Disease transmissibility and population size: Evidence after COVID19

NetSci X23 - Buenos Aires
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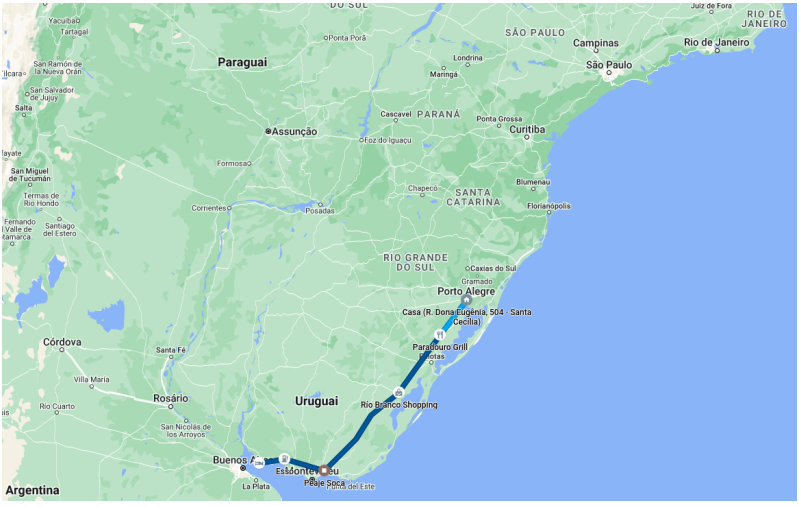
From Porto Alegre to Buenos Aires



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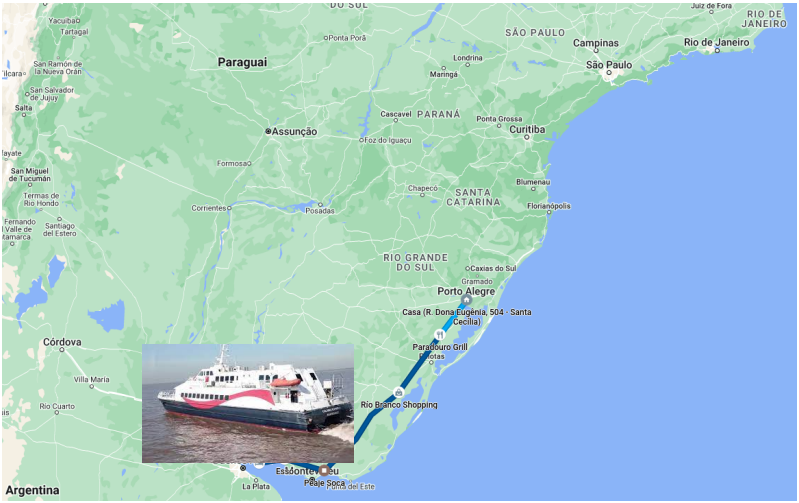
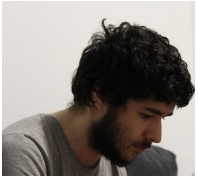
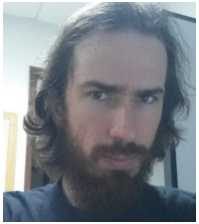


Socio-Physics Group @Instituto de Física-UFRGS




Collaborators

☞ **Ben-Hur Cardoso** (MSc IF-UFRGS, PhD candidate UF de S. Catarina, hired Petrobras)

☞ **William Pantaleão** (BS IF-UFRGS)

https://sites.google.com/view/sociophysics-networks

Urban **Scaling**

$$Y = \mathcal{K} X^{\beta}, \quad \beta \neq 1$$

Where X is the population size
and Y is some socioeconomic indicator like salaries, GDP, etc.

Mainstream in modeling epidemics

Modeling Infectious Diseases IN HUMANS AND ANIMALS,
M.J. Keeling & P. Rohani:

"We would not expect someone living in, for example, ... New York (population 8 million), to transmit an infectious disease over **80** *times more than someone living in ...* **Cambridge**, *Massachusetts (population 100,000)."*

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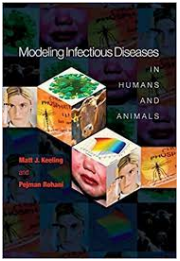

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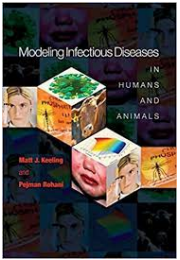
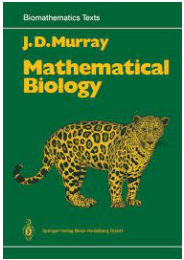
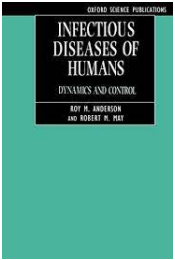




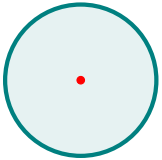


Mainstream in modeling epidemics

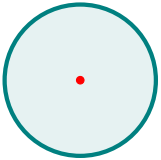
$$\boxed{\Rightarrow \beta \textit{ independent of } N \ (\textit{intensive})}$$

“Mass action hypothesis”

Scaling in the SIR-like models



$$\left|\frac{dS}{dt}\right| = \beta \frac{S}{N} I$$



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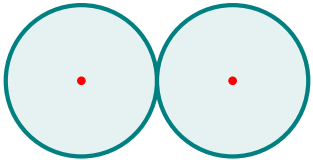
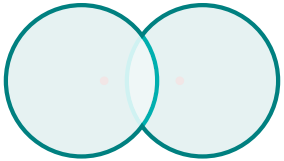
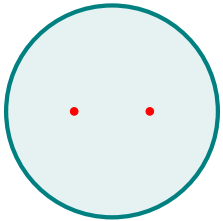
Scaling in the SIR-like models



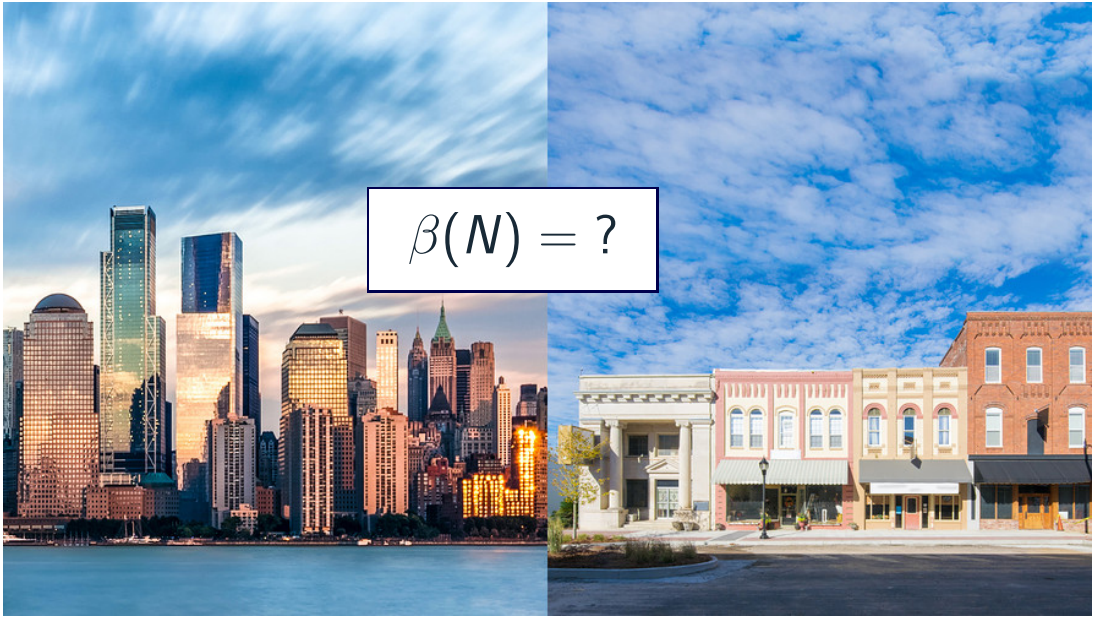
Scaling in the SIR-like models



Scaling in the SIR-like models



$$\left|\frac{dS}{dt}\right| = \hat{\beta}\frac{S}{N}I,\ \hat{\beta} = \begin{cases} \beta\ (\textit{intensive}) \\ 2\beta\ (\textit{extensive}) \\ ? \end{cases}$$


$\beta(N) = ?$

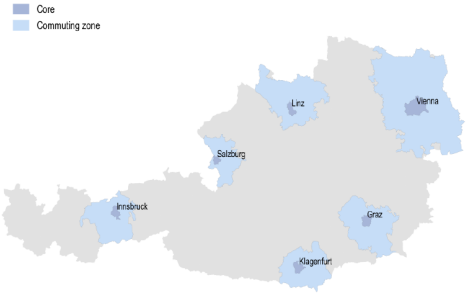
COVID-19

allowed us to address
and
answer this question

Aggregate data as **Functional Urban Areas** or equivalent

- *City* + its *commuting zone*
- A densely inhabited *city* and a less densely populated *commuting zone* whose labour market is highly integrated with the city
- Defined by the Organization for Economic Co-operation and Development (OECD) for metropolitan areas (EU).

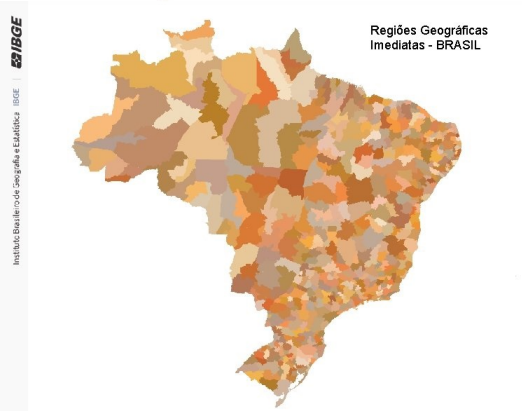
Europe: **Functional Urban Areas** (FUA)



Austria

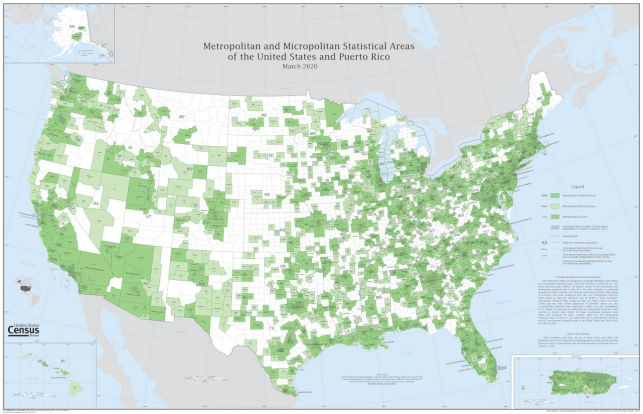
Brasil: **Regiões Geográficas Imediatas** (RGI)

Dependência e deslocamento da população em busca de bens, prestação de serviços e trabalho (IBGE)

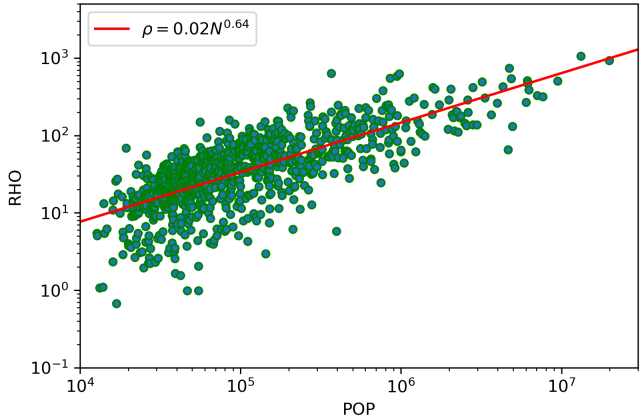


US: **Metropolitan Statistical Areas** (MSA)

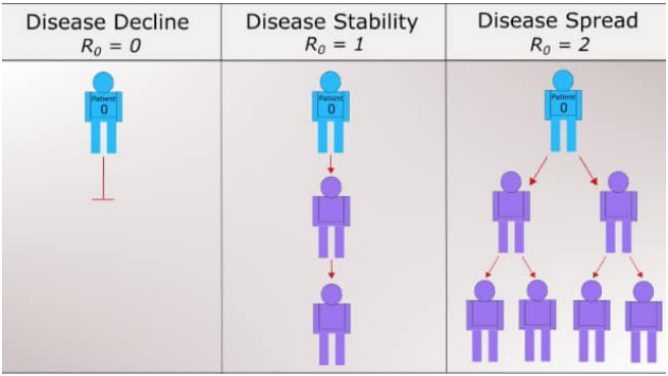
Metropolitan region ($>$ 50K) that consists of a city and surrounding communities that are linked by social and economic factors (OMB)



US (MSA): Density vs Population



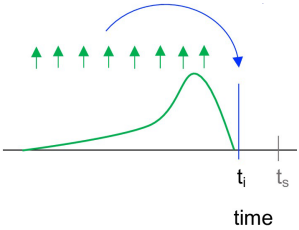
Basic Reproductive Number (R_0)



$$R_0 \propto \beta$$

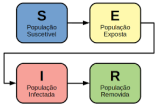
Estimation of R_0 and R_t

Epidemiological way (Cori et al)



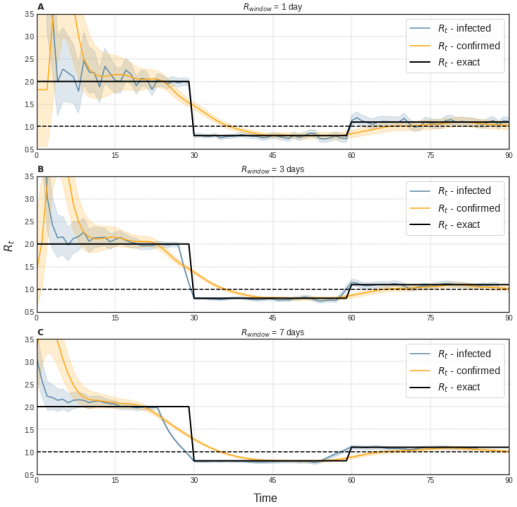
SIR

SEIR

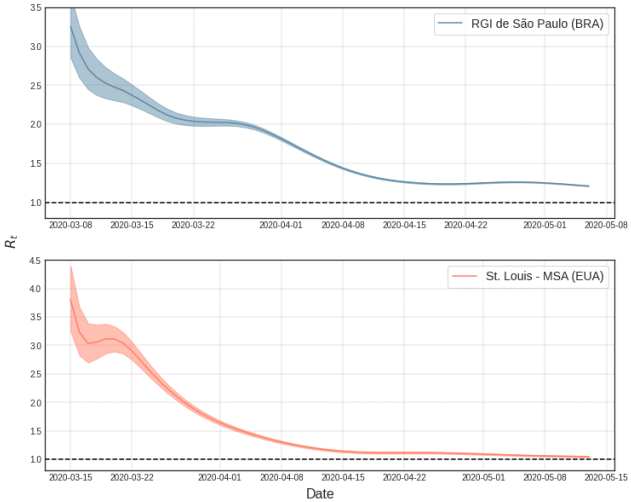


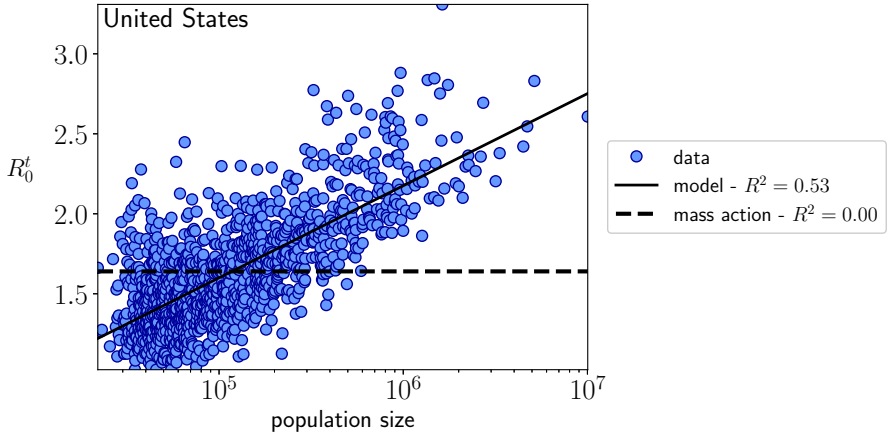
Test of Cori's method

$$R_t = \frac{I_t}{\sum_s \omega_s I_{t-t_m+s}}$$



Examples




United States
R_0^t
3.0
2.5
2.0
1.5
10^5
10^6
10^7
population size
data
model - $R^2 = 0.53$
mass action - $R^2 = 0.00$

"Anatomy" of R_0

The *basic reproductive number* R_0 can be factorized as

$$R_0 = p\tau\mathcal{C}$$

Where

- p: infection probability
- τ: infection period
- $\mathcal{C}$: *per capita* contact rate $(p\mathcal{C} \to \beta)$

Contact rate *vs* demography

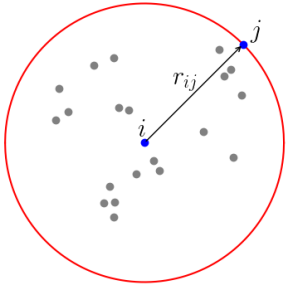
$$\mathcal{C} \sim N?$$

Em uma unidade demográfica com N pessoas.

- Mass action: $\mathcal{C}$ and, thus, R_0 are independent of demography
- Contact rate driven by population size ("scaling"):

$$\mathcal{C} = \mathcal{C}(N) \Rightarrow R_0 = R_0(N)$$

Phenomenological Urban Contact model

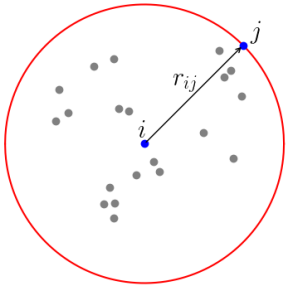


Liben-Nowell et al, PNAS (2005)

$$P_{ij} \propto \frac{1}{\text{rank}_i(j)}$$

$\text{rank}_i(j)$: number of people closer from i than j

Phenomenological Urban Contact model



$\text{rank}_i(j)$: number of people closer from i than j

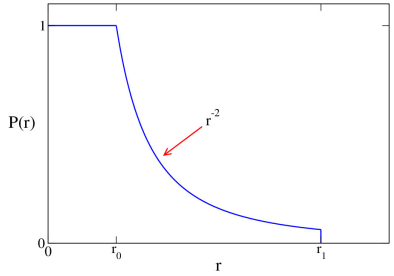
Liben-Nowell et al, PNAS (2005)

$$P_{ij} \propto \frac{1}{\text{rank}_i(j)} = \frac{1}{\rho \pi r_{ij}^2}, \quad \rho = N/A \text{ (density)}$$

$$\Rightarrow \mathcal{C} = \int P(r) \rho dA$$

$\mathcal{C}$ vs N

$$P(r) = \frac{{r_0}^2}{r^2}$$

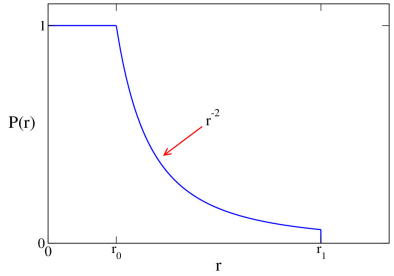


$$\rho\pi r_1^2 = N$$

$$\mathcal{C} = \int_0^{r_1} P(r)\rho dA =$$

$\mathcal{C}$ vs N

$$P(r) = \frac{r_0^2}{r^2}$$

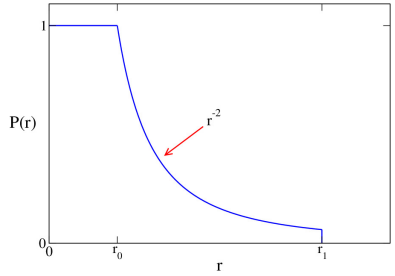


$$\rho \pi r_1^2 = N$$

$$\mathcal{C} = \int_0^{r_1} P(r)\rho dA = \int_0^{r_0} \rho\, 2\pi r dr + \int_{r_0}^{r_1} \left(\frac{r_0^2}{r^2}\right) \rho\, 2\pi r dr$$

$\mathcal{C}$ vs N

$$P(r) = \frac{r_0^2}{r^2}$$



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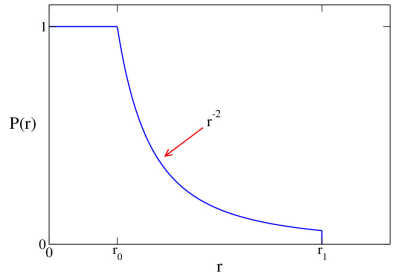
$$= \rho\pi r_0^2 \left[1 + \ln\left(\frac{r_1^2}{r_0^2}\right)\right] =$$

$\mathcal{C}$ vs N

$$P(r) = \frac{r_0^2}{r^2}$$



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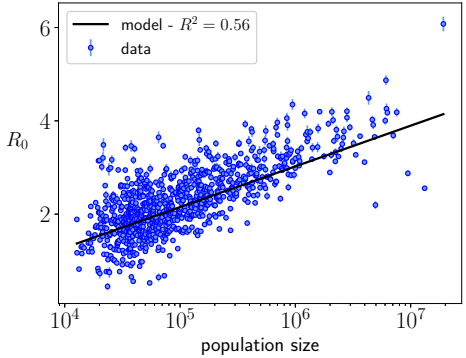
$$= \rho\pi r_0^2 \left[1 + \ln\left(\frac{r_1^2}{r_0^2}\right)\right] = \rho\pi r_0^2 \left[1 + \ln\left(\frac{N}{\rho\pi r_0^2}\right)\right]$$

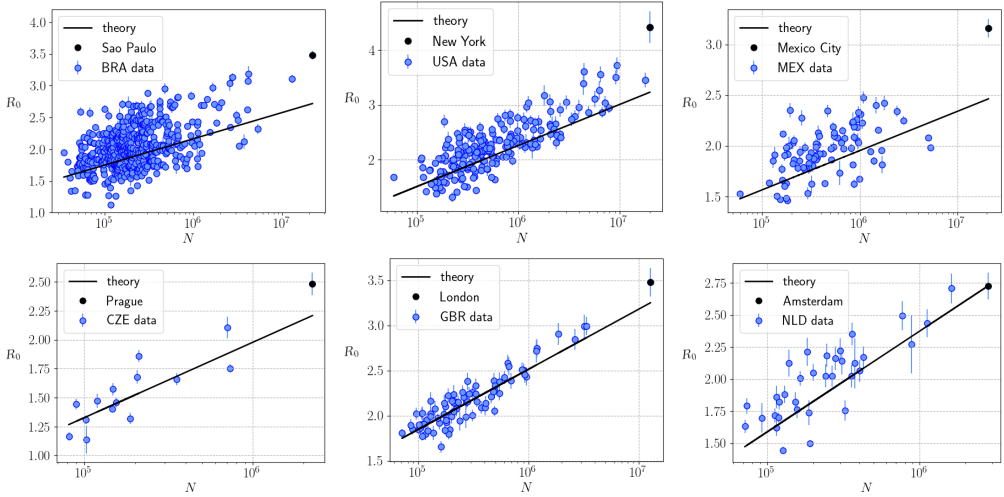
$$\mathcal{C} \sim \ln(N) \Rightarrow R_0 \propto \ln(N)$$

Results for the US *vs* law

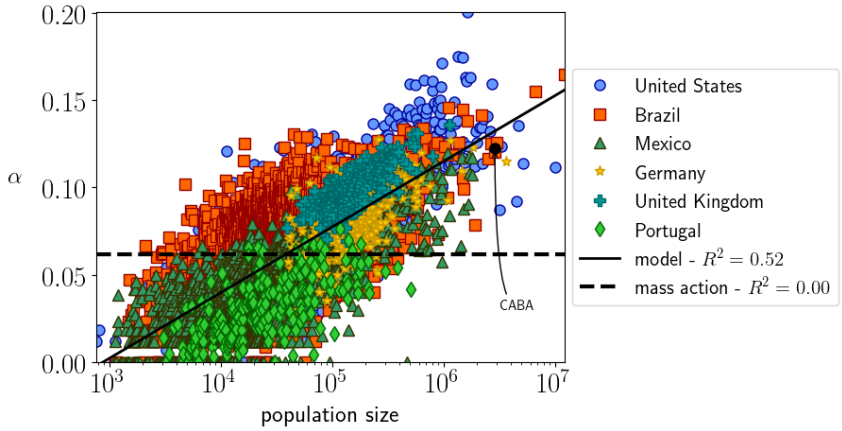


$$R_0 = -a + b \ln(N)$$

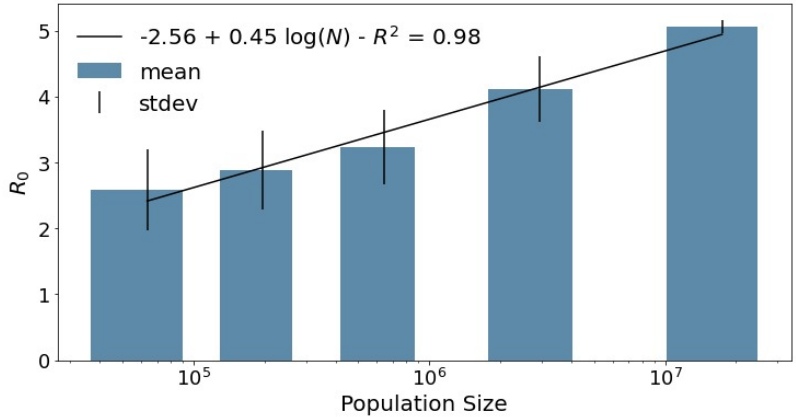
Six countries plus one big city (corr. coef. $R > 0.7$)



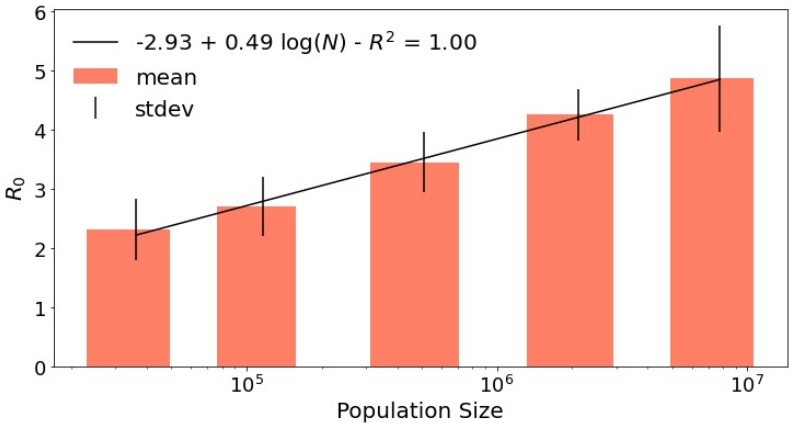
Us, Br, Mx, De, UK, Pt



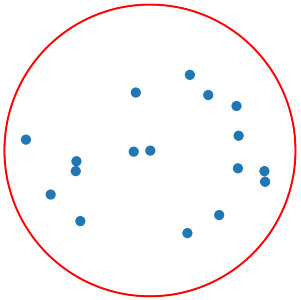
R0 *vs* N (log bin) - Brasil



R0 *vs* N (log bin) - US



Theory - Simulation



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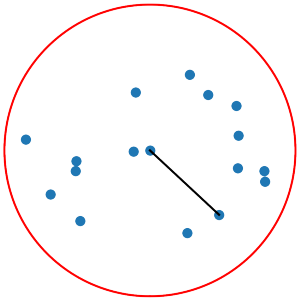

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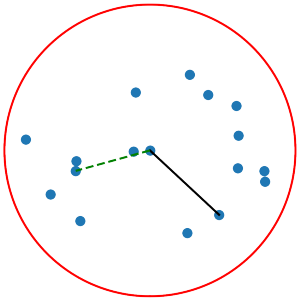

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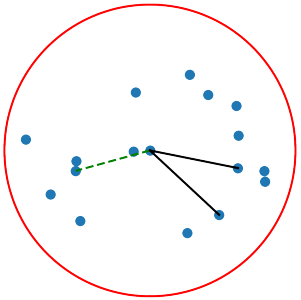

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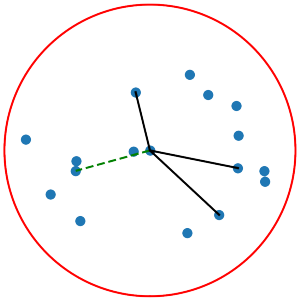

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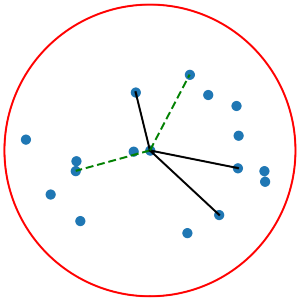
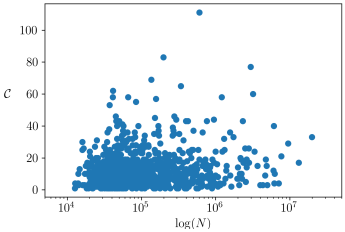
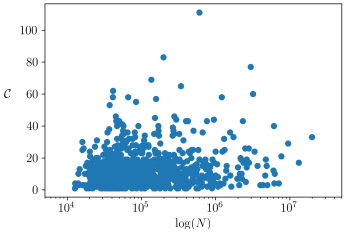


Simulation: $C \times N$

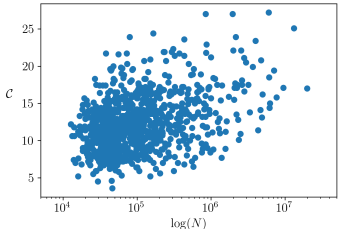


M = 1

Simulation: $C \times N$

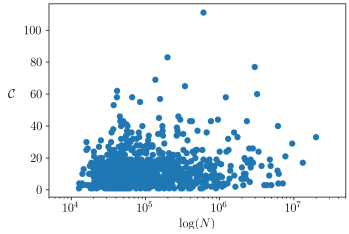


M = 1

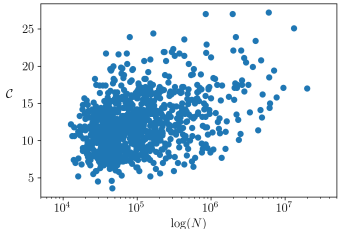


M = 10

Simulation: $C \times N$



M = 1



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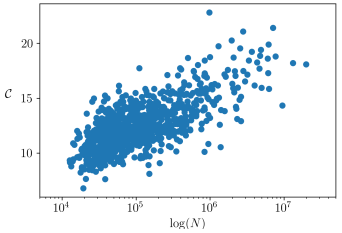
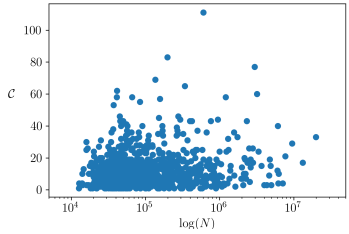
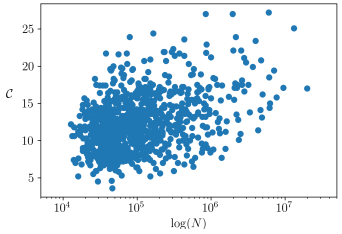


M = 50

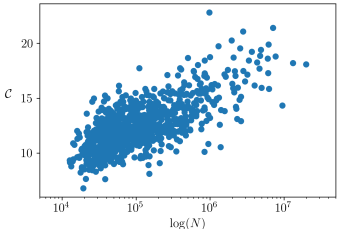
Simulation: $C \times N$



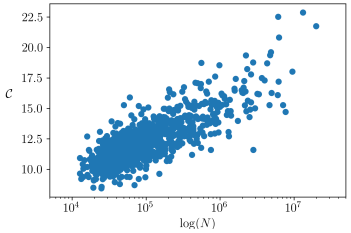
M = 1



M = 10

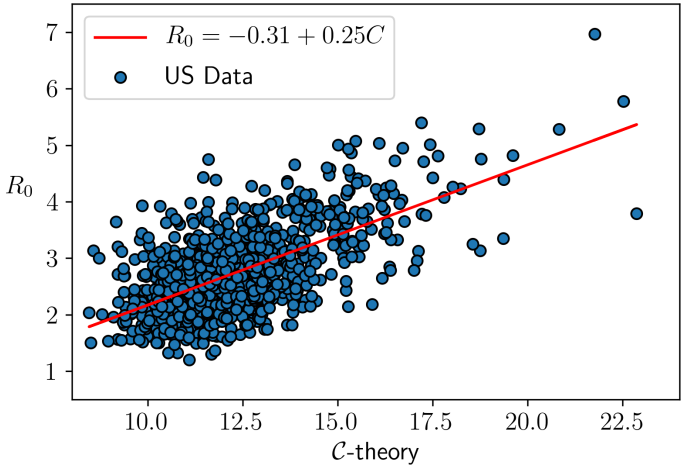


M = 50

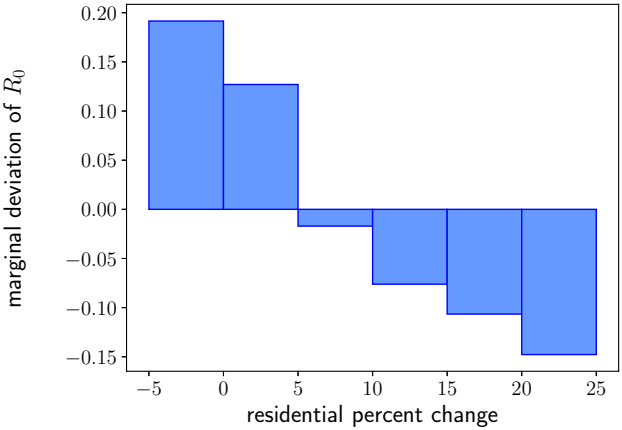


M = 100

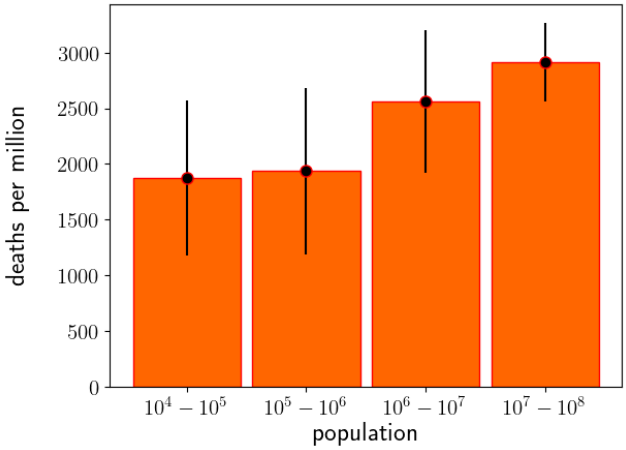
Theory - Simulation



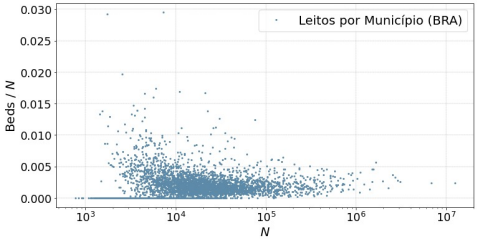
Deviation from mean behavior *vs* mobility (US)



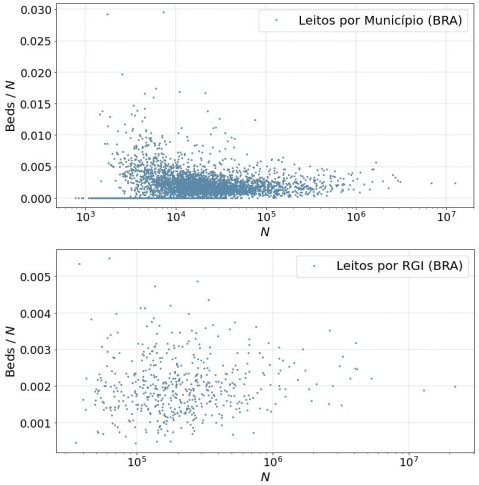
Deaths per capita, Brasil (1^{st} year)



Beds Brasil


Leitos por Município (BRA)
Beds / N
0.030
0.025
0.020
0.015
0.010
0.005
0.000
10^3
10^4
10^5
10^6
10^7
N

Beds Brasil



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  - Peak $\sim \ln N \leftarrow$ beds
  - General immunity (vaccination)

6. arXiv:2005.07791 [pdf, other] q-bio.PE physics.soc-ph

Urban Scaling of COVID-19 epidemics

Authors: Ben-Hur Francisco Cardoso, Sebastián Gonçalves

Universal scaling law for COVID-19 propagation in urban centers

Ben-Hur Francisco Cardoso, Sebastian Goncalves

doi: https://doi.org/10.1101/2020.06.22.20137604

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LETTER

Universal scaling law for human-to-human transmission diseases

Ben-Hur Francisco Cardoso[1] and Sebastián Gonçalves[1,2]

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Thank you!

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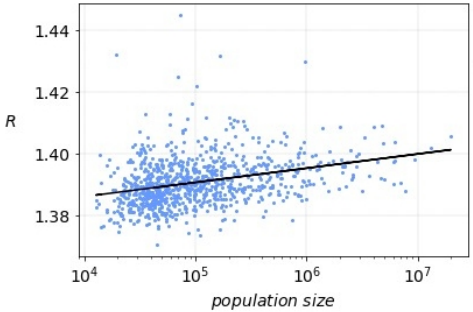
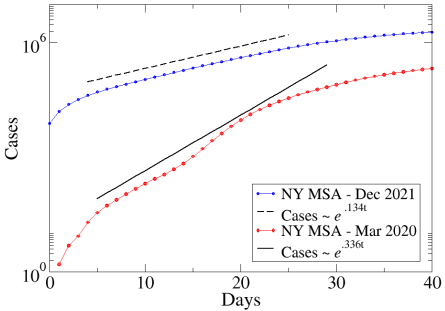
Omicrom (US)


1.44
1.42
1.40
1.38
R
10^4
10^5
10^6
10^7
population size


10^6
10^0
Cases
0
10
20
30
40
Days
NY MSA - Dec 2021
Cases ~ $e^{.134t}$
NY MSA - Mar 2020
Cases ~ $e^{.336t}$

Bases de Dados

US: cSSEGI Sand Data/COVID-19, github.com/CSSEGISandData/COVID-19.

US: County Population Totals: 2010-2019,
www.census.gov/data/datasets/time-series/demo/popest/2010s-counties-total.htm

BR: brasil IO/COVID-19, brasil.io/covid19/

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DE: cOVID-19 Germany GAE, github.com/jgehrcke/covid-19-germany-gae/

DE: kreisfreieStädte und Landkreisenach Fläche,
www.destatis.de/DE/Themen/Laender-Regionen/Regionales/Gemeindeverzeichnis/Administrativ/04-kreise.html