The Evolutionary Vaccination Dilemma in Complex Networks

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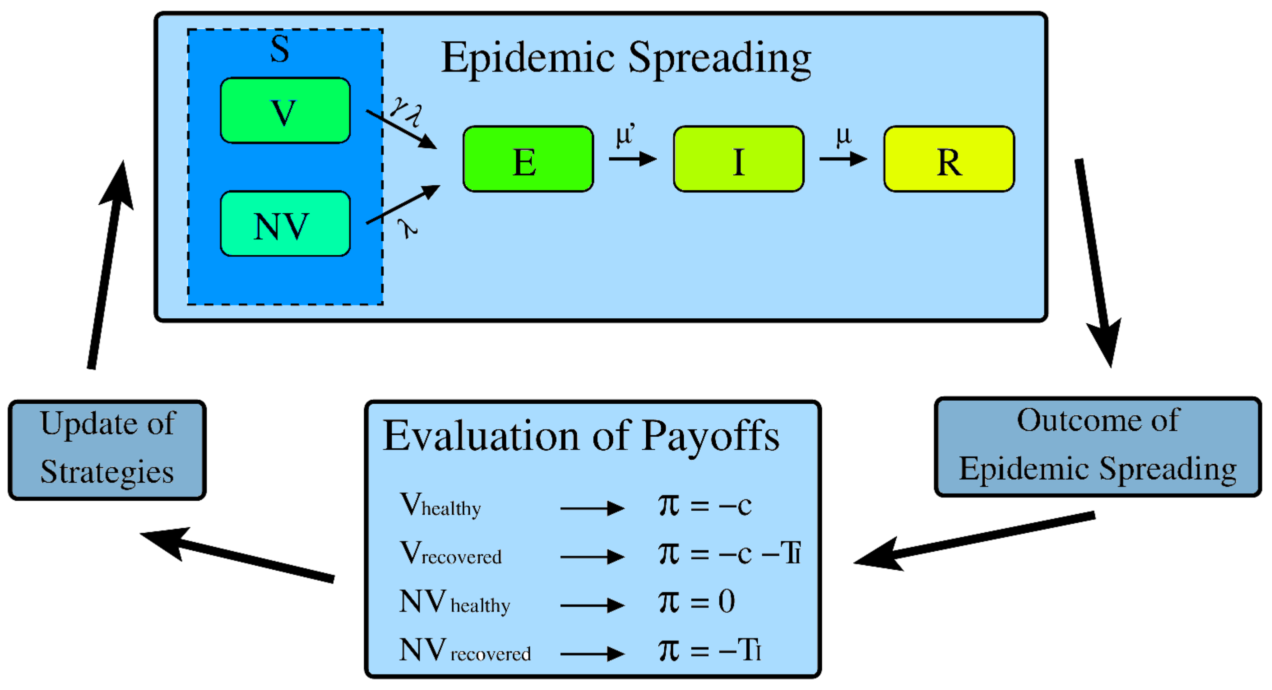
Motivation

The success of a vaccination campaign relies – among the many things – on the voluntary decision of individuals to take the vaccine. So, an individual who decides to get immunized is performing an act of *cooperation* towards the whole population because his/her decision implies a reduction in the probability of an epidemic outbreak. Here, we analyze the evolution of voluntary vaccination in networked populations by entangling the spreading dynamics of an influenza-like disease (encoded in a **Susceptible-Exposed-Infected-Recovered** (SEIR) model), with an evolutionary framework taking place at the end of each influenza season so that individuals take or not the vaccine upon their previous experience. To this aim, one may consider game theory to formulate a social dilemma in terms of the benefits associated to each of the behaviors: vaccination or not. The bi-dynamical process is run on a population of agents displaced on the nodes of a scale-free and homogeneous network. Our framework thus put in competition two well-known dynamical properties of scale-free networks: the fast propagation of diseases and the promotion of cooperative behaviors.

Model

1. Each of the agents is set with a given strategy s and an health state x. Then, a *SEIR propagation* is performed until no Infected subjects are present.
2. Assignation to each of the N individuals a payoff π_i ($i = 1, \dots, N$) that depends on their experience accumulated during the last SEIR propagation. Afterwards, agents evolve their strategies based on their previous experience.



$\lambda \longrightarrow$ Sane to Exposed prob.
$\gamma \longrightarrow$ vaccine quality $\in [0,1]$
$\mu \longrightarrow$ Exposed to Infected prob.
$\mu' \longrightarrow$ Infected to Recovered prob.
$\pi \longrightarrow$ payoff of agent
$c \longrightarrow$ vaccine cost $\in [0,1]$
$T_I \longrightarrow$ time units in infected state

Epidemic Spreading: The transition probabilities of an agent i, P^i, between the Susceptible and Exposed state in the Non-Vaccinated and Vaccinated cases are given by:

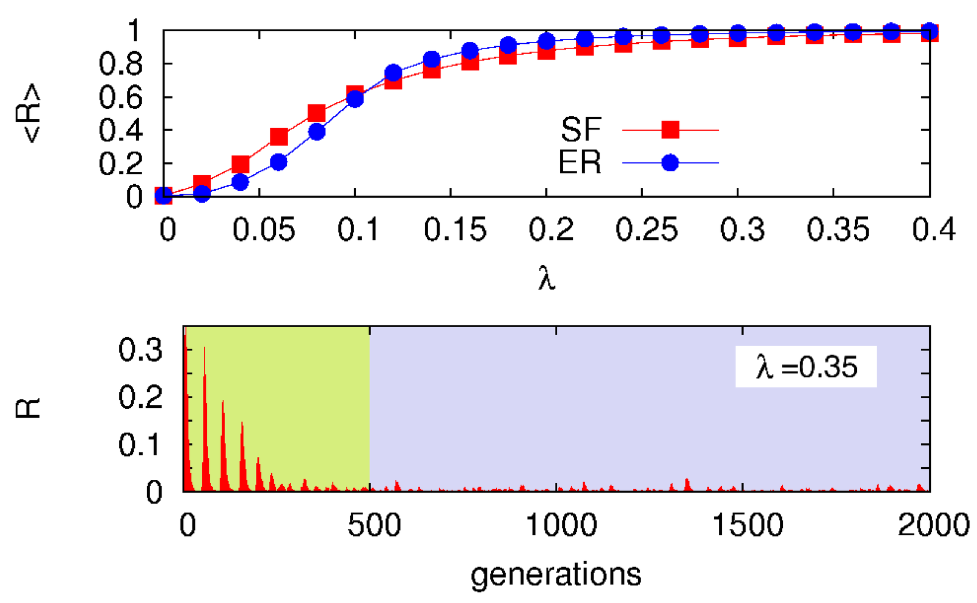
$$P^i_{S\to E} = 1 - (1-\lambda)^{\sum_{j=1}^{N} A_{ij} x_j}, \quad (1)$$

$$P^i_{S\to E} = 1 - (1-\gamma\cdot\lambda)^{\sum_{j=1}^{N} A_{ij} x_j}. \quad (2)$$

Vaccination Dilemma: The payoff scheme displayed above put the agents under a *Vaccination Dilemma*. To update their strategies, agents use the so-called *Fermi Rule* which mimics a not fully rational behavior:

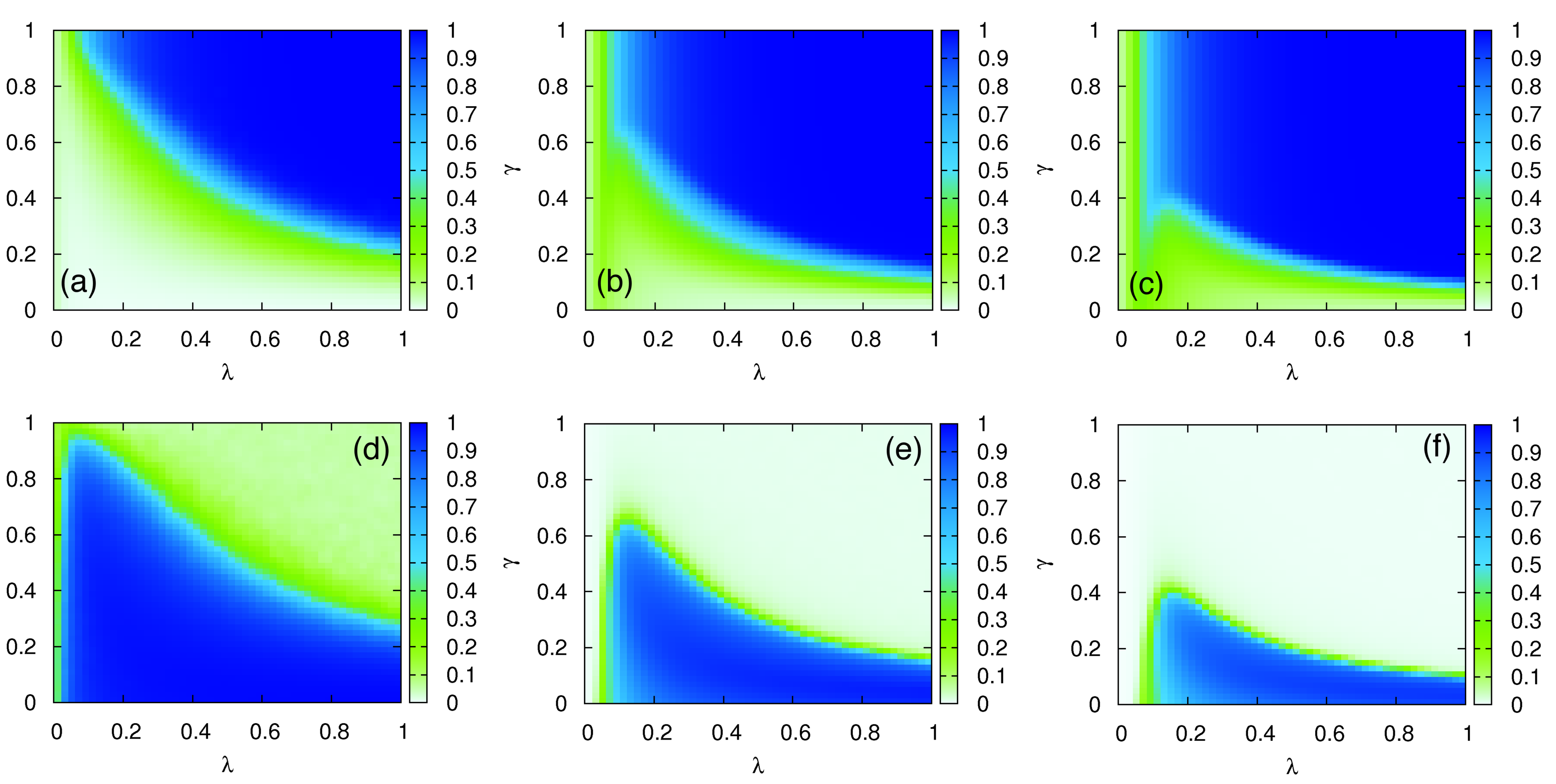
$$P_{s_j \to s_i} = \frac{1}{1+\exp\left[-\beta(\pi_j - \pi_i)\right]}, \quad (3)$$

Network Topologies: We will consider two of the most paradigmatic network models: Erdős-Rényi (ER) graphs and Barabási-Albert scale-free (SF) networks. In both cases we fix the size and the average degree.



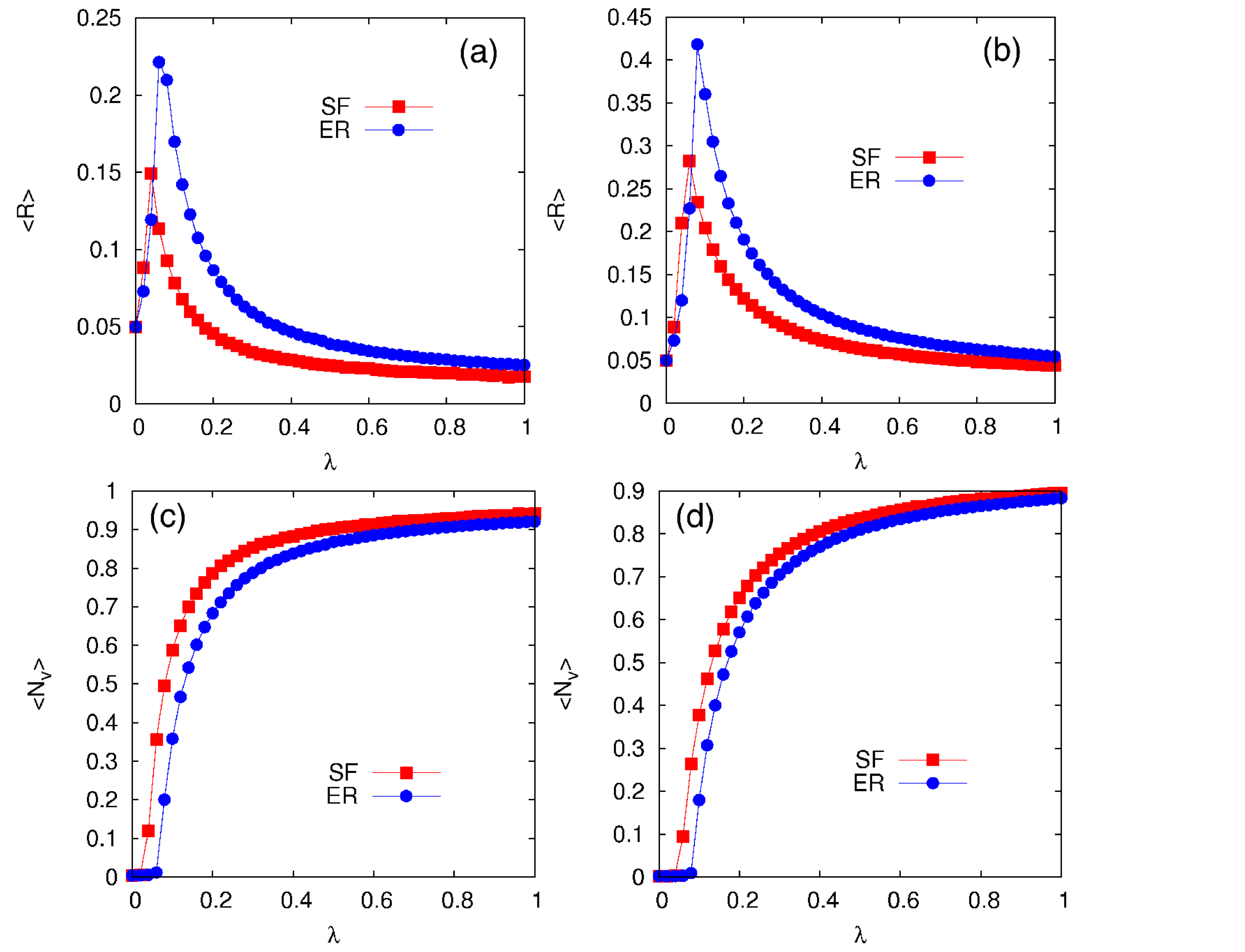
Macroscopic Behavior in SF networks

The macroscopic behavior of the system is well described by the average fraction of Recovered (top) $\langle R\rangle$, and Vaccinated (bottom), $\langle N_V\rangle$, individuals. Here, we display those quantities as a function of the infection probability λ and the vaccine quality γ for SF networks.



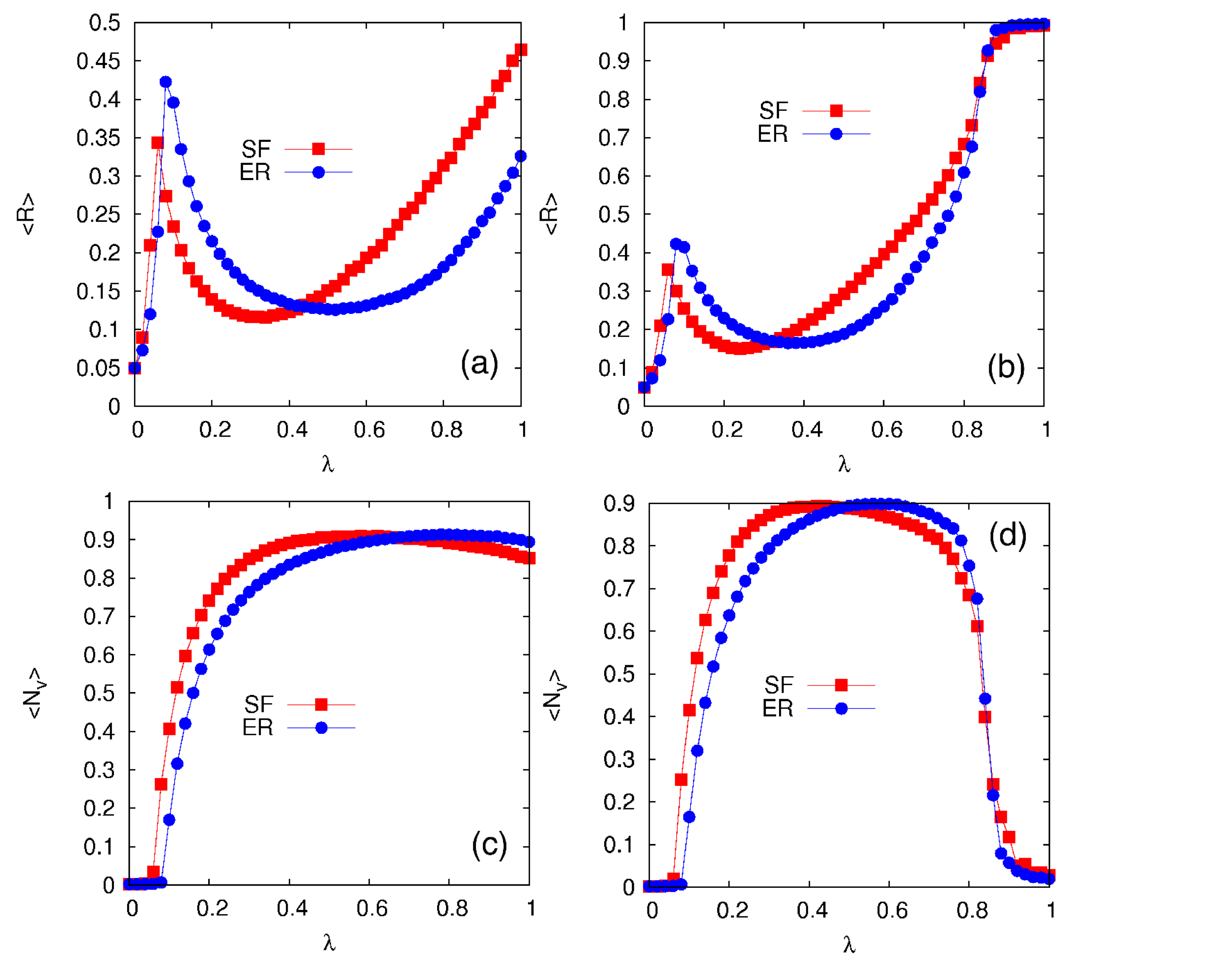
Microscopic Behavior – Perfect vaccine ($\gamma = 0$)

The microscopic behavior of the system can be illustrated through the epidemic $R(\lambda)$ (top) and vaccination $N_V(\lambda)$ (bottom).



Microscopic Behavior – Imperfect vaccine ($\gamma \neq 0$)

Epidemic $R(\lambda)$ (top) and Vaccination $N_V(\lambda)$ (bottom) diagrams for ER and SF networks when the vaccine is not perfect ($\gamma = 0.12$).



Conclusions

Perfect vaccine:

- Scale-free networks enhance both the vaccination behavior and the effective immunization of the population as compared with random graphs with homogeneous connectivity patterns.

Imperfect vaccine:

- For scale-free networks and low vaccine costs, there is a threshold value for the vaccine imperfection so that, for values lower than this threshold, vaccination behavior spans across the population and it is possible to suppress the disease for all the infection probabilities. Instead, when vaccine imperfection becomes large, agents are less prone to take it and the disease takes advantage of this risky behavior to spread more efficiently across the population.
- When imperfection appears, the better performance of scale-free network is broken and there is a crossover effect so that the number of infected (vaccinated) individuals increases (decreases) with respect to homogeneous networks when the probability of infection is large enough.

Bibliography

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