Integrating Spatial Resolution and Mobility Patterns in Models for Infectious Disease Dynamics

Martin J. Kühn
joint work with many others (see first slide)

Stakeholders’ meeting for the R2M2P2 Consortium

Utrecht, The Netherlands, 2025/05/16

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Das Startkapital für die Mobilität 4.0

GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung

HELMHOLTZ

DFG

UNIVERSITÄT BONN

DLR

The Team

Thanks to / joint work with:
Daniel Abele, Henrik Zunker, Julia Bicker, Sascha Korf, Anna Wendler, René Schmieding, Lena Plötzke, Patrick Lenz, Maximilian Betz, Carlotta Gerstein, Kilian Volmer, Hannah Tritzschak, Agatha Schmidt, Nils Waßmuth, Paul Johannssen, Julian Litz, Daniel Richter, Elisabeth Kluth…

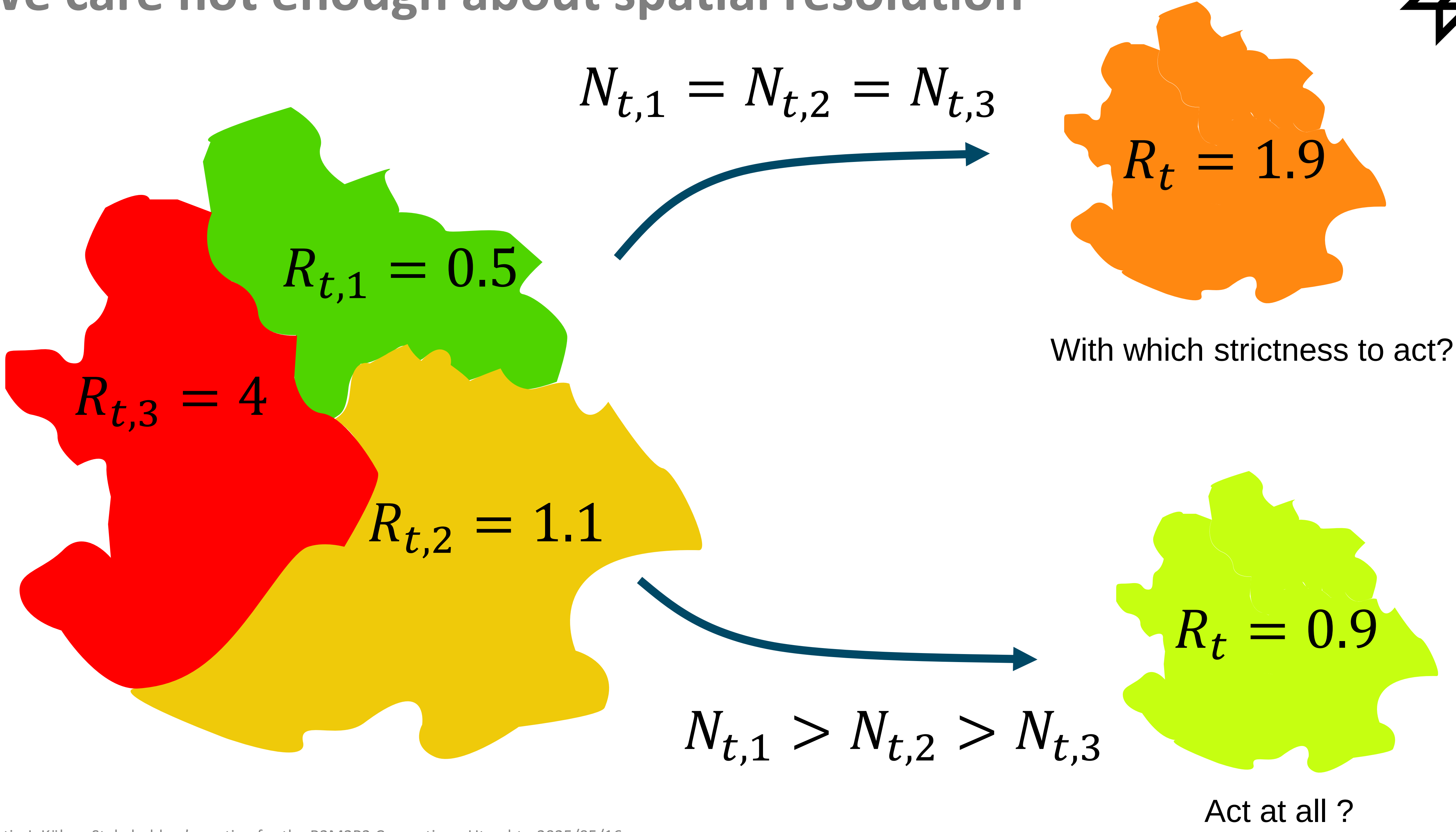
and

David Kerkmann, Khoa Nguyen, Ralf Hannemann-Tamas, Wadim Koslow, Margrit Klitz, Achim Basermann, Sebastian Binder, Martin Siggel, Jan Kleinert, Kathrin Rack, Annette Lutz, Michael Meyer-Hermann, Jan Hasenauer, Alexander Heinlein...

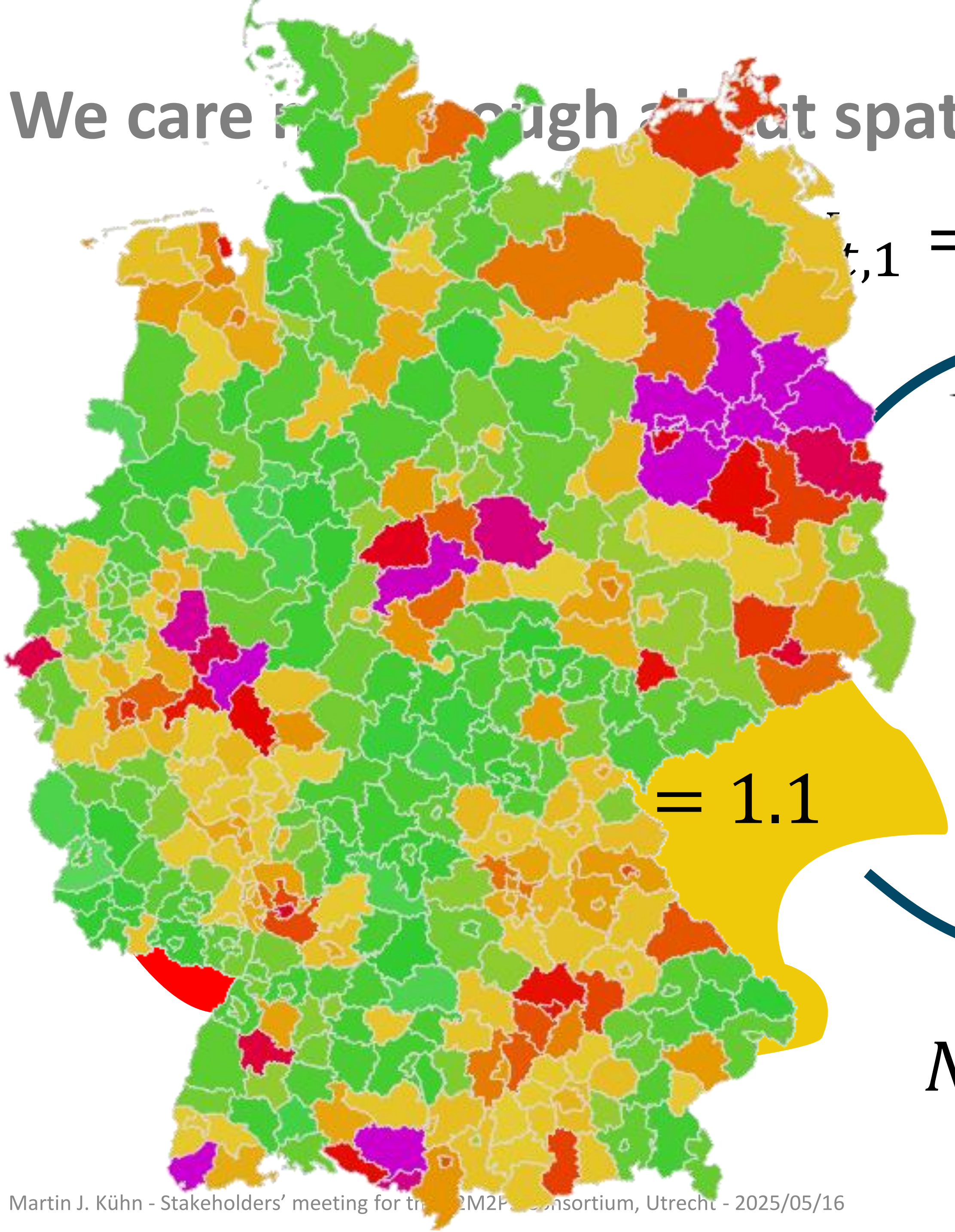
Institute of Software Technology, Department High-Performance Computing, **Predictive Simulation Software**

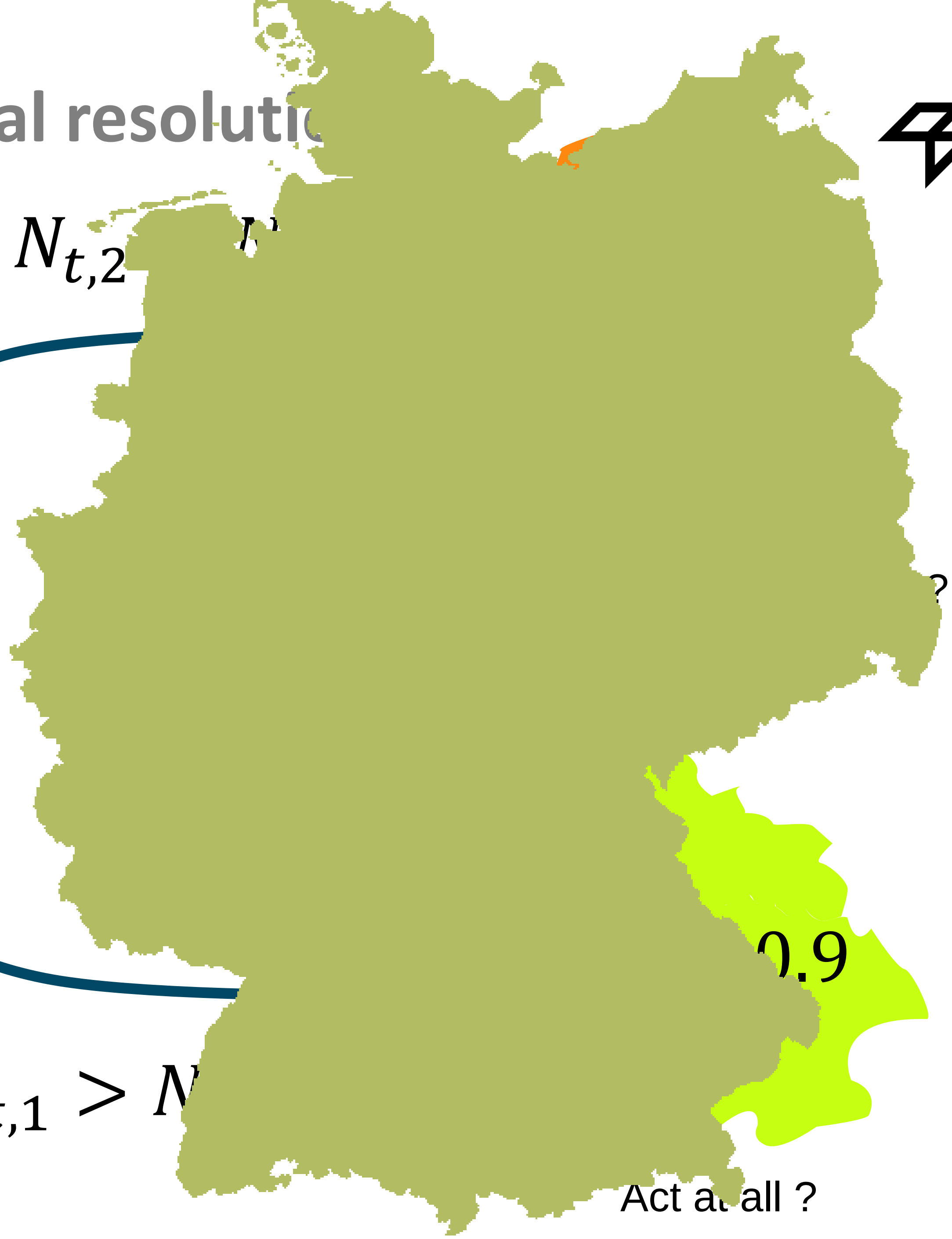
Life and Medical Sciences Institute and Bonn Center for Mathematical Life Sciences, **Mathematical-Epidemiological Modeling**

We care not enough about spatial resolution



We care r… ugh a… ut spatial resolutio…





$\ldots_{t,1} = N_{t,2}$

?

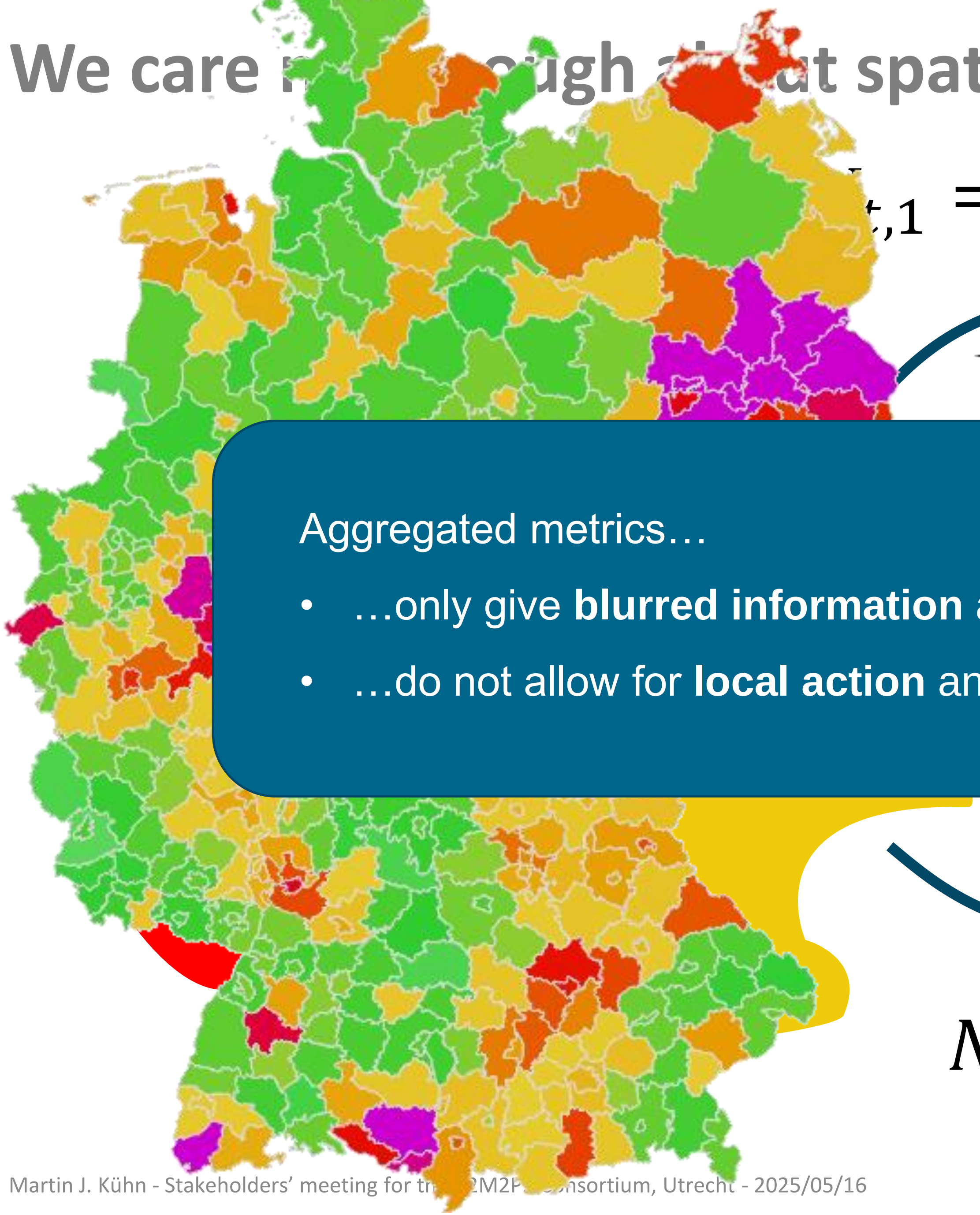
$= 1.1$

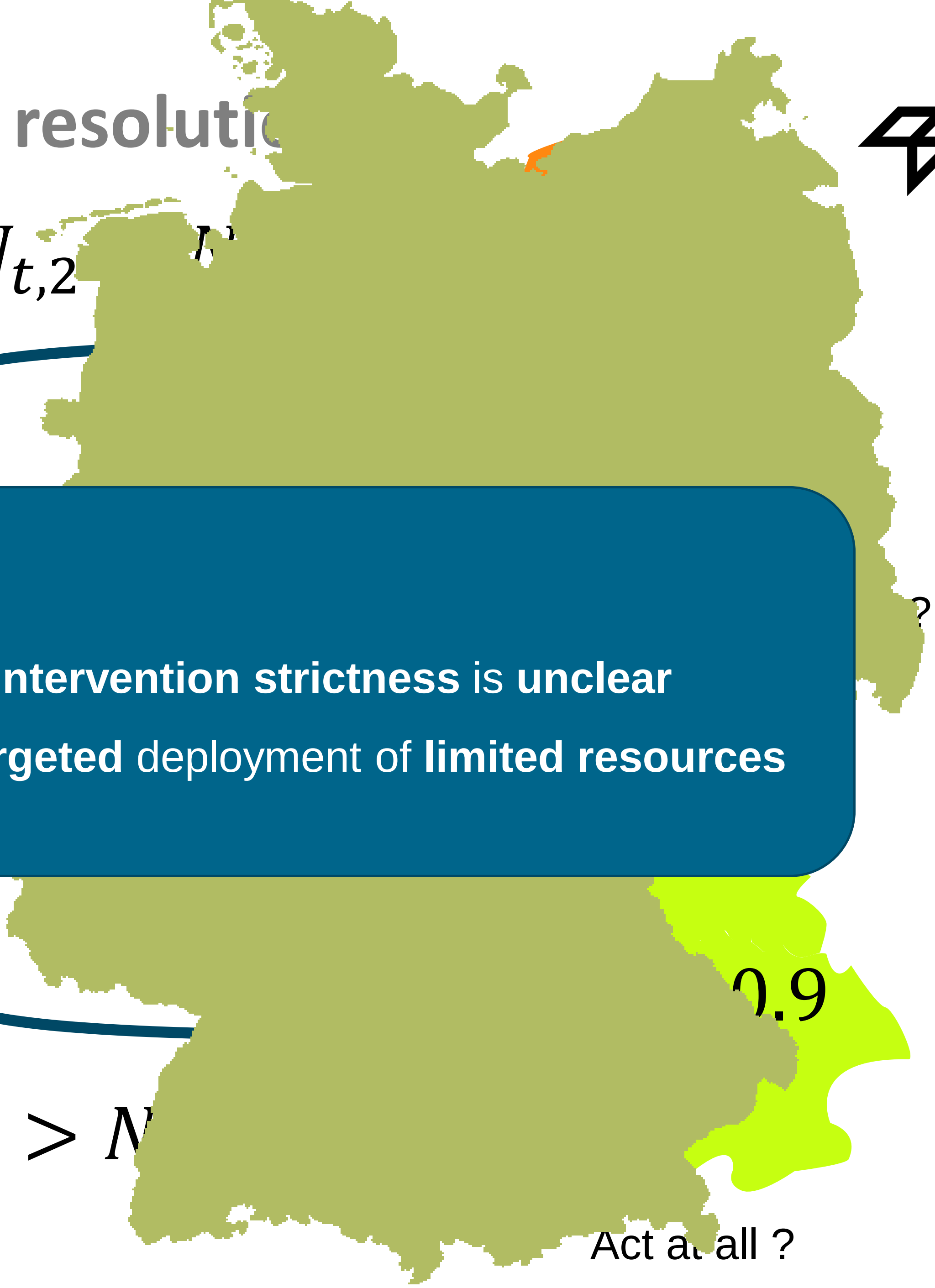
0.9

$N_{t,1} > N\ldots$

Act at all ?

We care … ough a… t spatial resoluti…





$N_{t,1} = N_{t,2}$ …

?

0.9

$N_{t,1} > N$…

Act a… all ?

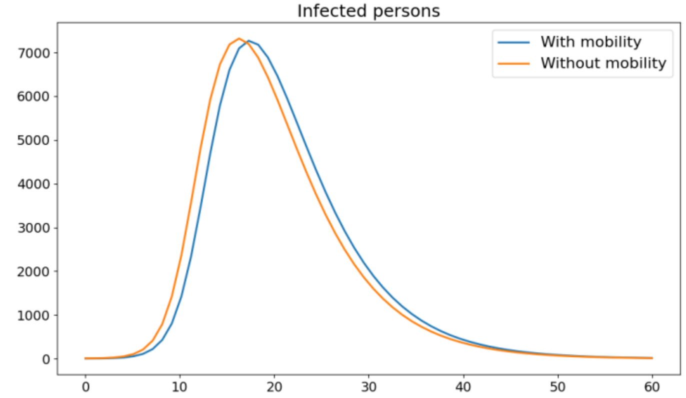
Aggregated metrics…

- …only give **blurred information** and **intervention strictness** is **unclear**
- …do not allow for **local action** and **targeted** deployment of **limited resources**

Missing out spatial resolution: Reasons and chances

ODE*-SIR-type models are too easy to implement…

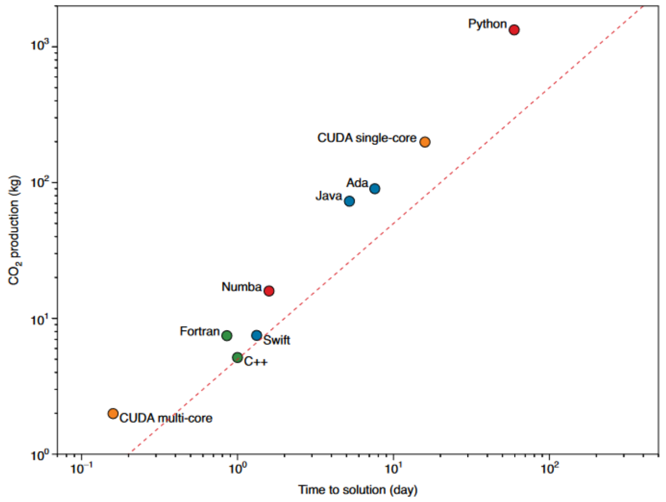
- „in the end, it will arrive anyway…“



→ If it looks like that, you do not use the degrees of freedom and power in spatially resolved models

- „you cannot do metapopulation models in a small time frame“

→ Do large-scale models in an efficient and scalable language (not R, not python…)



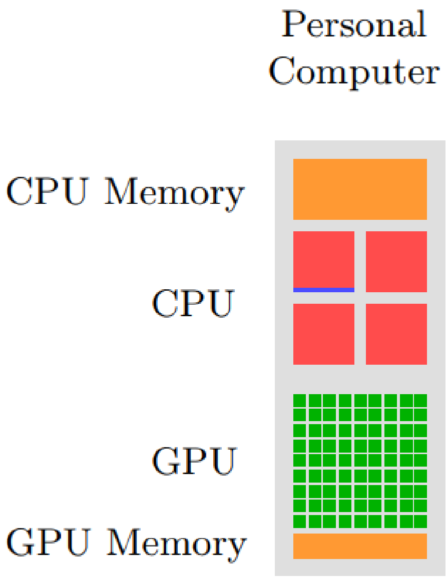
Portegies Zwart, Nature Astronomy (2020)

	Time
(c) C	1.00
(c) Rust	1.04
(c) C++	1.56
(c) Ada	1.85
(v) Java	1.89
(c) Chapel	2.14
(c) Go	2.83
(c) Pascal	3.02
(c) Ocaml	3.09
(v) C#	3.14
(v) Lisp	3.40
(c) Haskell	3.55
(c) Swift	4.20
(c) Fortran	4.20
(v) F#	6.30
(i) JavaScript	6.52
(i) Dart	6.67
(v) Racket	11.27
(i) Hack	26.99
(i) PHP	27.64
(v) Erlang	36.71
(i) Jruby	43.44
(i) TypeScript	46.20
(i) Ruby	59.34
(i) Perl	65.79
(i) Python	71.90
(i) Lua	82.91

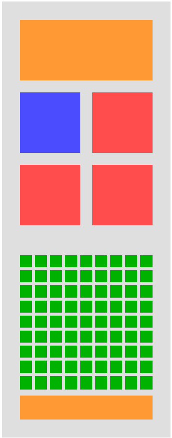
Pereira et al., SLE’17 (2017)

* ODE: Ordinary differential equations

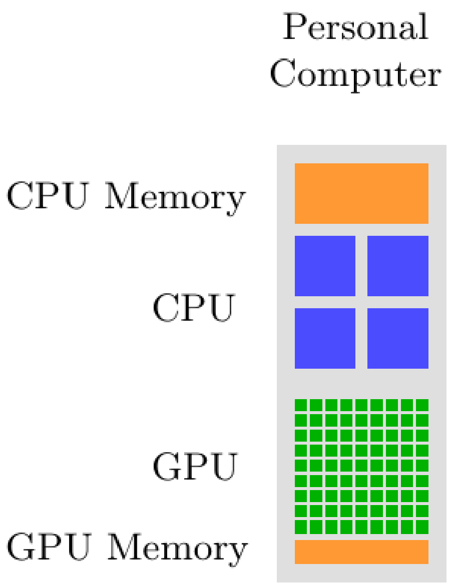
Missing out spatial resolution: Reasons and chances



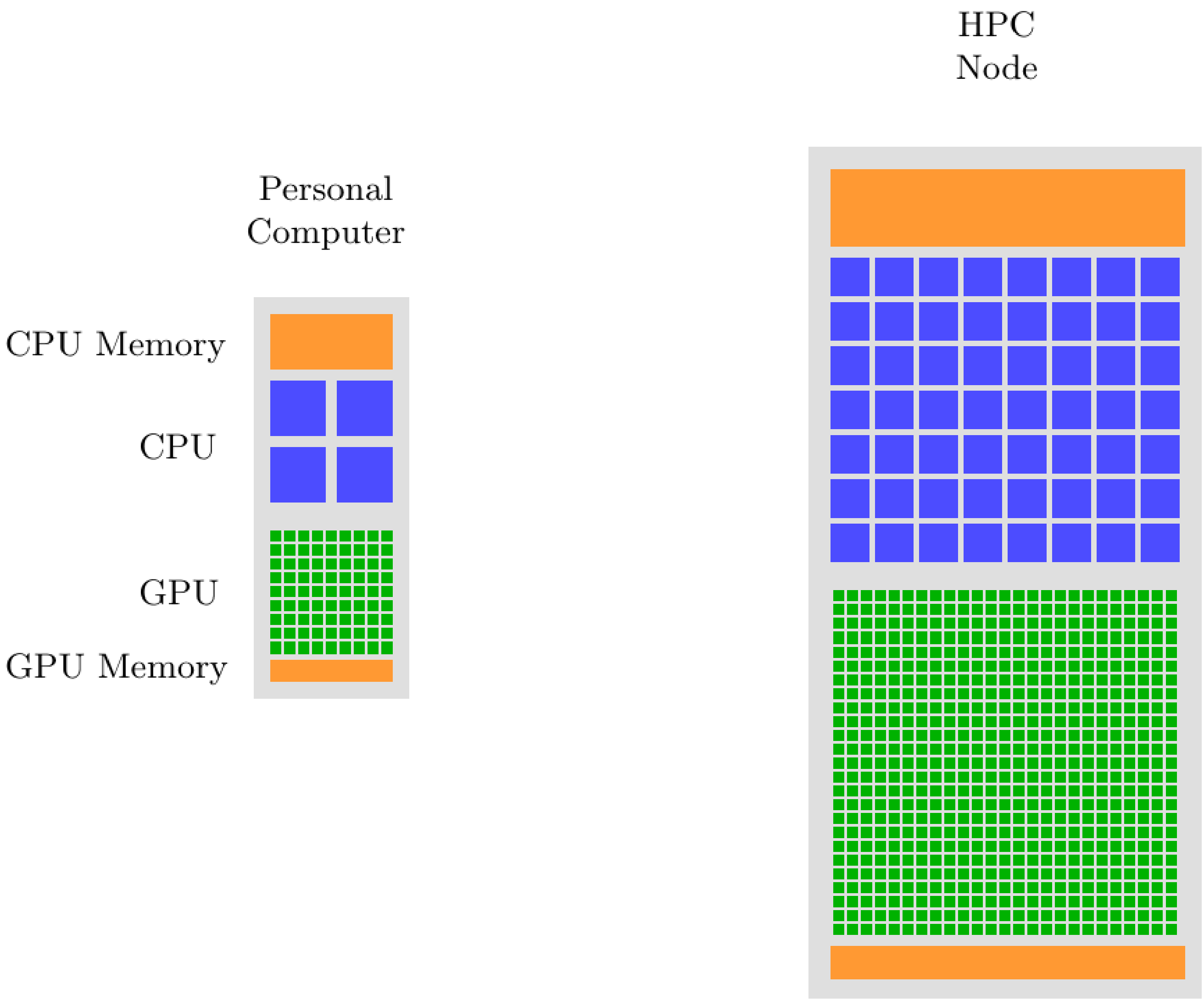
Missing out spatial resolution: Reasons and chances



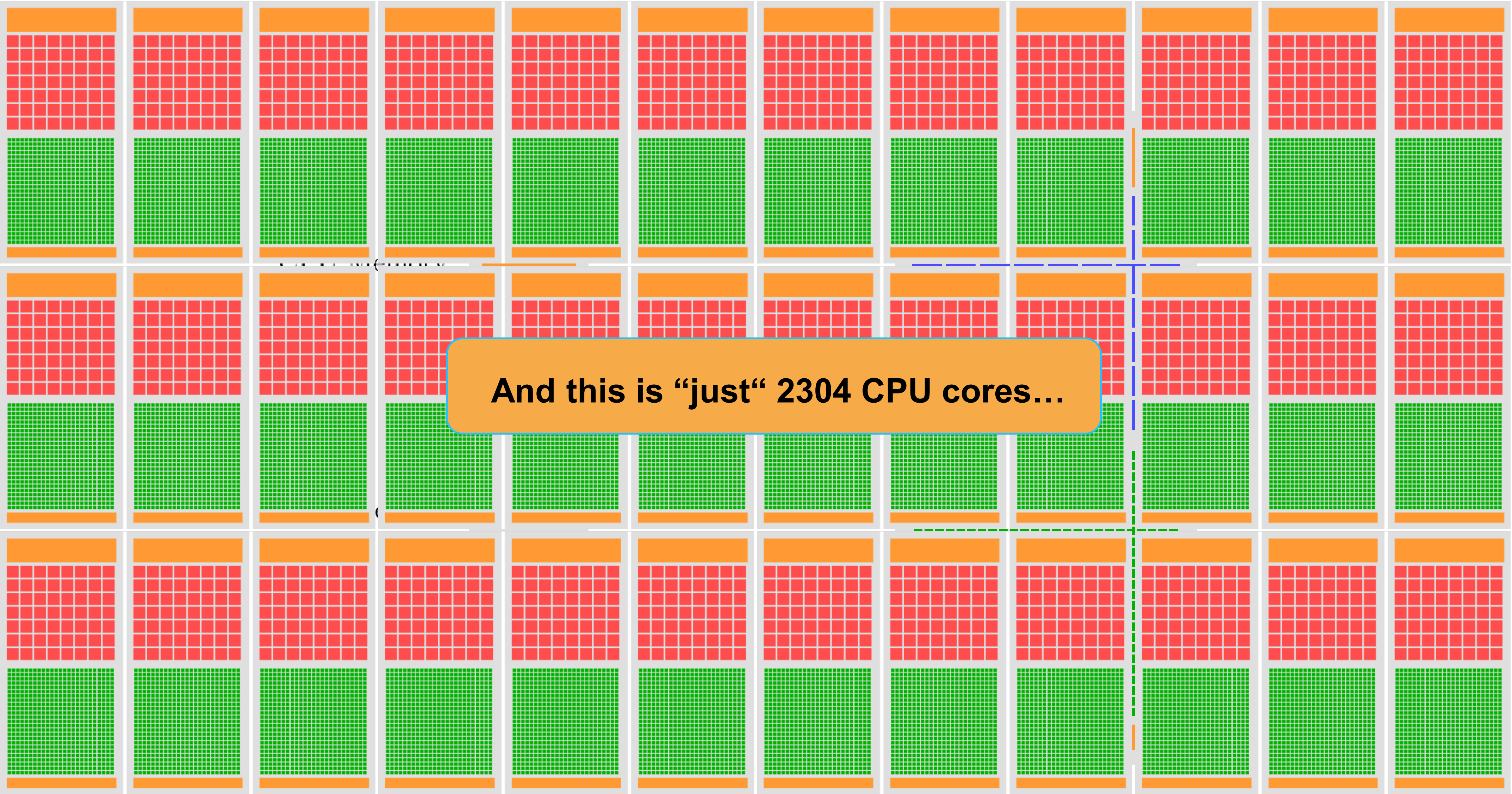
Missing out spatial resolution: Reasons and chances



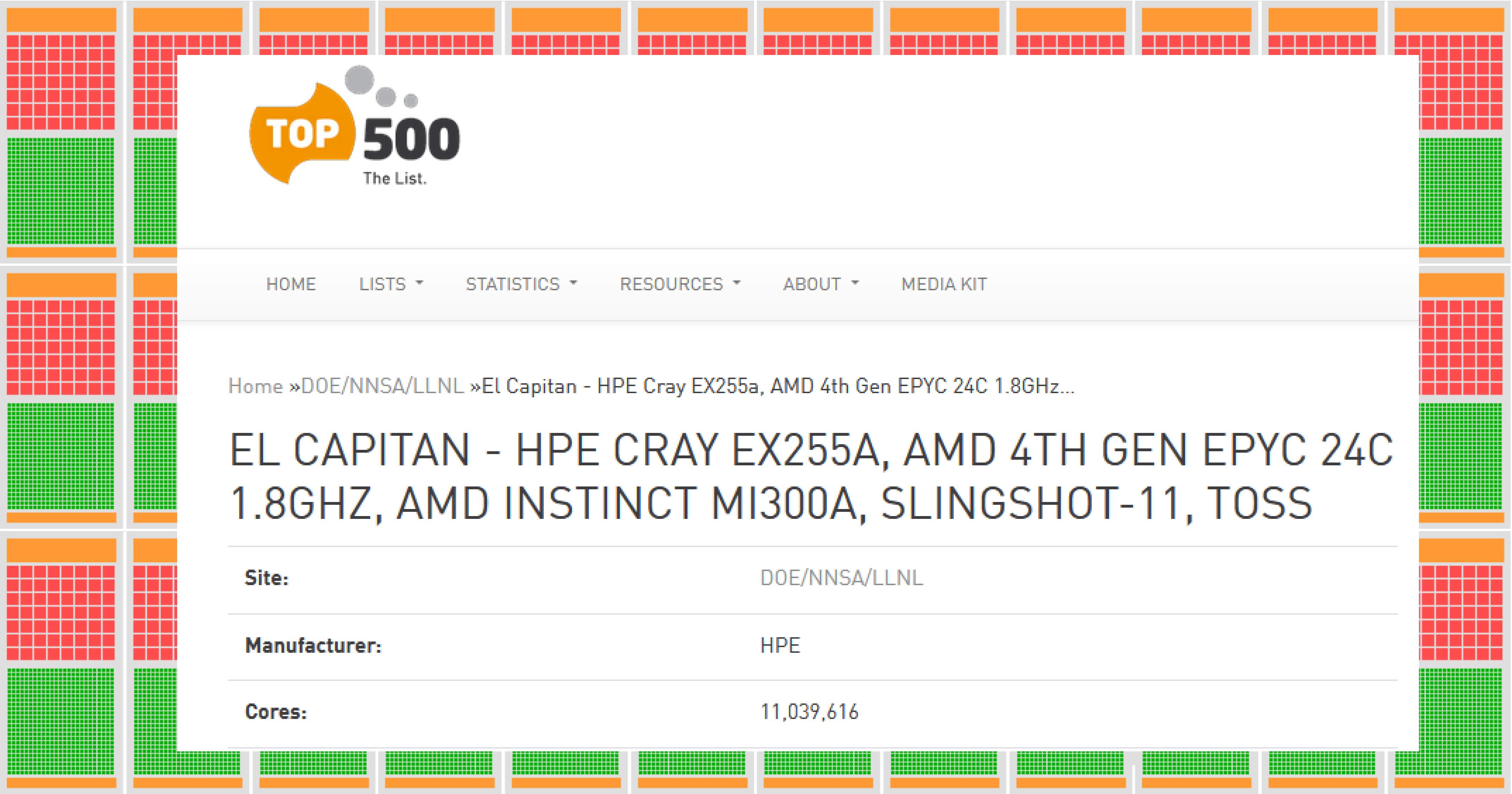
Missing out spatial resolution: Reasons and chances



Missing out spatial resolution: Reasons and chances



Missing out spatial resolution: Reasons and chances



TOP 500 The List.

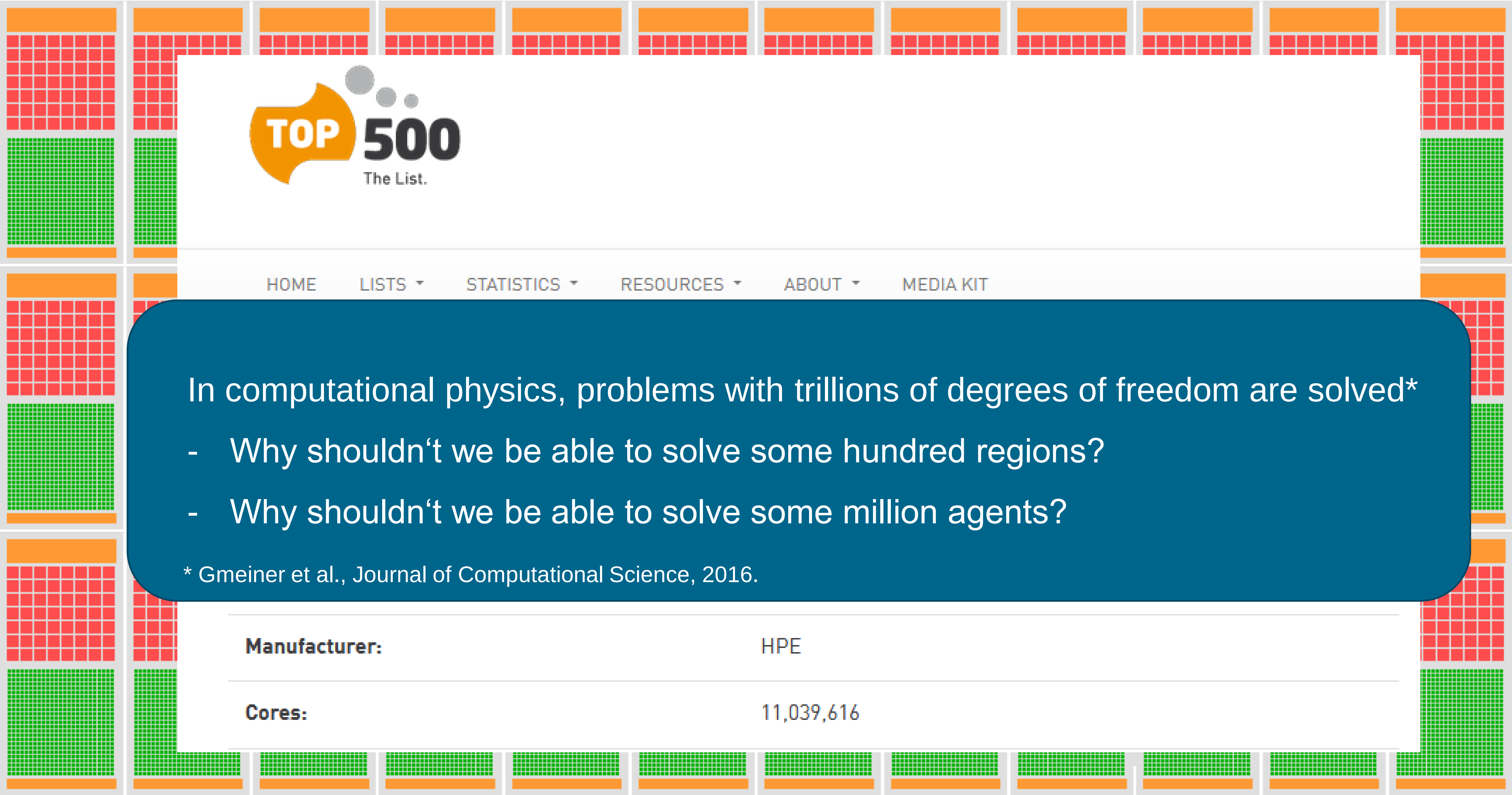
HOME LISTS STATISTICS RESOURCES ABOUT MEDIA KIT

Home »DOE/NNSA/LLNL »El Capitan - HPE Cray EX255a, AMD 4th Gen EPYC 24C 1.8GHz...

EL CAPITAN - HPE CRAY EX255A, AMD 4TH GEN EPYC 24C 1.8GHZ, AMD INSTINCT MI300A, SLINGSHOT-11, TOSS

Site:	DOE/NNSA/LLNL
Manufacturer:	HPE
Cores:	11,039,616

Missing out spatial resolution: Reasons and chances

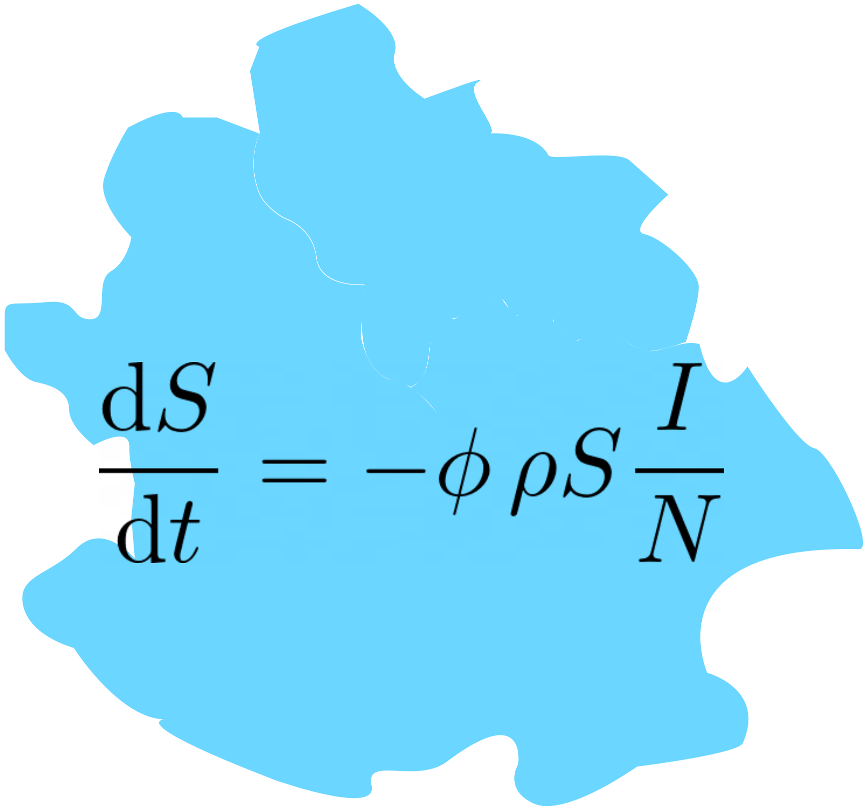


In computational physics, problems with trillions of degrees of freedom are solved*

- Why shouldn‘t we be able to solve some hundred regions?
- Why shouldn‘t we be able to solve some million agents?

* Gmeiner et al., Journal of Computational Science, 2016.

From simple ODE to metapopulation



$$\frac{\mathrm{d}S}{\mathrm{d}t} = -\phi\,\rho S\,\frac{I}{N}$$

S : Susceptible population

I : Infected/Infectious population

N : Total population

ϕ : Contact rate

ρ : Transmission probability

From simple ODE to metapopulation

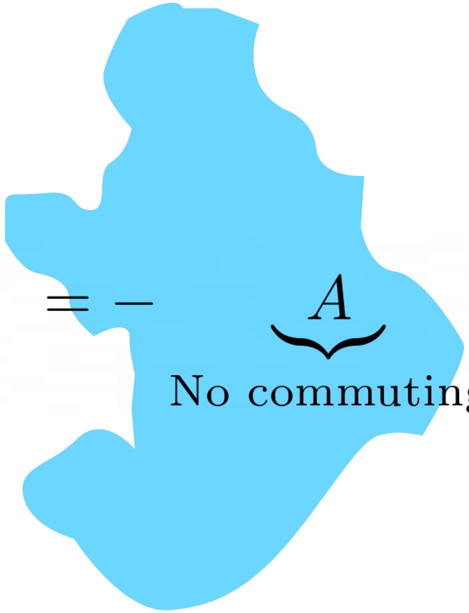
$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = -\phi\,\rho S_1 \frac{I_1}{N_1}$$

$$\frac{\mathrm{d}S_3}{\mathrm{d}t} = -\phi\,\rho S_3 \frac{I_3}{N_3}$$

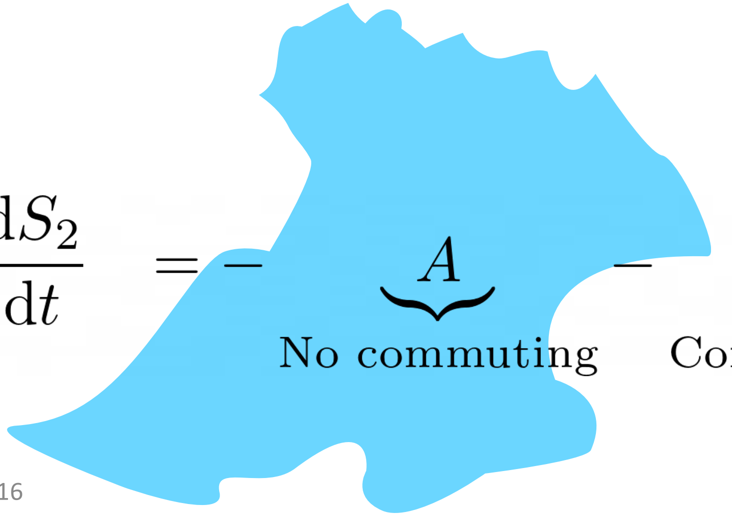
$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = -\phi\,\rho S_2 \frac{I_2}{N_2}$$

From simple ODE to metapopulation

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = -\underbrace{A}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$



$$\frac{\mathrm{d}S_3}{\mathrm{d}t} = -\underbrace{A}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$



$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = -\underbrace{A}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$

From simple ODE to metapopulation

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = -\underbrace{\frac{1}{2}\phi\,\rho\frac{I_1}{P_1}S_1}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$

h_{ij} : Commuter from region i to j

I^c : commuting infectious

I^r : remaining infectious

$$P_i = \sum_{j=1}^{n} h_{ij}$$

$$N_i = P_i - \sum_{j\neq i} h_{ij} + \sum_{j\neq i} h_{ji}$$

$$\frac{\mathrm{d}S_3}{\mathrm{d}t} = -\underbrace{\frac{1}{2}\phi\,\rho\frac{I_3}{P_3}S_3}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$

$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = -\underbrace{\frac{1}{2}\phi\,\rho\frac{I_2}{P_2}S_2}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$

Gerstein et al, in preparation, 2025

From simple ODE to metapopulation

$$\frac{\mathrm{d}S_1}{\mathrm{d}t} = -\underbrace{\frac{1}{2}\phi\,\rho\frac{I_1}{P_1}S_1}_{\text{No commuting}} - \underbrace{\frac{1}{2}\Big(\phi\,\rho\frac{I_1^r}{N_1}S_1^r + \phi\,\rho\frac{I_1^c}{N_1}S_1^r + \phi\,\rho S_1\sum_{j\neq 1}\frac{h_{1j}}{P_1}\frac{I_j^r + I_j^c}{N_j}\Big)}_{\text{Commuting}}$$

$$\frac{\mathrm{d}S_3}{\mathrm{d}t} = -\underbrace{\frac{1}{2}\phi\,\rho\frac{I_3}{P_3}S_3}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$

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$$\frac{\mathrm{d}S_2}{\mathrm{d}t} = -\underbrace{\frac{1}{2}\phi\,\rho\frac{I_2}{P_2}S_2}_{\text{No commuting}} - \underbrace{B}_{\text{Commuting}}$$

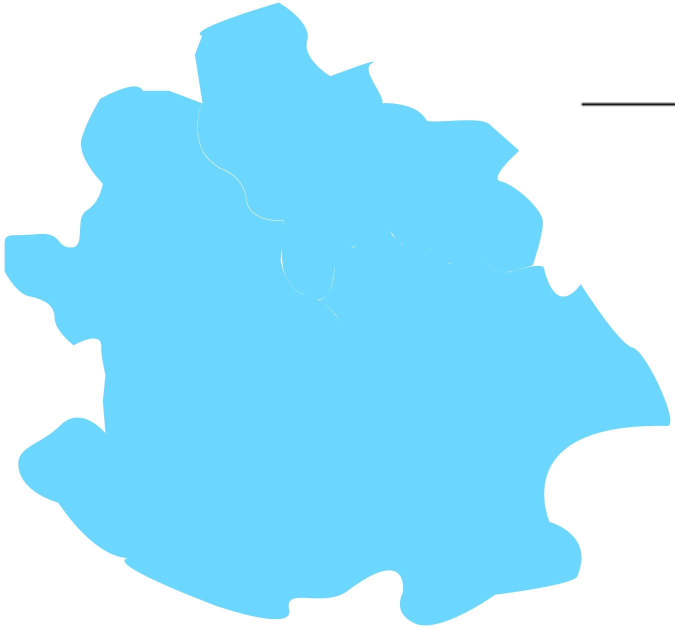
Gerstein et al, in preparation, 2025

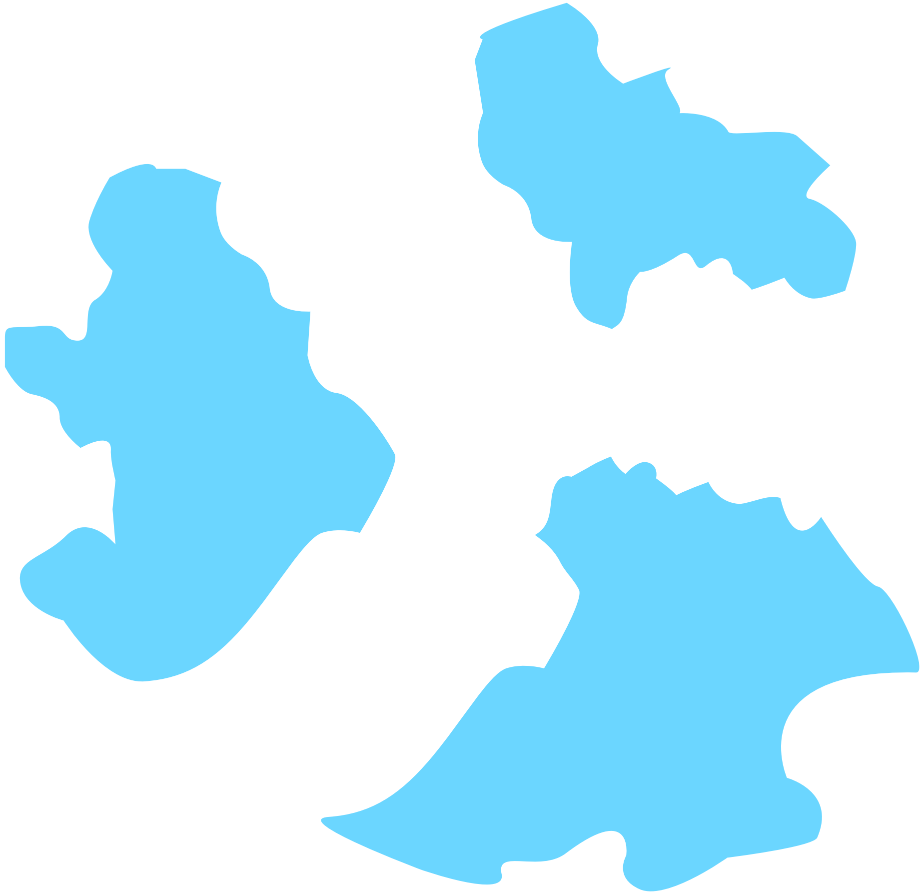
From simple ODE to metapopulation

→ For uniformly distributed cases, the models should return the same output

Basic reproduction numbers for different numbers of regions.

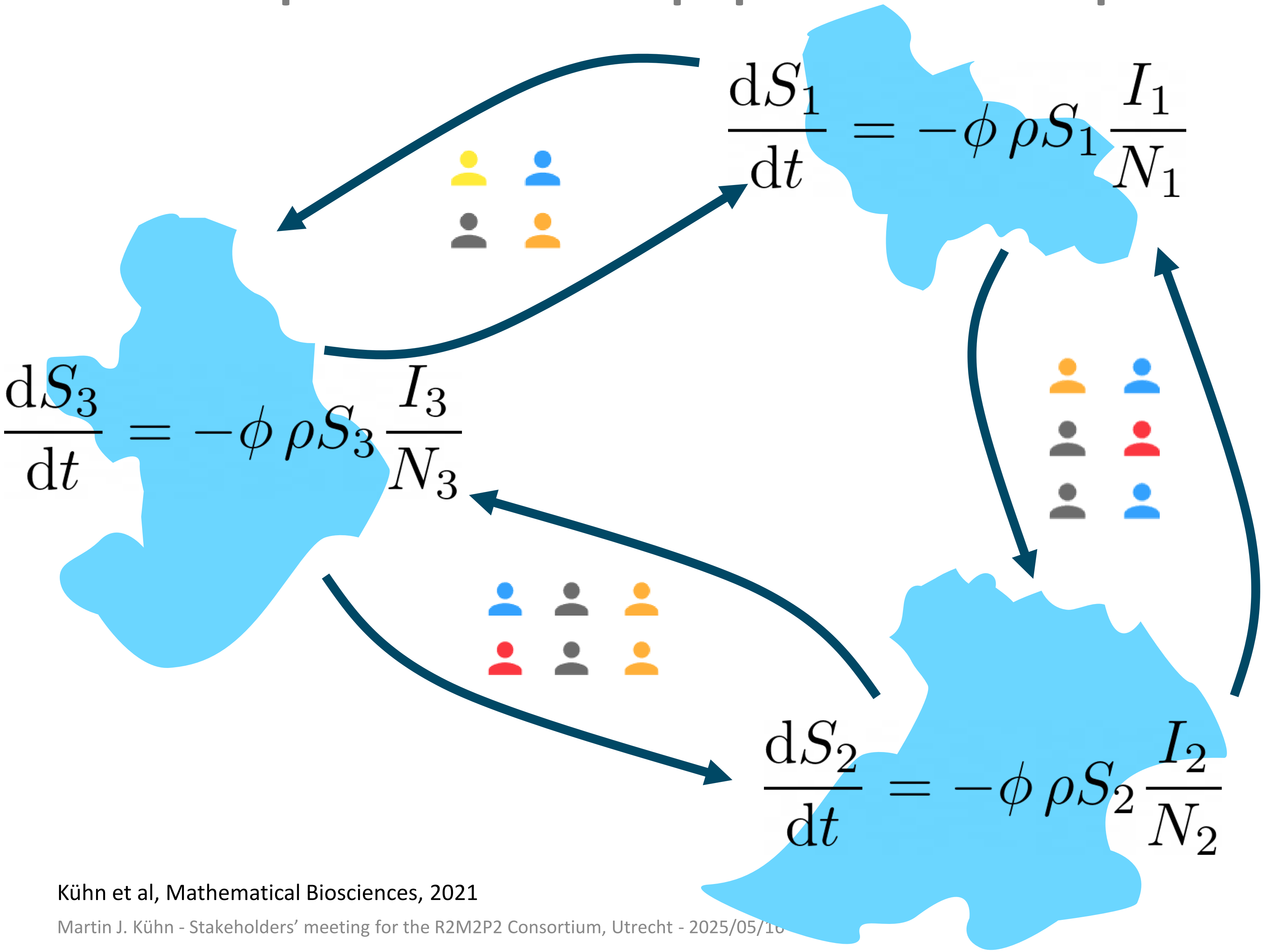
Number of Regions	Model A	Model B	Model C
1	4.48161	4.48161	4.48161
2	4.48161	[illegible]	4.48161
5	4.48161	[illegible]	4.48161
10	4.48161	[illegible]	4.48161
20	4.48161	[illegible]	4.48161
50	4.48161	6.67782	4.48161





Gerstein et al, in preparation, 2025

From simple ODE to metapopulation: A Graph-ODE alternative



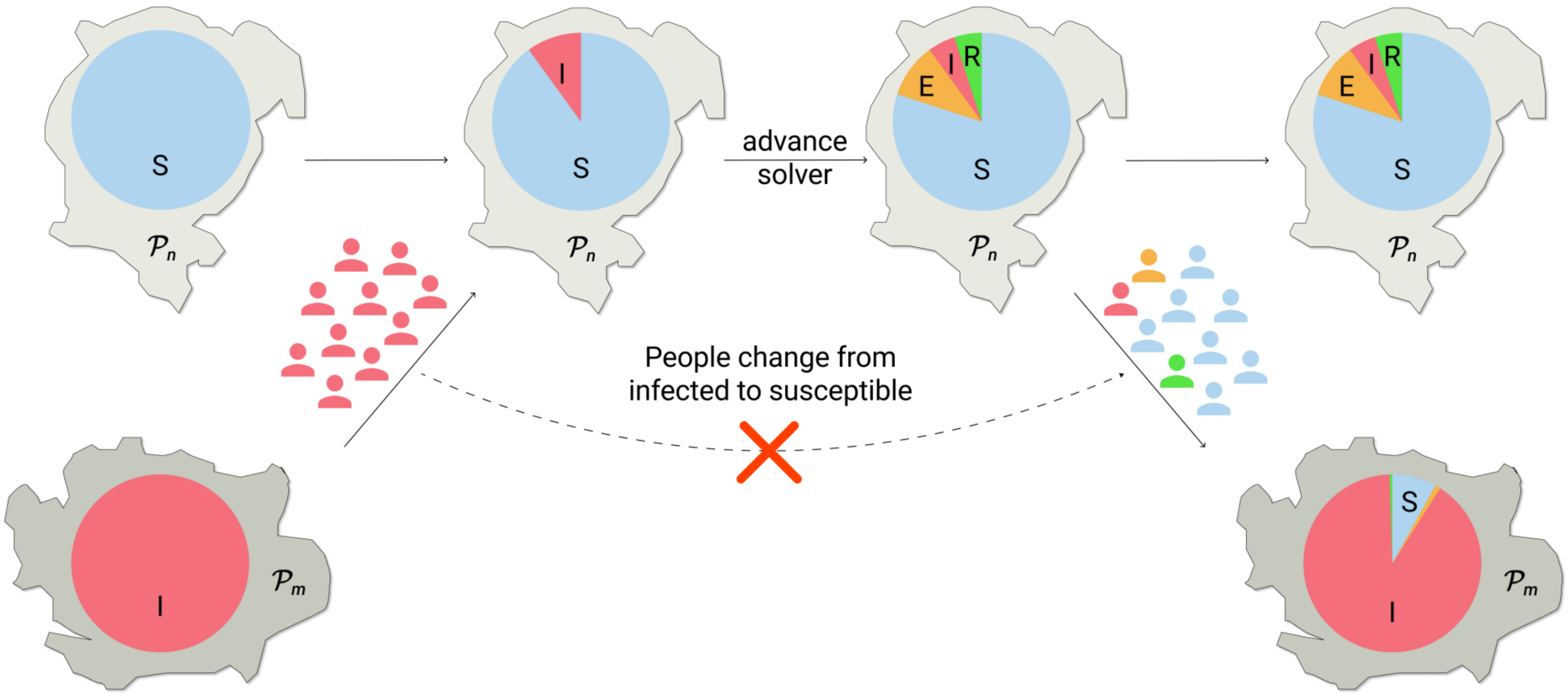
- Use a graph with regions as nodes
- One edge per, e.g., pair (infection state, age group)
- Advance nodes in parallel from t to t+0.5 and from t+0.5 to t+1

Advantage:
- Parallelism

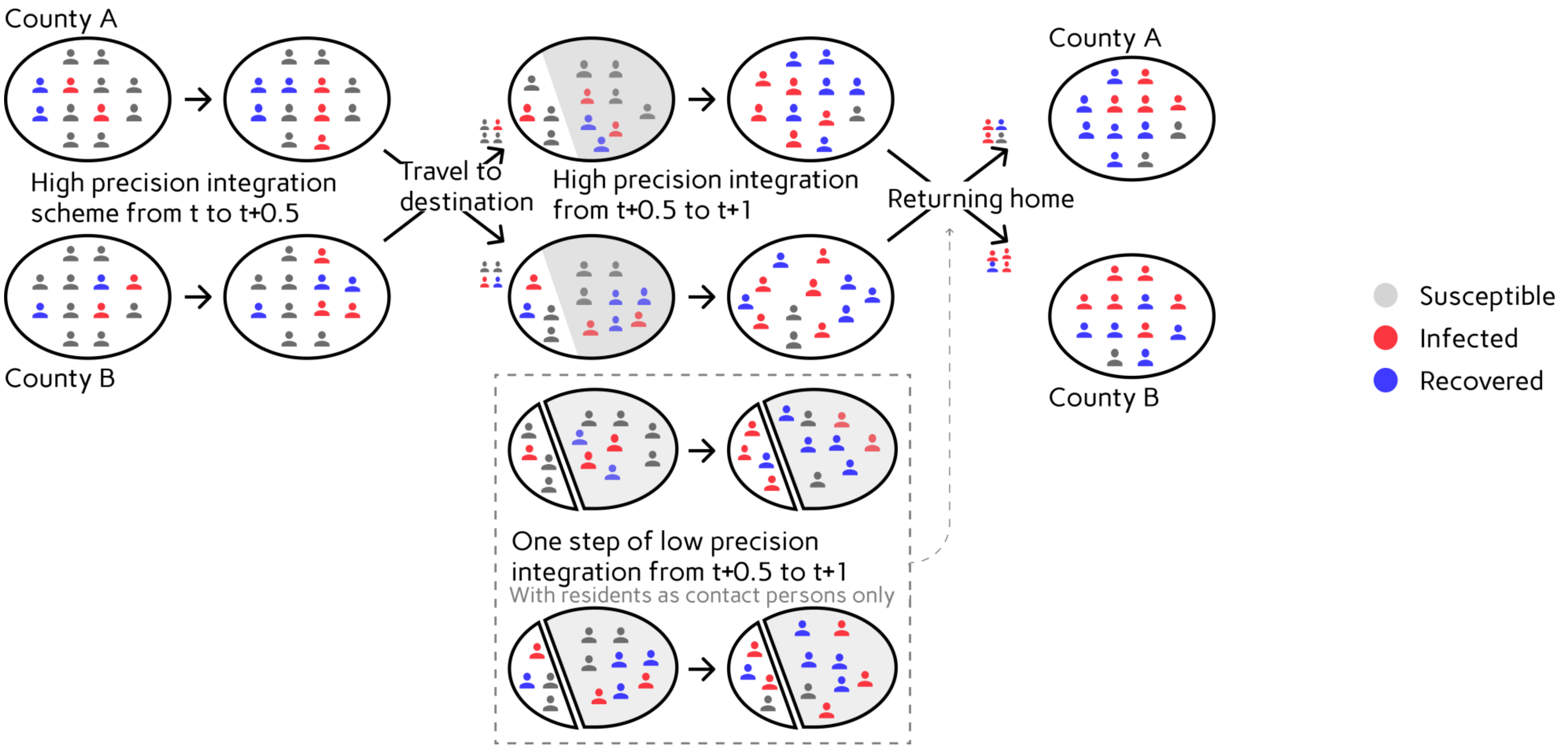
Disadvantage:
- Returning commuters need to be approximated
- Theory more complex

Kühn et al, Mathematical Biosciences, 2021

From simple ODE to metapopulation: A Graph-ODE alternative

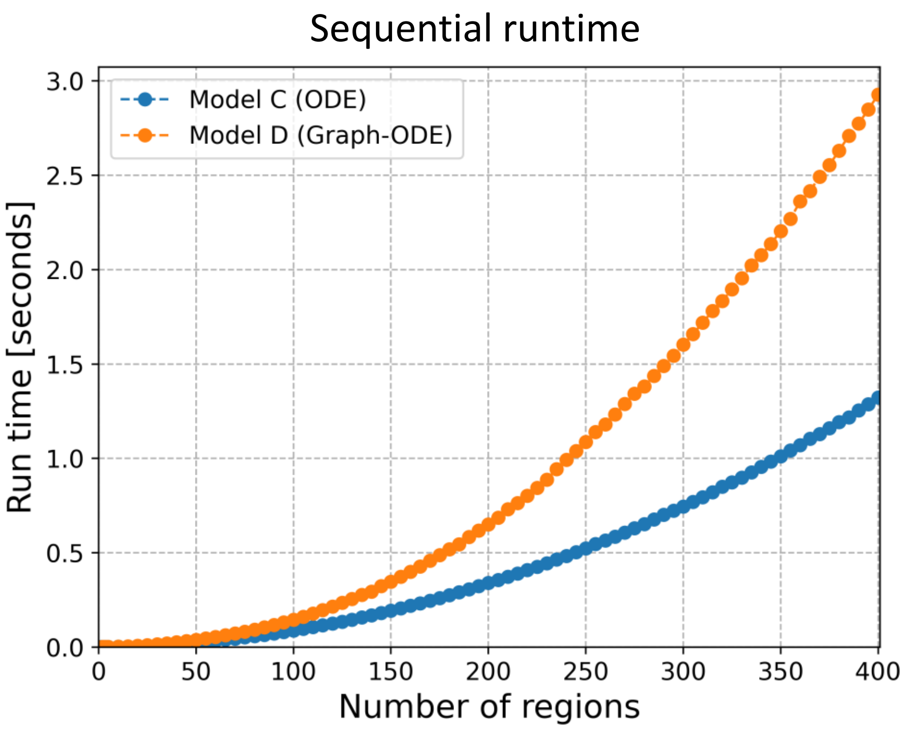


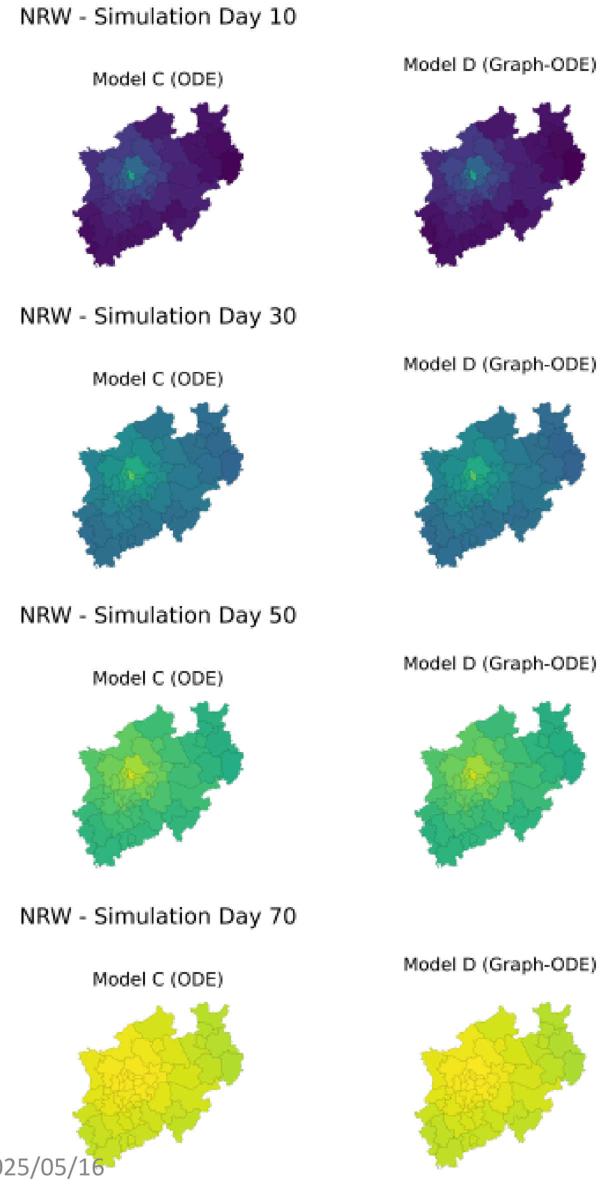
From simple ODE to metapopulation: A Graph-ODE alternative

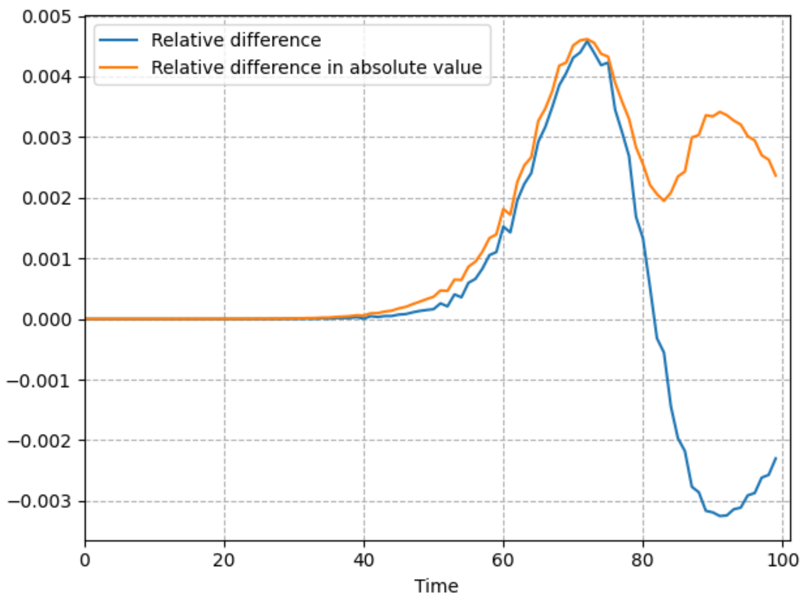


- Commuter return overshoots if number of commuters relative large; take from largest compartment
- Improvement to commuter extrapolation in development: Zunker et al, In preparation, 2025

ODE metapopulation vs. Graph-ODE metapopulation



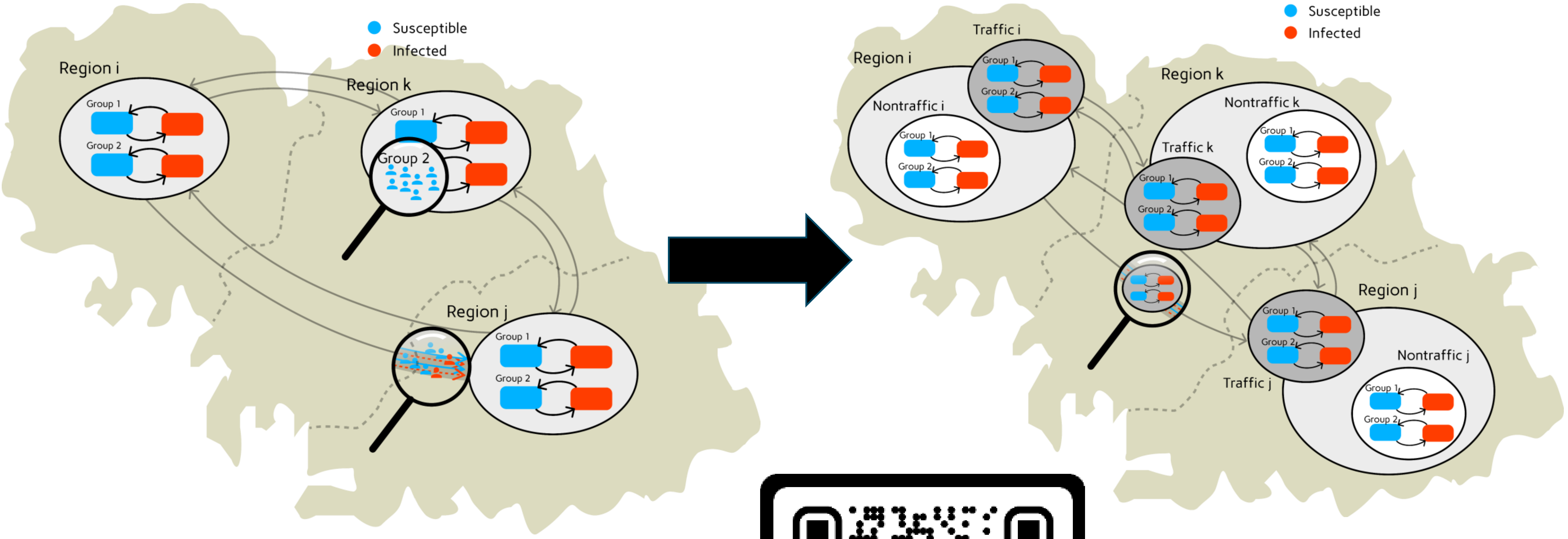




Gerstein et al, in preparation, 2025

Extension to travel-time aware Graph-ODE metapopulation model

DLR



Metapop (2024)

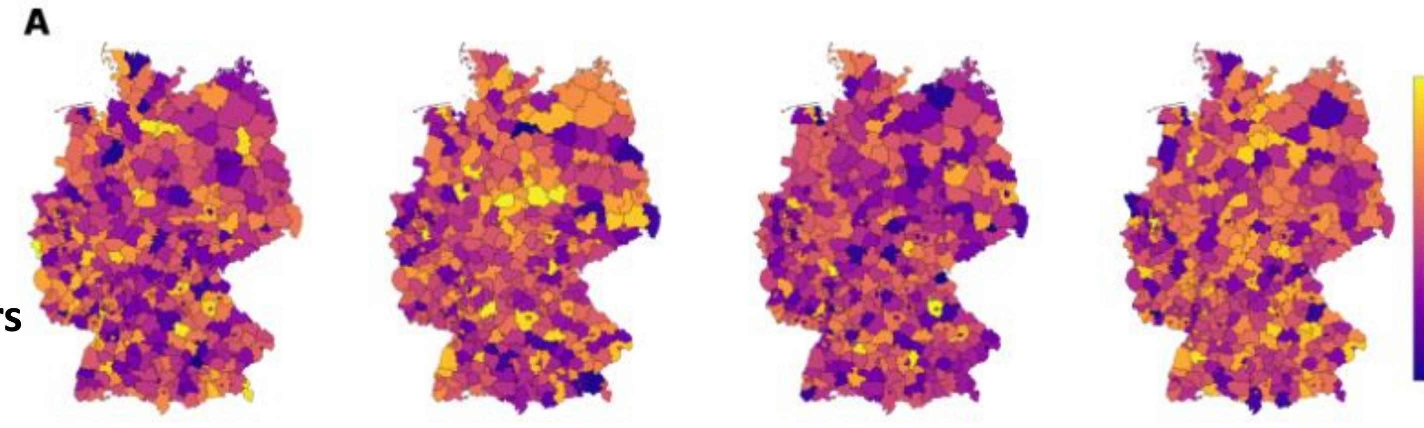
Zunker et al., PLOS Comp Bio, 2024.

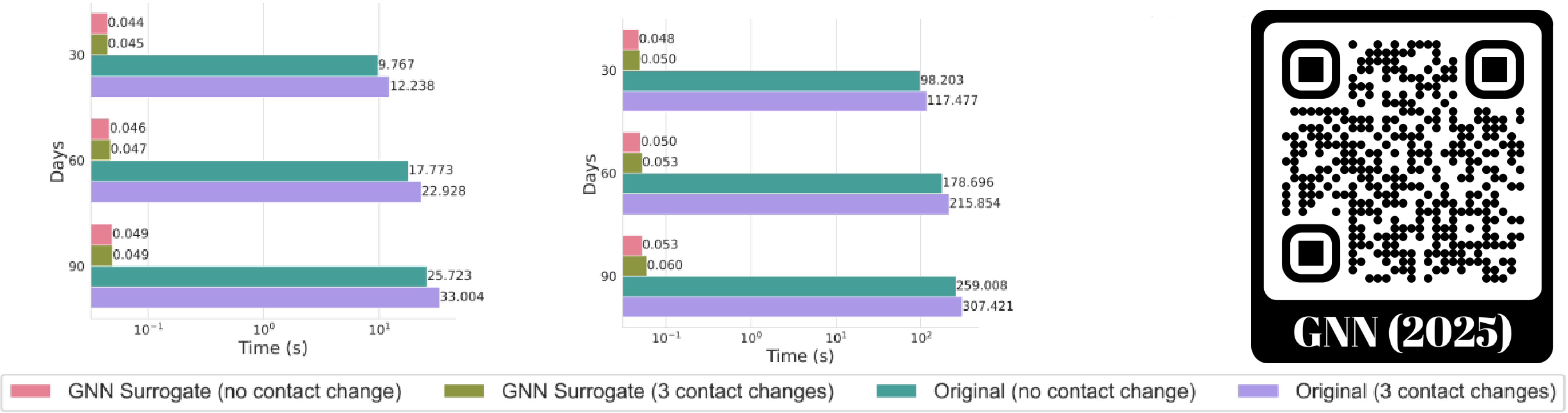
AI-based on-the-fly computation for web applications

- Simulate spatially resolved expert models
- Train spatially resolved AI surrogates (Graph Neural Networks) on expert model‘ outcomes

→ **Enables low-barrier web access for decision makers**

→ **Timely reaction for pandemic mitigation**



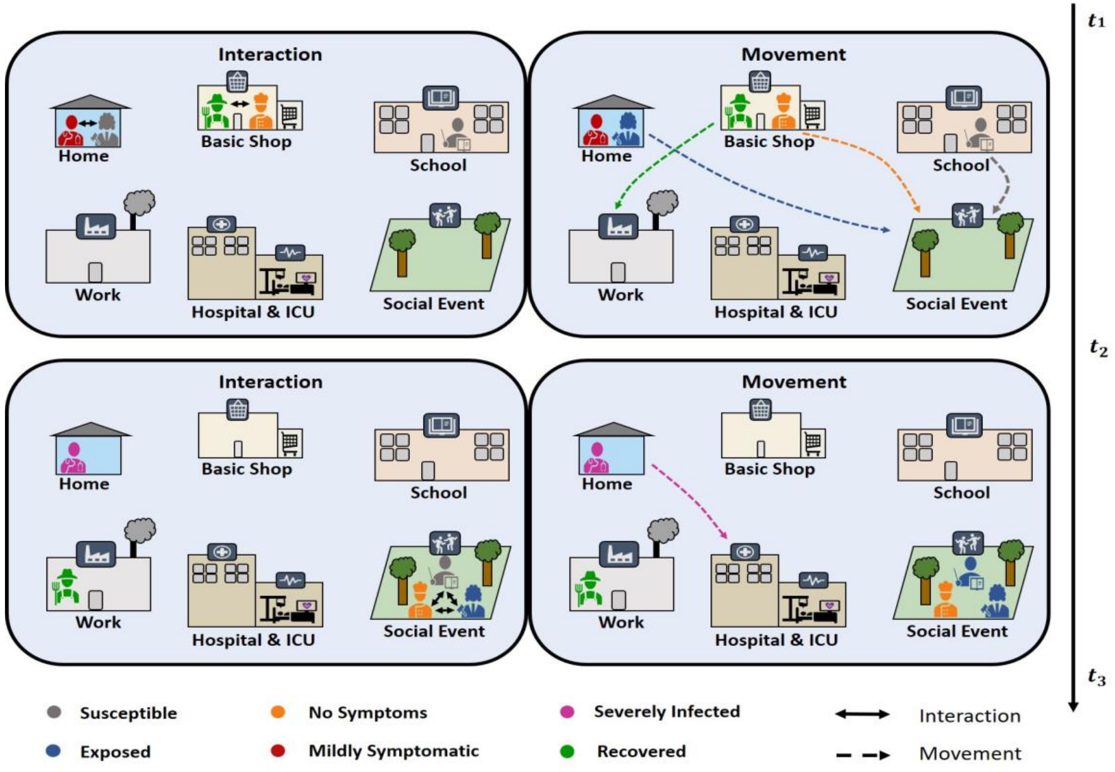


GNN (2025)

Schmidt et al. - Graph Neural Network Surrogates to leverage Mechanistic Expert Knowledge towards Reliable and Immediate Pandemic Response (2025)

Agent-based modeling

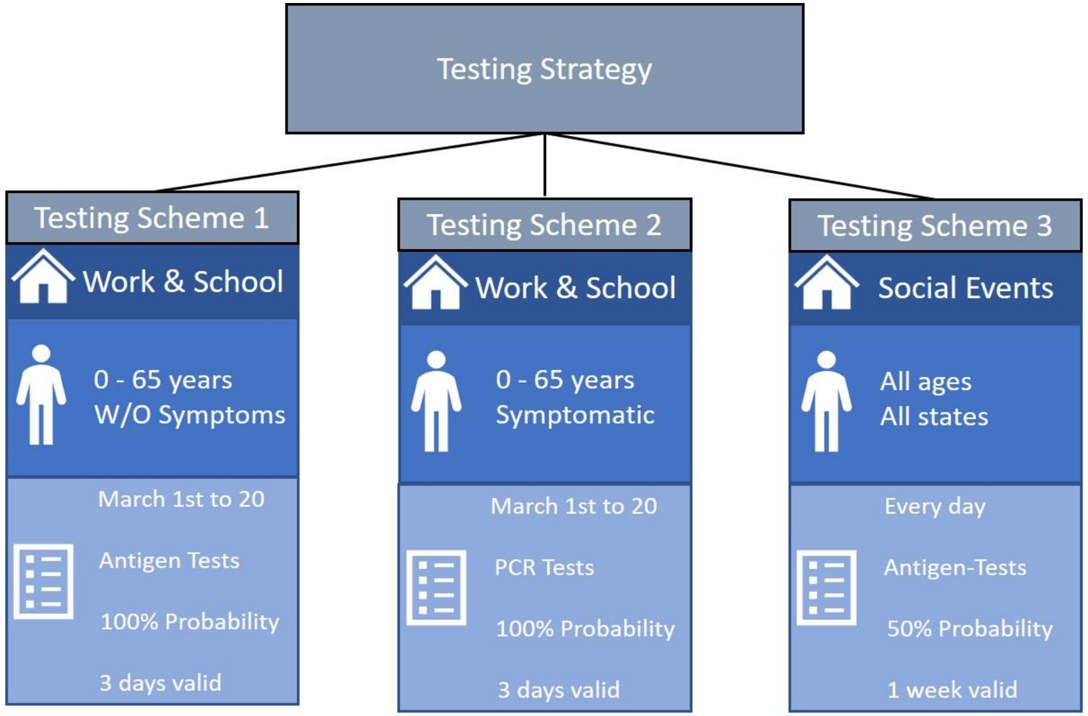
- Model individuals (or households) as individual agents
- Study and answer research questions on a “microscopic“ level (e.g. individual decisions, test strategies, viral load…)
- Computational cost scales (super)linearly with number of agents

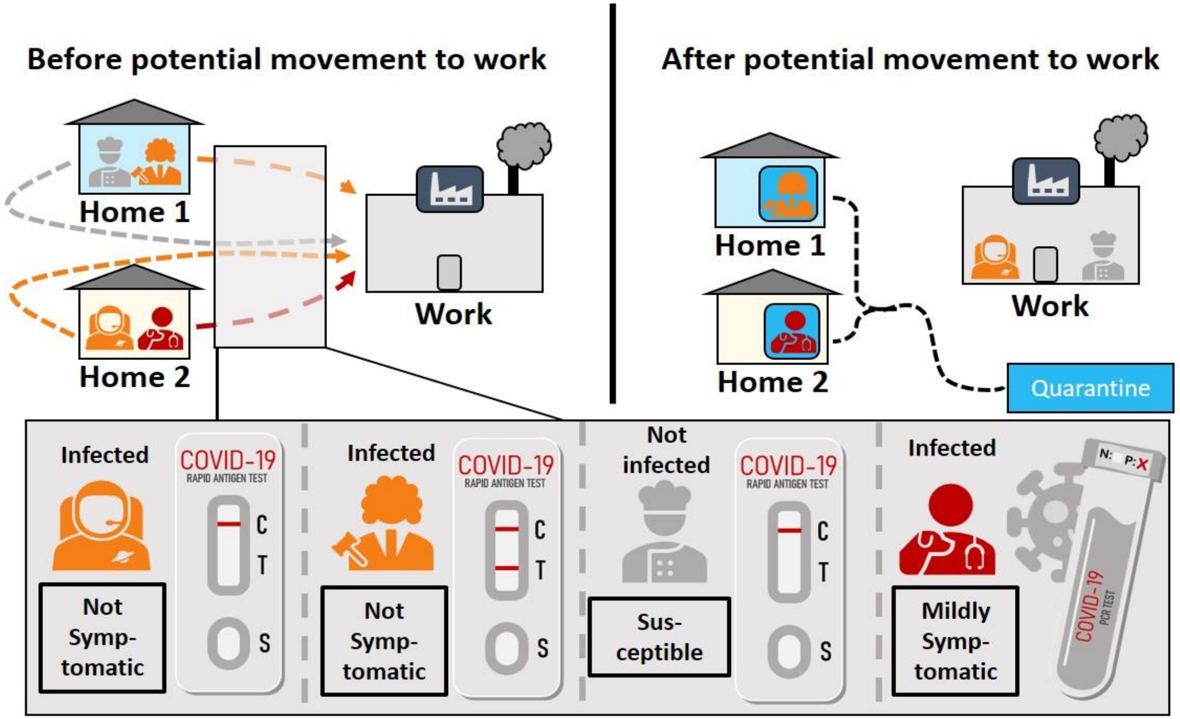


Algorithm 1: Trip-based agent-based simulation

$t \leftarrow t_0 \in \mathbb{R}$
while $t \leq t_{\max}$ **do**
  for *each location* **do**
    Execute agents’ interactions
  for *each agent* **do**
    Perform individual movement
  $t \leftarrow t + \Delta t$

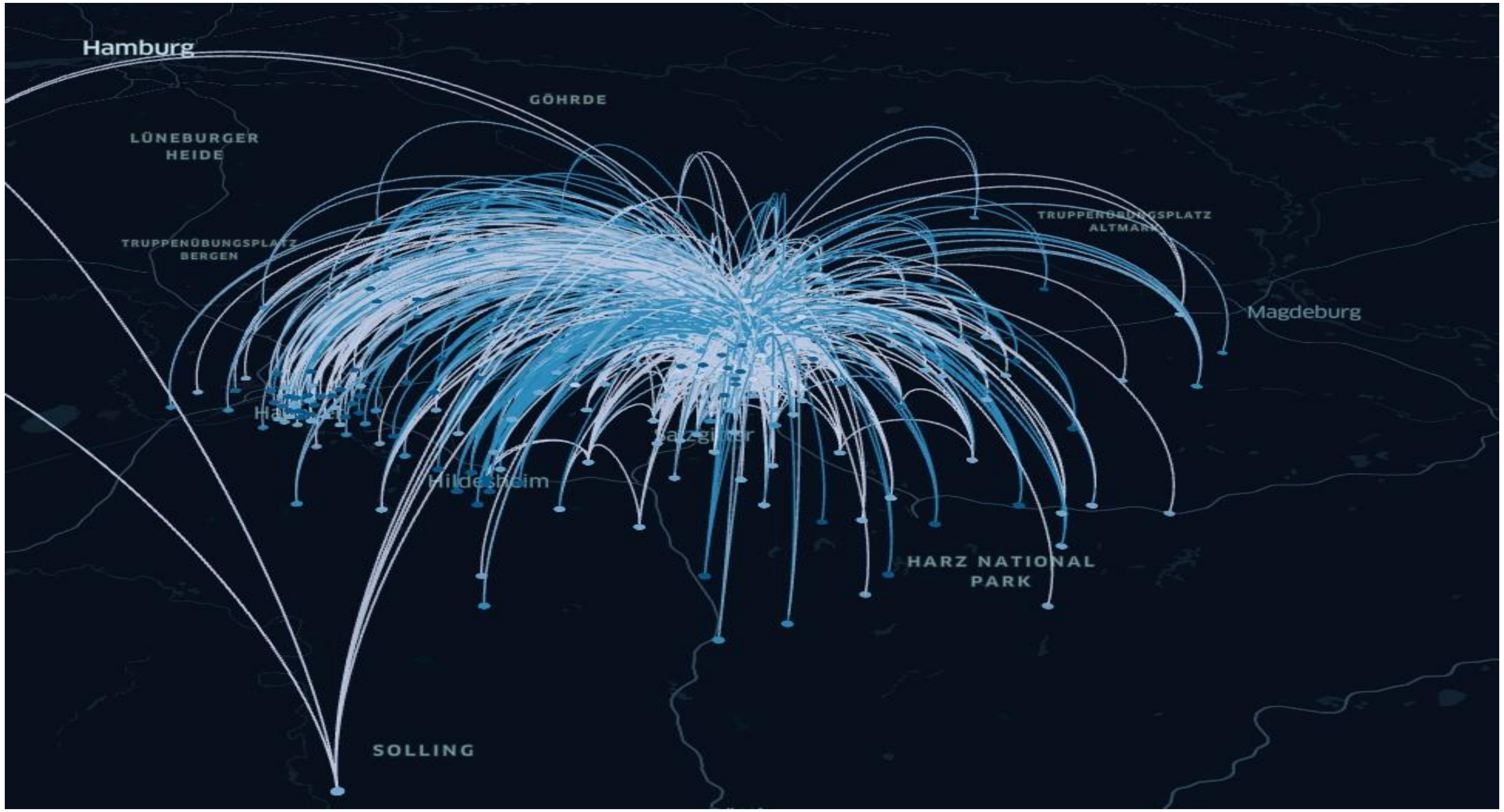
Agent-based modeling: Testing strategies





Agent-based modeling: Application to city-scale

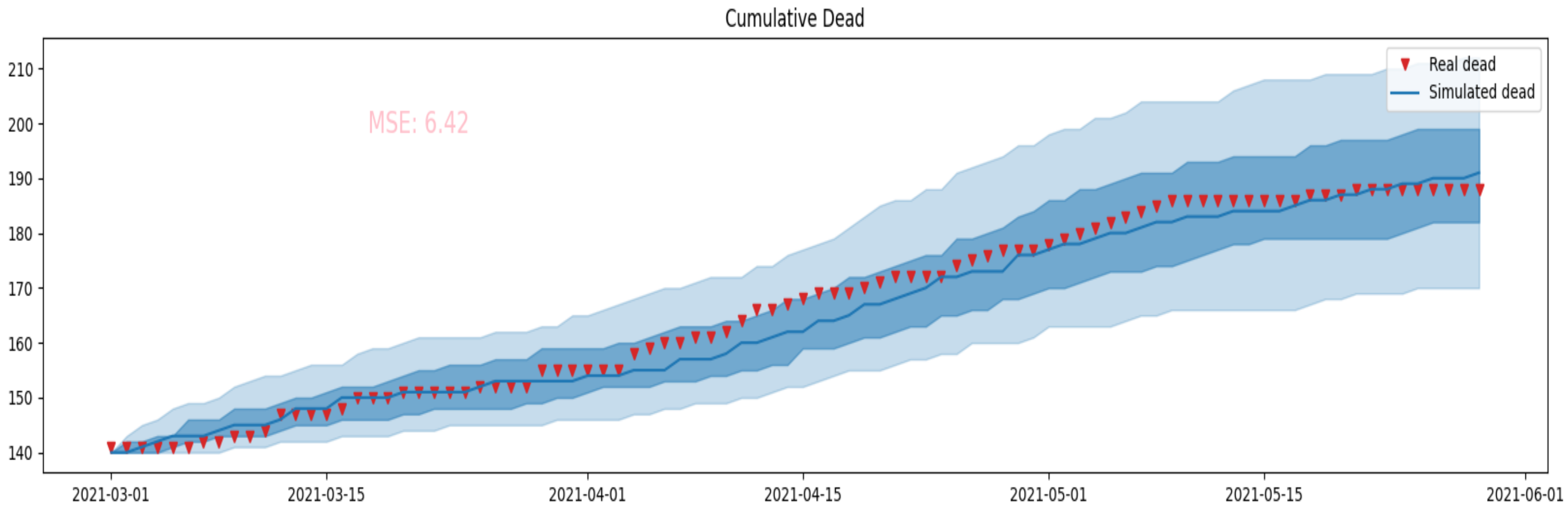
- Approximately 370.000 persons from Brunswick and the surrounding area
- Over 1.3 million trips per day

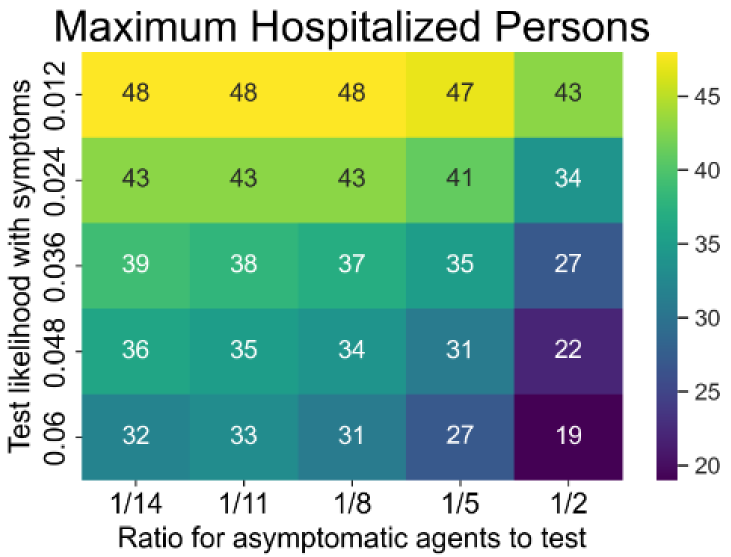


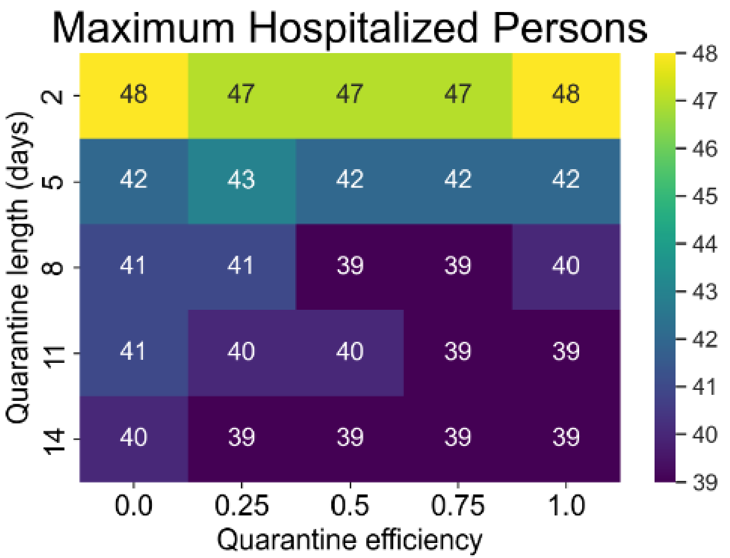
Kerkmann, Korf et al., Accepted for Computers in Biology and Medicine, 2025

ABM (2024)

Agent-based modeling: Application to city-scale



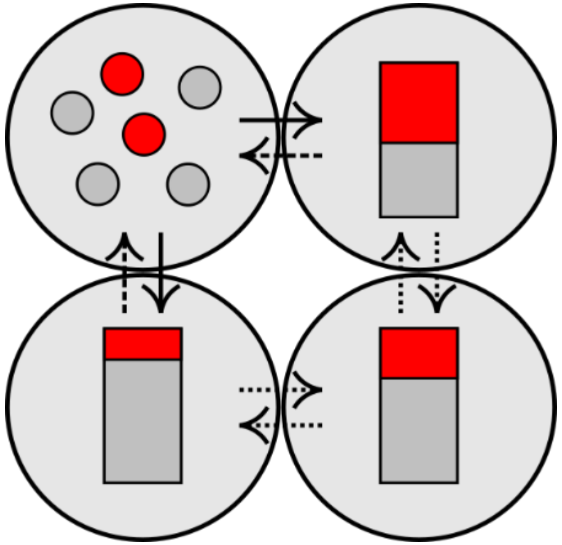




ABM (2024)

Kerkmann, Korf et al., Accepted for Computers in Biology and Medicine, 2025

Hybrid agent-metapopulation models: Spatial hybrid



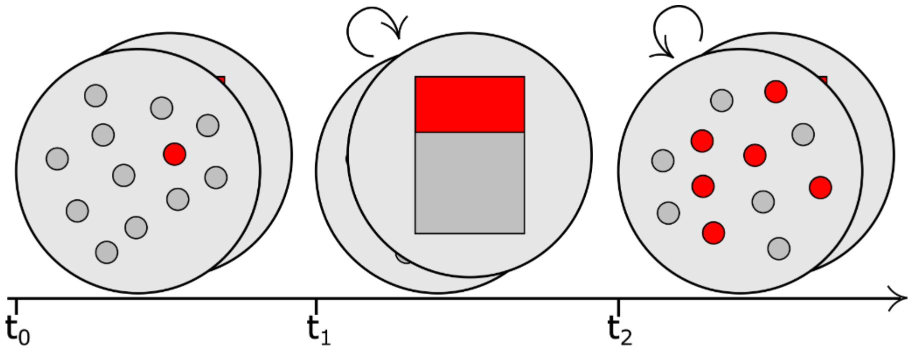
- Idea:
  - Interest in infection spread in particular region
  - Exclusive availability of data in specific region (or computational resources limited)
- Concept:
  - Agent-based model in region of interest (focus region)
  - ODE-based models for connected regions

→ **Detailed results** in focus region while considering **influence of connected regions** in **runtime efficient** manner

Bicker, Schmieding et al., Infectious Disease Modelling, 2025

Hybrid agent-metapopulation models: Temporal hybrid

- Idea:
  - Low case numbers:
    High stochasticity and individual behavior is important
  - High case numbers:
    Individual behavior is less influential and single simulation outcomes are close to averaged results

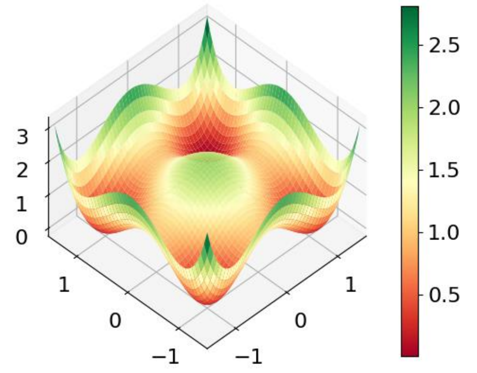


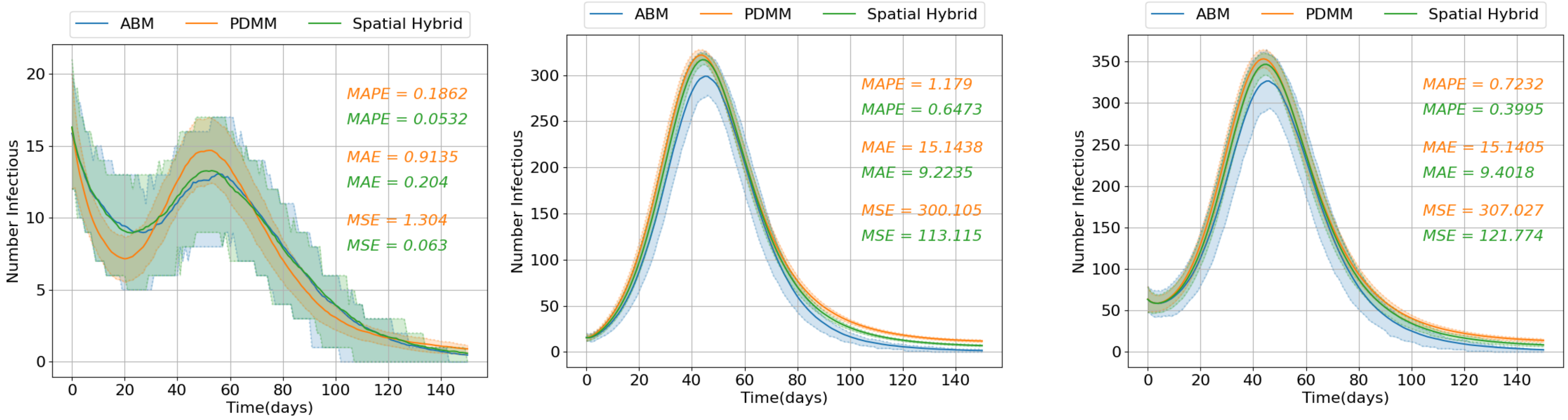
- Concept:
  Switch between agent-based and ODE-based model during the simulation according to a threshold value
  → Capture stochasticity and individual behavior when necessary for **accurate outcomes** while using **runtime advantage** when possible

Bicker, Schmieding et al., Infectious Disease Modelling, 2025

Proof-of-concept spatial hybrid model

- Setup: 8000 agents, 1% of population initially infected
- Focus region: $\Omega_1 = (-\infty, 0) \times (0, \infty)$
- Transmission rate in $\Omega_2 = (0, \infty) \times (0, \infty)$ corresponding to $R_0 = 2.4$
- Transmission rate in other regions corresponding to $R_0 = 0.8$

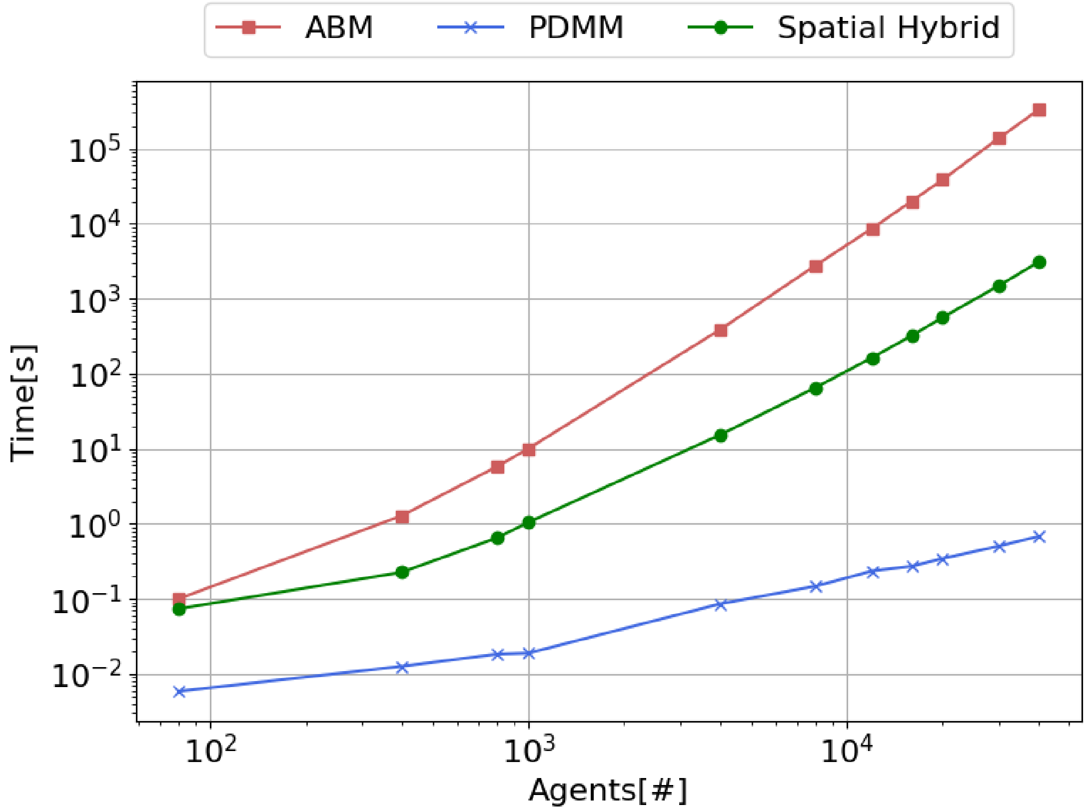




Bicker, Schmieding et al., Infectious Disease Modelling, 2025

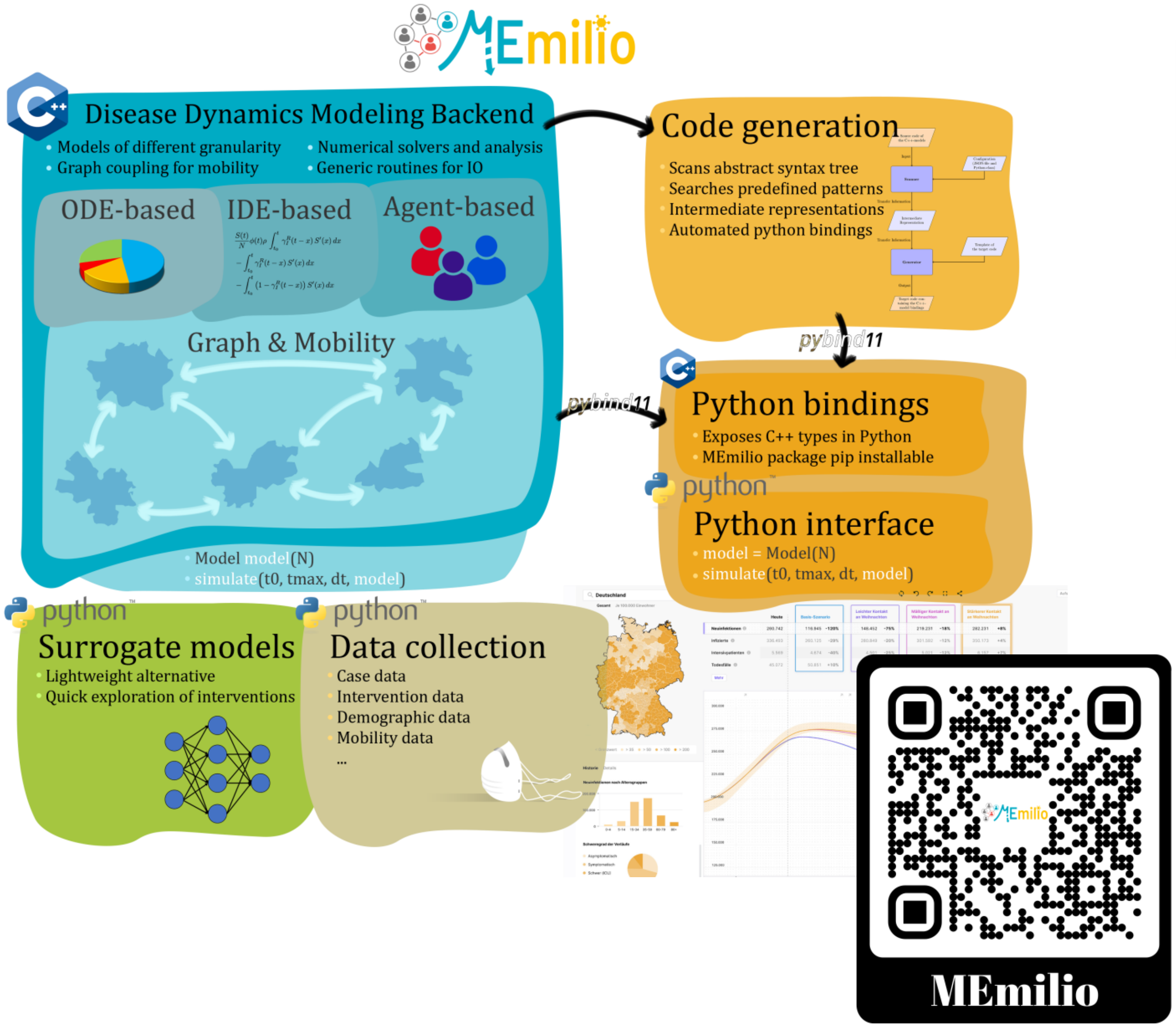
Proof-of-concept spatial hybrid model

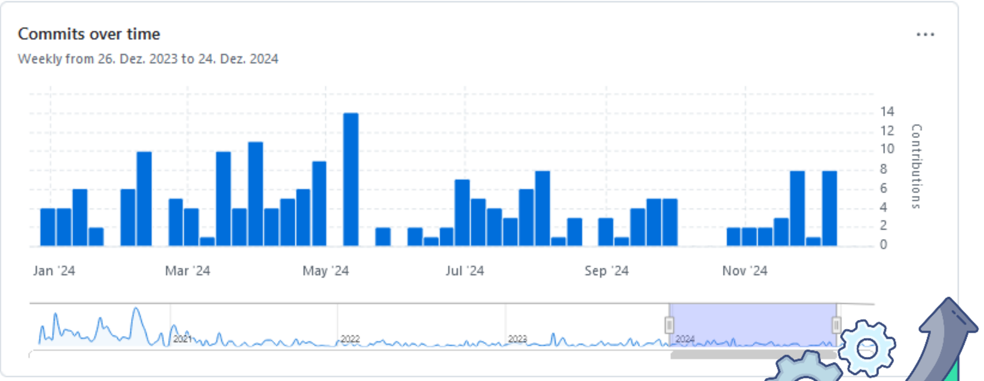
- Spatial-hybrid has same scaling behavior like ABM
- For **400 agents**: Runtime of spatial-hybrid **1 order of magnitude** lower than for ABM
- For **40,000 agents**: Spatial-hybrid reduces runtime by **98%**



Bicker, Schmieding et al., Infectious Disease Modelling, 2025

MEmilio:
A high performance Modular EpideMIcs simuLatIOn software





Contributors
- 2024: 20
- Overall: 36

Activity (on main) December 2024
- 11 active pull requests (5 merged)
- 13 active authors

Software, Unit Tests, Comments
- C++: ca. 650 (2023: ca. 300)
- Python: ca. 230 (2023: ca. 200)
- Code lines vs comments: 83k vs 31k

CI passing codecov 97%

Gefördert durch:
Bundesministerium für Digitales und Verkehr
mFUND Das Startkapital für die Mobilität 4.0
GEFÖRDERT VOM
Bundesministerium für Bildung und Forschung
HELMHOLTZ
DFG
DLR
UNIVERSITÄT BONN

Thanks to our funders! / Thank you for your attention!

Further reading:

- Gerstein et al., *Comparison and performance of metapopulation models (working title)*, In preparation, 2025
  → Let me know if you want to be informed on preprint

- Zunker et al., *Commuter exchange in Graph-ODE models (working title)*, In preparation, 2025
  → Let me know if you want to be informed on preprint

- Kerkmann, Korf et al. **Agent-based modeling for realistic reproduction of human mobility and contact behavior to evaluate test and isolation strategies in epidemic infectious disease spread**, *Accepted for publication in Computers in Biology and Medicine* (2025)

- Bicker et al., **Hybrid metapopulation agent-based epidemiological models for efficient insight on the individual scale: a contribution to green computing**. *Infectious Disease Modelling, 10(2), 571 (2025)*

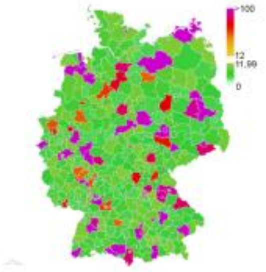
- Zunker et al., **Novel travel time aware metapopulation models and multi-layer waning immunity to assess late-phase epidemic and endemic scenarios**. *PLOS Computational Biology* 20(12): e1012630 (2024)

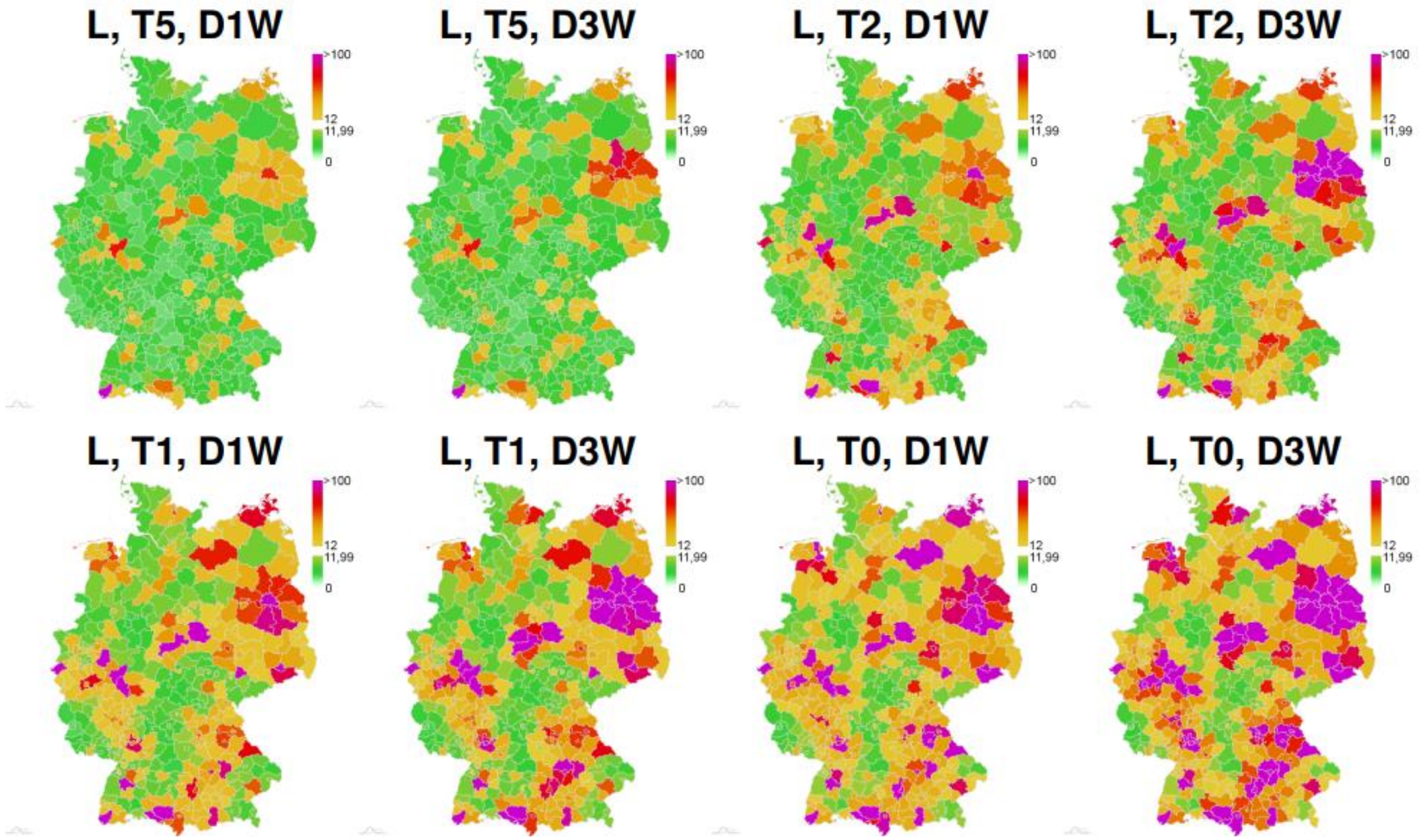
- Schmidt et al., **Graph Neural Network Surrogates to leverage Mechanistic Expert Knowledge towards Reliable and Immediate Pandemic Response** (2024)

- Kühn et al., **Assessment of effective mitigation and prediction of the spread of SARS-CoV-2 in Germany using demographic information and spatial resolution**. *Mathematical Biosciences* 339 (2021): 108648

Questions / Exchange ? → **Martin.Kuehn@DLR.de**

Application: Numerical assessment of the control strategy





Kühn et al., Regional opening strategies […], BMC Infectious Diseases, 2022.