BIOS27816: Population biology of infectious diseases of global health concern

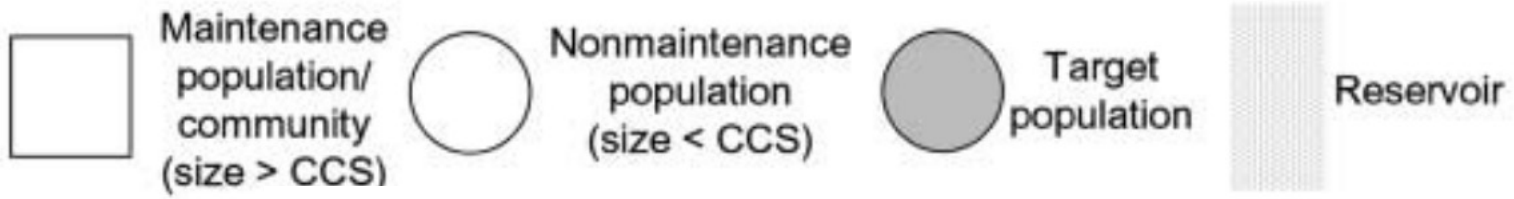
Transmission dynamics and interventions to control zoonotic diseases

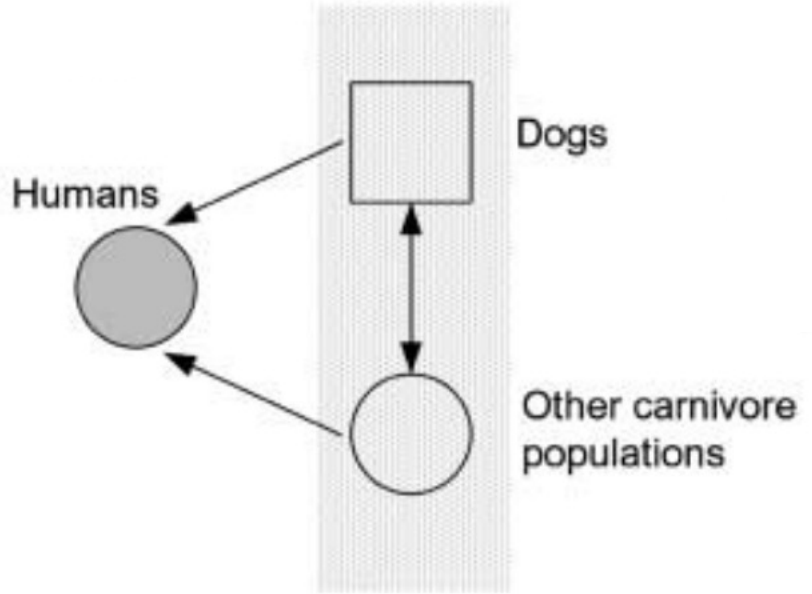
UChicago Center in Paris

Paris, France

January 2024

Defining terms in multi-species infections…



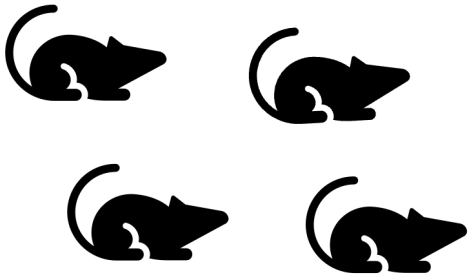


Haydon et al. 2002. *EID.*

Lembo et al. 2008. *J of Animal Ecology.*

spillover

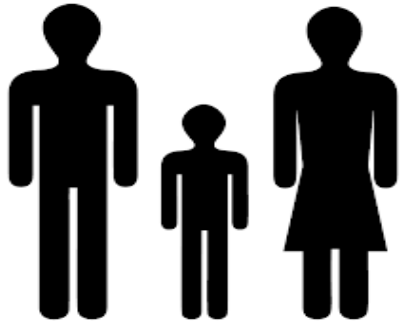
reservoir host



transmission

(can occur directly or via vector)

spillover host



Spillover occurs when a pathogen transmits from one species host to another

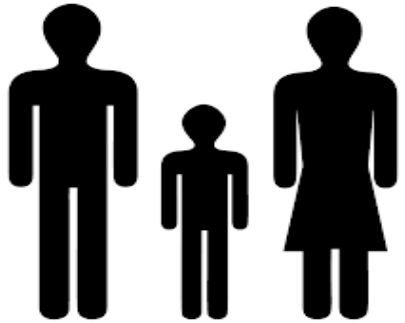
zoonosis

reservoir host

transmission

(can occur directly or via vector)

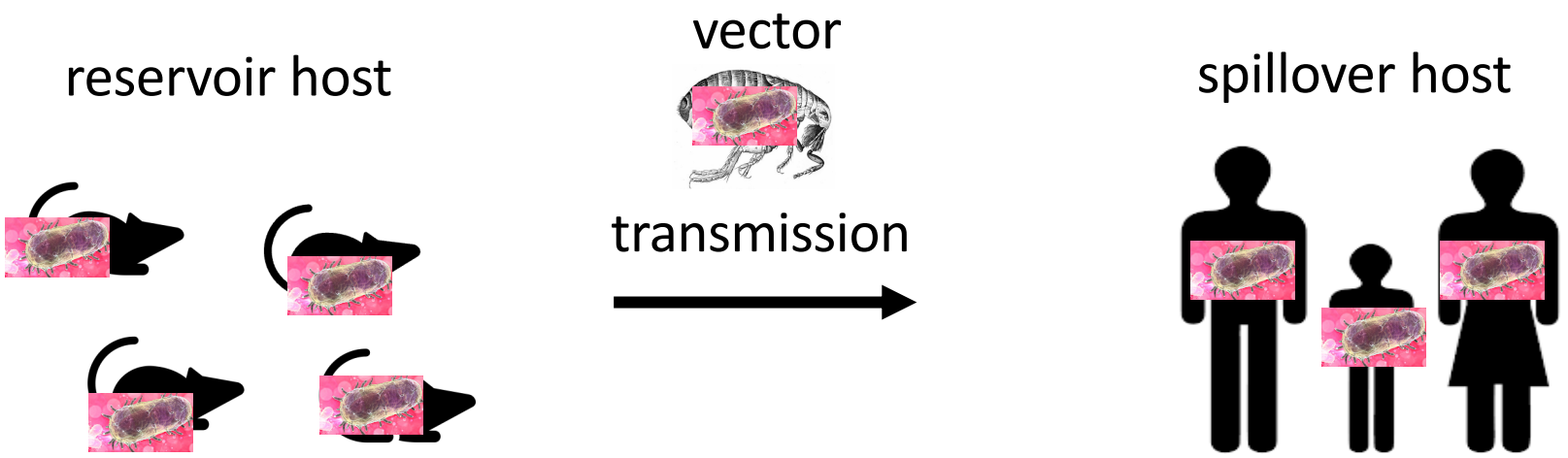
spillover host



Over 60% of all ‘emerging’ infectious diseases are **zoonotic**, meaning transmitted from an animal reservoir to a human host.

(Emerging infectious have newly appeared or are increasing in incidence or geographic range, or caused by NIAID priority pathogens)

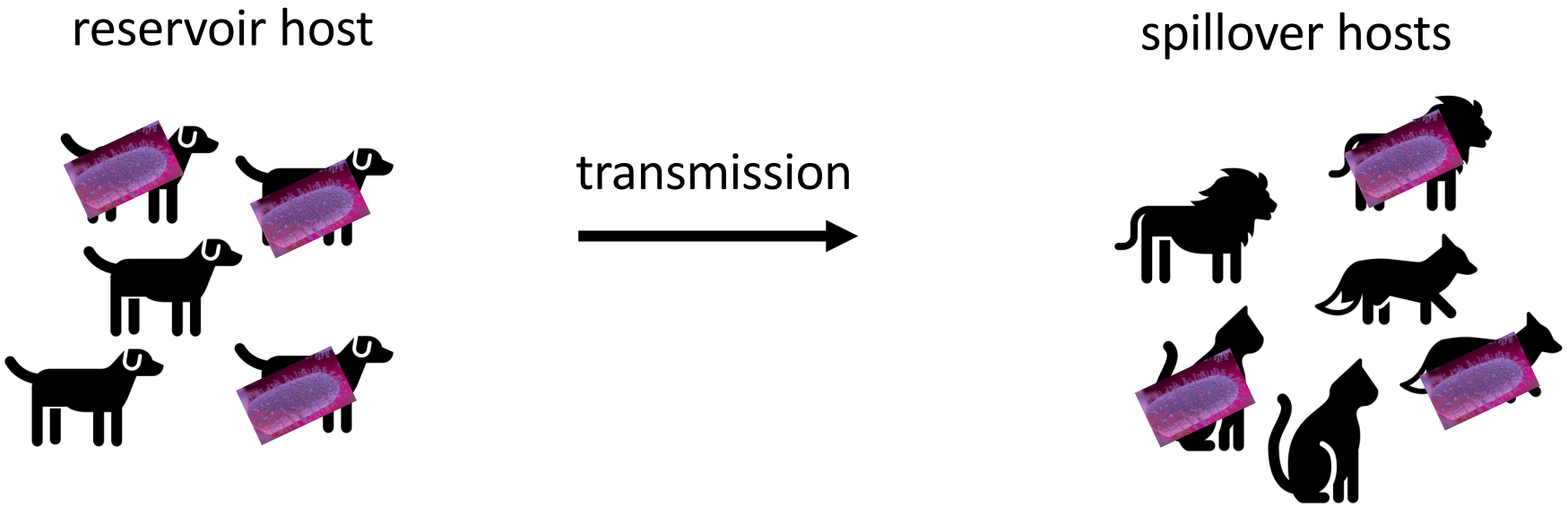
zoonosis



Over 60% of all ‘emerging’ infectious diseases are **zoonotic**, meaning transmitted from an animal reservoir to a human host.

Animal hosts are not vectors!

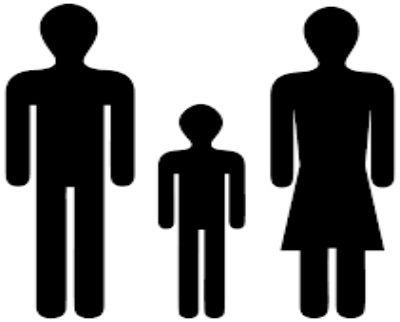
Pathogens can also spillover to alternative wildlife hosts.

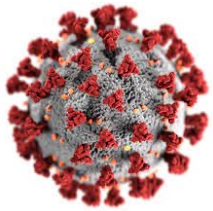


These pathogens **are not considered zoonoses** unless they spillover to humans!

spillback

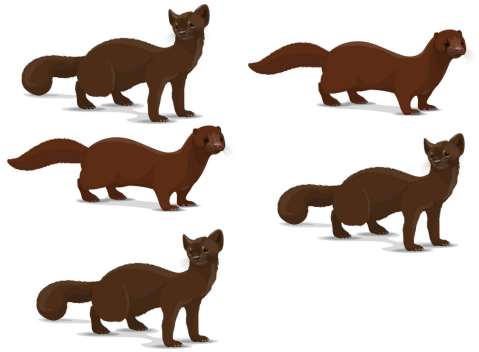
reservoir host





transmission

spillover host

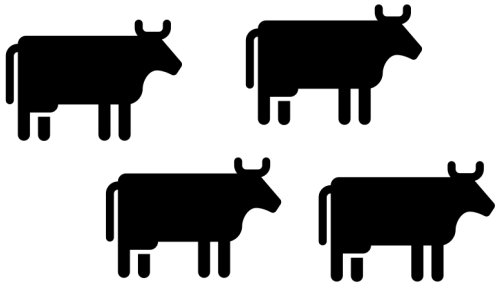


when pathogens transmit from a spillover host back to the original reservoir host

(example: transmission of SARS-CoV-2 from mink back to humans… interesting case because neither humans nor mink are actually the original reservoir host)

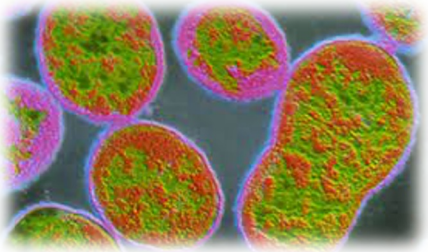
Spillback occurs among wildlife as well

reservoir host

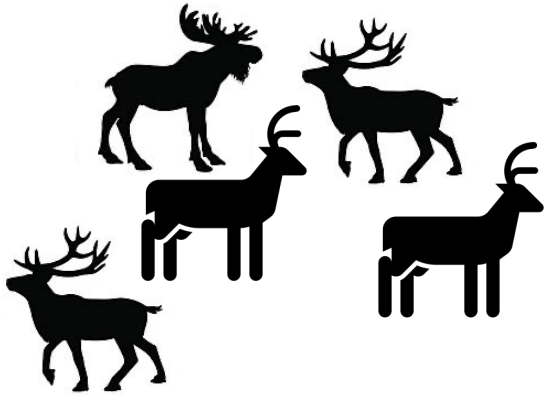


cattle

transmission



spillover hosts

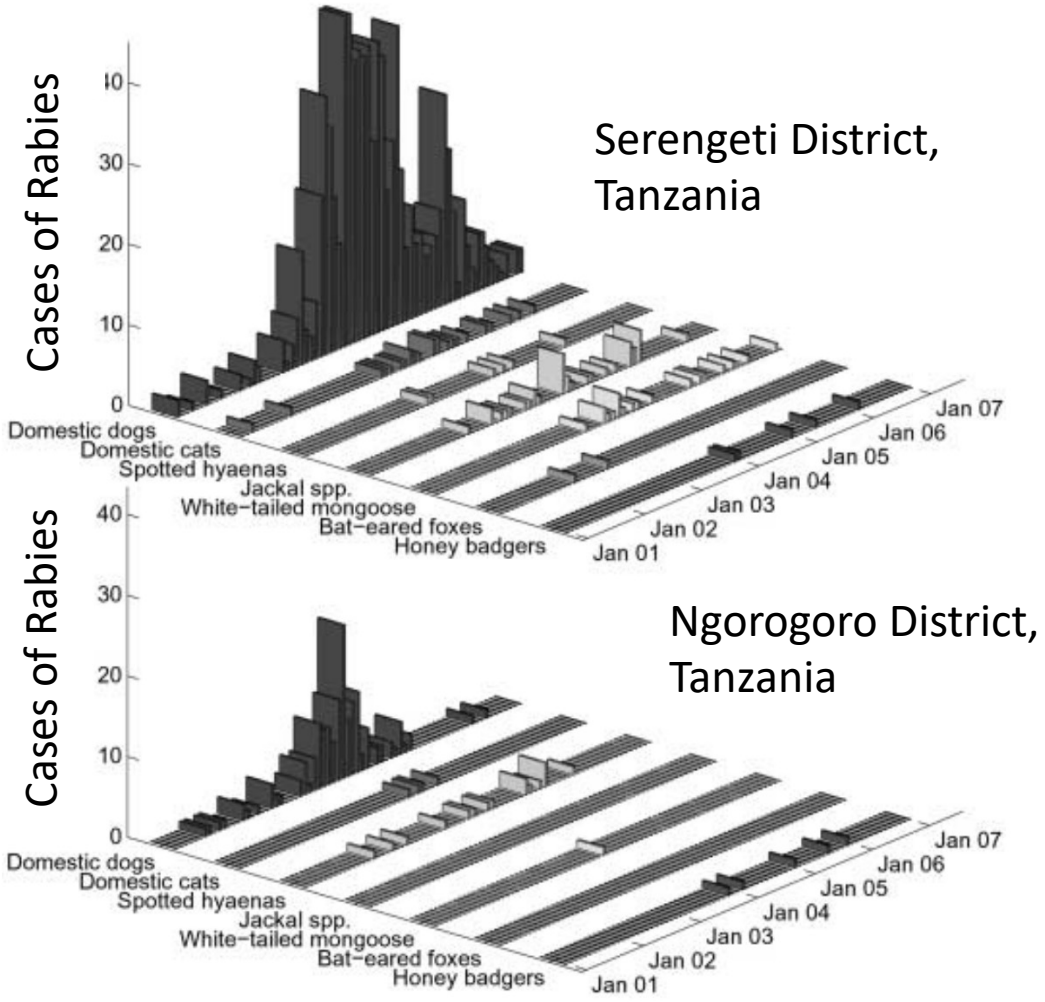


wild ungulate

Cattle sourced *Brucella* to wild ungulates in Yellowstone National Park, which now serve as a source for reinfection to cattle.

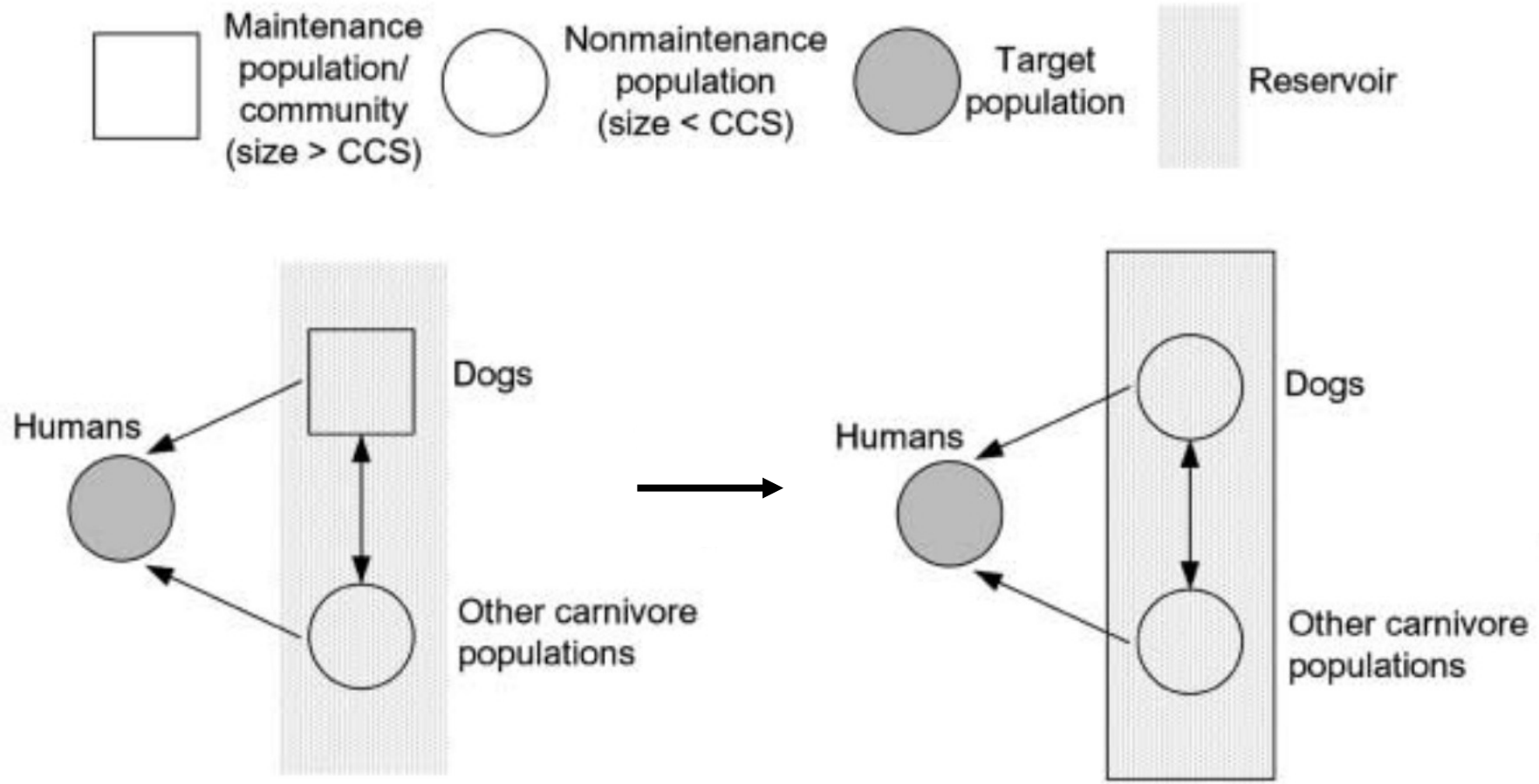
Dobson and Meagher. 1996. *Ecology.*

Pathogens can also spillover to alternative wildlife hosts.



Lembo et al. 2008. *J of Animal Ecology.*

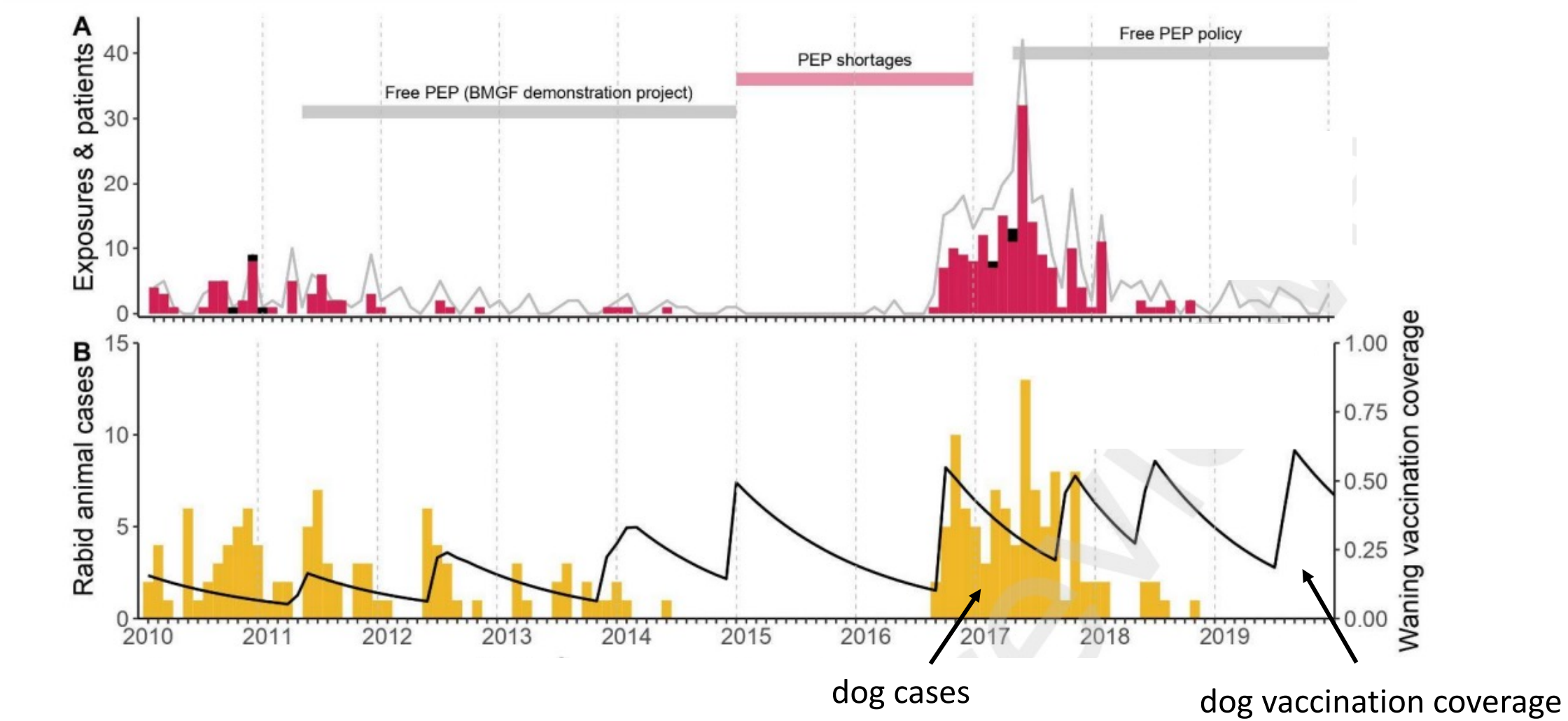
Vaccination of domestic dogs aims to shift the ecology of the system



Haydon et al. 2002. *EID.*

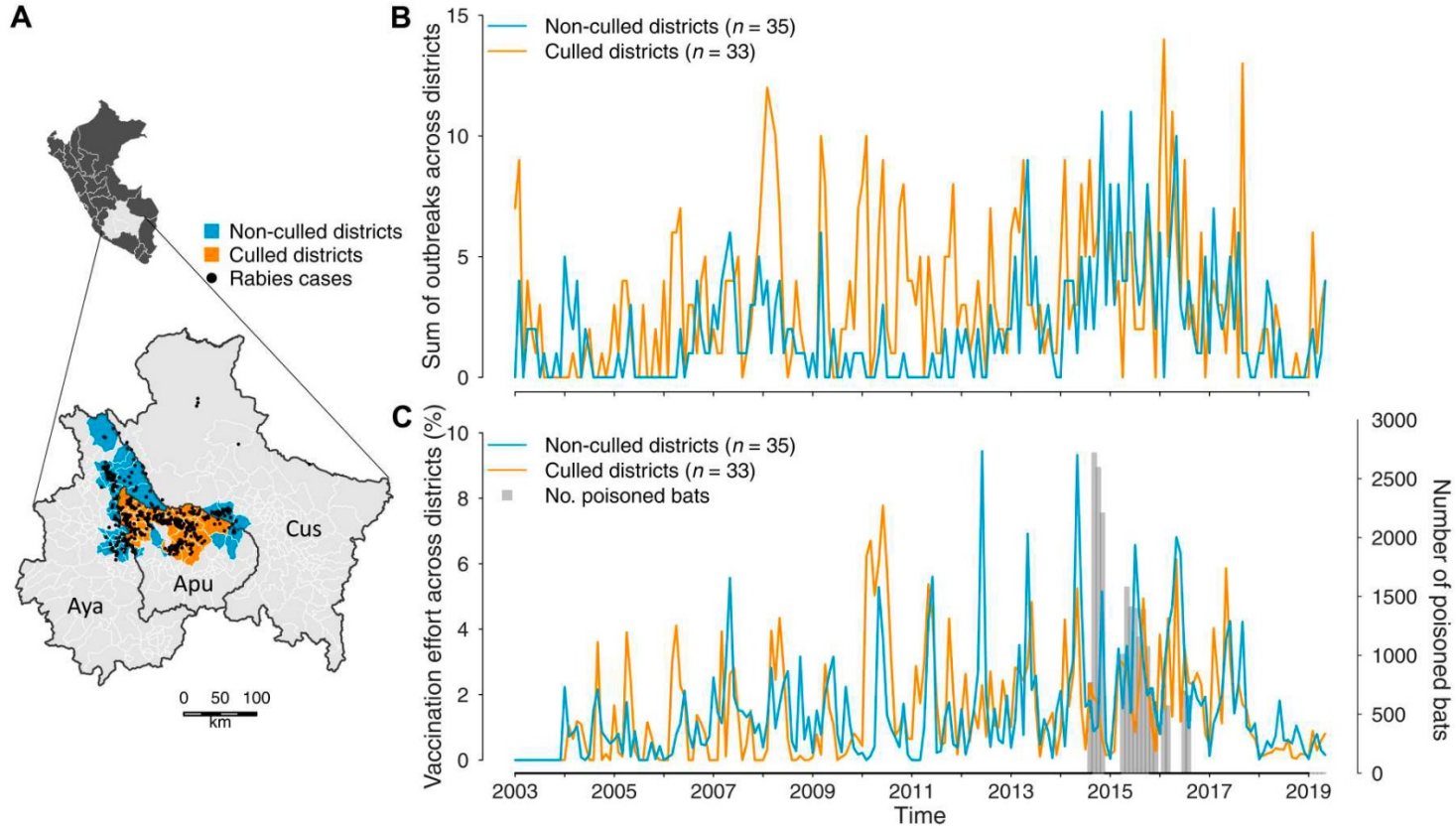
Lembo et al. 2008. *J of Animal Ecology.*

Vaccination of domestic dogs can successfully eradicate rabies from some systems.



Lushasi et al. 2023*. eLife.*

Culling of infected reservoir hosts is typically an ineffective mechanism of disease control: case study bat rabies



Viana et al. 2023. *Science Advances.*

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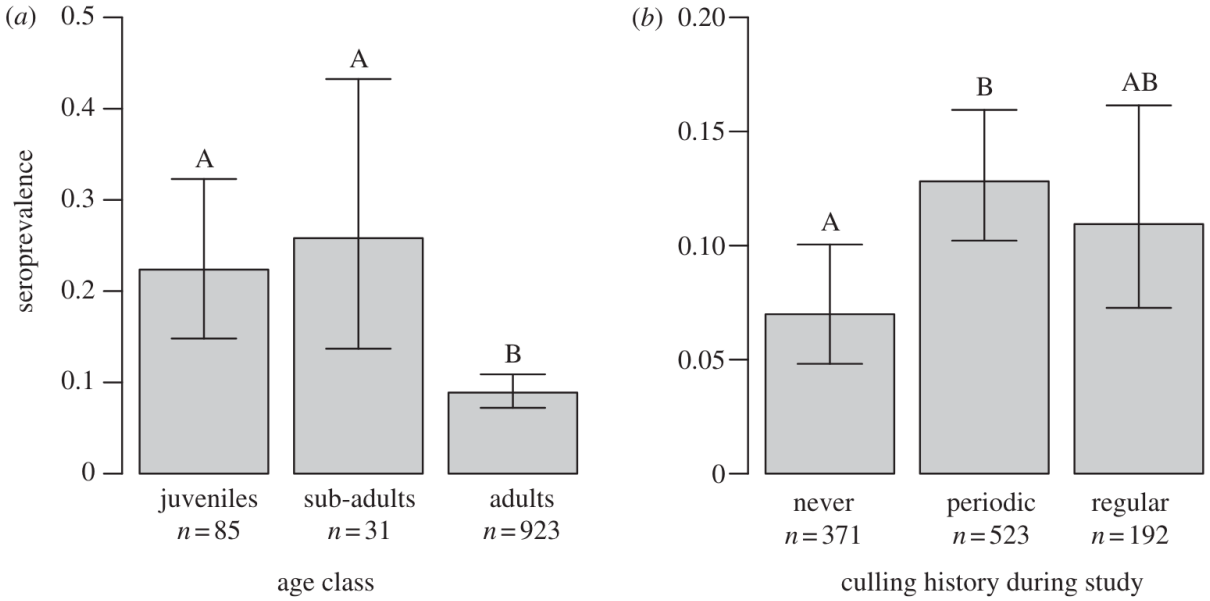
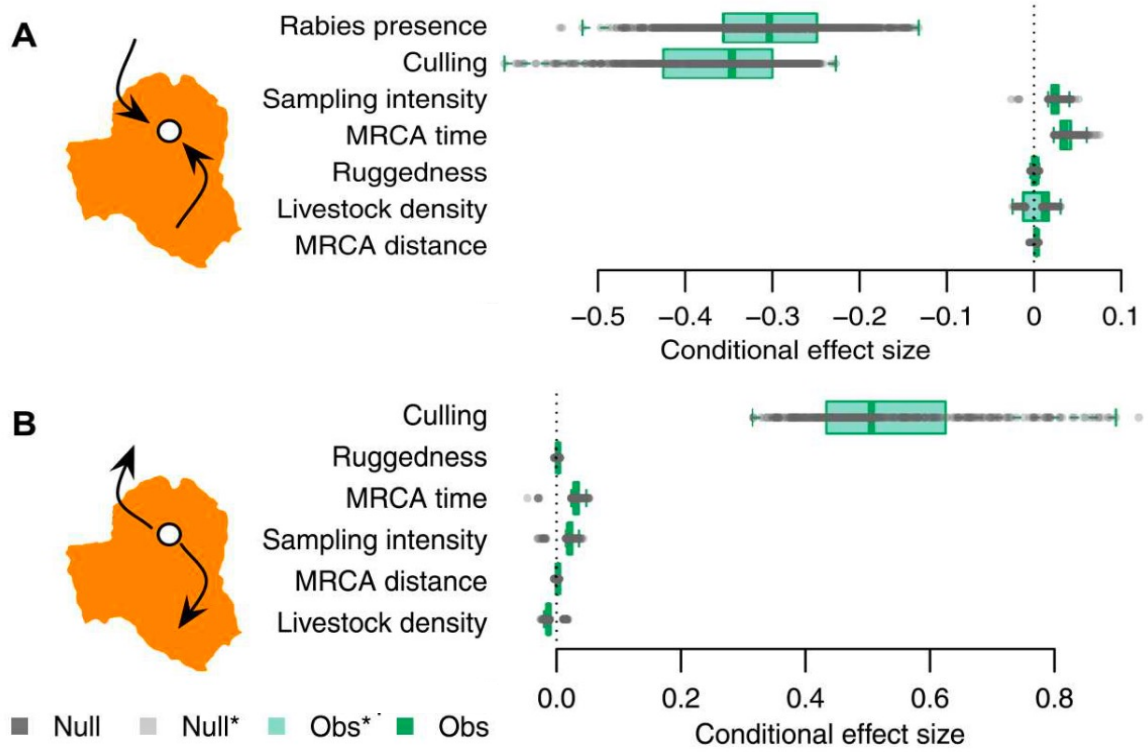
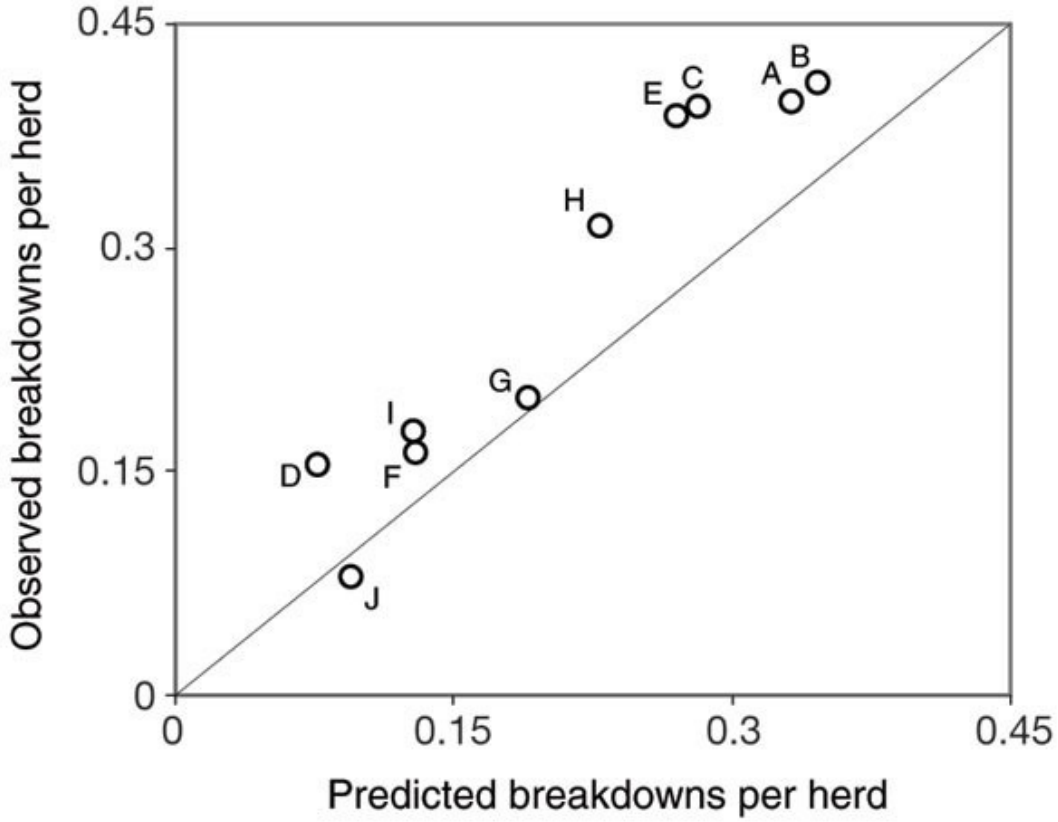


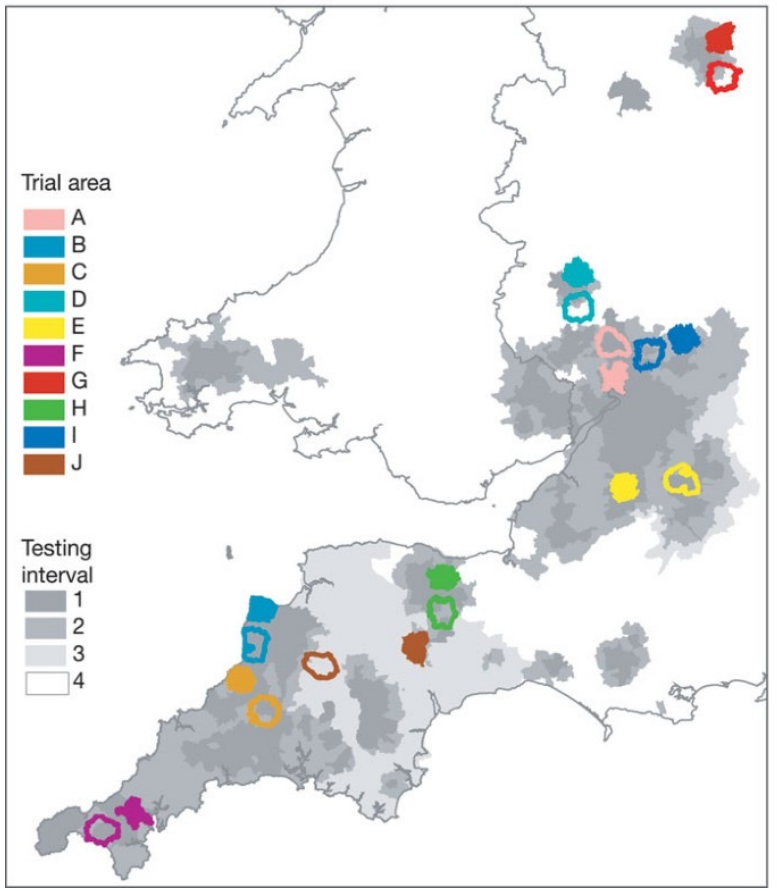


Streicker et al. 2012. *Proc Soc B.*

Viana et al. 2023. *Science Advances.*

Culling of infected reservoir hosts is typically an ineffective mechanism of disease control: Case study UK badgers and bovine TB



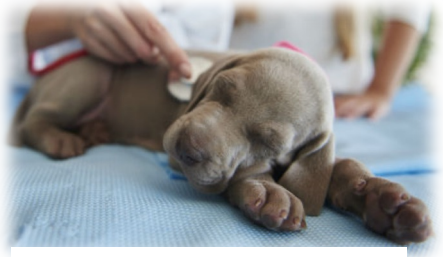


Donnelly et al. 2003. *Nature.*

Pathogens can be classed according to their host relationships.

Stage I

Transmits exclusively in animals



canine parvovirus

Stage II

Human cases from spillovers only

rabies virus

$R_0 < 1$

Stage III

Stuttering chains of transmission in humans

monkeypox (pre-2022)

$R_0 \approx 1$

Stage IV

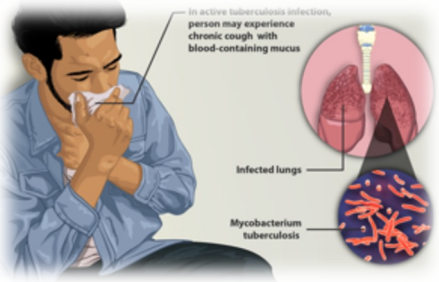
Sustained transmission and human outbreaks

Ebola virus (especially post-2014)

$R_0 > 1$

Stage V

Transmits exclusively in humans

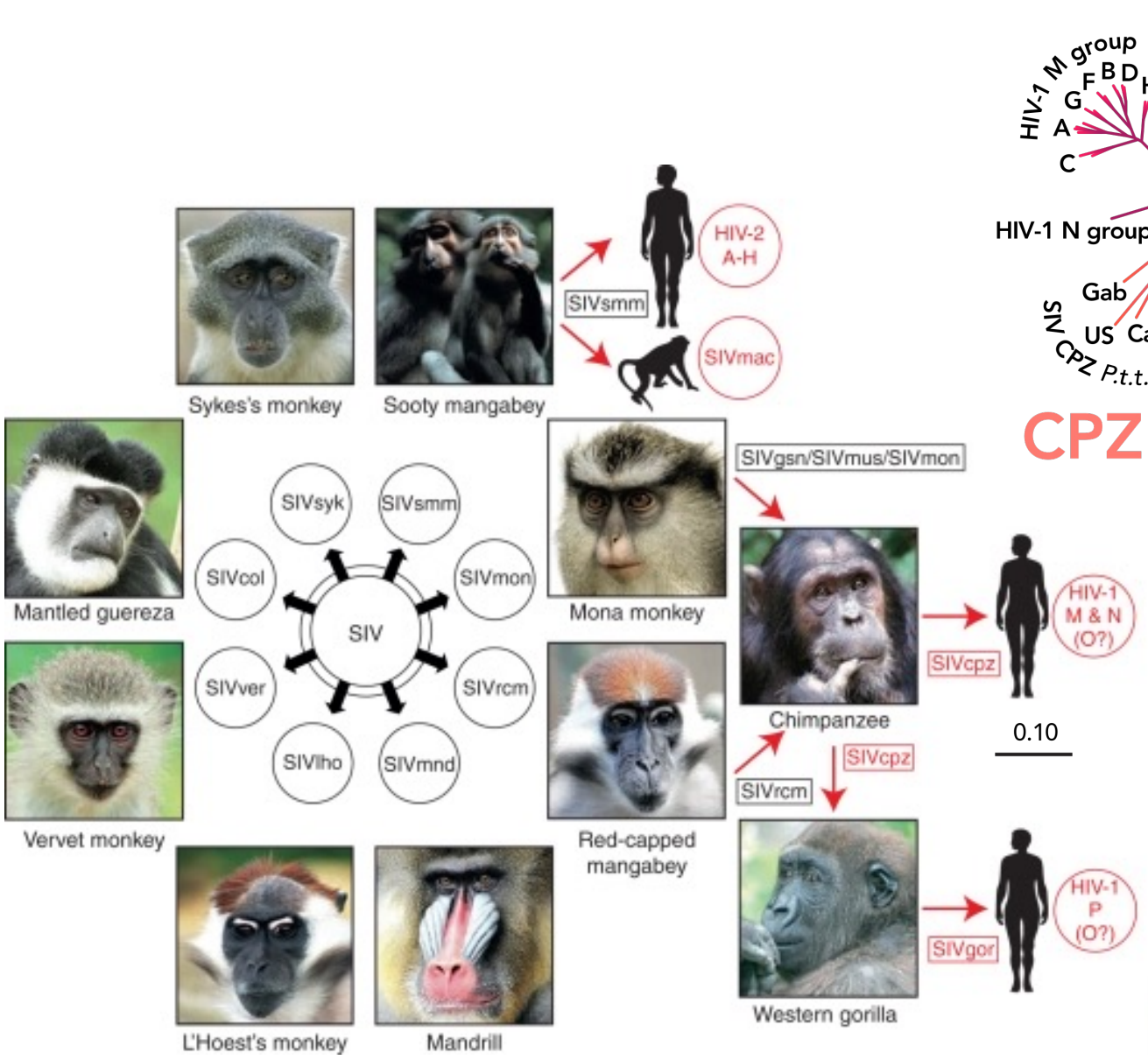


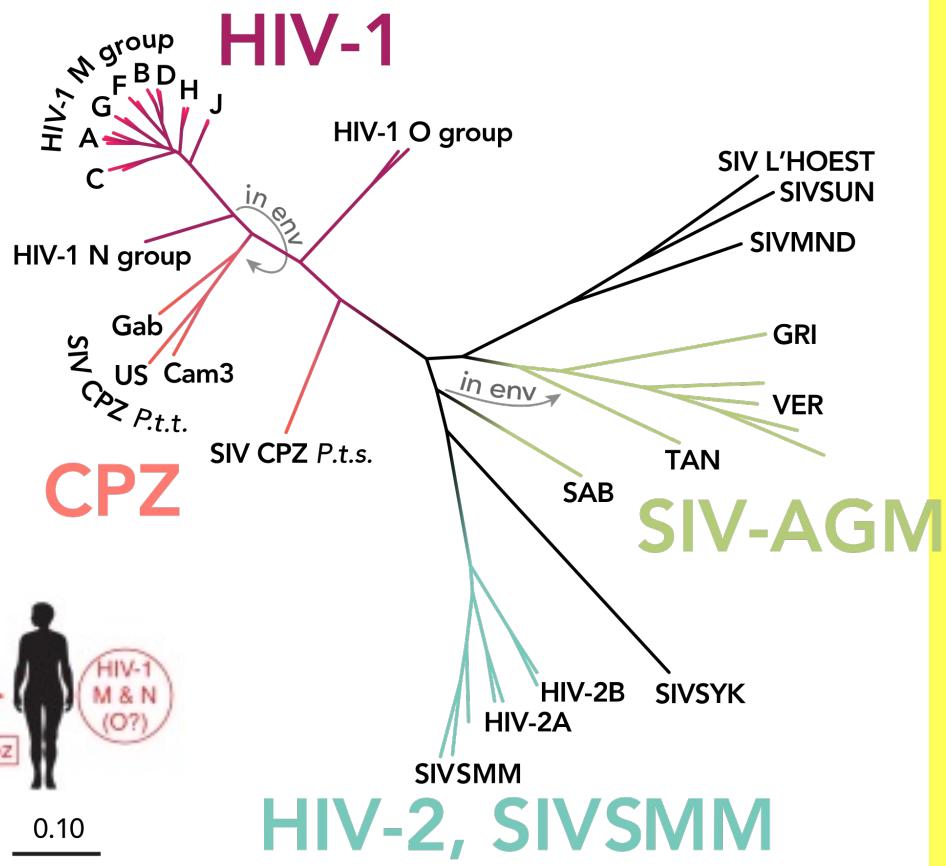
Tuberculosis

Zoonotic pathogens can be classed according to their R_0 in humans.

Lloyd-Smith et al. 2009. *Science.*

Most stage V pathogens once had an animal origin, as well!





Stage V

Transmits exclusively in humans

HIV

Sharp & Hahn. 2011. *Cold Spring Harb Perspect Med.*

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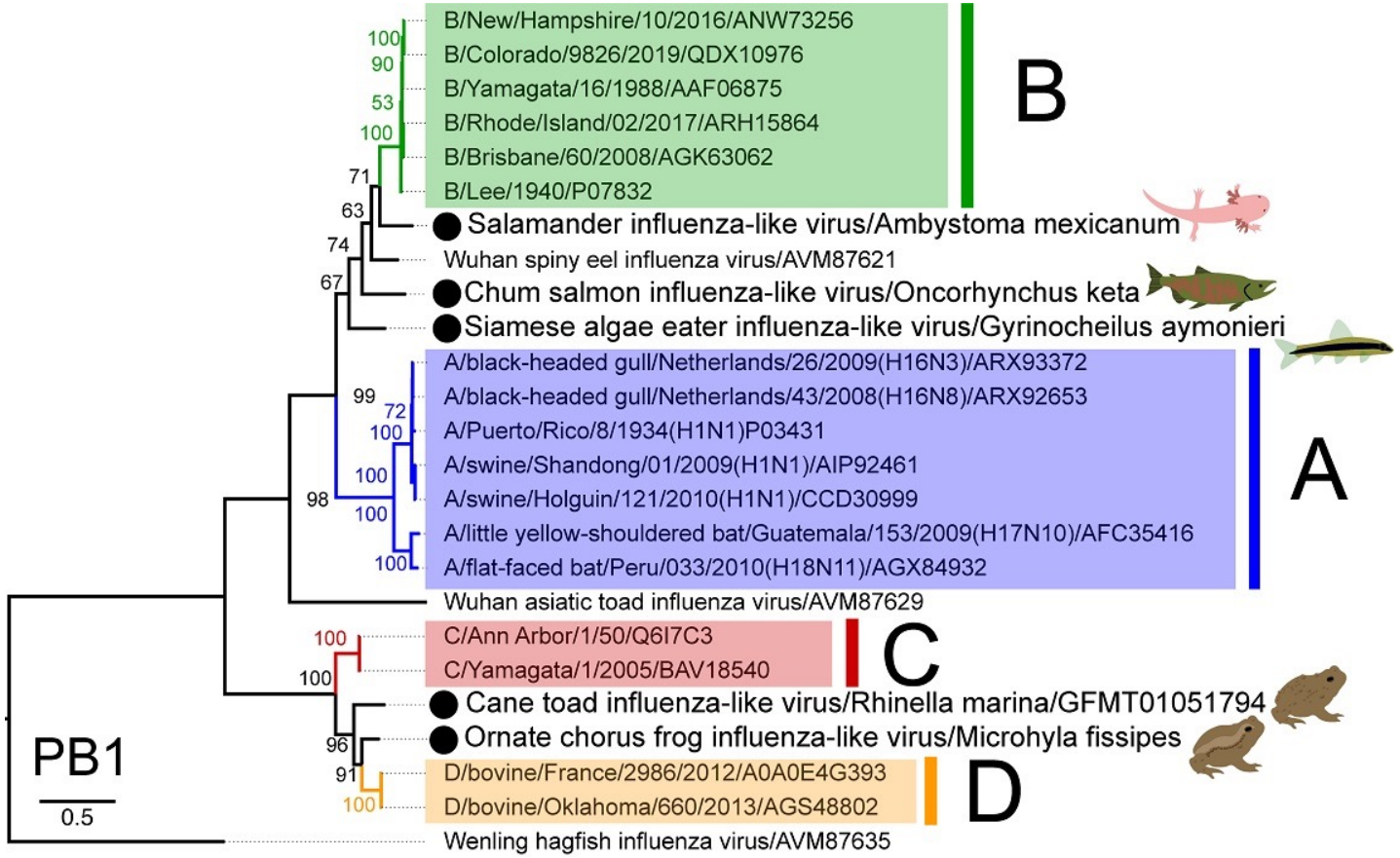
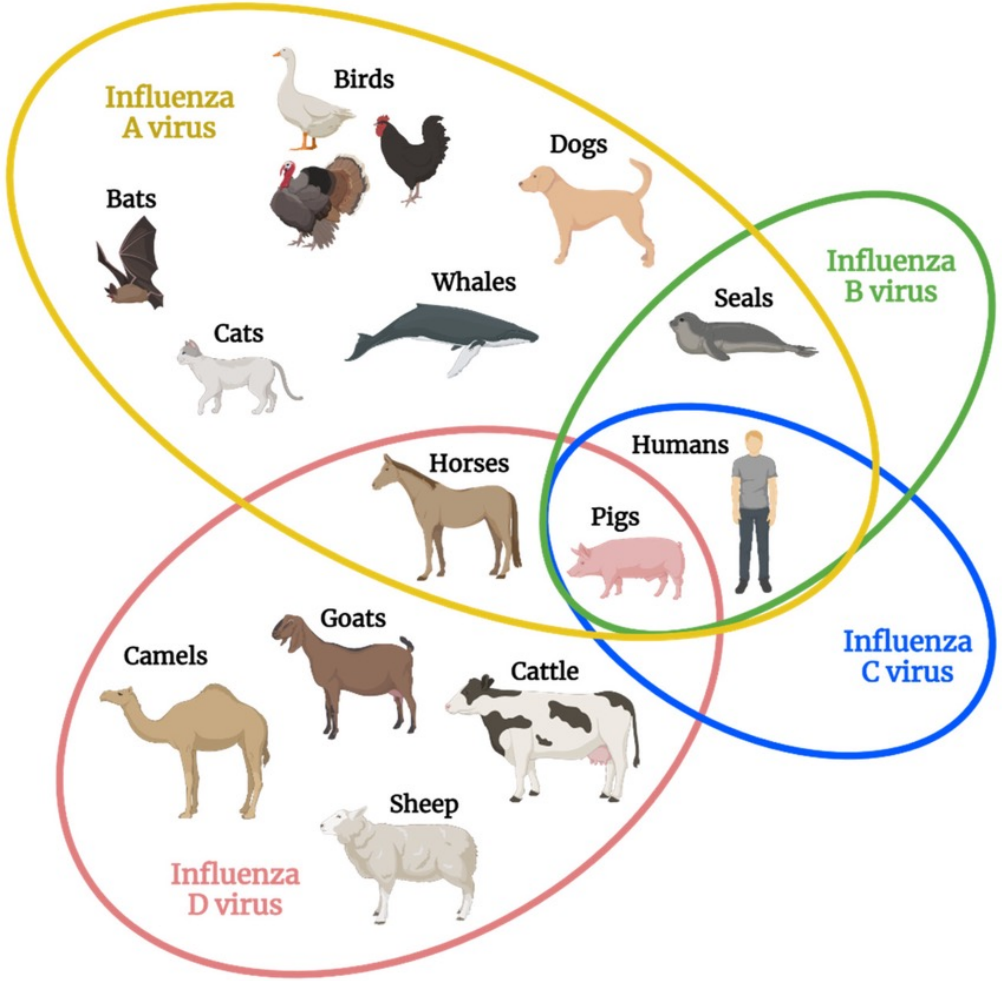
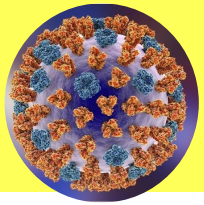


Parry et al. 2020. *Viruses.*



Skelton & Huber. 2022. *Viruses.*

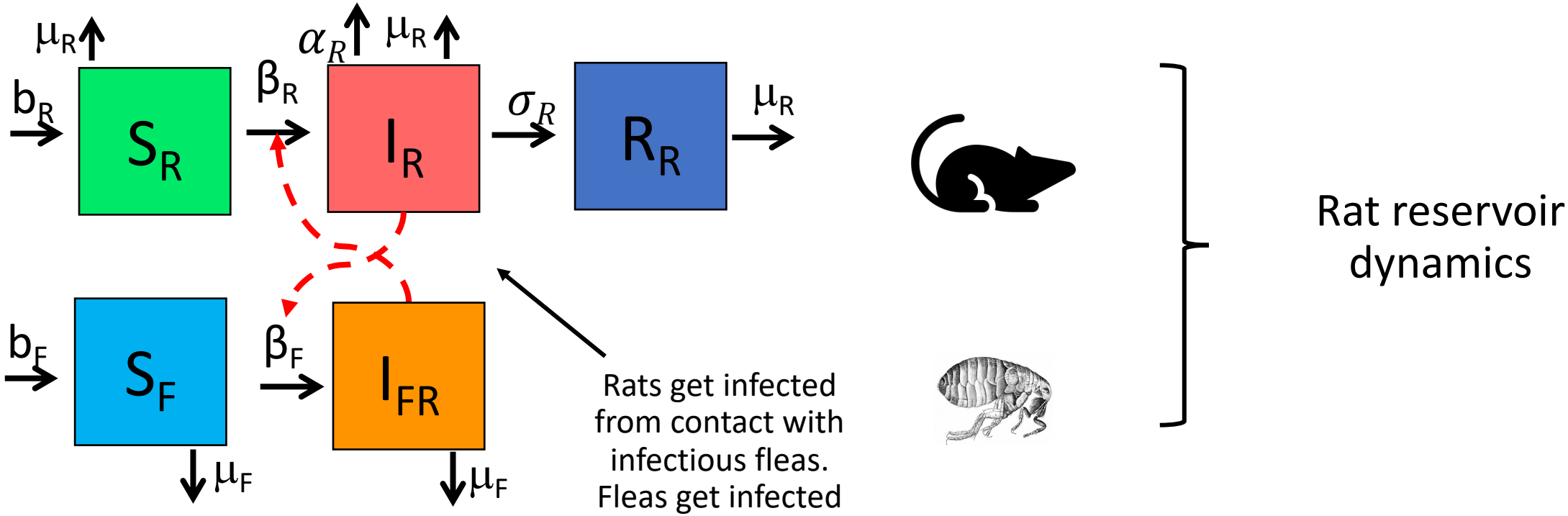
Stage V Transmits exclusively in humans



Influenza

Modeling **zoonotic pathogens** typically necessitates **modeling epidemic dynamics in multiple host populations**.

Plague has added complexity as a vector-borne pathogen!



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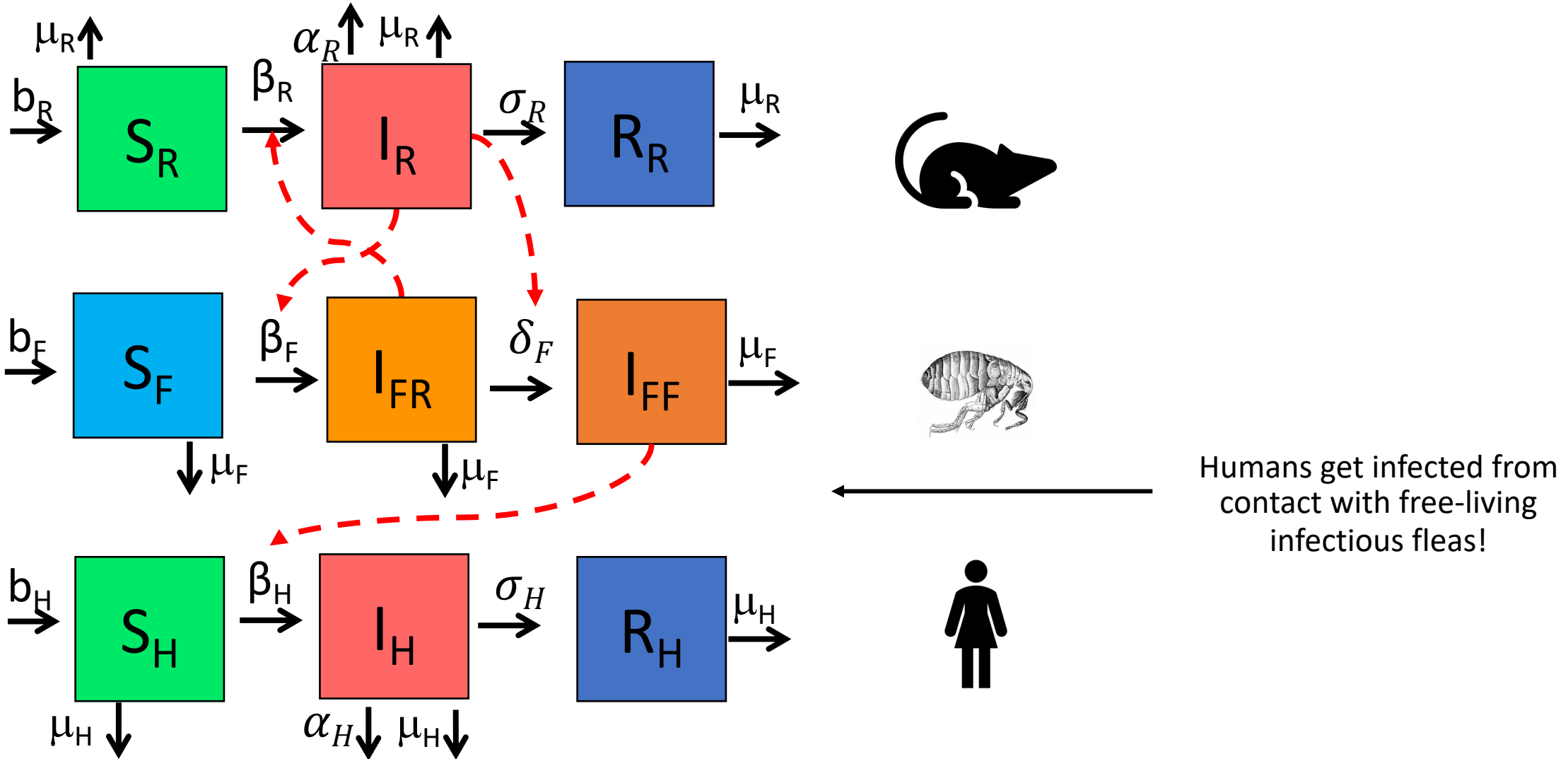

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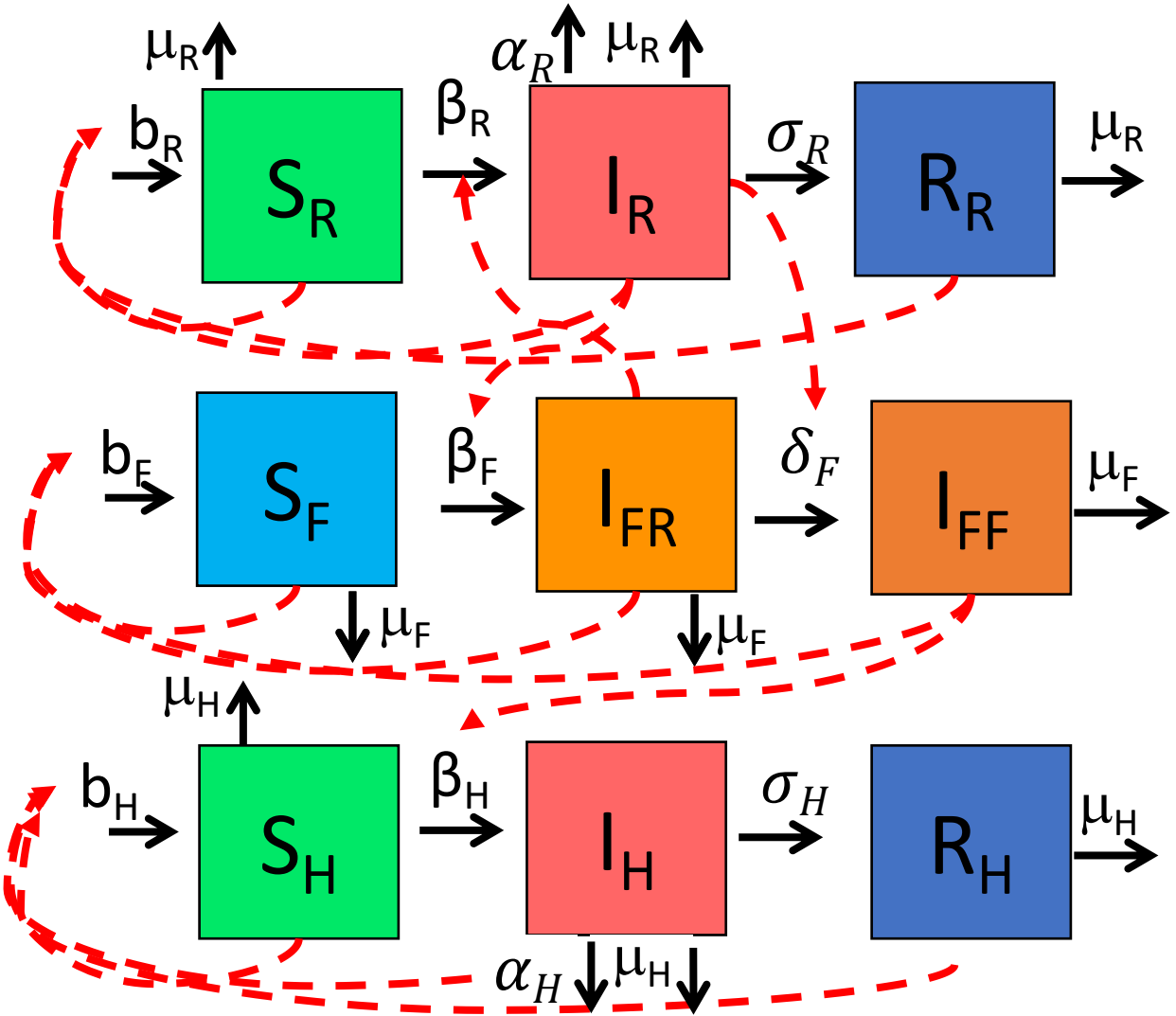
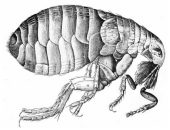
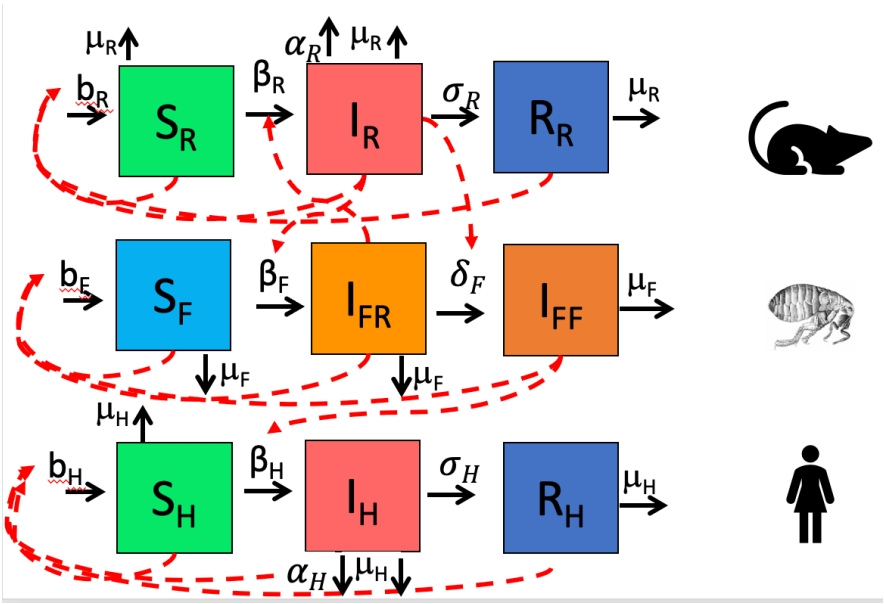




How many equations would we need to model this system?

A simple plague model



$$\frac{dS_R}{dt} = b_R(S_R + I_R + R_R) - \beta_R S_R I_{FR} - \mu_R S_R$$

$$\frac{dI_R}{dt} = \beta_R S_R I_{FR} - \mu_R I_R - \alpha_R I_R - \sigma_R I_R$$

$$\frac{dR_R}{dt} = \sigma_R I_R - \mu_R R_R$$

Rats

$$\frac{dS_F}{dt} = b_F(S_F + I_{FR} + I_{FF}) - \beta_F S_F I_R - \mu_F S_F$$

$$\frac{dI_{FR}}{dt} = \beta_F S_F I_R - \delta I_{FR} - \mu_F I_{FR}$$

$$\frac{dI_{FF}}{dt} = \delta I_{FR} - \mu_F I_{FF}$$

Fleas

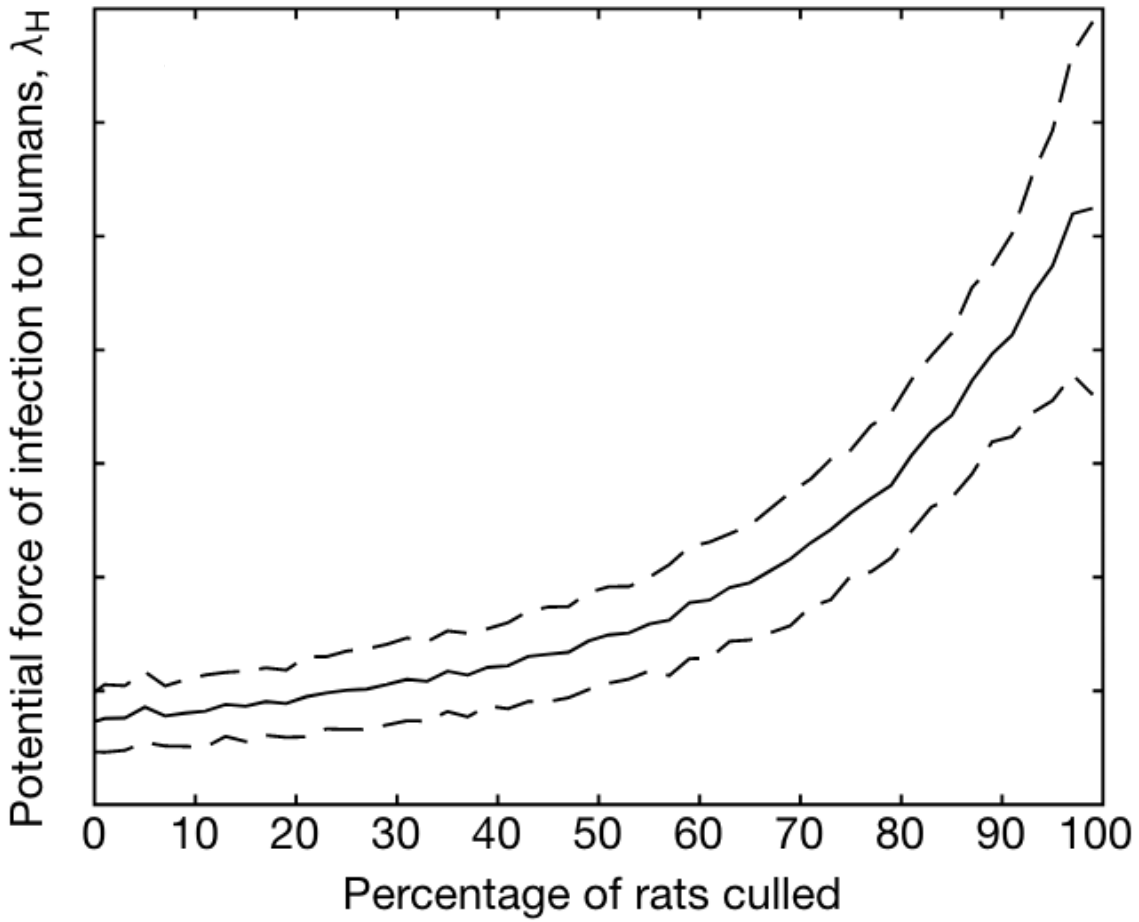
$$\frac{dS_H}{dt} = b_H(S_H + I_H + R_H) - \beta_H S_H I_{FF} - \mu_H S_H$$

$$\frac{dI_H}{dt} = \beta_H S_H I_{FF} - \mu_H I_H - \alpha_H I_H - \sigma_H I_H$$

$$\frac{dR_H}{dt} = \sigma_H I_H - \mu_H R_H$$

Humans

Fleas get infected from rats.
Humans get infected from free-living infected fleas!



"…from April 18 onwards, quantities of dead or dying rats were found in factories and warehouses…From the outer suburbs to the center of the town, in all the byways where the doctor's duties took him, in every thoroughfare, rats were piled up in garbage cans or lying in long lines in the gutters…On the fourth day the rats began to come out and die in batches…"

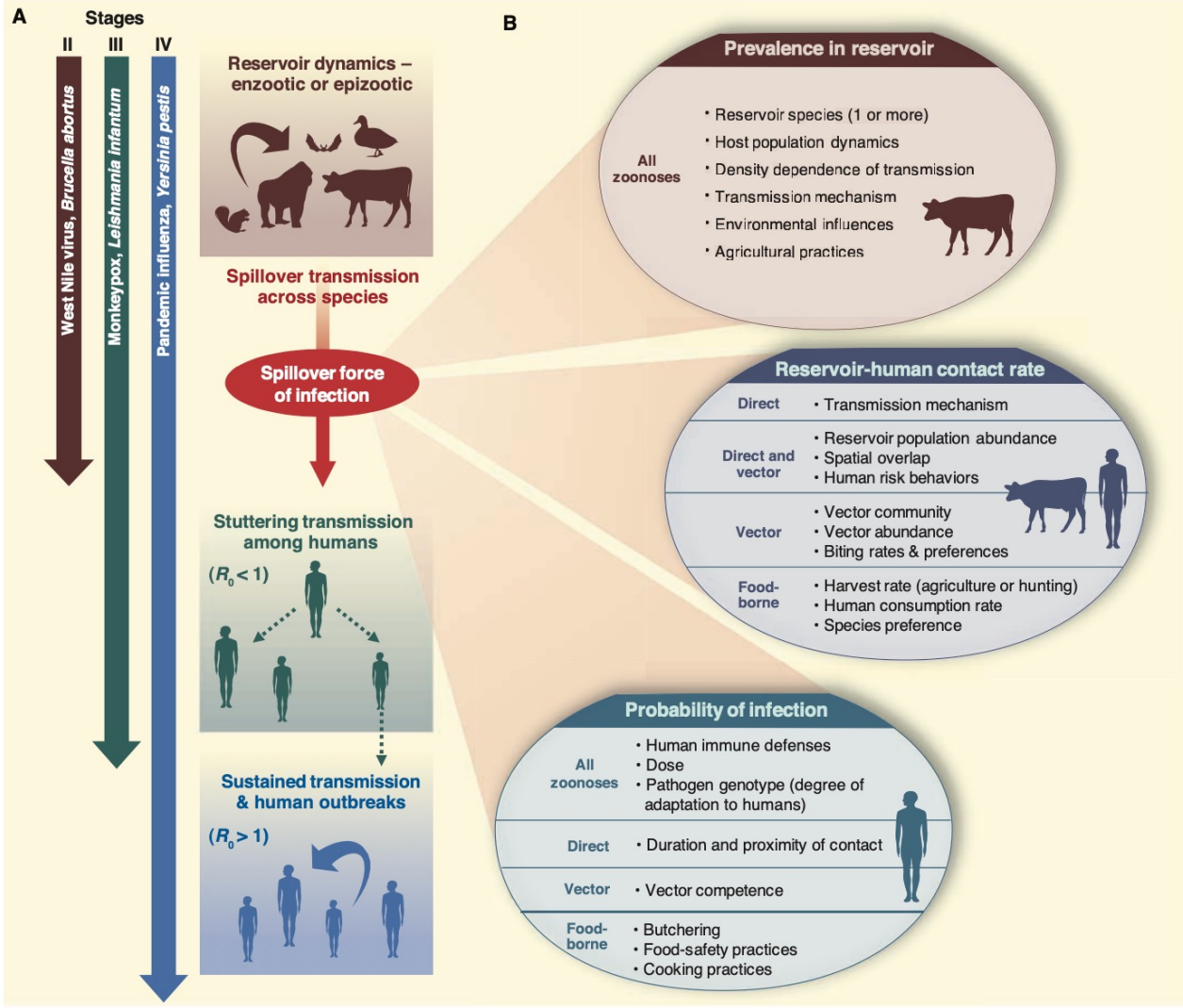
--*La Peste,* Albert Camus (1948)

Keeling and Gilligan. 2000. *Nature*.

The **force of infection** (FOI), λ, is the **rate at which susceptibles become infected**

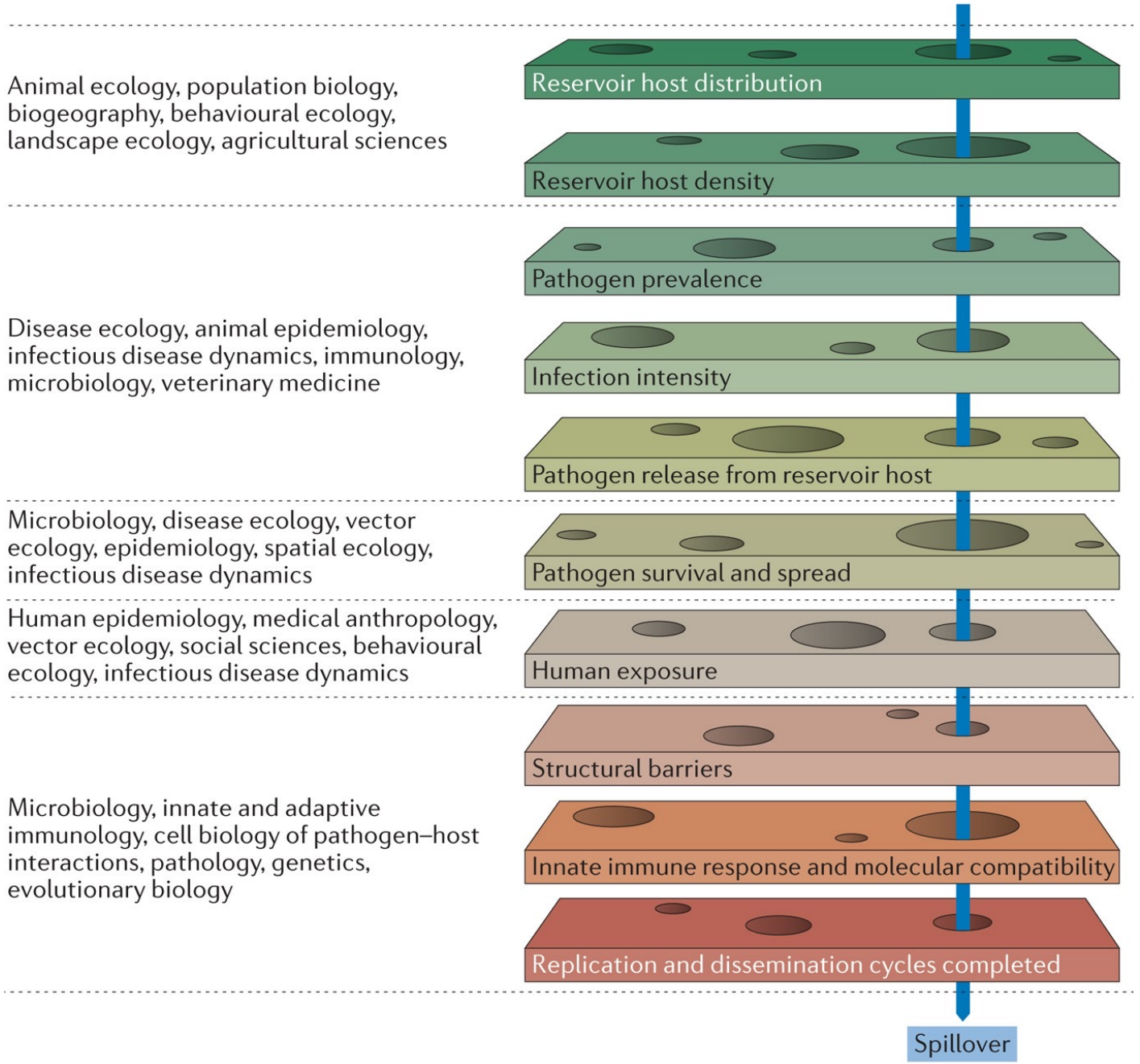
- For a single host pathogen: $\lambda = R_0 \frac{I}{N}$
- (**FOI = R_0 * proportion infected**)
- $\approx$ mirror image of $R_E = R_0 \frac{S}{N}$
- Also a finger on the epidemic pulse
- For multi-host pathogens, we can define the **spillover force of infection**
  - Comprised of:
  1. **Infectiousness** of the reservoir
  2. Reservoir-human **contact rates**
  3. **Susceptibility** in the human host

Keeling & Gilligan model λ_H for plague as proportional to the abundance of free-living infected fleas.

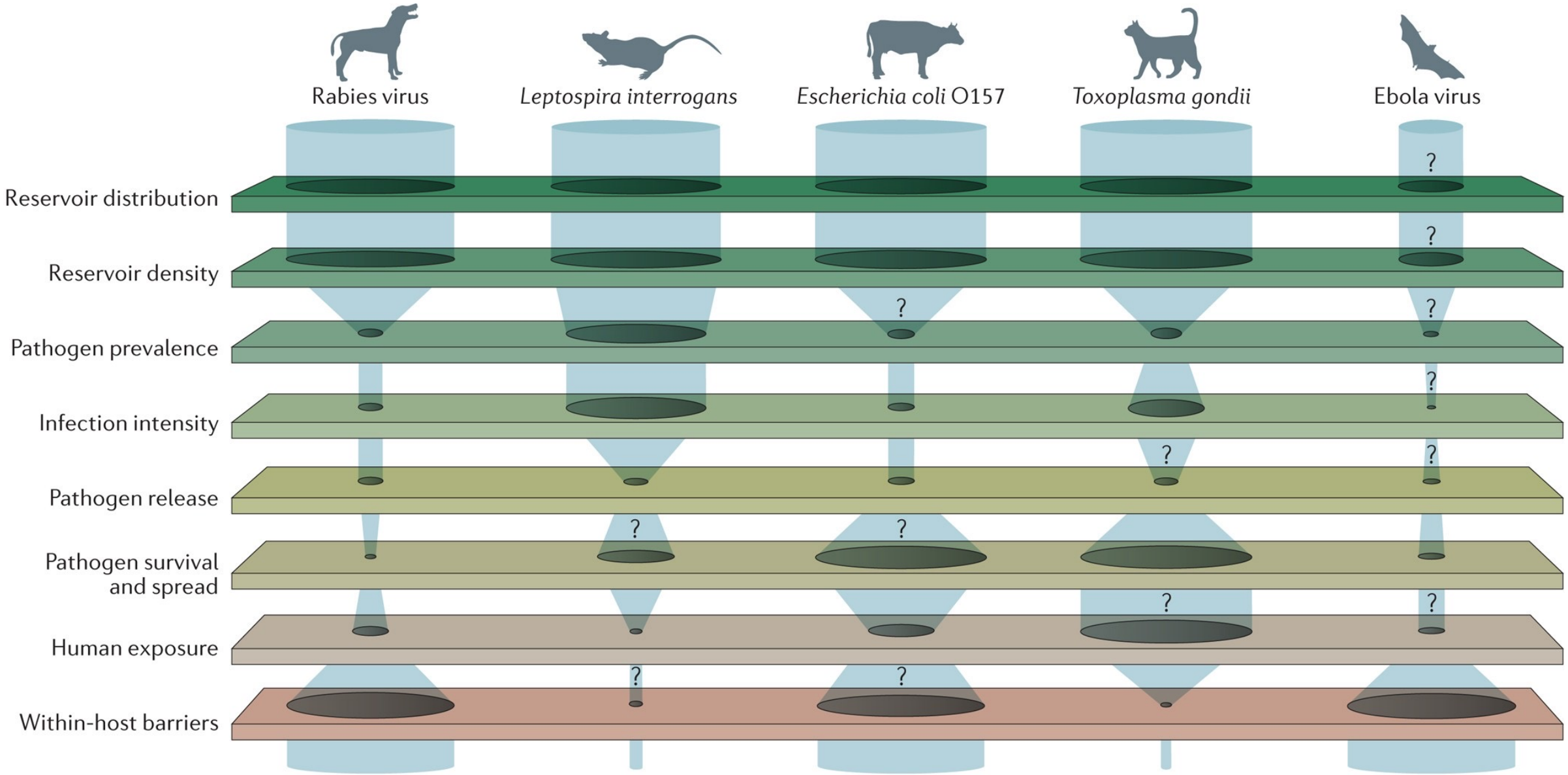


Lloyd-Smith et al. 2009. *Science.*

Zoonosis is a series of **improbable events**.



Plowright et al. 2017. *Nature Reviews Microbiology.*



Bottlenecks to spillover.

Plowright et al. 2017. *Nature Reviews Microbiology.*