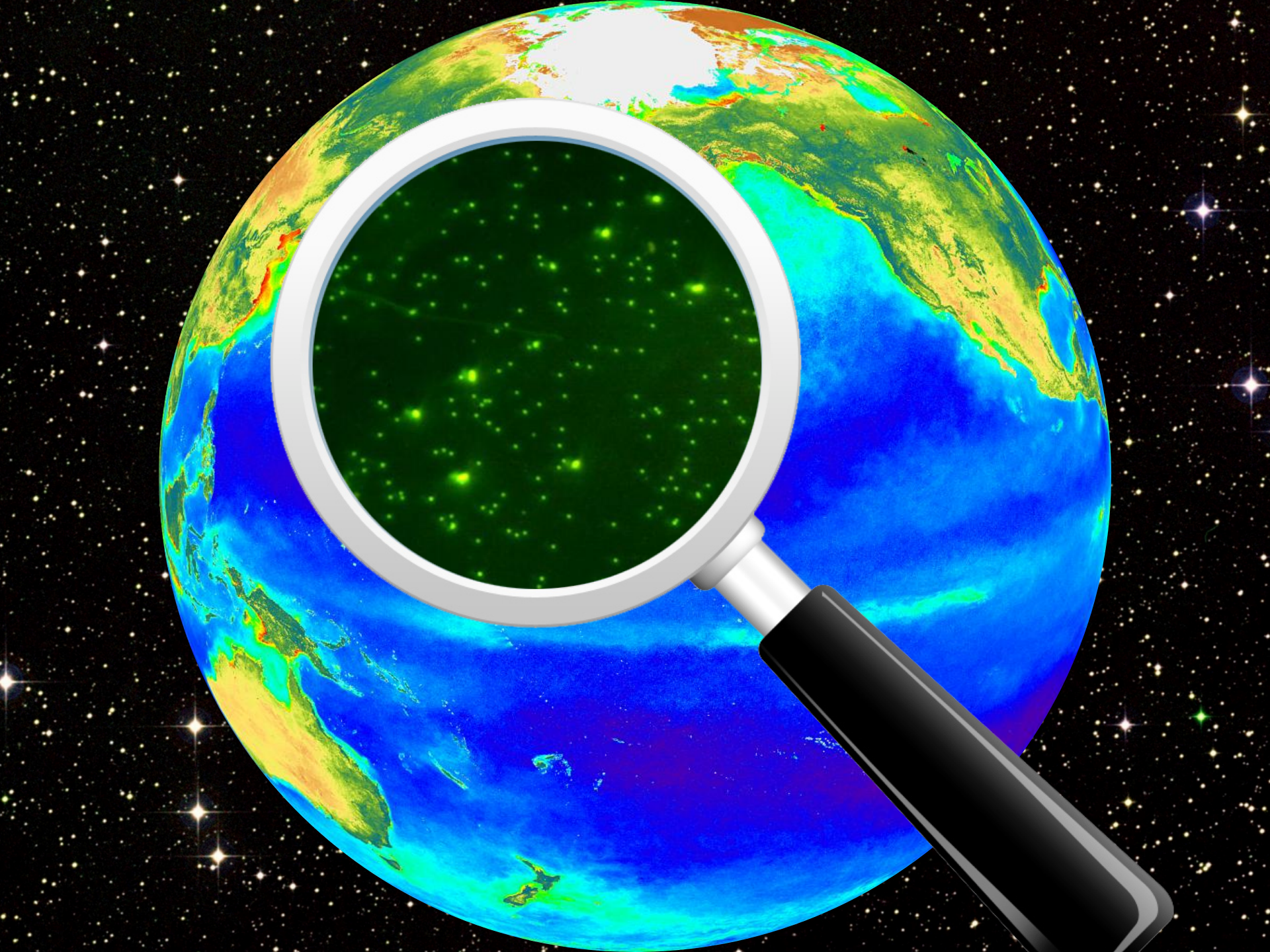

Contents lists available at ScienceDirect

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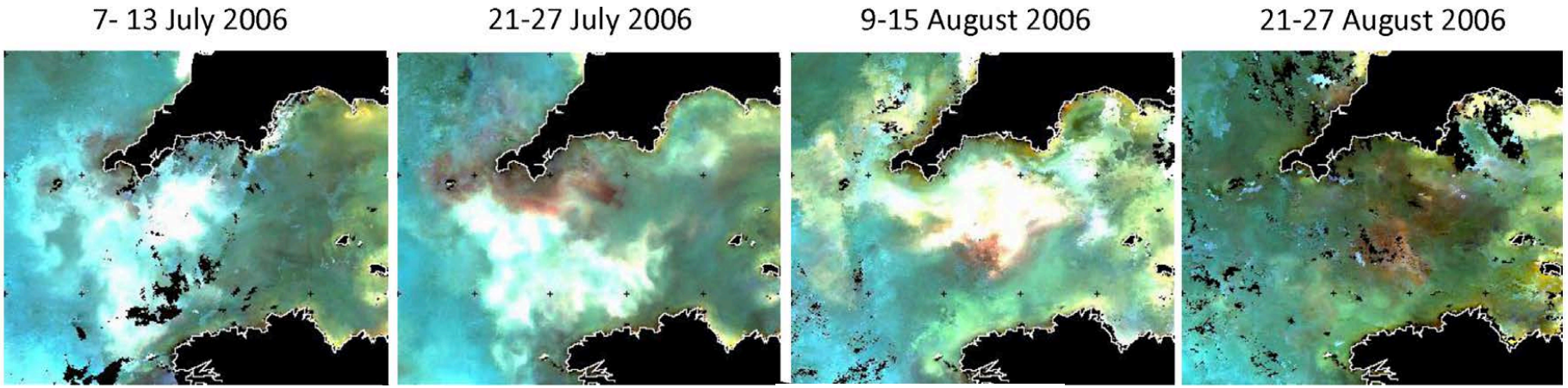
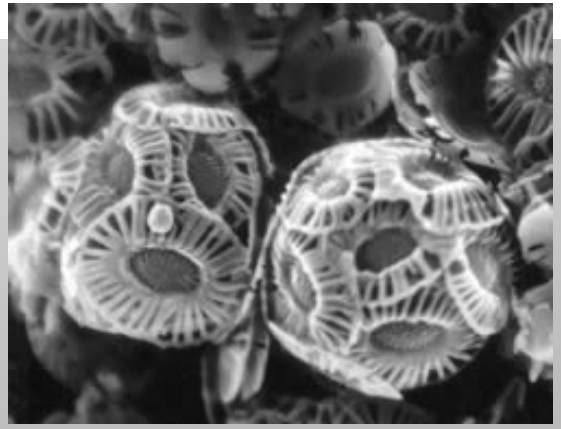
journal homepage: www.elsevier.com/locate/yviro

How many *Coccolithovirus* genotypes does it take to terminate an *Emiliania huxleyi* bloom?

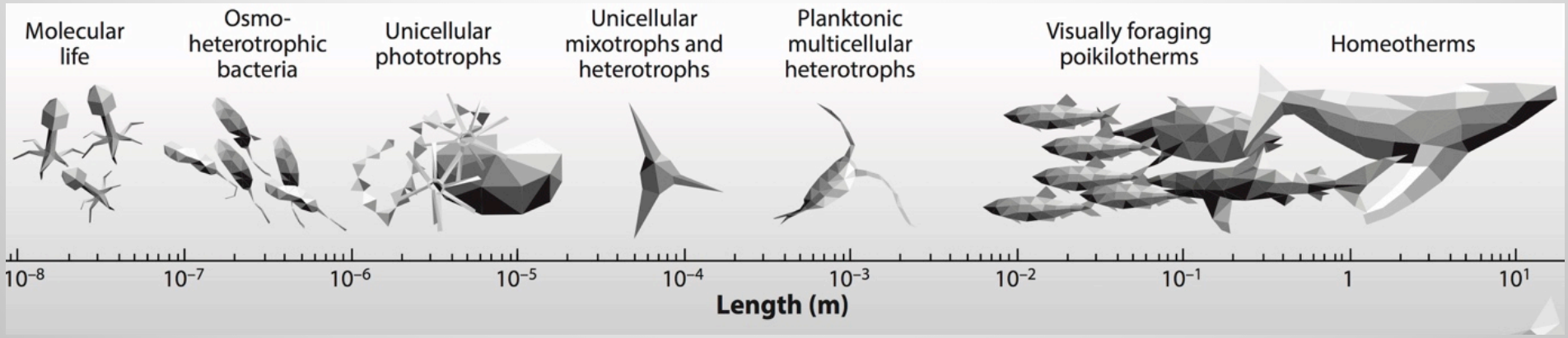
Andrea Highfield [a], Claire Evans [b], Anthony Walne [c], Peter I. Miller [c], Declan C. Schroeder [a,c,*]



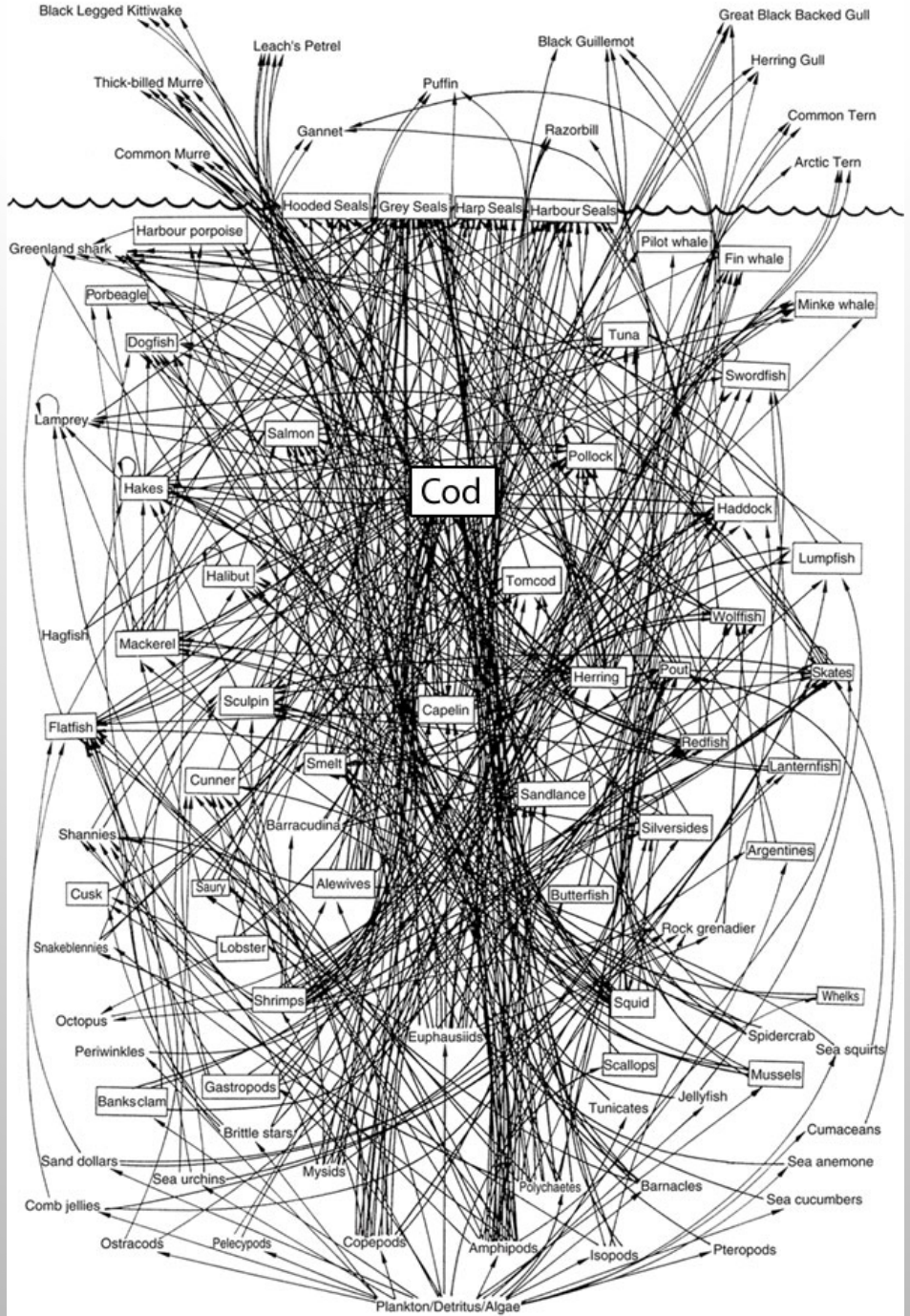


E. huxleyi ~4 µm in diameter
virus particle ~180 nm

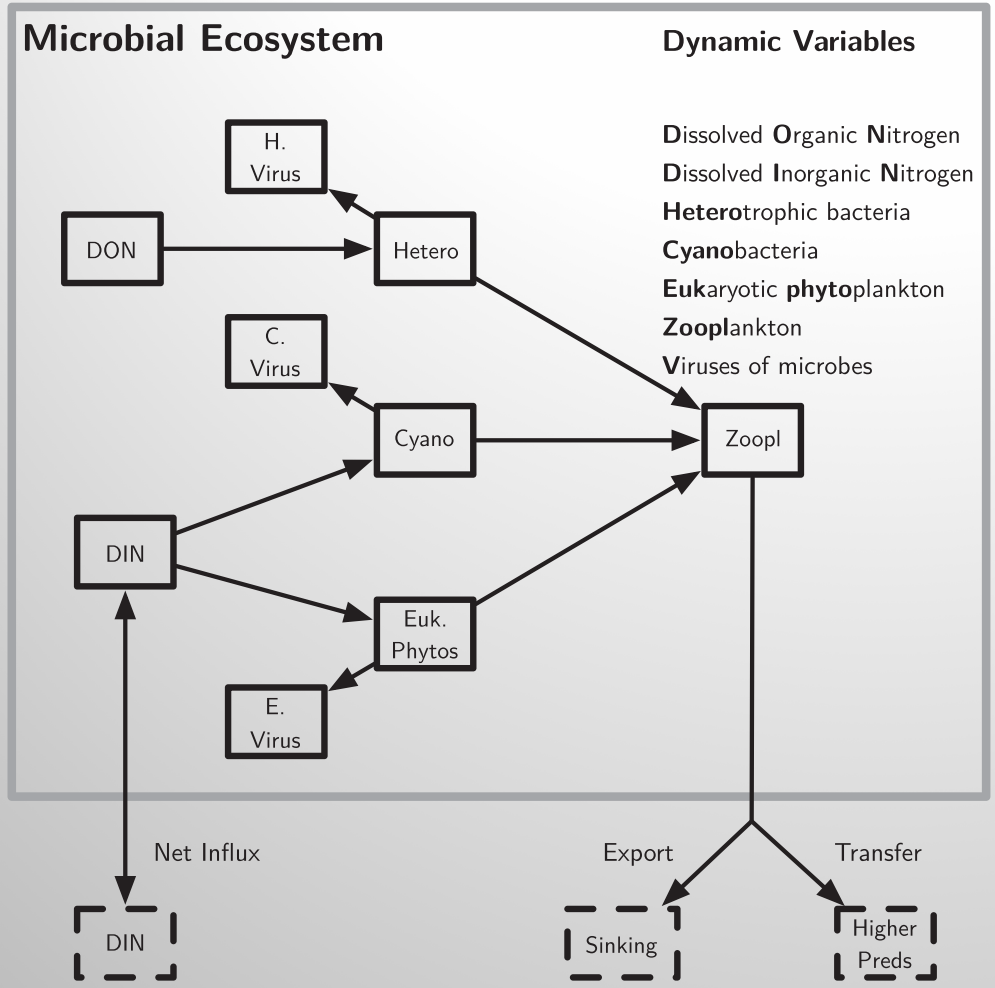
Keith Ryan & Willie Wilson



Ken Haste Andersen



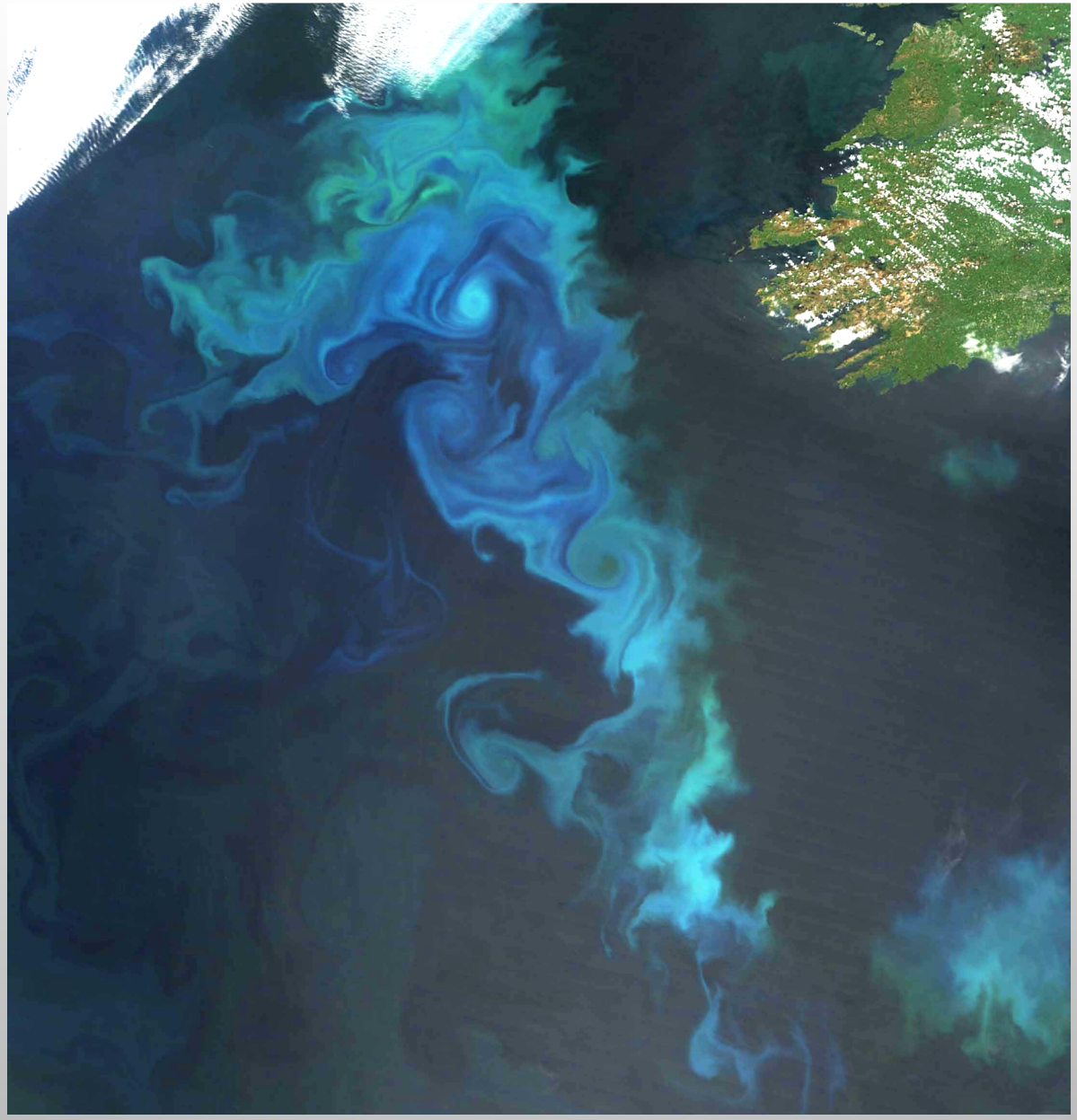
A simplified food web for the Northwest Atlantic. © IMMA



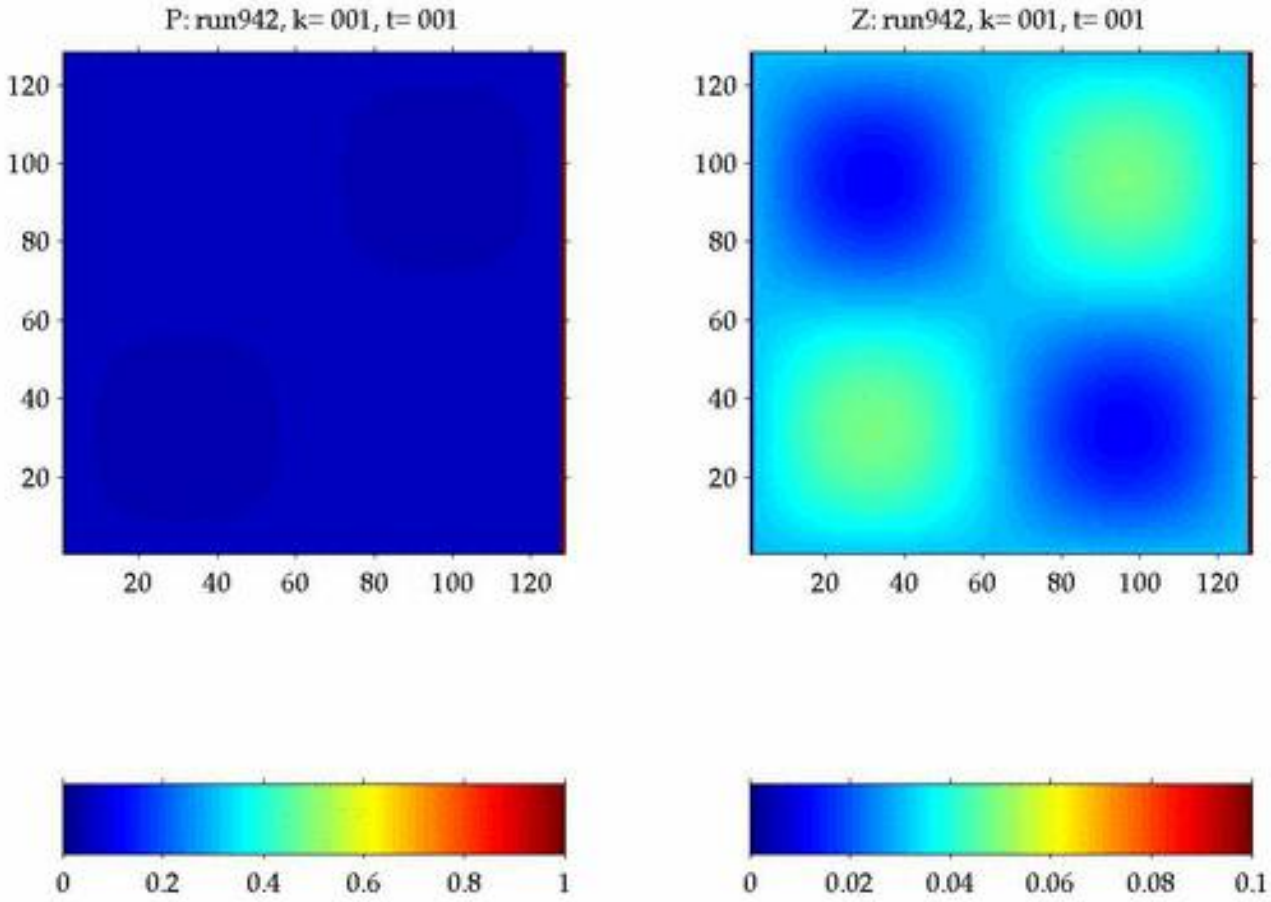
Weitz et al, 2015

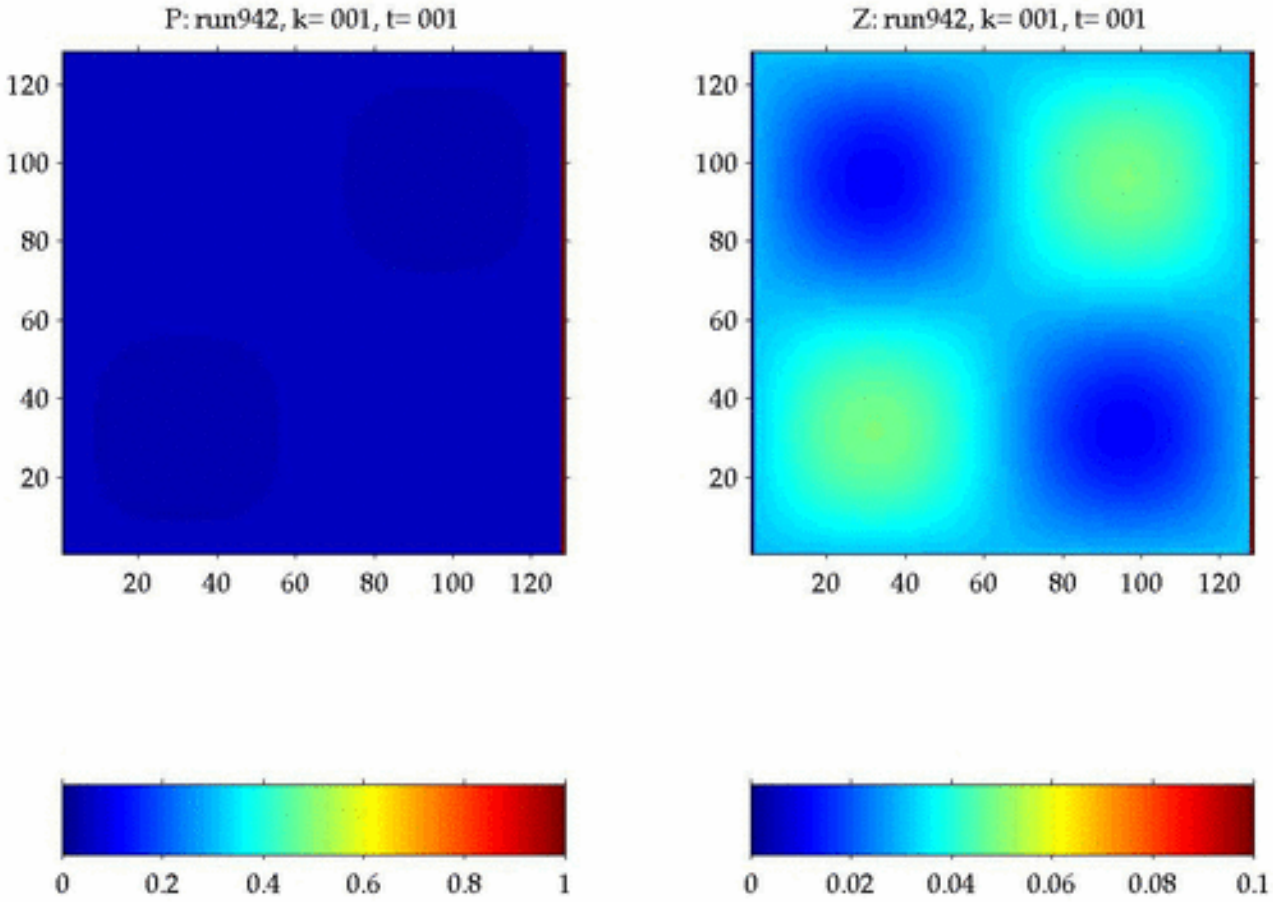
Consider a simple system

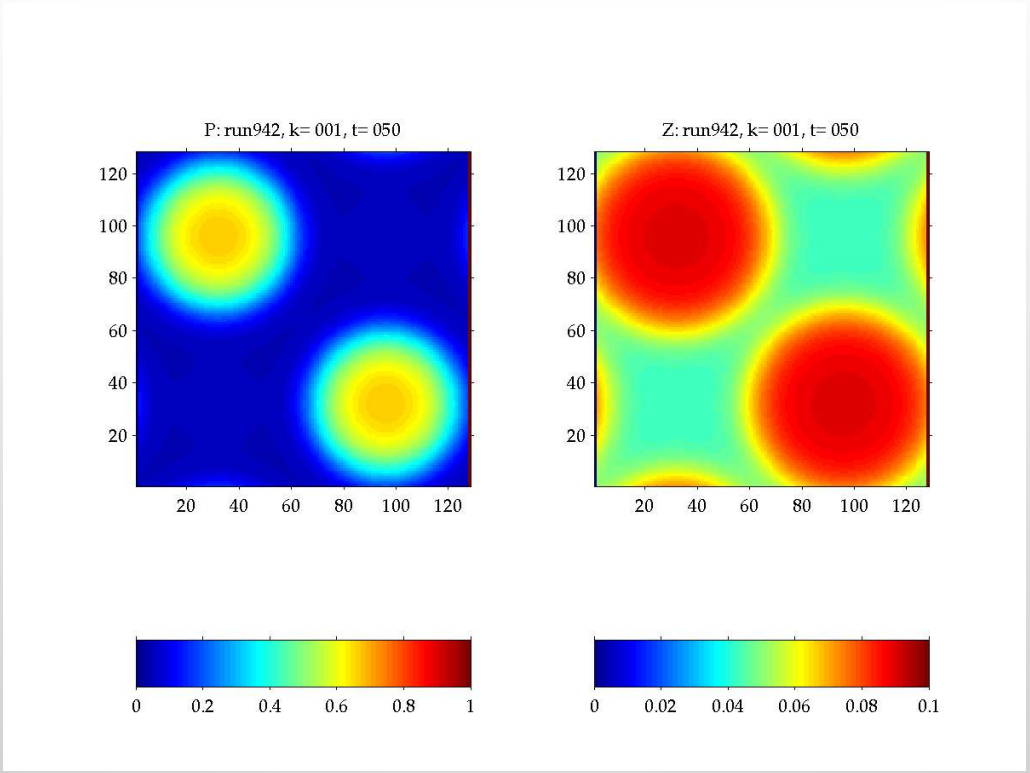
- Phytoplankton eat nutrients
- Zooplankton eat phytoplankton
- Zooplankton die



Diffusion alone

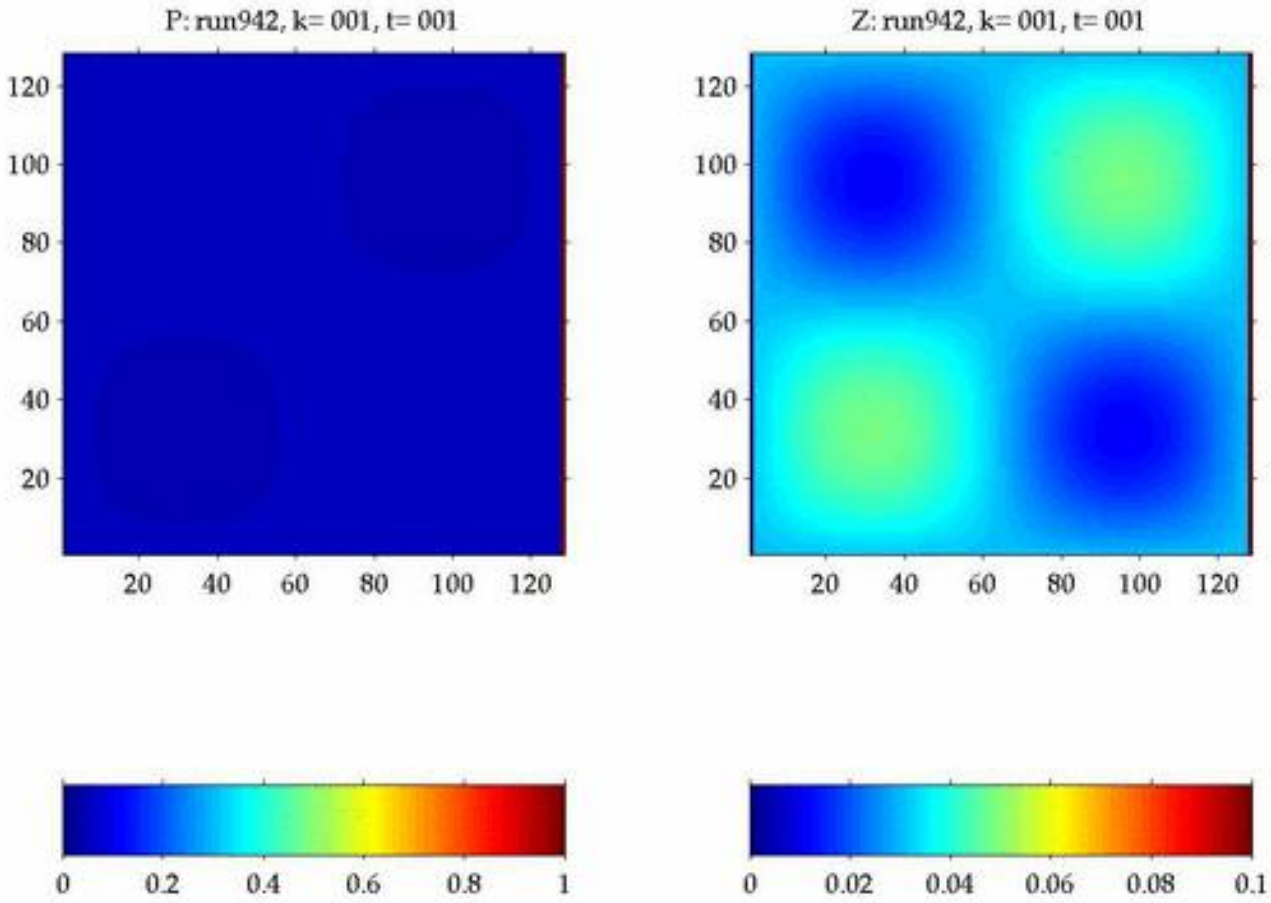


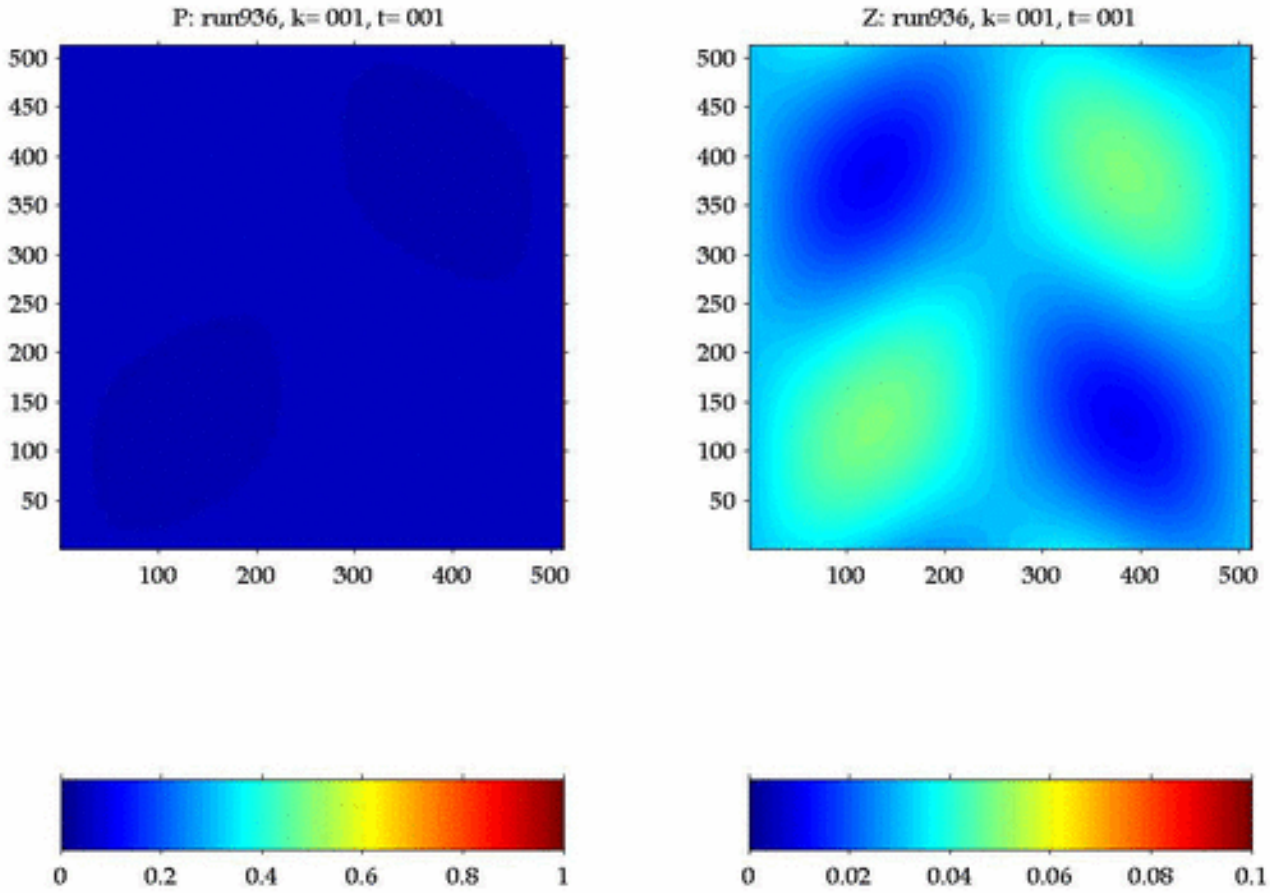

P: run942, k= 001, t= 001
120
100
80
60
40
20
20 40 60 80 100 120
0 0.2 0.4 0.6 0.8 1
Z: run942, k= 001, t= 001
120
100
80
60
40
20
20 40 60 80 100 120
0 0.02 0.04 0.06 0.08 0.1

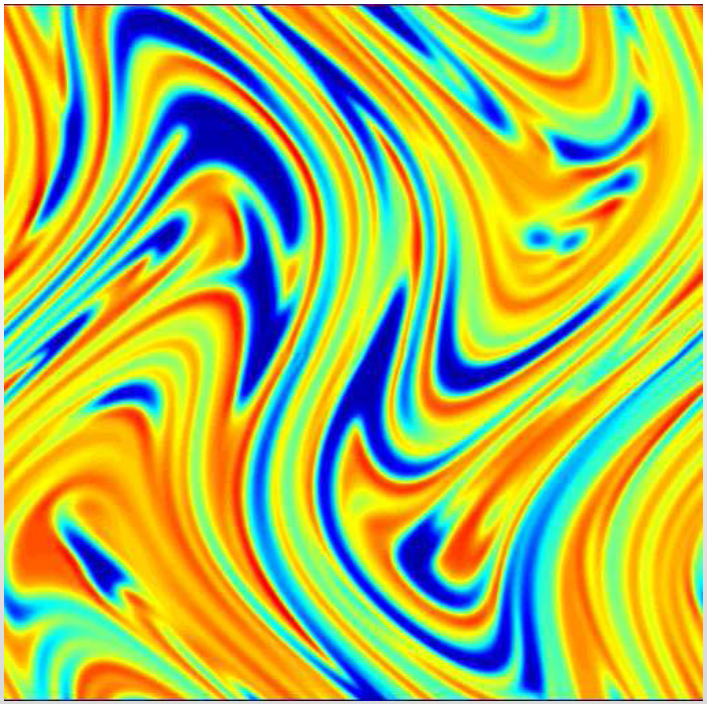


Reactive waves: $c \sim (\beta^* \kappa)^{1/2}$

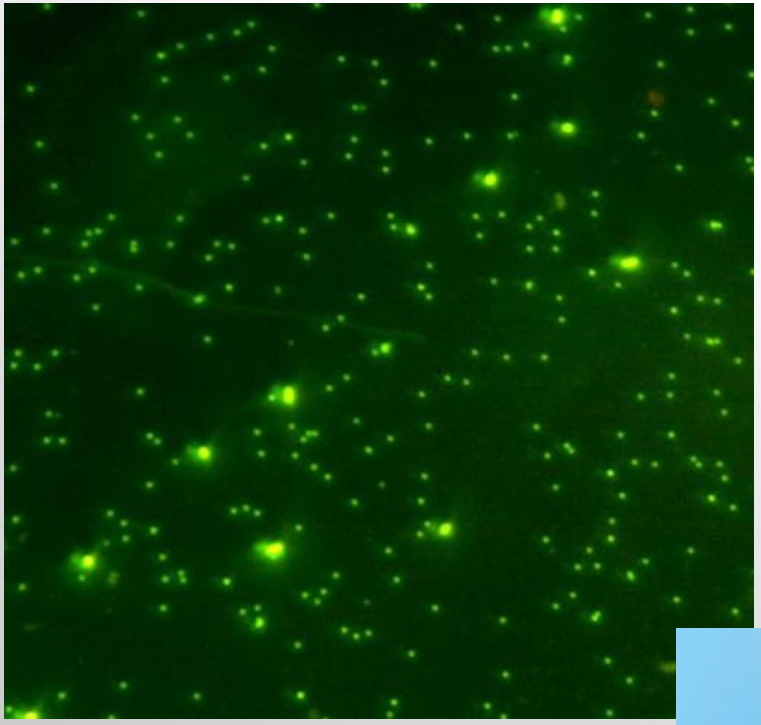
Stirring


P: run942, k= 001, t= 001
120
100
80
60
40
20
20 40 60 80 100 120
0 0.2 0.4 0.6 0.8 1
Z: run942, k= 001, t= 001
120
100
80
60
40
20
20 40 60 80 100 120
0 0.02 0.04 0.06 0.08 0.1


P: run936, k= 001, t= 001
500
450
400
350
300
250
200
150
100
50
100
200
300
400
500
0
0.2
0.4
0.6
0.8
1
Z: run936, k= 001, t= 001
500
450
400
350
300
250
200
150
100
50
100
200
300
400
500
0
0.02
0.04
0.06
0.08
0.1



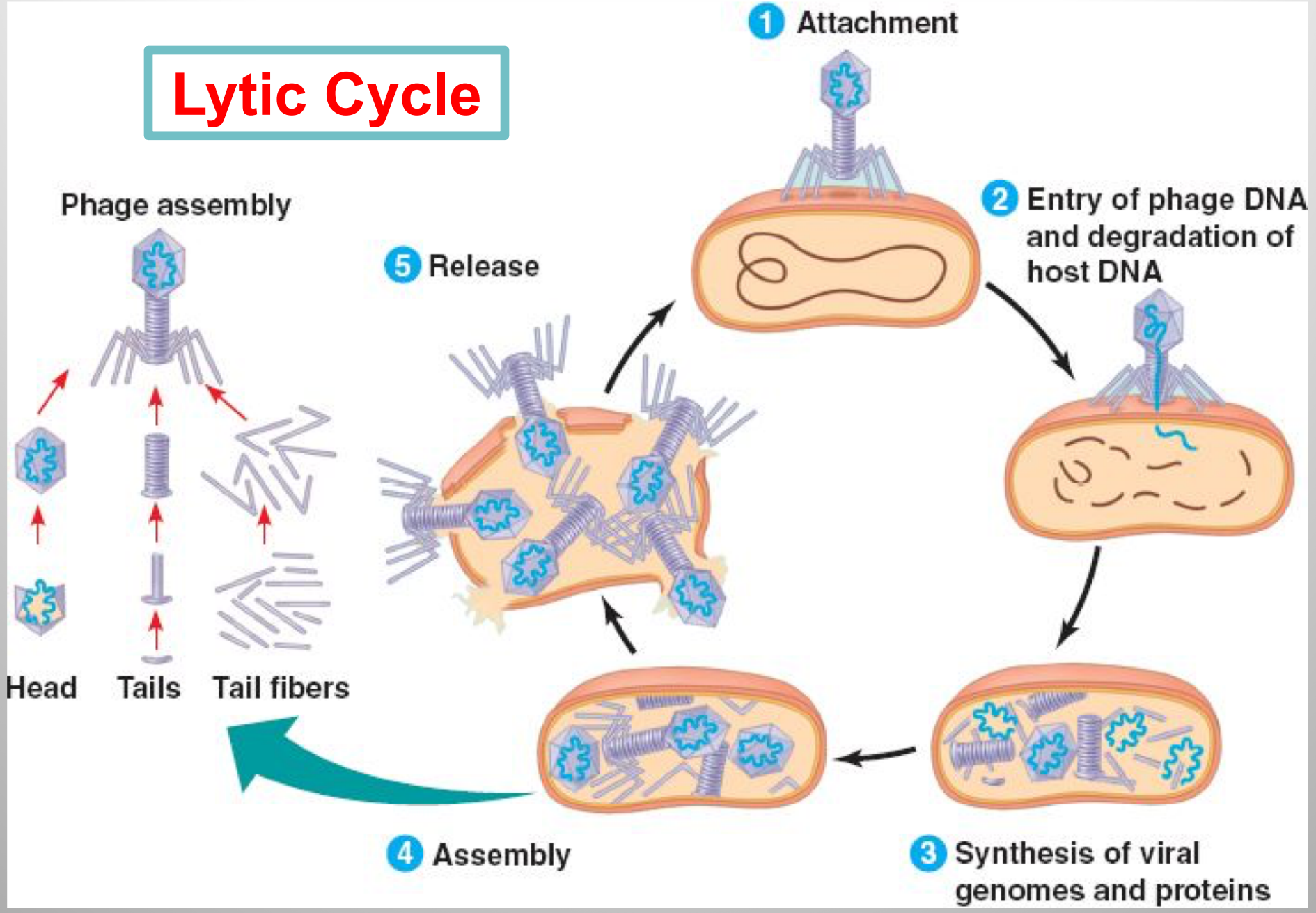
Filament width: $w_f \sim (\beta^* \kappa)^{1/2} / \lambda$



The estimated **10^{30} viruses** in the ocean, if stretched end to end, would span farther than the nearest 60 galaxies … (Curtis Suttle)

One million **viral particles** can be found in a teardrop of seawater … (A. Culley)

Lytic Cycle

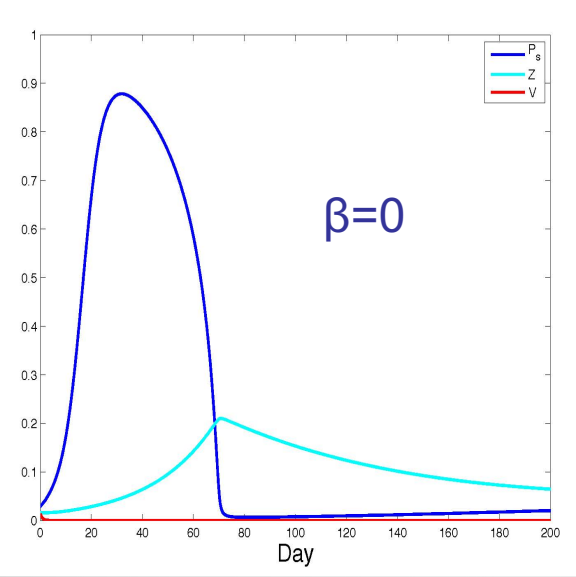

1 Attachment
2 Entry of phage DNA and degradation of host DNA
3 Synthesis of viral genomes and proteins
4 Assembly
5 Release
Phage assembly
Head
Tails
Tail fibers

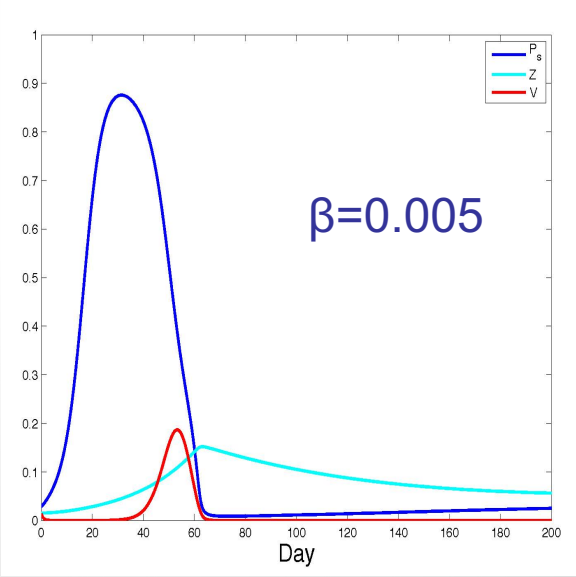
Including marine viruses

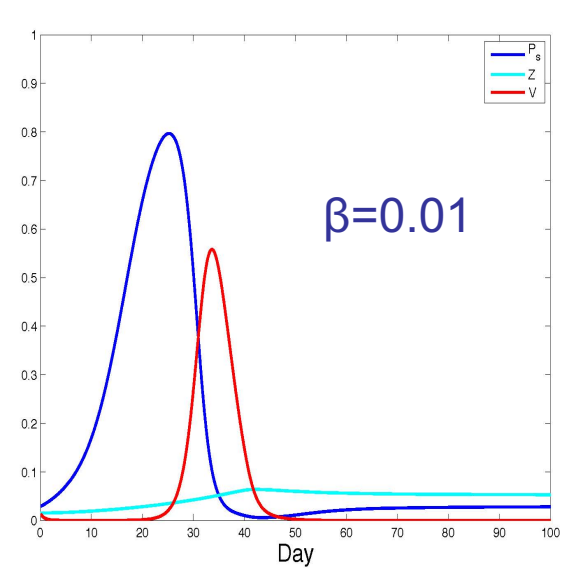
$$\frac{\partial P_s}{\partial t} = \text{Growth} - \text{Grazing} - \beta P_s V$$

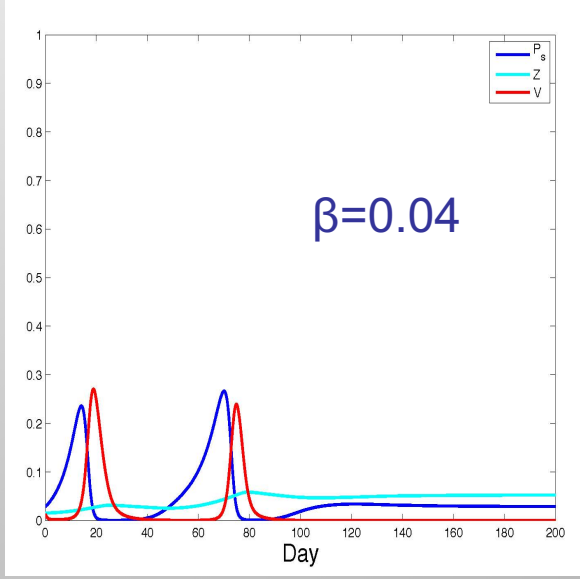
$$\frac{\partial P_i}{\partial t} = \beta P_s V - \text{Grazing} - \text{Mortality}$$

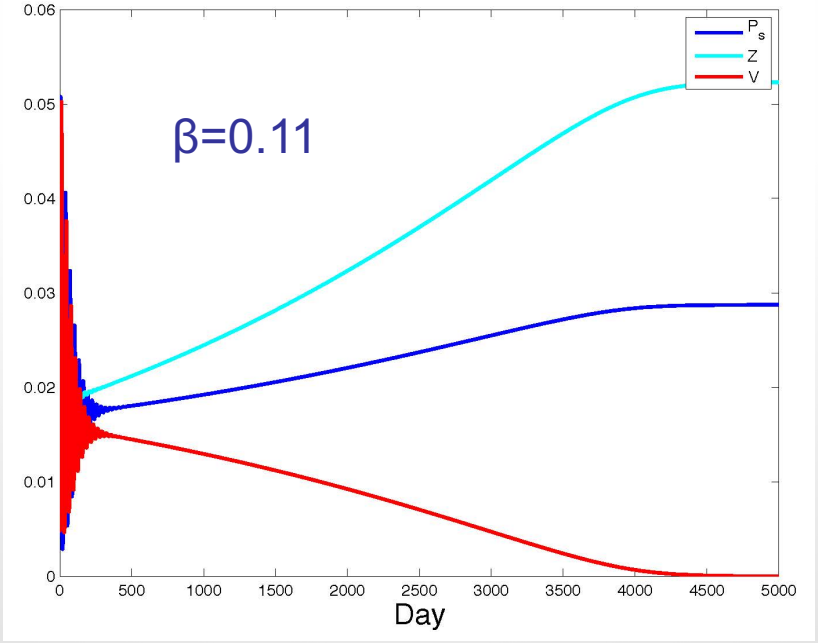
$$\frac{\partial V}{\partial t} = \gamma P_i - \text{Mortality}$$

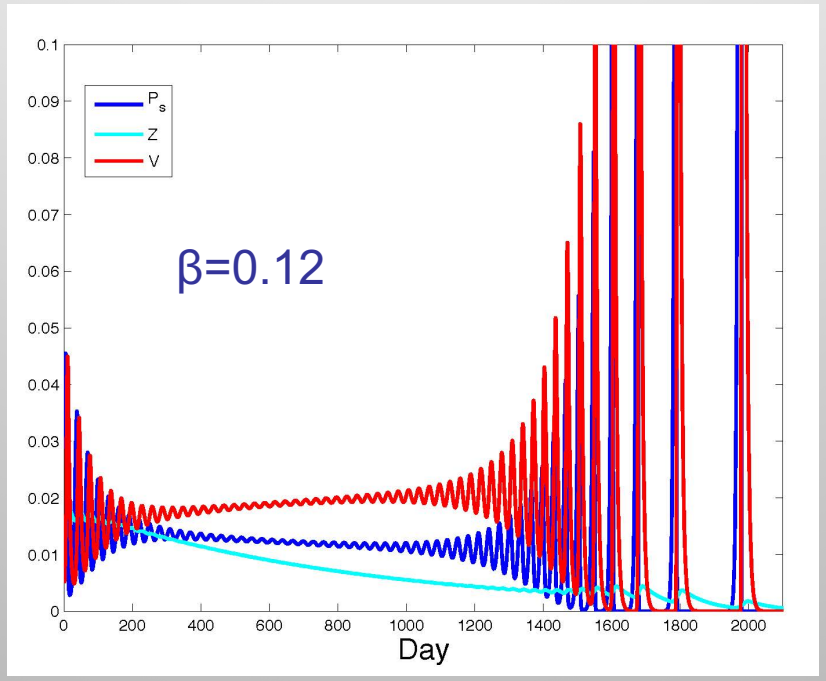

β=0
Ps
Z
V
Day


β=0.005
Ps
Z
V
Day

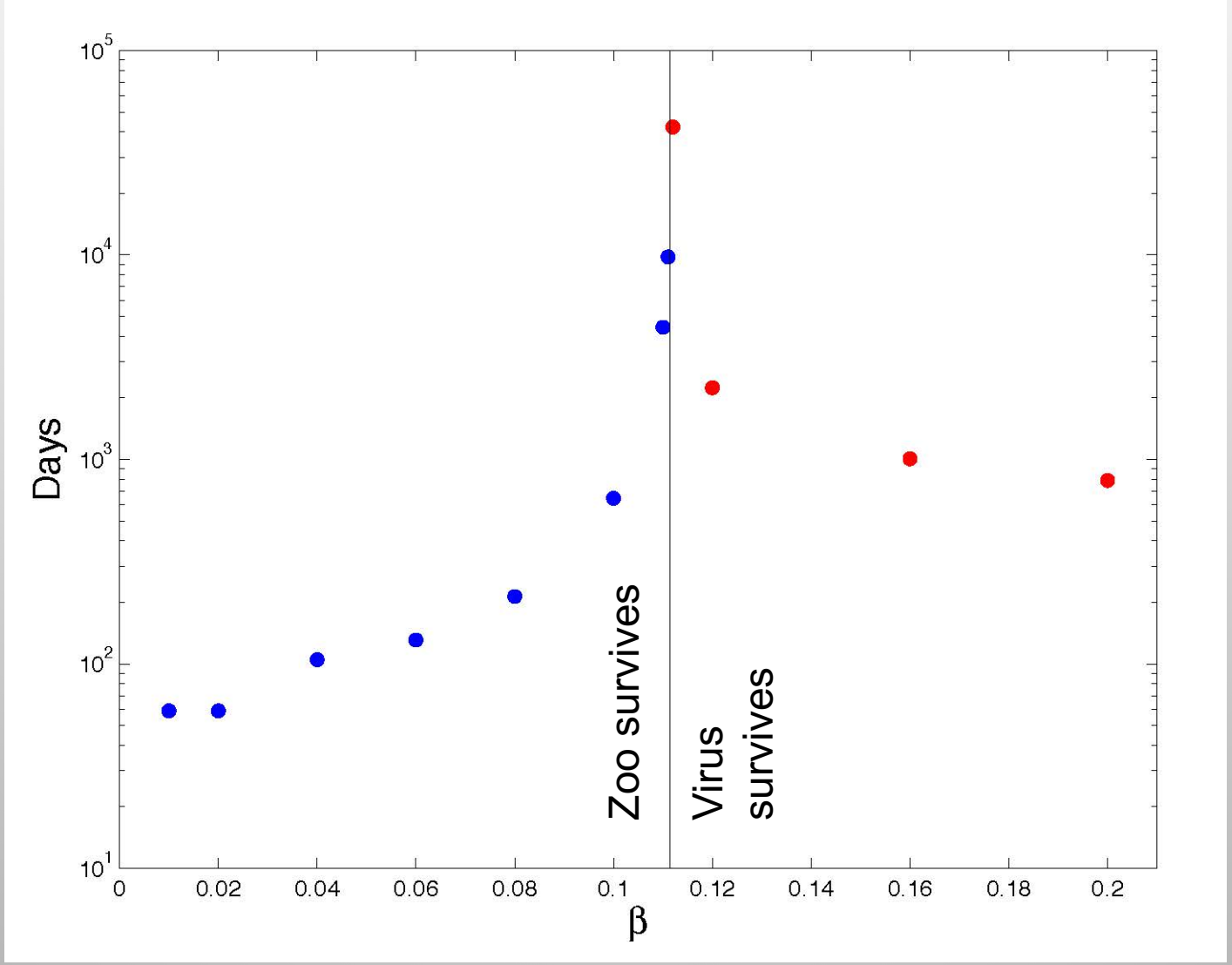

β=0.01
Ps
Z
V
Day


β=0.04
Ps
Z
V
Day

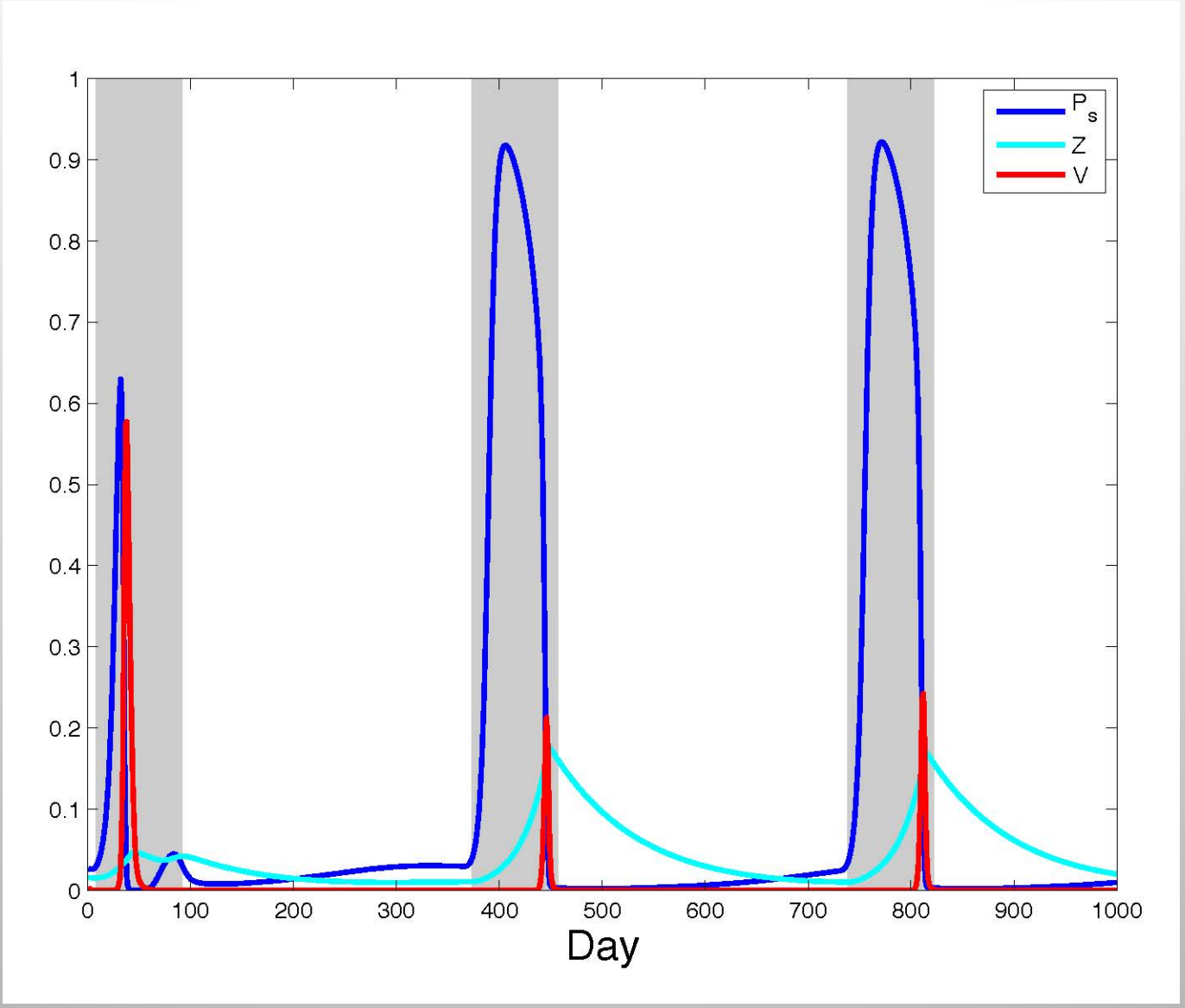

β=0.11
Ps
Z
V
0.06
0.05
0.04
0.03
0.02
0.01
0
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Day


β=0.12
Ps
Z
V
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Day

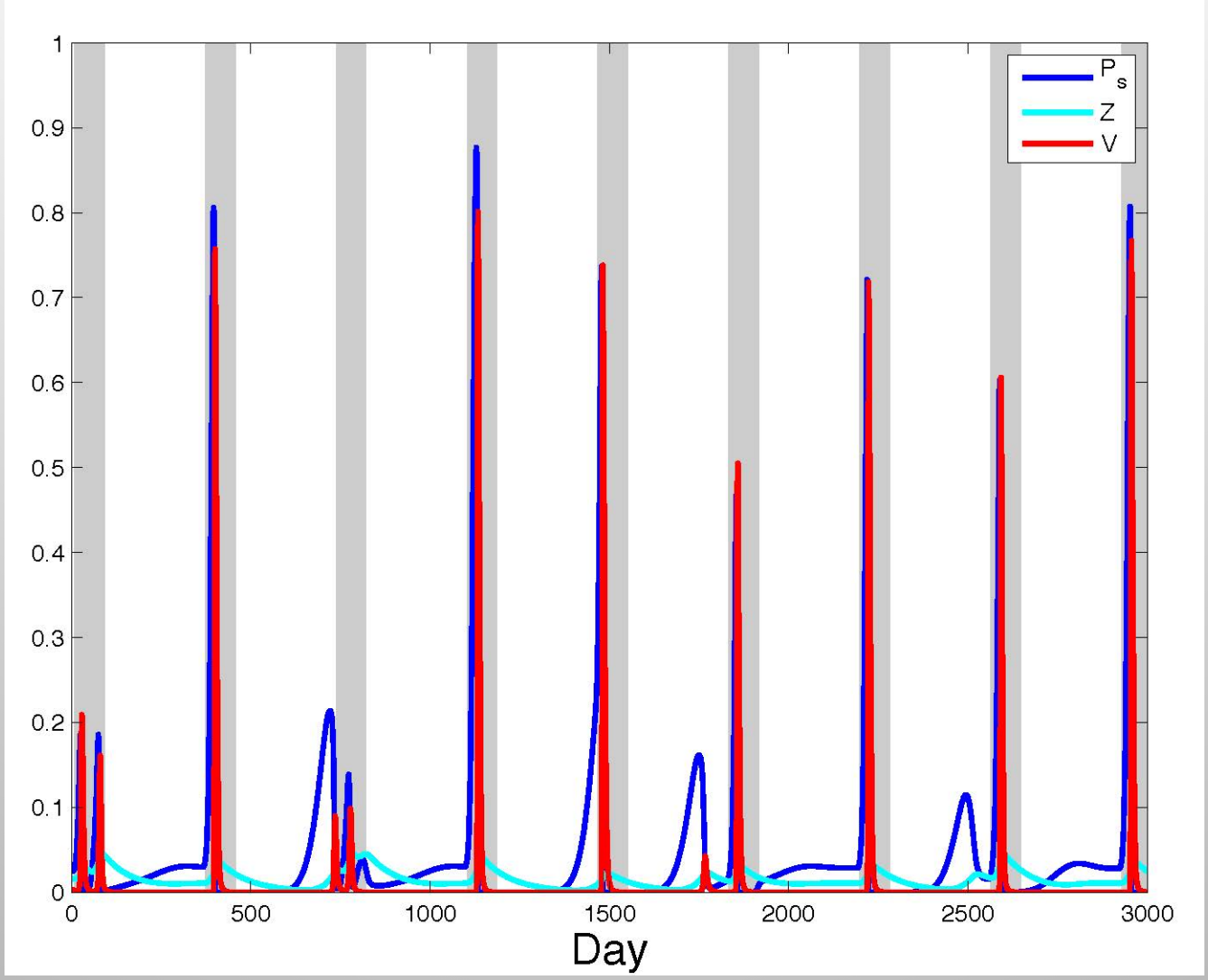
Days to extinction



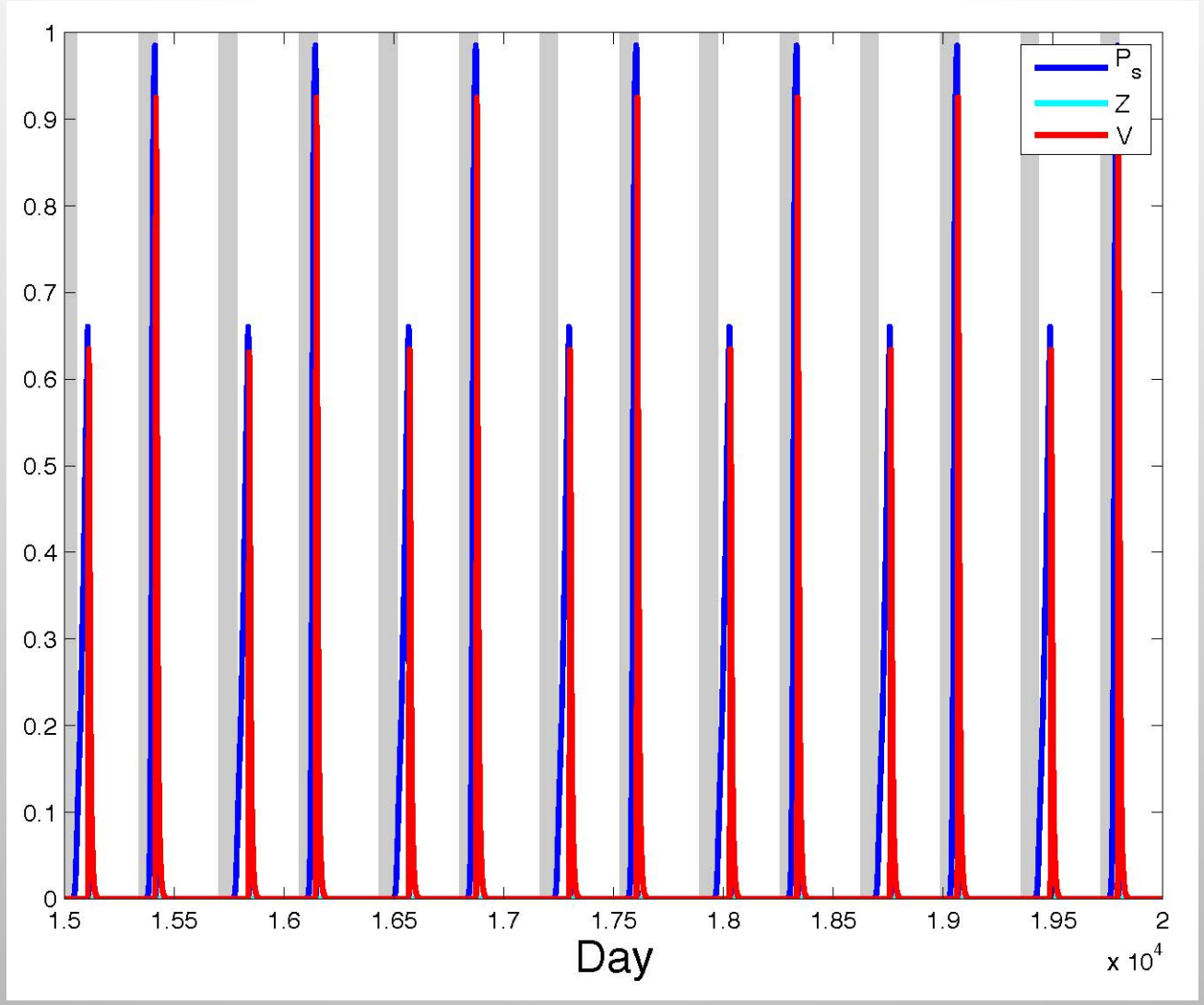
Co-existence through temporal variability of forcing



β=0.02

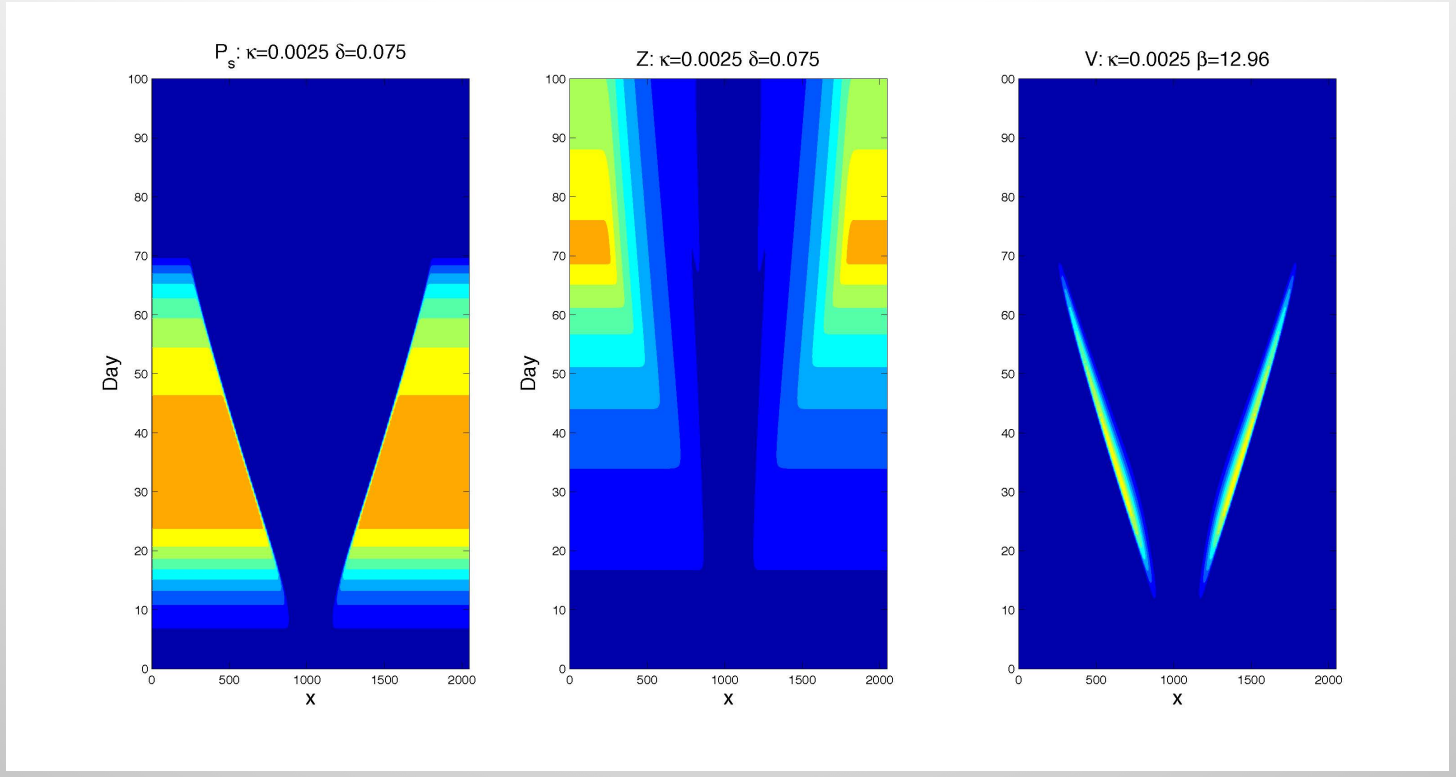

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
500
1000
1500
2000
2500
3000
Day
P s
Z
V

β=0.05

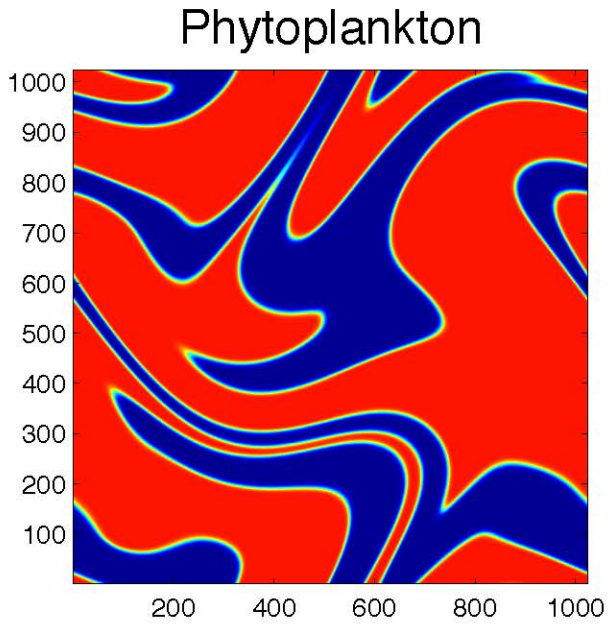

1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.5
1.55
1.6
1.65
1.7
1.75
1.8
1.85
1.9
1.95
2
Day
x 10^4
P_s
Z
V

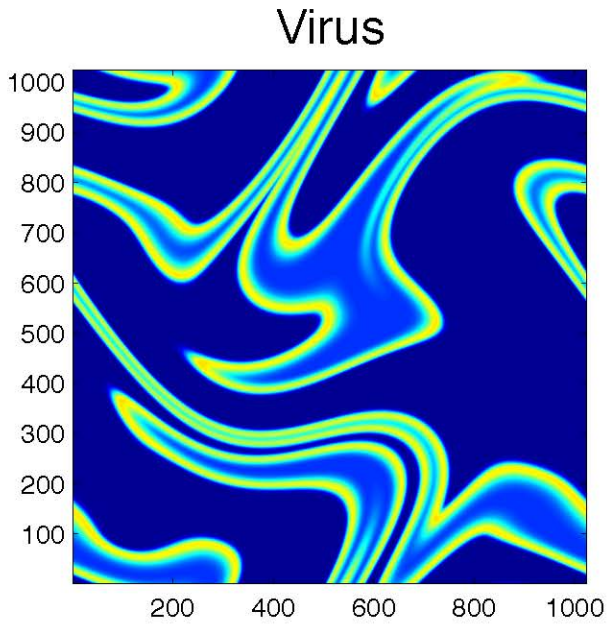
β=0.05

Spatial variability: diffusion

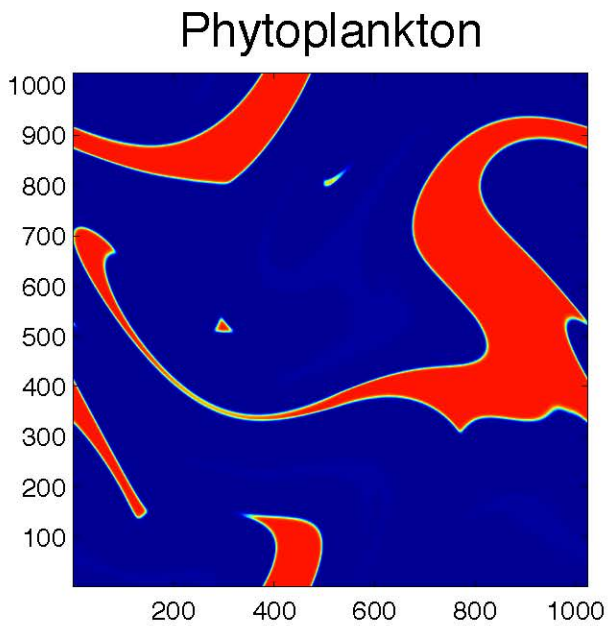


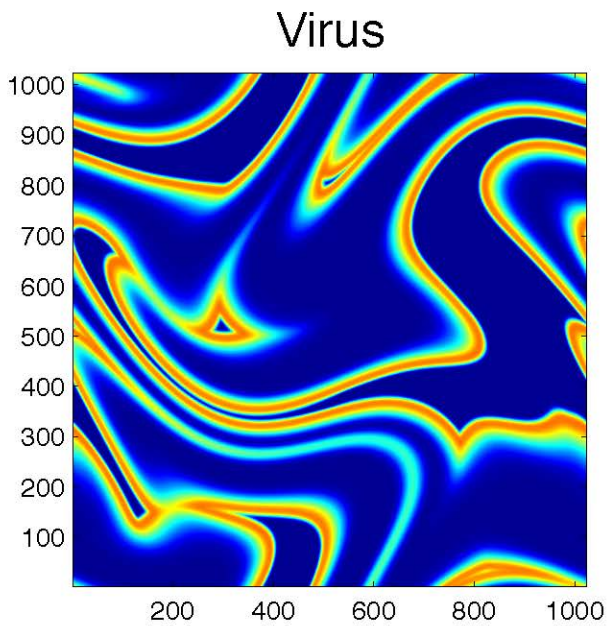
$$c \sim \sqrt{\kappa\beta}$$



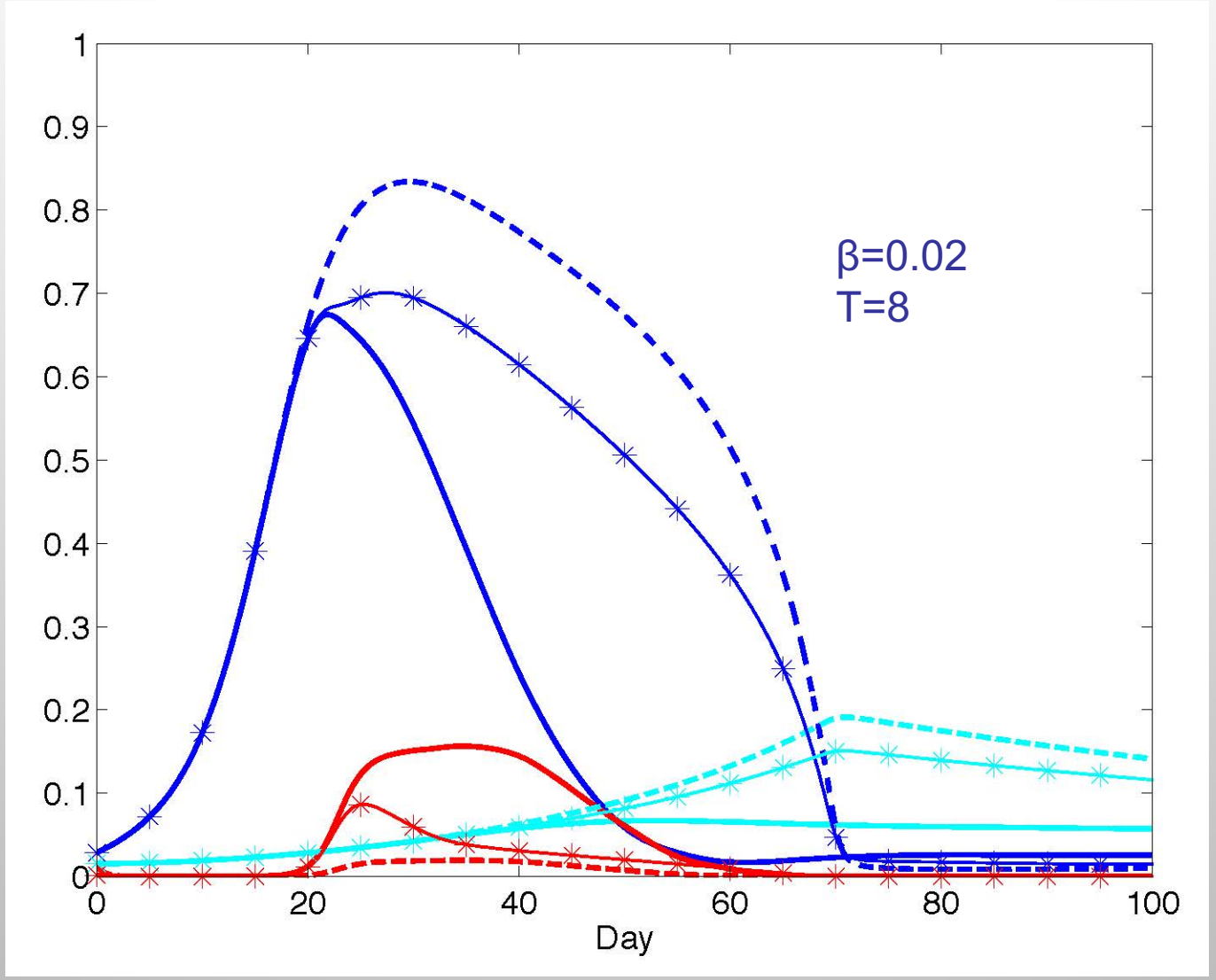


β=0.02
52% P>.5
11% V>.5

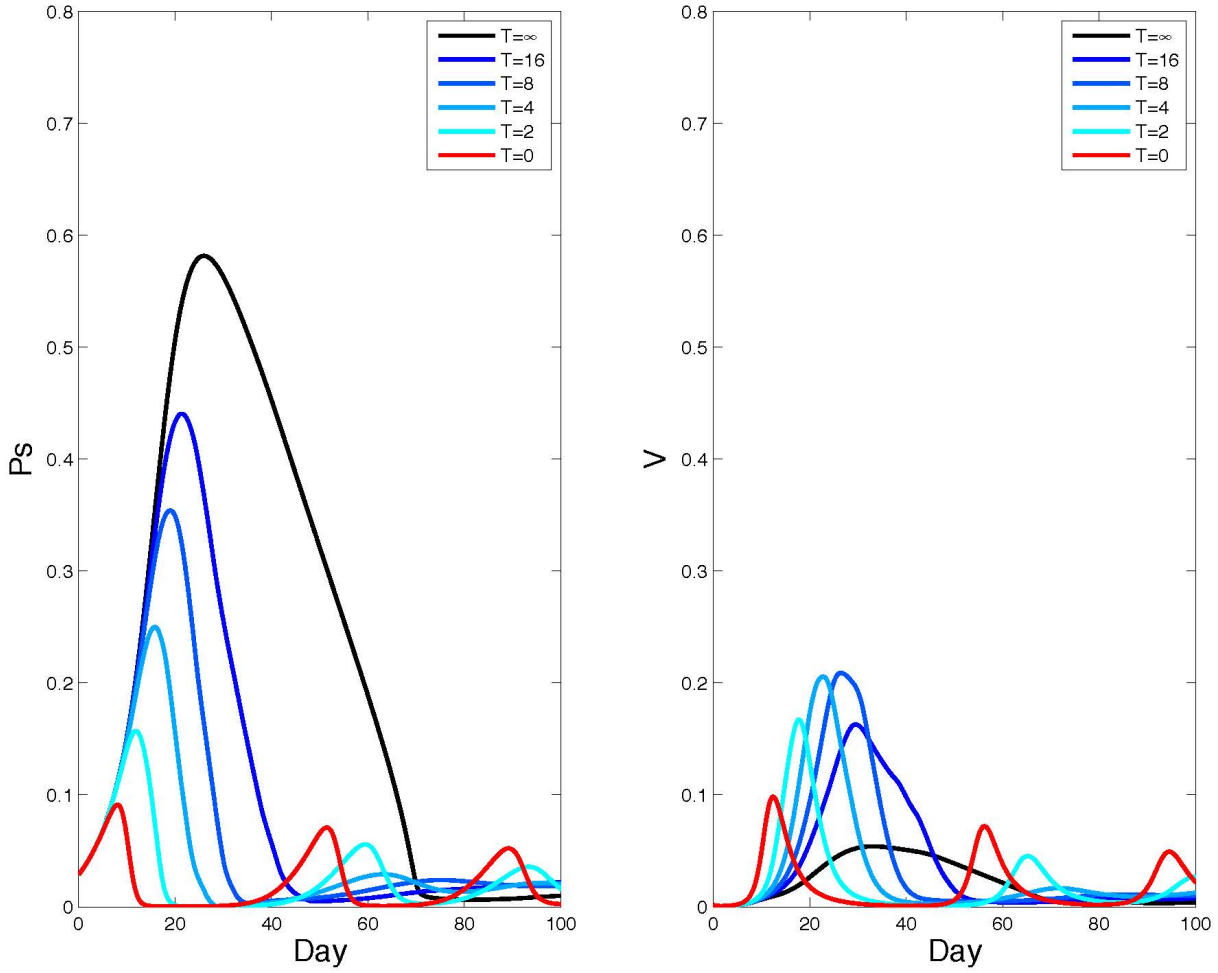


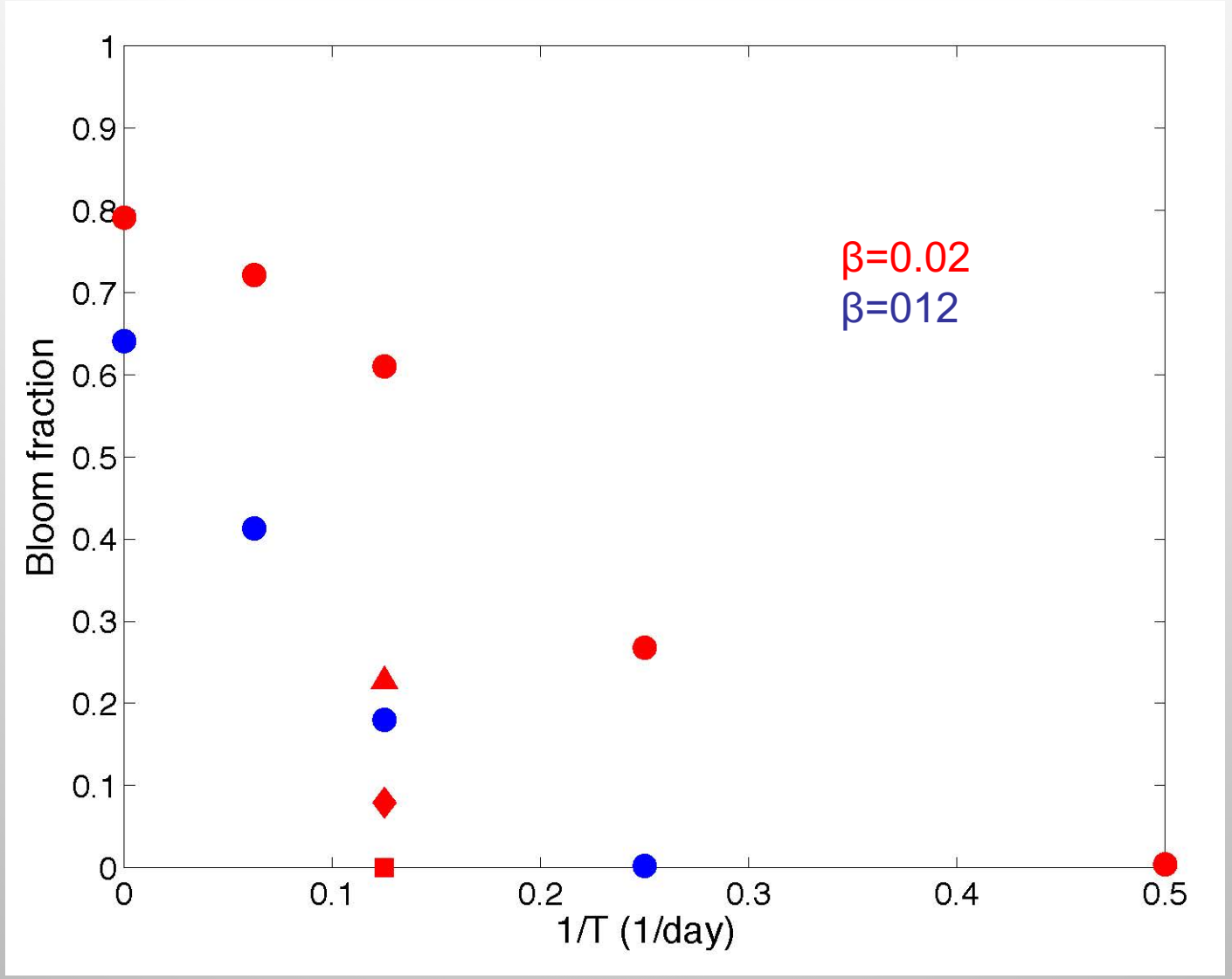


β=0.12
18% P>.5
17% V>.5


β=0.02
T=8
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
20
40
60
80
100
Day

Varying stirring strength




Bloom fraction
1/T (1/day)
β=0.02
β=012
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

- Time to reach equilibrium solution can be very long
- Co-existence of virus and zooplankton can occur with time varying forcing (nutrient/light input)
- Fluid flow acts as a transmission “vehicle” enhancing the spread of the epidemic
- Stirring and mixing reduces the duration of the bloom and can prolong the bloom of the virus …
- … and under certain circumstances can prevent the bloom from occurring

Richards (2017) J. Theoretical Biology

- Resistance and immunity
- Viral attacks on bacteria
- Ecosystem complexity
- Viruses in a submesoscale world?
- Does the presence of viruses affect the response of the system to environmental change?