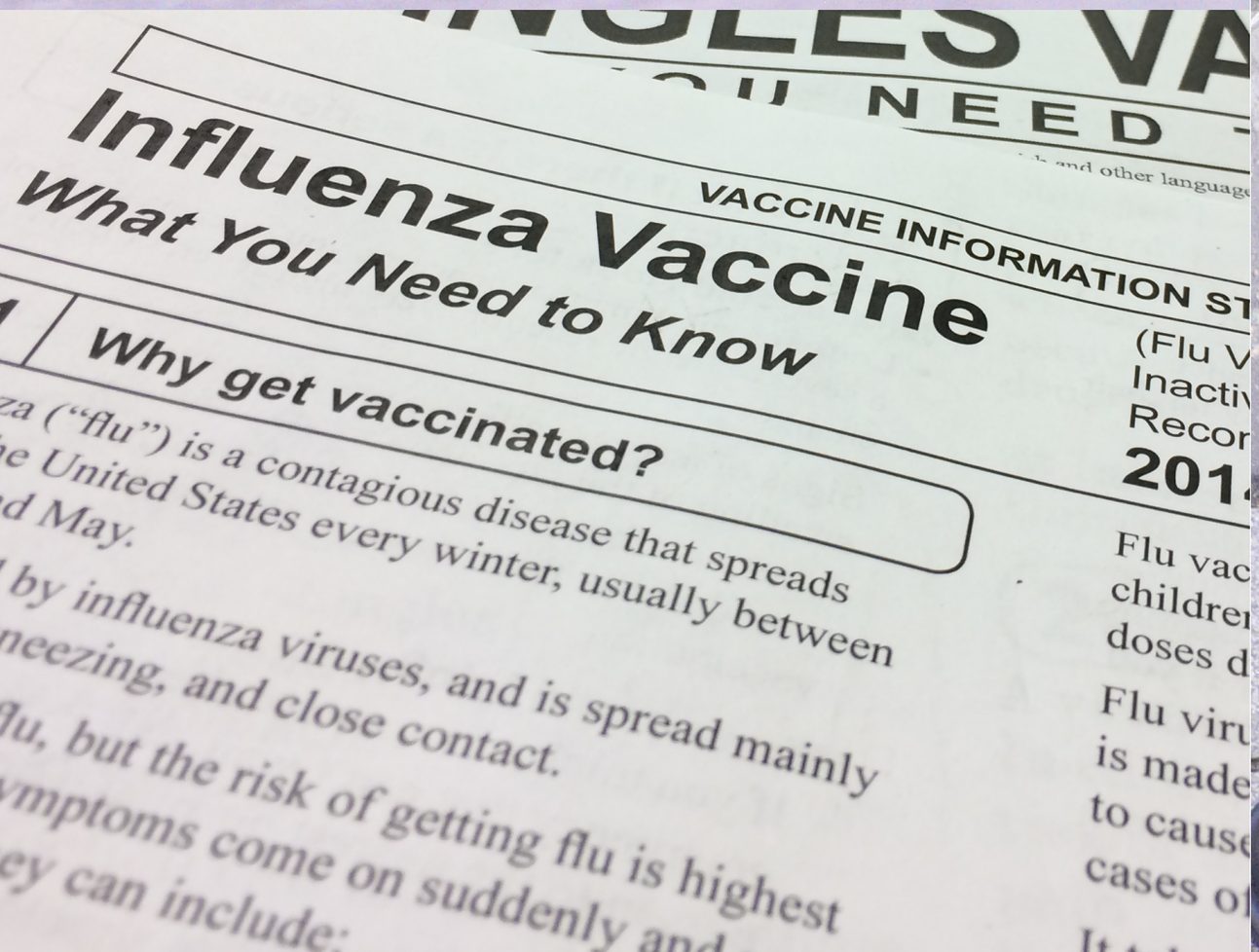
Can seasonal influenza be eradicated under voluntary vaccination?

Irena Papst, M.Sc.
PhD Candidate, Center for Applied Mathematics, Cornell University
April 6, 2018

Kevin O'Keeffe

Steven Strogatz


Influenza Vaccine
What You Need to Know
VACCINE INFORMATION ST
Why get vaccinated?
za ("flu") is a contagious disease that spreads
e United States every winter, usually between
d May.
by influenza viruses, and is spread mainly
neezing, and close contact.
lu, but the risk of getting flu is highest
mptoms come on suddenly and
ey can include:
Flu vac
childre
doses d
Flu viru
is made
to cause
cases o


it's that time again...
The Grand National: Page 61
www.metro.co.uk
FREE
Don't pan
BY SUZY AUSTIN

Vaccine coverage

Proportion of the population that is vaccinated

Vaccine coverage

Proportion of the population that is vaccinated

Vaccine coverage

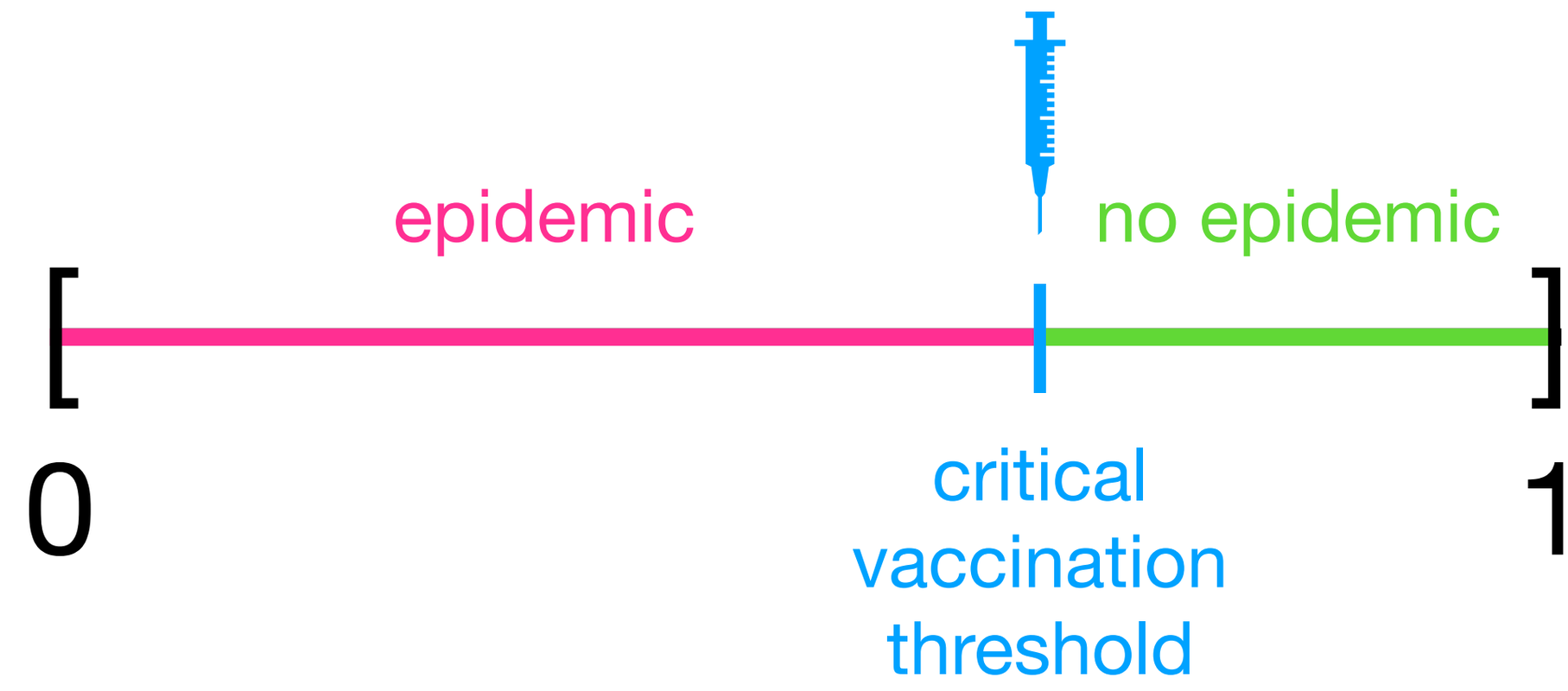
Proportion of the population that is vaccinated

Vaccine coverage

Proportion of the population that is vaccinated

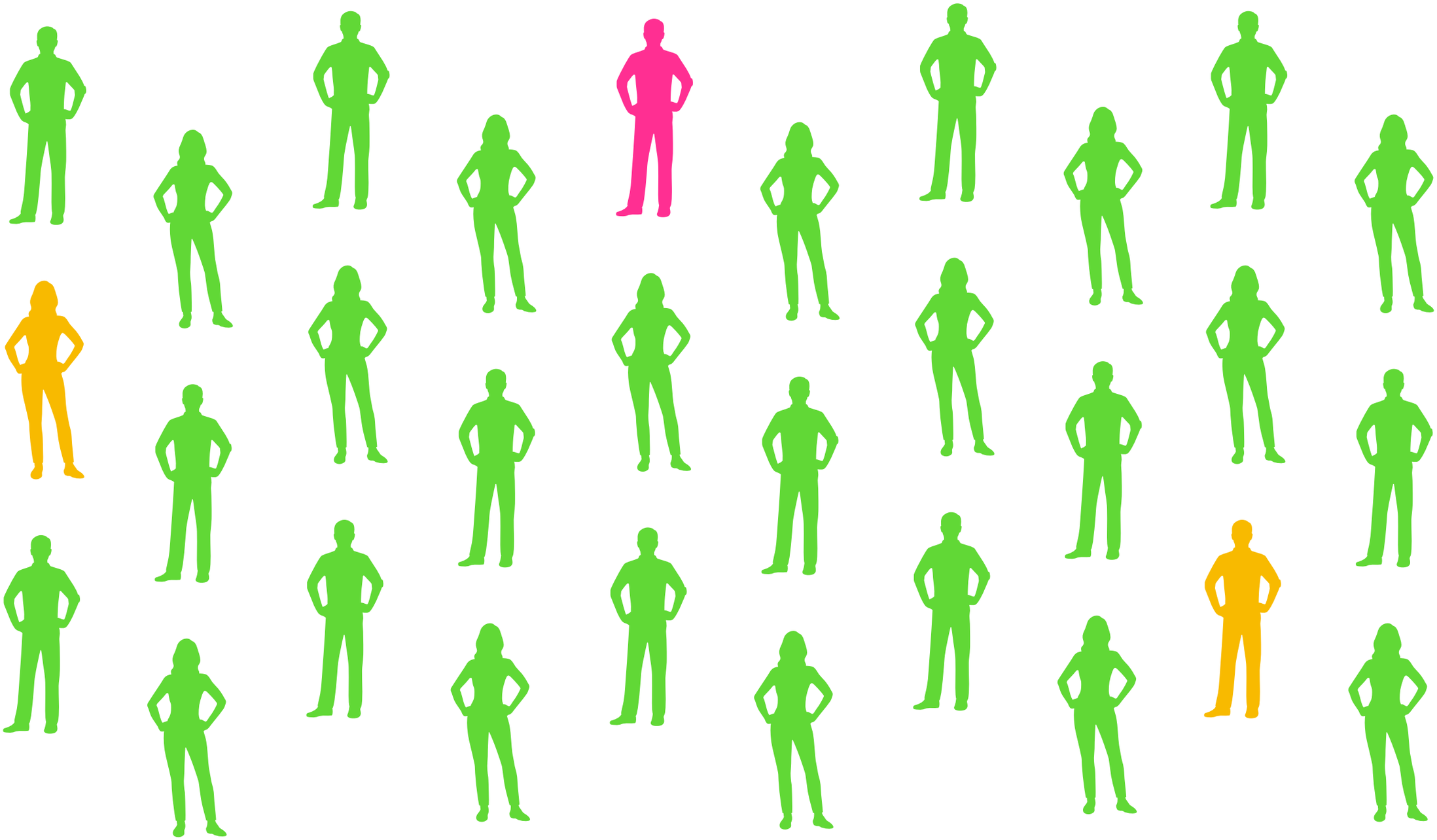
Vaccine coverage

Proportion of the population that is vaccinated



Herd immunity

Herd immunity



Central question

Central question

Can a population
self-organize
into herd immunity?

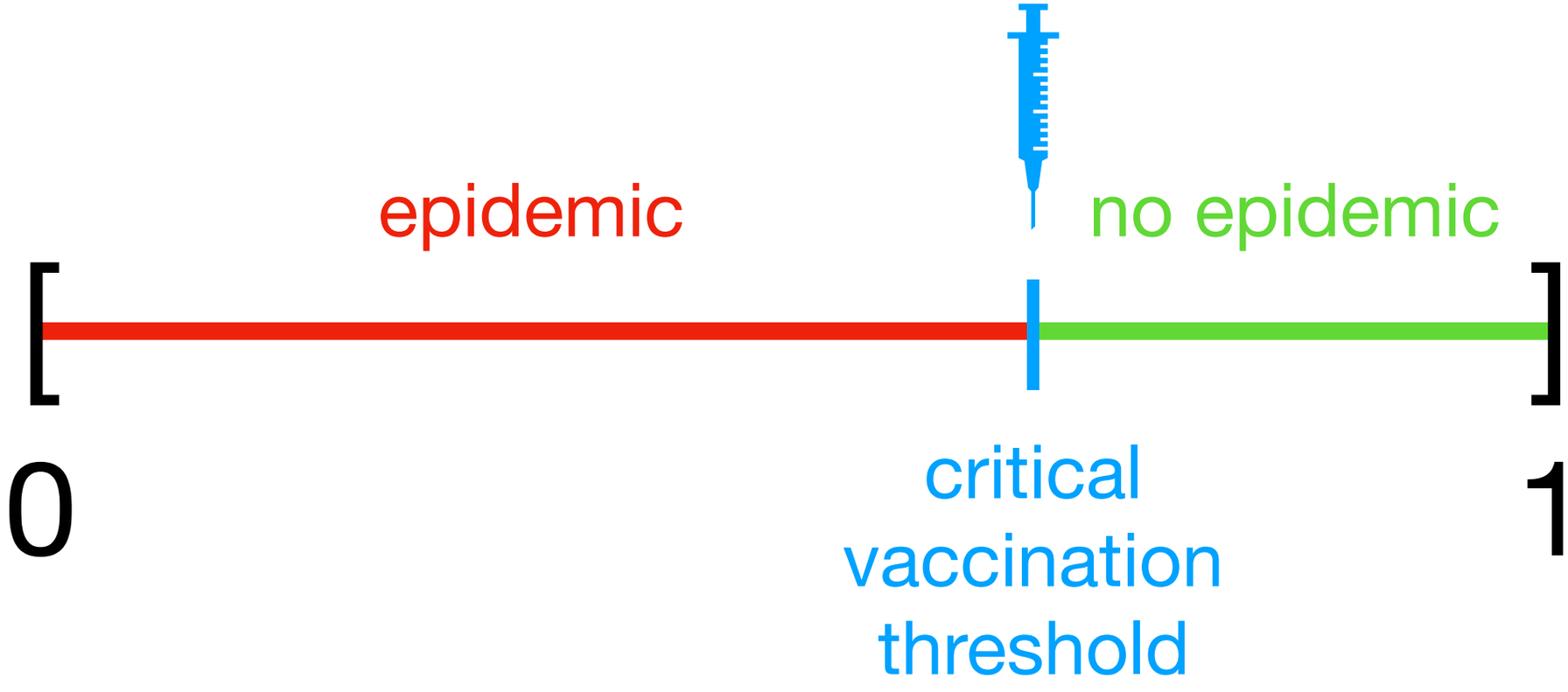
Previous result

Previous result

If there is *any* cost to the vaccine, coverage is suboptimal.

Previous result

If there is *any* cost to the vaccine, coverage is suboptimal.



Previous result

Previous result

- Game-theoretic approach

Previous result

- Game-theoretic approach
- Assumes perfect, global information

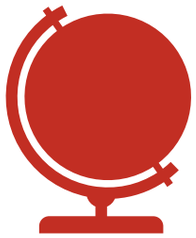
Previous result

- Game-theoretic approach
- Assumes perfect, global information

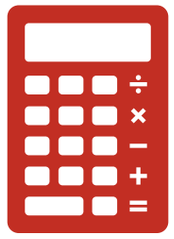
- Probability of getting sick

Previous result

- Game-theoretic approach
- Assumes perfect, global information

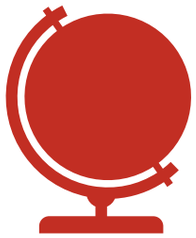


  - Probability of getting sick
- Implicitly involves "rational" behavior

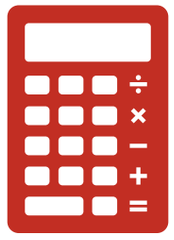


Previous result

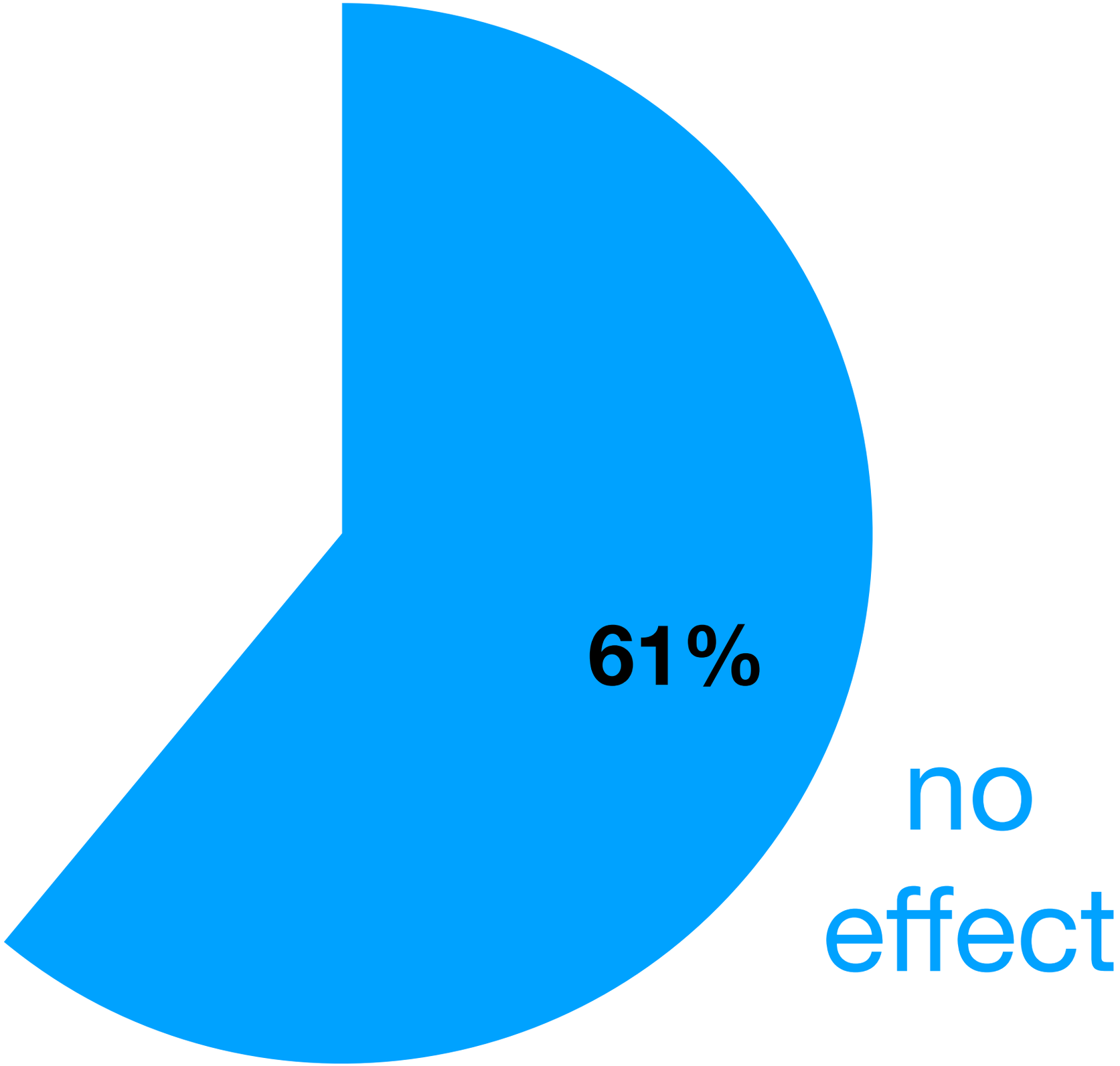
- Game-theoretic approach
- Assumes perfect, global information

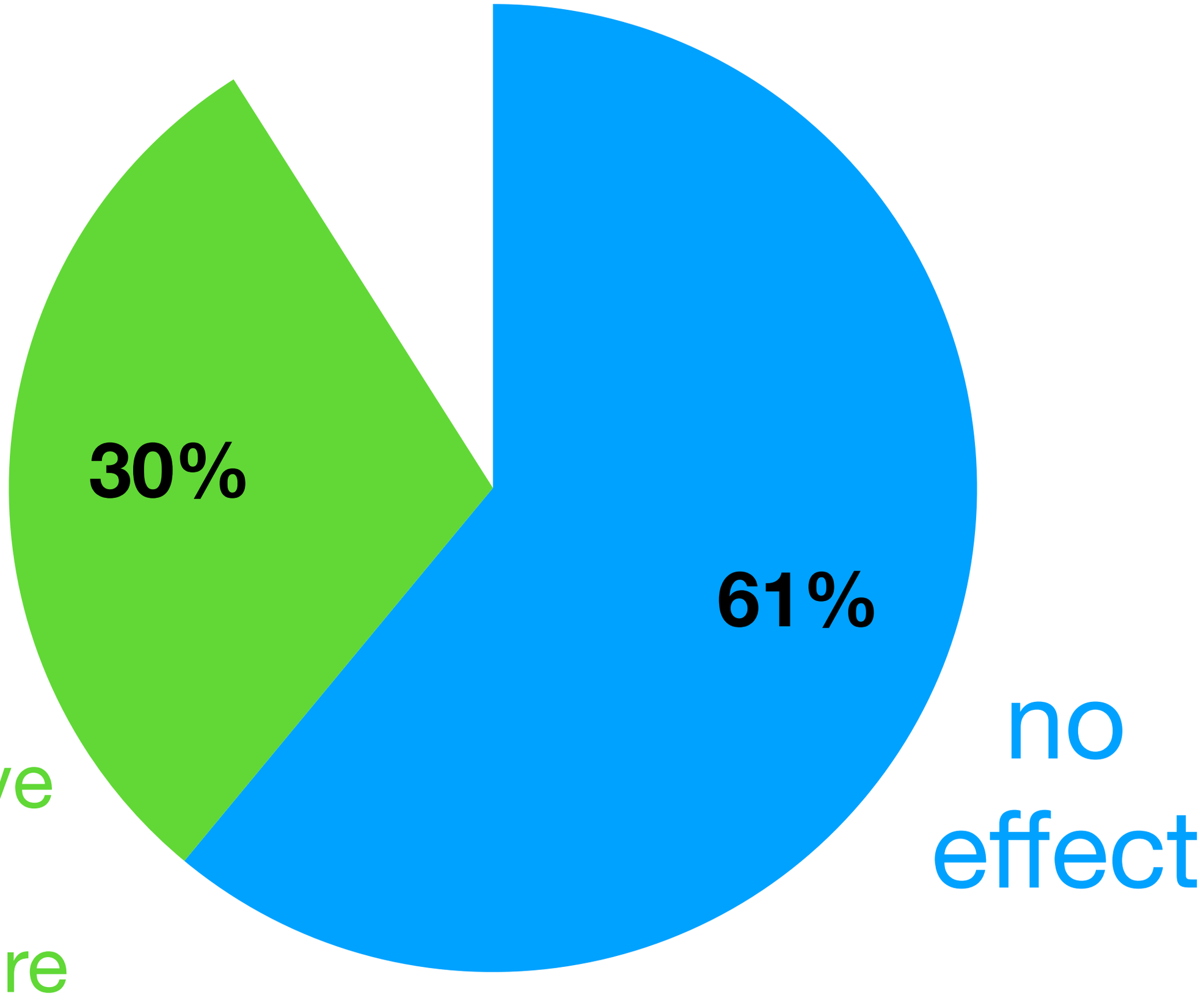


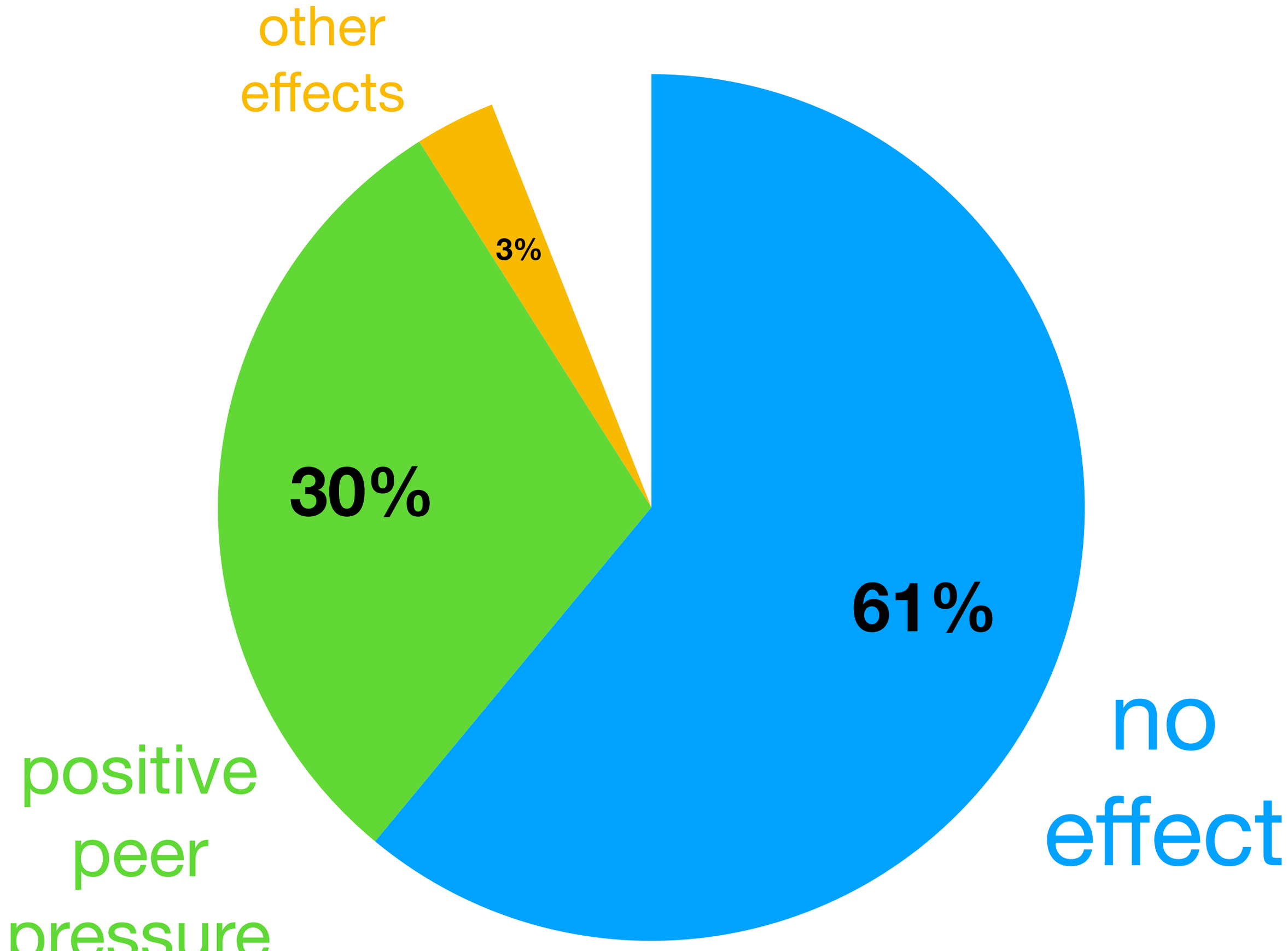
  - Probability of getting sick
- Implicitly involves "rational" behavior

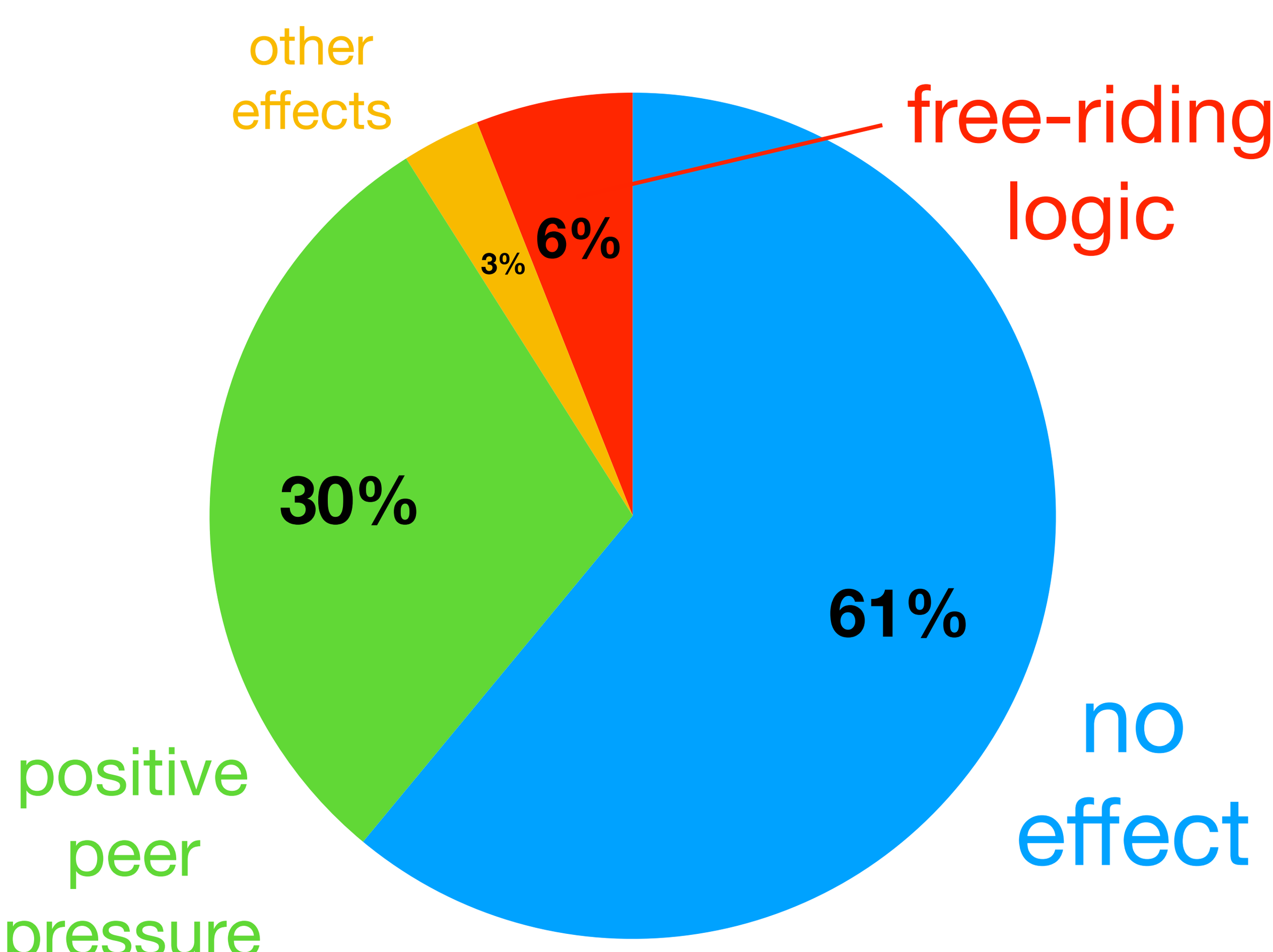


- Free-riding problem


61%
no
effect


30%
61%
positive peer pressure
no effect


other
effects
3%
30%
61%
positive
peer
pressure
no
effect


other effects
free-riding logic
6%
3%
30%
61%
positive peer pressure
no effect

Decision-making framework

Decision-making framework

- Local (individual-based) information

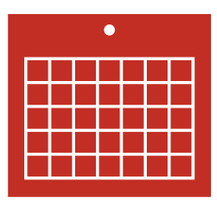
Decision-making framework

- Local (individual-based) information
- Discrete, annual flu seasons

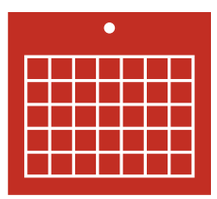
Decision-making framework

- Local (individual-based) information
- Discrete, annual flu seasons
- Decisions made between each season

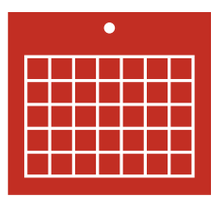
Decision-making framework

- Local (individual-based) information 
- Discrete, annual flu seasons 
  - Decisions made between each season
- Next decision based on outcome of last decision made

Decision-making framework

- Local (individual-based) information 
- Discrete, annual flu seasons 
  - Decisions made between each season
- Next decision based on outcome of last decision made
  - Winning = not having a bad experience *(with disease or vaccine)* 

Decision-making framework

- Local (individual-based) information 
- Discrete, annual flu seasons 
  - Decisions made between each season
- Next decision based on outcome of last decision made
  - Winning = not having a bad experience *(with disease or vaccine)* 
  - Win-stay, lose-shift

Notation

Notation

p_n proportion of population **vaccinated** in year *n*

Notation

p_n proportion of population **vaccinated** in year *n*

r vaccine **morbidity** probability (cost)

Notation

p_n proportion of population **vaccinated** in year *n*

r vaccine **morbidity** probability (cost)

s vaccine **success** probability

Notation

p_n	proportion of population **vaccinated** in year *n*
r	vaccine **morbidity** probability (cost)
s	vaccine **success** probability
$\phi(p)$	**final size**: proportion of the population infected over the course of an epidemic, starting with proportion *p* immune (successfully vaccinated)

Notation

p_n	proportion of population **vaccinated** in year *n*
r	vaccine **morbidity** probability (cost)
s	vaccine **success** probability
$\phi(p)$	**final size**: proportion of the population infected over the course of an epidemic, starting with proportion *p* immune (successfully vaccinated)
$\mathcal{R}_0$	**basic reproduction number**: average number of secondary cases generated by a primary case in a fully susceptible population

Notation

p_n	proportion of population **vaccinated** in year *n*
r	vaccine **morbidity** probability (cost)
s	vaccine **success** probability
$\phi(p)$	**final size**: proportion of the population infected over the course of an epidemic, starting with proportion *p* immune (successfully vaccinated)
$\mathcal{R}_0$	**basic reproduction number**: average number of secondary cases generated by a primary case in a fully susceptible population
p_{crit}	**critical vaccination threshold** to achieve herd immunity

Year *n*

Total population

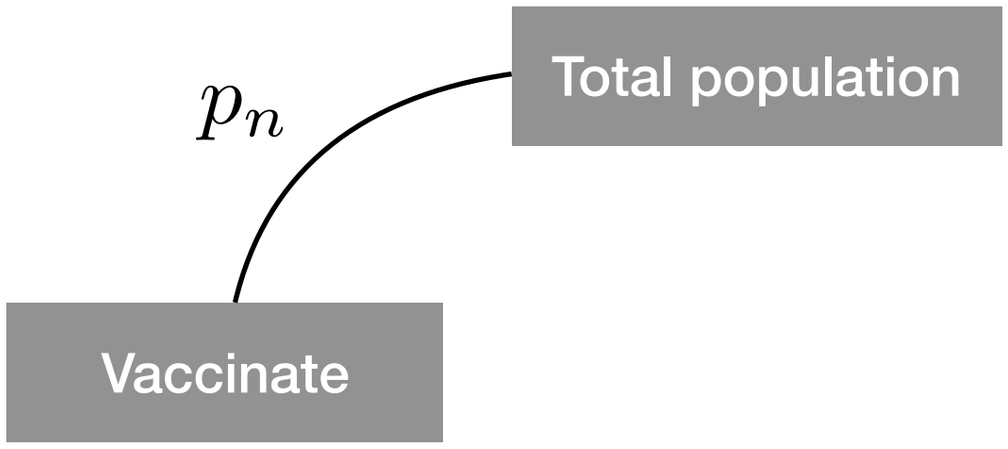
Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} =$$

Year *n*



Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} = \qquad + p_n \qquad + p_n$$

Year *n*

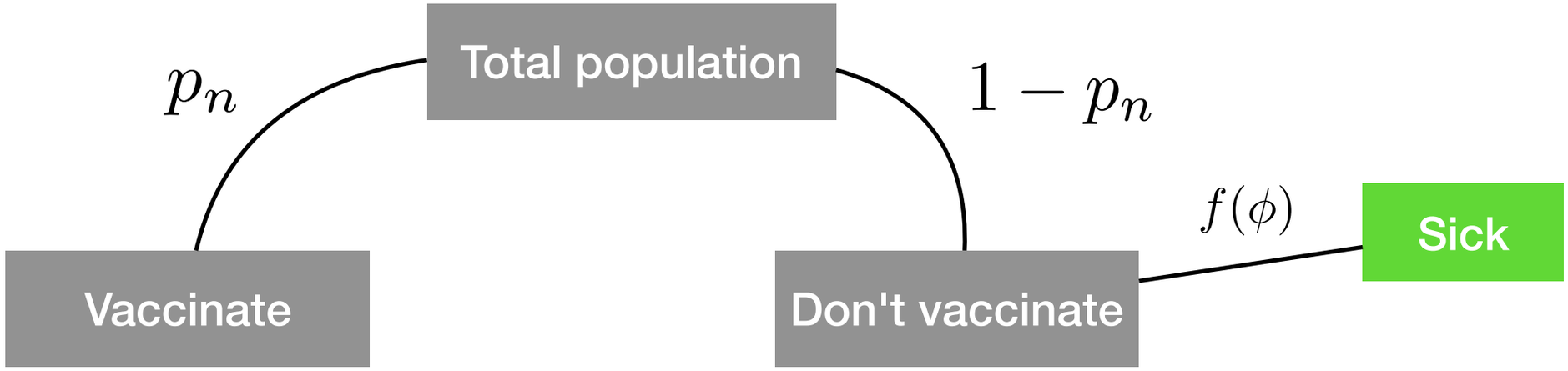
Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} = (1 - p_n) \qquad + p_n \qquad + p_n$$

Year *n*



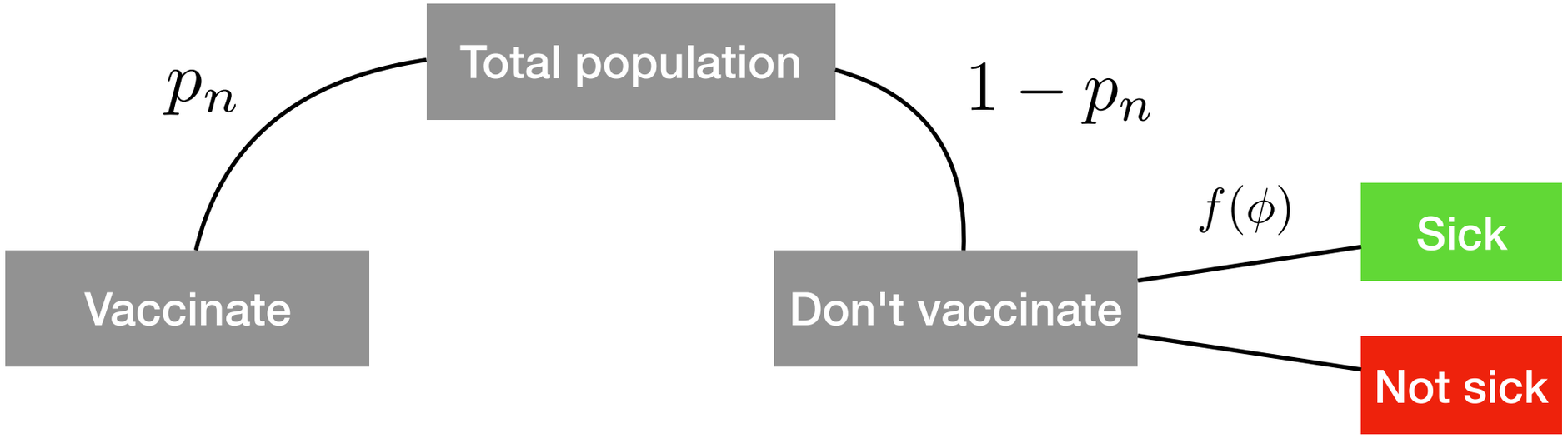
Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n \qquad + p_n$$

Year *n*



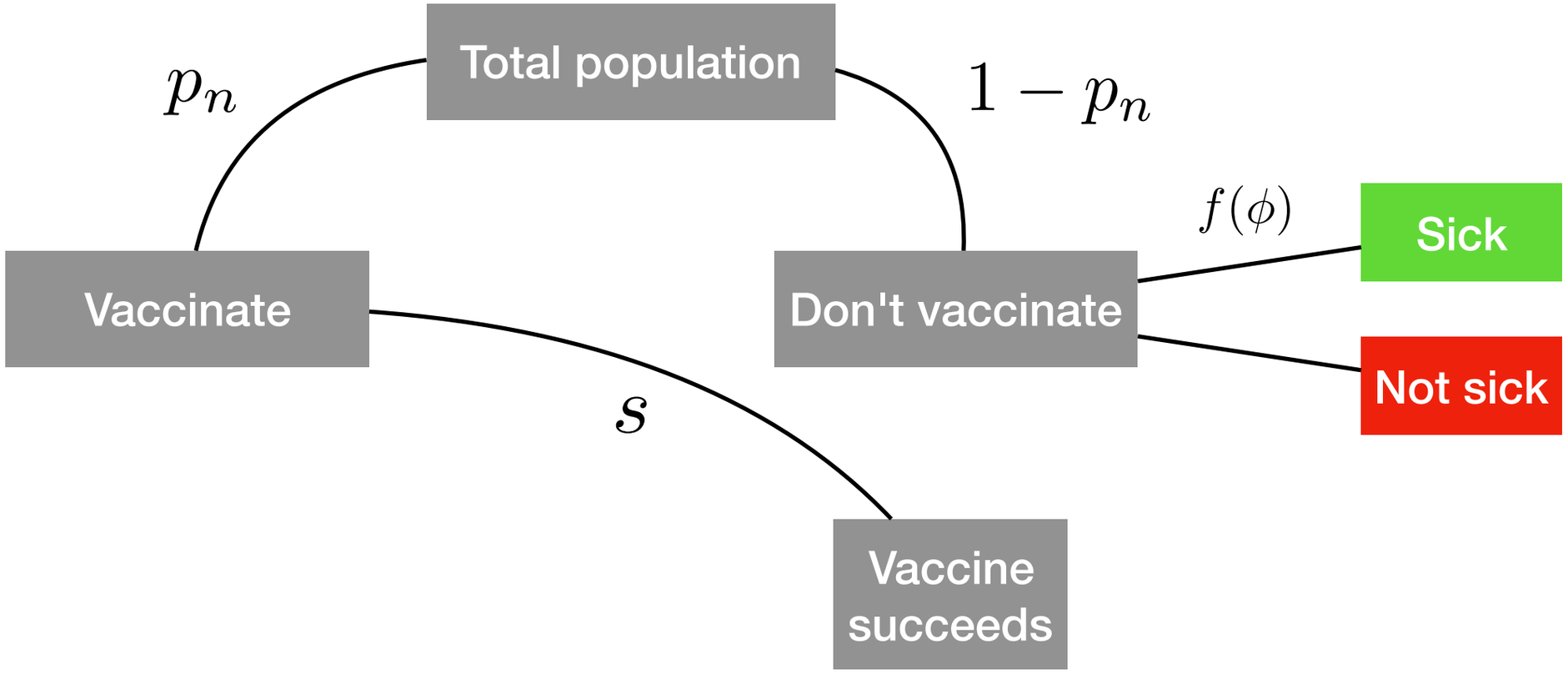
Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n \qquad\qquad + p_n$$

Year *n*



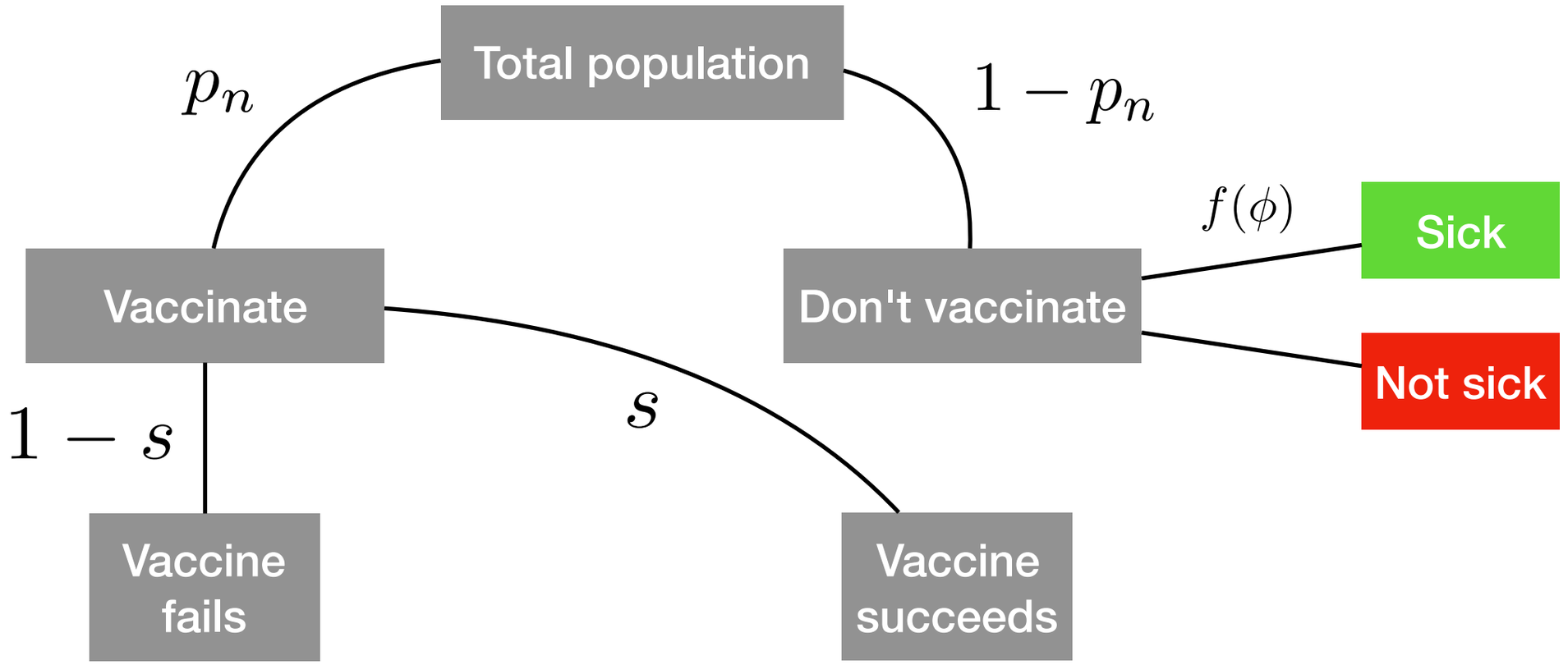
Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n s \qquad + p_n$$

Year *n*

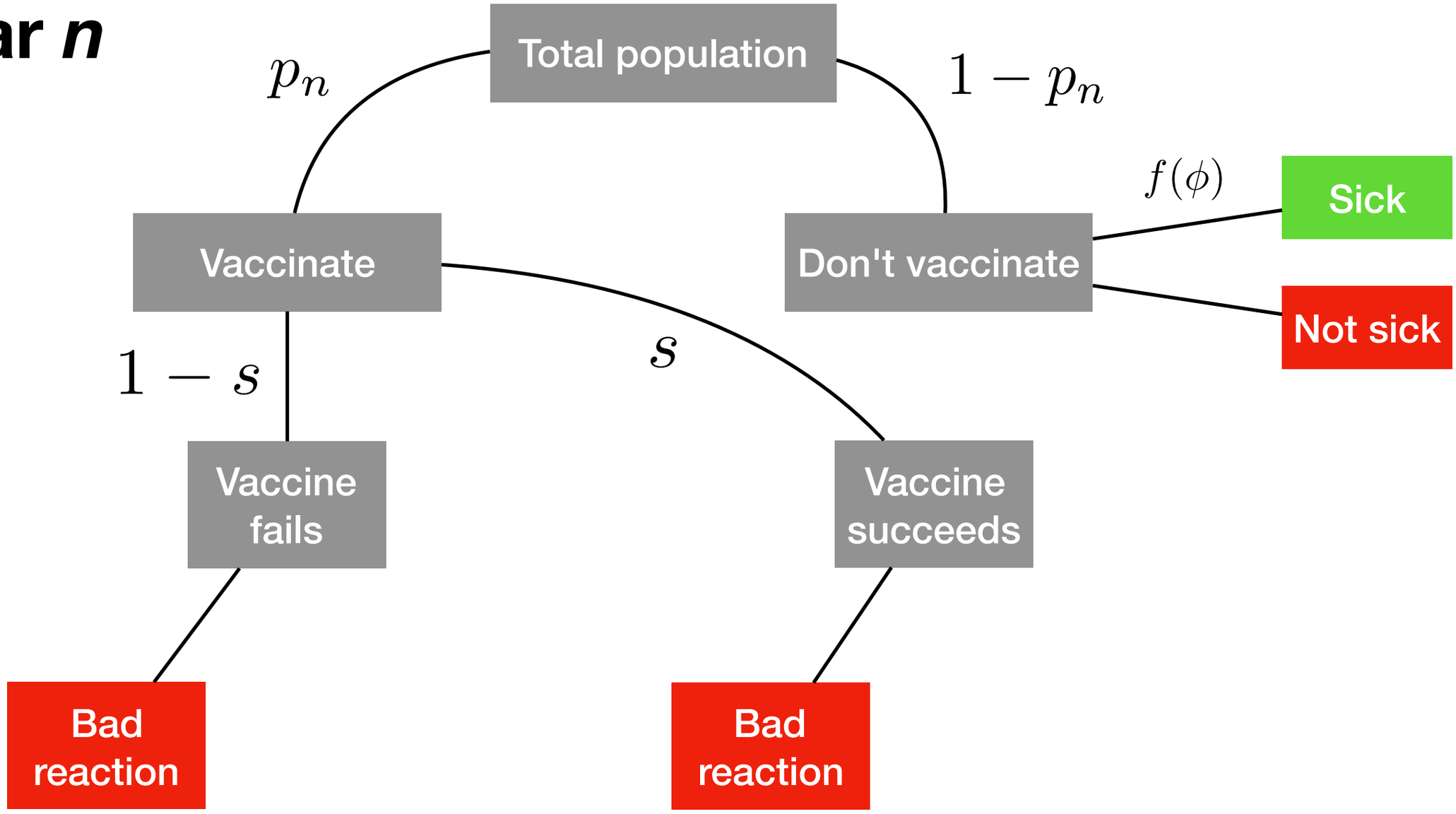


Year *n+1*

- Vaccinate
- Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n s \qquad + p_n(1 - s)$$

Year *n*



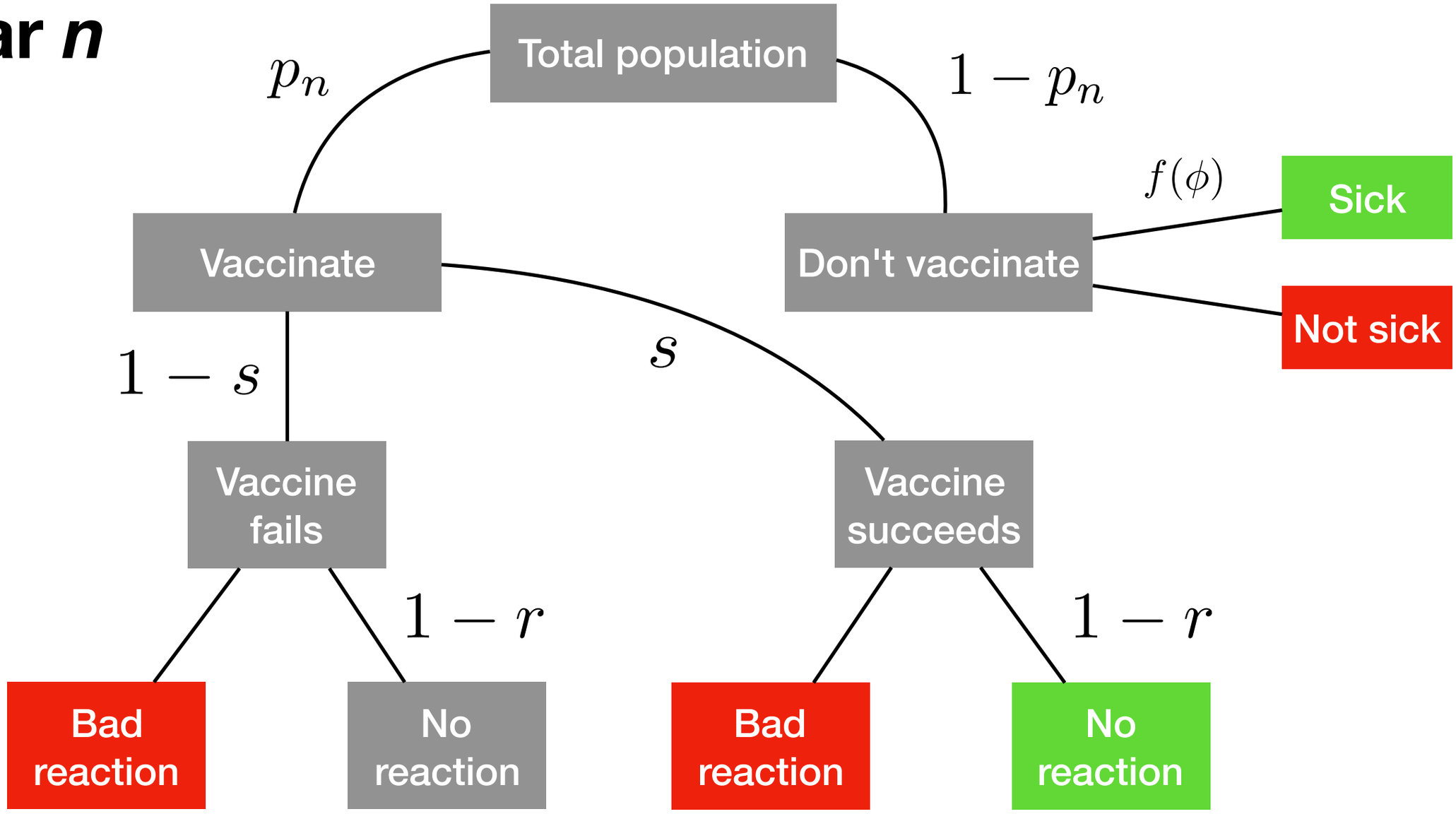
Year *n+1*

Vaccinate

Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n s \qquad + p_n(1 - s)$$

Year *n*

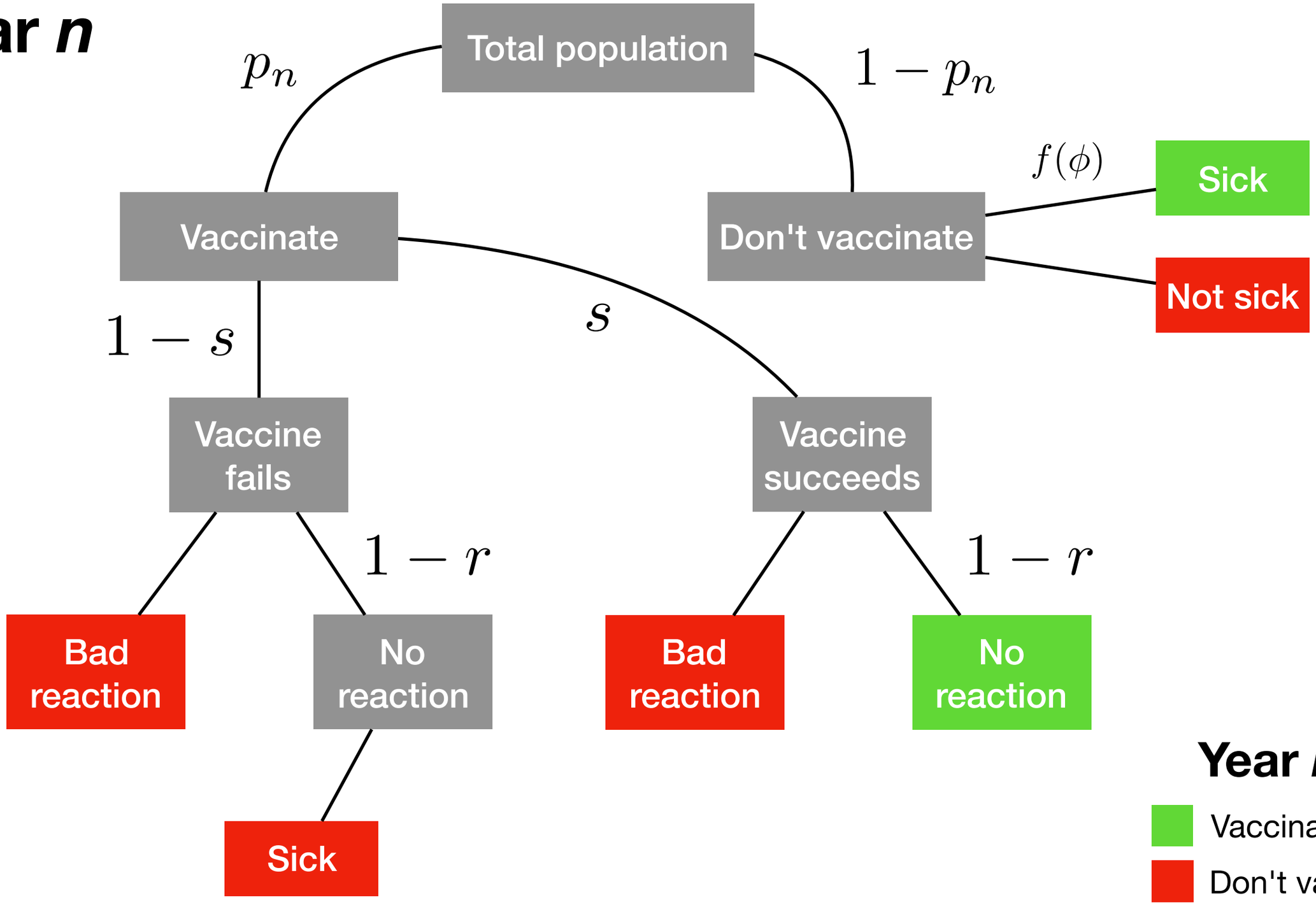


Year *n+1*

- Vaccinate
- Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n s(1 - r) + p_n(1 - s)(1 - r)$$

Year *n*

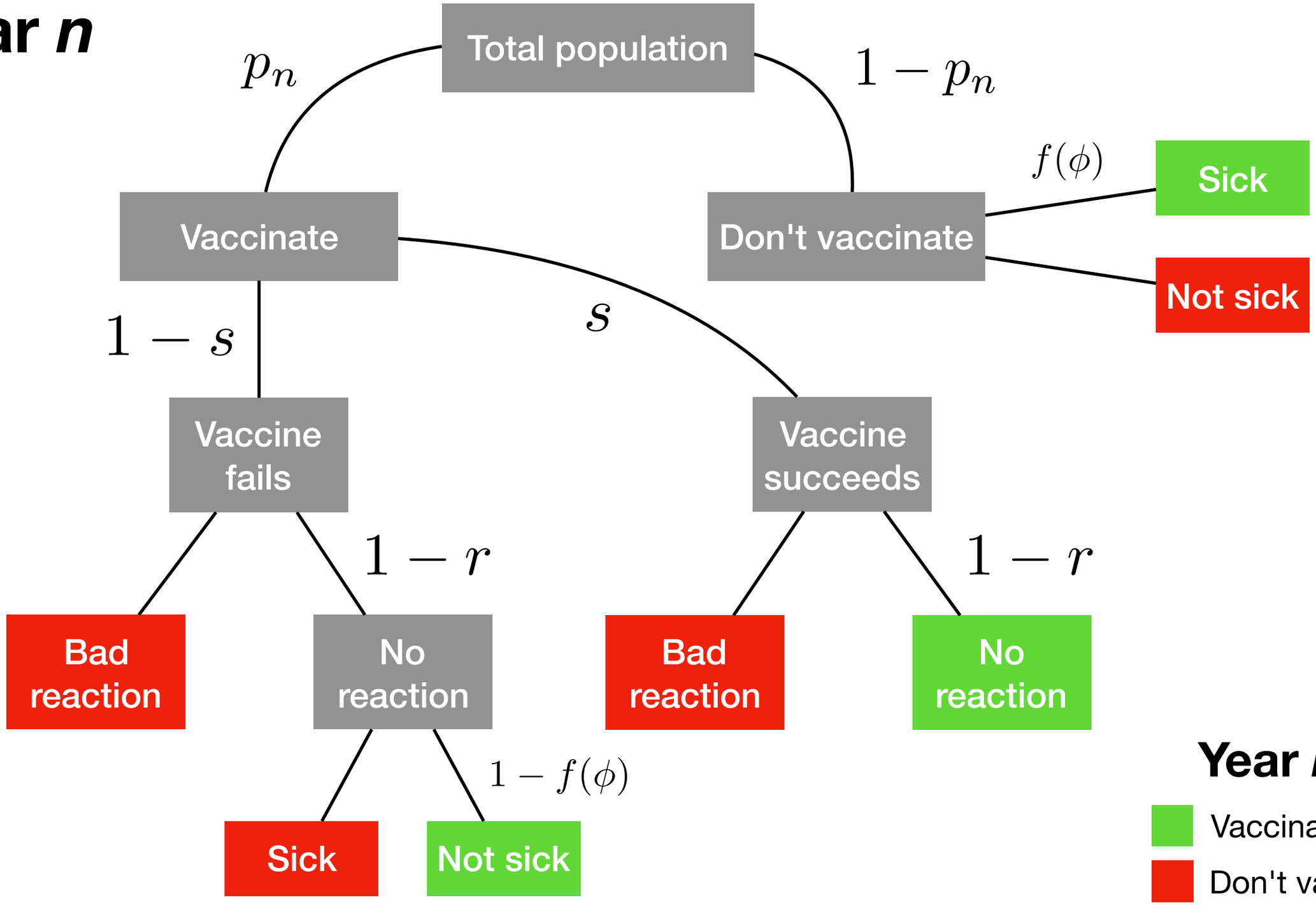


Year *n+1*

- Vaccinate
- Don't vaccinate

$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n s(1 - r) + p_n(1 - s)(1 - r)$$

Year *n*



Year *n+1*

Vaccinate

Don't vaccinate

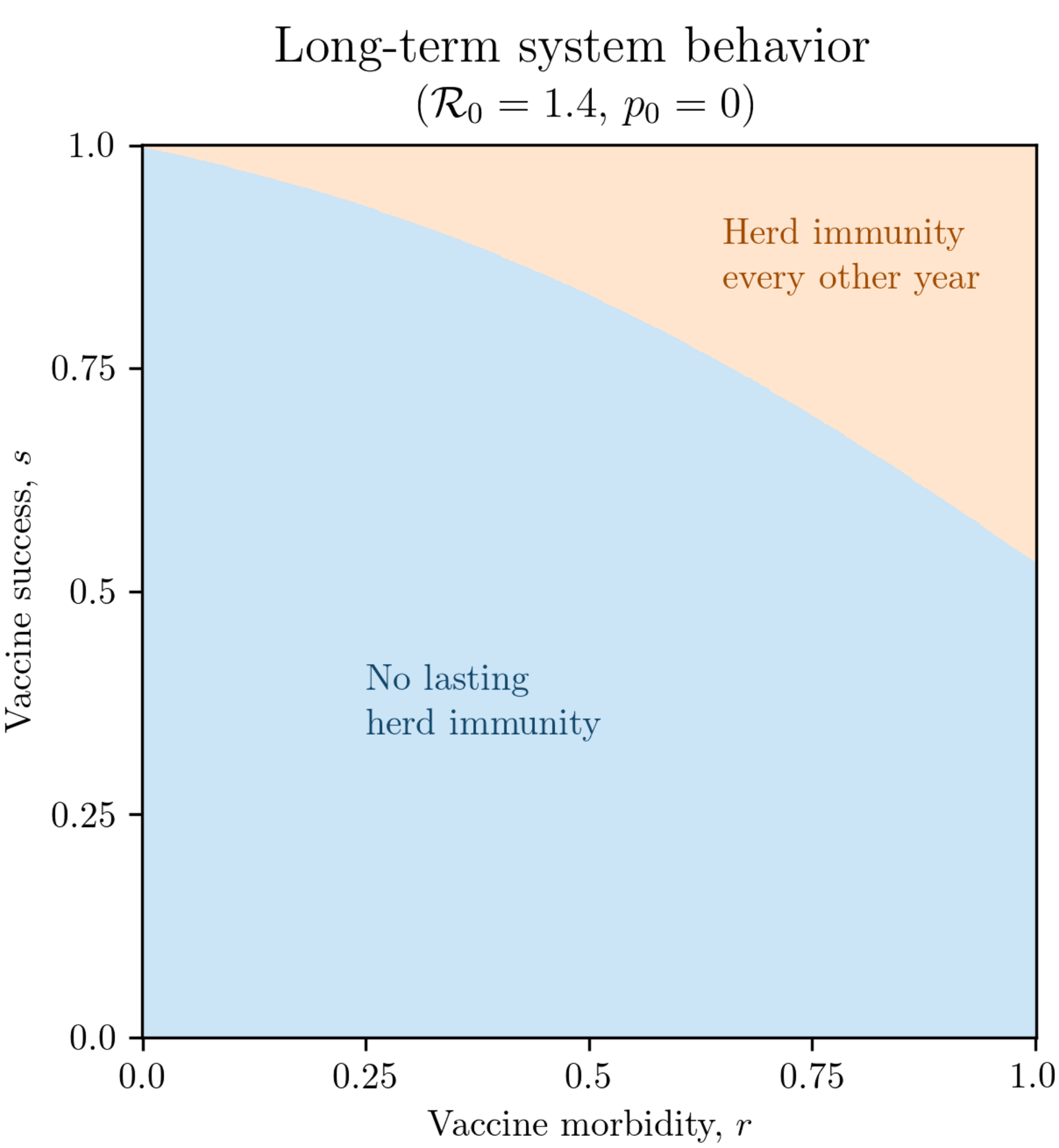
$$p_{n+1} = (1 - p_n)\frac{\phi(sp_n)}{1 - sp_n} + p_n s(1 - r) + p_n(1 - s)(1 - r)\left[1 - \frac{\phi(sp_n)}{1 - sp_n}\right]$$

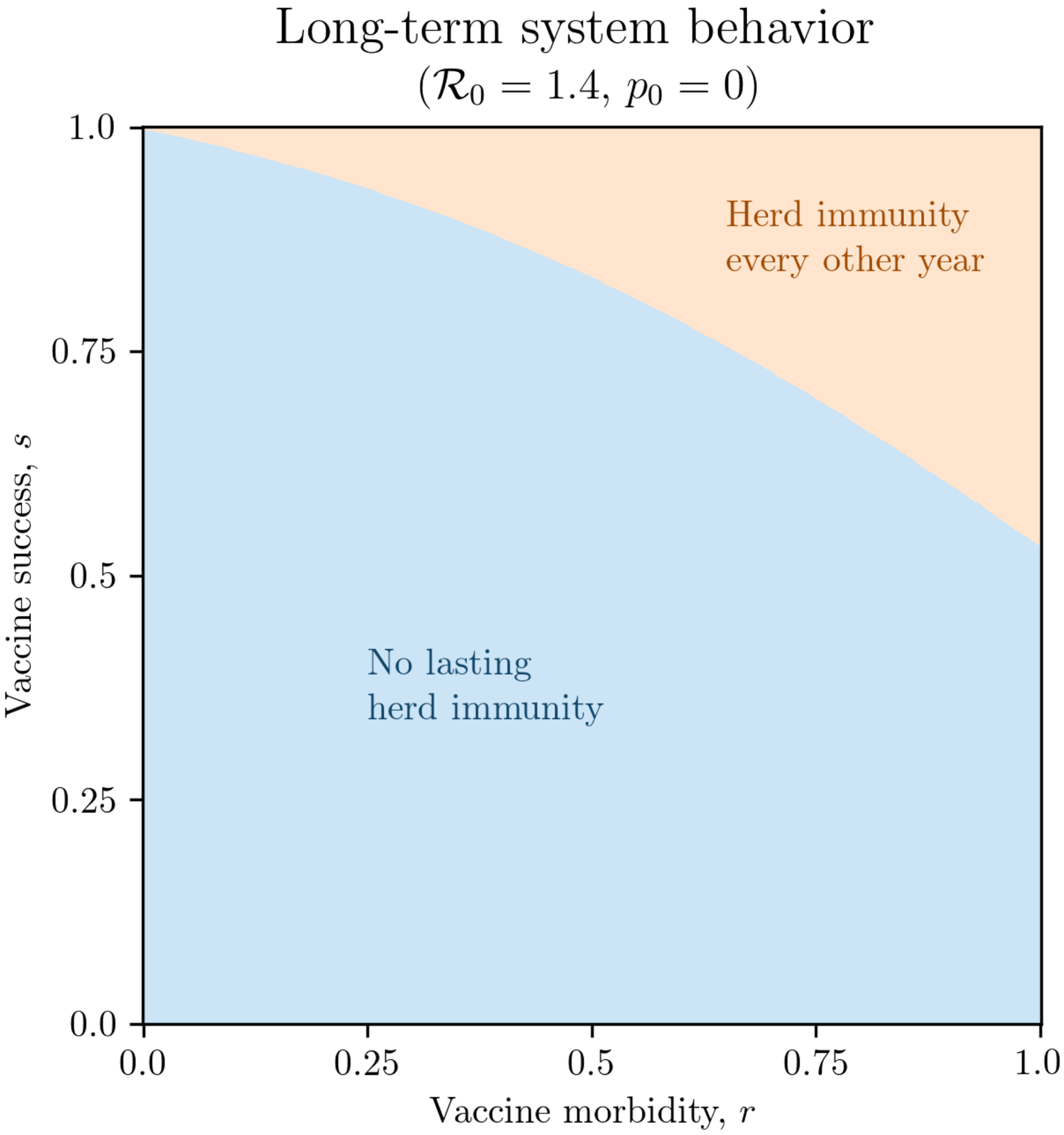
Central question

Central question

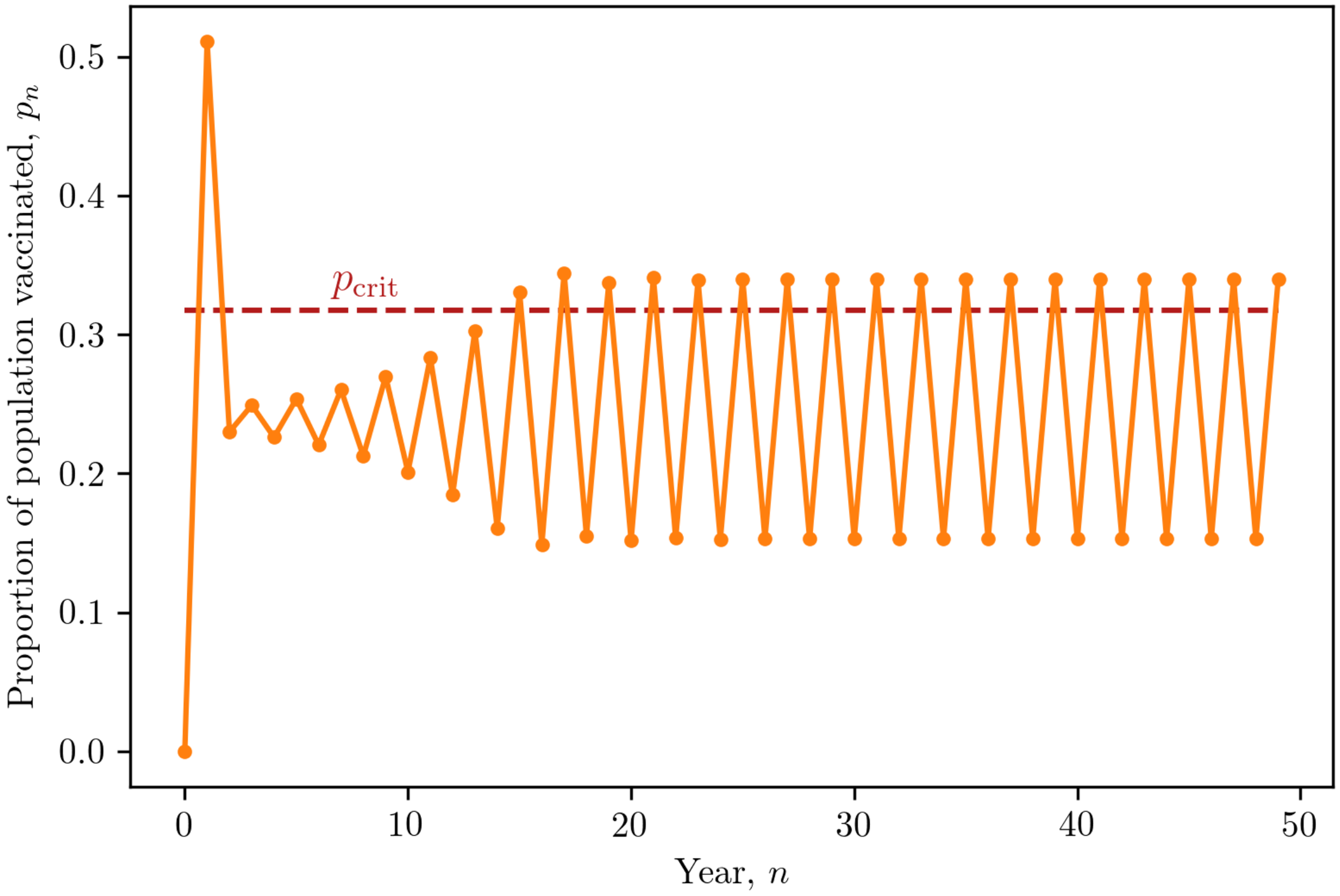
Can a population
self-organize
into herd immunity?

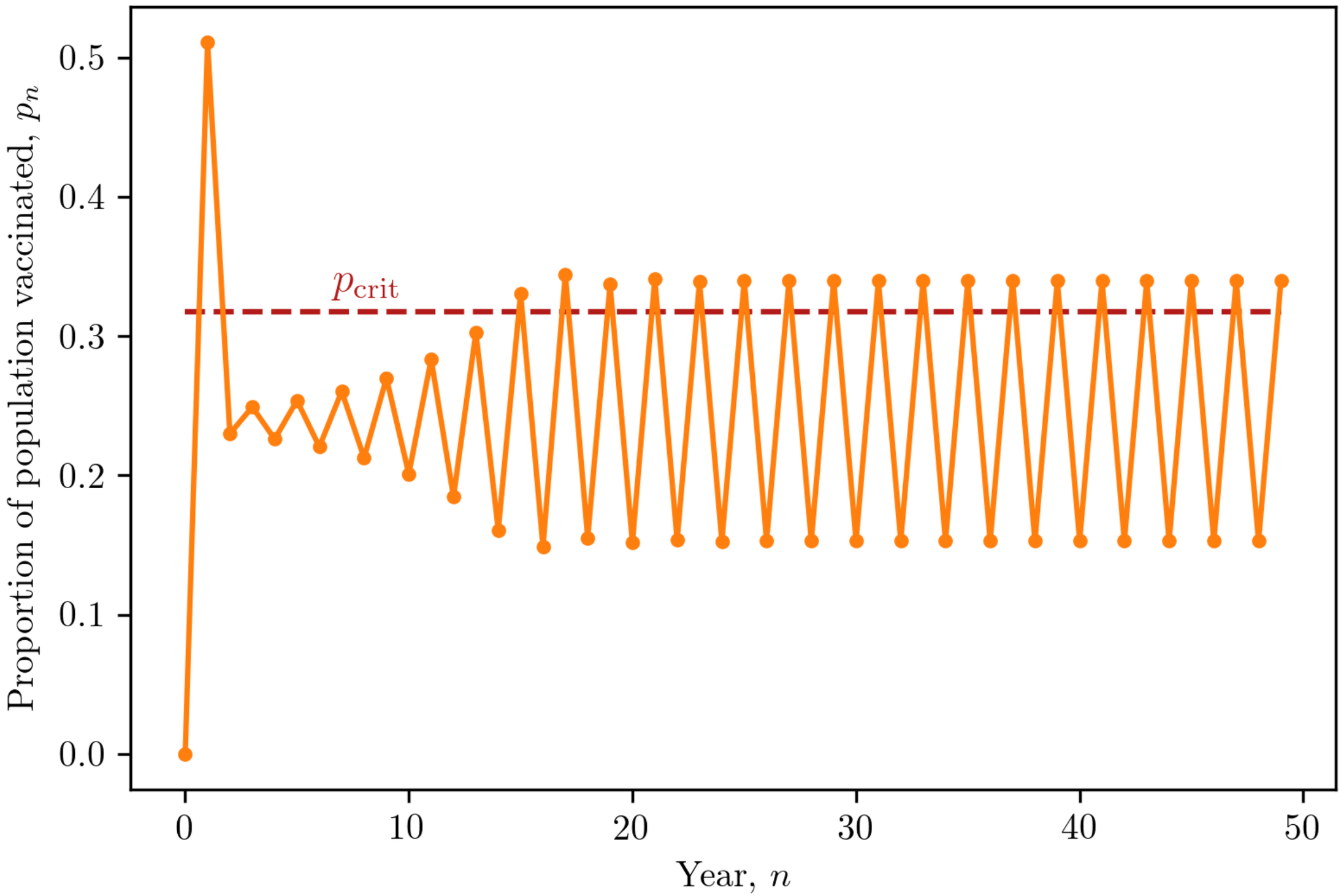
Model results


Long-term system behavior
($\mathcal{R}_0 = 1.4$, $p_0 = 0$)
Herd immunity
every other year
No lasting
herd immunity
Vaccine success, s
Vaccine morbidity, r
1.0
0.75
0.5
0.25
0.0
0.0
0.25
0.5
0.75
1.0

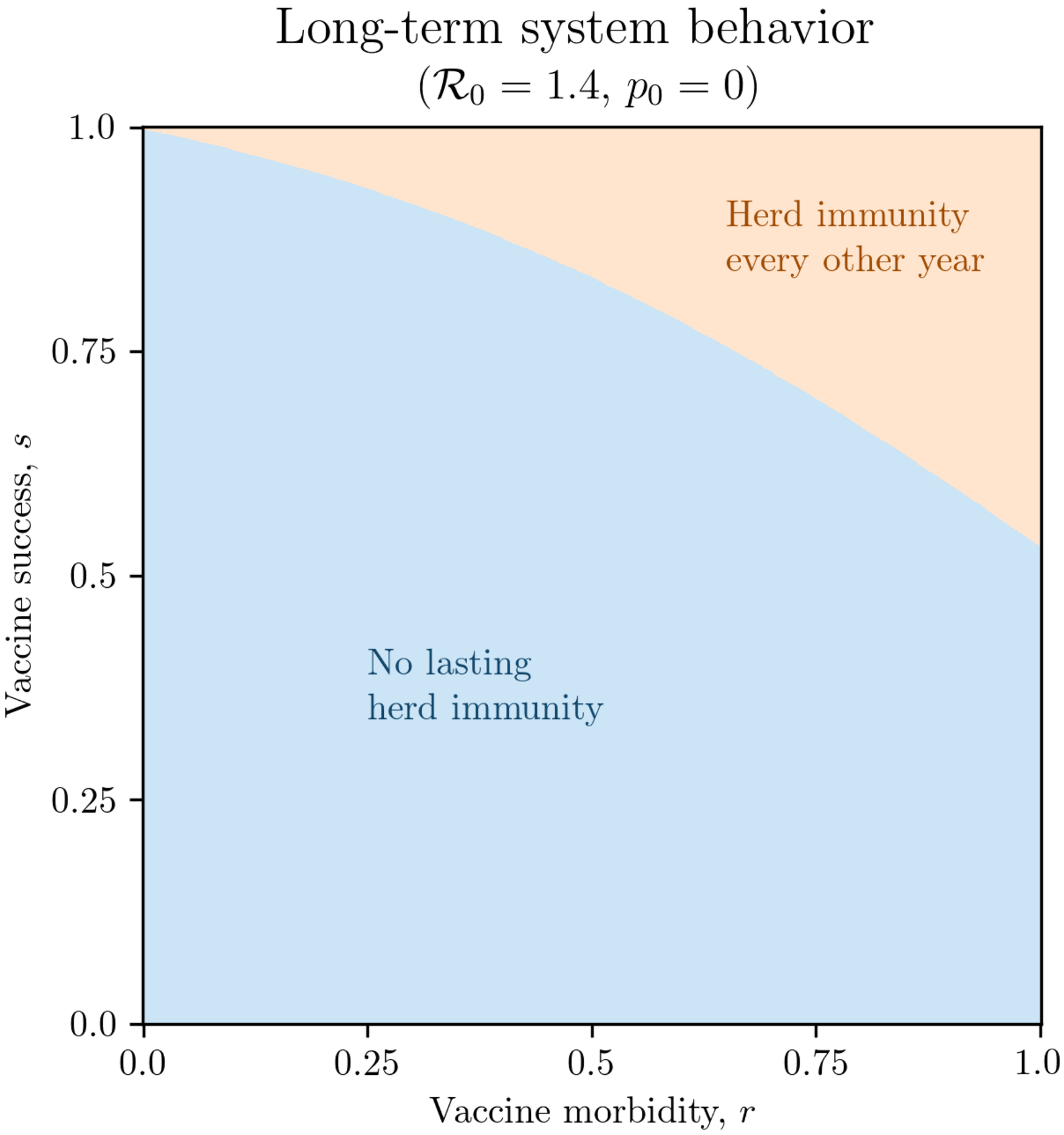


When there is *any* cost to the vaccine (i.e. $r > 0$), the system **cannot** self-organize into herd immunity.


Vaccine coverage level over time
($\mathcal{R}_0 = 1.4$, $r = 0.55$, $s = 0.9$)
Proportion of population vaccinated, p_n
0.0
0.1
0.2
0.3
0.4
0.5
p_{crit}
0
10
20
30
40
50
Year, n

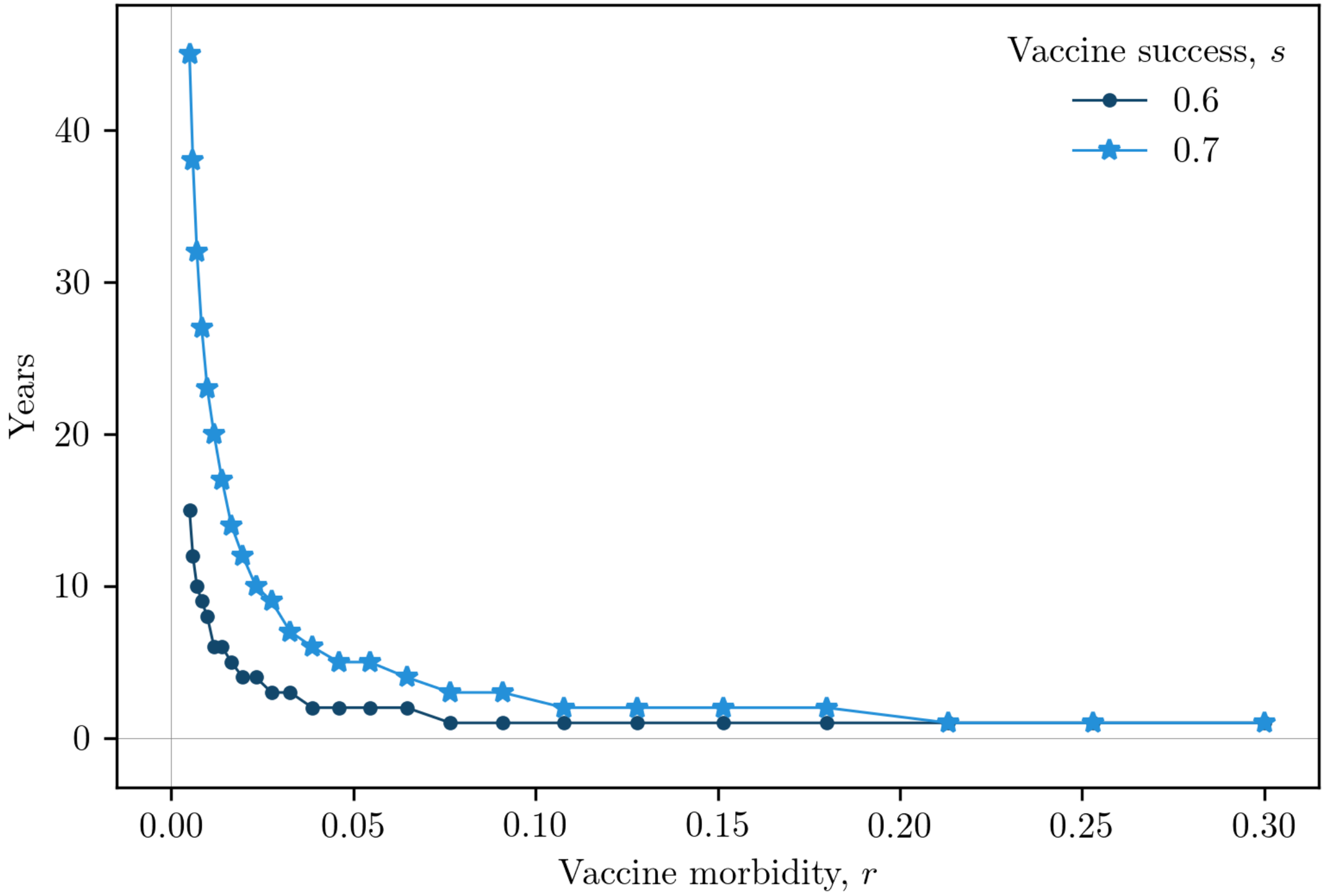


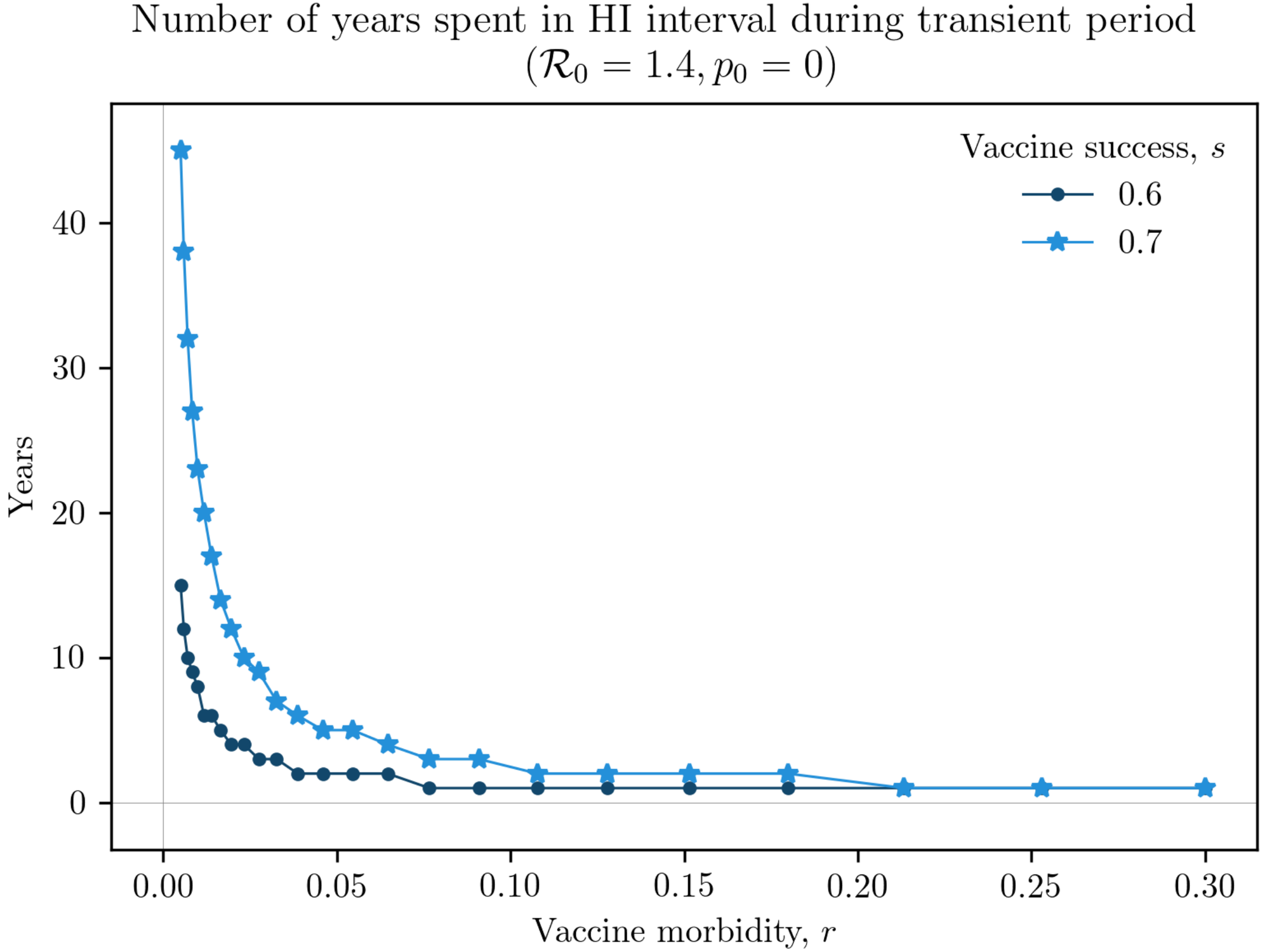
Even with a **cost** and **imperfect** vaccine, can achieve herd immunity **every other year**.



When there is *any* cost to the vaccine (i.e. $r > 0$), the system **cannot** self-organize into herd immunity.

Number of years spent in HI interval during transient period
$(\mathcal{R}_0 = 1.4, p_0 = 0)$





Long transients in the herd immunity interval open the door for public health **interventions**.

Long-term system behavior
with no vaccine cost ($\mathcal{R}_0 = 1.4$)

Converge to
inefficient, lasting
herd immunity

Lasting
herd immunity
from start

Converge to
optimal, lasting
herd immunity

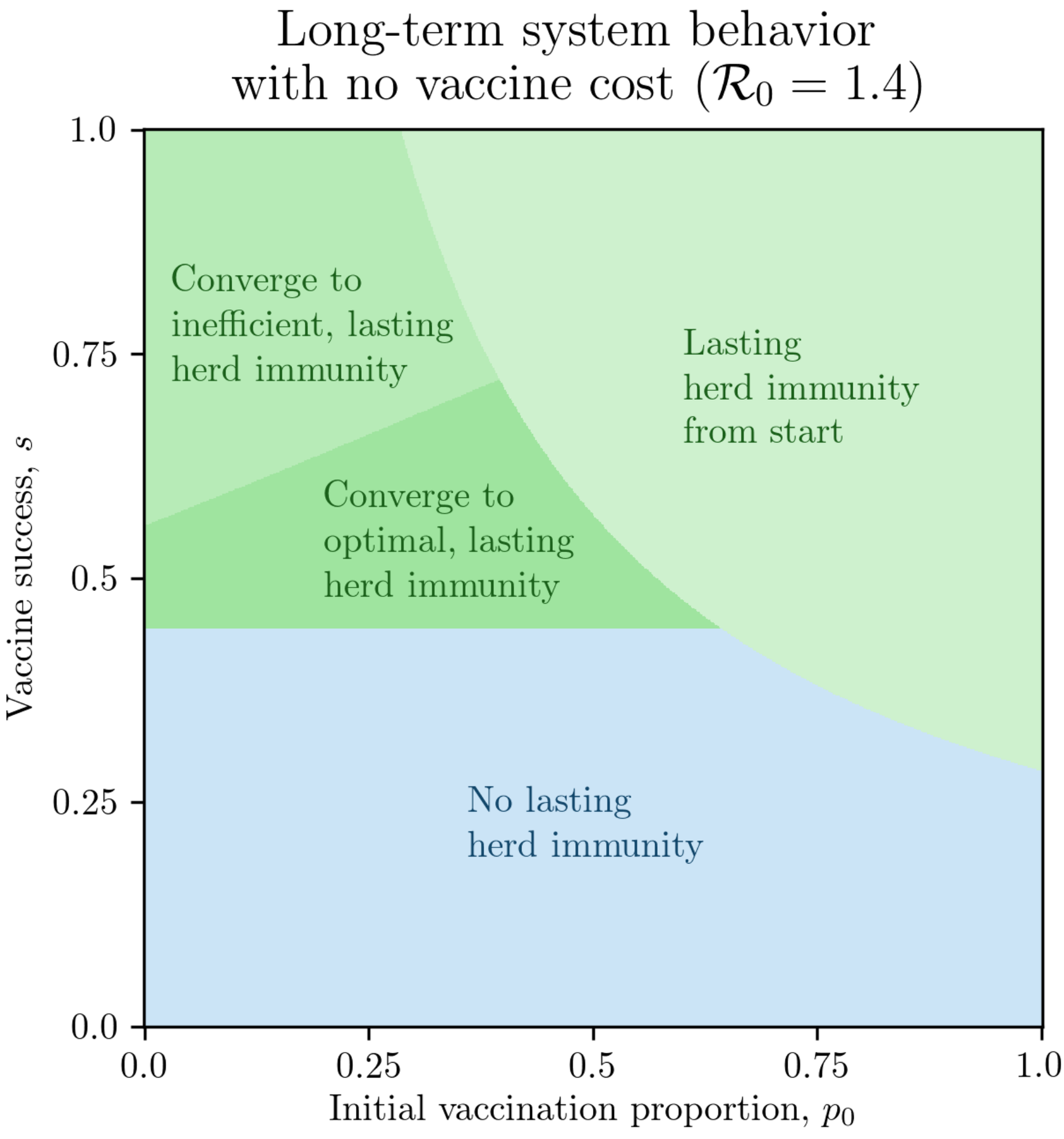
No lasting
herd immunity

1.0
0.75
0.5
0.25
0.0

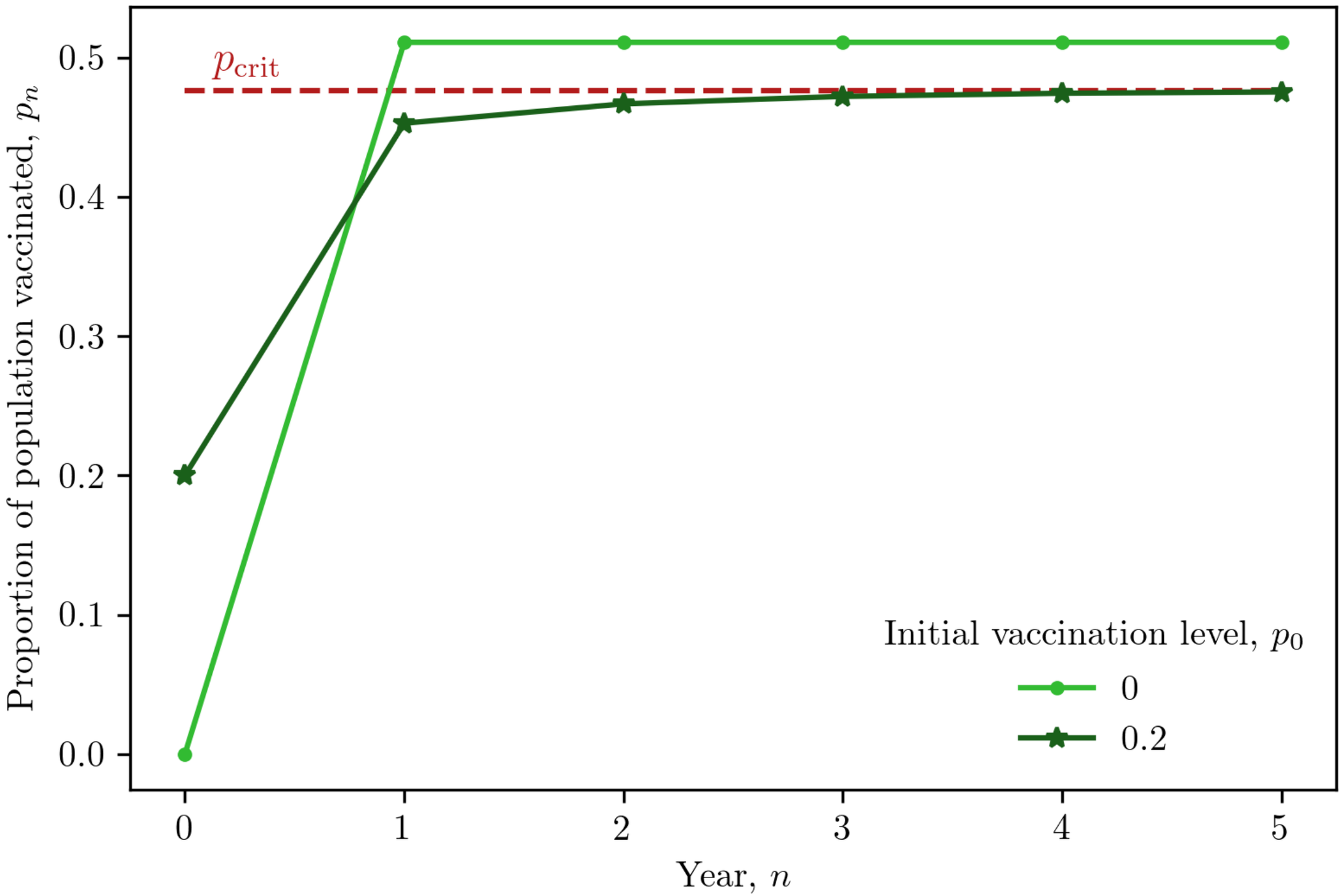
Vaccine success, s

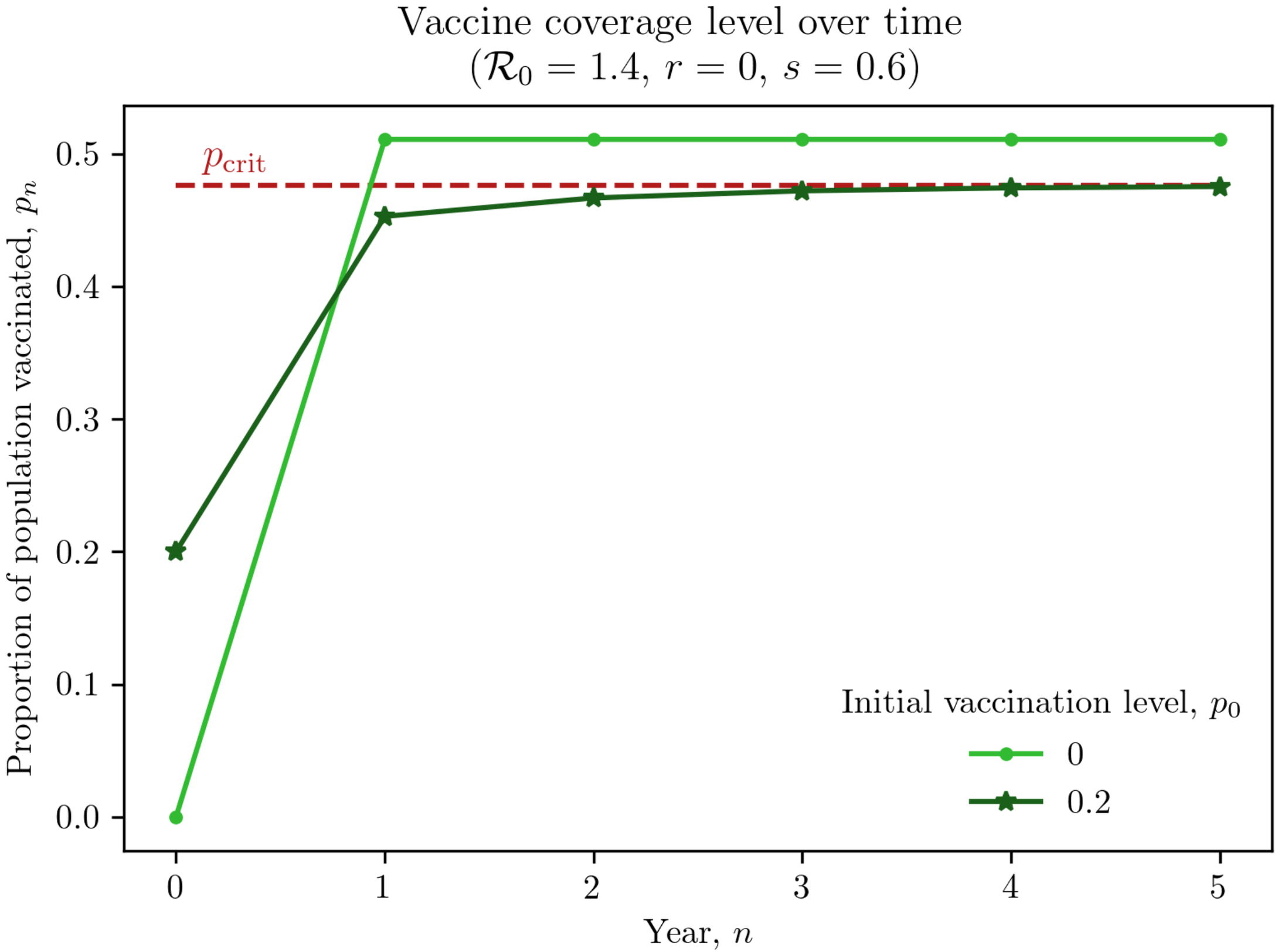
0.0
0.25
0.5
0.75
1.0

Initial vaccination proportion, p_0



Self-organized herd immunity **can** be achieved (with no vaccine cost) *even if* the vaccine is only **moderately effective**.


Vaccine coverage level over time
($\mathcal{R}_0 = 1.4$, $r = 0$, $s = 0.6$)
p_{crit}
Proportion of population vaccinated, p_n
0.0
0.1
0.2
0.3
0.4
0.5
0
1
2
3
4
5
Year, n
Initial vaccination level, p_0
0
0.2



Inefficient herd immunity results from an **overreaction** & **optimal** from **gradual learning**.

Thank you!

Thank you!

ip98@cornell.edu

@irenapapst