ICTP-SAIFR
Summer Workshop
Mathematical Models of Evolution
Sao Paulo
Jan 21-26, 2019

Support:
ARO; NSF – DimBio;
NSF – Bio Oc; NSF PoLS
Simons Foundation - SCOPE,
Georgia Tech

VIRUS ECOLOGY AND EVOLUTION:

FROM LYSIS TO LATENCY

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Thanks to many…

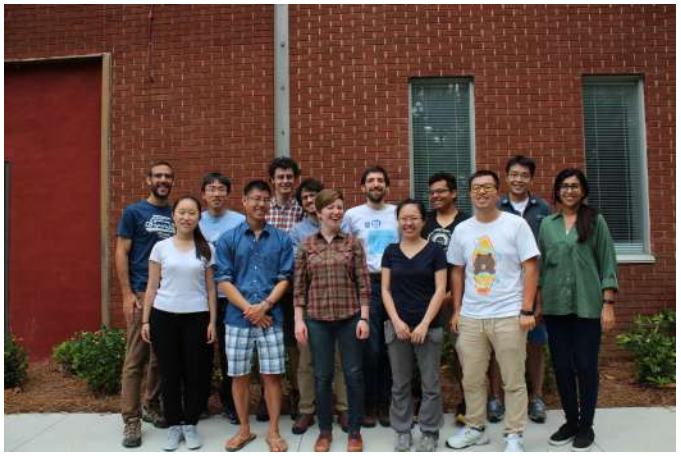
Collaborators **(**with **highlights)**

GT: Charles Wigington, Stephen Beckett, Luis Jover, **Guanlin Li**
LSU: Jennifer Brum
McMaster: Jonathan Dushoff
UIUC: **Rachel Whitaker**
UL-Lafayette: **Hayriye Gulbudak**
Utah State: **Michael Cortez**

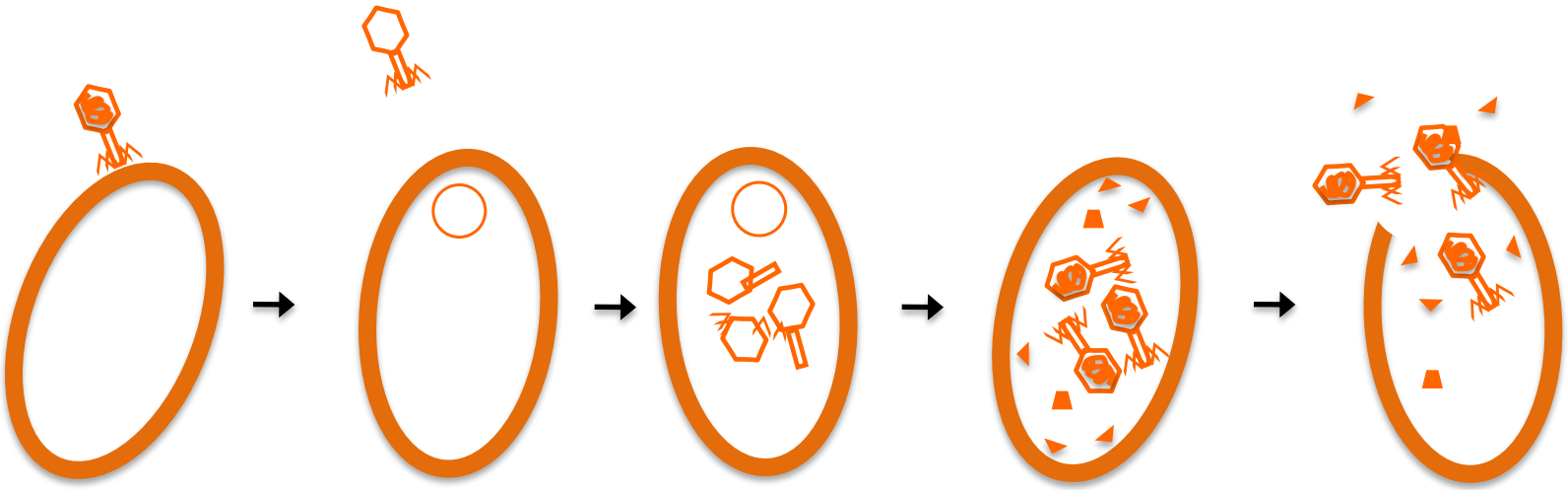
Continuum of Persistence Workshop

NIMBioS Working Group (w/Wilhelm)

Group at GT



The life of a bacterial virus (phage)



Levin et al, 1977

Vol. 111, No. 977 The American Naturalist January–February 1977

RESOURCE-LIMITED GROWTH, COMPETITION, AND PREDATION: A MODEL AND EXPERIMENTAL STUDIES WITH BACTERIA AND BACTERIOPHAGE

Bruce R. Levin, Frank M. Stewart, and Lin Chao

Zoology Department, University of Massachusetts, Amherst, Massachusetts 01002; and Mathematics Department, Brown University, Providence, Rhode Island 02912

"One Resource, One Prey, One Predator"

3. *One Resource, One Prey, One Predator*

With one population at each trophic level the equilibrium conditions are:

$$\hat{r} + (\hat{n} + \hat{m})\phi(\hat{r})/\rho = C, \tag{9}$$

$$\phi(\hat{r})/e - \gamma\hat{p} = \rho, \tag{10}$$

$$\hat{m} = \gamma(1 - e^{-\rho\hat{l}})\hat{n}\hat{p}/\rho, \tag{11}$$

$$(be^{-\rho\hat{l}} - 1)\gamma\hat{n} = \rho. \tag{12}$$

Idea:
Phage = Predators, Bacteria = Prey

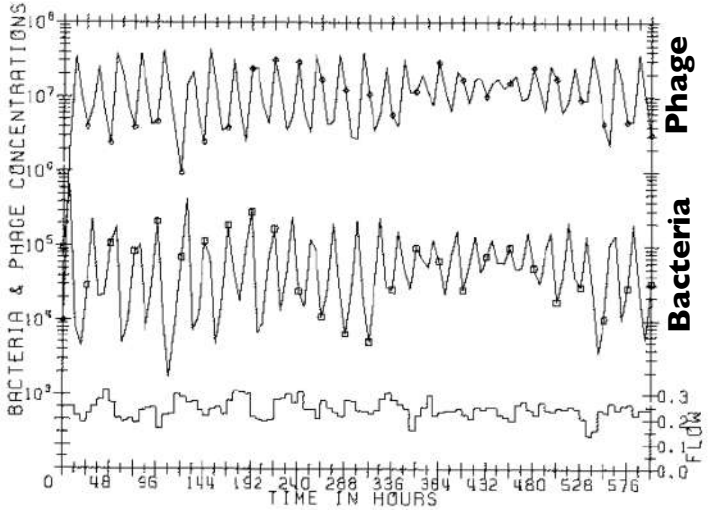
Attributed to:
Allan Campbell 1961 (Evolution):

"The simple predator. If a virulent phage and a susceptible bacterium are mixed in an open growth system, such as a chemostat…"

CONDITIONS FOR THE EXISTENCE OF BACTERIOPHAGE[1]

Allan Campbell
Department of Biology, University of Rochester

Received June 21, 1960



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CONDITIONS FOR THE EXISTENCE OF BACTERIOPHAGE[1]

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"Predator" Fitness at the Individual Scale

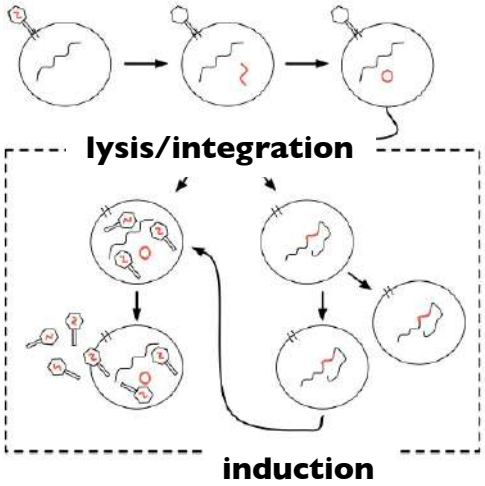
Burst size: Start with 1 phage, and after infection and lysis, there are 100s (or more) progeny.

"Predator" Fitness at the Population Scale

Per-capita growth rate: The growth rate of the total number of virus particles.

But do viruses of microbes do more than kill or prepare to kill?

Lysogeny – 'Lessons from a Simple System'



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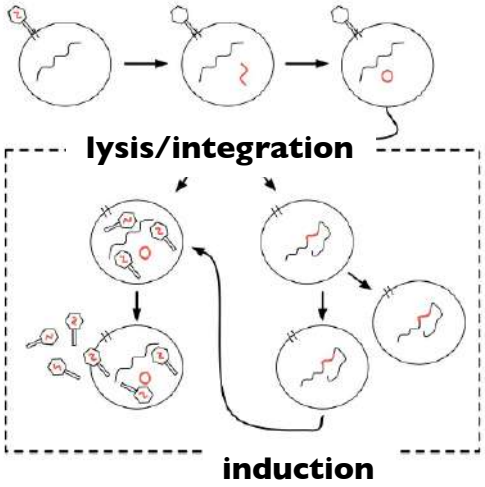
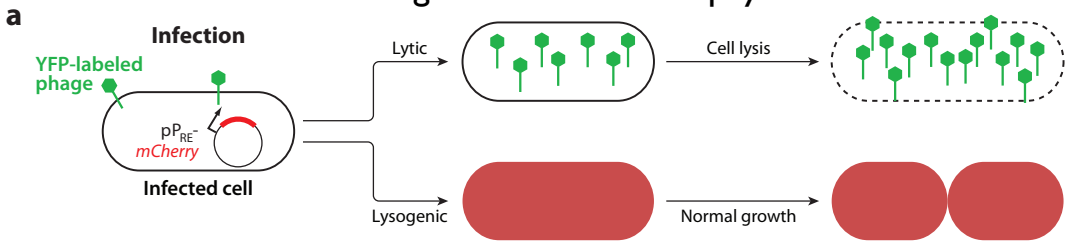
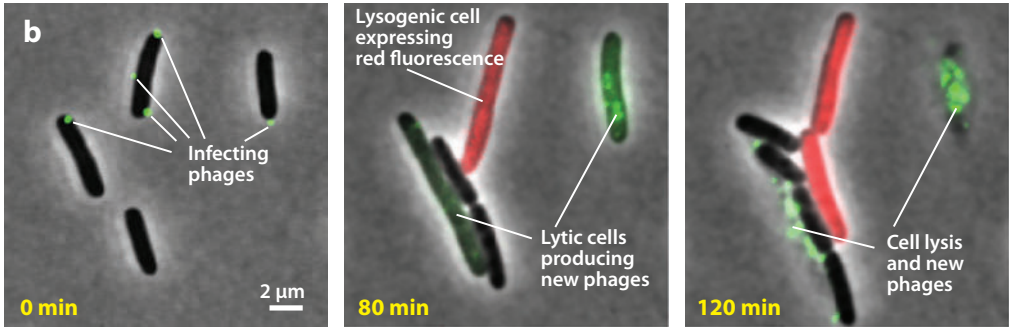


Golding et al. Ann Rev. Biophys. 2011





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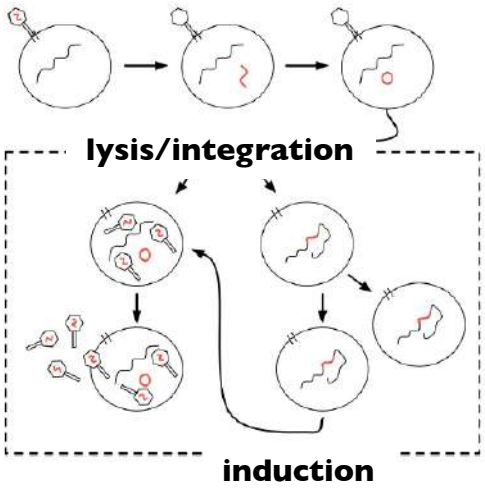

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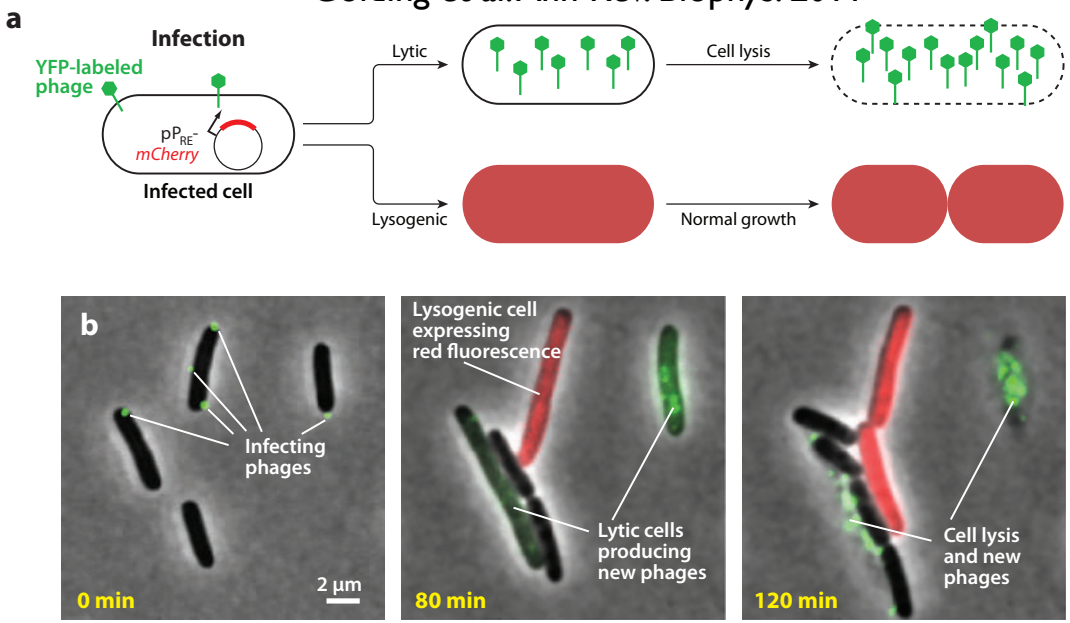

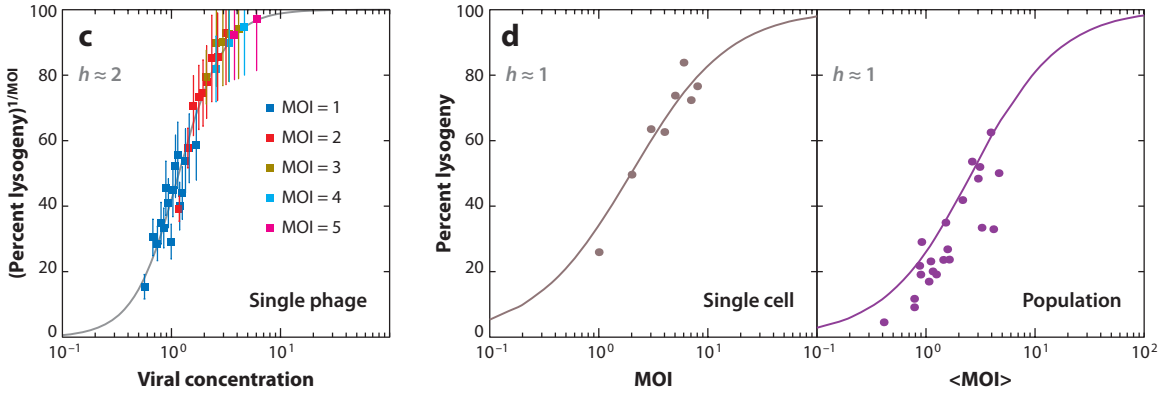

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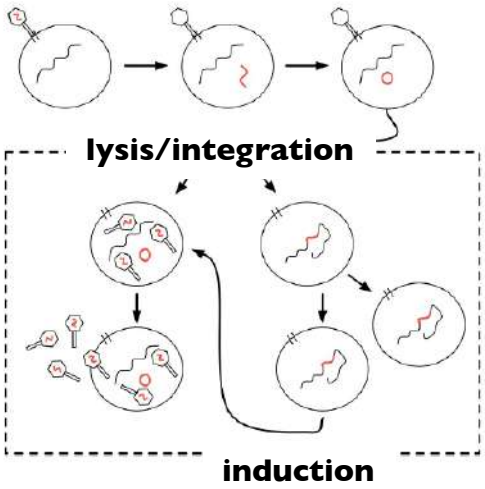

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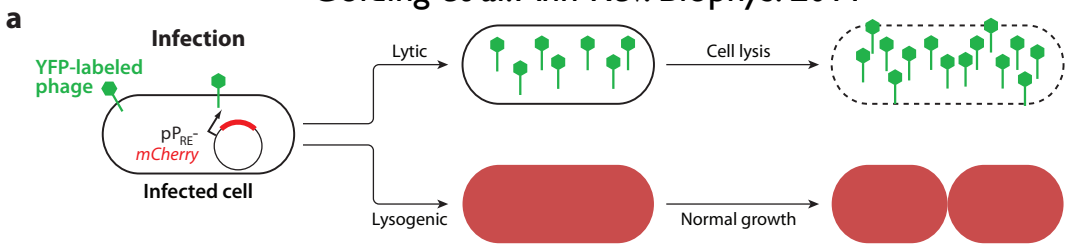
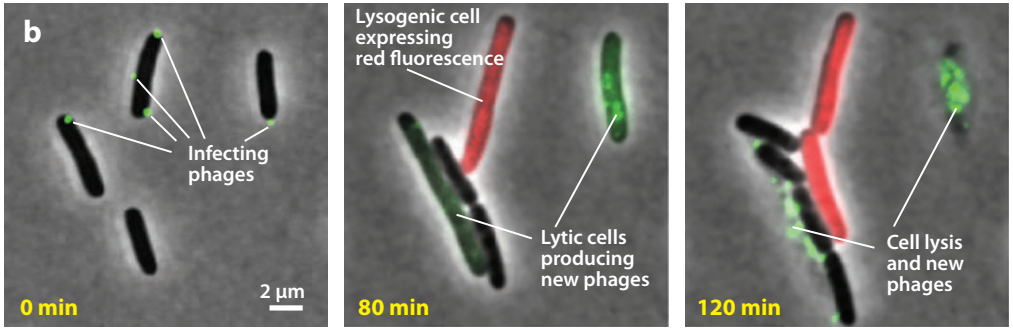
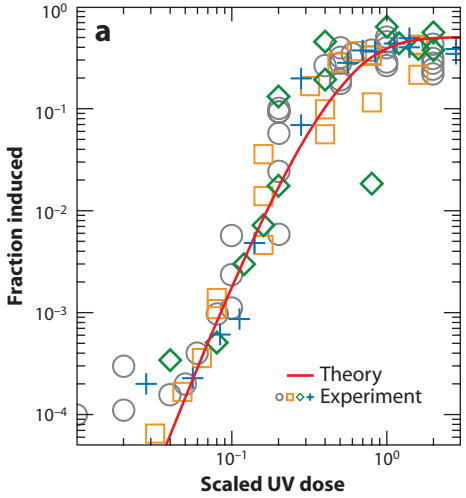
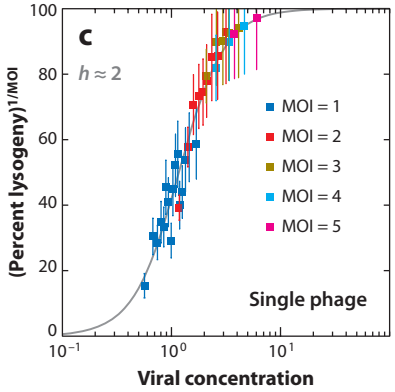
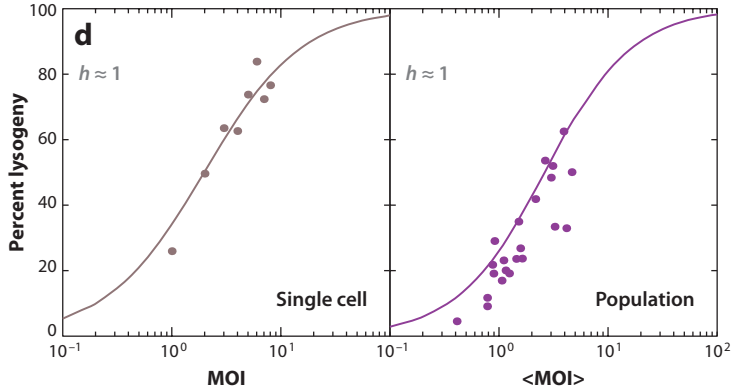










Why Be Temperate? Ala Stewart and Levin, 1984

THEORETICAL POPULATION BIOLOGY 26, 93–117 (1984)

The Population Biology of Bacterial Viruses: Why Be Temperate

FRANK M. STEWART AND BRUCE R. LEVIN

Department of Mathematics, Brown University, Providence, Rhode Island 02912, and Department of Zoology, University of Massachusetts, Amherst, Massachusetts 01003

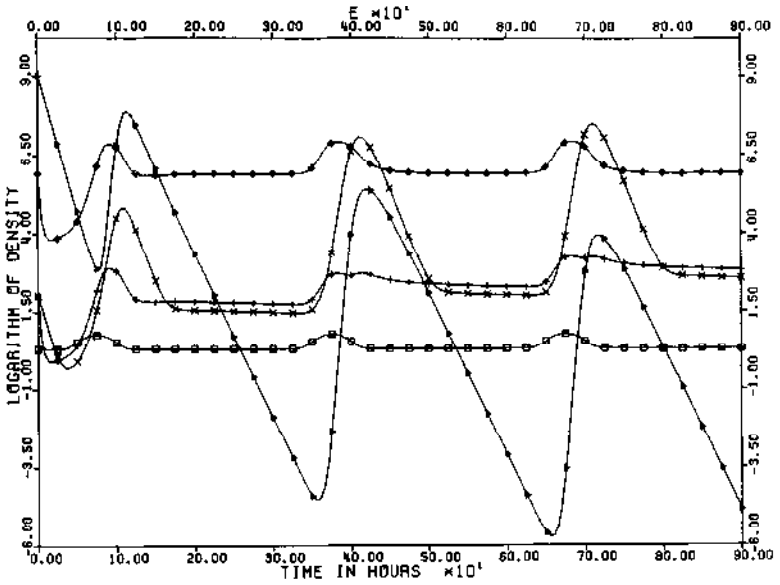
Received May 23, 1983

$$\dot{r} = \rho(C - r) - e\psi(r)(L + (1 - \alpha_S)S),$$

$$\dot{L} = \psi(r)L + \lambda\delta_T ST - (\rho + \xi + \tau)L,$$

$$\dot{S} = (1 - \alpha_S)\,\psi(r)S - \delta_T ST + \tau L - \rho S,$$

$$\dot{T} = \xi\beta_T L + \beta_T(1 - \lambda)\,\delta_T ST - \delta_T LT - \rho T.$$



Feast or Famine Hypothesis

Premise: temperate phage do better when few hosts are available and extracellular mortality rate are high.

Caveat: "In spite of the intuitive appeal of this low density hypothesis, we are unable to obtain solutions consistent with it using the model presented here."

Sure lysogeny can happen in some cases, but in the environment, do viruses typically do more than kill or prepare to kill?

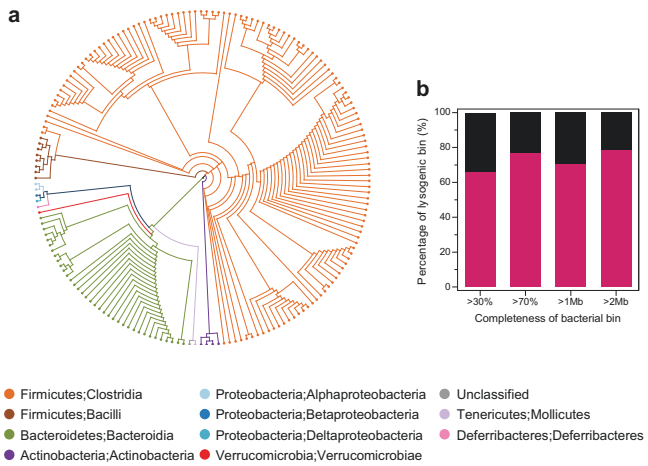
Increasing evidence of latent infections in microbiomes

The ISME Journal (2018) 12:1127–1141
https://doi.org/10.1038/s41396-018-0061-9

ARTICLE

Lysogeny is prevalent and widely distributed in the murine gut microbiota

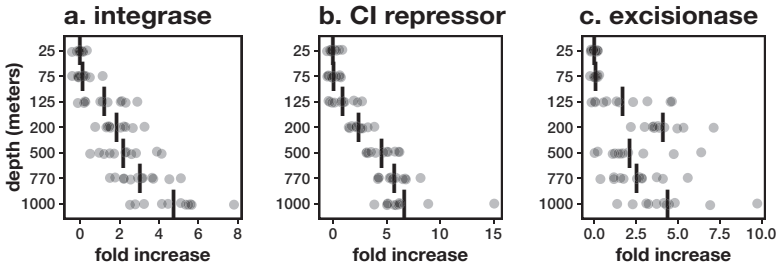
Min-Soo Kim[1] · Jin-Woo Bae[1]



Bacteriophage Distributions and Temporal Variability in the Ocean's Interior

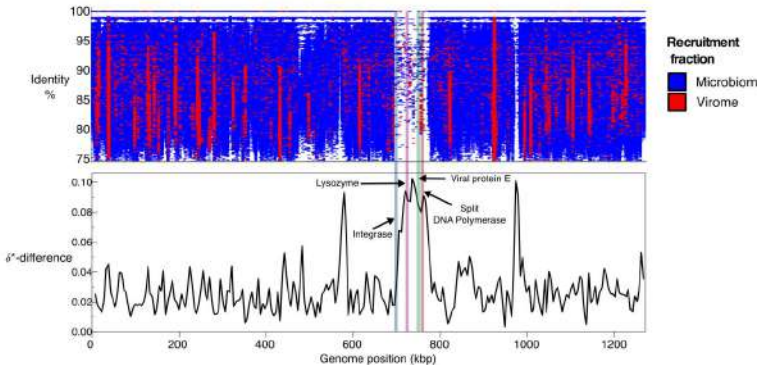
Received 17 October 2017 Accepted 25 October 2017 Published 28 November 2017

Elaine Luo, Frank O. Aylward,* Daniel R. Mende, Edward F. DeLong
Daniel K. Inouye Center for Microbial Oceanography: Research and Education, University of Hawaii, Honolulu, Hawaii, USA



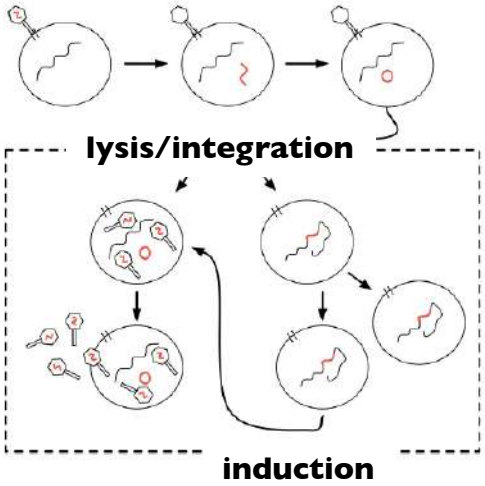
A novel oceanic uncultured temperate cyanophage lineage

José Flores-Uribe[1], Alon Philosof[1], Itai Sharon[2,3], and Oded Béjà[1]*

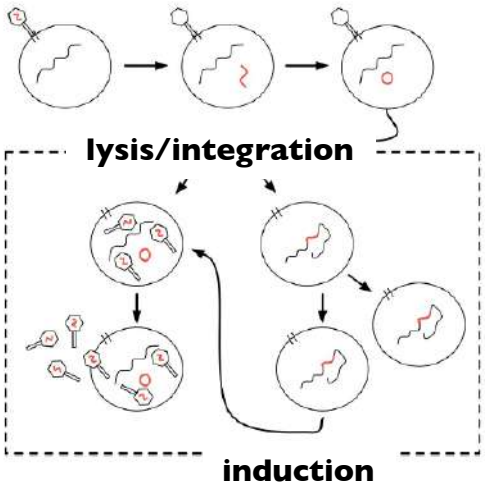


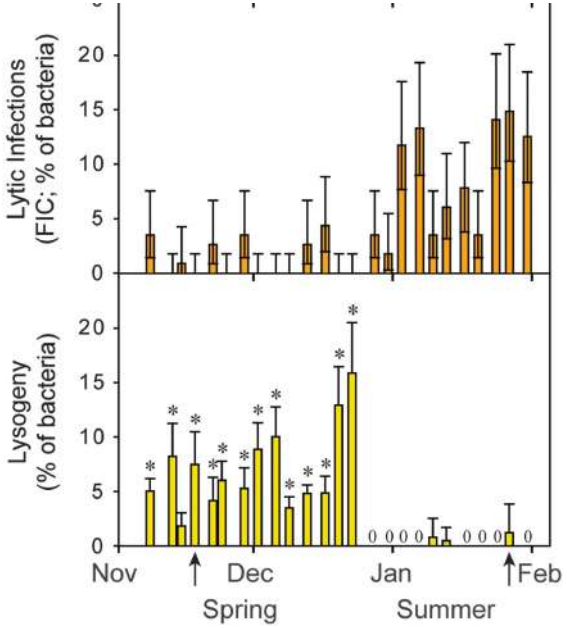
May. 17, 2018; doi: http://dx.doi.org/10.1101/325100.

Lysogeny and Plankton Blooms:



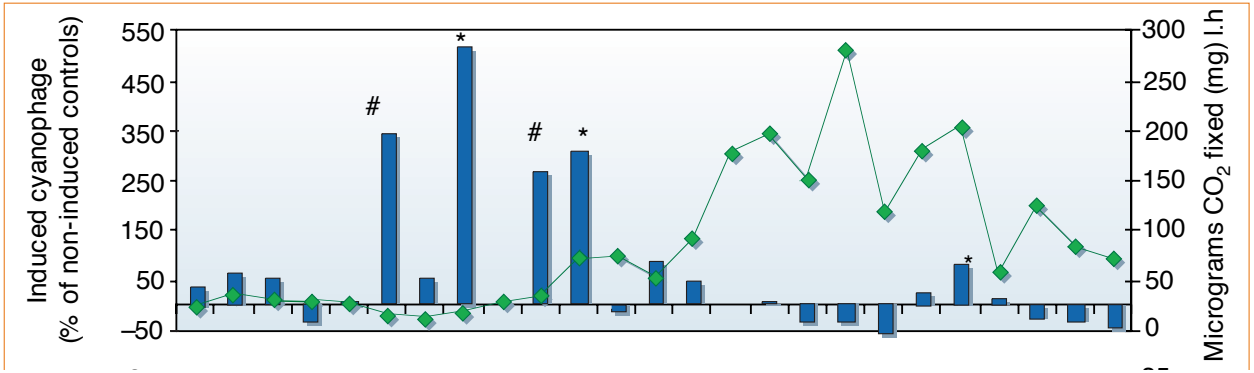
Lysogeny and Plankton Blooms: An Inverse Relationship with Plankton Density





'Seasonal Timebombs': Lysogeny prevalent given low productivity and lysis elevated at high productivity

Brum et al. ISME J. 2015

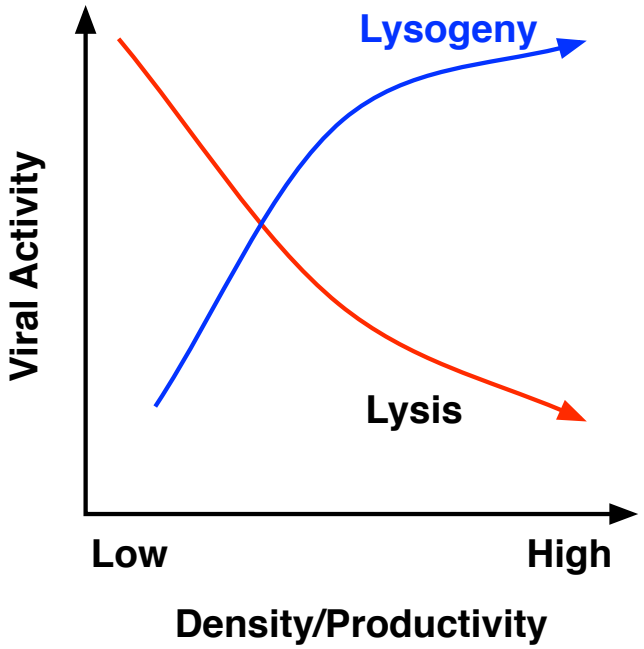


Lysogeny as adaption to poor host conditions.

"Occurrence of lysogeny (is) at times of low host availability, resource limitation or adverse environmental conditions."

McDaniel et al. Nature, 2002

An Alternative Hypothesis: "Piggyback-the-Winner"



Piggyback-the-winner – lysogeny is positively correlated with increases in host density and productivity.

Knowles et al. Nature 2016

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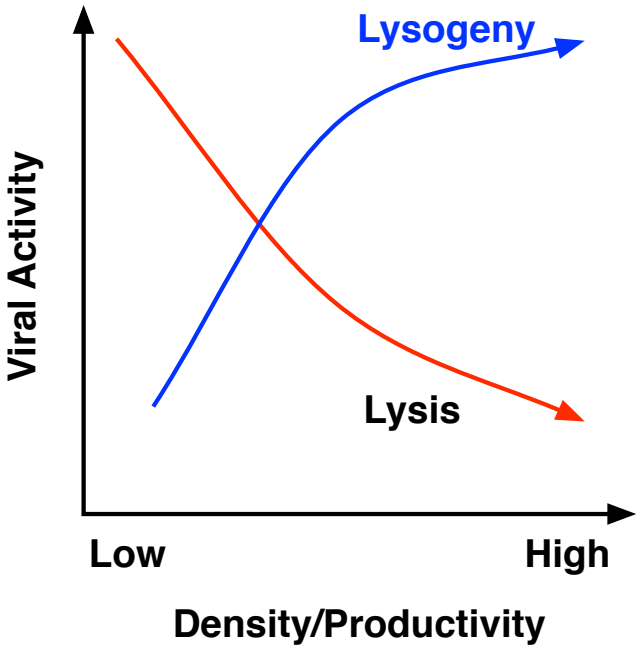

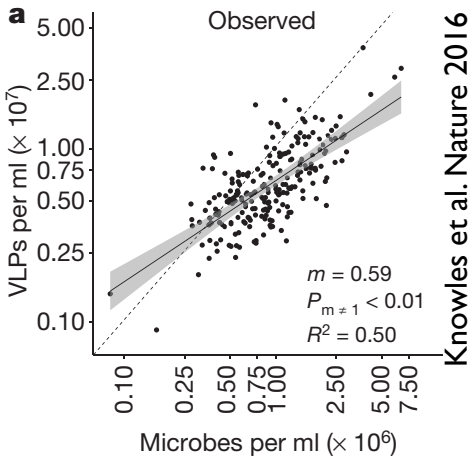

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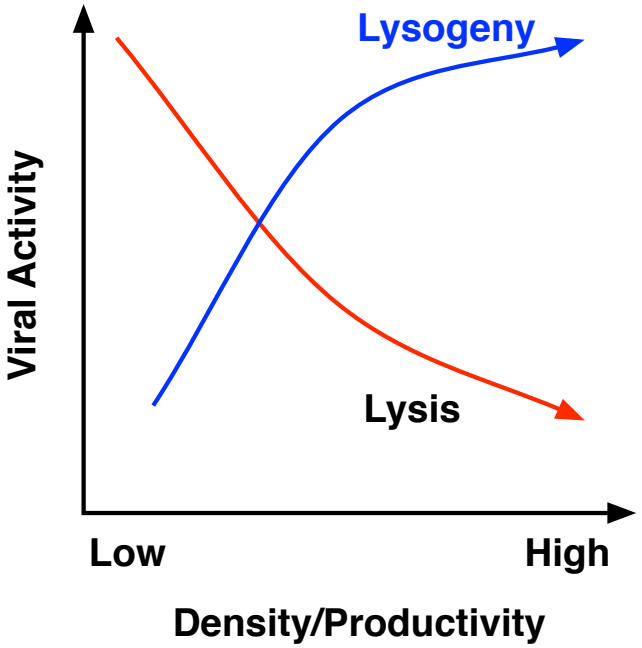

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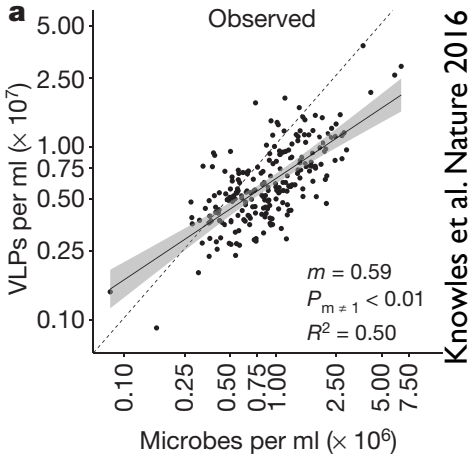
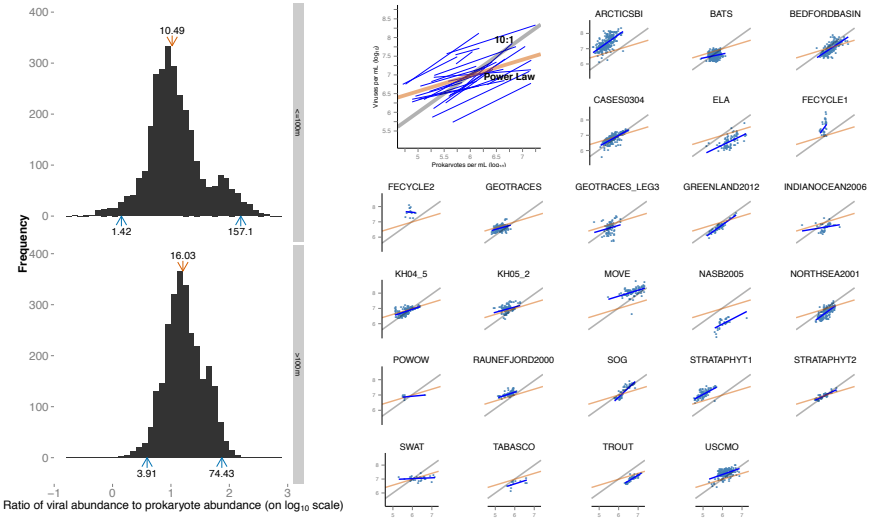
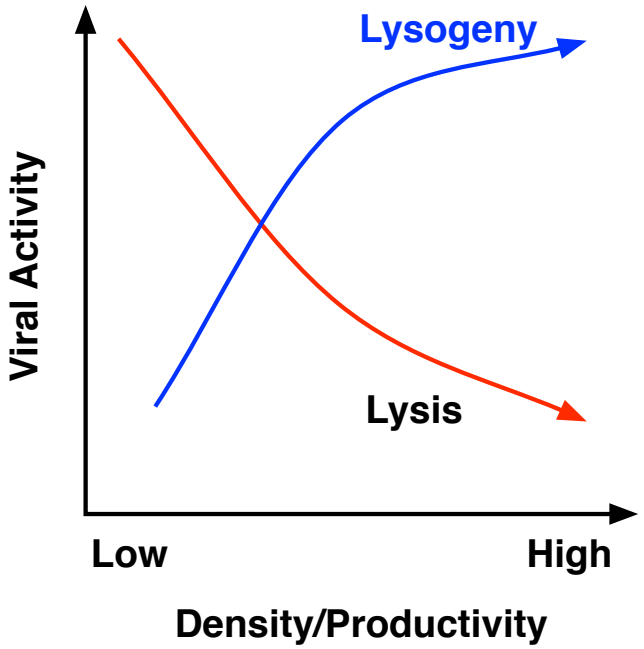




Wigington et al., Nat. Micro, 2016 (thanks to NIMBioS workshop)

Piggyback-the-Winner: Re-examining the theoretical framework



Piggyback-the-winner – lysogeny is positively correlated with increases in host density and productivity.

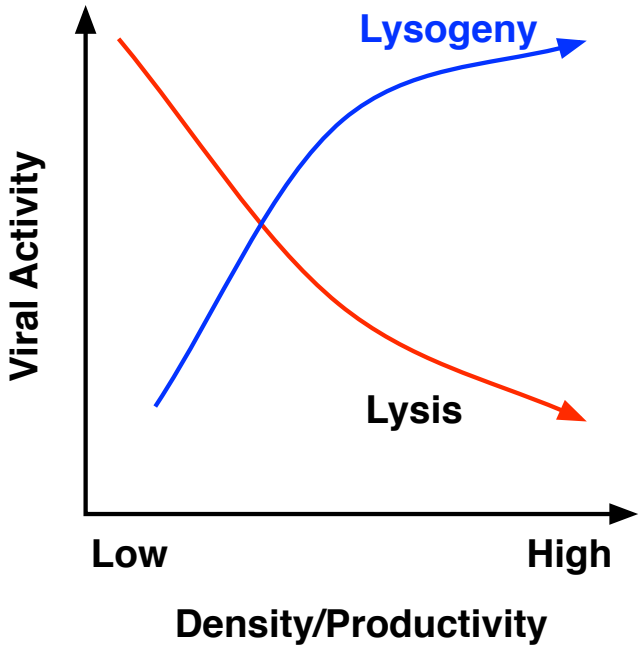
Knowles et al. Nature 2016

However, there is no lysogeny in the PtW model. Rather, the PtW model is a lytic model where the lysis and viral release increases with increasing cell abundance.

$$\overbrace{\frac{dN}{dt}}^{\text{mcirobial cell change}} = \overbrace{rN(1-N/K)}^{\text{microbial growth}} - \overbrace{\phi NP}^{\text{lysis}} - \overbrace{dN}^{\text{microbial mortality}}$$

$$\overbrace{\frac{dV}{dt}}^{\text{viral particle change}} = \overbrace{\beta\phi NV\frac{N}{K}}^{\text{viral release}} - \overbrace{mV}^{\text{viral decay}}$$

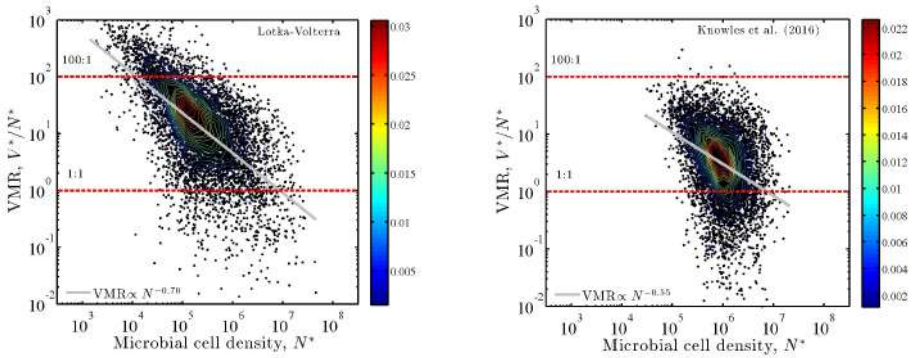
Piggyback-the-Winner: Re-examining the theoretical framework



Piggyback-the-winner – lysogeny is positively correlated with increases in host density and productivity.

Knowles et al. Nature 2016

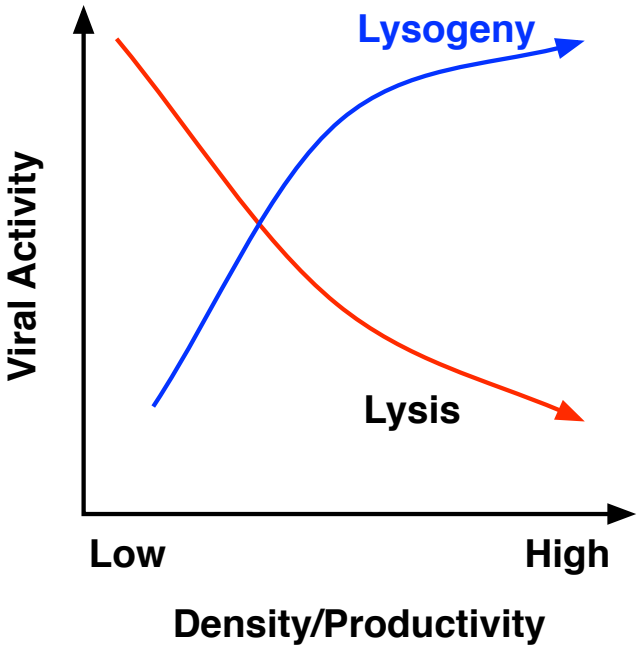
And, the PtW model yields similar patterns of virus and microbial density relationships as do Lotka-Volterra (i.e., classic) models:

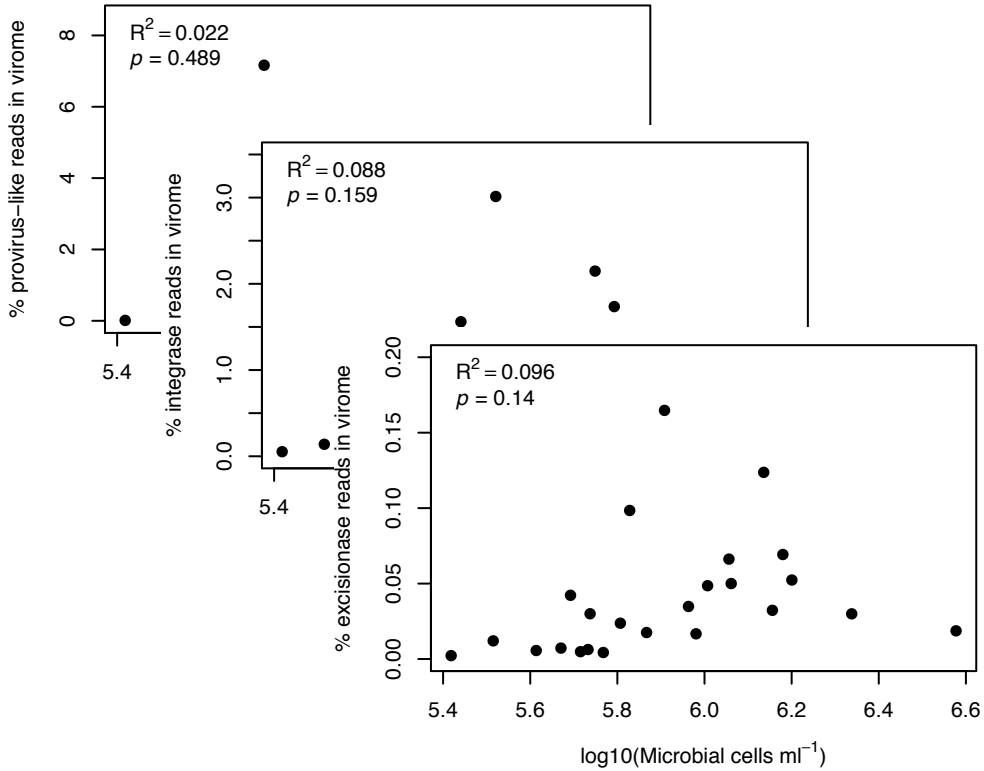


PtW is not required for negative relationships to emerge between VMR and microbial densities

Weitz et al., Nature 2017

Piggyback-the-Winner: Re-examining the metagenomics evidence (pt 1)





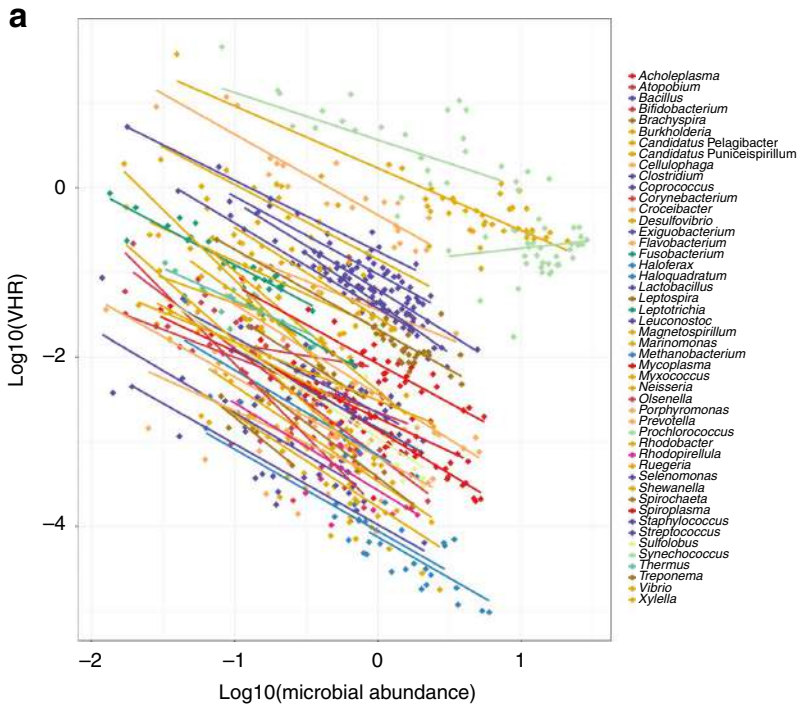
Piggyback-the-winner – lysogeny is positively correlated with increases in host density and productivity.

Knowles et al. Nature 2016

Absence of evidence for a positive correlation between lysogeny proxies and microbial cell density.

Weitz et al., Nature 2017 & response from Knowles & Rohwer, Nature 2017

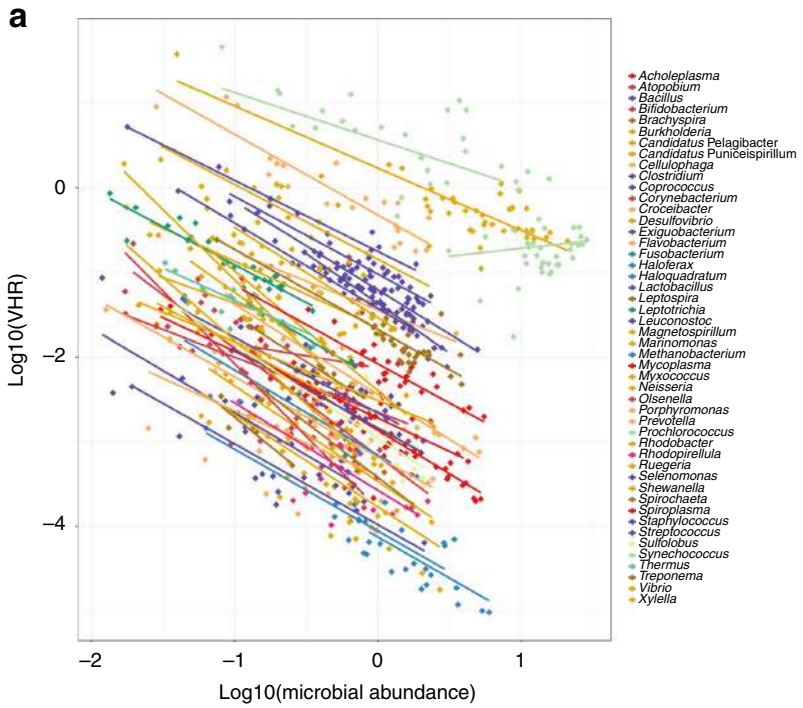
Piggyback-the-Winner: Re-examining the metagenomics evidence (pt 2)

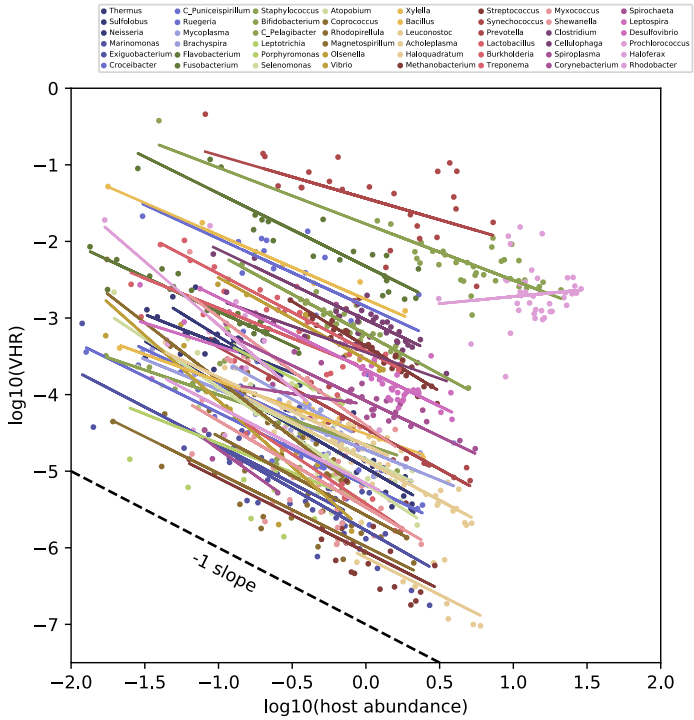


"findings [i.e., the decline of the ratio of viruses-to-microbes] corroborate the recently proposed Piggyback-the-Winner theory"

Coutinho et al., Nat. Comm (2017)

Piggyback-the-Winner: Re-examining the metagenomics evidence (pt 2)



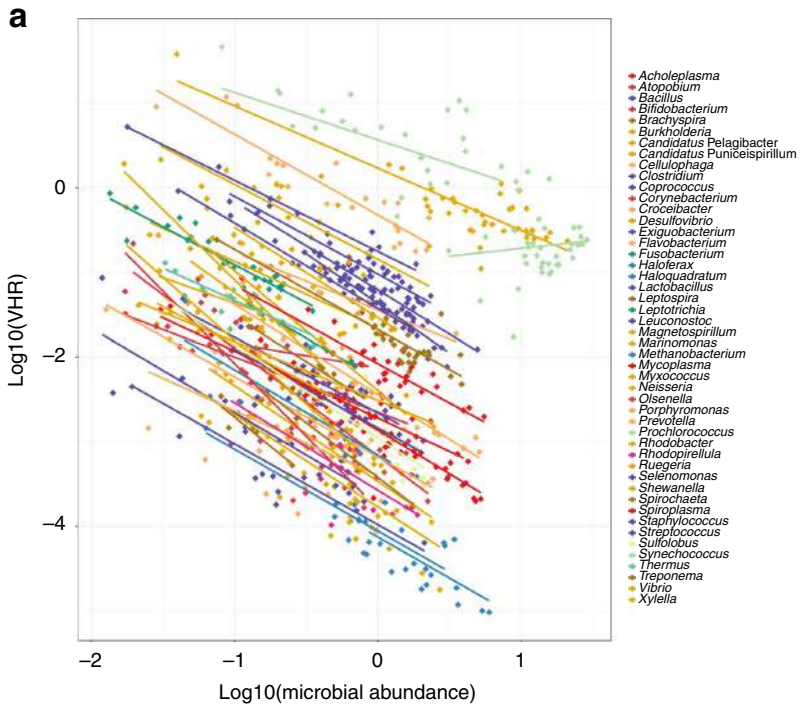


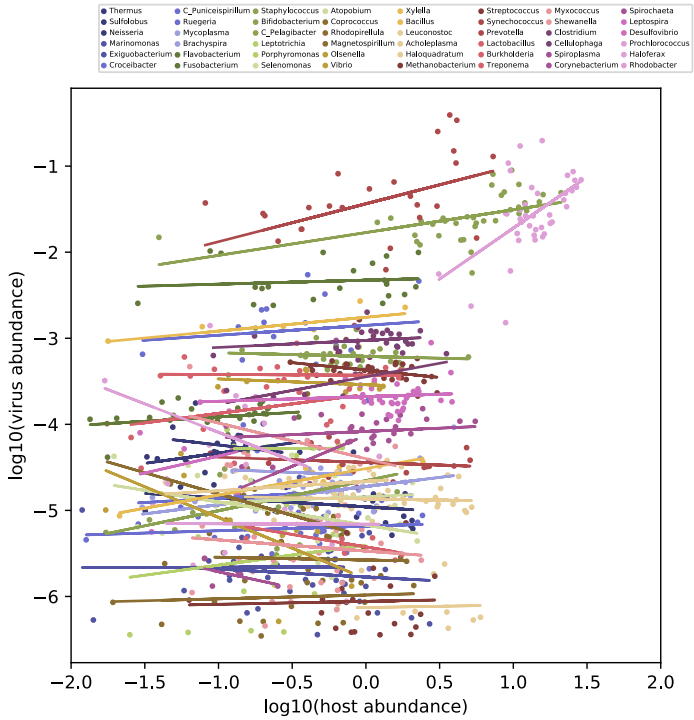
"findings [i.e., the decline of the ratio of viruses-to-microbes] corroborate the recently proposed Piggyback-the-Winner theory"

But... if $y/x \sim x^{-1}$

Coutinho et al., Nat. Comm (2017)

Piggyback-the-Winner: Re-examining the metagenomics evidence (pt 2)





"findings [i.e., the decline of the ratio of viruses-to-microbes] corroborate the recently proposed Piggyback-the-Winner theory"

Coutinho et al., Nat. Comm (2017)

But... if $y/x \sim x^{-1}$, then virus abundances are <u>unrelated</u> to host abundances. This is a <u>counter-indicator</u> for PtW.

Alrasheed, Jin & Weitz, Nat. Comm (2019) *forthcoming*

What environmental conditions should favor lysogeny rather than lysis?

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<u>On old lesson:</u>

A bird in the hand is worth two in the bush.

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A new puzzle:

*A virus in the cell is worth **N** in the bloom.*

What environmental conditions should favor lysogeny rather than lysis?

<u>*On old lesson:*</u>

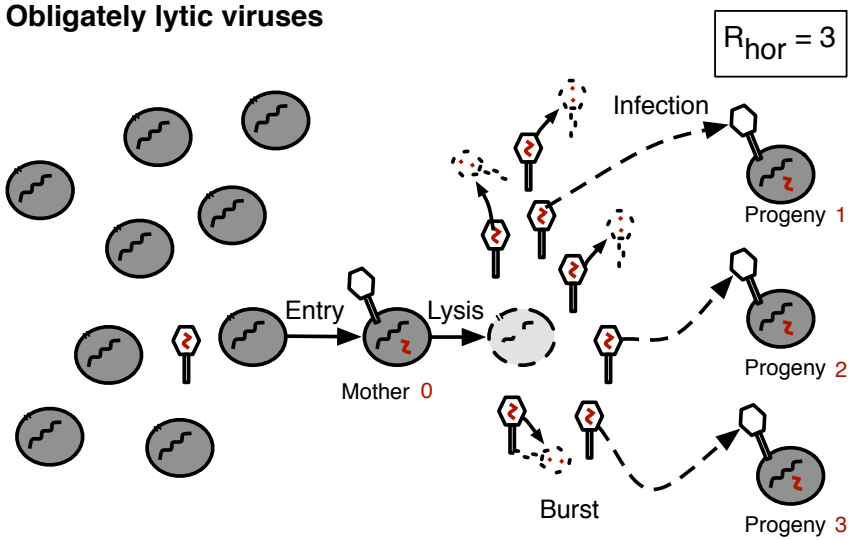
A bird in the hand is worth two in the bush.

<u>A new puzzle:</u>

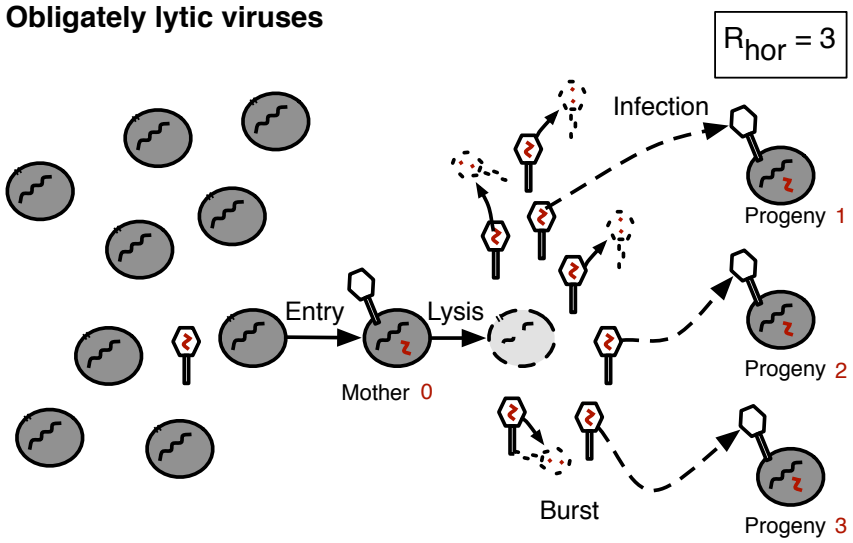
*A virus in the cell is worth **N** in the bloom.*

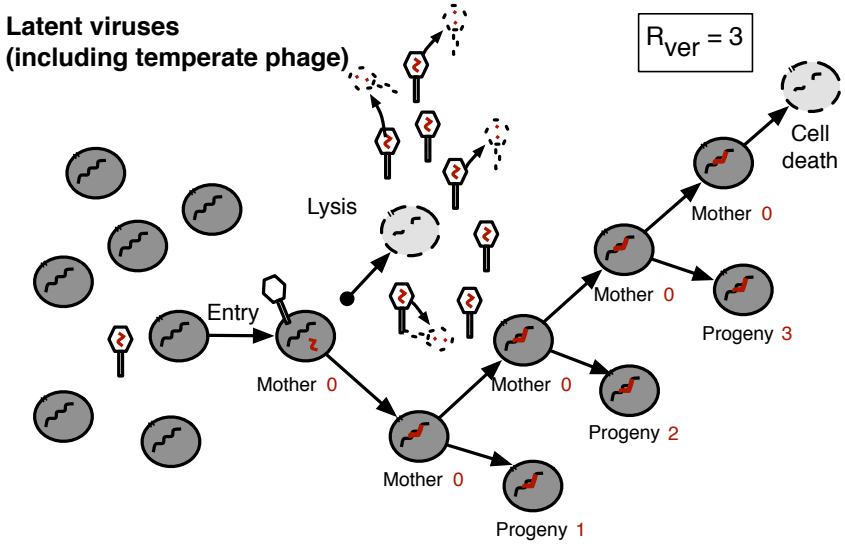
But, what is ***N***?

Viral proliferation at the individual level for *lytic strategies*

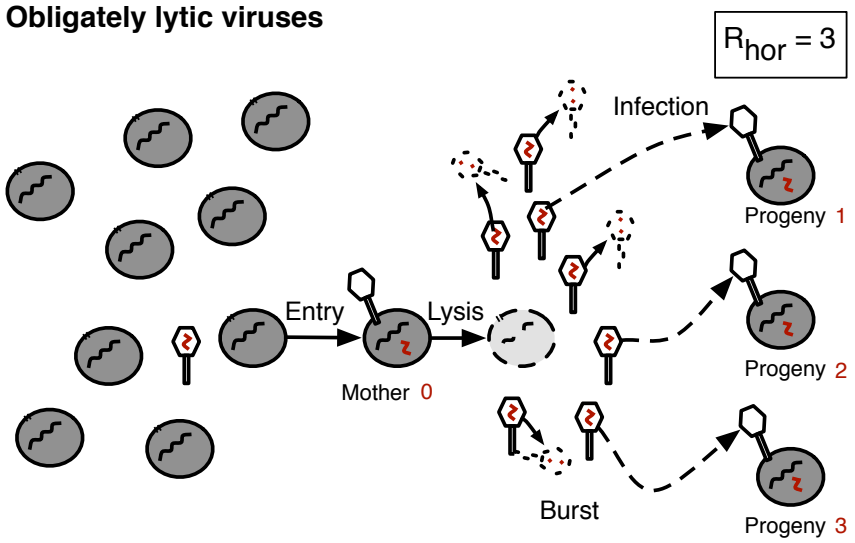


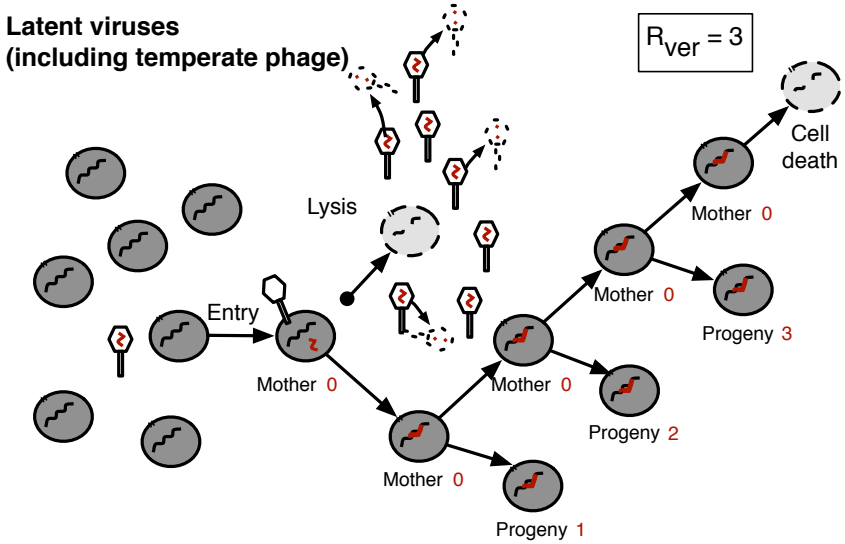
Viral proliferation at the individual level for *lytic strategies* and *latent strategies*





Viral proliferation at the individual level for *lytic strategies* and *latent strategies*

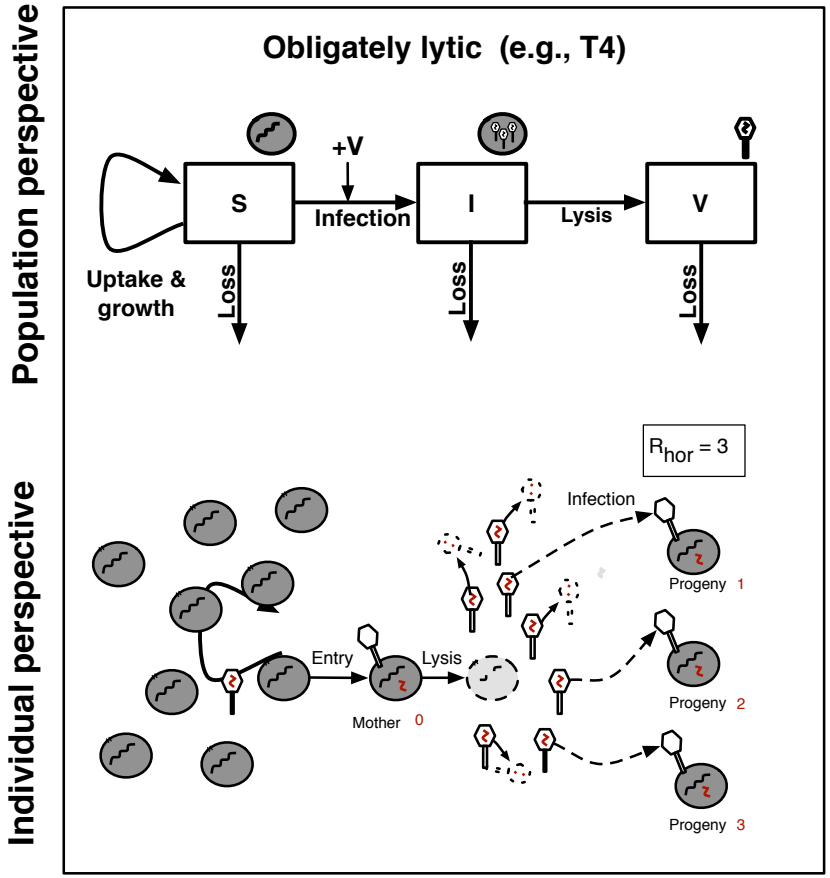




Two vastly different strategies can lead to the same 'fitness' at the individual level.

How does this depend on cell densities?

Population dynamics of lytic viruses



$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1-N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \overbrace{\phi SV}^{\text{infection}} - \overbrace{\eta I}^{\text{lysis}} - \overbrace{d' I}^{\text{cell death}}$$

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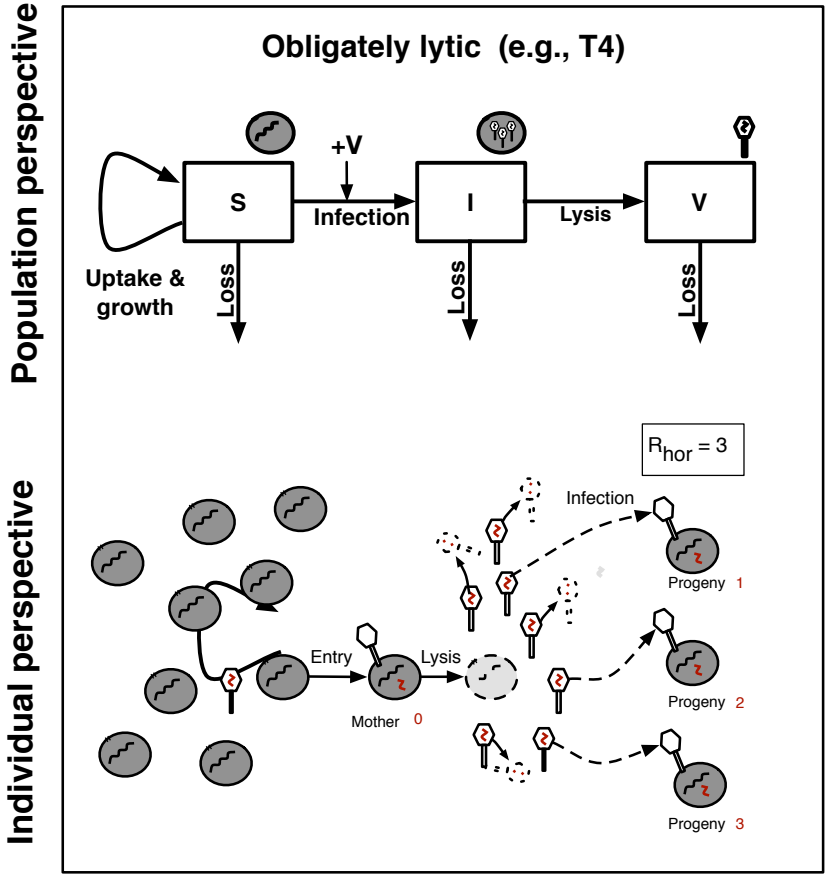
Population dynamics of lytic viruses



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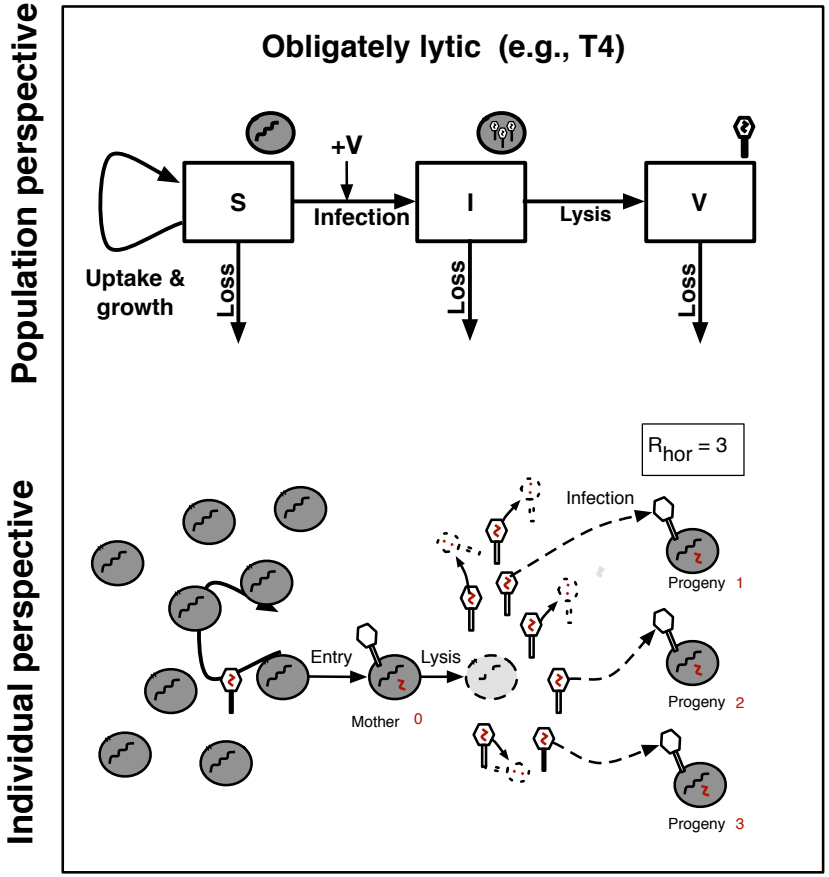
Viruses increase in population, within infected cells given exclusively horizontal transmission when

$$\mathcal{R}_{hor} = \beta\left(\frac{\phi S^*}{\phi S^* + m}\right)\left(\frac{\eta}{\eta + d'}\right)$$

is greater than 1

Population dynamics of lytic viruses



$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1 - N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \overbrace{\phi SV}^{\text{infection}} - \overbrace{\eta I}^{\text{lysis}} - \overbrace{d' I}^{\text{cell death}}$$

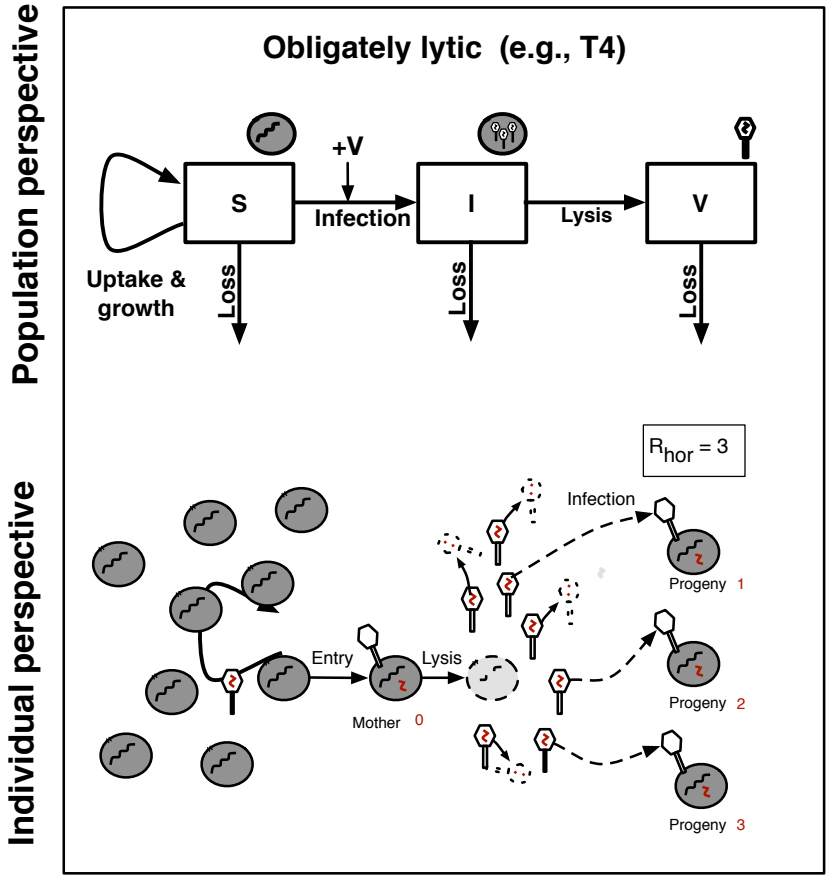
$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\beta\eta I}^{\text{lysis}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$

Viruses increase in population, within infected cells given exclusively <u>horizontal transmission</u> when

$$\mathcal{R}_{hor} = \text{Burst size} \left(\text{Probability of viral adsorption to host before decay} \right) \left(\text{Probability of lysis before washout} \right)$$

is greater than 1

Population dynamics of lytic viruses



$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\,(1-N/K)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

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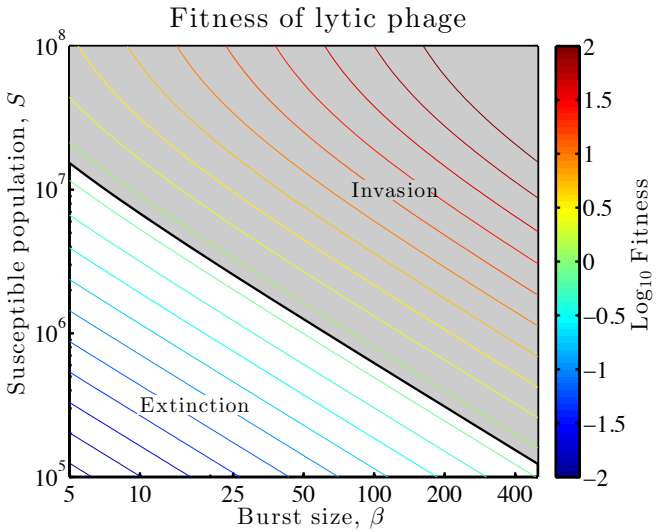
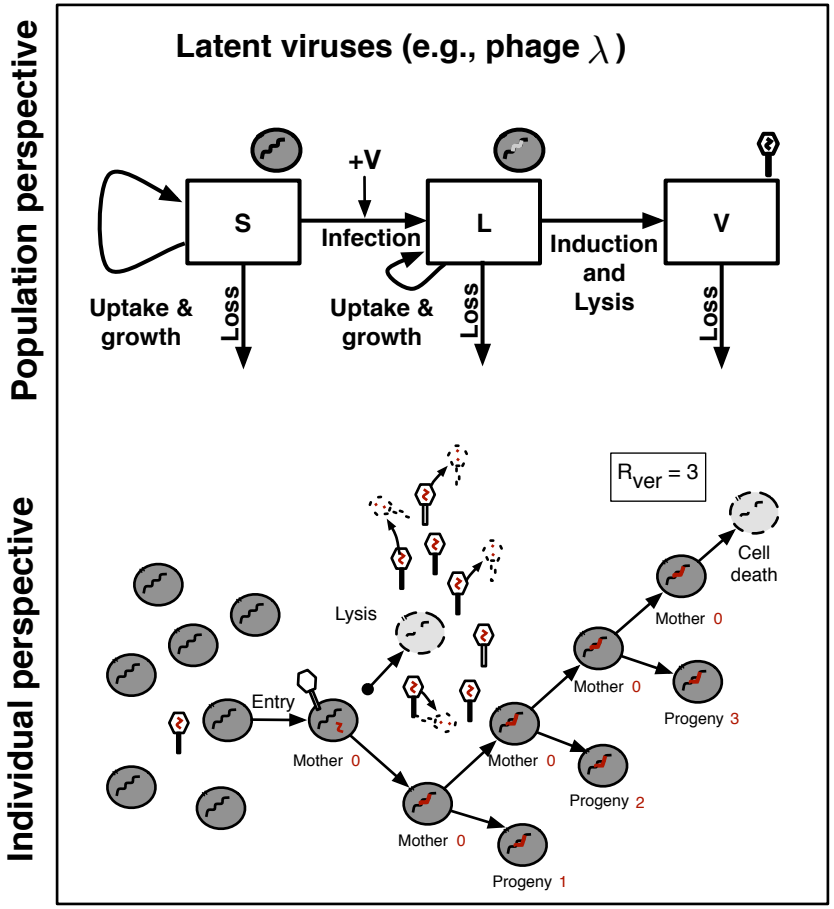


Population dynamics of latent viruses

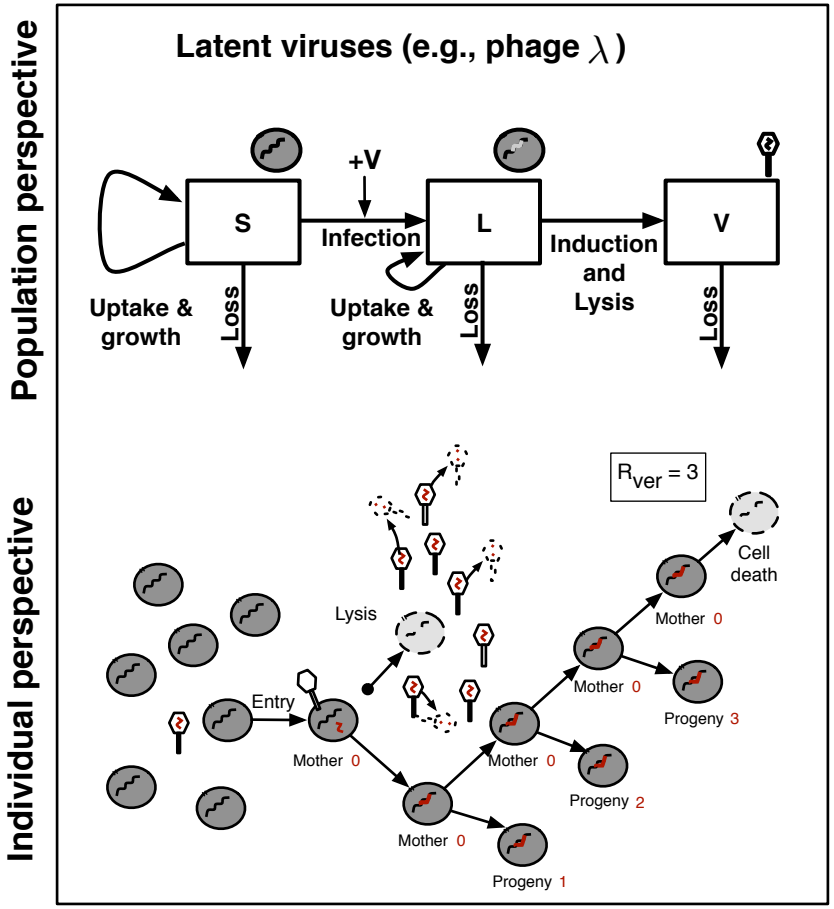


$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1-N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{\mathrm{d}L}{\mathrm{d}t} = \overbrace{qb'L\left(1-N/K\right)}^{\text{lysogen growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{p\eta L}^{\text{lysis}} - \overbrace{d'L}^{\text{cell death}}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\beta p\eta L}^{\text{lysis}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$

Population dynamics of latent viruses



$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1-N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{\mathrm{d}L}{\mathrm{d}t} = \overbrace{qb'L\left(1-N/K\right)}^{\text{lysogen growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{p\eta L}^{\text{lysis}} - \overbrace{d'L}^{\text{cell death}}$$

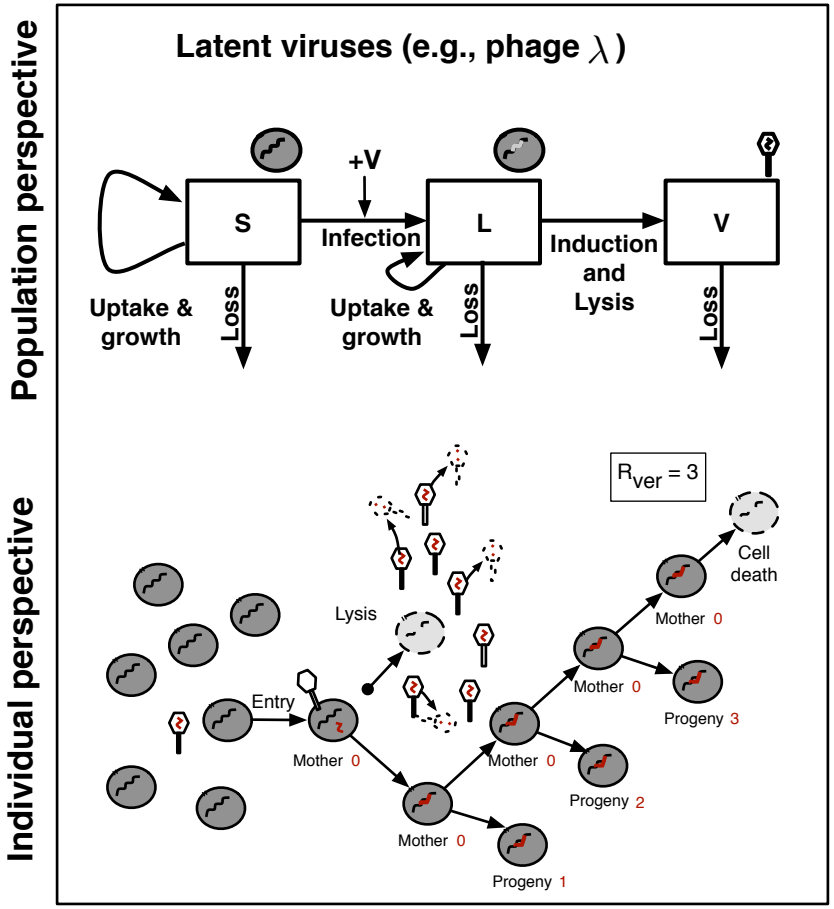
$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\beta p\eta L}^{\text{lysis}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$

Viruses increase in population, within infected cells given exclusively <u>vertical transmission</u> when

$$\mathcal{R}_{ver} = \frac{b'\left(1-\frac{S^*}{K}\right)}{d'}$$

is greater than 1

Population dynamics of latent viruses



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$$\frac{\mathrm{d}L}{\mathrm{d}t} = \overbrace{qb'L\left(1-N/K\right)}^{\text{lysogen growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{p\eta L}^{\text{lysis}} - \overbrace{d'L}^{\text{cell death}}$$

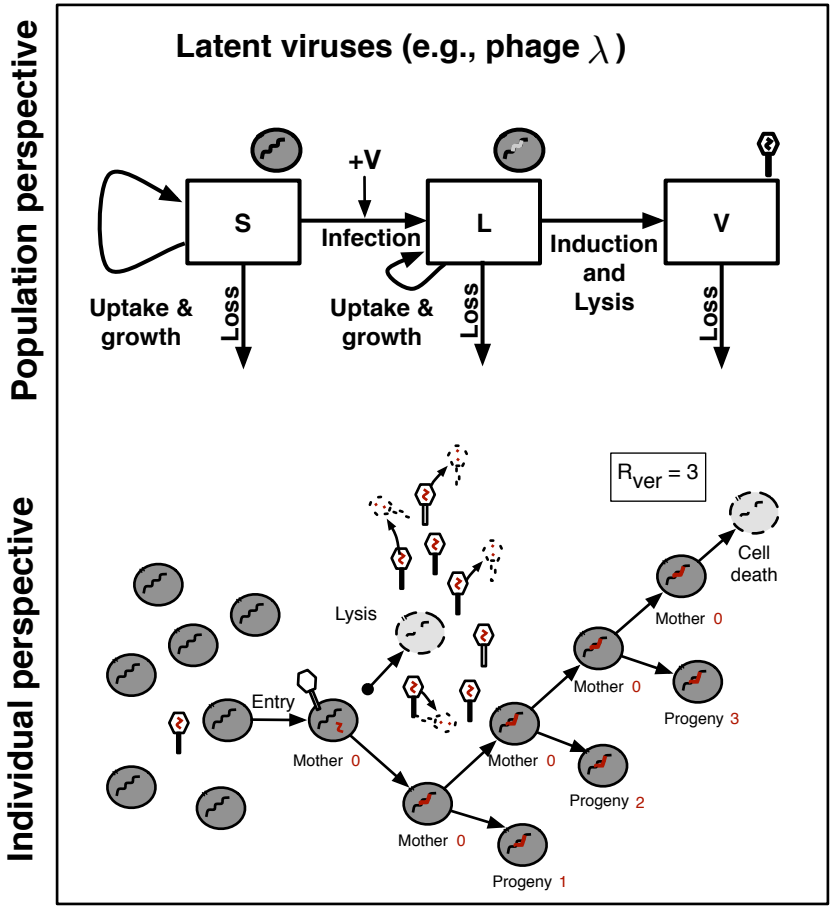
$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\beta p\eta L}^{\text{lysis}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$

Viruses increase in population, within infected cells given exclusively <u>vertical transmission</u> when

$$\mathcal{R}_{ver} = \frac{\text{Density-dependent cell division per unit time}}{\text{1/(Cell lifetime)}}$$

is greater than 1

Population dynamics of latent viruses



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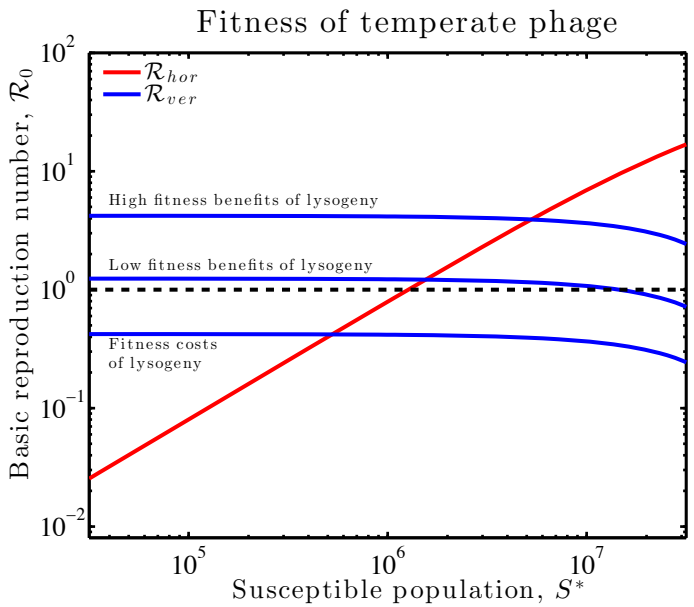
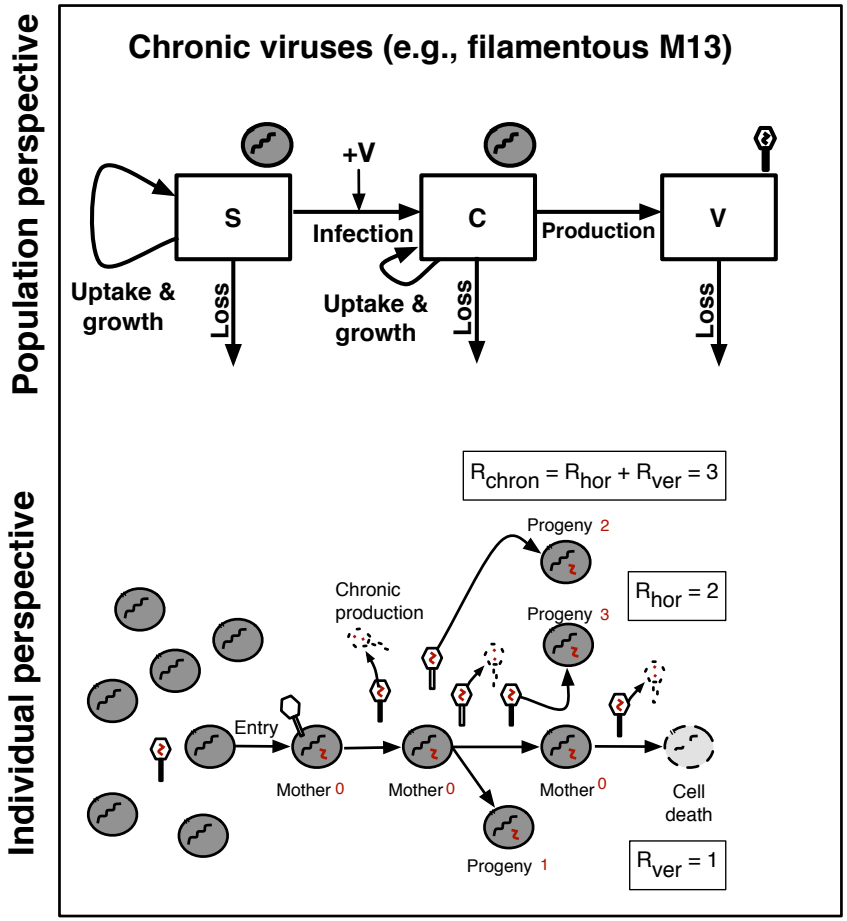


Population dynamics of chronic viruses

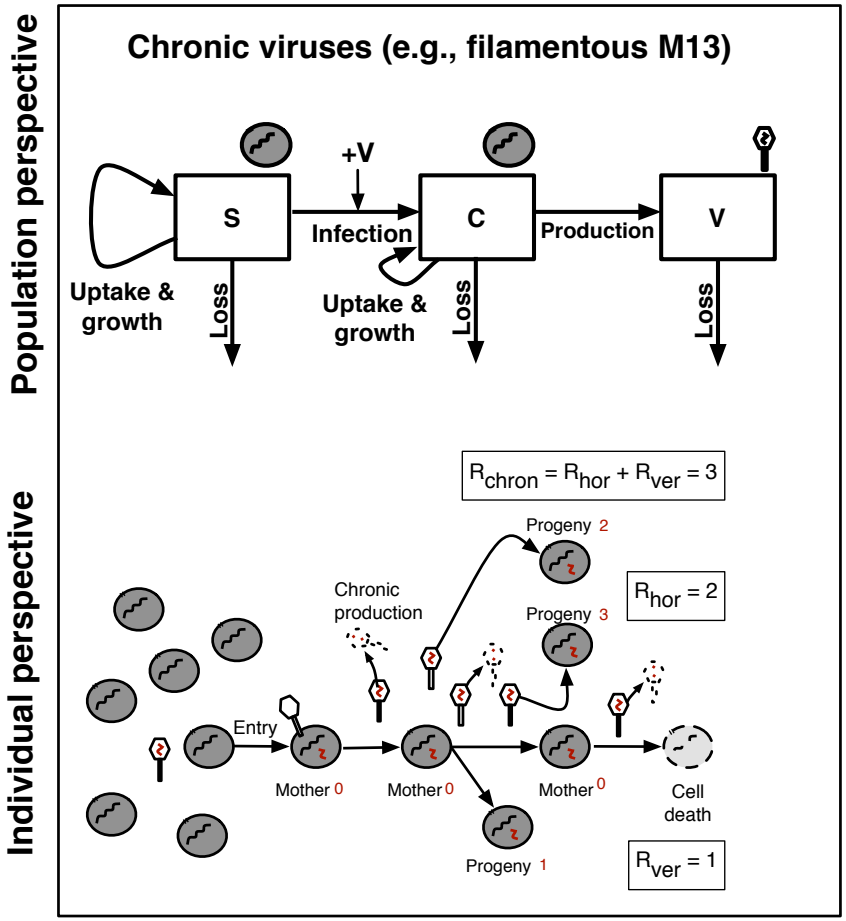


$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1-N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \overbrace{b'I\left(1-N/K\right)}^{\text{logistic growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{d'I}^{\text{cell death}}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\alpha I}^{\text{virion production}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$

Population dynamics of chronic viruses



$$\frac{dS}{dt} = \overbrace{bS(1-N/K)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{dI}{dt} = \overbrace{b'I(1-N/K)}^{\text{logistic growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{d'I}^{\text{cell death}}$$

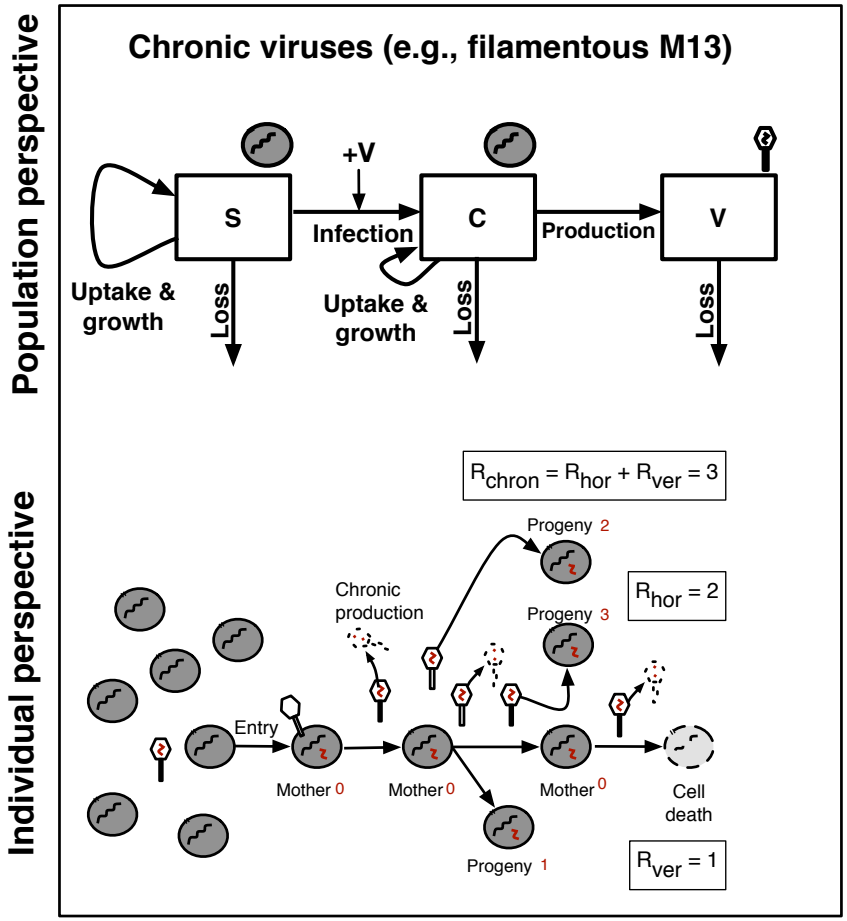
$$\frac{dV}{dt} = \overbrace{\alpha I}^{\text{virion production}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$

Viruses increase in population, within infected cells given <u>mixed transmission</u> when

$$\mathcal{R}_{chron} \equiv \overbrace{\frac{\alpha}{d'}\left(\frac{\phi S^*}{\phi S^* + m}\right)}^{\text{horizontal}} + \overbrace{\frac{b'(1-S^*/K)}{d'}}^{\text{vertical}}$$

is greater than 1

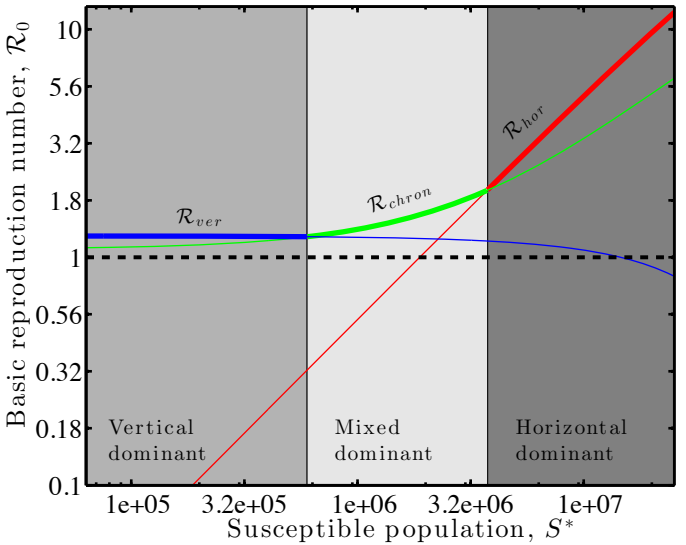
Population dynamics of chronic viruses



$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1-N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

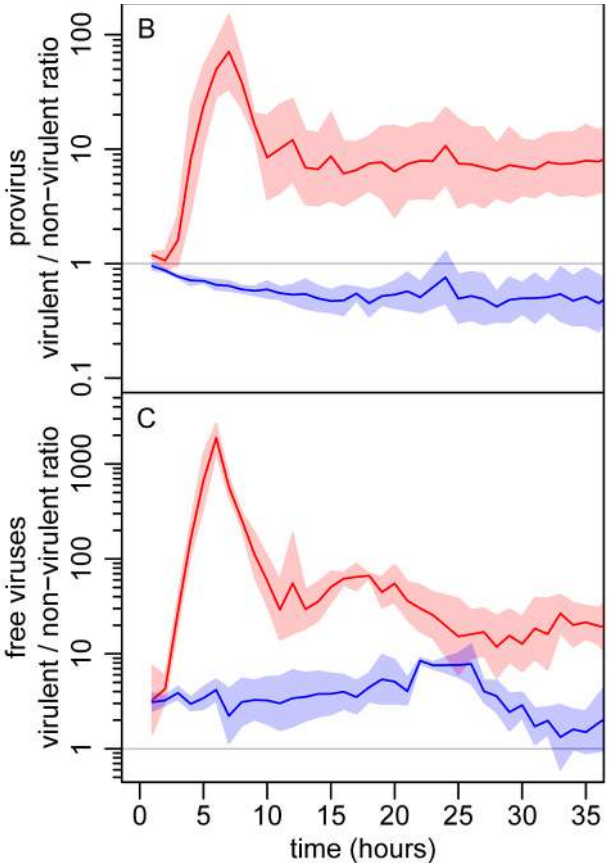
$$\frac{\mathrm{d}I}{\mathrm{d}t} = \overbrace{b'I\left(1-N/K\right)}^{\text{logistic growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{d'I}^{\text{cell death}}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\alpha I}^{\text{virion production}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$



Weitz et al. "Viral fitness across a continuum from lysis to latency". biorxiv: 296897

Value of strategies is context-dependent (i.e., dependent on susceptible cells)

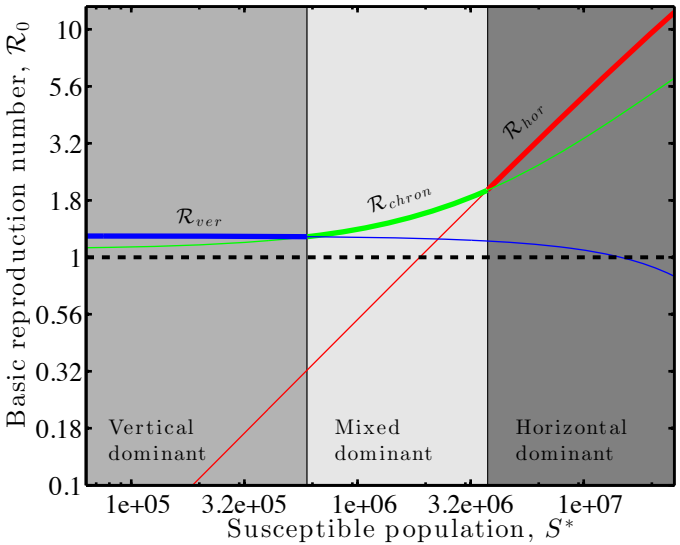


Berngruber et al., 2003, phage lambda and *E. coli*, with initial 1% prevalence (red) and 100% prevalence (blue)

$$\frac{\mathrm{d}S}{\mathrm{d}t} = \overbrace{bS\left(1-N/K\right)}^{\text{logistic growth}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{dS}^{\text{cell death}}$$

$$\frac{\mathrm{d}I}{\mathrm{d}t} = \overbrace{b'I\left(1-N/K\right)}^{\text{logistic growth}} + \overbrace{\phi SV}^{\text{infection}} - \overbrace{d'I}^{\text{cell death}}$$

$$\frac{\mathrm{d}V}{\mathrm{d}t} = \overbrace{\alpha I}^{\text{virion production}} - \overbrace{\phi SV}^{\text{infection}} - \overbrace{mV}^{\text{viral decay}}$$



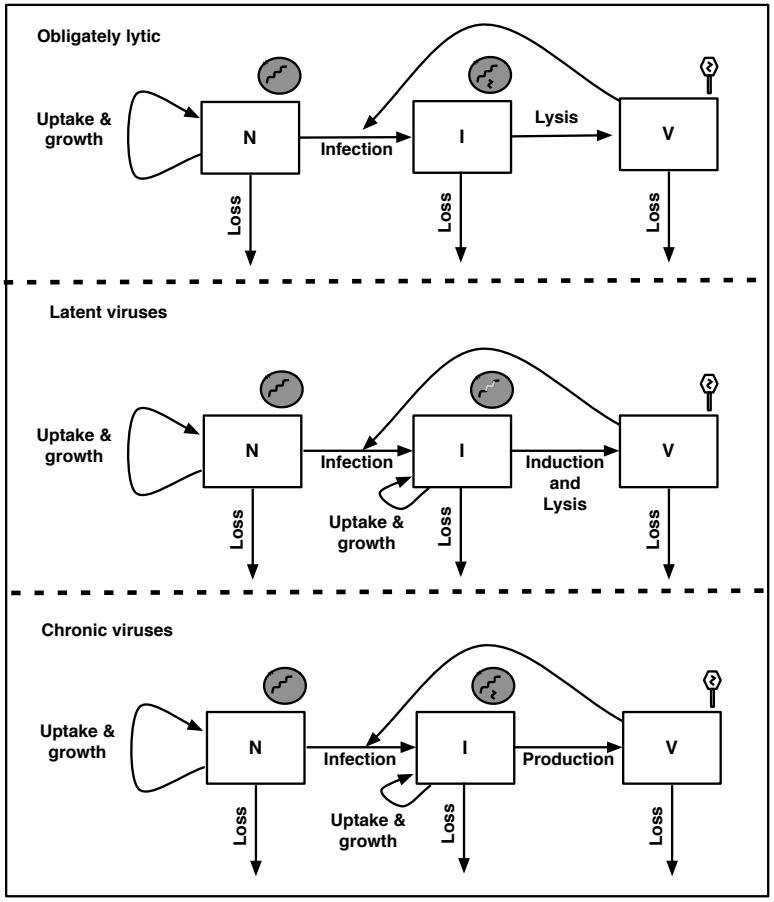
Weitz et al. "Viral fitness across a continuum from lysis to latency". biorxiv: 296897

What environmental conditions should favor lysogeny rather than lysis?

Answering this question requires a unified metric, e.g.,:

$\mathcal{R}_0$: *the average number of new infected cells produced by a single (typical) infected cell and its progeny virions in an otherwise susceptible population.*

Compilation of basic reproductive numbers



$$\mathcal{R}_{hor} = \frac{\beta\phi S^*}{\phi S^* + m}\left(\frac{\eta}{\eta + d'}\right)$$

$$\mathcal{R}_{ver} = \frac{b'\left(1 - \frac{S^*}{K}\right)}{d'}$$

$$\mathcal{R}_{chron} \equiv \overbrace{\frac{\alpha}{d'}\left(\frac{\phi S^*}{\phi S^* + m}\right)}^{\text{horizontal}} + \overbrace{\frac{b'(1 - S^*/K)}{d'}}^{\text{vertical}}$$

Compilation of basic reproductive numbers

Technical note:
All of these basic reproduction numbers were calculated using the 'Next-generation matrix' (NGM) method, popularized by Diekmann et al. J. Roy. Soc. Interface (2010). Yet results from NGM recipes become hard to interpret when infection modes traverse paths.

$$\mathcal{R}_{hor} = \frac{\beta\phi S^*}{\phi S^* + m}\left(\frac{\eta}{\eta + d'}\right)$$

$$\mathcal{R}_{ver} = \frac{b'\left(1 - \frac{S^*}{K}\right)}{d'}$$

To come soon:
New interpretable approach to analyzing generalized infection dynamics (including lysis, latency, and switches between).

$$\mathcal{R}_{chron} \equiv \overbrace{\frac{\alpha}{d'}\left(\frac{\phi S^*}{\phi S^* + m}\right)}^{\text{horizontal}} + \overbrace{\frac{b'(1 - S^*/K)}{d'}}^{\text{vertical}}$$

Li, Cortez & Weitz, in prep

A broader perspective:

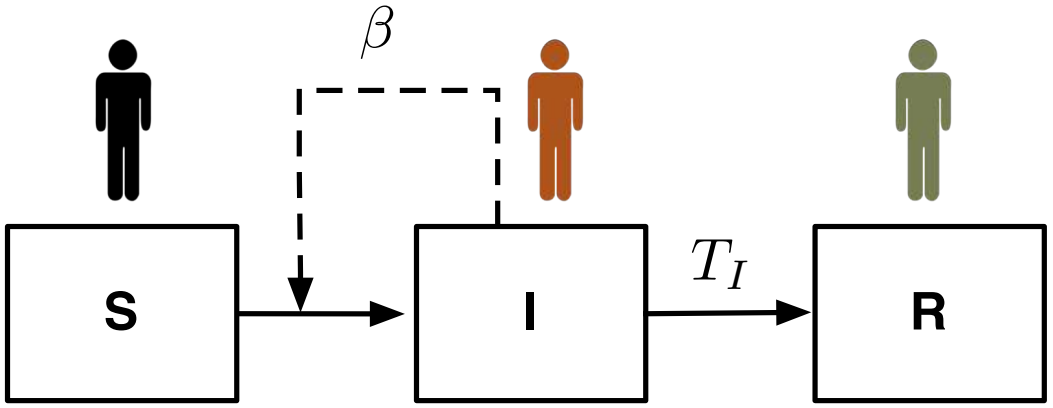
Wait, isn't "R_0" a concept from epidemiology?

And you told me that viruses were predators?

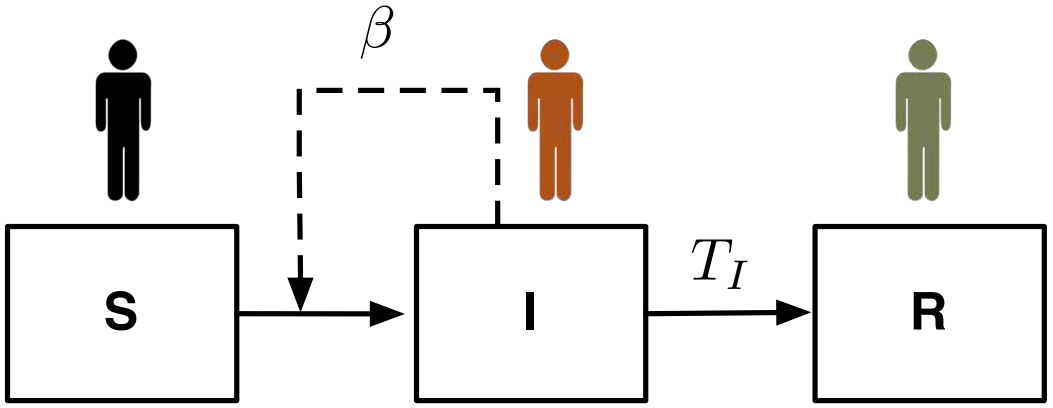
Yes, I did.

But, viruses are obligate intracellular parasites, and so it is time to unify the eco-evolutionary study of virus dynamics (as applied to viruses of microbes) with the epidemiological study of virus dynamics.

SIR model: susceptible-infected-recovered



SIR model: susceptible-infected-recovered

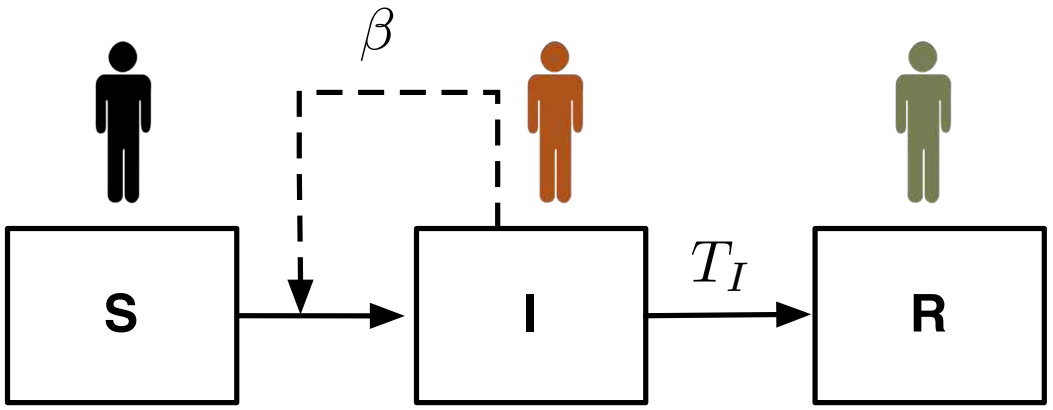


$$\frac{dS}{dt} = -\beta S \frac{I}{N}$$

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

$$\frac{dR}{dt} = \frac{I}{T_I}$$

SIR model: susceptible-infected-recovered



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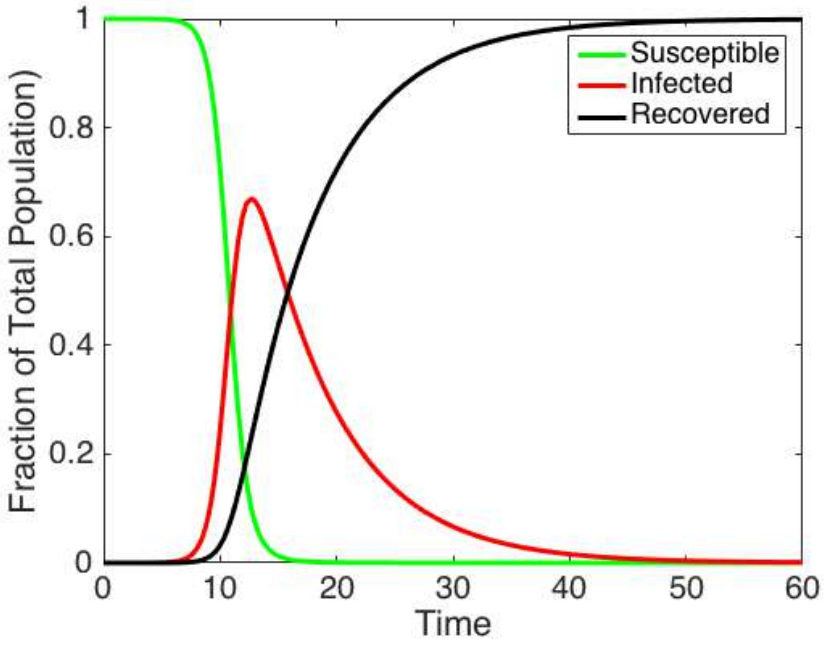
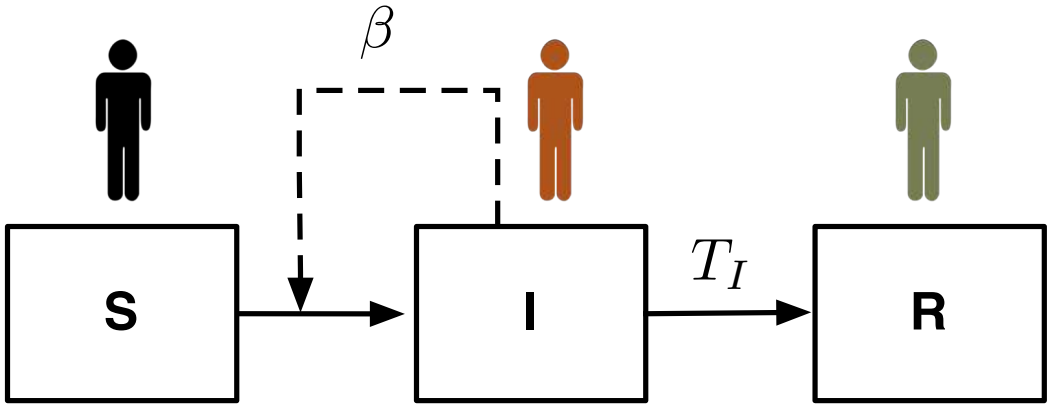
$$\frac{dR}{dt} = \frac{I}{T_I}$$



Infected population changes exponentially at onset of an epidemic

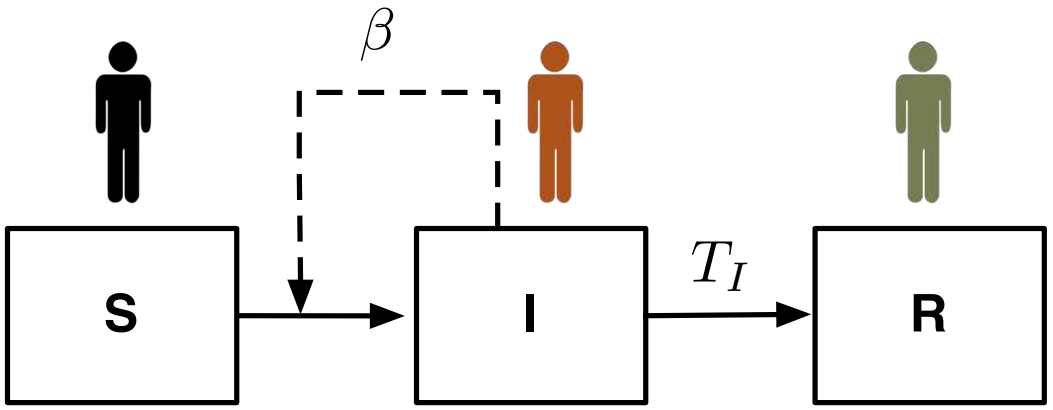


At onset $S \approx N$

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

$$\frac{dI}{dt} \approx I \frac{\beta T_I - 1}{T_I}$$

Infected population changes exponentially at onset of an epidemic



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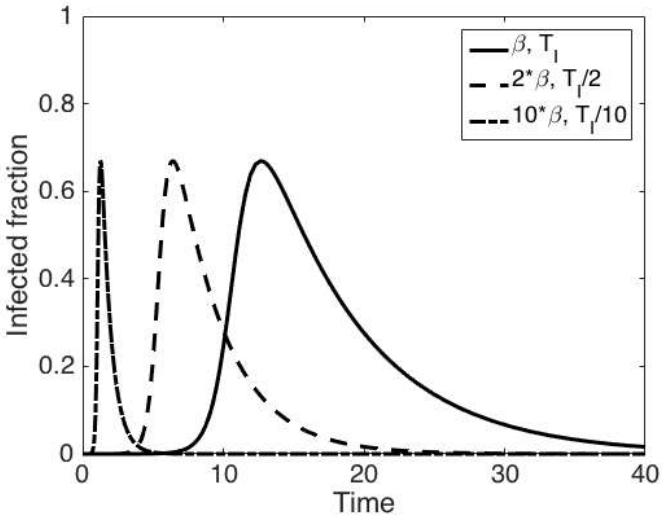

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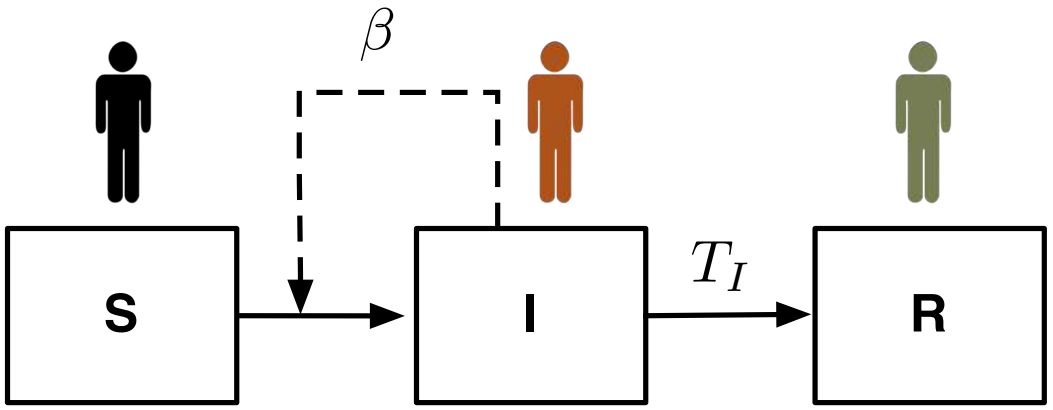

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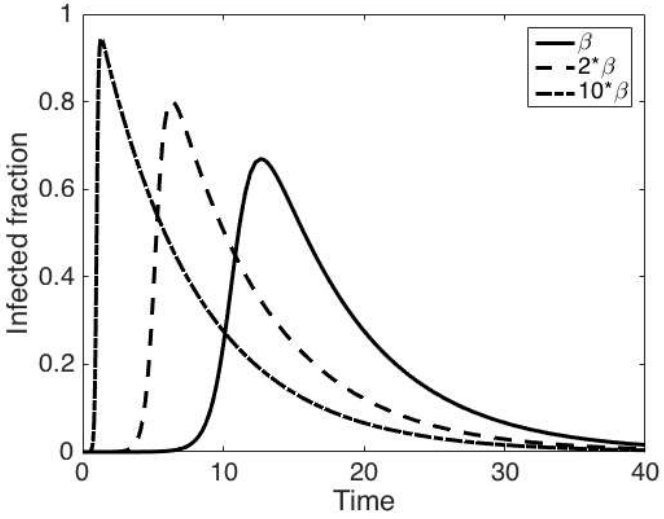
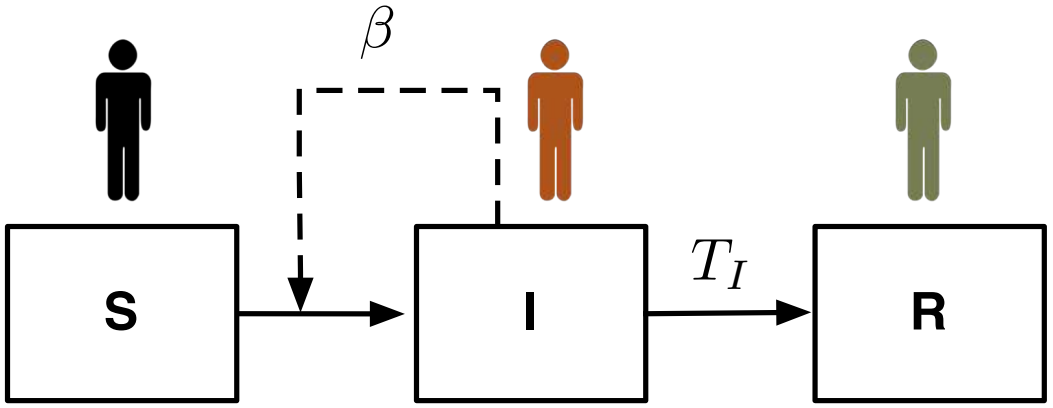
$$\frac{dI}{dt} = \beta I \frac{S}{N} - \frac{I}{T_I}$$

$$\frac{dI}{dt} \approx I \frac{\beta T_I - 1}{T_I}$$



Infected population changes exponentially at onset of an epidemic

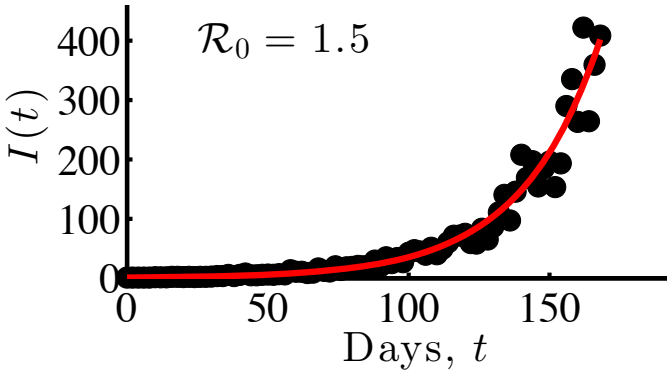


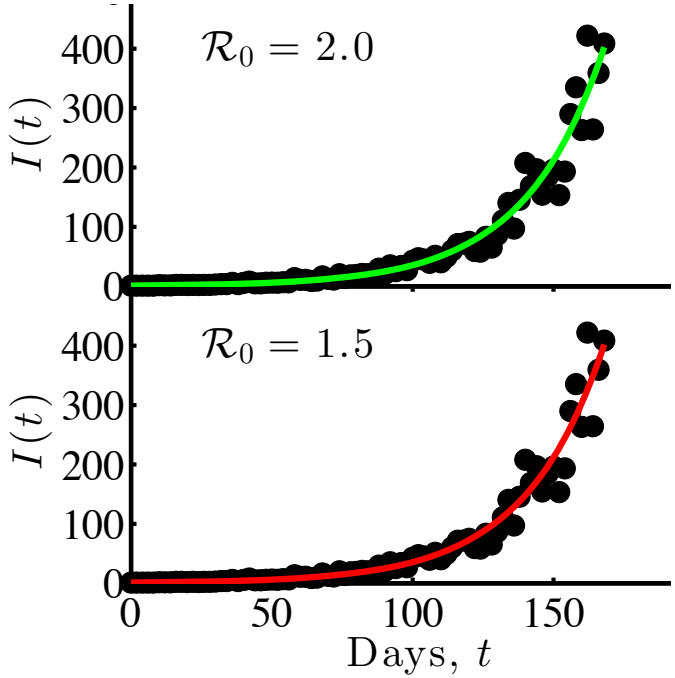
At onset $S \approx N$

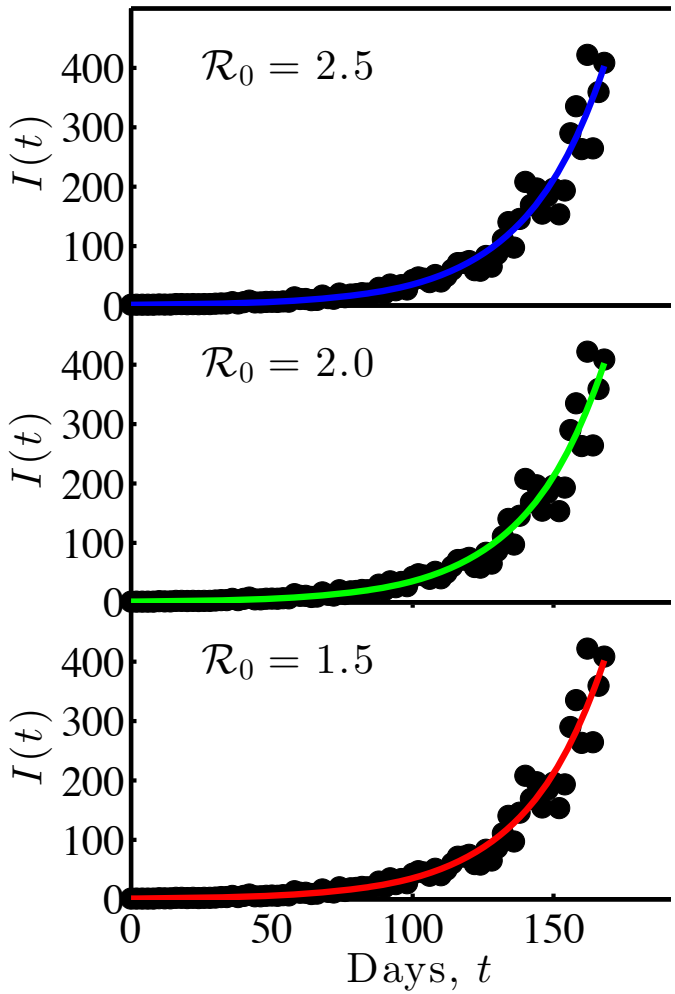
$$\frac{dI}{dt} = \beta I \frac{S}{N} - \frac{I}{T_I}$$

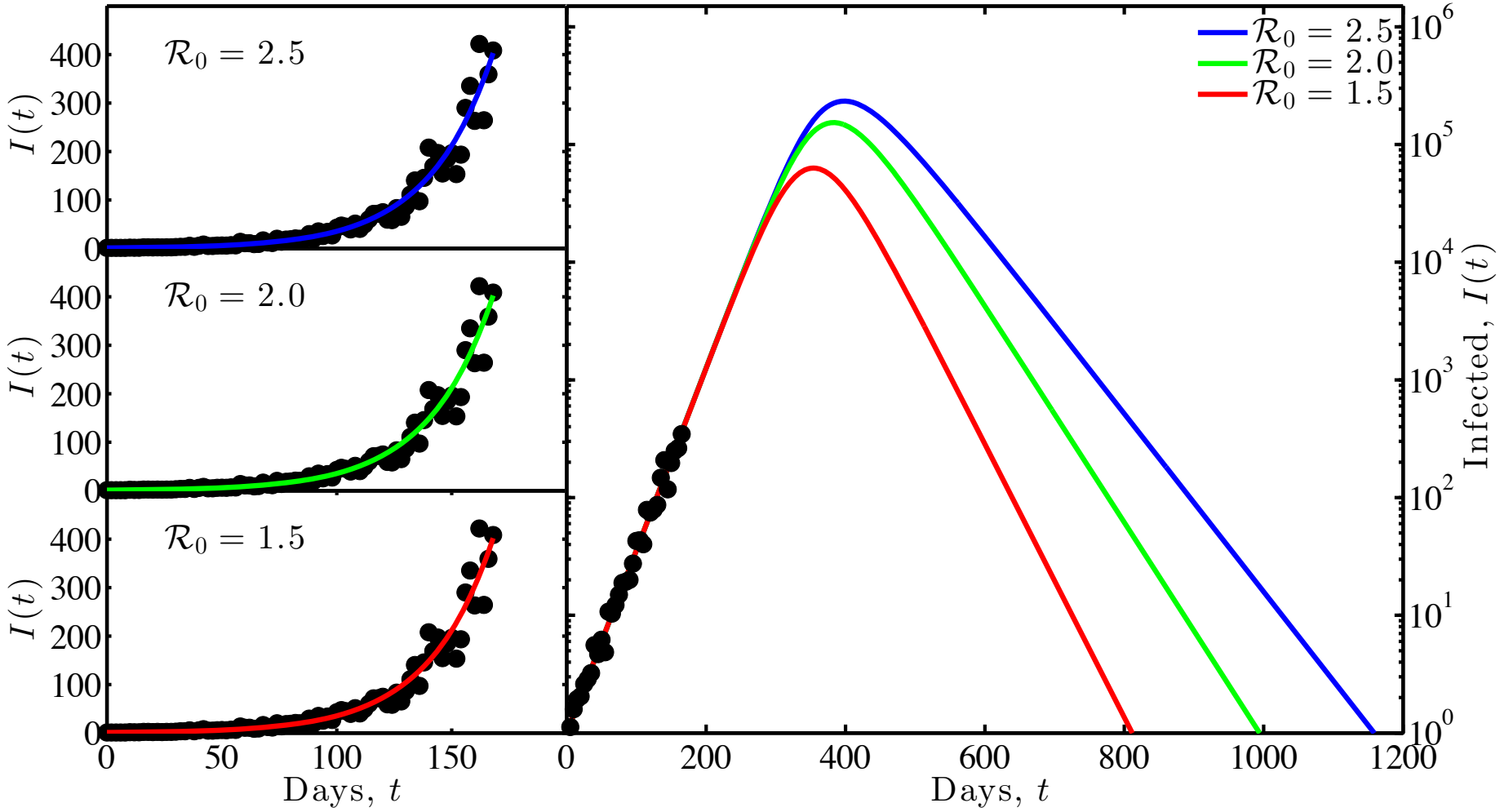
$$\frac{dI}{dt} \approx I \frac{\beta T_I - 1}{T_I}$$

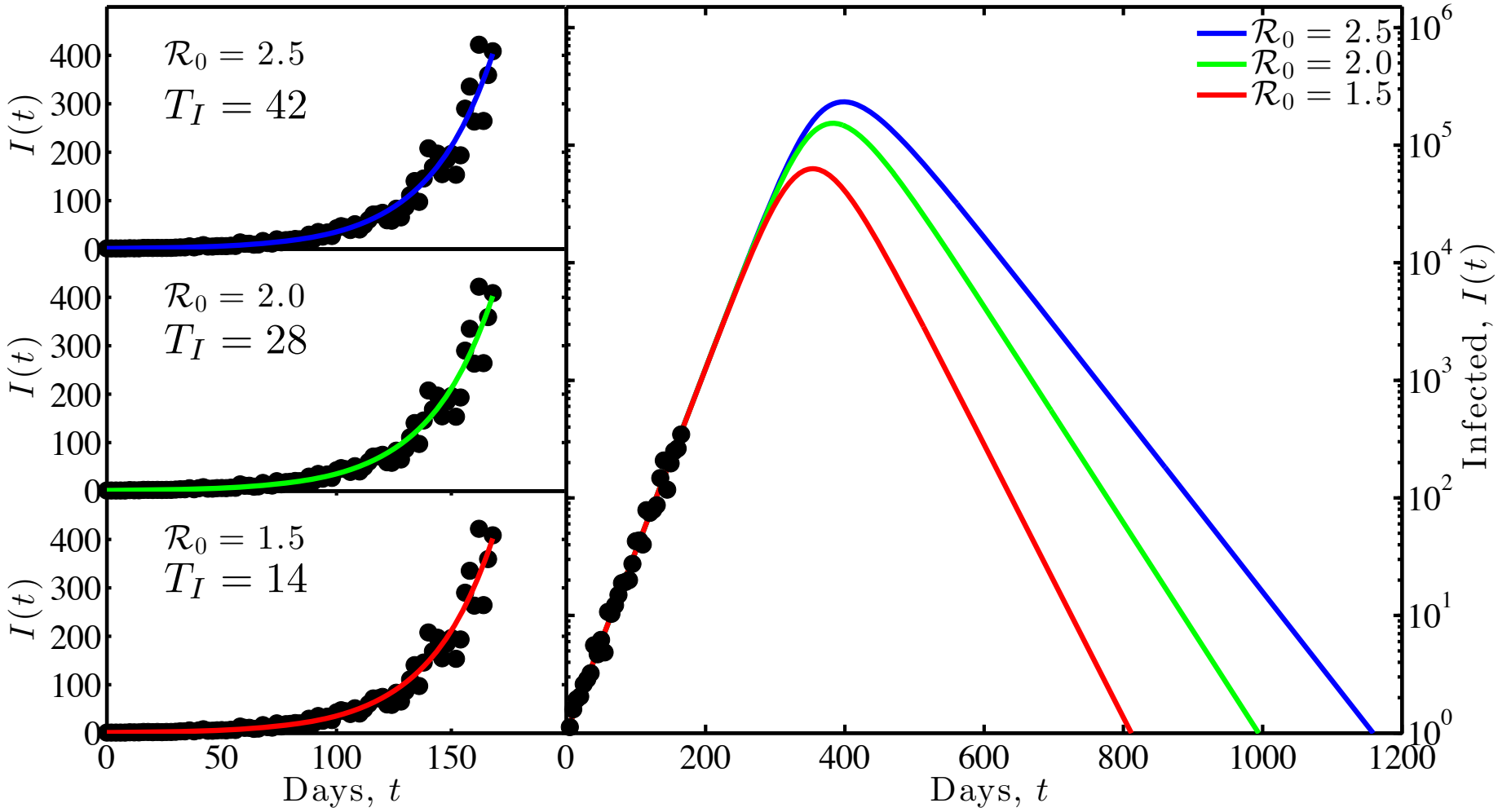
R0: # of infections due to a single infectious individual in an otherwise susceptible population.


$\mathcal{R}_0 = 1.5$
400
300
200
100
0
$I(t)$
0
50
100
150
Days, t


$\mathcal{R}_0 = 2.0$
$\mathcal{R}_0 = 1.5$
$I(t)$
$I(t)$
400
300
200
100
0
400
300
200
100
0
0
50
100
150
Days, t


$\mathcal{R}_0 = 2.5$
$\mathcal{R}_0 = 2.0$
$\mathcal{R}_0 = 1.5$
$I(t)$
0
100
200
300
400
0
50
100
150
Days, t


$\mathcal{R}_0 = 2.5$
$\mathcal{R}_0 = 2.0$
$\mathcal{R}_0 = 1.5$
$I(t)$
0
100
200
300
400
0
50
100
150
Days, t
0
200
400
600
800
1000
1200
Days, t
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Infected, $I(t)$



R_0 increases with T_I (infectious period) even with the same initial speed, i.e. it is not the same as growth rate.

(see Park, Champredon, Weitz & Dushoff, Epidemics, 2019)

Why Be Temperate? Ala Stewart and Levin, 1984

THEORETICAL POPULATION BIOLOGY 26, 93–117 (1984)

The Population Biology of Bacterial Viruses: Why Be Temperate

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Department of Mathematics, Brown University, Providence, Rhode Island 02912, and Department of Zoology, University of Massachusetts, Amherst, Massachusetts 01003

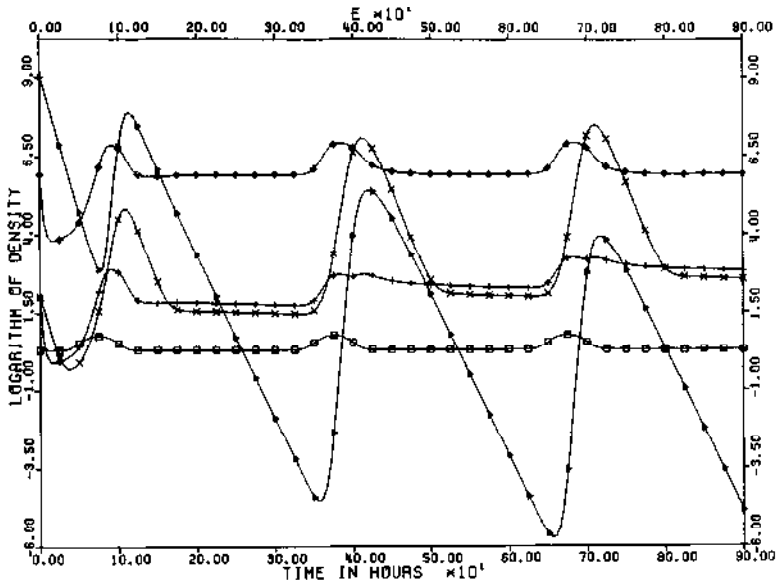
Received May 23, 1983

$$\dot{r} = \rho(C - r) - e\psi(r)(L + (1 - \alpha_S)S),$$

$$\dot{L} = \psi(r)L + \lambda\delta_T ST - (\rho + \xi + \tau)L,$$

$$\dot{S} = (1 - \alpha_S)\,\psi(r)S - \delta_T ST + \tau L - \rho S,$$

$$\dot{T} = \xi\beta_T L + \beta_T(1 - \lambda)\,\delta_T ST - \delta_T LT - \rho T.$$

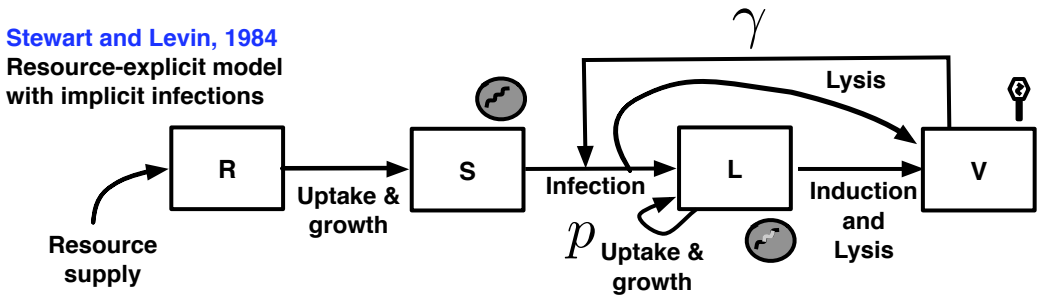


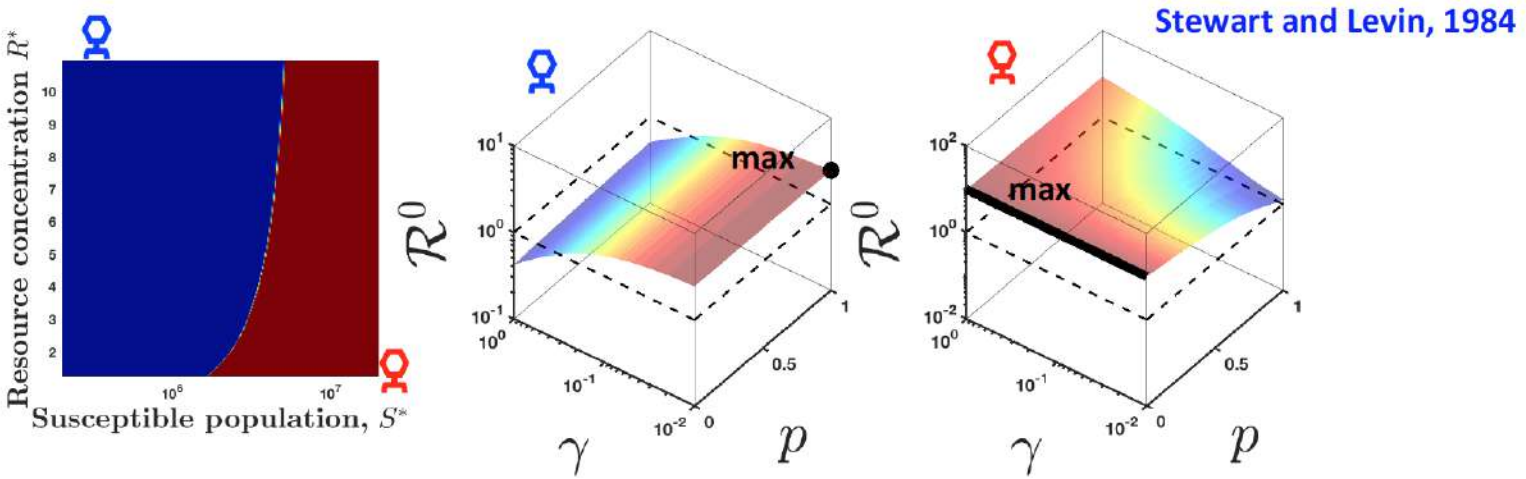
Feast or Famine Hypothesis

Premise: temperate phage do better when few hosts are available and extracellular mortality rate are high.

Caveat: "In spite of the intuitive appeal of this low density hypothesis, we are unable to obtain solutions consistent with it using the model presented here."

Why Be Temperate? Ala Stewart and Levin, 1984

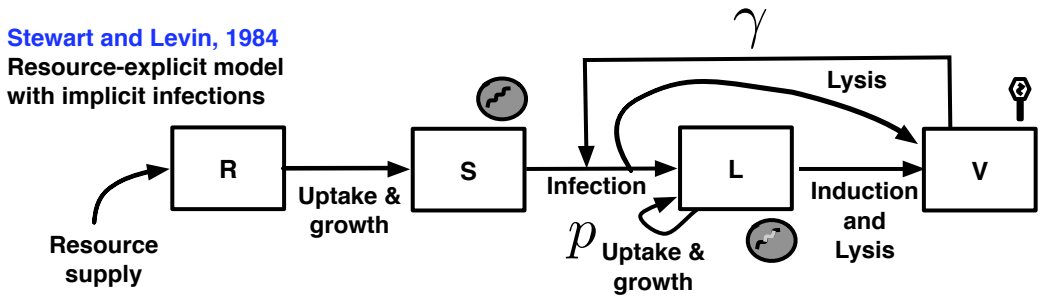


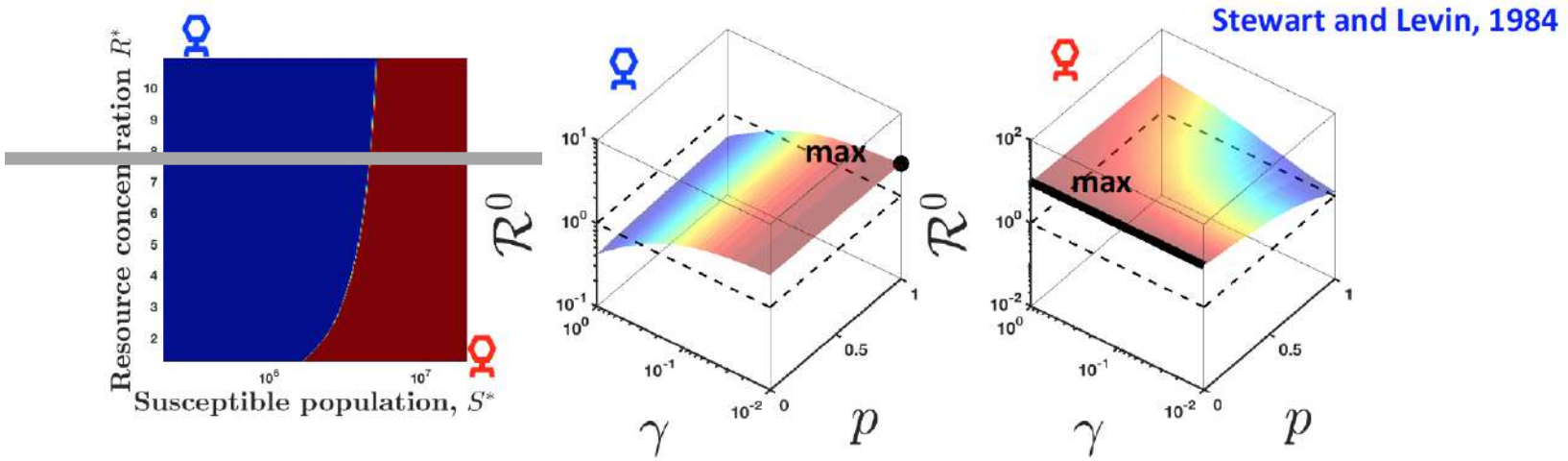


p Probability of lysogeny upon infection

γ Probability rate of induction

Why Be Temperate? Ala Stewart and Levin, 1984





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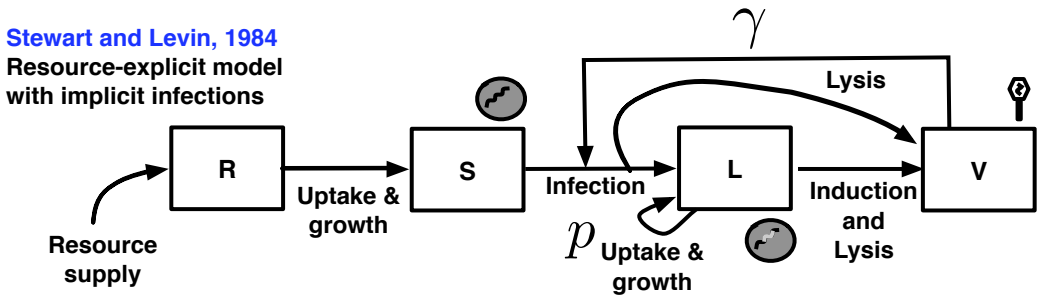
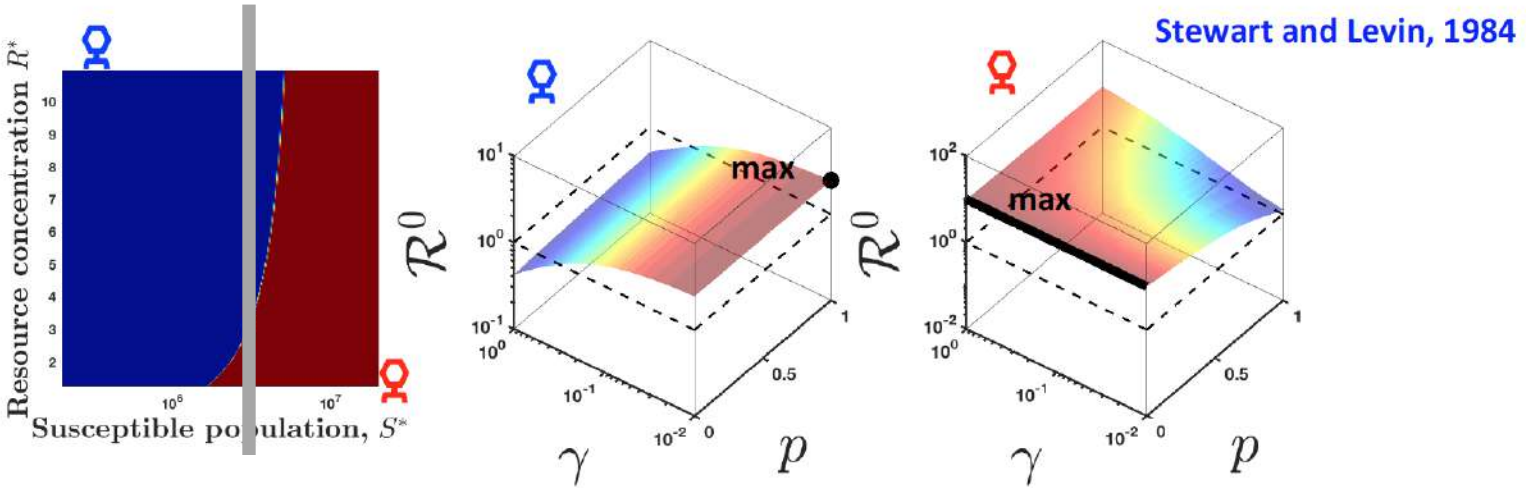
Why Be Temperate? Ala Stewart and Levin, 1984

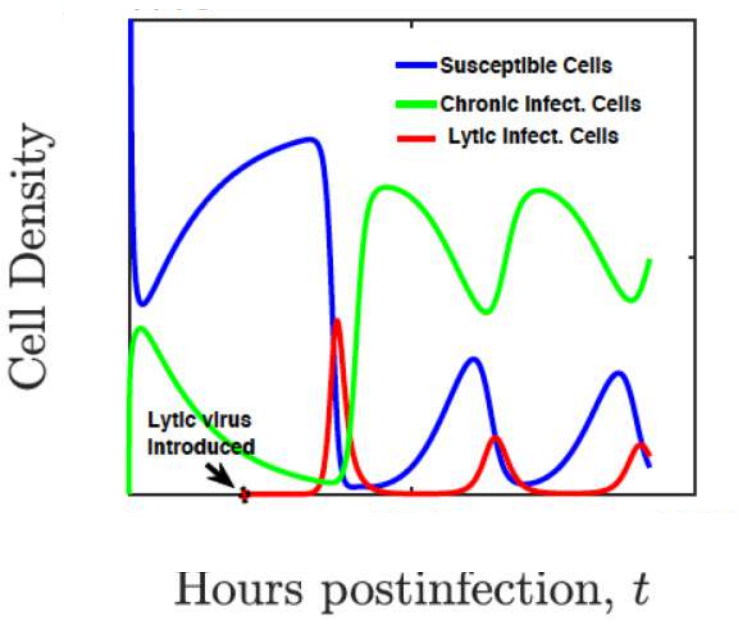




p Probability of lysogeny upon infection

γ Probability rate of induction

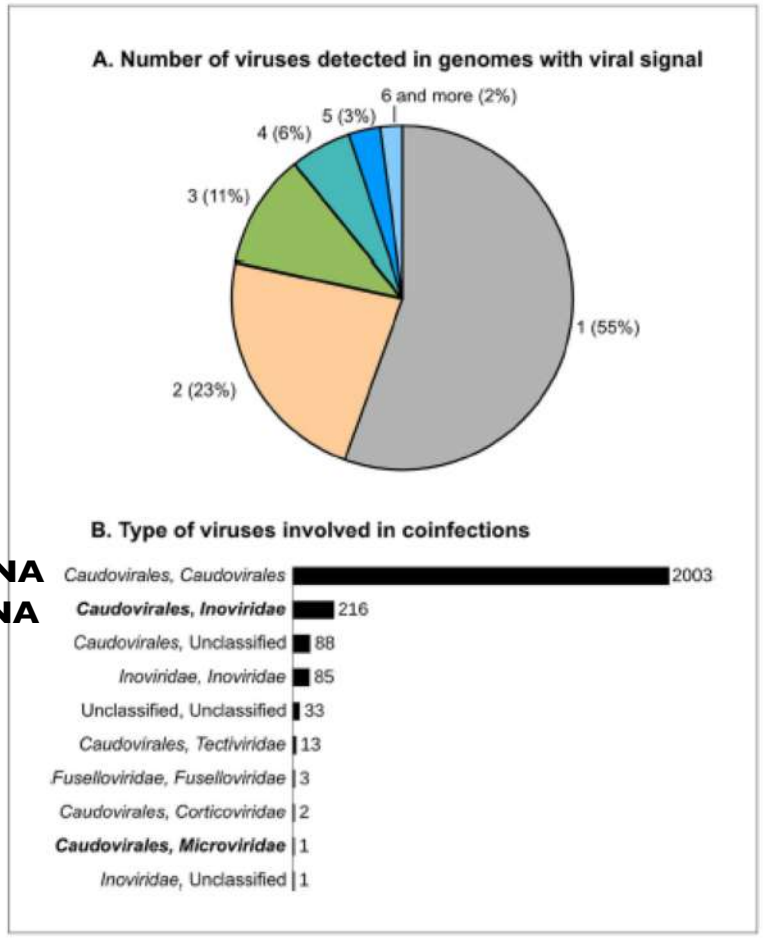
Heterogeneous viral strategies & a dynamical basis for an unexpected consequence



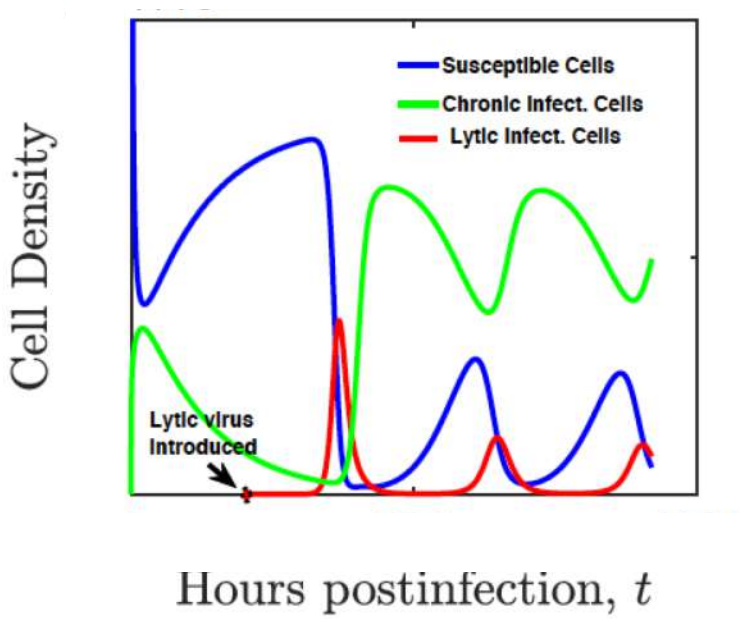
Could lytic viruses "help" chronic/temperate viruses by reducing niche competition?

Heterogeneous viral strategies promote coexistence in virus-microbe systems, Gulbudak & Weitz, JTB 2019, biorxiv 297127

Heterogeneous viral strategies & a dynamical basis for an unexpected consequence



Roux et al., eLife 2015



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Perspectives and Directions

1. Lysogeny and other forms of chronic/inefficient infections remain under-studied, particularly in relevant, ecological contexts.

2. We examine fitness of viruses that infect microbes by adapting the epidemiological concept of the basic reproduction number "R_0".

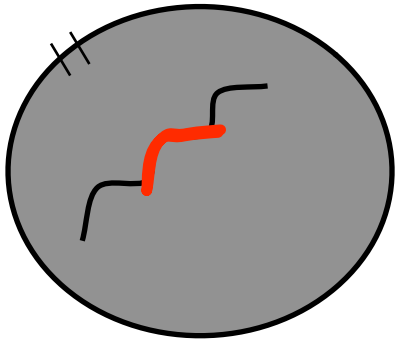
3. R_0 framework reveals mechanisms and broad ecological drivers for why lysogeny can outperform lysis (at least in the short term).

4. Ongoing work: extension to evolutionary dynamics, both within and between strategy classes.

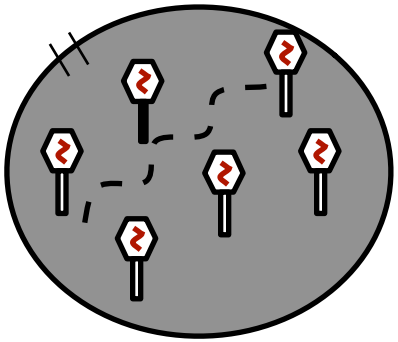
5. Many open questions remain: viral competition within hosts, feedback between strategies and ecosystem functioning, and relevance of non-lytic strategies *in situ*…

And one last question…
what is a virus?

Virion

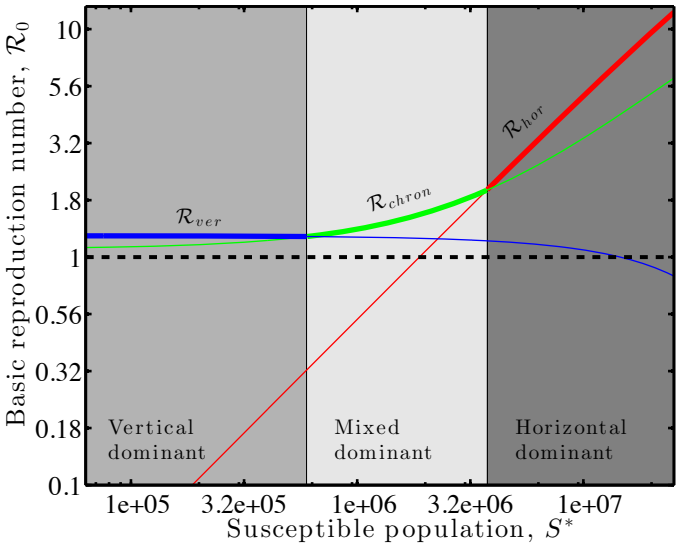


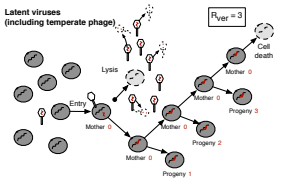
Lysogen

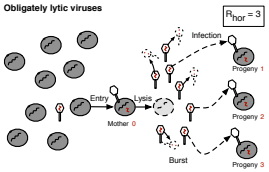


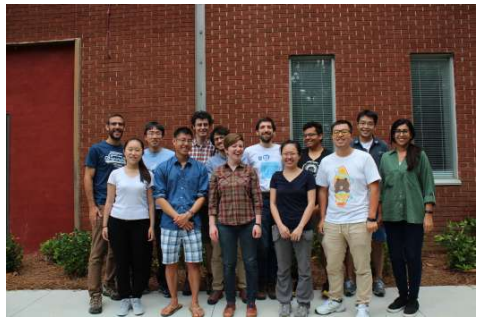
Lytically
Infected cell

Questions?









More details:

Re-examination of the relationship between marine virus and microbial cell abundances. Wigington et al., Nat. Micro 2016

Lysis, lysogeny, and virus-microbe ratios, Weitz et al. Nature 2017

Heterogeneous viral strategies promote coexistence in virus-microbe systems, Gulbudak & Weitz, J. Theor. Biol. 2019; biorxiv 297127

Viral fitness across a continuum from lysis to latency, Weitz, Li, Gulbudak, Cortez, and Whitaker., biorxiv 296897 (in review)

Alrasheed, Jin, & Weitz, Nat. Comm, 2019 (forthcoming)

On the fitness and evolution of temperate phage, Li, Cortez & Weitz, in prep

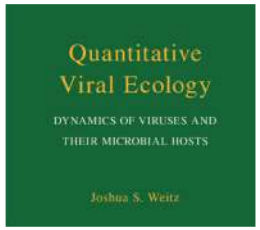
Acknowledgements

GT: Guanlin Li

UIUC: Rachel Whitaker

UL-Lafayette: Hayriye Gulbudak

Utah State: Michael Cortez



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