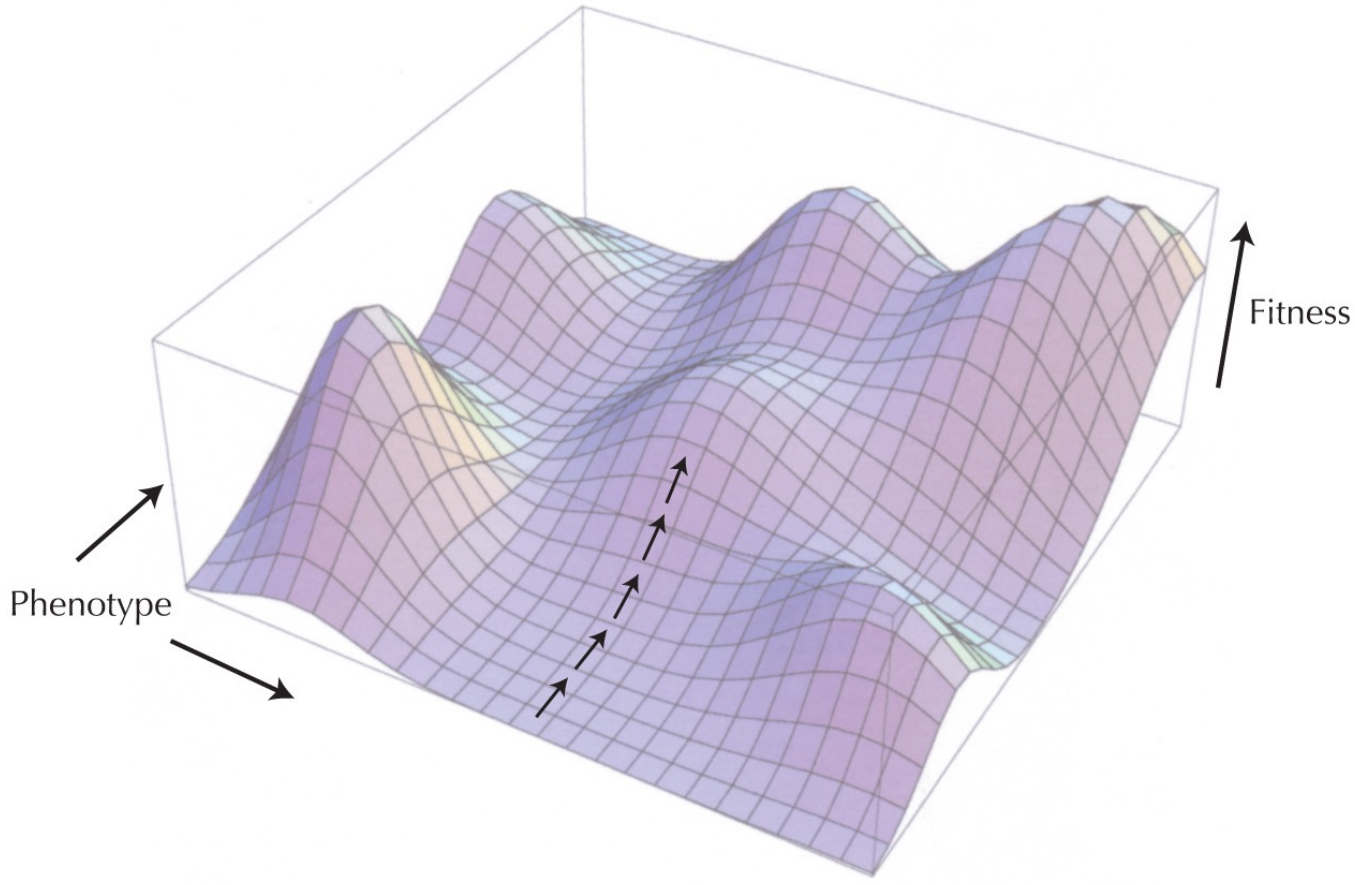
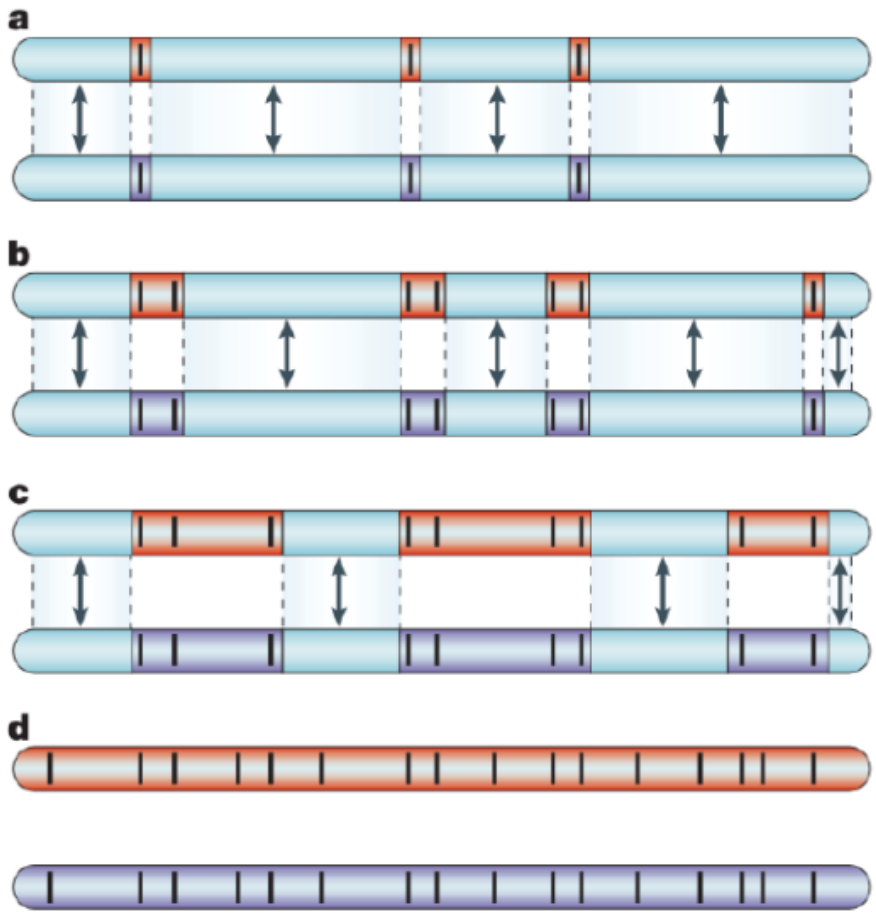
Selection



The genic concept of speciation



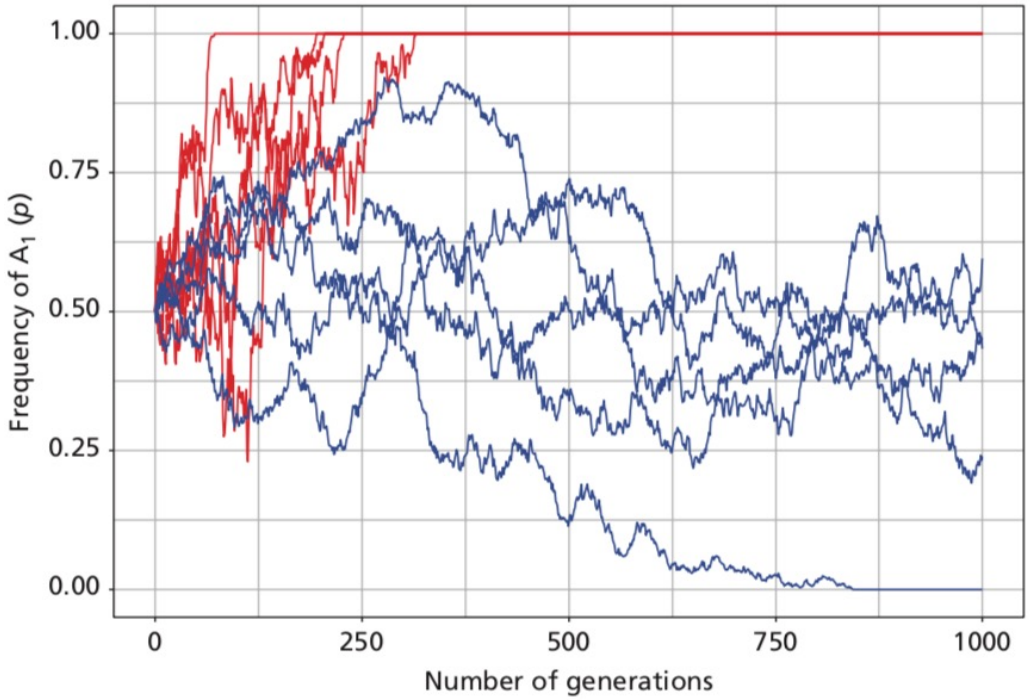
Divergent loci resist gene flow

Gene flow continues but linkage builds and divergent regions grow

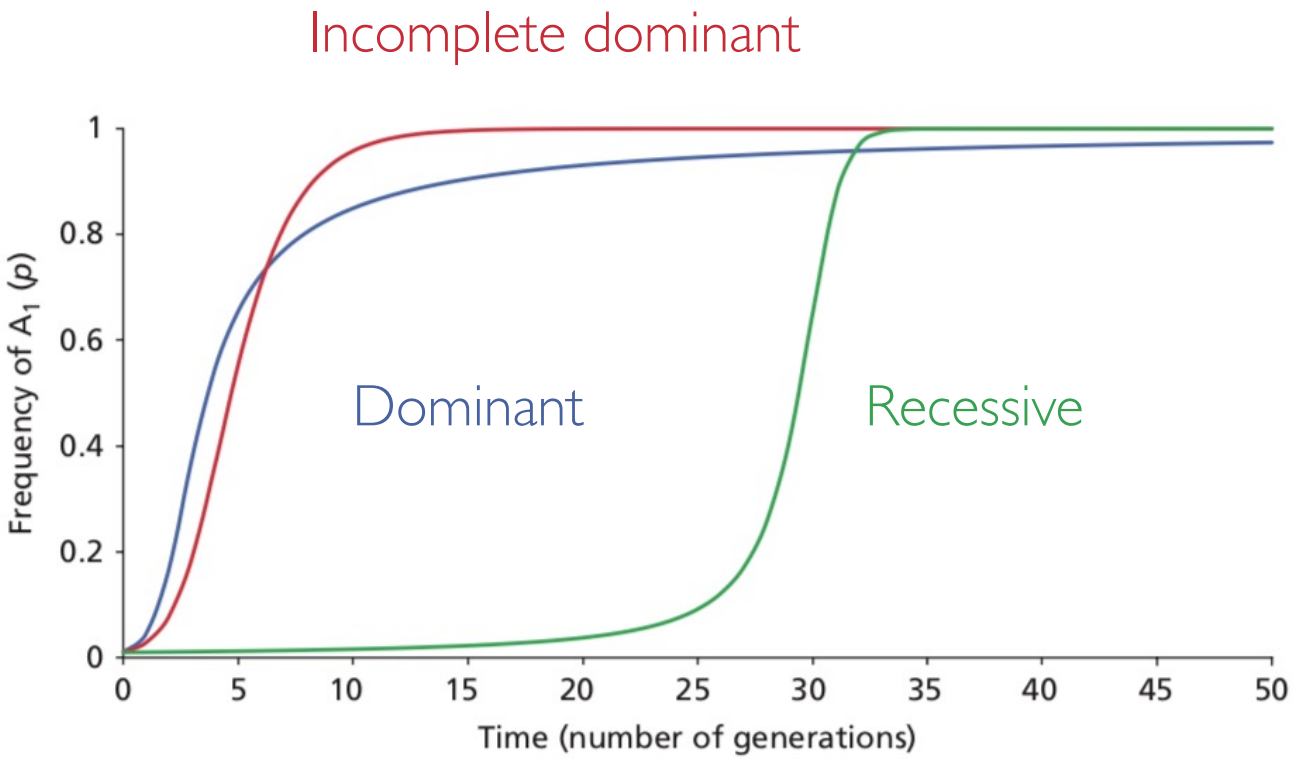
Complete reproductive isolation evolves

Wu (2001) **J Evo Bio**
Wu & Ting (2001) **Nat Rev Gen**

Selection and drift at the genetic level

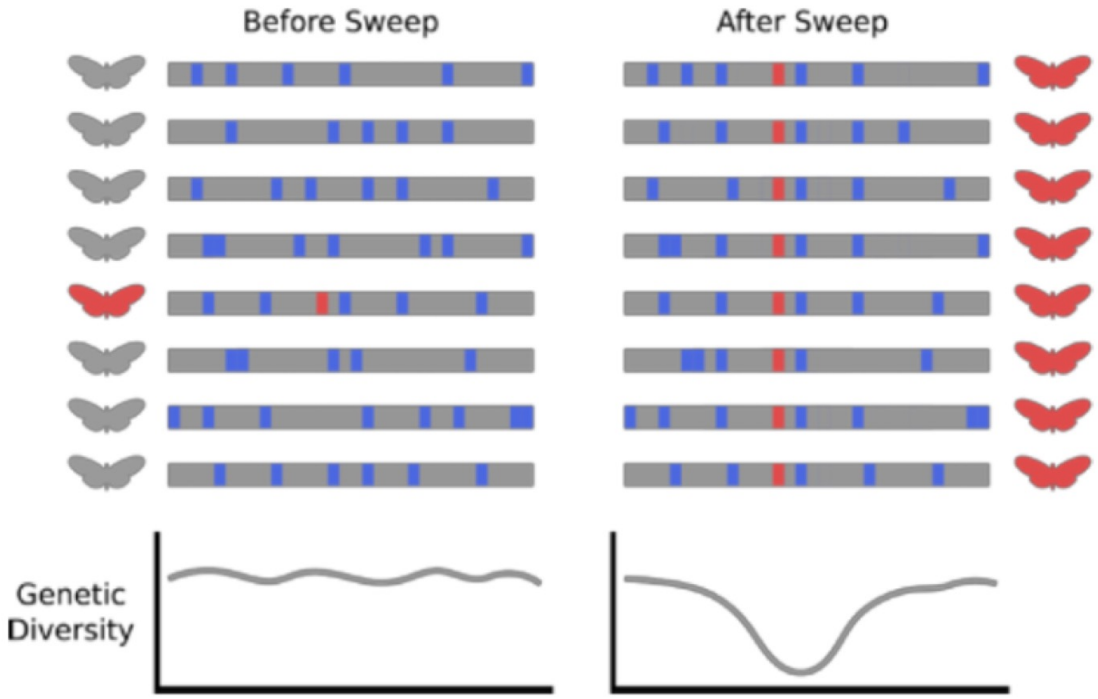


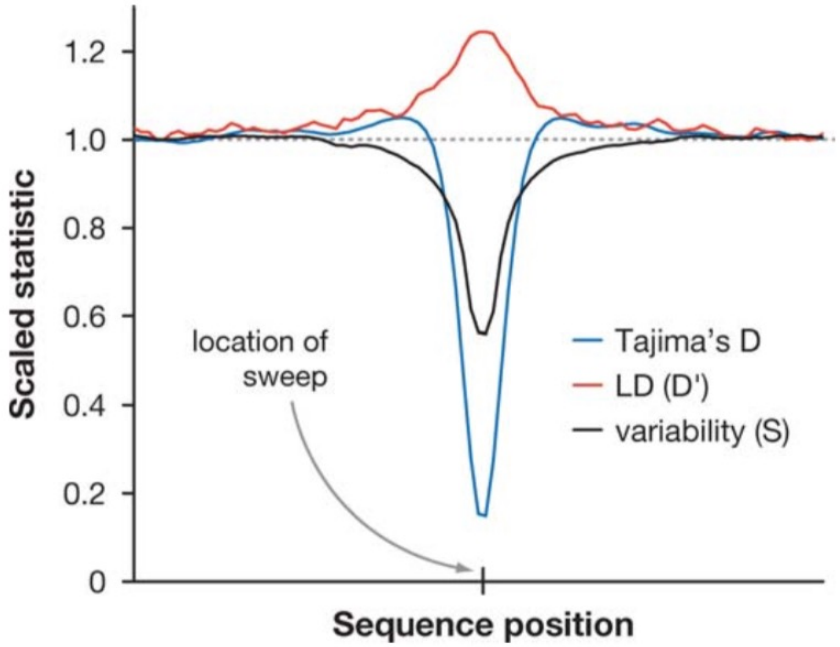
Genetic drift



Directional selection

Genetic signatures of selective sweeps

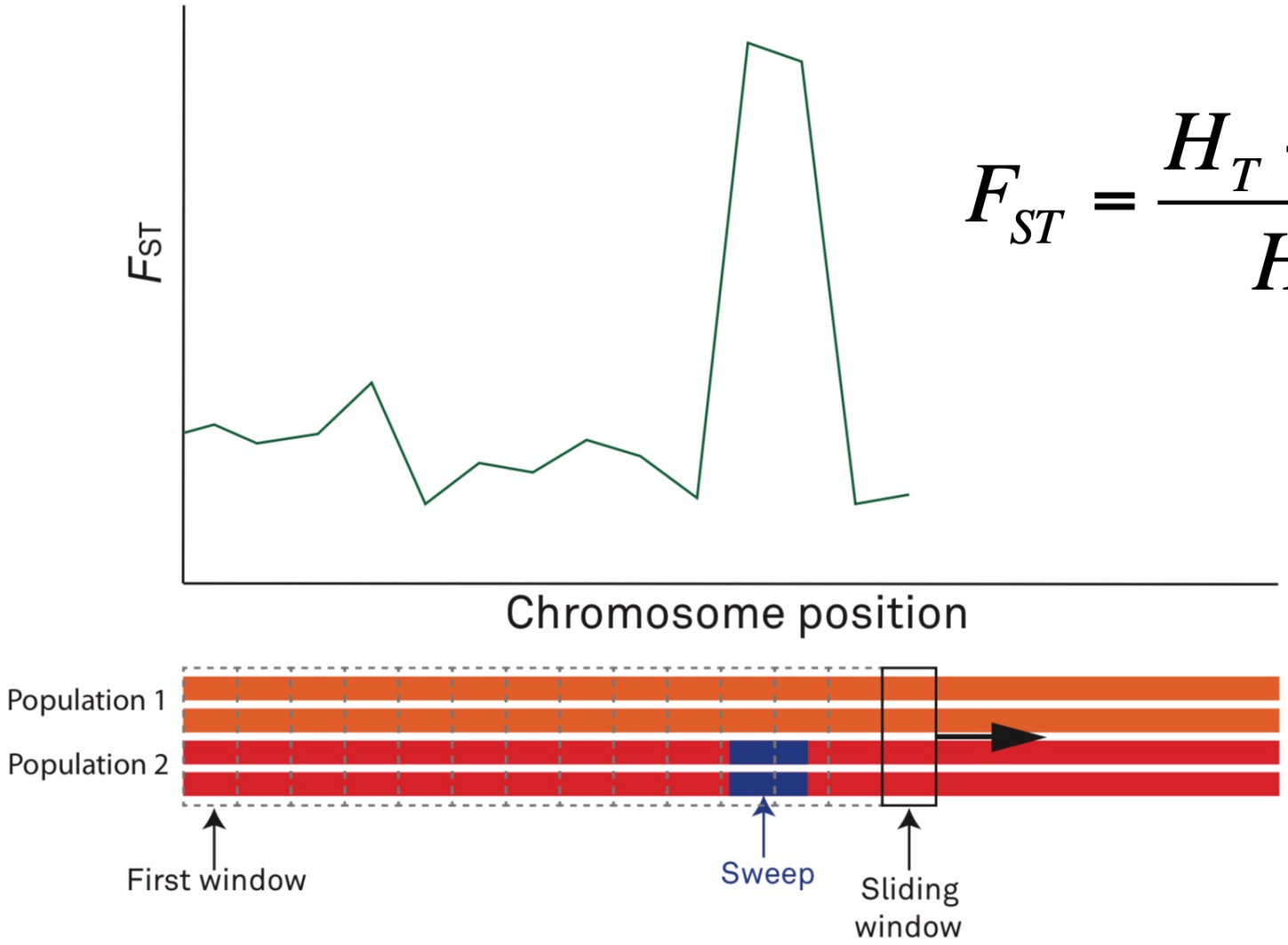




Nielsen (2005) *Nat Rev Gen*

- Reduced genetic diversity/variation
- Increased linkage disequilibrium
- Increased genetic differentiation compared to other populations

Genetic differentiation to detect selection



$$F_{ST} = \frac{H_T - H_S}{H_T}$$

An idea predating genomic data

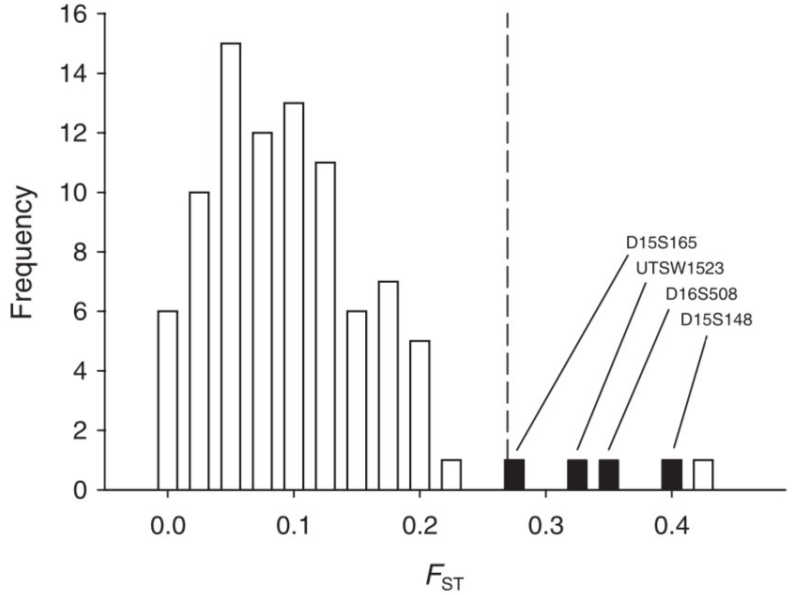
DISTRIBUTION OF GENE FREQUENCY AS A TEST OF THE THEORY OF THE SELECTIVE NEUTRALITY OF POLYMORPHISMS[1,2]

R. C. LEWONTIN AND JESSE KRAKAUER

$$E\left[\mathrm{var}\left(F_{ST}\right)\right] : \mathrm{var}\left(F_{FST}\right)$$

Lewontin & Krakauer (1973) Genetics

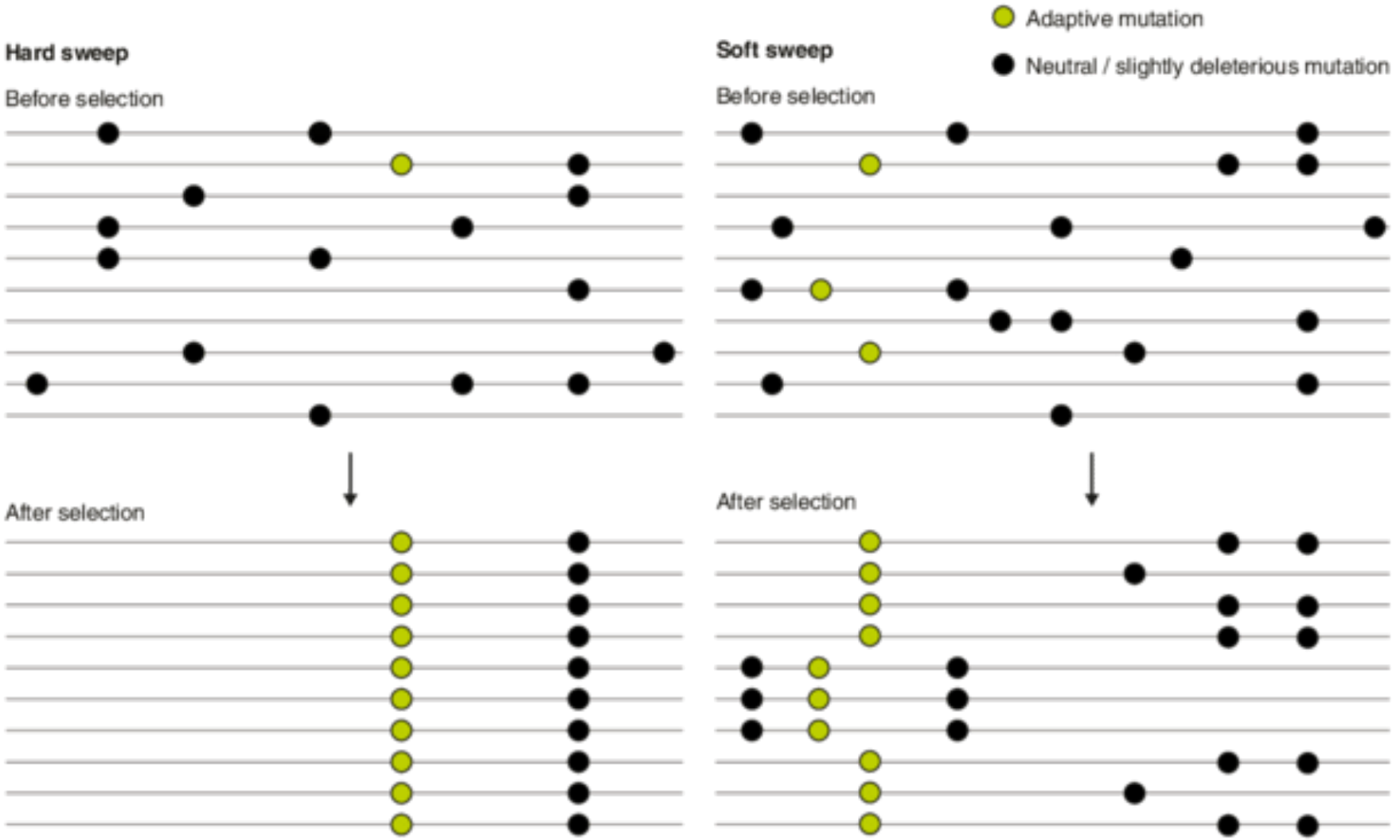
Microsatellite loci putatively under selection in humans



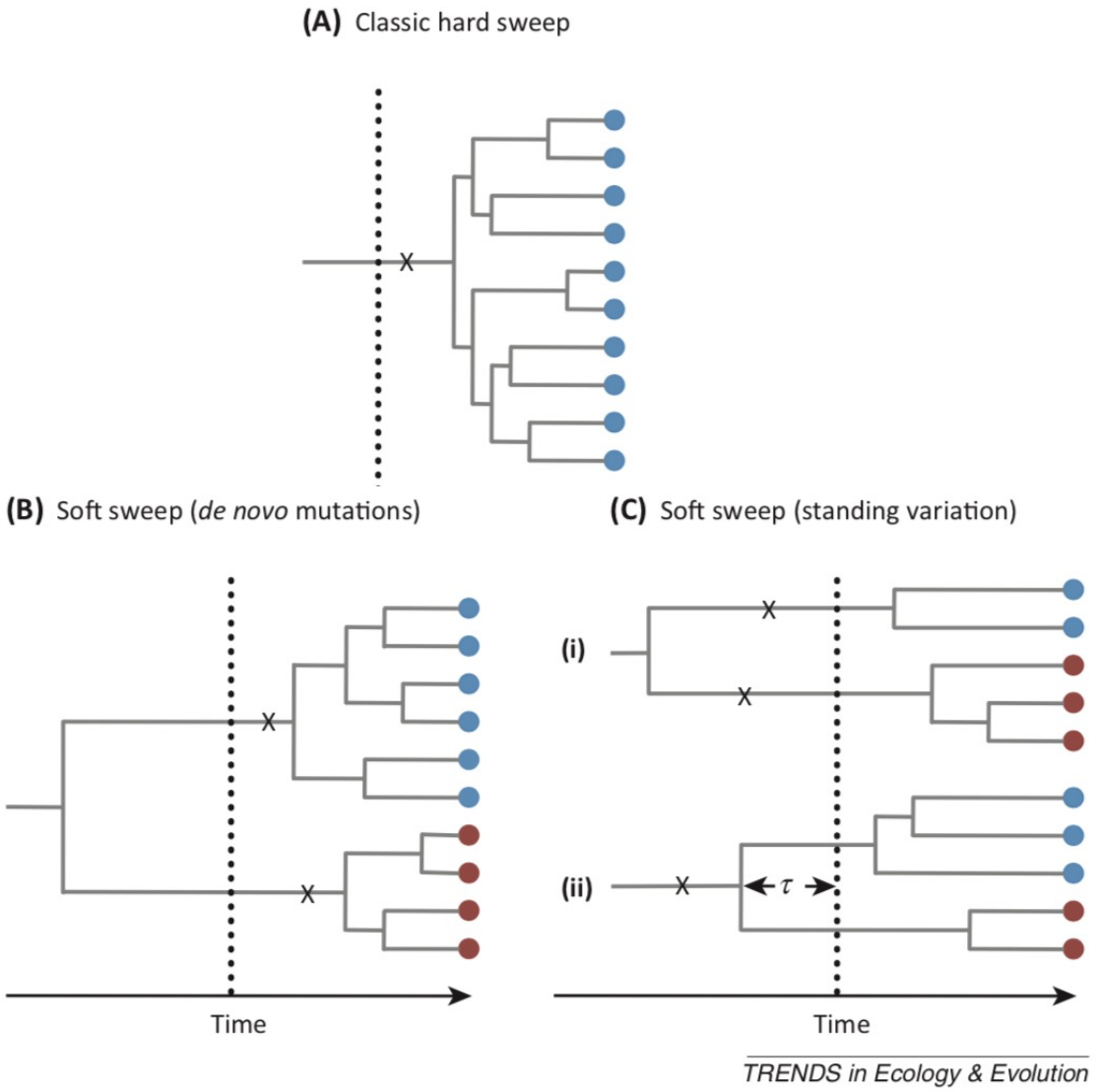
Storz et al (2004) *MBE*

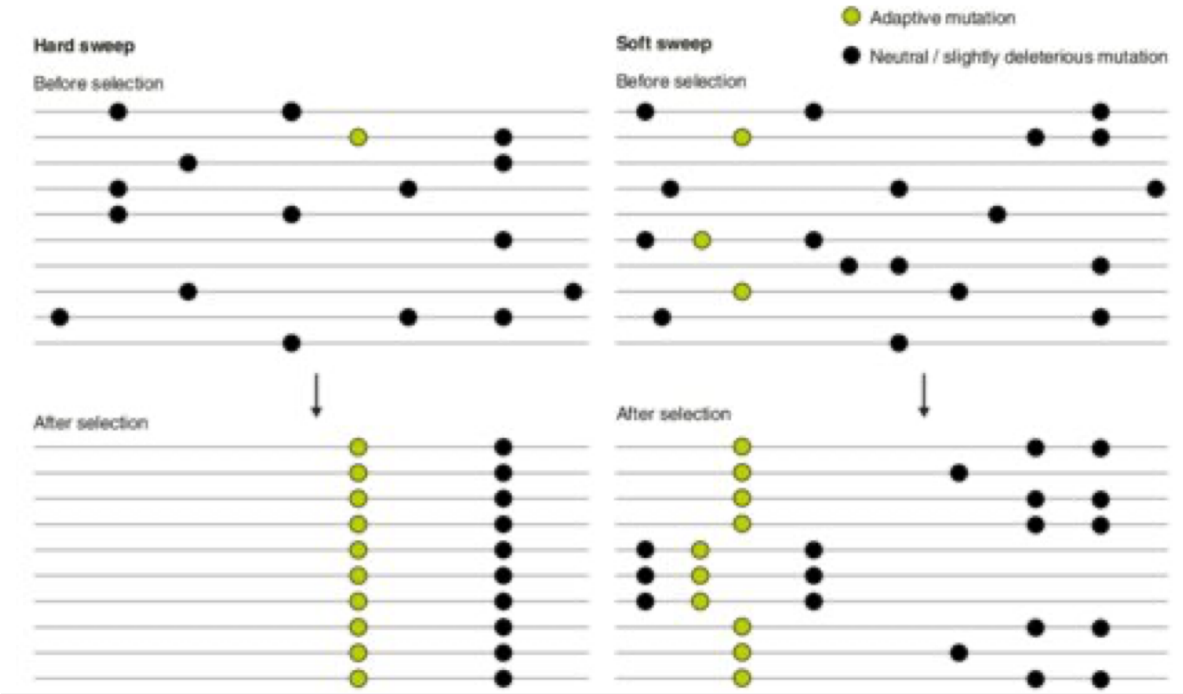
Outlier detection

Hard sweep and soft sweep



Types of sweep: hard vs soft

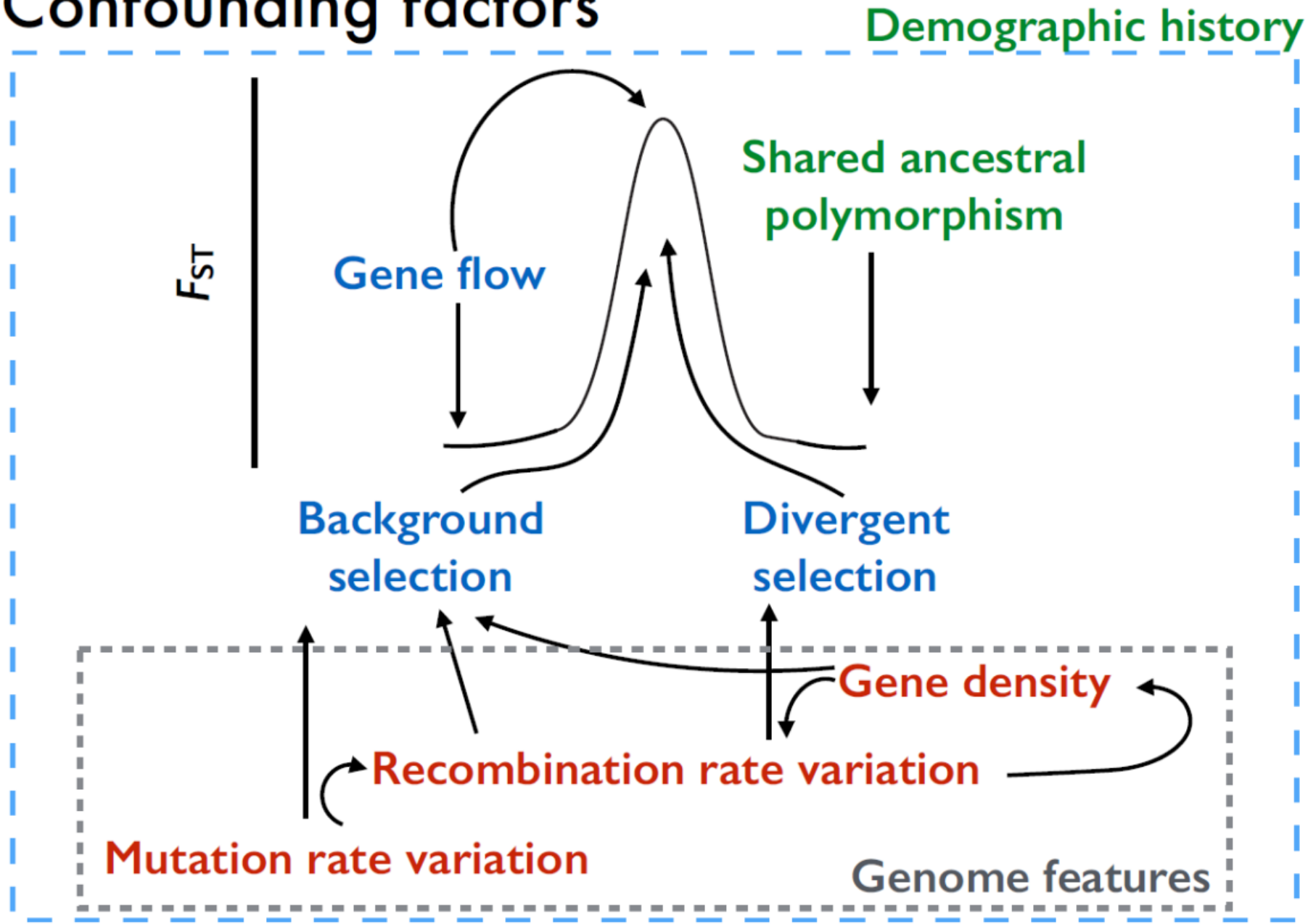


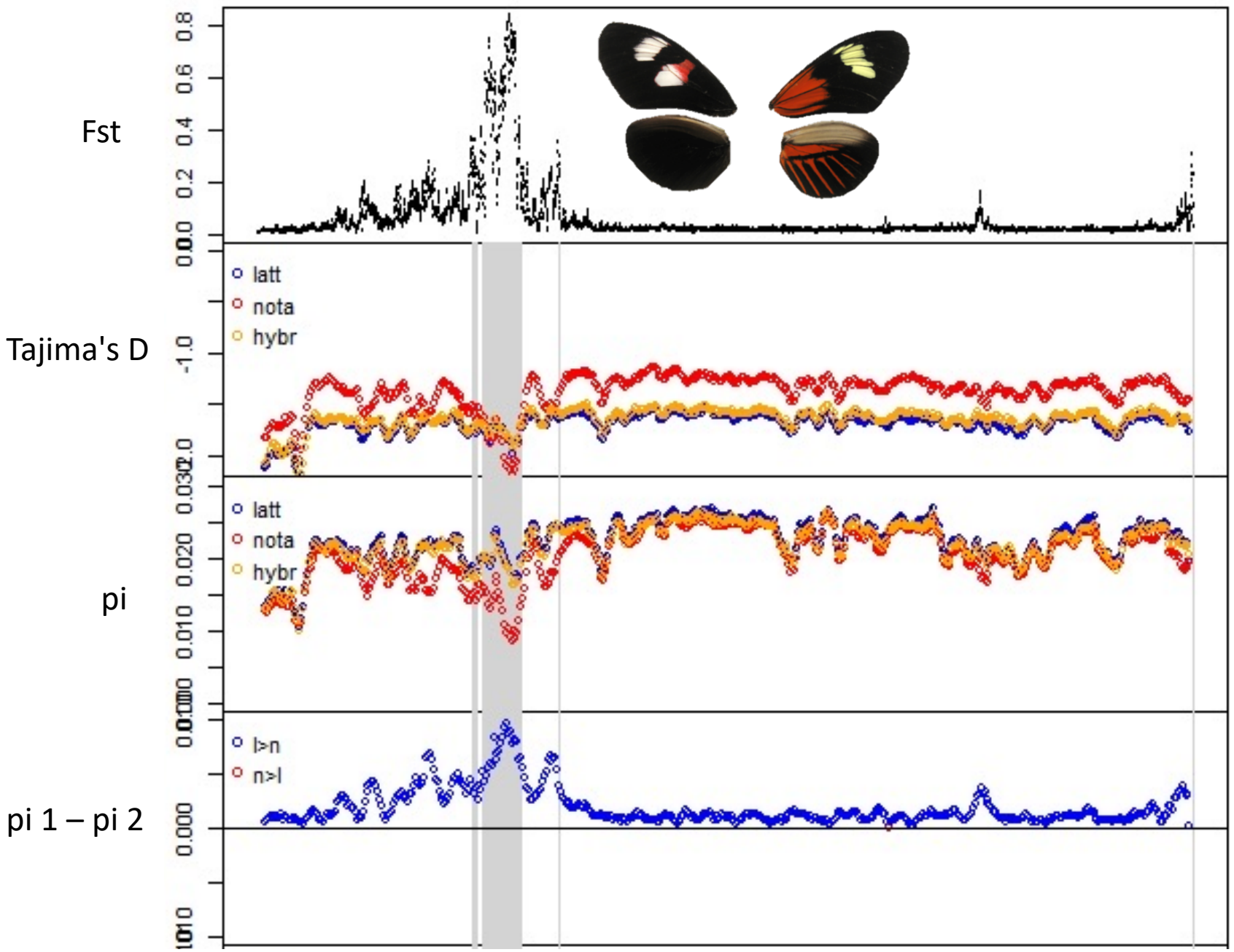


Standing variation and independent de novo mutations

Messer & Petrov (2013) TREE

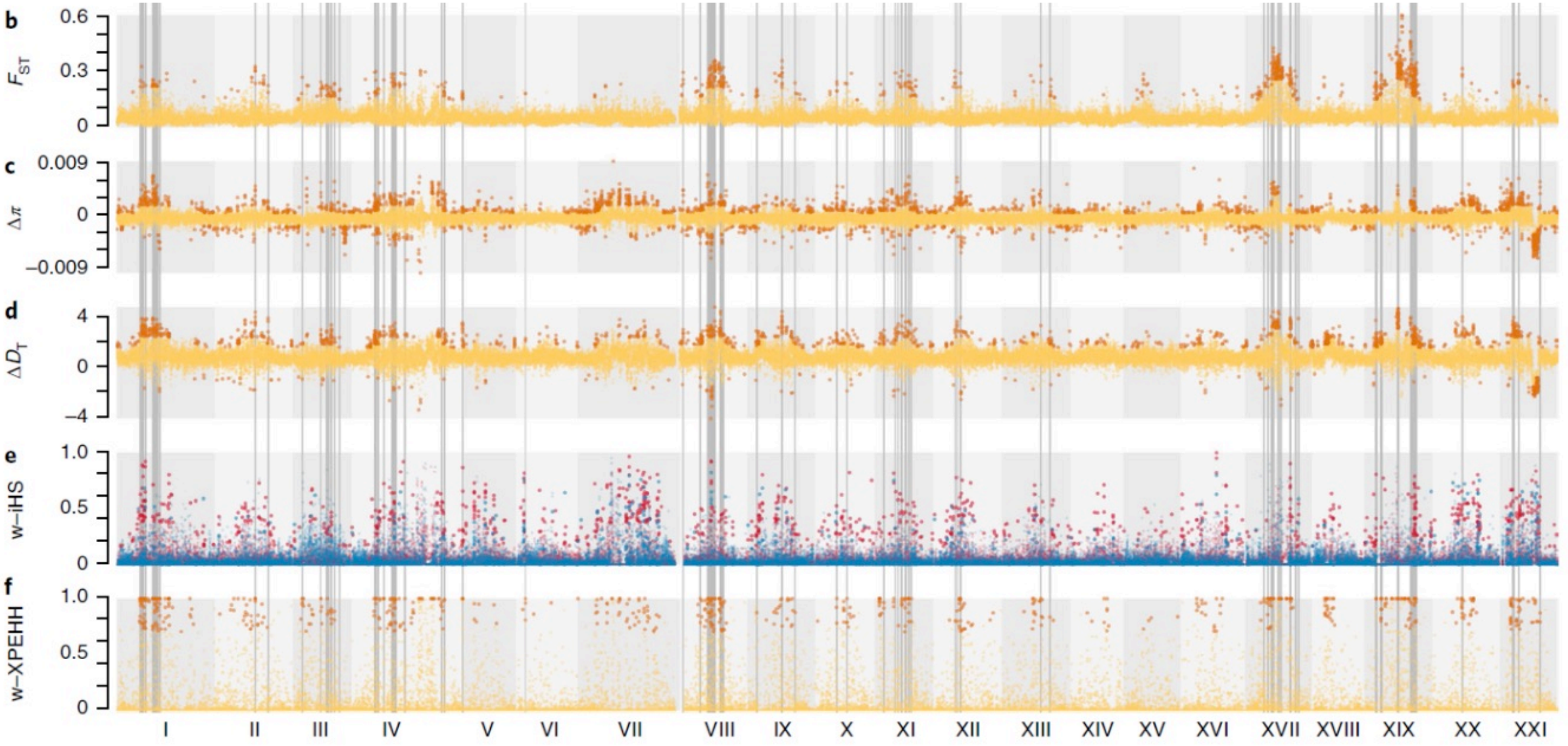
Confounding factors

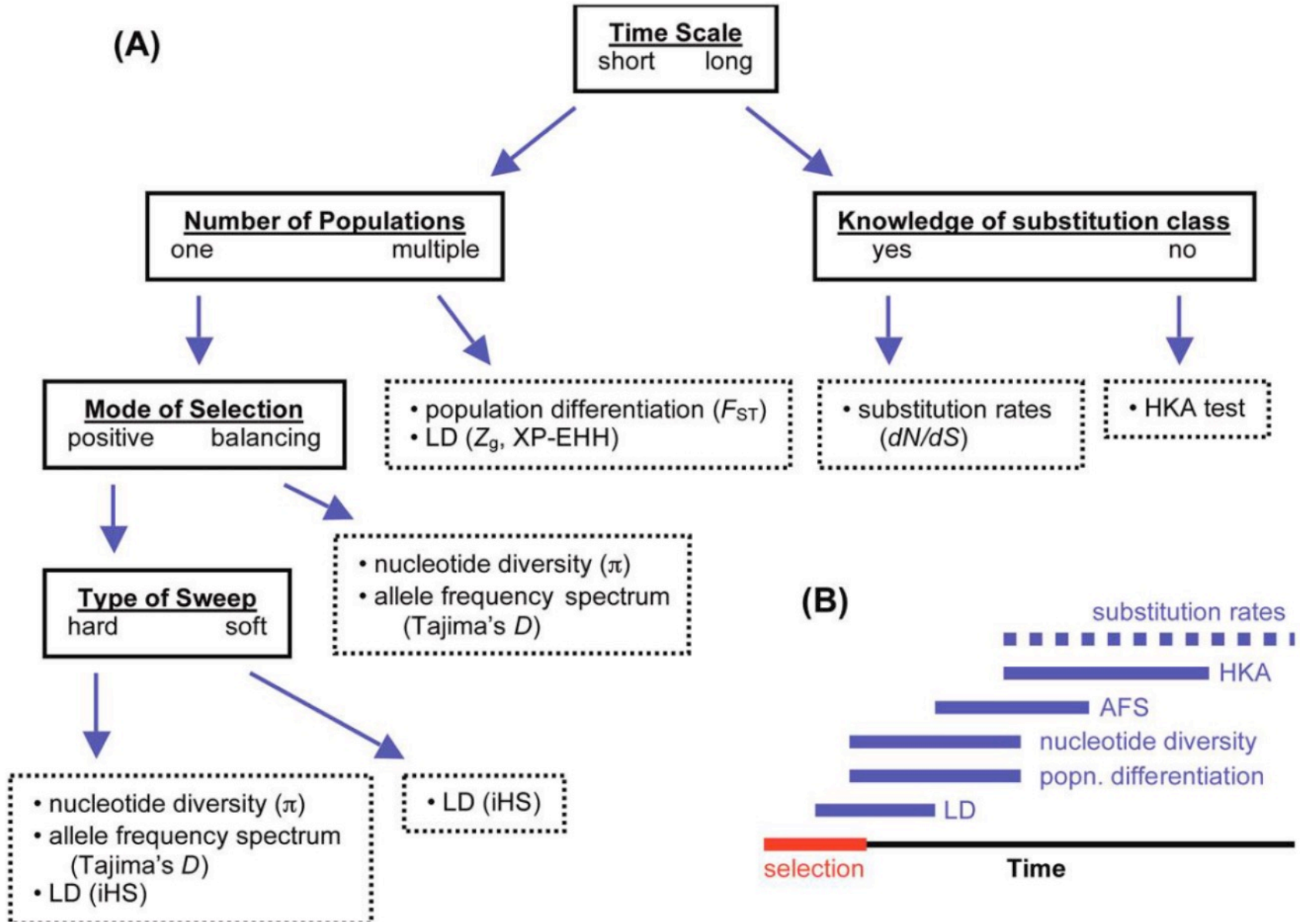



Fst
Tajima's D
pi
pi 1 – pi 2
latt
nota
hybr
l>n
n>l

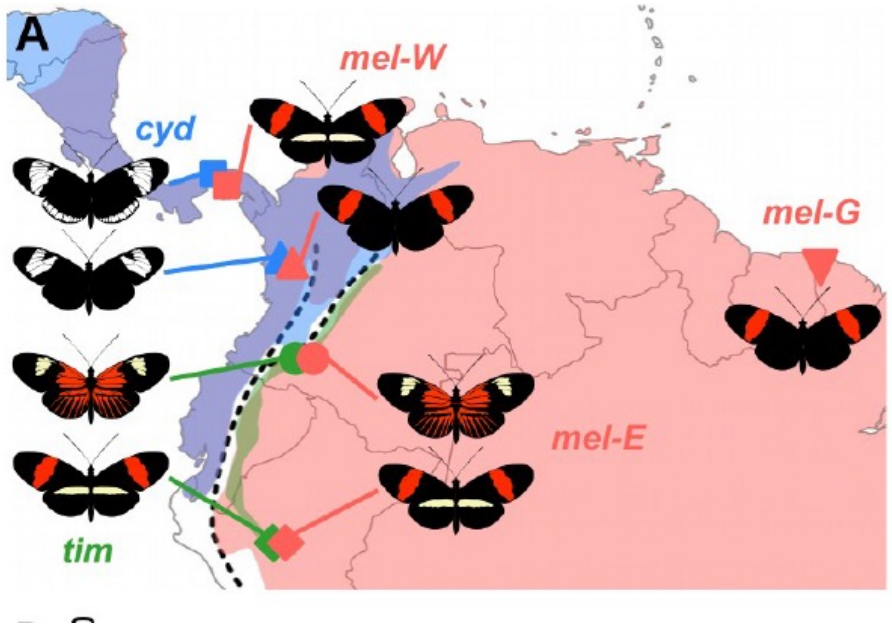
Use different statistics

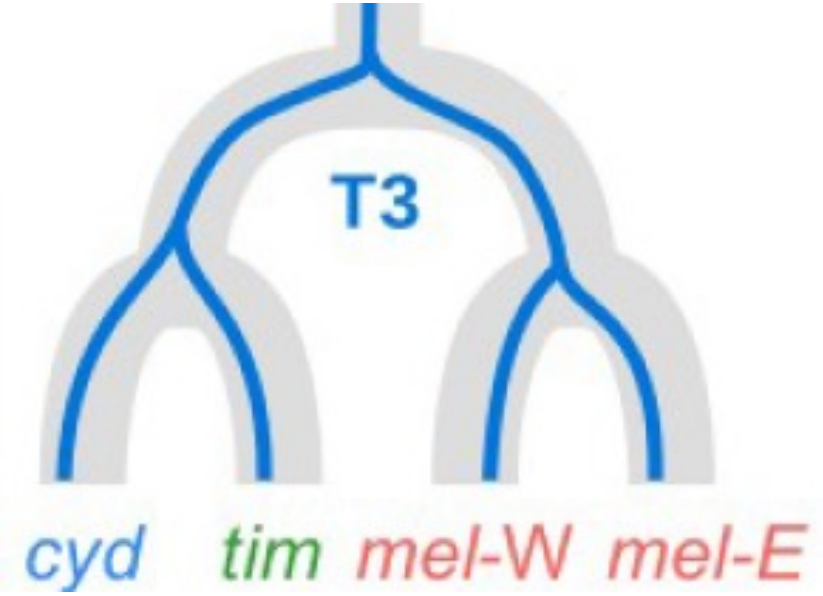
Marques et al., 2018, Nature Ecol Evol



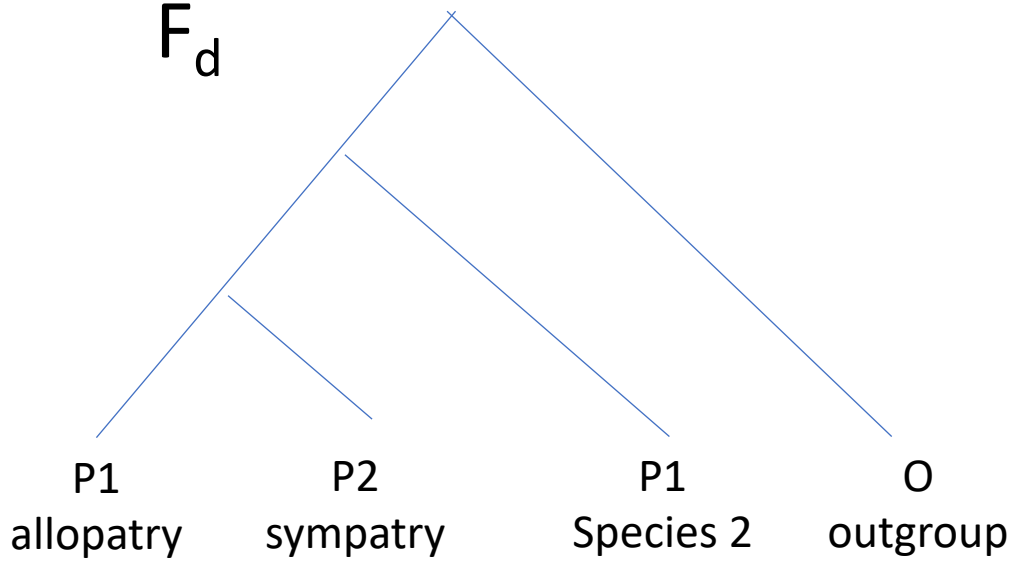


Hohenlohe et al. 2010 Int J Plant Sci



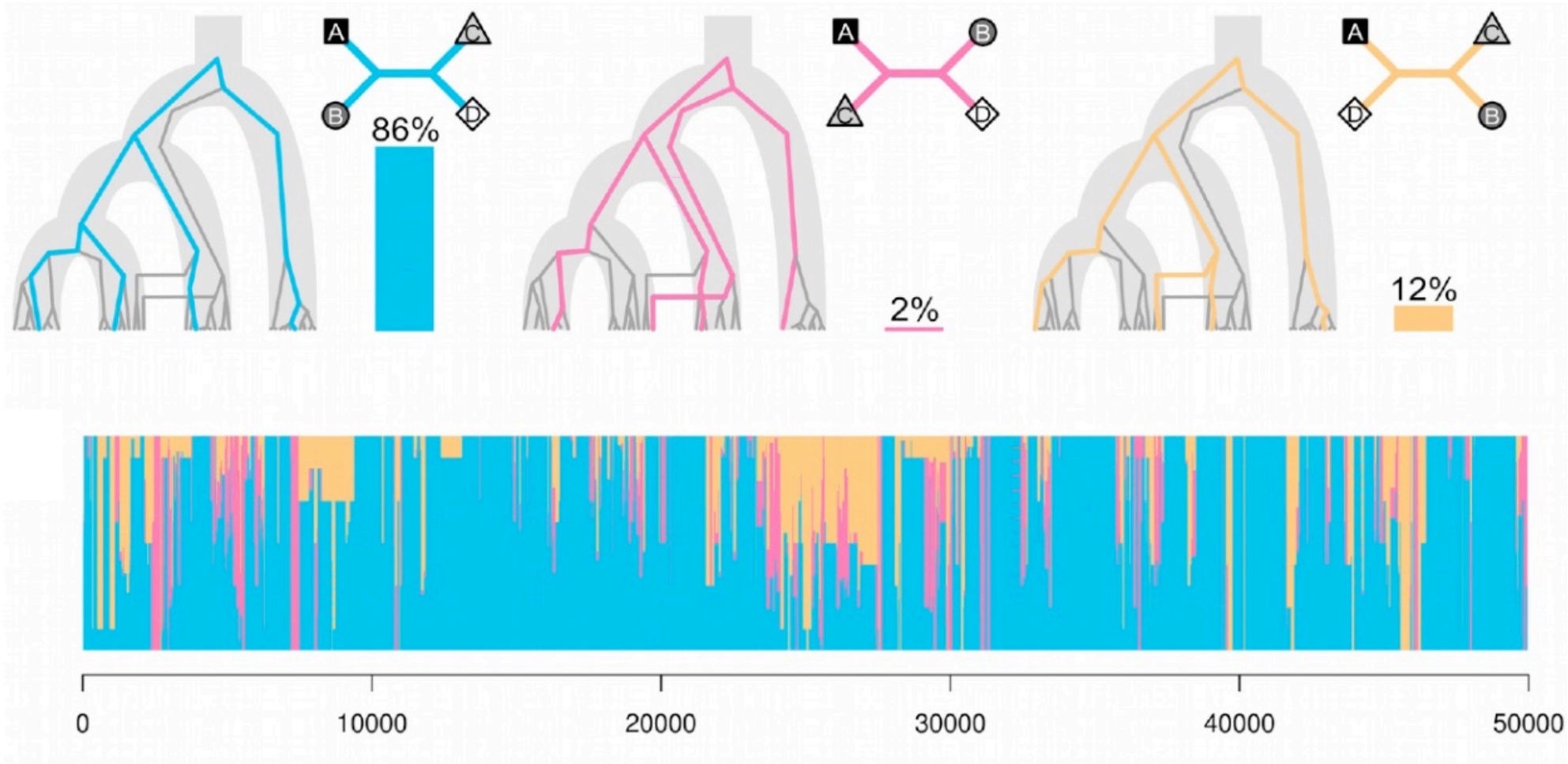


F_d



Enciso-Romero, 2017, MolEcol

TWISST: Visualizing gene trees across the genome



See tutorial on https://github.com/simonhmartin/twisst

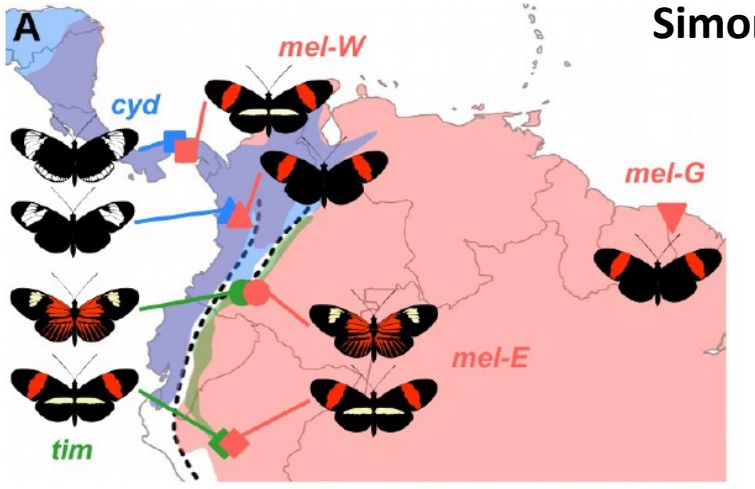
Martin & van Belleghem, 2017

Signatures and statistics to detect candidate barrier loci

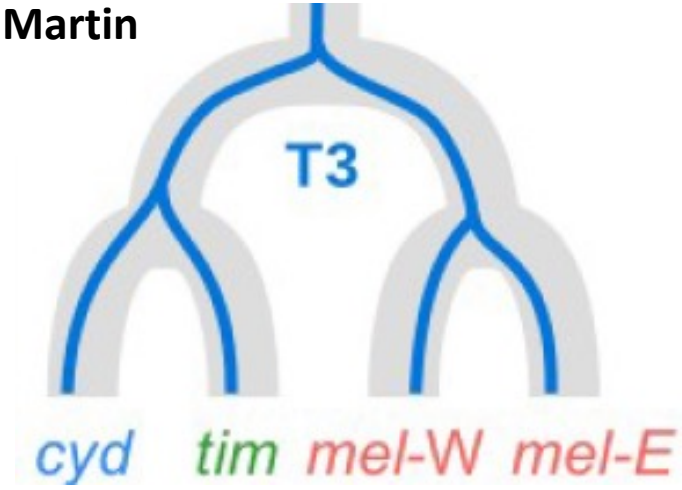
- Locally restricted gene flow
  - Reduced f_d
  - Gmin
- Increased differentiation and potentially divergence
  - Increased Fst -> PBS
  - Inreased dxy
  - increased Δpi
- Selective sweep signals in one or both populations
  - Increased Haplotype Length, e.g. iHS and XP-EHH
  - Reduced pi
  - Negative Tajima’s D

Detecting regions under divergent selection and barriers to gene flow

- If high gene flow -> F_{ST} is a good measure for detecting regions under divergent selection or barrier loci
- If the taxa are divergent enough -> d_{xy} may work best, particularly if levels of gene flow are not very high and in cases of secondary contact Ideally correct for differences in pi with an outgroup.
- If the taxa are very young and gene flow is not very high, f_d or TWISST might help if allopatric and parapatric populations were sequenced



Simon Martin



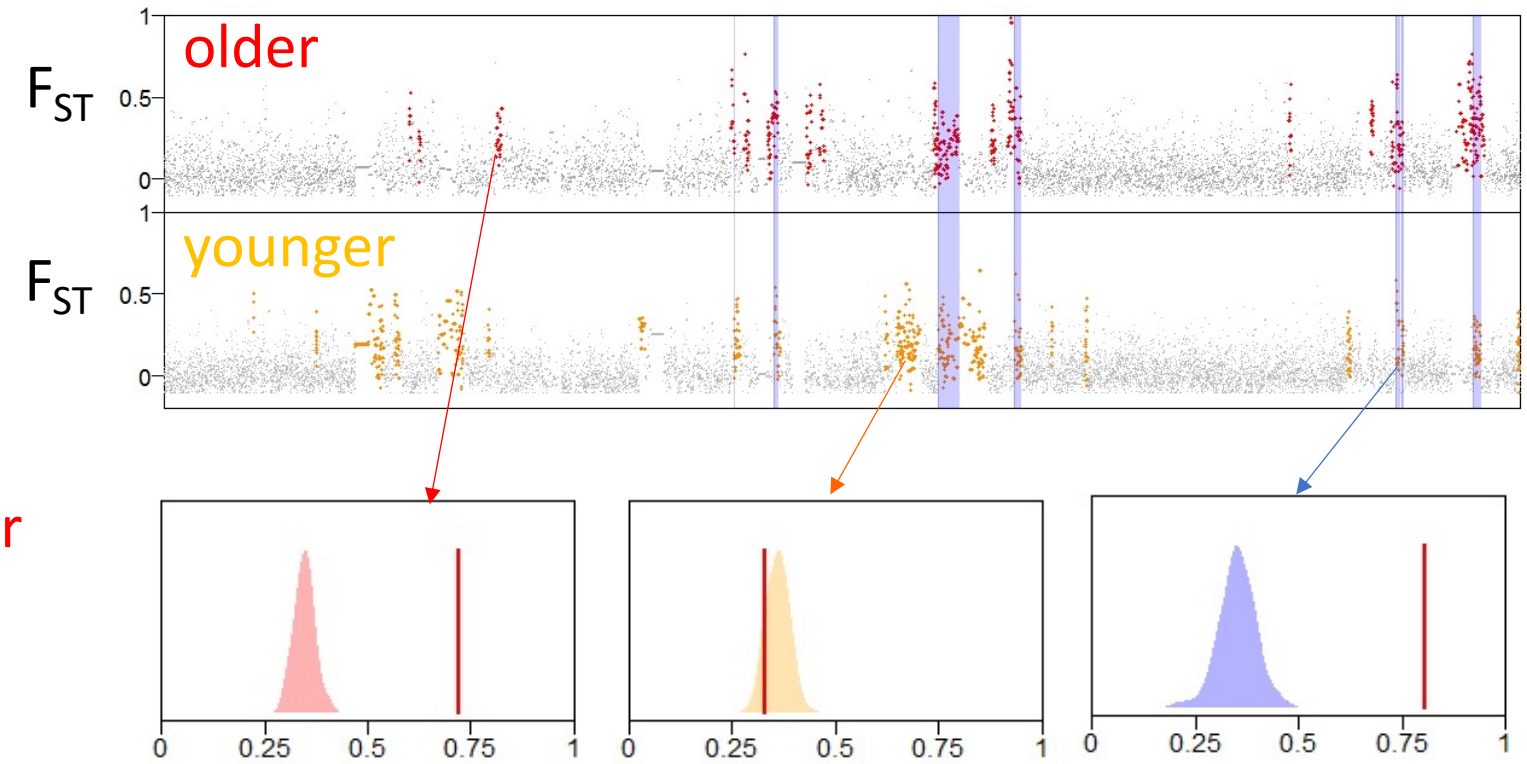
Detecting regions under divergent selection and barriers to gene flow

- If rates of gene flow between the two taxa compared is high, $\mathbf{F_{ST}}$ is a good measure for detecting regions under divergent selection or barrier loci
- If the taxa are divergent enough, $\mathbf{d_{xy}}$ may work best, particularly if levels of gene flow are not very high and in cases of secondary contact. Ideally correct for differences in pi with an outgroup.
- If the taxa are very young and gene flow is not very high, $\mathbf{f_d}$ or TWISST might help if allopatric and parapatric populations were sequenced
- If there is no gene flow, it is better to search for signatures of selective sweeps (e.g. iHS, XP-EHH, Tajima's D). However, inferring if these regions are involved in speciation is difficult.

Enrichment of selection statistics support the action of selection

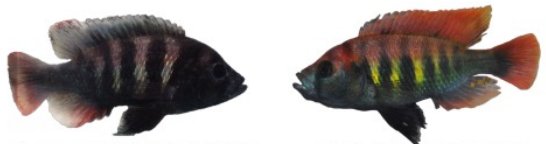
Selection statistics:

d_{xy}
Tajima's D
Δpi
XP-EHH
iHS

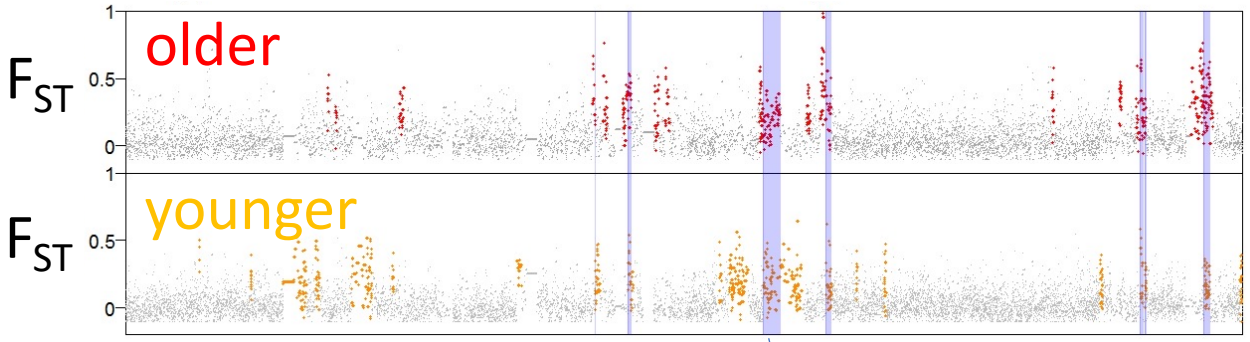


Selection in the older pair

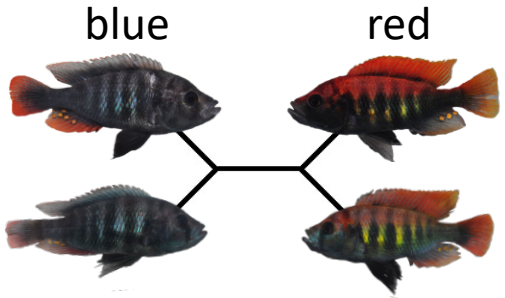
Selection in the younger pair

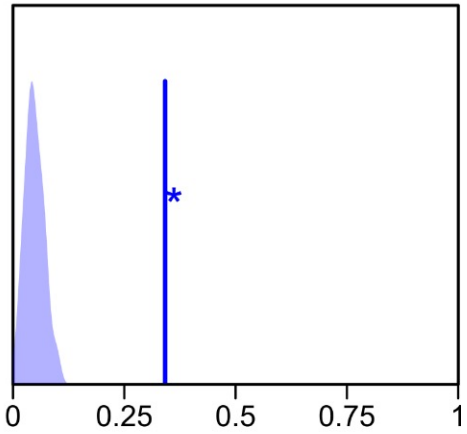


Example: Highly differentiated regions shared by both species pairs show parallel allele frequency differences



Species group by color



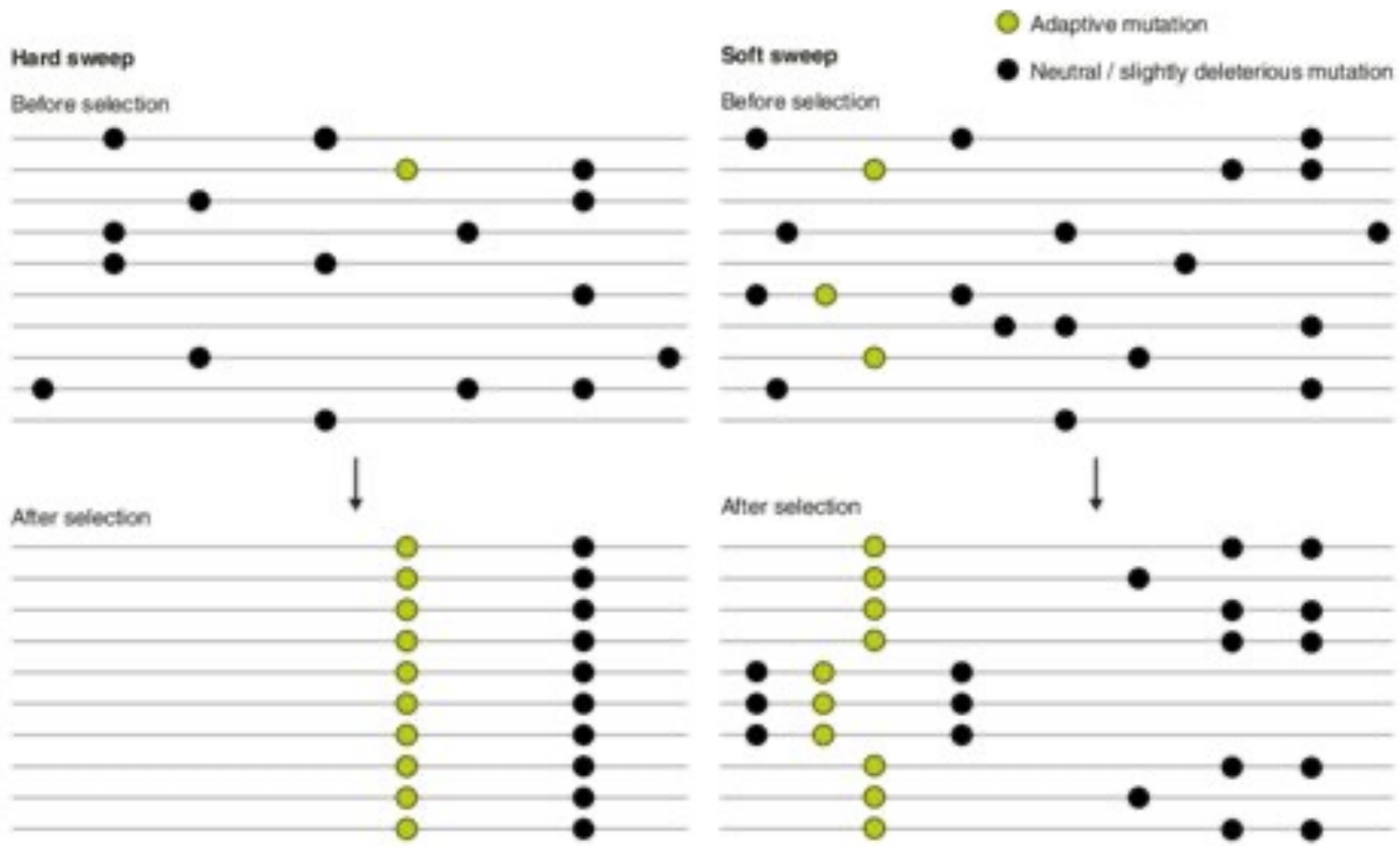


%shared HDRs with color topology

TWISST
(Martin & Van Belleghem, 2017)

Meier *et al.*, 2018, MBE

Hard vs soft sweep



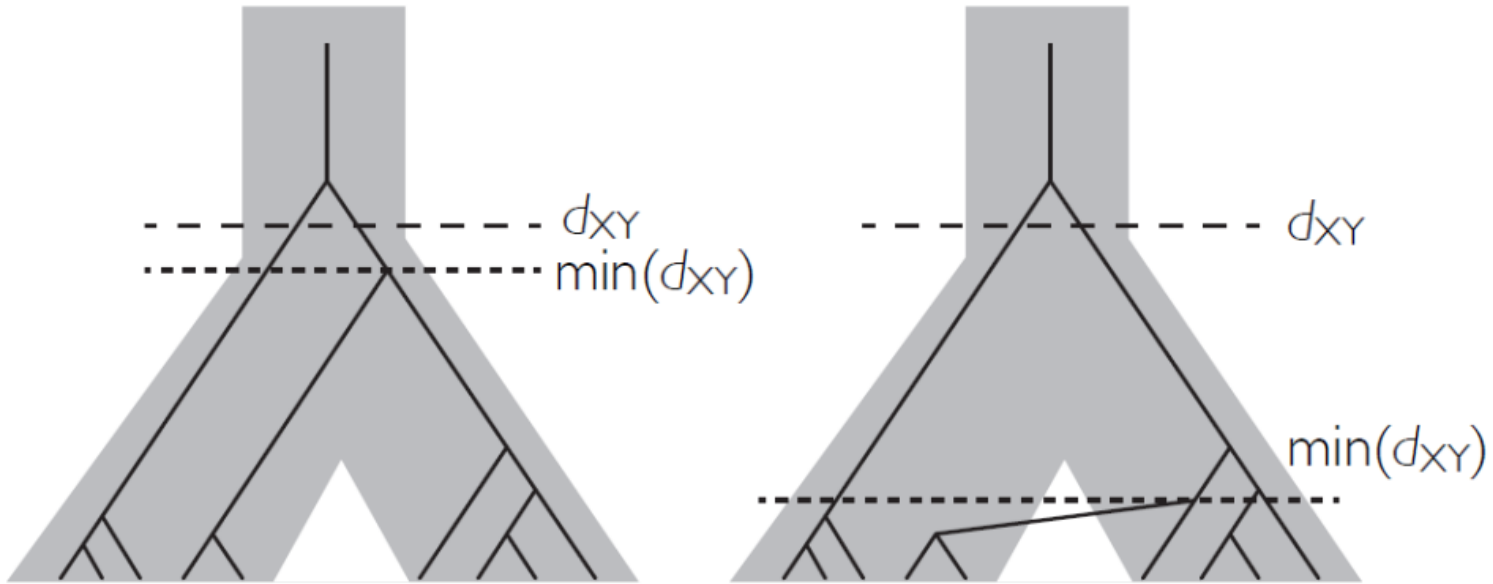
Absolute measures of divergence

$$d_{XY} = \sum_{ij} x_i y_j d_{ij}$$

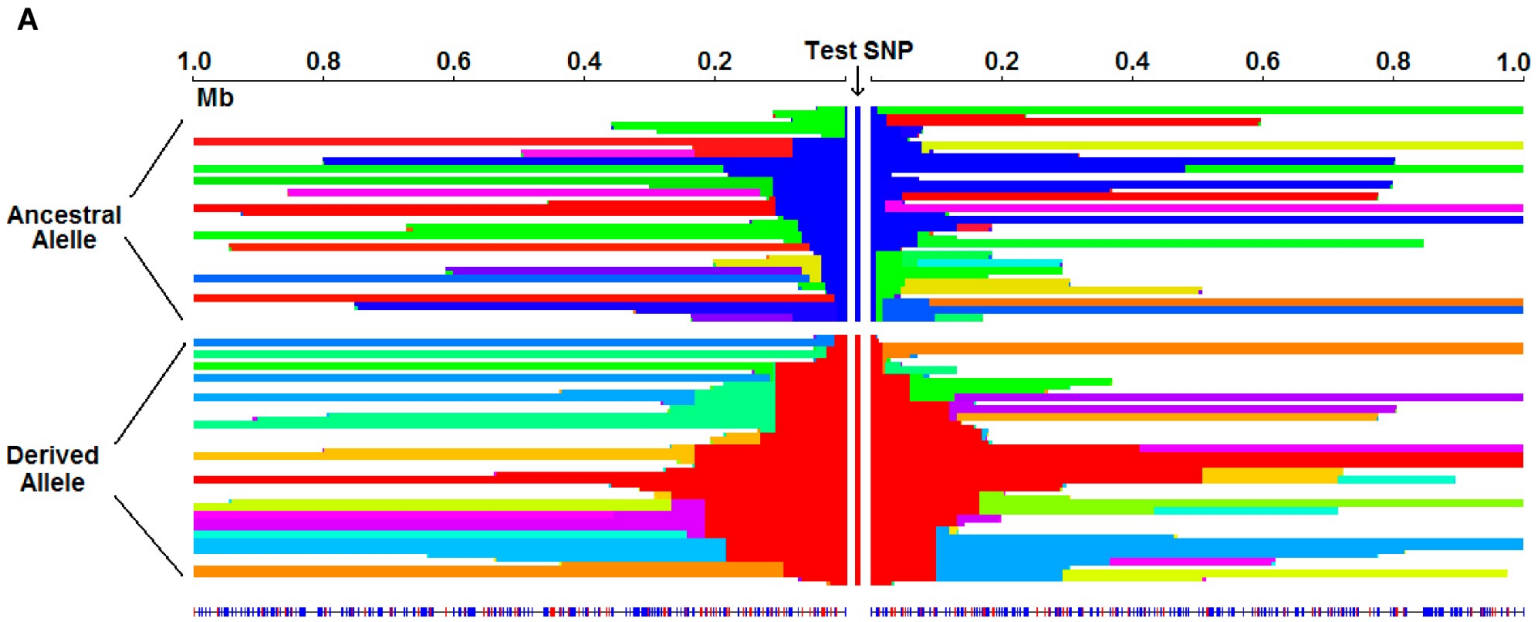
Average number of pairwise differences between two populations

Pop A	Pop B
ACTGTC	ATTAGC
ATTGTC	ACTGGC
ACTGTC	ACTAGC
ATTGTC	ATTAGC

Here d_{XY} is 0.375



iHS and XP-EHH



iHS: within a population

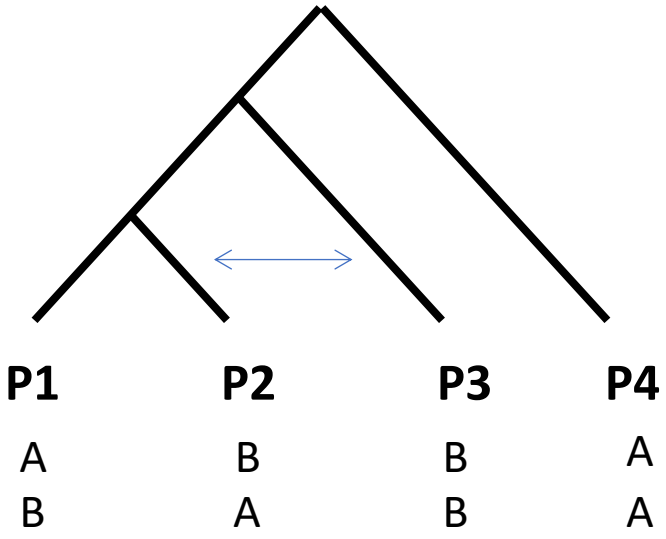
iHS (integrated haplotype score) compares haplotype lengths **within a population**
-> an allele under selection will lead to increased haplotype length relative to other haplotypes in the same region
-> useful to detect **ongoing/incomplete sweeps**

XP-EHH: beetween populations

XP-EHH (cross population extended haplotype homozygosity) compares haplotype lengths **between populations**
-> a population that had a sweep has increased haplotype lengths relative to the haplotypes in the other population in the same region
-> most powerful with **complete sweeps** restricted to one population

Sliding window introgression: f_d

f_d can be applied to smaller number of ABBA and BABA sites than D and is thus ideal for sliding windows.
ABBA and BABA patterns are computed from allele frequencies and the f test of the four populations is standardized by the maximum value it could get which would be the scenario of complete mixing between P2 and P3. P2 and P3 are thus both set to PD which is the taxon with higher derived allele frequency of P2 and P3.



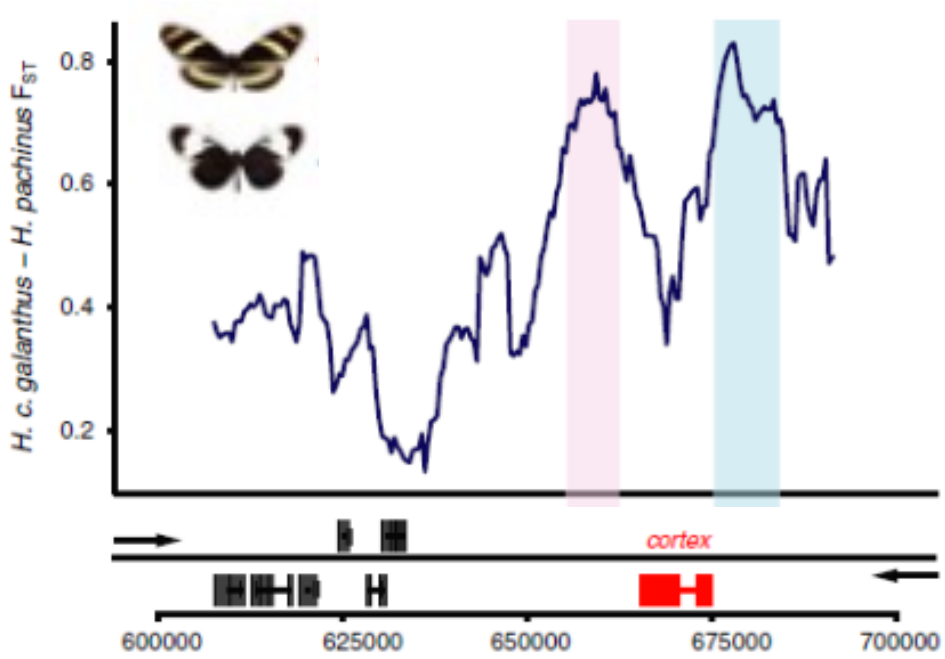
$$C_{ABBA}(i) = (1 - \hat{p}_{i1})\hat{p}_{i2}\hat{p}_{i3}(1 - \hat{p}_{i4})$$

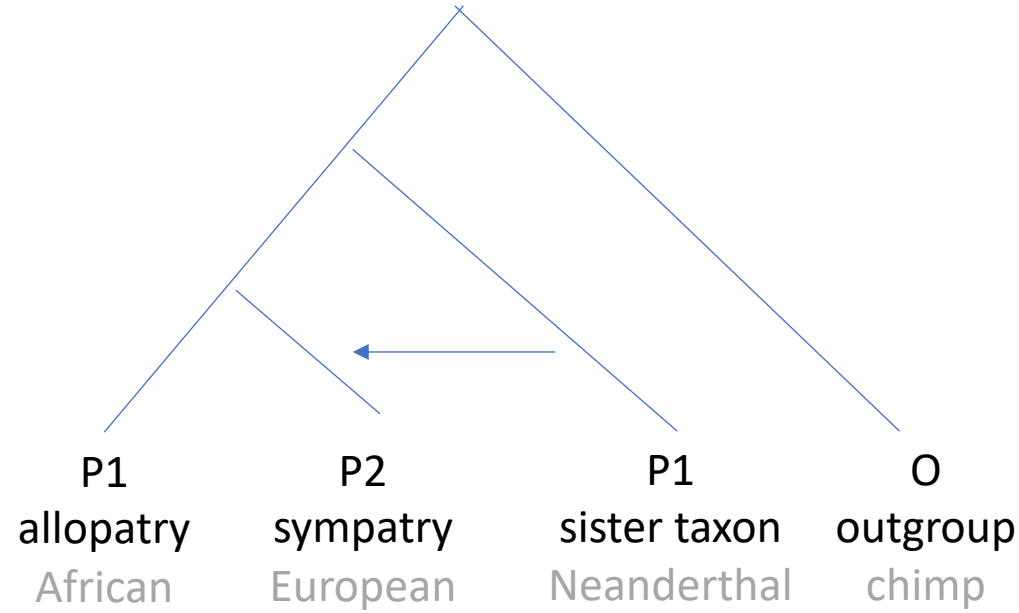
$$C_{BABA}(i) = \hat{p}_{i1}(1 - \hat{p}_{i2})\hat{p}_{i3}(1 - \hat{p}_{i4})$$

$$\hat{f}_d = \frac{S(P_1, P_2, P_3, O)}{S(P_1, P_D, P_D, O)}$$

PD=P2 or P3
(taxon with higher
derived allele frequency)

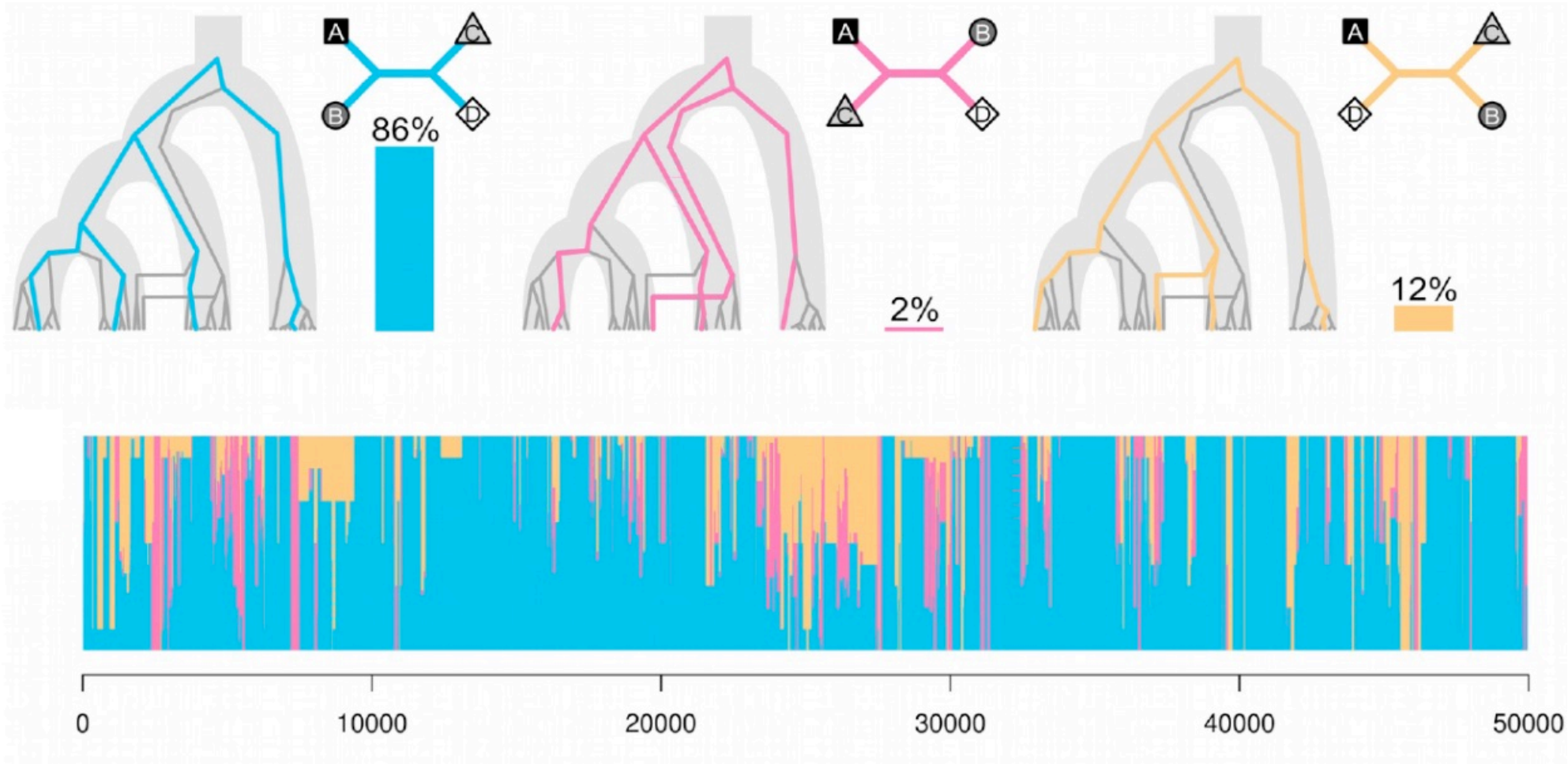
f_d can be used to find regions of reduced gene flow if allopatric and sympatric populations exist or alternatively, of adaptive introgression





Enciso-Romero, 2017, MolEcol

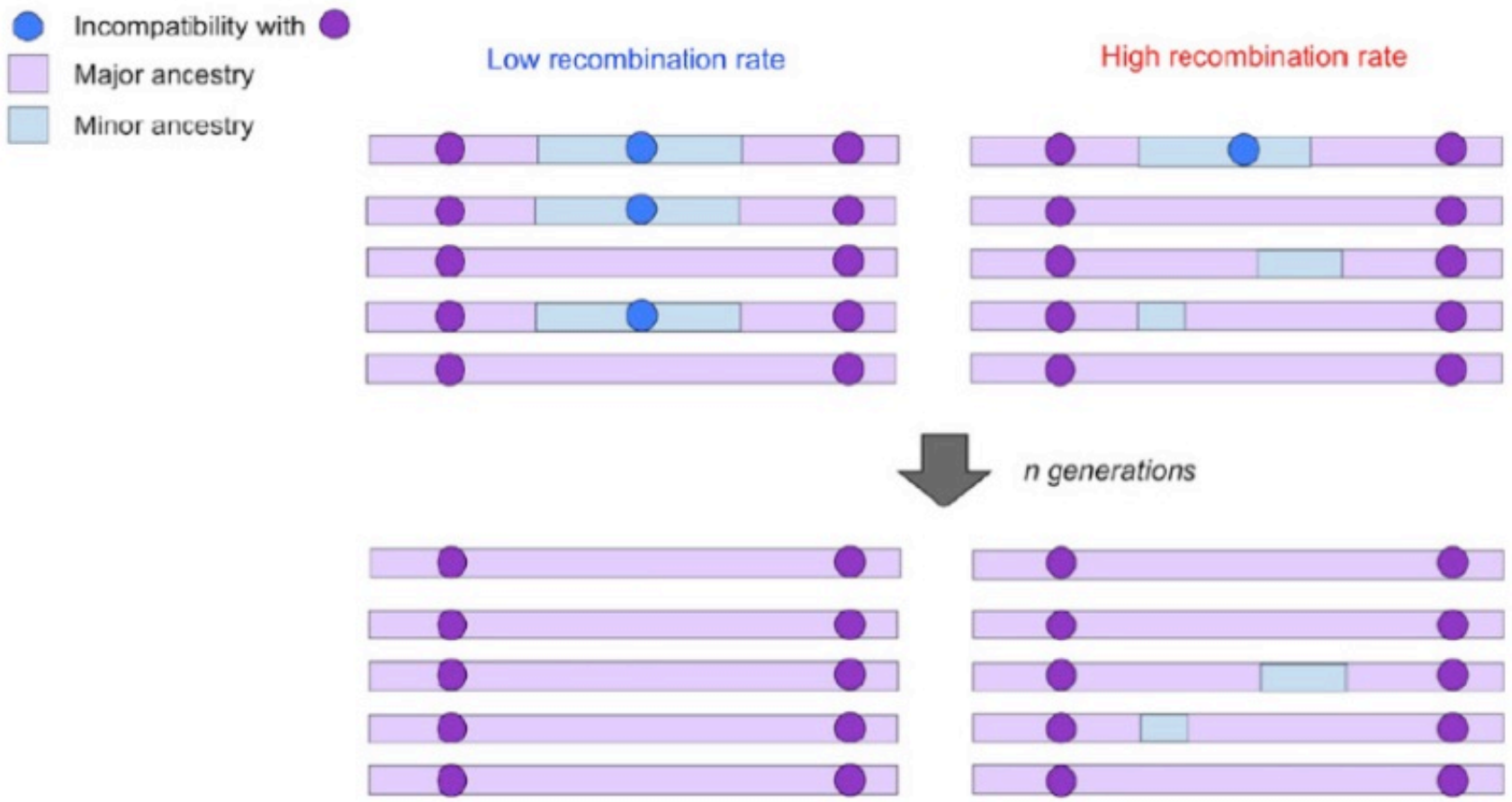
TWISST: Visualizing gene trees across the genome



See tutorial on https://github.com/simonhmartin/twisst

Martin & van Belleghem, 2017

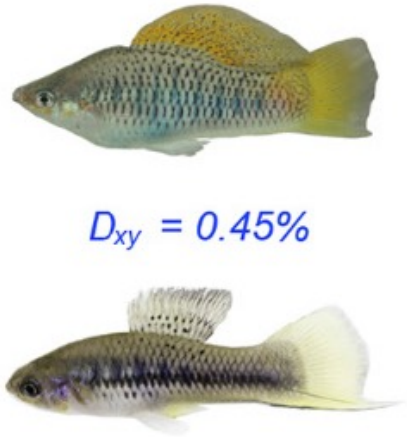
Less introgression in regions of low recombination



Schumer et al., 2018

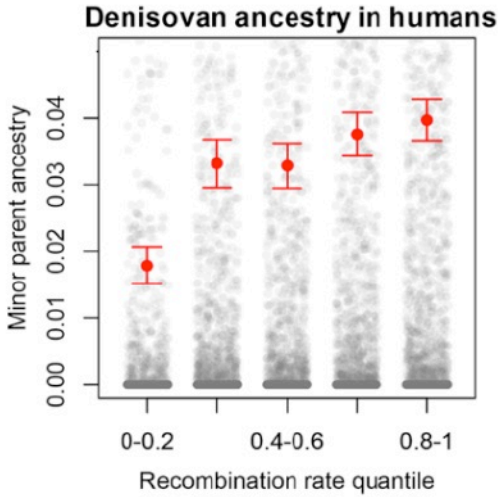
Empirical evidence

Minority parent of hybrids between X. malinche and X. birchmanni

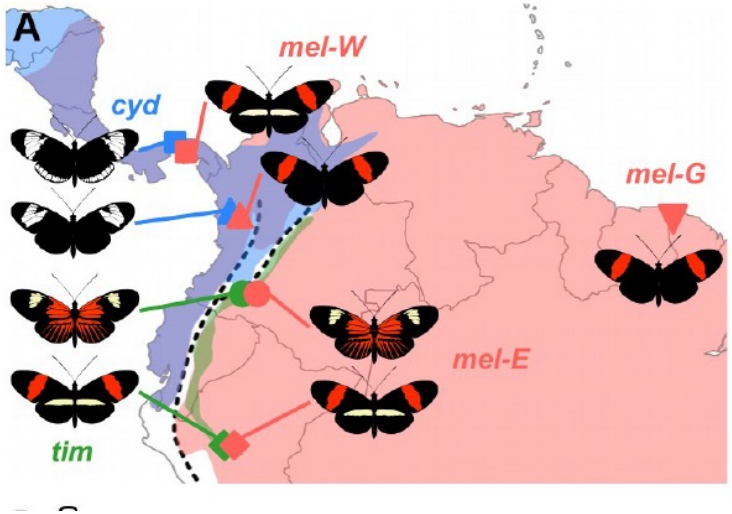


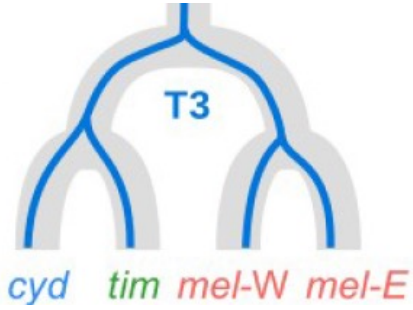
Schumer et al., 2018
Juric et al., 2016

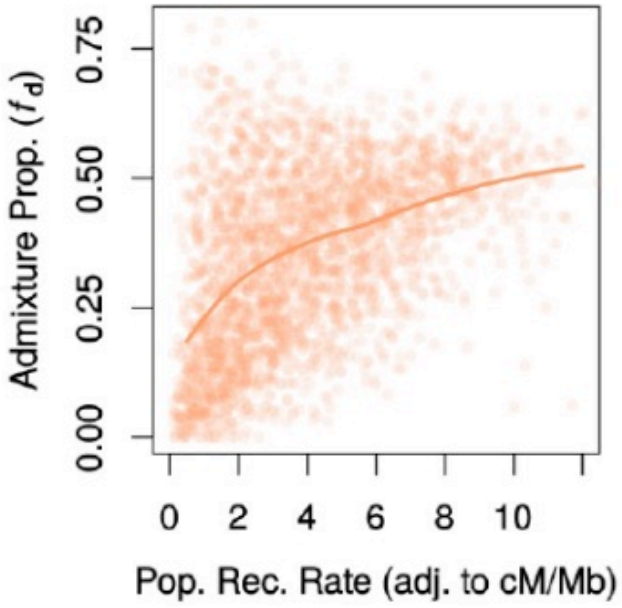
Denisovan or Neanderthal ancestry in humans



Introgression from sympatric species in *Heliconius*







Martin et al., accepted Plos Biol