Conference "Cooperation and major evolutionary transitions"
Kevli Institute for Theoretical Physics, U.C. Santa Barbara
February 8, 2013; 10:30-11:15

Self-Sacrificing of Social Amoeba

cell-to-cell interaction via a signaling chemical shaped by cheating risk.

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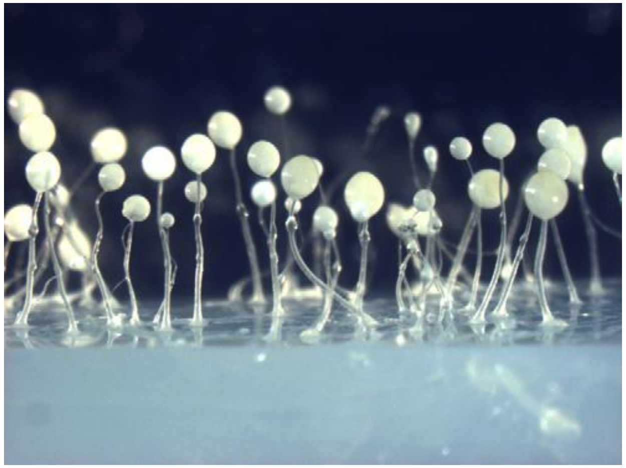
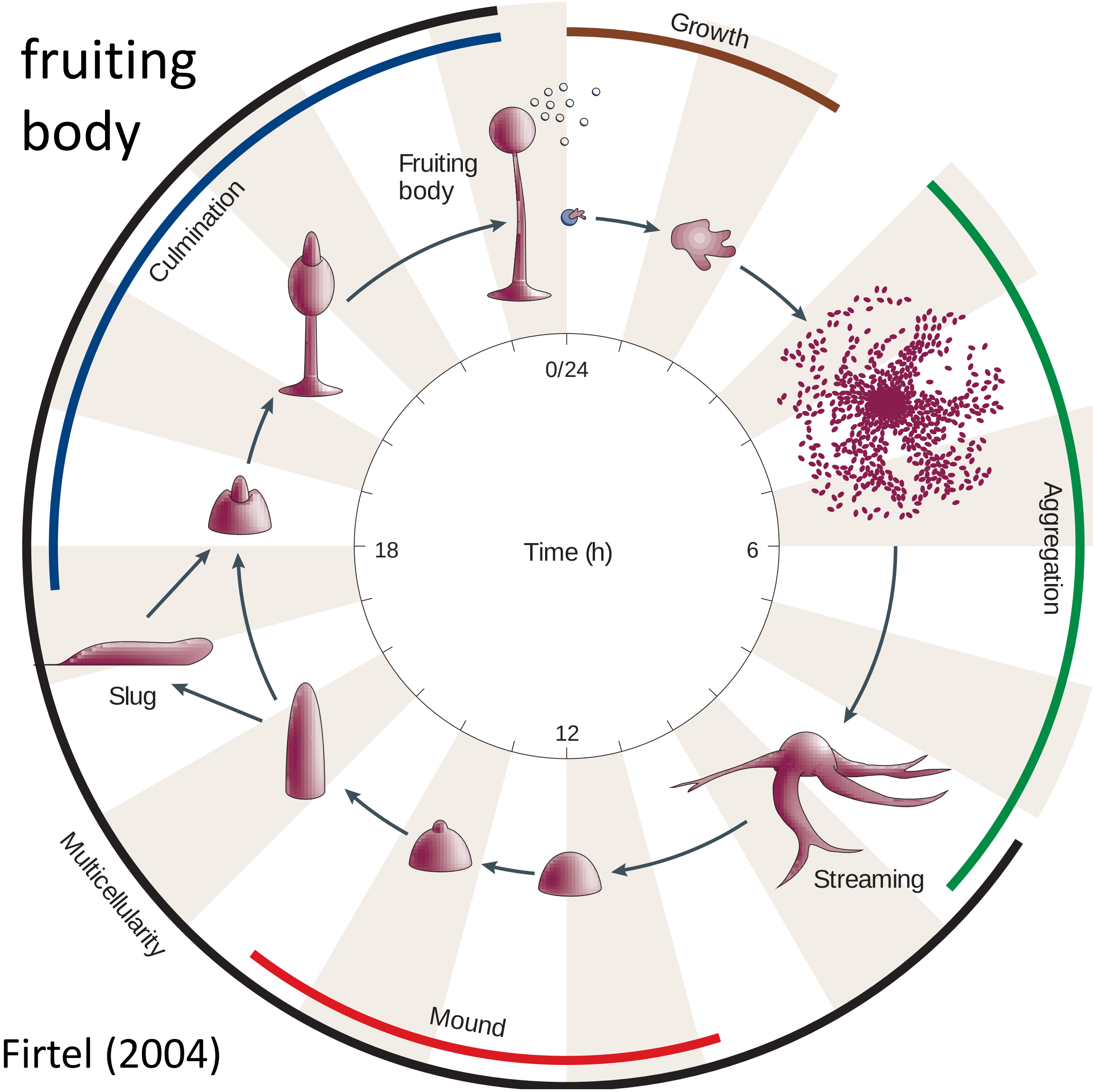
Dictyostelium discoideum



Strassmann&Queller (2011)

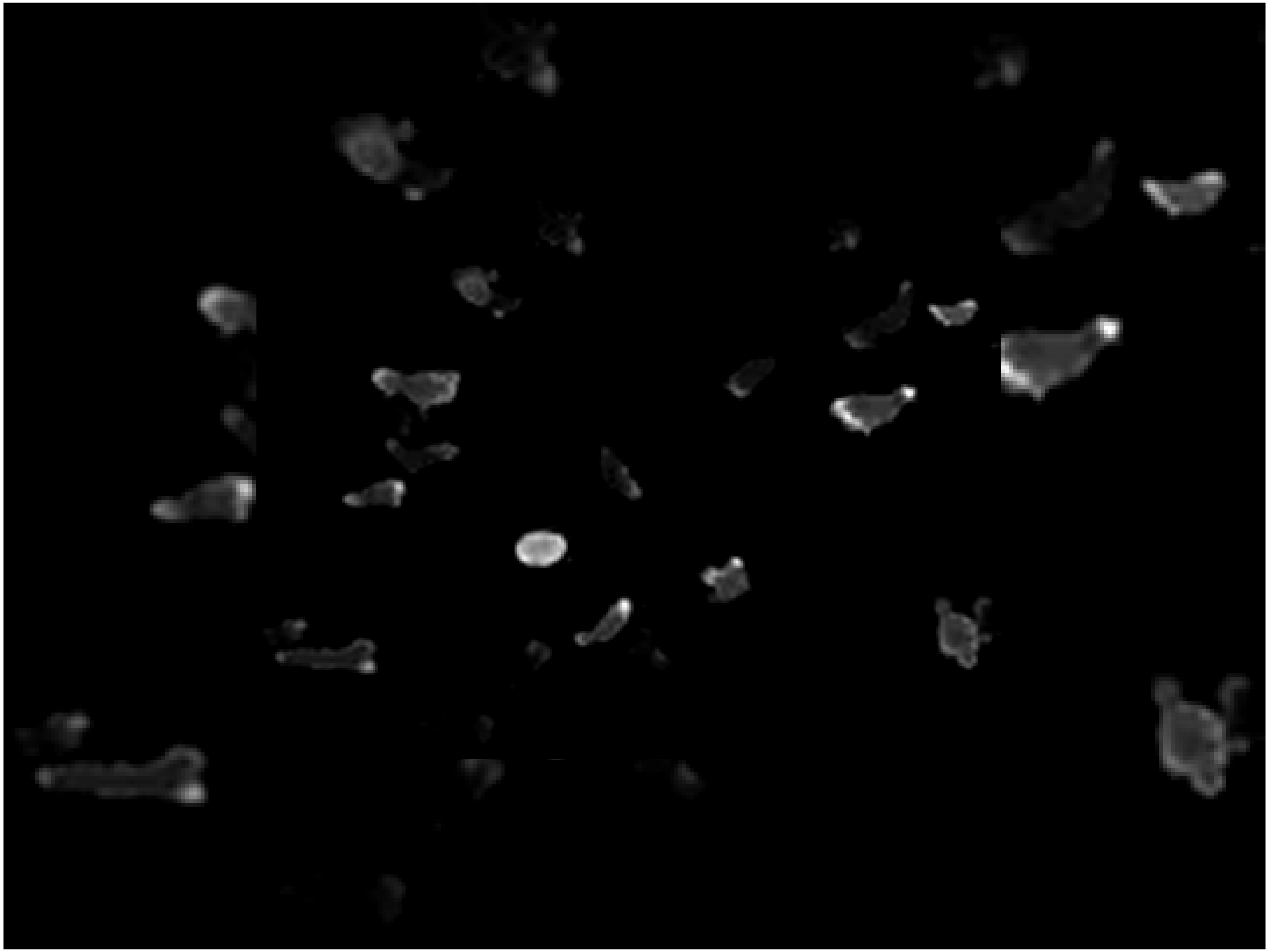
fruiting body

Slug



Chisholm & Firtel (2004)

Aggregation of cells



http://dictybase.org

Formation of fruiting body

http://dictybase.org

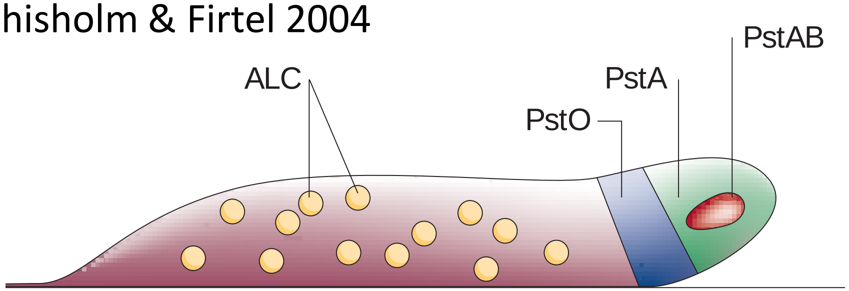
Becoming stalk is altruism.

fruiting body

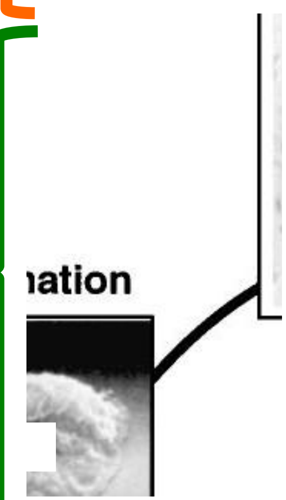
assemblage

Spore

Chisholm & Firtel 2004



Stalk



pre-spore cells

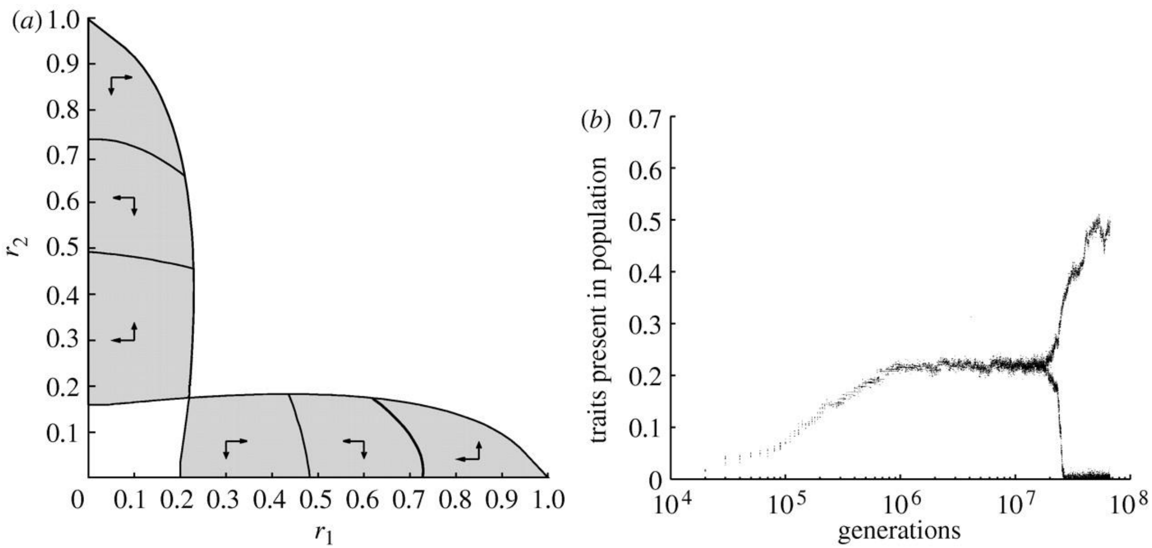
pre-stalk cells

Aubry&Firtel (1999)

In evolutionary game models on the stalk/spore ratio each strain (genotype) has its own value of contribution to stalk vs. spore.

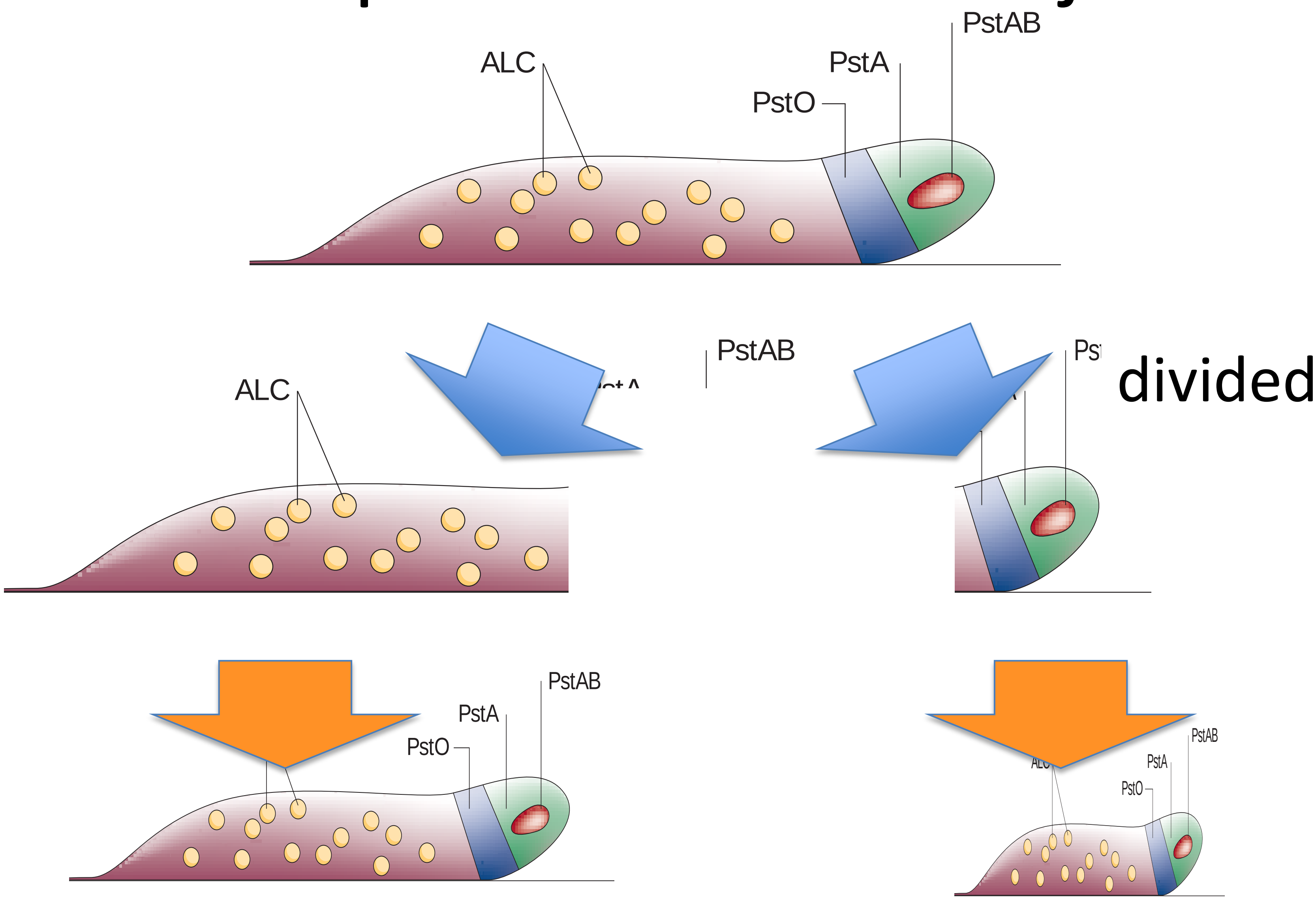
for example

Brännström Å , & Dieckmann U 2005. Dimorphic evolutionary dynamics after branching. Proc. R. Soc. B 2005;272:1609-1616



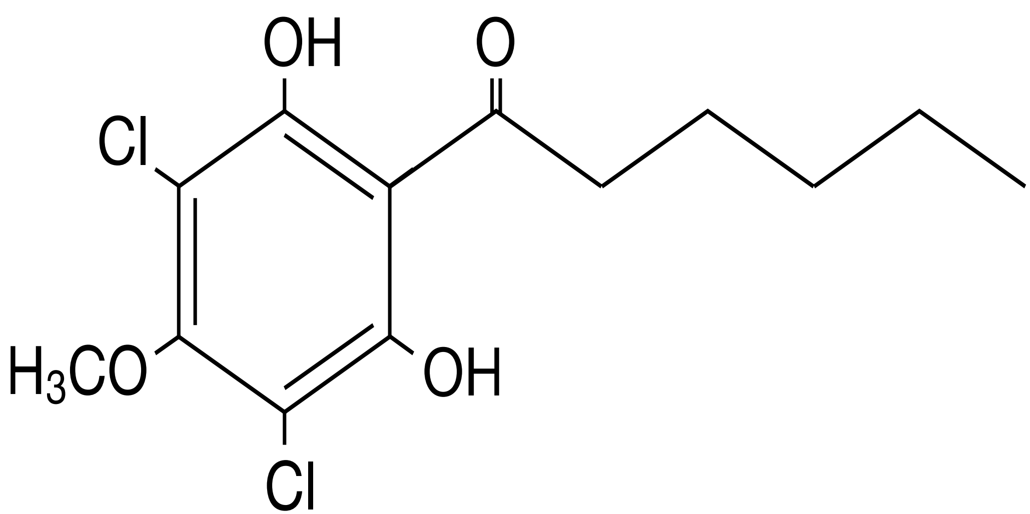
PROCEEDINGS OF THE ROYAL SOCIETY B

Ratio of pre-stalk cells is adjusted.

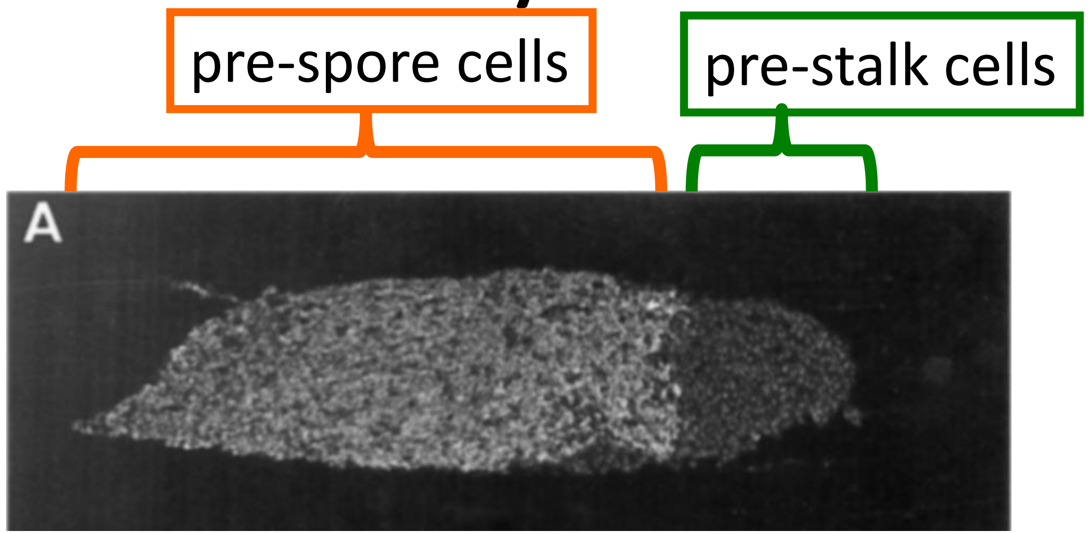


A signaling chemical that makes prespore cells become prestalk cells

DIF-1

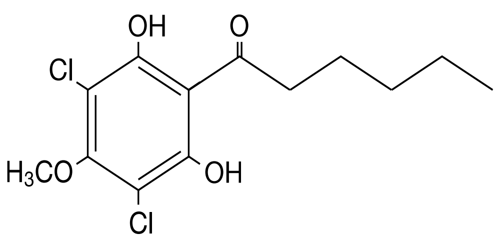


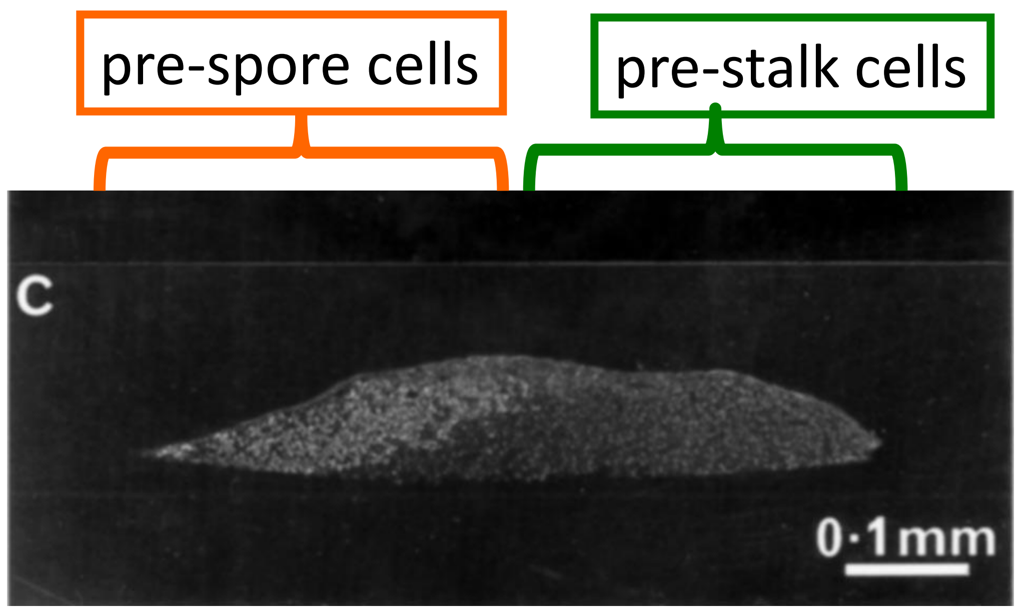
Fraction of Pre-stalk cells increases by DIF-1



control

DIF-1





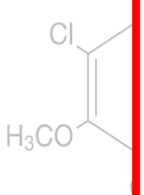
super abundant DIF-1

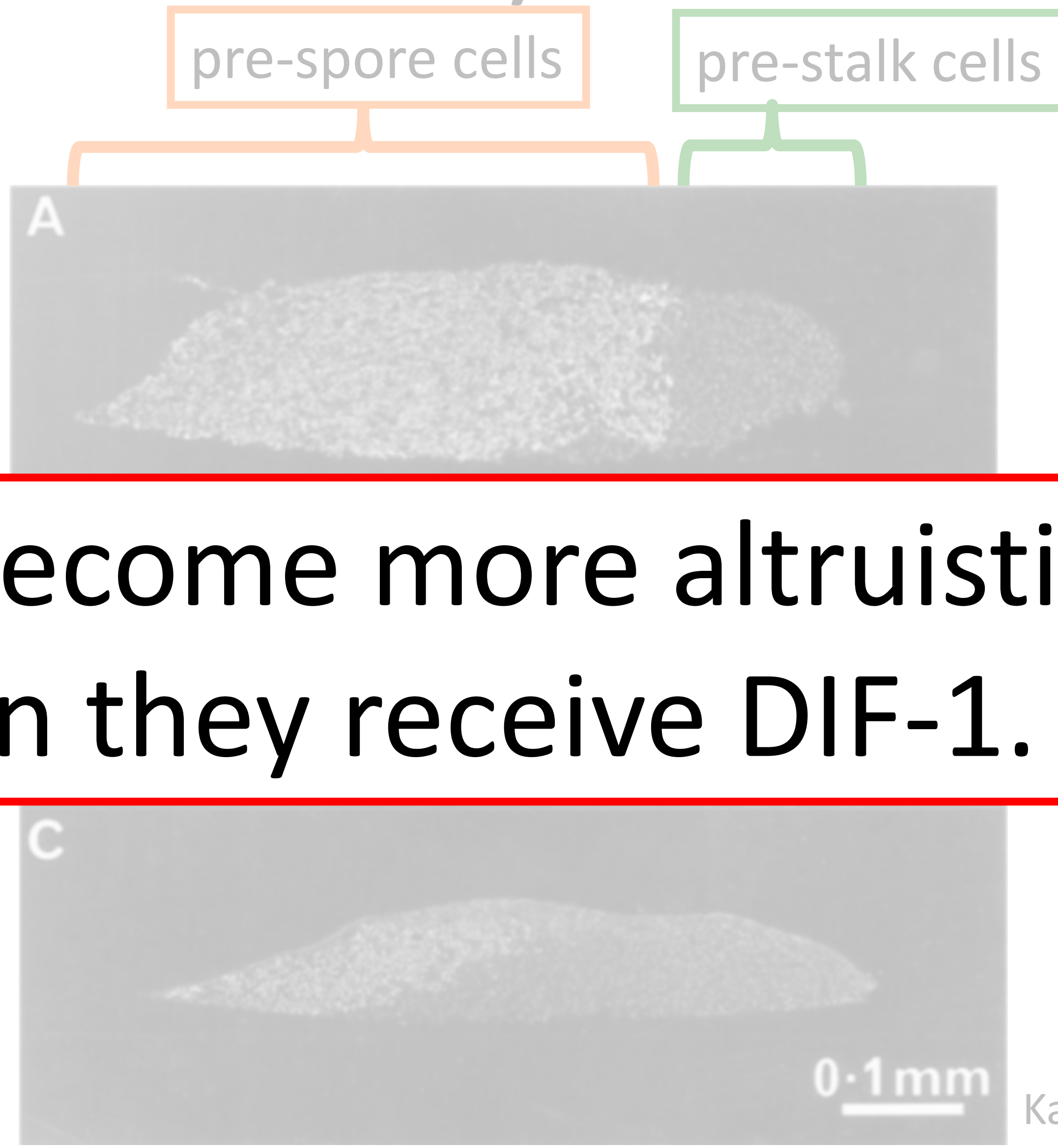
Kay et al. 1999

Fraction of Pre-stalk cells increases by DIF-1

control

DIF-1



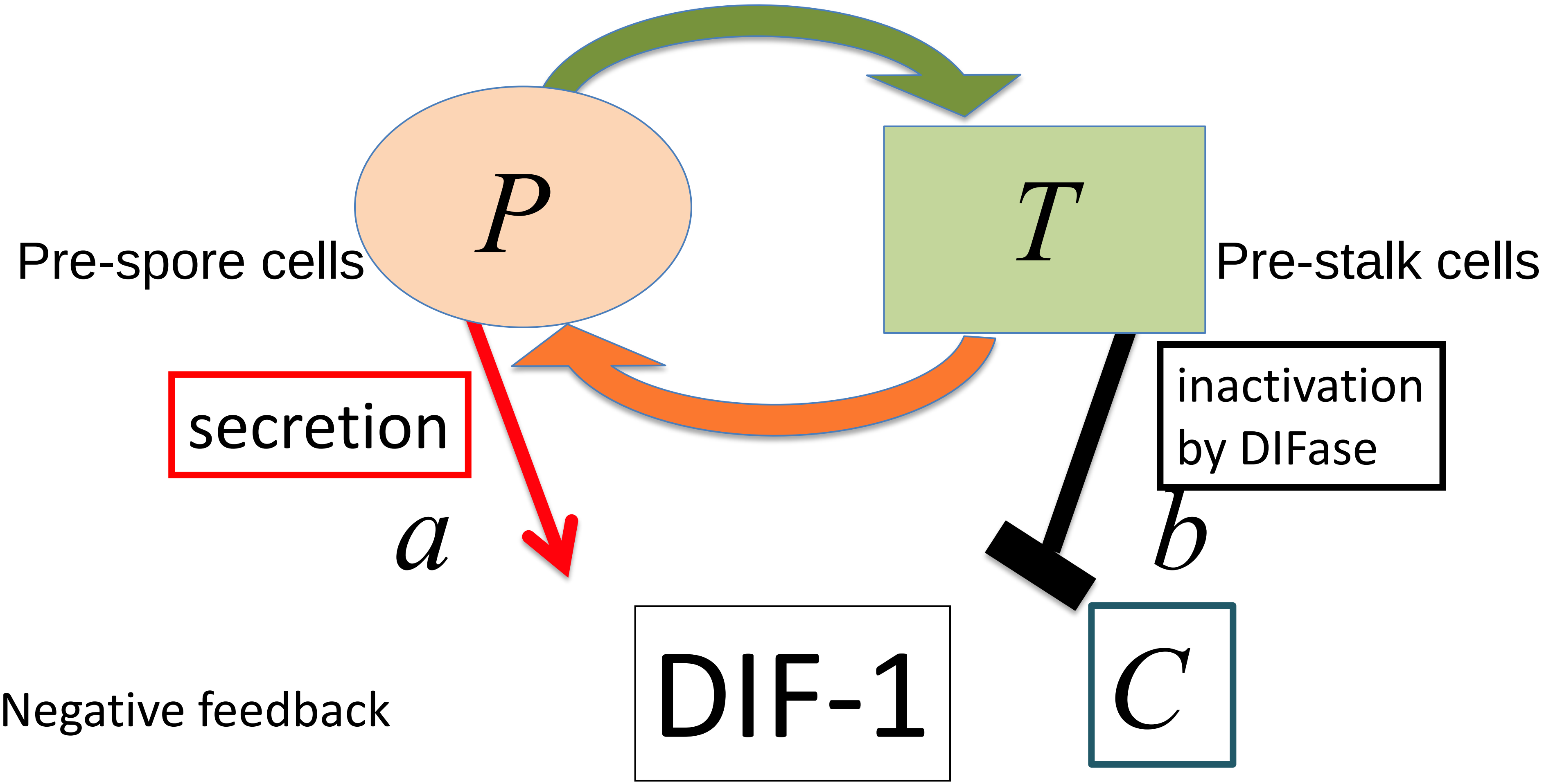


super abundant DIF-1

Cells become more altruistic when they receive DIF-1.

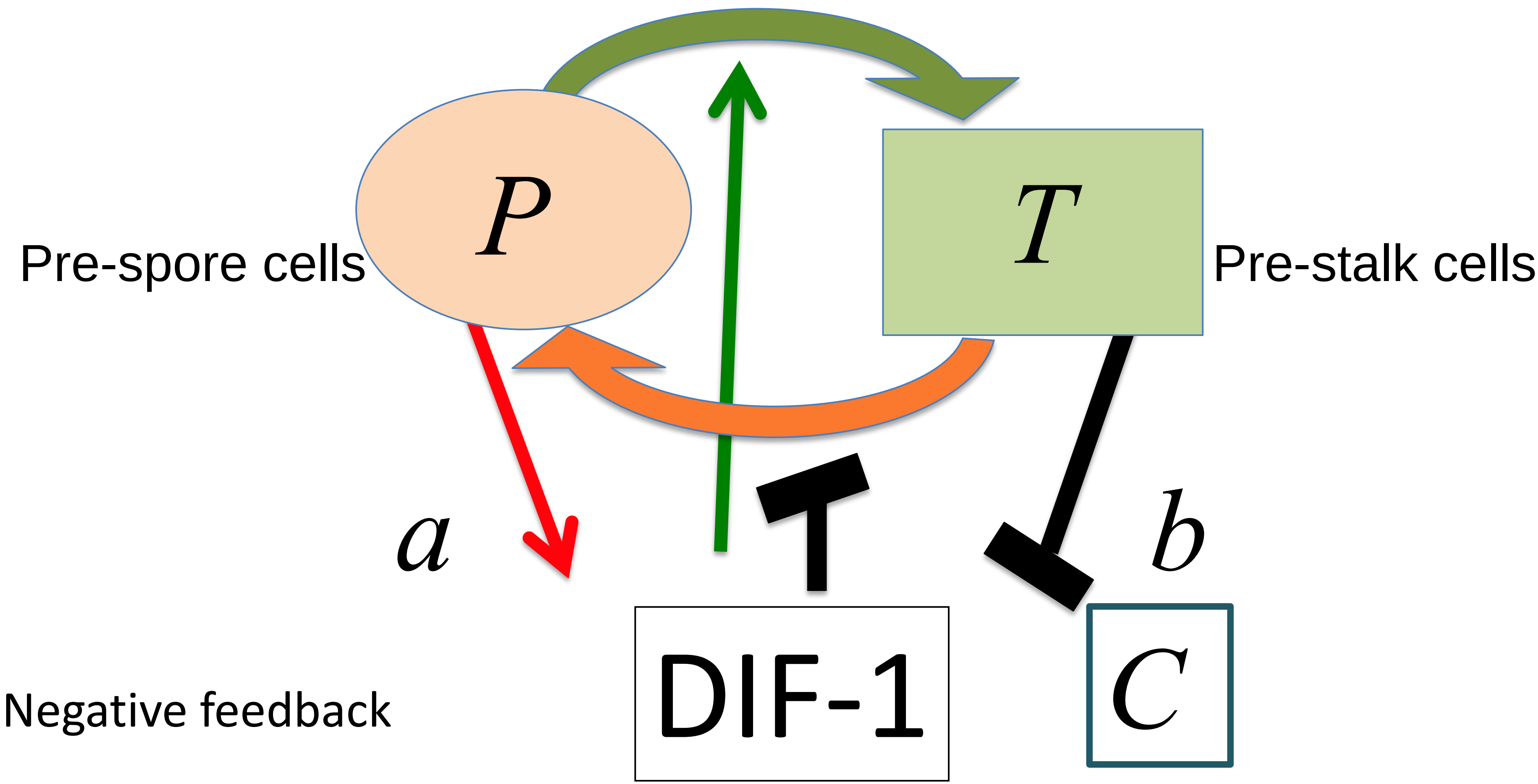
Kay et al. 1999

Cell differentiation mediated by DIF-1

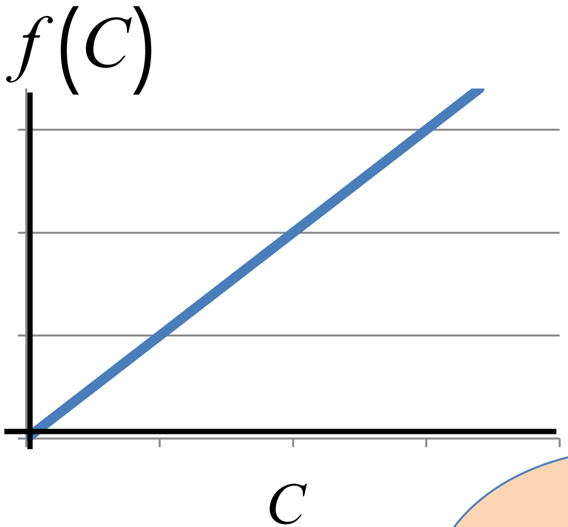


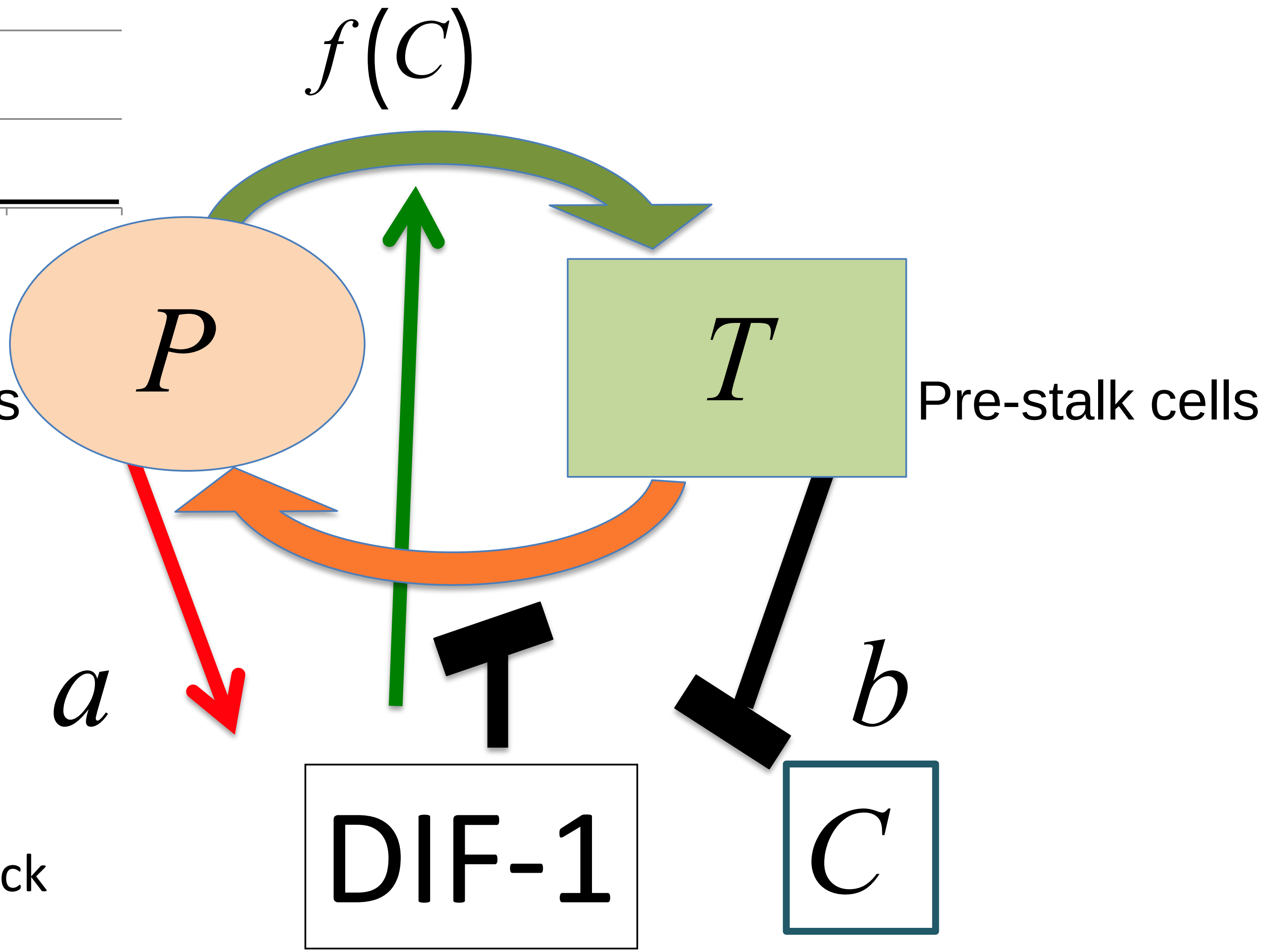
Negative feedback

Cell differentiation mediated by DIF-1



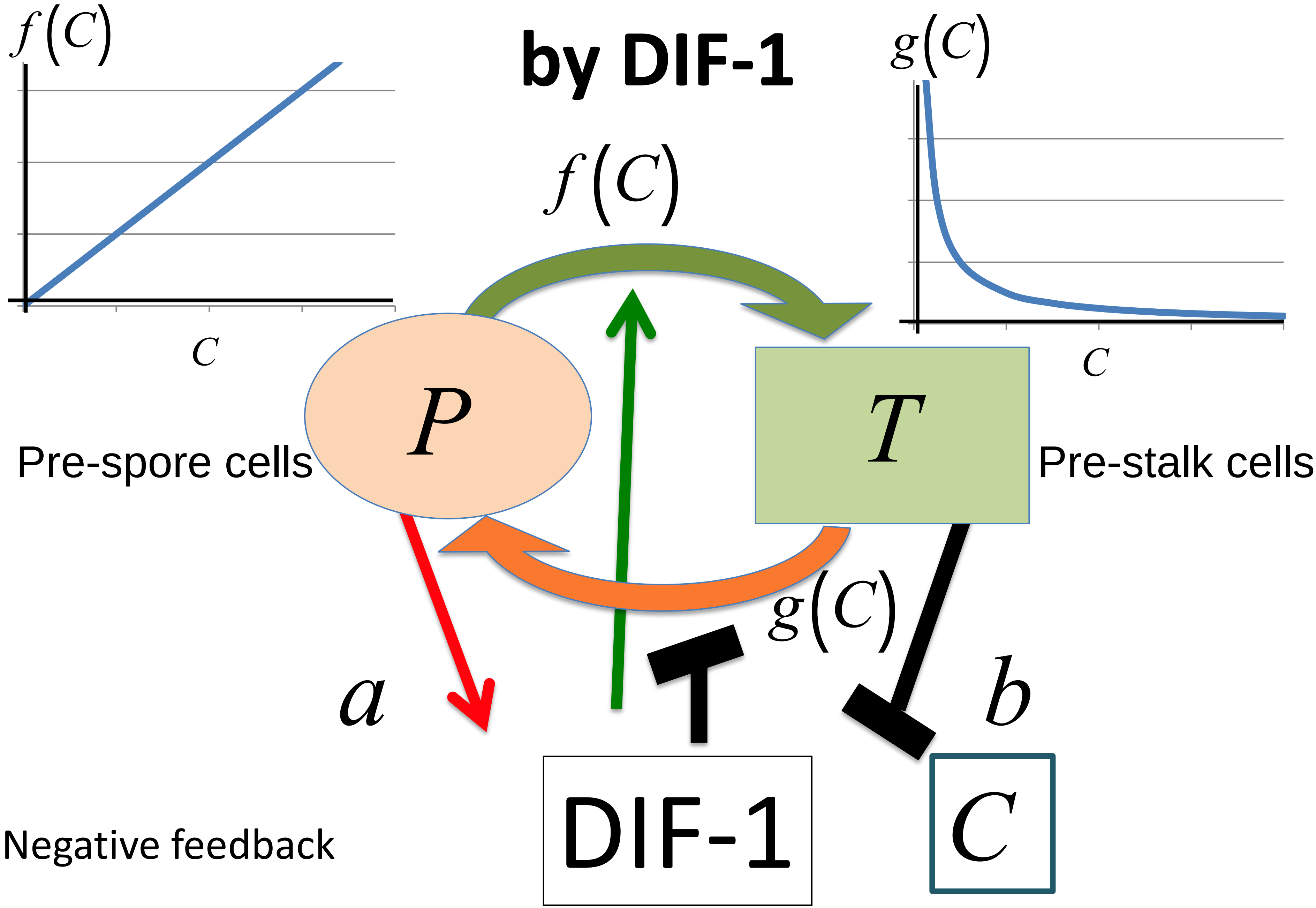
Cell differentiation mediated by DIF-1





Negative feedback

Cell differentiation mediated by DIF-1



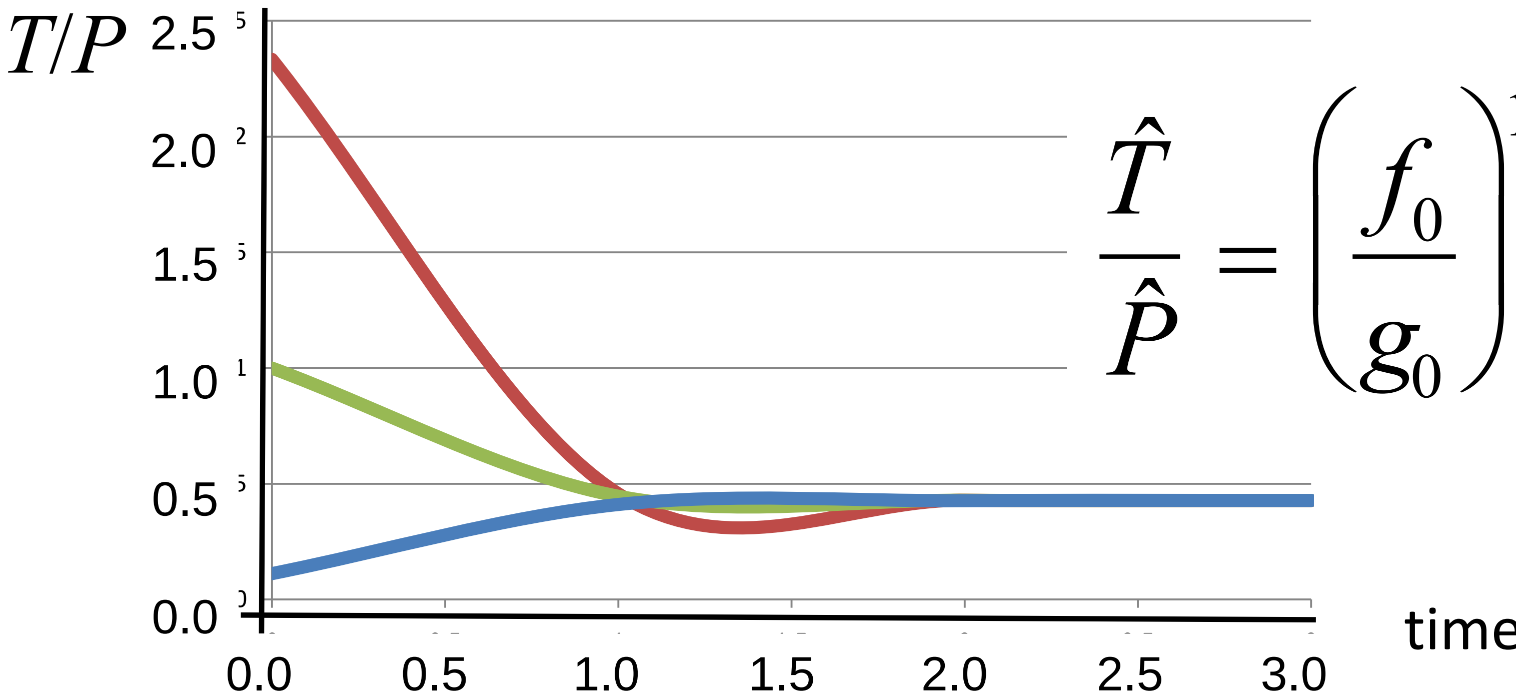
Kinetics of DIF-1 and cells

$$\frac{dT}{dt} = f(C)P - g(C)T$$ (Pre-stalk cells)

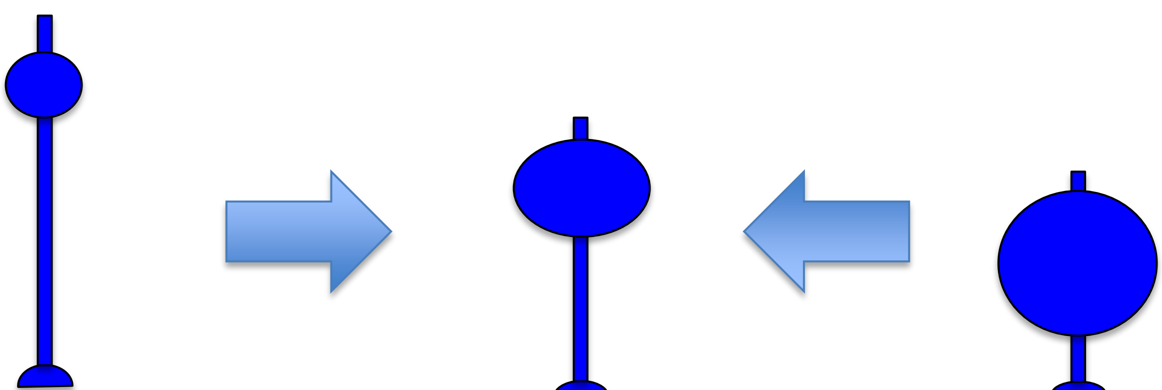
$$\frac{dC}{dt} = aP - bCT$$ (DIF-1)

$$N = P + T$$ (Total cell number)

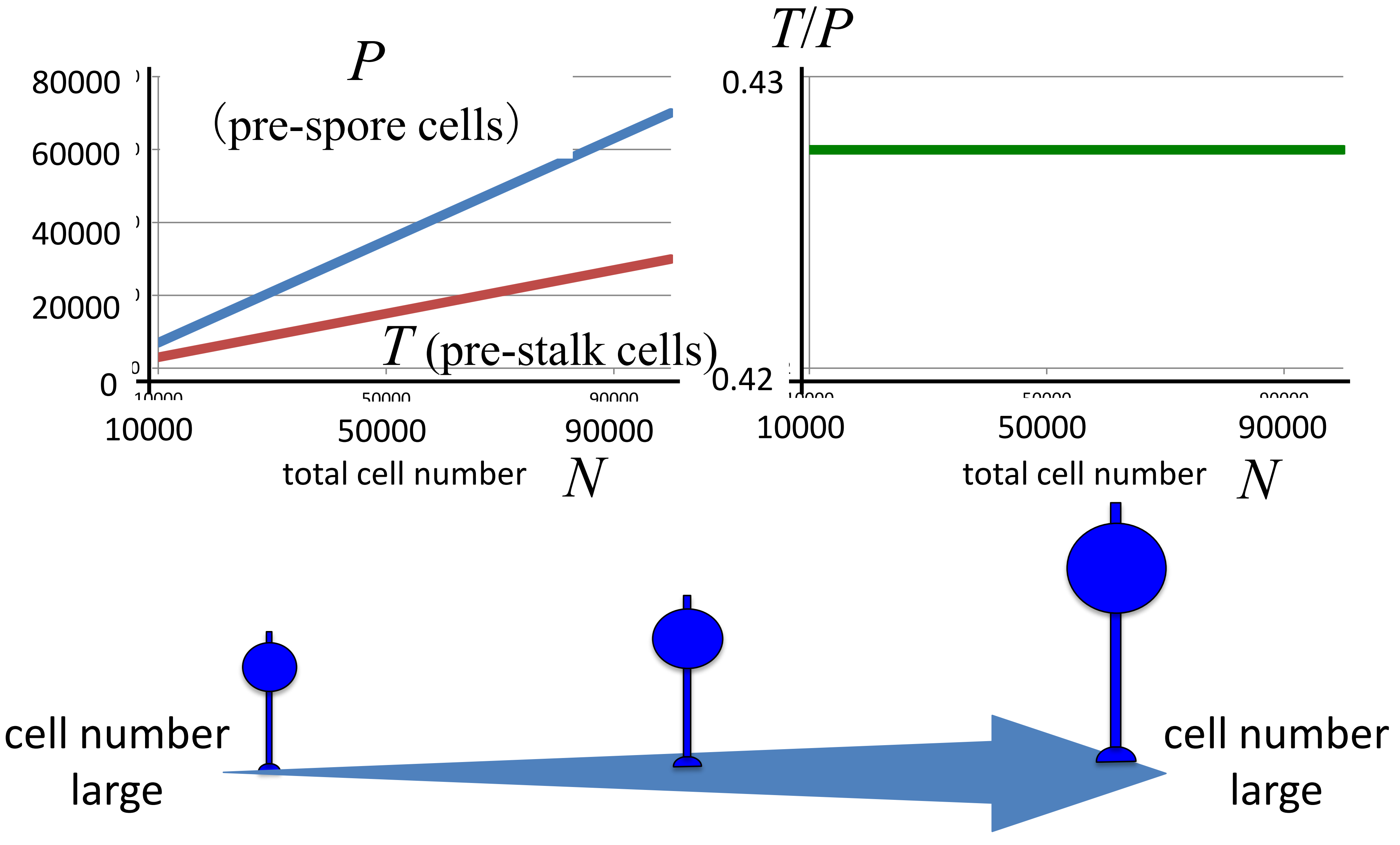
T/P ratio converges to a constant



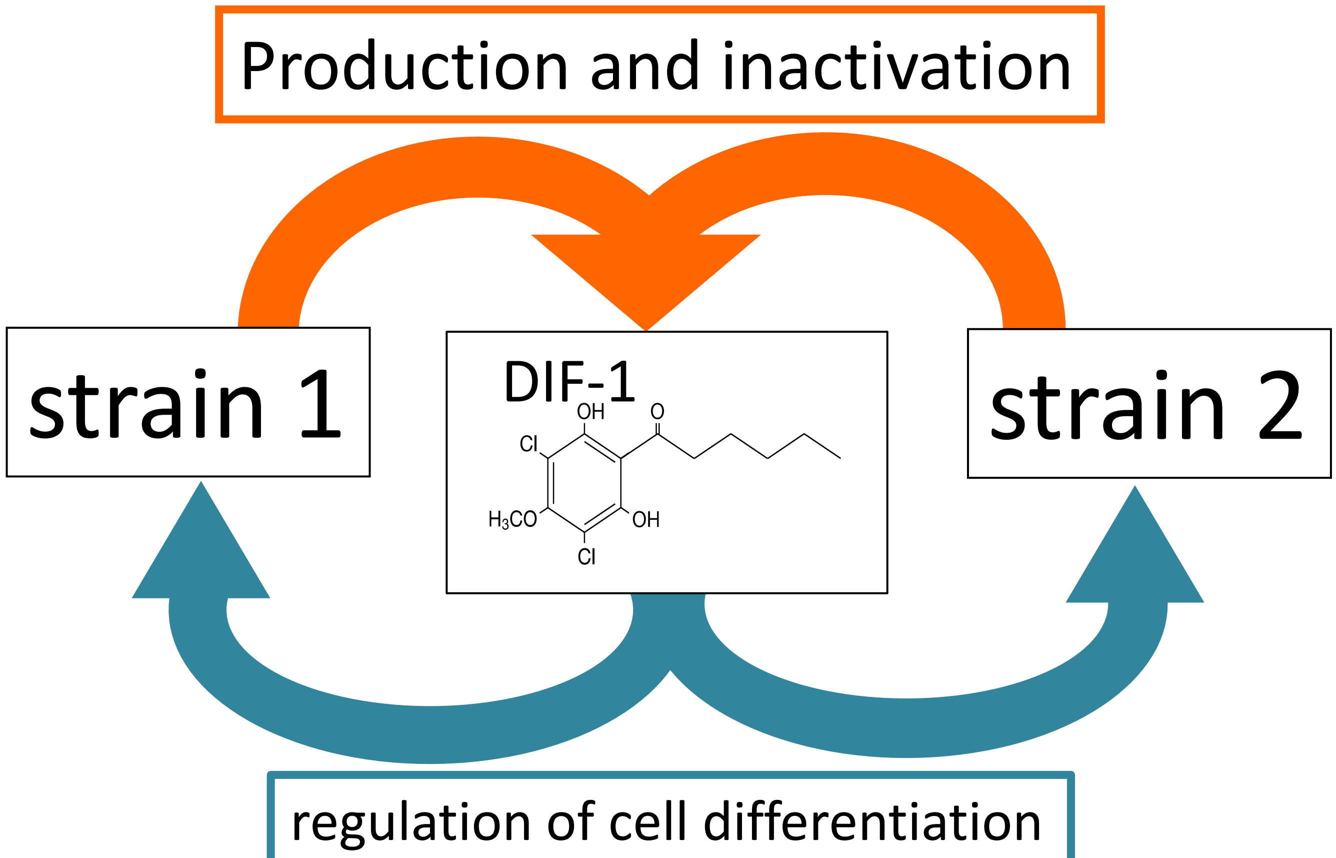
$$\frac{\hat{T}}{\hat{P}} = \left(\frac{f_0}{g_0}\right)^{1/3}\left(\frac{a}{b}\right)^{2/3}$$



T/P ratio is independent of total cell number



A mixture of cells of two strains share DIF-1



In a mixture of multiple strains,

$$\frac{dT_1}{dt} = f_1(C)P_1 - g_1(C)T_1$$ (Pre-stalk cells)

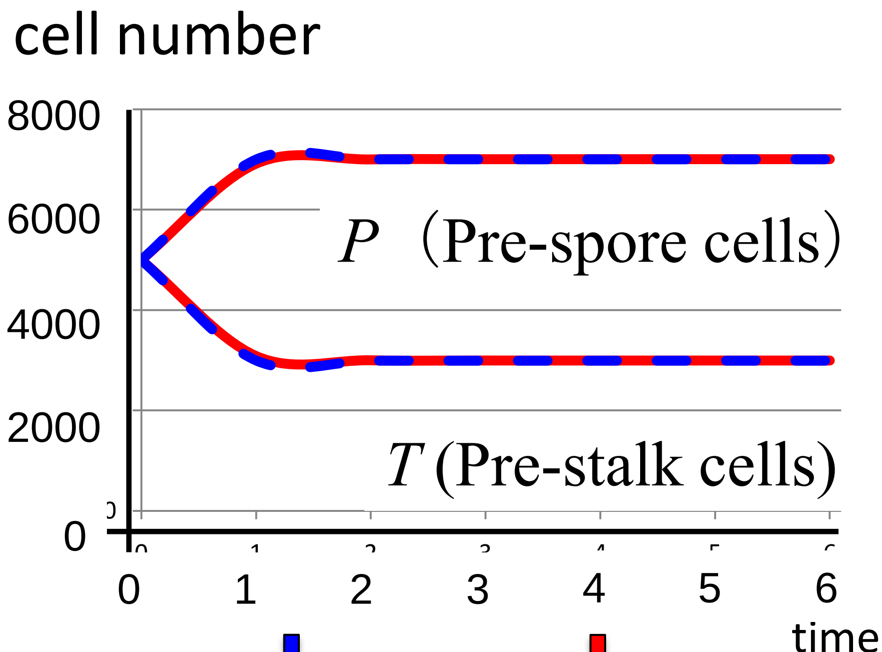
$$\frac{dT_2}{dt} = f_2(C)P_2 - g_2(C)T_2$$ (Pre-stalk cells)

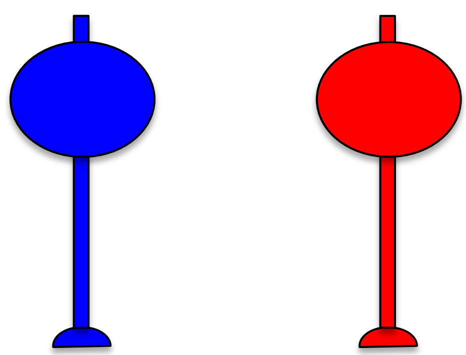
$$\frac{dC}{dt} = \sum_i \left(a_i P_i - b_i C T_i\right)$$ (DIF-1)

$$N_i = P_i + T_i$$

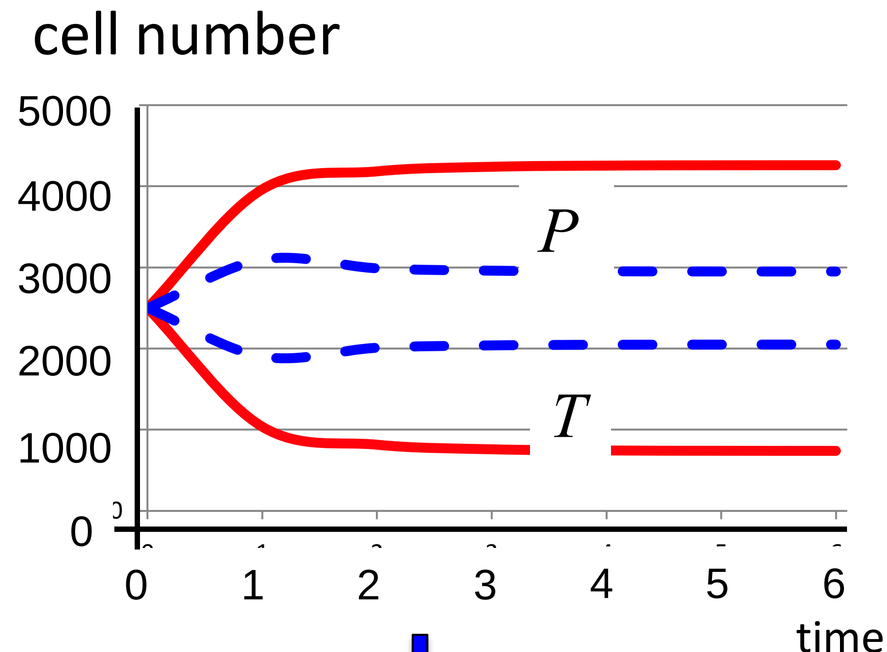
Contribution to Stalk/Spore may differ between strains

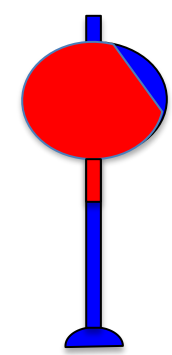
a single strain





a mixture of two strains





Red is a Facultative Cheater

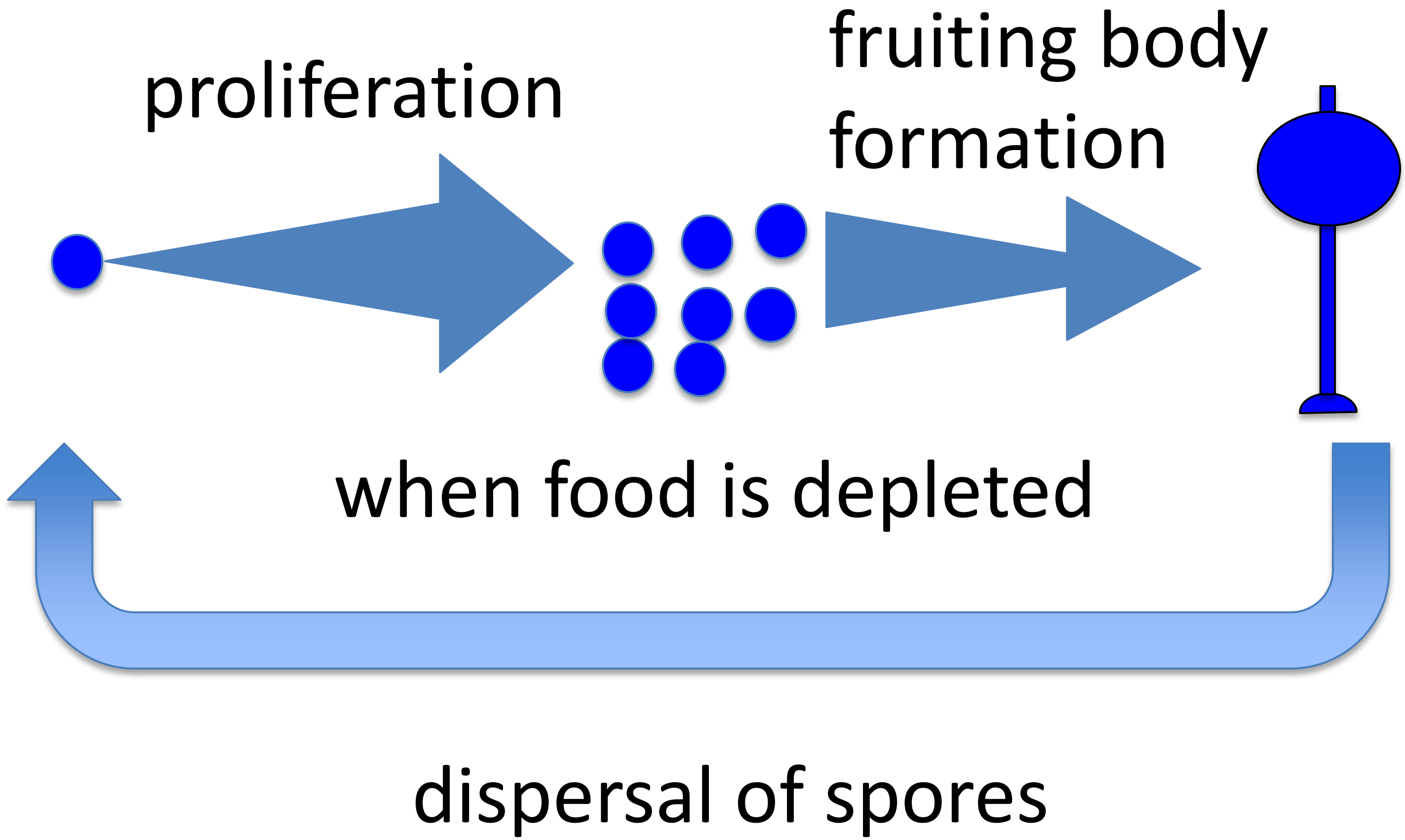
Stalk/spore ratio of each strain when mixed:

$$\frac{\hat{T}_i}{\hat{P}_i} = \frac{f_{0i}}{g_{0i}}\hat{C}^2 \qquad i=1,\ 2 \qquad \hat{C} = \frac{\sum_j a_j \hat{P}_j}{\sum_j b_j \hat{T}_j}$$

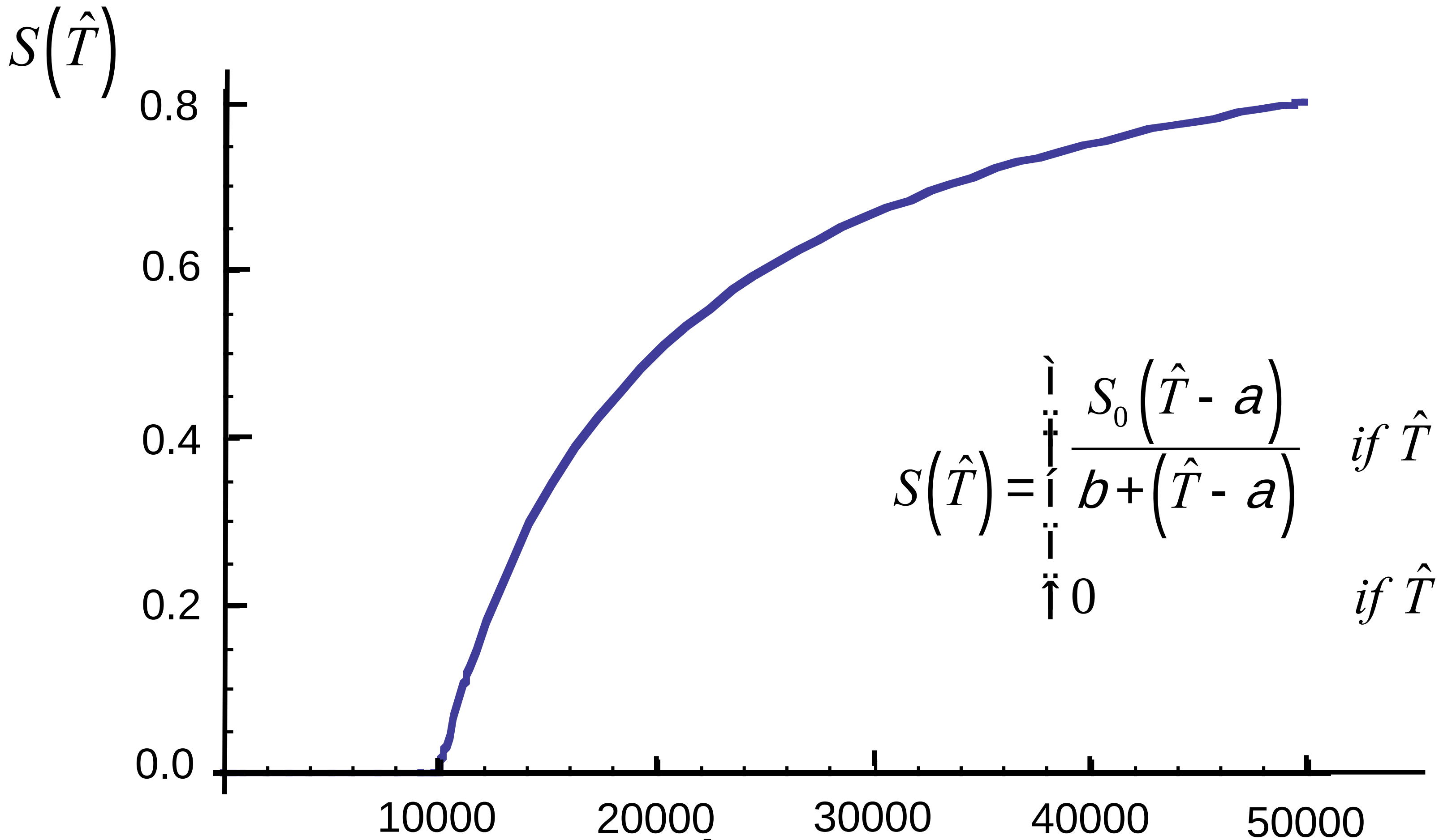
Stalk/spore ratio of a single strain fruiting body:

$$\frac{\hat{T}}{\hat{P}} = \left(\frac{f_0}{g_0}\right)^{1/3}\left(\frac{a}{b}\right)^{2/3}$$

Evolution


proliferation
fruiting body formation
when food is depleted
dispersal of spores

Dispersal and settlement success of spores



$$S(\hat{T}) = \begin{cases} \dfrac{S_0(\hat{T} - \alpha)}{\beta + (\hat{T} - \alpha)} & if\ \hat{T} - \alpha > 0 \\ 0 & if\ \hat{T} - \alpha \le 0 \end{cases}$$

α=10000, β=5000, S_0=1.0

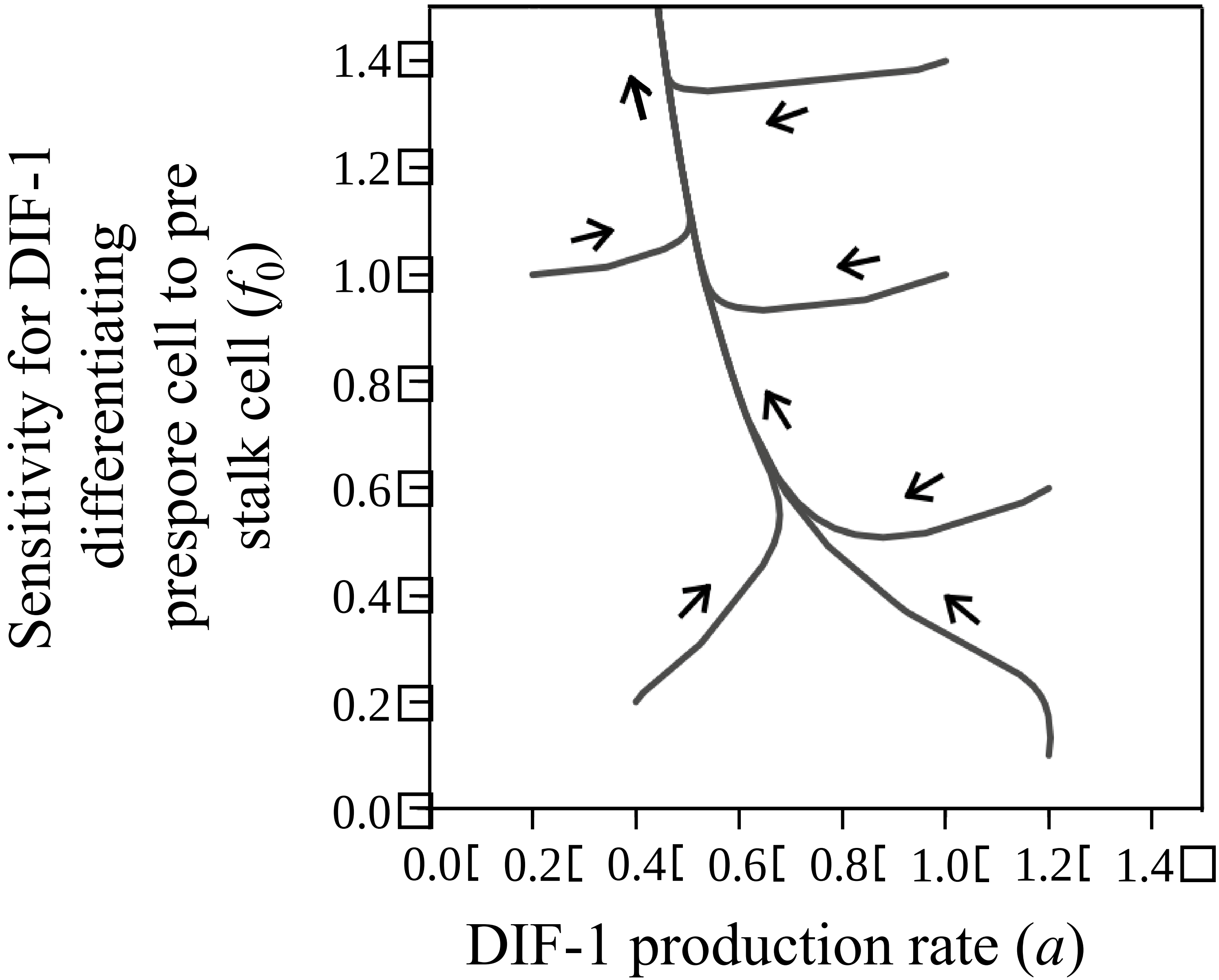
f_0	Rate of transition from prespore cell to prestalk cell
g_0	Rate of transition from prestalk cell to prespore cell
a	Rate of production of DIF-1 per prespore cell
b	Rate of decomposition of DIF-1 by prestalk
k	Cost of DIF-1 production

Fitness

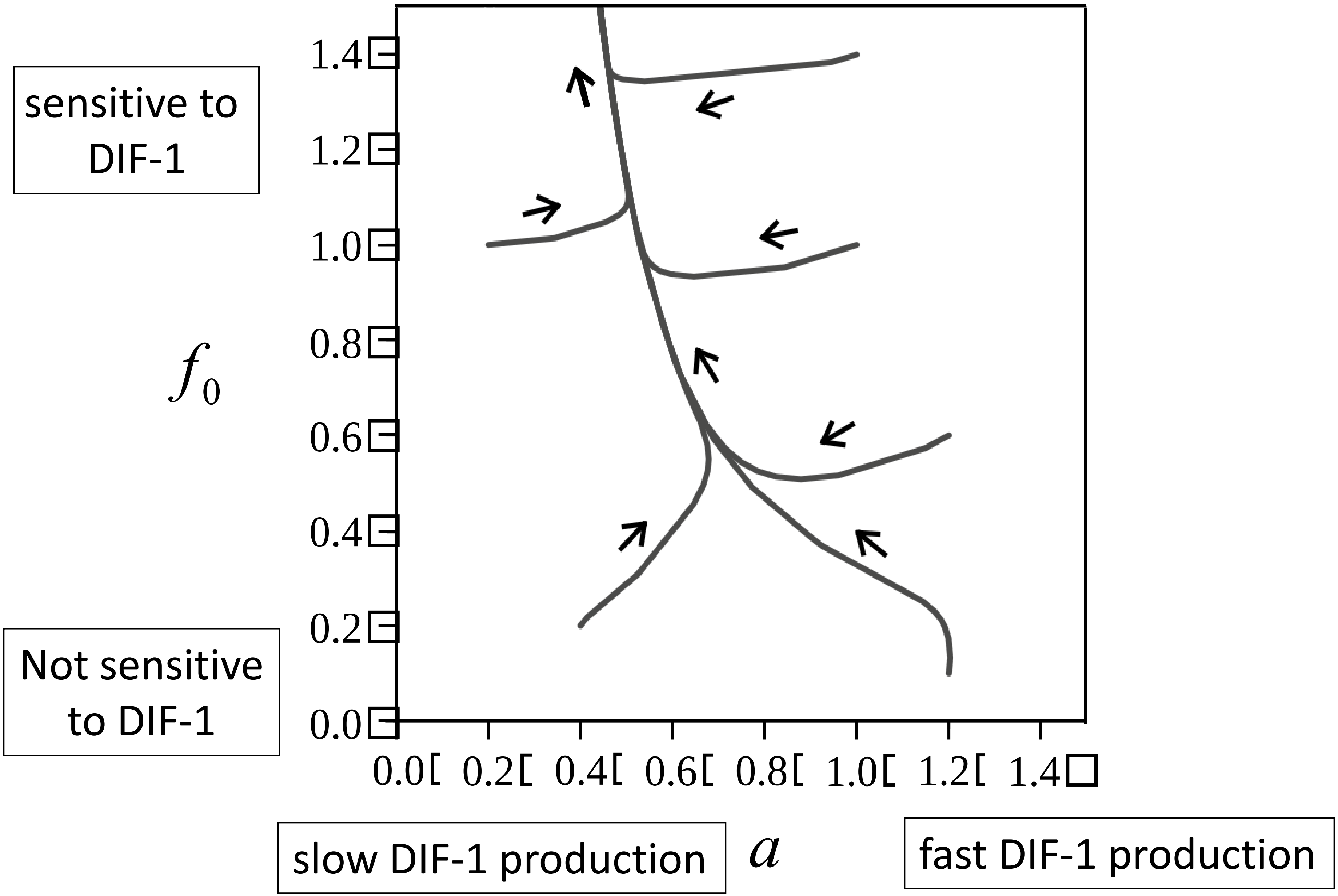
$$W_i = \underbrace{\hat{P}_i}_{\text{Number of Spores}} \bullet \underbrace{S\left(\hat{T}_i\right)}_{\text{Dispersal success}} \underbrace{e^{-k a_i}}_{\text{Cost of DIF-1 production}}$$

A mutant who is close to their parental type invades, and
it may replace the old type.
After a long time, the species changes its property slowly.

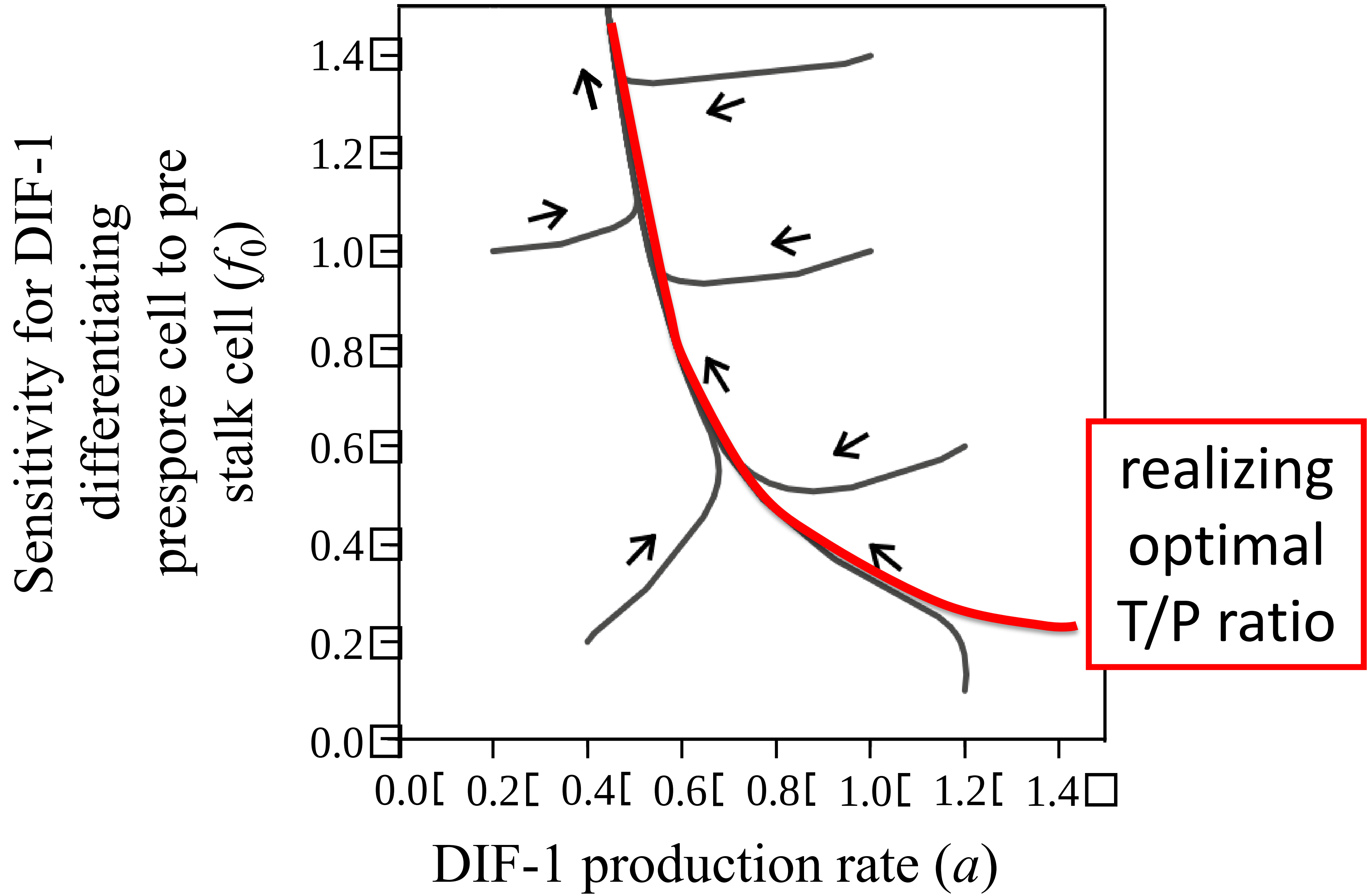
Evolutionary trajectory



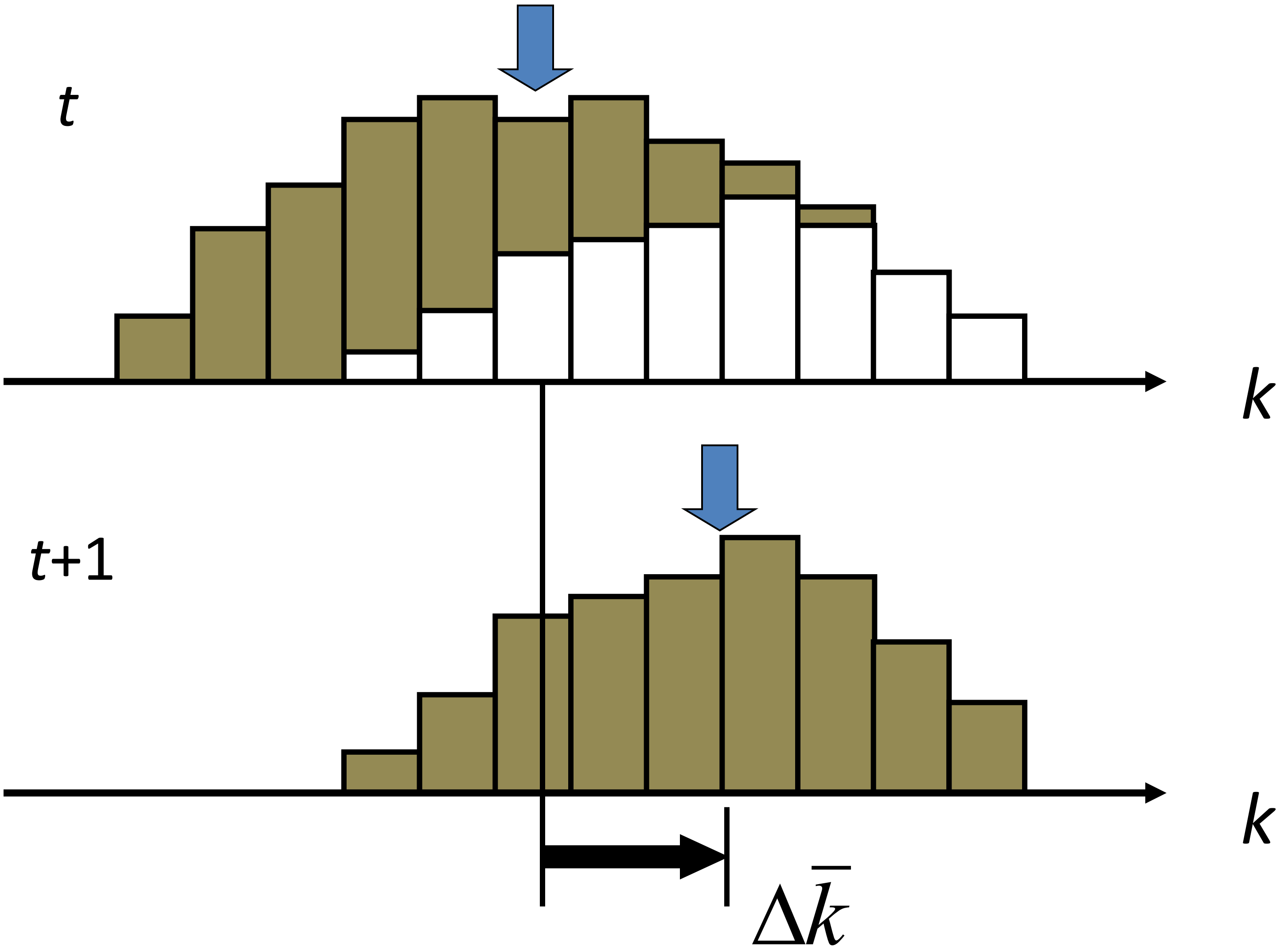
Evolutionary trajectory

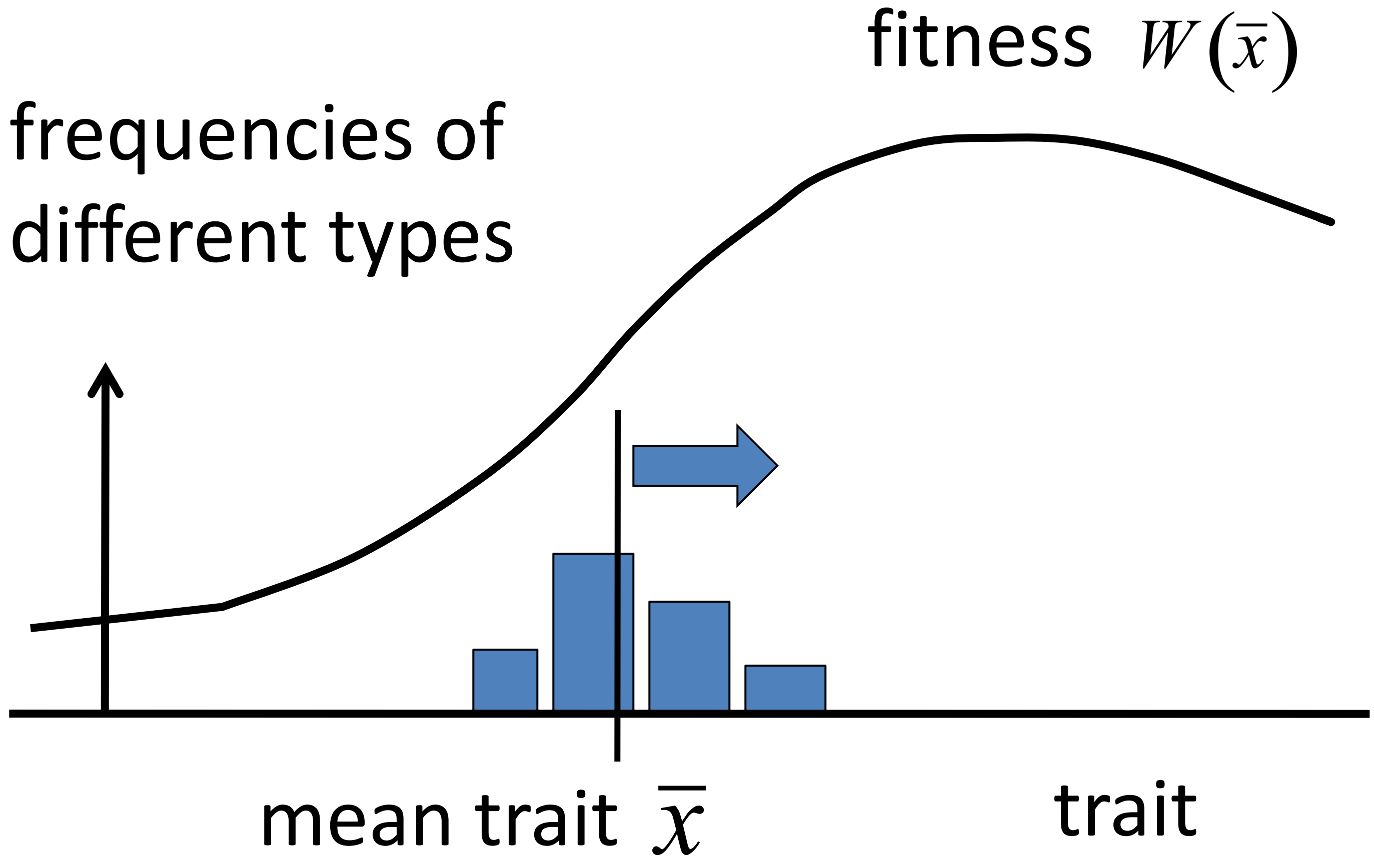


Evolutionary trajectory



Response of a population to natural selection





fitness $W(\bar{x})$
frequencies of different types
mean trait $\bar{x}$
trait

Under weak selection,

change in the mean trait in a generation

$$\Delta\bar{k} = \mathrm{Var}\left[k_i\right] \bullet \frac{d\ln W}{dk}$$

variance of the trait within a population

selection gradient

Strength of Natural Selection

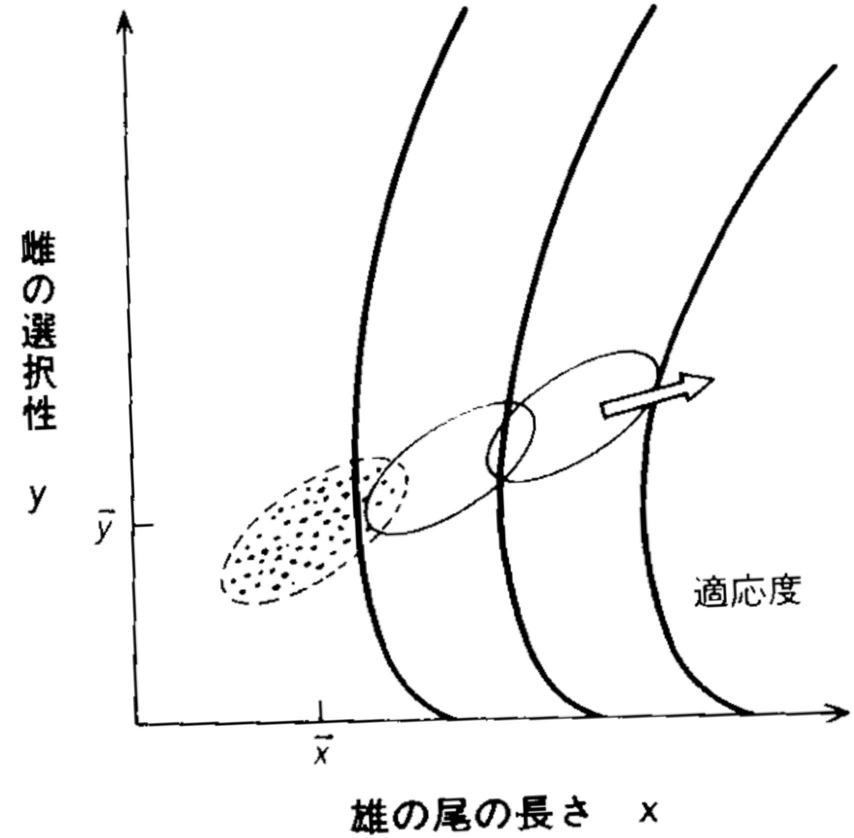
If there are two traits,

$$w(x,y) = w(\bar{x},\bar{y}) + (x-\bar{x})\frac{\partial w}{\partial x} + (y-\bar{y})\frac{\partial w}{\partial y} + \ldots.$$

$$\Delta\bar{x} = \mathrm{Var}[x]\frac{\partial \ln W}{\partial x} + \mathrm{Cov}[x,y]\frac{\partial \ln W}{\partial y}$$

$$\Delta\bar{y} = \mathrm{Cov}[x,y]\frac{\partial \ln W}{\partial x} + \mathrm{Var}[y]\frac{\partial \ln W}{\partial y}$$

One generation change when there are two traits



$$\begin{pmatrix} \Delta\bar{x} \\ \Delta\bar{y} \end{pmatrix} = \begin{pmatrix} \mathrm{Var}[x] & \mathrm{Cov}[x,y] \\ \mathrm{Cov}[x,y] & \mathrm{Var}[y] \end{pmatrix} \begin{pmatrix} \dfrac{\partial \ln W}{\partial x} \\ \dfrac{\partial \ln W}{\partial y} \end{pmatrix}$$

Evolutionary Dynamics

$$\begin{pmatrix}\Delta\bar{a}\\ \Delta\bar{f}_0\end{pmatrix} \quad \begin{pmatrix}G_a & B\\ \cdots & \cdots\end{pmatrix}\begin{pmatrix}\beta_a\\ \cdots\end{pmatrix}$$

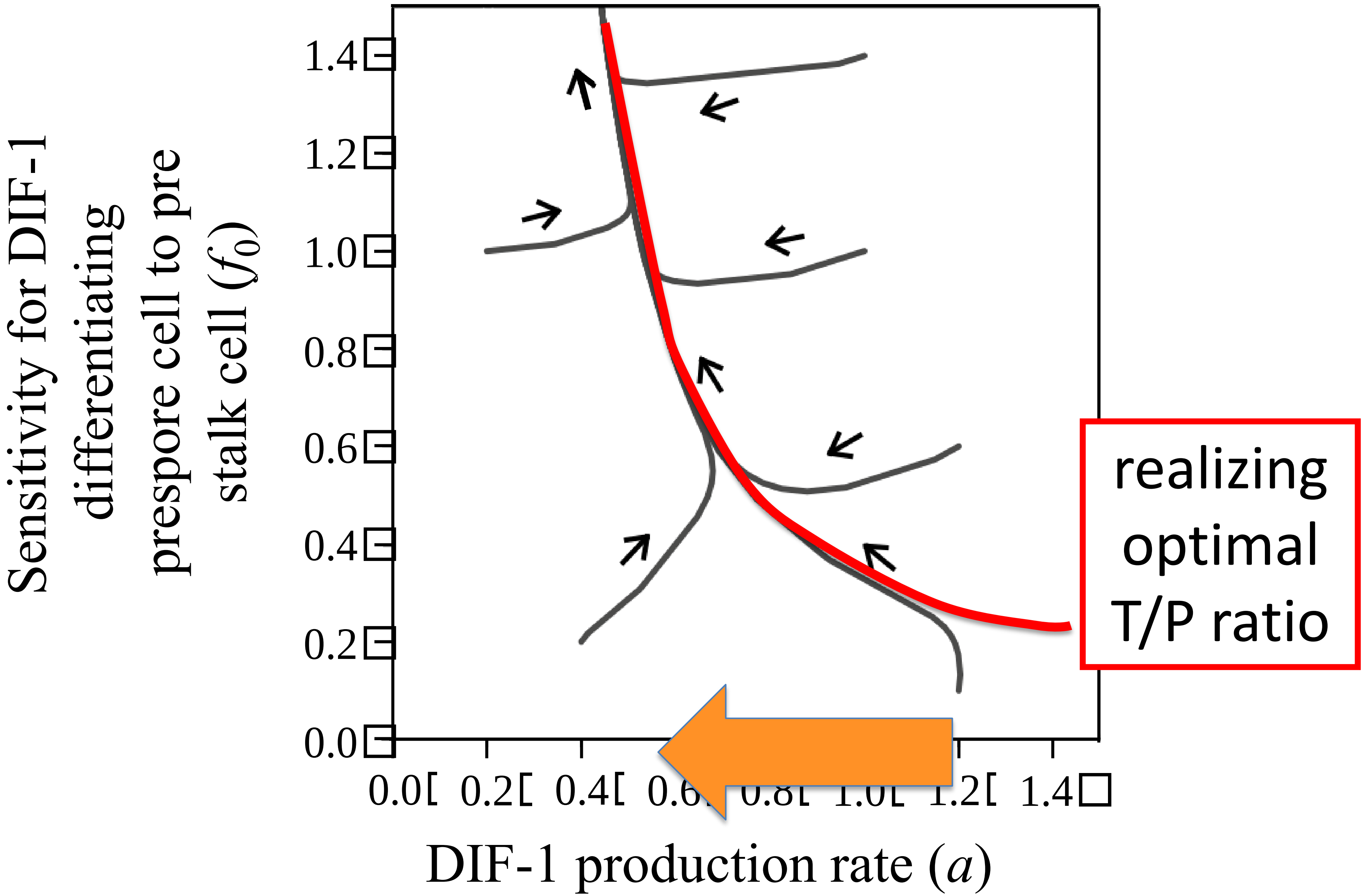
Selection to realize the optimal stalk size

Selection to reduce the DIF-1 production

$$\beta_a = \frac{\partial \ln W}{\partial a} = \left(\frac{1}{S}\frac{dS}{dT} - \frac{1}{N-T}\right)\frac{\partial T}{\partial a} - k$$

$$\beta_{f_0} = \frac{\partial \ln W}{\partial f_0} = \left(\frac{1}{S}\frac{dS}{dT} - \frac{1}{N-T}\right)\frac{\partial T}{\partial f_0}$$

Evolutionary trajectory



When a fruiting body consists of cells of a single strain

evolution of the optimal stalk/spore ratio that maximizes the number of successfully dispersed spores.

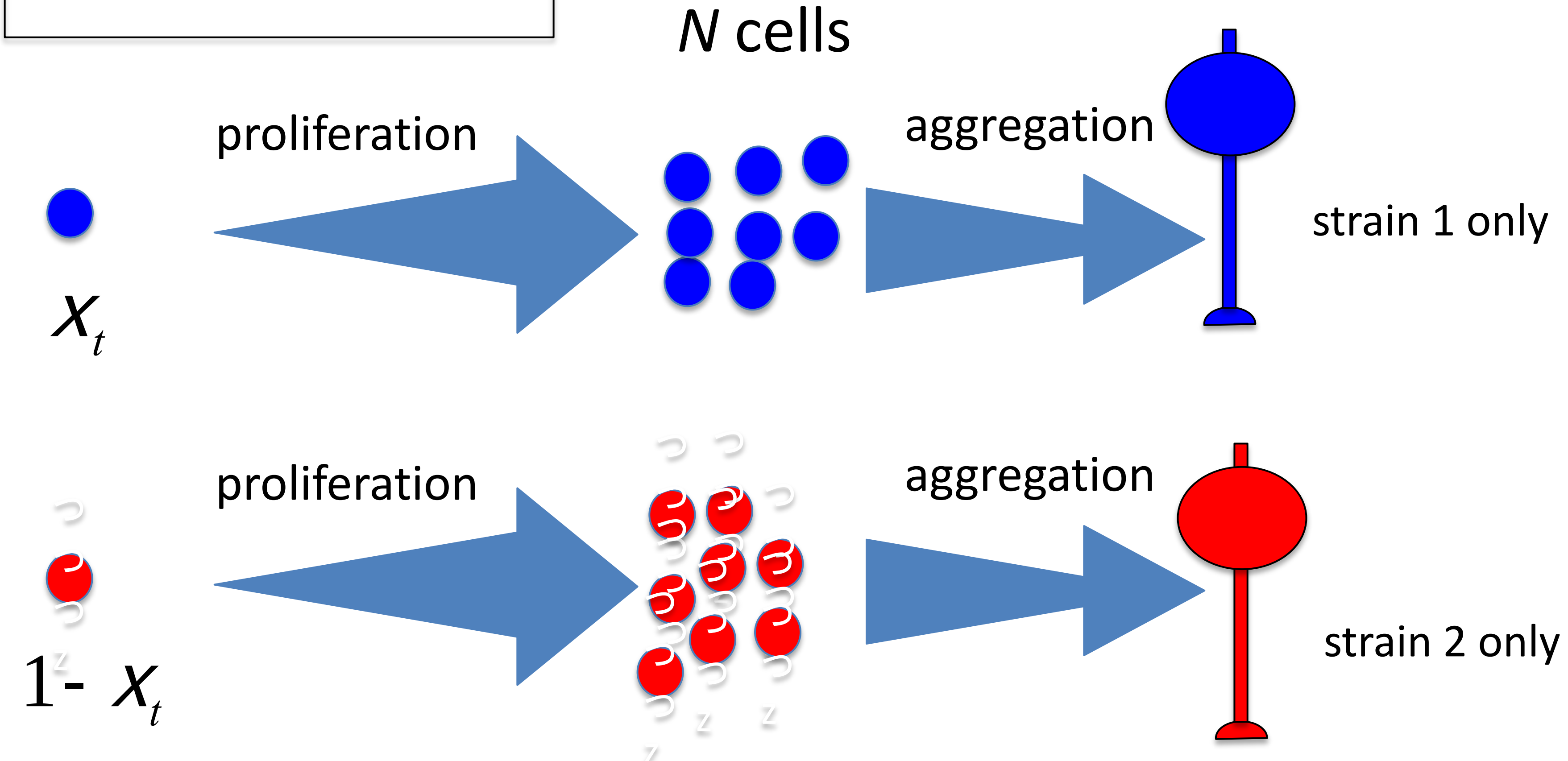
followed by a slow evolution toward reduced DIF-1 production and enhanced sensitivity to DIF-1

When some fruiting bodies are mixtures of multiple strains,

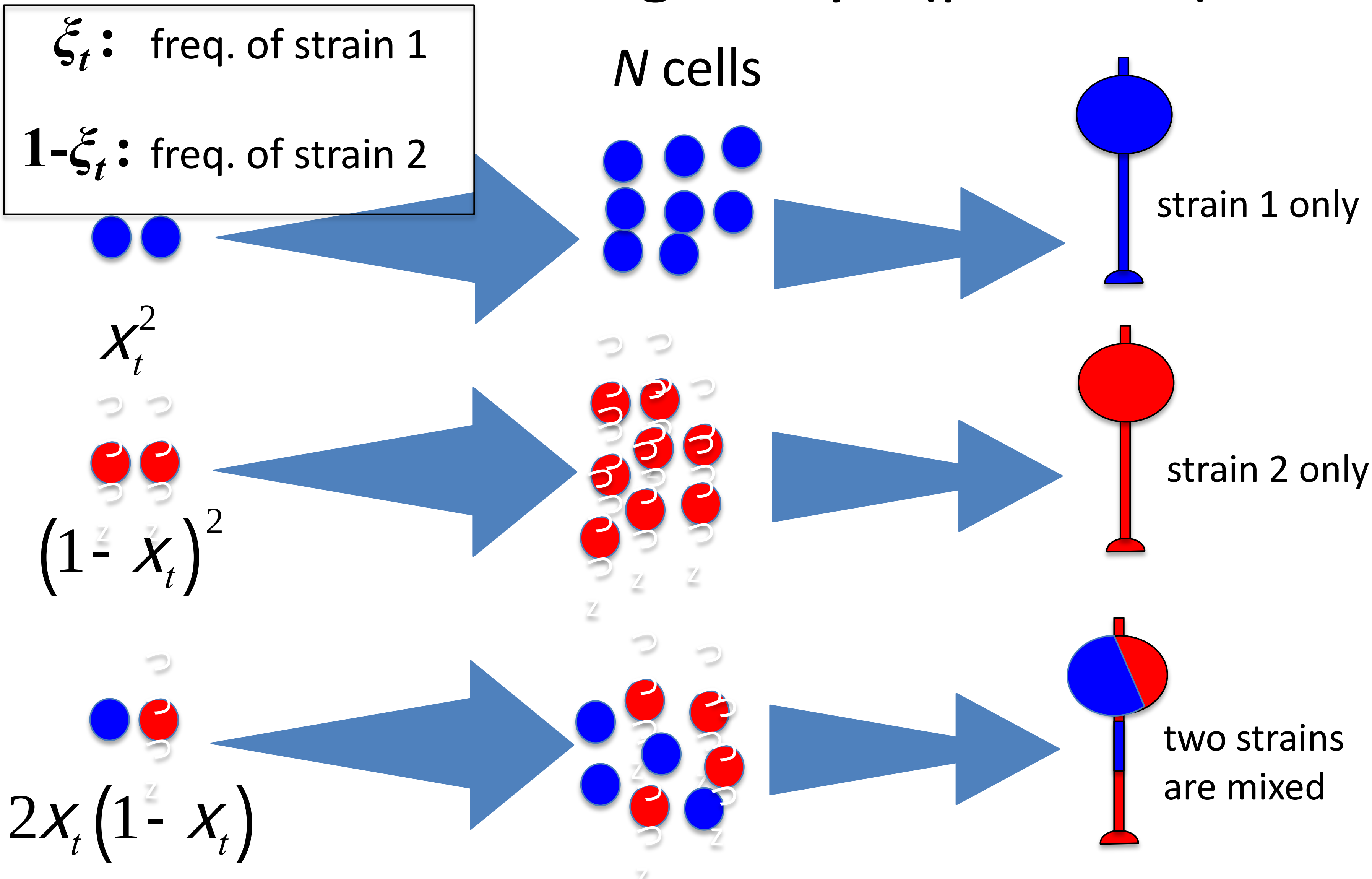
When cells originated from a single spore form a fruiting body (prob. $1-m$)

ξ_t : freq. of strain 1

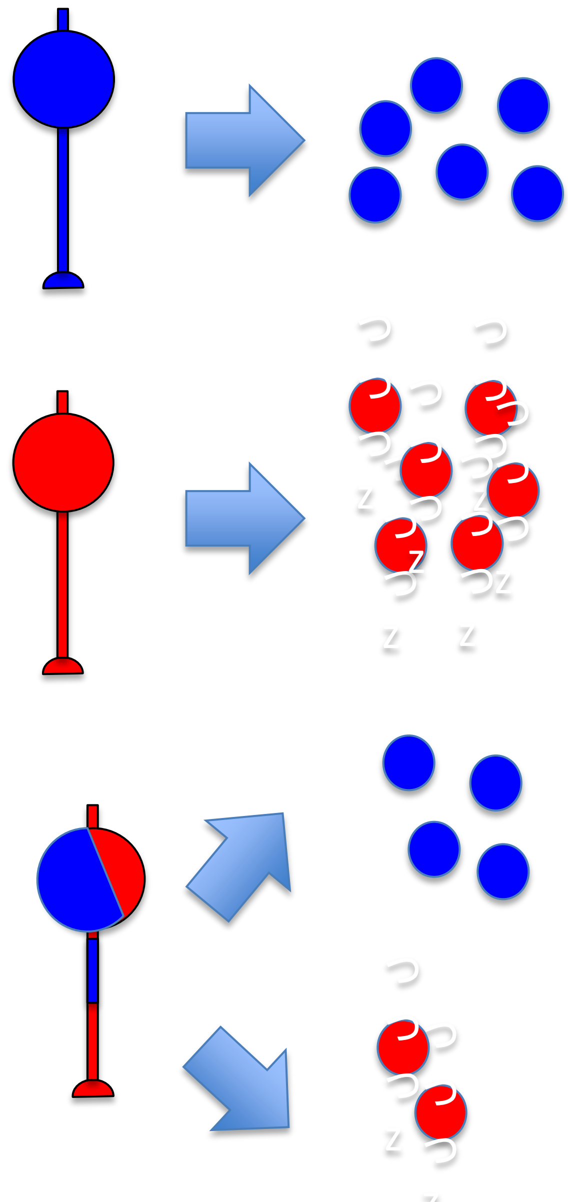
$1-\xi_t$: freq. of strain 2



When cells originated from two spores form a fruiting body (prob. m)



No. of spores from a fruiting body



$$W_1 = S\left(\hat{T}_1\right)\hat{P}_1 e^{-k\,a_1}$$

$$W_2 = S\left(\hat{T}_2\right)\hat{P}_2 e^{-k\,a_2}$$

$$W_1^{mix} = S\left(\hat{T}_1^* + \hat{T}_2^*\right)\hat{P}_1^{mix} e^{-k\,a_1}$$

$$W_2^{mix} = S\left(\hat{T}_1^* + \hat{T}_2^*\right)\hat{P}_2^{mix} e^{-k\,a_2}$$

No. of spores of strain 1

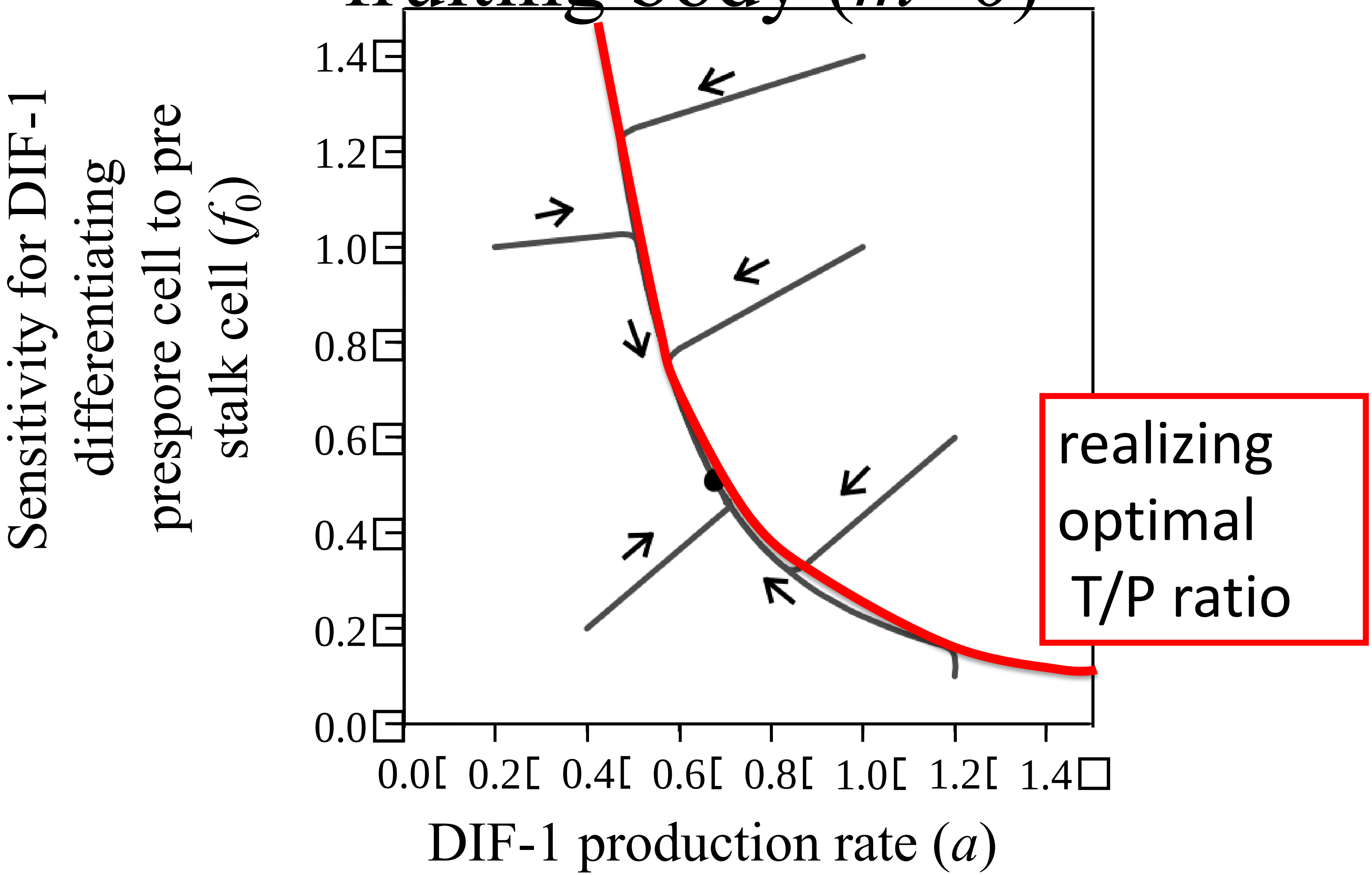
$$R_1 = \underbrace{\left\{(1-m)\xi + m\xi^2\right\}}_{\text{freq. of fruiting body of strain 1 only}} X_1 + \underbrace{\left\{2m\xi(1-\xi)\right\}}_{\text{freq. of fruiting body with both strains}} X_1^{mix}$$

No. of spores of strain 2

$$R_2 = \underbrace{\left\{(1-m)(1-\xi) + m(1-\xi)^2\right\}}_{\text{freq. of fruiting body of strain 2 only}} X_2 + \underbrace{\left\{2m\xi(1-\xi)\right\}}_{\text{freq. of fruiting body with both strains}} X_2^{mix}$$

$$\xi^{next} = \frac{R_1}{R_1 + R_2}$$

When two strains are mixed in a fruiting body (m>0)



Selection gradients when cells of two strains can be mixed

Selection reducing DIF-1 producion rate

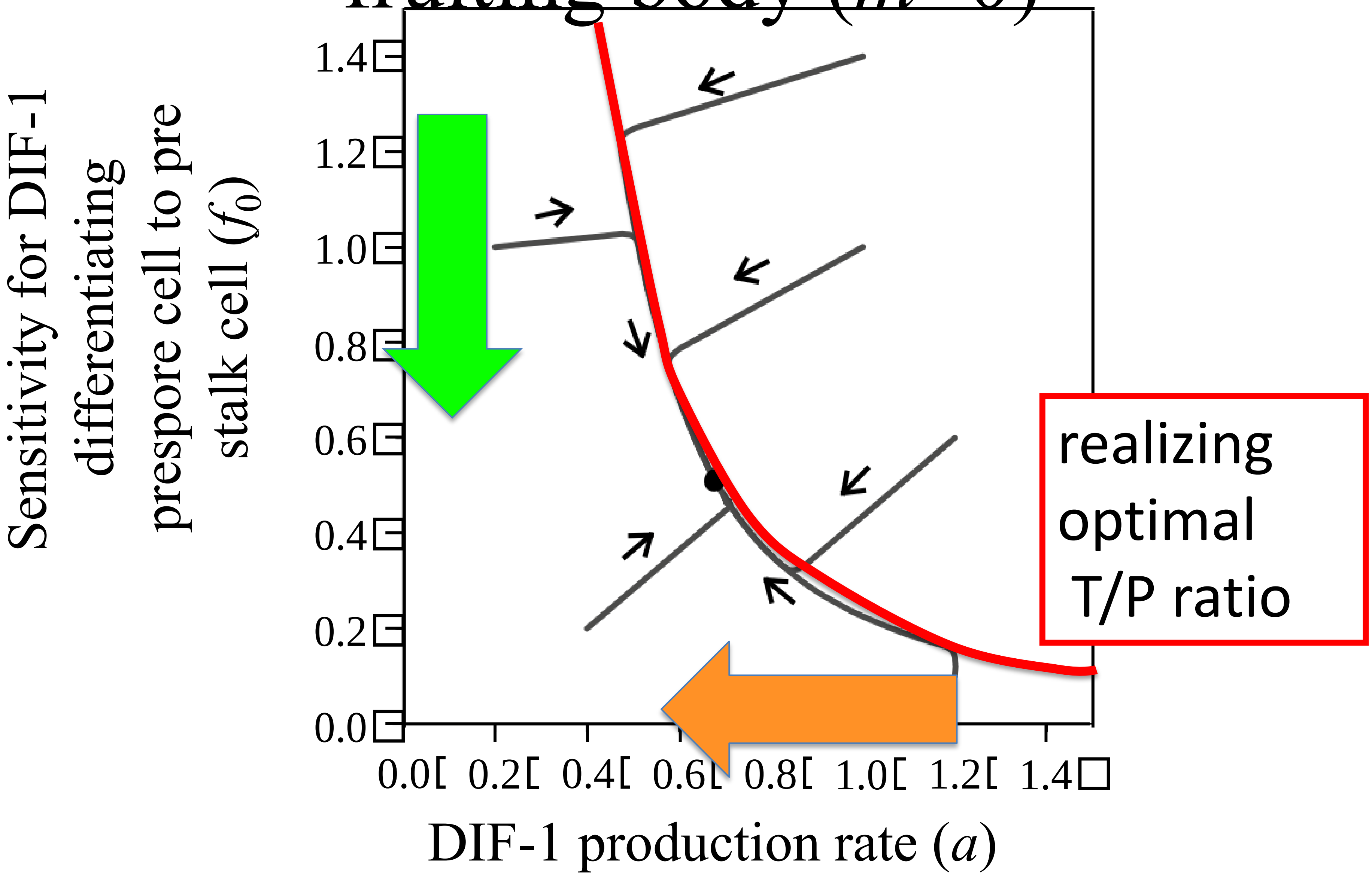
$$\beta_a = \left(\frac{1}{S}\frac{dS}{dT} - \frac{1}{N-T}\right)\left\{(1-m+m\xi)\frac{\partial T_1}{\partial a} + m(1-2\xi)\left(\frac{\partial T_1^*}{\partial a} + \frac{\partial T_2^*}{\partial a}\right)\right\} - k$$

$$\beta_{f_0} = \left(\frac{1}{S}\frac{dS}{dT} - \frac{1}{N-T}\right)\left\{(1-m+m\xi)\frac{\partial T_1}{\partial f_0} + m(1-2\xi)\left(\frac{\partial T_1^*}{\partial f_0} + \frac{\partial T_2^*}{\partial f_0}\right)\right\} - \frac{2mN}{T(N-T)^2}\frac{1}{f_0}$$

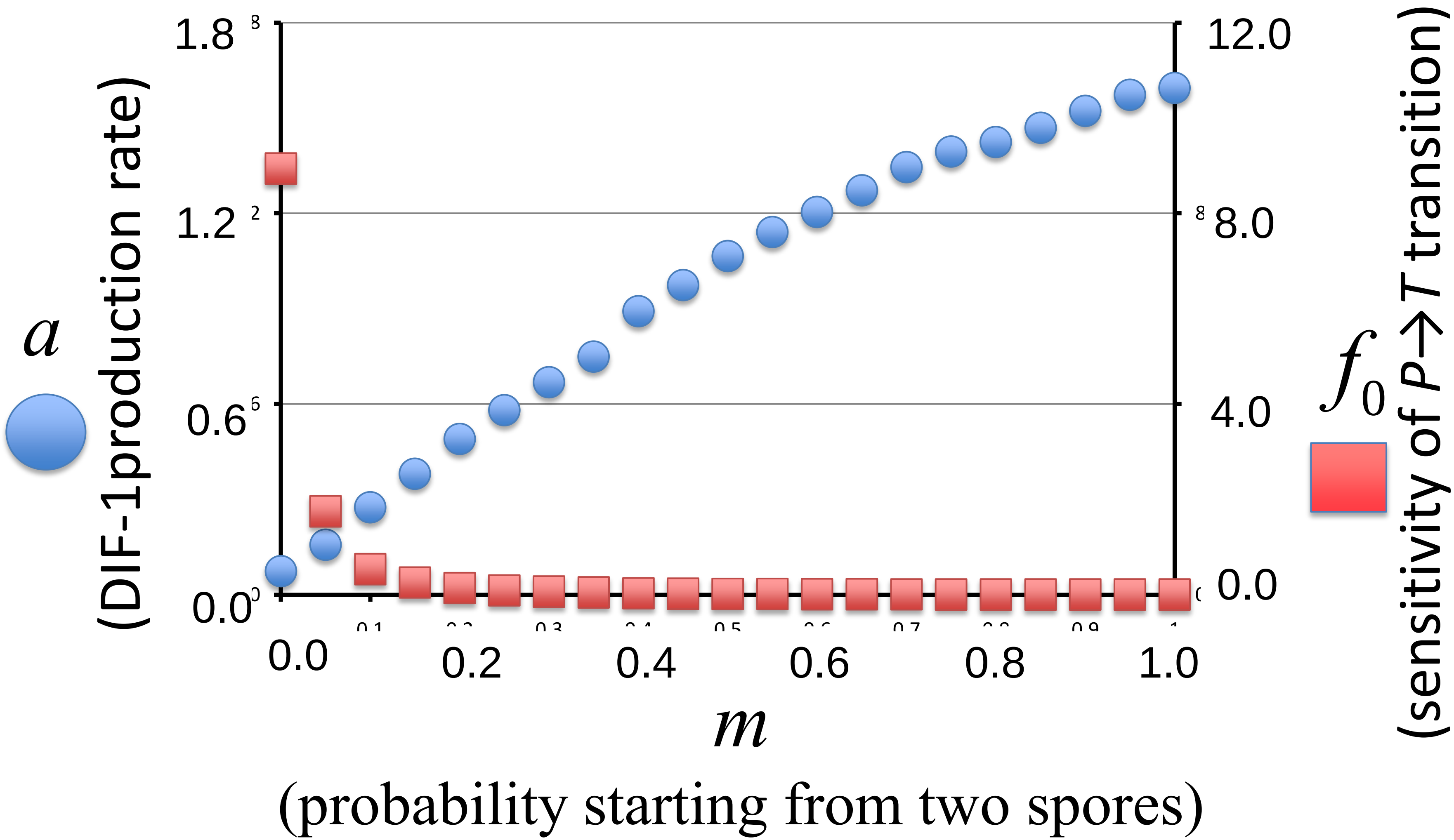
Selection realizing the optimal stalk size

Selection reducing sensitivity to DIF-1

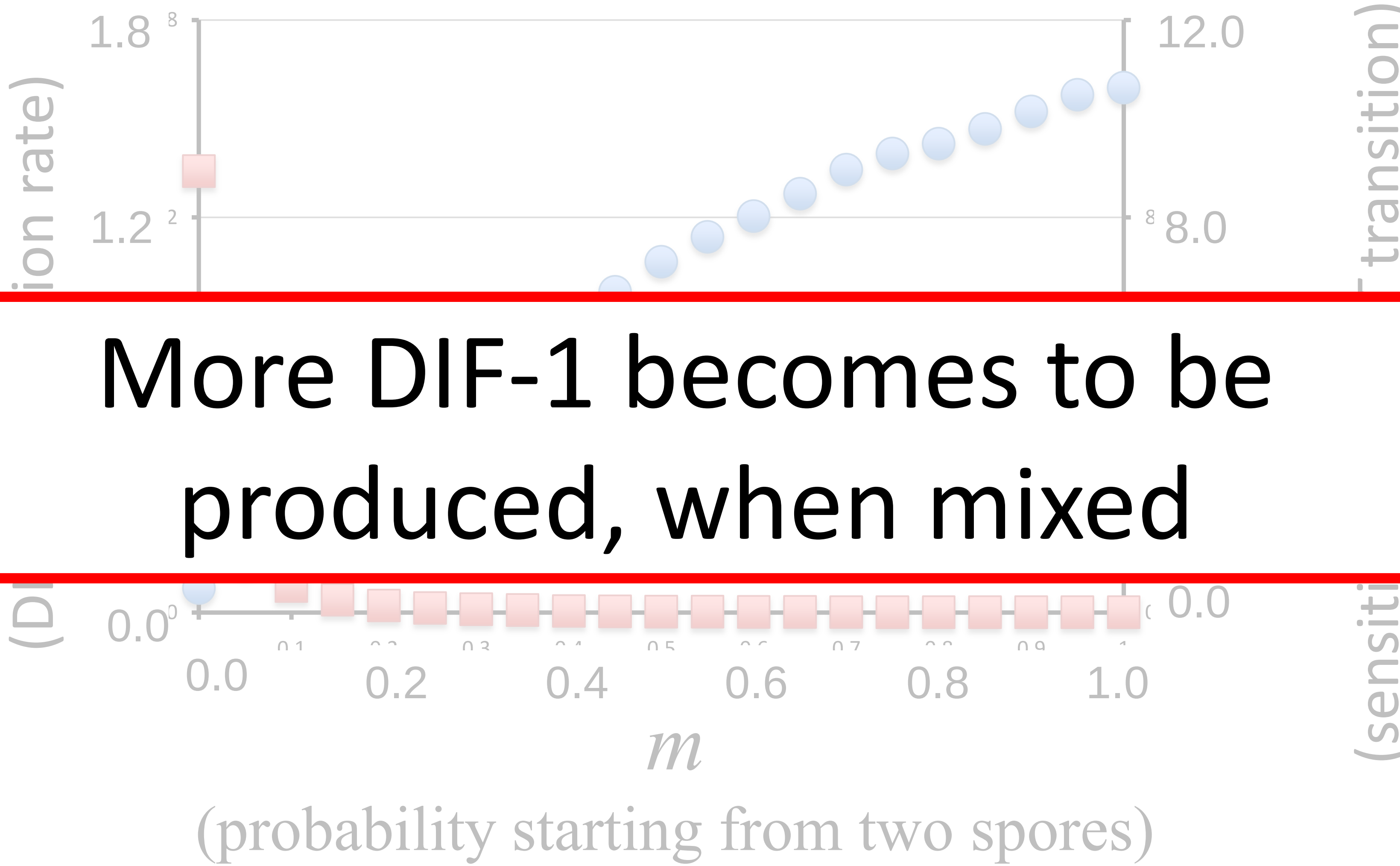
When two strains are mixed in a fruiting body (m>0)



When two strains are mixed in a fruiting body ($m \neq 0$)



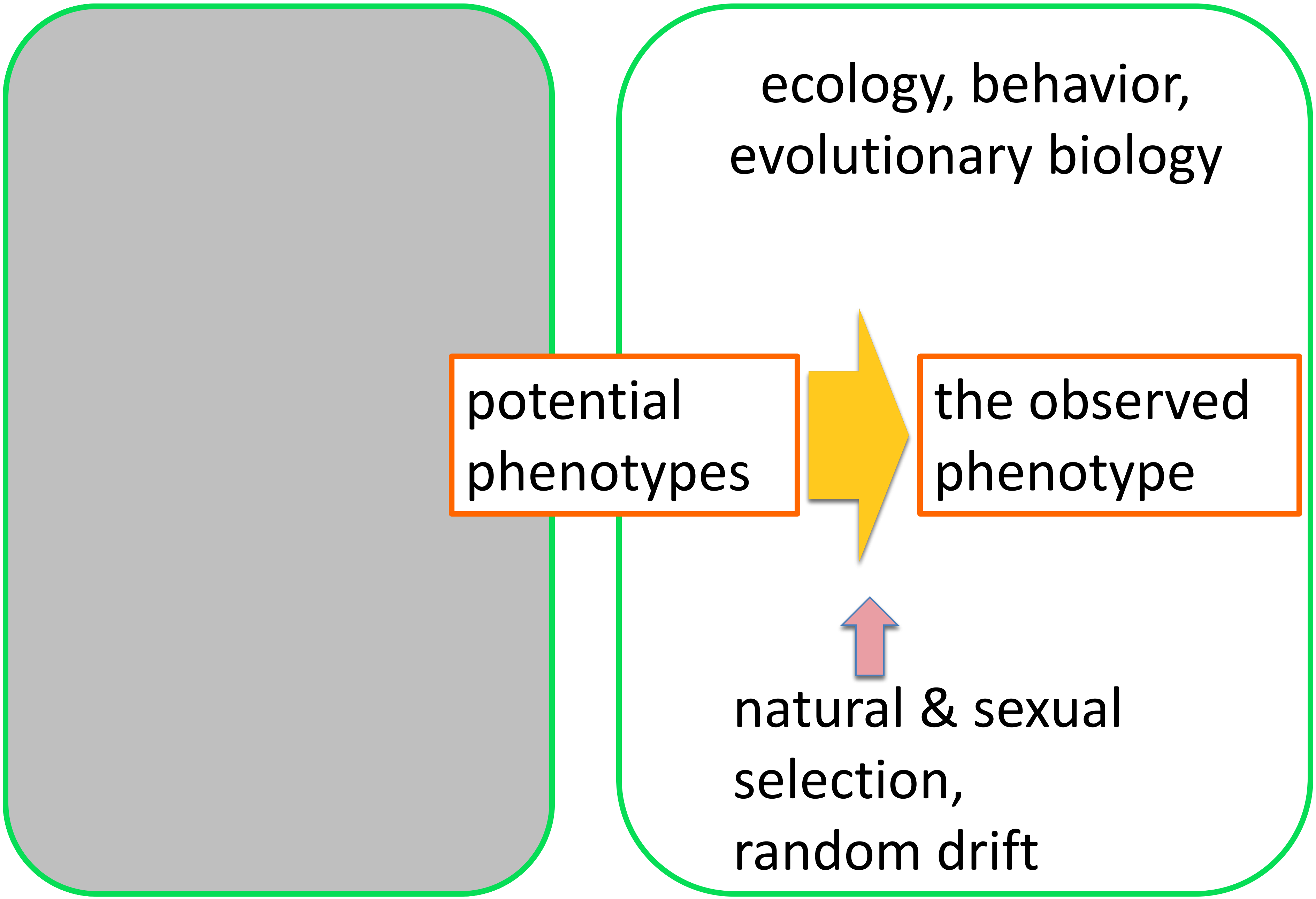
When two strains are mixed in a fruiting body ($m \neq 0$)

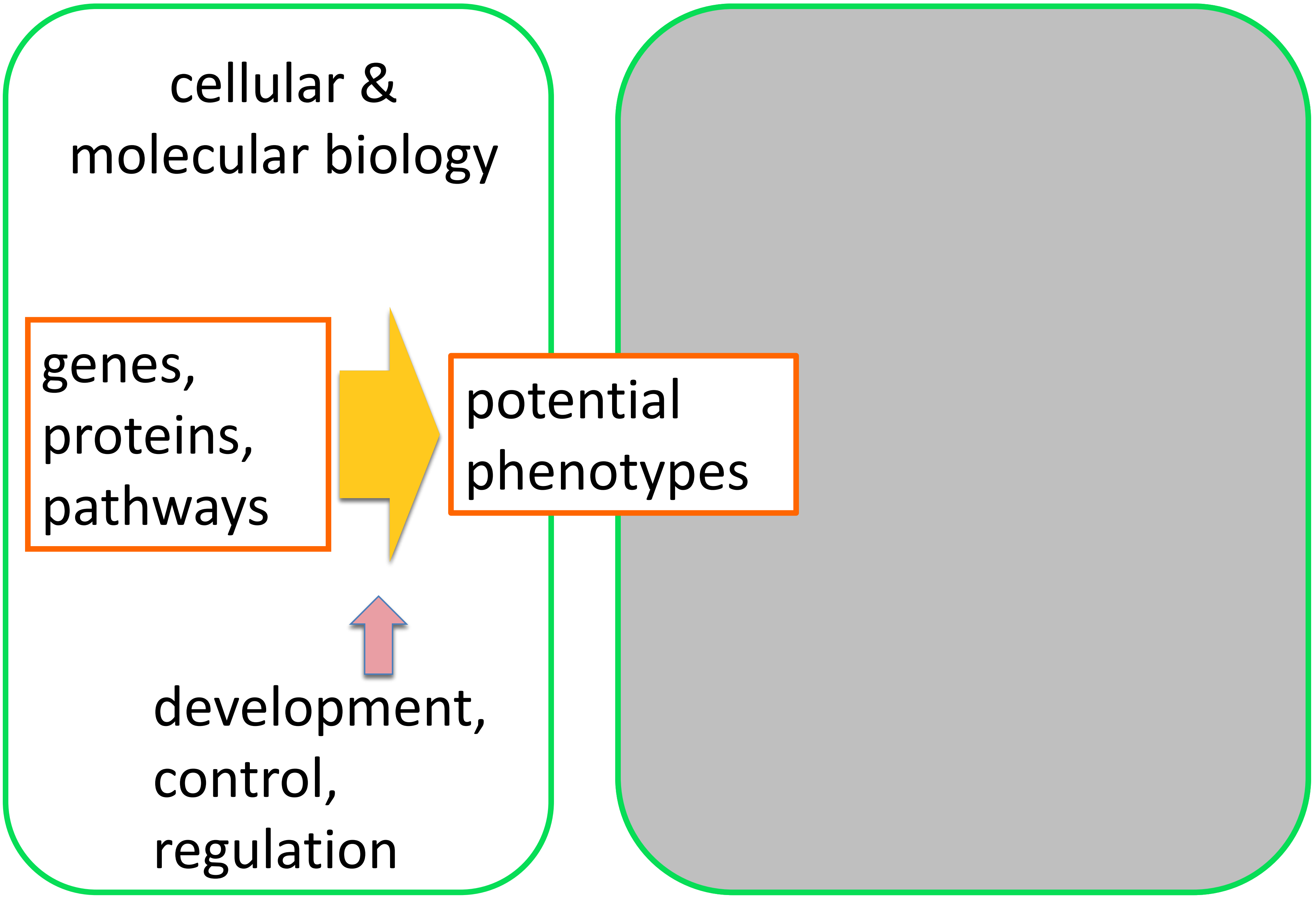


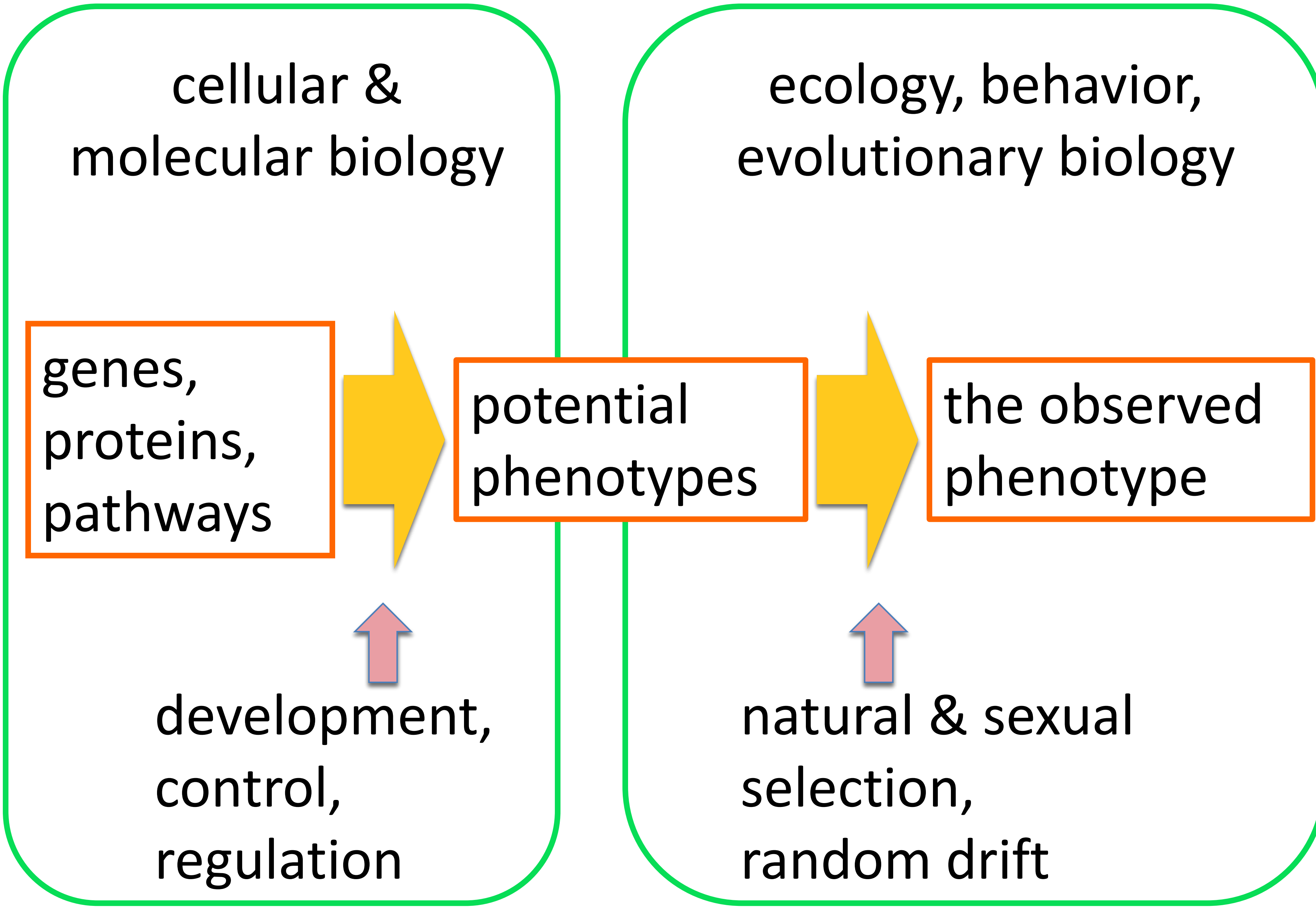
More DIF-1 becomes to be produced, when mixed

Conclusion

- When not mixed, DIF-1 production evolves smaller with the optimal stalk/spore ratio maintained.
- When multiple strains are mixed, more DIF-1 will be produced.
- But the stalk/spore ratio remains close to the optimal.


ecology, behavior,
evolutionary biology
potential
phenotypes
the observed
phenotype
natural & sexual
selection,
random drift


cellular &
molecular biology
genes,
proteins,
pathways
potential
phenotypes
development,
control,
regulation


cellular & molecular biology
ecology, behavior, evolutionary biology
genes, proteins, pathways
potential phenotypes
the observed phenotype
development, control, regulation
natural & sexual selection, random drift

When gene network / molecular mechanisms of the trait expression and social interactions are known, evolutionary models incorporating them may provide more useful/testable predictions.

Thank you.