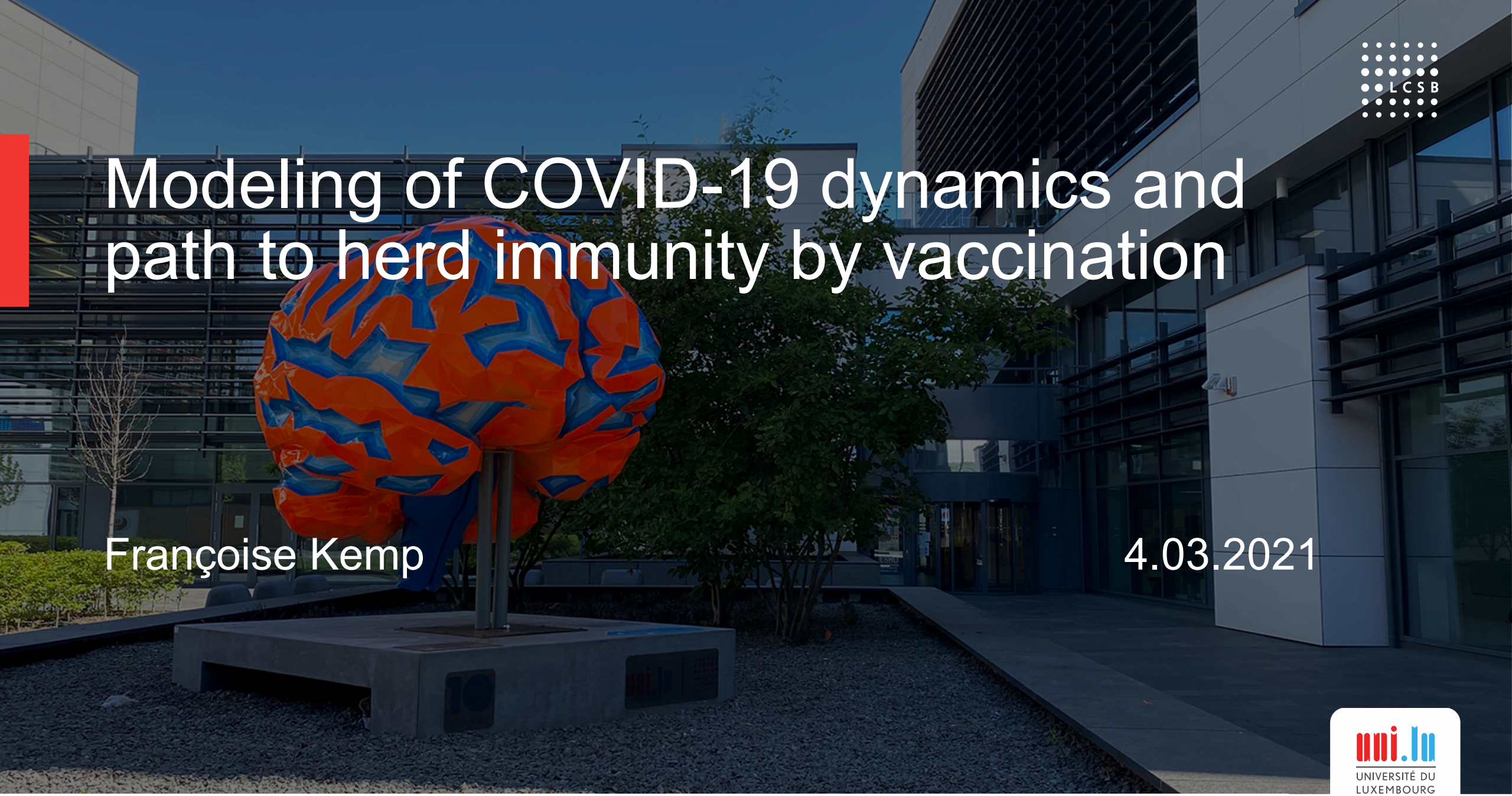


Modeling of COVID-19 dynamics and path to herd immunity by vaccination

Françoise Kemp

4.03.2021

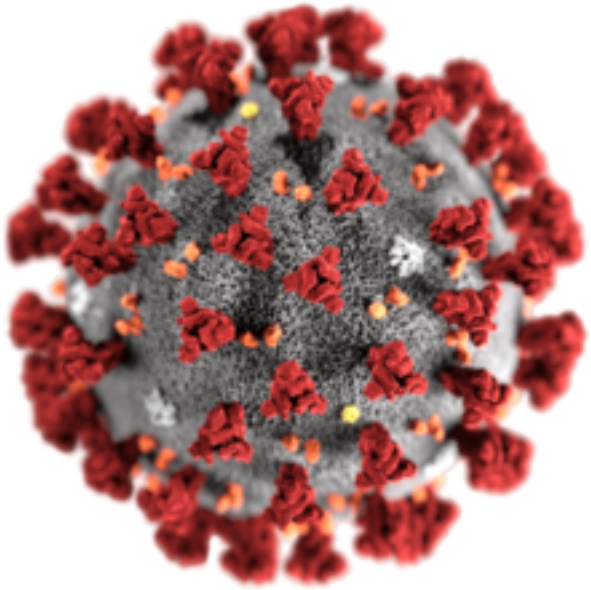
Coronavirus around the world

Total deaths

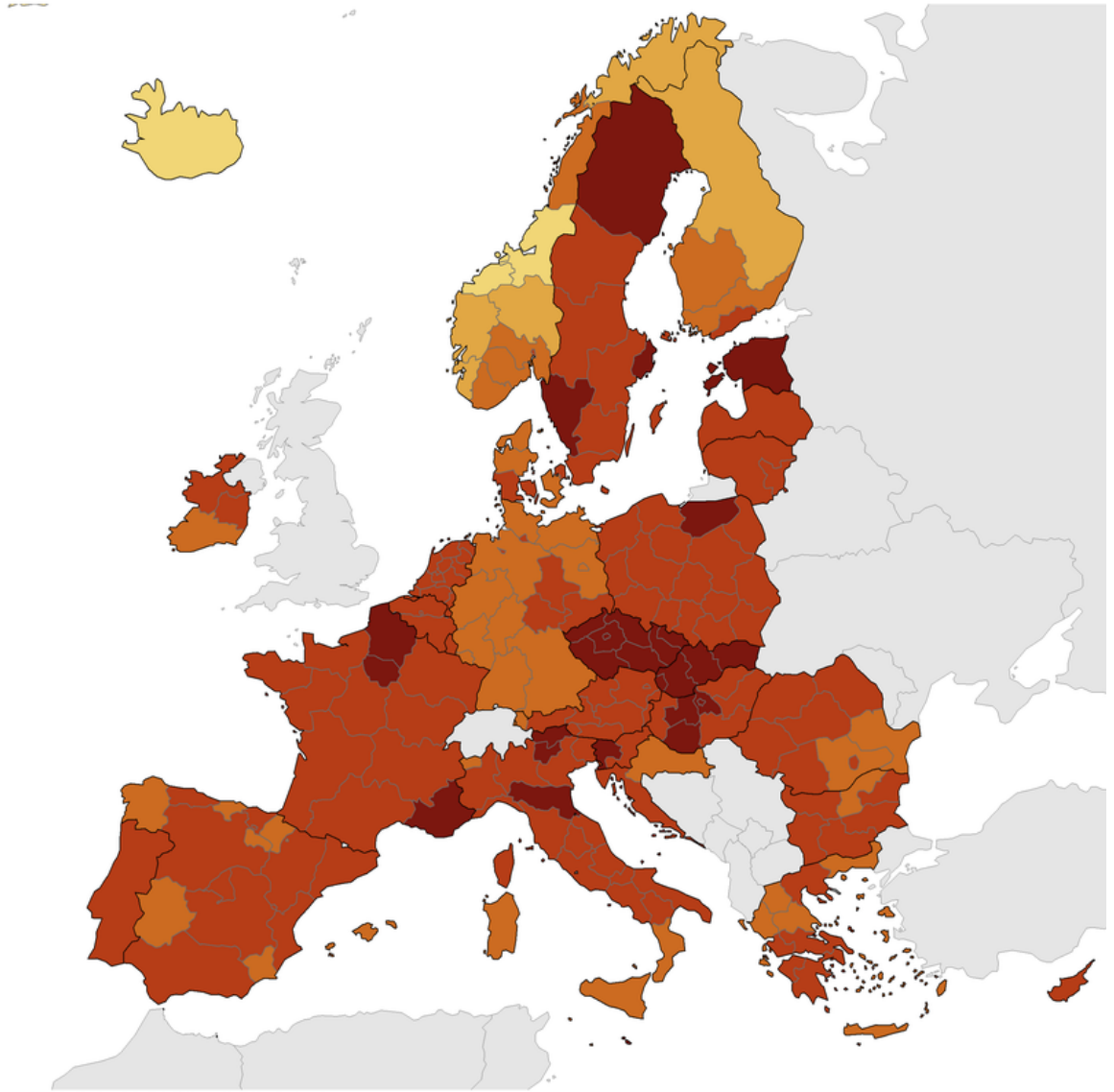
2.5 million

Total confirmed cases

115 million



Situation in Europe

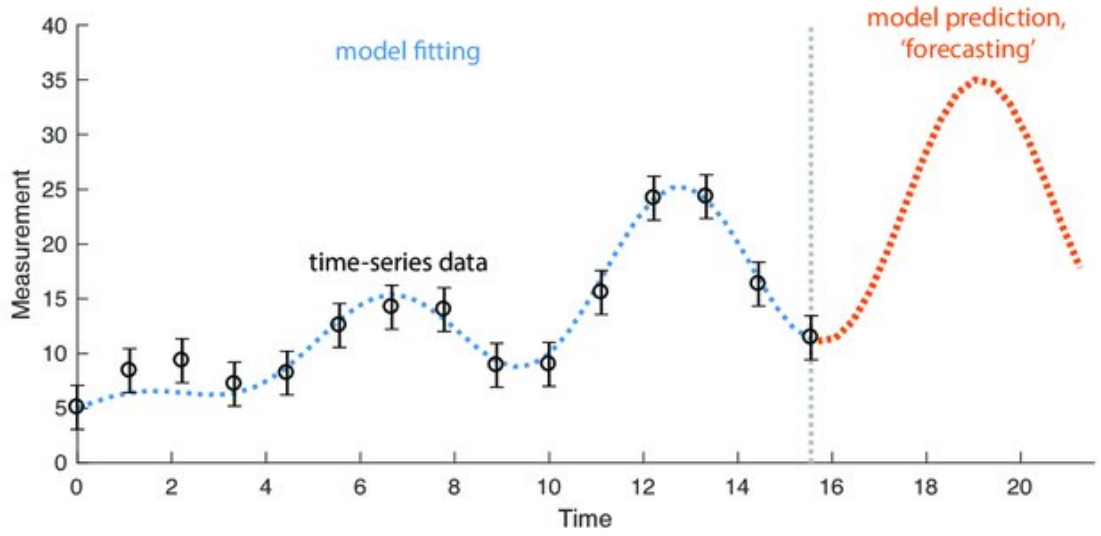


Situation in Luxembourg

Total deaths	Total confirmed cases
648	56110 (9%)
Latest daily figure	Latest daily figure
4	206
new deaths	new cases

Modeling and forecasting

- disease forecast could aid public health responses by informing key preparation and mitigation efforts
- major tool to understand its diffusion
- fit the observed data well can be simulated forward in time to make predictions about the future state of the system, a task known as forecasting
- modeling and forecasting the spread of COVID-19 remains a challenge



Motivation of the model

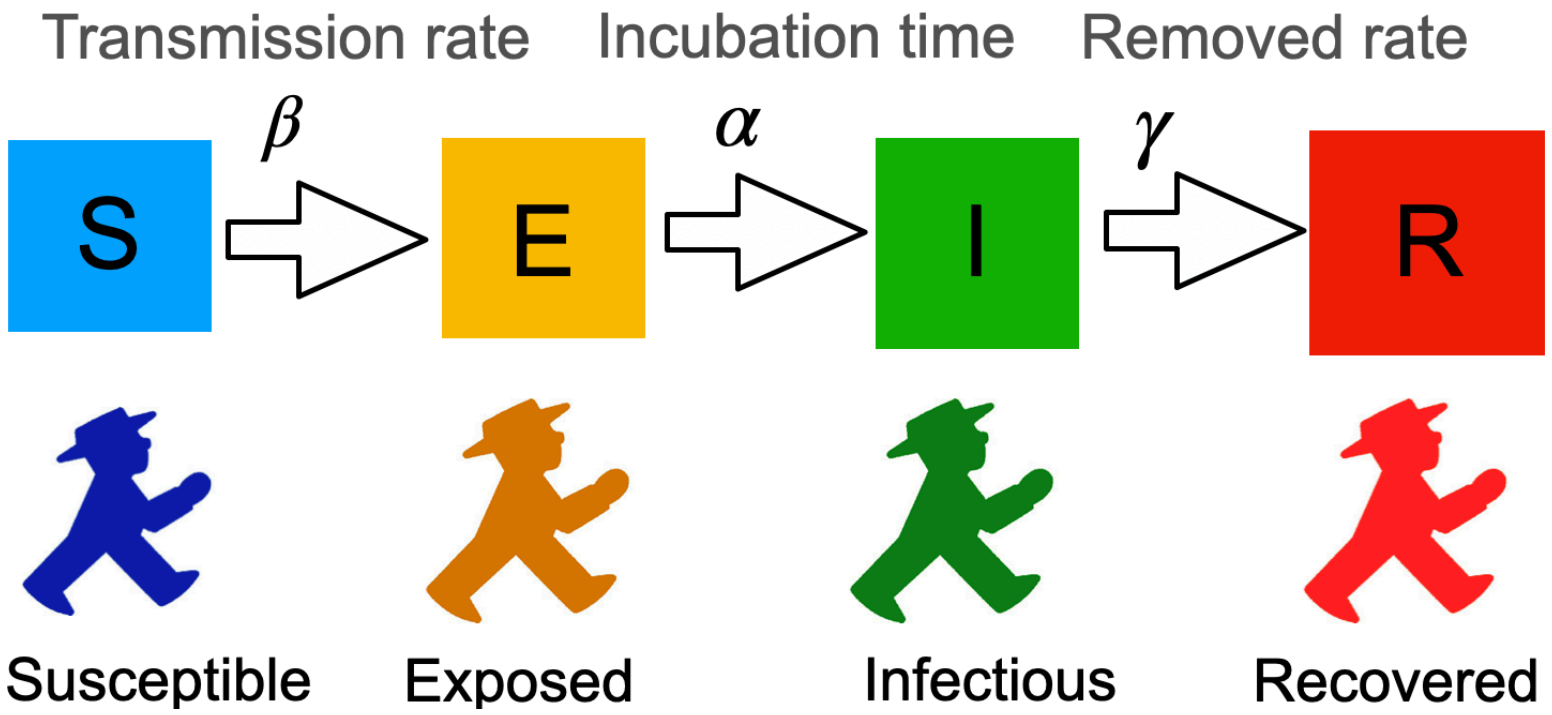
- Being confronted with soaring numbers of infections, sickness and dead
- Puts a major constraint on hospital logistics
- Simulate ICU and hospital bed needs in the upcoming week

https://ec.europa.eu/jrc/en/news/forecasting-covid-19-impact-icu-bed-demand-lombardy

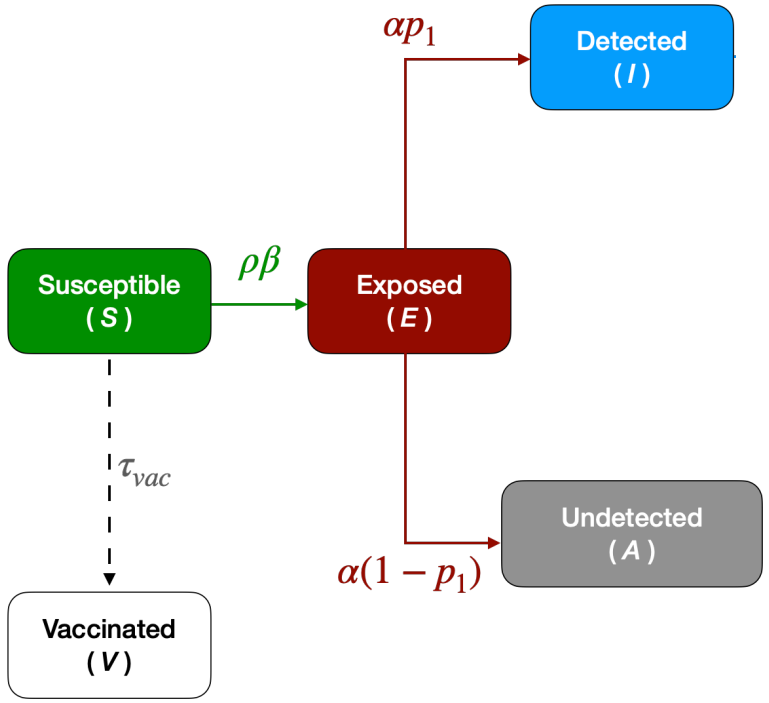
https://gdkangshen.en.made-in-china.com/product/dNrmjxaJhWVv/China-Electric-Hospital-Bed-Medical-Bed-Clinic-Bed-for-Sale.html

Basic SEIR Model

- Formulated by Kermack and McKendrick in 1927
- Compartment model

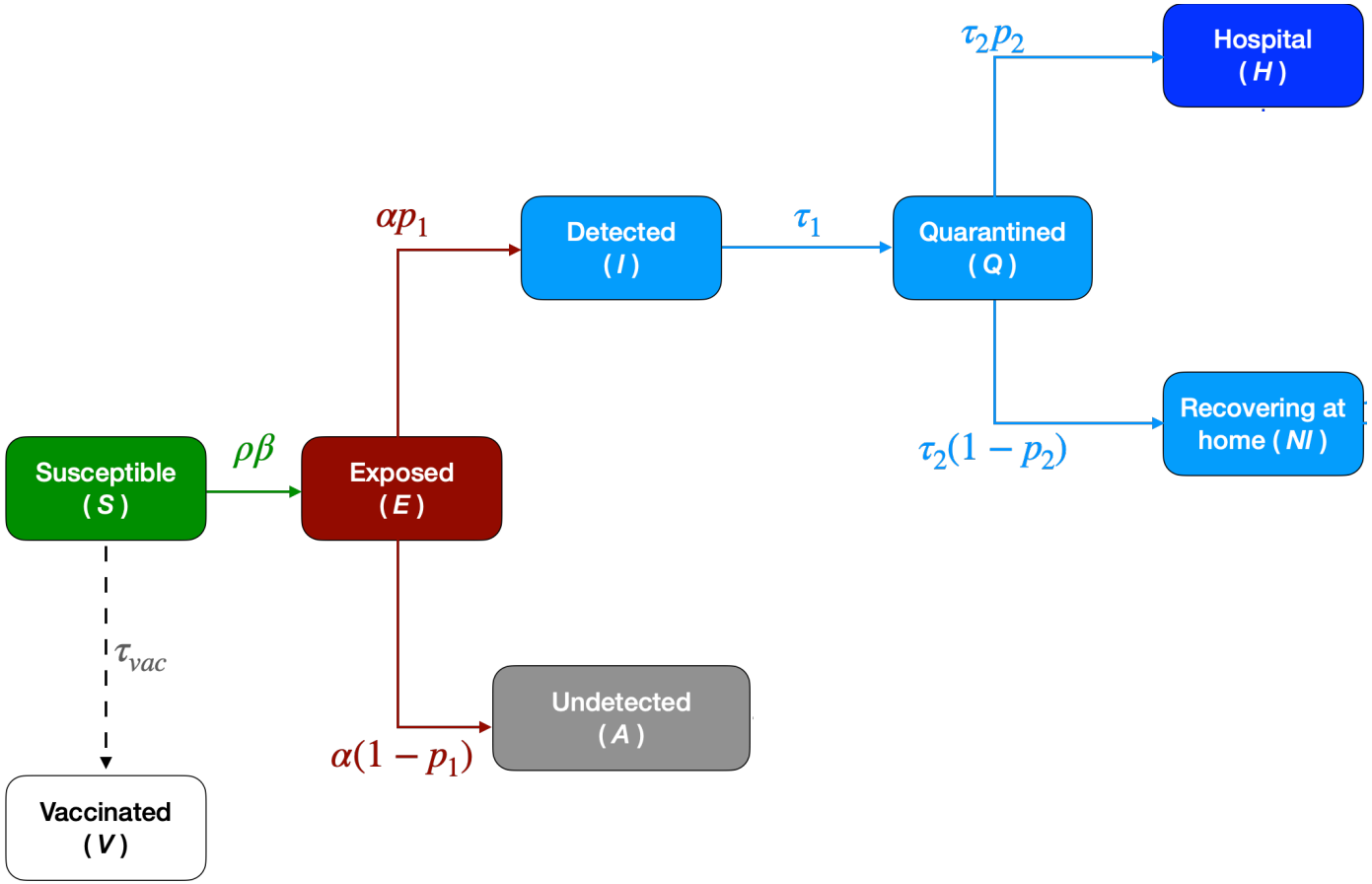


Scheme of extended SEIR model for ICU/hospital

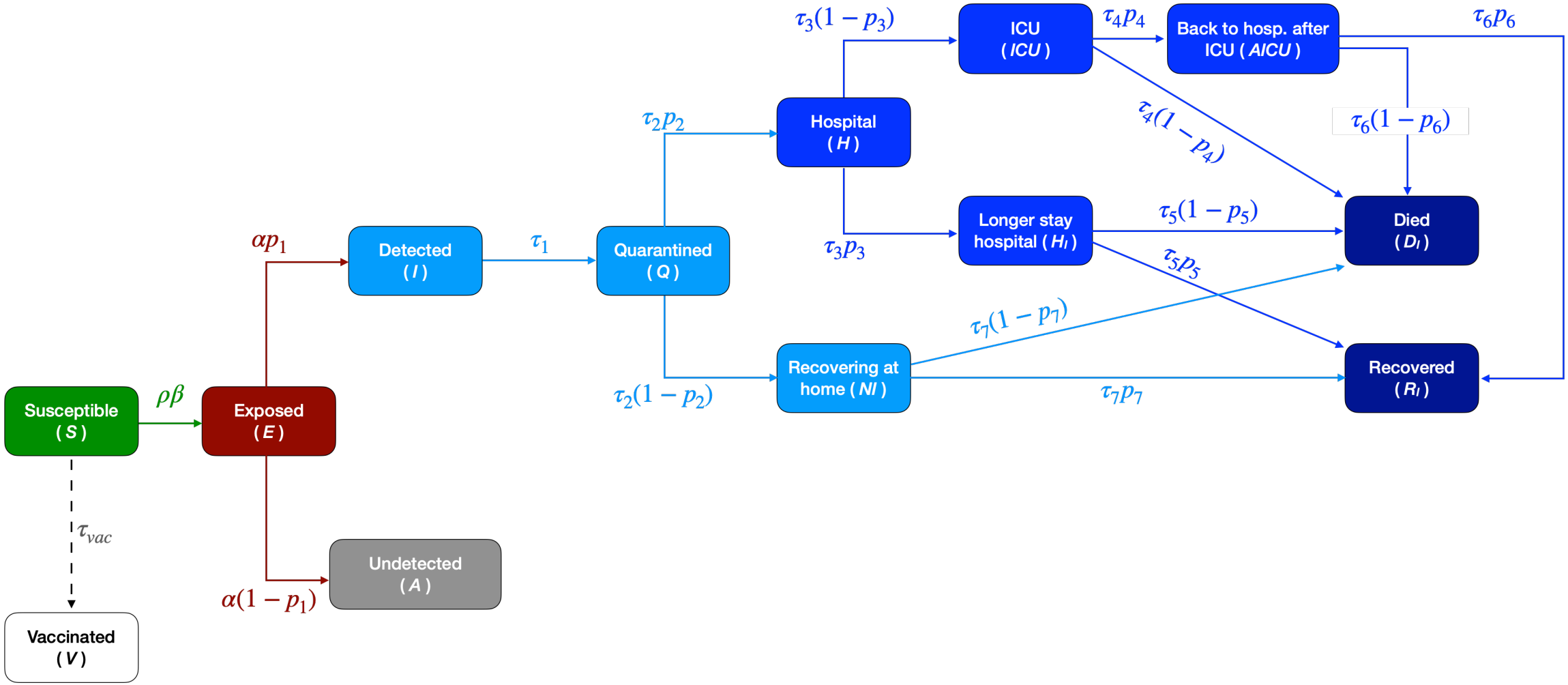


Parameter	Description	Units
ρ_n	social distancing $(n = 0, \ldots, 14)$	$adim.$
β	average contact rate	$days^{-1}$
α	$(\text{mean incubation period})^{-1}$	$days^{-1}$
τ_1	$(\text{mean time in } I)^{-1}$	$days^{-1}$
τ_2	$(\text{mean time in } Q)^{-1}$	$days^{-1}$
τ_3	$(\text{mean time in } H)^{-1}$	$days^{-1}$
τ_4	$(\text{mean time in } ICU)^{-1}$	$days^{-1}$
τ_5	$(\text{mean time in } Hl)^{-1}$	$days^{-1}$
τ_6	$(\text{mean time in } AICU)^{-1}$	$days^{-1}$
τ_7	$(\text{mean time in } NI)^{-1}$	$days^{-1}$
τ_8	$(\text{mean time in } A)^{-1}$	$days^{-1}$
τ_9	$(\text{mean time in } NII)^{-1}$	$days^{-1}$
p_1	probability of $E \to I$	$adim.$
p_2	probability of $Q \to H$	$adim.$
p_3	probability of $H \to Hl$	$adim.$
p_4	probability of $ICU \to AICU$	$adim.$
p_5	probability of $Hl \to R_{II}$	$adim.$
p_6	probability of $AICU \to R_{II}$	$adim.$
p_7	probability of $N_I \to R_{II}$	$adim.$
p_9	probability of $NII \to R_A$	$adim.$

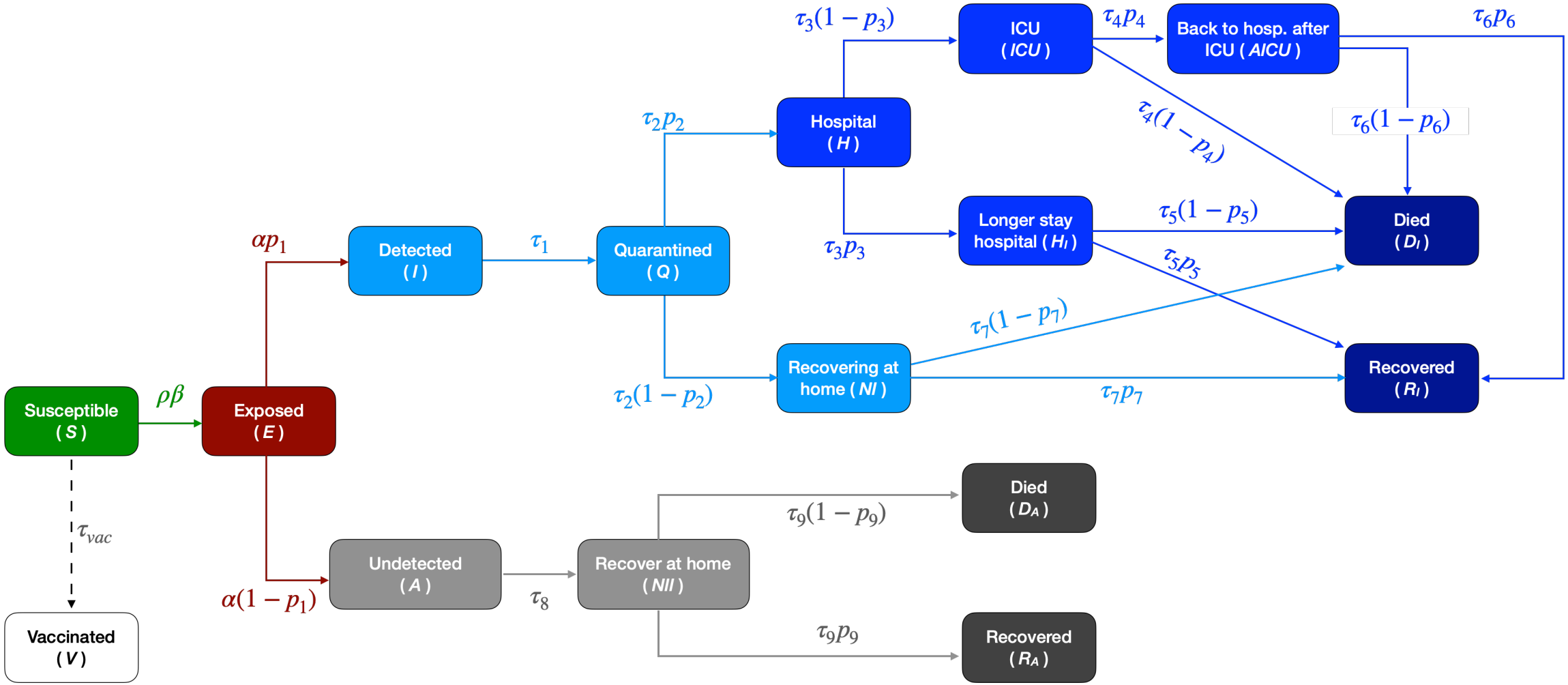
Scheme of extended SEIR model for ICU/hospital



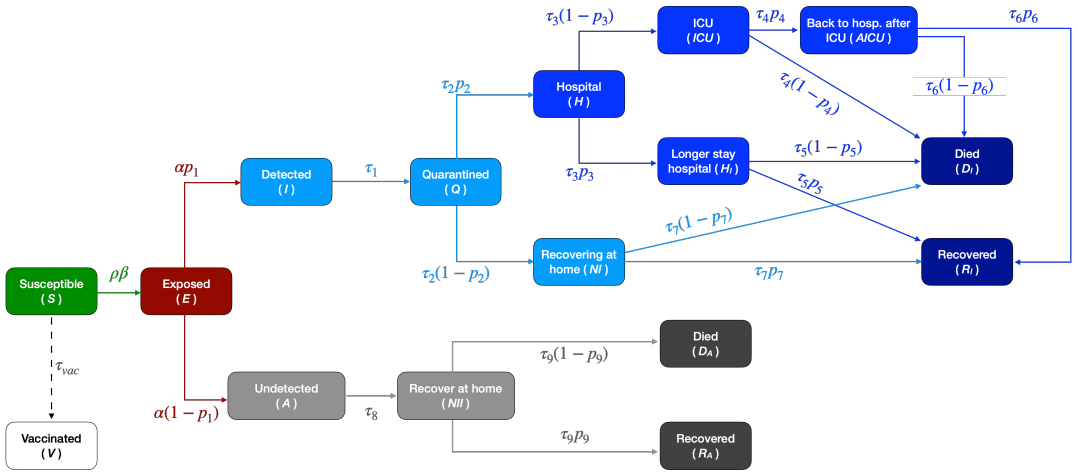
Scheme of extended SEIR model for ICU/hospital



Scheme of extended SEIR model for ICU/hospital



Scheme of extended SEIR model for ICU/hospital



- System of 18 ODE
- 22 parameters
- 18 variables

$$\frac{dS}{dt} = -\rho\beta(A + I_{\cdot})S - \tau_{vac} ,$$
$$\frac{dE}{dt} = \rho\beta S(A + I_{\cdot}) - \alpha E ,$$
$$\frac{dI}{dt} = \alpha p_1 E - \tau_1 I ,$$
$$\frac{dQ}{dt} = \tau_1 I - Q\tau_2 p_2 - (1-p_2)\tau_2 Q ,$$
$$\frac{dH}{dt} = p_2\tau_2 Q - p_3 H\tau_3 - (1-p_3)H\tau_3 ,$$
$$\frac{dHl}{dt} = p_3 H\tau_3 - Hl\tau_5(1-p_5) - \tau_5 p_5 Hl ,$$
$$\frac{dICU}{dt} = (1-p_3)H\tau_3 - p_4\tau_4 ICU - (1-p_4)ICU\tau_4 ,$$
$$\frac{dAICU}{dt} = \tau_4 p_4 ICU - p_6 AICU\tau_6 - AICU(1-p_6)\tau_6 ,$$
$$\frac{dR_I}{dt} = p_6\tau_6 AICU + p_5\tau_5 Hl ,$$
$$\frac{dR_{I1}}{dt} = p_7\tau_7 NI ,$$
$$\frac{dNI}{dt} = (1-p_2)\tau_2 Q - \tau_7(1-p_7)NI - p_7\tau_7 NI ,$$
$$\frac{dD_{I,hom}}{dt} = (1-p_7)\tau_7 NI ,$$
$$\frac{dD_{I,hos}}{dt} = (1-p_6)\tau_{6,d} AICU + (1-p_5)\tau_5 Hl + \tau_4(1-p_4)ICU ,$$
$$\frac{dA}{dt} = (1-p_1)\alpha E - \tau_8 A ,$$
$$\frac{dNII}{dt} = \tau_8 A - \tau_9(1-p_9)NII - p_9\tau_9 NII ,$$
$$\frac{dD_A}{dt} = \tau_9(1-p_9)NII ,$$
$$\frac{R_A}{dt} = \tau_9 p_9 NII .$$
$$\frac{dV}{dt} = \tau_{vac} ,$$

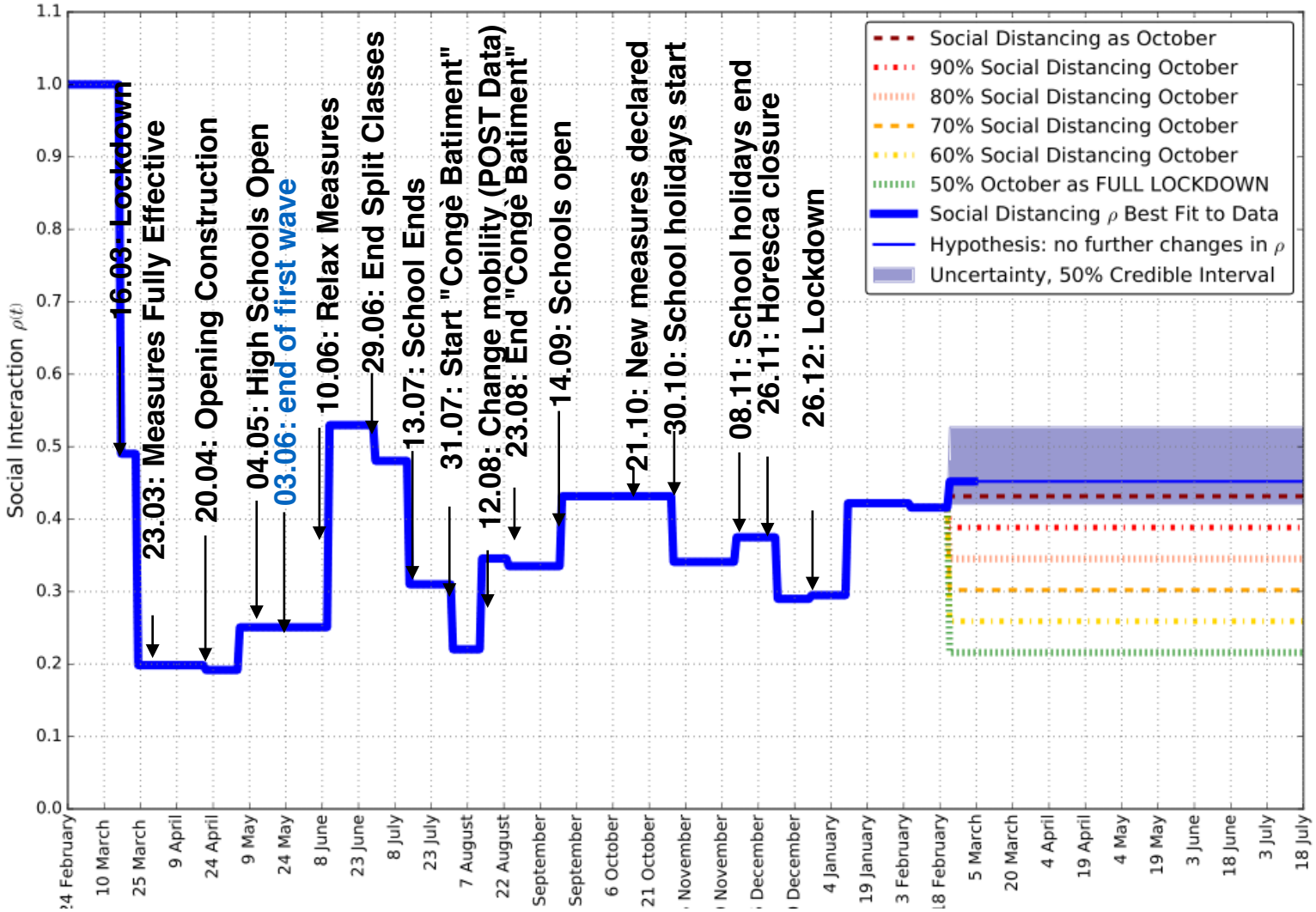
Social interaction is the driver of the epidemic

- Social distancing key in order to reduce the spread
- Implemented as a piecewise constant function of time

$$\frac{dS}{dt} = -\rho\beta(A + I)S - \tau_{vac}$$

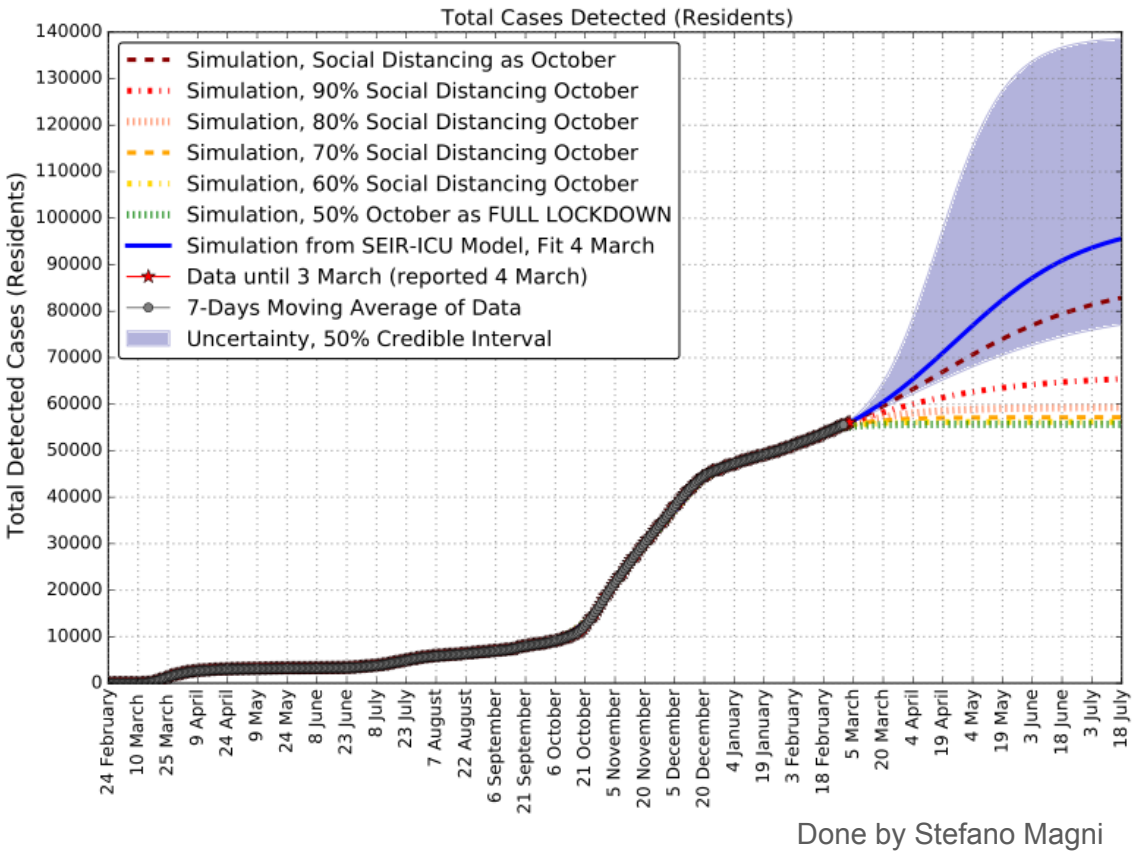
$$\frac{dE}{dt} = \rho\beta(A + I)S - \alpha E$$

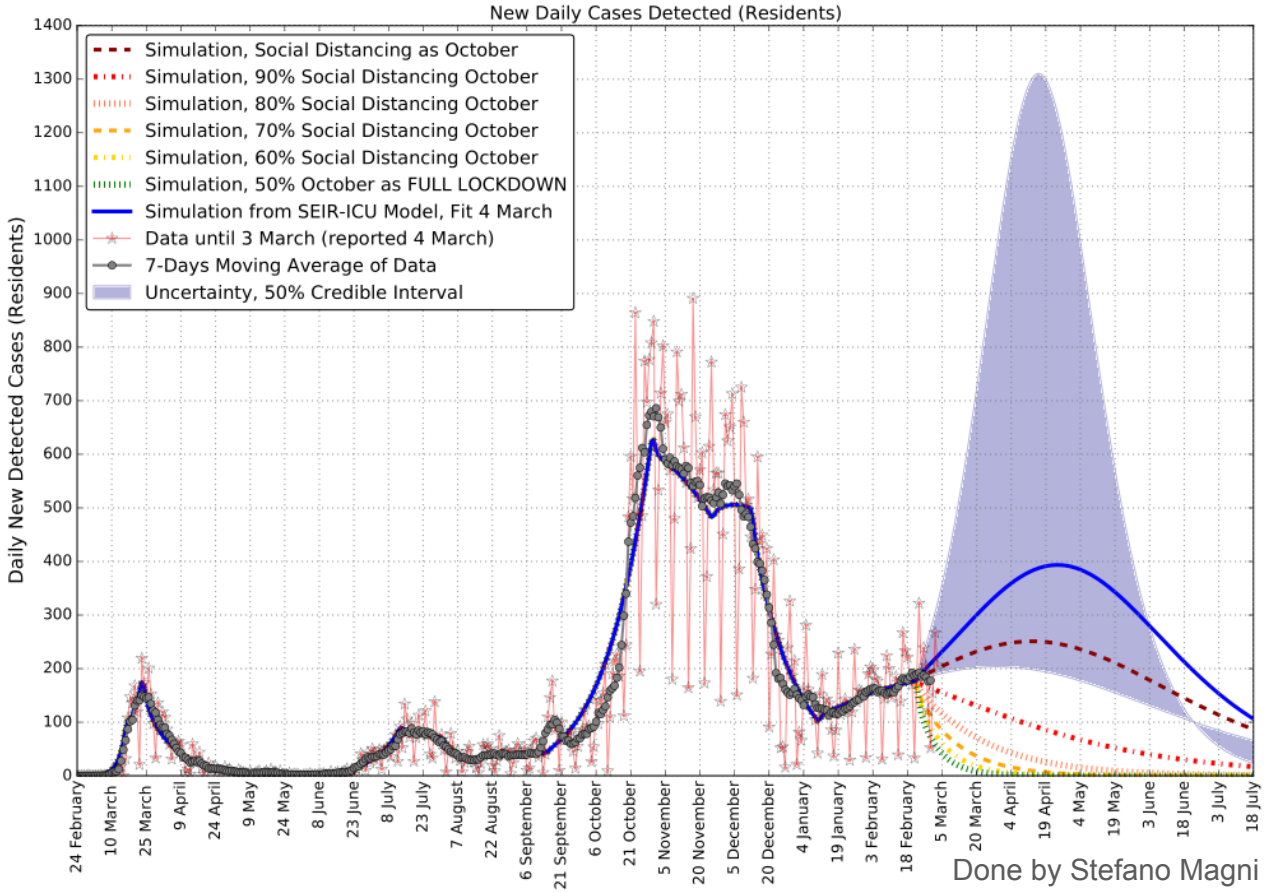
Change of rho for Luxembourg



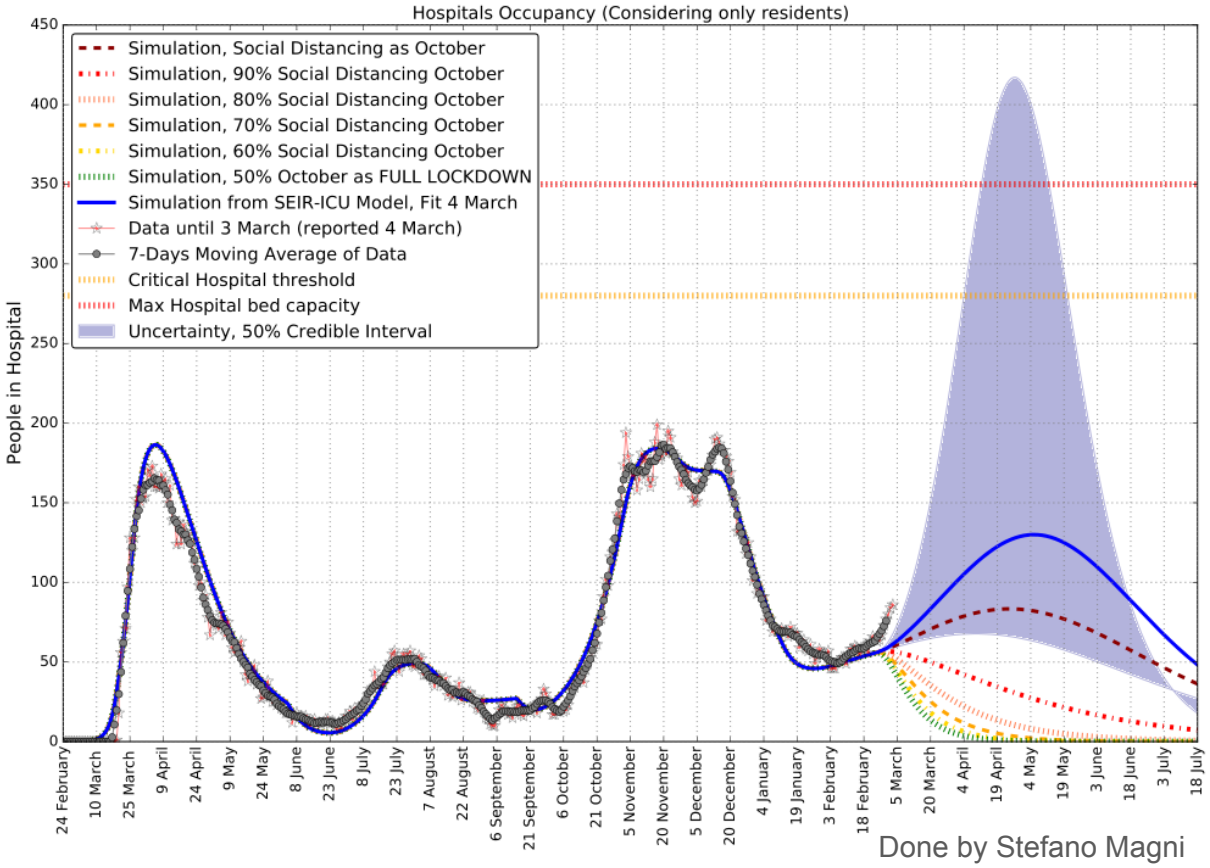
Projections for Luxembourg

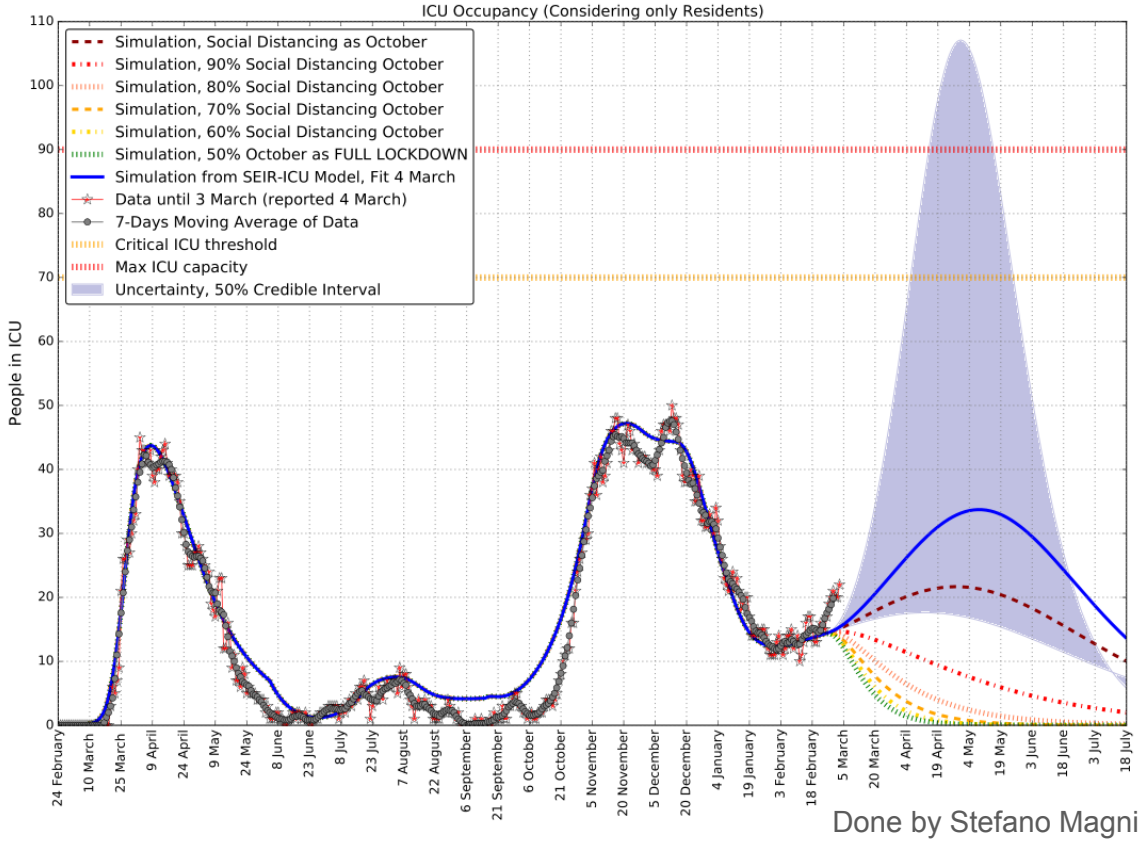
9% of population had a detected COVID-19 infection





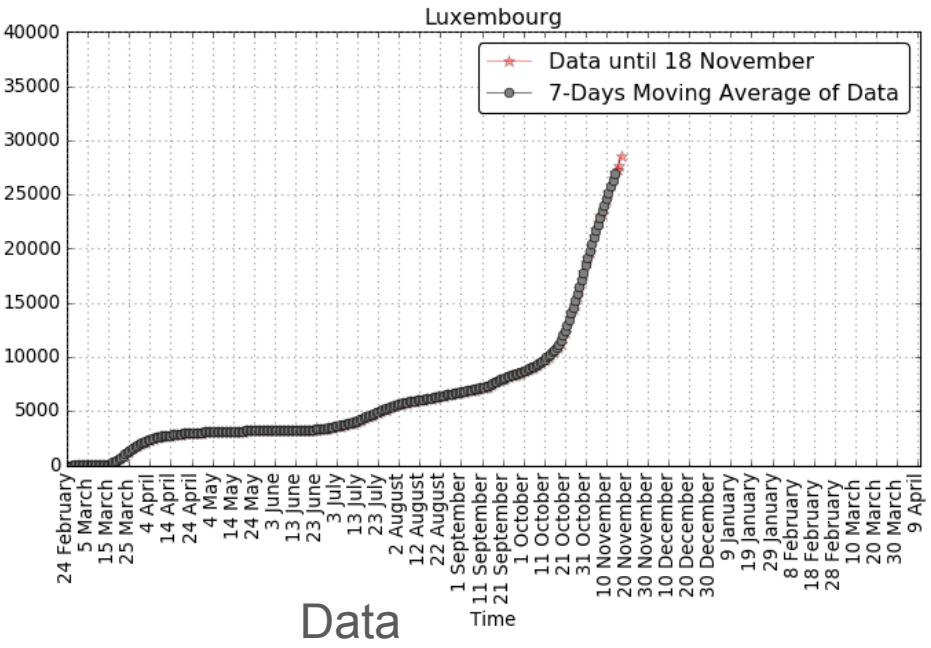
Projections for Luxembourg





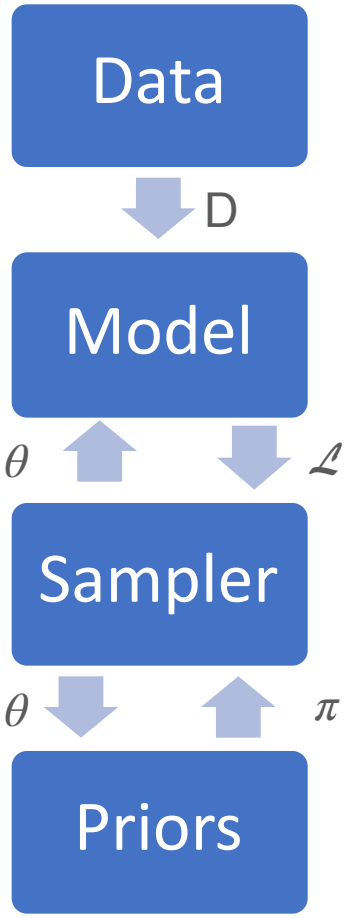
Schematic MCMC

INPUT



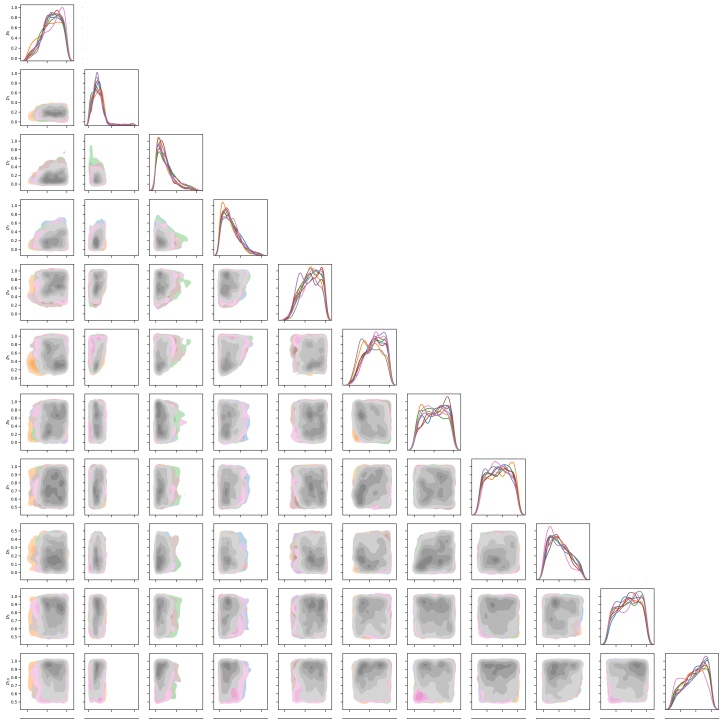
Data

PROCESS



MCMC

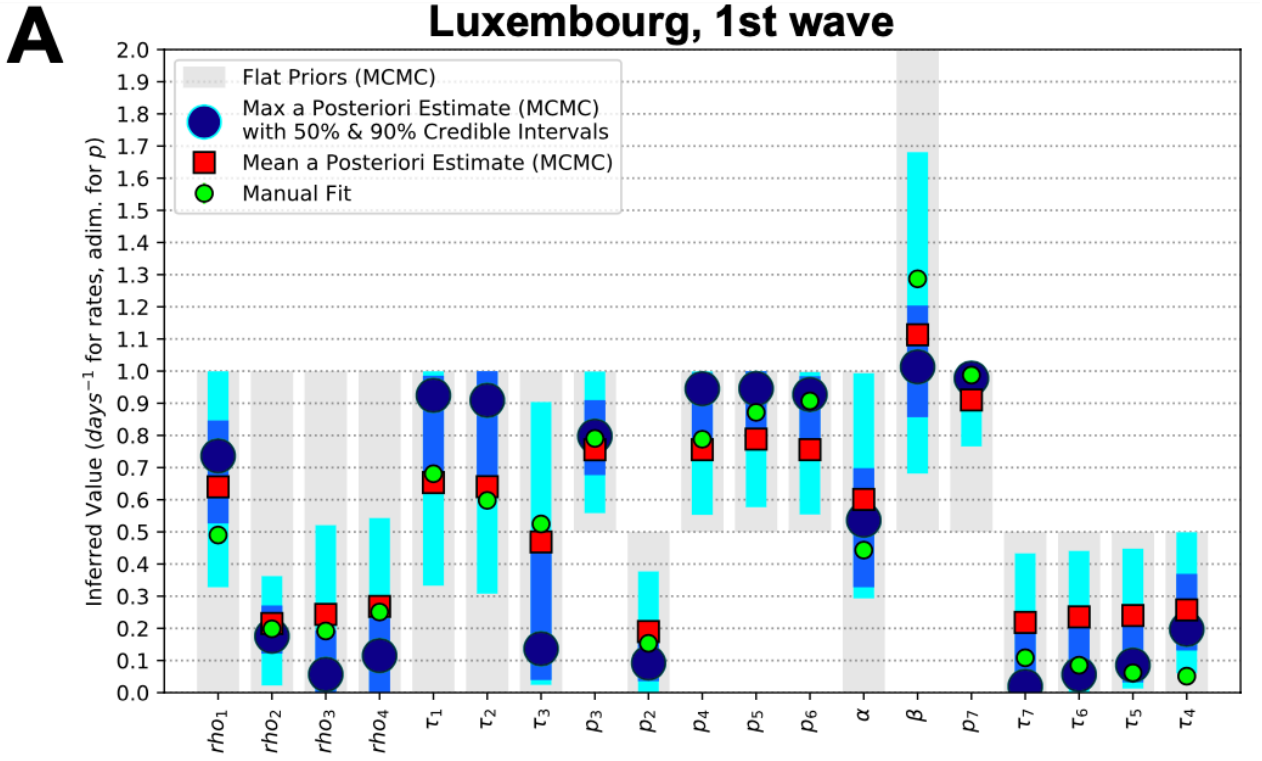
OUTPUT

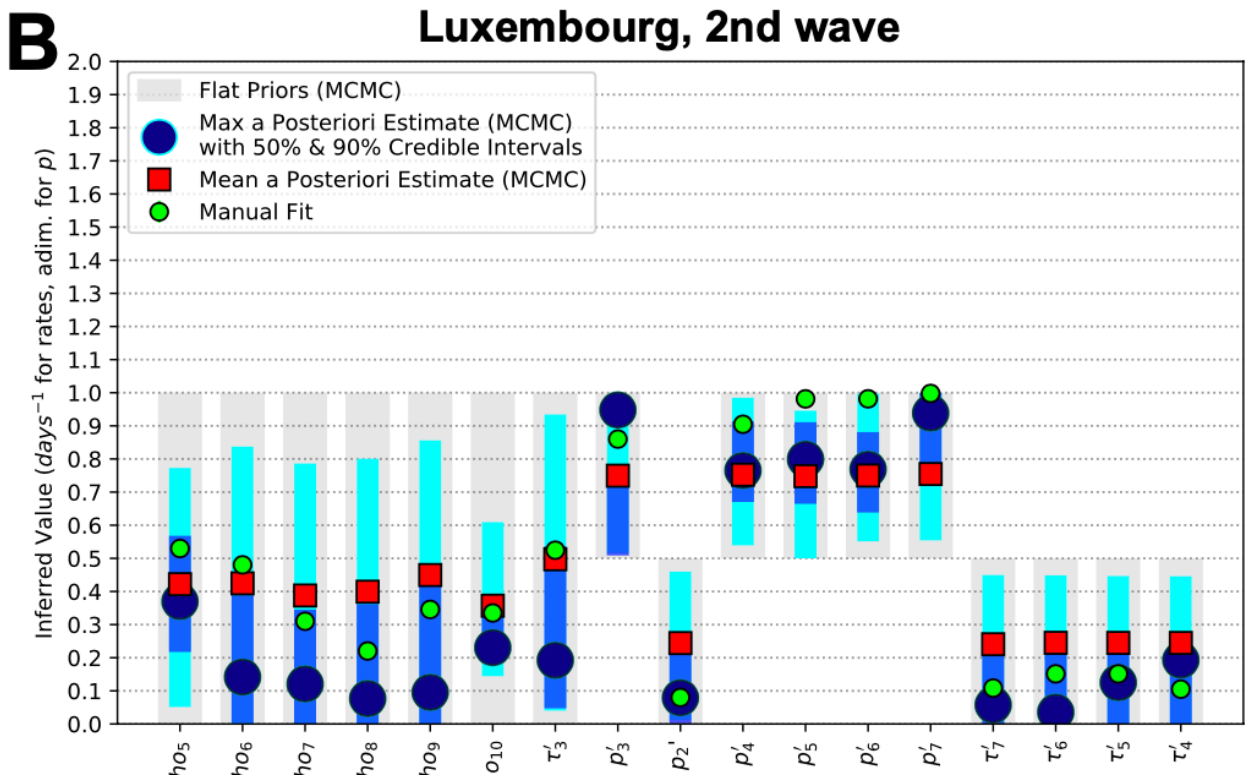


Posterior

Changes in the parameter

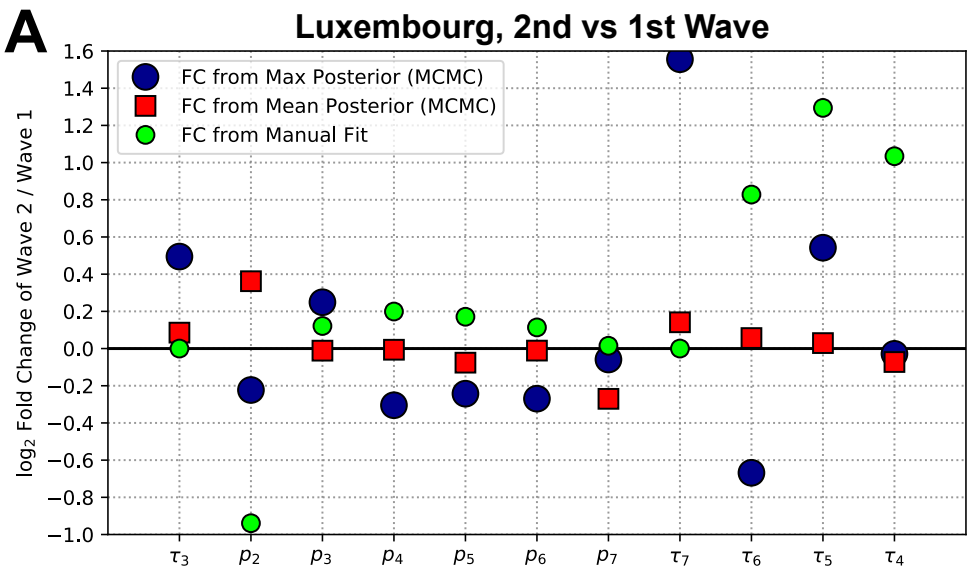
- Very close either to the maximum or the mean posteriori estimate
- Fully consistent with our manually calibrated set

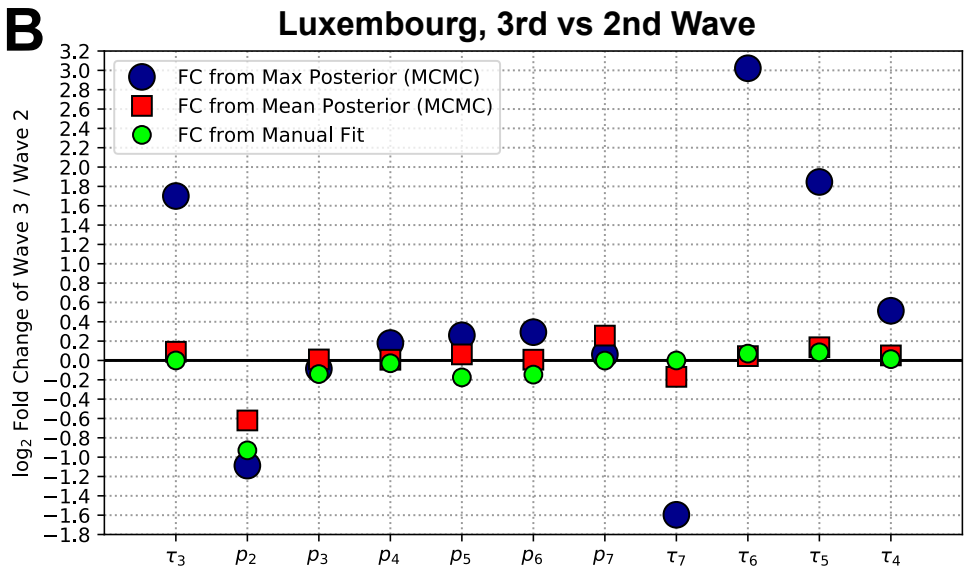




Fold changes between the different waves

- Changes observed by different fitting methods
- p_2 decreased between the subsequent waves



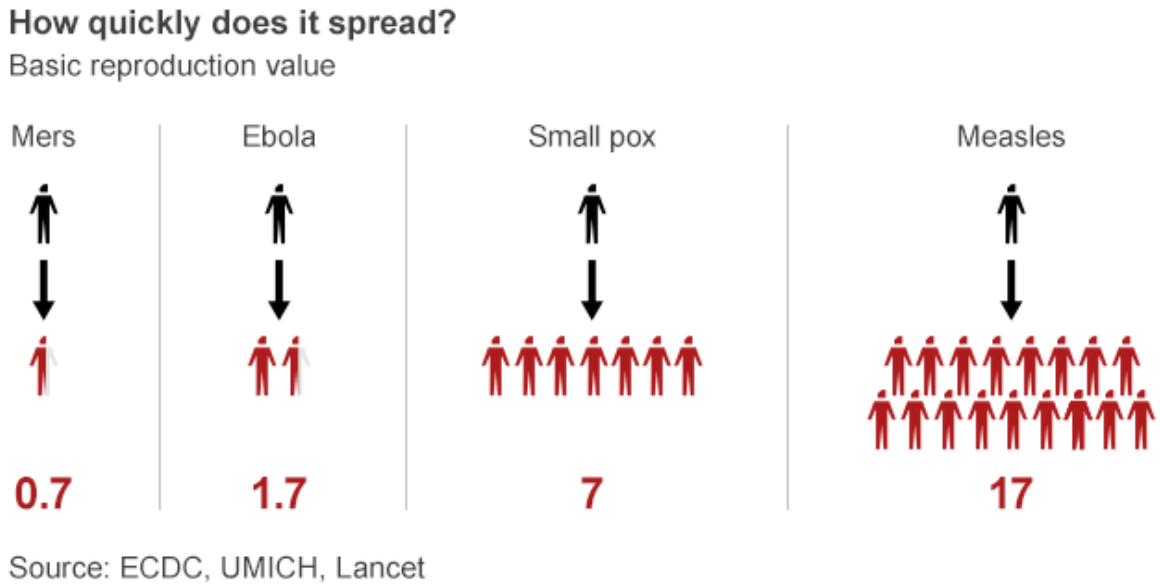


Parameter	Manual fit Luxembourg		
	1st wave	2nd	3rd
β	1.287	-	-
α	0.4433	-	-
τ_1	0.6808	-	-
τ_2	0.5979	-	-
τ_3	0.5246	-	-
τ_4	0.0513	0.1050	0.106
τ_5	0.0617	0.1514	0.1605
τ_6	0.0853	0.1514	0.1590
τ_7	0.1084	0.1084	-
p_1	0.31	0.41	-
p_2	0.1534	0.08	0.042
p_3	0.7906	0.86	0.78
p_4	0.7906	0.9048	0.8868
p_5	0.8717	0.9814	0.8692
p_6	0.9072	0.9816	0.8868
p_7	0.9876	0.9979	0.997

Basic reproduction

- signifying the average number of cases each infected person will cause, if no action is taken. "0" refers to "time zero" (beginning) of the epidemic
- $R_0 = \frac{\beta}{\gamma}$
- R_0 < 1 the disease cannot invade the population
- R_0 > 1 invasion is possible and infection can spread
- obtained by next generation matrix method
- R_0 is one of the eigenvalues

$$R_0 = \beta[\frac{(1-p_1)}{\tau_8} + \frac{p_1}{\tau_1}]$$

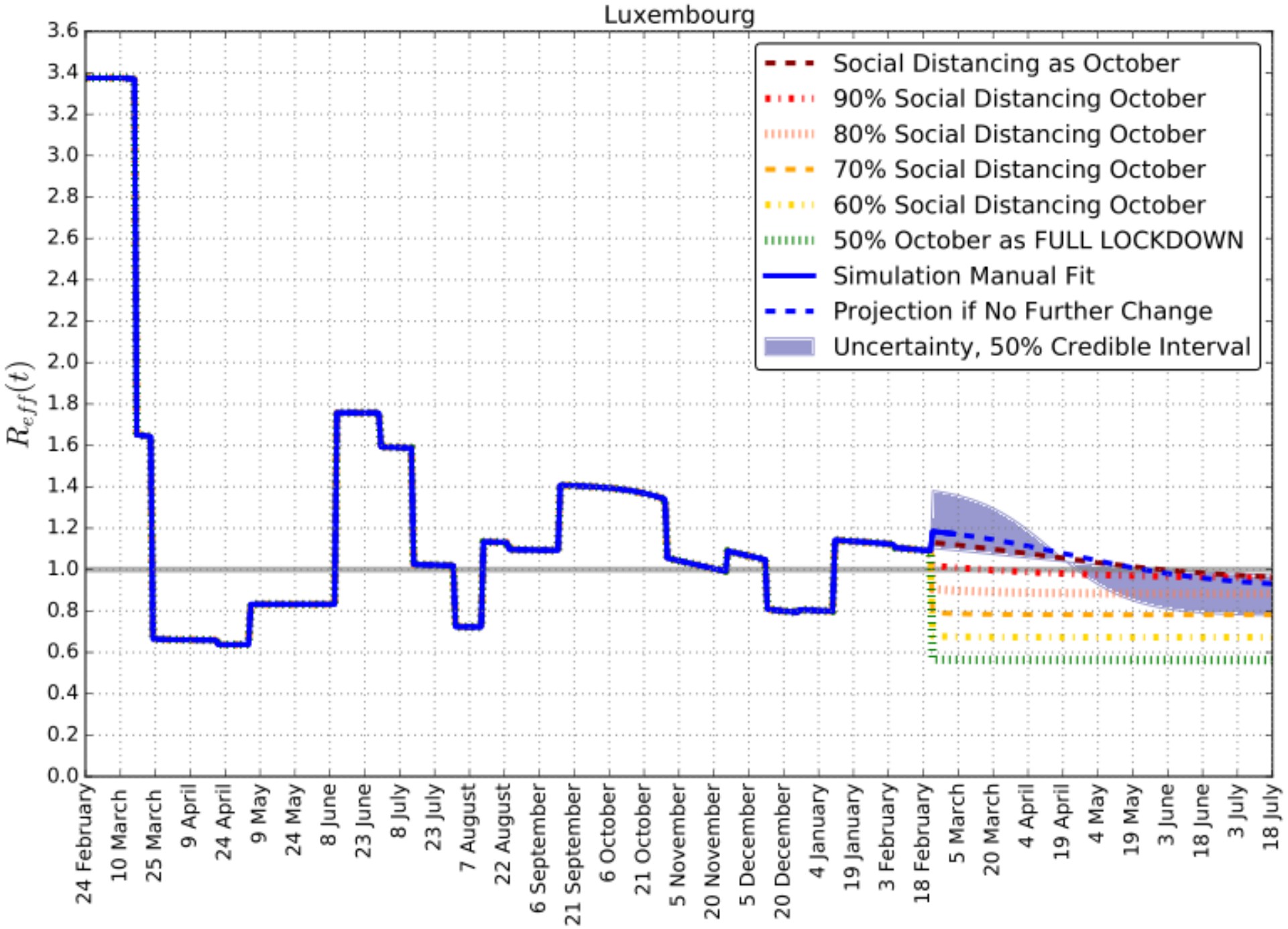


Effective reproduction number

- R_e calculated at different time points during the epidemic, i.e. the average number of expected infected persons by a primary case in a population of
- susceptible and infected individuals

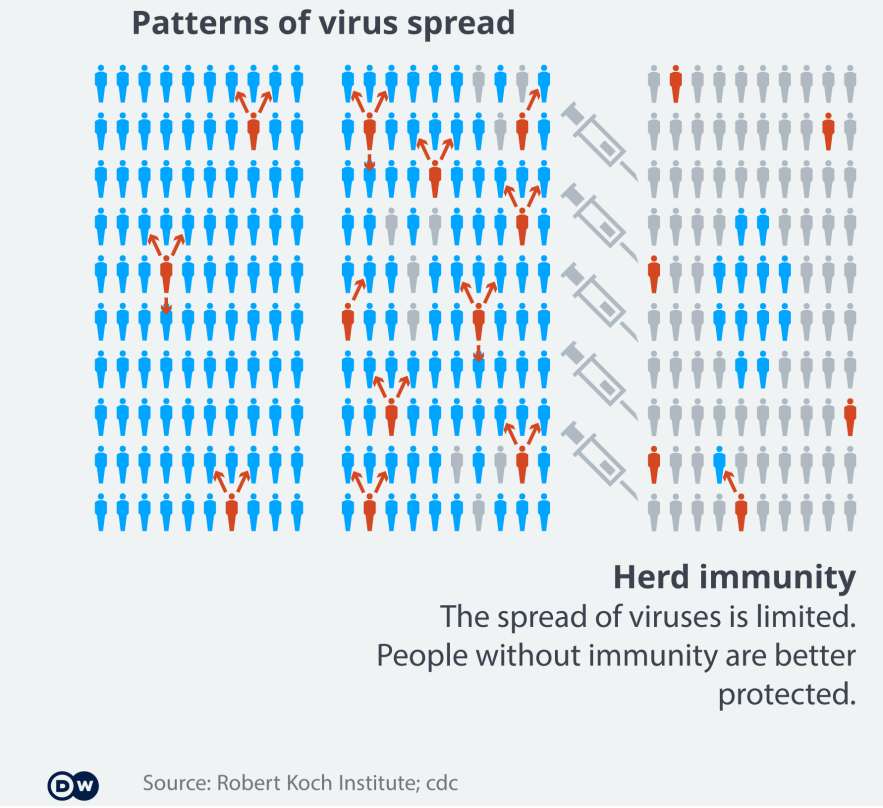
$$R_{eff} = \rho(t)\beta[\frac{1-p_1}{\tau_8} + \frac{p_1}{\tau_1}]\frac{S(t)}{N}$$

R- effective


Luxembourg
$R_{eff}(t)$
Social Distancing as October
90% Social Distancing October
80% Social Distancing October
70% Social Distancing October
60% Social Distancing October
50% October as FULL LOCKDOWN
Simulation Manual Fit
Projection if No Further Change
Uncertainty, 50% Credible Interval
3.6
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
24 February
10 March
25 March
9 April
24 April
9 May
24 May
8 June
23 June
8 July
23 July
7 August
22 August
6 September
21 September
6 October
21 October
5 November
20 November
5 December
20 December
4 January
19 January
3 February
18 February
5 March
20 March
4 April
19 April
4 May
19 May
3 June
18 June
3 July
18 July

Herd immunity

- also known as 'population immunity'
- a population is immune either through vaccination or immunity developed through previous infection
- vaccines train our immune systems to create proteins that fight disease



Vaccination in Luxembourg

	Journée du 02.03.2021	Total
Personnes vaccinées - Dose 1	817	**28 476**
Personnes vaccinées - Dose 2	525	**11 984**
Total des doses administrées	**1 342**	**40 460**

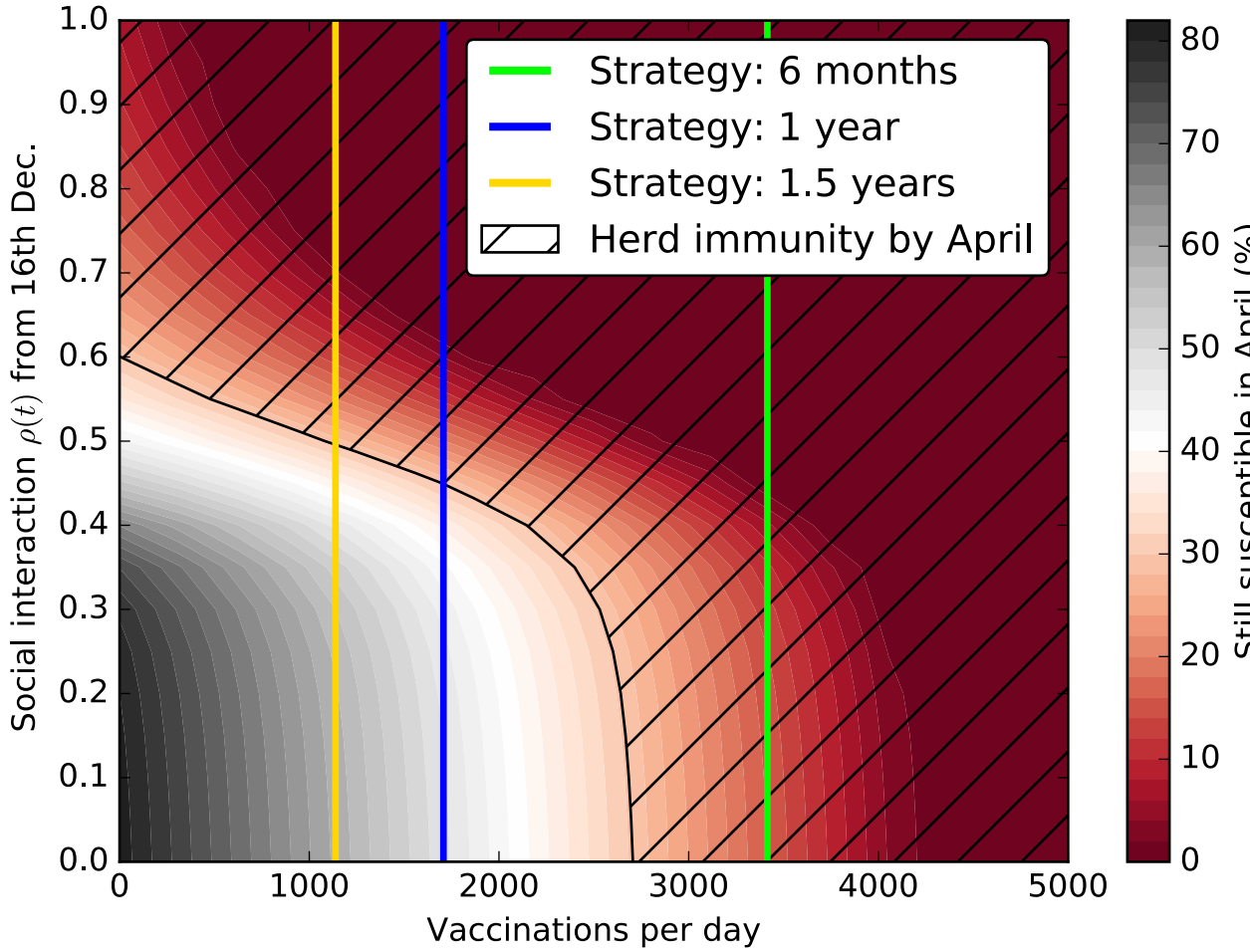
1.95% fully vaccinated Luxembourgish population
203 doses per day

Herd immunity by April

- The interplay between the vaccination dynamics and social interaction
- 3 potential vaccination strategies (6 months, 1 year and 1.5 years)
- Estimate for herd immunity:

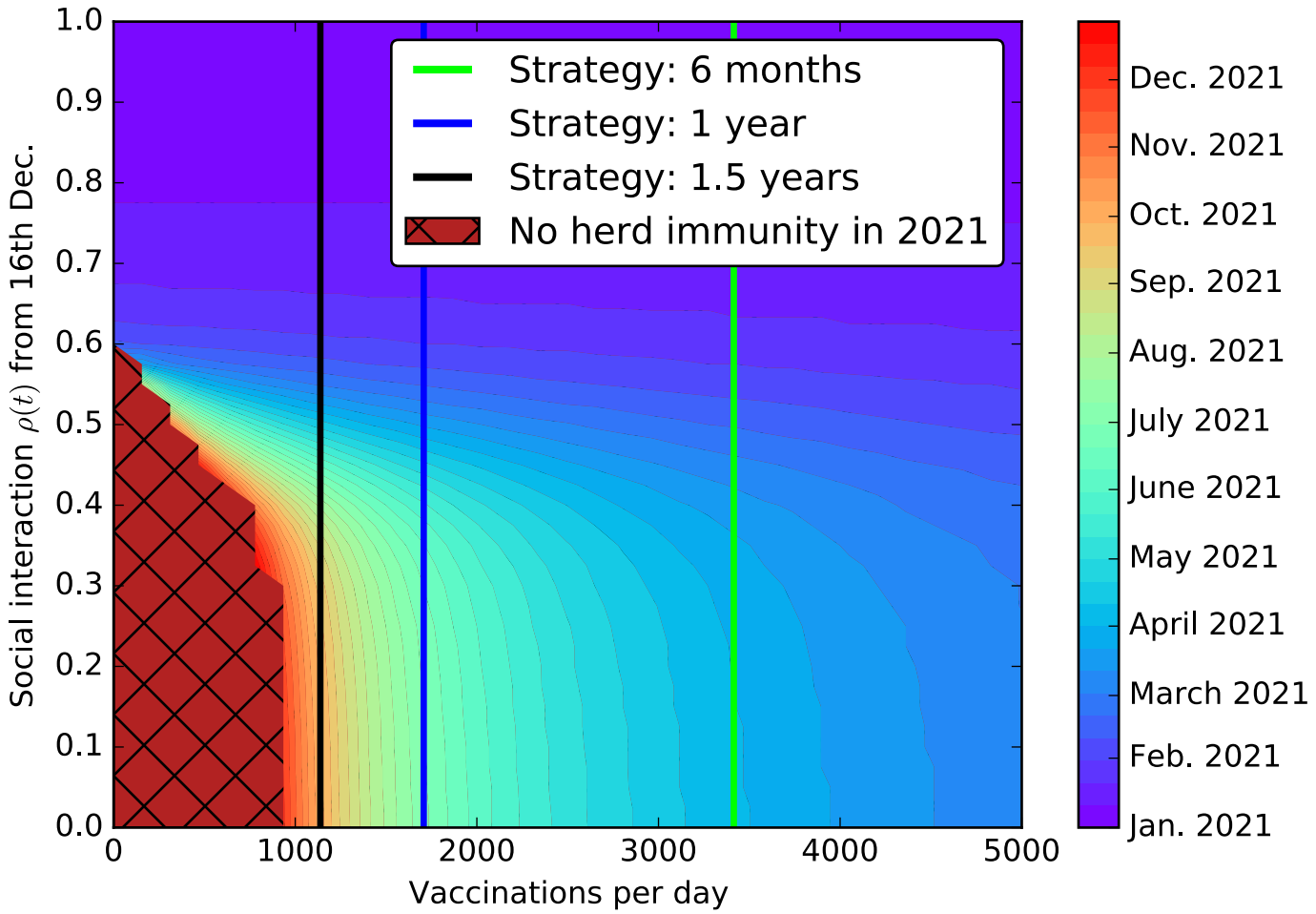
$$p_c = 1 - \frac{1}{R_0}$$

- 70% of population needing to be immune



Herd immunity for 2021

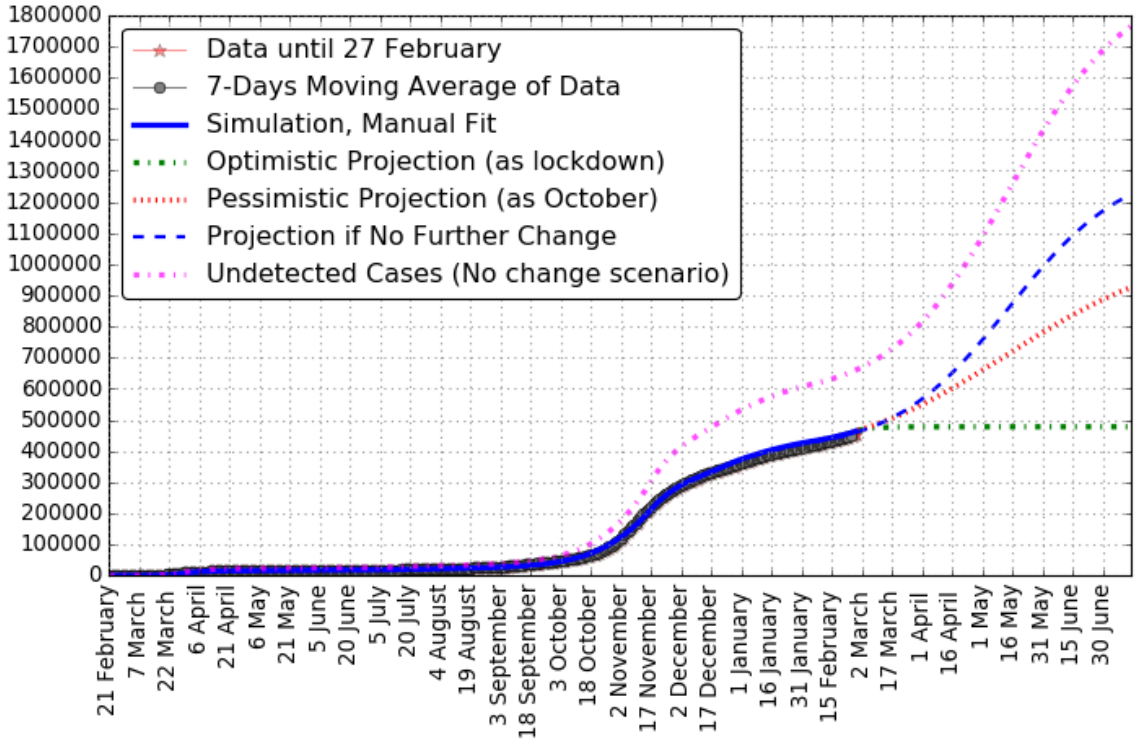
- All three vaccination strategies might lead to herd immunity in 2021



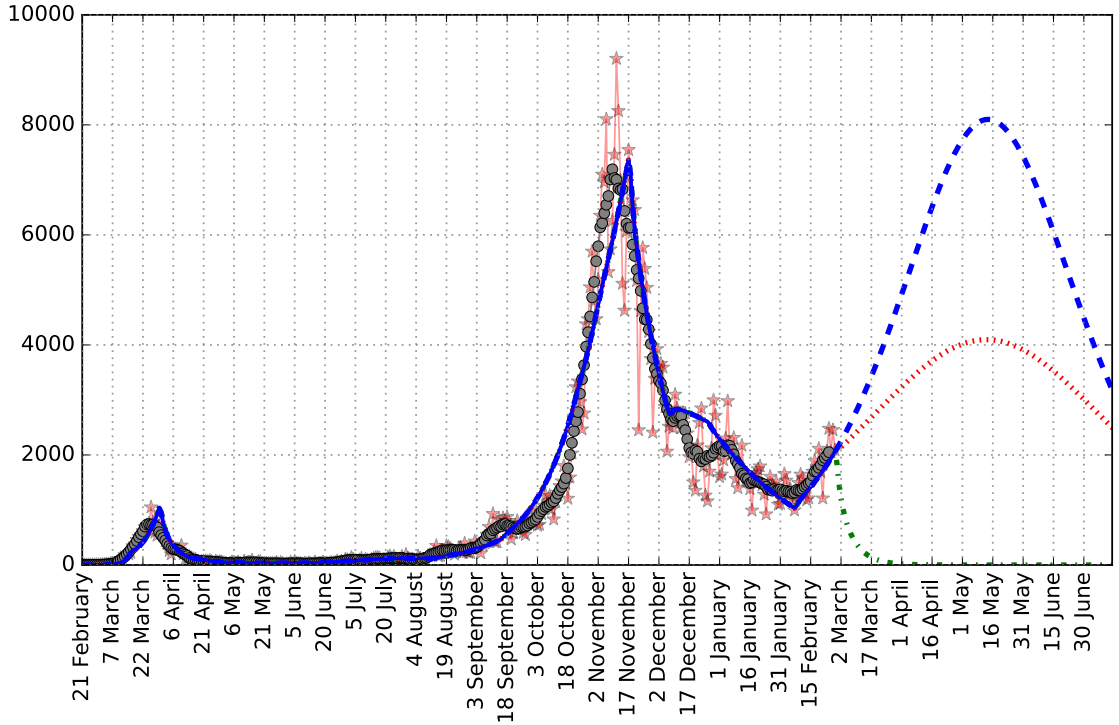
Corona in Austria

Projections of Austria

Total cases



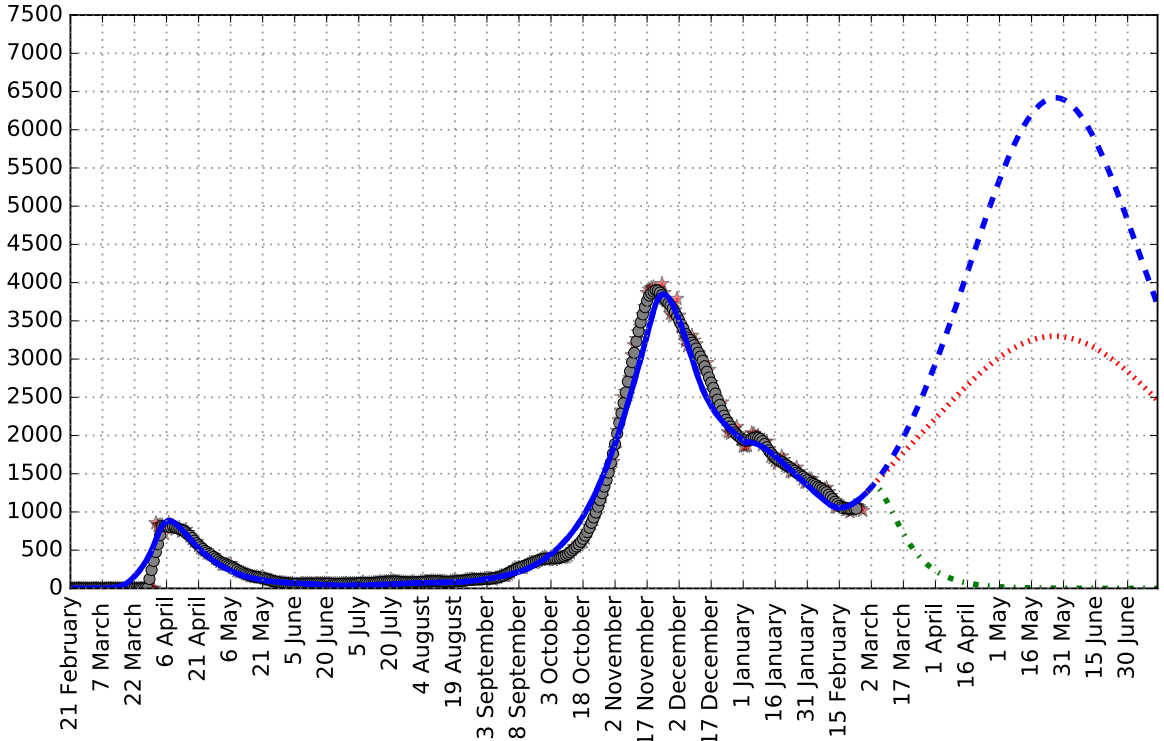
Daily new cases



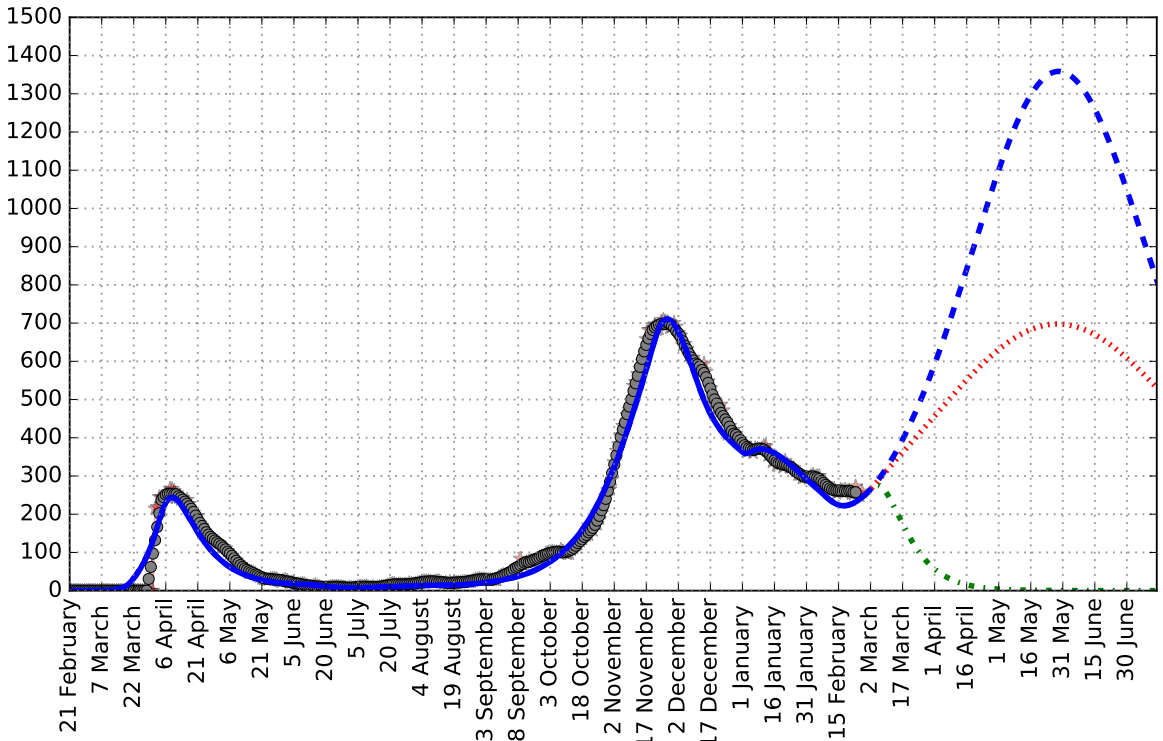
5.64% of population had a detected COVID-19 infection

Projections of Austria

Hospital

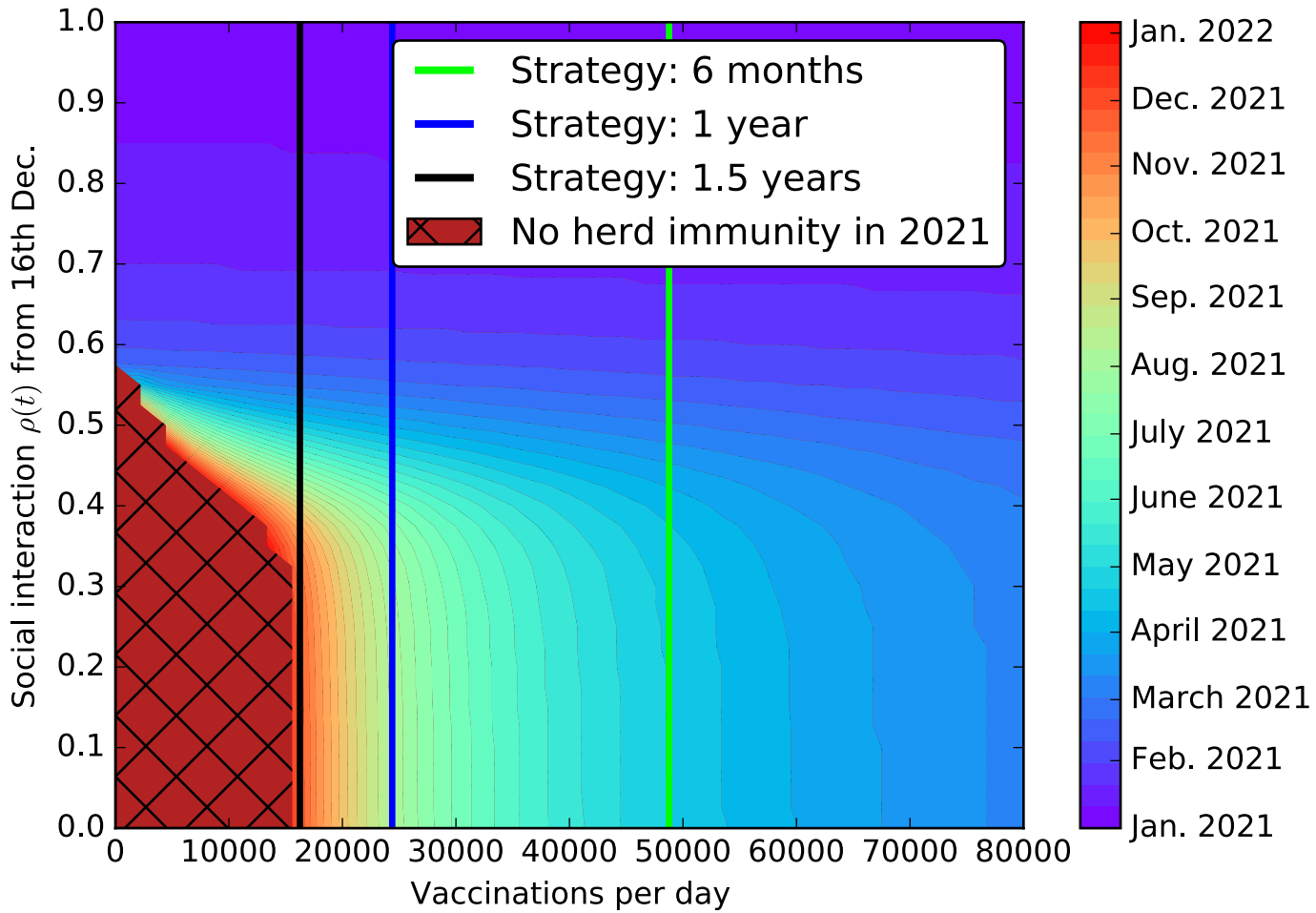


ICU



Herd immunity for 2021 in Austria

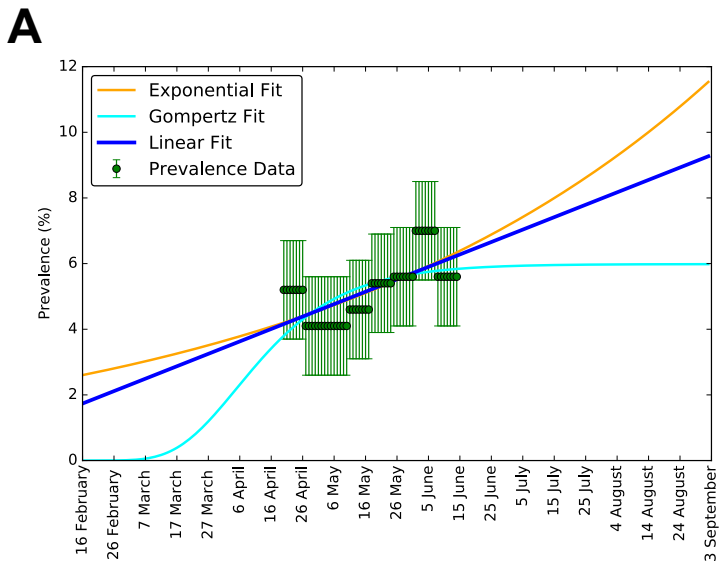
- 68% of population needing to be immune

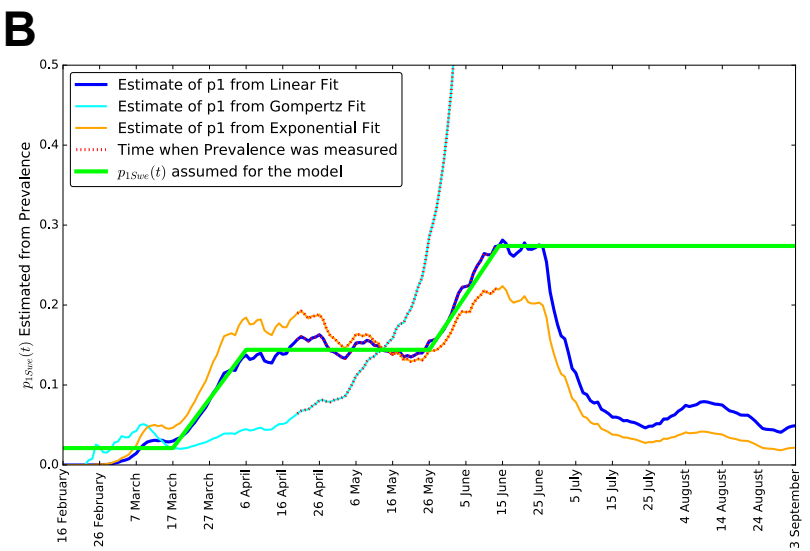


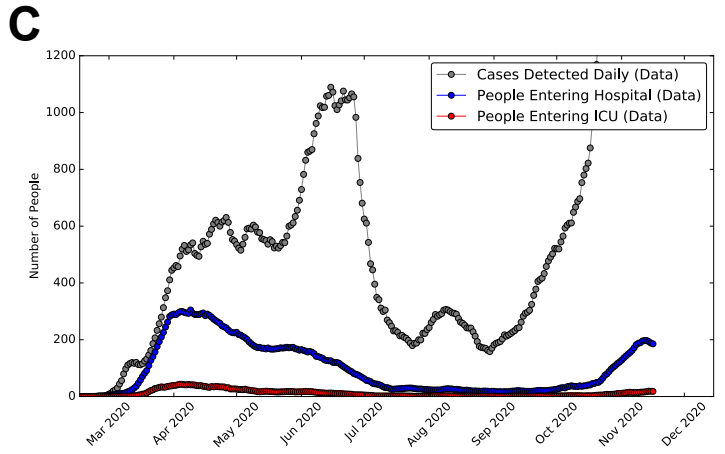
Corona in Sweden

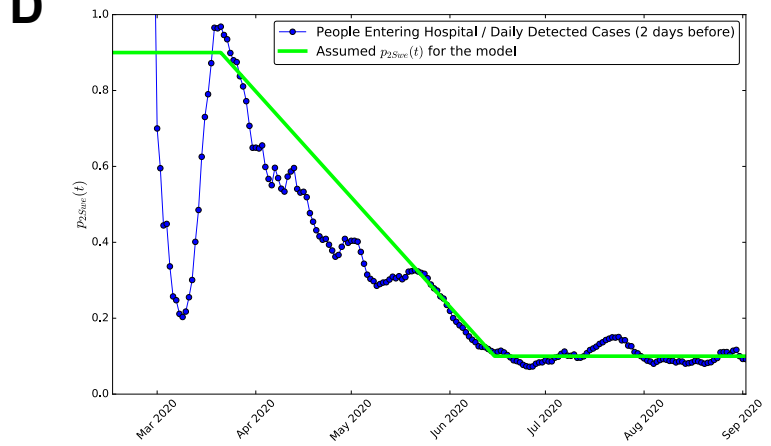
Time-dependent probabilities of detection and hospitalization

- Different strategies and experienced a different epidemic dynamics



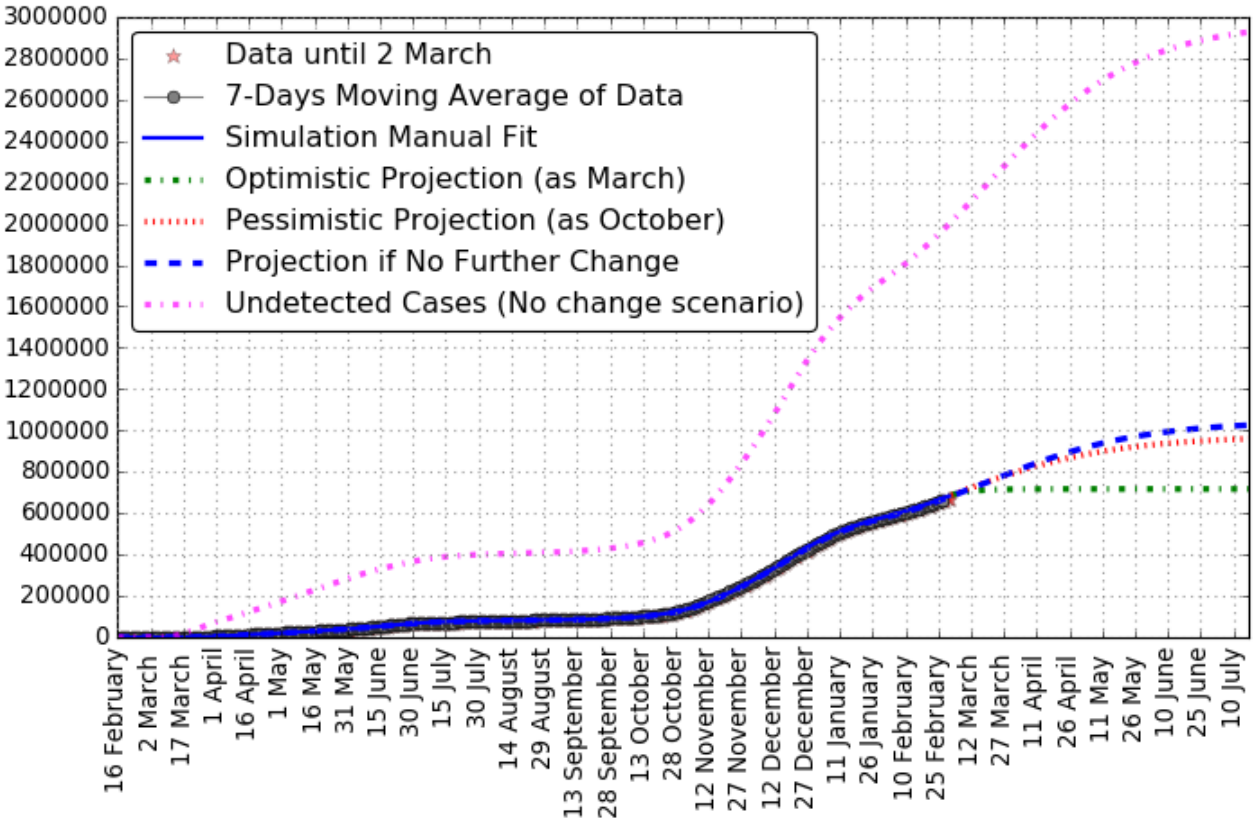




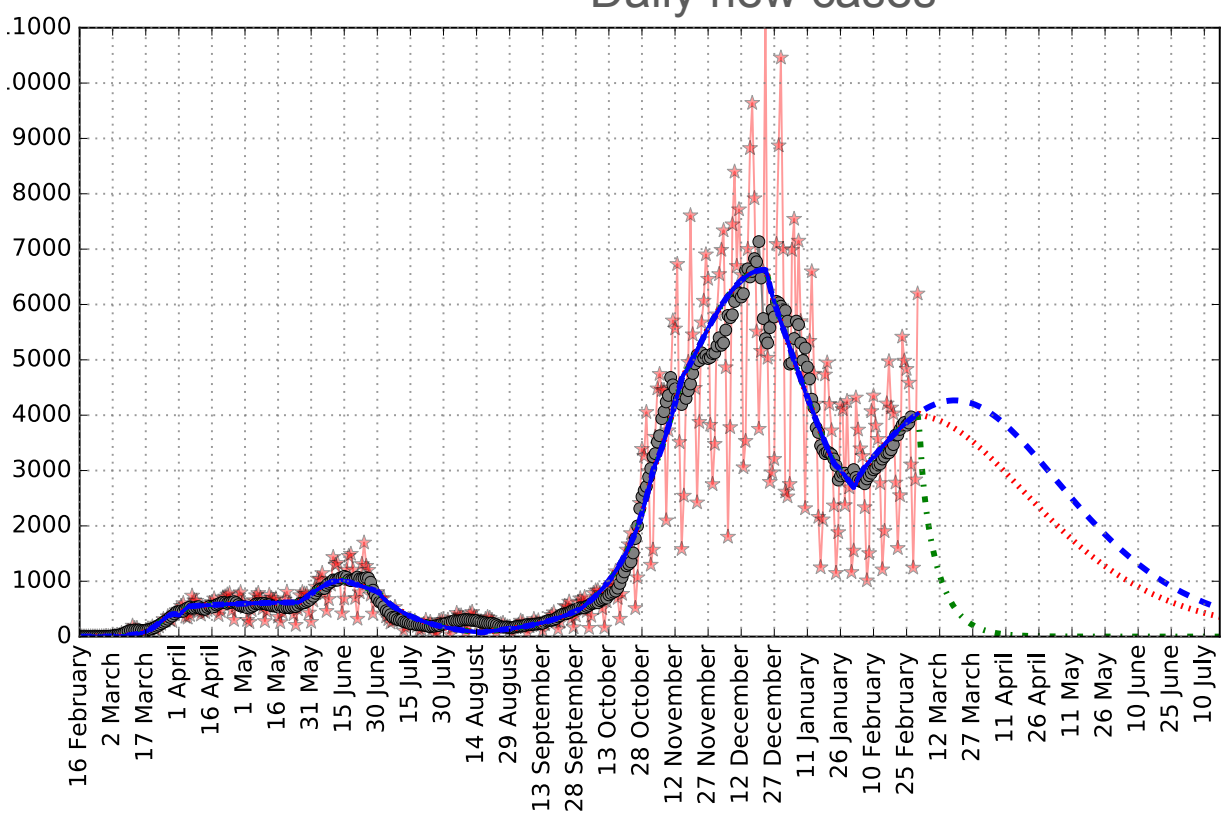


Projections of Sweden

Total cases



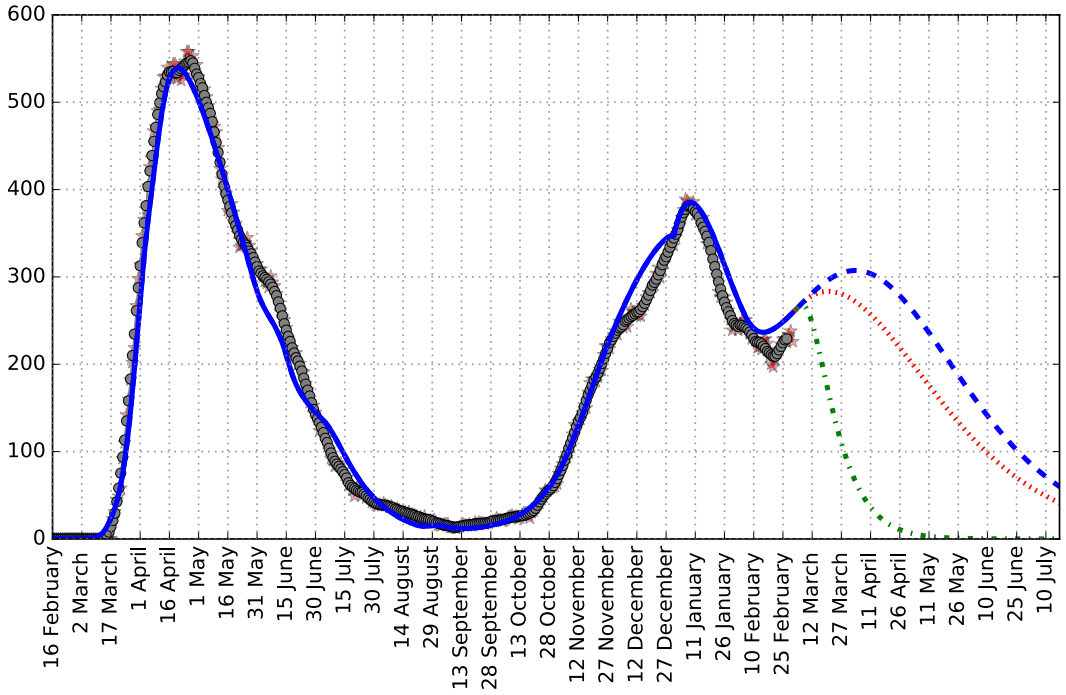
Daily new cases



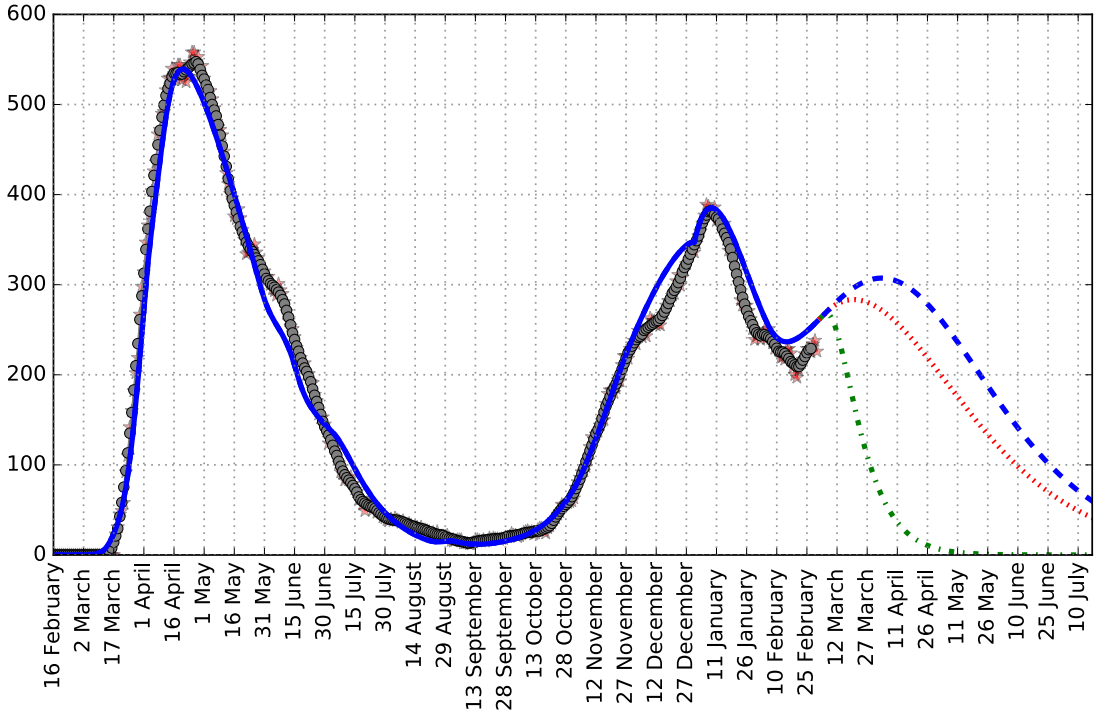
6.8% of population had a detected COVID-19 infection

Projections of Sweden

Hospital

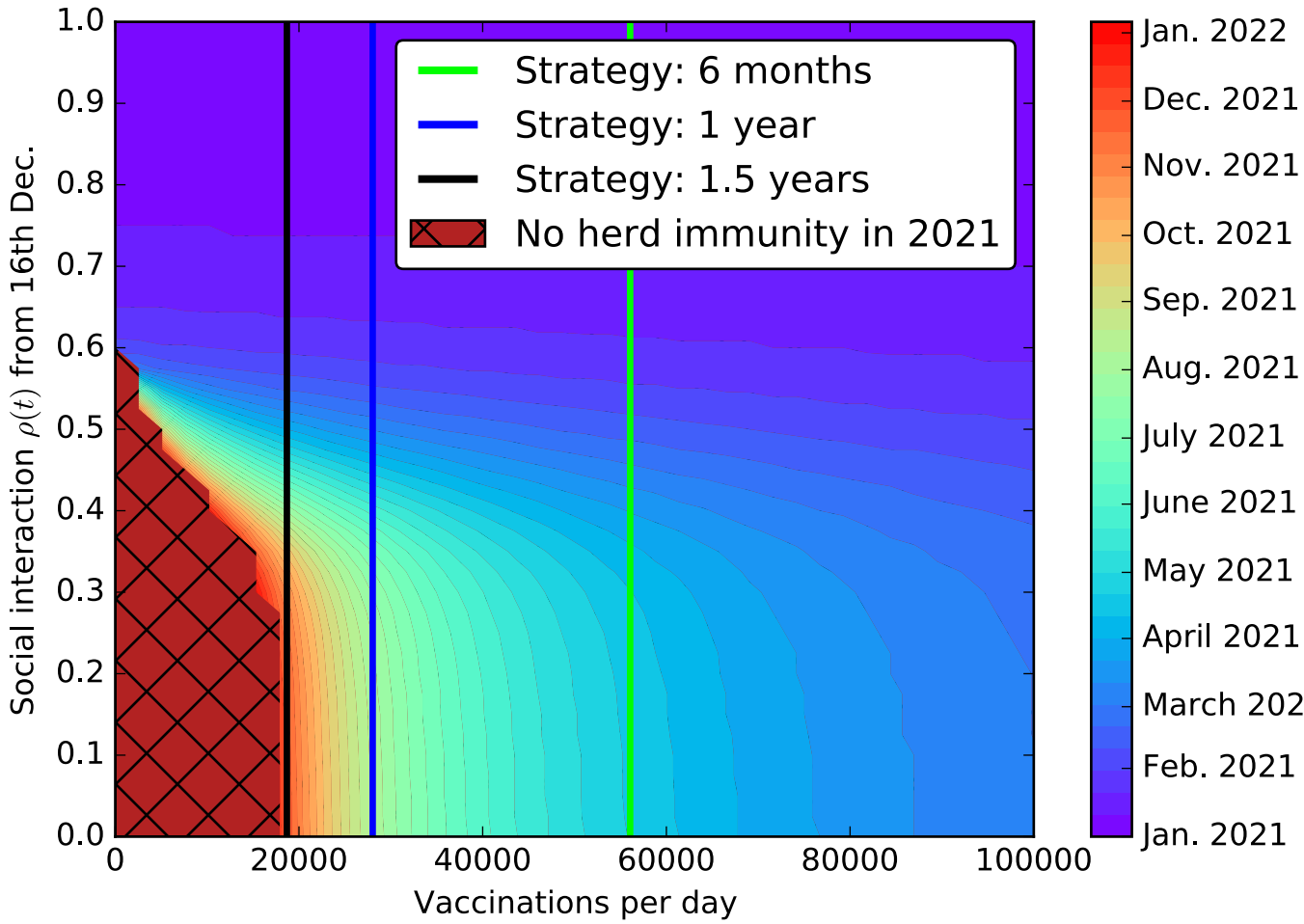


ICU



Herd immunity for 2021 in Sweden

- 75% of population needing to be immune



Summary of the talk

- model which describes all the stages of COVID-19
- Allows to describe the situation in Luxembourg, Austria and Sweden
- provides data-based estimations of the interplay between social measures and vaccination rollouts
- Luxembourg has the highest fraction of infected

Thanks for your attention

Supported
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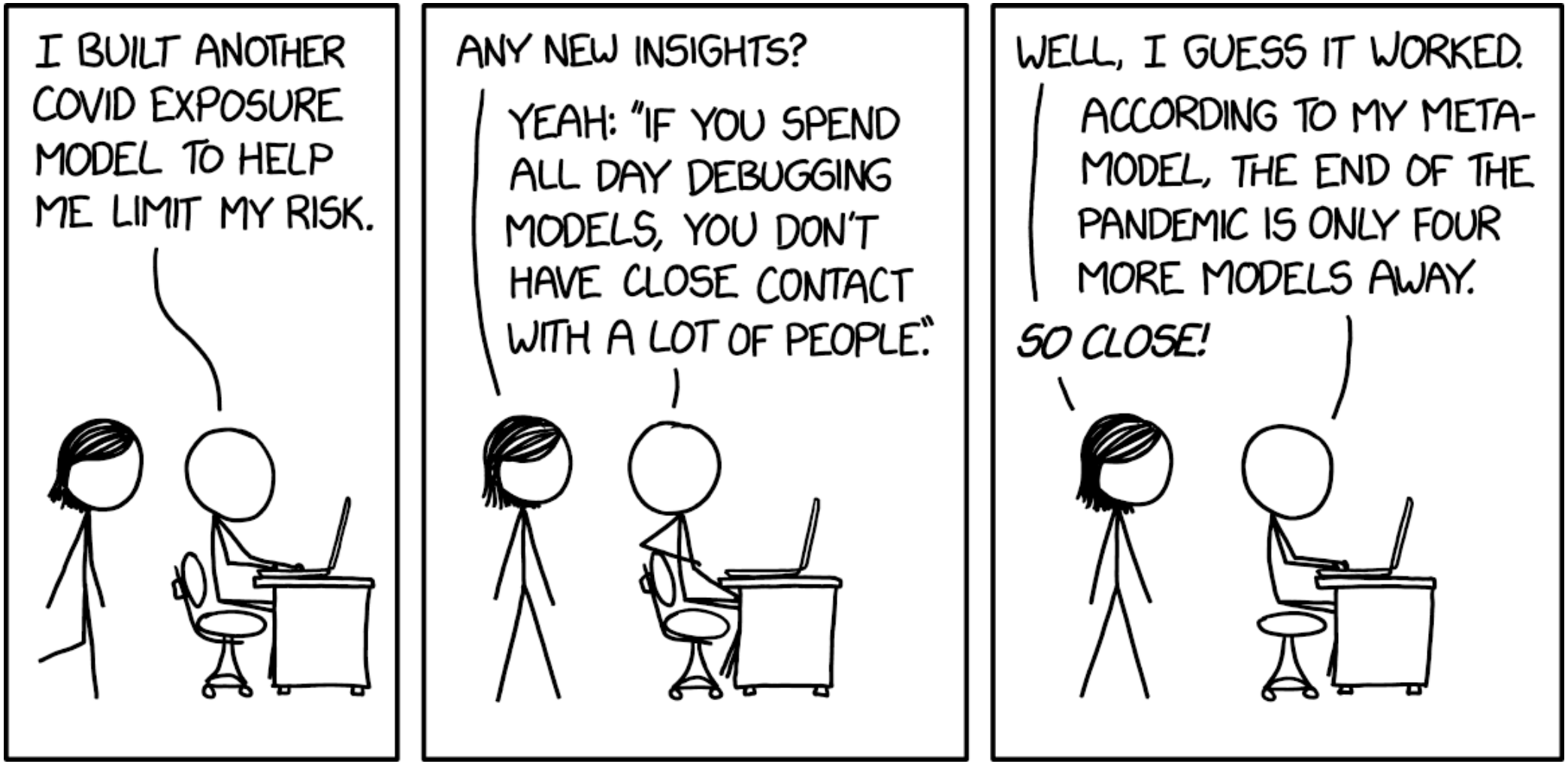
I BUILT ANOTHER COVID EXPOSURE MODEL TO HELP ME LIMIT MY RISK.
ANY NEW INSIGHTS?
YEAH: "IF YOU SPEND ALL DAY DEBUGGING MODELS, YOU DON'T HAVE CLOSE CONTACT WITH A LOT OF PEOPLE."
WELL, I GUESS IT WORKED.
ACCORDING TO MY META-MODEL, THE END OF THE PANDEMIC IS ONLY FOUR MORE MODELS AWAY.
SO CLOSE!