Characterizing the spread of CoViD-19:

Canada, USA, and Germany

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CAIMS- PIMS Coronavirus Modelling Conference

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Outline

- Introducing a new modelling framework: pypm.ca
- Simple model to characterize the "spread" of CoViD-19
- Comparative statistics with weak model dependence
  - Growth: general community transmission [Fire hazard]
  - Size: fraction of population who are contagious [Number of fires]
- Modelling complications
  - Localized infection outbreaks
  - Reporting anomalies, reporting noise
- Point and interval estimation
- Application to provincial and state public data (Canada, USA, Germany)
- Summary of findings

pyPM.ca: python Population Modeller

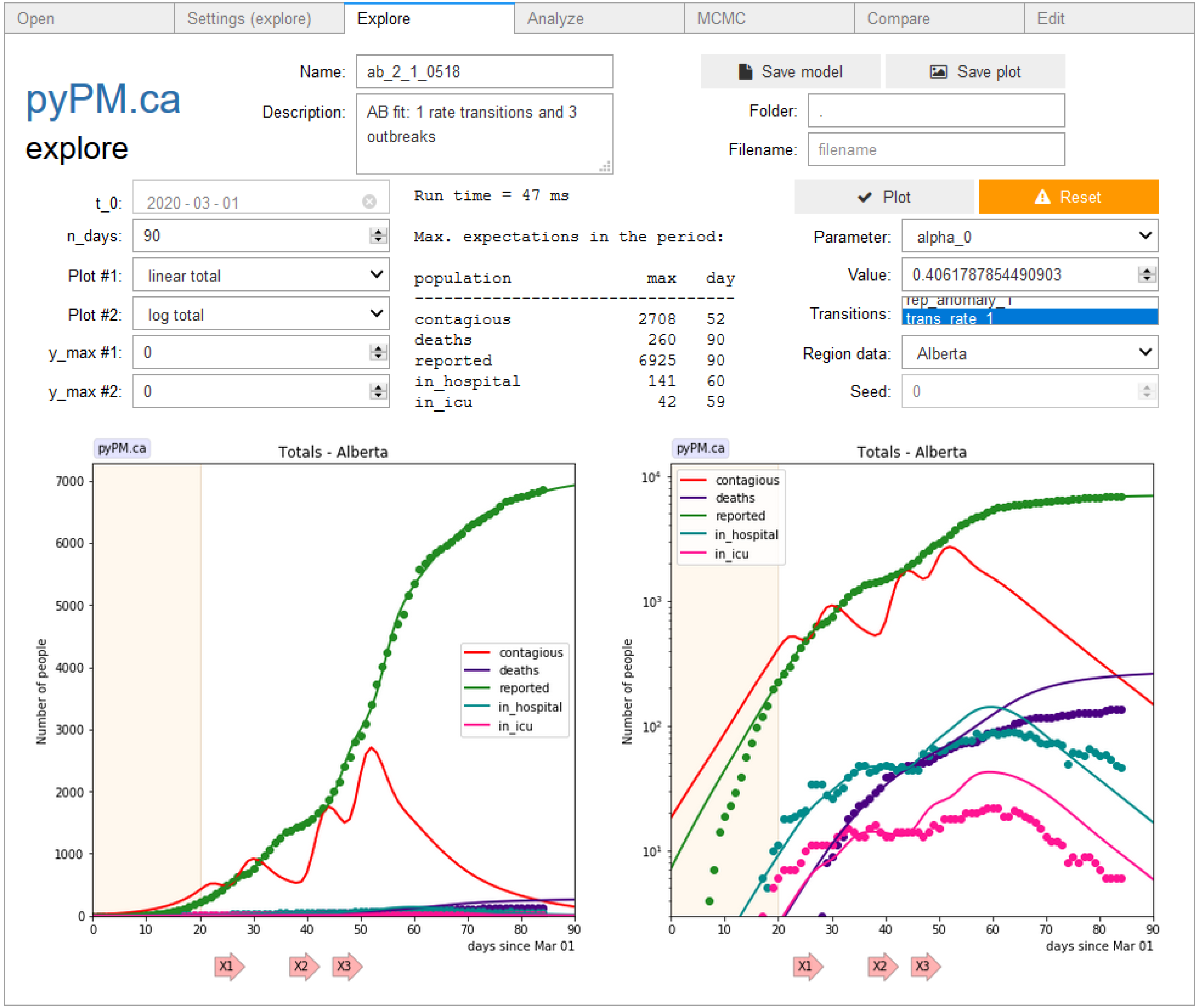
- A general framework for building population models: pypmca
  - Time-difference equations allow arbitrary time delay distributions
  - Model objects are built from “population” objects and “connection” objects
    - Separates model design from numerical implementation
  - Model objects can evolve expectation values and can produce simulated data

- A technical graphical user interface: ipypm
  - Interact with data and models, explore parameter space
  - Fit models to data to estimate and constrain parameters

- Open source on pypi/github
  - See: www.pypm.ca
  - Single click startup on the PIMS syzygy Jupyter hubs (across Canada)

Technical GUI

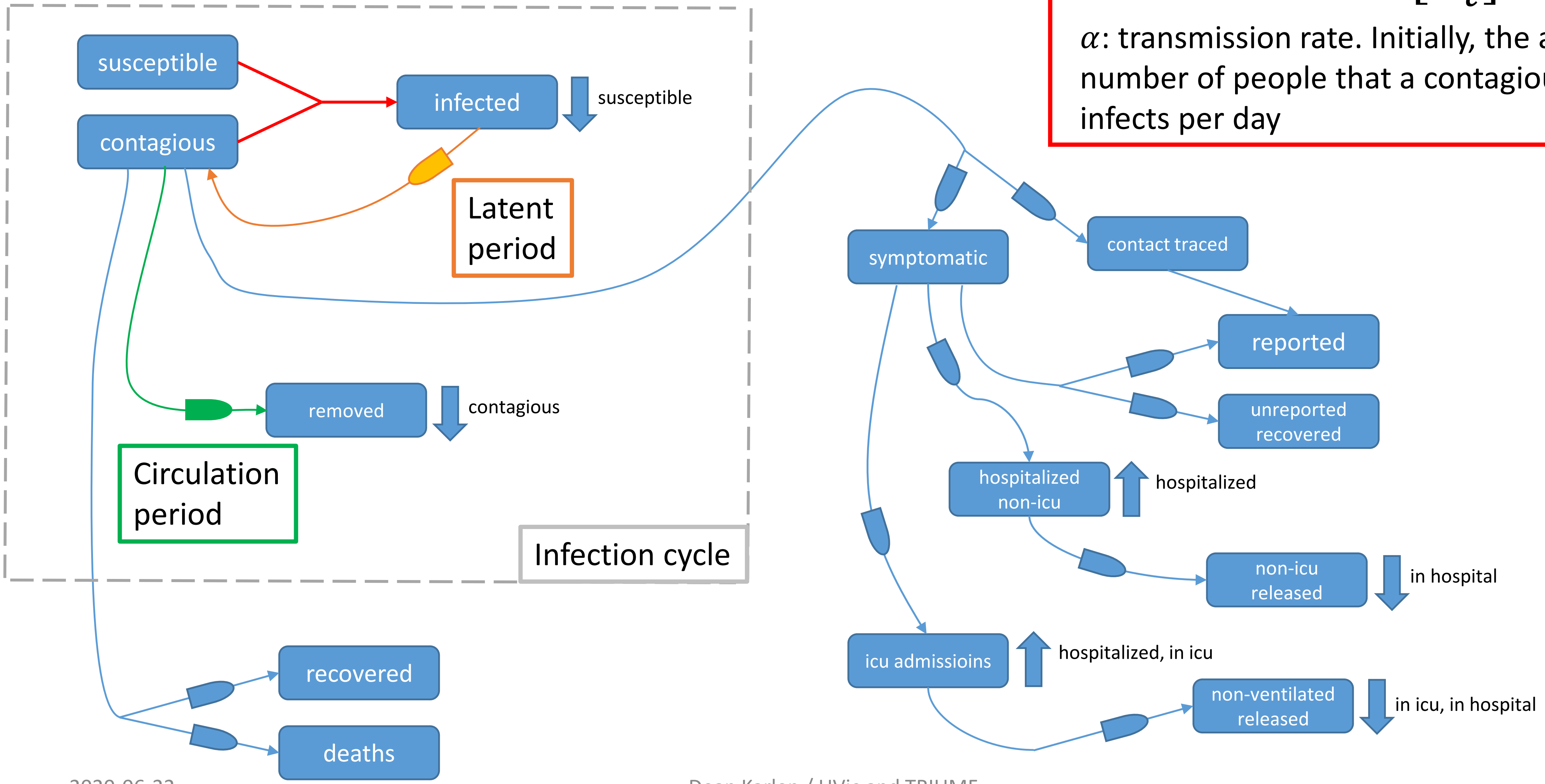
- Runs within Jupyter notebook using ipywidgets
- Interactively adjust parameters
- Access data and models in notebook cells for further analysis



Simple pyPM.ca model

$$E[\Delta I_{t+1}] = \alpha \frac{E[S_t]}{E[N_t]} E[C_t]$$

α: transmission rate. Initially, the average number of people that a contagious person infects per day



Characterizing growth of the epidemic

- The “steady state” solution to the infection cycle equations is exponential growth (or decline): characterized by δ:

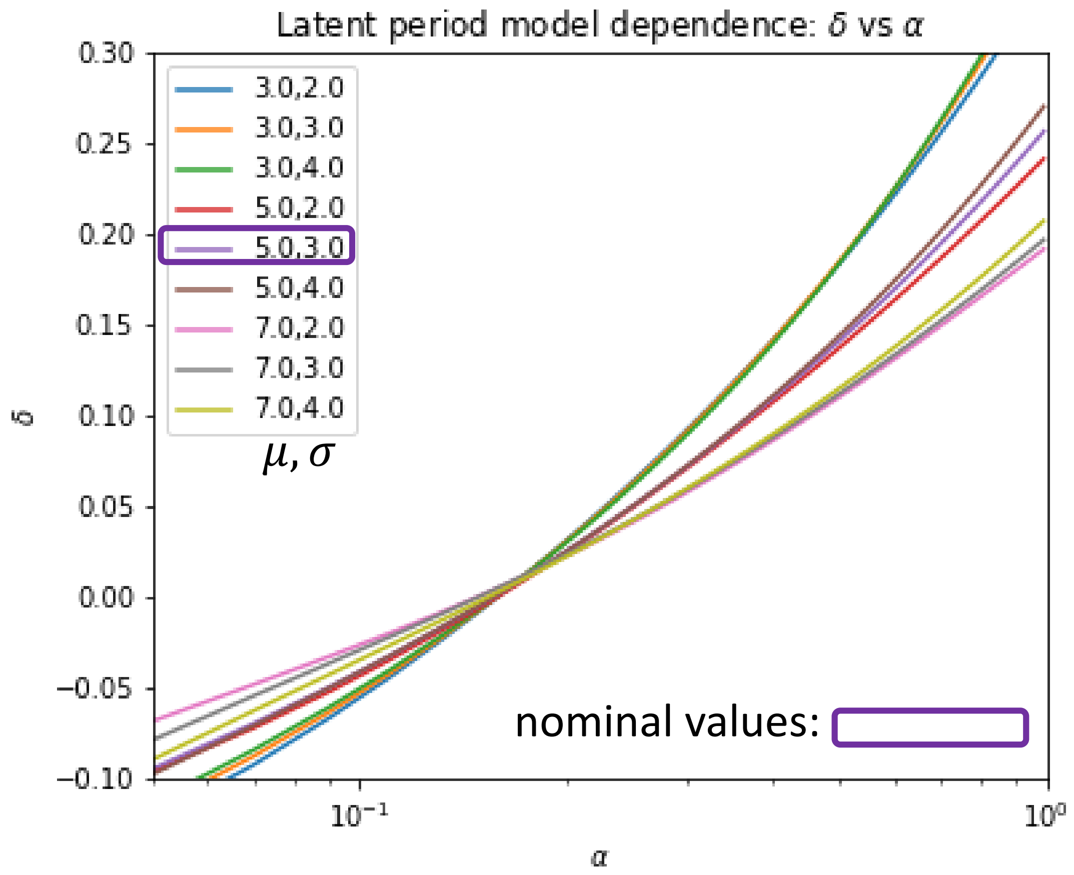
$$E[C_{t+1}] = (1+\delta)E[C_t]$$

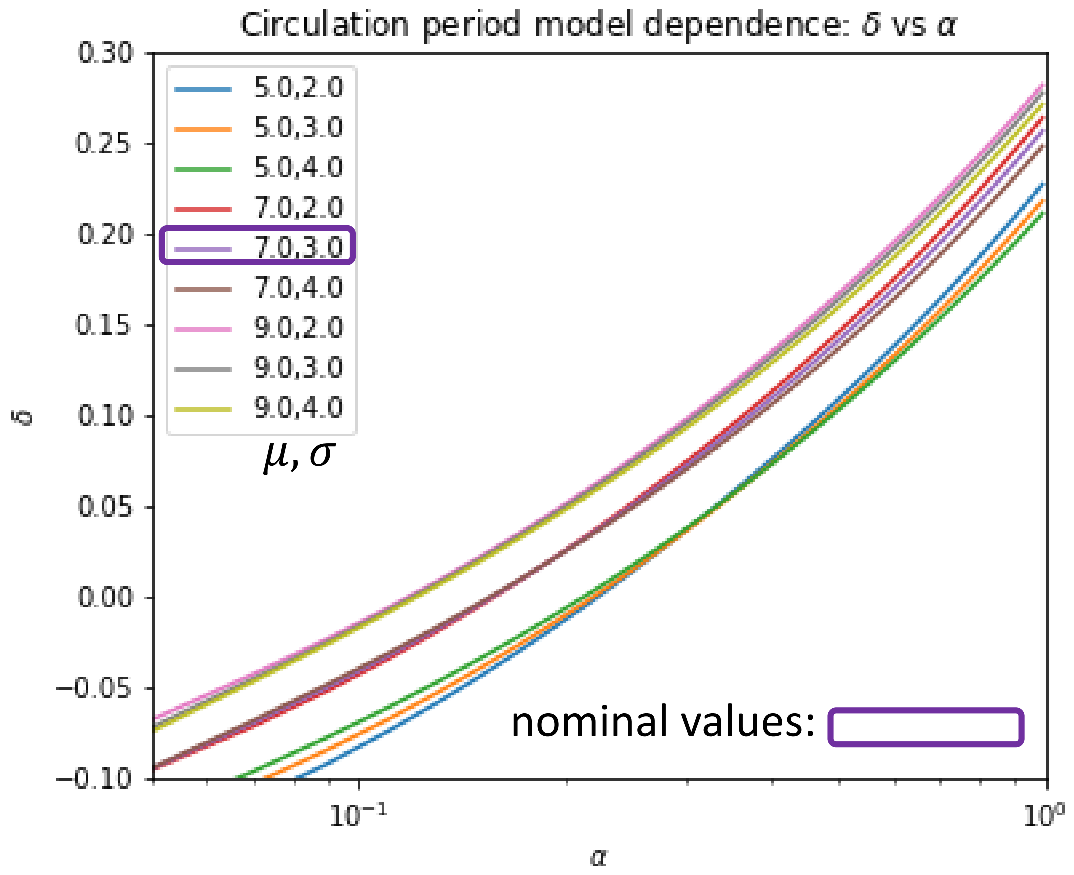
  - C_t: size of the circulating contagious population on day t
  - Note: δ is often referred to as r in epidemiology literature

- Parameters like α or R alone do not determine the growth (δ)
  - In the pyPM model: must specify the latent and circulation period delay distributions
- Proposal: to reduce dependence on model assumptions, use $\hat{\delta}$ to characterize growth
  - Since models do not incorporate δ as a fundamental parameter, convert model “growth” parameter estimates (like $\hat{\alpha}$) to $\hat{\delta}$

Model sensitivity to latent/circulation periods

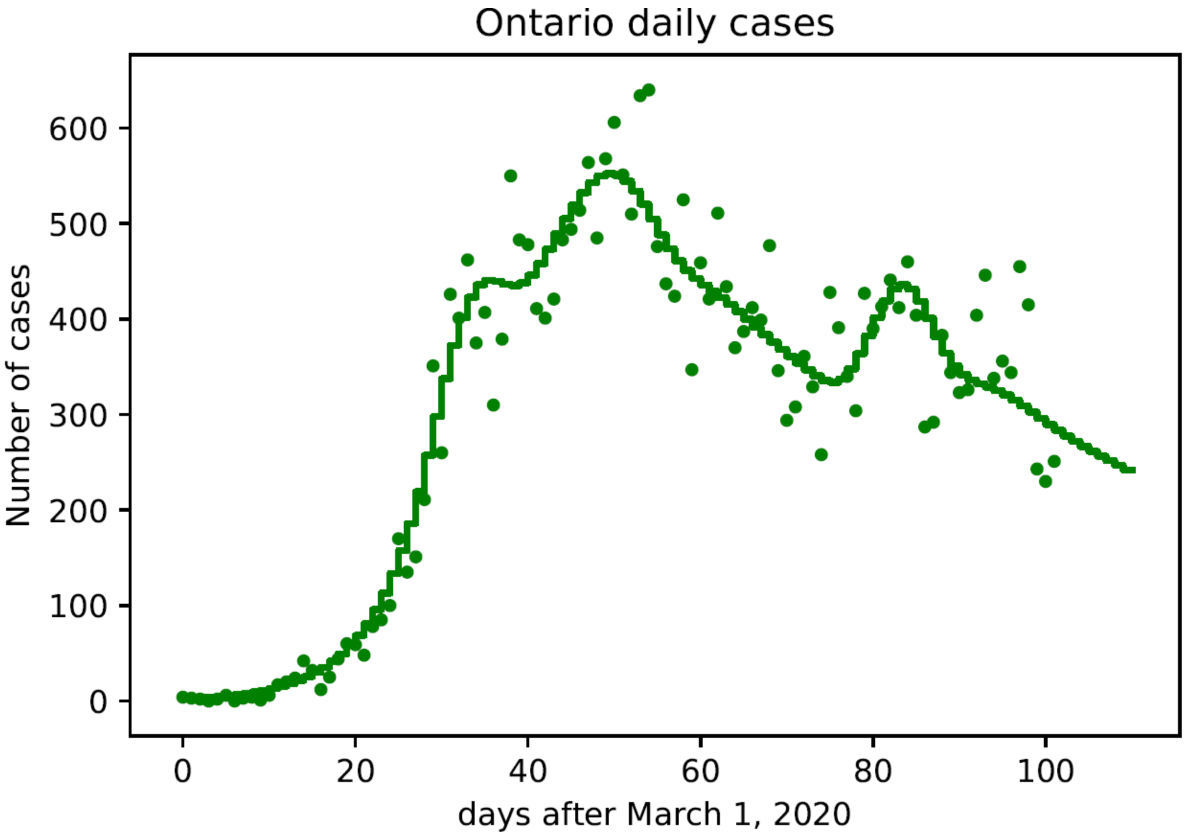
- Model prediction for growth rate is sensitive to the latent period and circulation period distributions

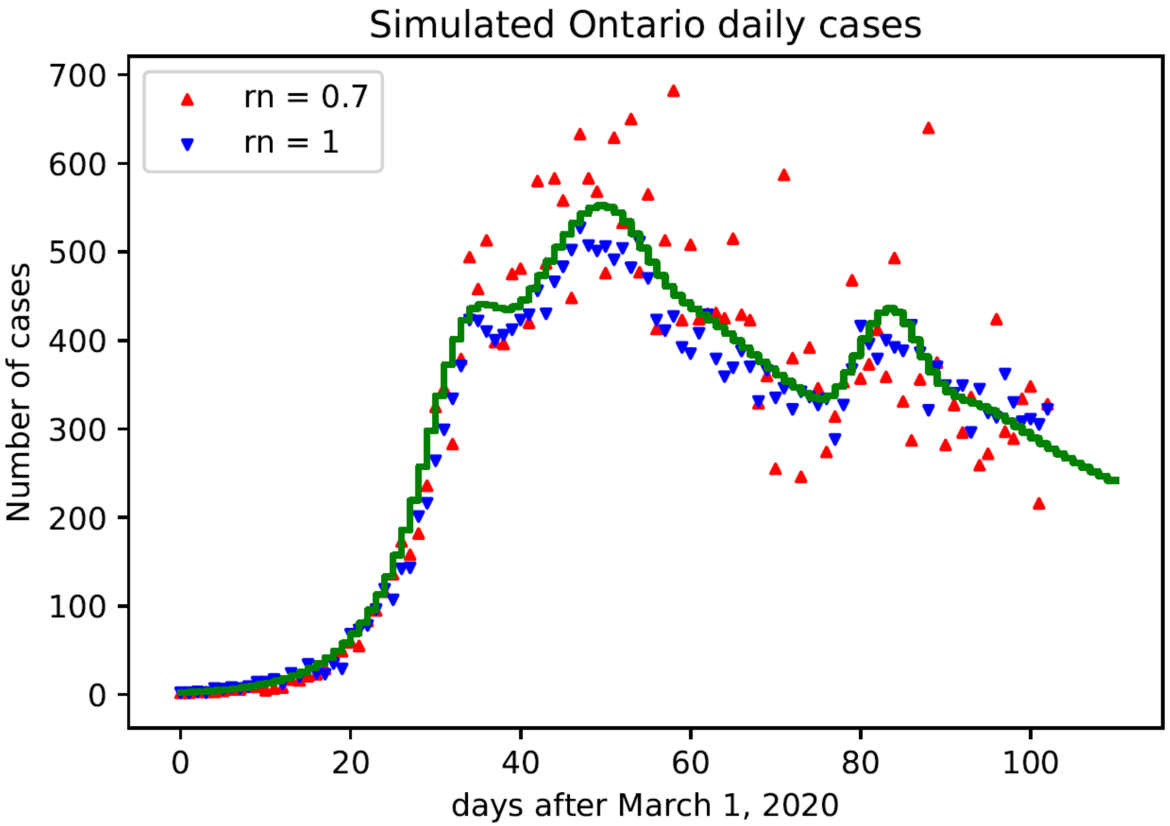




Point and interval estimation for δ

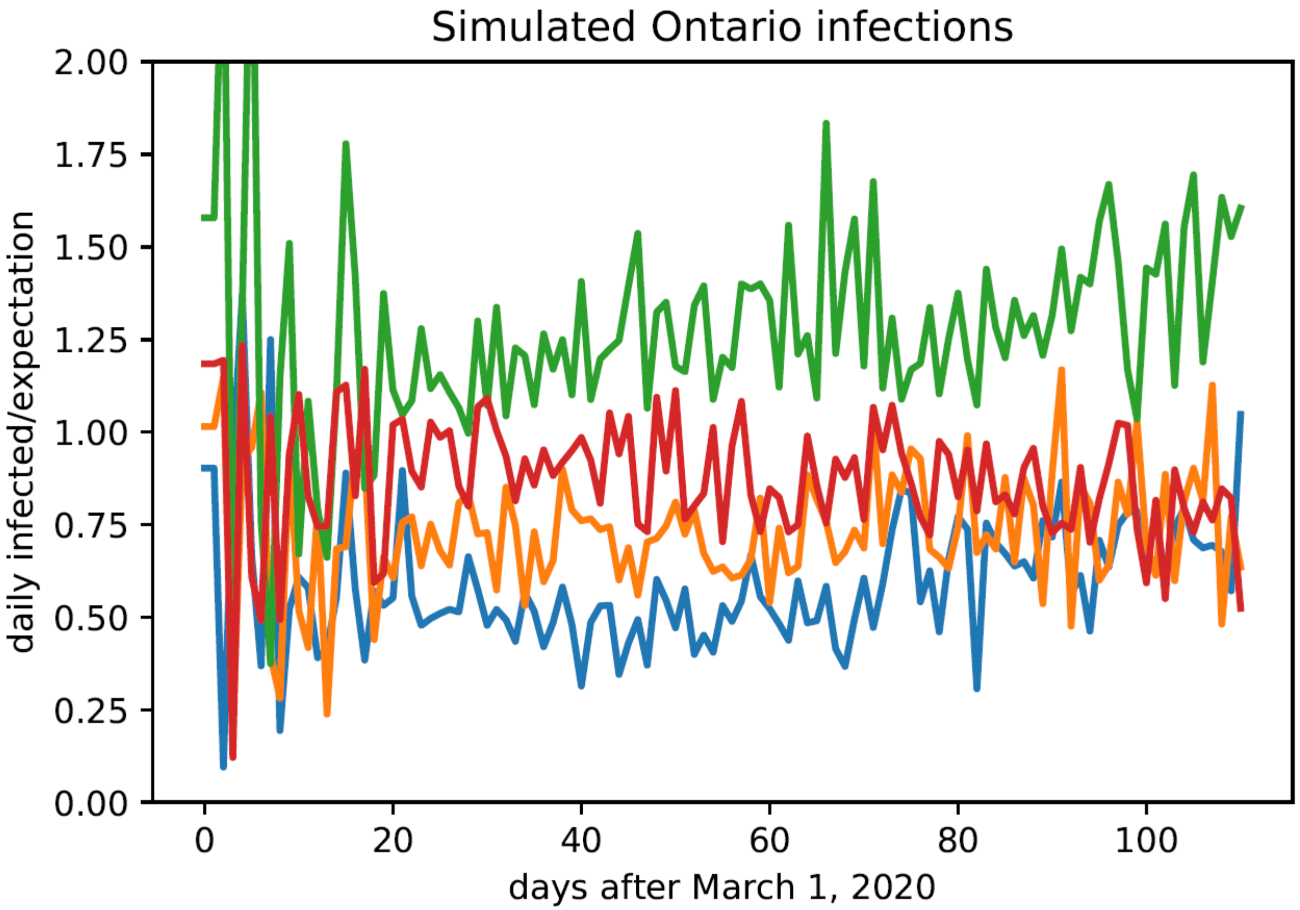
- Defining a proper likelihood to perform MLE is challenging:
  - daily case variance far exceeds that expected in a model with independent infected individuals being tested as they become symptomatic:





Point and interval estimation for δ

- Defining a proper likelihood to perform MLE is challenging
  - Daily cases are not outcomes of independent random variables



Point and interval estimation for δ

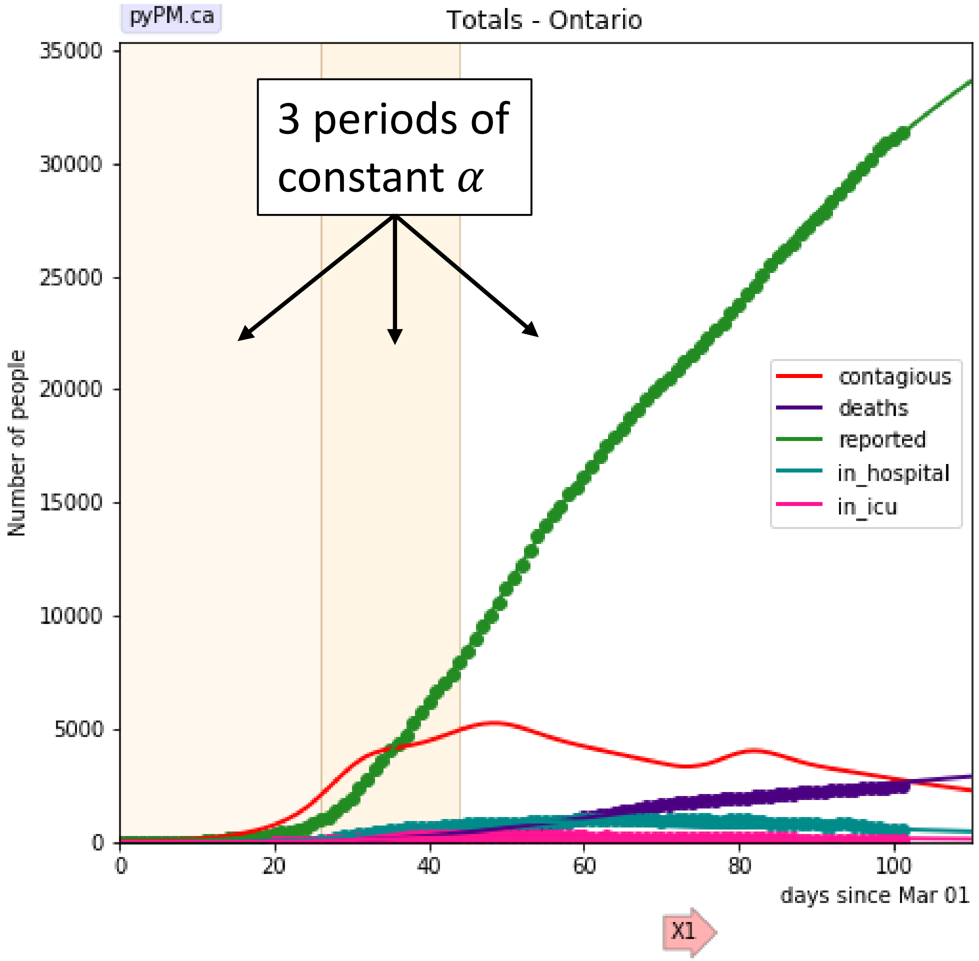
- Defining a proper likelihood to perform MLE is challenging
  - Localized infection outbreaks: large/fast burst of cases
    - Meat packing plants in Alberta and several US states, for example
  - When these occur during a period where social distancing policy is being followed consistently, indicators for general community transmission ($\hat{\alpha}$ or $\hat{\delta}$) should be unaffected

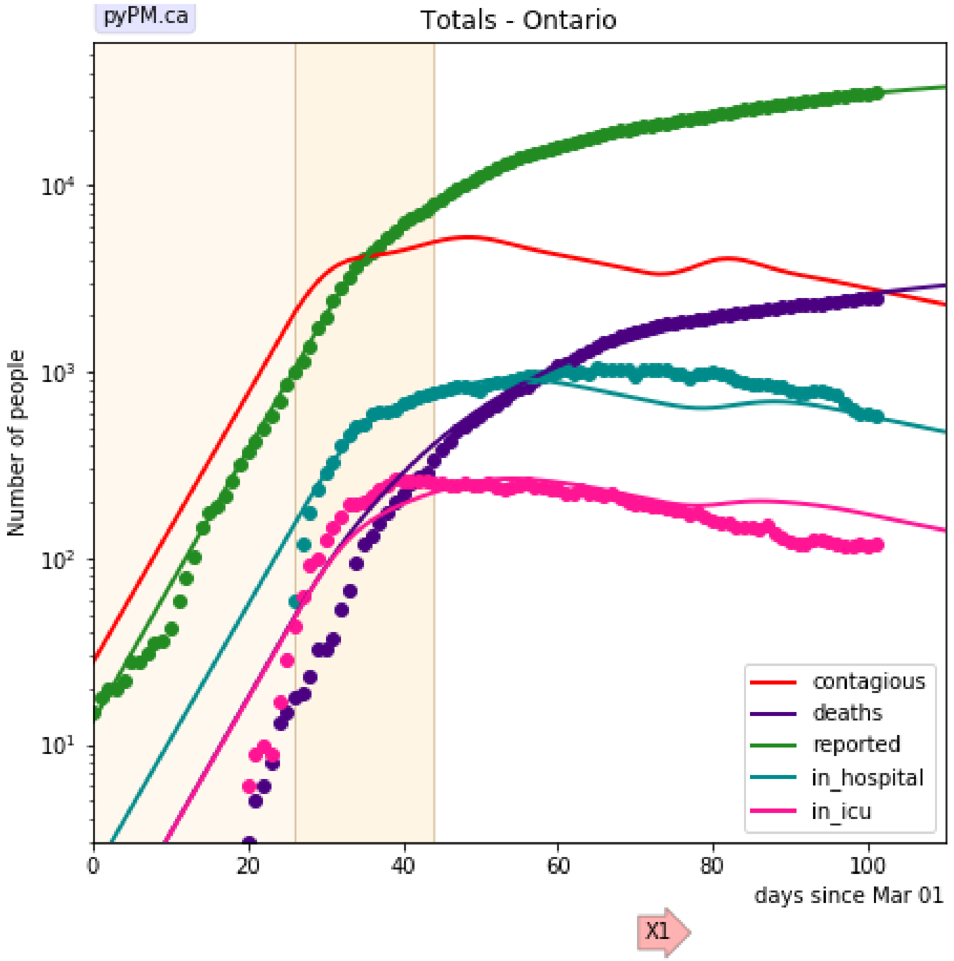
  - A burst of infections is added to the model to handle these cases

  - A burst of reported cases is added to the model to handle situations where a large number of new reports are released due to a backlog

Point and interval estimation for δ

- Given the challenges in defining the likelihood:
  - use an ad-hoc approach for point estimation: fit to cumulative cases

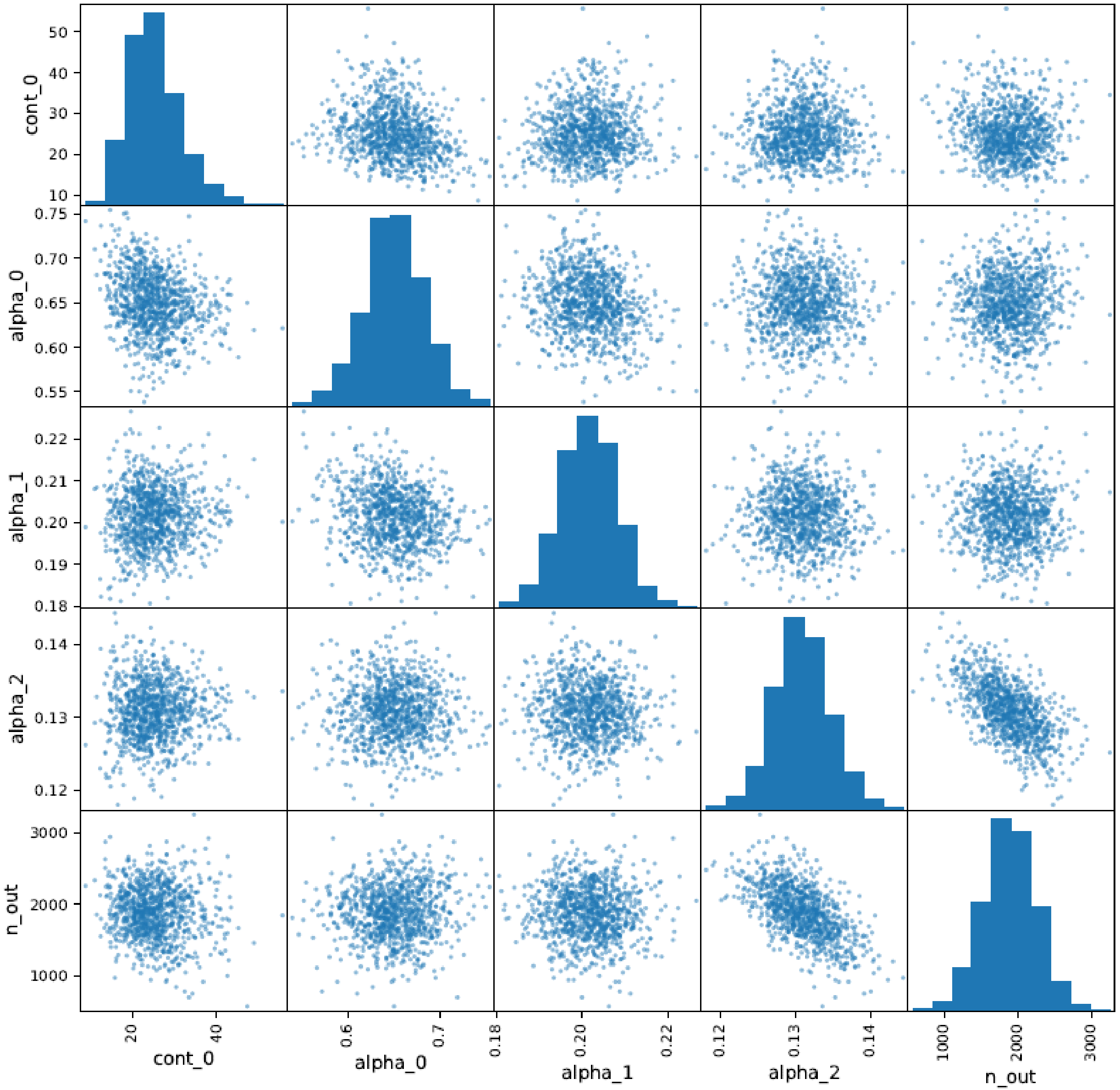




Interval estimation for δ

- Do fits to many simulated samples
  - Adjust reporting noise and infection cycle negative binomial parameters to match goodness of fit of data

parameter	truth	mean	σ_{stat}	bias (in σ_{stat})
cont_0	27.6	25.2	6.2	-0.39
alpha_0	0.642	0.650	0.033	0.24
alpha_1	0.199	0.202	0.007	0.40
alpha_2	0.131	0.131	0.004	-0.03
outbreak_1_n	1924	1888	363	-0.10



Systematic interval

- α : systematic error exceeds Ontario statistical error
- δ : systematic error similar to Ontario statistical error

ℓ_μ	ℓ_σ	c_μ	c_σ	$\hat{\alpha}_0$	$\hat{\alpha}_1$	$\hat{\alpha}_2$	$\hat{\delta}_0$	$\hat{\delta}_1$	$\hat{\delta}_2$
3	2	7	3	0.520	0.196	0.137	0.191	0.028	−0.019
3	3	7	3	0.526	0.197	0.136	0.194	0.029	−0.019
3	4	7	3	0.536	0.199	0.135	0.198	0.029	−0.019
5	2	7	3	0.645	0.197	0.132	0.173	0.023	−0.018
5	3	7	3	0.642	0.199	0.131	0.179	0.025	−0.017
5	4	7	3	0.644	0.201	0.130	0.185	0.026	−0.018
7	2	7	3	0.773	0.196	0.128	0.157	0.024	−0.005
7	3	7	3	0.772	0.197	0.127	0.163	0.025	−0.009
7	4	7	3	0.769	0.199	0.126	0.170	0.023	−0.016
5	3	5	2	0.751	0.264	0.187	0.175	0.020	−0.021
5	3	5	3	0.789	0.266	0.184	0.176	0.022	−0.019
5	3	5	4	0.823	0.265	0.177	0.178	0.024	−0.018
5	3	7	2	0.616	0.196	0.131	0.178	0.024	−0.017
5	3	7	3	0.642	0.199	0.131	0.179	0.025	−0.017
5	3	7	4	0.672	0.202	0.129	0.180	0.026	−0.017
5	3	9	2	0.556	0.159	0.101	0.182	0.028	−0.012
5	3	9	3	0.581	0.160	0.101	0.185	0.028	−0.015
5	3	9	4	0.590	0.164	0.100	0.183	0.028	−0.017
			mean	0.658	0.203	0.135	0.179	0.025	-0.016
			σ_{sys}	0.099	0.032	0.025	0.010	0.003	0.004
			σ_{stat}	0.033	0.007	0.004	0.008	0.004	0.003
			$\sigma_{\mathrm{sys}}/\sigma_{\mathrm{stat}}$	3.0	4.7	6.6	1.2	0.7	1.5

Table 3: Estimates for growth parameters for Ontario data under different latent and circulation period parameters. For these fits, the transmission rate transition dates and the outbreak date were fixed.

Characterizing the size of the epidemic

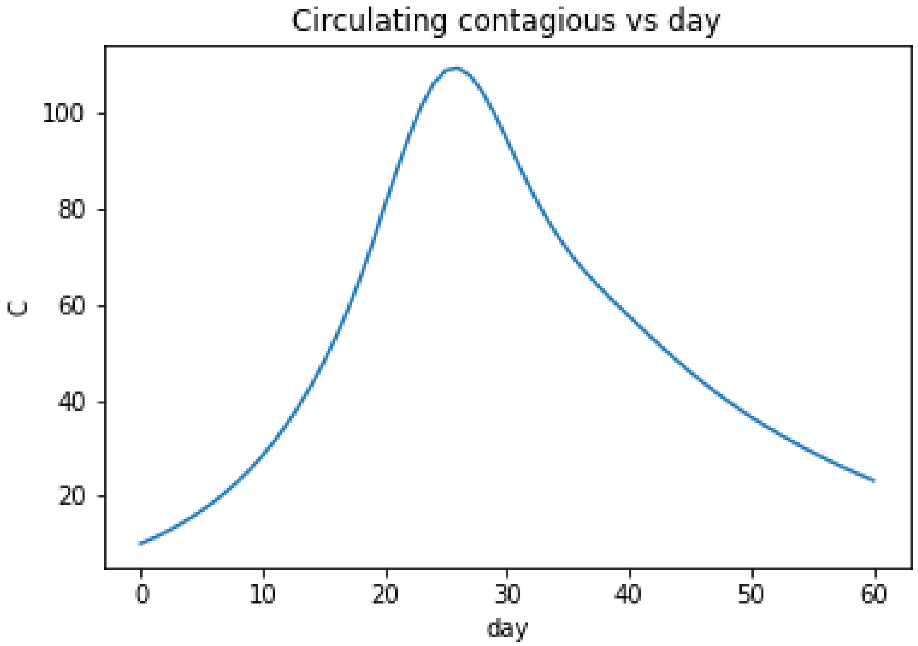
- Size of circulating contagious population?
  - Captures the size, but large scaling uncertainties (eg. asymptomatic fraction, fraction of symptomatic tested)
  - If size is to be used as a relative indicator (comparing different regions or different periods of the epidemic in a region) remove systematic scaling factors that are in common
- Proposal: Uncorrected circulating contagious population: *UC*

$$UC = C\ \frac{\text{total cases}}{\text{total infections}}$$

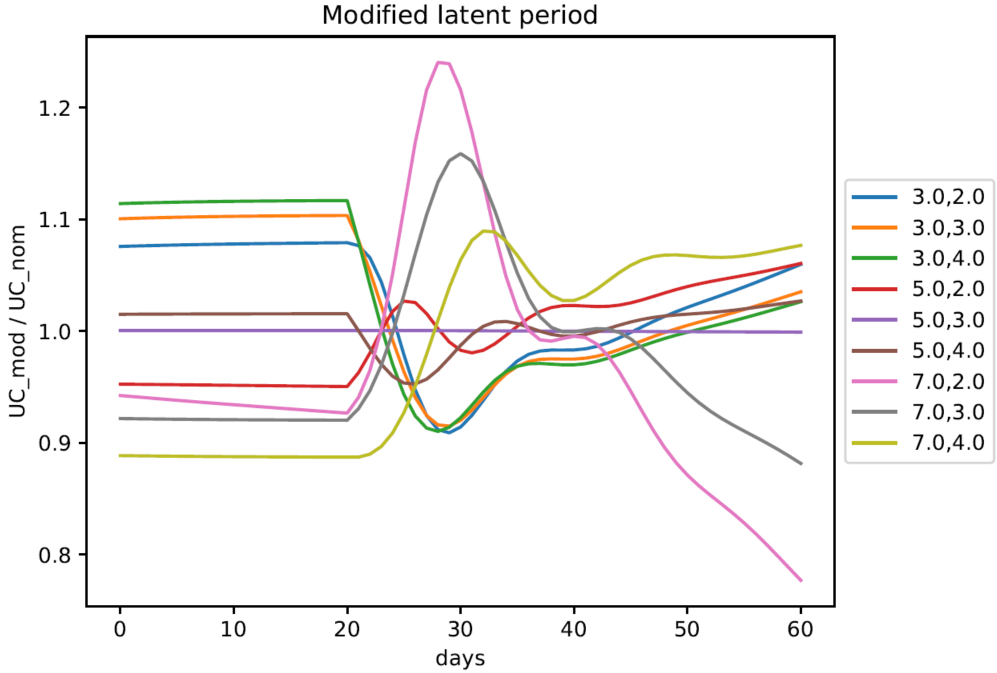
  - *UC* is less dependent on these common scaling uncertainties

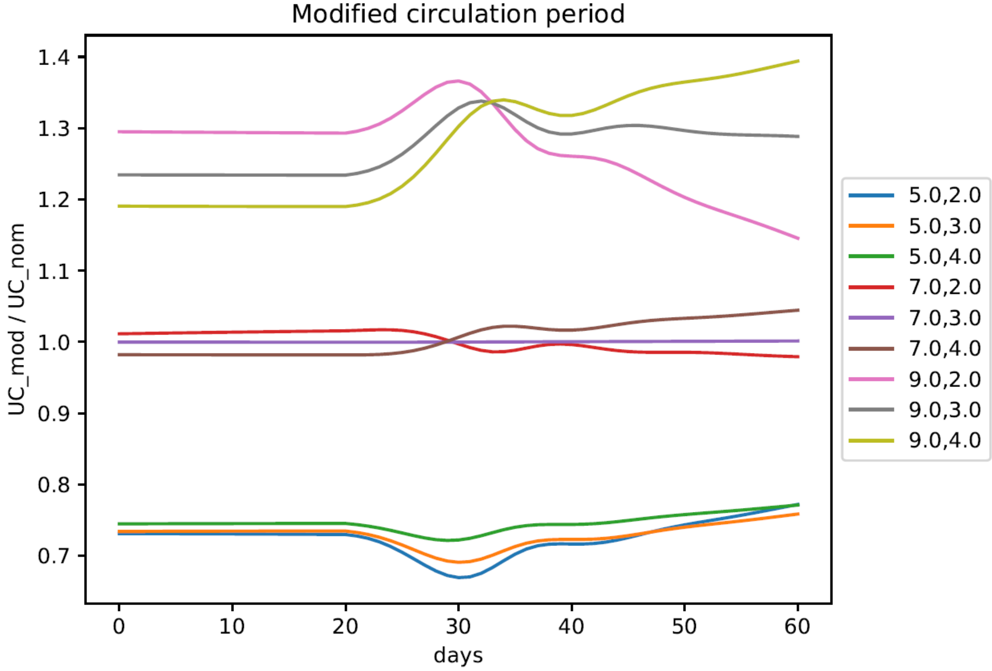
UC model dependence

- Example for this simple epidemic history:



While model dependence is order 30% size varies by several orders of magnitude



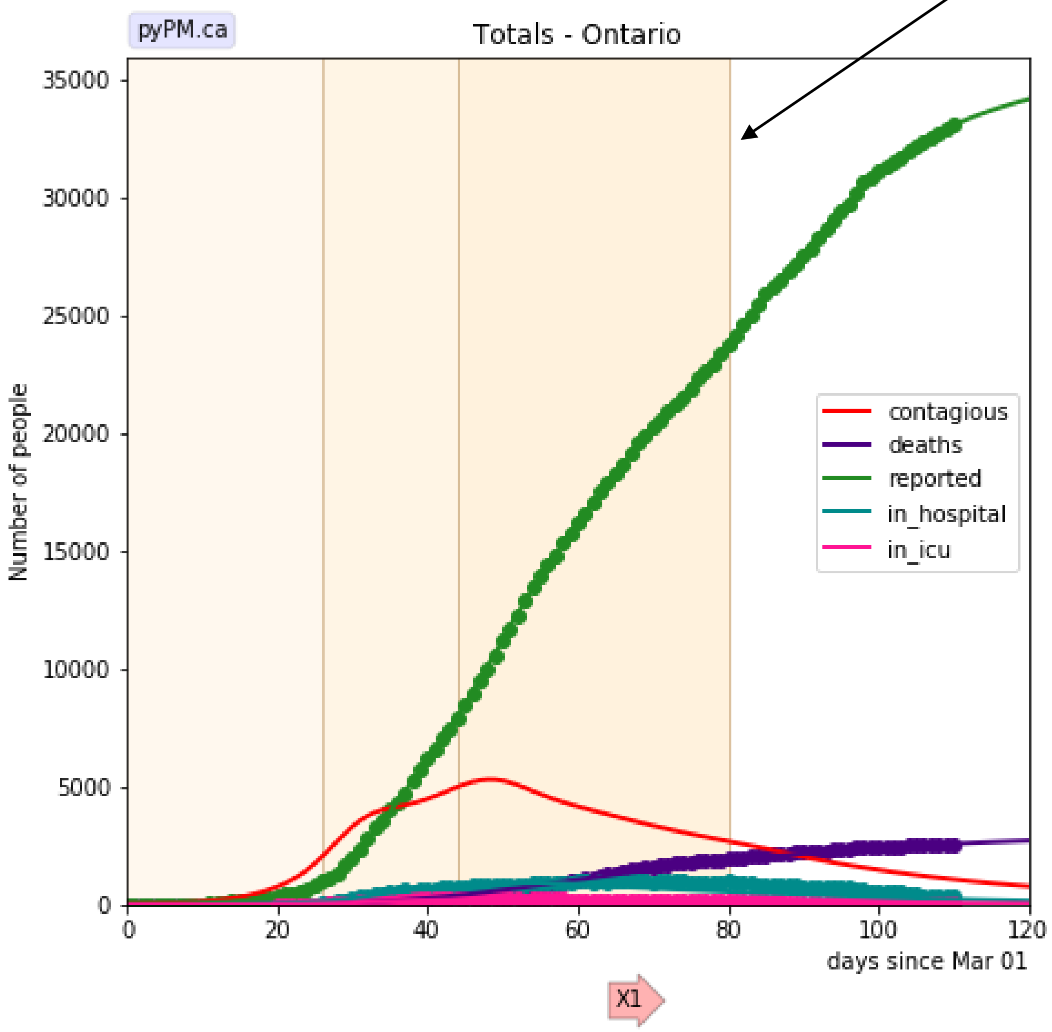


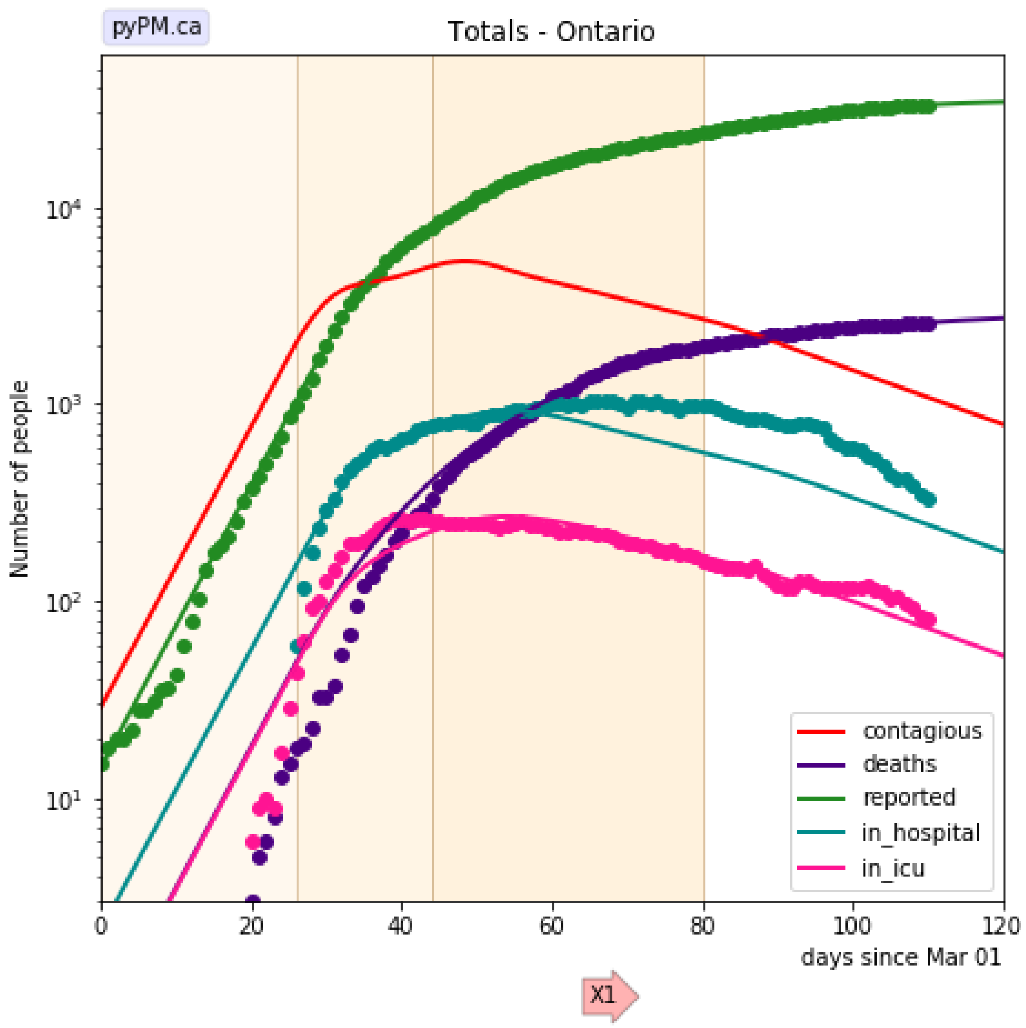
Provincial data

Data: March 1 – June 19, 2020

Ontario

Added May 19 transition to measure relaxation

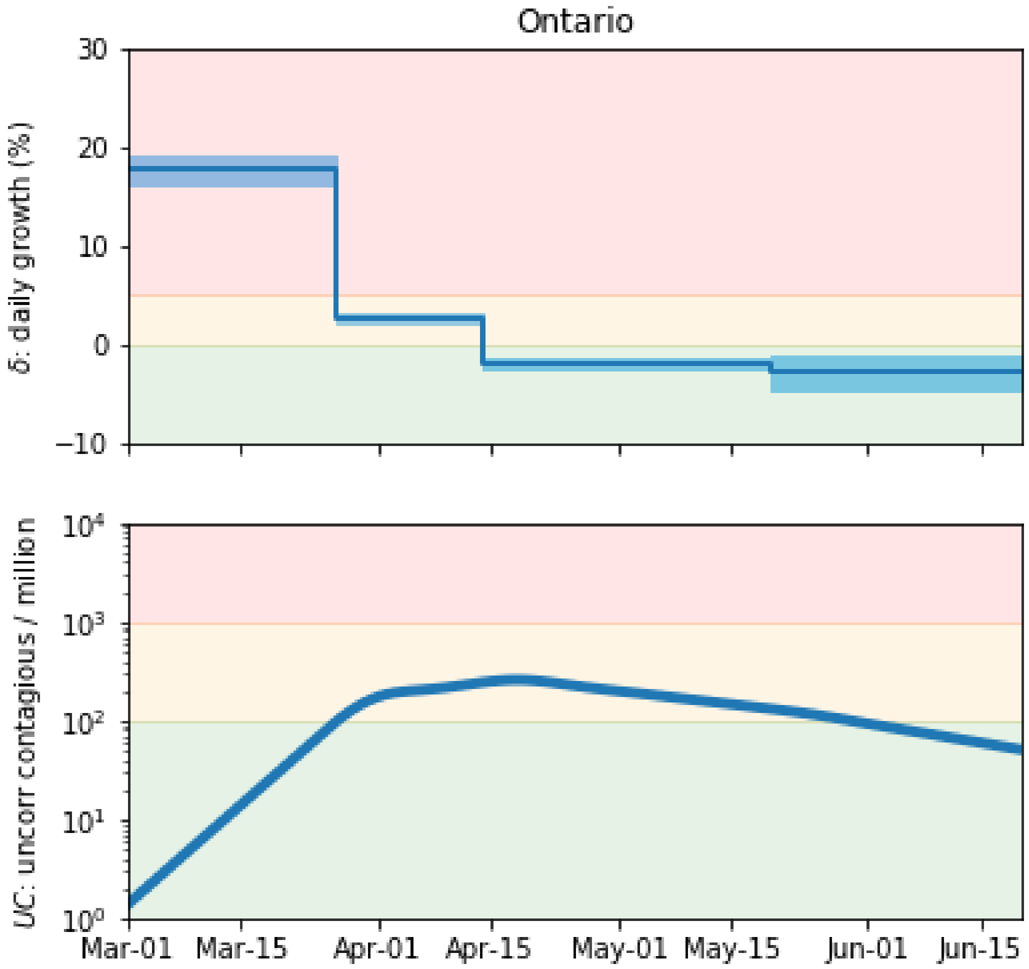




Ontario

Growth rate:
[fire hazard]

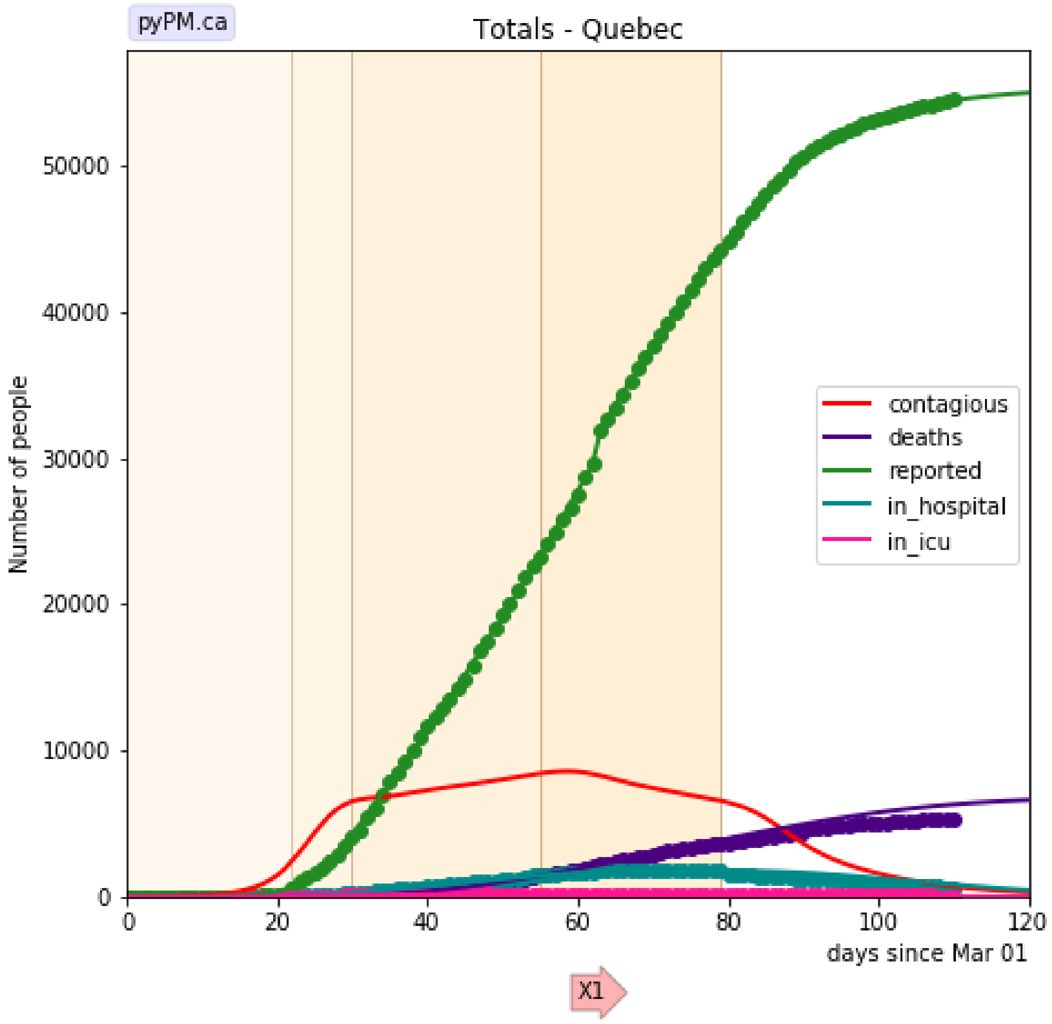
Size of epidemic:
[number of fires]

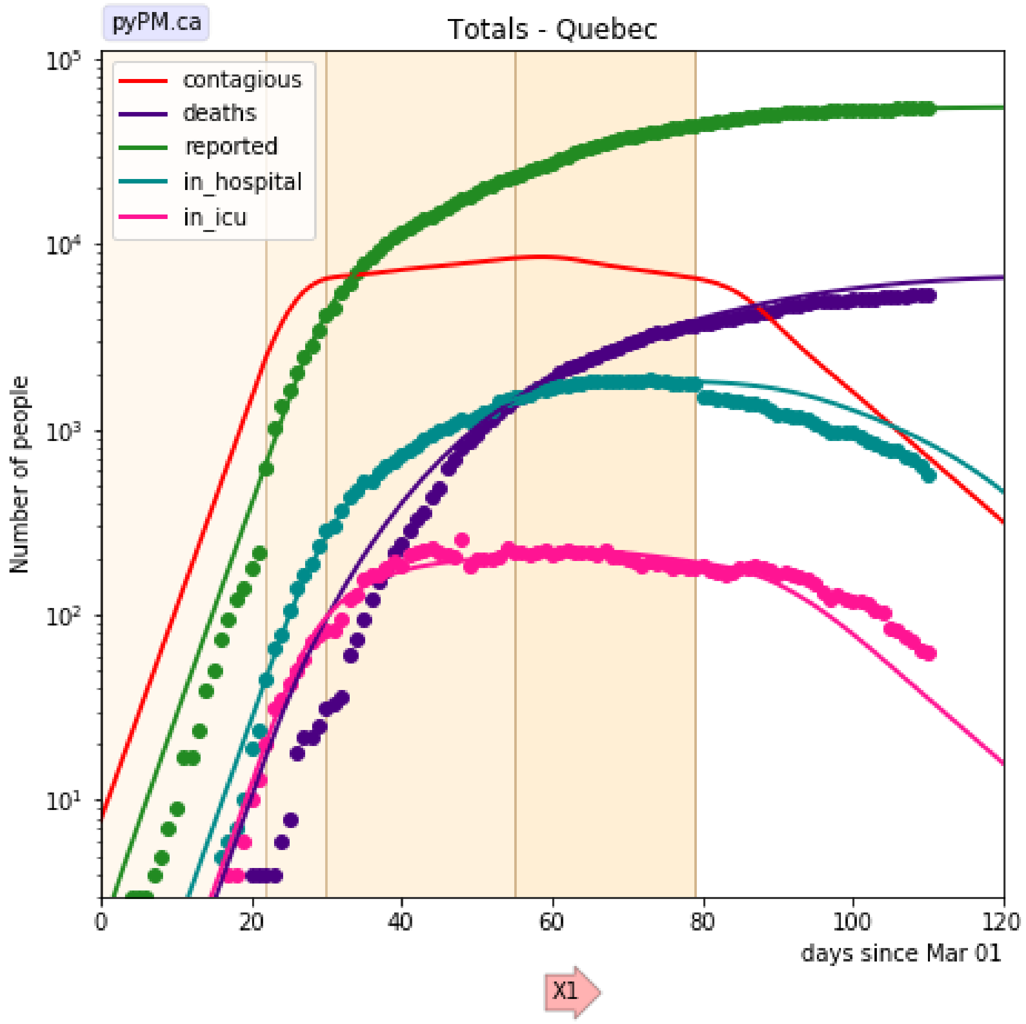


95% CL stat intervals

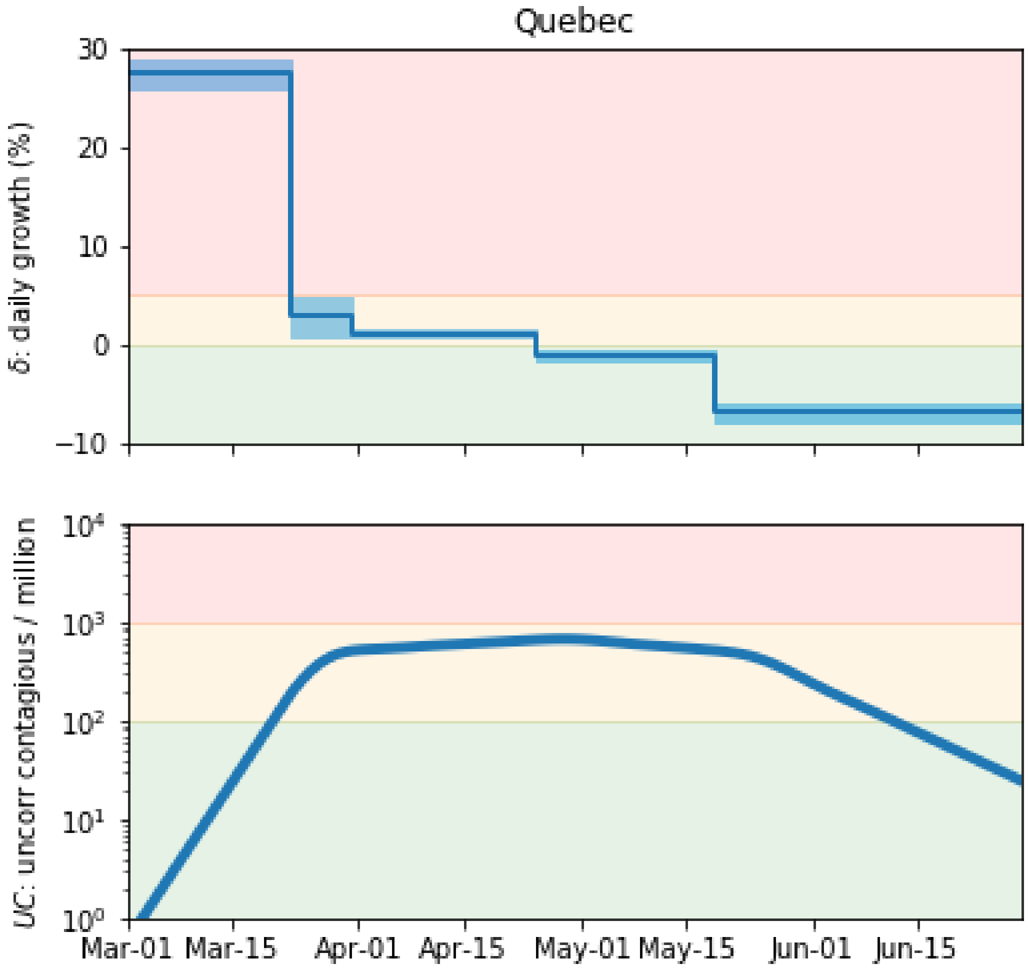
Quebec

Early case data not used in fit.
Testing availability in early March uneven.

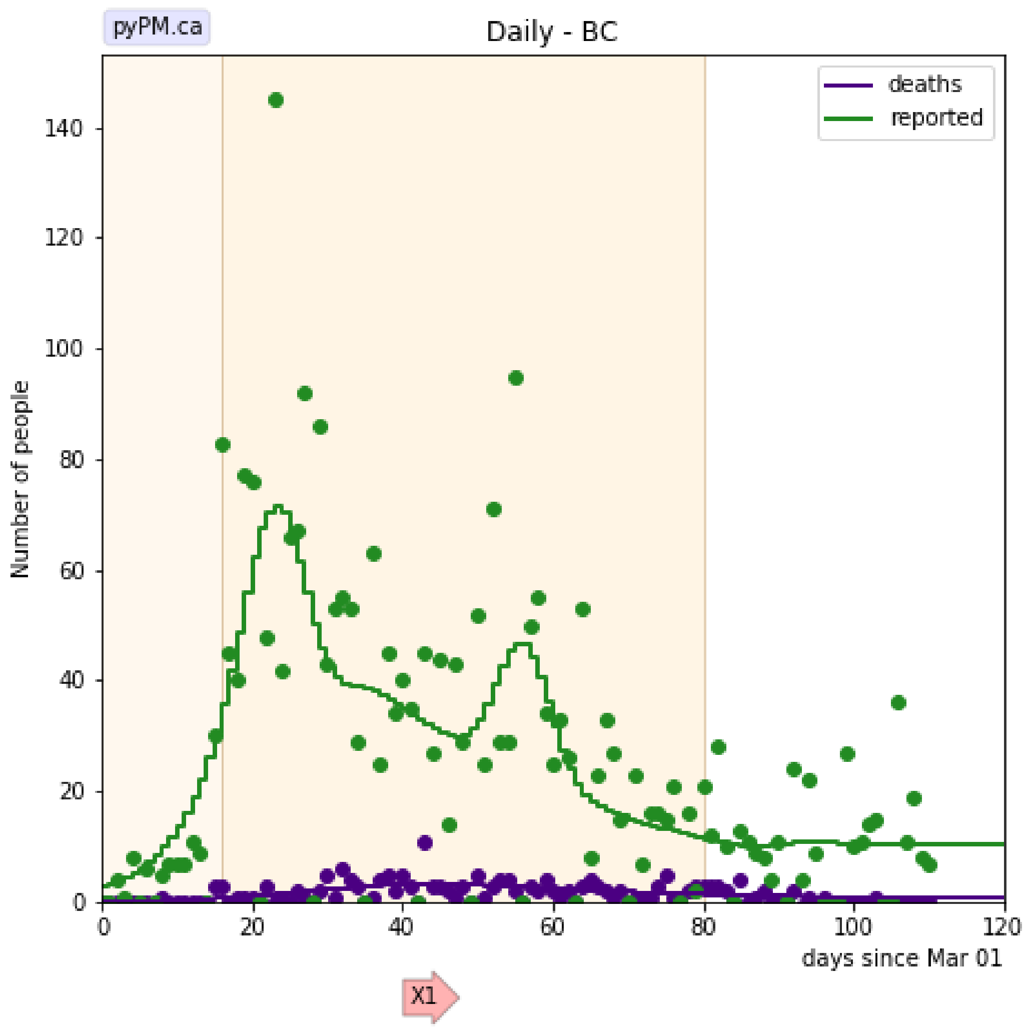


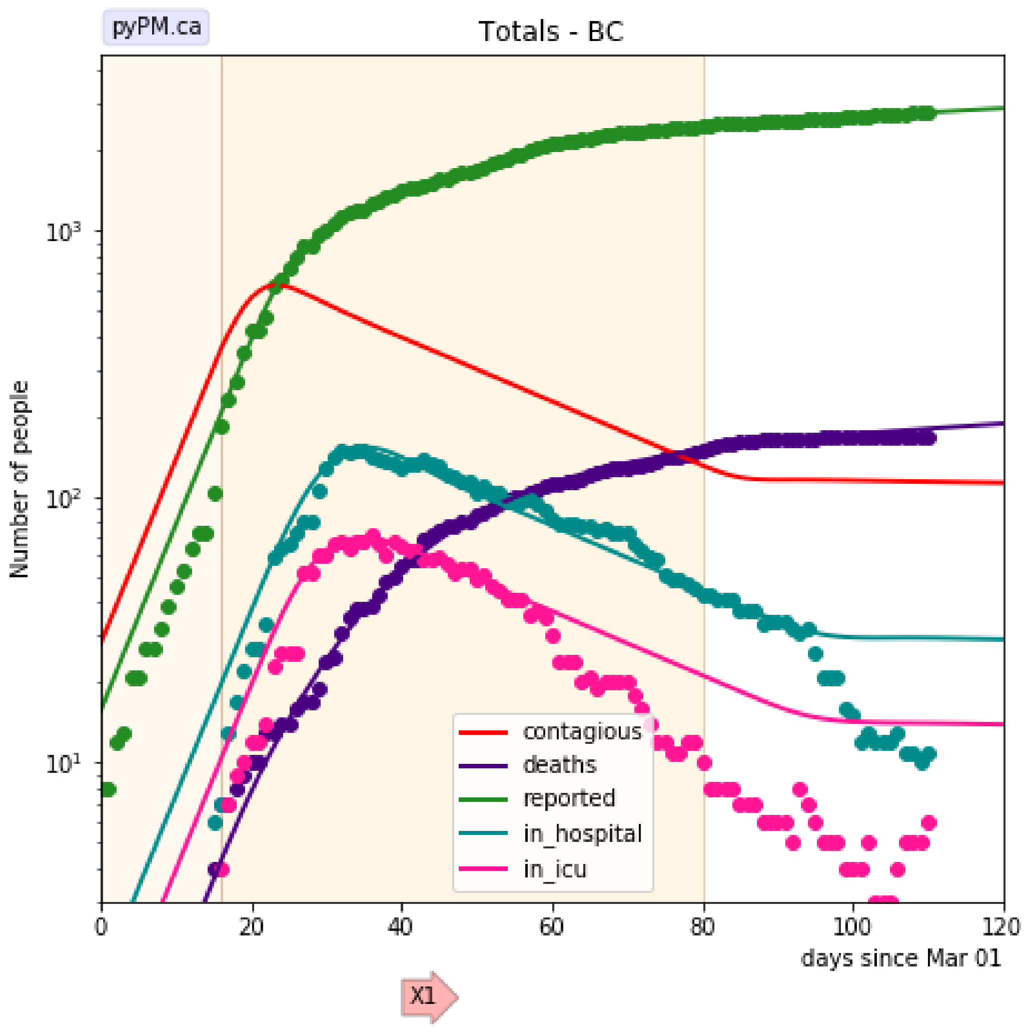


Quebec

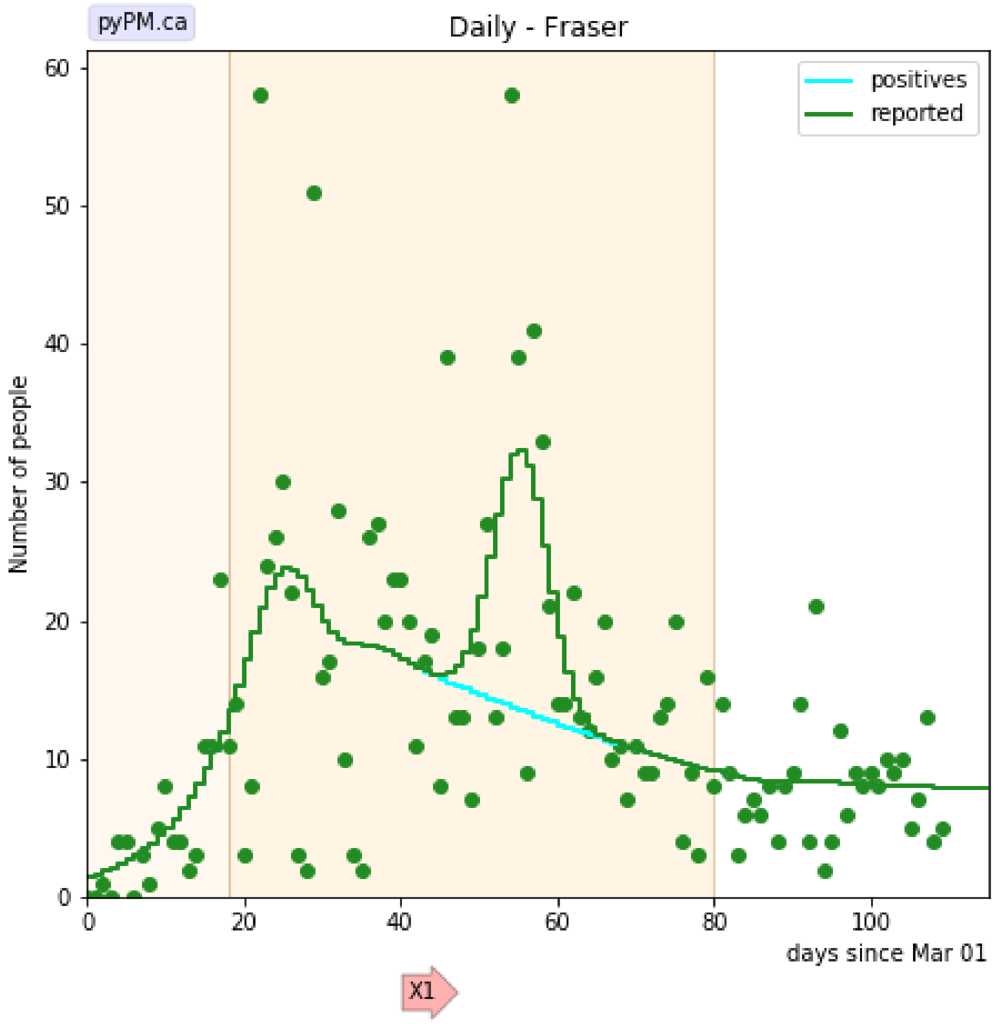

Quebec
δ: daily growth (%)
30
20
10
0
−10
UC: uncorr contagious / million
10^4
10^3
10^2
10^1
10^0
Mar-01 Mar-15 Apr-01 Apr-15 May-01 May-15 Jun-01 Jun-15

BC

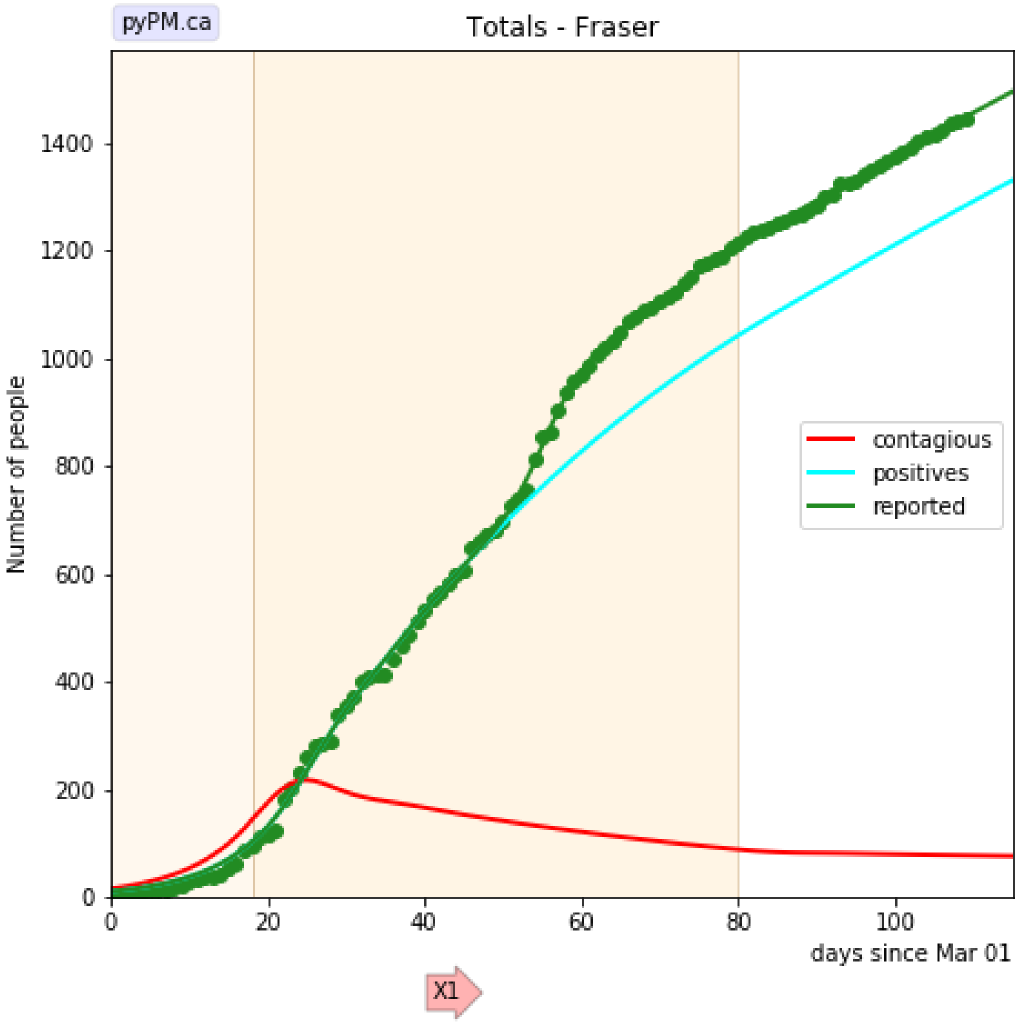

pyPM.ca
Daily - BC
deaths
reported
Number of people
0
20
40
60
80
100
120
140
0
20
40
60
80
100
120
days since Mar 01
X1


pyPM.ca
Totals - BC
Number of people
10^3
10^2
10^1
contagious
deaths
reported
in_hospital
in_icu
0
20
40
60
80
100
120
days since Mar 01
X1

BC: Fraser HA

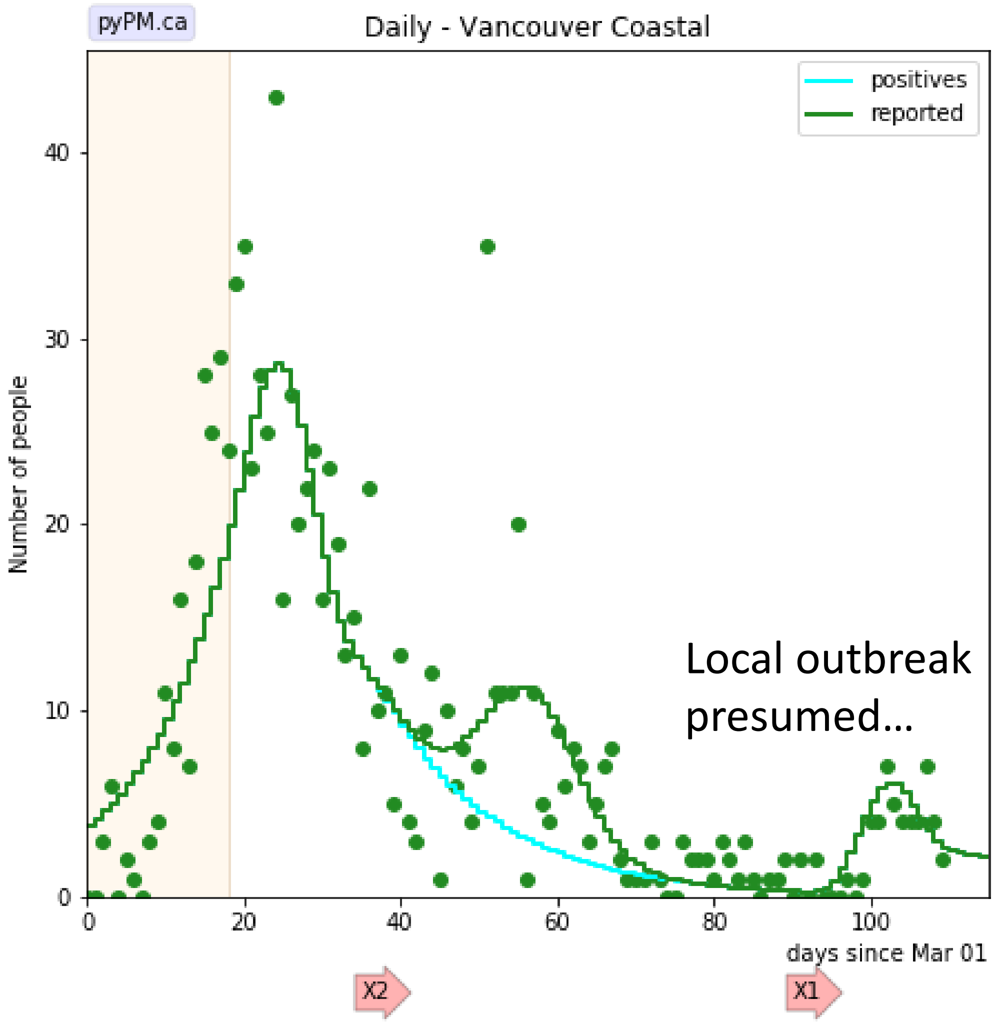


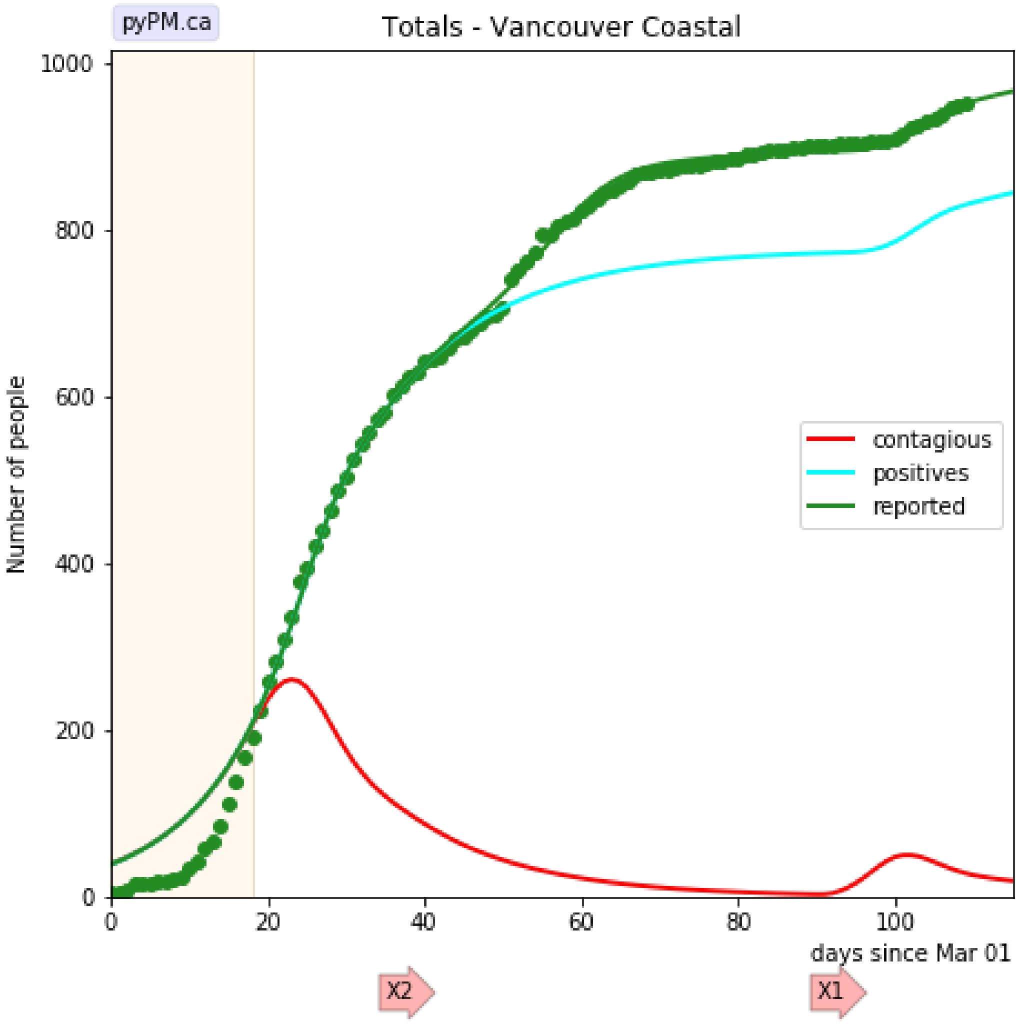
pyPM.ca
Daily - Fraser
positives
reported
Number of people
days since Mar 01
X1



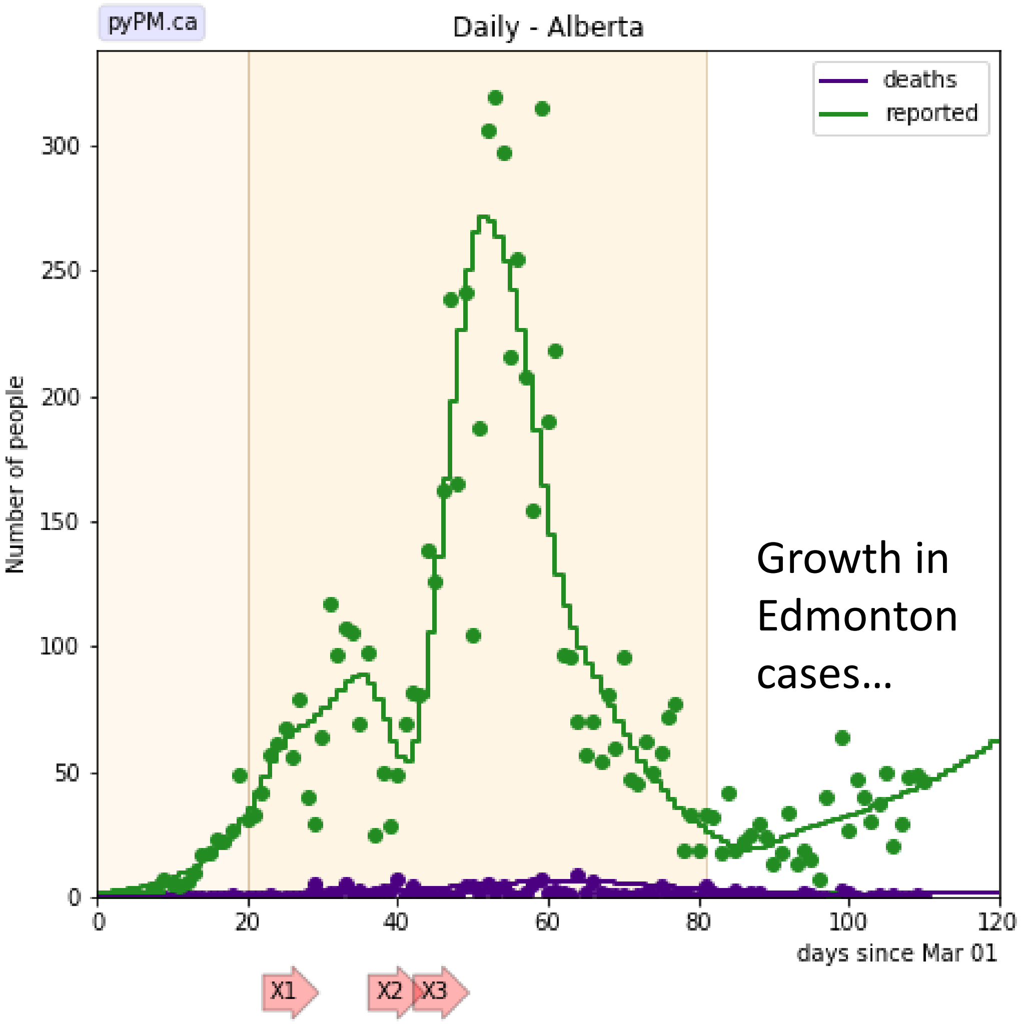
pyPM.ca
Totals - Fraser
contagious
positives
reported
Number of people
days since Mar 01
X1

BC: Vancouver Coastal HA

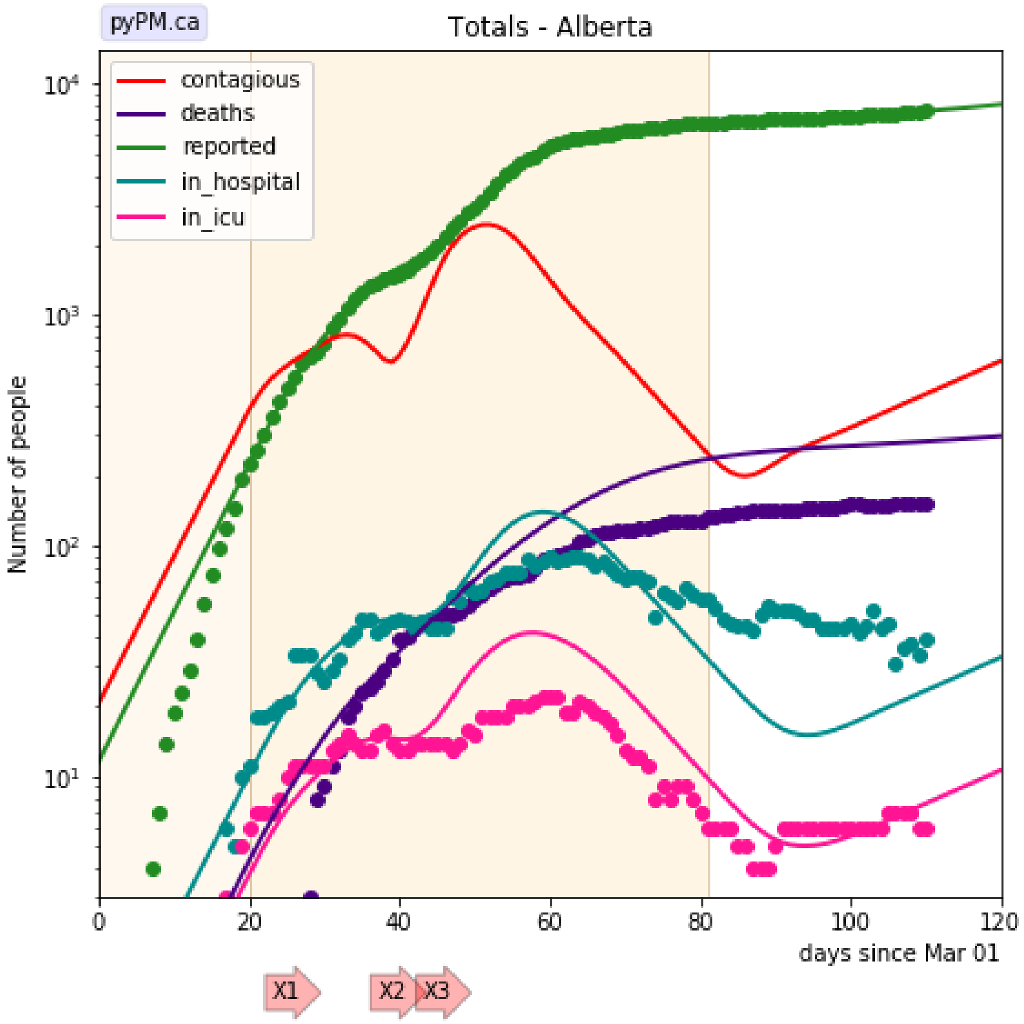




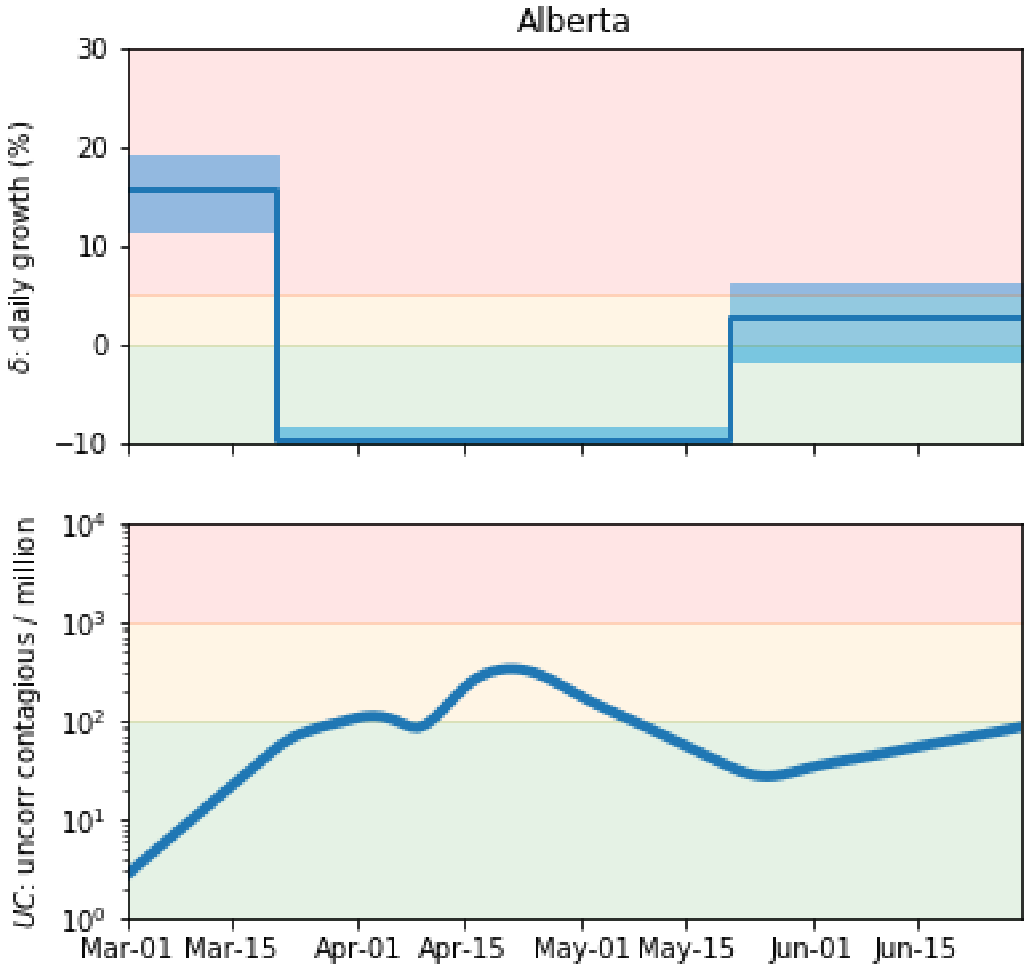
Alberta



Growth in Edmonton cases…



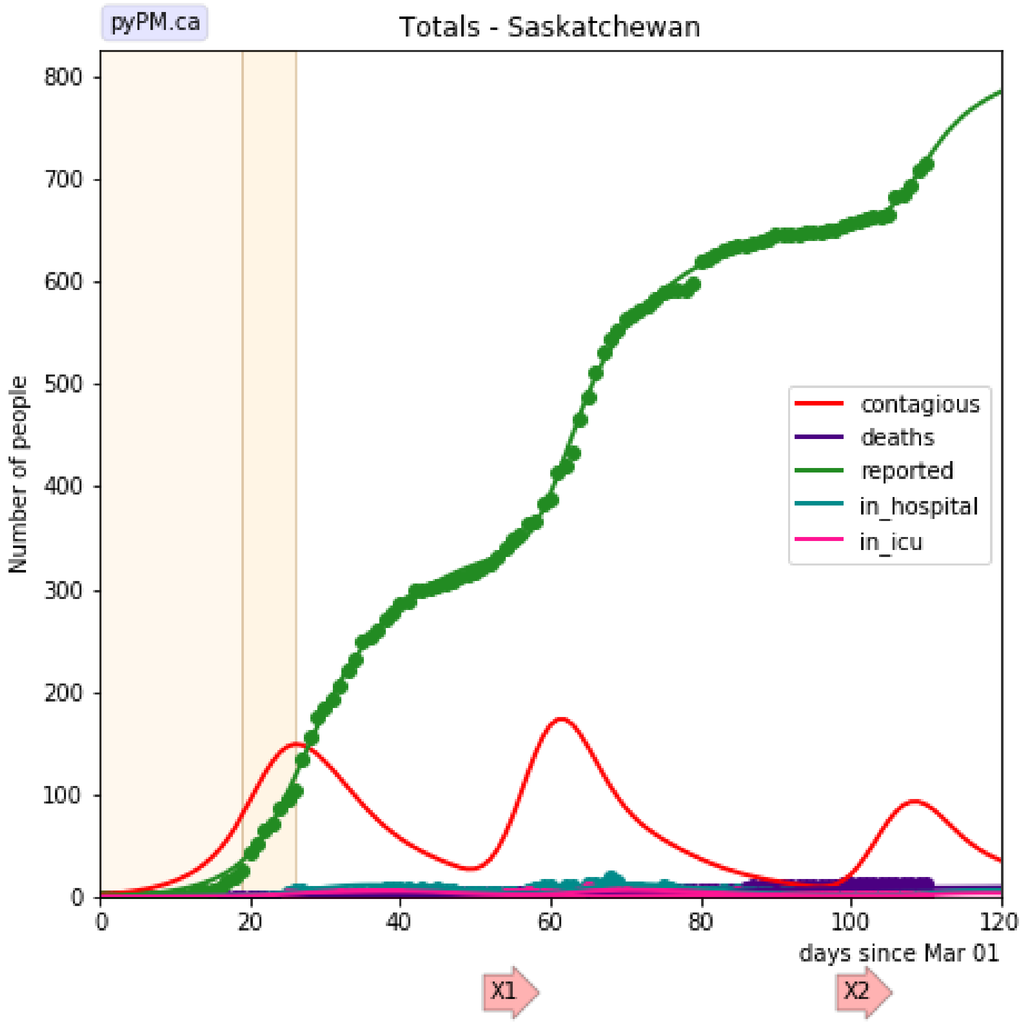
Alberta

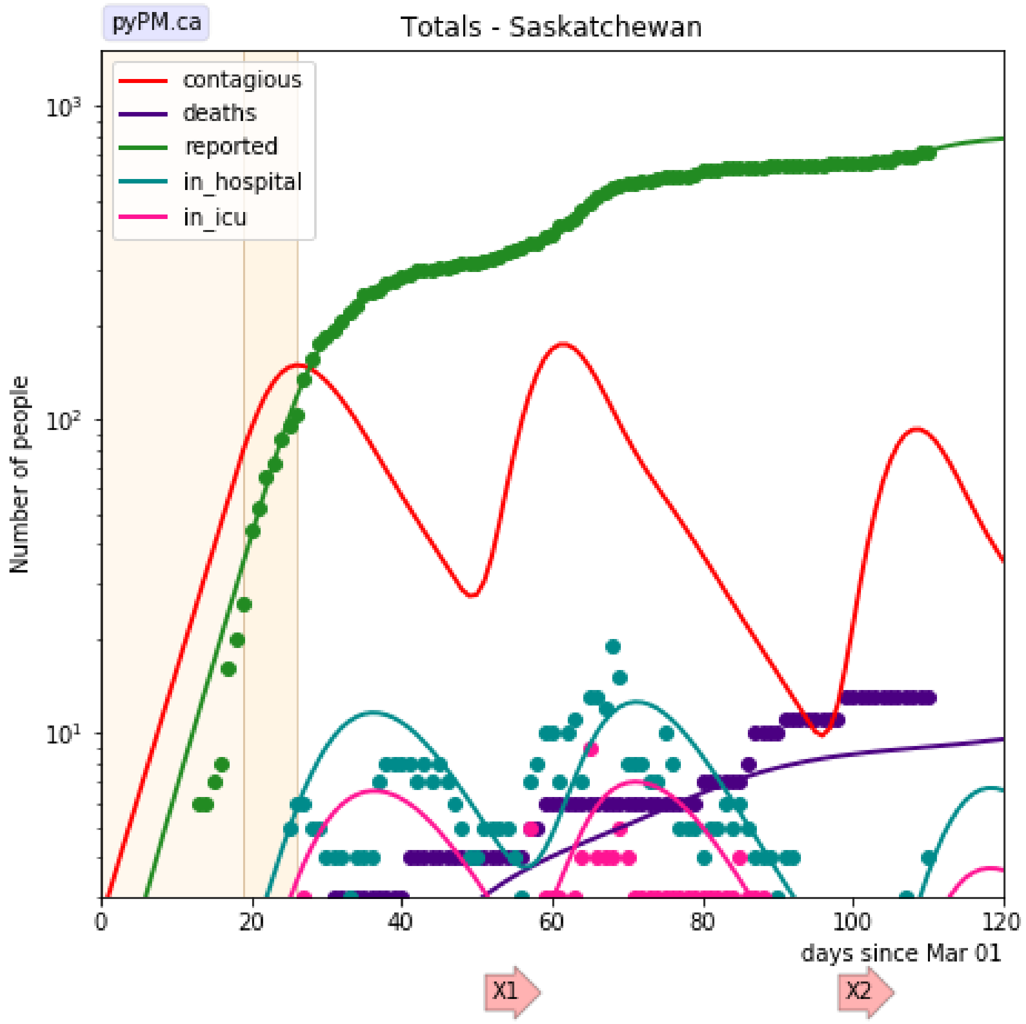


Need to wait for more data to say if $\delta > 0$

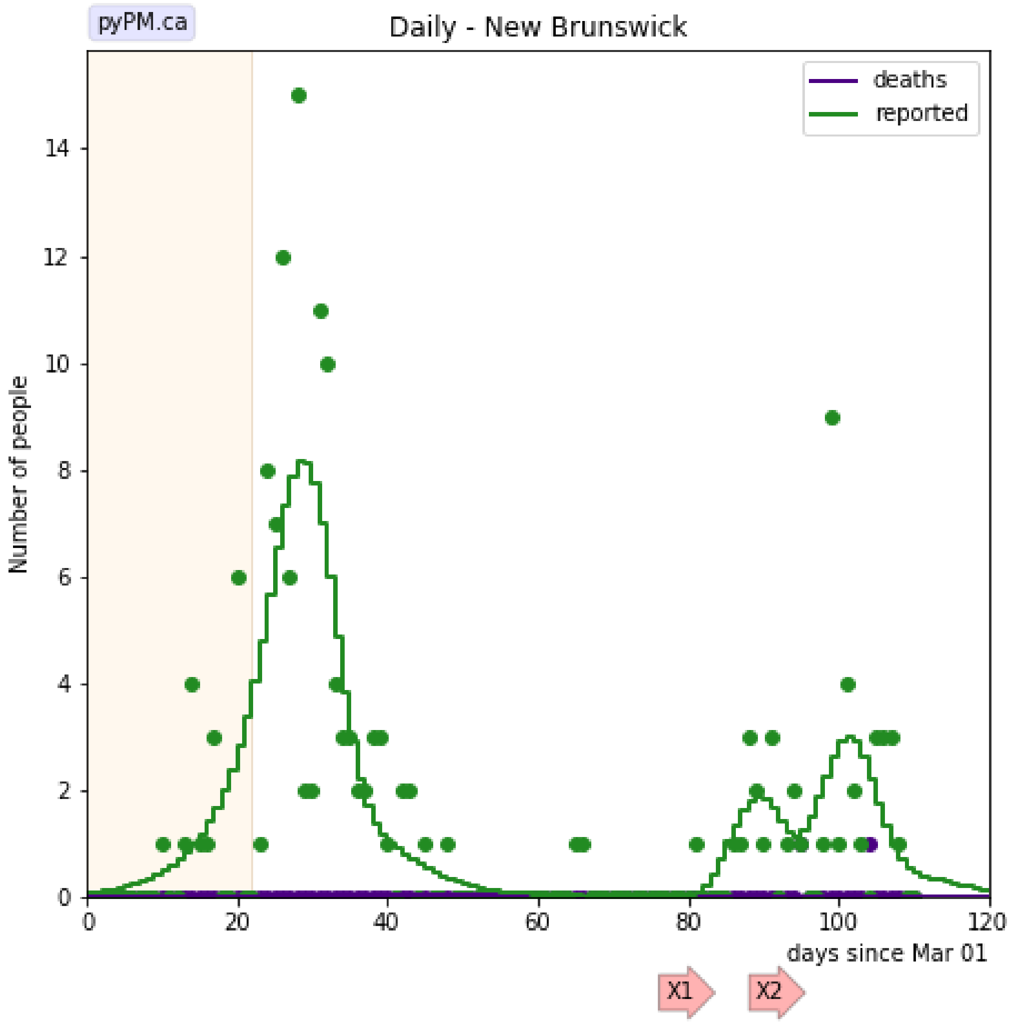
Saskatchewan

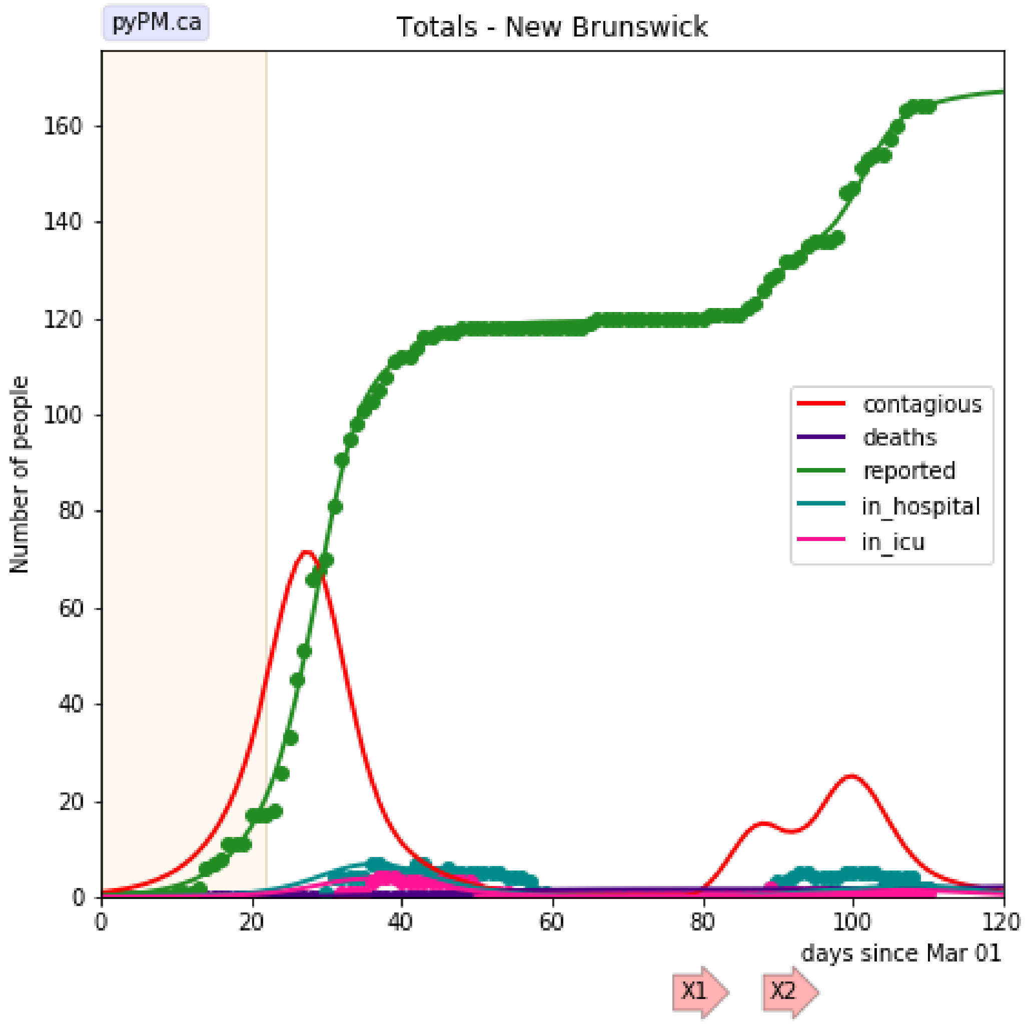
Outbreaks in Far Northern communities





New Brunswick





German state data

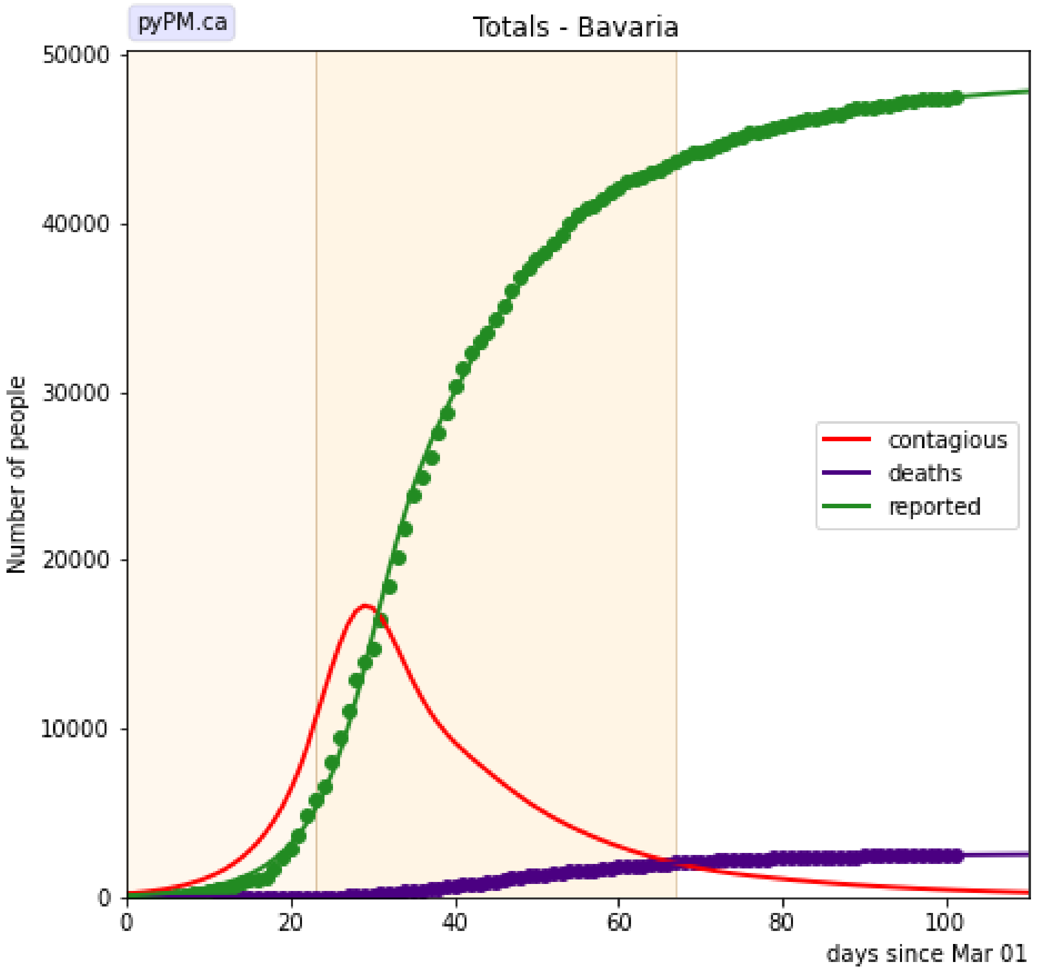
Data: March 1 – June 10, 2020 (update on June 19)

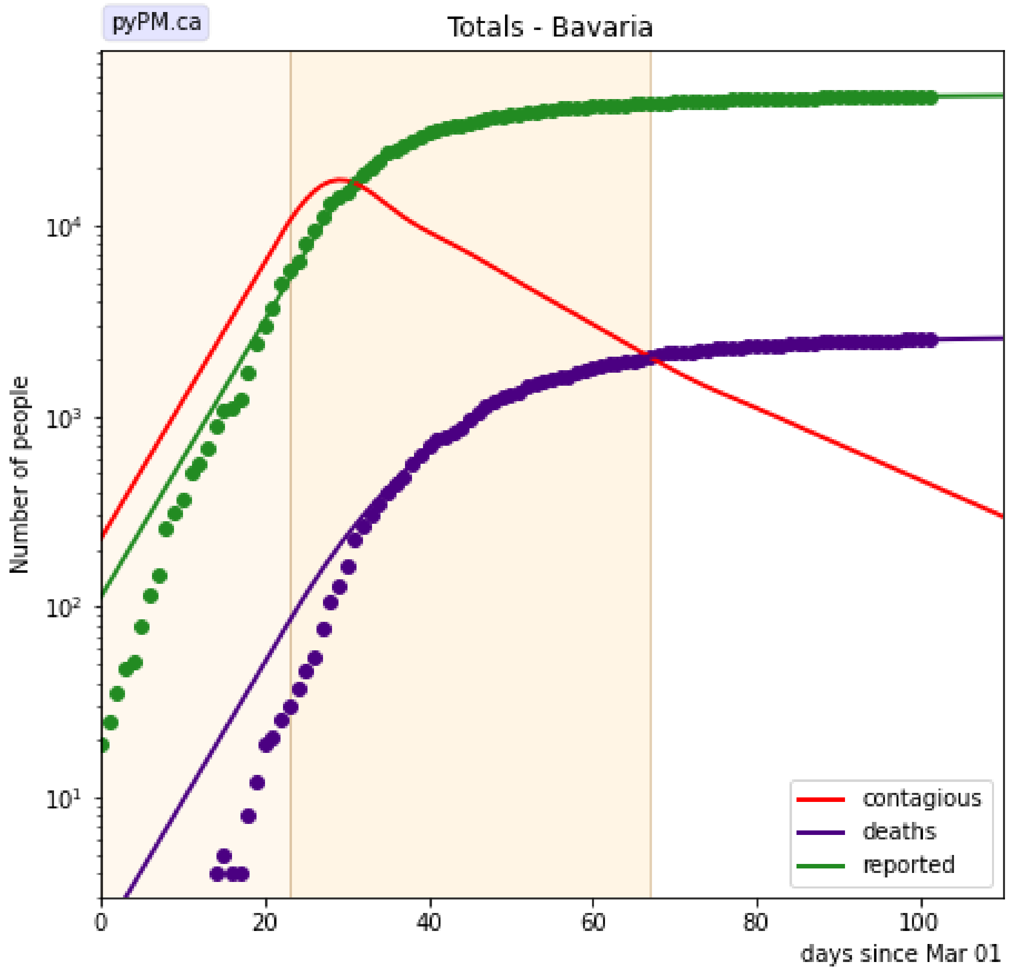
Lockdown measures: March 22

Relaxation of measures: May 6

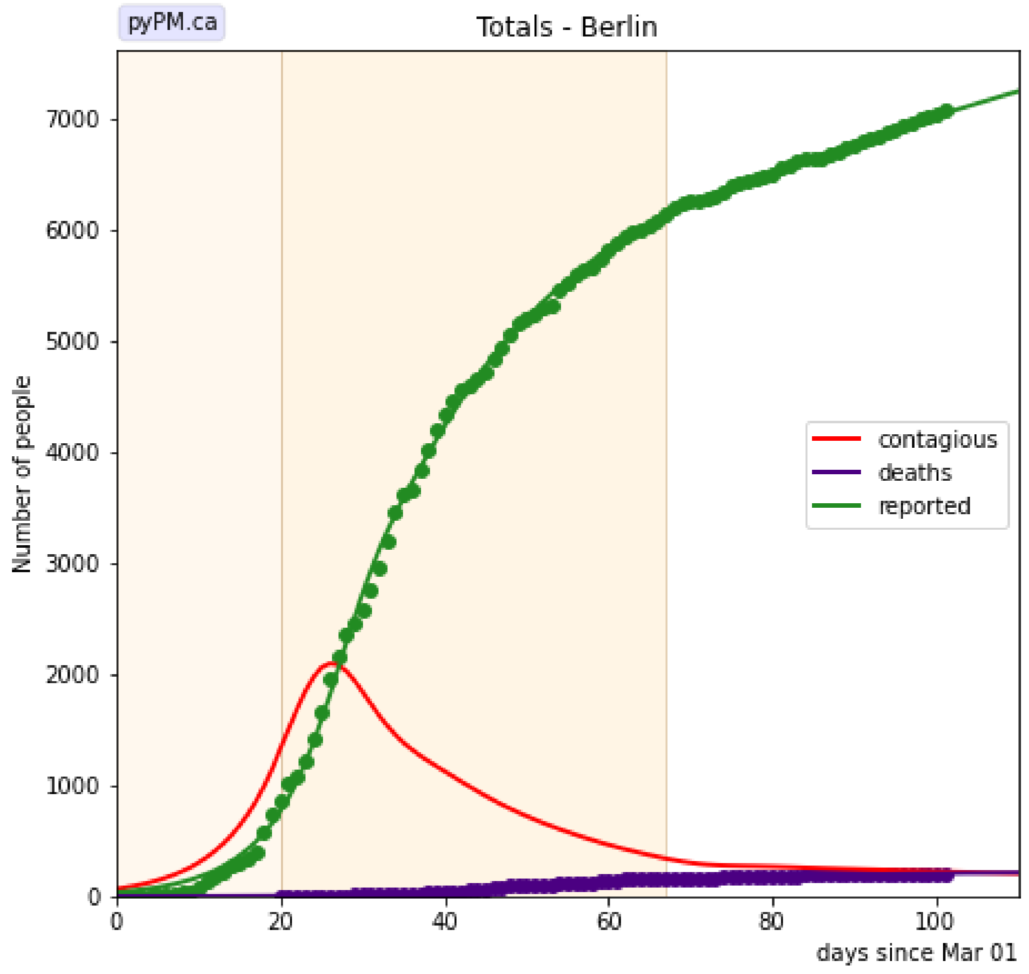
Bavaria

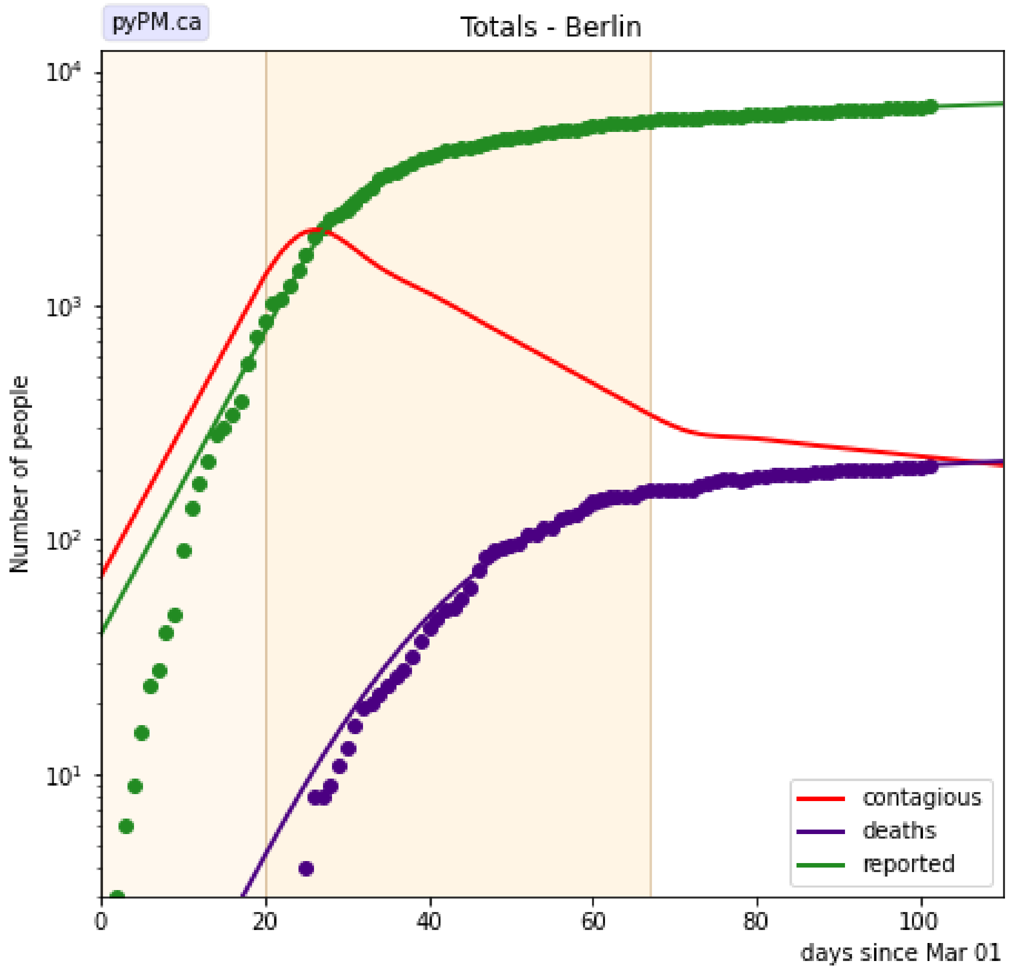
Data from 16 German states very similar to each other



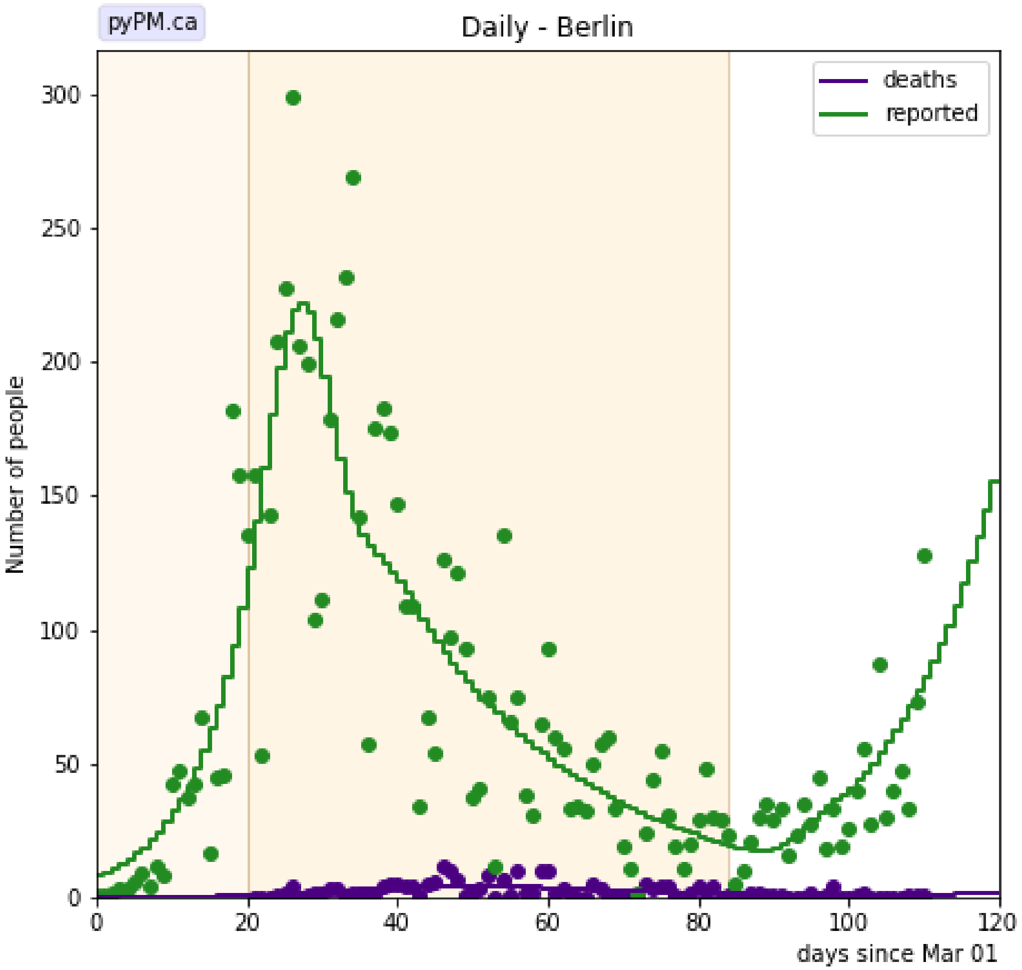


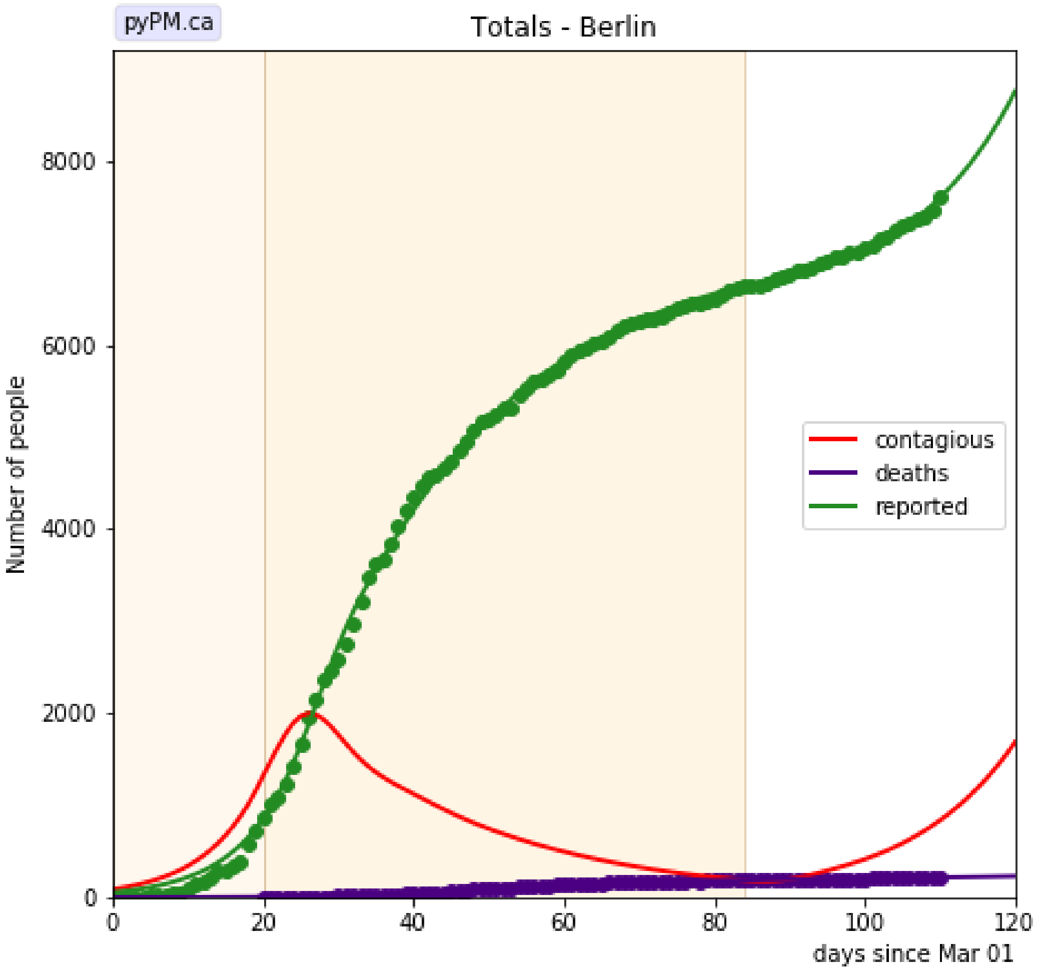
Berlin (through June 10)



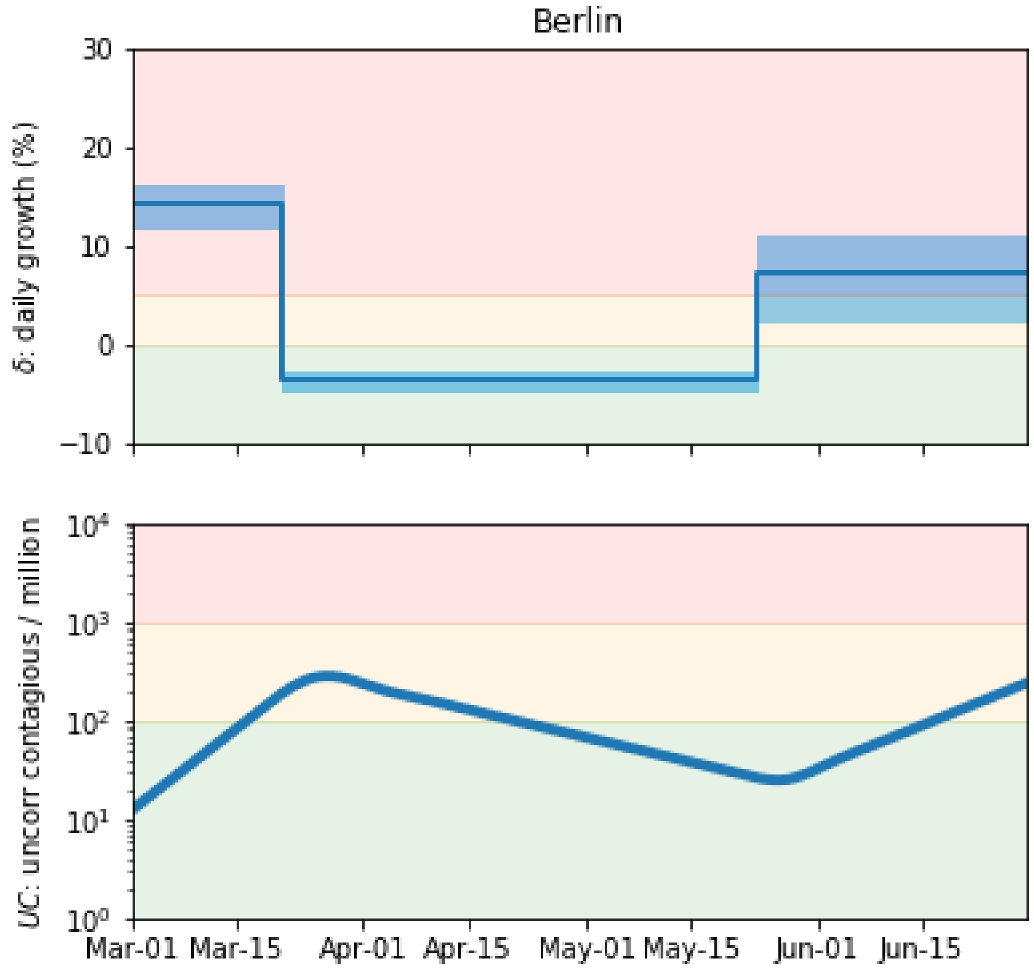


Berlin (through June 19)





Berlin (through June 19)



The only German state experiencing growth

US state data

Data: March 1 – June 17, 2020

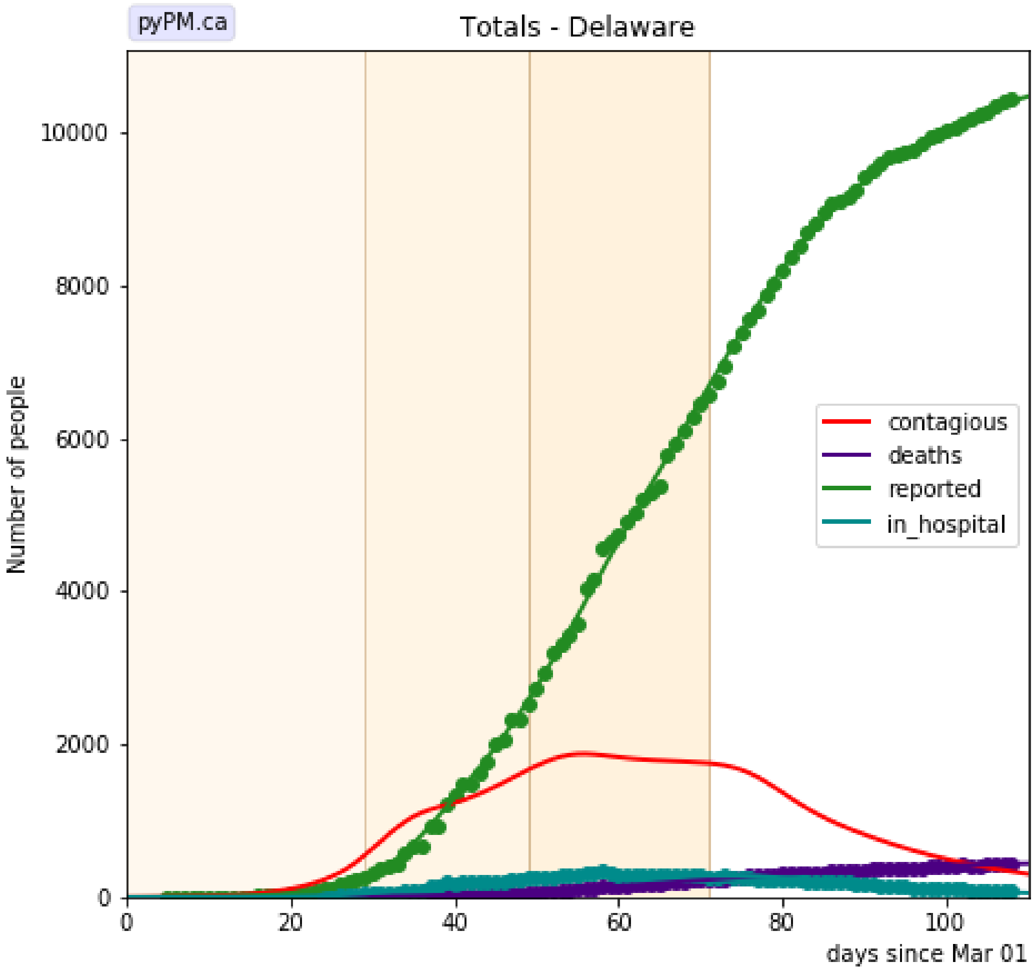
Lockdown measures: varies

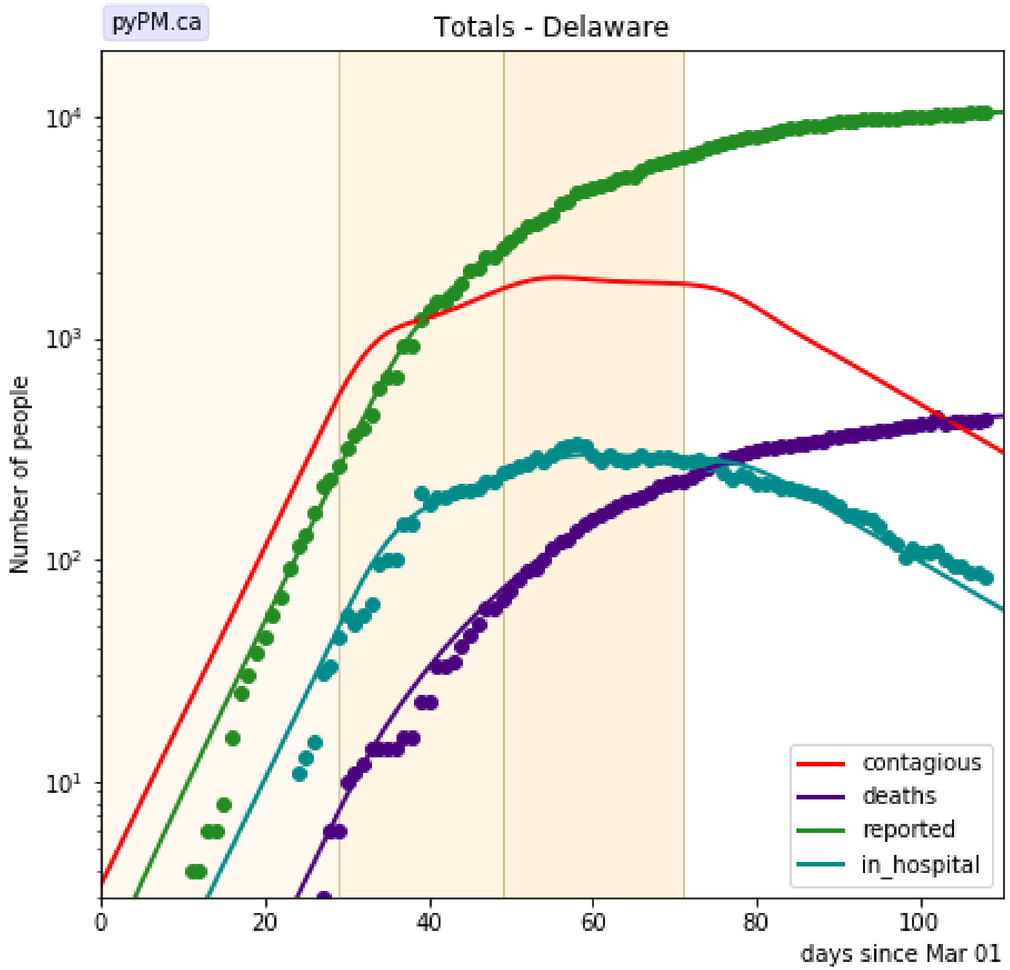
Relaxation of measures: varies. I use Memorial weekend as a transition date

US state data

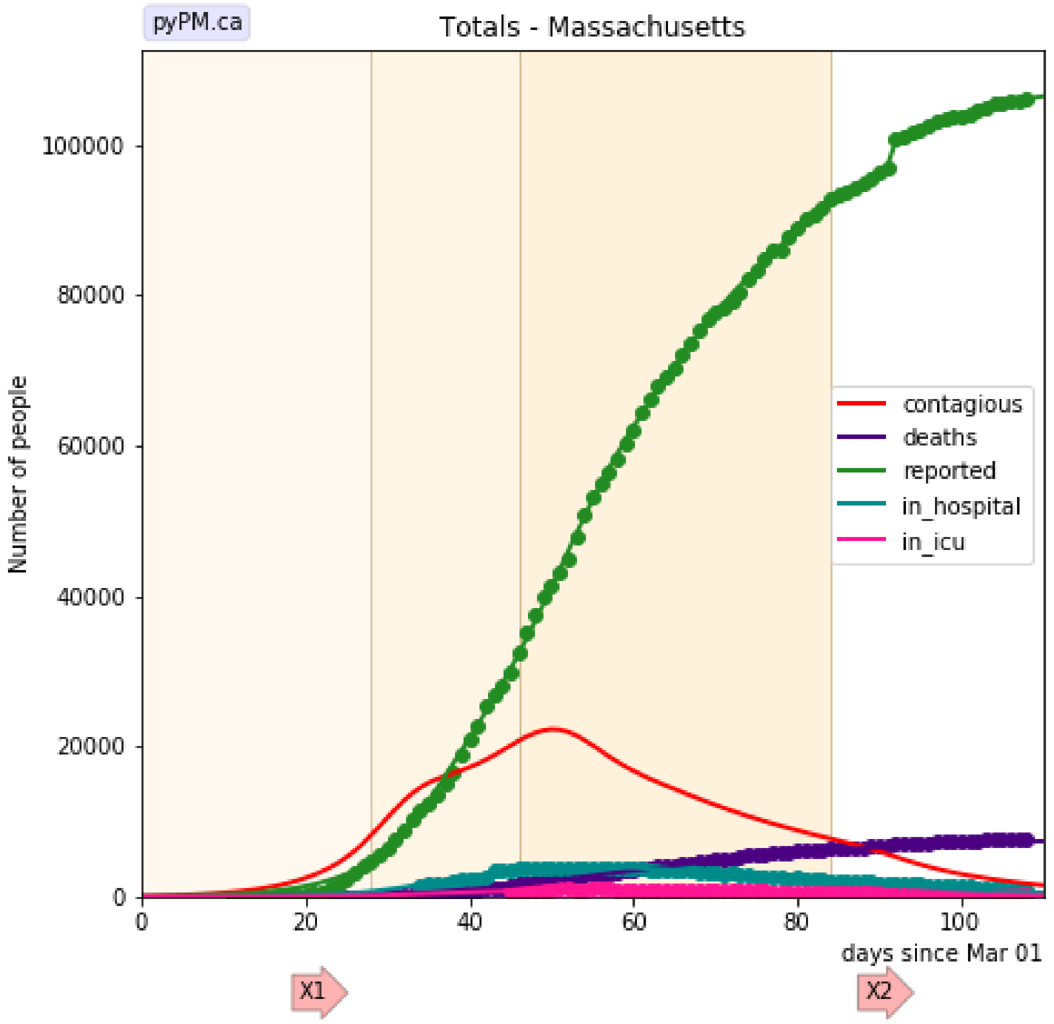
- Large variation in growth and size of epidemic
- For many: hospitalization growth/decline follow trajectories predicted by model (following case data – supports the use of case data)
- For many states currently experiencing growth: hospitalization growth starting to depart from case growth
  - Possibly due to unequal sampling case/hospitalization by age?

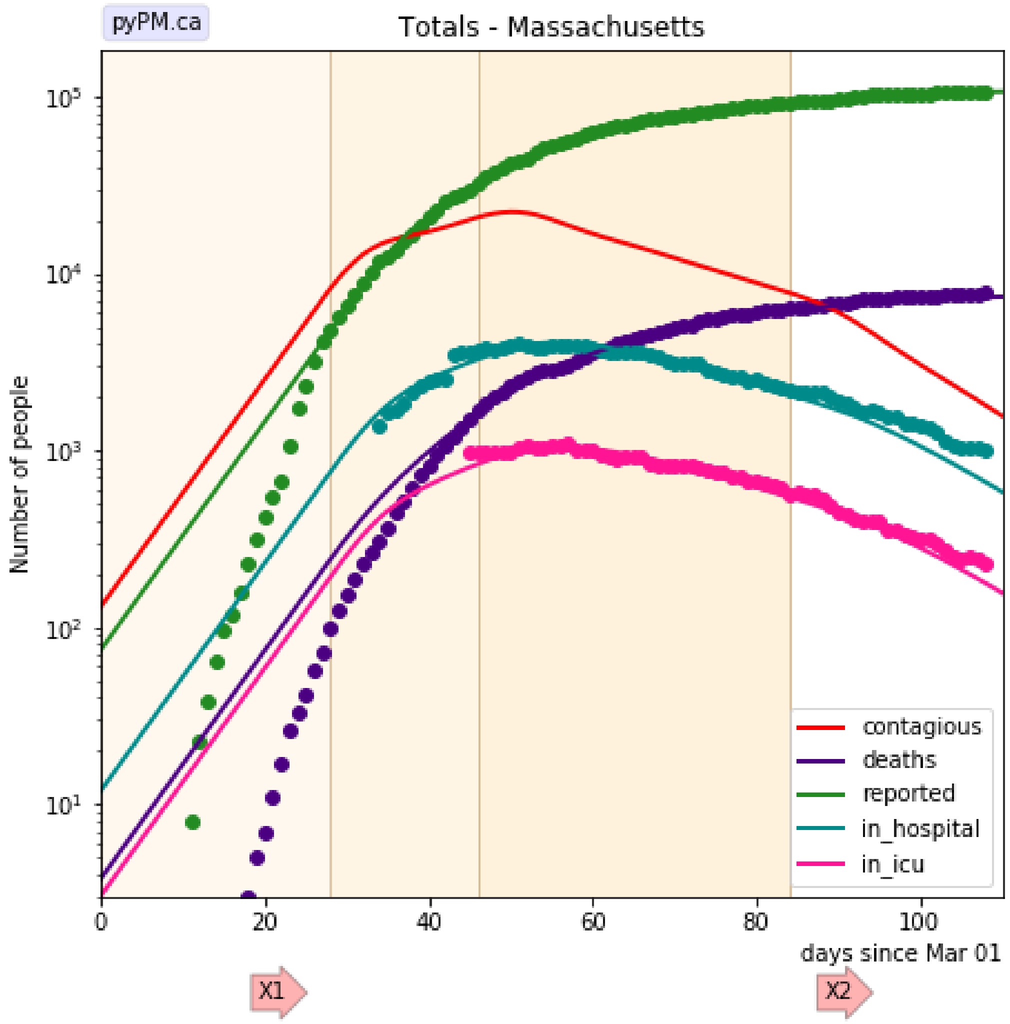
Delaware


pyPM.ca
Totals - Delaware
Number of people
10000
8000
6000
4000
2000
0
0
20
40
60
80
100
days since Mar 01
contagious
deaths
reported
in_hospital

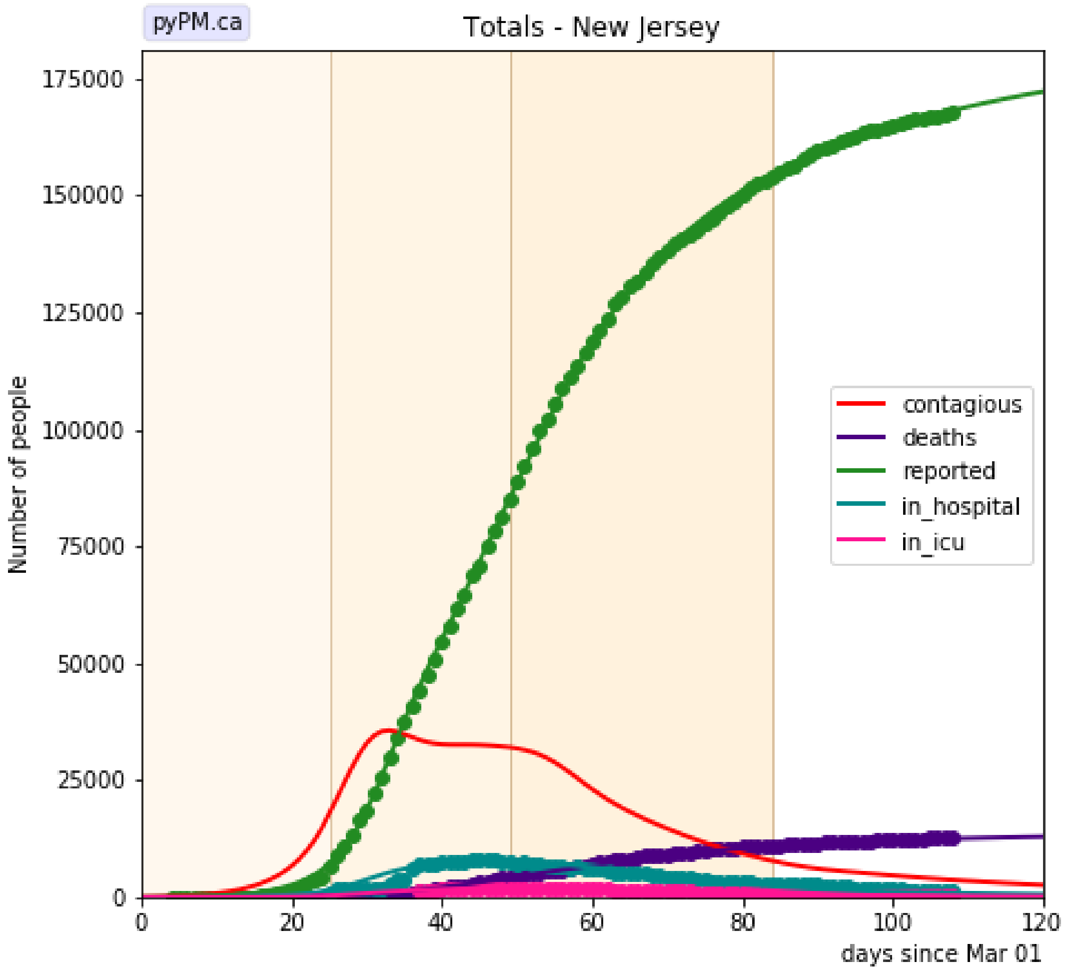

pyPM.ca
Totals - Delaware
Number of people
10^4
10^3
10^2
10^1
0
20
40
60
80
100
days since Mar 01
contagious
deaths
reported
in_hospital

Massachusetts

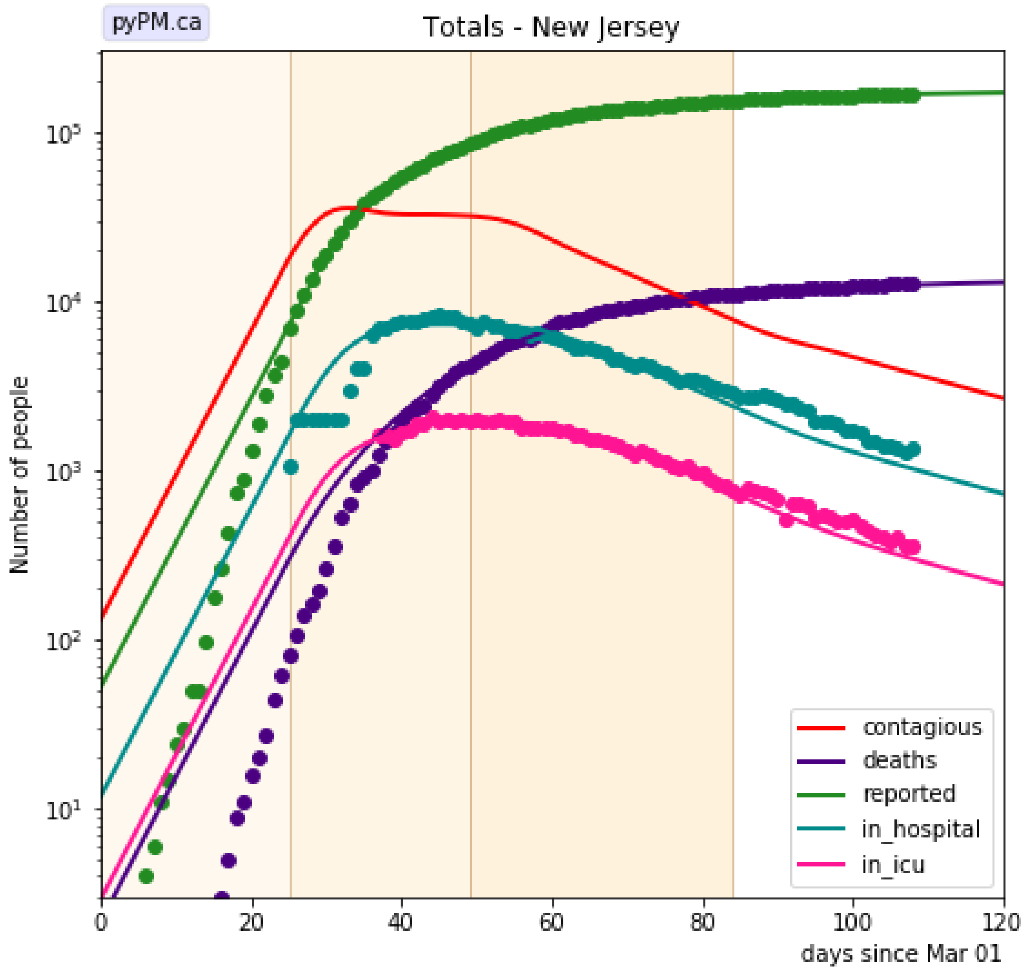




New Jersey

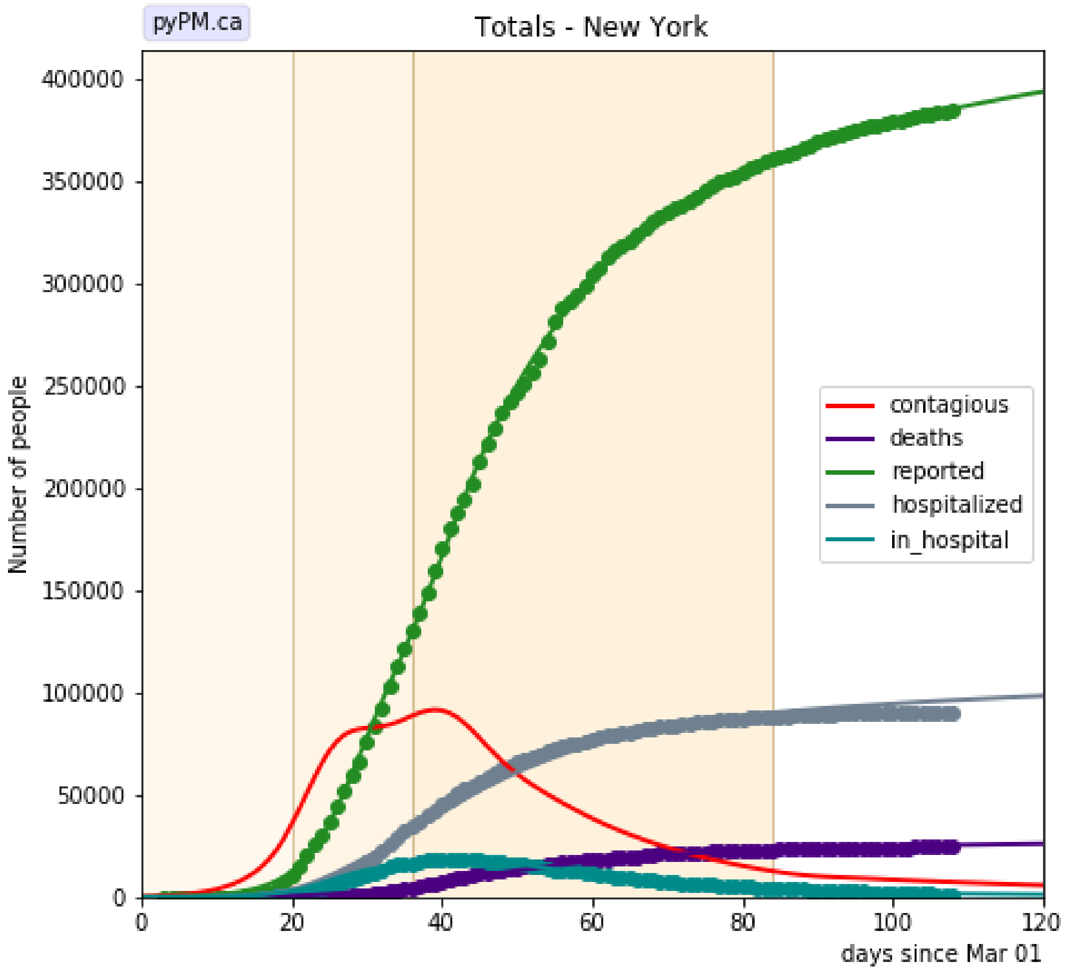


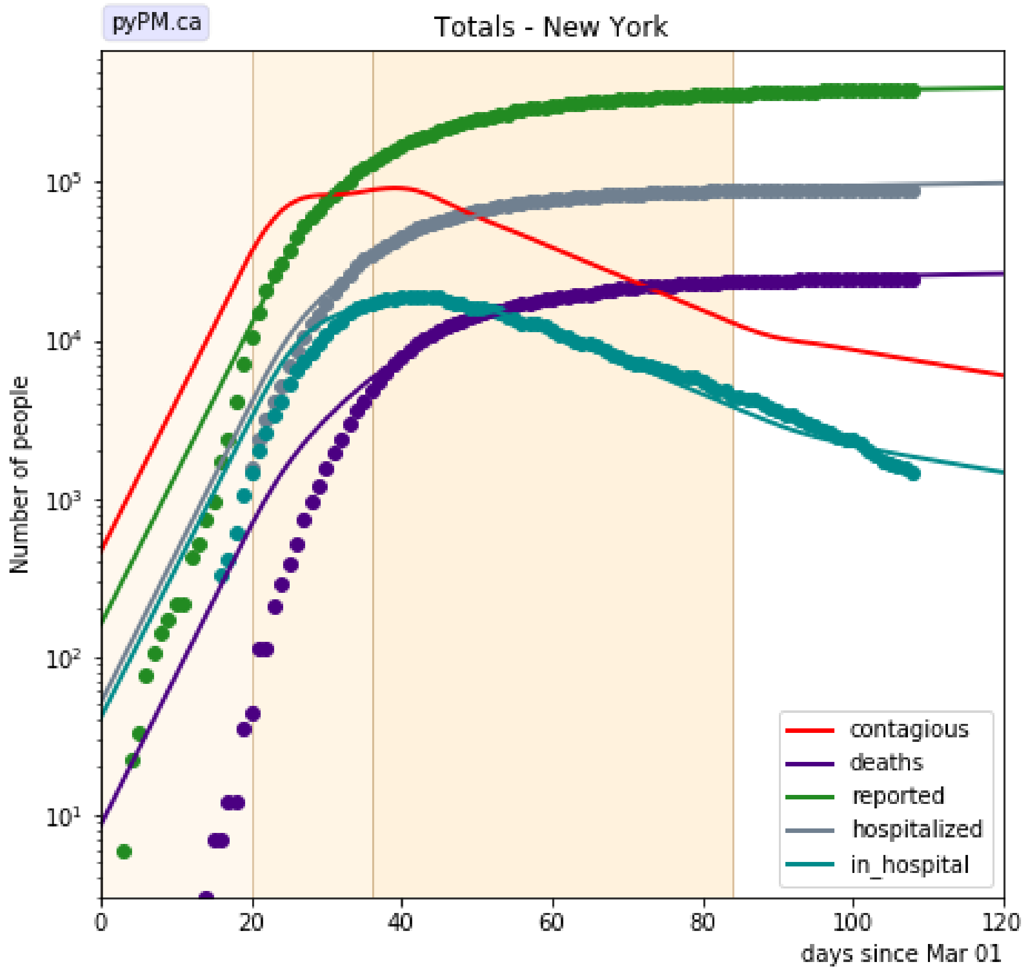
pyPM.ca
Totals - New Jersey
Number of people
175000
150000
125000
100000
75000
50000
25000
0
0
20
40
60
80
100
120
days since Mar 01
contagious
deaths
reported
in_hospital
in_icu



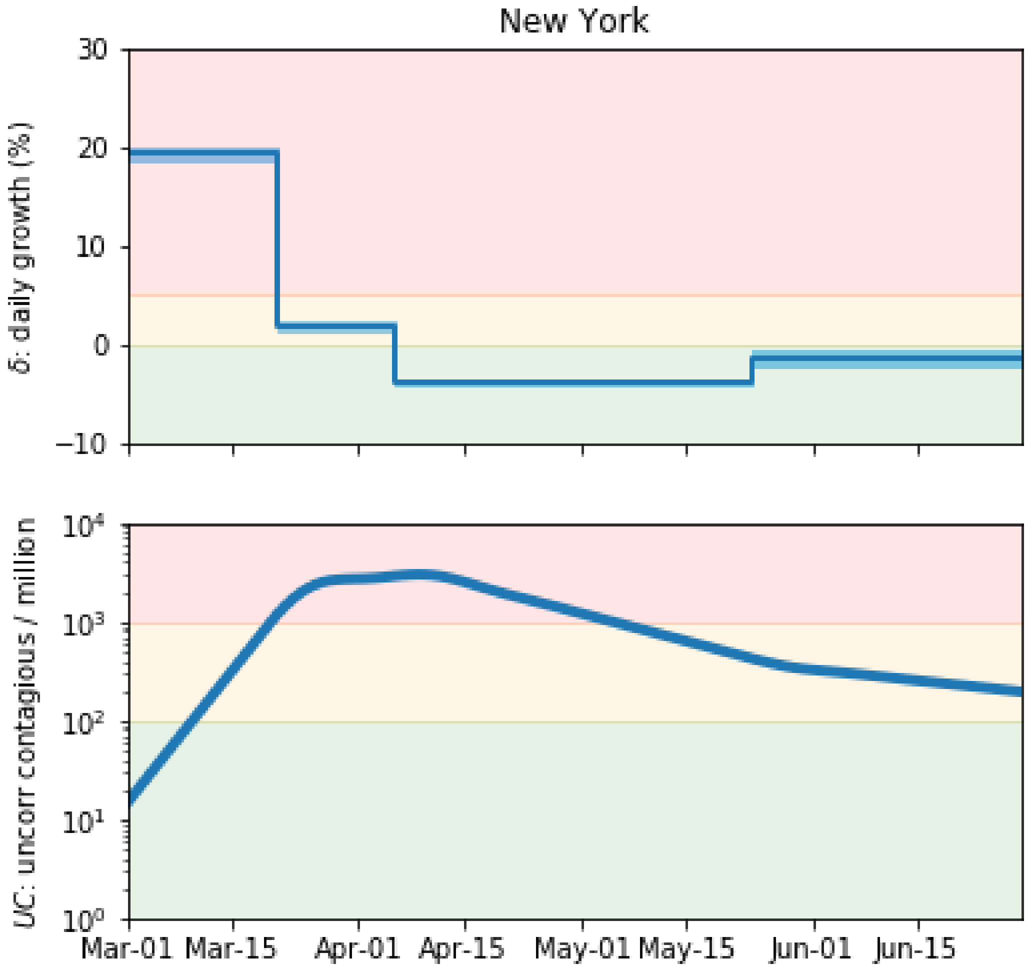
pyPM.ca
Totals - New Jersey
Number of people
10^5
10^4
10^3
10^2
10^1
0
20
40
60
80
100
120
days since Mar 01
contagious
deaths
reported
in_hospital
in_icu

New York


pyPM.ca
Totals - New York
Number of people
400000
350000
300000
250000
200000
150000
100000
50000
0
0
20
40
60
80
100
120
days since Mar 01
contagious
deaths
reported
hospitalized
in_hospital

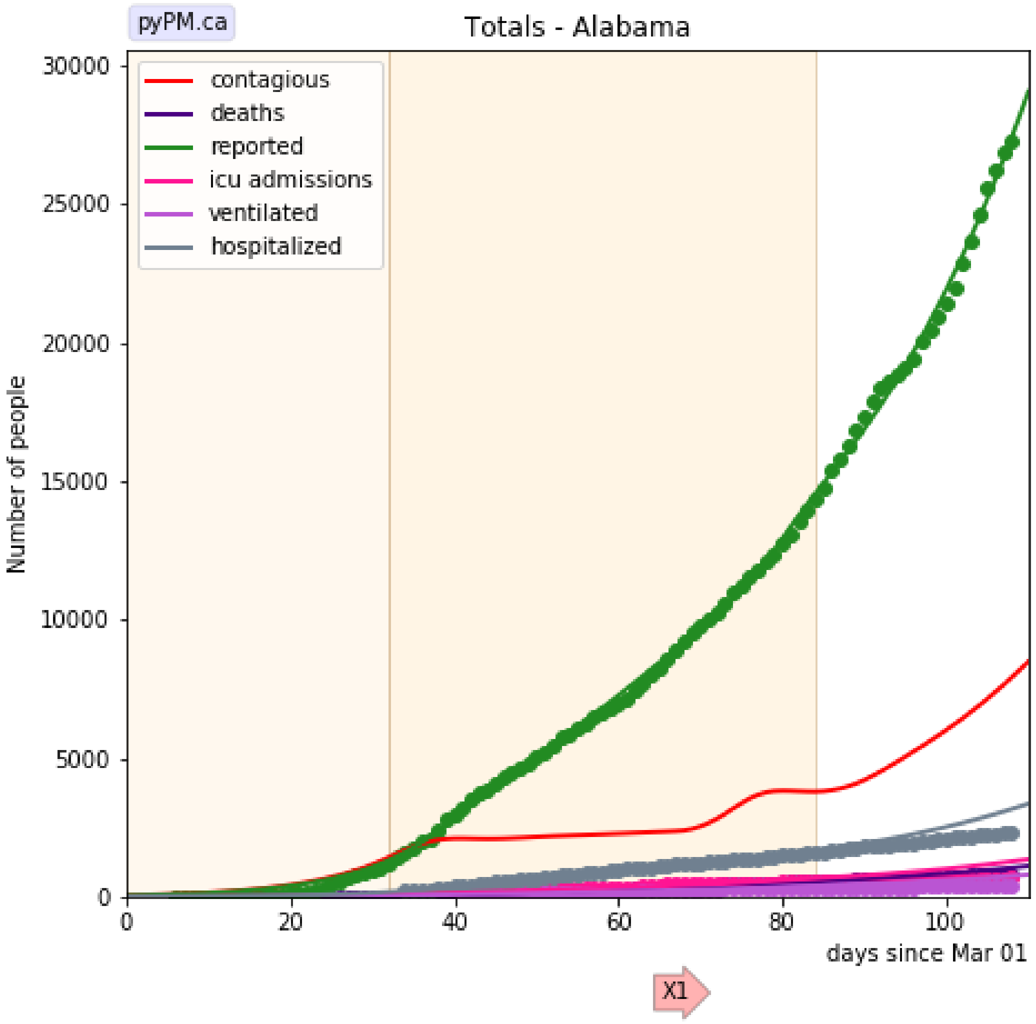

pyPM.ca
Totals - New York
Number of people
10^5
10^4
10^3
10^2
10^1
0
20
40
60
80
100
120
days since Mar 01
contagious
deaths
reported
hospitalized
in_hospital

New York

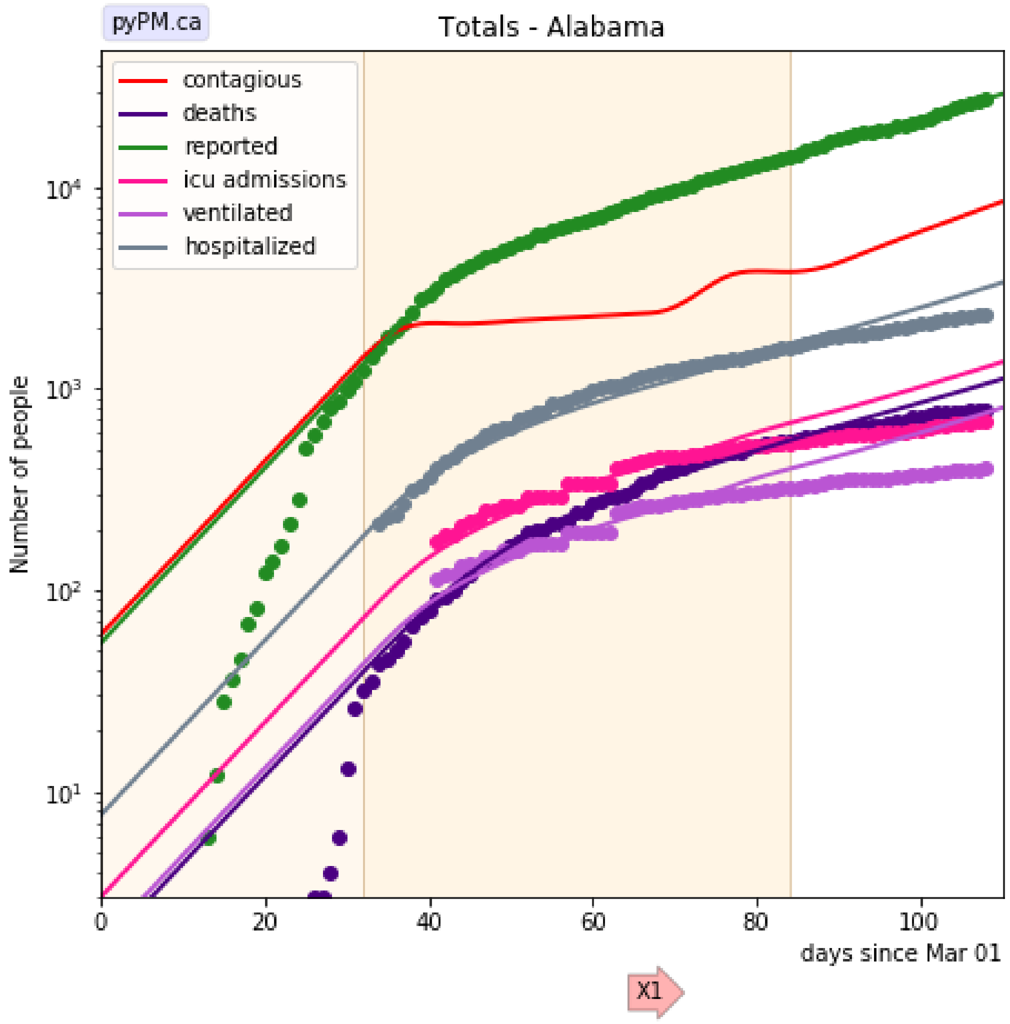


New York
30
20
10
0
−10
δ: daily growth (%)
10^4
10^3
10^2
10^1
10^0
UC: uncorr contagious / million
Mar-01 Mar-15 Apr-01 Apr-15 May-01 May-15 Jun-01 Jun-15

Alabama

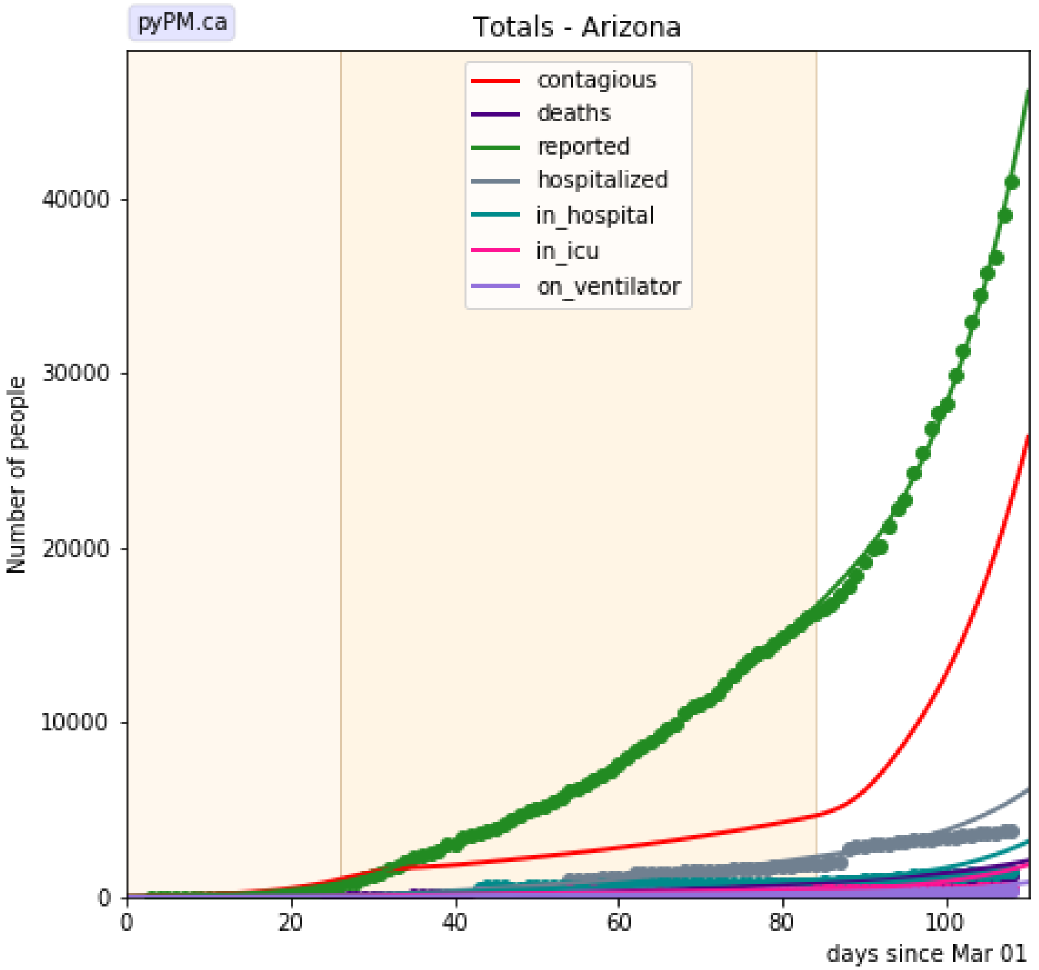


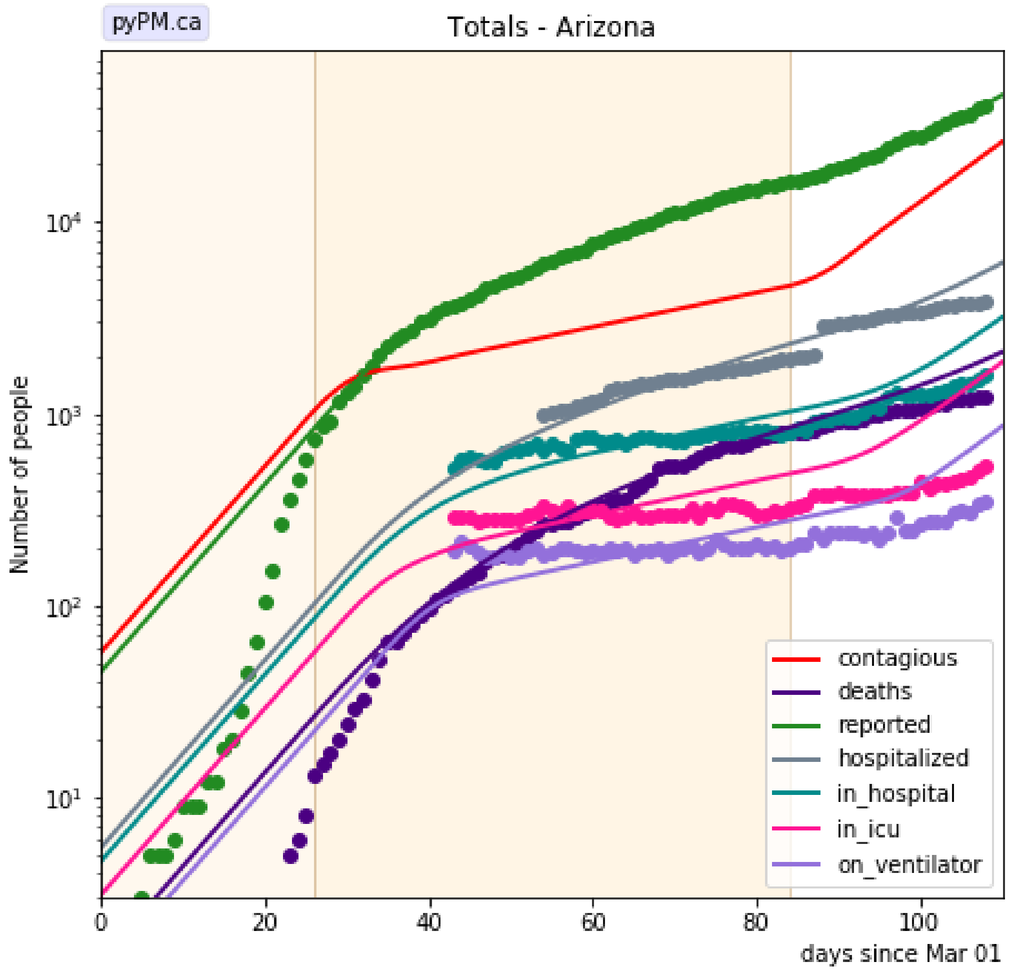
pyPM.ca
Totals - Alabama
contagious
deaths
reported
icu admissions
ventilated
hospitalized
Number of people
days since Mar 01
X1



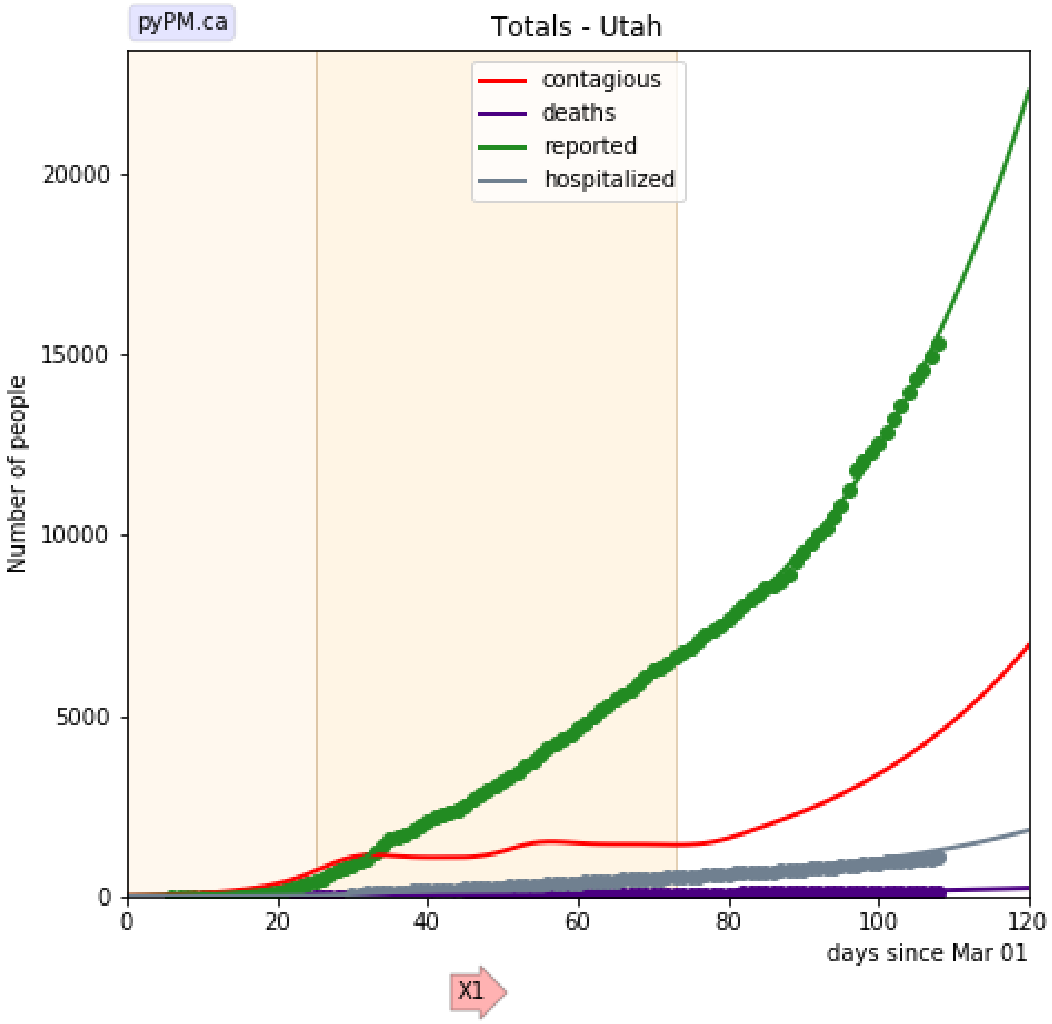
pyPM.ca
Totals - Alabama
contagious
deaths
reported
icu admissions
ventilated
hospitalized
Number of people
days since Mar 01
X1

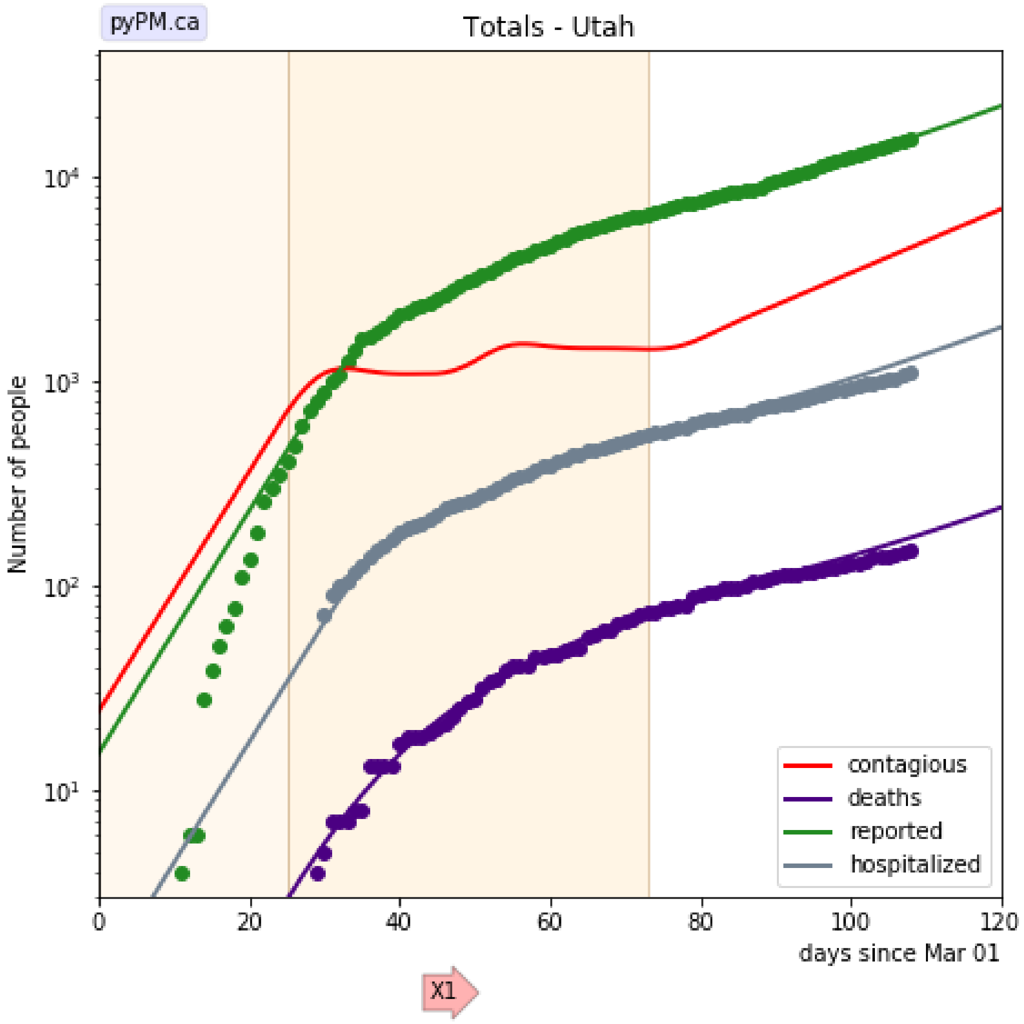
Arizona


pyPM.ca
Totals - Arizona
contagious
deaths
reported
hospitalized
in_hospital
in_icu
on_ventilator
Number of people
days since Mar 01
0
10000
20000
30000
40000
0
20
40
60
80
100

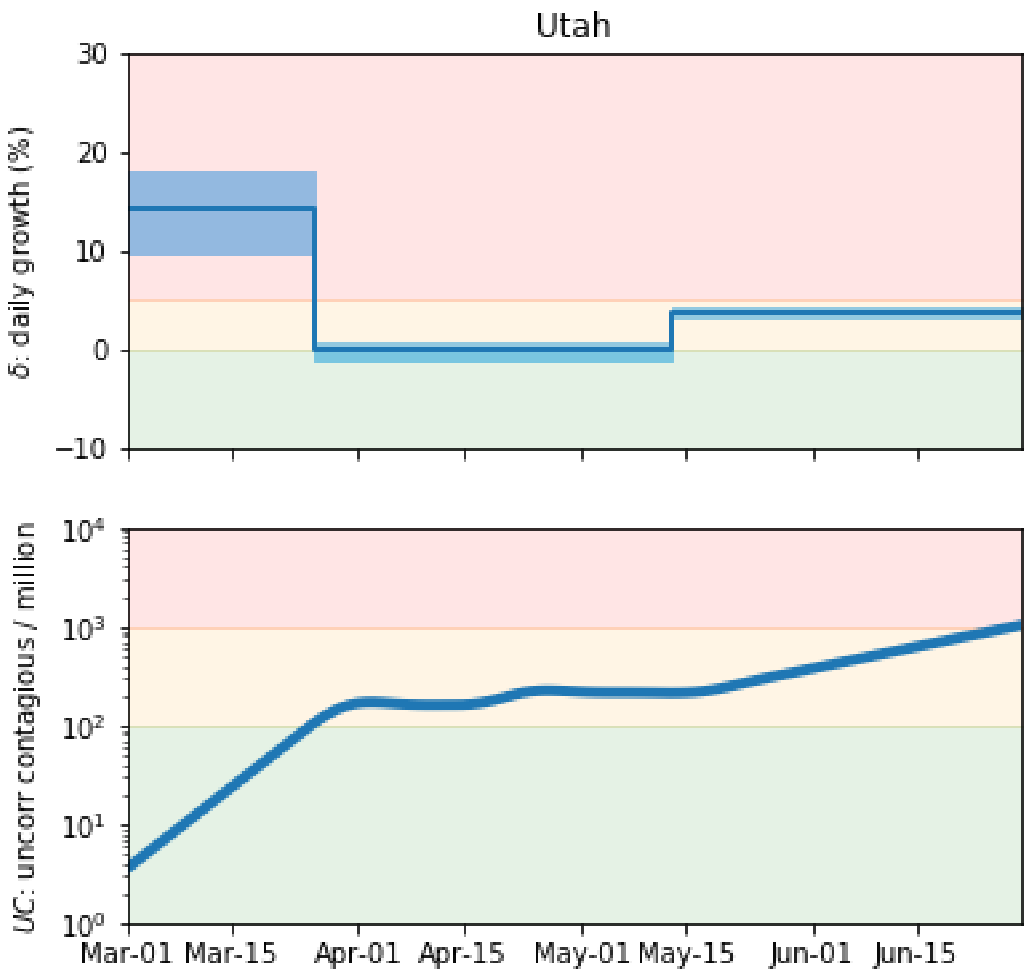

pyPM.ca
Totals - Arizona
contagious
deaths
reported
hospitalized
in_hospital
in_icu
on_ventilator
Number of people
days since Mar 01
10^1
10^2
10^3
10^4
0
20
40
60
80
100

Utah


pyPM.ca
Totals - Utah
contagious
deaths
reported
hospitalized
Number of people
0
5000
10000
15000
20000
0
20
40
60
80
100
120
days since Mar 01
X1

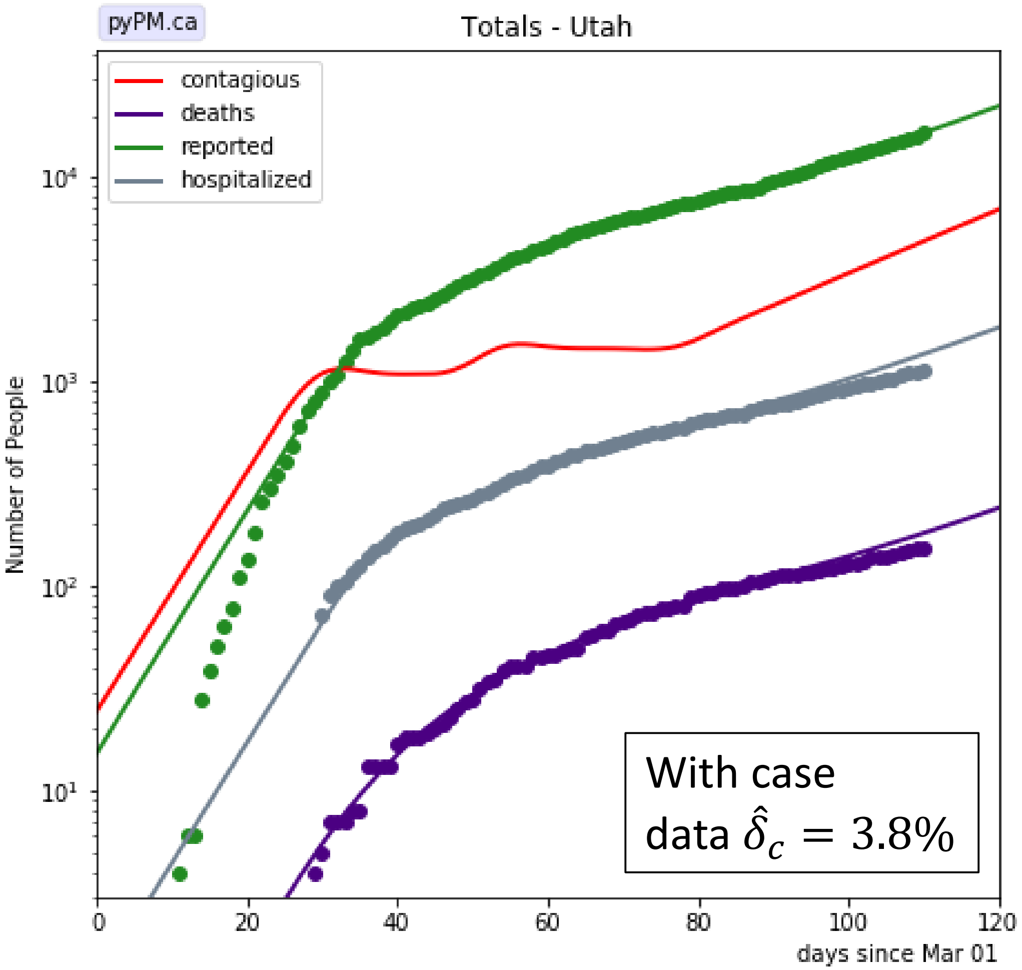

pyPM.ca
Totals - Utah
contagious
deaths
reported
hospitalized
Number of people
10^1
10^2
10^3
10^4
0
20
40
60
80
100
120
days since Mar 01
X1

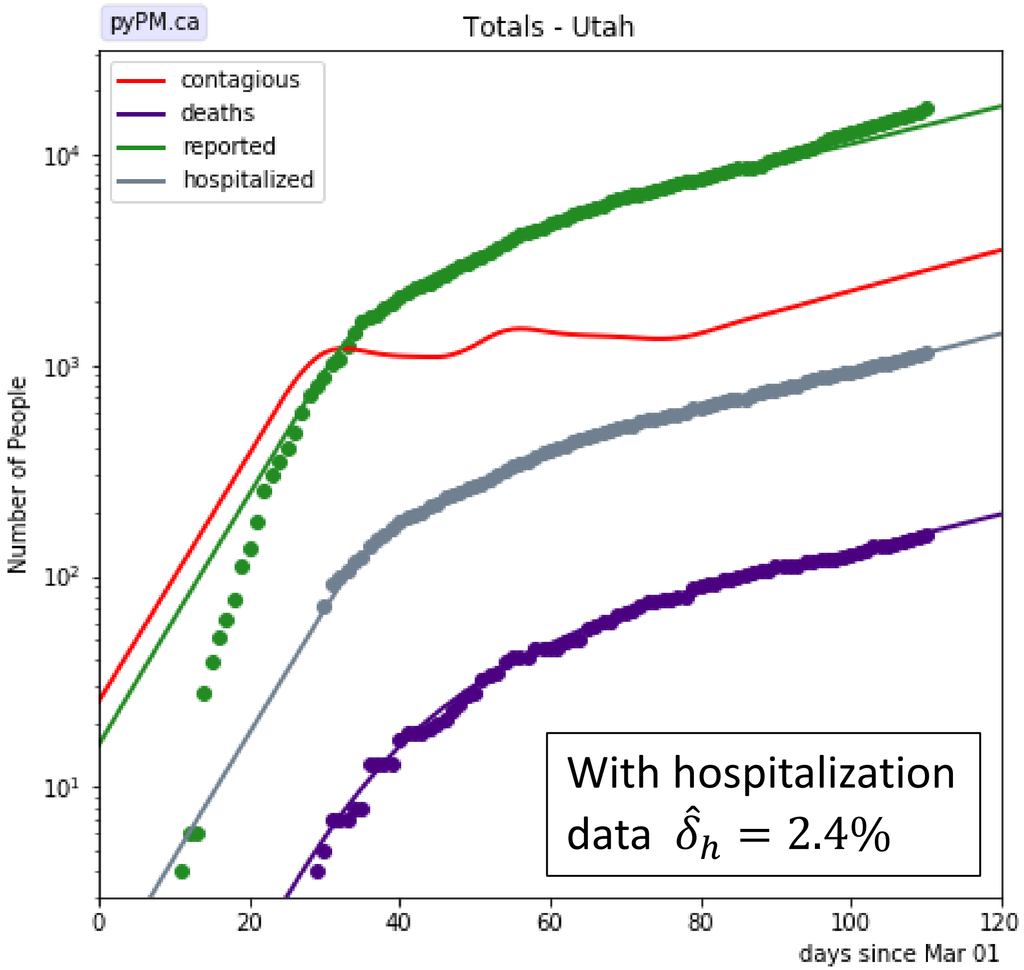
Utah



Utah
30
20
10
0
−10
δ: daily growth (%)
10^4
10^3
10^2
10^1
10^0
UC: uncorr contagious / million
Mar-01 Mar-15 Apr-01 Apr-15 May-01 May-15 Jun-01 Jun-15

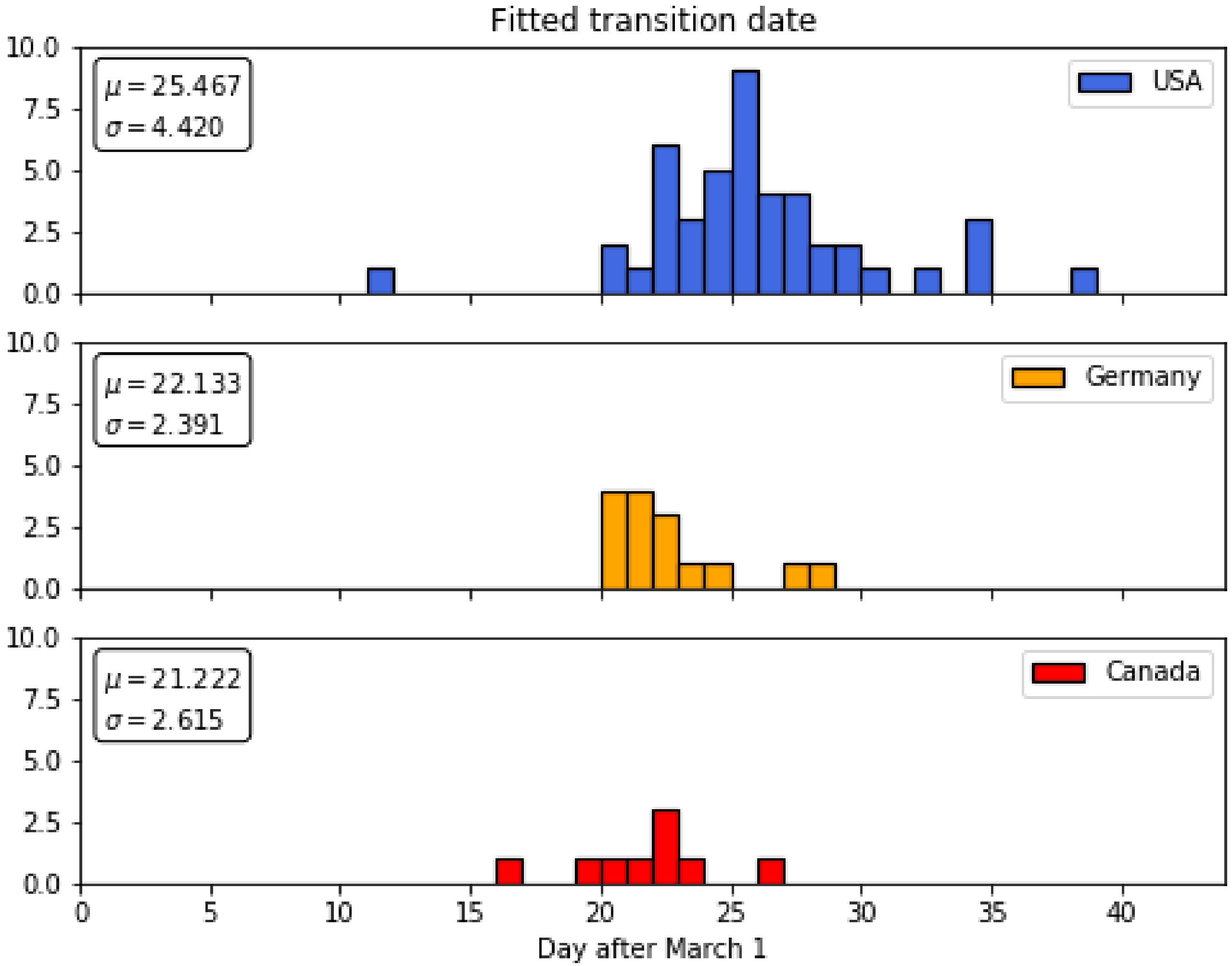
Utah


pyPM.ca
Totals - Utah
contagious
deaths
reported
hospitalized
Number of People
10^1
10^2
10^3
10^4
0
20
40
60
80
100
120
days since Mar 01
With case data $\hat{\delta}_c = 3.8\%$


pyPM.ca
Totals - Utah
contagious
deaths
reported
hospitalized
Number of People
10^1
10^2
10^3
10^4
0
20
40
60
80
100
120
days since Mar 01
With hospitalization data $\hat{\delta}_h = 2.4\%$

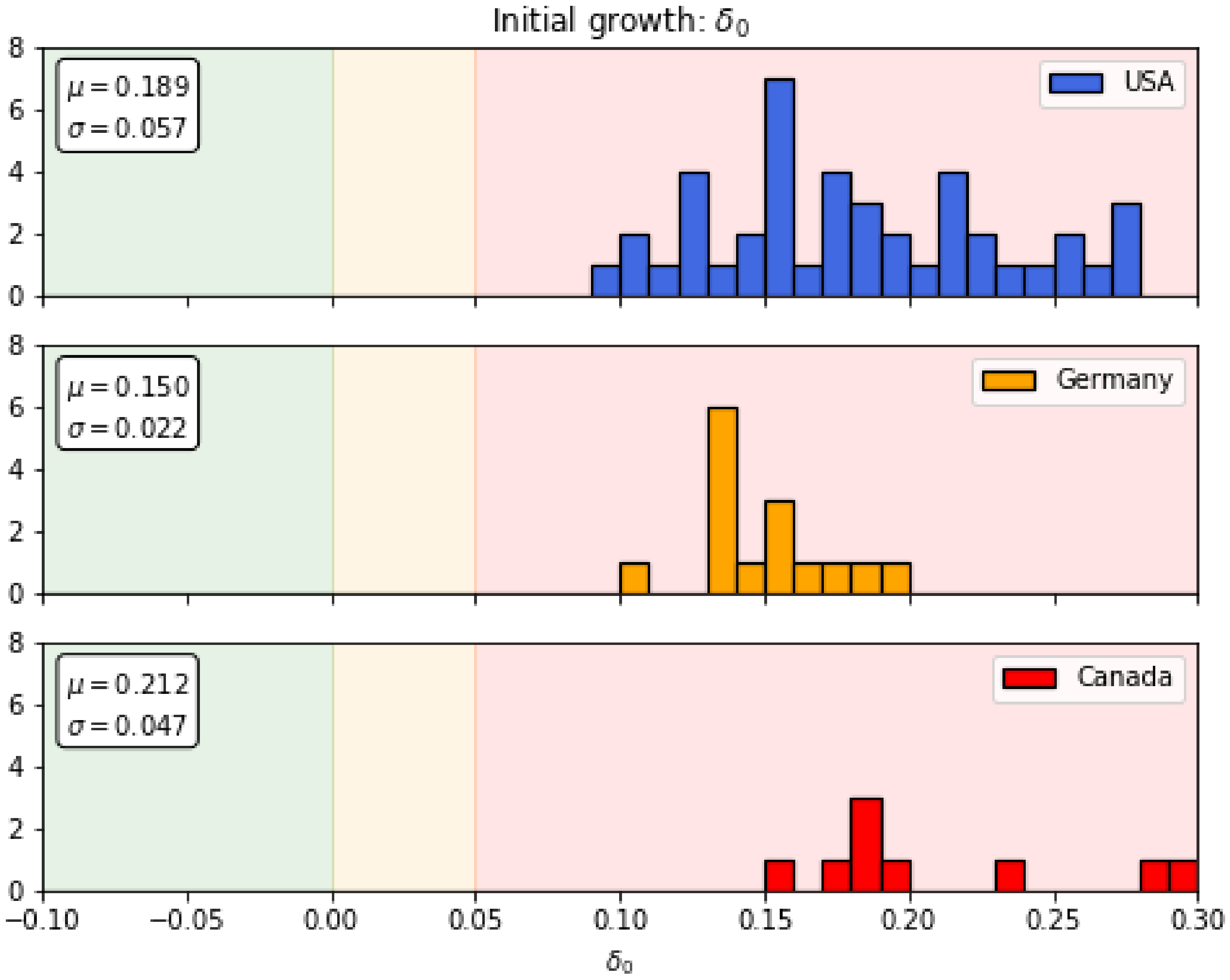
Aggregate comparisons

Date of transition to reduced growth



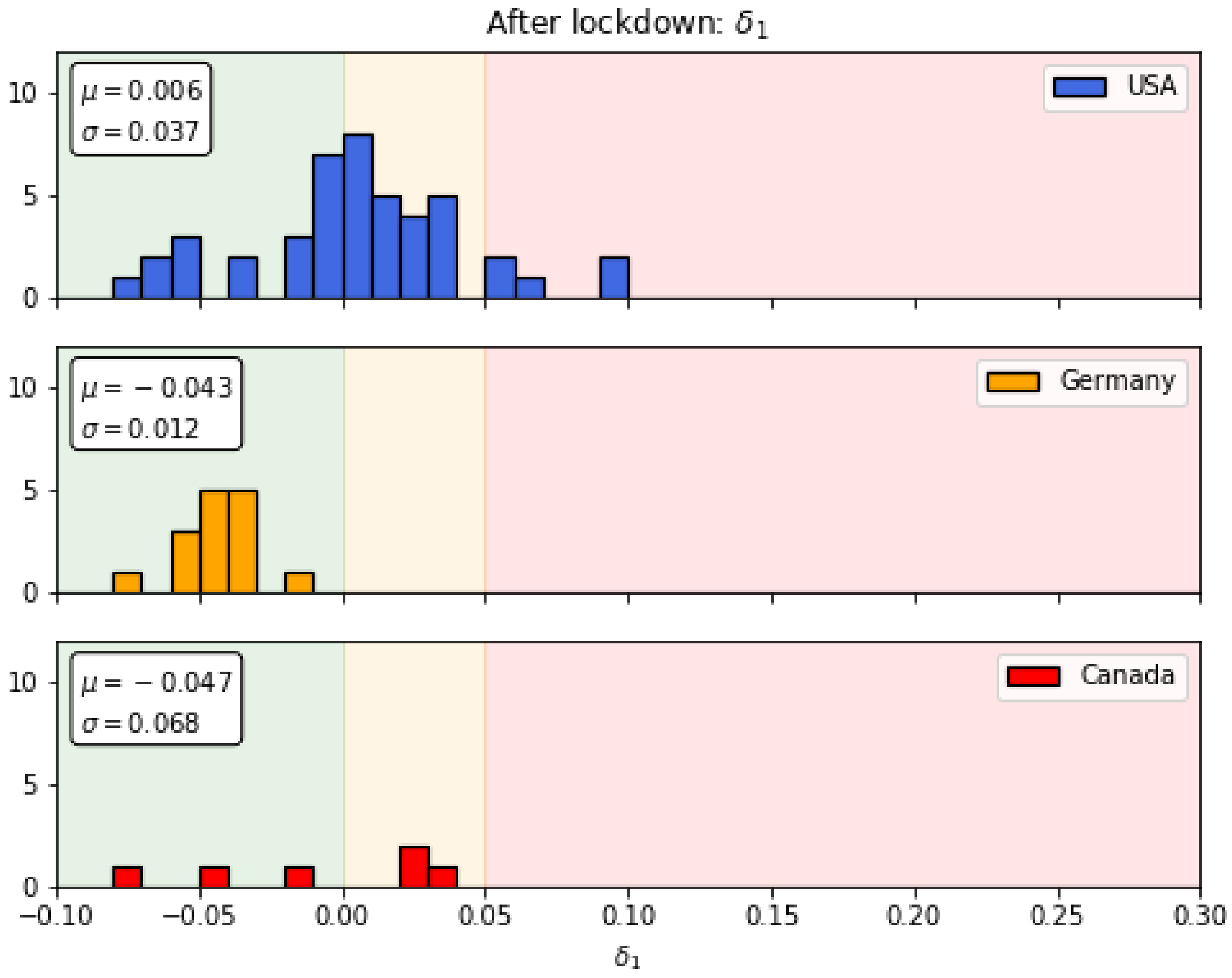
Growth: Early March

$\sigma_\delta \approx 0.02$

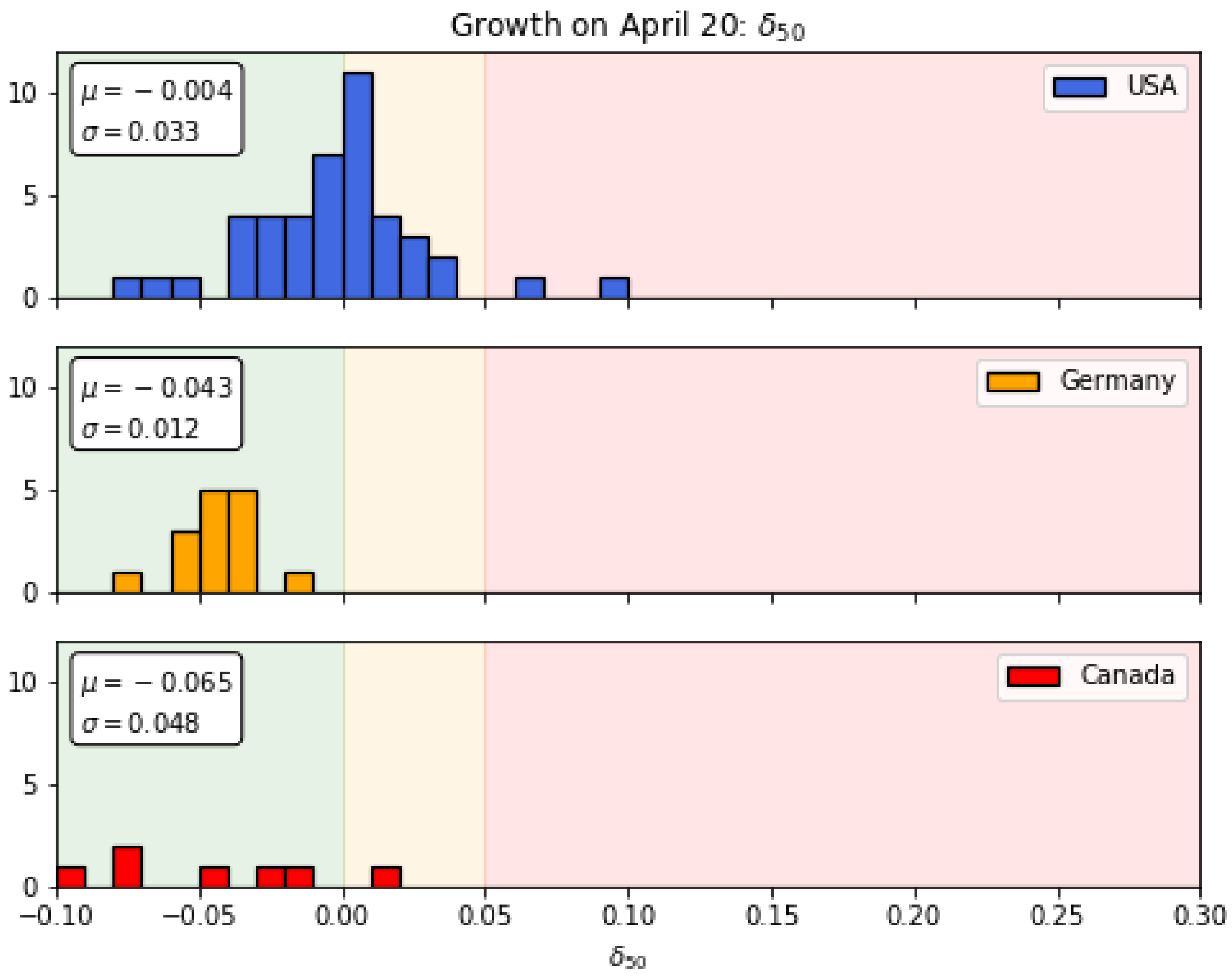


Growth following transition

$\sigma_\delta \approx 0.006$

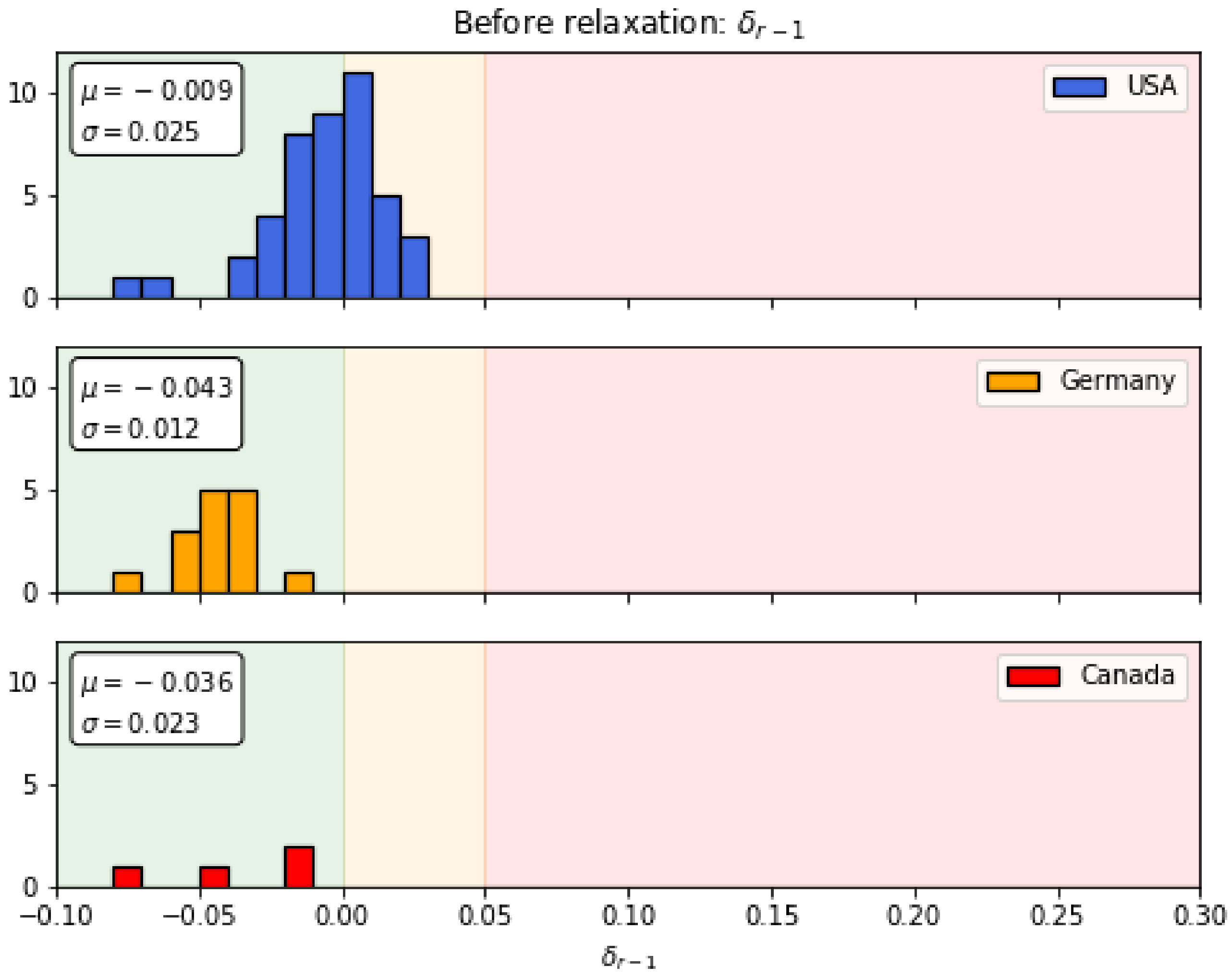


Growth on April 20



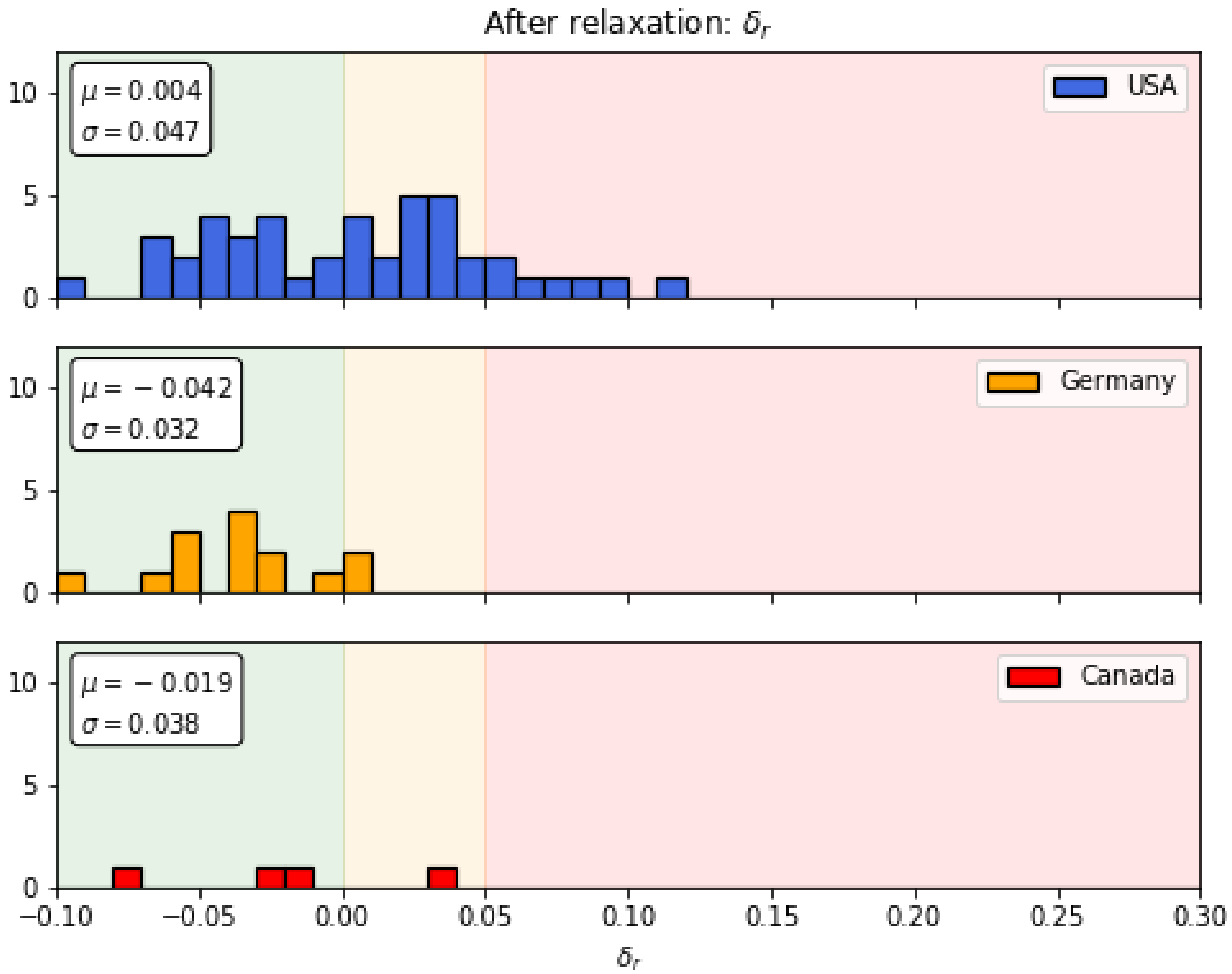
Growth before relaxation

$\sigma_\delta \approx 0.005$

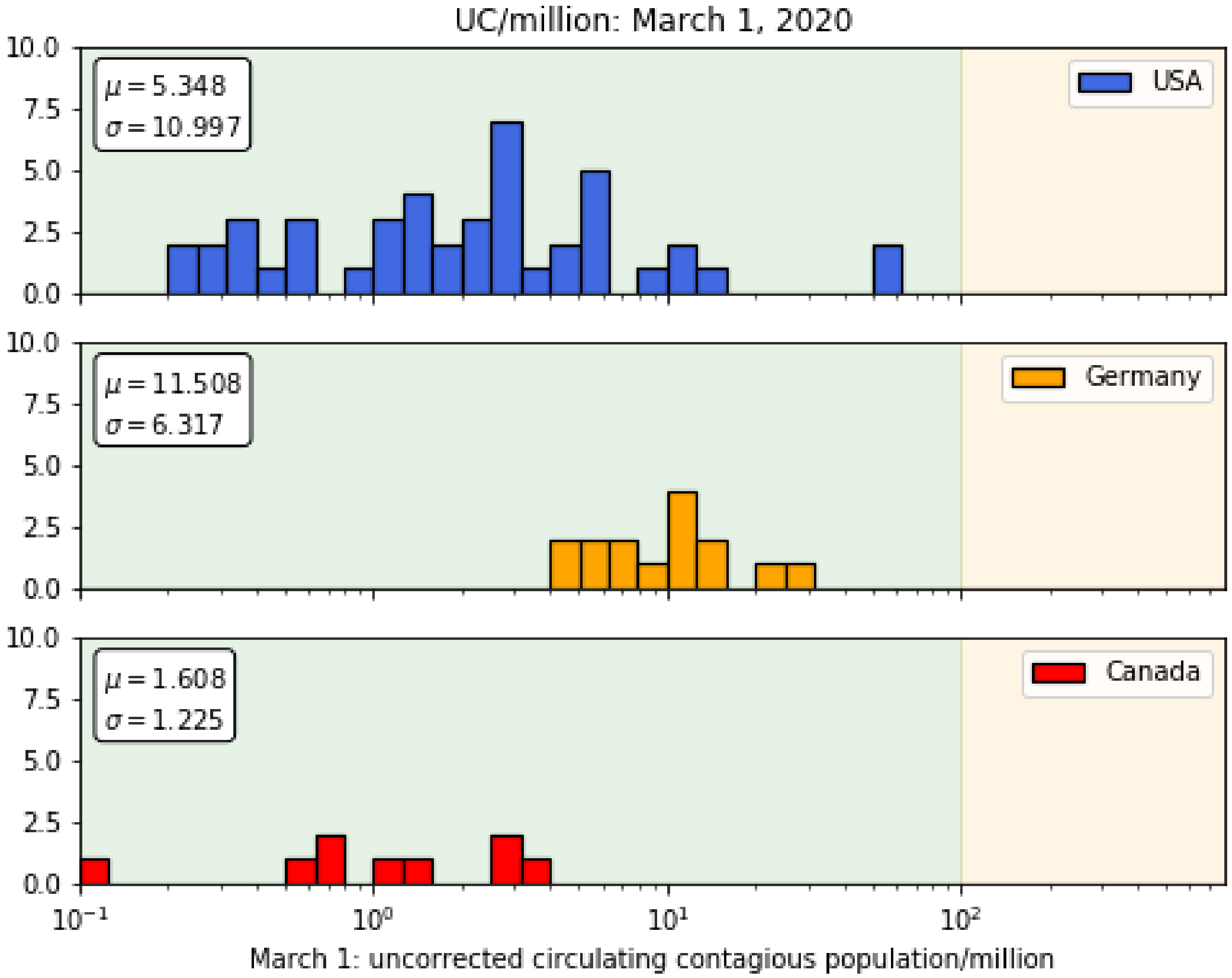


Growth after relaxation

$\sigma_\delta \approx 0.015$

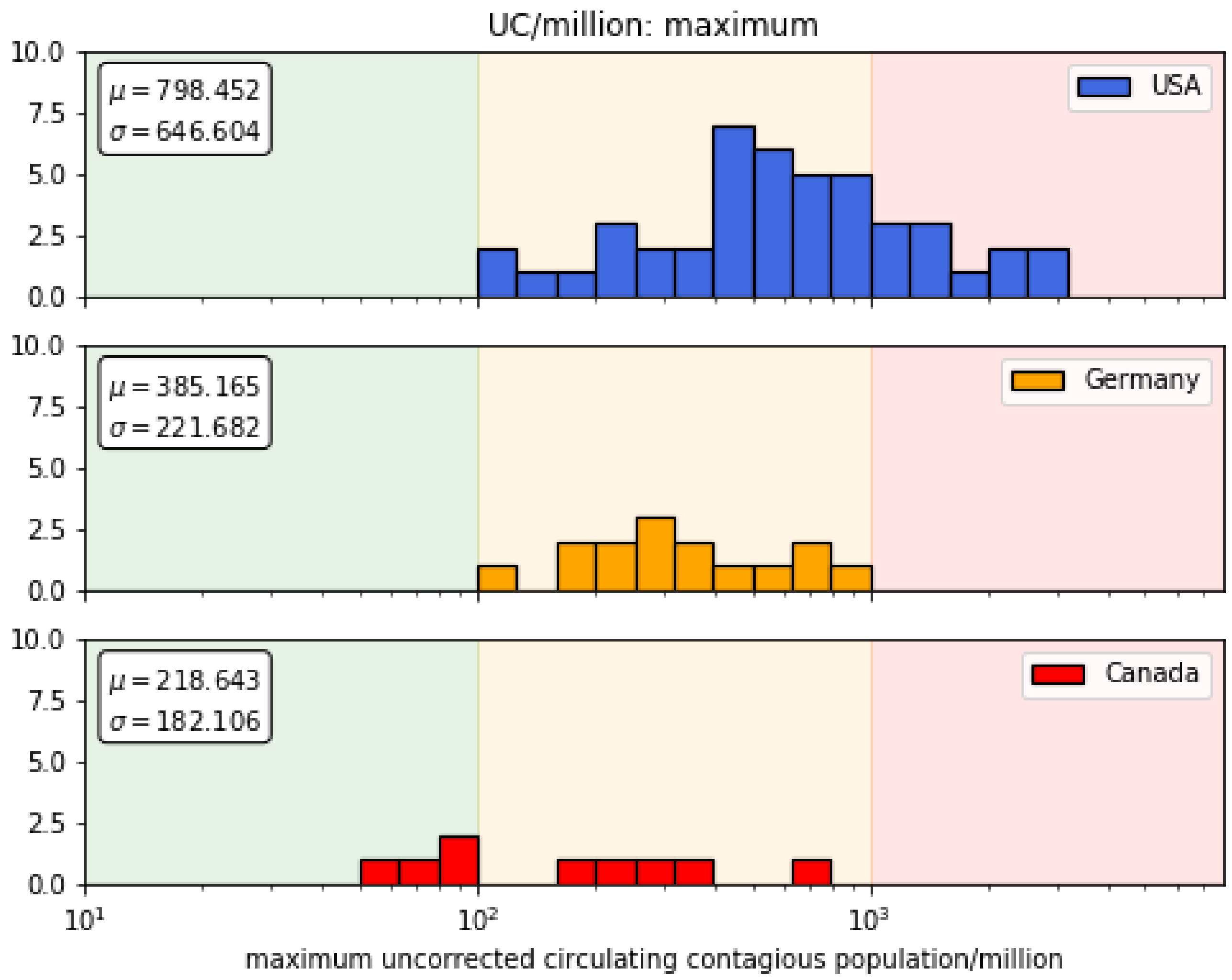


Size: March 1

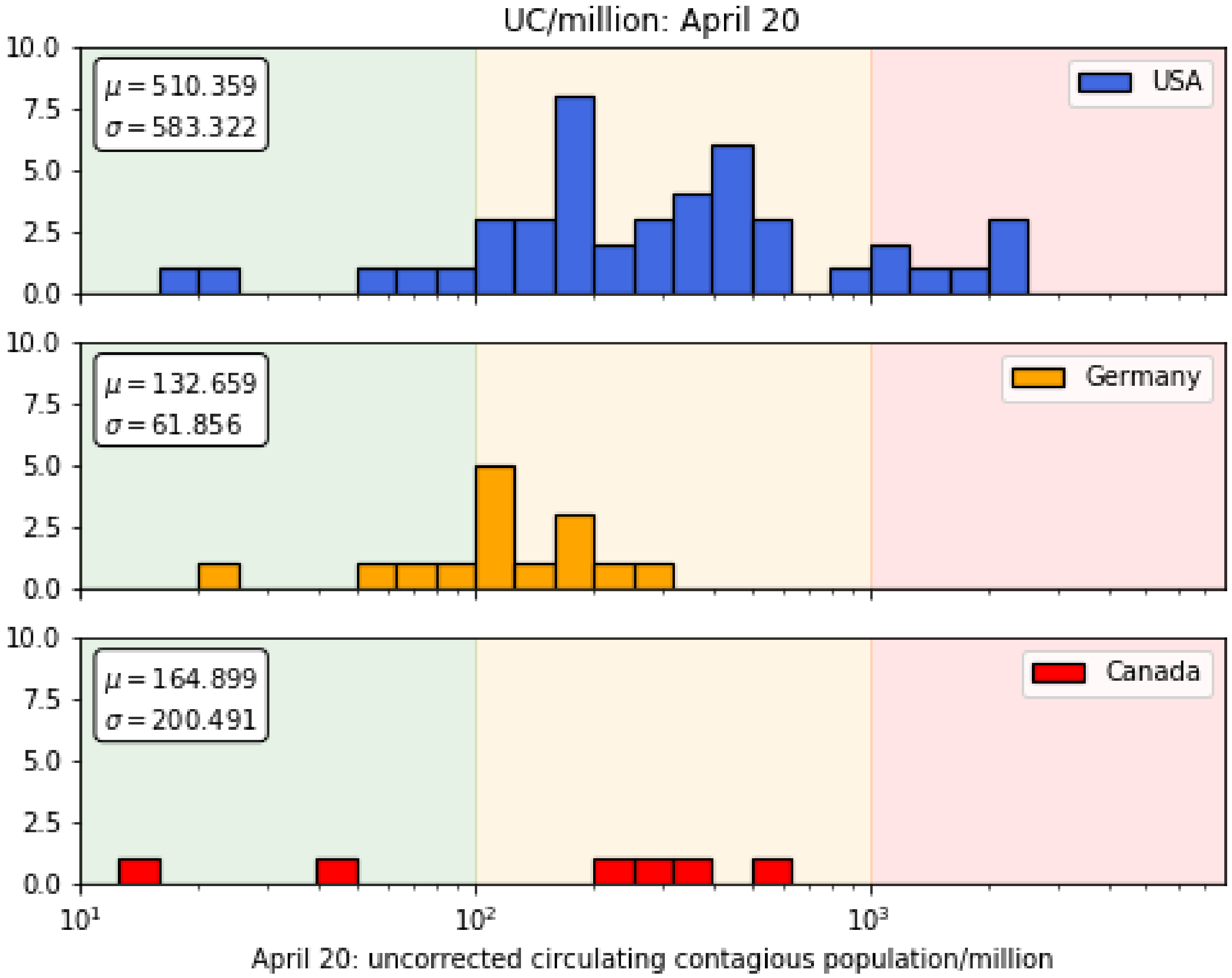


UC/million: March 1, 2020
$\mu = 5.348$
$\sigma = 10.997$
USA
$\mu = 11.508$
$\sigma = 6.317$
Germany
$\mu = 1.608$
$\sigma = 1.225$
Canada
10.0
7.5
5.0
2.5
0.0
10^{-1}
10^{0}
10^{1}
10^{2}
March 1: uncorrected circulating contagious population/million

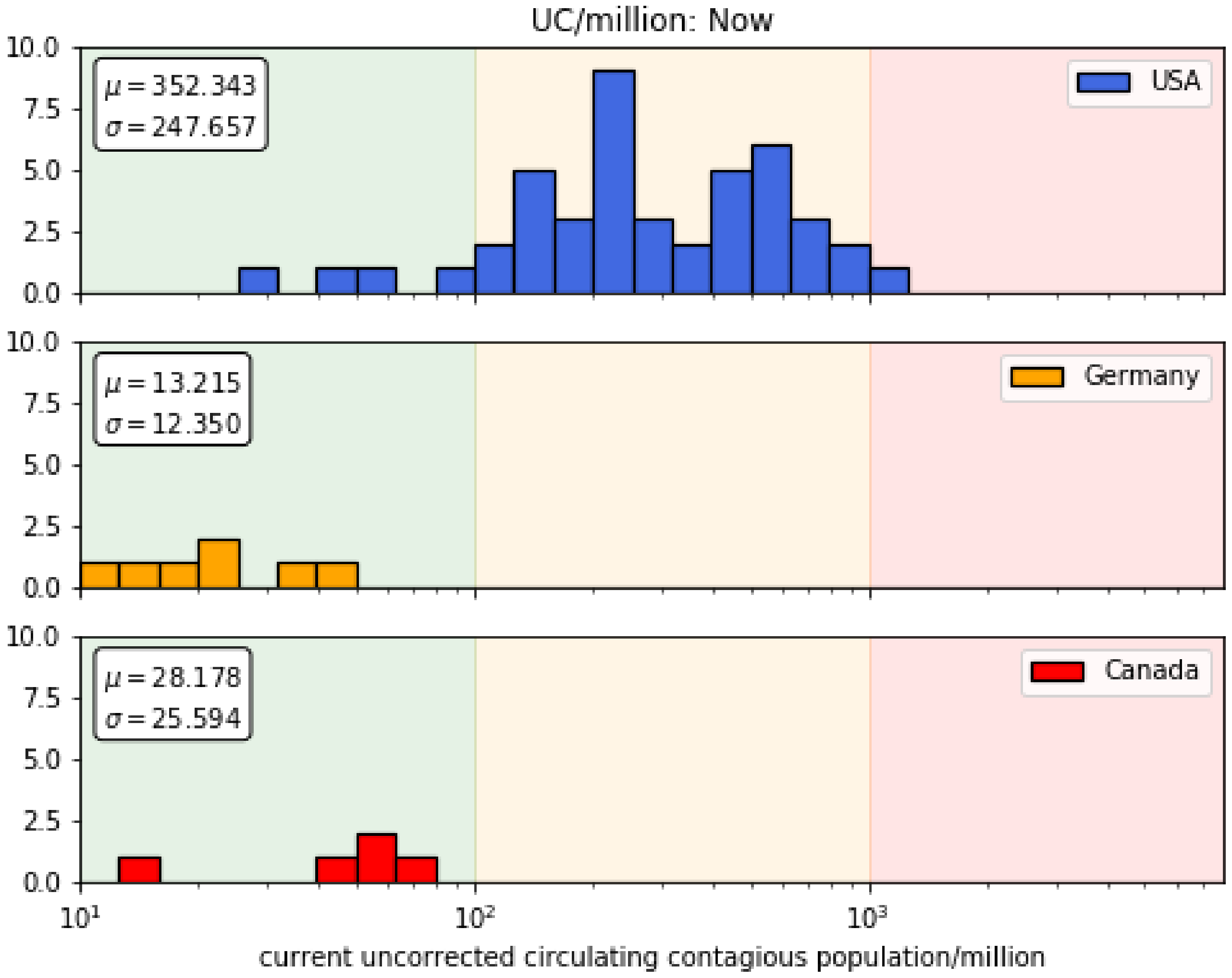
Maximum size



Size on April 20

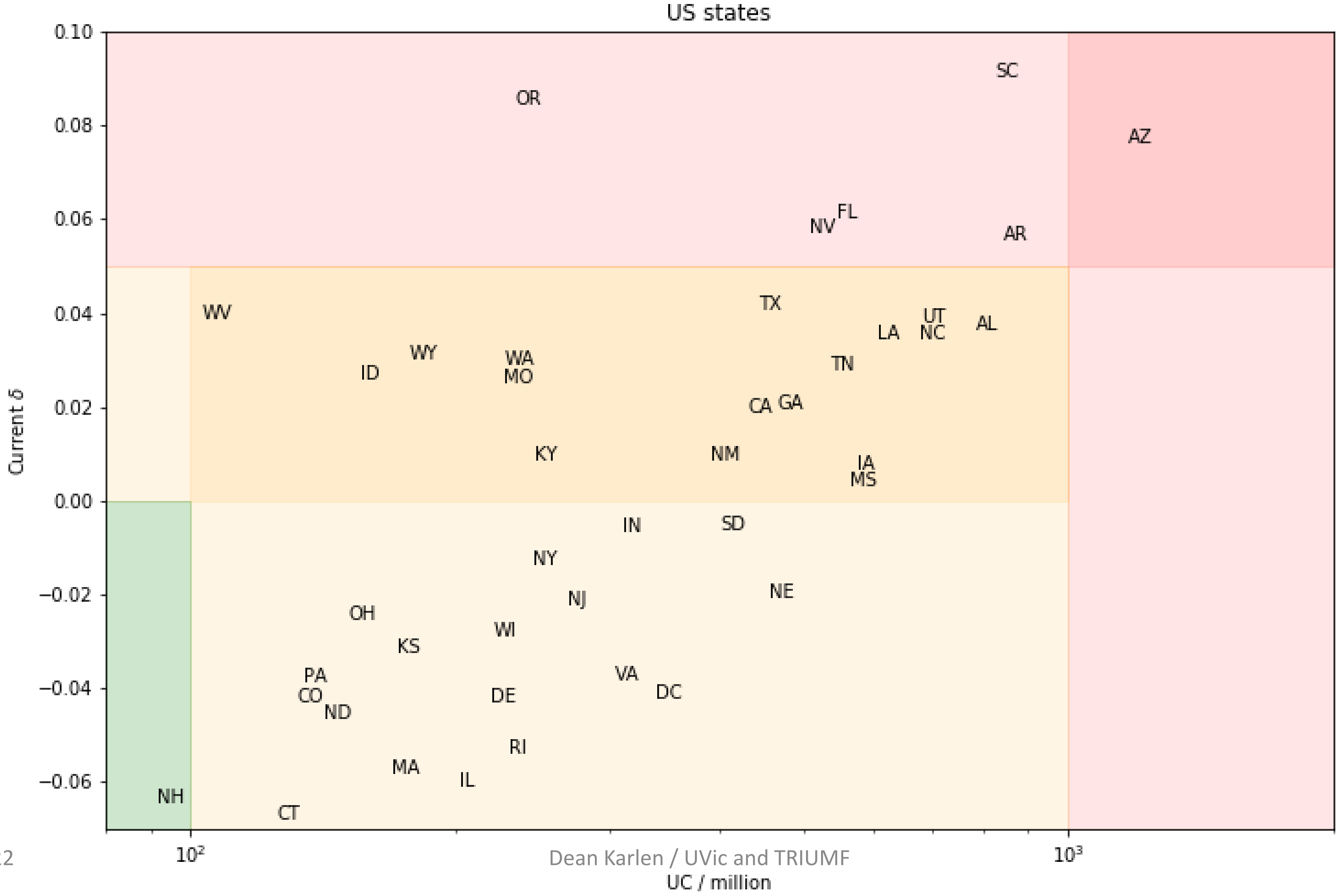


Size: June 22



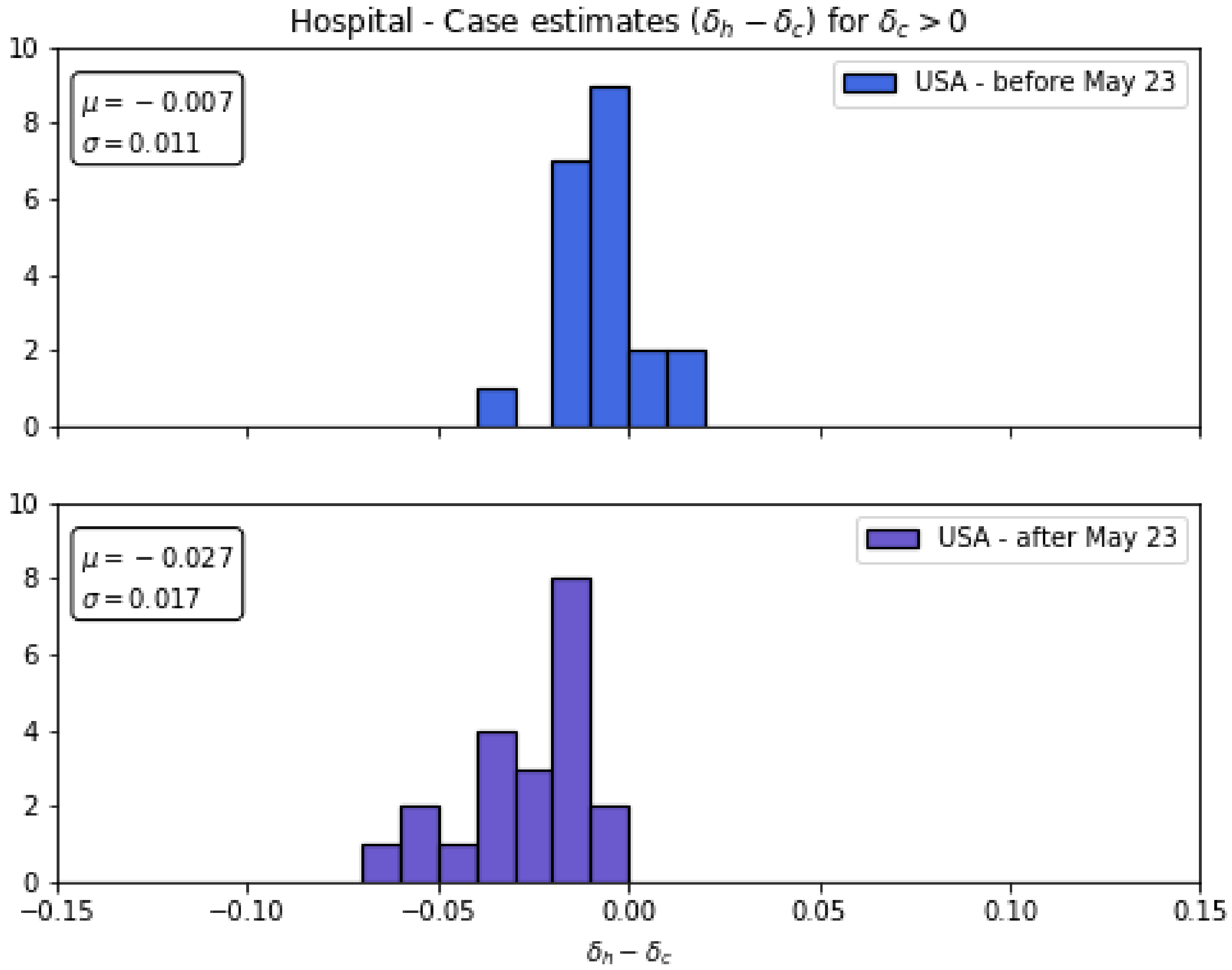
UC/million: Now
$\mu = 352.343$
$\sigma = 247.657$
USA
$\mu = 13.215$
$\sigma = 12.350$
Germany
$\mu = 28.178$
$\sigma = 25.594$
Canada
10.0
7.5
5.0
2.5
0.0
10^1
10^2
10^3
current uncorrected circulating contagious population/million

Situation in US states



Hospitalization growth less than case growth

- In states currently experiencing exponential growth:
  - Prior to May 23: hospitalization and case data show same growth
  - After May 23: hospitalization growth is 2% less than case growth
- Hospitalization samples an older population
  - Evidence that CoViD is growing faster in younger populations after May 23?



Summary

- Proposal to use metrics that are less model dependent to characterize growth and size of epidemic
  - Allows for comparison/checks between different analyses/models
  - A small number of growth periods are sufficient to characterize case data
    - Not necessary to report daily changing growth parameter
- US states have much broader response distributions compared to Canada and Germany
  - Better for measuring/modelling effects of social distancing!
- Case data characterization generally confirmed by hospitalization data
  - Do not discount the value of case data!
  - Deviation is seen for states with growth following May 23

- Preprint and results available here: www.pypm.ca