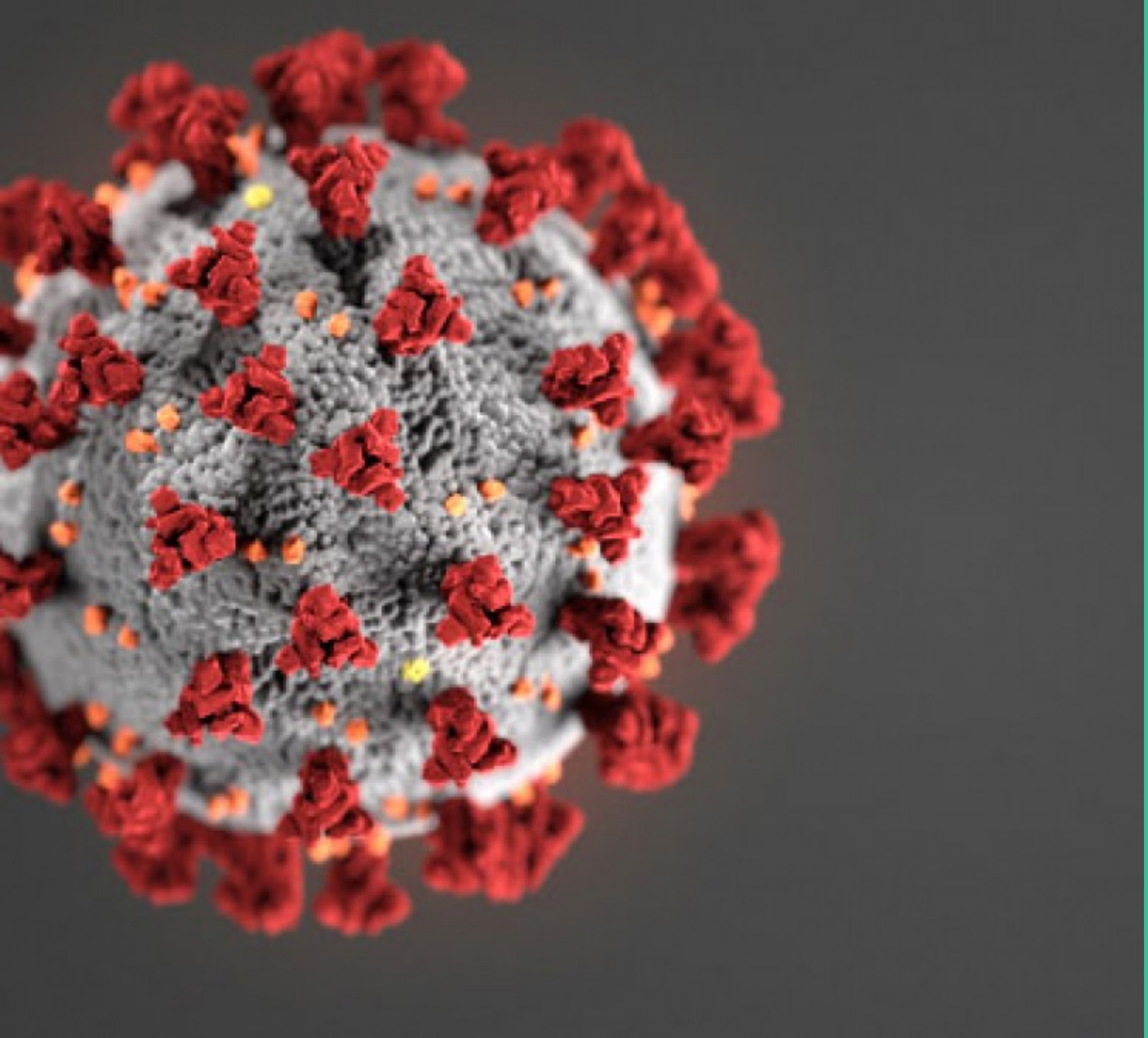

Investigating Vaccination Strategies for COVID-19 in Ireland

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Motivation

- Global concern – 183 million cases and 3.9 million deaths (WHO, July 6th 2021)
- Assess our current vaccine strategy – are we close to achieving herd immunity?
- Can we use the model to predict future ‘waves’ of infections?

Objectives

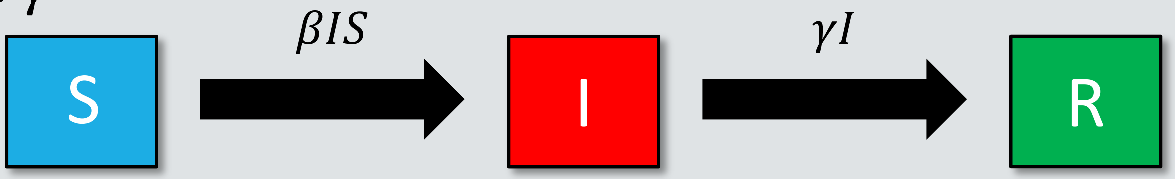
- Has Ireland adopted the optimal vaccination strategy?
- Review the work of the Irish Epidemiological Modelling Advisory Group (IEMAG)
- Construct a SEIR-type multi-population model for COVID-19 in Ireland
- Capture vaccination rates in model
- Fit vaccination model to actual cases and deaths from January 2021
- Compare current vaccine rollout with other plausible strategies

Infectious Disease Modelling

- Population is divided into compartments
- People enter (+) or leave (-) compartments at various rates
- System of ODEs to describe rate of change
- Rates can be constant (non time-dependent) or time-dependent (usually proportional to the number of individuals in the compartment itself).

Basic SIR Model

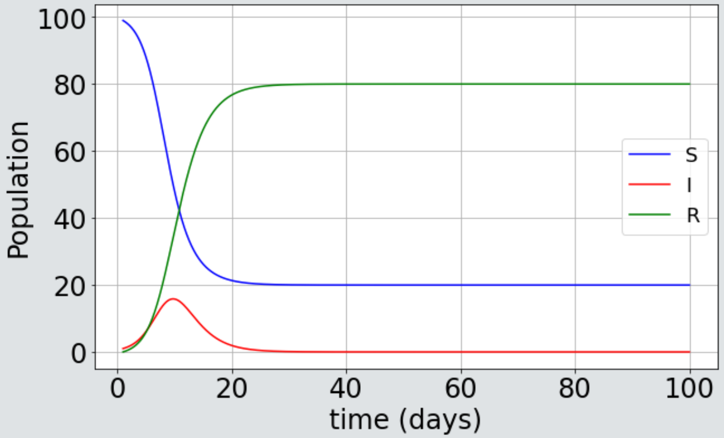
- {S, I, R} := {Susceptible, Infected, Removed}
- Closed population ($S(t) + I(t) + R(t) = N \quad \forall t \geq 0$)
- Contact rate β
- Removal rate γ



$$\frac{dS}{dt} = -\beta IS$$

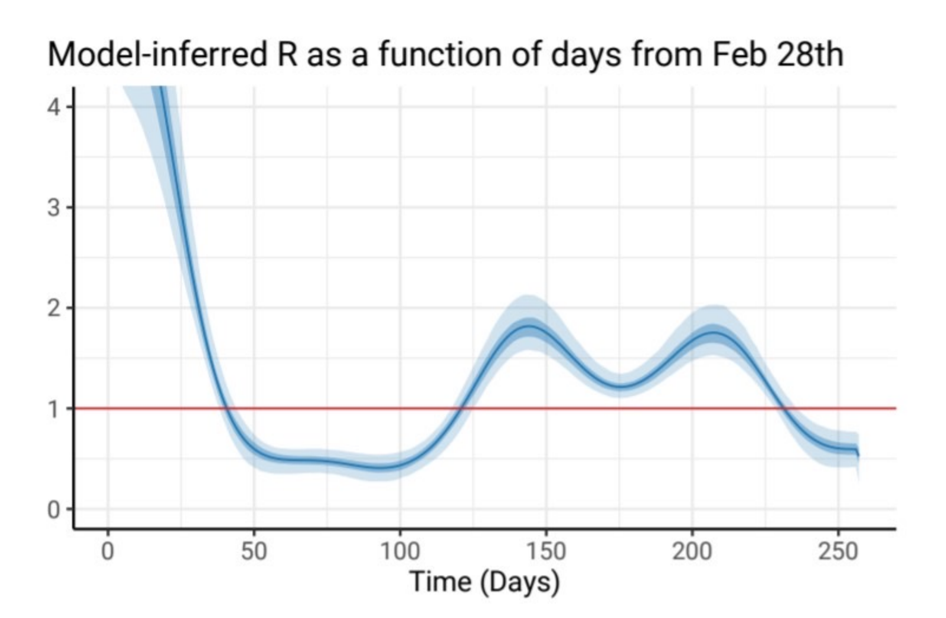
$$\frac{dI}{dt} = \beta IS - \gamma I$$

$$\frac{dR}{dt} = \gamma I$$



IEMAG

- Advisory group to National Public Health Emergency Team (NPHET)
- Technical notes available https://www.gov.ie/en/publication/dc5711-irish-epidemiology-modelling-advisory-group-to-nphet-technical-notes/
- Model as of November 12th 2020 serves as foundation for vaccination model



Irish Epidemiological Modelling Advisory Group (2020)

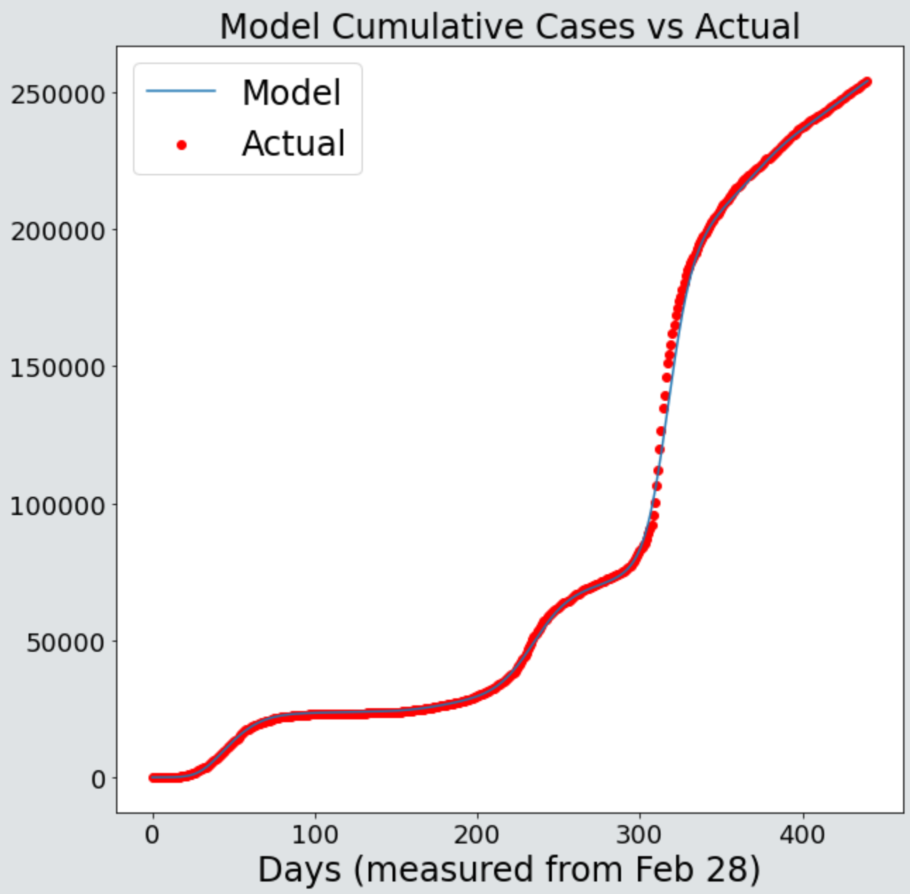
IEMAG

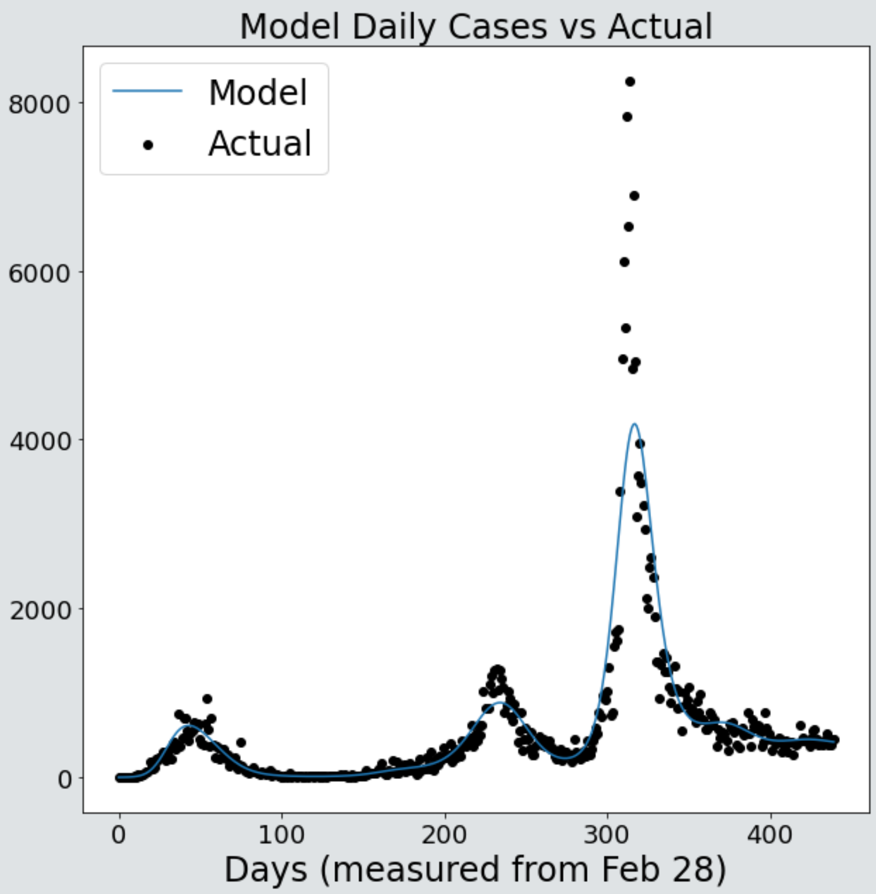
Closed SEIR-type model with six infectious compartments

$$\frac{dS}{dt} = -\beta S\left(I_p + hI_a + iI_i + I_{t1} + jI_{t2} + I_n\right)/N$$
$$\frac{dE}{dt} = \beta S\left(I_p + hI_a + iI_i + I_{t1} + jI_{t2} + I_n\right)/N - \frac{1}{L}E$$
$$\frac{dI_p}{dt} = \frac{(1-f)}{L}E - \frac{1}{C-L}I_p$$
$$\frac{dI_a}{dt} = \frac{f}{L}E - \frac{1}{D}I_a$$
$$\frac{dI_i}{dt} = \frac{q}{C-L}I_p - \frac{1}{D-C+L}I_i$$
$$\frac{dI_{t1}}{dt} = \frac{\tau}{C-L}I_p - \frac{1}{T}I_{t1}$$
$$\frac{dI_{t2}}{dt} = \frac{1}{T}I_{t1} - \frac{1}{D-C+L-T}I_{t2}$$
$$\frac{dI_n}{dt} = \frac{(1-q-\tau)}{C-L}I_p - \frac{1}{D-C+L}I_n$$
$$\frac{dR}{dt} = \frac{1}{D}I_a + \frac{1}{D-C+L}I_i + \frac{1}{D-C+L-T}I_{t2} + \frac{1}{D-C+L}I_n,$$

Irish Epidemiological Modelling Advisory Group (2020)

Implementation of IEMAG model





Improvements – Age Cohorts

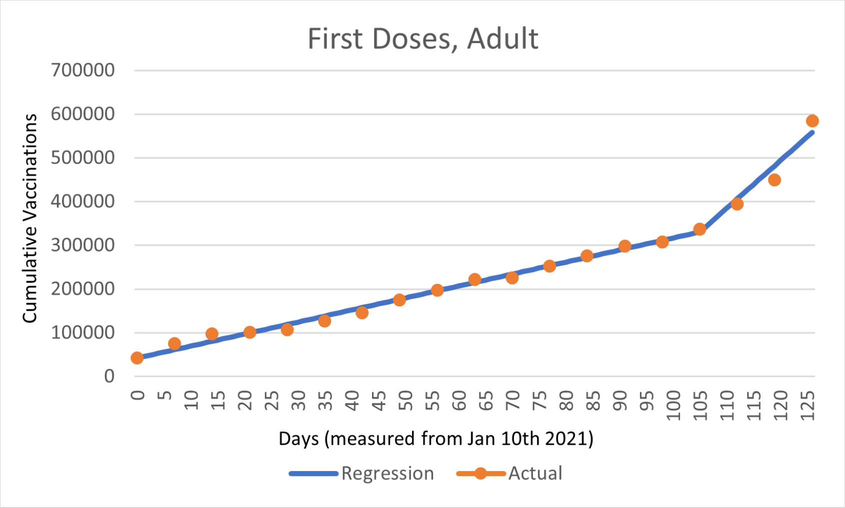
- Population in IEMAG model is homogeneous
- Death rates in particular differ widely between young people and seniors
- Vaccination model separates population by three age cohorts:

    i. Youth population (aged 0-24)
    ii. Adult population (aged 25-64)
    iii. Senior population (aged 65+)

- Contact rate β varies by age group – now nine contact rates rather than one

Improvements – Vaccinations

- Key factor to be introduced to any model on COVID-19 from early 2021
- Three time-dependent vaccination rates $v_i(t)$ for each age cohort
- Data source: ECDC data contains weekly updates regarding vaccinations, broken down into age bands
- Linear regression methods used to infer vaccination rates



Assumptions

- Closed model neglecting natural births and deaths
- Parameters constant among age cohorts unless denoted otherwise (death rates δ_i, vaccinations $\nu_i(t)$)
- Recovery from COVID-19 $\Rightarrow$ full immunity
- Vaccine administered is homogenised for simplification
- Vaccine has a non-perfect efficacy

The Model (Compartments)

- $i, j = \{youth, adult, senior\}$
- Compartments denoted as follows,

Notation	Compartment
S_0	Fully susceptible (no vaccine)
S_1	One vaccine dose
S_2	Two vaccine doses
E	Exposed
IP	Infected (presymptomatic)
IA	Infected (asymptomatic)

Notation	Compartment
IS	Infected (symptomatic)
IT	Awaiting test results
R	Recovered
$Ailing$	Dying
D	Deceased
$Cases$	Confirmed Cases

The Model (Parameters)

Parameters	Biological Description
L	Latent period
C	Incubation period
D	Infectious period
N_i	Population
h	Reduction in β from asymptomatic compartment
f	Proportion asymptomatic
T	Period from symptom onset to test
q	Proportion who do not isolate
η	Reduction in infection (two doses)
ω	Reduction in infection (one dose)
τ	Time between vaccine doses
δ_i	Infected fatality rate
t_d	Period spent in ailing compartment

$$\frac{dS_{0i}}{dt} = -\frac{S_{0i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) - \nu_i(t)$$

$$\frac{dS_{1i}}{dt} = \nu_i(t) - \omega\frac{S_{1i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) - \frac{S_{1i}}{\tau}$$

$$\frac{dS_{2i}}{dt} = \frac{S_{1i}}{\tau} - \eta\frac{S_{2i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right)$$

$$\frac{dE_i}{dt} = -\frac{S_{0i} + \omega S_{1i} + \eta S_{2i}}{N_i}\left(\sum_j \beta_{ij}(IP_j + hIA_j + qIS_j)\right) - \frac{E_i}{L}$$

$$\frac{dIP_i}{dt} = \frac{E_i}{L} - \frac{IP_i}{C-L}$$

$$\frac{dIA_i}{dt} = f\frac{IP_i}{C-L} - \frac{IA_i}{D-C+L}$$

$$\frac{dIS_i}{dt} = (1-f)\frac{IP_i}{C-L} - \frac{IS_i}{D-C+L}$$

$$\frac{dIT_i}{dt} = g(1-f)\frac{IP_i}{C-L} - \frac{IT_i}{T}$$

$$\frac{dR_i}{dt} = \frac{IA_i}{D-C+L} + (1-\delta_i)\frac{IS_i}{D-C+L}$$

$$\frac{d(Ailing_i)}{dt} = \delta_i\frac{IS_i}{D-C+L} - \frac{Ailing_i}{t_d}$$

$$\frac{dD_i}{dt} = \frac{Ailing_i}{t_d}$$

$$\frac{d(Cases_i)}{dt} = \frac{IT_i}{T}$$

The Model

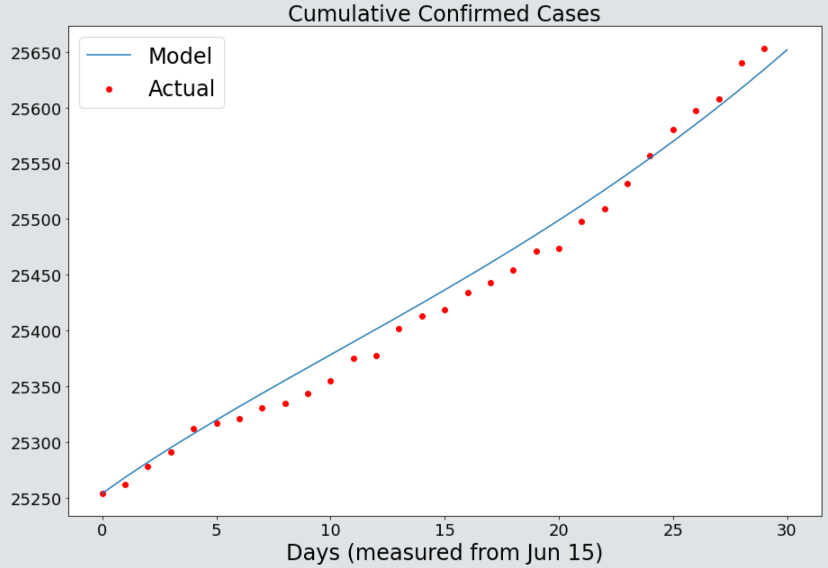
Contact Matrix

- β_{ij} := the contact rate that population i holds with an infected individual from population j.
- $\{C, A, S\} := \{youth, adult, senior\}$
- Nine contact rates in total, represented by matrix below

$$\begin{pmatrix} \beta_{CC} & \beta_{CA} & \beta_{CS} \\ \beta_{AC} & \beta_{AA} & \beta_{AS} \\ \beta_{SC} & \beta_{SA} & \beta_{SS} \end{pmatrix}$$

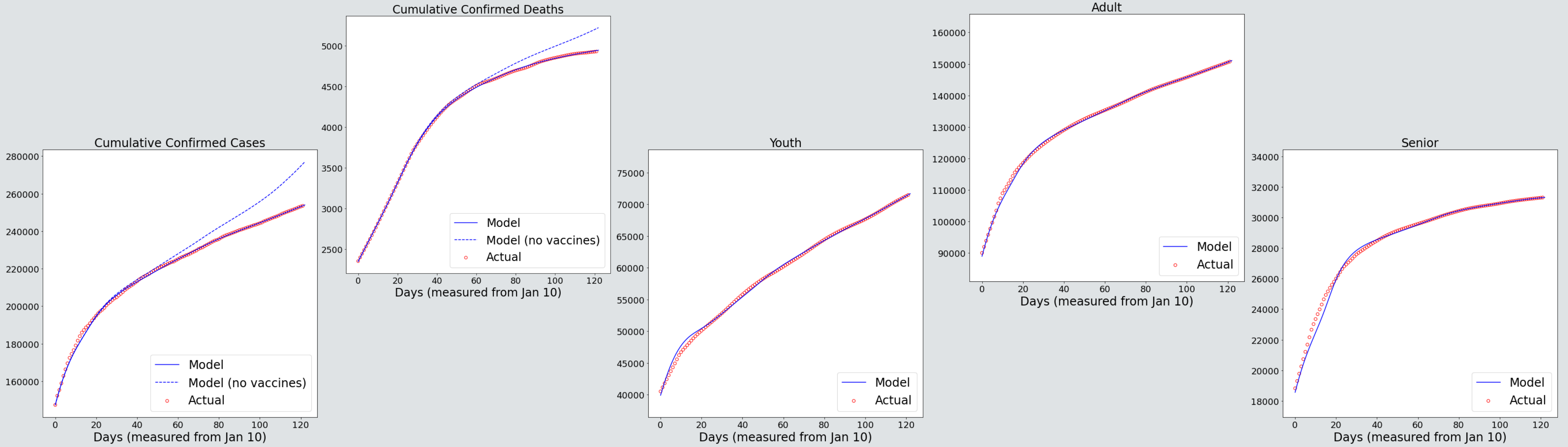
Fitting to June-July 2020

- Goal: Optimise evolution of contact rates to fit model to June – July 2020 period
- Relationship between contact rates had to be established
- Optimise in period where contact rates approximately constant
- Minimized cost function: L^2 norm of log differences between model cases vs actual



Fitting to January-May 2021

- Goal: Optimise evolution of contact rates to fit model to January – May 2021 period
- Contact rates assumed to increase linearly



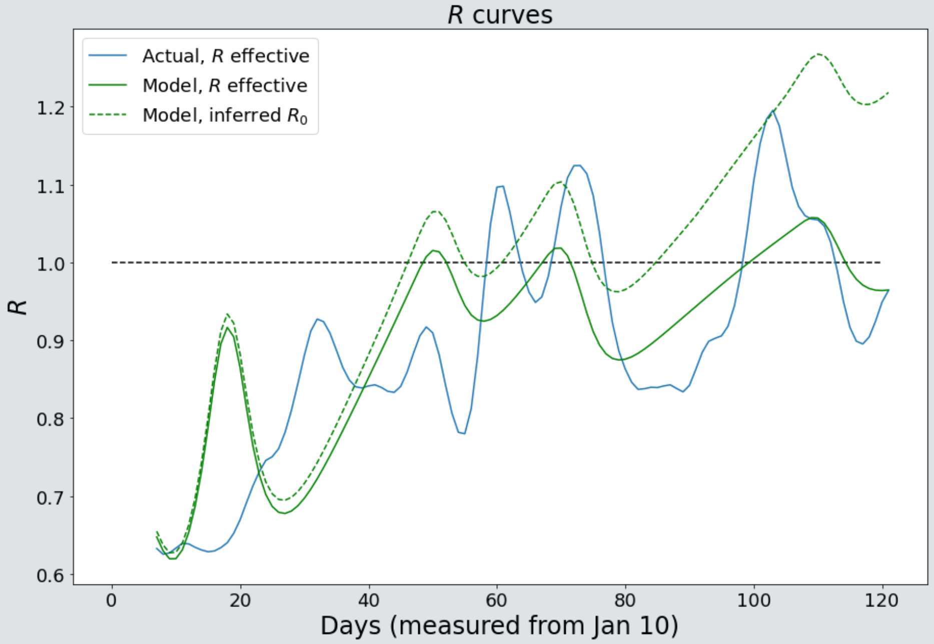
Effective Reproductive Number

- Reproductive number – average number of secondary cases per infected case
- Can be derived analytically in certain models (original IEMAG model)
- R_{eff} is estimated in vaccine model from 7 day growth rate of cases r on logarithm scale

$$R_{eff}(r) = \left(1 + r(D - C + L)\right)\left(1 + \frac{rL}{M}\right)^M$$

Accounting for vaccinations,

$$R = \frac{R_{eff}(r)}{1 - (\omega * P_{onedose} + \eta * P_{twodoses})}$$

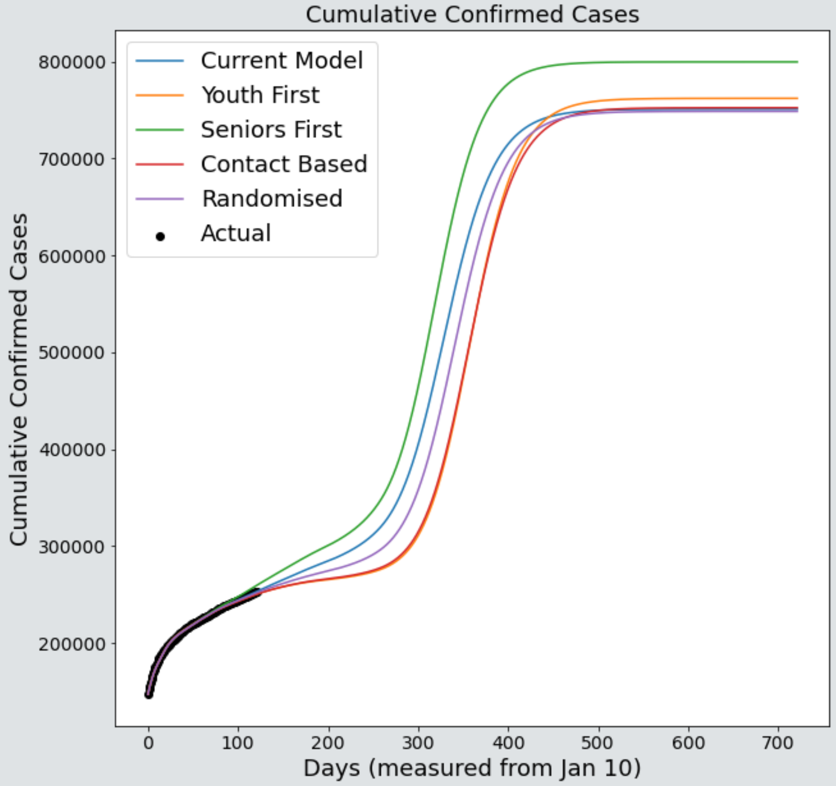


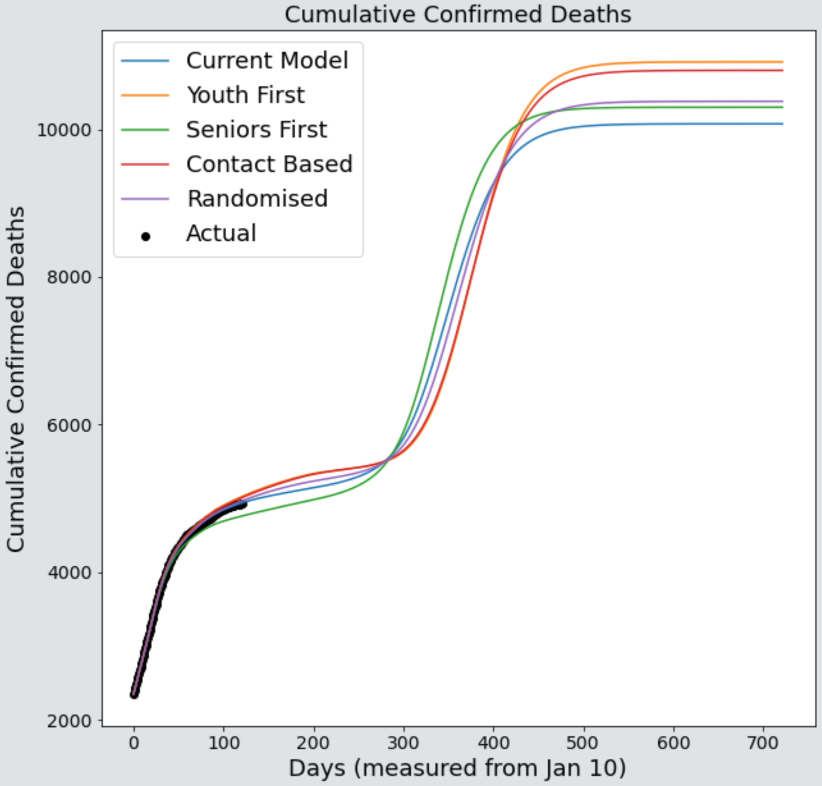
Vaccination Strategies

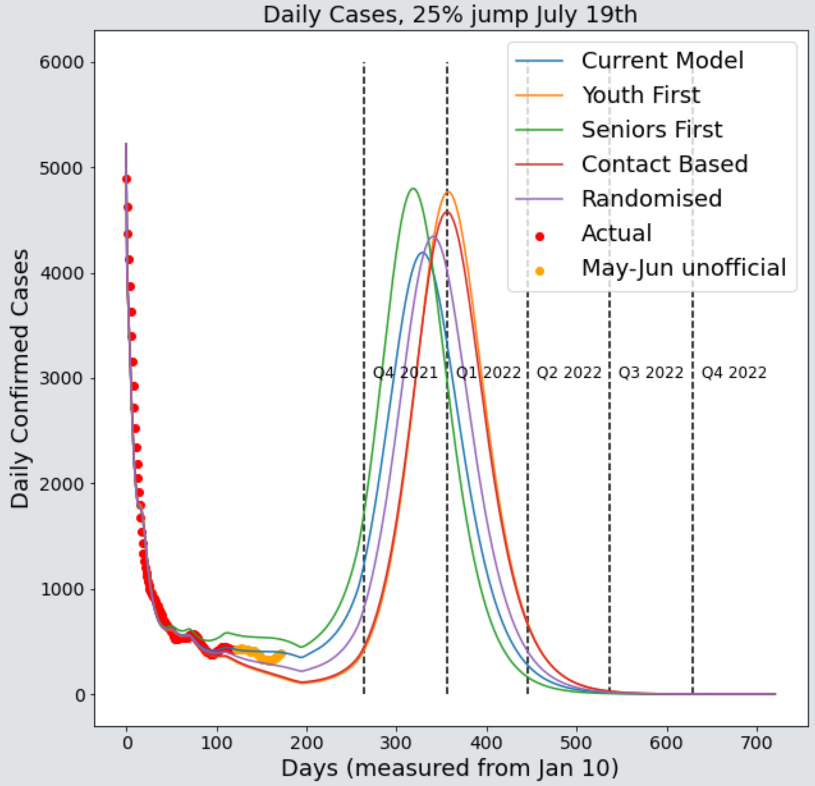
- Current model (A mix of Seniors and Adults followed by Youths)
- Youth First (Youths, Adults, Seniors)
- Seniors First (Seniors, Adults, Youths)
- Contact Based (Adults, Youths, Seniors)
- Randomised (all cohorts vaccinated equally)

Modelled up to May 11th 2021 as well as future projection to end of 2022 that allows for a 25% increase in contact rates on July 19th 2021

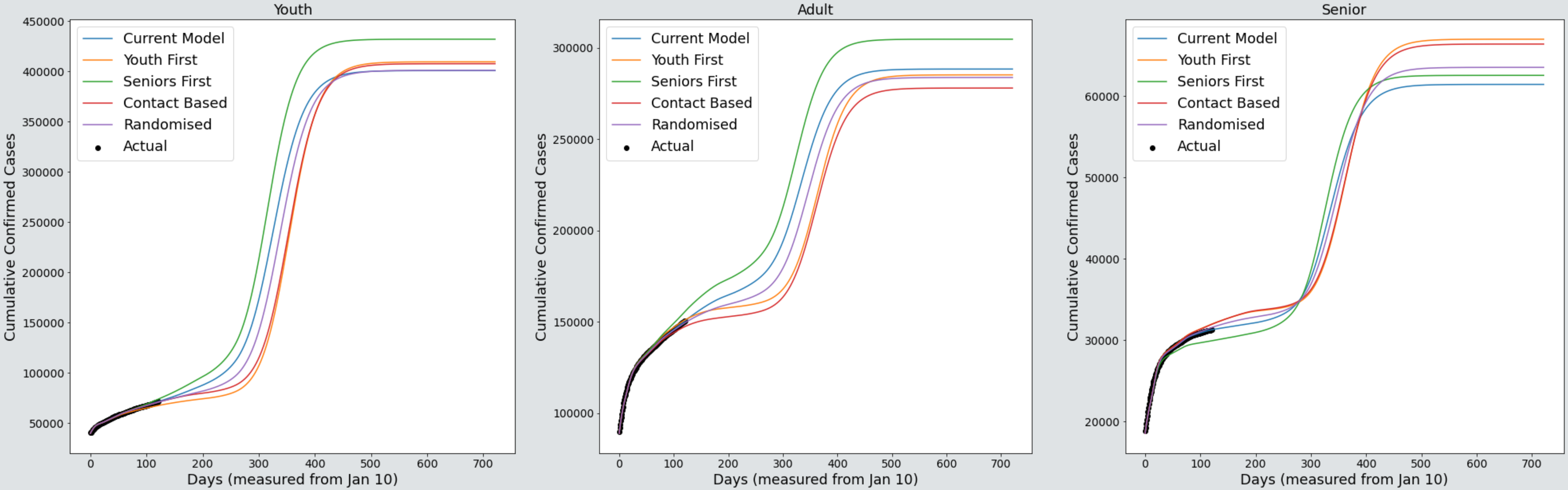
Vaccination Strategies







Vaccination Strategies



Vaccination Strategies

Strategy	Cases May 11th 2021	Deaths May 11th 2021	Cases December 31st 2022	Deaths December 31st 2022
Current Model	253,960	4,947	750,856	10,073
Youth First	251,083	5,036	761,967	10,912
Seniors First	260,312	4,768	799,553	10,298
Contact Based	250,871	5,021	752,287	10,797
Randomised	252,547	4,975	748,576	10,378

Limitations in Model

- Set upper bounds for contact rates β_{ij} in future simulation – hard to infer
- Treats all vaccines equally
- Efficacy against disease may wane over time subject to new variants
- Two factors which significantly diminish the "fourth wave" post July 19th :

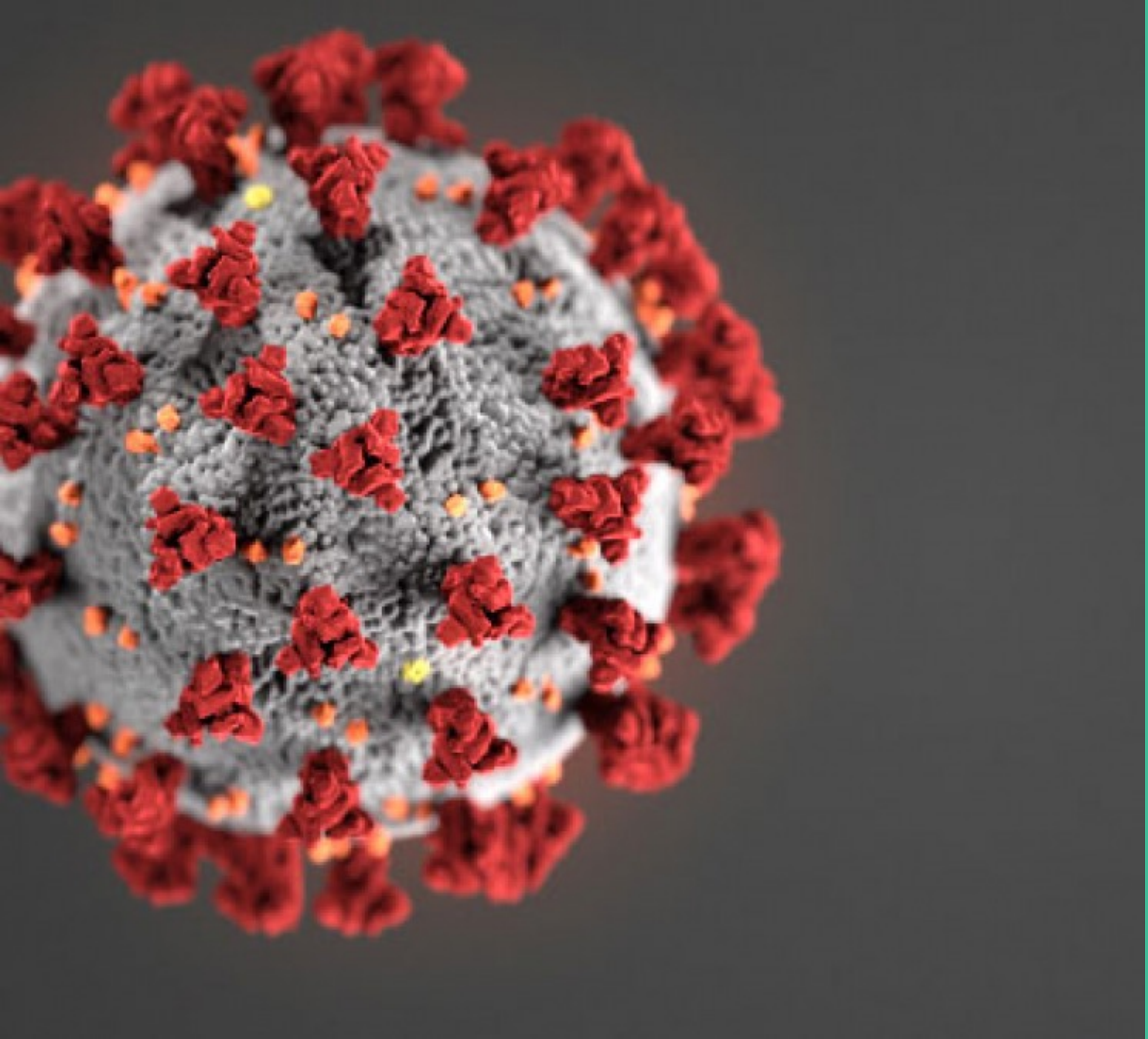
  i. Increasing vaccine efficacy to 90% - increase proportion of MRNA vaccines administered
  ii. Vaccinating through youth population – model ends vaccination once all aged 18+ are vaccinated

Conclusion

- Results indicate that our current vaccine rollout has been effective in minimizing COVID-19 deaths in the long term
- However, a wider immunity coverage is needed to prevent another wave

Next Steps:

- Fitting the model to COVID-19 data post HSE cyber attack
- Distinguishing between different vaccines in the population
- Investigate waning immunity and more transmissible variants



Thank You!

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