Physics and Epidemics

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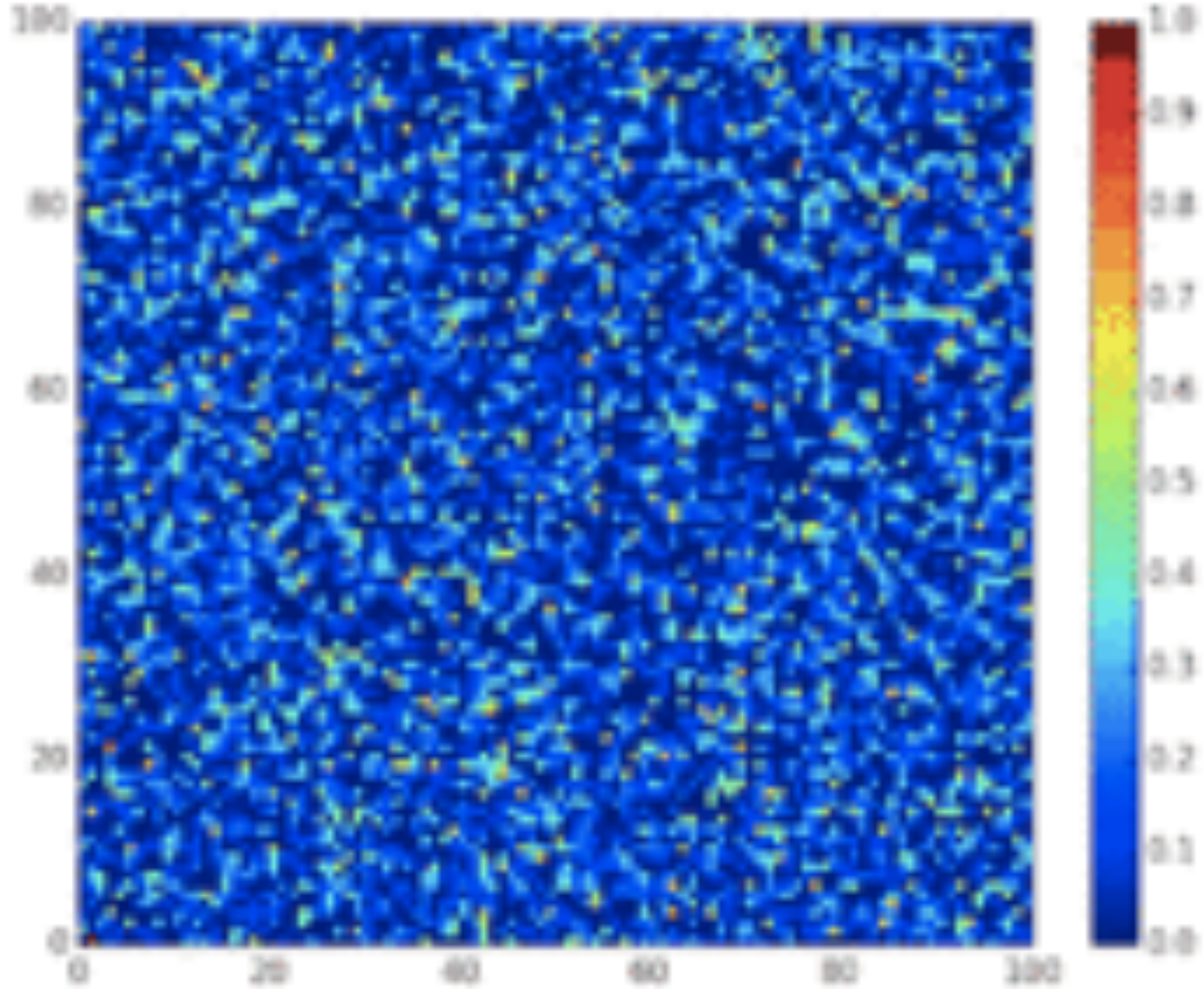
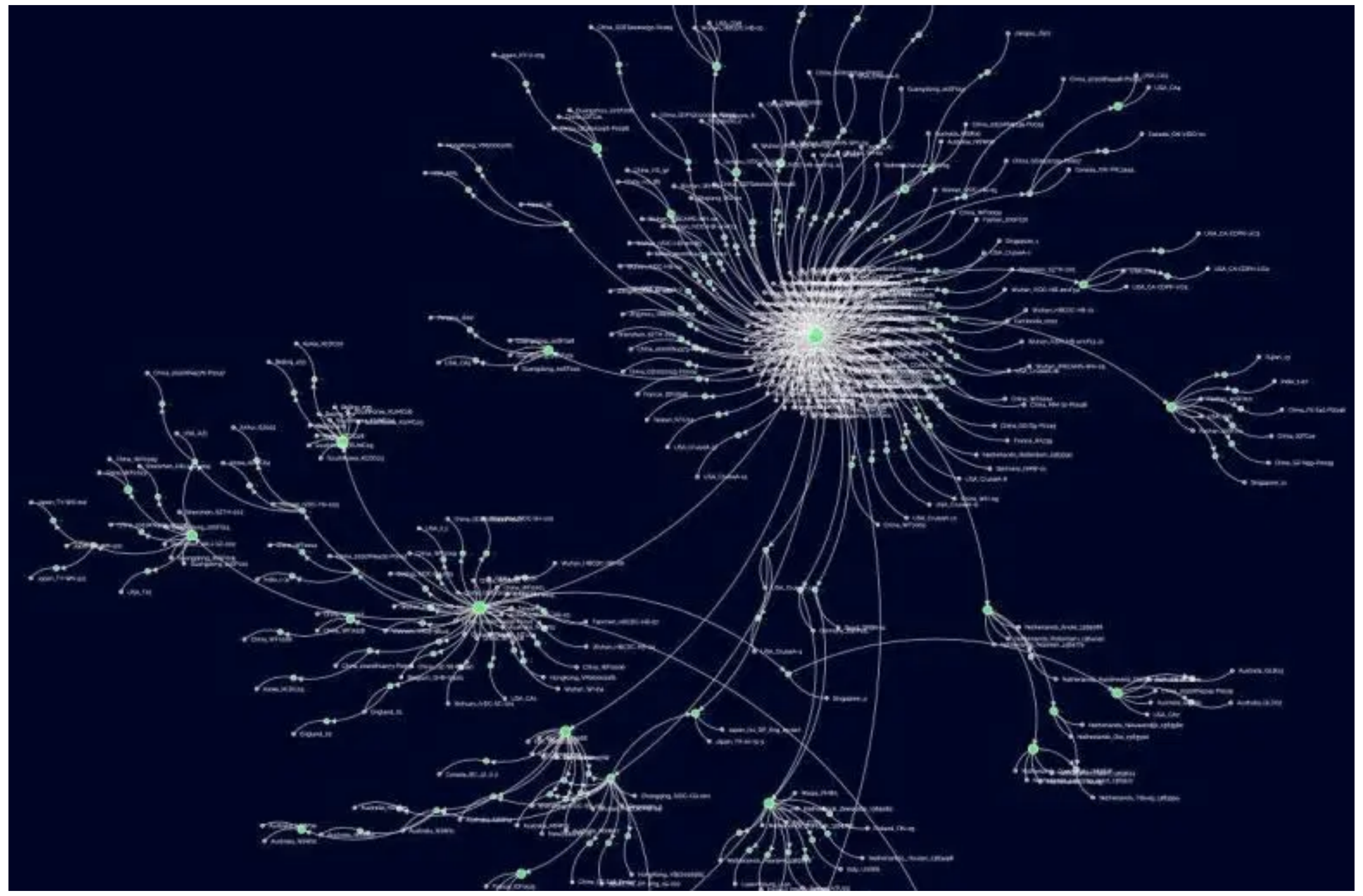




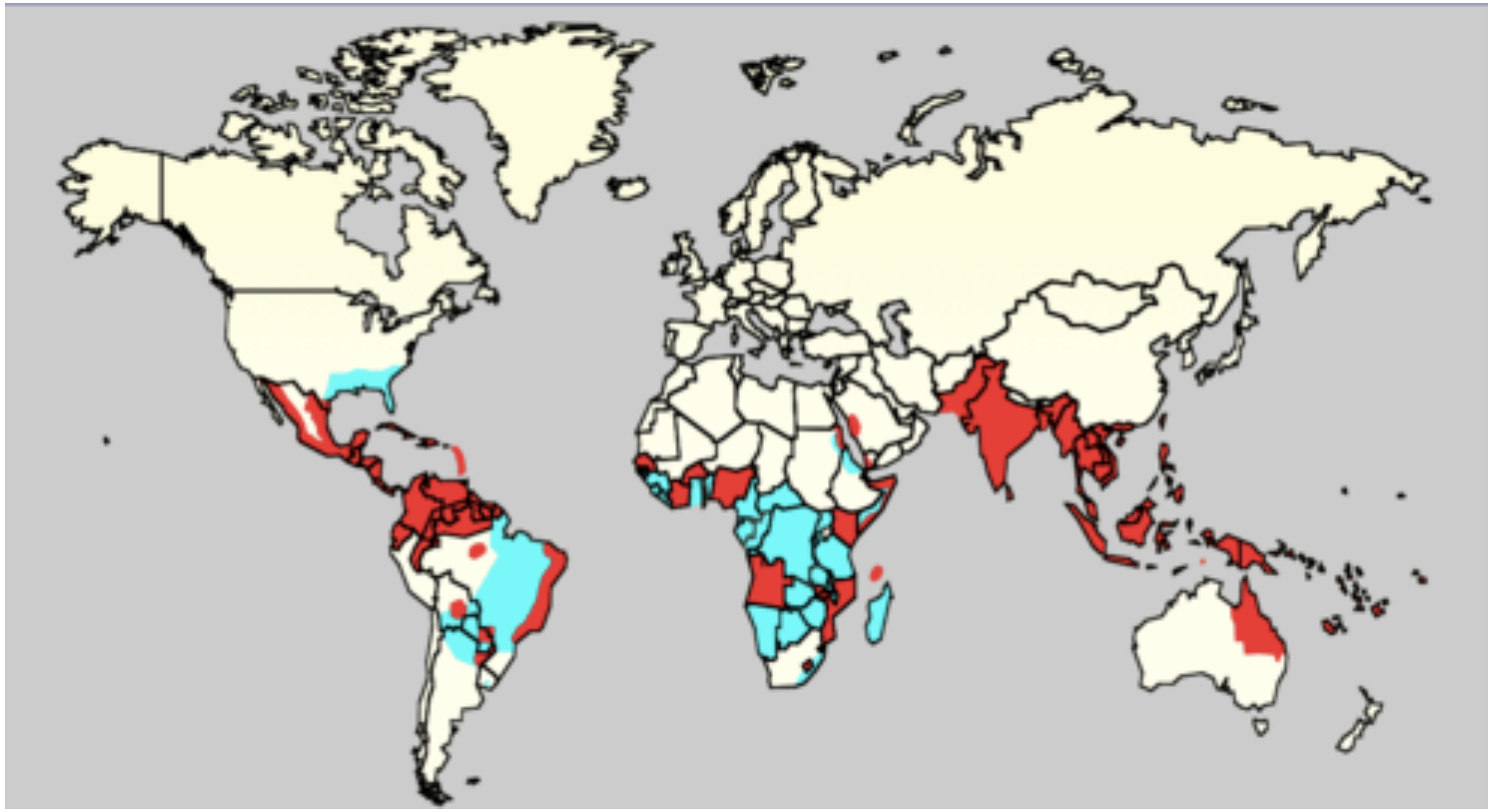
Introduction

* Recent and current epidemics
* Compartmental Models
* The physics of Networks
* Epidemics on Networks
* An Experimental Effort

A recent Epidemics

- 2019–2020: Dengue fever epidemic.

- Affected countries: several countries of Southeast Asia (including Philippines, Malaysia, Vietnam, Bangladesh, Pakistan, Thailand, Singapore, Laos).

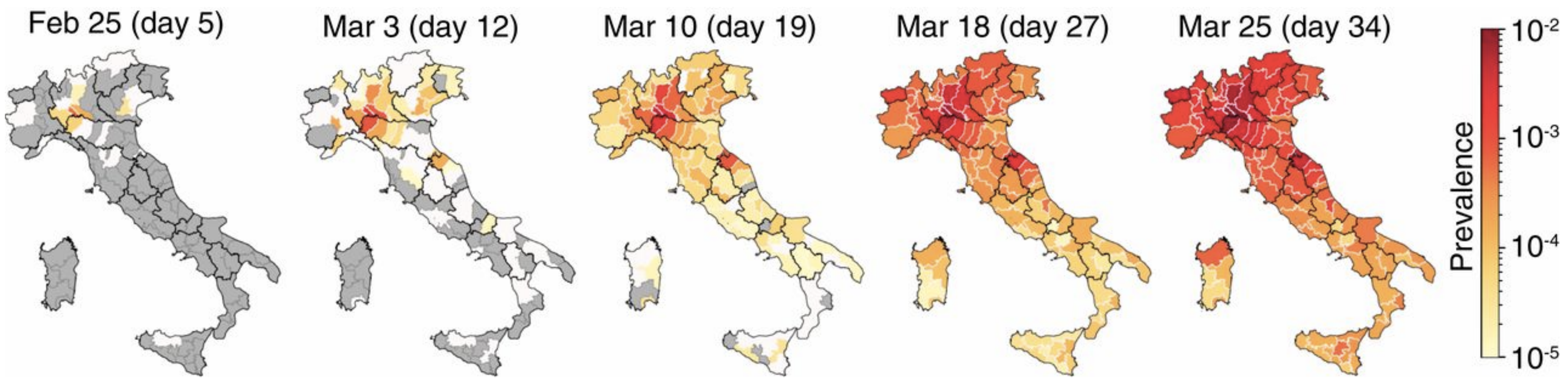


- Transmitted by the Aedes aegypti mosquito
- 3-14 days between infection and symptoms
- 80% asymptomatic or mild symptoms
- 5% severe symptoms
- <1% letal

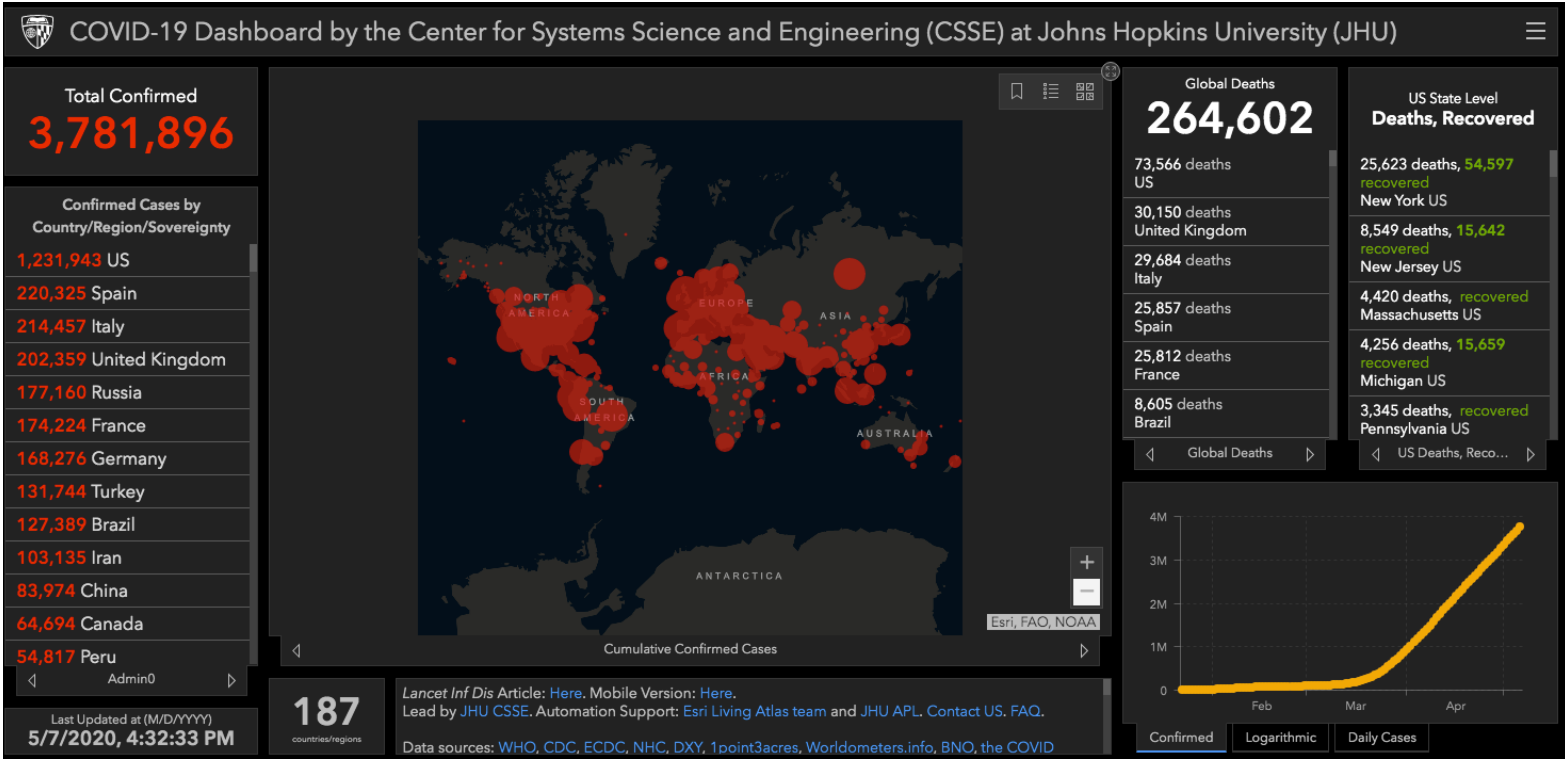
- Countermeasures: vaccination, elimination of stagnating water, elimination of Aedes aegypti

The current ~~Epidemics~~ Pandemics

* Virus name: Sars-Cov-2
* Disease name: COVID-19 (COrona VIrus Disease 2019)
* First appearance: early December 2019, Wuhan, China
* OMS announcement: Feb. 11th 2020
* “Spill-over”: animal to human transmission
* Dec. 31st 2019 Pneumonia of unknown origin reported by the City of Wuhan (Hubei, China)
* Jan 9th 2020 the Chinese CDC reported that a new coronavirus (initially called 2019- nCoV and now called SARS-CoV-2) has been identified: genomic sequence published.
* Mar. 11th 2020 OMS declared COVID-19 as a pandemic.



The current ~~Epidemics~~ Pandemics

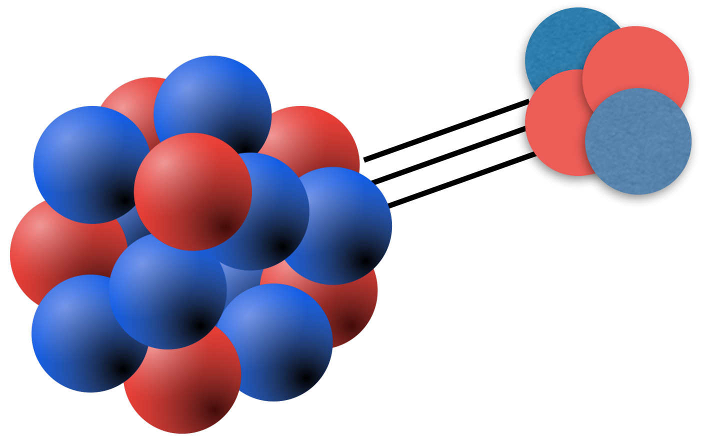
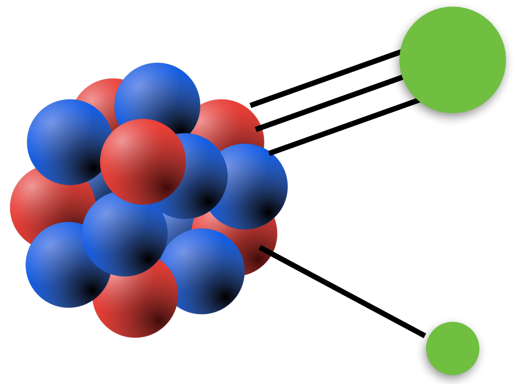
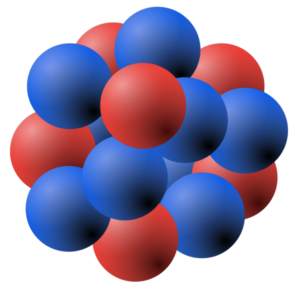


Compartmental Models

An example from Nuclear Physics

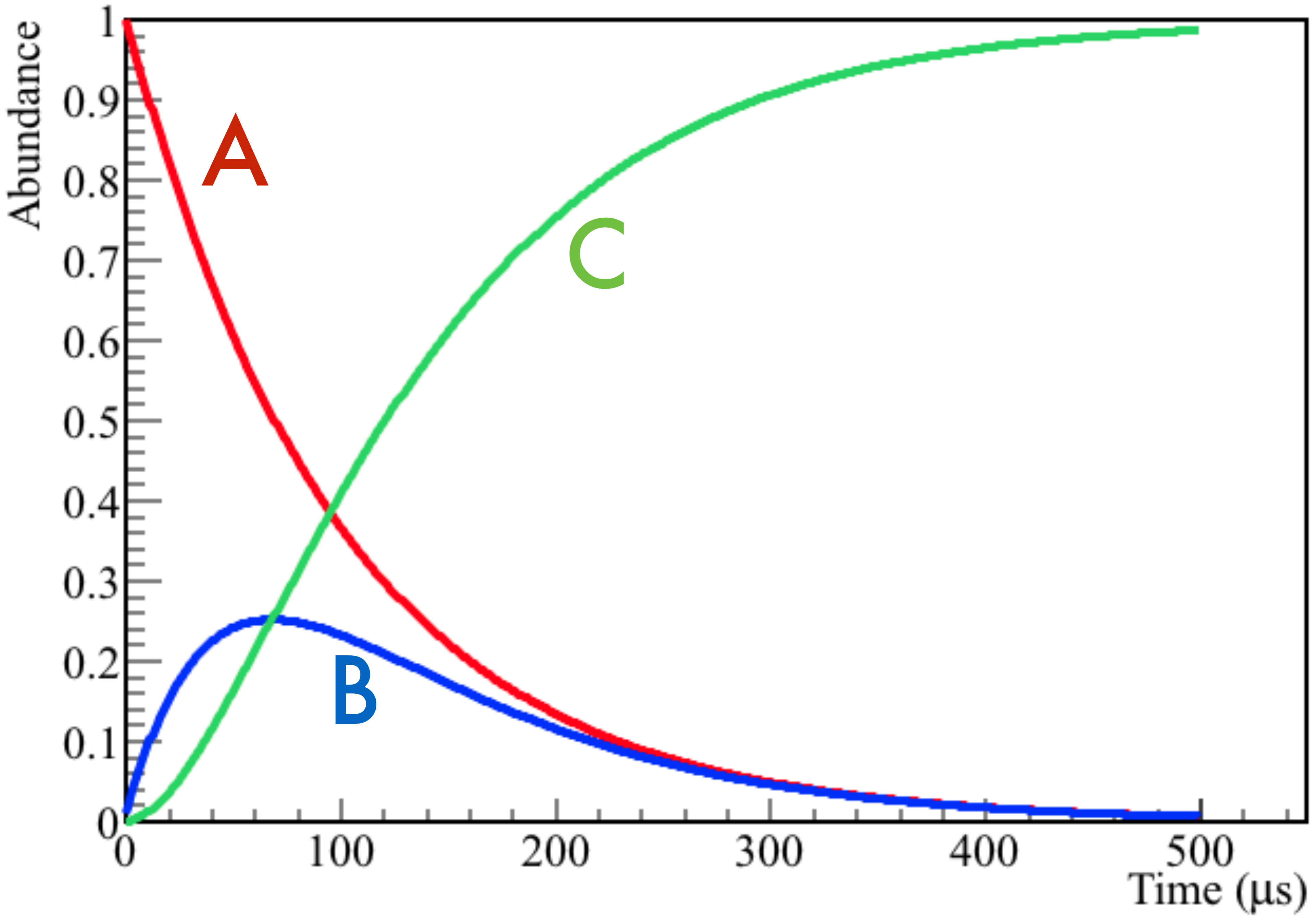
Compartments:

Unstable nucleus A $\xrightarrow{\lambda_A}$ Unstable nucleus B $\xrightarrow{\lambda_B}$ Stable nucleus C

$$\frac{dN_A}{dt} = -\lambda_A N_A$$

$$\frac{dN_B}{dt} = \lambda_A N_A - \lambda_B N_B$$



An example from Nuclear Physics

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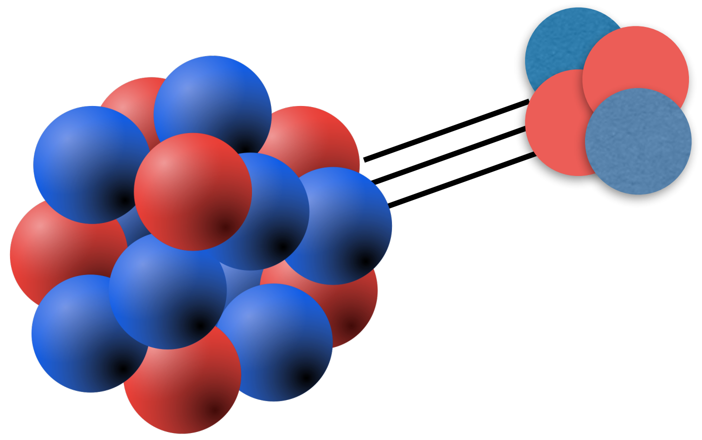
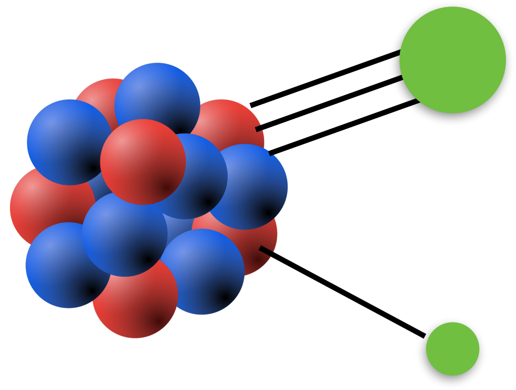
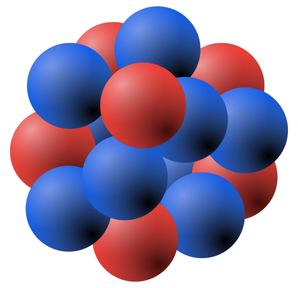

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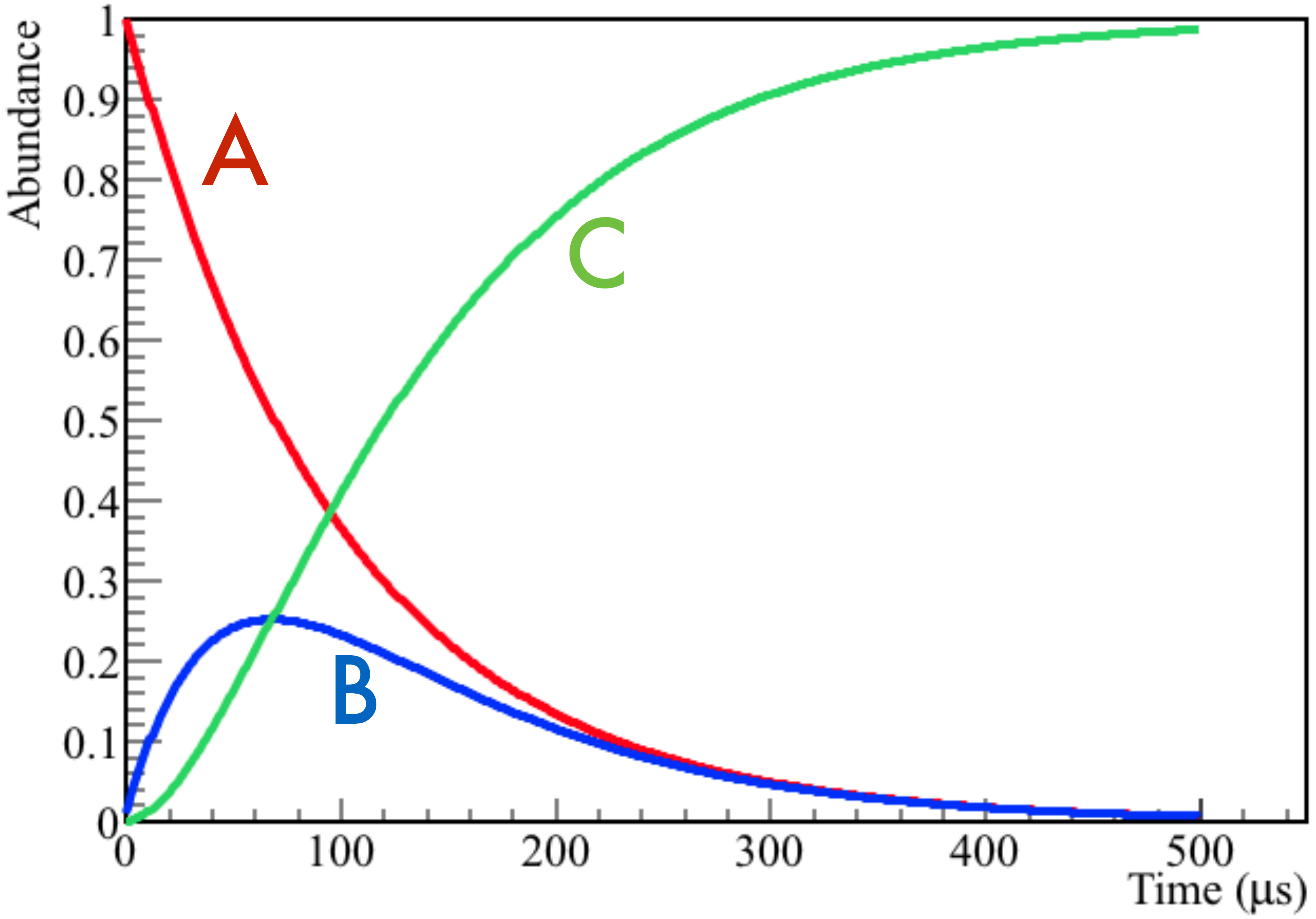
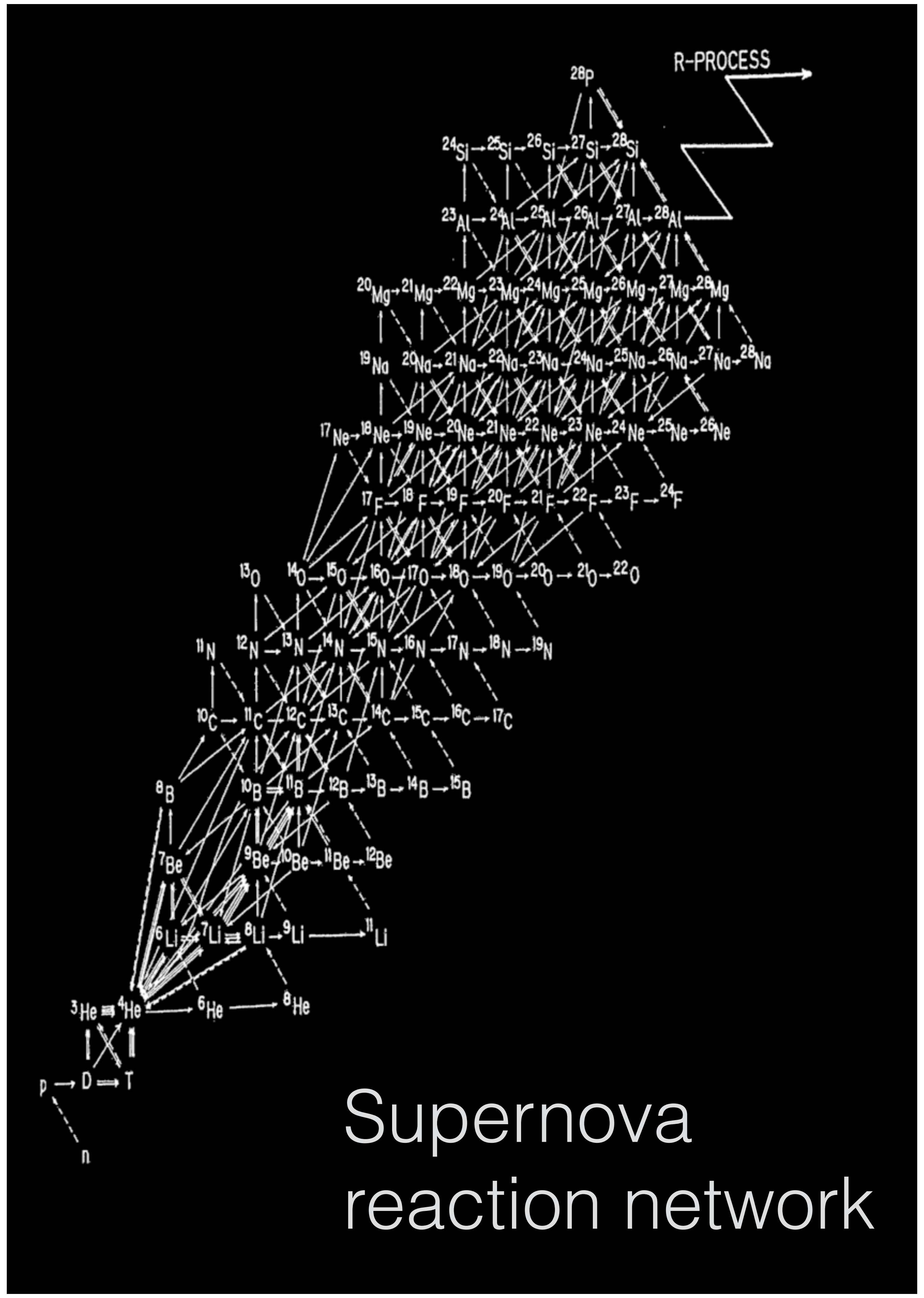
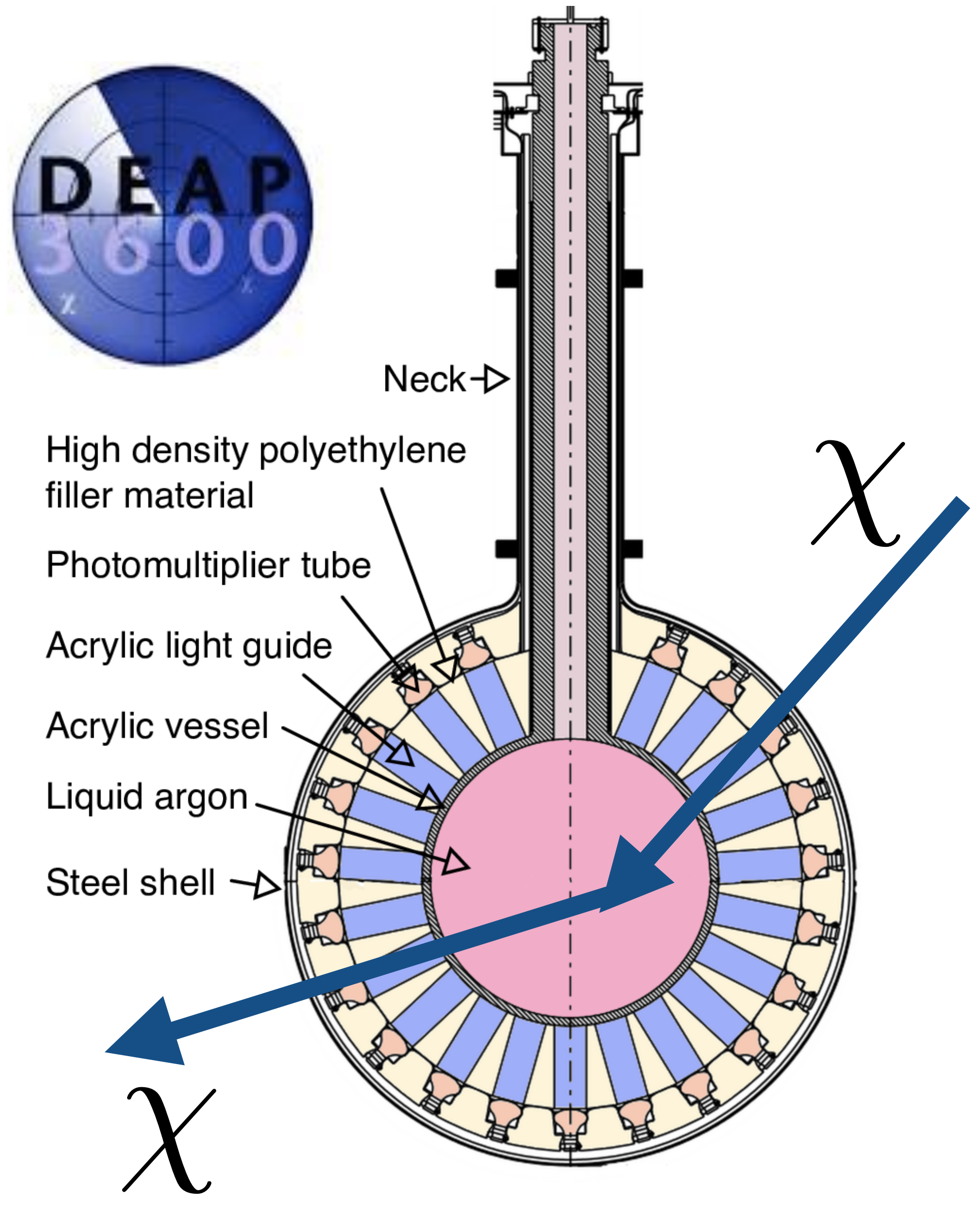
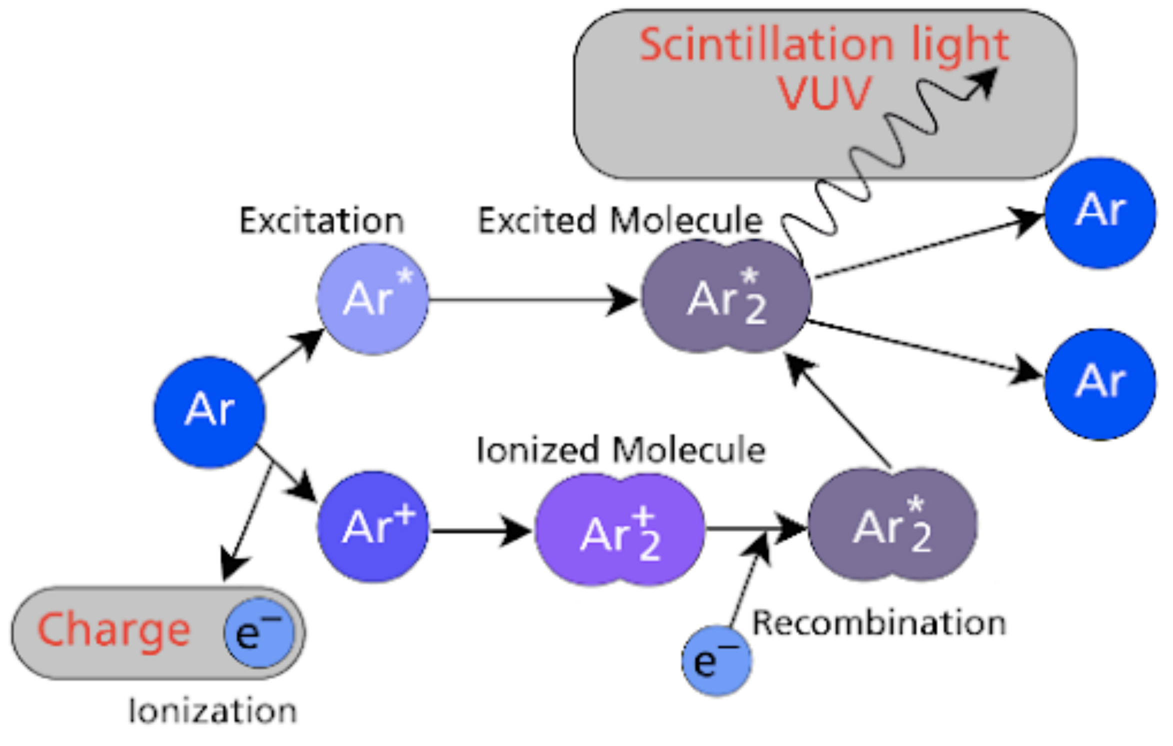
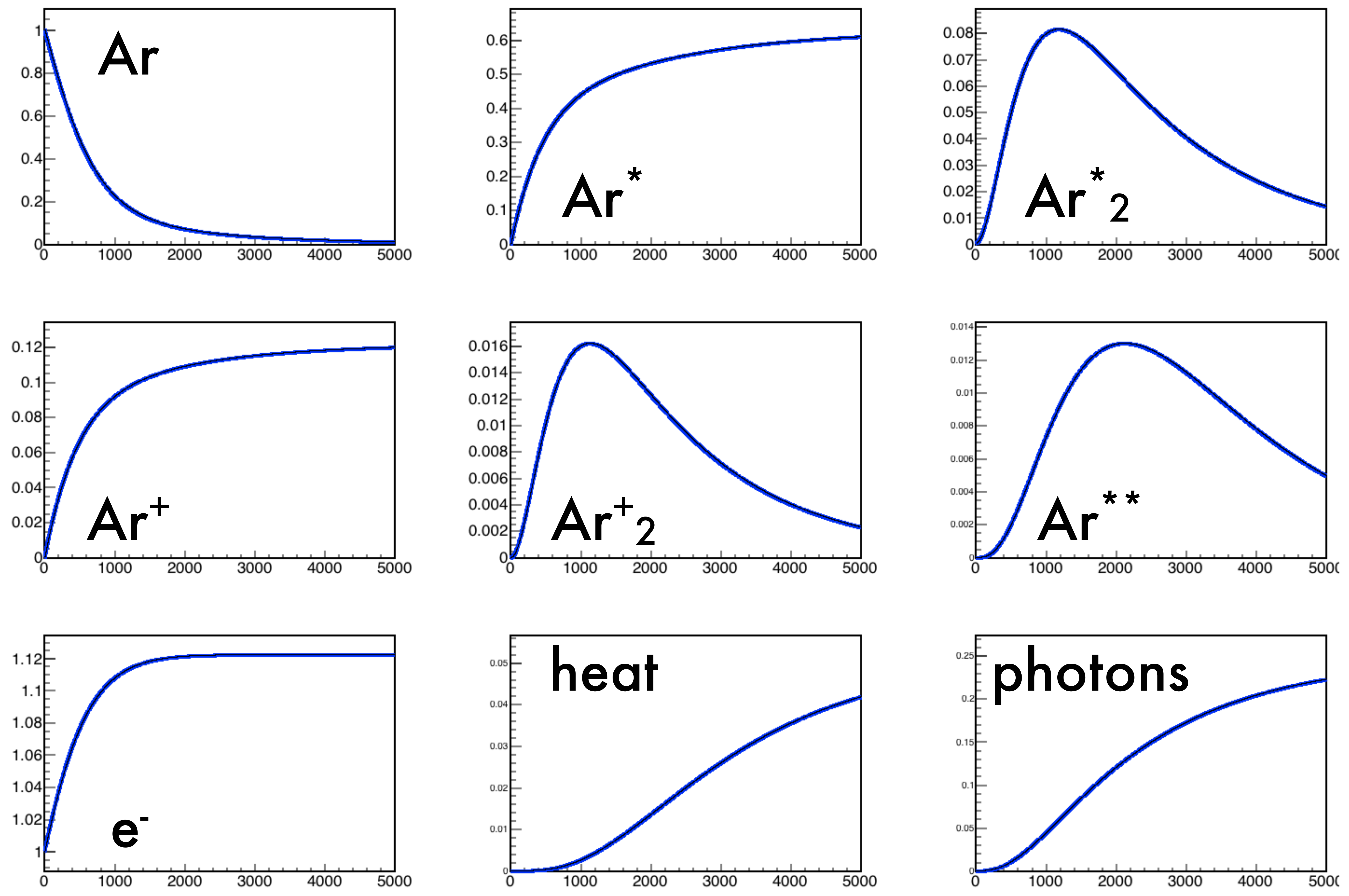




An example from Dark Matter Searches

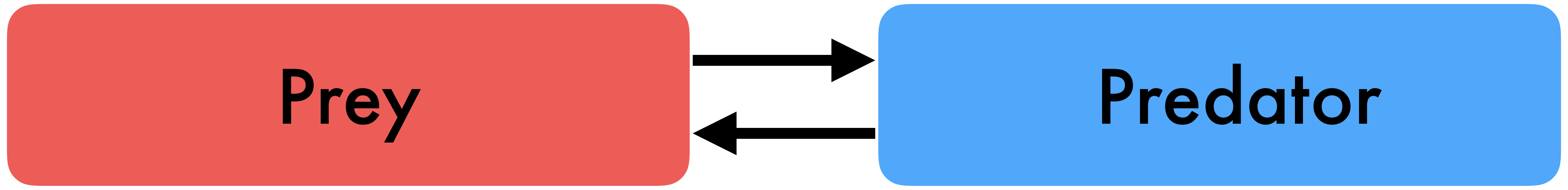






$$\dot{x}_1 = -k_1 x_1 x_e - k_2 x_1 x_2 + k_3 x_3 - k_4 x_1 x_e - k_5 x_1 x_4 + k_6 x_e x_5$$
$$\dot{x}_2 = k_1 x_1 x_e - k_2 x_1 x_2 + k_7 x_6$$
$$\dot{x}_3 = k_2 x_1 x_2 - k_3 x_3$$
$$\dot{x}_4 = k_4 x_1 x_e - k_5 x_1 x_4$$
$$\dot{x}_5 = k_5 x_1 x_4 - k_6 x_e x_5$$
$$\dot{x}_6 = k_6 x_e x_5 - k_7 x_6$$
$$\dot{x}_e = k_4 x_1 x_e - k_6 x_5 x_e$$
$$\dot{x}_h = k_7 x_6$$
$$\dot{x}_\gamma = k_3 x_3$$

An early Example: Predator-Prey Models

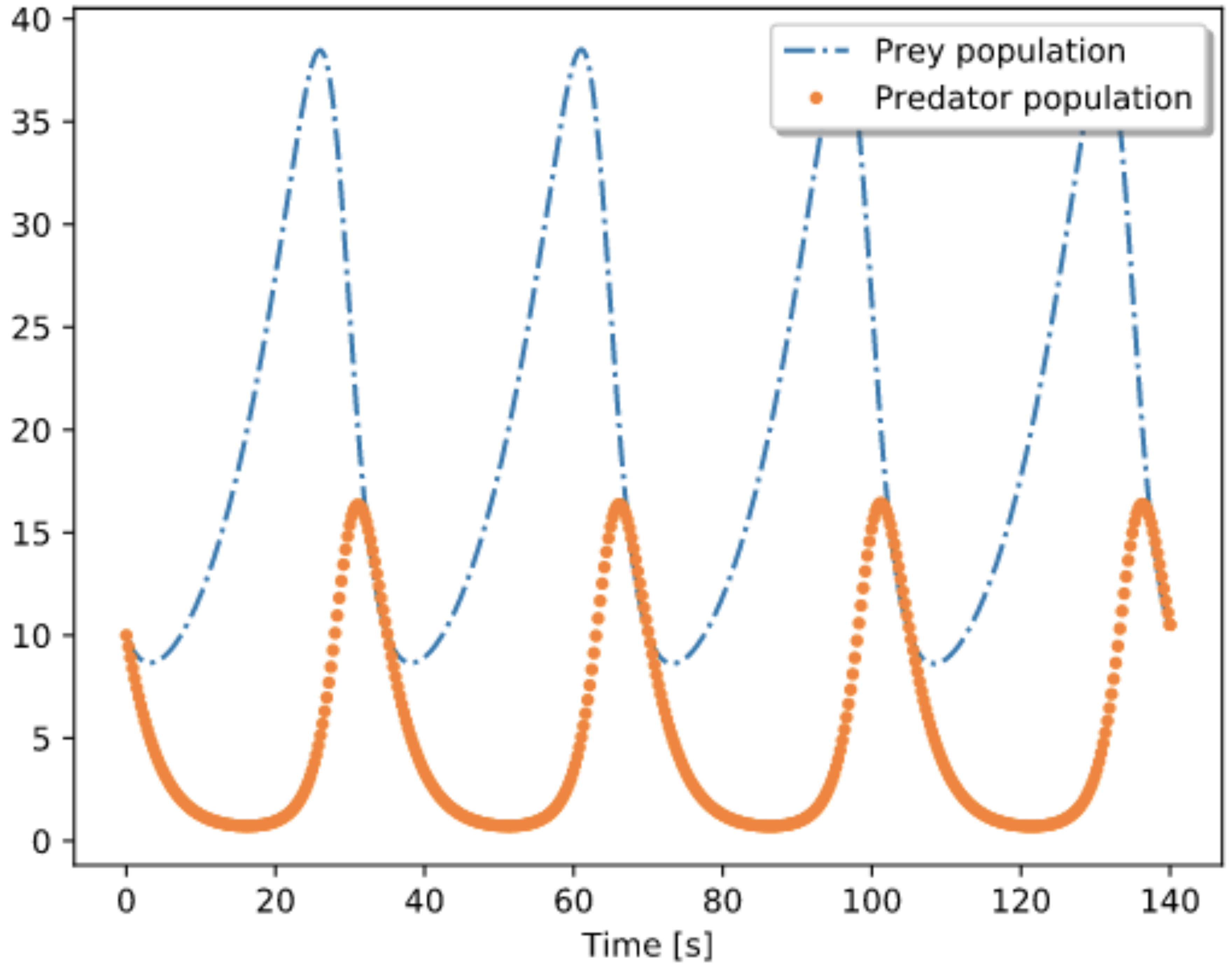


V. Volterra
(1860–1940)

A.J. Lotka
(1880–1949)

$$\frac{dx}{dt} = \alpha x - \beta x y,$$

$$\frac{dy}{dt} = \delta x y - \gamma y,$$



- Simple model, but interesting phase space
- Oscillatory solutions
- Two equilibria: extinction (unstable), constant population
- Chaotic solutions with >3 competing species.

SIR Model

“As a matter of fact, all epidemiology, concerned as it is with the variation of disease from time to time or from place to place, must be considered mathematically, however many variables as implicated, if it is to be considered scientifically at all.”

Sir Ronald Ross, MD

Sir Ronald Ross
(1857–1932)

Susceptible $\xrightarrow{\beta}$ Infected $\xrightarrow{\gamma}$ Recovered

$$\frac{dS}{dt} = -\frac{\beta I S}{N},$$

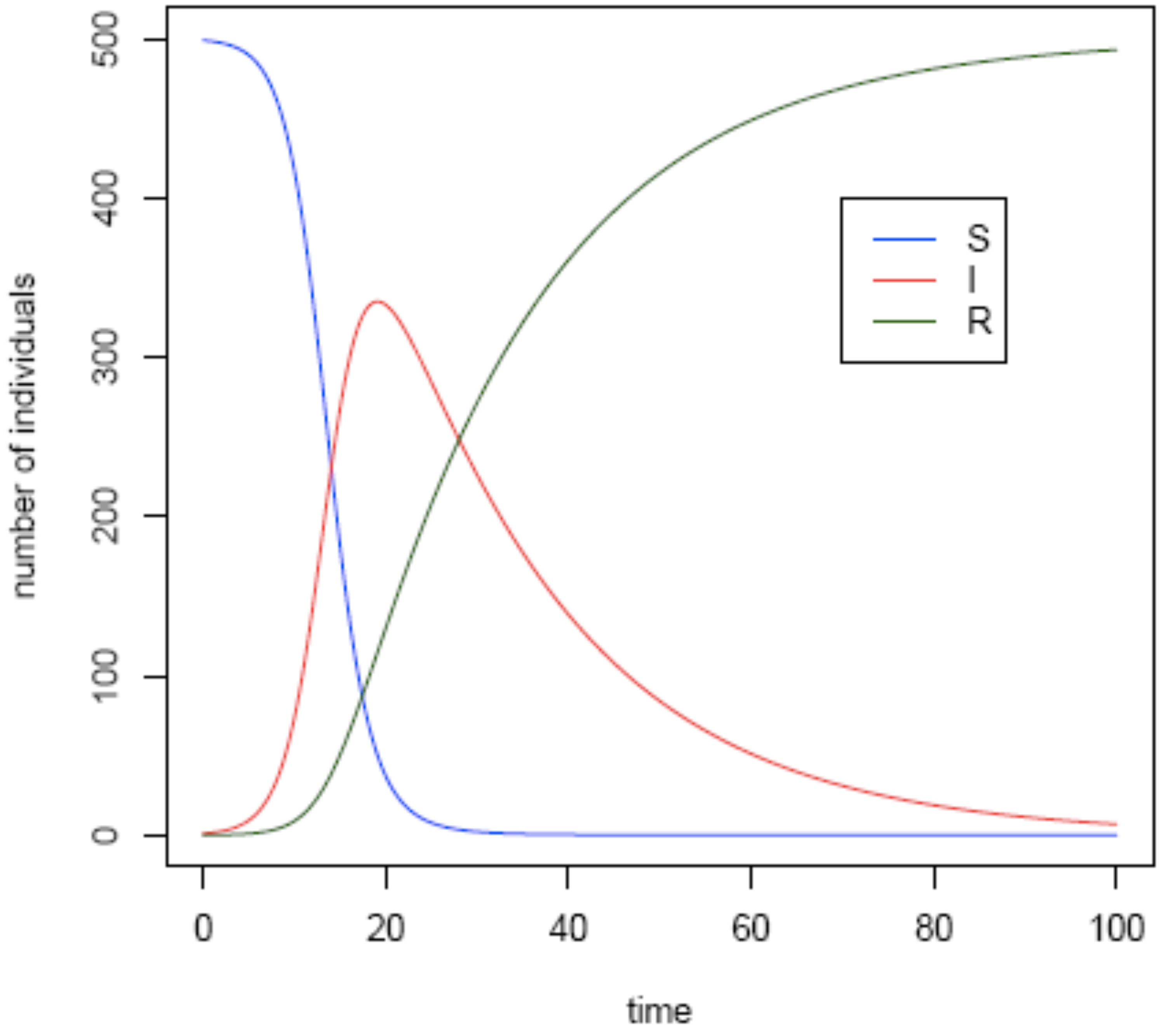
$$\frac{dI}{dt} = \frac{\beta I S}{N} - \gamma I,$$

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

$$R_0 = \frac{\beta}{\gamma}$$

$$\dot{S} + \dot{I} + \dot{R} = 0$$

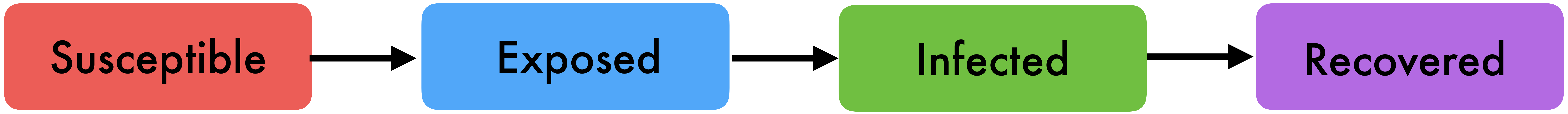
$$S + I + R = N$$



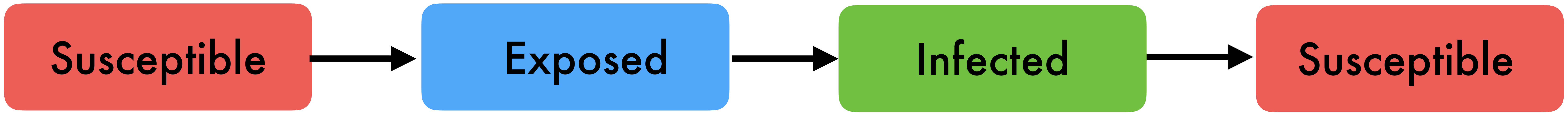
More Compartmental Models

SIRD

SEIR



SEIS



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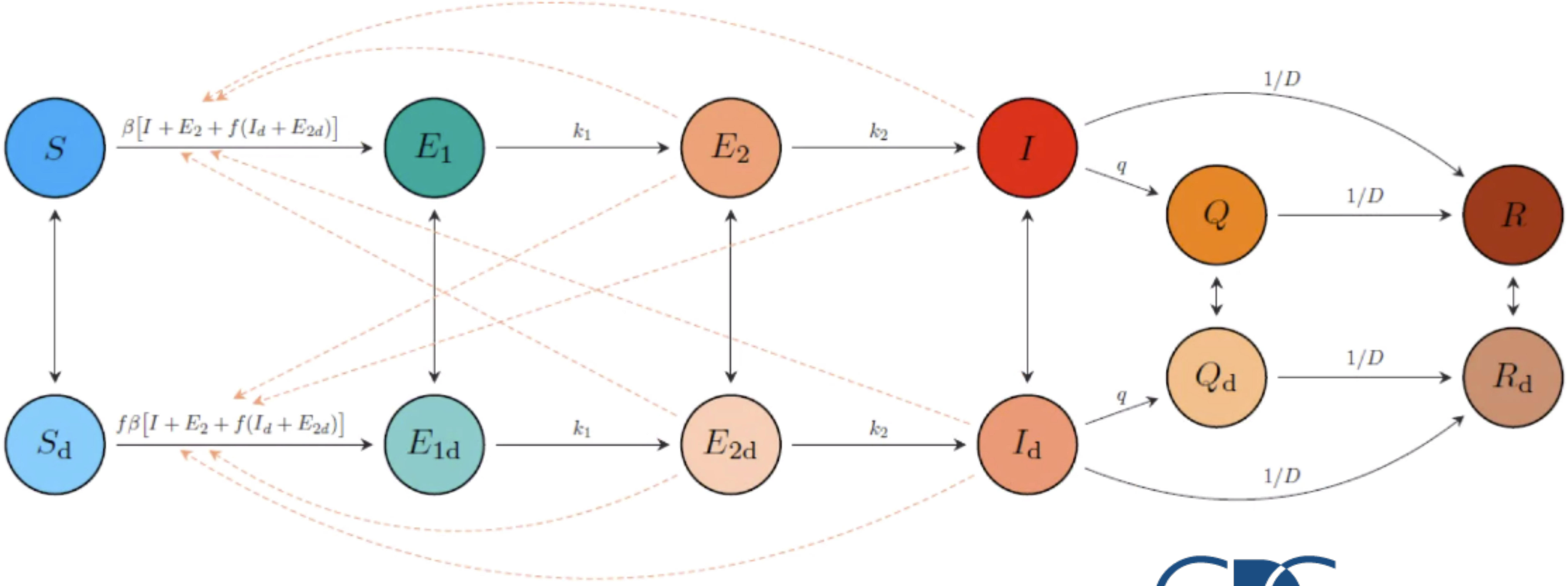
Even more Compartmental Models



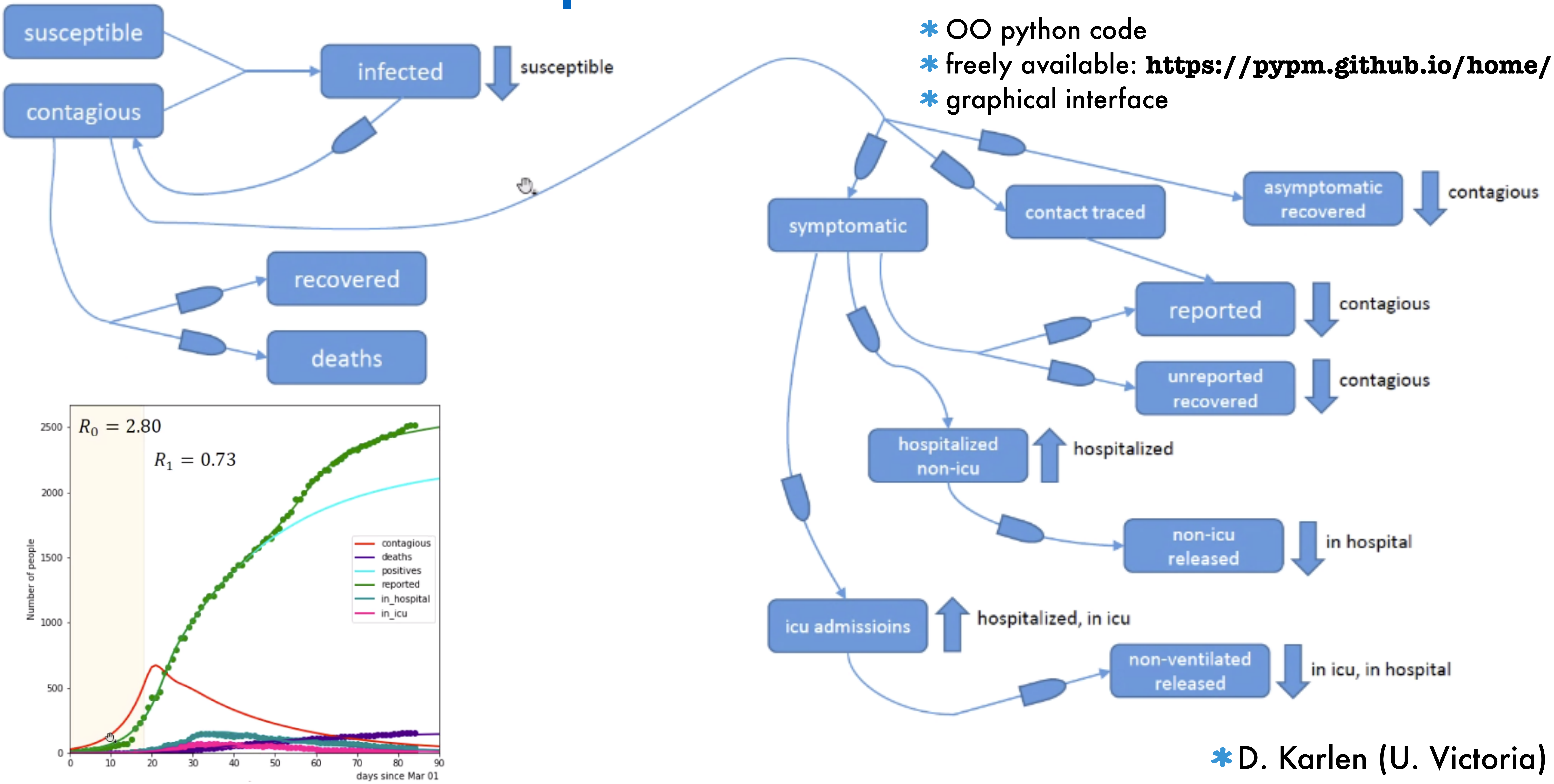
$$\frac{dS}{dt} = -\beta\left[I + E_2 + f(I_d + E_{2d})\right]\frac{S}{N} - u_d S + u_r S_d$$
$$\frac{dE_1}{dt} = \beta\left[I + E_2 + f(I_d + E_{2d})\right]\frac{S}{N} - k_1 E_1 - u_d E_1 + u_r E_{1d}$$
$$\frac{dE_2}{dt} = k_1 E_1 - k_2 E_2 - u_d E_2 + u_r E_{2d}$$
$$\frac{dI}{dt} = k_2 E_2 - qI - \frac{I}{D} - u_d I + u_r I_d$$
$$\frac{dQ}{dt} = qI - \frac{Q}{D} - u_d Q + u_r Q_d$$
$$\frac{dR}{dt} = \frac{I}{D} + \frac{Q}{D} - u_d R + u_r R_d,$$

$$\frac{dS_d}{dt} = -f\beta\left[I + E_2 + f(I_d + E_{2d})\right]\frac{S_d}{N} + u_d S - u_r S_d$$
$$\frac{dE_{1d}}{dt} = f\beta\left[I + E_2 + f(I_d + E_{2d})\right]\frac{S_d}{N} - k_1 E_{1d} + u_d E_1 - u_r E_{1d}$$
$$\frac{dE_{2d}}{dt} = k_1 E_{1d} - k_2 E_{2d} + u_d E_2 - u_r E_{2d}$$
$$\frac{dI_d}{dt} = k_2 E_{2d} - qI_d - \frac{I_d}{D} + u_d I - u_r I_d$$
$$\frac{dQ_d}{dt} = qI_d - \frac{Q_d}{D} + u_d Q - u_r Q_d$$
$$\frac{dR_d}{dt} = \frac{I_d}{D} + \frac{Q_d}{D} + u_d R - u_r R_d.$$

BC Centre for Disease Control

A discrete-time compartmental Models

- OO python code
- freely available: **https://pypm.github.io/home/**
- graphical interface



- D. Karlen (U. Victoria)

SIRD Model

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

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

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

$$\frac{dD}{dt} = \mu I,$$

SIRD Model

$$\frac{dS}{dt} = -\frac{\beta I S}{N},$$

$$\frac{dI}{dt} = \frac{\beta I S}{N} - \gamma I - \mu I,$$

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

$$\frac{dD}{dt} = \mu I,$$

Dynamic parameters

$$\beta = \beta_0 e^{-\beta_1 (t - t_0)}$$

Infection rate

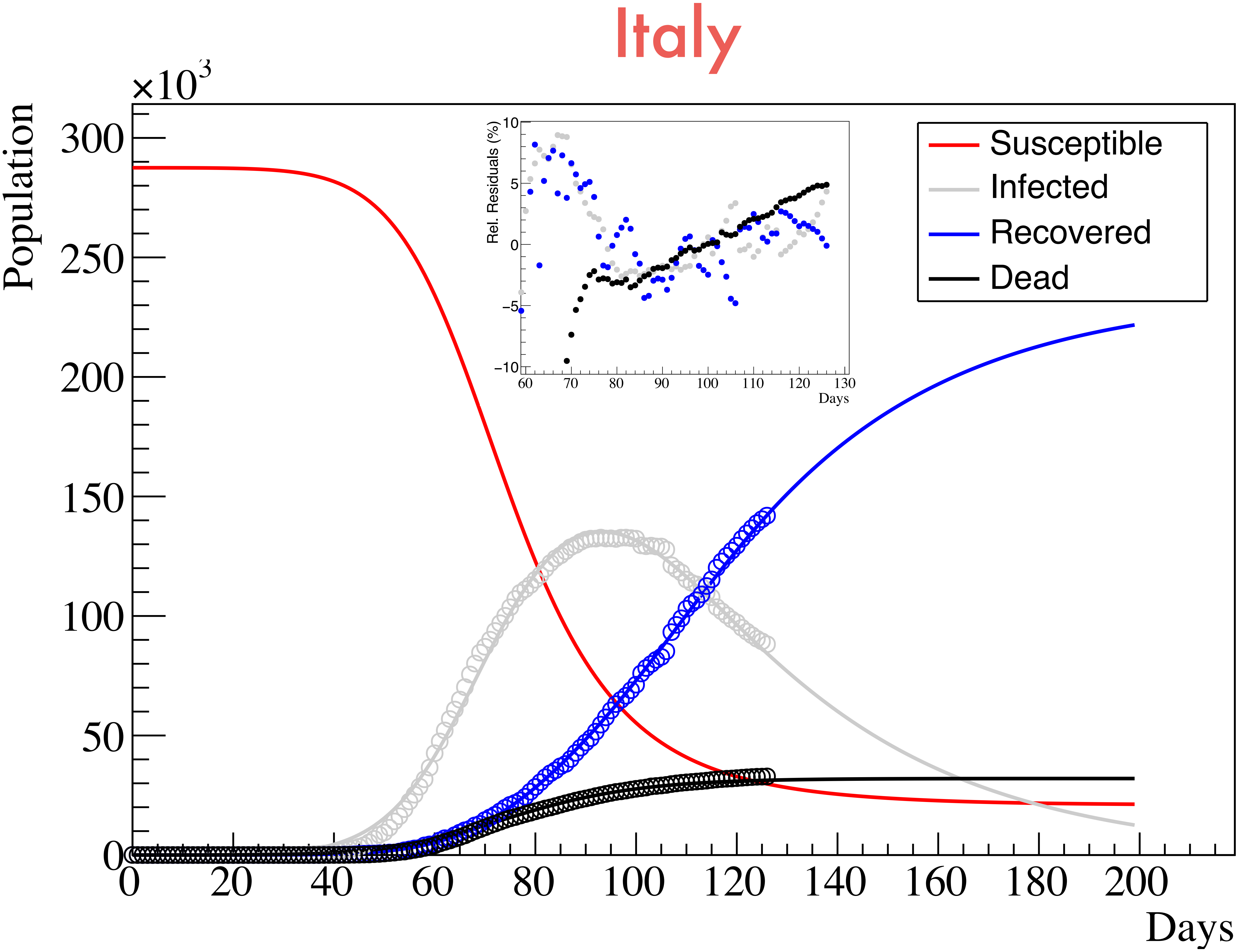
$$\gamma = \gamma_0 + \frac{\gamma_0}{1 + e^{\gamma_1 (t - t_0)}}$$

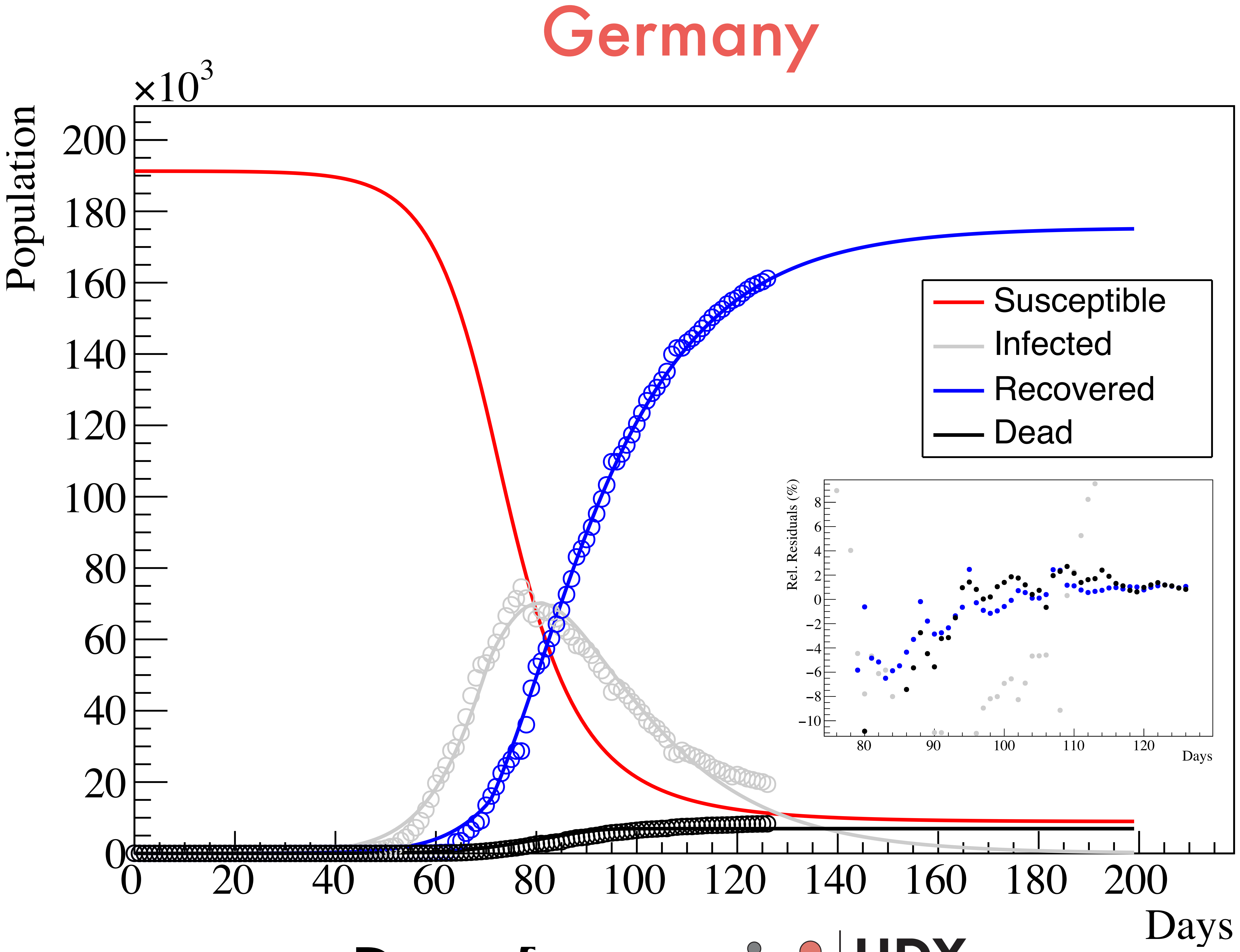
Recovery rate

$$\mu = \mu_0 - \frac{\mu_0}{1 + e^{\mu_1 (t - t_0)}}$$

Mortality rate

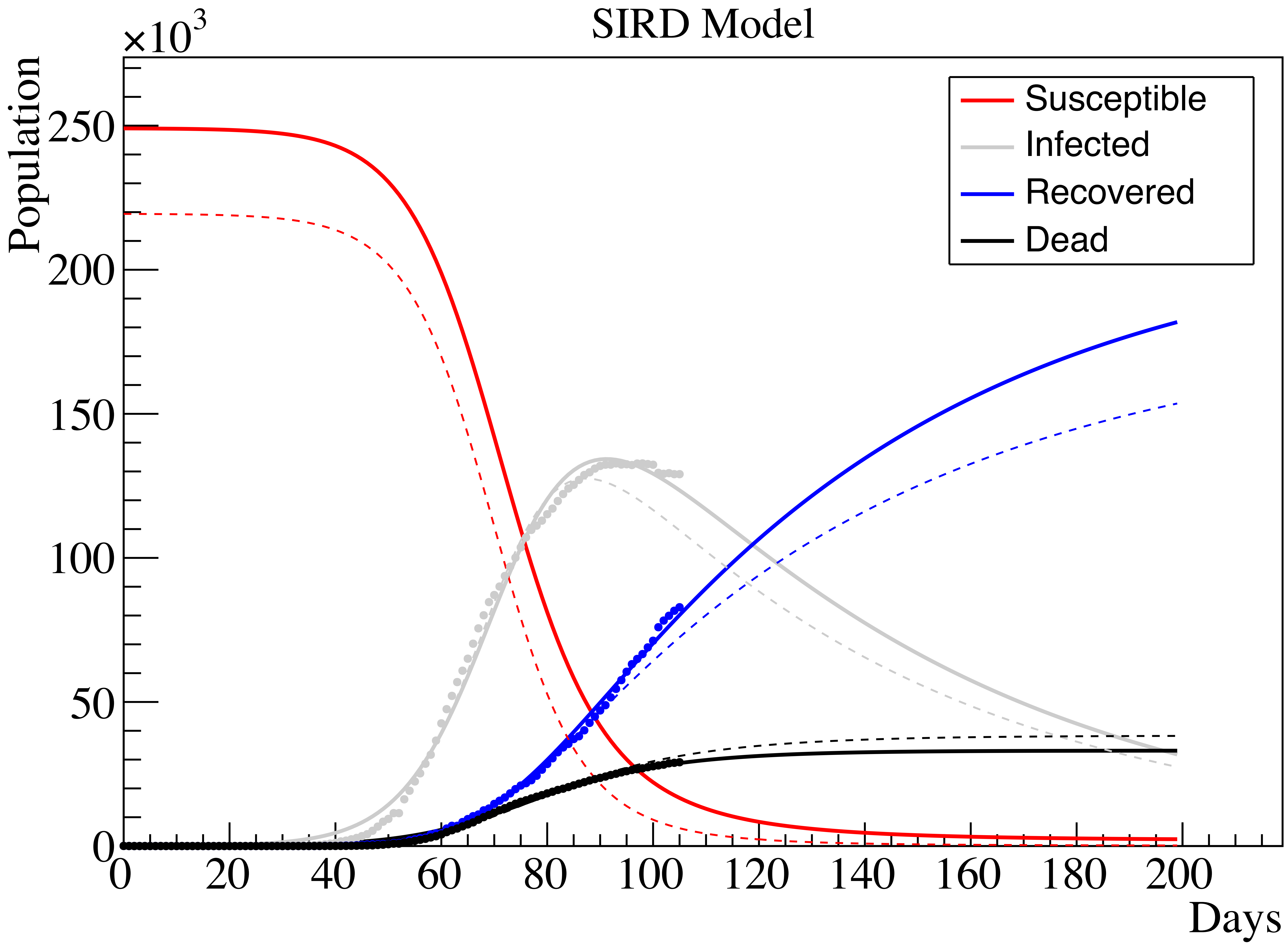
"Dynamic" SIRD Model





Data from: HDX Humanitarian Data Exchange

“Dynamic” SIRD Model: 1week forecast



Stochastic SIR Model

- 100 realizations of a stochastic process
- Gillespie Algorithm (developed for chemistry)
- Poisson-like process (fixed rate)

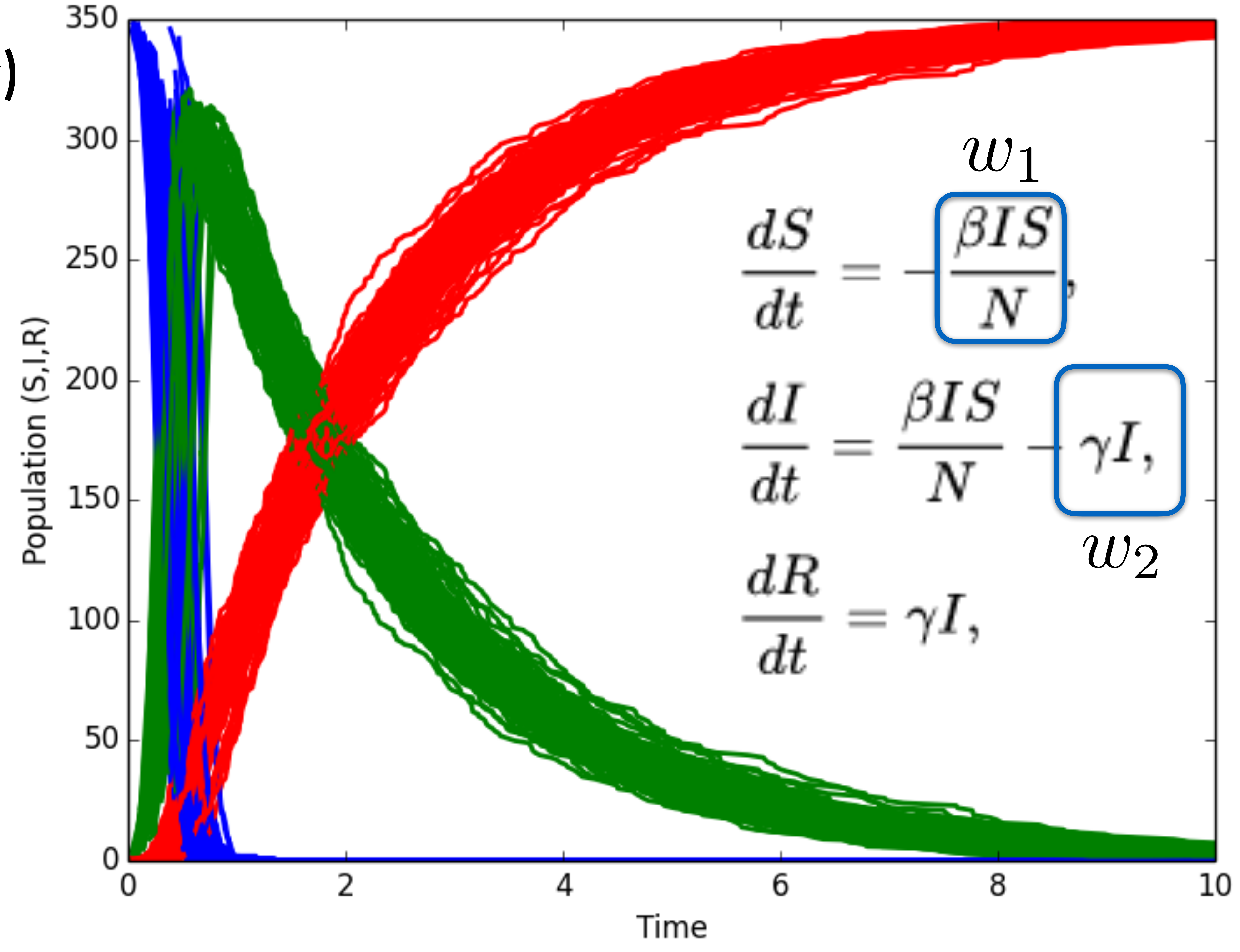
$$p(0) = e^{-rt} \Rightarrow p(k>0) = 1 - e^{-rt}$$

$$dt = -\frac{1}{r}\ln\left(\frac{1}{\mathrm{rdm}(0{,}1)}\right) \longrightarrow t = t + dt$$

$$w = w_1 + w_2$$

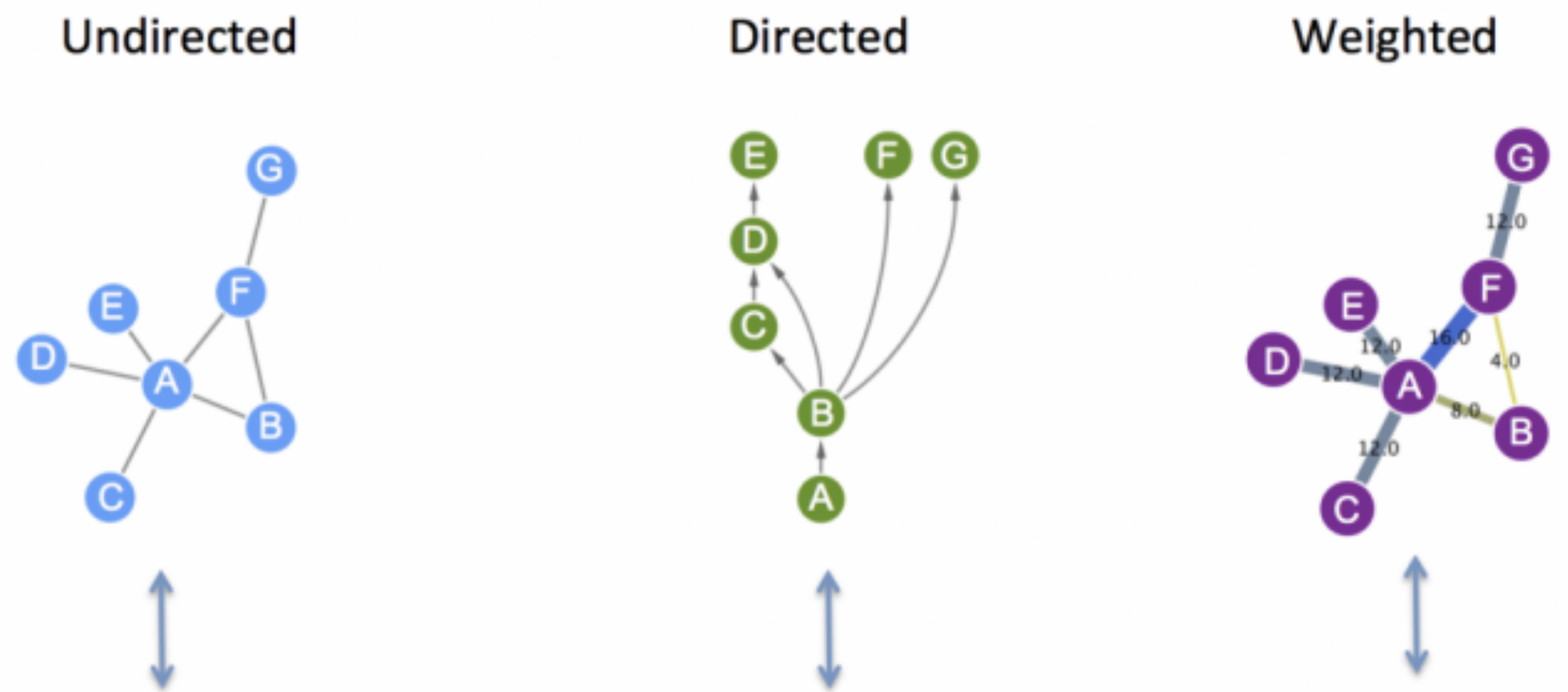
$$\text{if } \mathrm{rdm}(0{,}1) < w_1/w \Rightarrow \begin{cases} S-- \\ I++ \end{cases}$$

$$\text{if } \mathrm{rdm}(0{,}1) > w_1/w \Rightarrow \begin{cases} I-- \\ R++ \end{cases}$$



Network Models

Networks



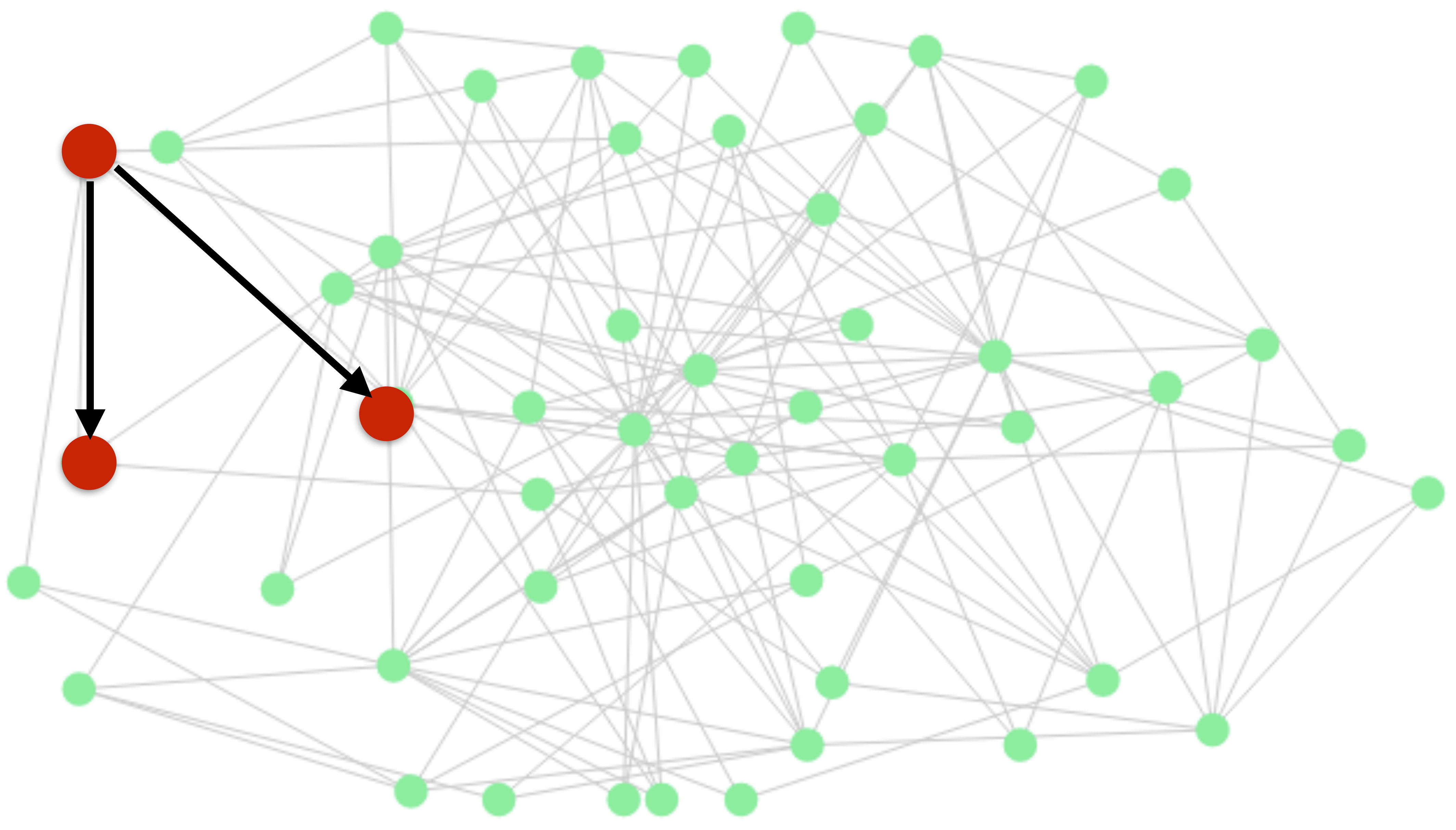
	A	B	C	D	E	F	G	Degree
A	0	1	1	1	1	1	0	5
B	1	0	0	0	0	1	0	2
C	1	0	0	0	0	0	0	1
D	1	0	0	0	0	0	0	1
E	1	0	0	0	0	0	0	1
F	1	1	0	0	0	0	1	3
G	0	0	0	0	0	1	0	1

	A	B	C	D	E	F	G	Out-degree
A	0	1	0	0	0	0	0	1
B	0	0	1	1	0	1	1	4
C	0	0	0	1	0	0	0	1
D	0	0	0	0	1	0	0	1
E	0	0	0	0	0	0	0	0
F	0	0	0	0	0	0	0	0
G	0	0	0	0	0	0	0	0

	A	B	C	D	E	F	G	Degree
A	0	8	12	12	12	16	12	72
B	8	0	0	0	0	4	0	12
C	12	0	0	0	0	0	0	12
D	12	0	0	0	0	0	0	12
E	12	0	0	0	0	0	0	12
F	16	4	0	0	0	0	12	32
G	12	0	0	0	0	12	0	24

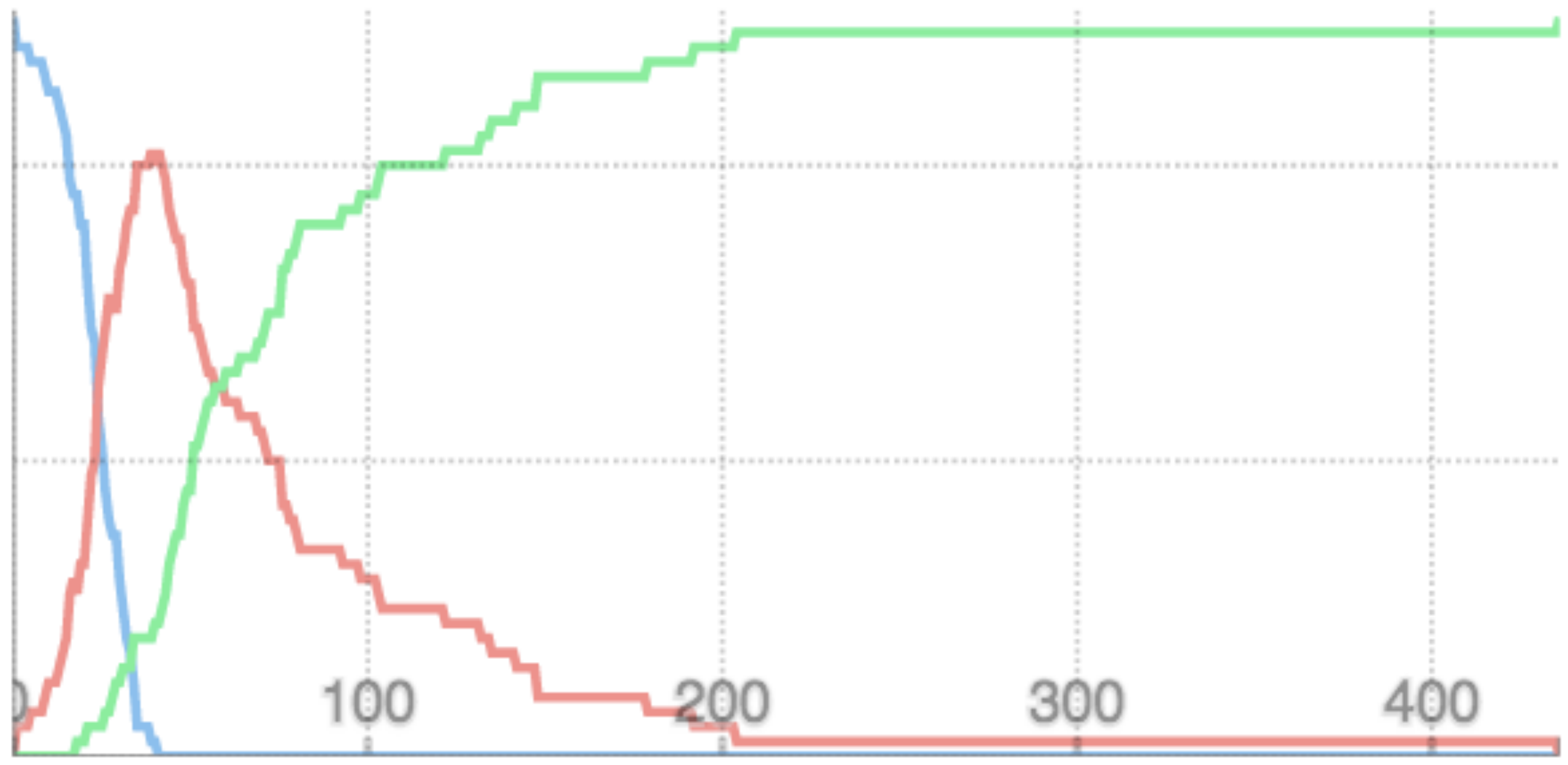
Adjacency matrices

SIR(D) on Networks



Montecarlo-like simulation:

Random network N(V,E): V vertices, E edges
Vertex = Person
p: probability of infecting a neighbour
q: probability to recover



In physics terms, such procedure realizes a diffusion process on a network:

- Phase transitions
- Equilibrium
- ...

Network Topology

Many systems can be modelled as networks:

* Biological systems / reactions
* Electrical grids
* Technological networks
* Bibliographical networks
* Internet
* Social networks

Networks are not like regular lattices

* Hierarchical structure
* Presence of “hubs”
* Show power-law distributions
* Can be dynamic
* (Un)directed

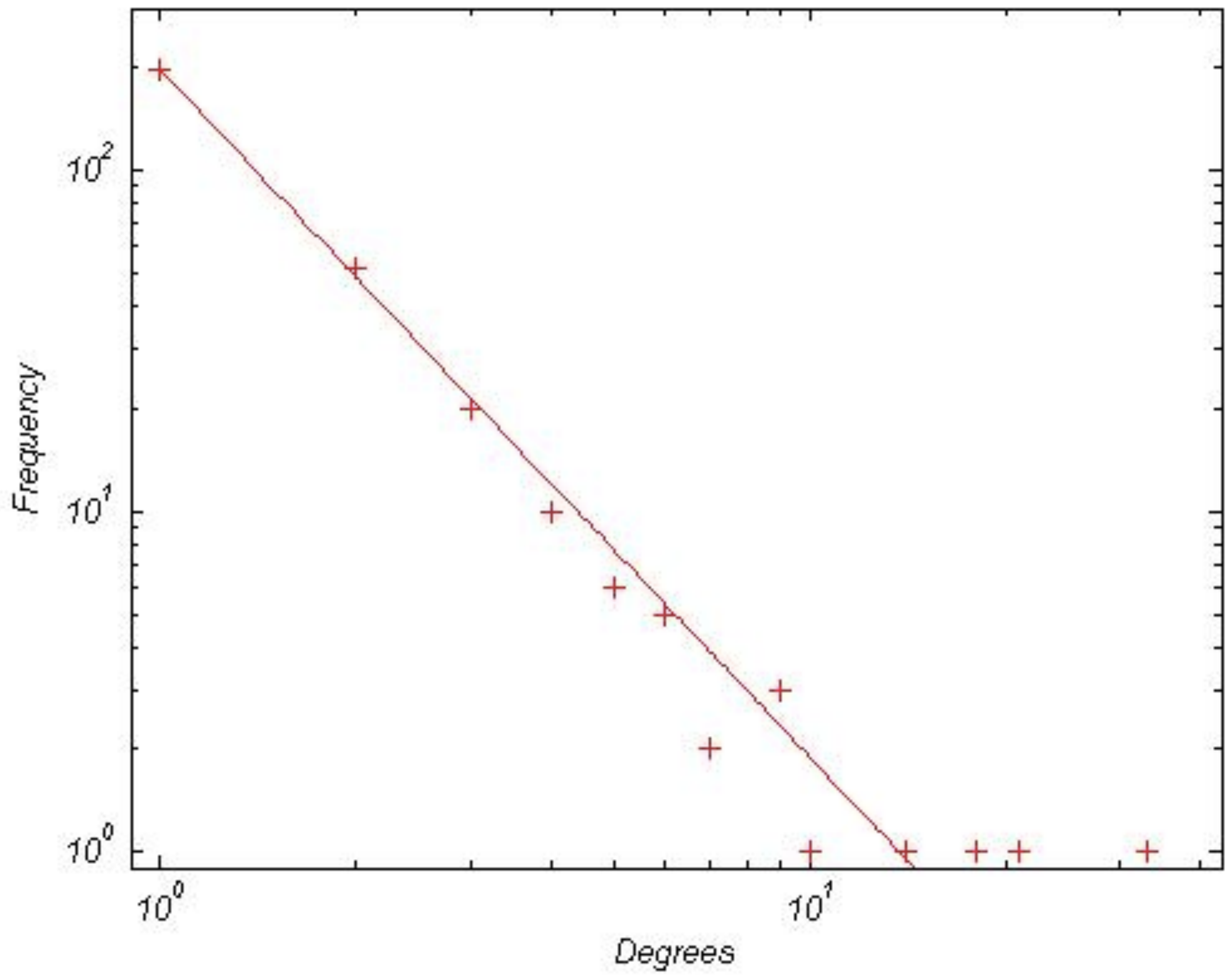
Relevant: contacts are not random

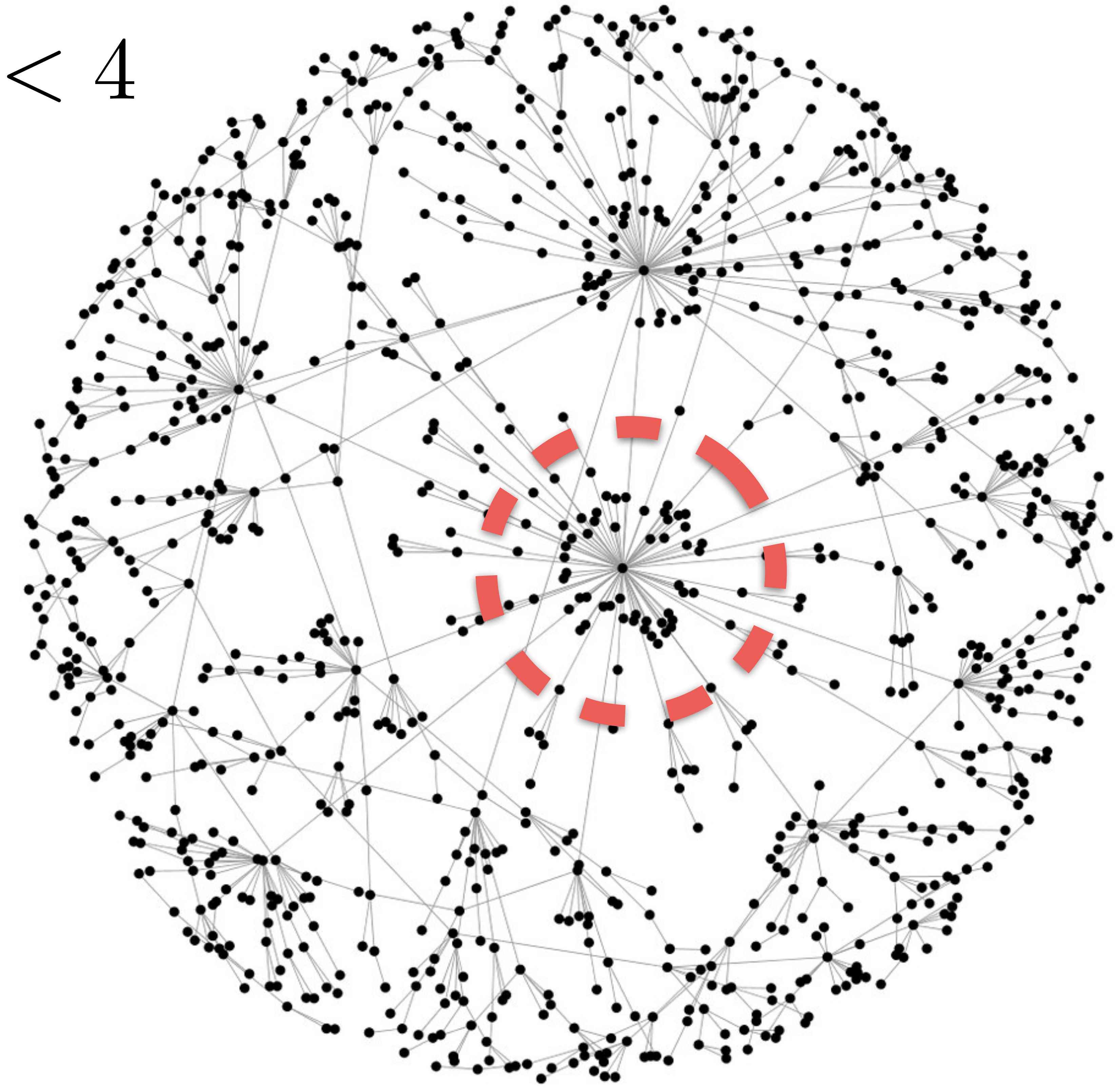
Can implement behavioural feedback (“rewiring”)

Scale-free Networks

Social networks (among many others) <u>seem</u>* to be "scale-free" networks or at least they exhibit "fat tails": high-order vertices are not rare.

Scale-free networks: $P(k) \sim k^{-\alpha}$ $\quad 2 < \alpha < 4$





High degree nodes are not so rare!

(*) https://arxiv.org/pdf/1801.03400.pdf

Epidemics on Scale-free Networks

How can we use the knowledge of the network topology for developing an efficient immunization strategy?

Random immunization:

$$g(\lambda) = 1 - \frac{\langle k \rangle}{\lambda \langle k^2 \rangle}$$

Immunization threshold

Targeted immunization: target a fraction gN of nodes with highest degree

$$g(\lambda) \sim e^{-\frac{2}{m\lambda}}$$

Immunization threshold

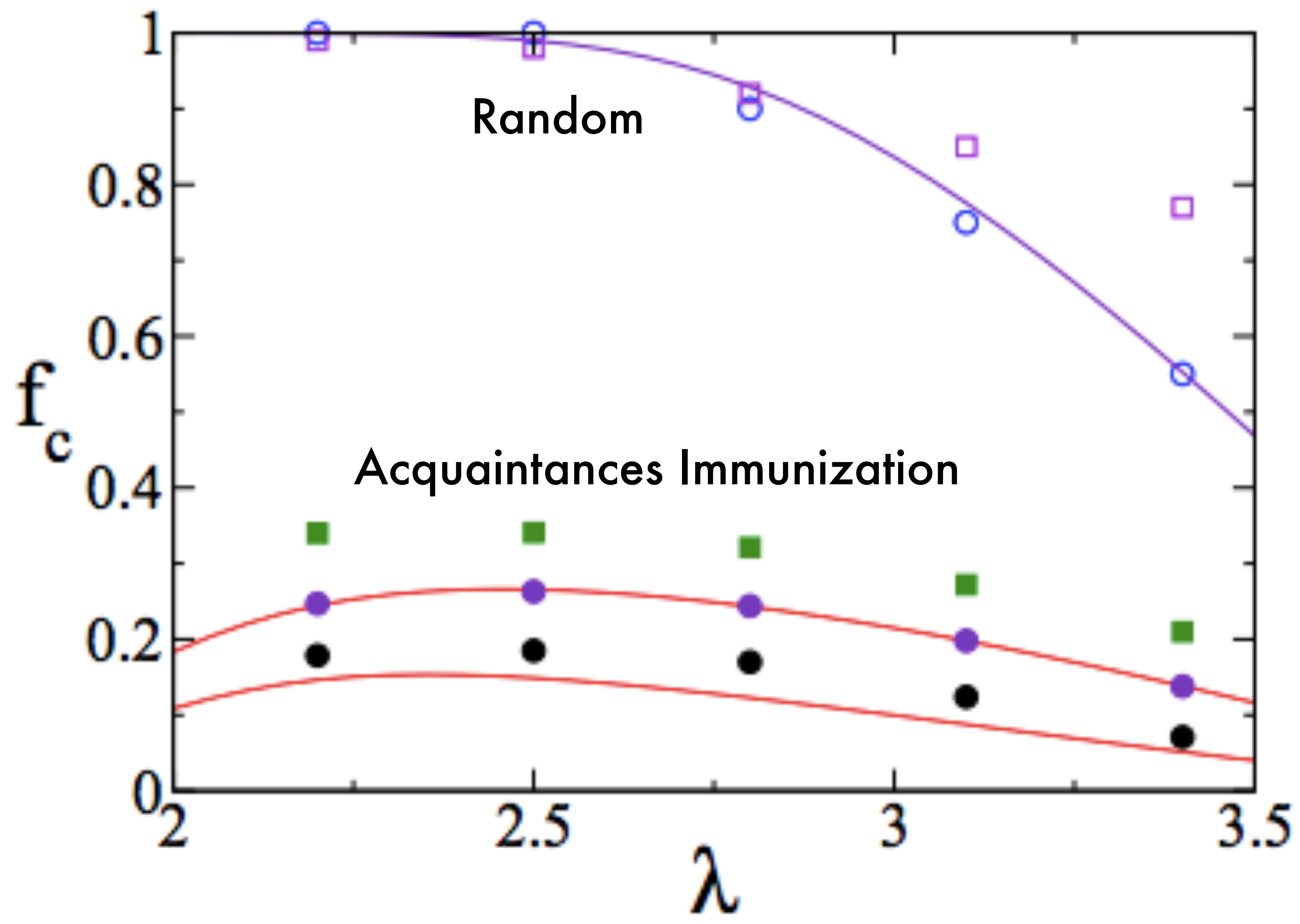
For scale-free networks with γ=3 and m=min degree

Social networks seem to be "heavy tailed" –> target the most connected nodes (targeted immunization). Problem: how to know the network topology?

A strategy w/o knowledge of the topology

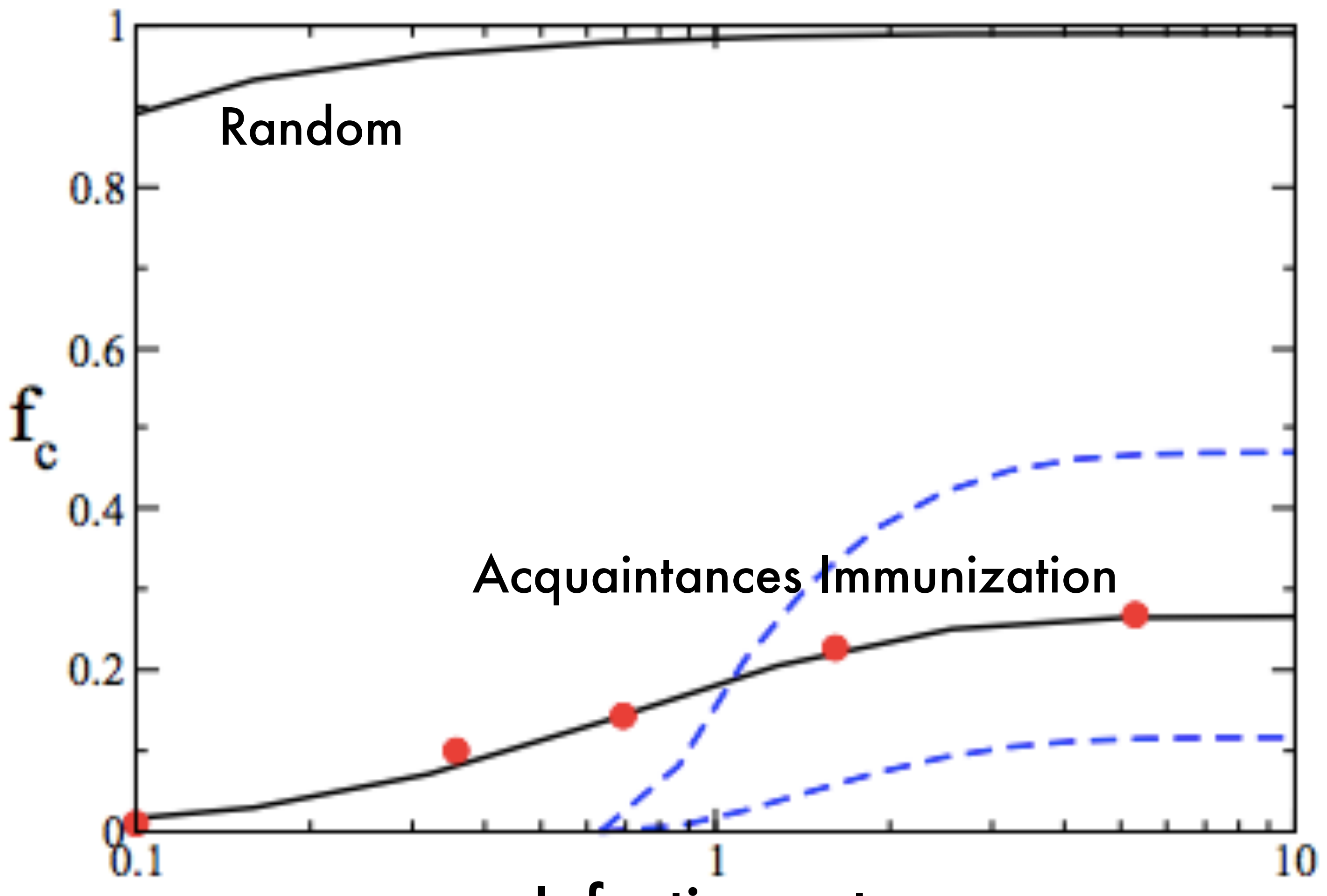
Efficient Immunization Strategies for Computer Networks and Populations

Reuven Cohen *,[1] Shlomo Havlin,[1] and Daniel ben-Avraham[2]
[1] *Minerva Center and Department of Physics, Bar-Ilan University, Ramat-Gan, 52900, Israel*
[2] *Department of Physics, Clarkson University, Potsdam NY 13699-5820, USA*



Select a random node set
Ask these nodes to "point" towards their acquaintances
With high probability they will point towards high-degree nodes
Immunize the acquaintance.

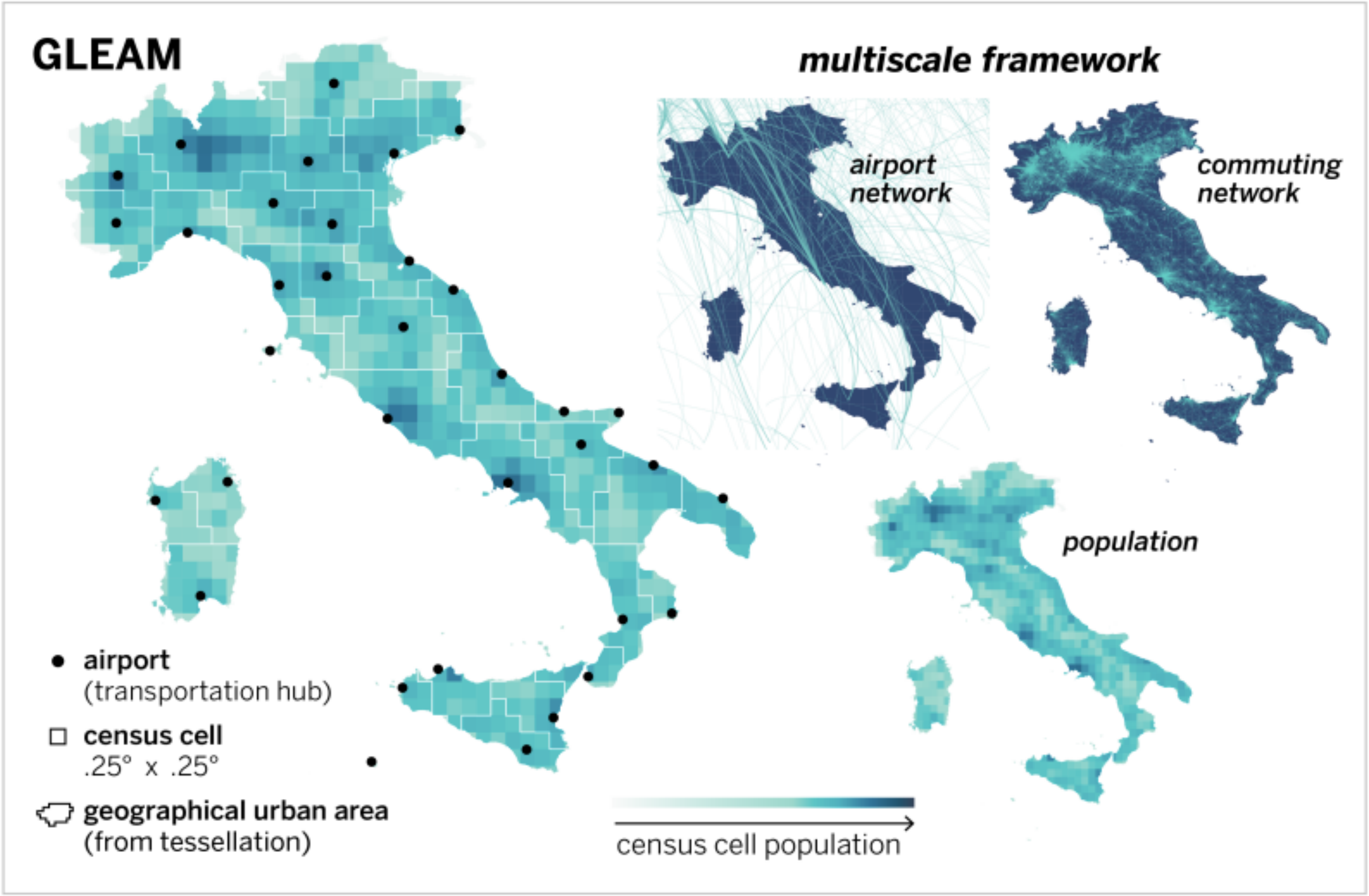
LOCAL strategy: does not require knowledge of the network: the topology is "reconstructed" by pointing.

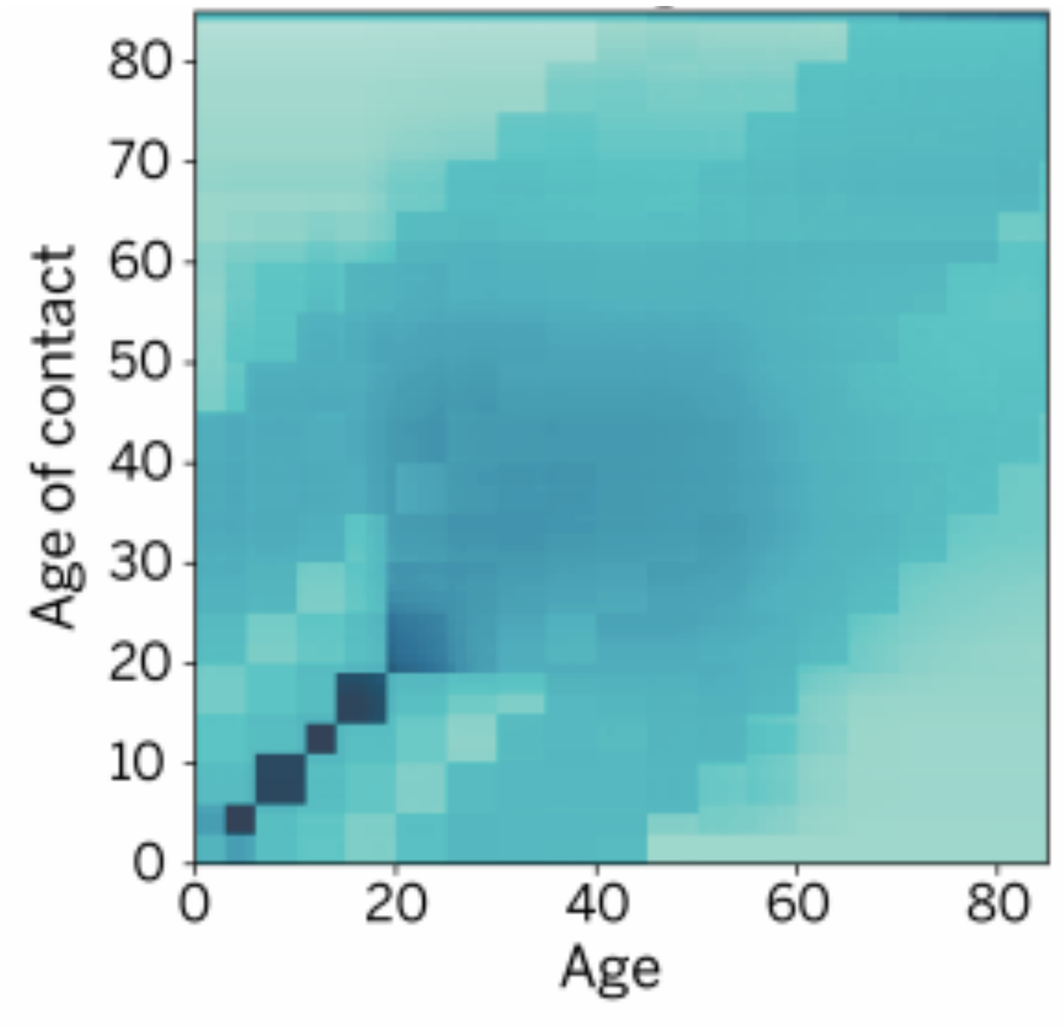


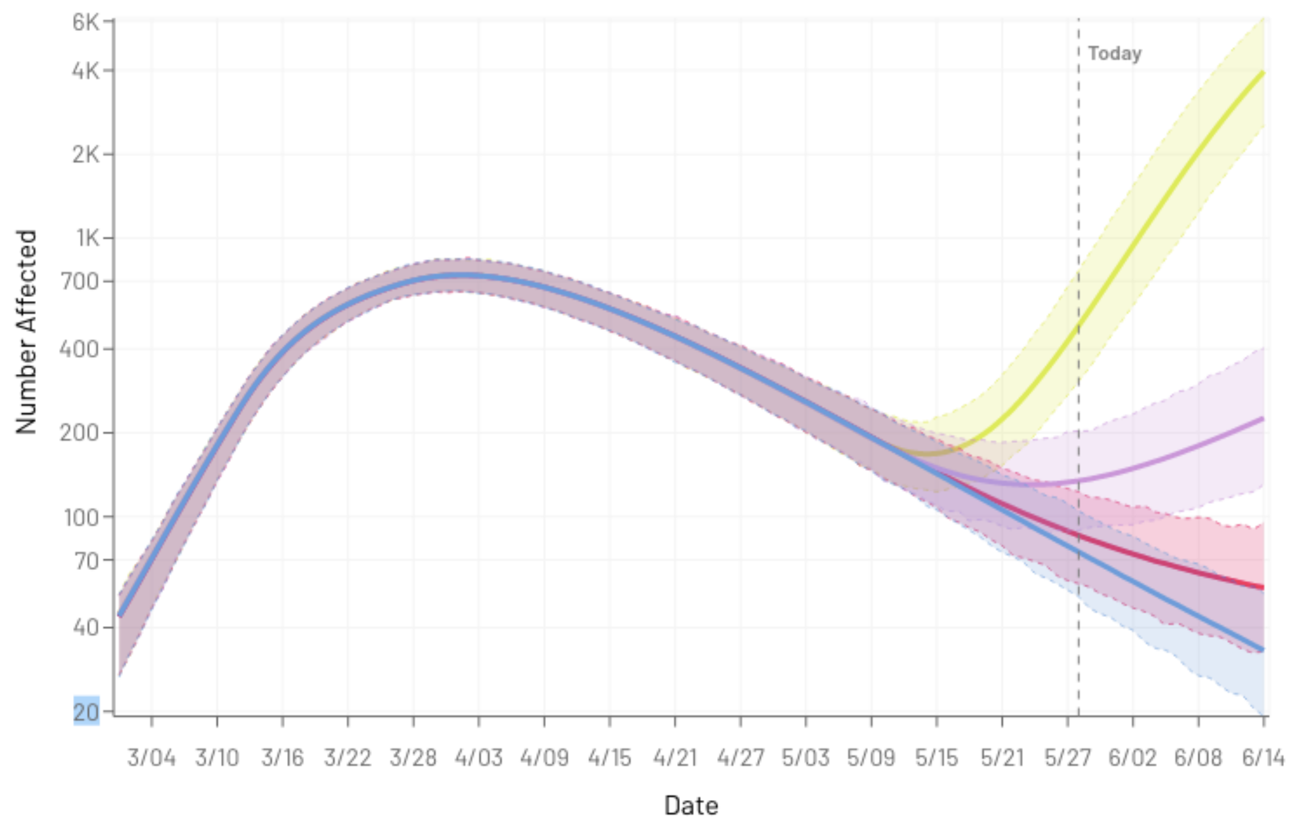
f_C: immunization threshold (for stopping the epidemic)

A state-of-the-art Network Model (GLEAM)

Global Epidemic and Mobility Model

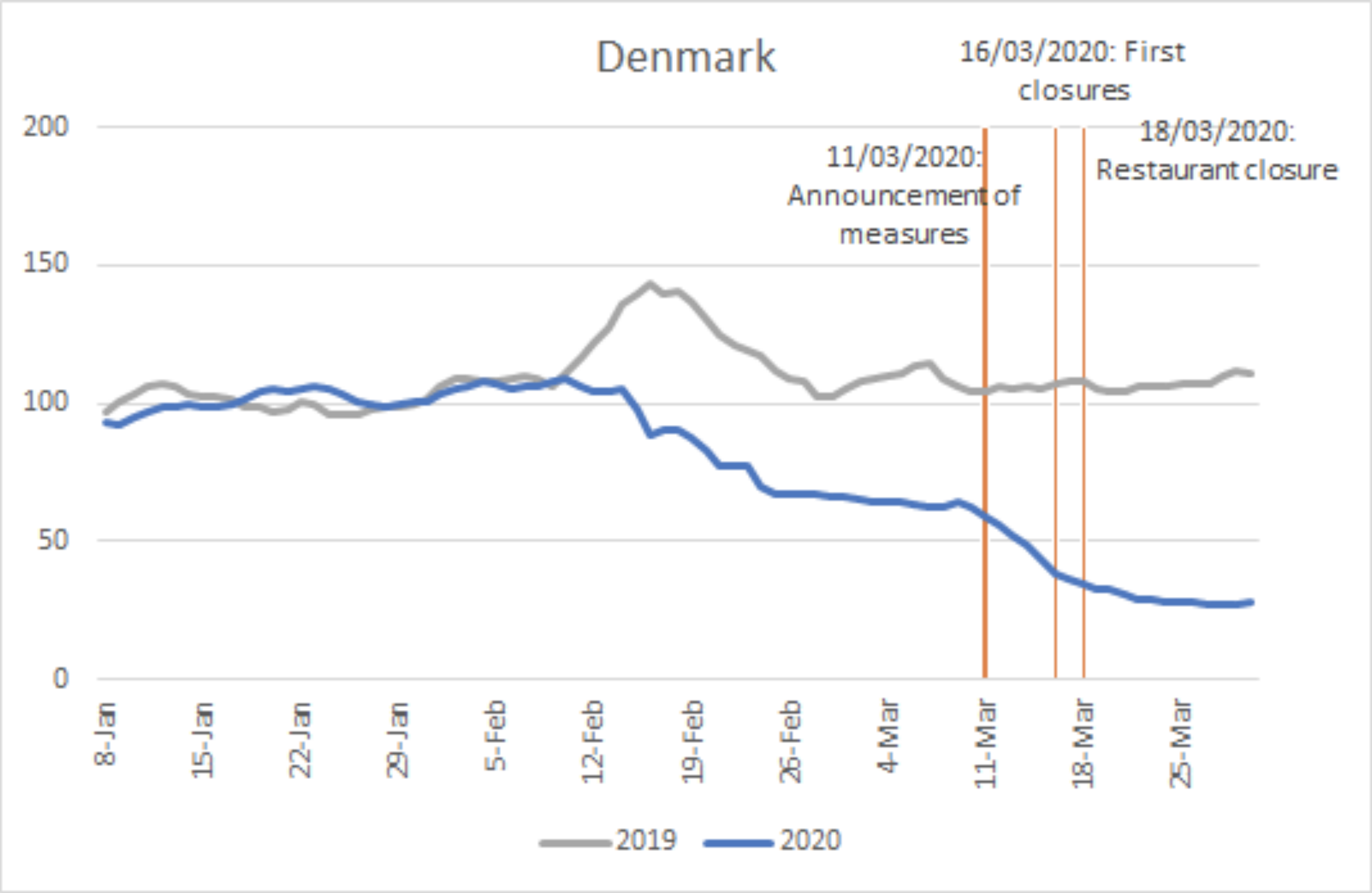






https://covid19.gleamproject.org/

Further challenges: modelling social behaviour



https://www.bruegel.org/2020/04/social-distancing-did-individuals-act-before-governments/

Catarina Midões (Oxera)

Experimental Effort:
From Dark Matter to Ventilators

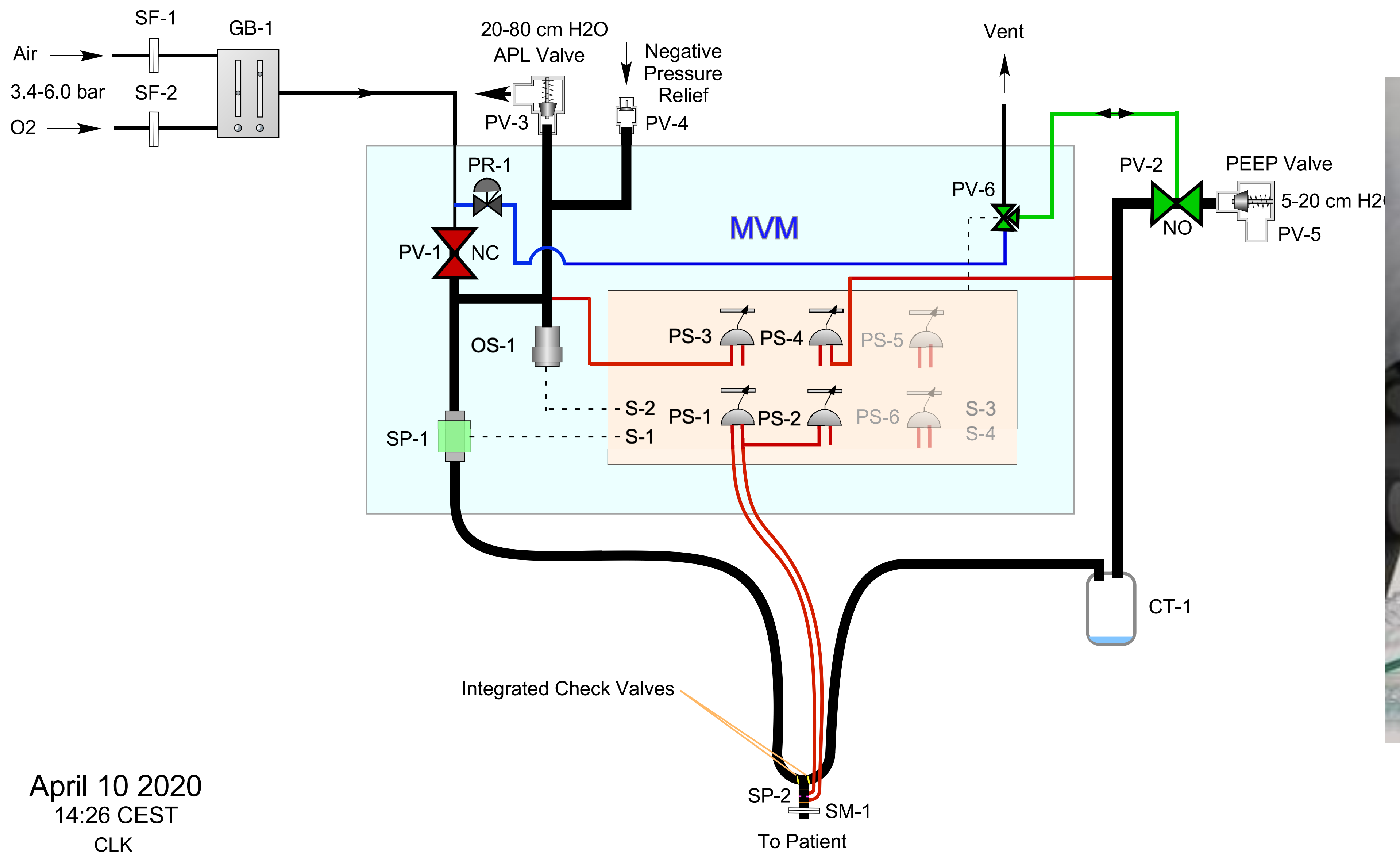
The Project

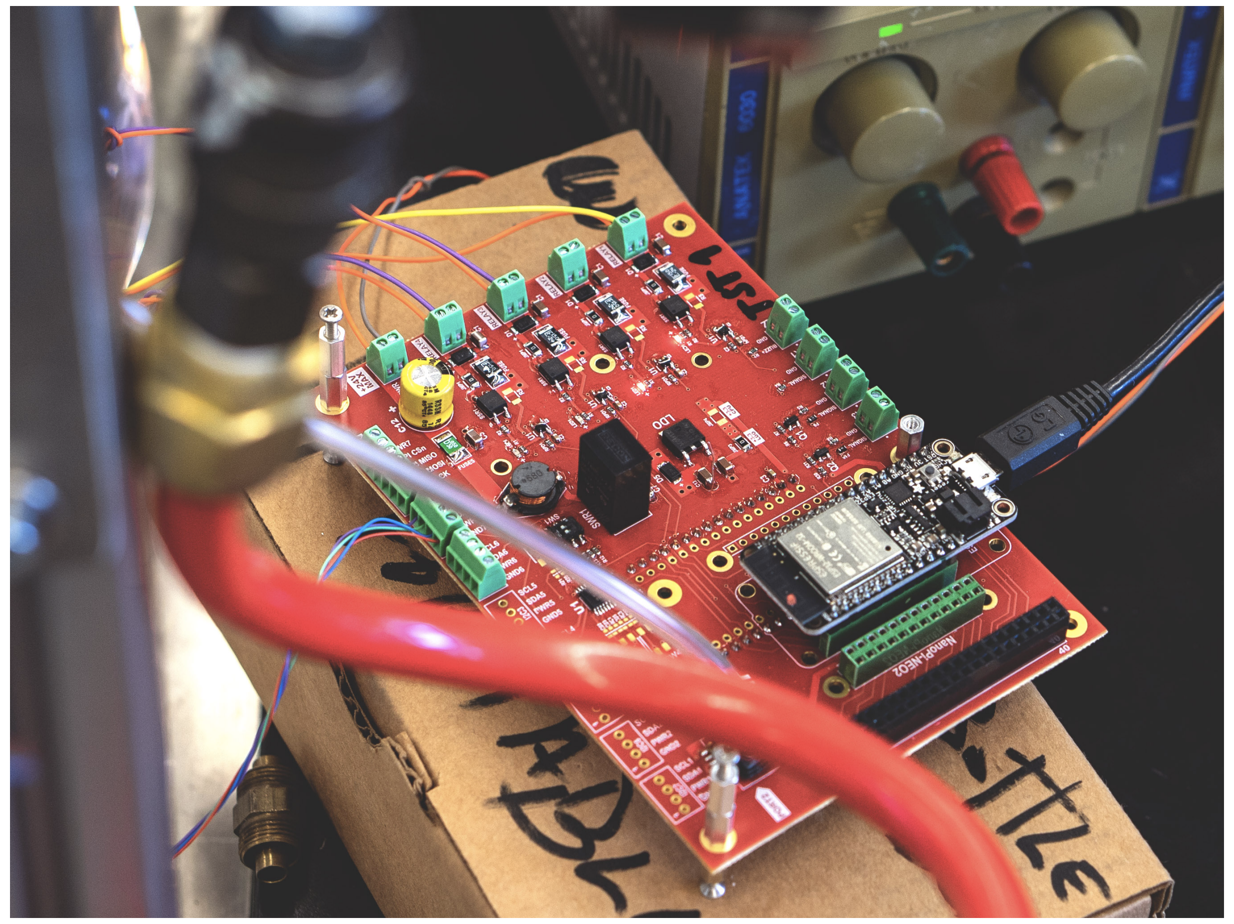
MILANO VENTILATORE MECCANICO

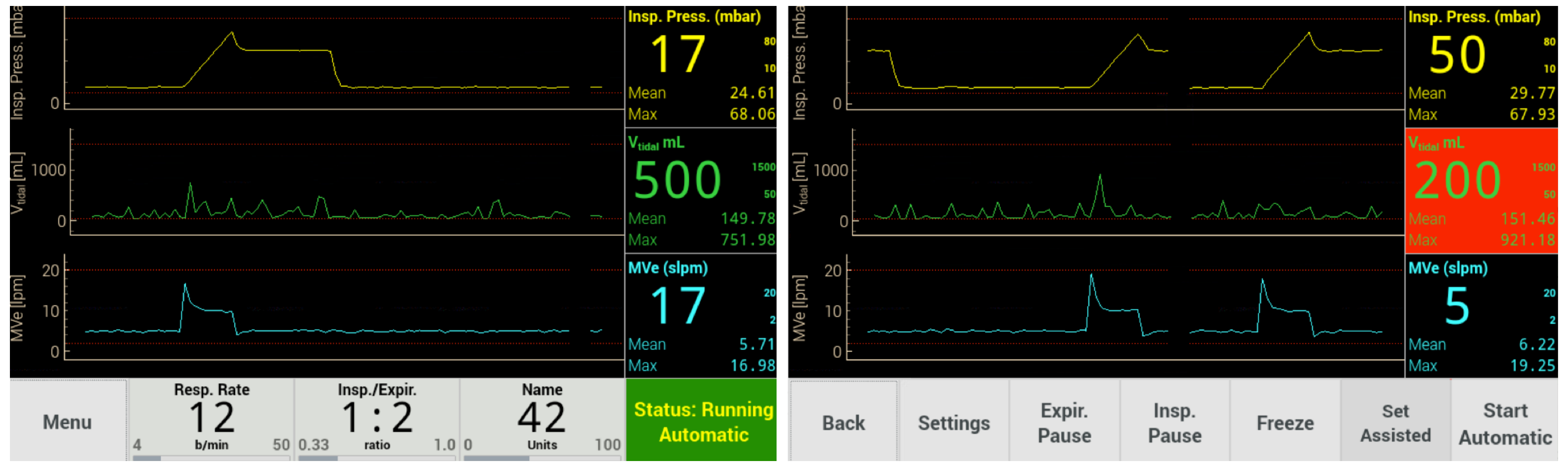
**Mechanical Ventilator Milano (MVM):
A Novel Mechanical Ventilator Designed for Mass Production in Response to the COVID-19 Pandemic**

https://arxiv.org/pdf/2003.10405.pdf

MVM (Mechanical Ventilator Milano)



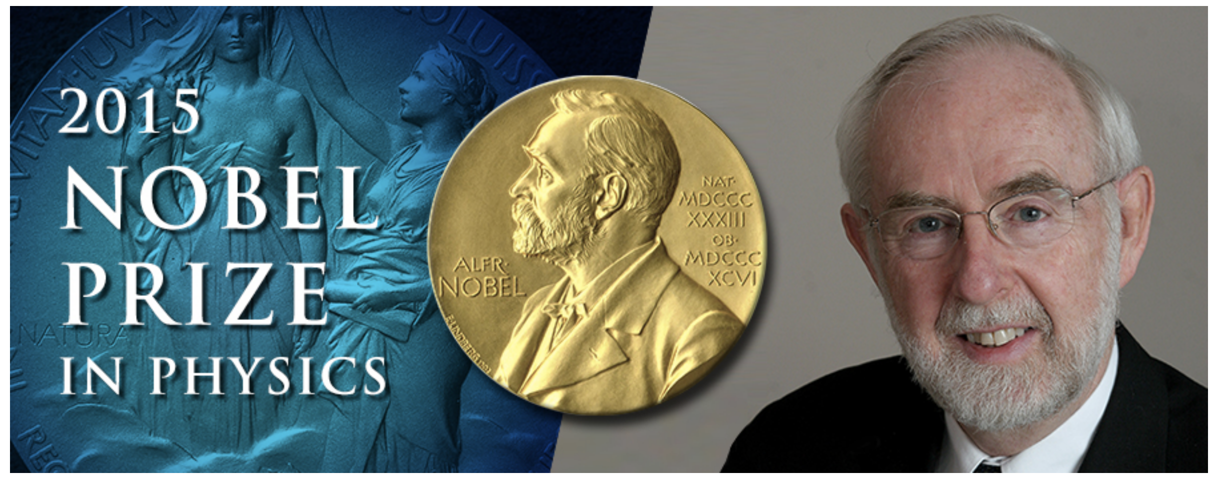




* Designed for rapid mass production:made with off-the-shelf parts.
* Based on R. Manley (1930–1991) ventilator design: reliability.
* Optimal use of supply chain for parts
* International availability
* Minimal requirements: electricity and O_2 source
* Optimized for COVID-19 patients

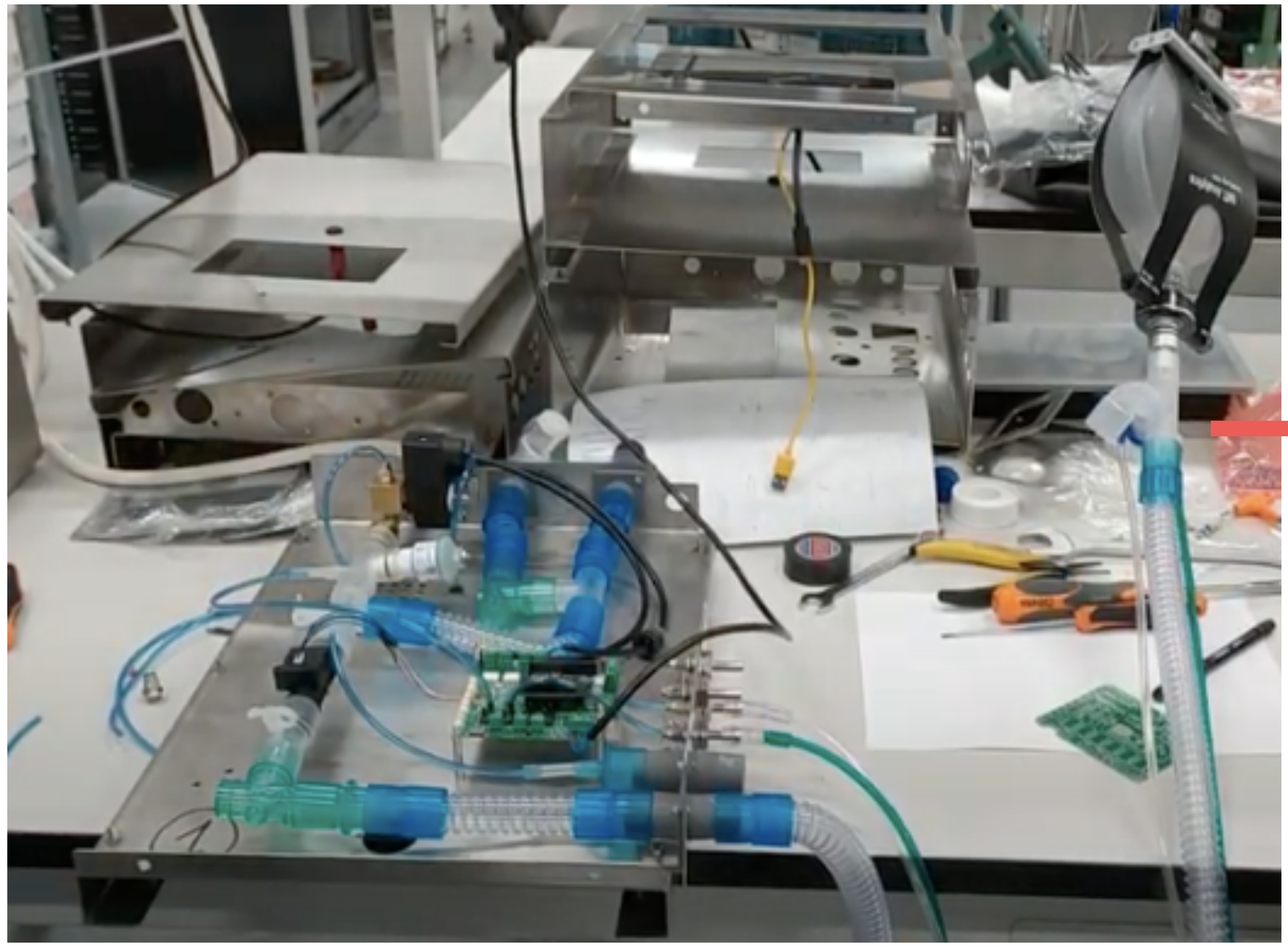
* Started by C. Galbiati (Princeton and Gran Sasso Institute, spokesperson DarkSide Collaboration)

MVM: Model exported to other countries



"A project like this wasn't in my plans. But COVID-19 has changed a lot of people's plans. I'm very pleased to be working on it."
A. McDonald (Queen's U. Canada), 2015 Nobel laureate

TRIUMF



Canadian Nuclear Laboratories
Laboratoires Nucléaires Canadiens

SNOLAB

On May 1, MVM received approval from the US Food and Drug Administration
On May 27, Government of Canada signed with VEXOS a 10k units contract

Fermilab

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* Epidemiology: highly interdisciplinary field
* Mathematical modelling plays a major role
* Highlighted (only some) contributions coming from physics
* Valuable for policy makers
* Challenges: (dynamical) network of contacts, human behaviour

* Activity present also on the experimental side!

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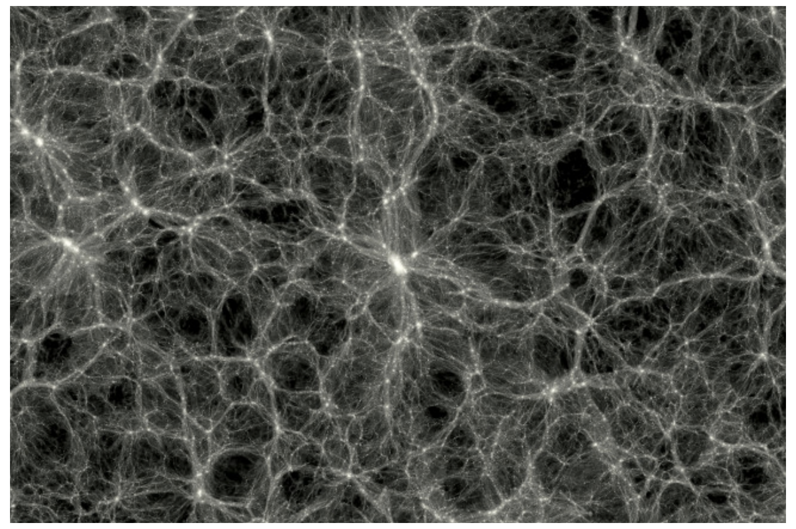

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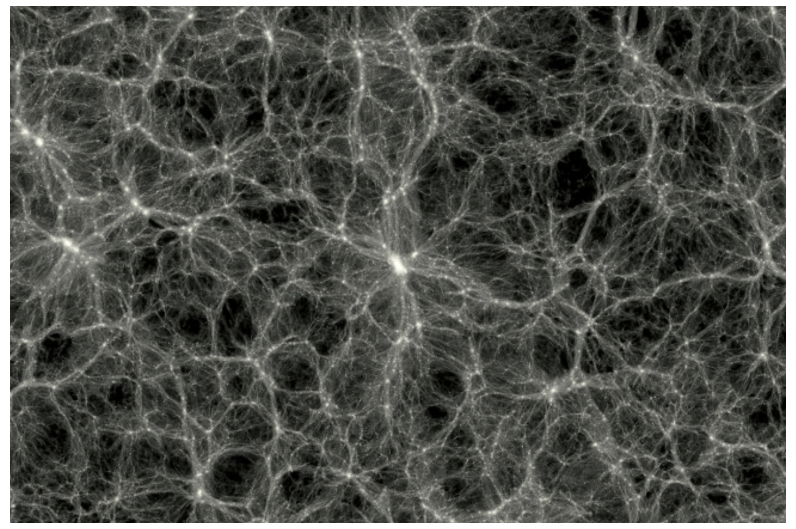

High value of fundamental physics research

Danke für Ihre Aufmerksamkeit!

Thank you for your attention!