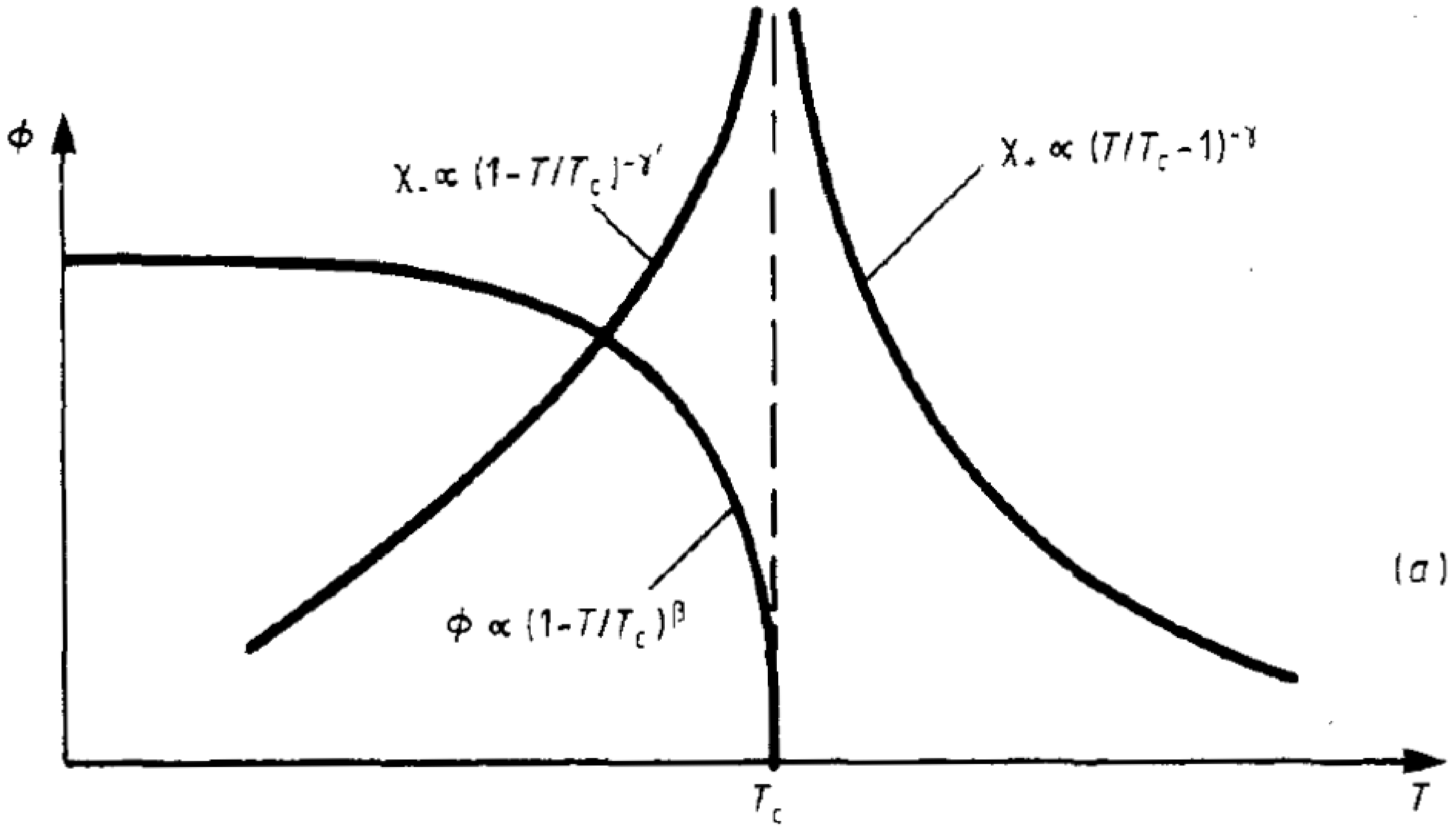




isotropic
“disordered”

Derivative of order parameter (divergence)

K Binder **(1987)**



Fisher Information and sensitivity

A way of measuring the amount of information that an observable random variable X has about an unknown parameter θ

$$F(\theta) = \int_x \left(\frac{\partial \ln(p(x|\theta))}{\partial \theta} \right)^2 p(x|\theta)dx$$

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Fisher Information and sensitivity

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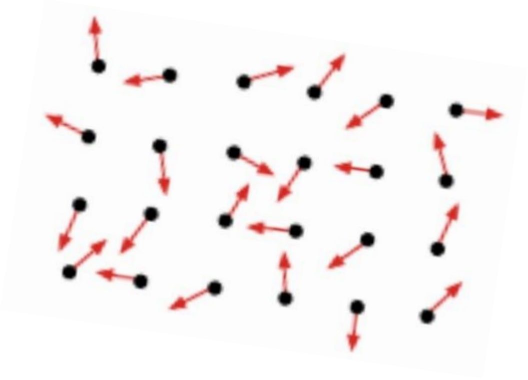

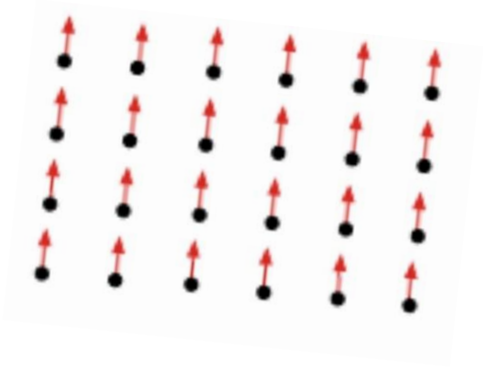

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Fisher Information and order parameters

$$G(T,\theta_i) = U(S,\phi_i) - TS - \phi_i\theta_i$$

$$\boxed{F_{ij}(\theta) = \beta \frac{\partial \phi_i}{\partial \theta_j}}$$

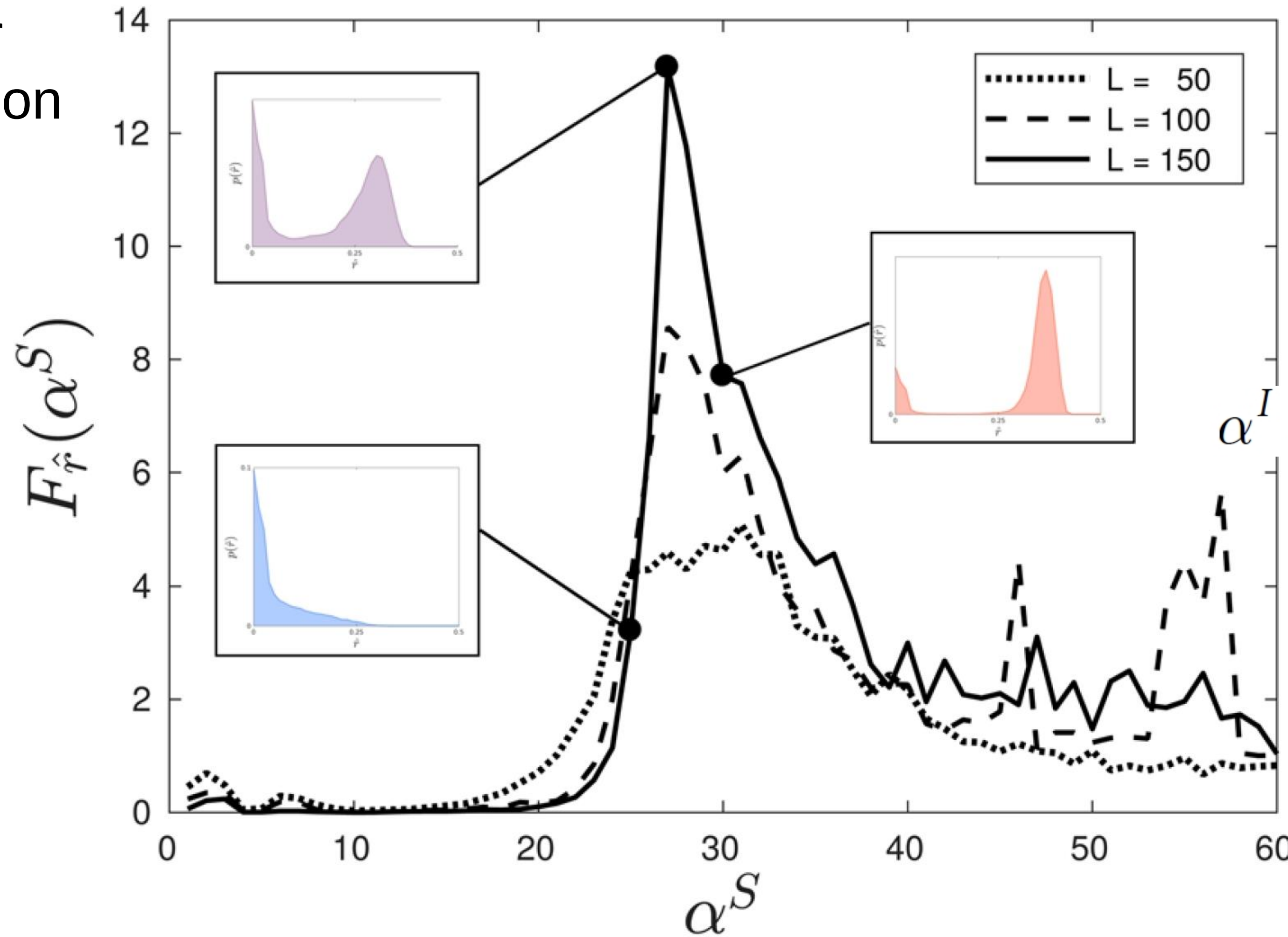
Fisher information matrix

Rate of change of the order parameter

M. Prokopenko, J. T. Lizier, O. Obst, X. R. Wang, Relating Fisher information to order parameters, *Physical Review E*, 84, 041116, 2011.

Spatial morphology: Fisher information

Fisher information



$\alpha^I = -27.5$

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Population partitions: residential areas and destination zones

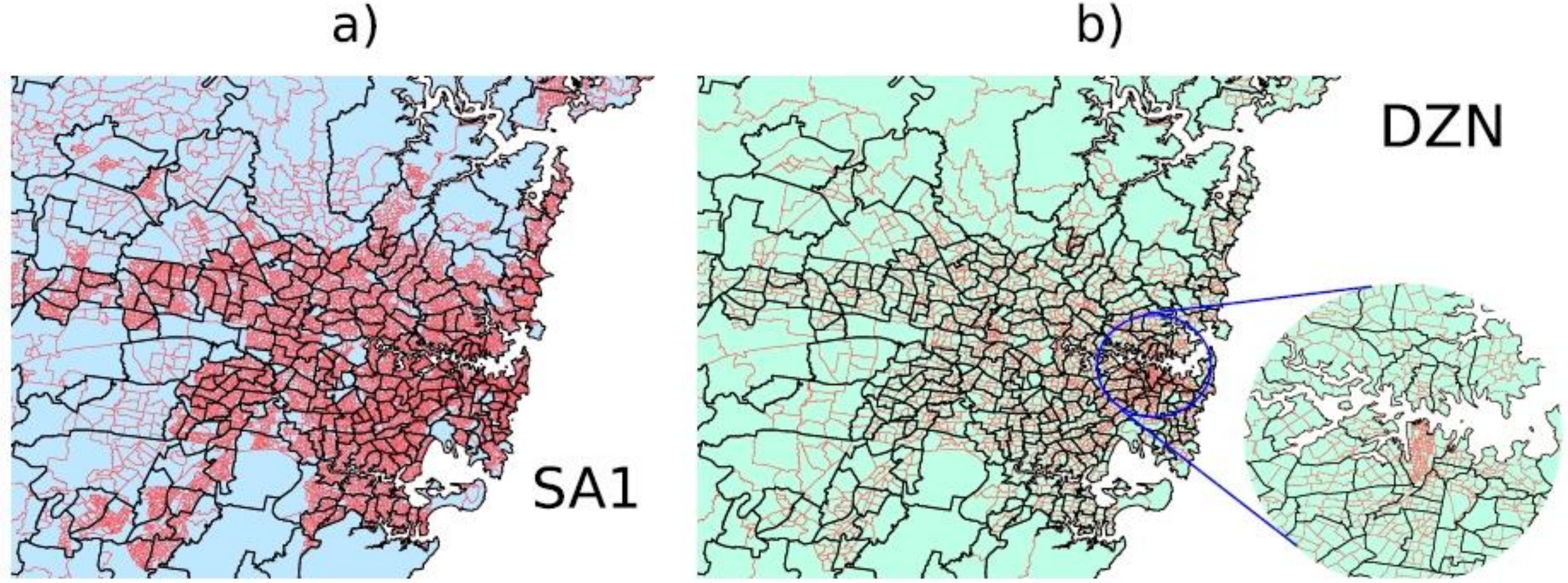
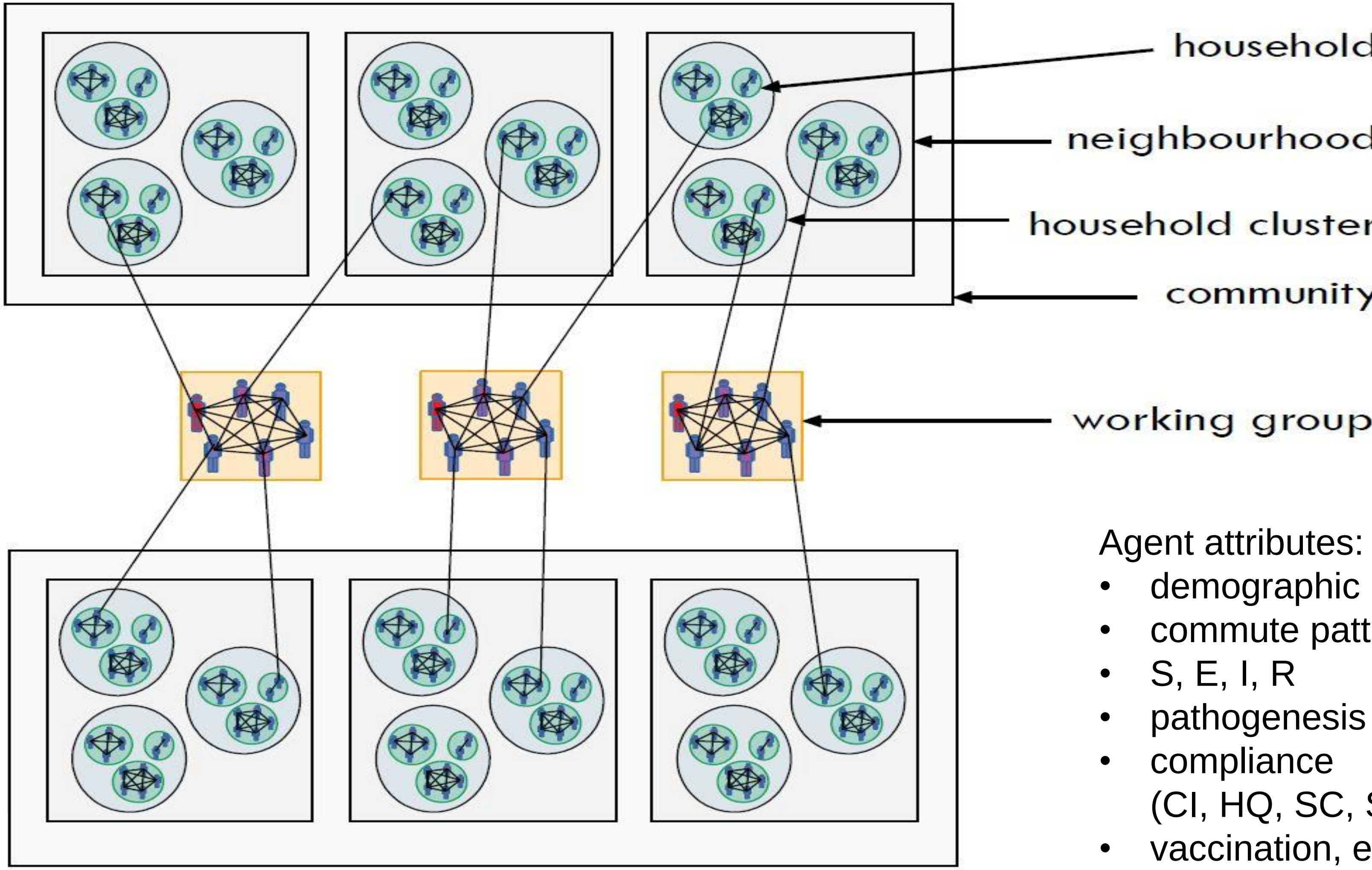


Fig. 1 Maps of the Greater Sydney region illustrating the distribution of population partitions. (a) A map of the Greater Sydney region showing SA2 (black) and SA1 (red) population partitions. (b) A map of the same area showing SA2 (black) and DZN (red) partitions. The inset in (b) zooms in on the Sydney 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.

"Same storm, different boats"



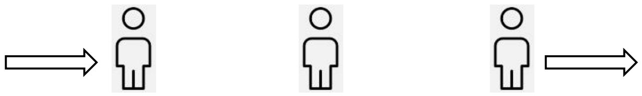
Agent attributes:

- 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.

Features of our ABM (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

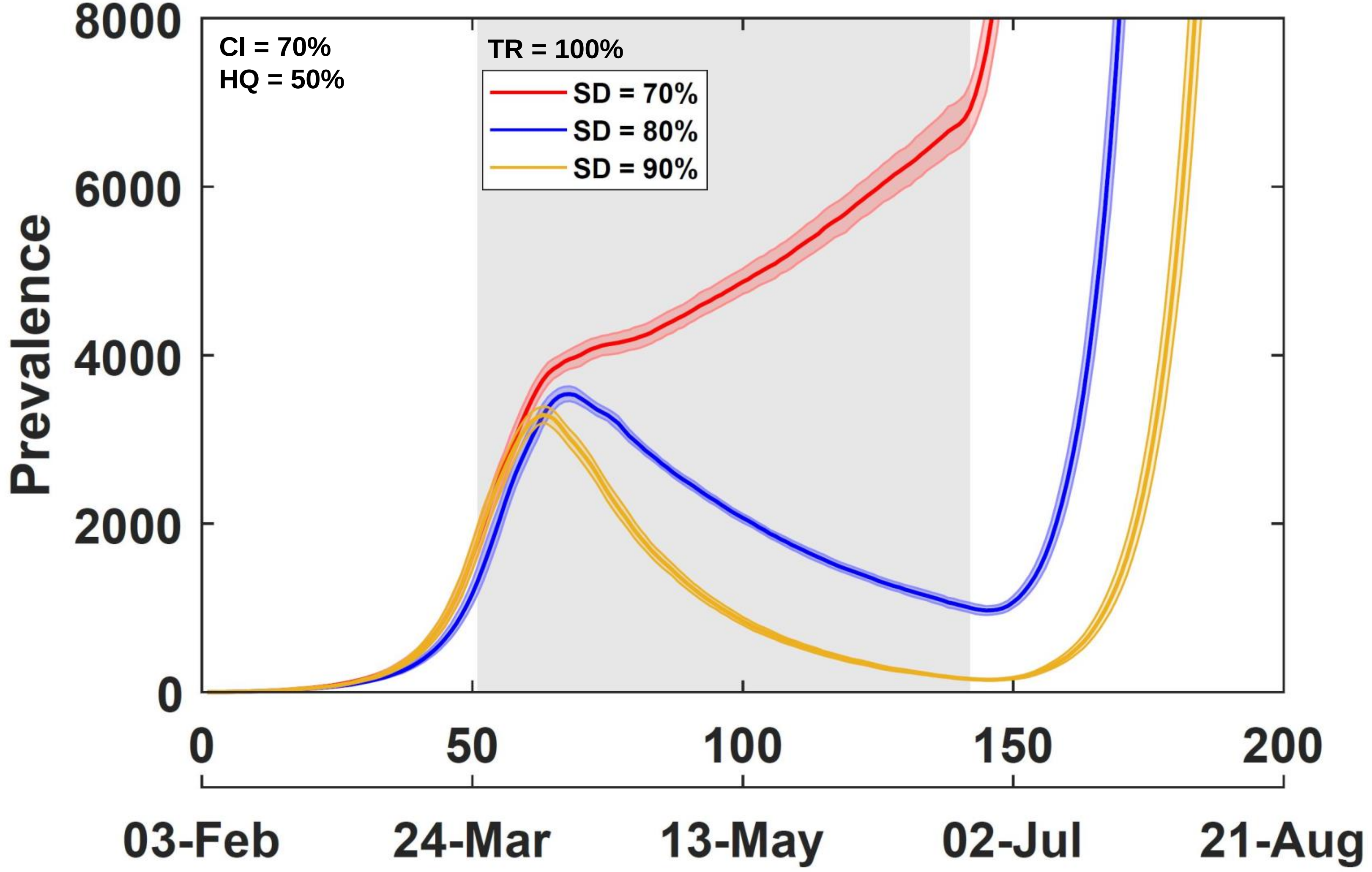


- vaccine efficacy split across components (infection, symptoms, transmission)
- varying compliance with lockdown ("stay-at-home" restrictions)

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.

Tipping point in compliance with lockdown



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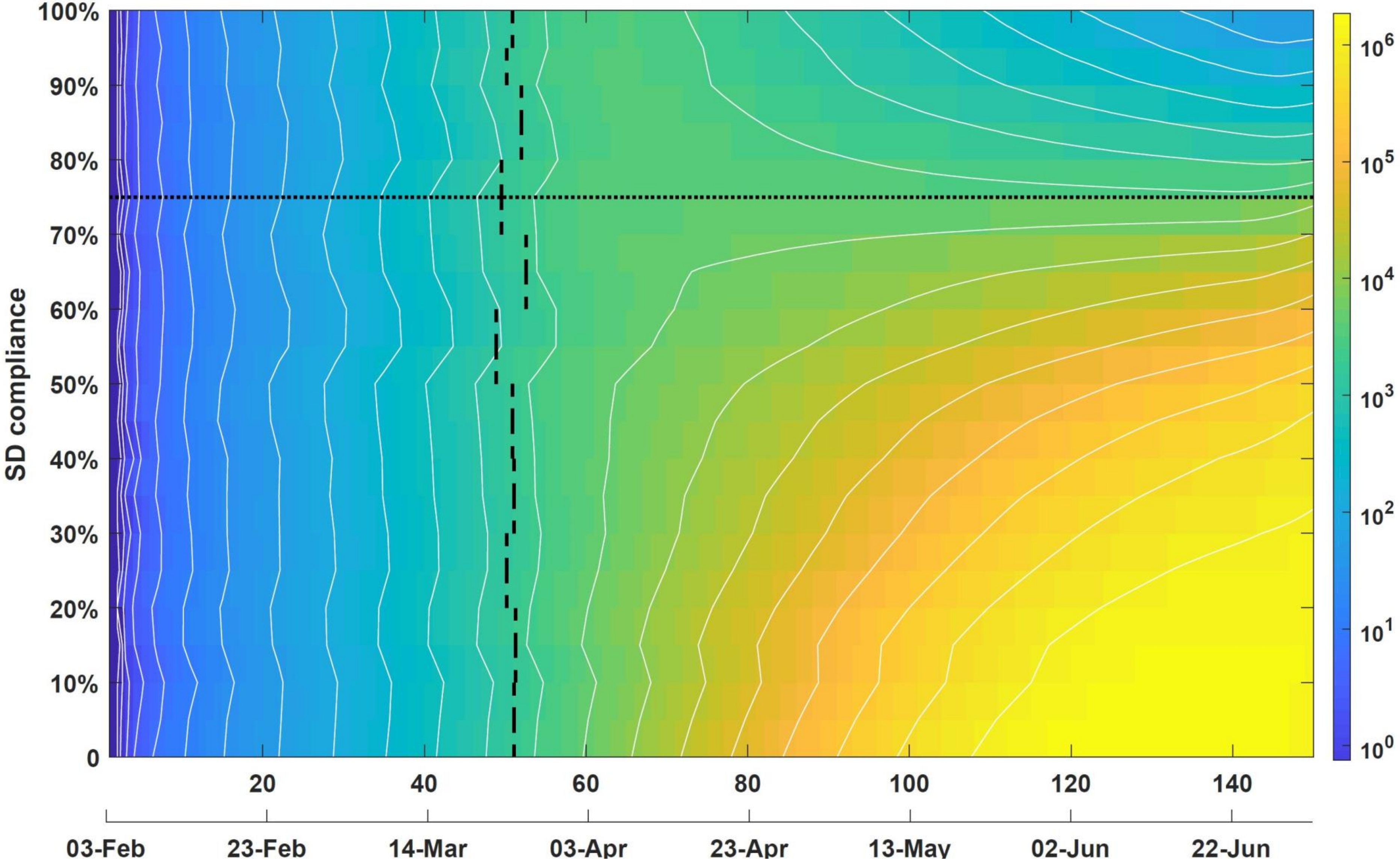
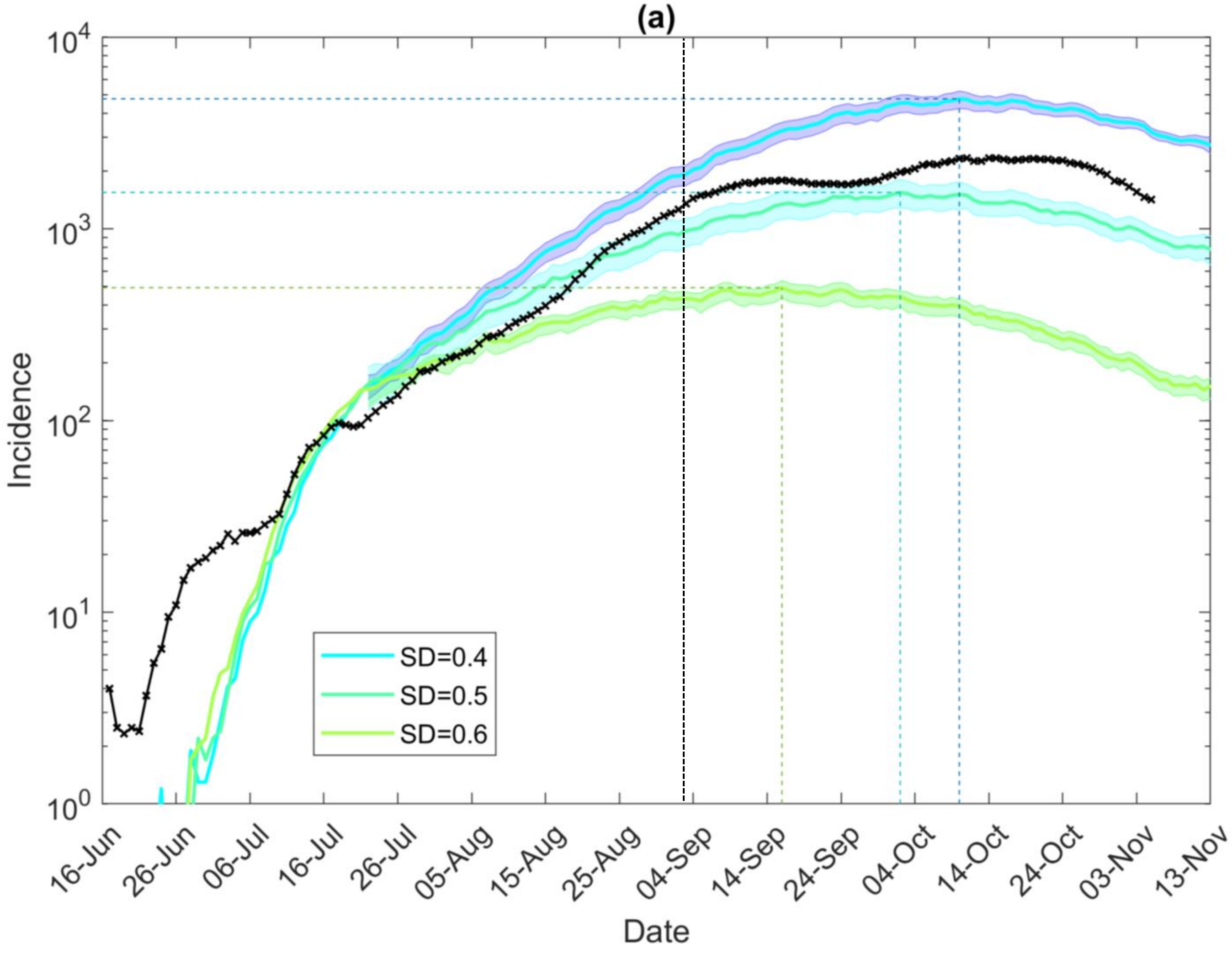
Tipping point (phase transition) in compliance



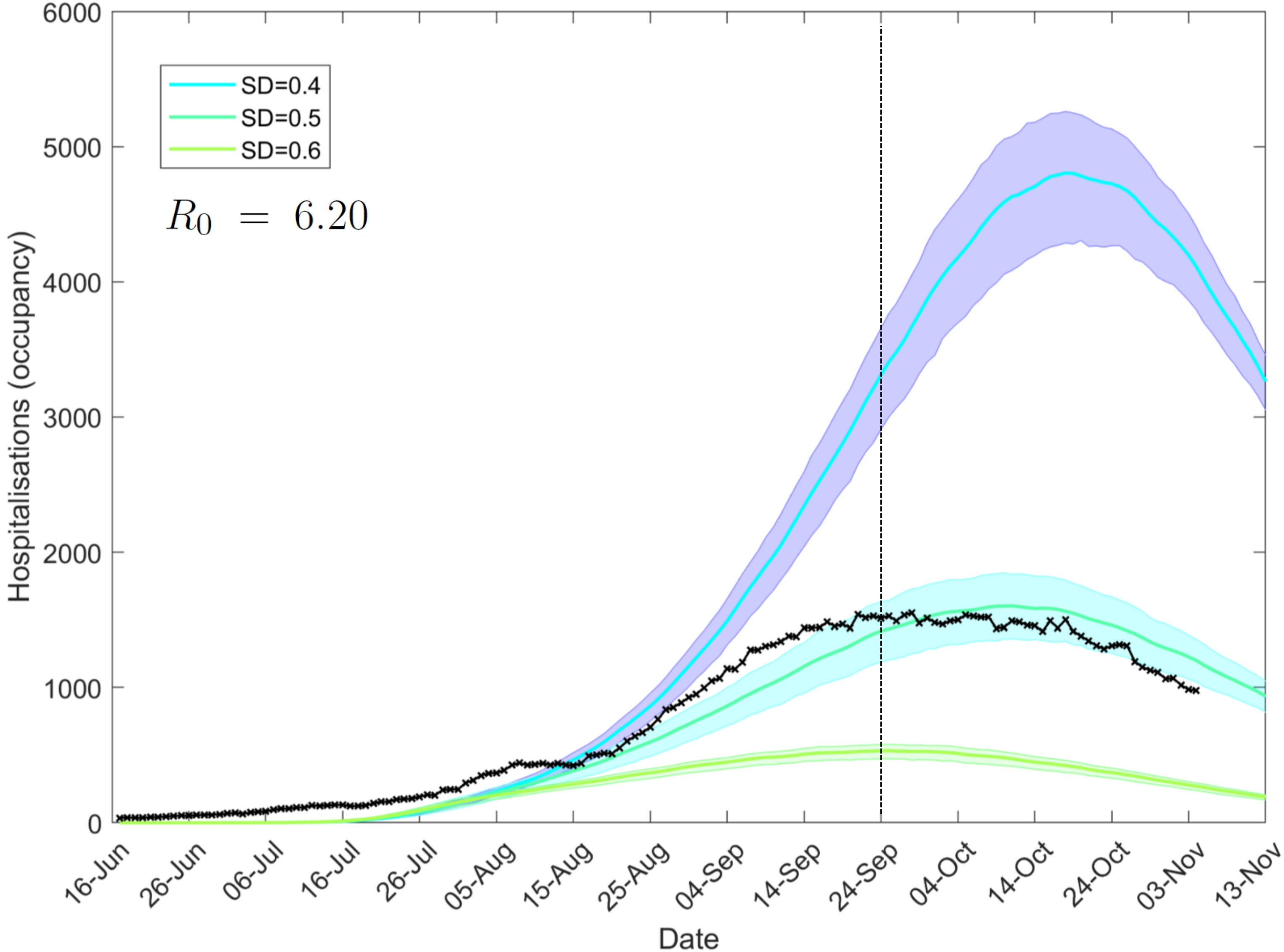
The Delta variant: SD compliance scenarios (25 August → 5 November 2021)

$R_0 = 6.20$

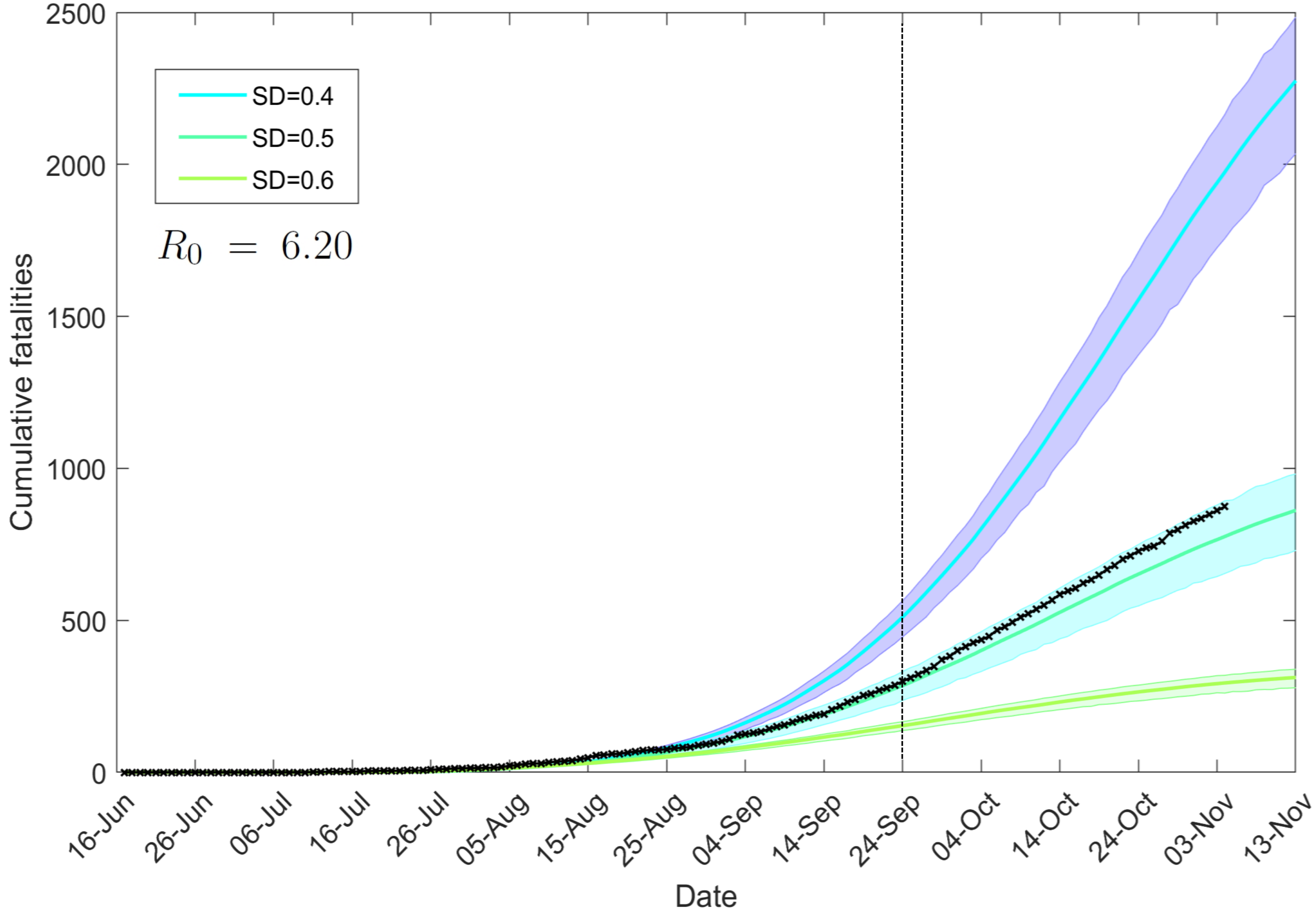


S. L. Chang, O. M. Cliff, C. Zachreson, M. Prokopenko, Simulating Transmission Scenarios of the Delta Variant of SARS-CoV-2 in Australia, *Frontiers in Public Health,* 10, 10.3389/fpubh.2022.823043, 2022.

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



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



Behaviour-induced critical regimes

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

- tipping points in pandemic response:
  compliance with lockdown orders

- amplification effects of NPIs on disease burden:
  compliance with lockdown orders

References

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