Fundamentals of Ecology

Week 8, Ecology Lecture 6

Cara Brook

February 23, 2023

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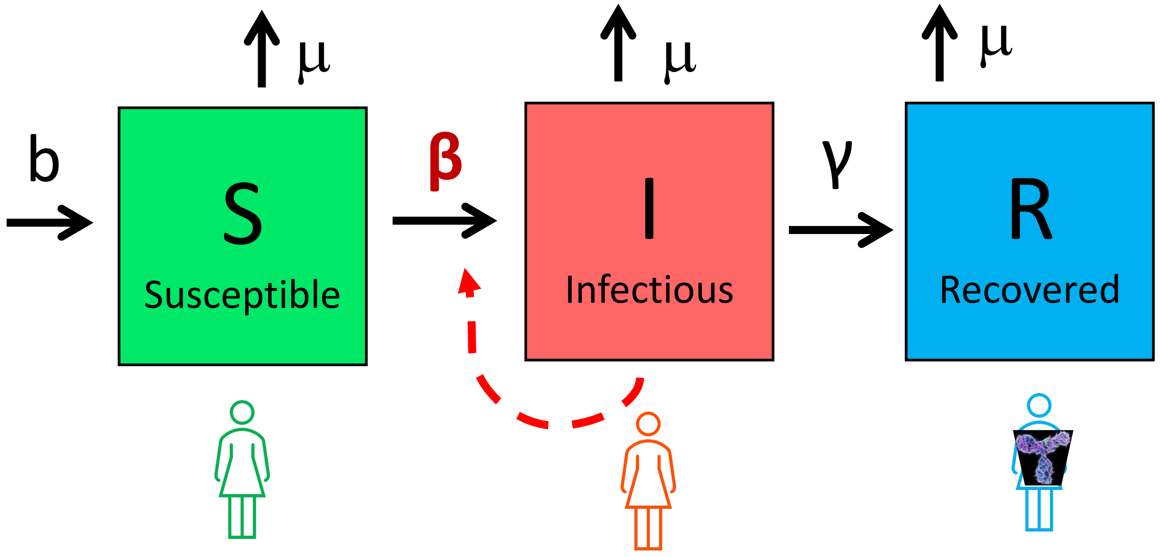
- We can leverage this RE equation to describe the proportion of the population needed to vaccinate to eradicate a pathogen: $P_V = 1 – 1/R_0$
- Vaccination dates back to antiquity but does not work equally well for all pathogen types and faces many challenges because most pathogens do not follow the simplistic dynamics of measles.

We can adapt the simple SIR model to better match our pathogen of interest and our corresponding data.

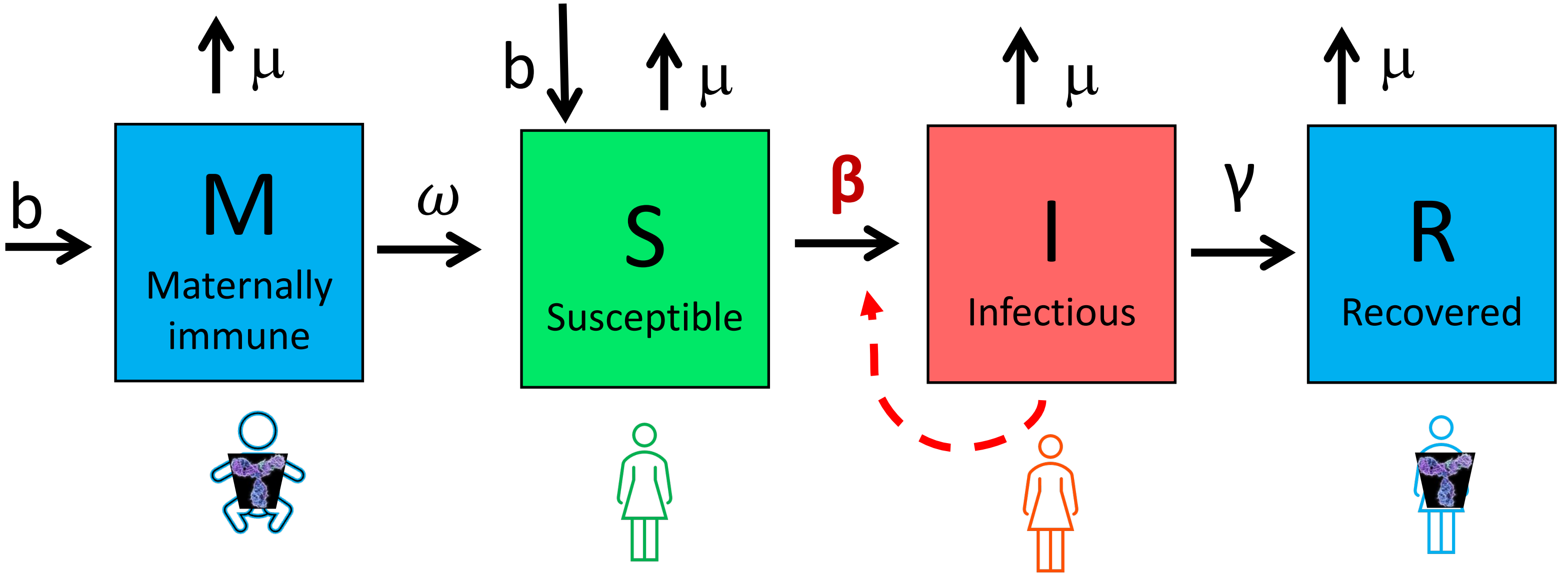
$$\frac{dS}{dt} = b(S + I + R) - \beta SI - \mu S$$

$$\frac{dI}{dt} = \beta SI - \gamma I - \mu I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$



Incorporating Maternal Immunity



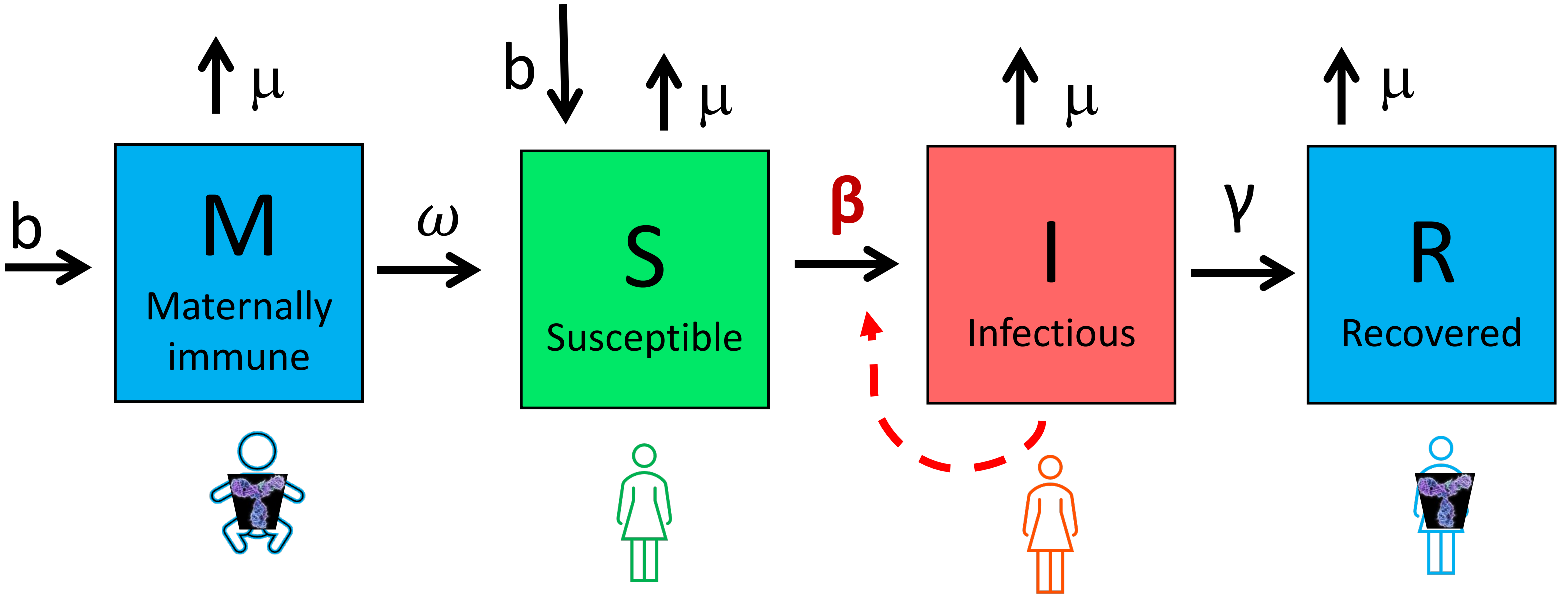
Incorporating Maternal Immunity

$$\frac{d\boldsymbol{S}}{dt} = b\boldsymbol{S} - \beta\boldsymbol{S}\boldsymbol{I} - \mu\boldsymbol{S}$$

$$\frac{d\boldsymbol{I}}{dt} = \beta\boldsymbol{S}\boldsymbol{I} - \gamma\boldsymbol{I} - \mu\boldsymbol{I}$$

$$\frac{d\boldsymbol{R}}{dt} = \gamma\boldsymbol{I} - \mu\boldsymbol{R}$$

What does our new equation look like?



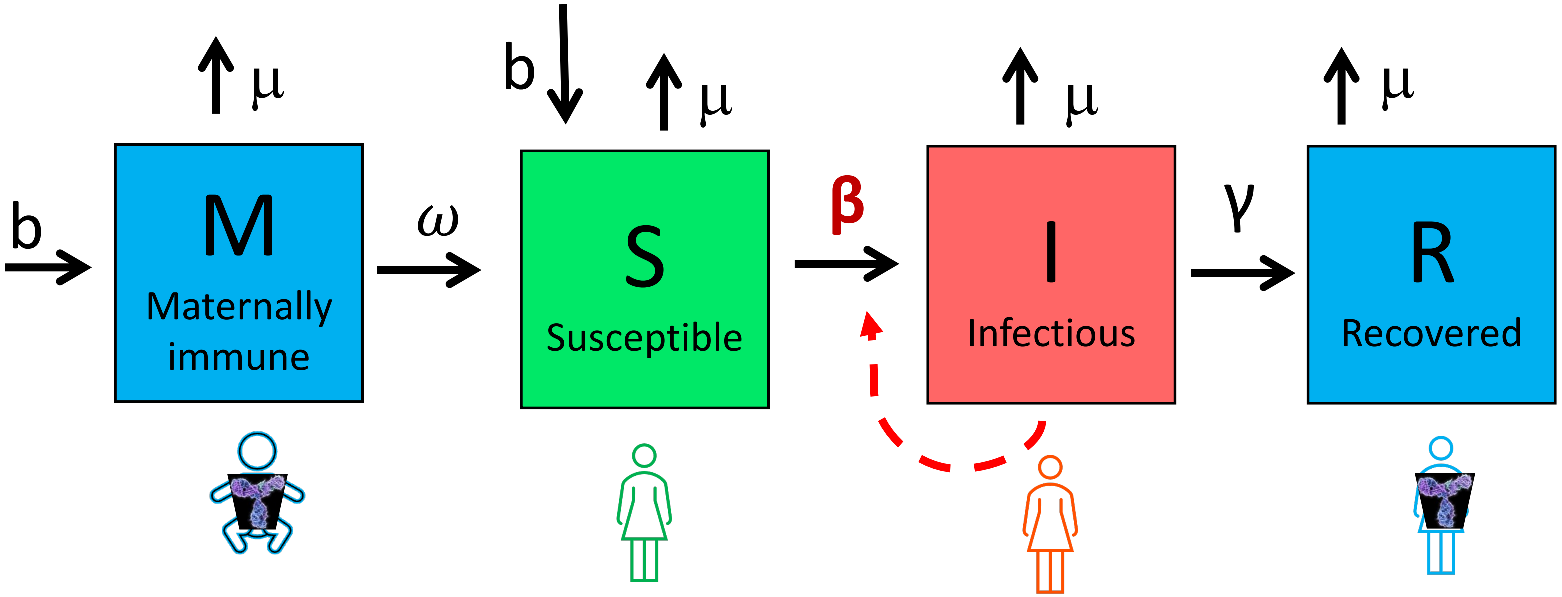
Incorporating Maternal Immunity

$$\frac{dM}{dt} = b(I + R) - \omega M - \mu M$$

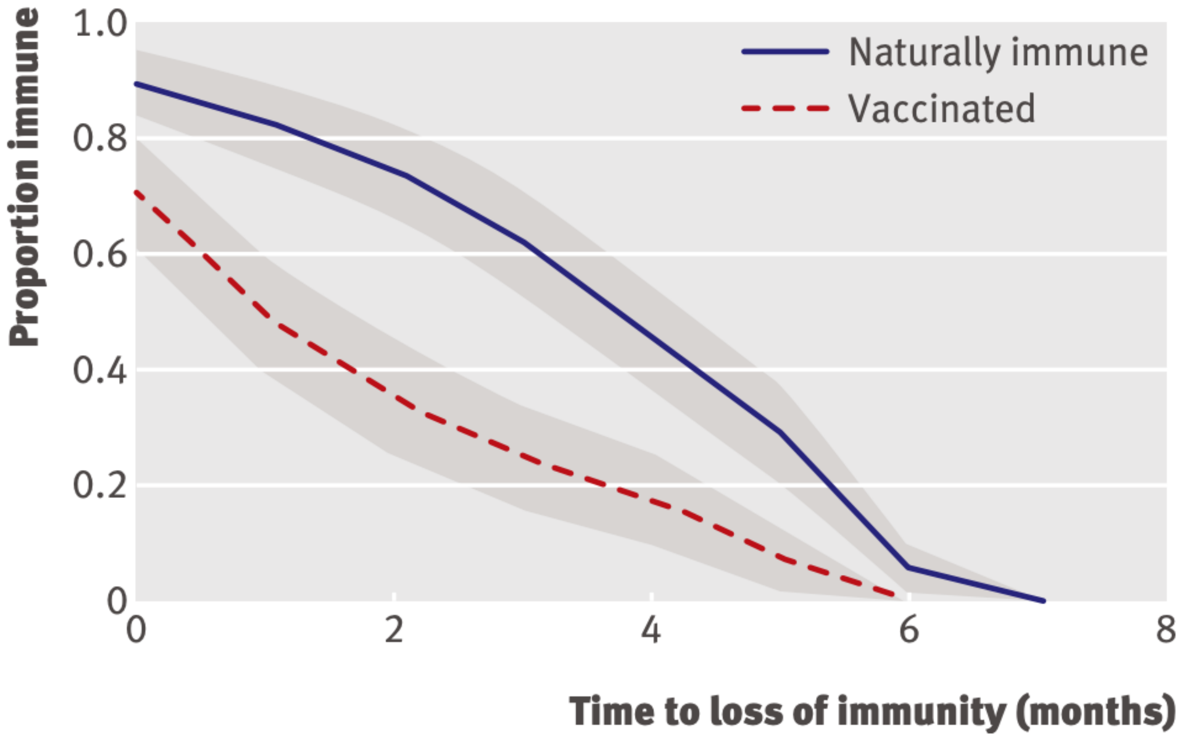
$$\frac{dS}{dt} = \omega M + bS - \beta SI - \mu S$$

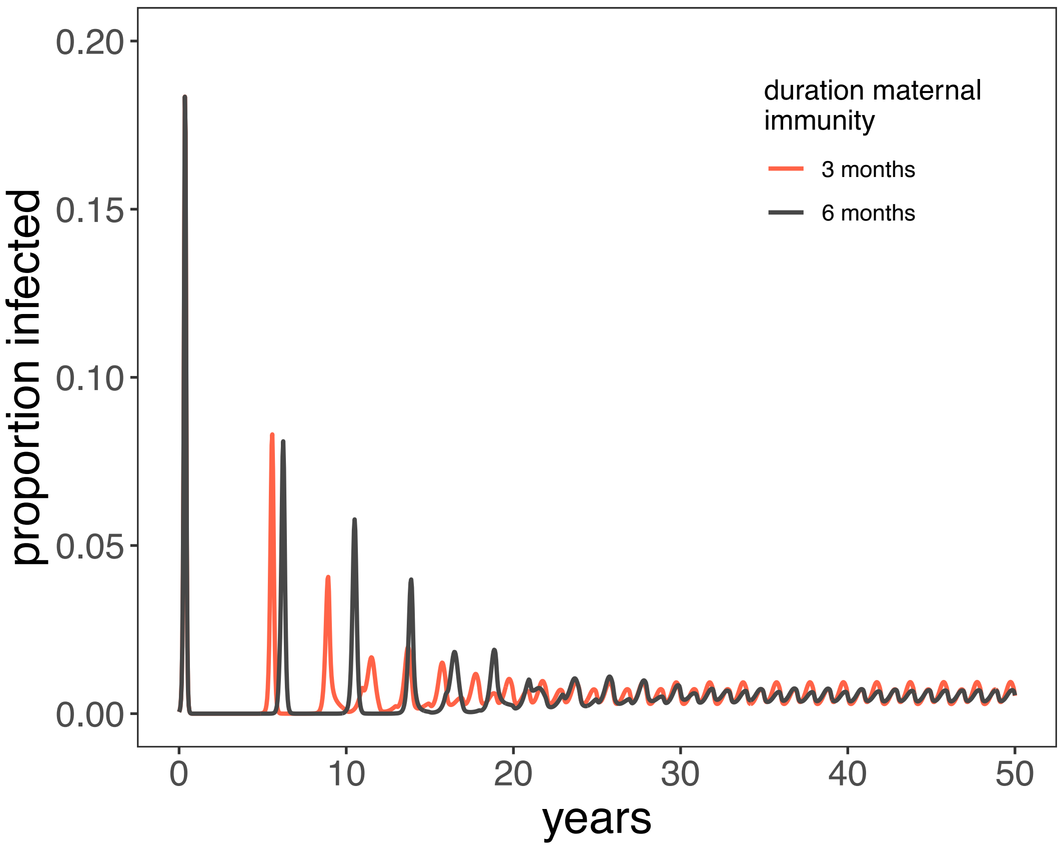
$$\frac{dI}{dt} = \beta SI - \gamma I - \mu I$$

$$\frac{dR}{dt} = \gamma I - \mu R$$



Duration of maternal immunity for measles for naturally infected vs. vaccinated mothers → will impact dynamical predictions!



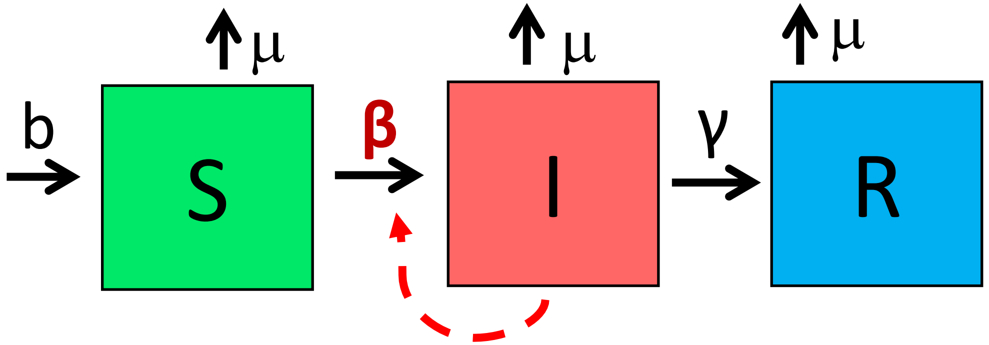


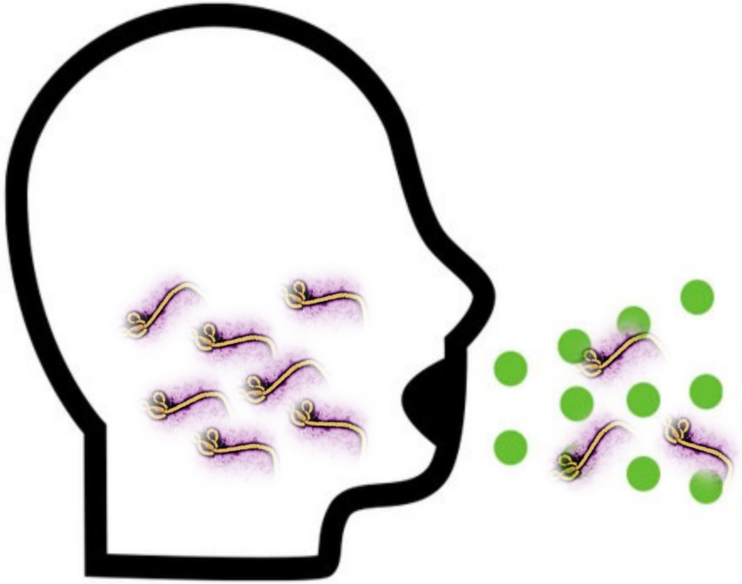
Leuridan et al. 2010. *BMJ.*

incorporating maternal immunity

Pathogens exhibit **diverse transmission mechanisms** that require tailored modeling structures

- **Directly-transmitted** diseases are transmitted via exchange of bodily fluids
  - Droplet (> 5 microns) spread or direct contact
  - Includes sexually-transmitted pathogens, though often modeled with a more complex contact network
  - Smallpox *(Variola* spp.), HIV, Mononucleosis (*Epstein Barr virus*)
- **Indirectly-transmitted** diseases are transmitted via droplets retained in air
  - Droplets < 5 microns in diameter
  - Measles, COVID (*SARS-CoV-2*)





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- **Environmentally-transmitted** pathogens are transmitted outside of the host (e.g. water-borne, food-borne)
  - Examples: Cholera *(Vibrio cholerae*)*,* Salmonellosis (*Salmonella* spp. bacteria), White-Nosed Syndrome (*Pseudogymnoascus destructans*)

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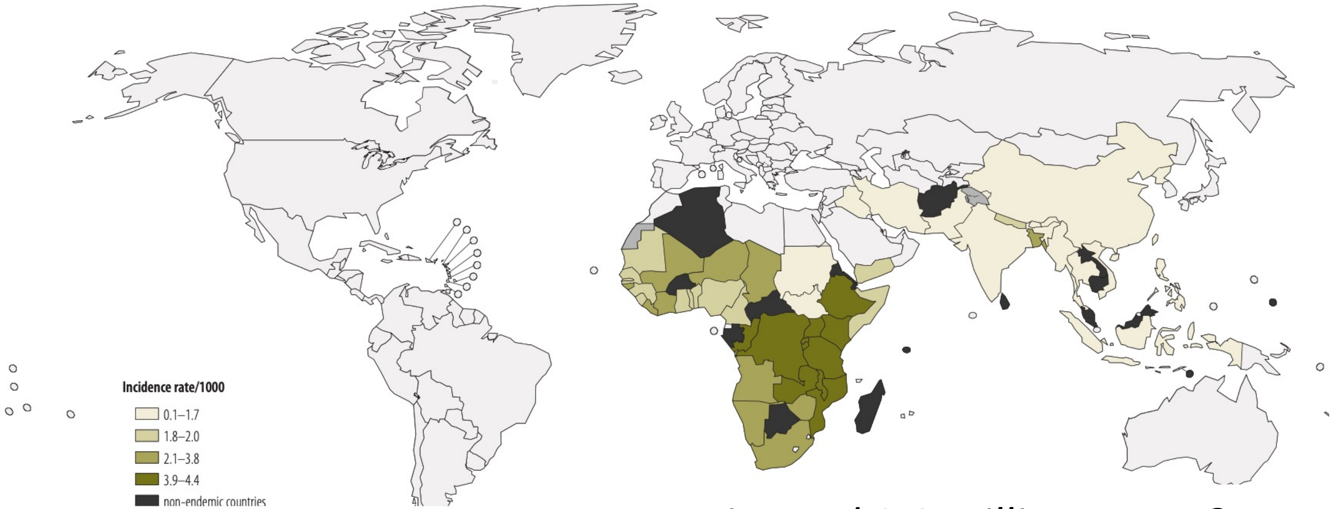
Global Burden of Cholera, 2012



Estimated 2.8 million cases & 95,000 deaths annually

Ali et al. 2012. *WHO Bulletin.*

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  - Examples: Cholera (*Vibrio cholerae*), Salmonellosis (*Salmonella* spp. bacteria), White-Nosed Syndrome (*Pseudogymnoascus destructans*)
  - Here, the **environmental reservoir** is often modeled as its own population

$$\frac{dB}{dt} = \varphi I B$$

$$\frac{dS}{dt} = b(S + I + R) - \beta S B - \mu S$$

$$\frac{dI}{dt} = \beta S B - \gamma I - \mu I - \alpha I$$

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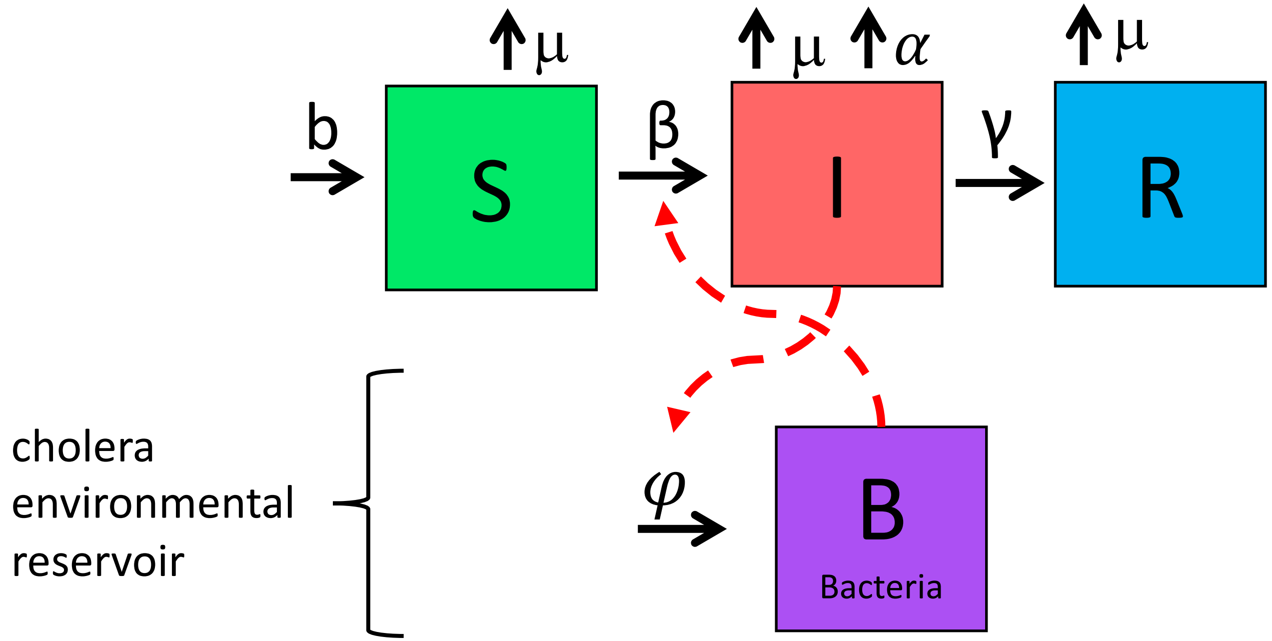

Codeço 2001. *BMC Infectious Diseases.*

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- **Vertically-transmitted** pathogens are transmitted mother-to-child *in utero*
  - Examples: HIV, *Herpes simplex virus*, *Cytomegalovirus*, Rubella, Zika

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- In untreated HIV+ mothers, rate of vertical transmission for HIV = 15-45%
- Reduced to <1% for those on ART, though global access to ART is geographically heterogenous

ART coverage for those in need, from WHO

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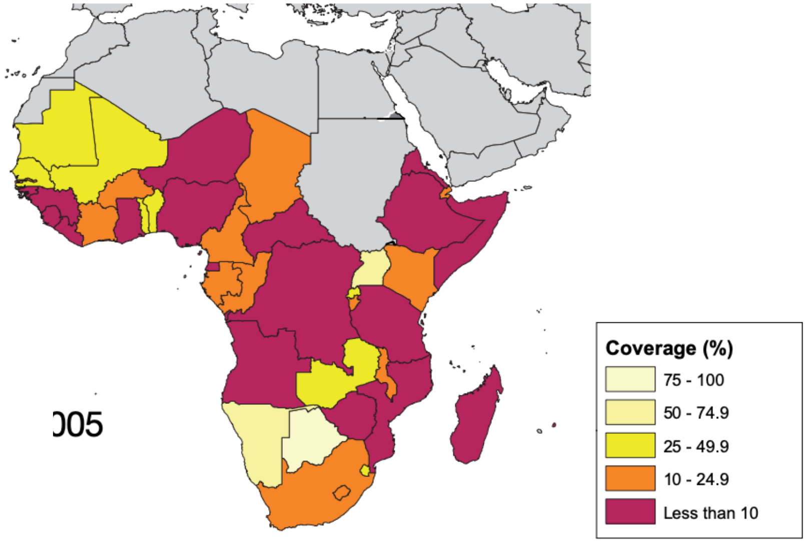

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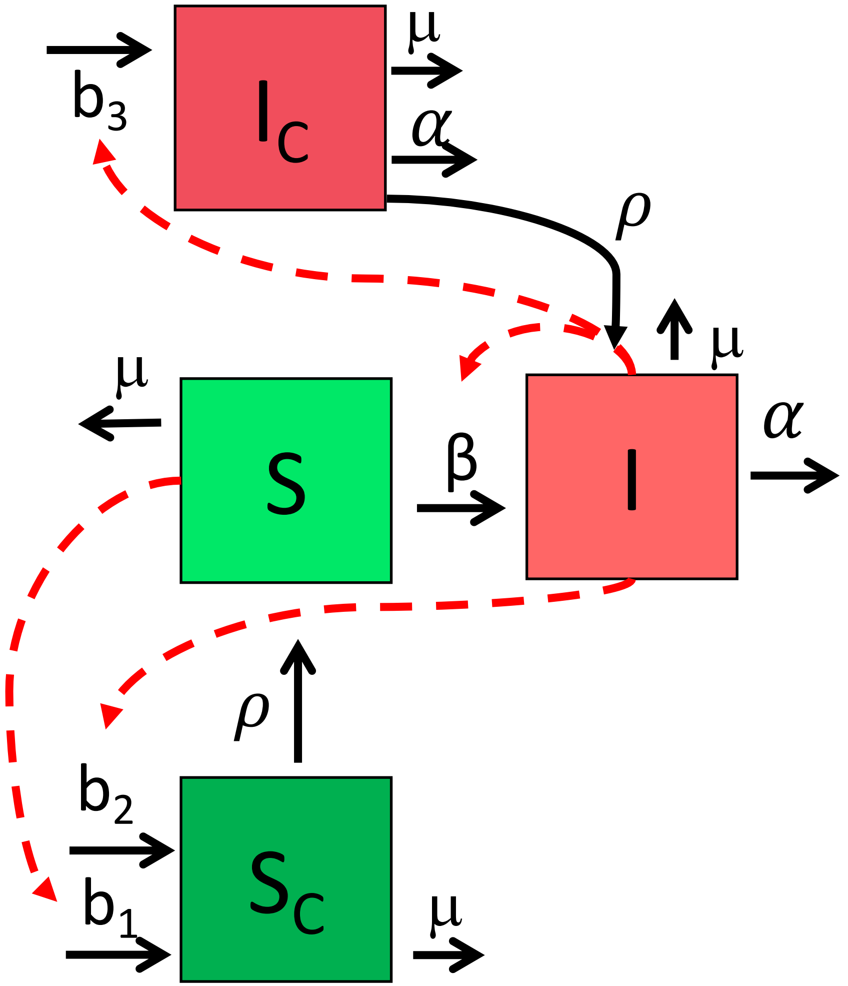

$$\frac{dS}{dt} = \rho S_C - \beta S(I_C + I) - \mu S$$

$$\frac{dI}{dt} = \beta S(I_C + I) + \rho I_C - \mu I - \alpha I$$

$$\frac{dS_C}{dt} = b_1 S + b_2 I - S_C(\rho + \mu)$$

$$\frac{dI_C}{dt} = b_3 I - I_C(\rho + \mu + \alpha)$$

Yusuf et al. 2021. *Chaos and Fractals.*

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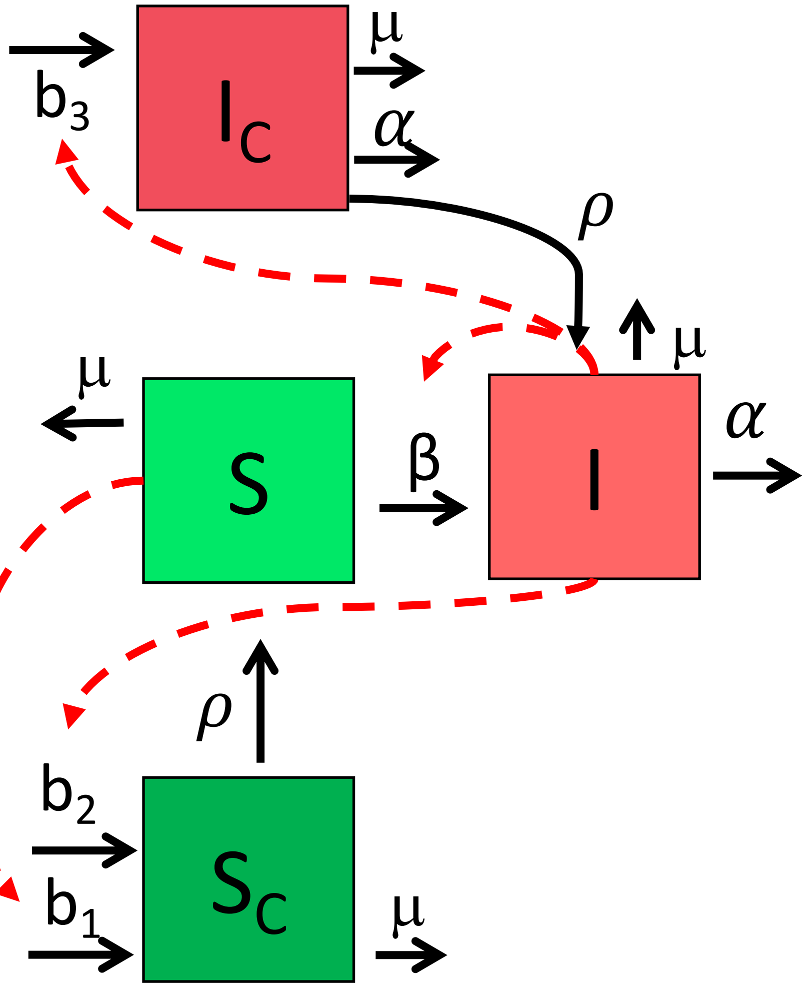

$$\frac{dS}{dt} = \rho S_C - \beta S(I_C + I) - \mu S$$

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$$\frac{dS_C}{dt} = b_1 S + b_2 I - S_C\,(\rho + \mu)$$

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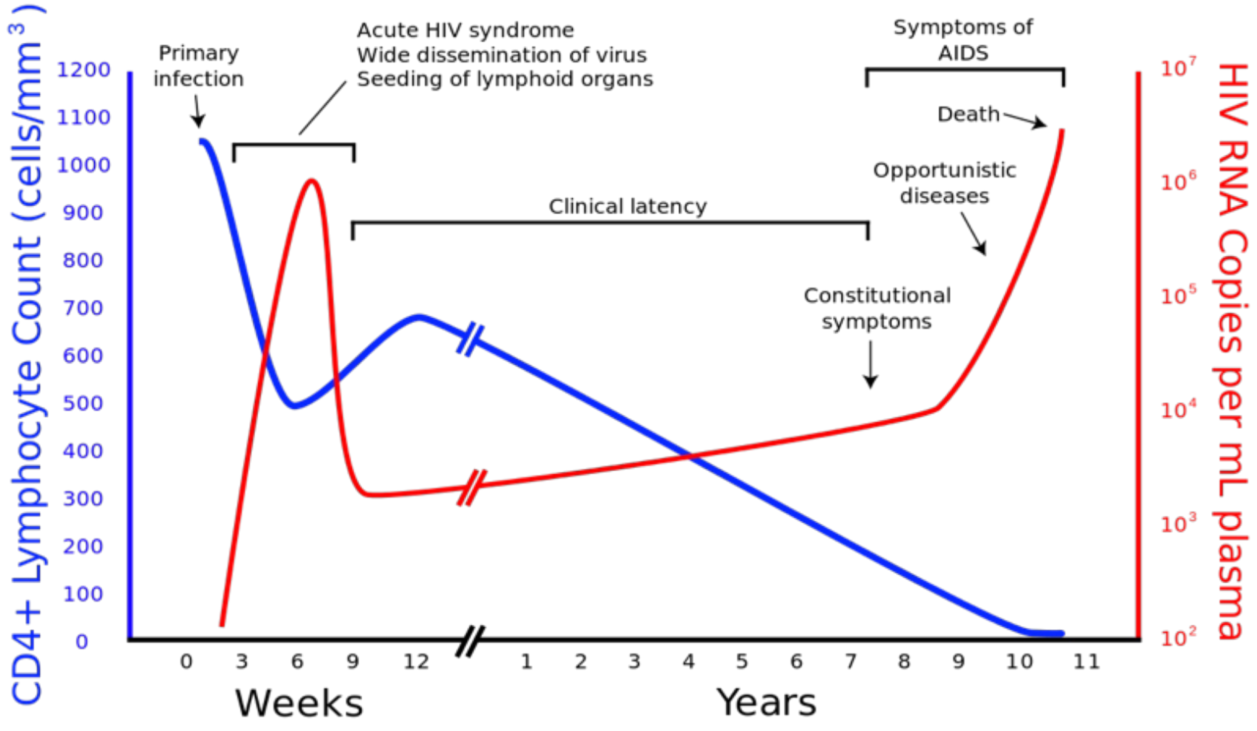
Vertical AND horizontal transmission!

Yusuf et al. 2021. *Chaos and Fractals.*

A brief interlude with some extra details about HIV



- First recognized by newspapers in 1981 as gay men and injecting drug users in the US began reporting to hospitals with rare pneumonias and skin cancers
- Widespread fear and intense stigma attributed to ‘gay cancer’
- Virus co-discovered in 1983 by American Robert Gallo and Insitut Pasteur team, Françoise Barree-Sinoussi and Luc Montagnier

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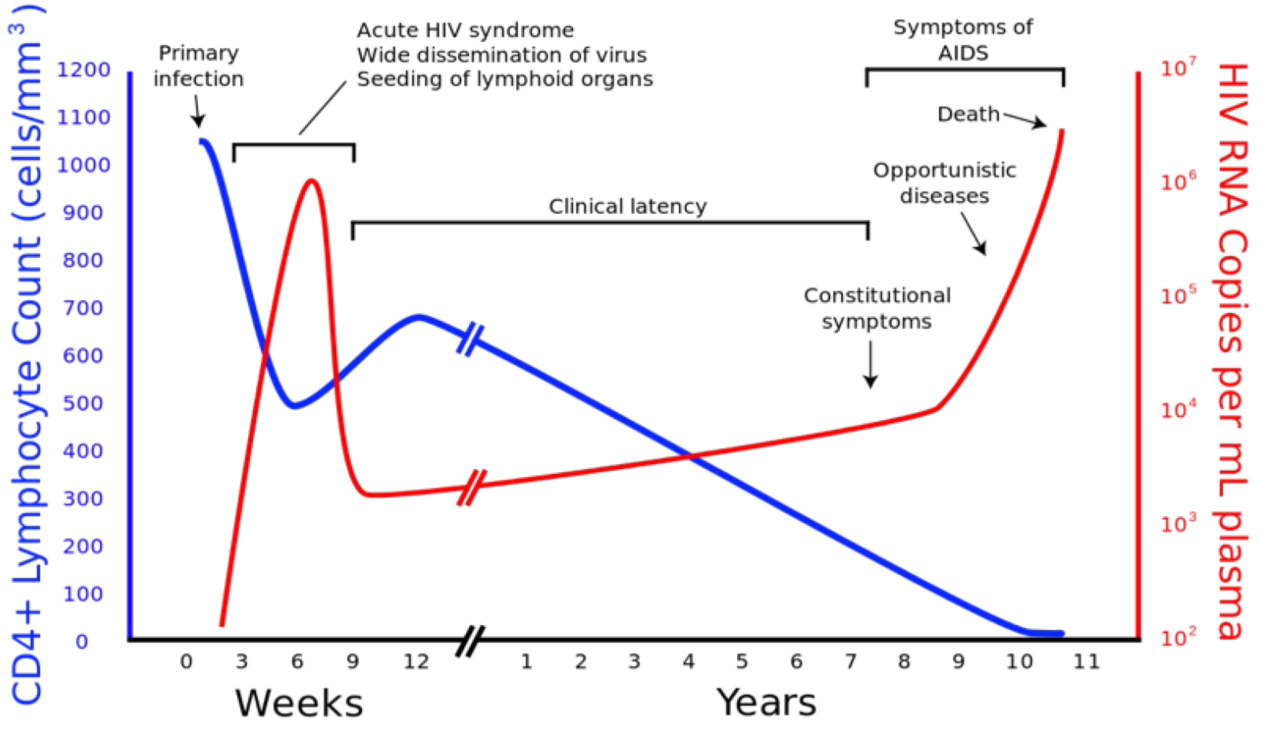

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- Virus co-discovered in 1983 by American Robert Gallo and Insitut Pasteur team, Françoise Barree-Sinoussi and Luc Montagnier
- Early cases concentrated in gay men, injecting drug users, and hemophiliacs. Later understood that everyone was at risk
- *Immunocompromised patients pose risk for virus evolution.*

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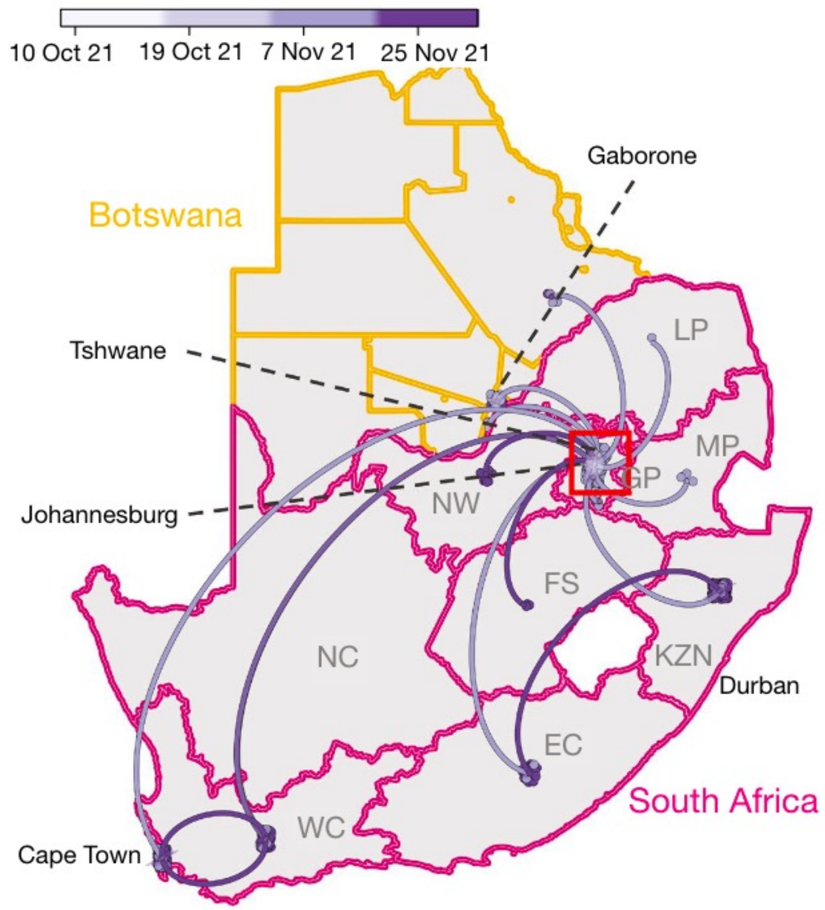
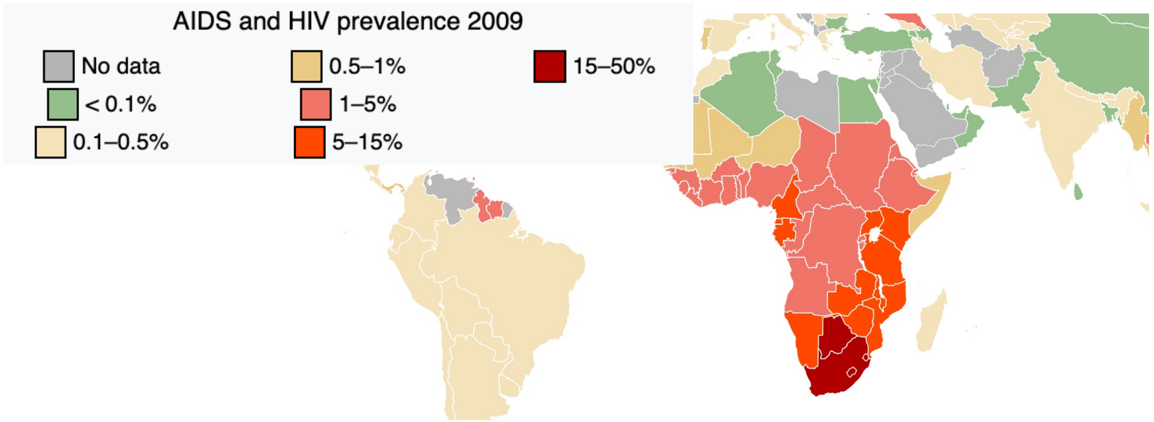
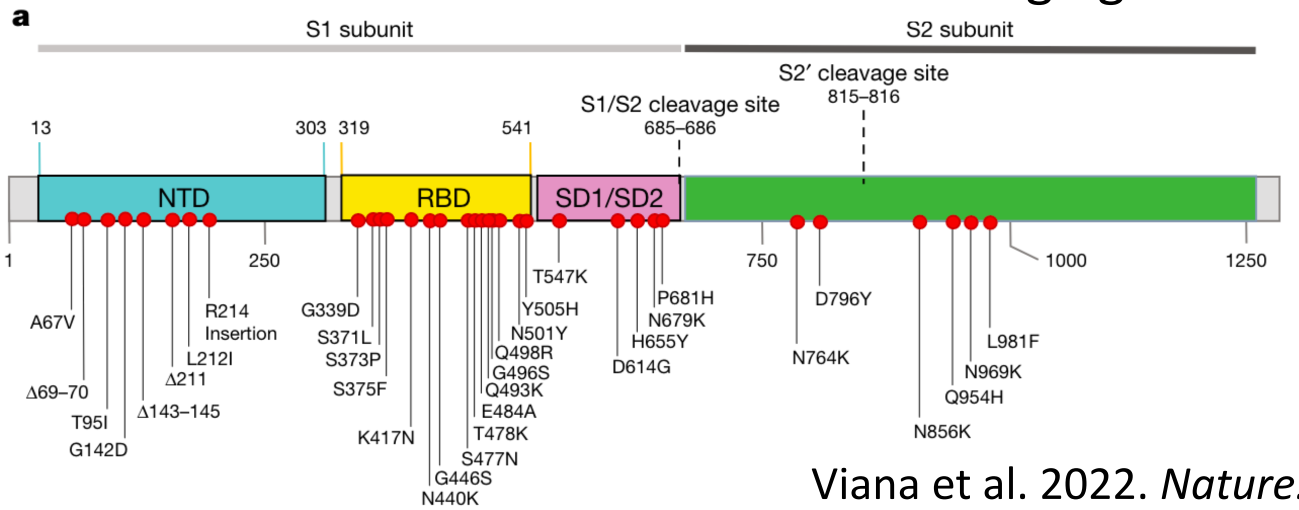


Botswana HIV prevalence = 24.8%

South Africa HIV prevalence = 19%



>30 spike protein mutations in emerging Omicron



Viana et al. 2022. *Nature.*

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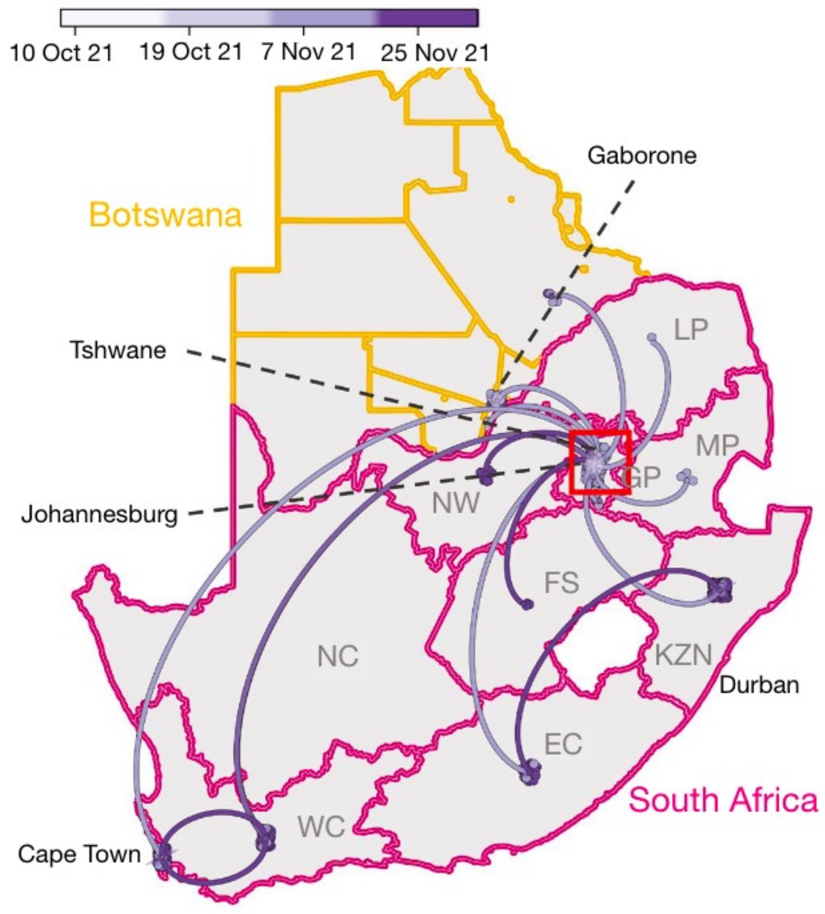

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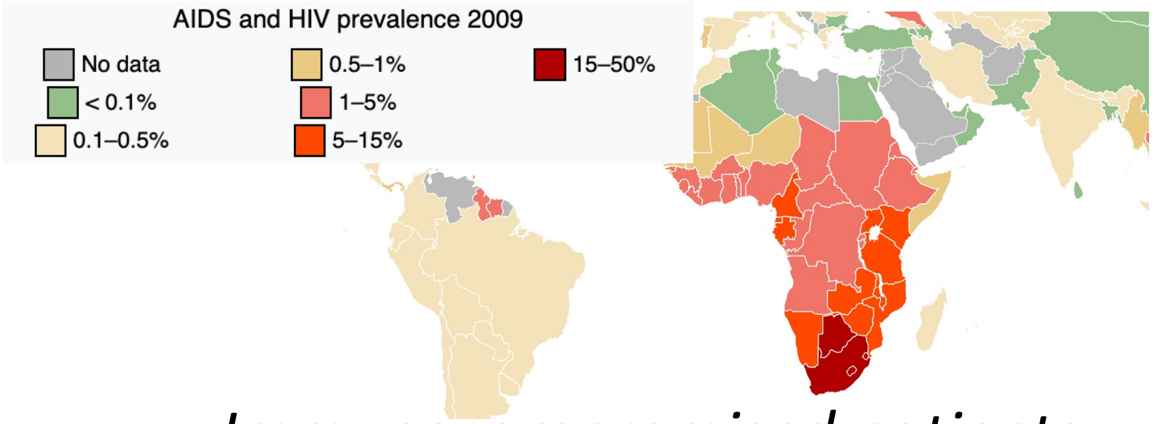

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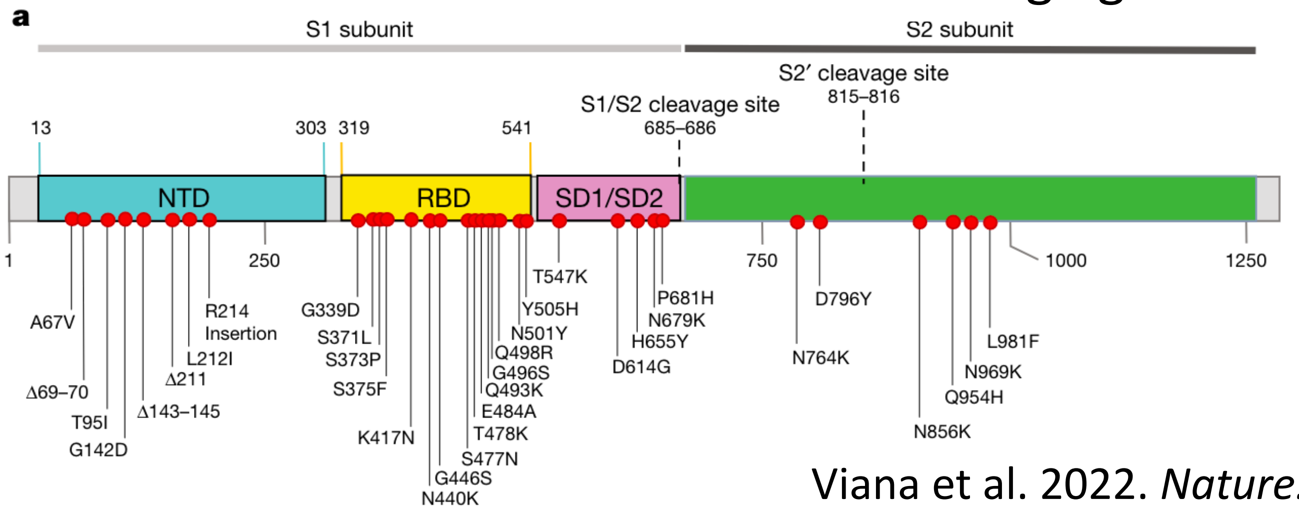

“**Ecology** has a synonym which is **ALL**.”

-John Steinbeck

The Log from the Sea of Cortez (1941)

Viana et al. 2022. *Nature.*

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  - Euclidean **vector**: a quantity with a magnitude and direction

    $\longrightarrow$

  - Epidemiological **vector**: an agent that carries and transmits an infectious patient into another living organism

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  - Malaria: Mosquito-borne protozoan *Plasmodium spp.*
  - "Arboviruses": Mosquito-borne viruses, including Dengue, Zika, Yellow fever virus, West Nile virus, Chikungunya virus
  - Sleeping sickness, also known as African trypanosomiasis: tsetse fly vector and protozoan pathogen (trypanosome)
  - Chagas disease: kissing bug vector and trypanosome pathogen
  - Plague: flea vector and bacterial pathogen (*Yersinia pestis)*

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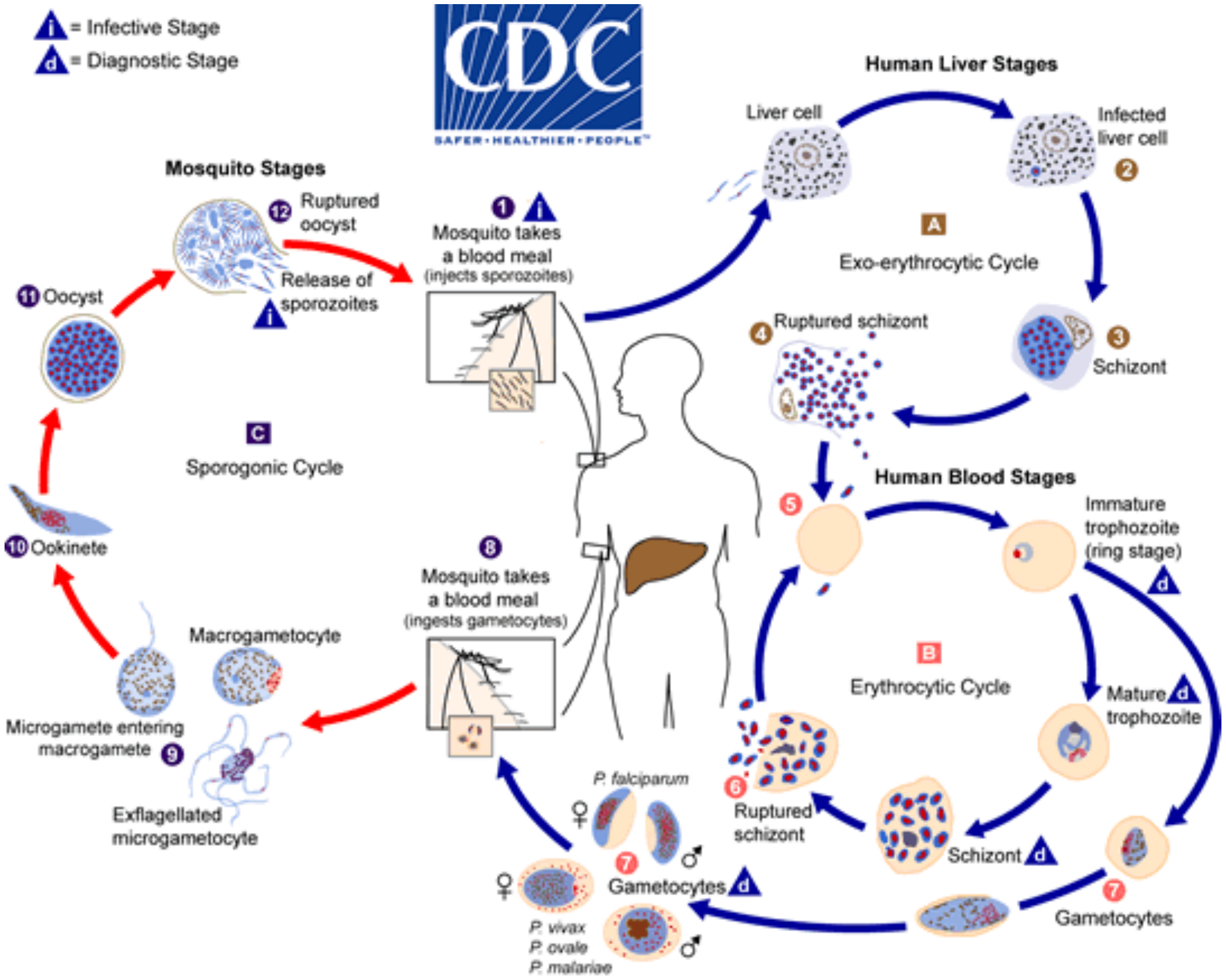
Malaria

- 4 main human ***Plasmodium* parasites** (*falciparum, vivax, malariae, ovalae*).
- Over 200 *Plasmodium* spp. globally, infecting birds, reptiles, and other mammals (rodents, bats, primates)

Distribution *Plasmodium falciparum*

Distribution *Plasmodium vivax*



Guerra et al. 2006. *Trends in Parasitology*

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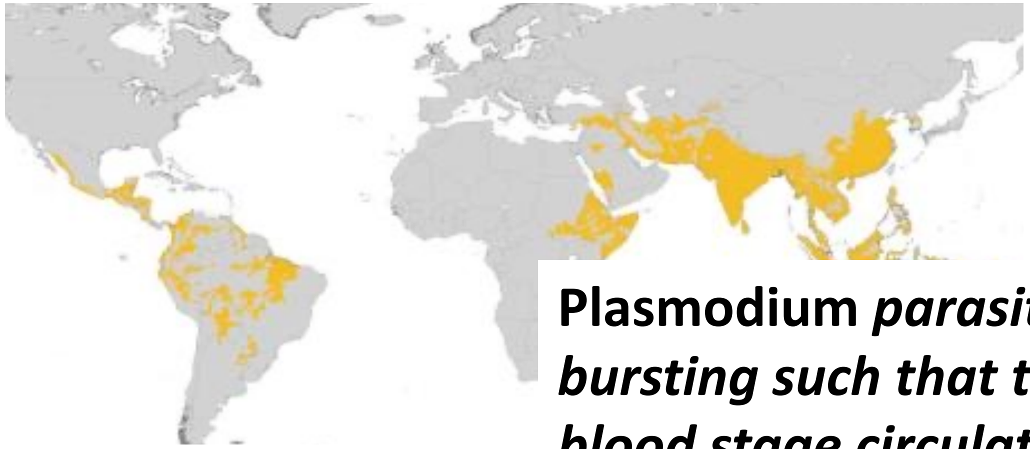

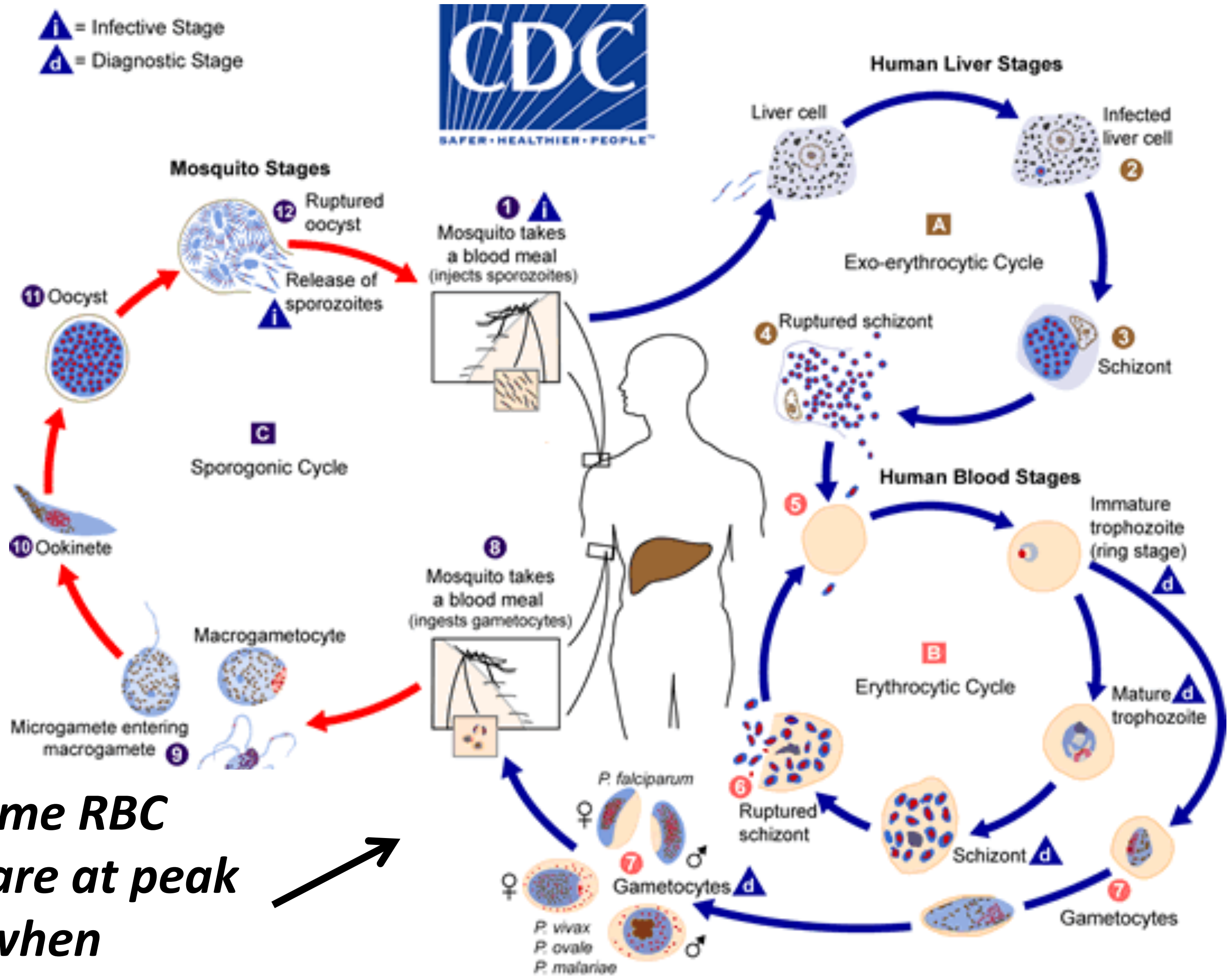

Plasmodium parasites time RBC bursting such that they are at peak blood stage circulation when mosquito vectors are feeding at dusk!

Guerra et al. 2006. *Trends i*

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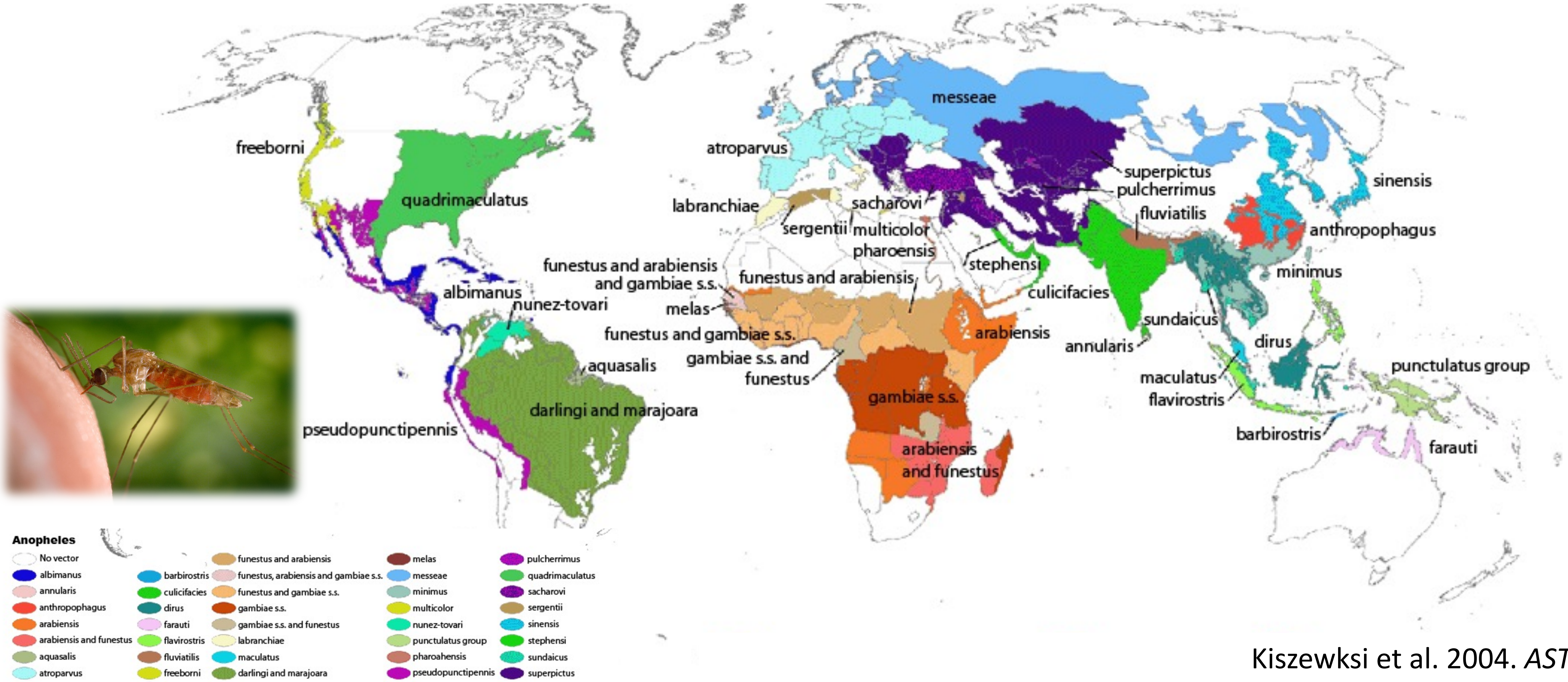
- Over 200 *Plasmodium* spp. globally, infecting birds, reptiles, and other mammals (rodents, bats, primates)
- >400 global species of ***Anopheles* mosquito**, >100 that can transmit human malaria
- ~30-40 *Anopheles* spp. most commonly implicated in human malaria transmission!



Kiszewksi et al. 2004. *ASTMH.*

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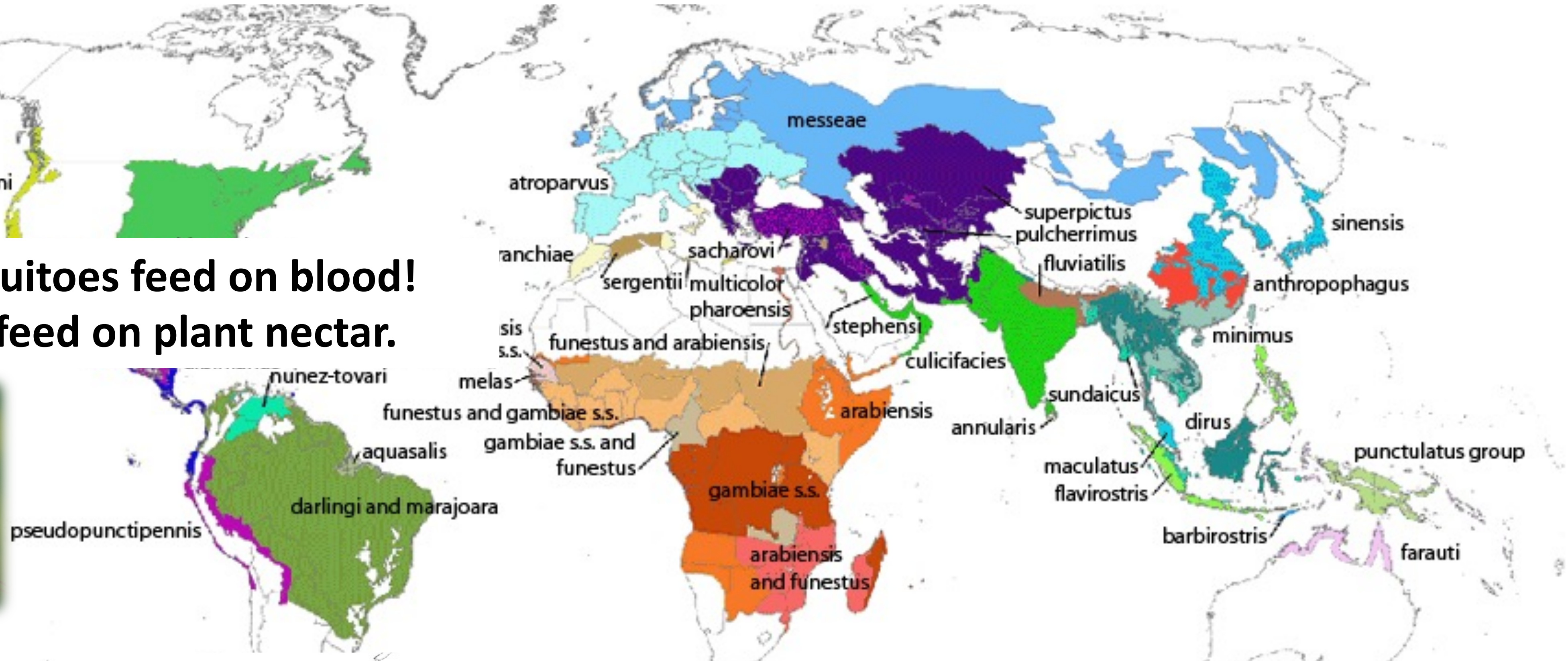
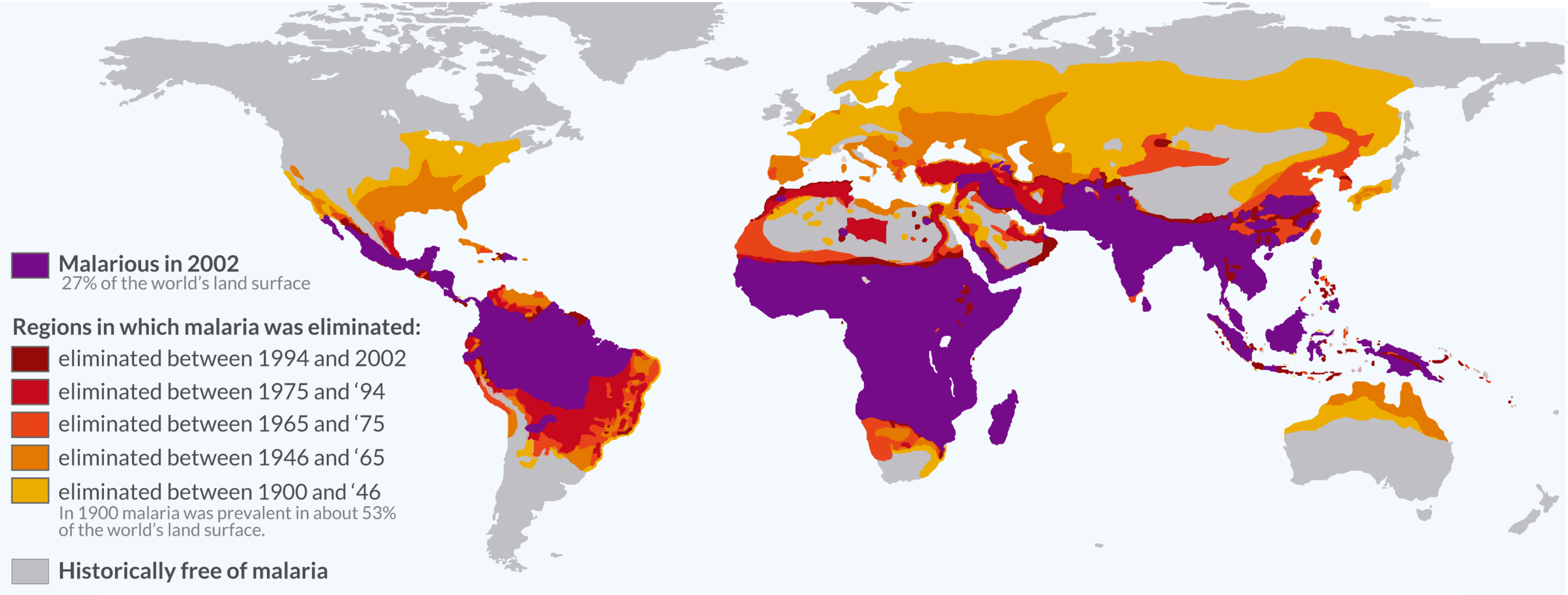
Only female mosquitoes feed on blood!
Male mosquitoes feed on plant nectar.



Kiszewksi et al. 2004. *ASTMH.*

Malaria has been eliminated from many regions where it was previously endemic, including the US.



Still one of the leading causes of child mortality globally – responsible for about half a million childhood deaths a year, 80% in Africa.

OurWorldinData.org

Malaria models have played a critical role in public health policy for over a century.

- 1911: British medical Dr. Sir Ronald Ross developed the first model of malaria while working in the Indian Medical Service.
  - He had already won the 1902 Nobel prize in physiology and medicine for discovering the life cycle of avian malaria

$$\frac{dS_H}{dt} = b_H(S_H + I_H) + \sigma I_H - \beta_H S_H I_M - \mu_H S_H$$

$$\frac{dI_H}{dt} = \beta_H S_H I_M - \sigma I_H - \mu_H I_H - \alpha I_H$$

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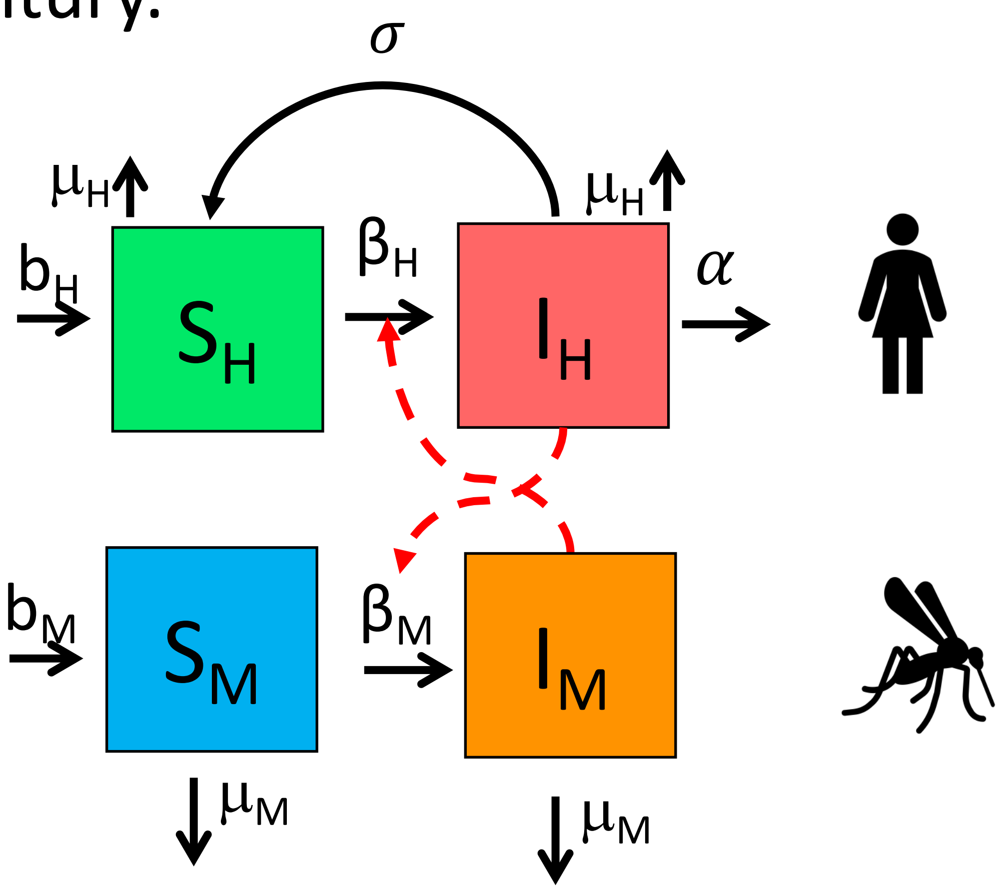

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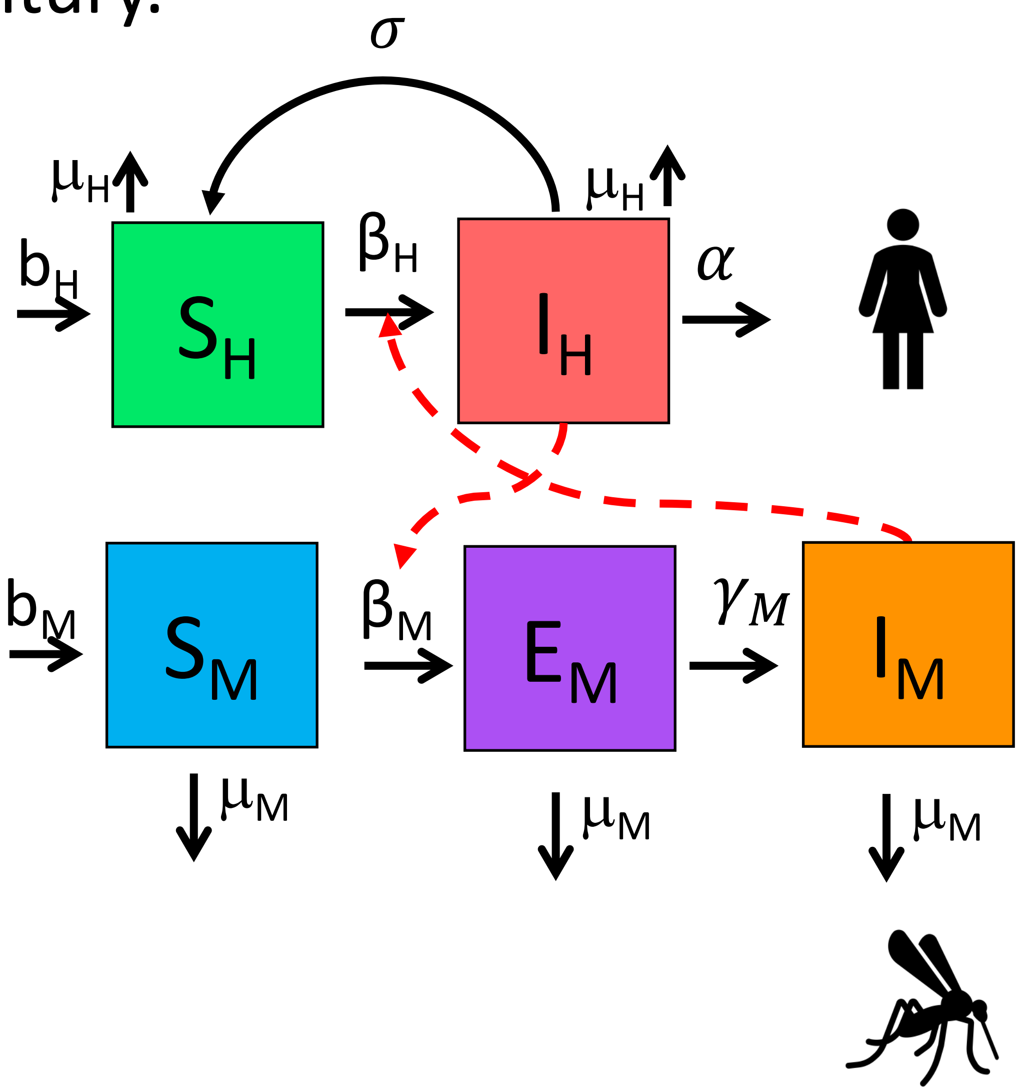
- 1911: British medical Dr. Sir Ronald Ross developed the first model of malaria while working in the Indian Medical Service.
- 1957: MacDonald modified this model to include the latent period of the parasite developing in the mosquito.
  - He implicated the survivorship of the female mosquito as the weakest link in the life cycle!

$$\frac{dS_M}{dt} = b_M(S_M + E_M + I_M) - \beta_M S_M I_H - \mu_M S_M$$

$$\frac{dE_M}{dt} = \beta_M S_M I_H - \mu_M E_M - \gamma_M E_M$$

$$\frac{dI_M}{dt} = \gamma_M E_M - \mu_M I_M$$



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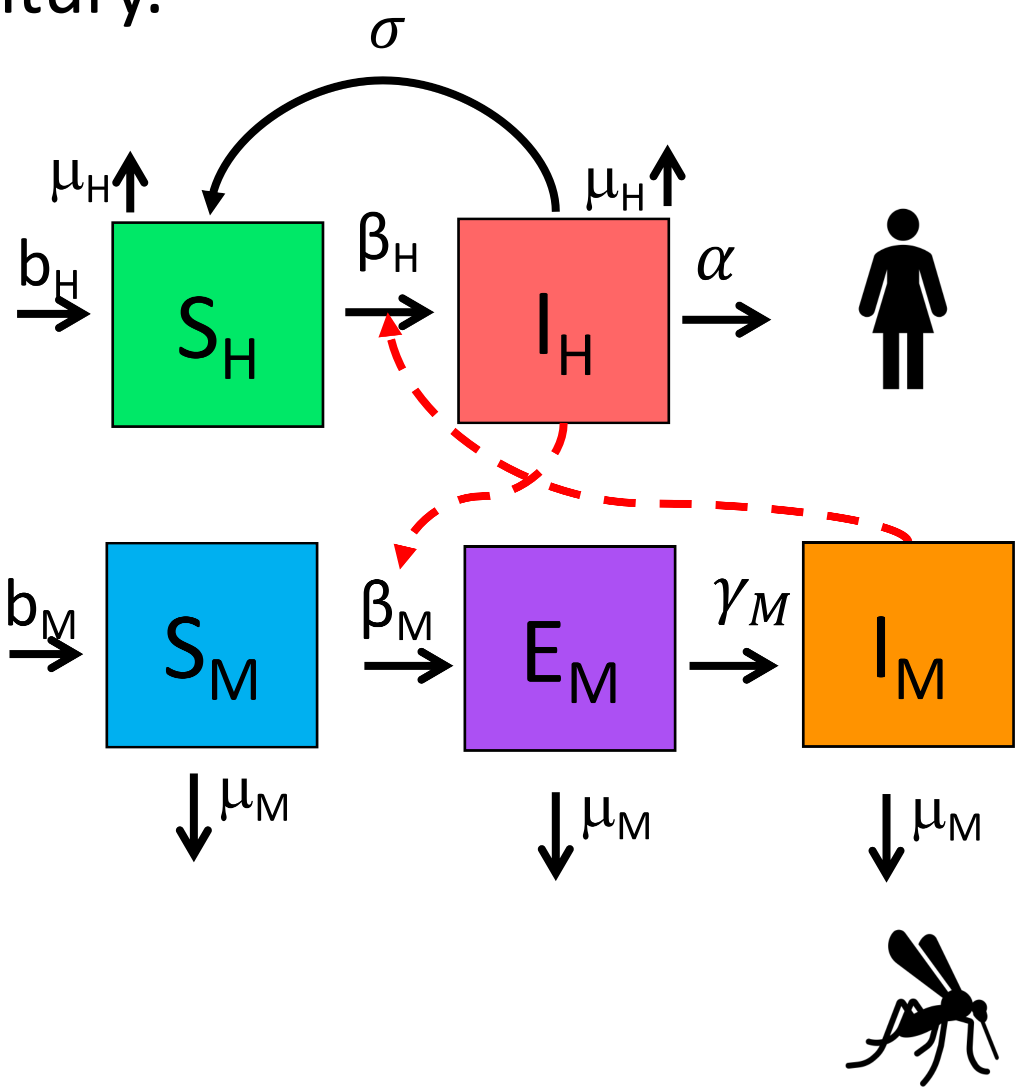

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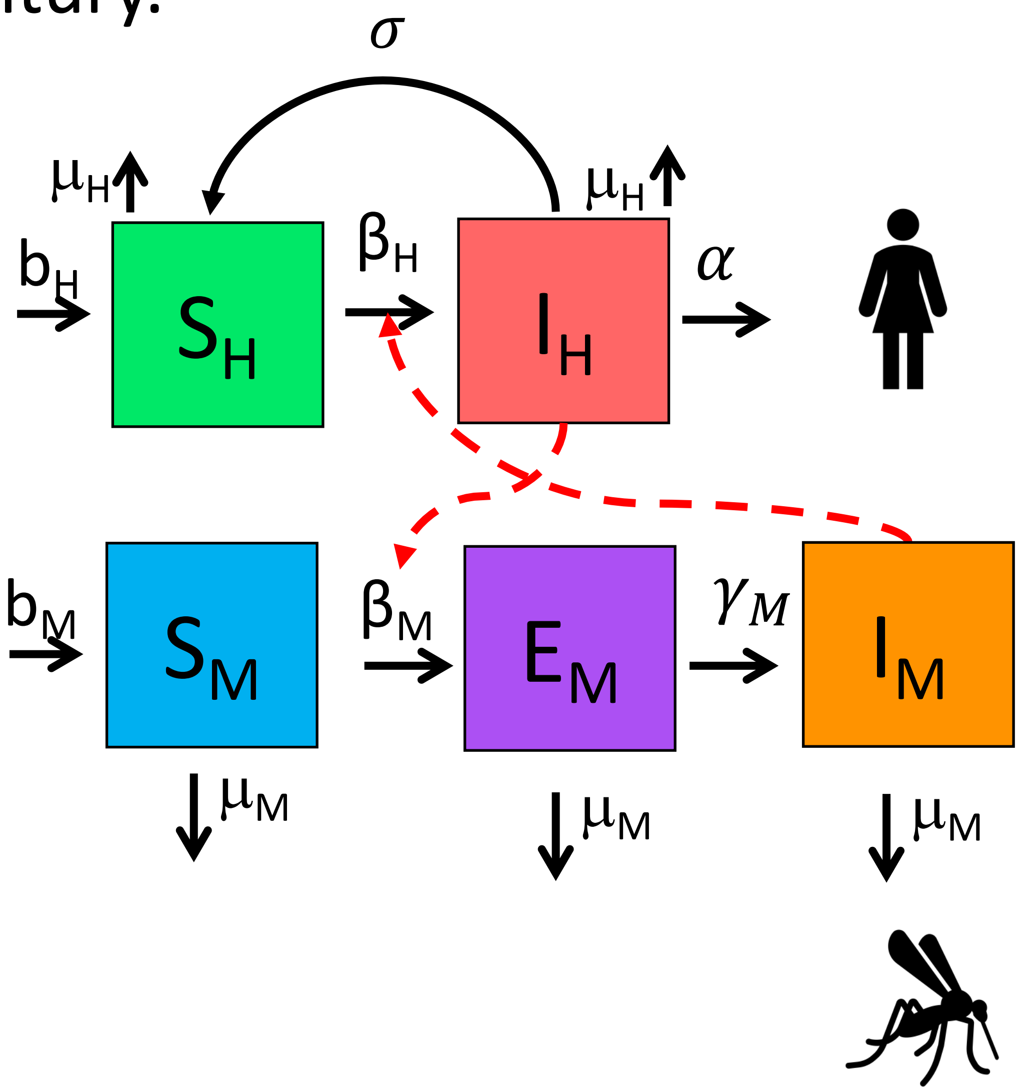

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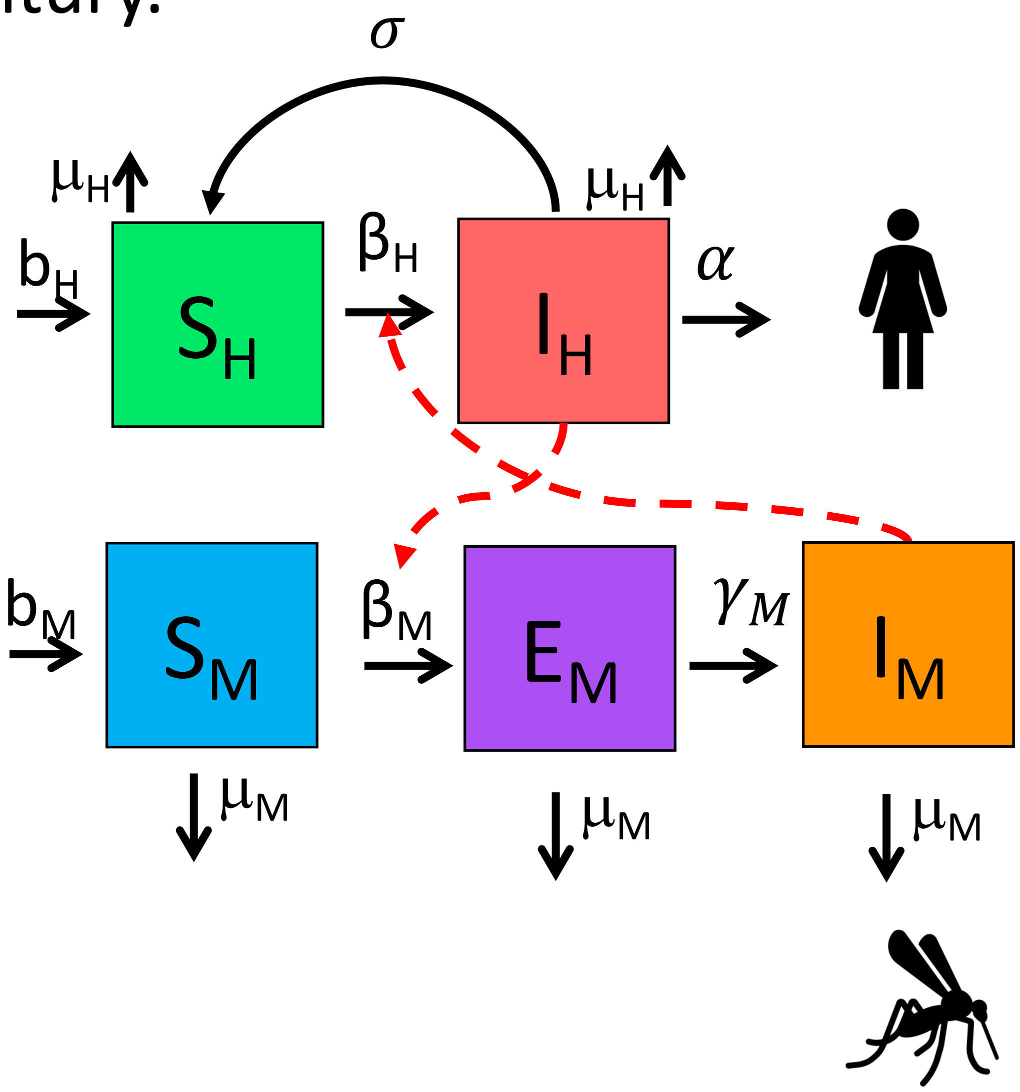

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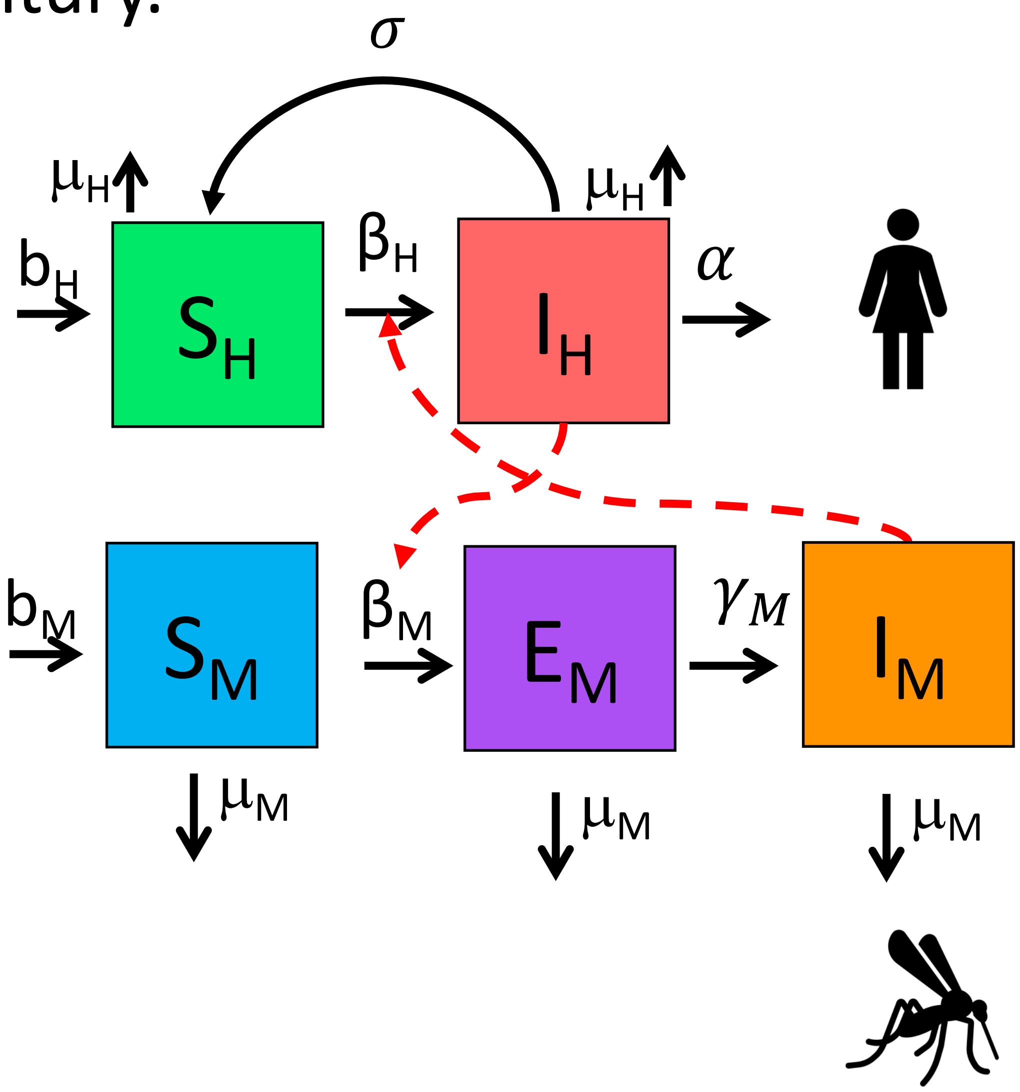

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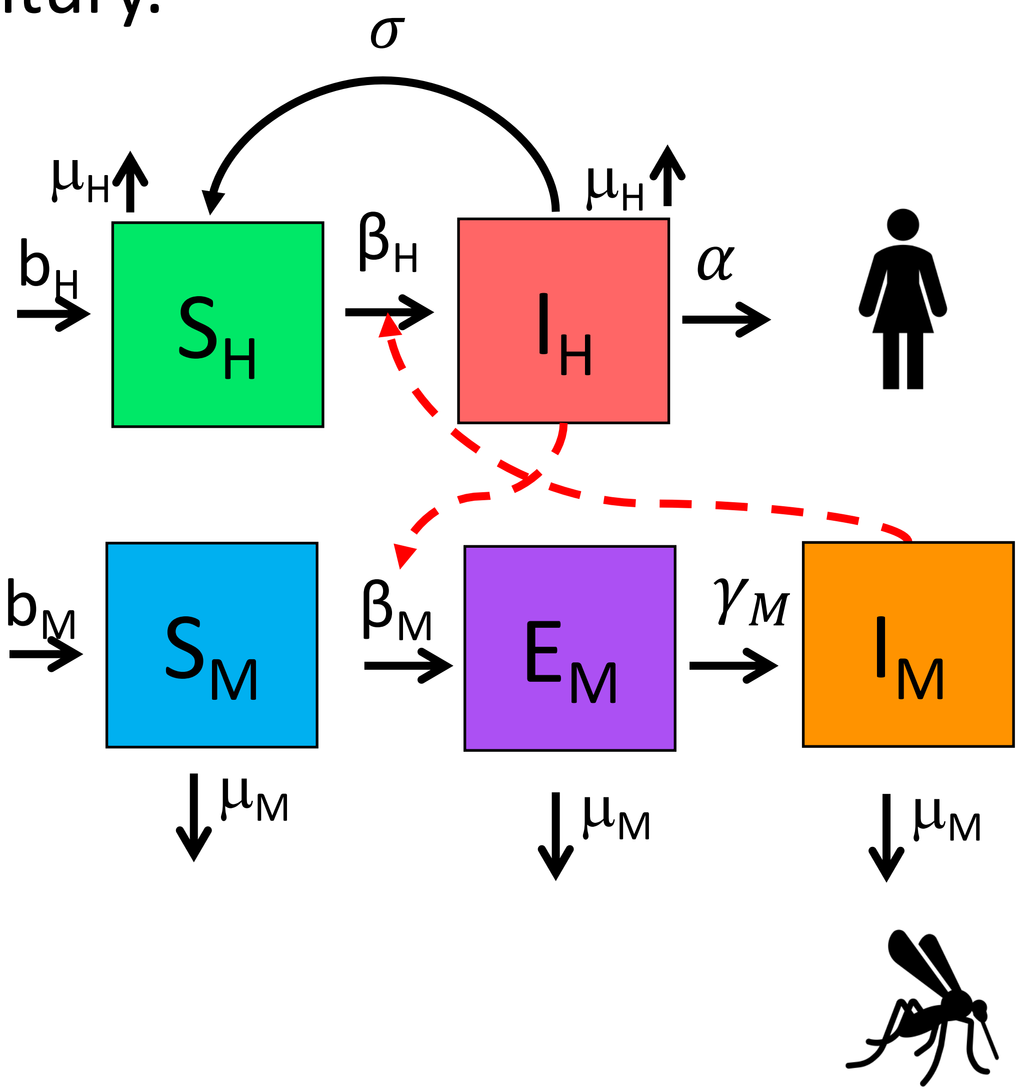

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"**Ecology** has a synonym which is **ALL**."

-John Steinbeck

The Log from the Sea of Cortez (1941)

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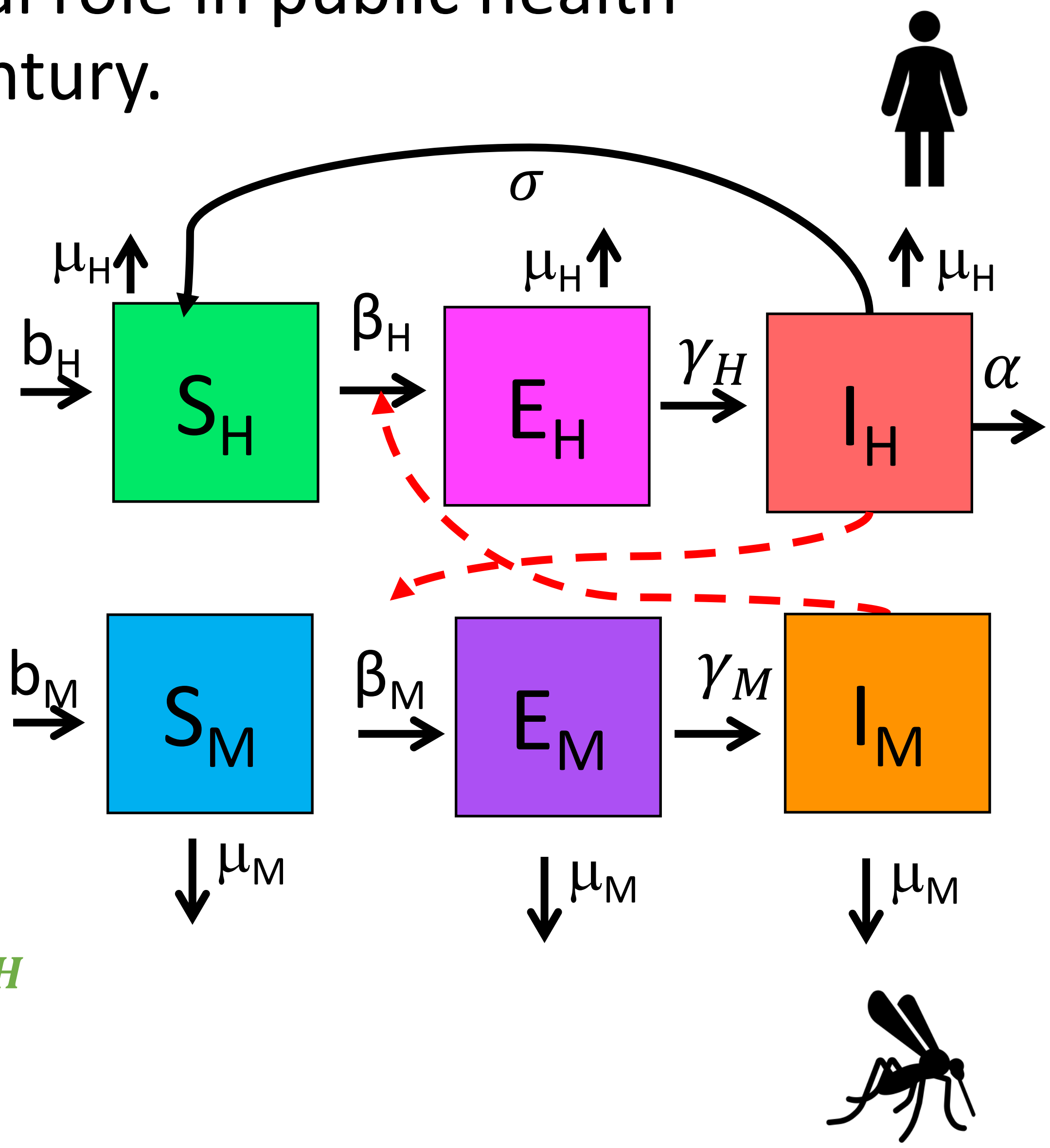
- 1991: Anderson and May extended model to show latency in the human population.



$$\frac{dS_H}{dt} = b_H(S_H + E_H + I_H) + \sigma I_H - \beta_H S_H I_M - \mu_H S_H$$

$$\frac{dE_H}{dt} = \beta_H S_H I_M - \gamma_H E_H - \mu_H E_H$$

$$\frac{dI_H}{dt} = \gamma_H E_H - \sigma I_H - \mu_H I_H - \alpha I_H$$

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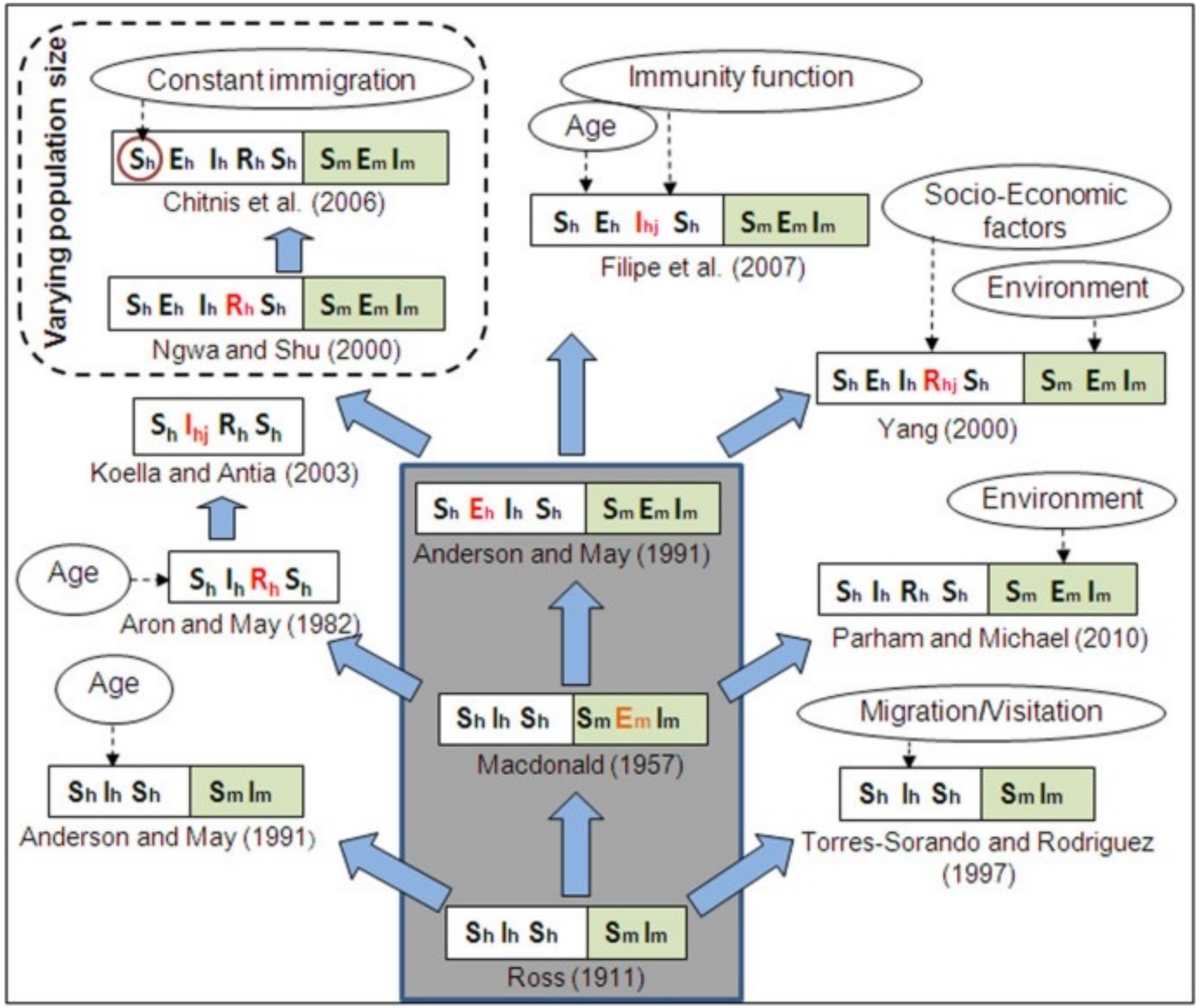
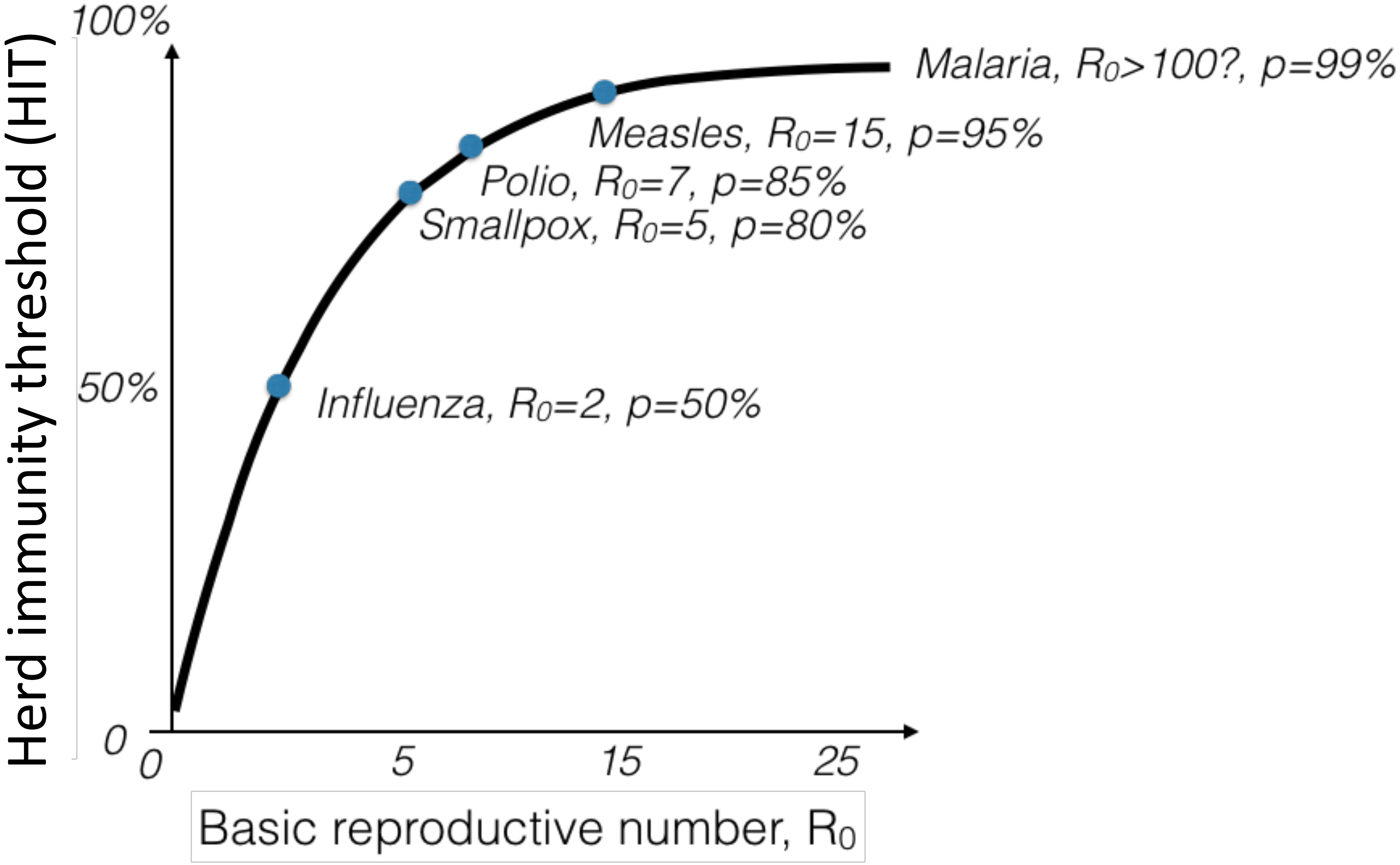


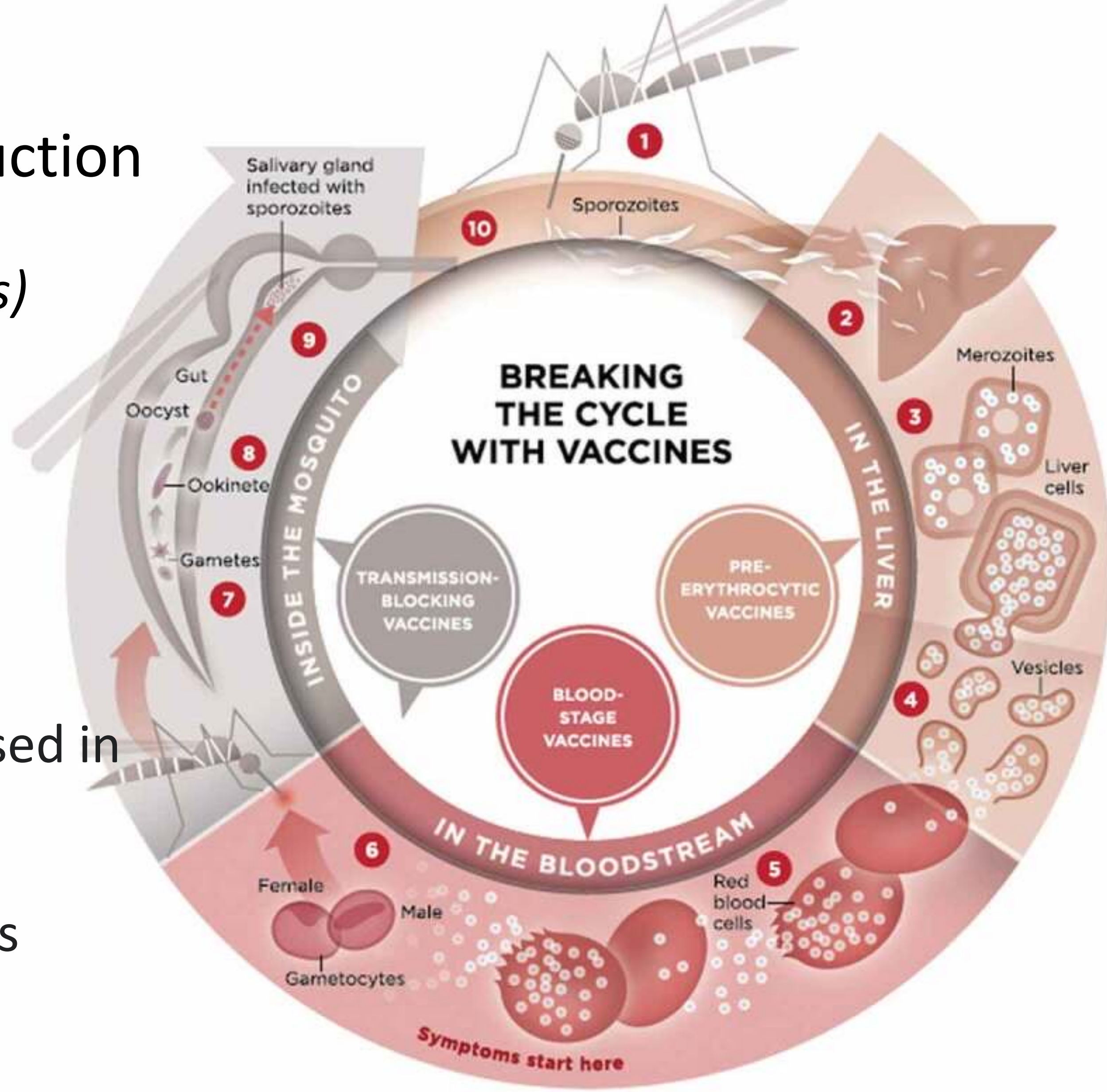
Mandal et al. 2011. *Malaria Journal.*

Challenges to malaria elimination



Challenges to malaria elimination

- High parasite diversity: sexual reproduction in 4+ *Plasmodium* species
  - Fast evolution of resistance *(e.g. to drugs)*
- Many possible vectors! Potentially additional possible reservoirs!
- Latent cases as burden is reduced
- Vaccine candidates: what life stage to target?
  - *Mosquirix* pre-erythrocytic vaccine licensed in 2022
  - Requires at least 3 doses in children <2
  - Does not eliminate pathogen but reduces severe malaria burden and burden of hospitalization



Pathogens exhibit **diverse transmission mechanisms** that require tailored modeling structures

- **Vector-borne** diseases (a type of indirect transmission) are transmitted via blood-feeding arthropod (mosquitoes, ticks, fleas)
  - Malaria: Mosquito-borne protozoan *Plasmodium spp.*
  - "Arboviruses": Mosquito-borne viruses, including Dengue, Zika, Yellow fever virus, West Nile virus, Chikungunya virus
  - Sleeping sickness, also known as African trypanosomiasis: tsetse fly vector and protozoan pathogen (trypanosome)
  - Chagas disease: kissing bug vector and trypanosome pathogen
  - Plague: flea vector and bacterial pathogen (*Yersinia pestis)*

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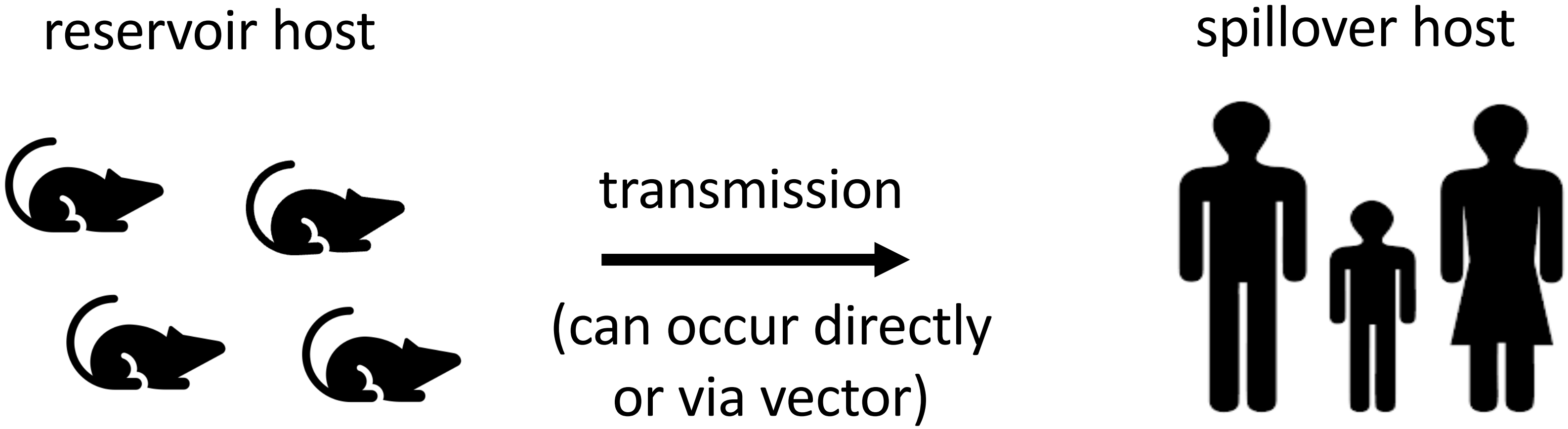
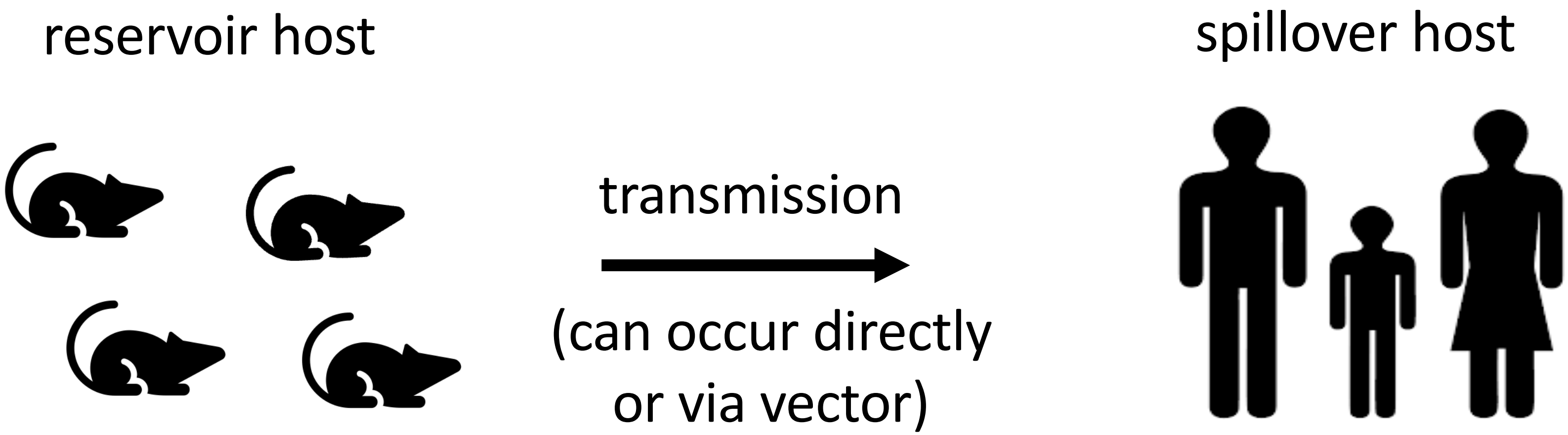
Plague is BOTH vector-borne and zoonotic!

spillover



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

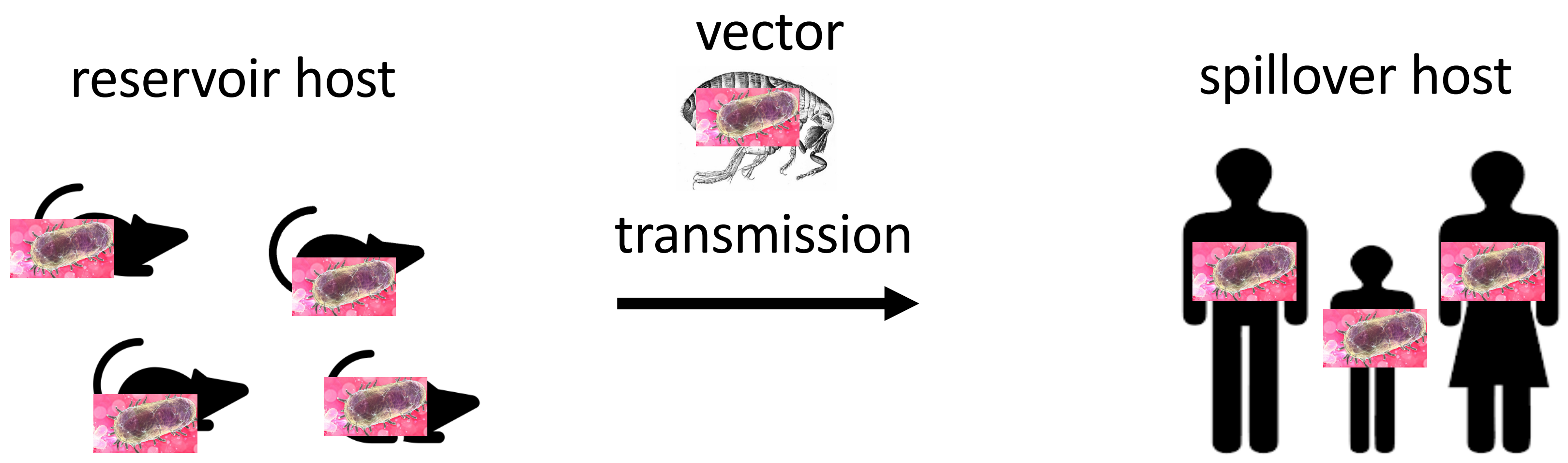
zoonosis



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)

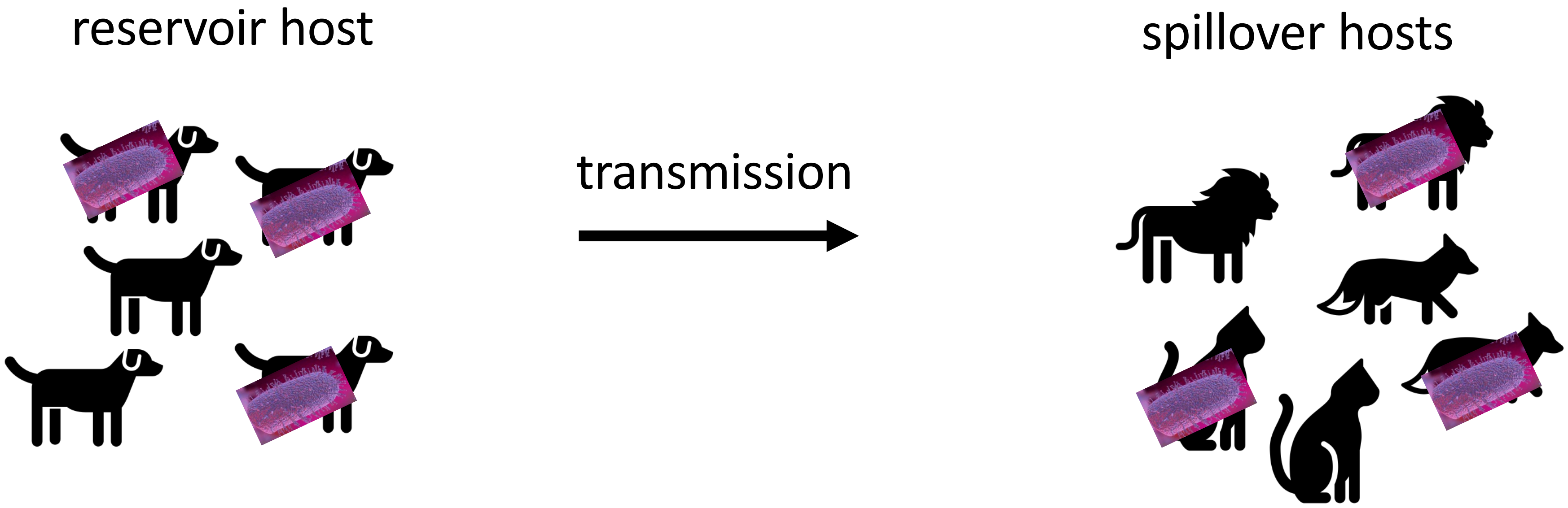
zoonosis



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

Animal hosts are not vectors!

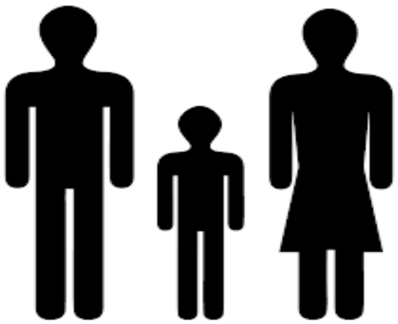
Pathogens can also spillover to alternative wildlife hosts.

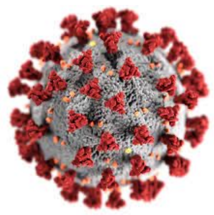


These pathogens **are not considered zoonoses** unless they spillover to humans!

spillback

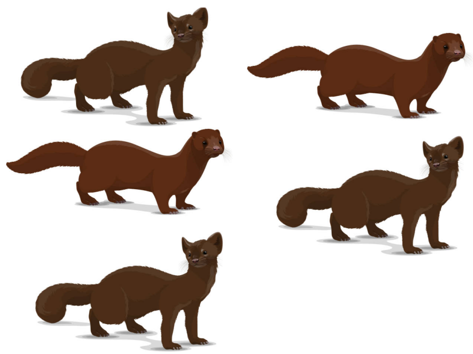
reservoir host





transmission

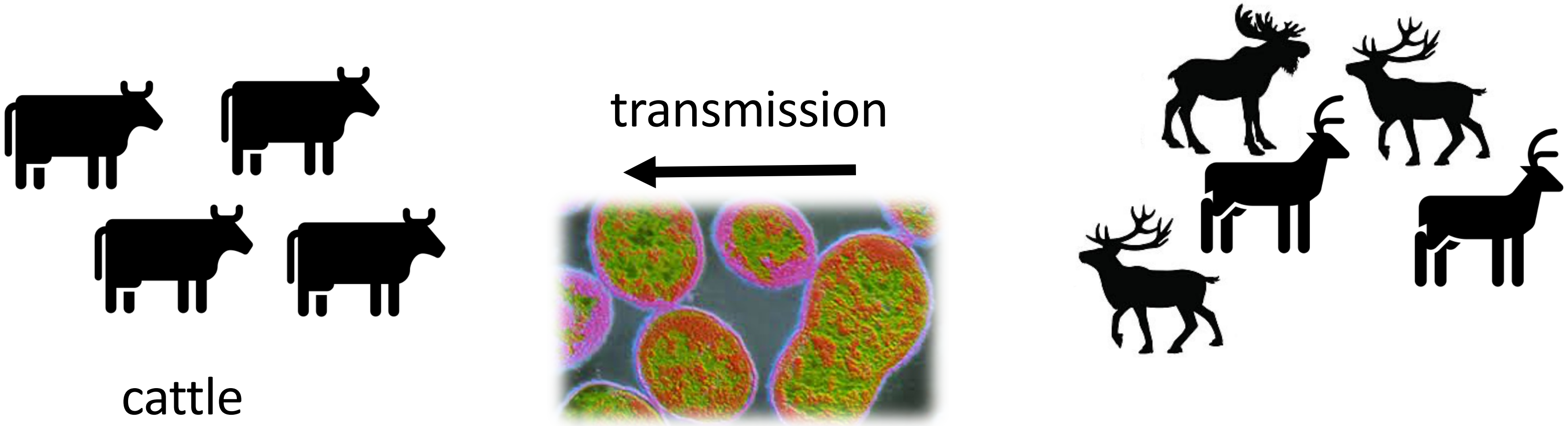
spillover host



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)

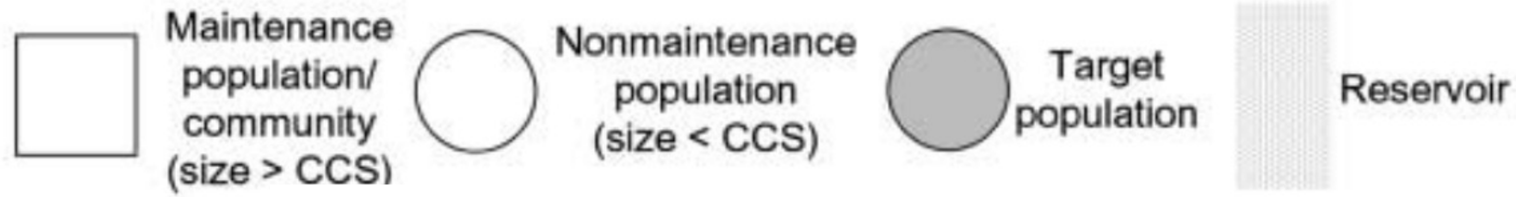
Spillback occurs among wildlife as well



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.*

Defining terms in multi-species infections…



Haydon et al. 2002. *EID.*

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

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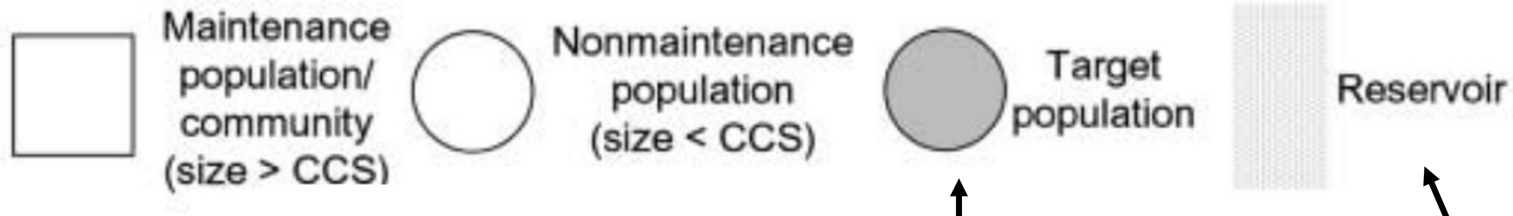

population of interest to the study

population[s] sourcing pathogen to target population

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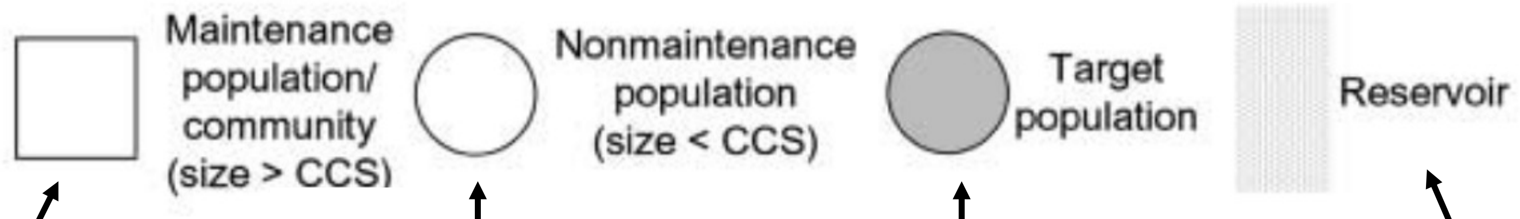

population can sustain endemic transmission of pathogen

spillover hosts only

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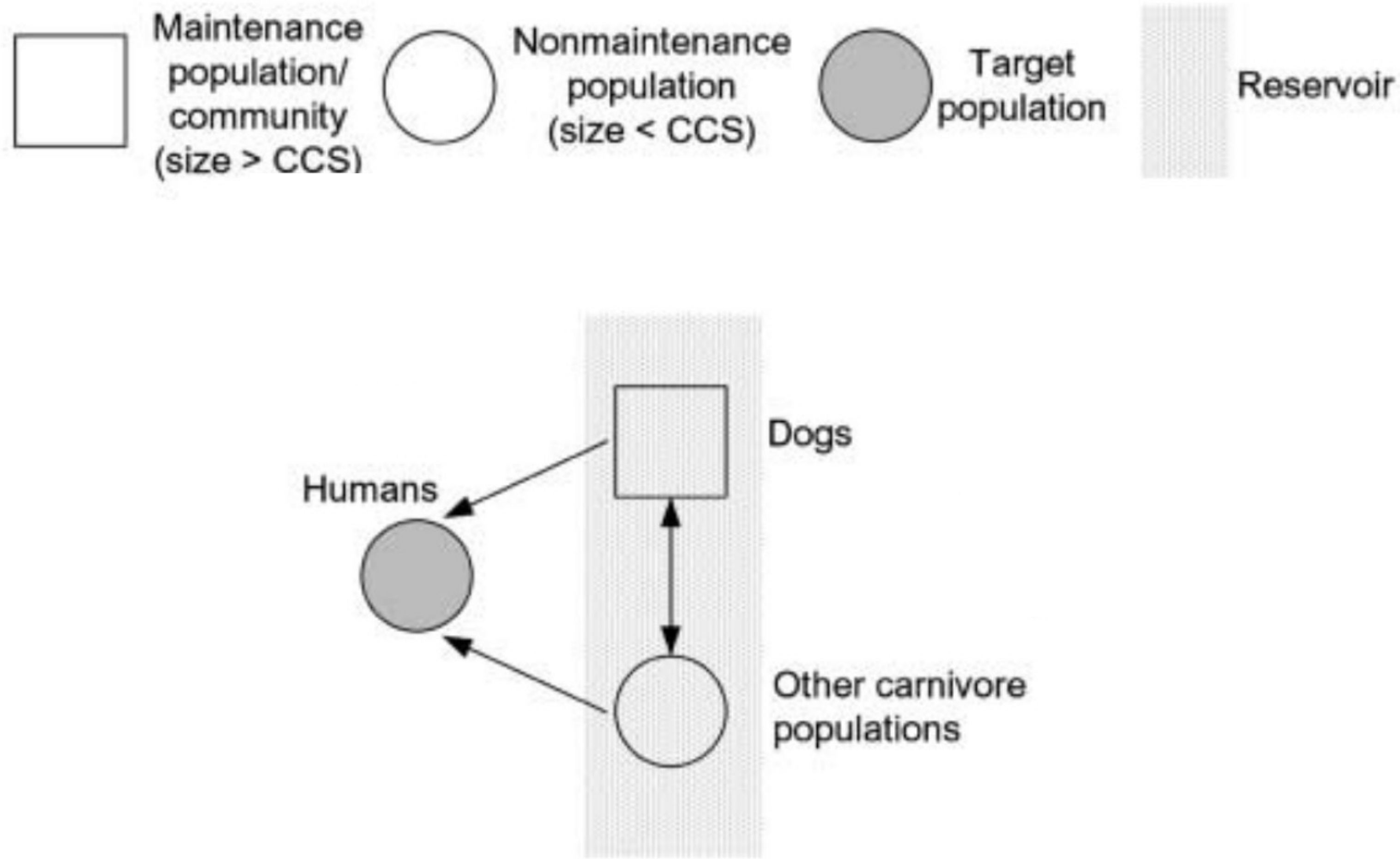

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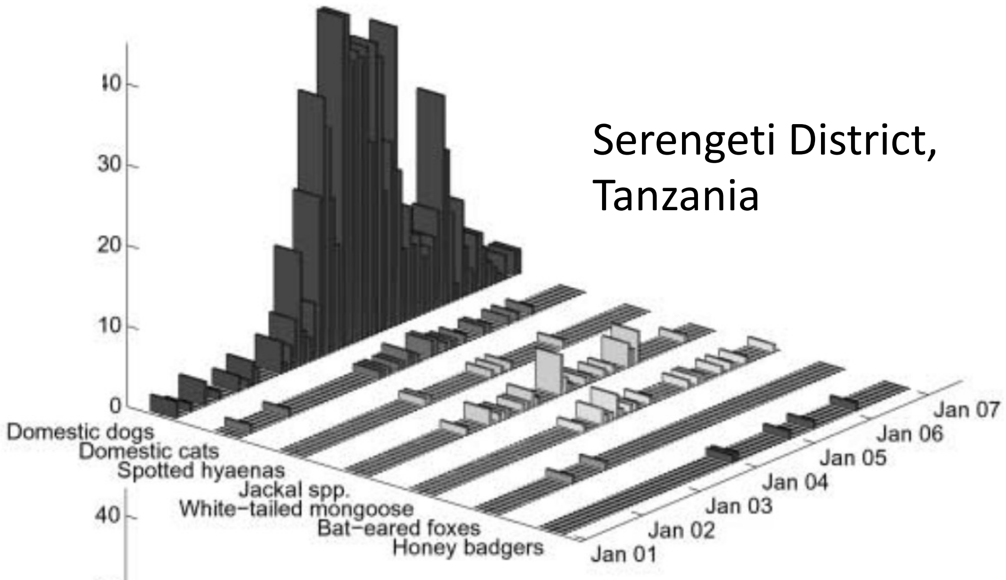
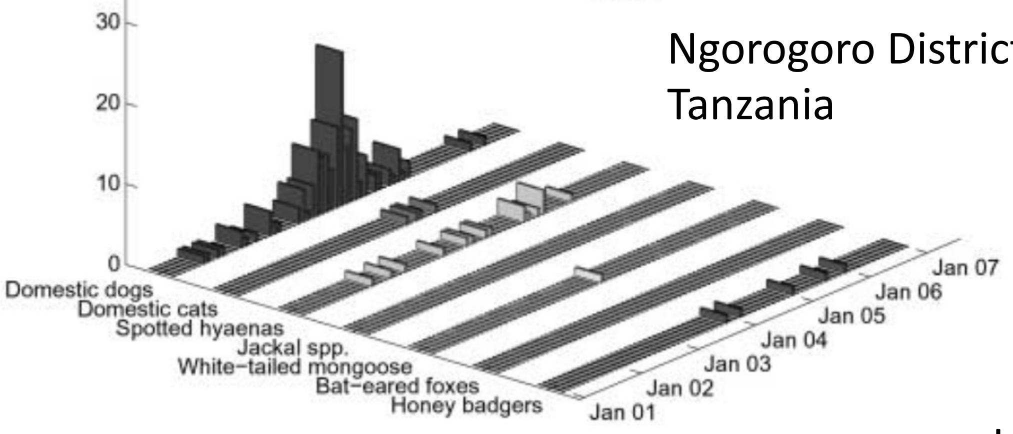


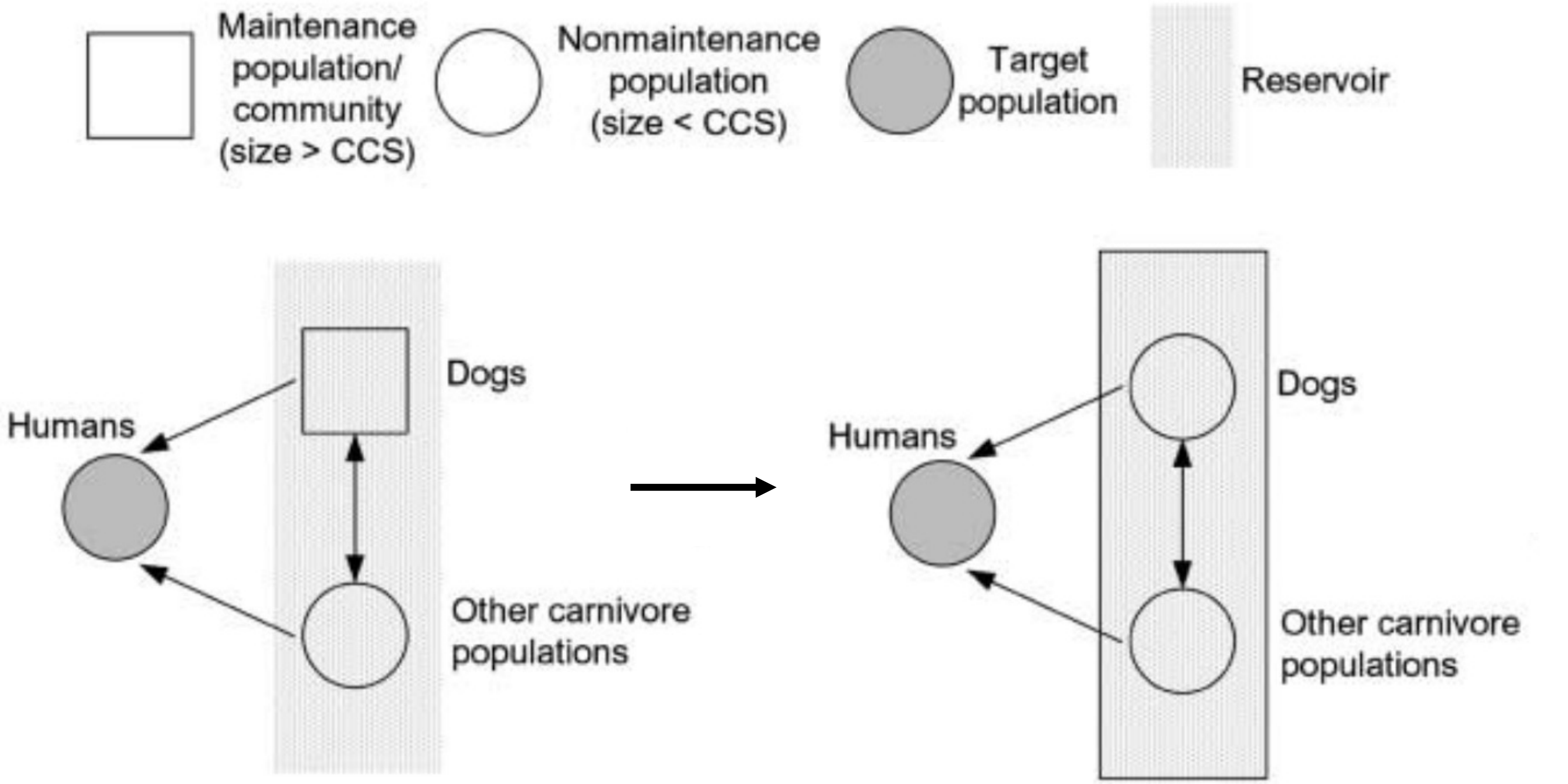
Serengeti District, Tanzania



Ngorogoro District, Tanzania

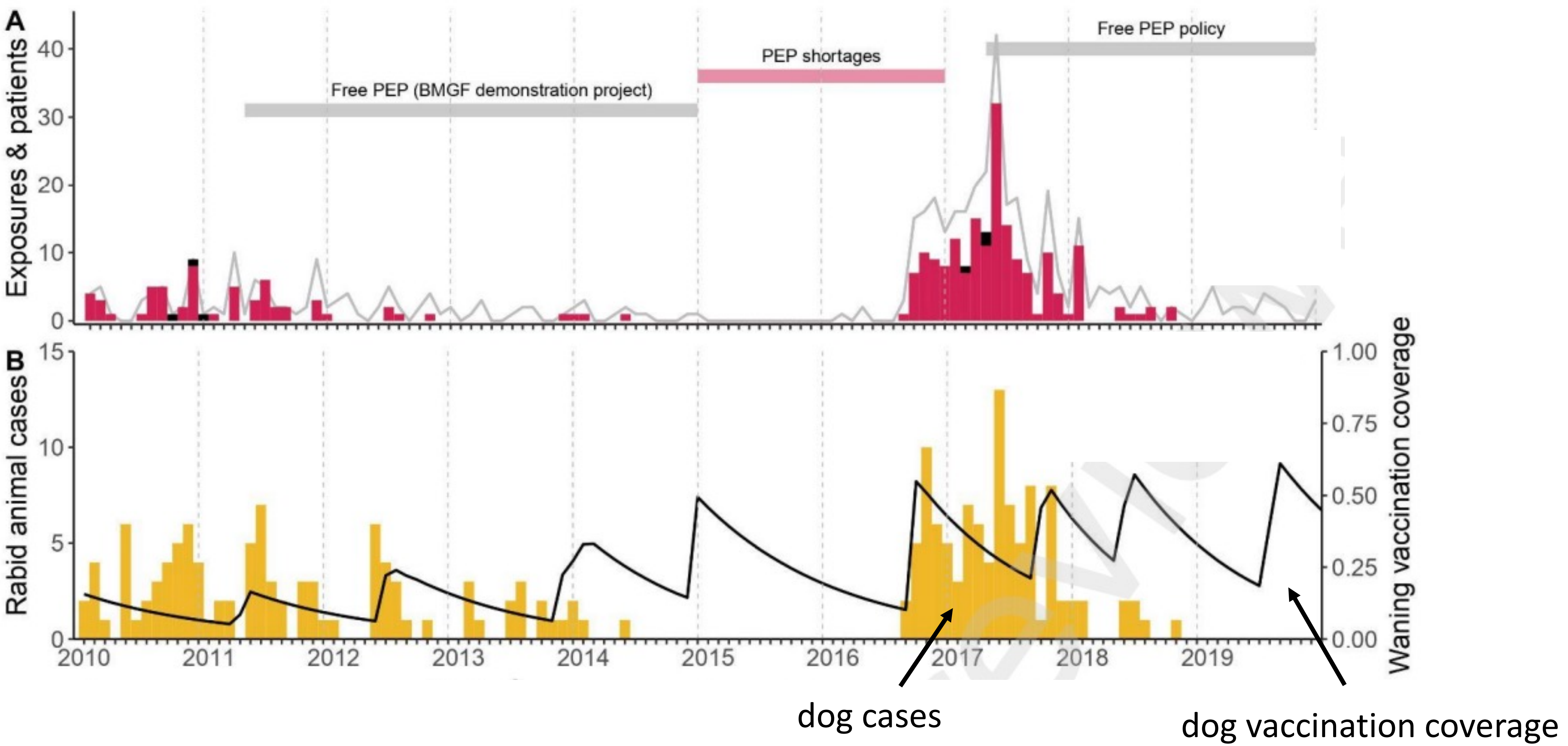
Lembo et al. 2008. *J of Animal Ecology.*

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.

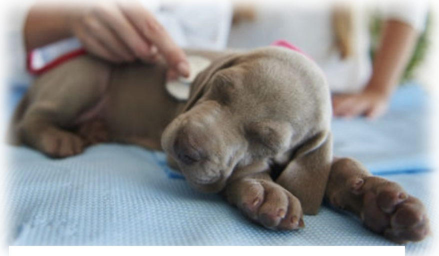


Lushashi et al. *In Revision. The Lancet.*

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

Stage III

Stuttering chains of transmission in humans

monkeypox (pre-2022)

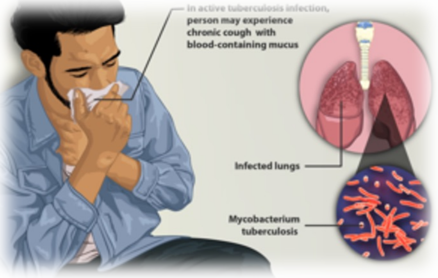
Stage IV

Sustained transmission and human outbreaks

Ebola virus (especially post-2014)

Stage V

Transmits exclusively in humans



Tuberculosis

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

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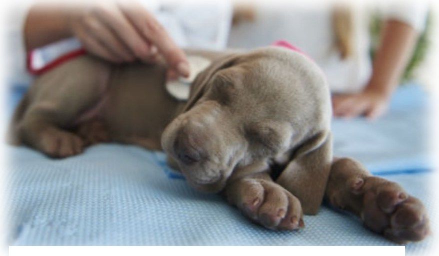

canine parvovirus

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

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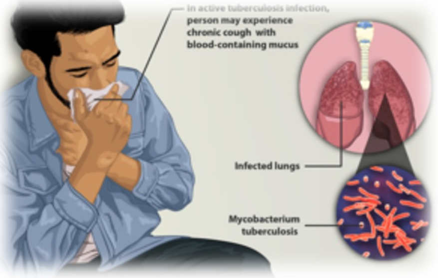
Ebola virus (especially post-2014)

$R_0 > 1$

Stage V

Transmits exclusively in humans

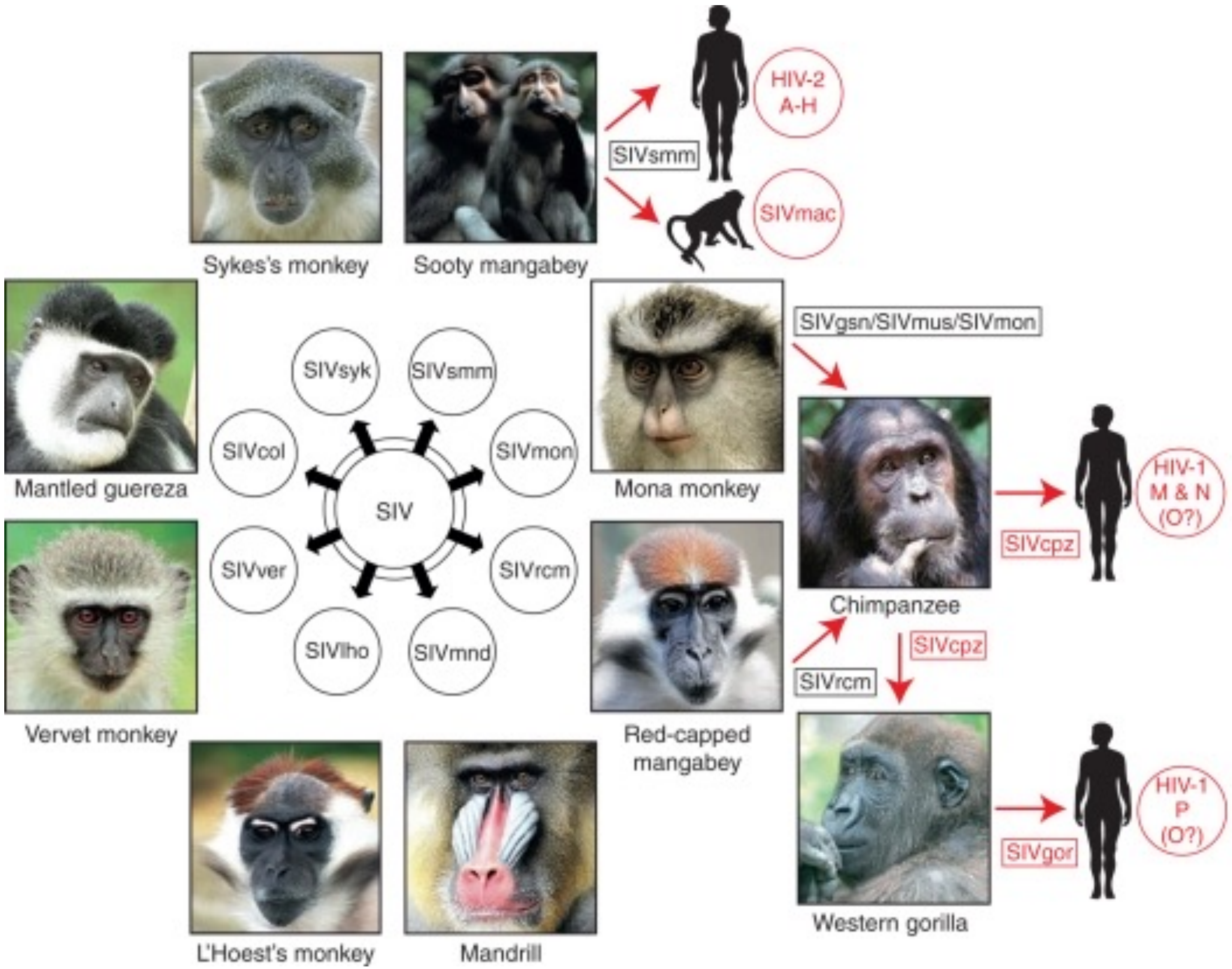


Tuberculosis

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.*