

The genomics of organismal diversification

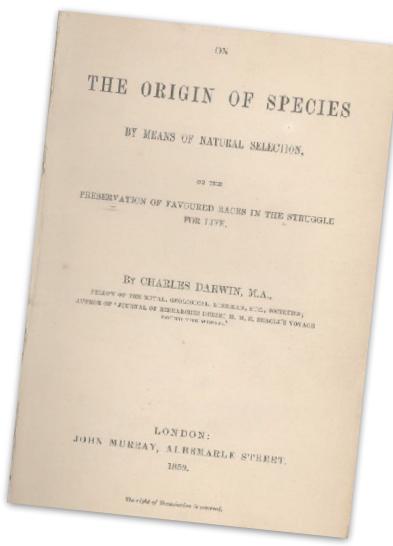


Walter Salzburger
Zoological Institute



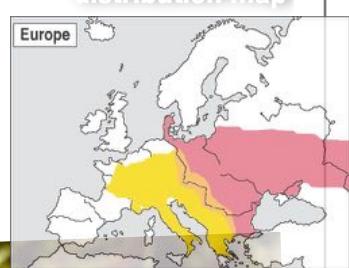
“The process by which different kinds of living organism are believed to have developed from earlier forms during the history of the earth.”

The Oxford Advanced Learner's Dictionary



①Charles R. Darwin (1809-1882)

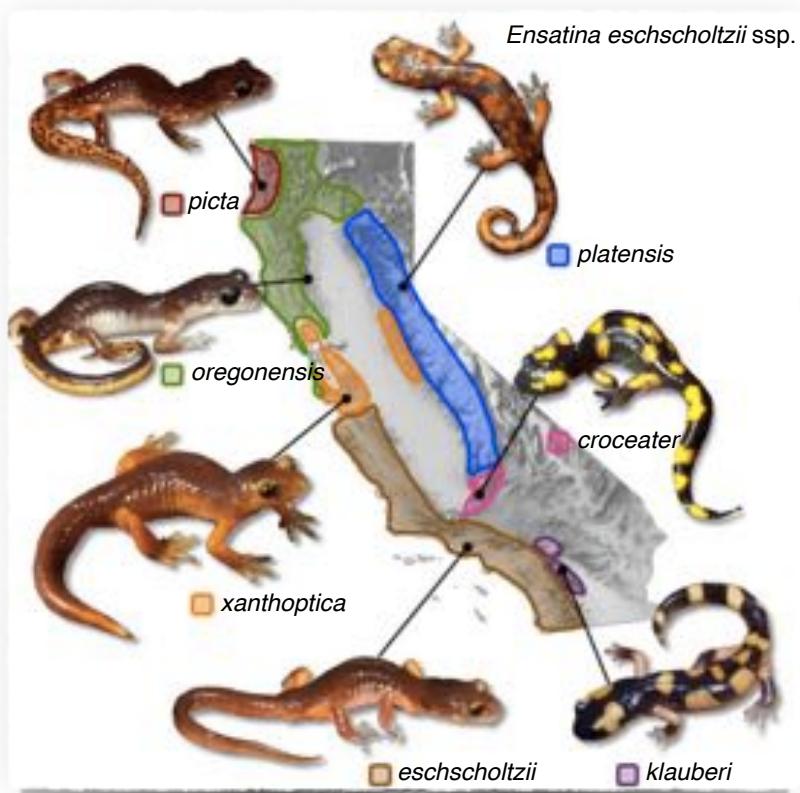
What is a species?



ⓘ Hybrid zone between yellow- and fire-bellied toad

What is a species?

ring species



Stebbins (1994)

ⓘ *Ensatina eschscholtzii* inhabits the western part of the USA

What is a species?

Individuals within a species are variable and there is usually no “ideal” or “typical” individual.

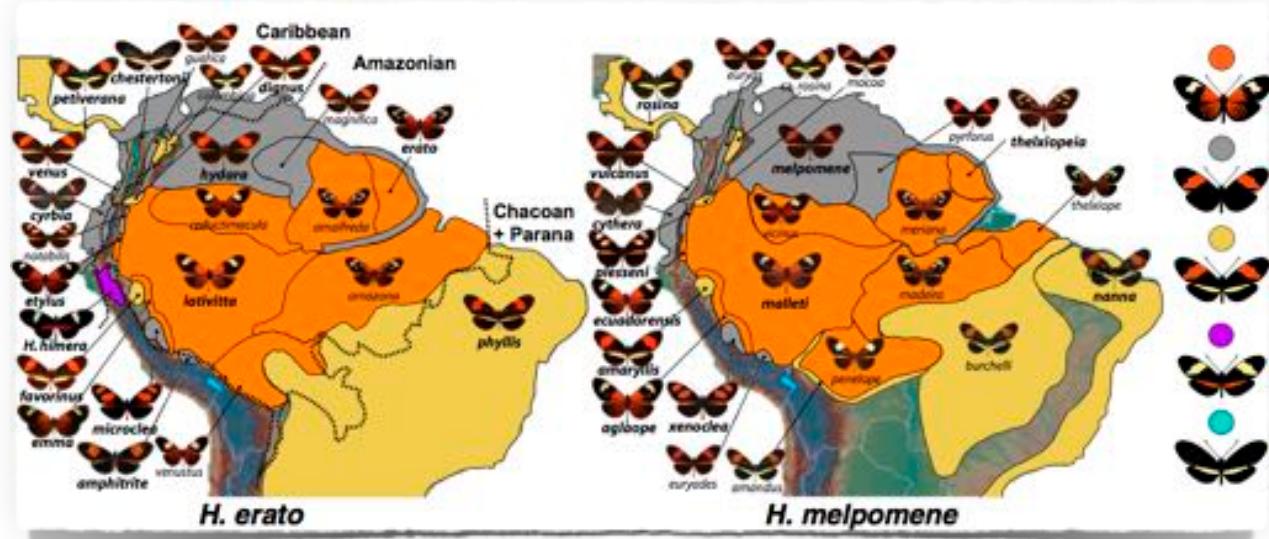


image: www.heliconius.org

① *Heliconius erato* and *H. melpomene* are morphologically similar because of mimicry

Species concepts

The category species is defined according to a species concept

biological species concept

A species is a group of interbreeding natural populations that is reproductively isolated from other such groups (Mayr 1963).

cohesion species concept

A species is the most inclusive populations of individuals having the potential for phenotypic cohesion through intrinsic cohesion mechanisms (Templeton 1989).

ecological species concept

A species is a lineages (or a closely related sets of lineages), which occupies an adaptive zone minimally different from that of any other lineage in range and which evolve separately from all lineages outside its range (Van Valen 1976).

evolutionary species concept

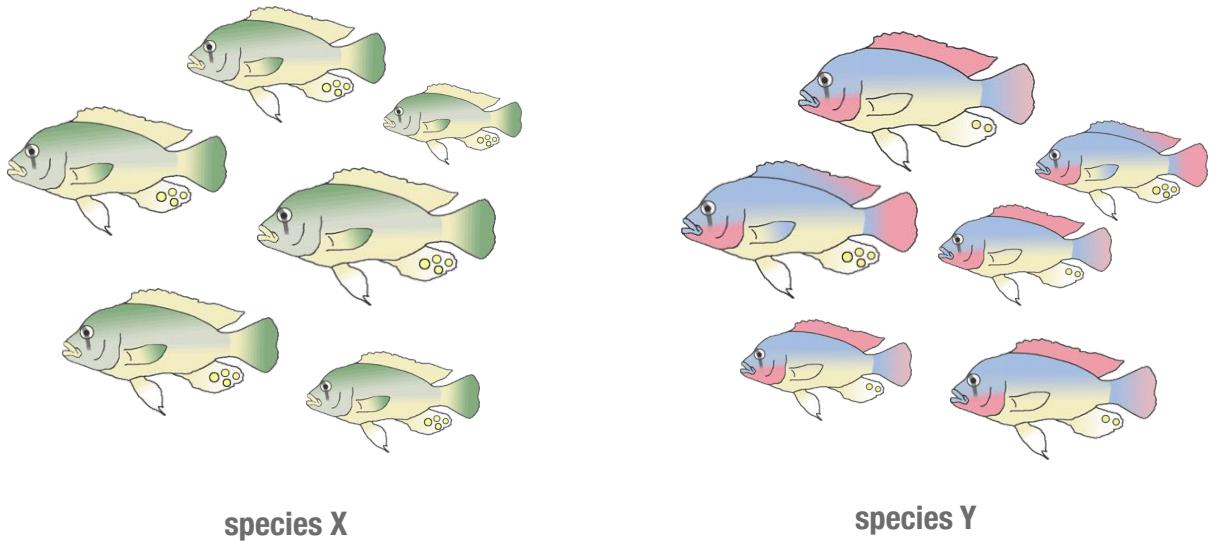
A species is a single lineage of ancestral-descendant lineages that evolve separately from other such lineages and have their own evolutionary tendencies and historical fate (Simpson 1961; Wiley 1978).

phylogenetic species concepts

A species is the smallest monophyletic group of common ancestry (de Querioz & Donoghue 1988). A phylogenetic species is a basal cluster of organisms that is diagnosably distinct from other such clusters (Cracraft 1989)

Biological species concept

Members of a species share a gene pool; selection and drift operate within species.



ⓘ Evolutionary biologists interpret species as independent evolutionary units

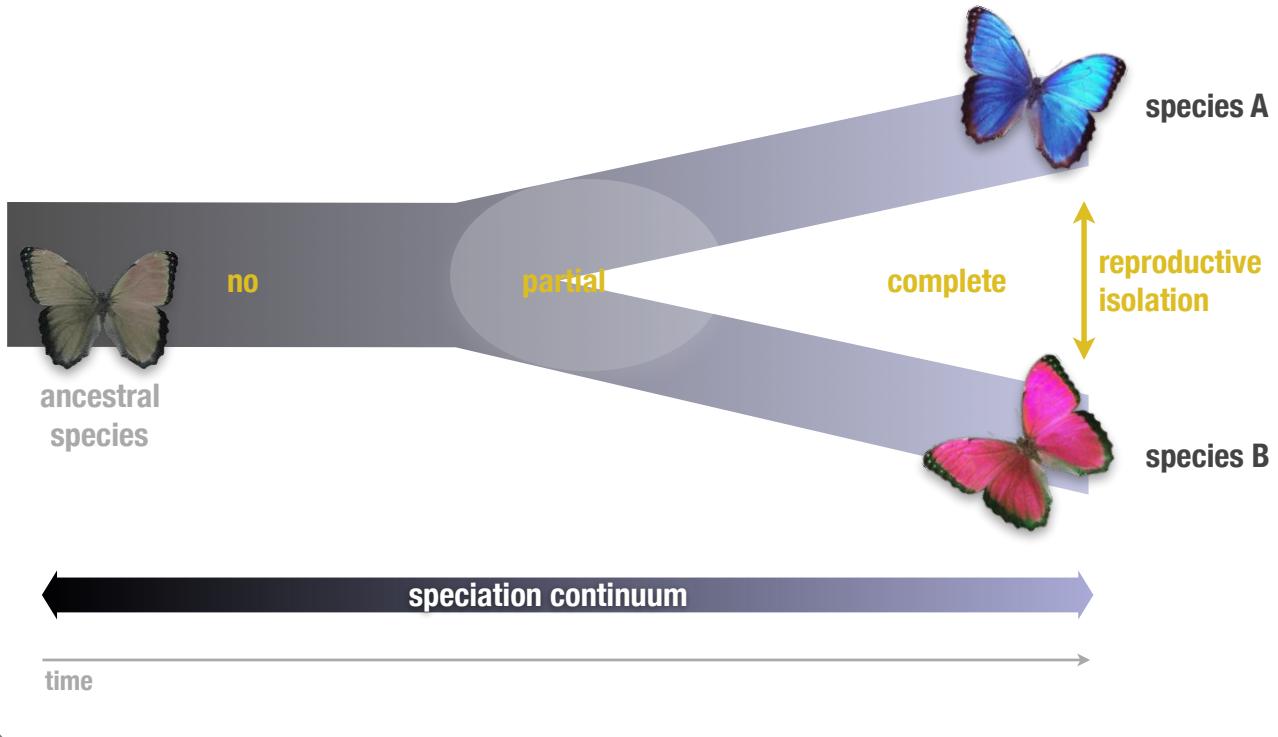
Biological species concept

A species is a group of interbreeding natural populations that is reproductively isolated from other such groups (Mayr 1963).

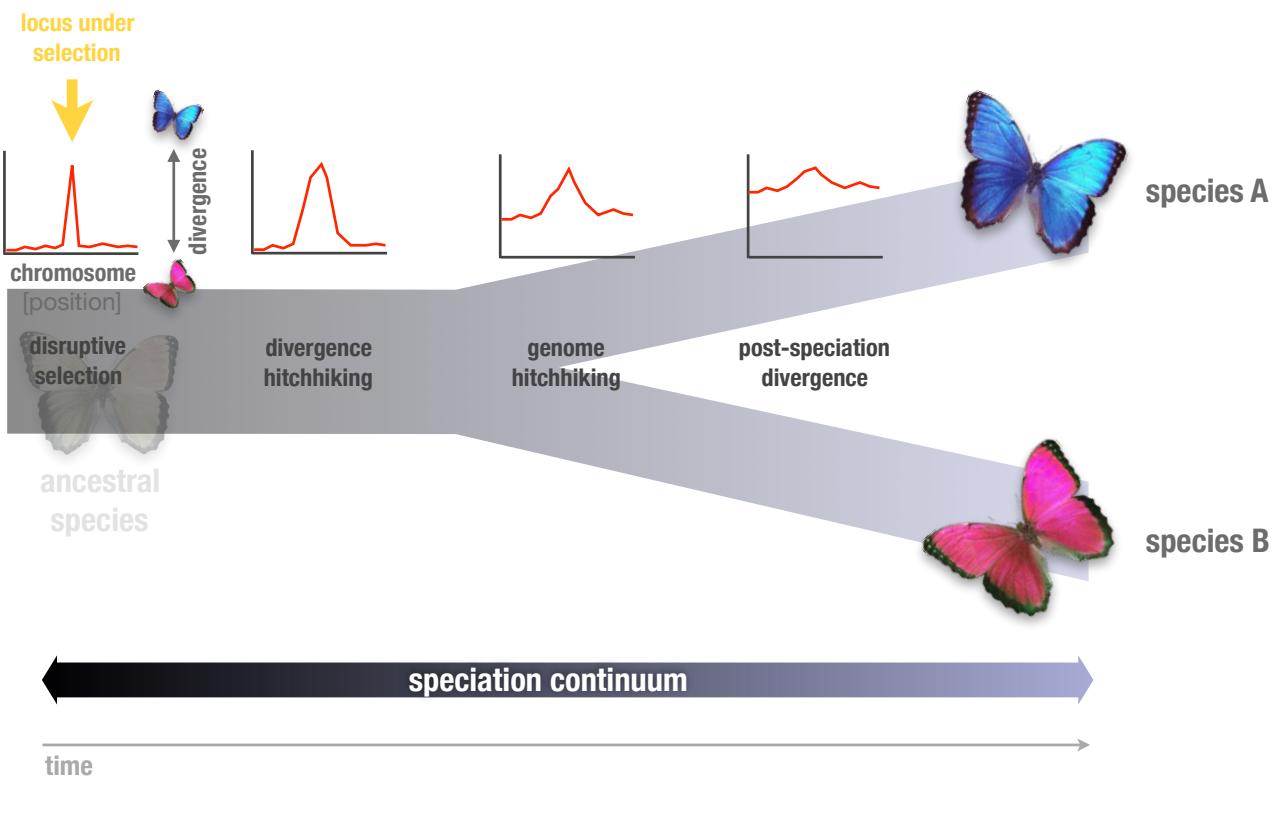


ⓘ The biological species concept places the category species within the framework of population genetics

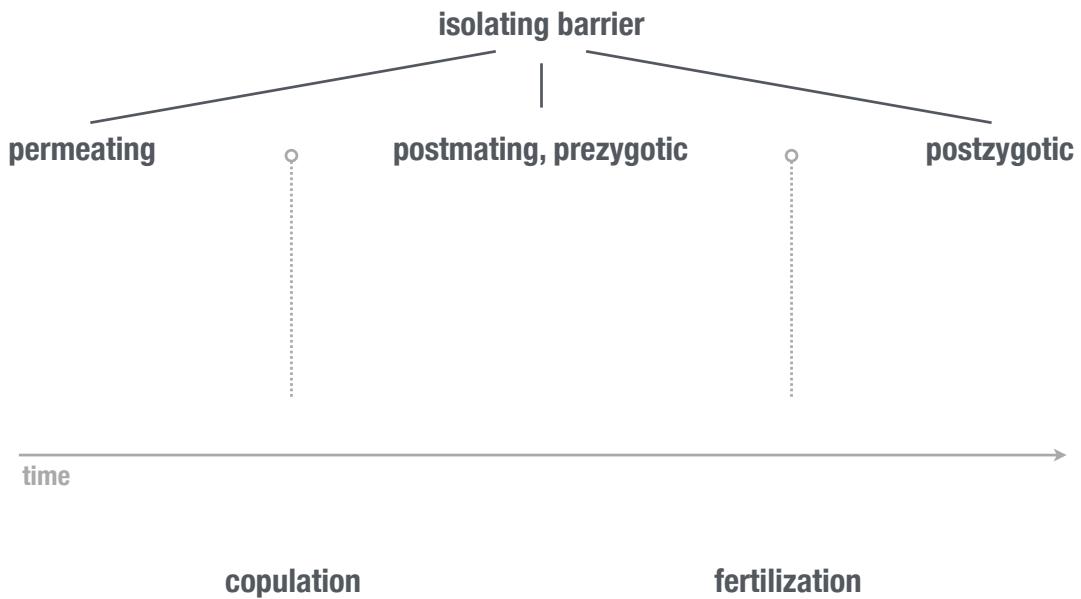
Reproductive isolation



Reproductive isolation



Reproductive isolation



Geographic conditions

allopatric speciation



parapatric speciation



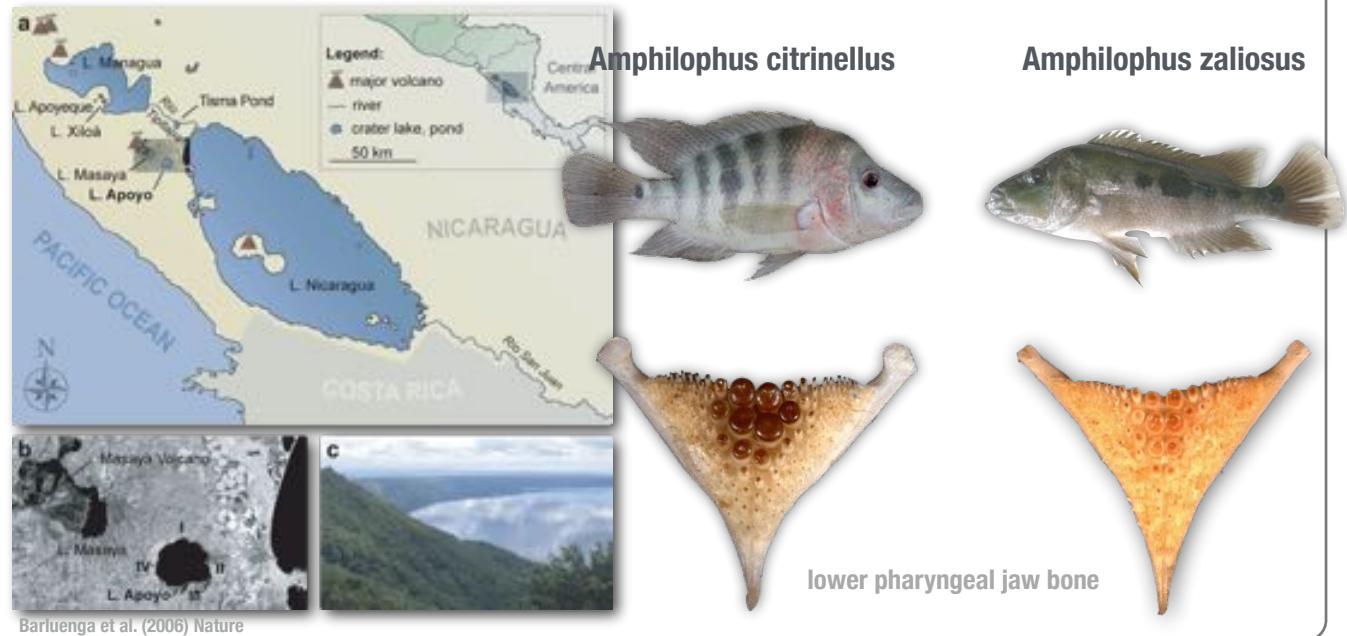
sympatric speciation



time

↓

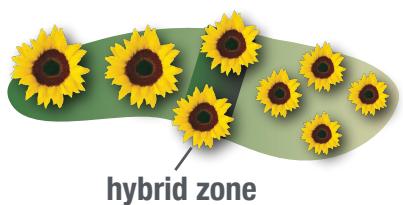
Sympatric speciation



ⓘ The Laguna de Apoyo is a small volcanic crater lake in Nicaragua

Parapatric speciation

Clinal models



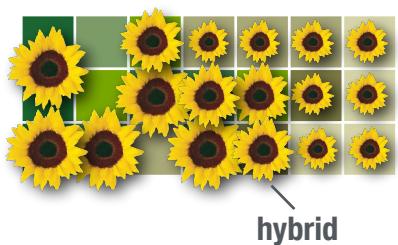
colonization



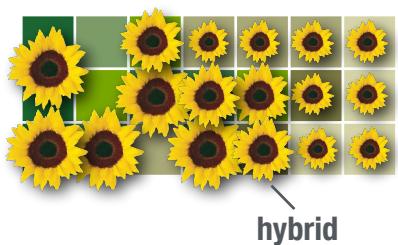
local adaptation



reproductive isolation



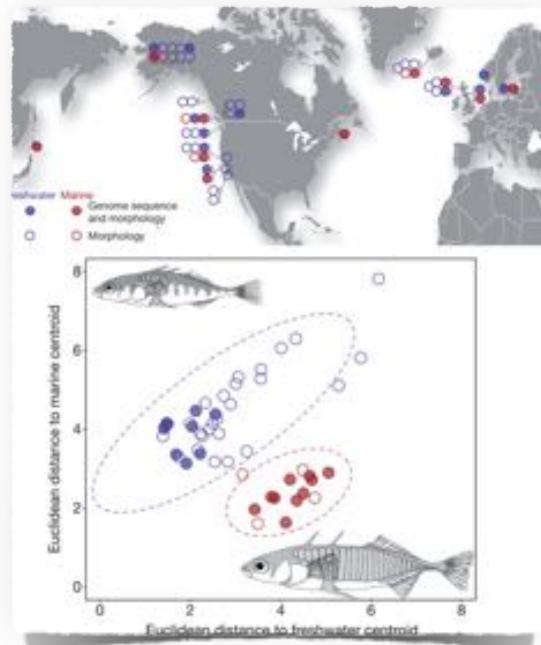
"Stepping-stone" models



Ecological speciation

The evolution of reproductive isolation between populations by adaptation to different environments.

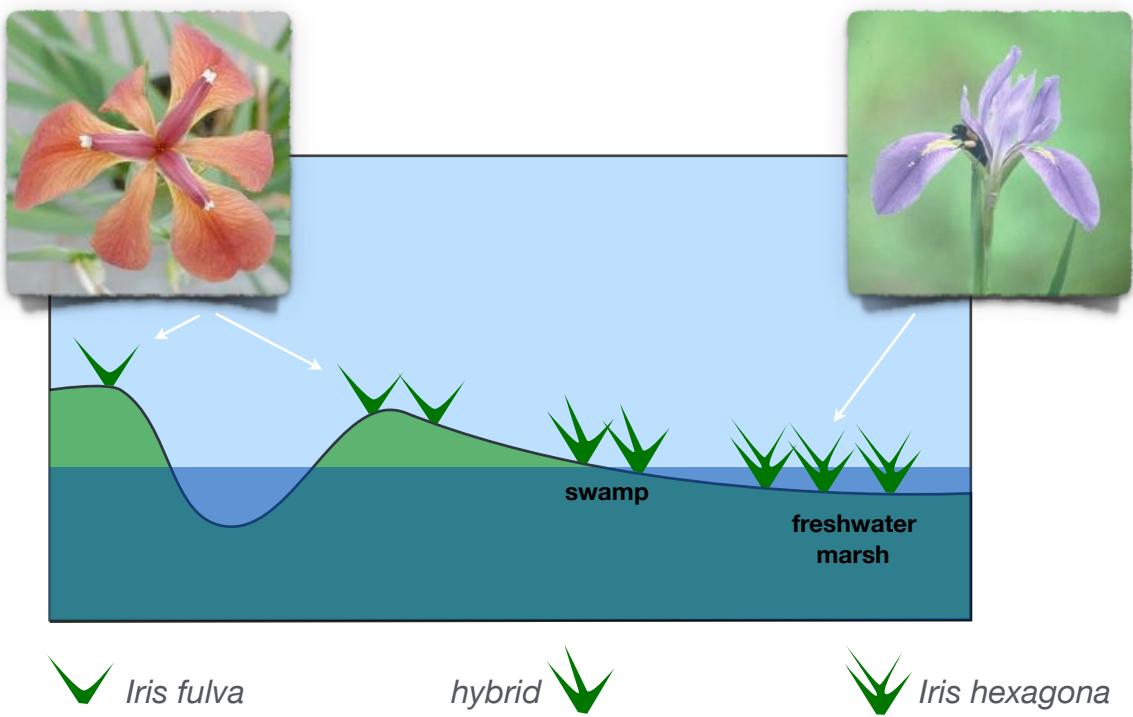
threespine
stickleback



Jones et al. (2012) Nature

- ① Ecological speciation can happen in allopatry, parapatry and sympatry

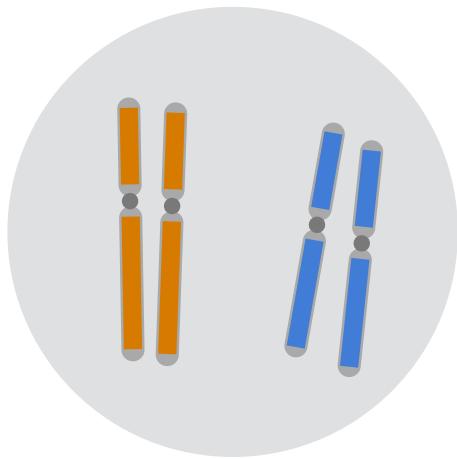
Hybrid speciation



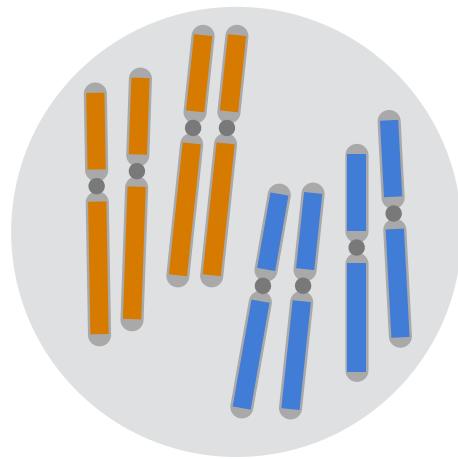
from: Arnold & Bennett (1993)

- ① Luisiana irises

Polyplloid speciation



diploid
($2n=4$)



tetraploid
($4n=8$)

Natural selection

- ... is the process by which the forms of organisms in a population that are best adapted to the environment increase in frequency relative to less well-adapted forms over a number of generations (Ridley 2004)



images: www.idscaro.net, www.wikipedia.com

Sexual selection

- ▶ ... is the selection on mating behavior, either through:
competition among members of one sex (usually males) for access to members of the other sex or through
choice by members of one sex (usually females) for certain members of the other sex
(Ridley 1996)



Natural selection

Sexual selection

Both natural and sexual selection operate if the following conditions are met:

reproduction

organisms must reproduce to form new generations

heredity

offspring resemble parents ("like must produce like")

trait variation

individuals in natural populations vary in (adaptive) traits

variation in fitness

individuals in natural populations vary in the number of their offspring that survive to reproduce ('lifetime reproductive success')

Natural selection

Sexual selection

There are fundamental difference between natural and sexual selection:

	fitness	competitors
sexual selection	individual fitness	other members of the same sex
natural selection	fitness of the genotype	other individuals in the same population

Natural variation

Natural populations show variation at all levels, from gross morphology to DNA sequences. Selection can only operate, if heritable variation exists.

Heritable natural variation is generated by two processes, mutation and recombination.

New mutations are only transmitted to the next generation, if they occur in germinal tissue.

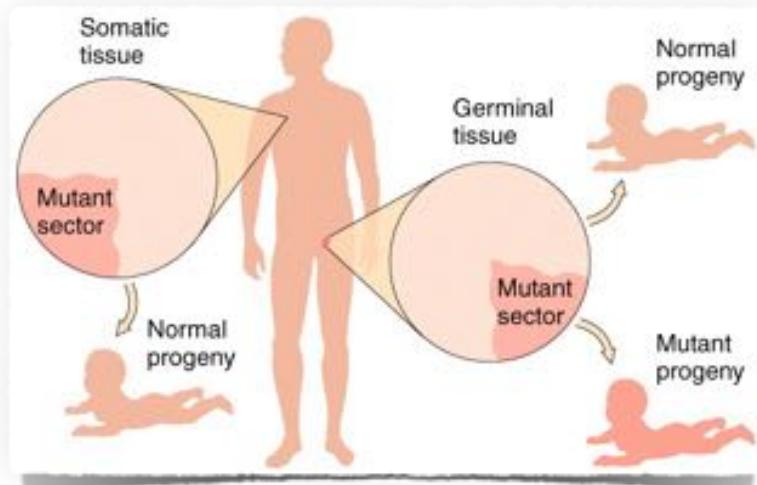
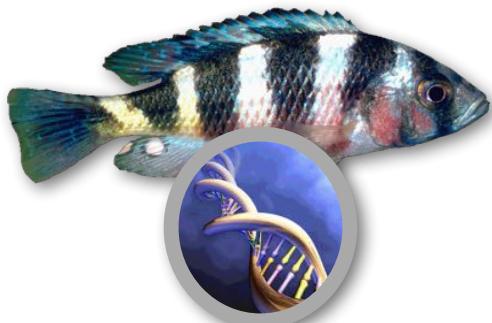


image: mun.ca

Phenotypic evolution

phenome



heritable variation in:

morphology
ecology
behavior

genome

ATG AAC GTA TGG AGG...
Met Asn Val Trp Arg

**genome
structure**
and/or
**coding
sequence**

ATG AAC GCA TGG AGG...
Met Asn Ala Trp Arg

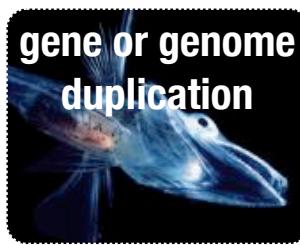
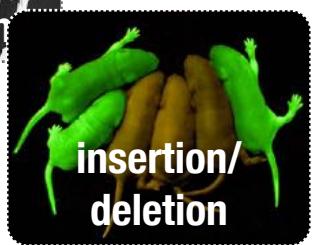
and/or
**regulatory
regions**



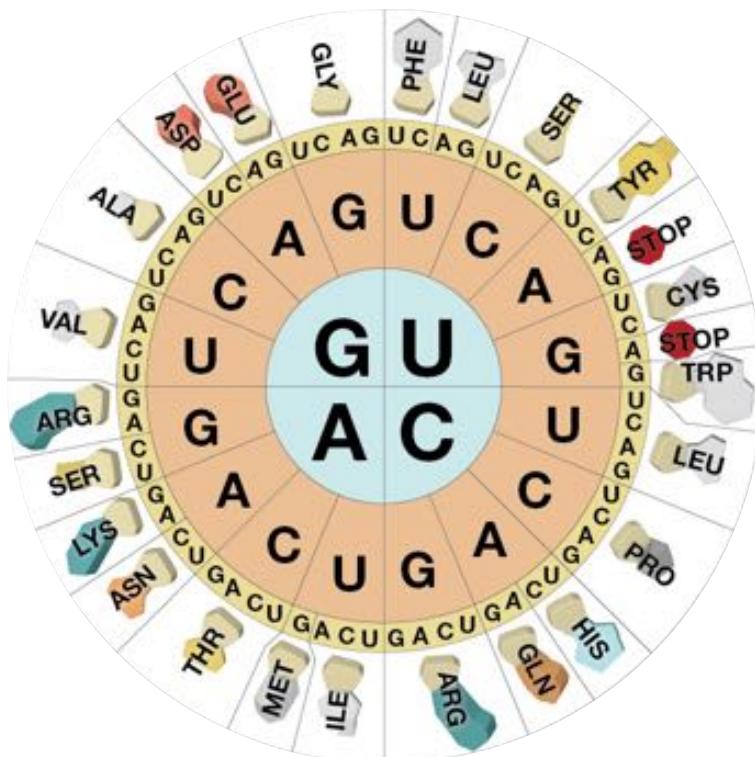
Molecular evolution

**“The primary cause of evolution is the
mutational change of genes”**

Nei & Kumar (2000)



Molecular evolution



Molecular evolution

original DNA sequence:

CCG	CTC	GTC	AAC	TAG
GLY	GLU	GLN	LEU	ILE

synonymous mutation:

$C > T$

CCG	CTT	GTC	AAC	TAG
GLY	GLU	GLN	LEU	ILE

non-synonymous mutation:

$A > C$

CCG	CTC	GTC	CAC	TAG
GLY	GLU	GLN	ILE	ILE

frameshift mutation:

insert C

CCG	CCT	CGT	CAA	ACTA
GLY	GLY	ALA	VAL	ASP

stop mutation:

$G > A$

CCG	CTC	ATC	AAC	TAG
GLY	GLU	STOP!		

Molecular evolution

The rate of non-synonymous (dN) to synonymous (dS) substitution informs about the selective pressure that has acted on a protein coding gene:

$dN/dS << 1$: purifying selection

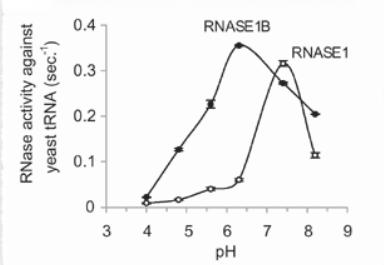
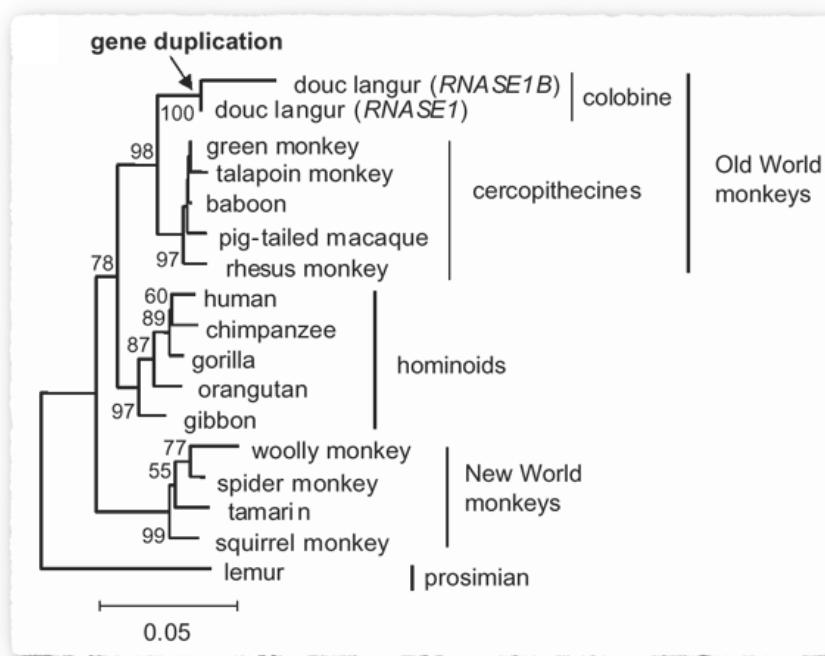
$dN/dS = 1$: neutrality

$dN/dS > 1$: positive selection (adaptive sequence evolution)

Molecular evolution

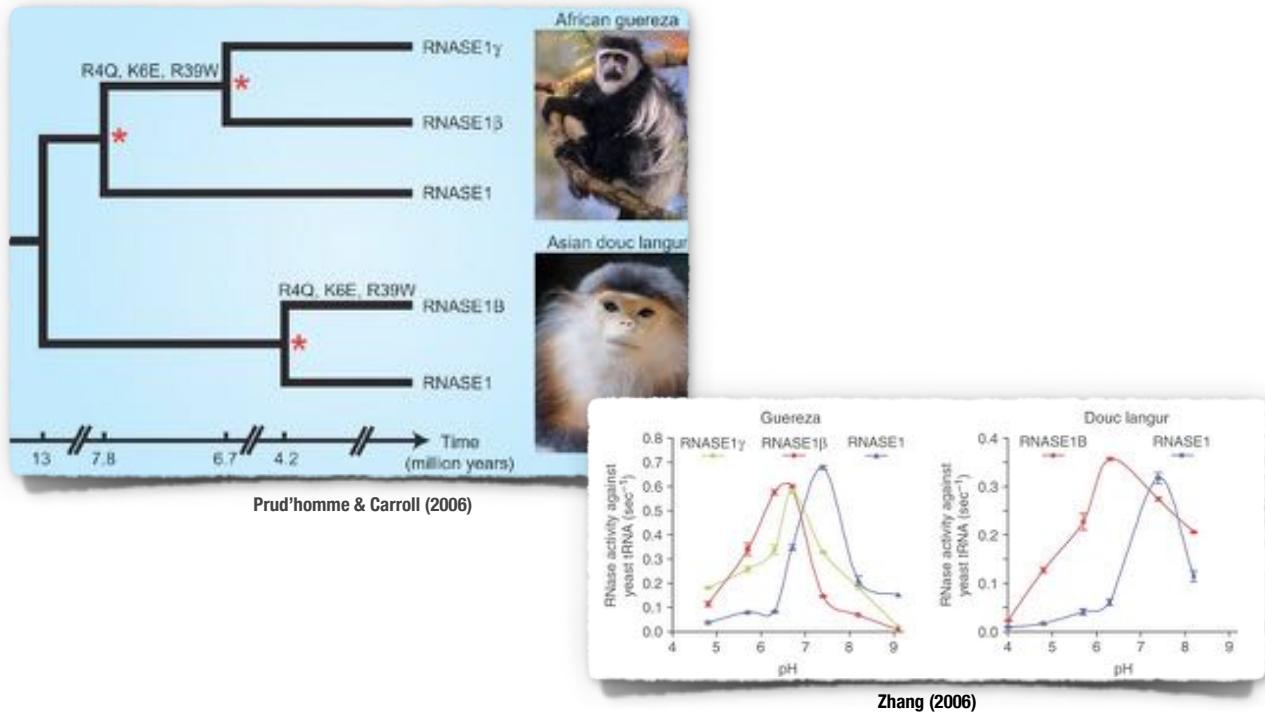
$Ka/Ks = 4.026$

Pancreatic ribonuclease in colobine monkeys



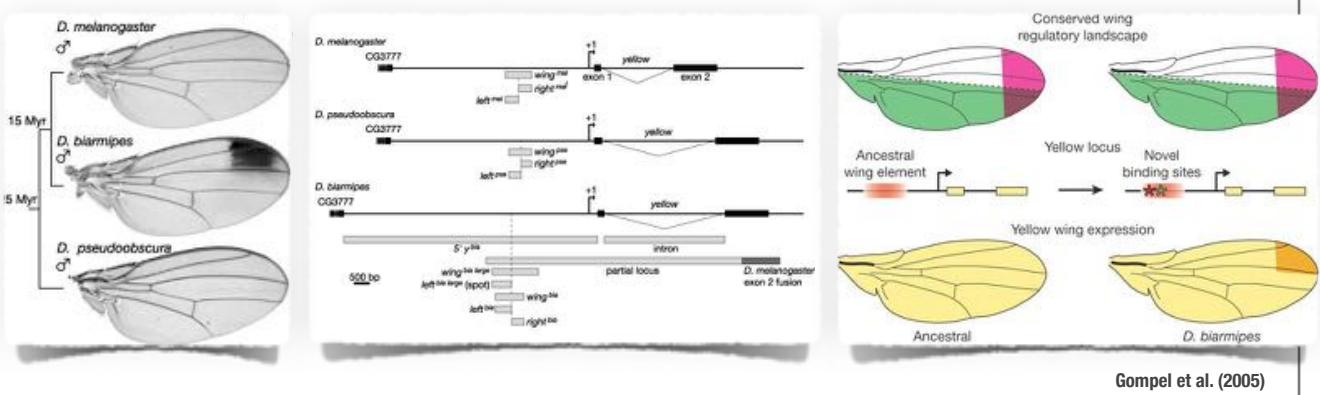
Molecular evolution

Pancreatic ribonuclease in leaf-eating monkeys



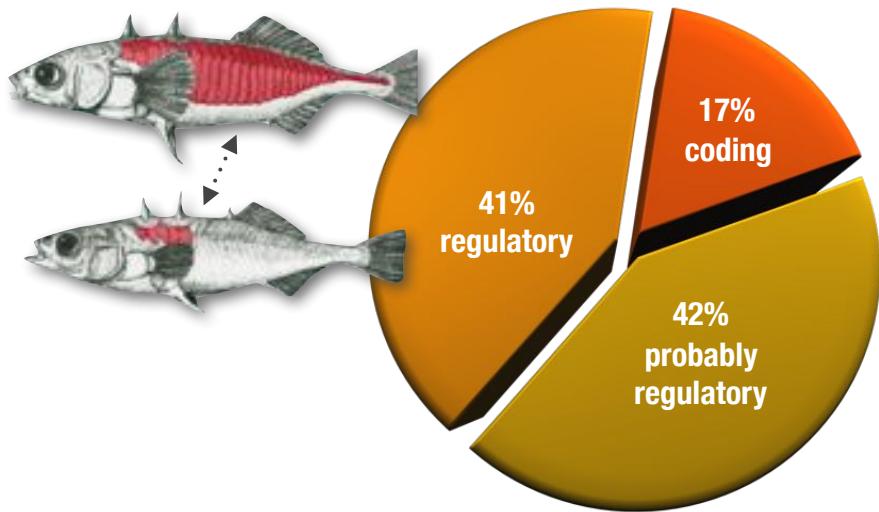
Molecular evolution

cis-regulatory evolution in fruitless



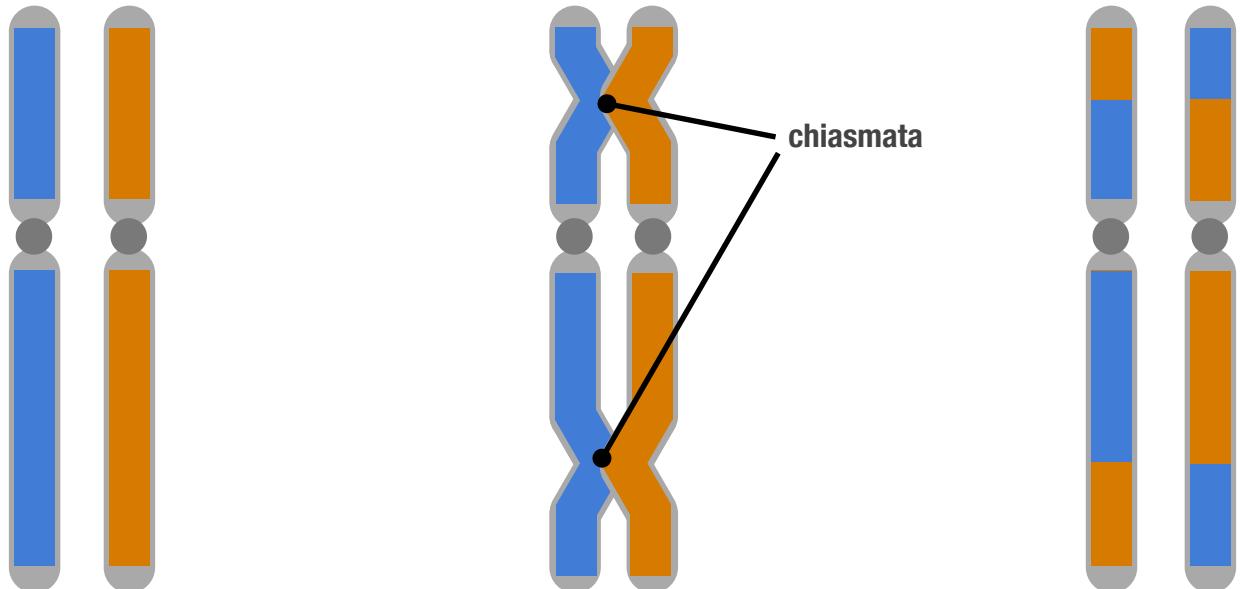
Molecular evolution

regulatory evolution in three spine sticklebacks



Chromosomal rearrangements

Recombination



Chromosomal rearrangements



deletion



duplication



inversion



reciprocal translocation

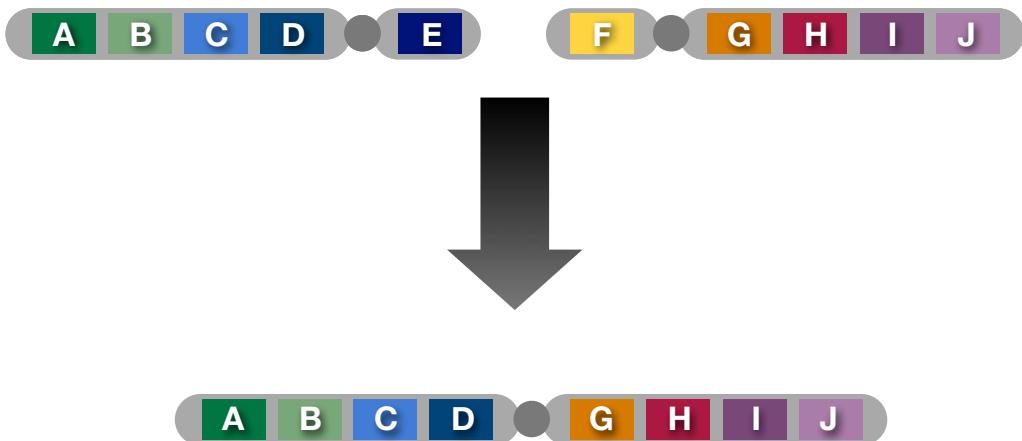
Chromosomal rearrangements

Chromosomal fission



Chromosomal rearrangements

Chromosomal fusion



Chromosomal rearrangements

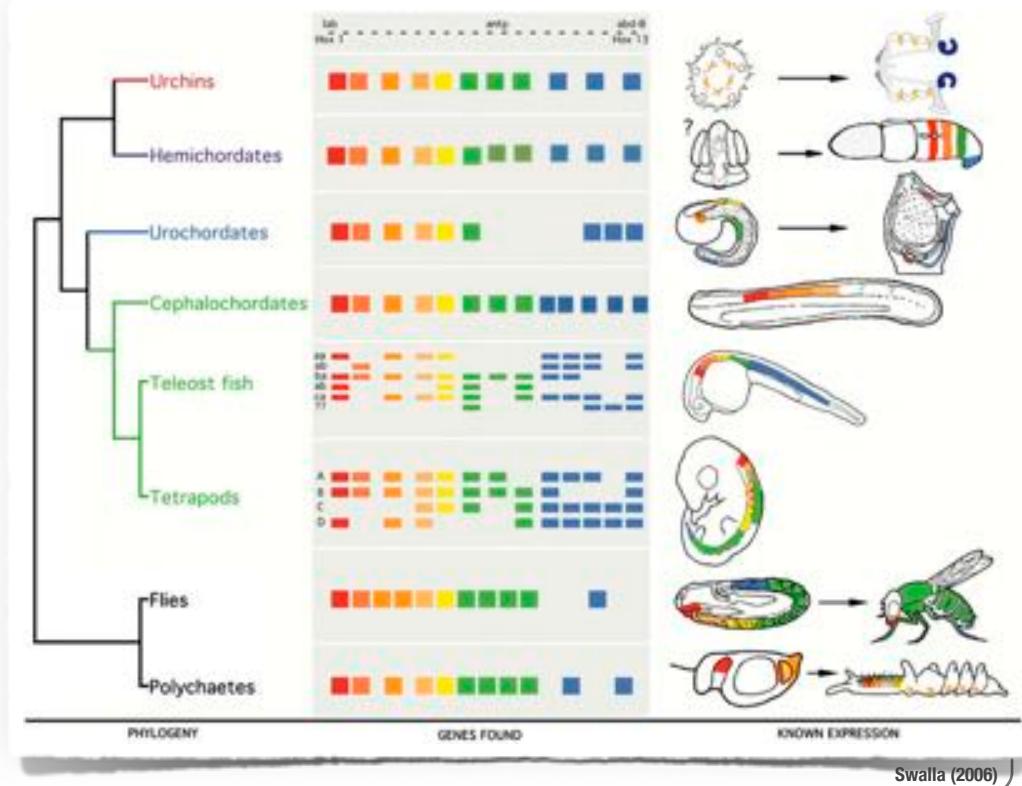
Chromosomal rearrangements in muntjac deers



images: wdr.de, mun.ca

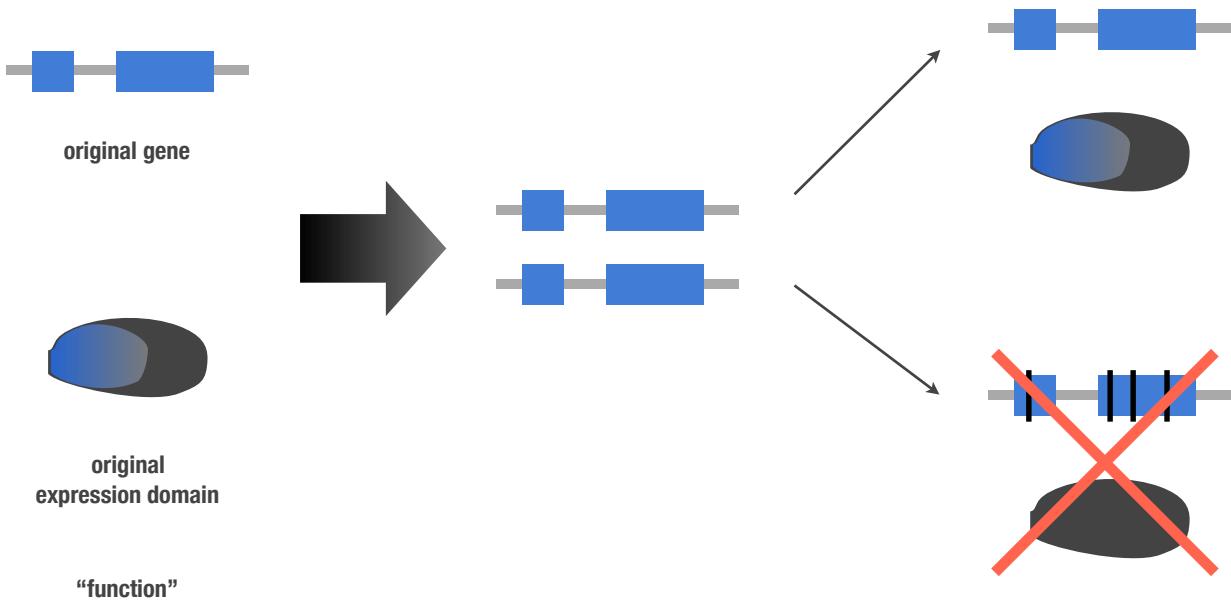
Gene and genome duplications

Hox gene clusters



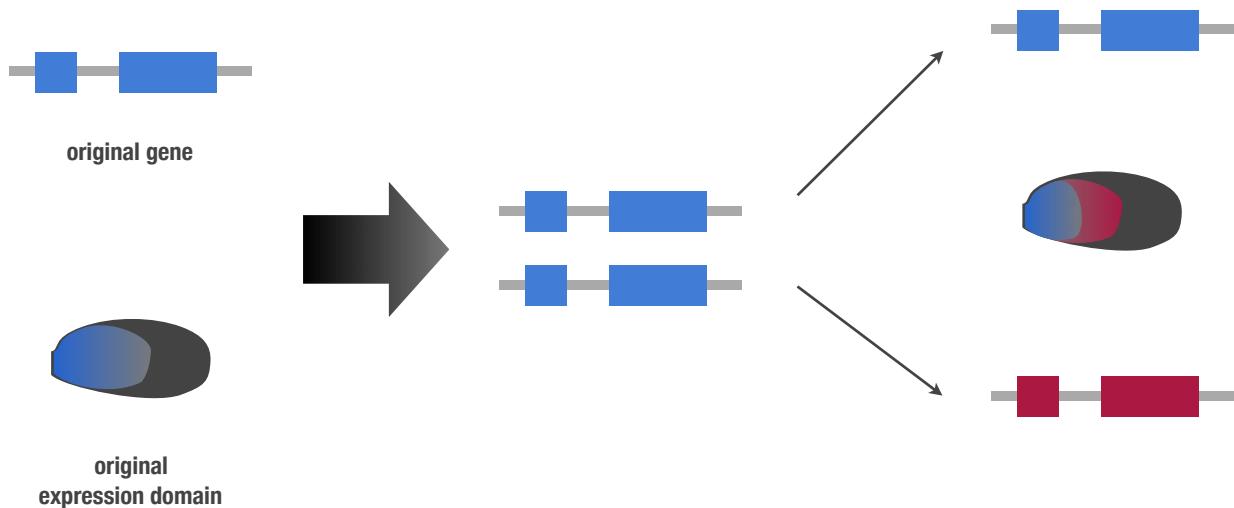
Gene and genome duplications

non-functionalization



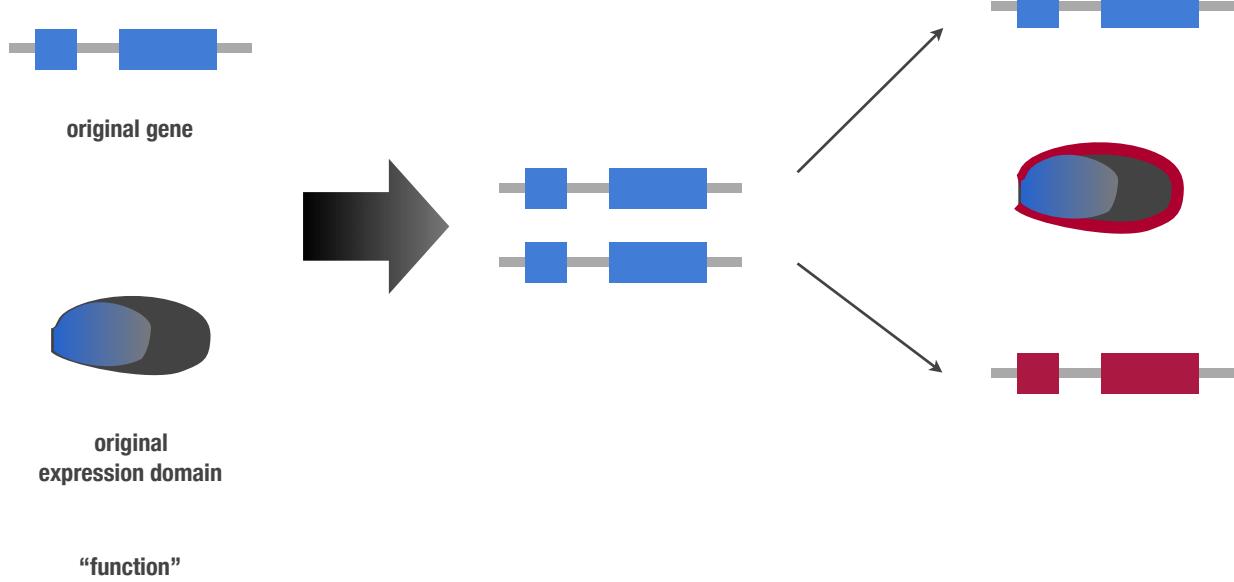
Gene and genome duplications

sub-functionalization



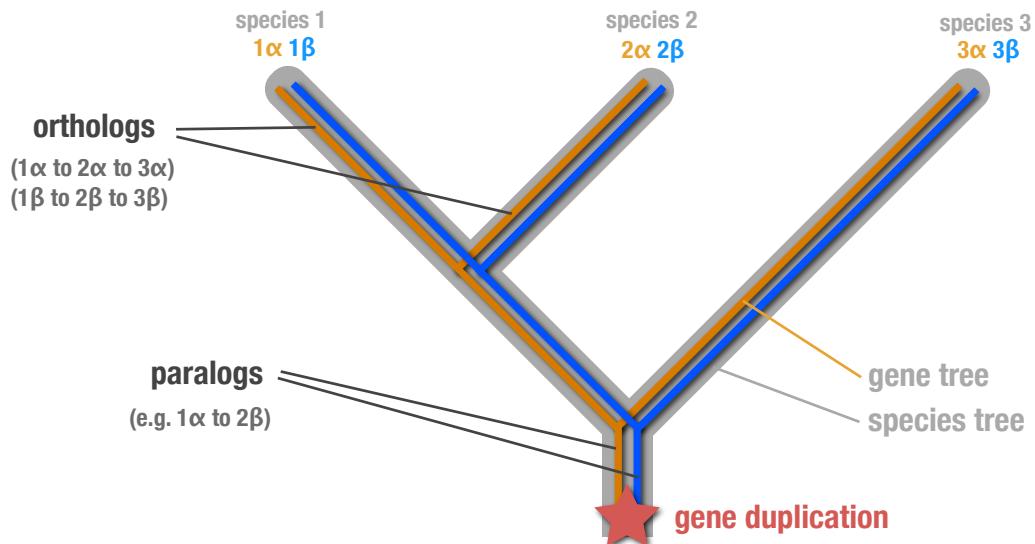
Gene and genome duplications

neo-functionalization

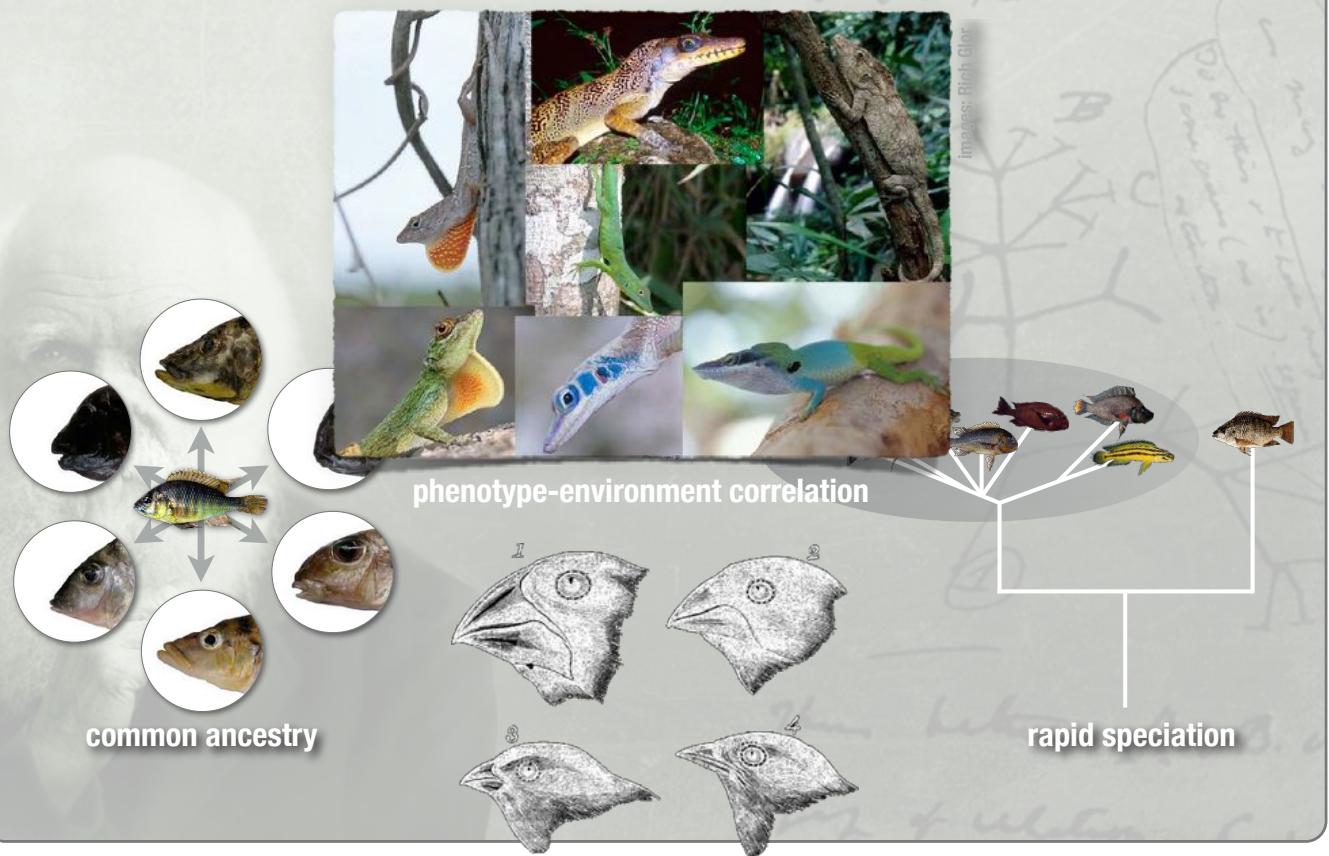


Gene and genome duplications

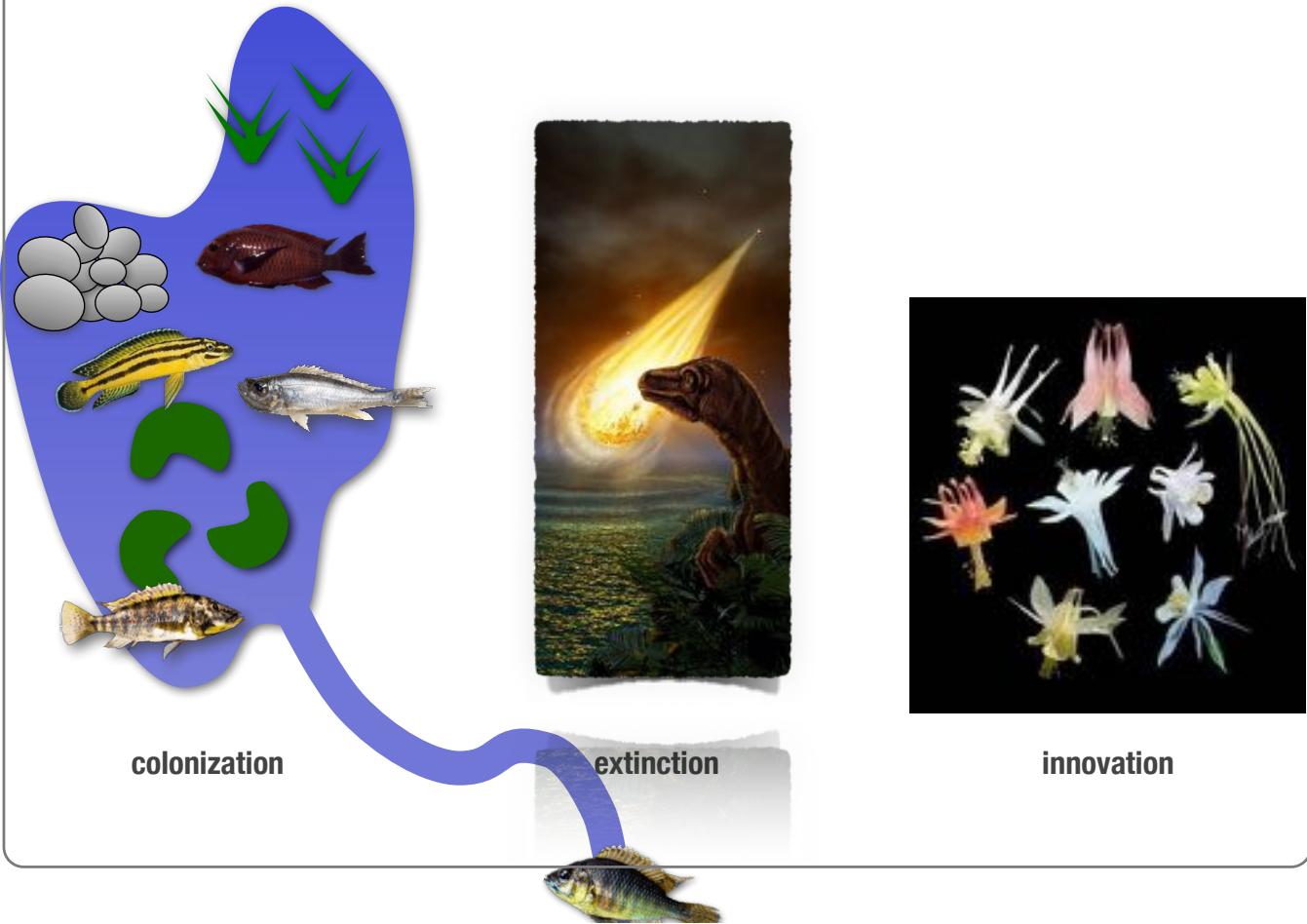
Caveats and pitfalls in phylogenetic inference: mixing paralogs with orthologs



Adaptive radiation

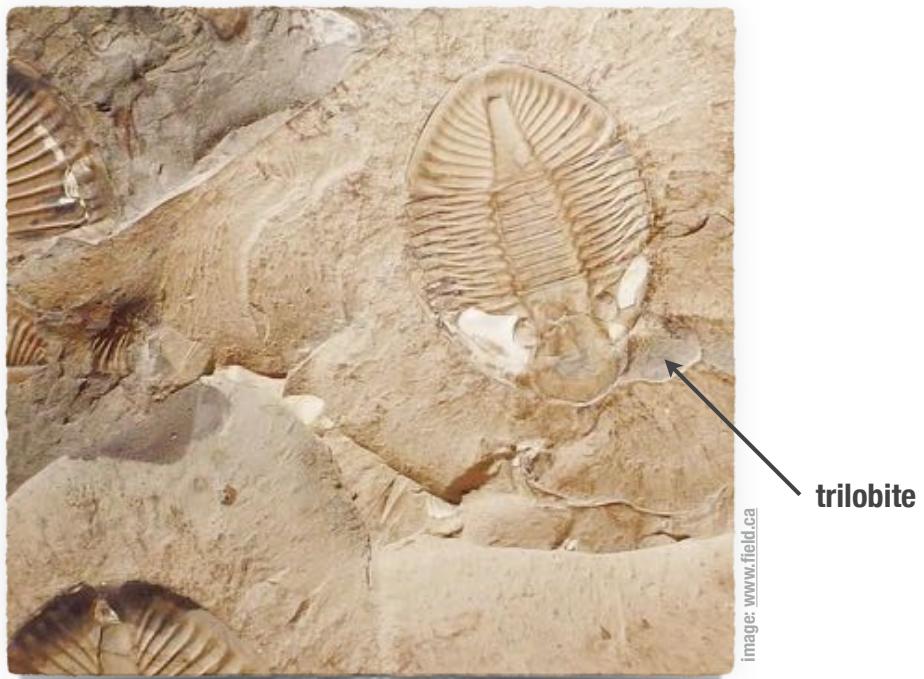


Ecological opportunity



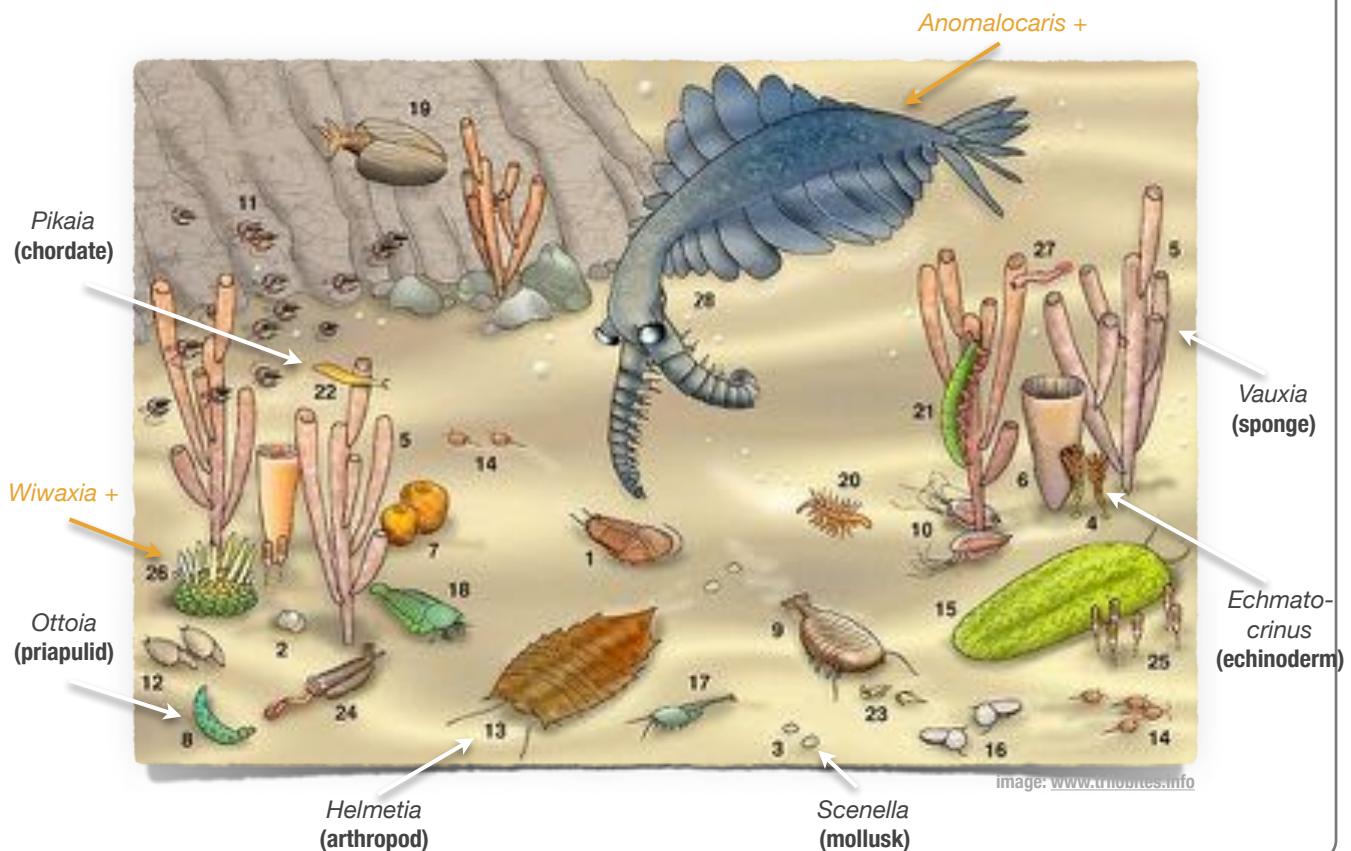
Cambrian explosion

The ‘Cambrian evolutionary radiation’ most likely was an adaptive radiation.



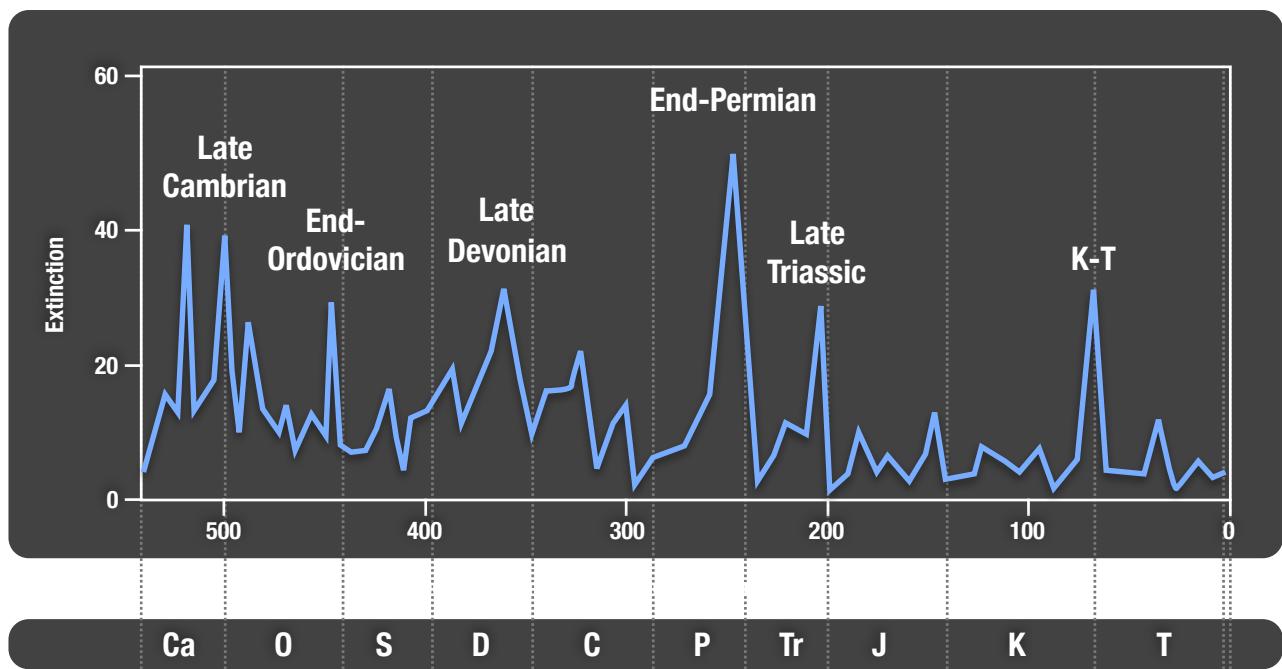
①The Burgess shale are fossil-rich deposits in the Yoho NP in British Columbia discovered by Charles D. Walcott in 1909

Cambrian explosion



Extinction

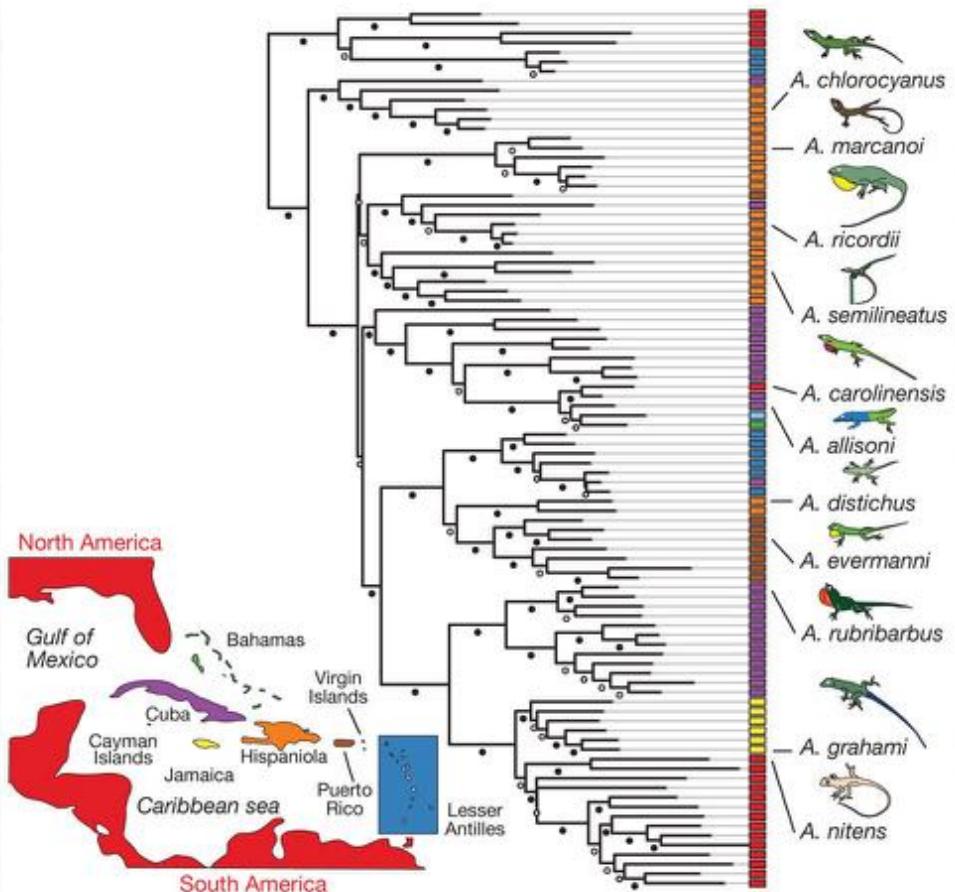
The ‘big five’ mass extinctions (based on marine fossils)



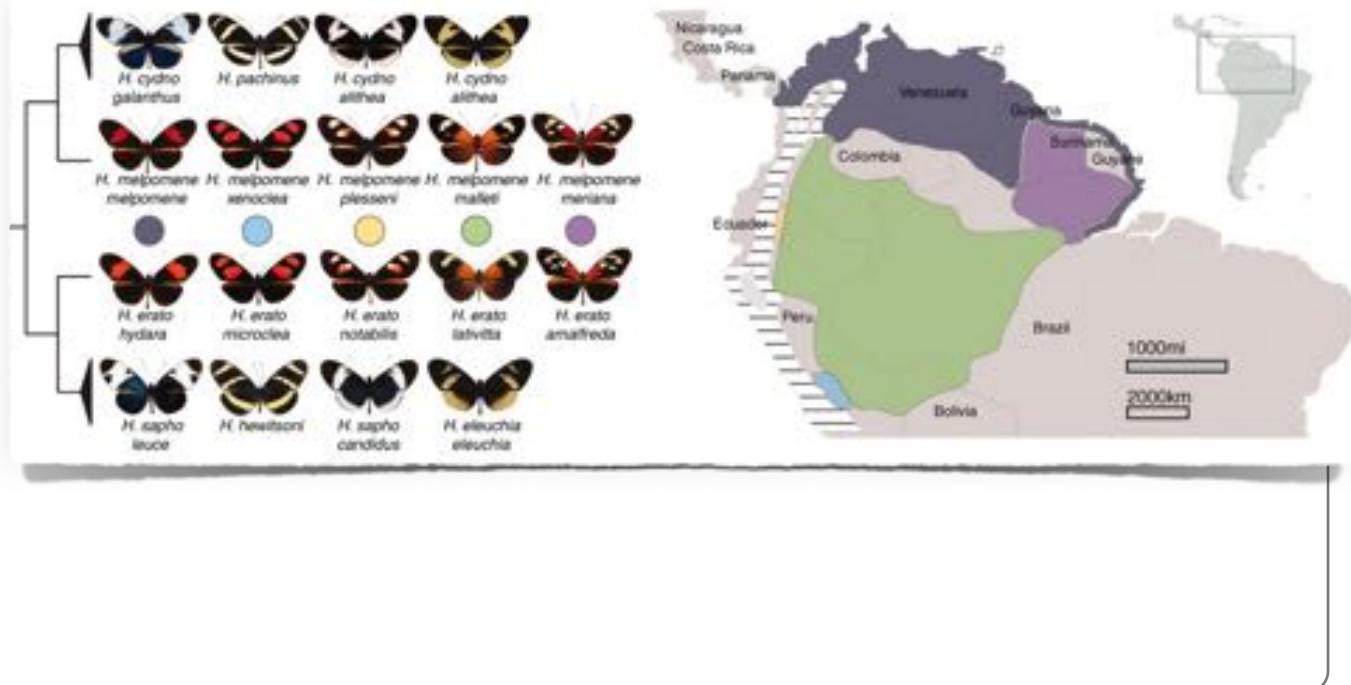
Radiating Genomes



Anolis

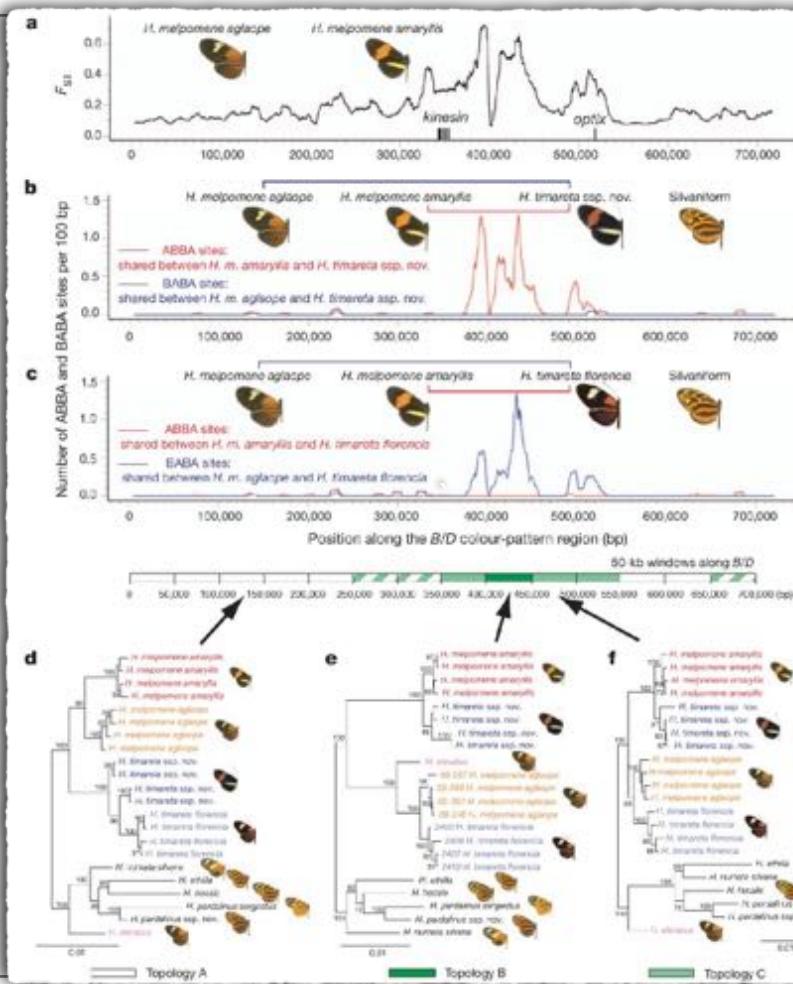


Heliconius



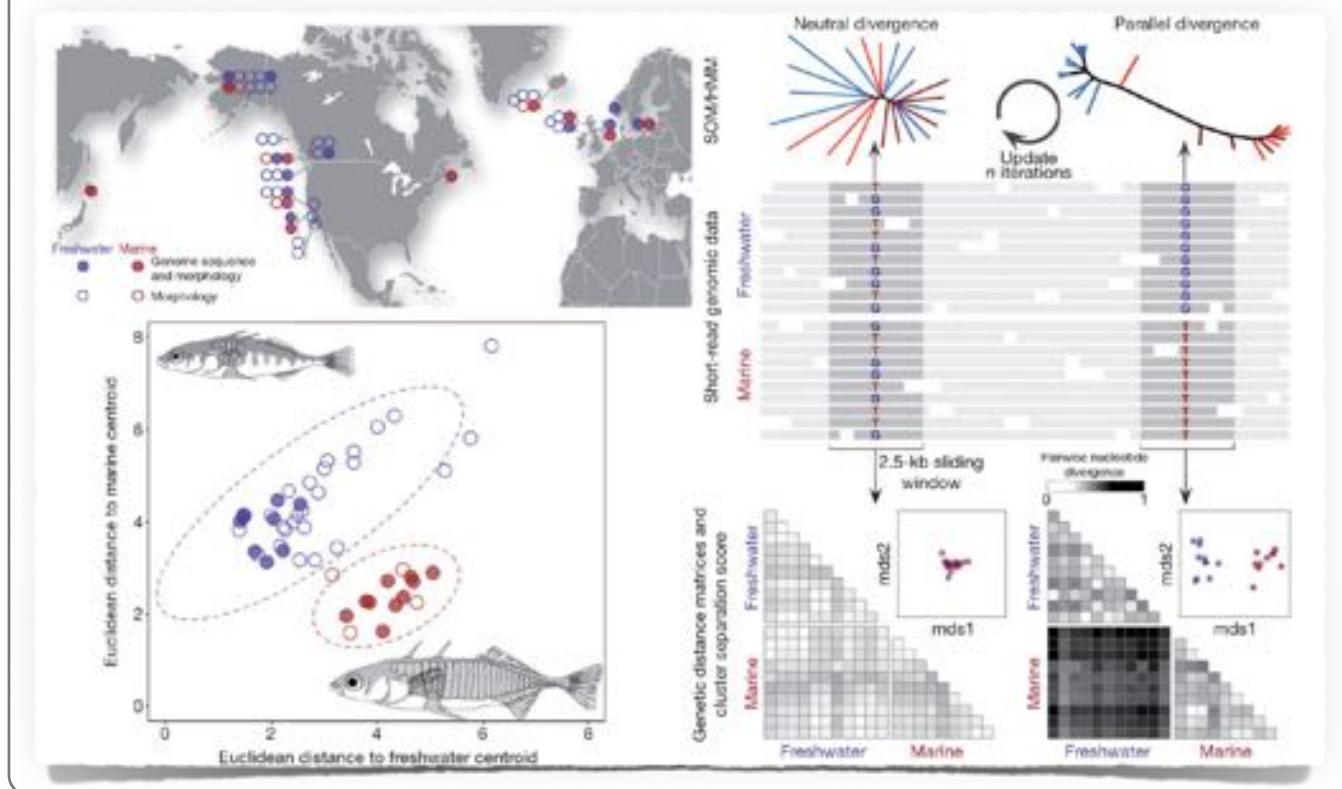
••• R Reed et al. (2011) Science

Heliconius



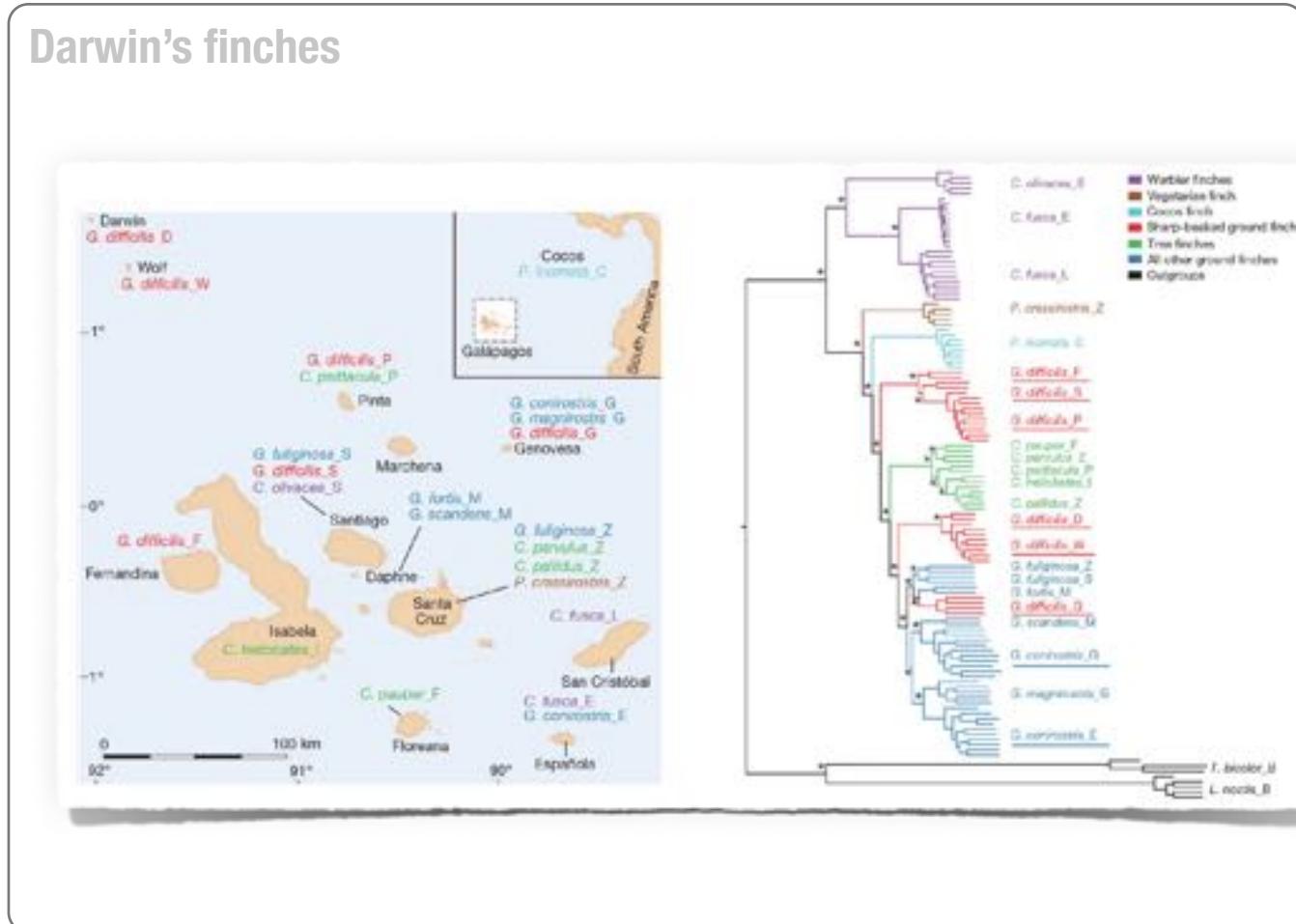
••• The Heliconius Genome Consortium (2012) Nature

Stickleback



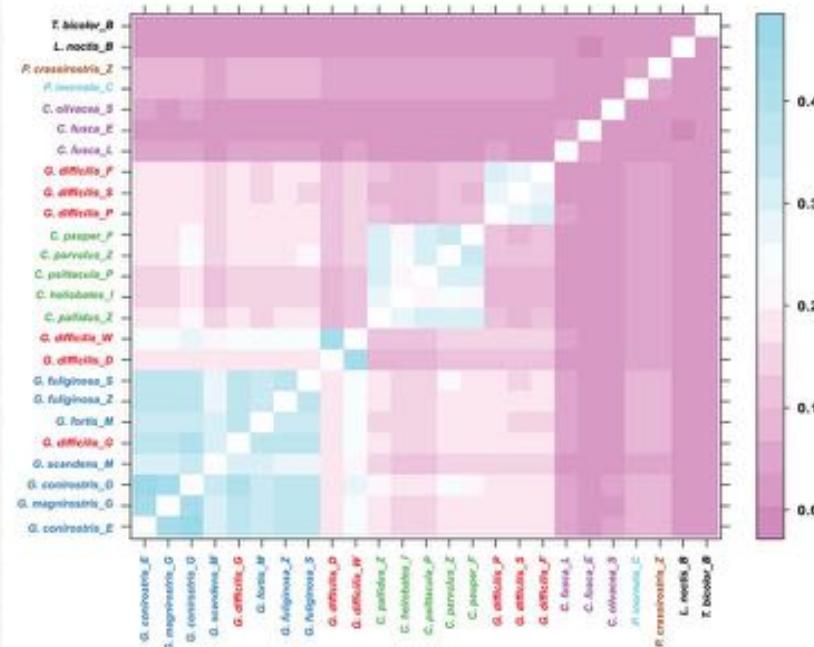
••• FC Jones et al. (2012) Nature

Darwin's finches



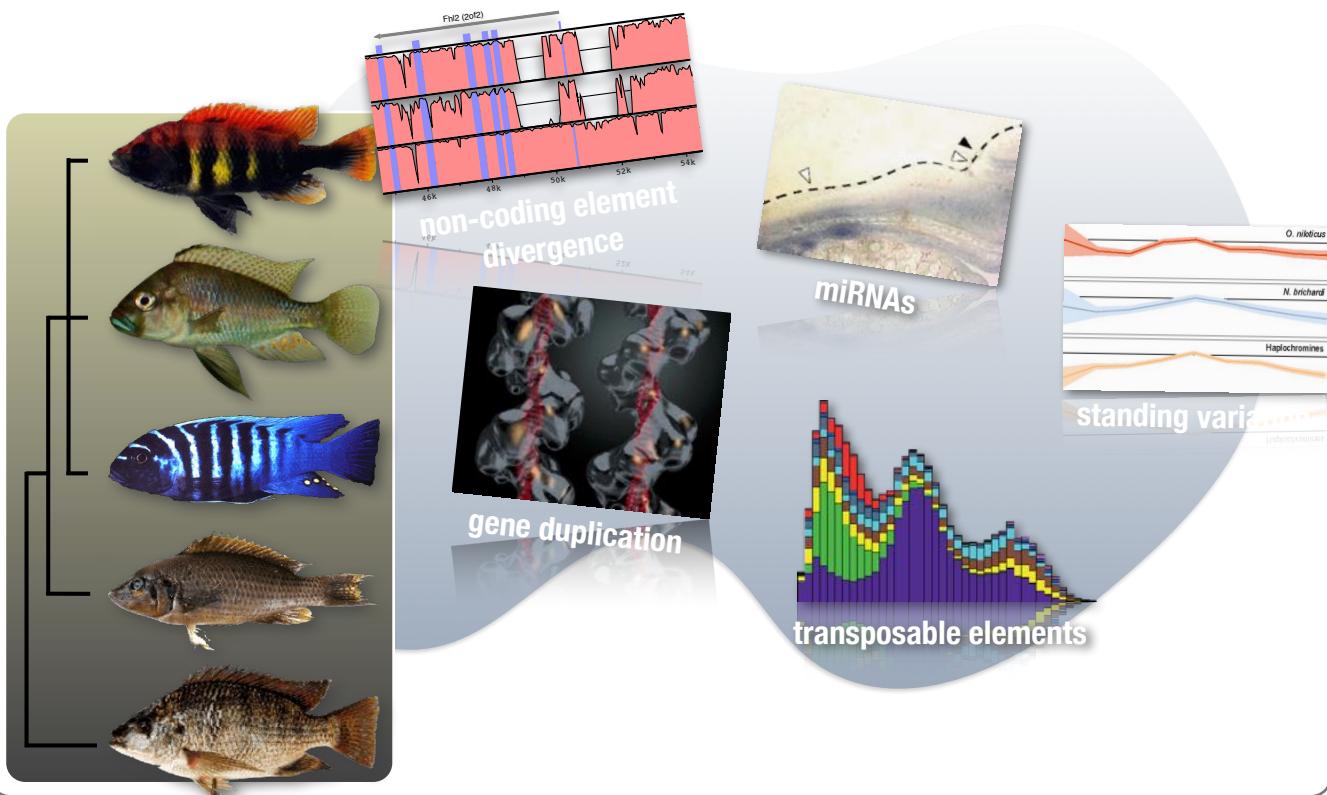
••• S Lamichhaney et al. (2015) Nature

Darwin's finches



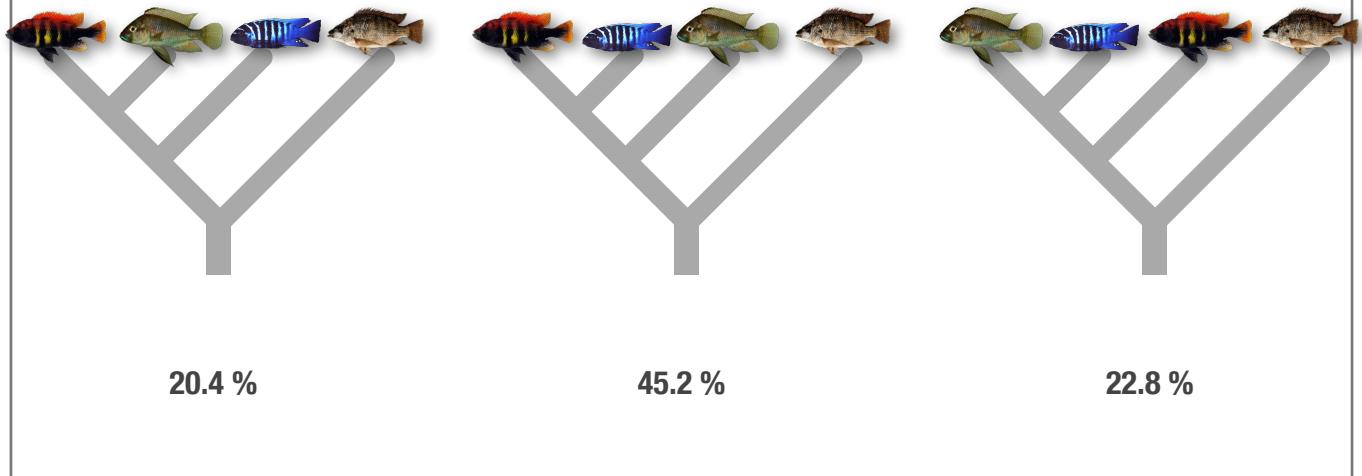
••• S Lamichhaney et al. (2015) Nature

cichlids



••• D Brawand et al. (2014) Nature

cichlids



••• D Brawand et al. (2014) Nature

radiating genomes

	genomes	gene duplications	mobile elements	regulatory changes	accelerated coding evolution	miRNAs	inversions	hybridization introgression
	1	n/r	YES	maybe	n/r	n/r	n/r	n/a
	5 (>100)	YES	YES	YES	YES	YES	n/r	YES
	1 (>100)	n/r	n/r	n/r	n/r	n/r	n/r	YES
	1 (>100)	n/r	YES	maybe	n/r	YES	n/r	YES
	1 (>100)	n/r	n/r	YES	n/r	n/r	YES	YES

••• D Berner & W Salzburger (2015) Trends in Genetics