



中央研究院
生物多樣性研究中心

Comparative and Evolutionary Genomics

Isheng Jason Tsai

[2021 version]

Compare genomes

- genome assembly
- evolution (at what timescale?)
- link/associate genotype to phenotype

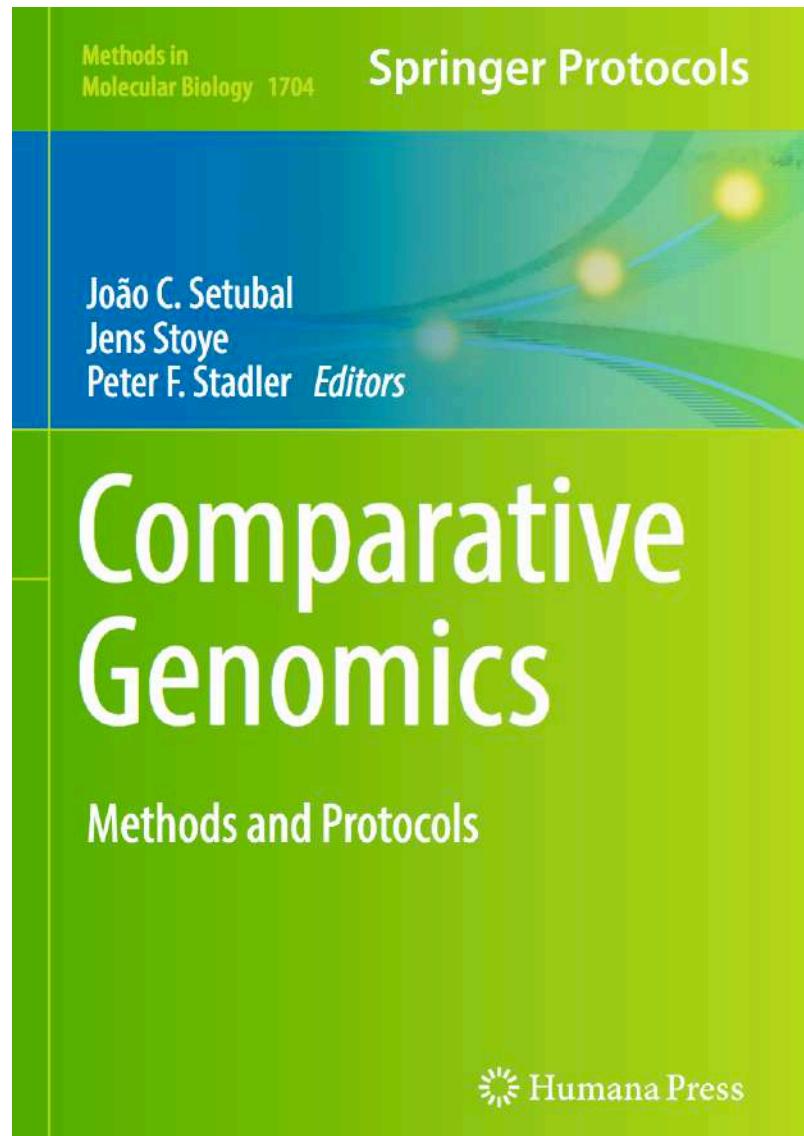
Lecture outline

Announcements

1. Concept of homology
2. Inferring homology
 1. Orthology prediction methods
 2. Caveats
3. Inferring synteny
4. Visualisation

5. Applications
 1. Phylogenomics
 2. Genome duplications
 3. Case studies

Recommended book



Comparative Genomics

Methods and Protocols

Edited by

João C. Setubal

Department of Biochemistry, Institute of Chemistry, University of São Paulo, São Paulo, SP, Brazil

Jens Stoye

Faculty of Technology and Center for Biotechnology (CeBiTec), Bielefeld University, Bielefeld, Germany

Peter F. Stadler

*Bioinformatics Group, Department of Computer Science, Interdisciplinary Center for Bioinformatics,
University of Leipzig, Leipzig, Germany*

 **Humana Press**

<https://link.springer.com/book/10.1007%2F978-1-4939-7463-4>

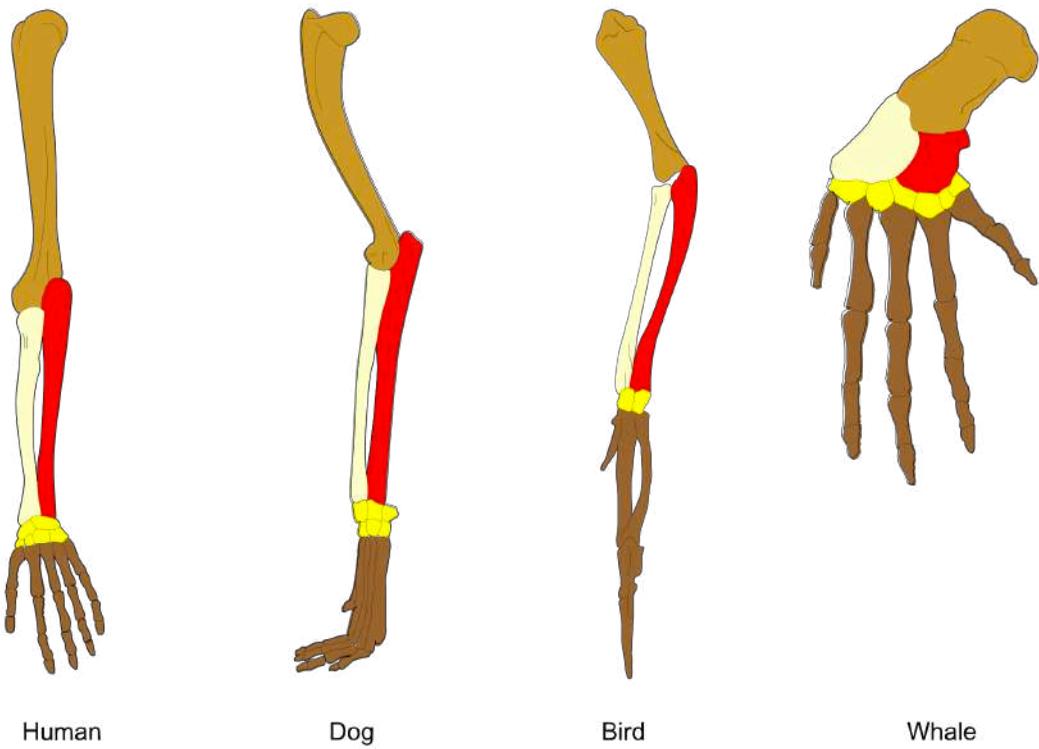
Homology

Termed before Darwin's time!



Sir Richard Owen KCB FRS (20 July 1804 – 18 December 1892) was an English [biologist](#), [comparative anatomist](#) and [paleontologist](#).

Homology

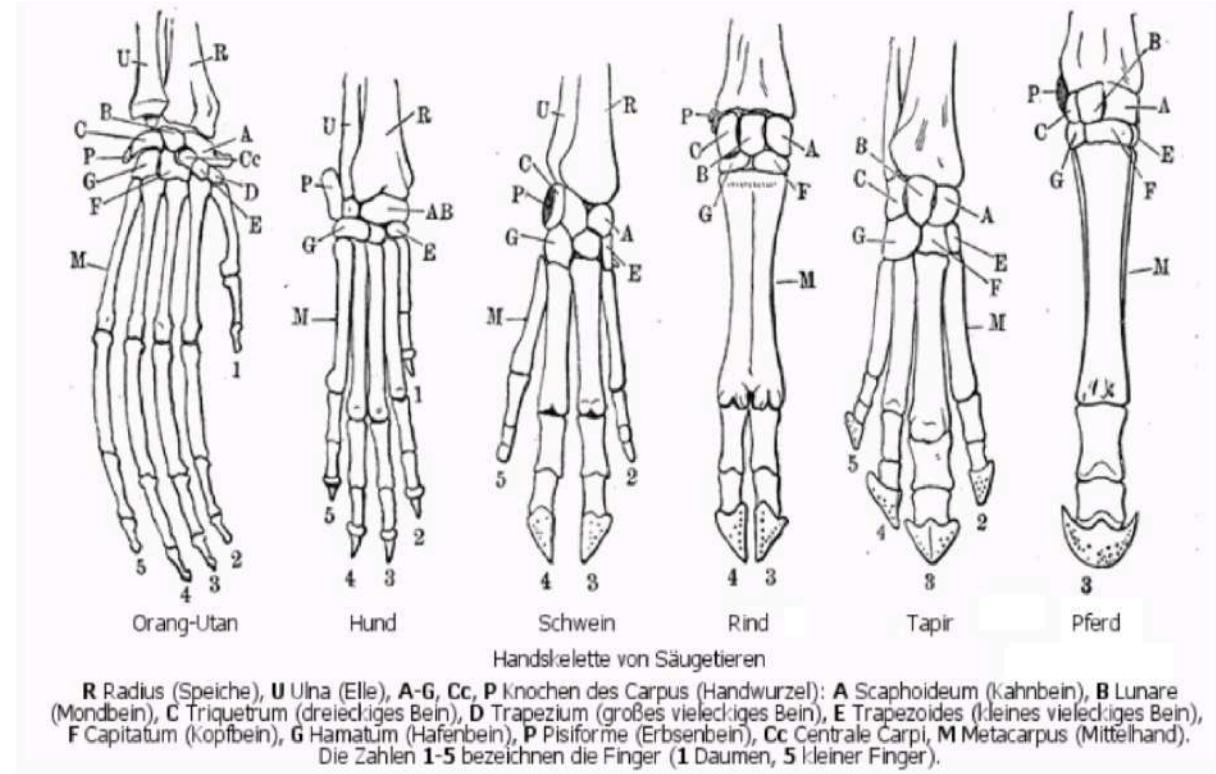


Human

Dog

Bird

Whale

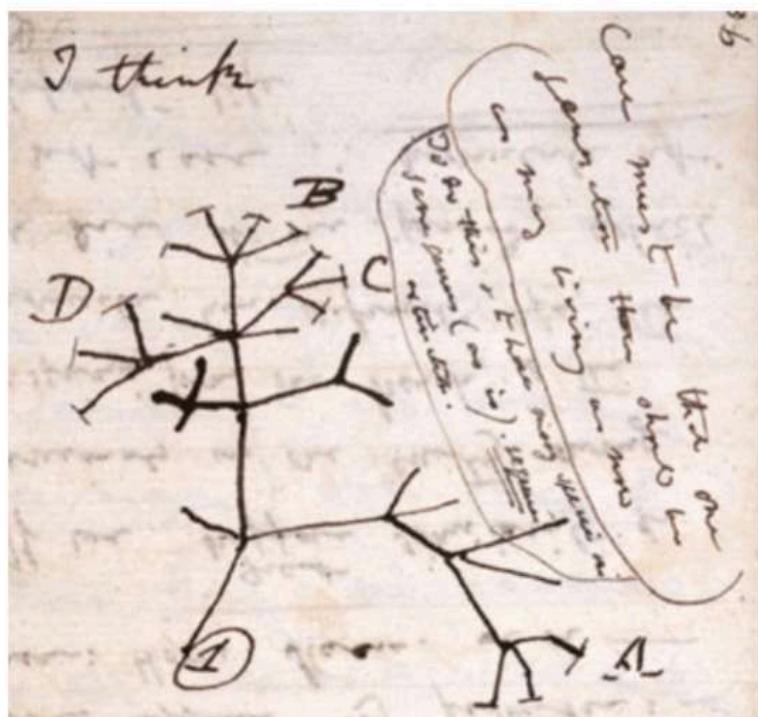


“the same organ in different animals under every variety of form and function” – Richard Owen

Owen 1843, p.379

[https://en.wikipedia.org/wiki/Homology_\(biology\)](https://en.wikipedia.org/wiki/Homology_(biology))

Darwin later reformulated homology as a result of “descent with modification”



CHAPTER VI.

DIFFICULTIES ON THEORY.

Difficulties on the theory of descent with modification—Transitions—Absence or rarity of transitional varieties—Transitions in habits of life—Diversified habits in the same species—Species with habits widely different from those of their allies—Organs of extreme perfection—Means of transition—Cases of difficulty—*Natura non facit saltum*—Organs of small importance—Organs not in all cases absolutely perfect—The law of Unity of Type and of the Conditions of Existence embraced by the theory of Natural Selection, 154

CHAPTER XIII.

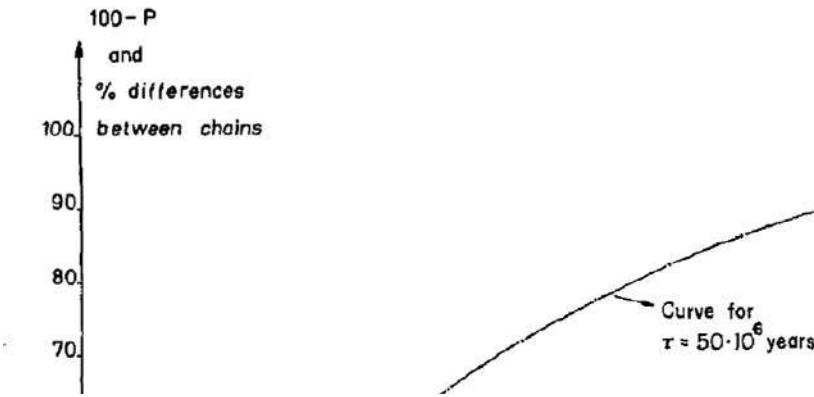
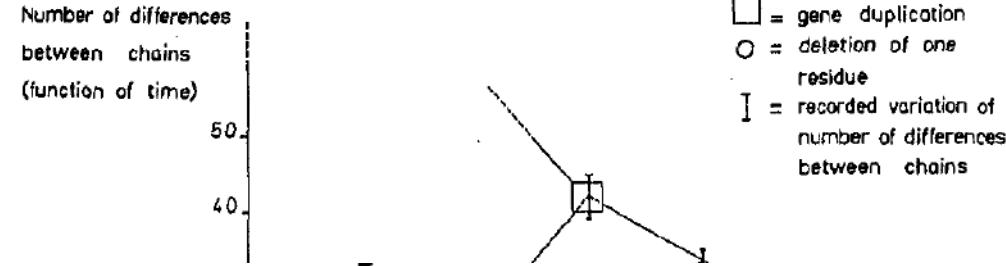
MUTUAL AFFINITIES OF ORGANIC BEINGS: MORPHOLOGY: EMBRYOLOGY: RUDIMENTARY ORGANS.

CLASSIFICATION, groups subordinate to groups—Natural system—Rules and difficulties in classification, explained on the theory of descent with modification

Homology

Homologs (any features: genes, trait, morphology) share **ancestry**

Ancestral sequences and Molecular clock (Emile Zuckerkandl and Linus Pauling)



There may thus exist a molecular evolutionary clock.

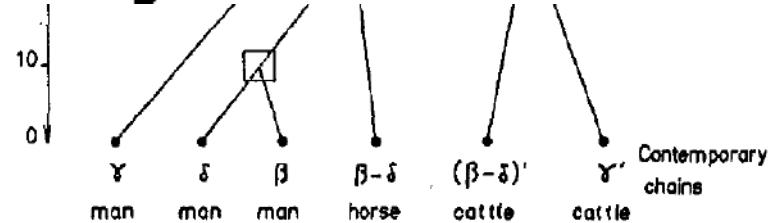
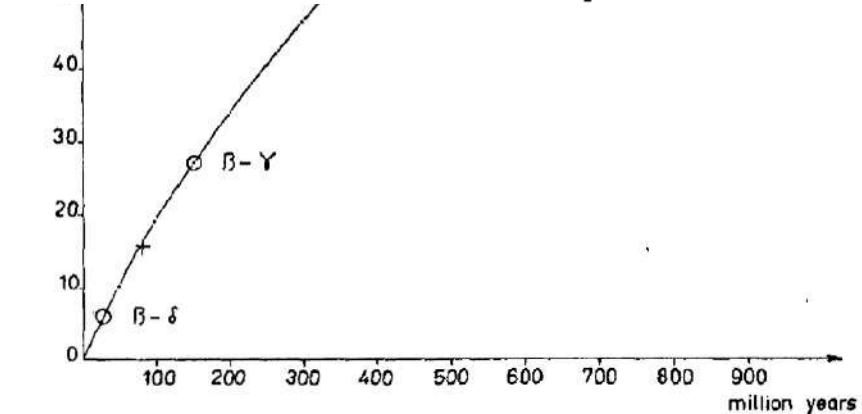


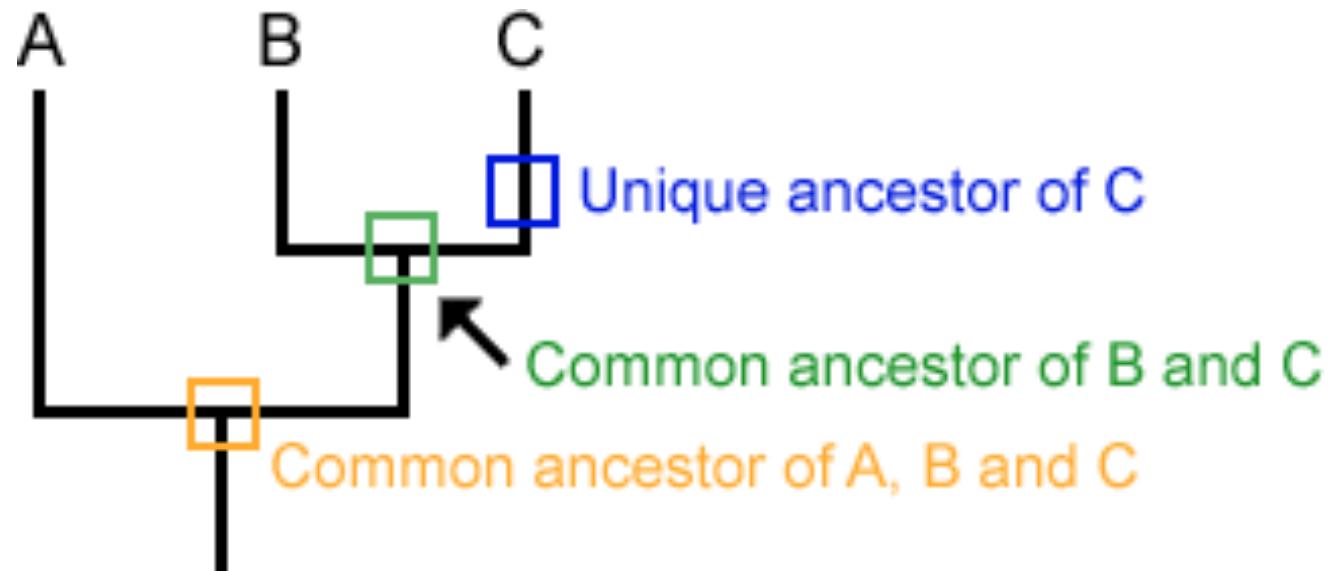
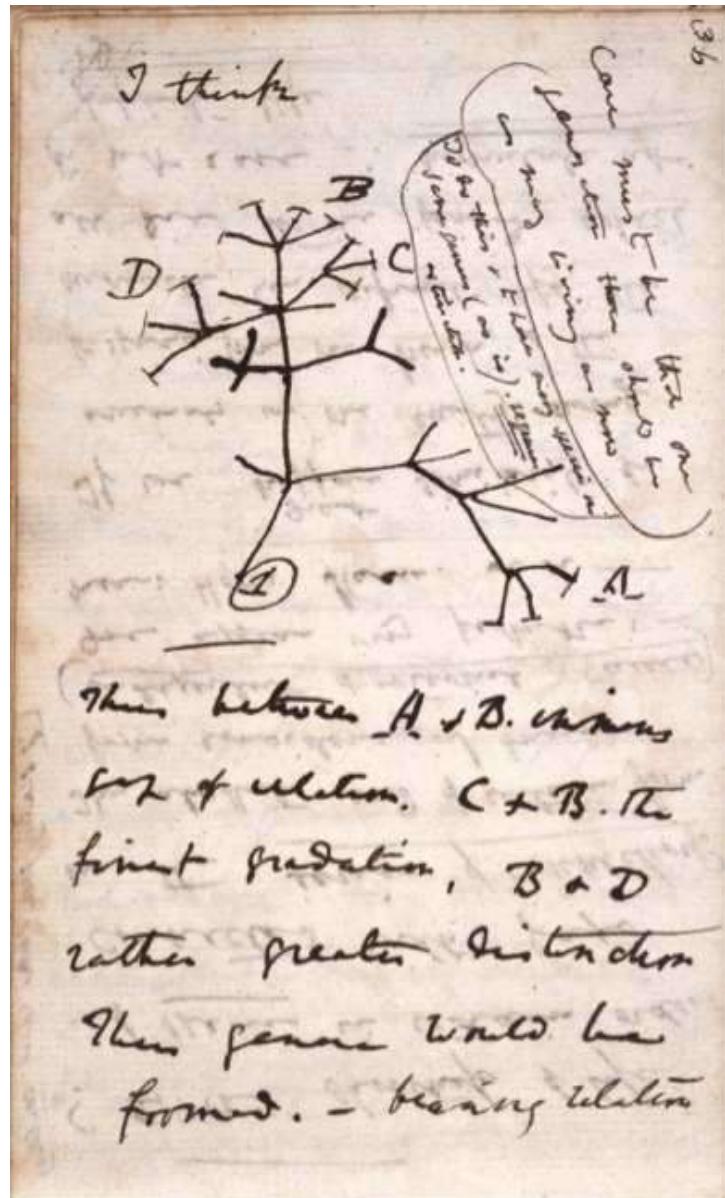
FIG. 4. Probable evolutionary relationship of some mammalian hemoglobin chains.

"Zuckerkandl and Pauling hypothesized that orthologous proteins evolved through divergence from a common ancestor. Consequently, by comparing the sequence of hemoglobin in currently extant organisms, it became possible to predict the 'ancestral sequences' of hemoglobin and, in the process, its evolutionary history up to its current forms"



Evolutionary divergence and convergence in proteins
Zuckerkandl, E. and Pauling, L (1965)

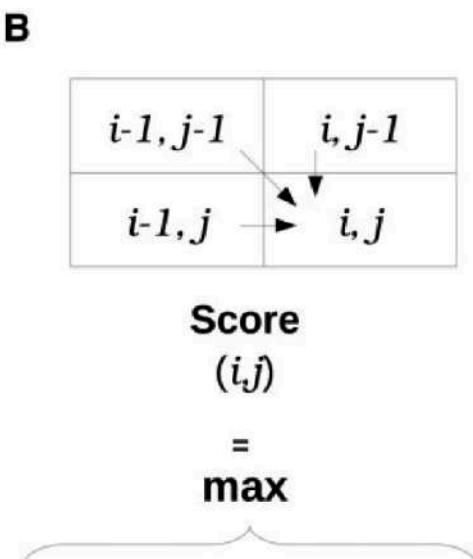
Relationships between sequences recapitulate evolutionary relationships



A mathematical framework for sequence alignments

A match +5 mismatch -4 gap -1

	A	T	C	G	
0	0	0	0	0	
A	0	5	-1	-1	-1
T	0	4	10 ← 9	8	
G	0	3	9	8	14



- Score $(i-1, j-1)$ + Match / Mismatch
- Score $(i, j-1)$ + gap
- Score $(i-1, j)$ + gap

C

Best Alignment :
(Score = 38)

ATCG
|| |
AT G

Table 1. An excerpt of the PAM1 amino acid substitution matrix

10 ⁴ P ^a		Ala	Arg	Asn	Asp	Cys	Gln	...	Val
		A	R	N	D	C	Q	...	V
Ala	A	9867	2	9	10	3	8	...	18
Arg	R	1	9913	1	0	1	10	...	1
Asn	N	4	1	9822	36	0	4	...	1
Asp	D	6	0	42	9859	0	6	...	1
Cys	C	1	1	0	0	9973	0	...	2
Gln	Q	3	9	4	5	0	9876	...	1
...
Val	V	13	2	1	1	3	2	...	9901

^aEach numeric value represents the probability that an amino acid from the i-th column be substituted by an amino acid in the j-th row (multiplied by 10 000).

A brief history of bioinformatics

Jeff Gauthier, Antony T Vincent, Steve J Charette, Nicolas Derome
Briefings in Bioinformatics (2018) <https://doi.org/10.1093/bib/bby063>

1970-2000s – Paradigm shifts and parallel advances in biology and computer science

- Protein sequencing to DNA sequencing (faster / cheaper)
- Use DNA sequences to infer phylogenetic trees
- Sequence of marker genes and genomes
- Beyond sequences (structural bioinformatics)

- Faster computers
- GPUs
- Free software movement
- New Programming languages (Perl created by Larry Wall in 1987)

- Internet
- Online databases (NCBIs)

A brief history of bioinformatics

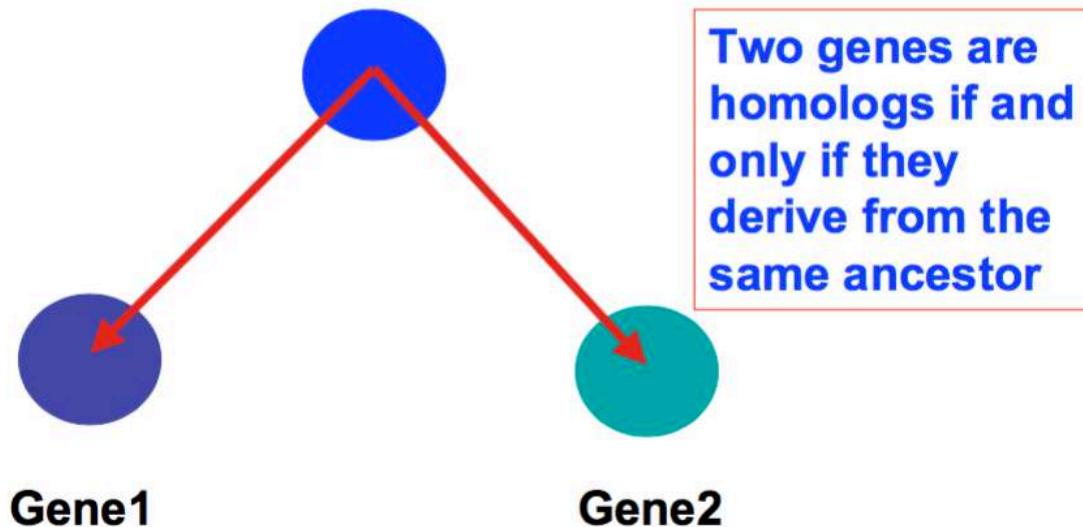
Jeff Gauthier, Antony T Vincent, Steve J Charette, Nicolas Derome
Briefings in Bioinformatics (2018) <https://doi.org/10.1093/bib/bby063>

Search for similarity , collinearity, conservation of morphological characters

Search for similarity

One of the most frequent activity in Bioinformatics

Common ancestor



Homology is almost uniquely inferred by sequence similarity

Beware ; why?

~~Significant homology~~

55% married?
45% grandmom?

~~Weak homology~~

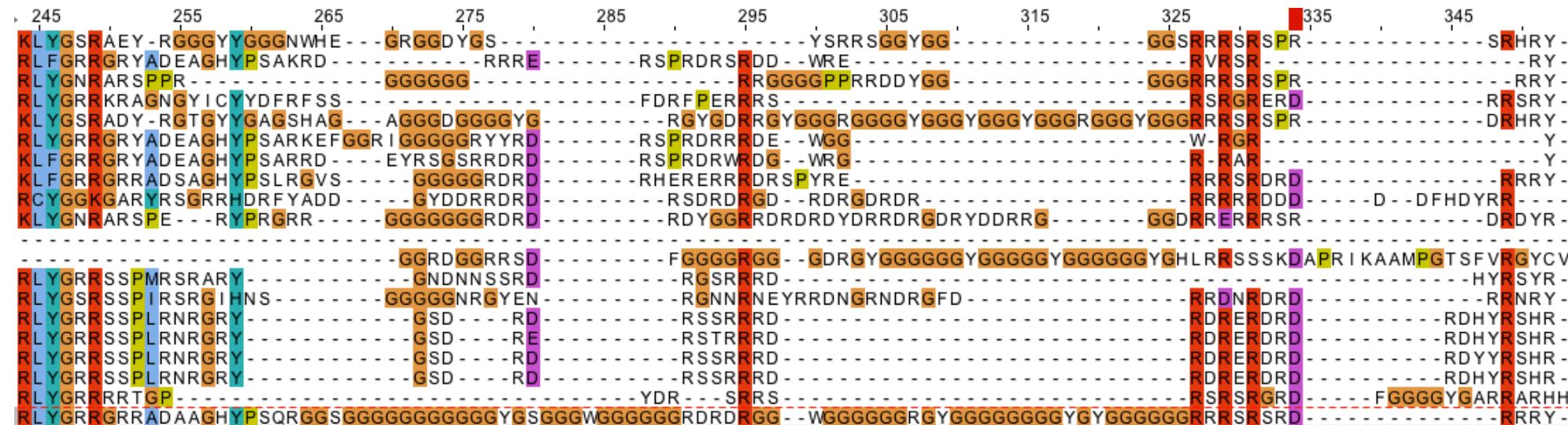
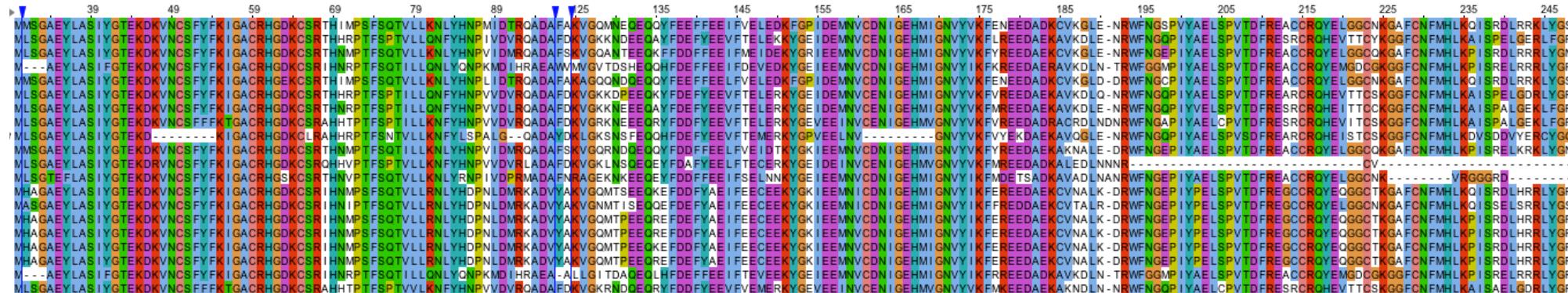
If you think about the meaning of homology,
then it really makes no sense

Significant similarity

Weak similarity

Extension of homology to sequences

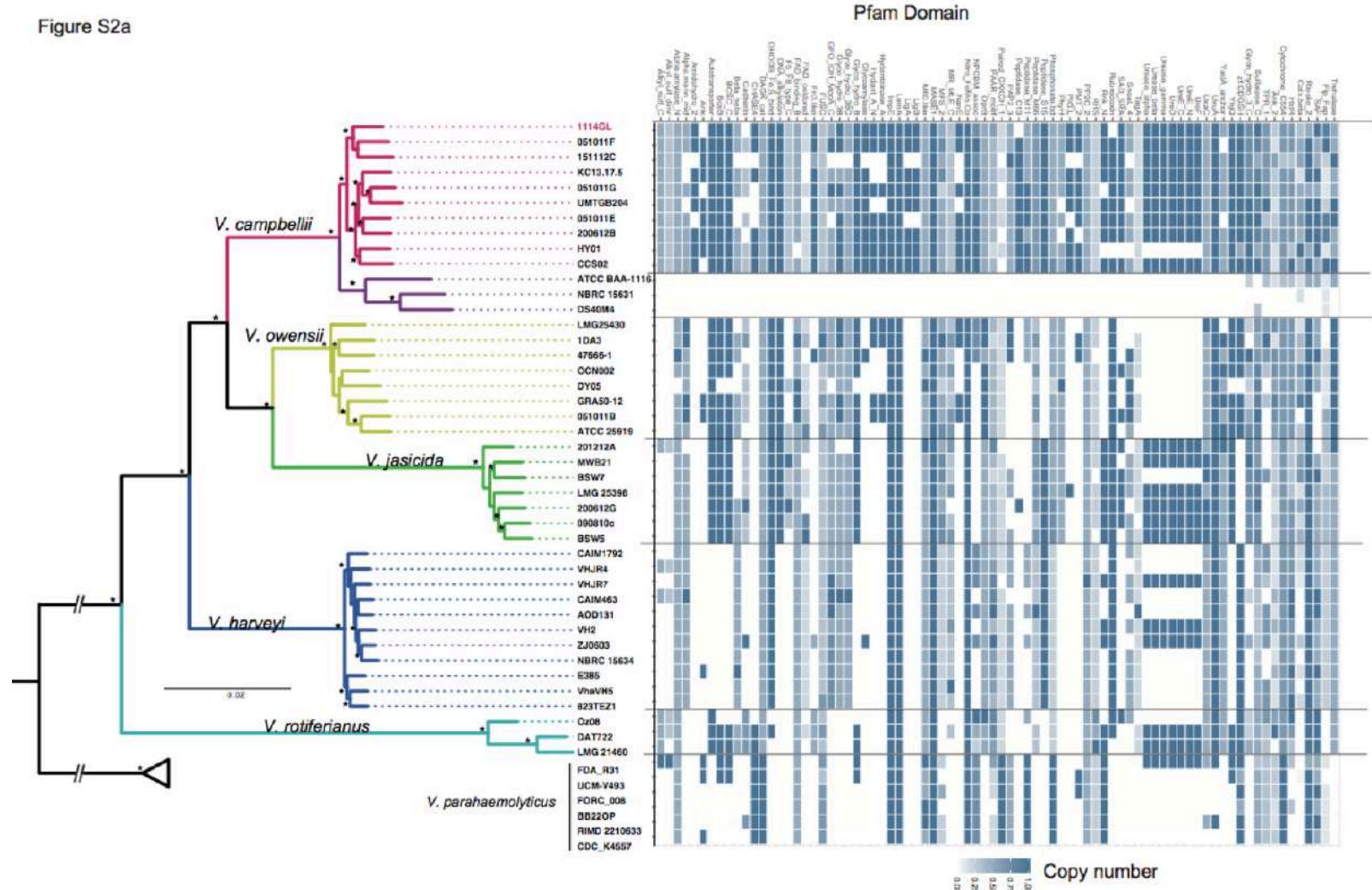
Two sequences are homologous if they share the same a common ancestor



Extension of homology to genomes / species

Similarity of individual sequences at different levels (sequence similarity ; domain combinations)

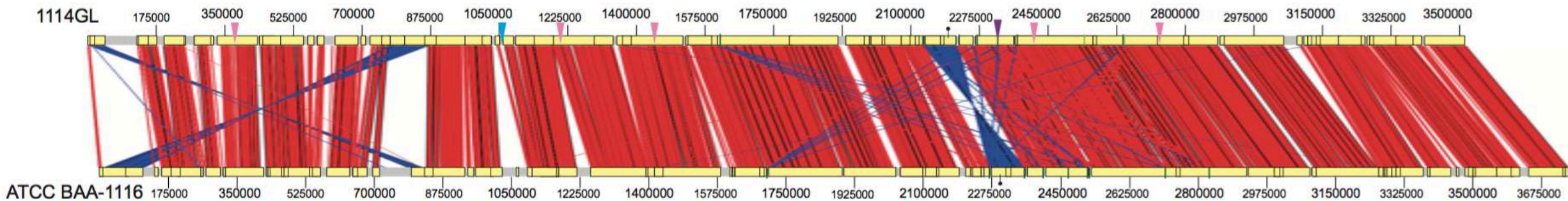
Figure S2a



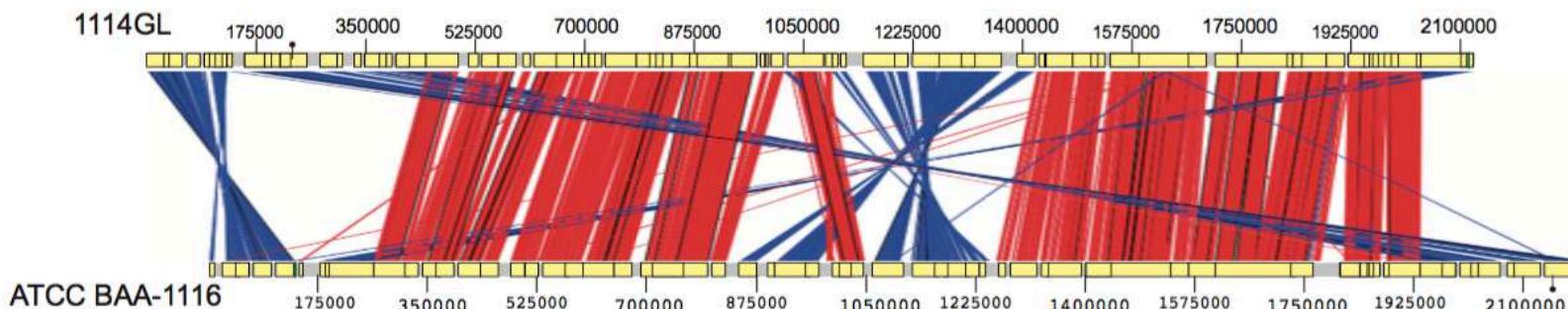
Extension of homology to genomes / species

Similarity of individual features (ordering and rearrangement)

(a) Chromosome I



(b) Chromosome II



- ▼ Gap
- ▼ Inter-scaffold gap
- ▲ The insertion including two genes with Big_2 domains
- Ori
- rRNA operon
- Partial rRNA operon

Structural Dynamics of Eukaryotic Chromosome Evolution

Evan E. Eichler^{1*} and David Sankoff²

Large-scale genome sequencing is providing a comprehensive view of the complex evolutionary forces that have shaped the structure of eukaryotic chromosomes. Comparative sequence analyses reveal patterns of apparently random rearrangement interspersed with regions of extraordinarily rapid, localized genome evolution. Numerous subtle rearrangements near centromeres, telomeres, duplications, and interspersed repeats suggest hotspots for eukaryotic chromosome evolution. This localized chromosomal instability may play a role in rapidly evolving lineage-specific gene families and in fostering large-scale changes in gene order. Computational algorithms that take into account these dynamic forces along with traditional models of chromosomal rearrangement show promise for reconstructing the natural history of eukaryotic chromosomes.

Comparative genomics in 2003

Group	Species	Common	Size (Mb)	Chromosome (1N)	Gene no.	Repeat %
Mammal	<i>Homo sapiens</i>	Human	2900	23	30,000	46
Mammal	<i>Mus musculus</i>	House mouse	2500	20	30,000	38
Fish	<i>Takifugu rubripes</i>	Tiger pufferfish	400	22 (?)	30,000	<10
Urochordate	<i>Ciona intestinalis</i>	Sea squirt	155	14	16,000	~10
Insect	<i>Anopheles gambiae</i>	Malaria mosquito	280	3	14,000	16
Insect	<i>Drosophila melanogaster</i>	Fruit fly	137	4	13,600	2
Nematode	<i>Caenorhabditis elegans</i>	Nematode worm	97	6	19,100	<1
Apicomplexa	<i>Plasmodium falciparum</i>	Human malaria parasite	23	14	5,300	<1
Apicomplexa	<i>Plasmodium yoelli</i>	Rodent malaria parasite	25	14	5,300	<1
Dictyosteliida	<i>Dictyostelium discoideum</i> *	Social amoeba	34	6	2,800	<1
Protozoan	<i>Leishmania major</i> *	Intracellular parasite	34	36	9,800	<1
Fungi	<i>Saccharomyces cerevisiae</i>	Brewer's yeast	12	16	5,700	2.4
Fungi	<i>Schizosaccharomyces pombe</i>	Fission yeast	13.8	3	4,900	0.35
Microsporidium	<i>Encephalitozoon cuniculi</i>	Intracellular parasite	2.5	11	2,000	<0.1
Angiosperm	<i>Arabidopsis thaliana</i>	Mustard weed	125	5	25,500	14
Angiosperm	<i>Oryza sativa</i>	Rice	400	12	32000–50000	?

Chromosomal Rearrangements and Repeats: Cause or Consequence?

Centromeric and Telomeric Regions— Sites of Rapid Genomic Change

Duplications: Engines of Gene and Genome Evolution?

Synteny: Fragile Versus Random Breakage Model?

HOMOLOGY, GENES, AND EVOLUTIONARY INNOVATION



GÜNTER P. WAGNER

Günter Wagner has thought long and hard about homology in relation to character identity, and in his new book he goes into great detail about why we should use **character identity as the basis for the homology of morphological characters**. For readers of *Systematic Biology*, the book is also a reminder that every **morphological character used in a phylogenetic analysis is a hypothesis of homology, and that great care is needed when deciding whether morphological characters in different organisms are likely to be homologs**.

...He also writes that “This book, although ostensibly about homology, is really a book on evolutionary developmental biology” (p. 3). Wagner argues that “the origin of novel characters and novel body plans is one of the most important but least researched questions in evolutionary biology” (p. 3)....

Summary (I)

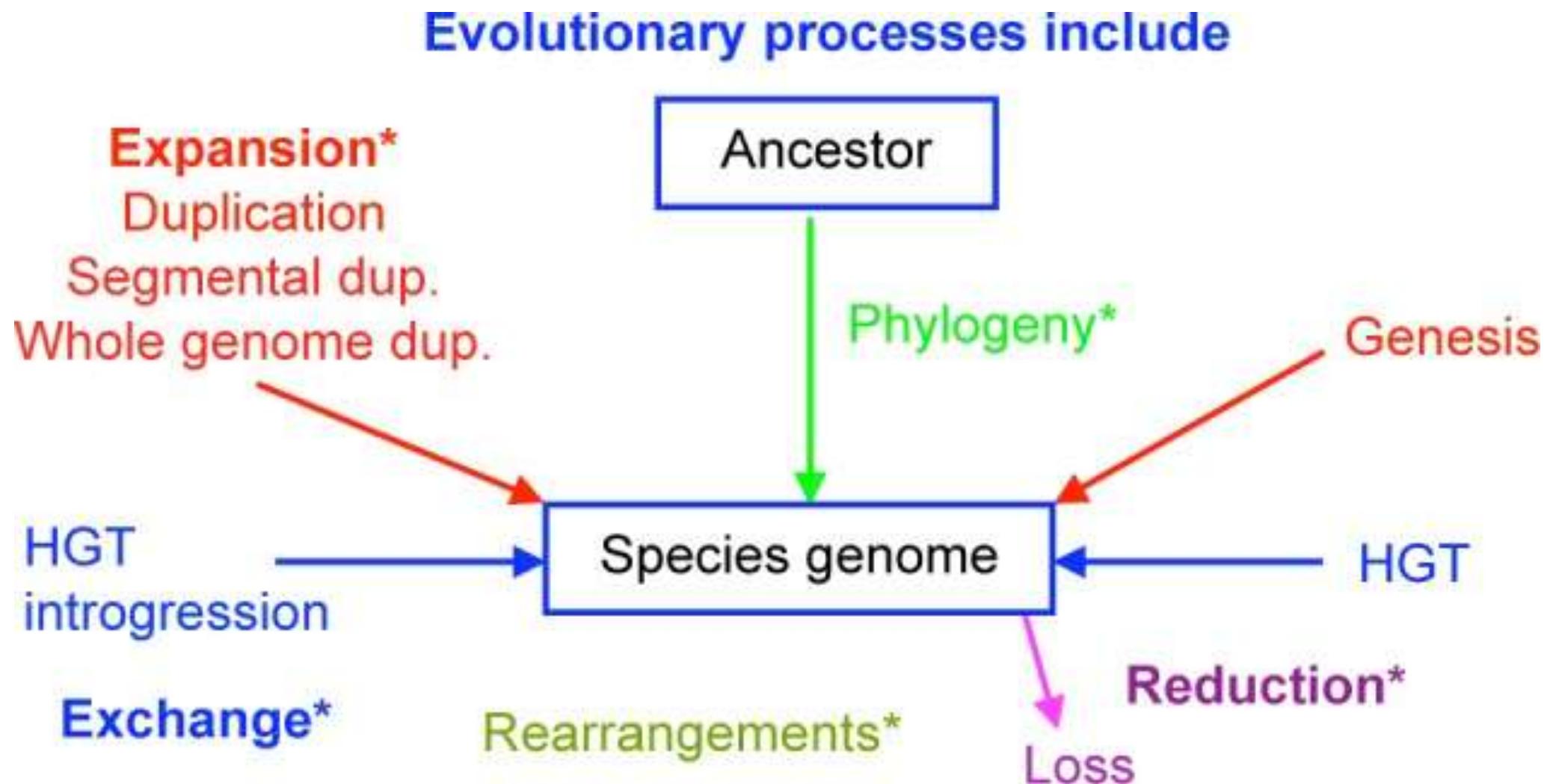
Compare multiple genomes now a norm

Similarity and differences between genomes

Use genomes to study evolution of these species:

- At various resolution (whole genome, chromosomes, regions, genes, base pairs)
- Identify the genomic basis of key phenotypes

Evolution process of a genome

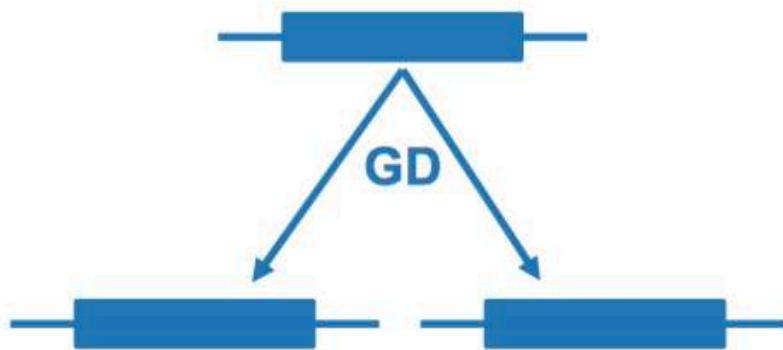


Sources of gene innovation

(Intuitive as genome gain genes of new functions)

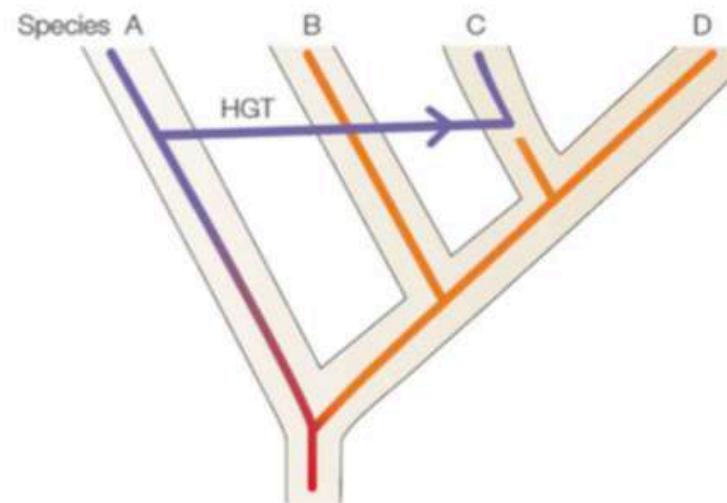
Gene duplication (GD)

Any duplication of a region of DNA that contains a gene



Horizontal gene transfer (HGT)

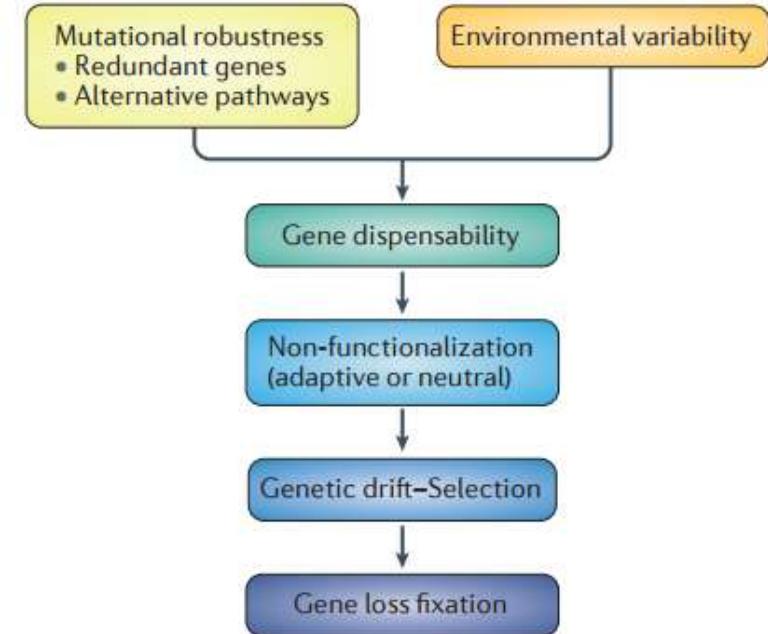
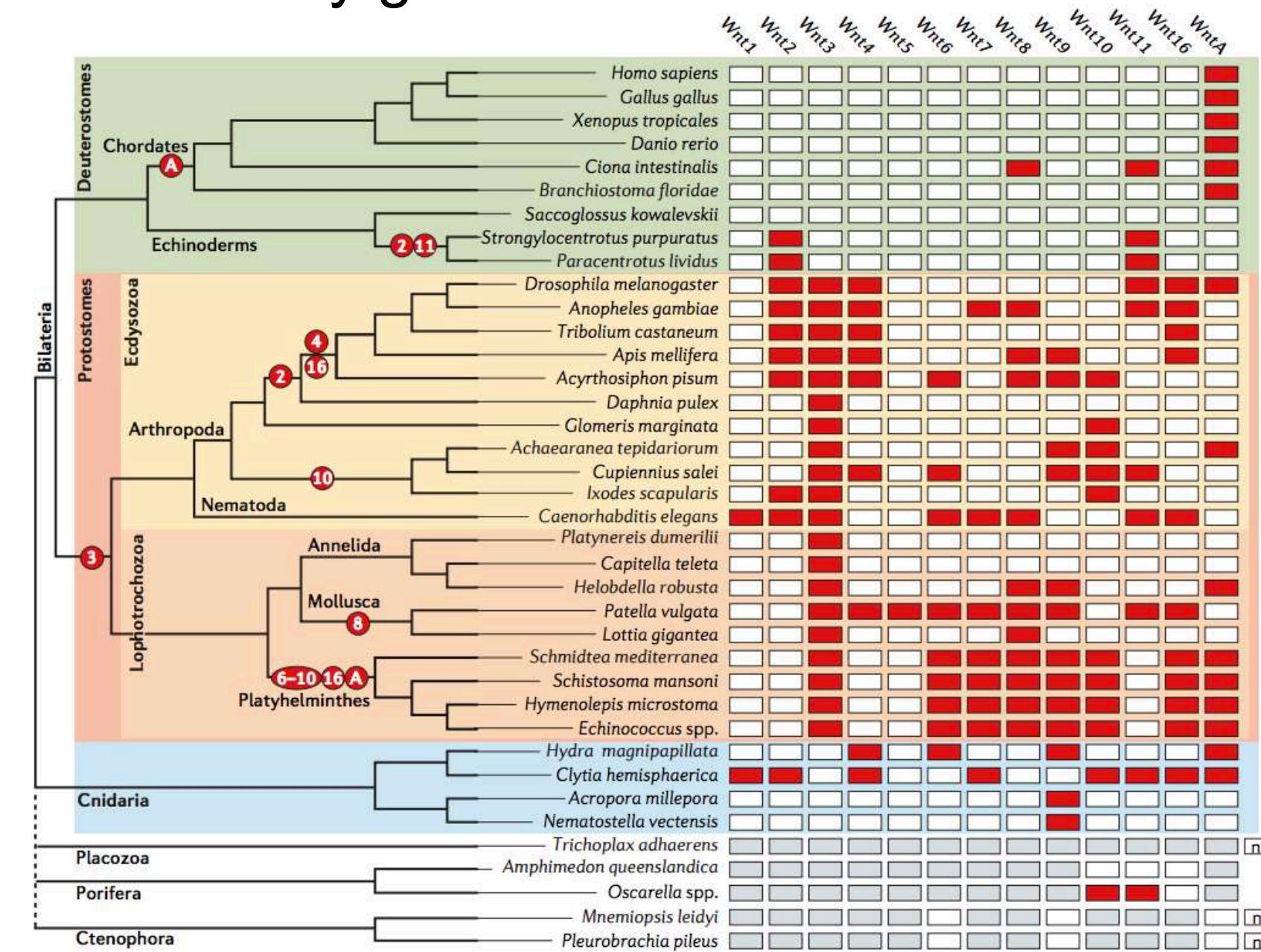
Exchange of genes between organisms other than through reproduction



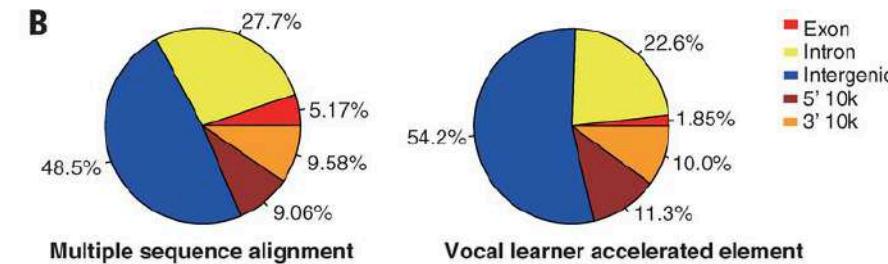
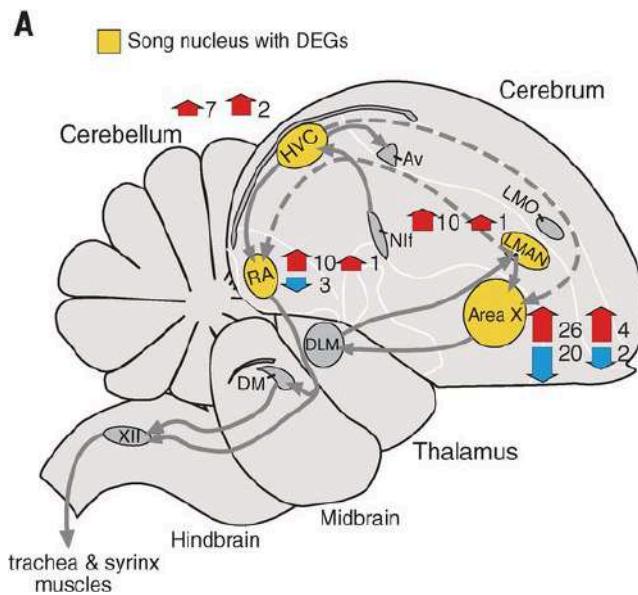
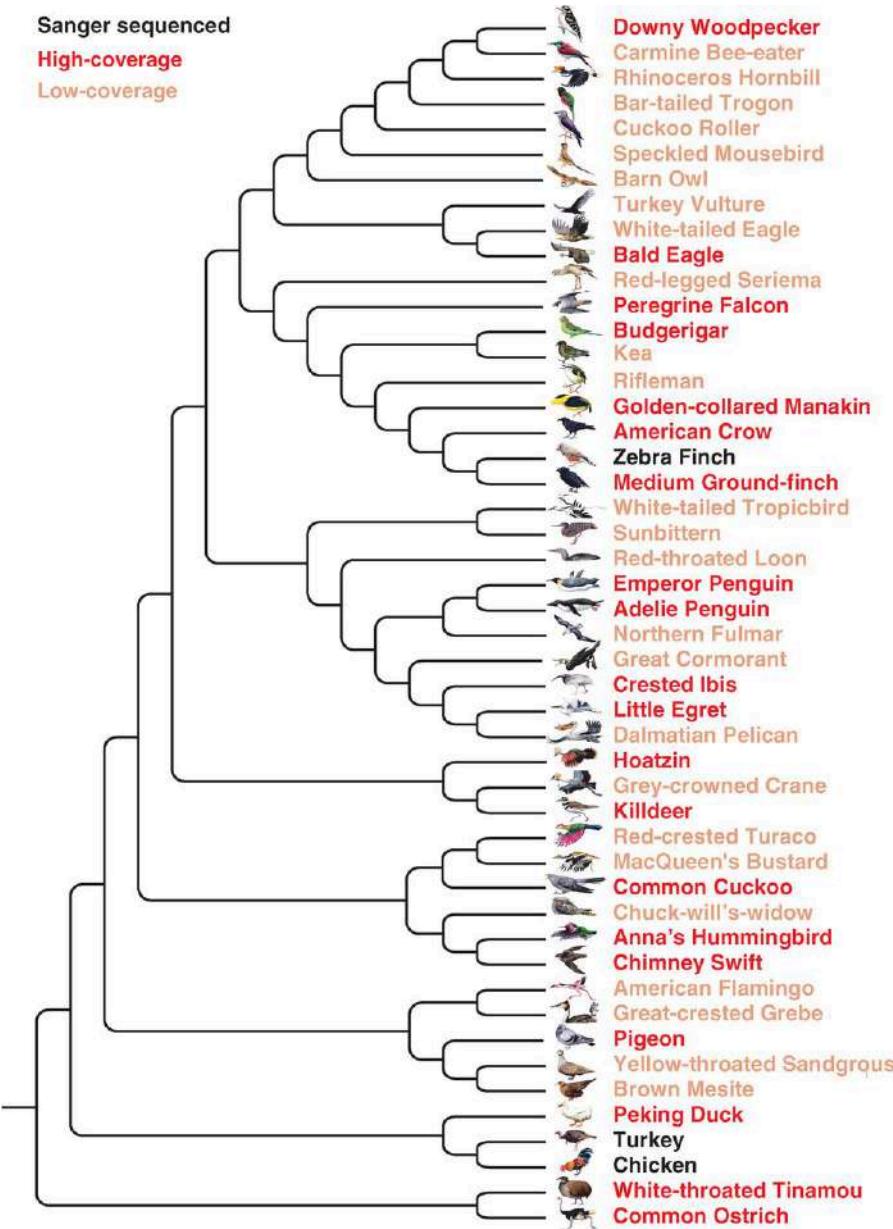
- ❖ Plant organic material decay
- ❖ Starch catabolism
- ❖ Degradation of host tissues
- ❖ Toxin production

- ❖ Xenobiotic catabolism
- ❖ Toxin production
- ❖ Degradation of plant cell walls
- ❖ Wine fermentation

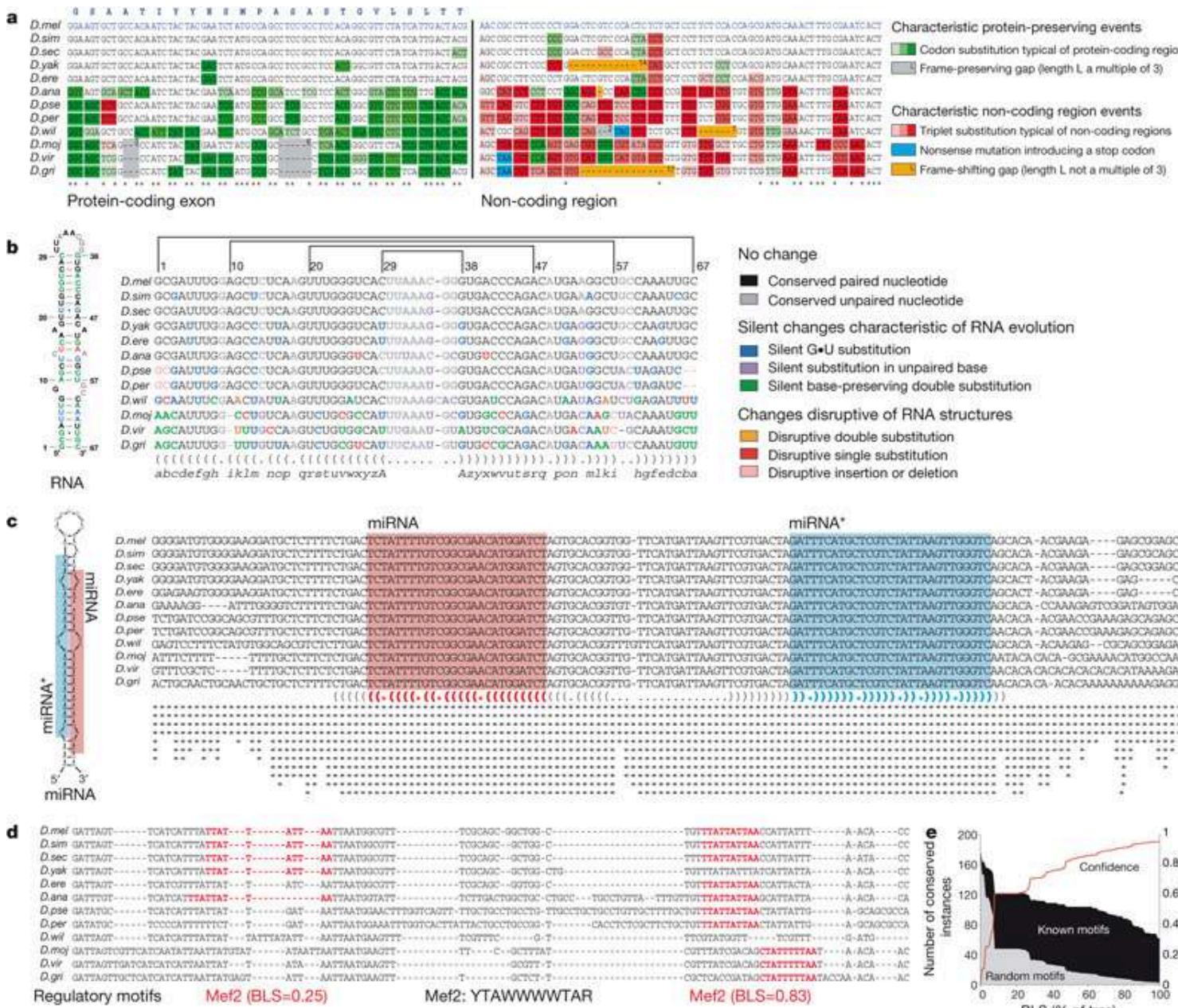
Evolution by gene loss



Reveal the evolutionary relationships among species



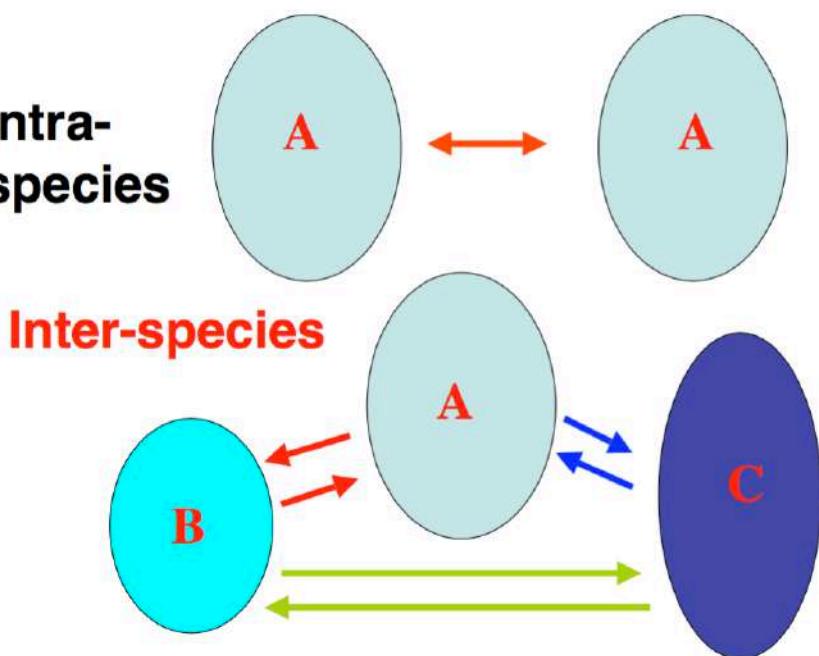
Link evolutionary processes with function



Clark et al (2007)

Comparing genomes

- Alignment of homologous regions
 - Inter-genomic: aligning genomic sequences from different species
 - Intra-genomic aligning genomic sequences from the same species
- Different levels of resolution
 - Comparative mapping (markers)
 - Synteny (~ gene content)
 - Colinearity (gene content + order conservation)
 - DNA-based alignments (base-to-base mapping)

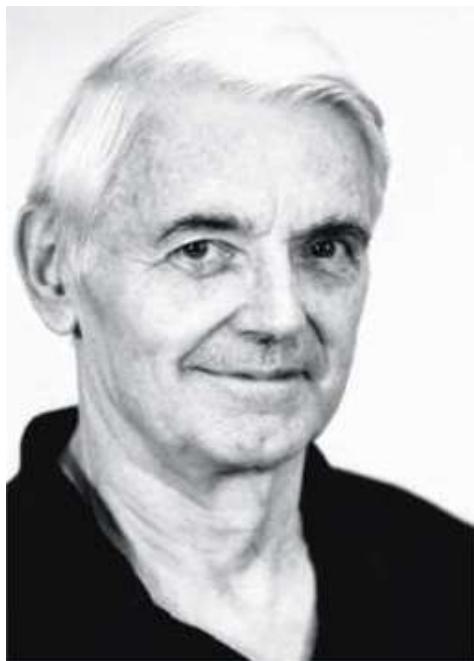


Orthology

Refining how homologous genes are related

DISTINGUISHING HOMOLOGOUS FROM
ANALOGOUS PROTEINS (1970)

WALTER M. FITCH



1929 - 2011

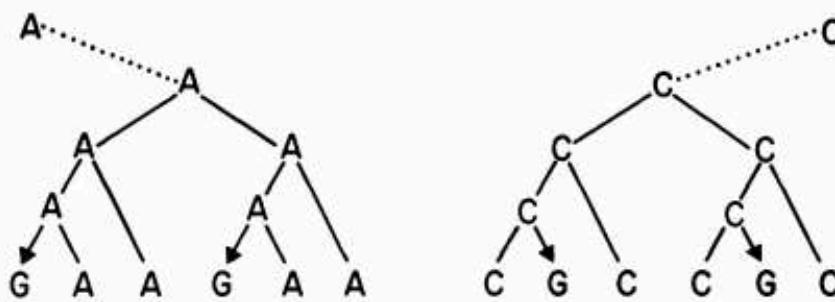
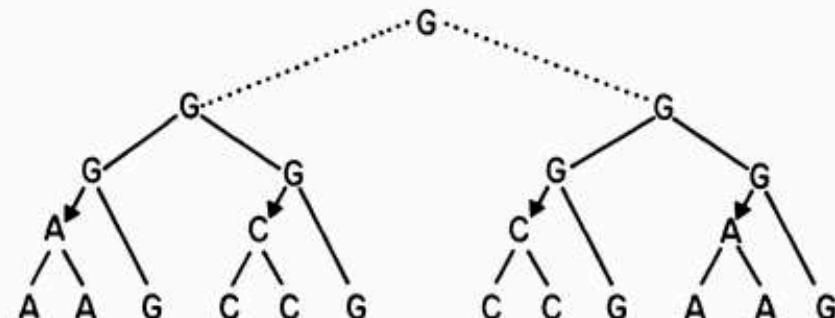
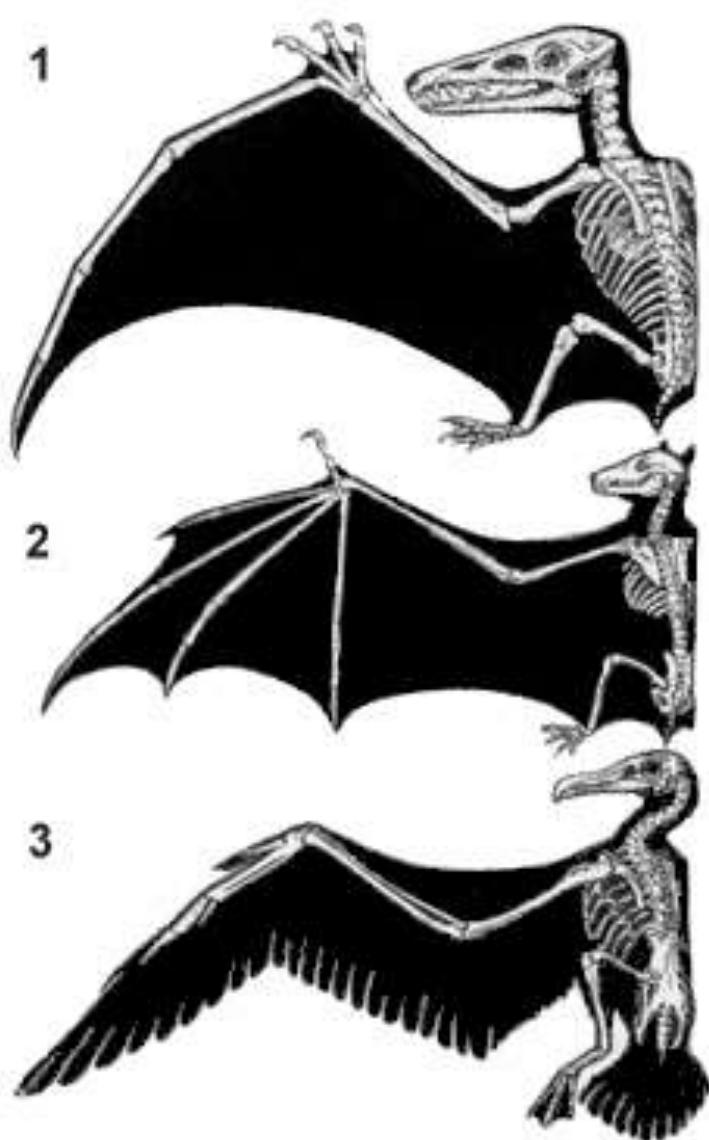


FIG. 1.—Distinguishing convergent from divergent types of nucleotide replacement patterns. Given are two groups of species (related within each group as shown by the solid lines) together with the nucleotide present at a specific position of the gene for each member species as shown at the branch tips. Given also the requirement that the ancestral nucleotide must permit the descendant nucleotides to be obtained in the minimum number of replacements, the ancestral nucleotide of the upper two groups must be set as G, with the required replacements indicated by the arrows. Were one to postulate a common ancestor for the two groups, no new mutations would need to be assumed; hence, this kind of pattern is called the divergent types. The lower two groups are identical except for rearranging the nucleotides at the branch tips, but now, in order to account for descendants in only four nucleotide replacements, the ancestral nucleotide of the lower two groups must be A and C. To postulate a common ancestor for these two groups would require, unlike the upper pair, an additional mutation. This situation shows different ancestral characters apparently converging toward the same descendant character, and hence is called the convergent type. One can calculate the frequency with which one might expect each type to be found in examining a large number of such nucleotide positions and compare that value to what is in fact found for a particular set of proteins. An abnormally large number of either type is evidence favoring that type of relation between the two groups examined.

Homology

The wings of pterosaurs (1), bats(2) and birds (3) are **analogous** as wings, but **homologous** as forelimbs.

Independently evolved – convergent evolution



From homology to orthology

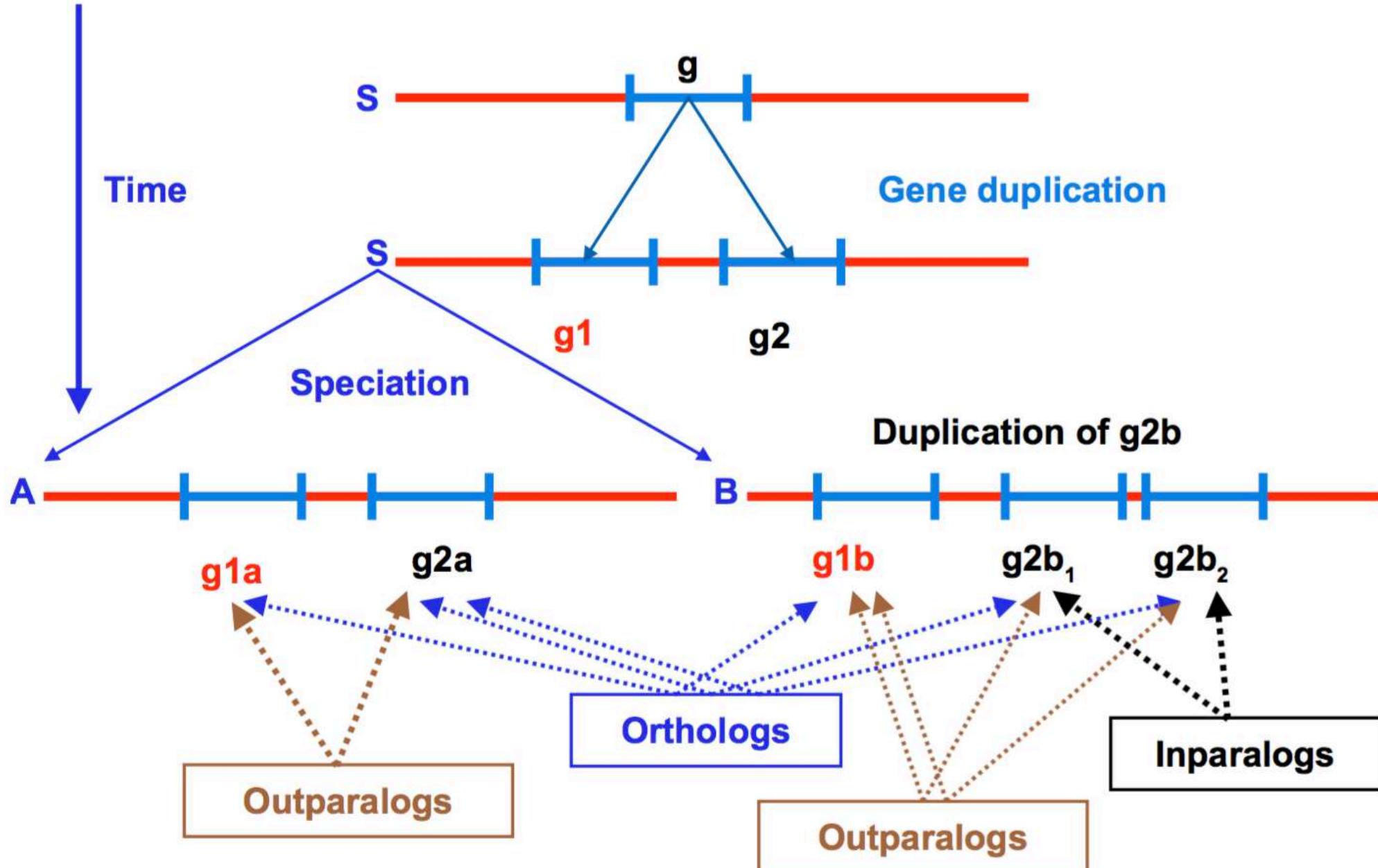
Homologues are sequences derived from a common ancestor...

- What are then orthologues? and paralogues?

Original definition of orthology and paralogy by Walter Fitch
(1970, Systematic Zoology 19:99-113):

*"Where the homology is **the result of gene duplication** so that both copies have descended side by side during the history of an organism, (for example, alpha and beta hemoglobin) the genes should be called **paralogous** (para = in parallel).*

*Where the homology is **the result of speciation** so that the history of the gene reflects the history of the species (for example alpha hemoglobin in man and mouse) the genes should be called **orthologous** (ortho = exact)."*



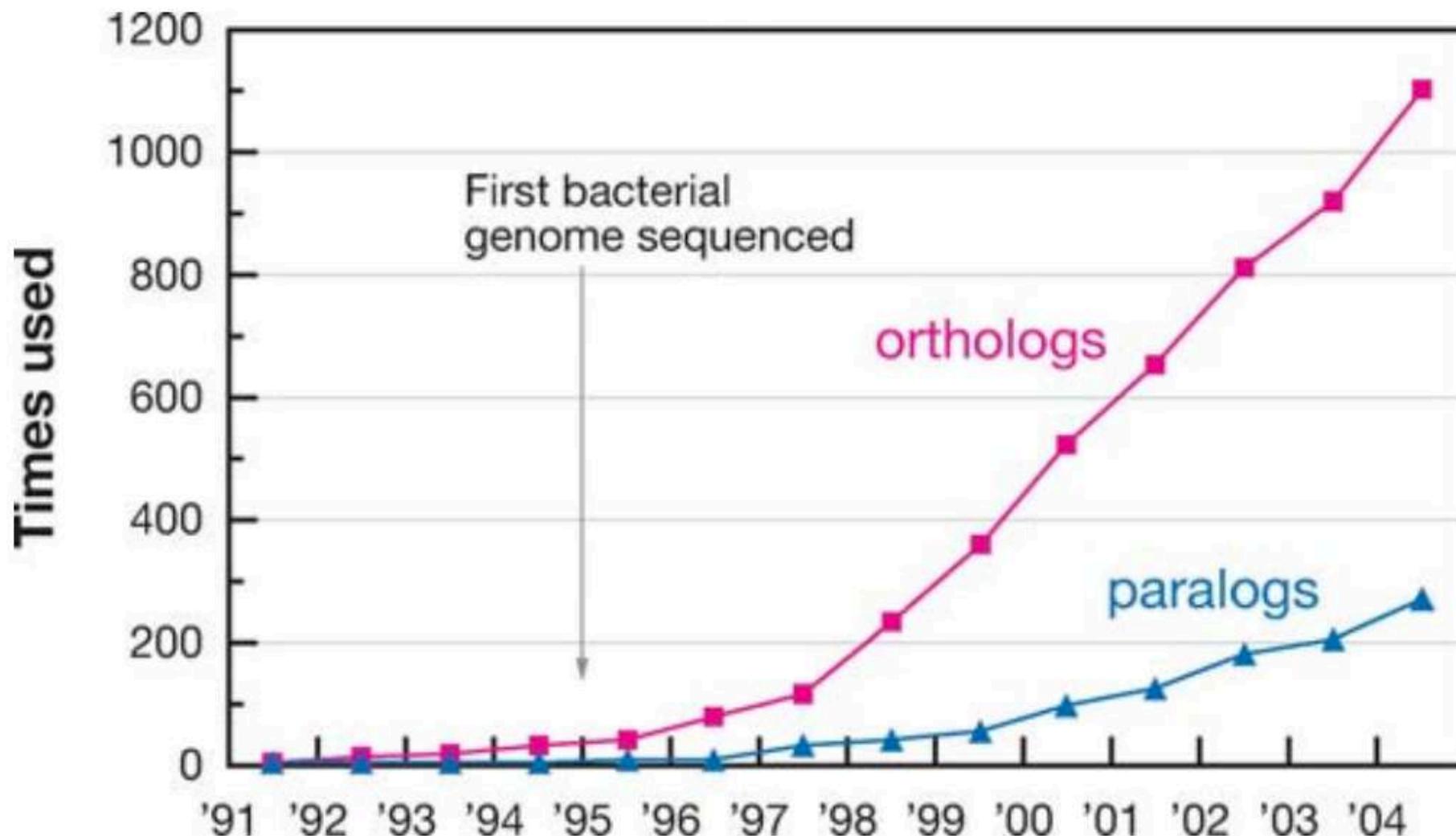
Why is orthology important?

Orthologs detection is of fundamental importance in:

- Reconstruction of the evolution of species and their genomes (**Phylogenomics**);
- Evolutionary studies of biological systems;
- Annotation of newly sequenced organisms;
- Functional genomics (transfer of functional annotation predicted on “orthology-function conjecture”);
- Gene organization in a given species.

Accurate determination of evolutionary relationships between orthologous gene families is of utmost importance for such goals.

Usage of “ortholog” and “paralog”



Corollary

- Orthology definition is purely on evolutionary terms (not functional, not synteny...)
- There is no limit on the number of orthologs or paralogs that a given gene can have (when more than one ortholog exist, there is nothing such as “*the true ortholog*”)
- Many-to-Many orthology relationships do exist (co-orthology)
- No limit on how ancient/recent is the ancestral relationship of orthologs and paralogs
- Orthology is non-transitive (as opposed to homology)

More precise definitions

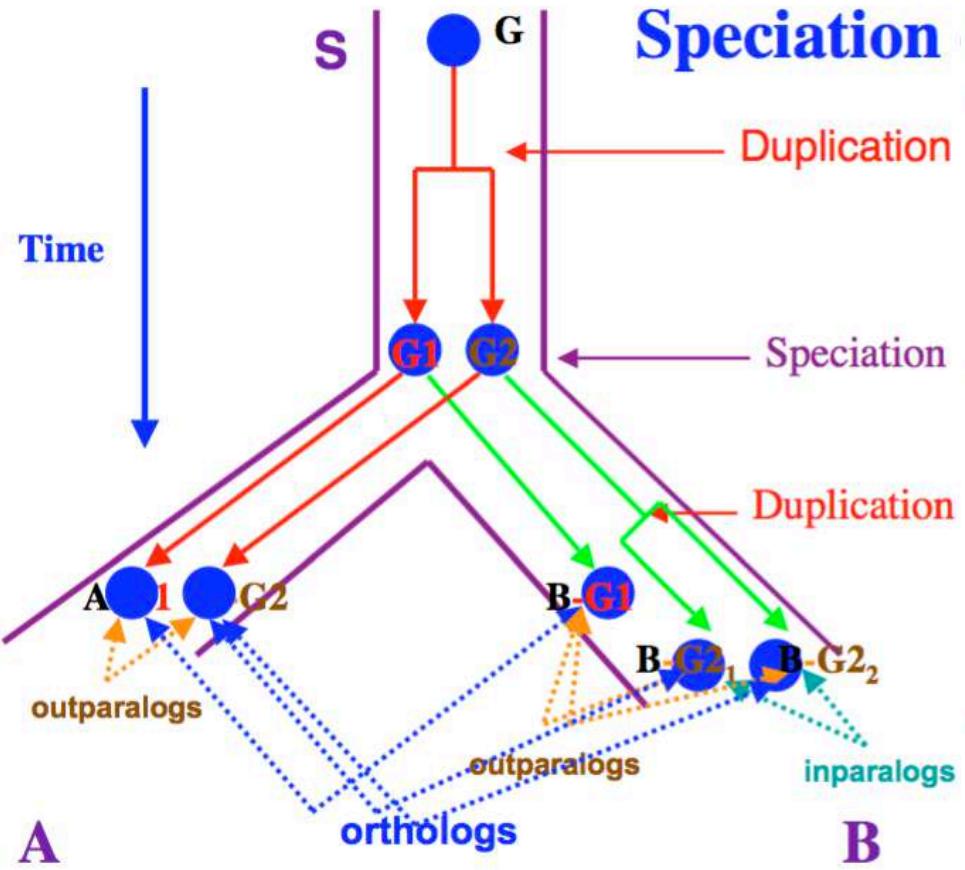


Table 1 Homology: terms and definitions

Homologs	Genes sharing a common origin
Orthologs	Genes originating from a single ancestral gene in the last common ancestor of the compared genomes.
Pseudoorthologs	Genes that actually are paralogs but appear to be orthologous due to differential, lineage-specific gene loss.
Xenologs	Homologous genes acquired via XGD by one or both of the compared species but appearing to be orthologous in pairwise genome comparisons.
Co-orthologs	Two or more genes in one lineage that are, collectively, orthologous to one or more genes in another lineage due to a lineage-specific duplication(s). Members of a co-orthologous gene set are inparalogs relative to the respective speciation event.
Paralogs	Genes related by duplication
Inparalogs (symparalogs)	Paralogous genes resulting from a lineage-specific duplication(s) subsequent to a given speciation event (defined only relative to a speciation event, no absolute meaning).
Outparalogs (alloparalogs)	Paralogous genes resulting from a duplication(s) preceding a given speciation event (defined only relative to a speciation event, no absolute meaning).
Pseudoparalogs	Homologous genes that come out as paralogs in a single-genome analysis but actually ended up in the given genome as a result of a combination of vertical inheritance and HGT.

Importance of assigning correct orthology

Important implications for phylogeny: only sets of orthologous genes are expected to reflect the underlying species evolution (although there are many exceptions)

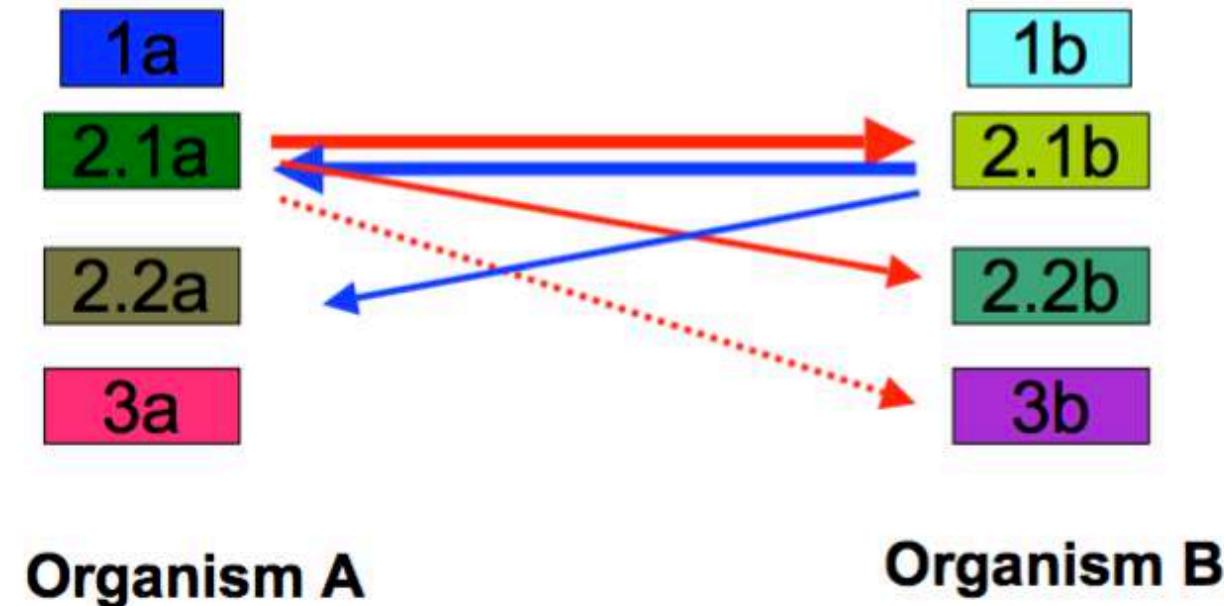
The most exact way of **comparing two (or more) genomes** in terms of their gene content. Necessary to uncover how genomes evolve.

Implications for **functional inference**: orthologs, as compared to paralogs, are more likely to share the same function

Ortholog inference methods

How to detect orthologous genes?

- The most intuitive way: **Best Reciprocal Hit (RBH)**

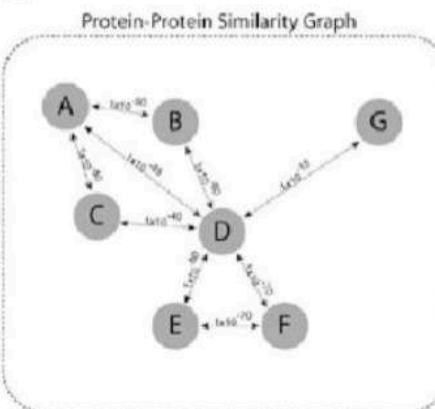


2.1a **2.1b** **Best Reciprocal Hits**

Sequence by clustering

mcl: The Markov Cluster Algorithm <http://micans.org/mcl/> (Stijn Van Dongen)

A



Generate weighted transition matrix using BLAST E-Values as weights (-logE)

B

Weighted Transition Matrix

	A	B	C	D	E	F	G
A	100	50	50	45	0	0	0
B	50	100	0	60	0	0	0
C	50	0	100	40	0	0	0
D	45	60	40	100	80	70	15
E	0	0	0	80	100	70	0
F	0	0	0	70	70	100	0
G	0	0	0	15	0	0	100

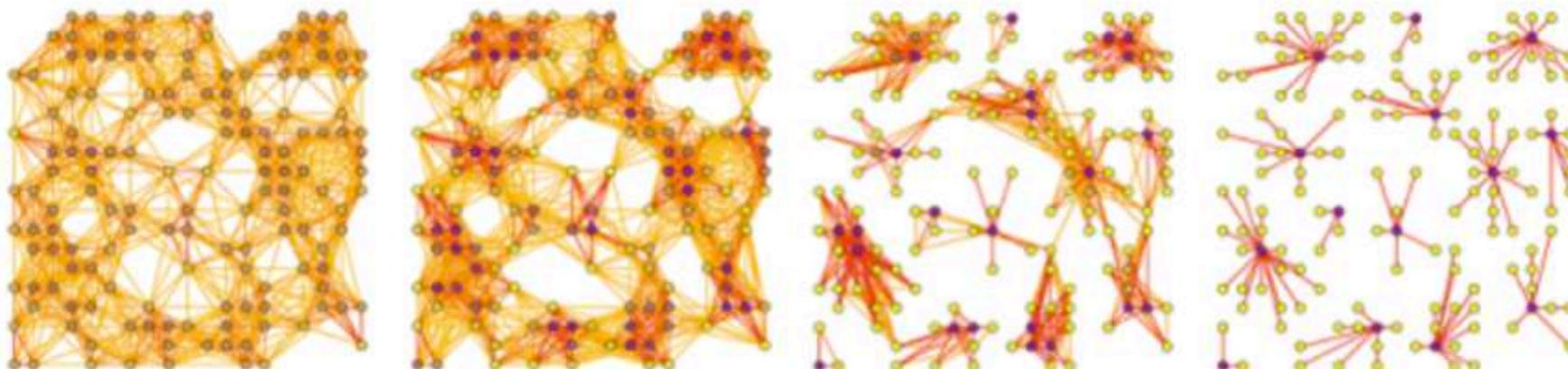
Transform weights into column-wise transition probabilities

Markov Matrix

	A	B	C	D	E	F	G
A	0.42	0.24	0.20	0.11	0.00	0.00	0.00
B	0.20	0.48	0.24	0.15	0.00	0.00	0.00
C	0.20	0.00	0.40	0.10	0.00	0.00	0.00
D	0.18	0.28	0.16	0.24	0.32	0.29	0.13
E	0.00	0.00	0.00	0.19	0.40	0.29	0.00
F	0.00	0.00	0.00	0.17	0.28	0.42	0.00
G	0.00	0.00	0.00	0.04	0.00	0.00	0.87

Example of a protein–protein similarity graph for seven proteins (A–F), circles represent proteins (nodes) and lines represent detected BLASTp similarities with E-values (also shown)

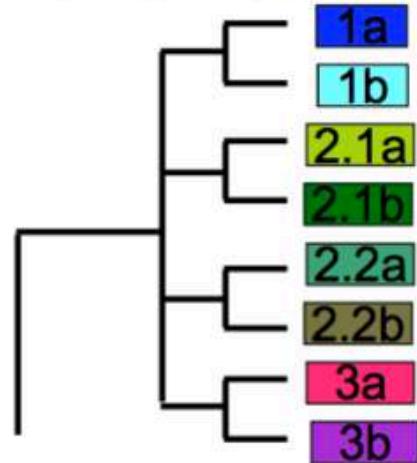
Produce clusters (gene families) using different inflation parameter



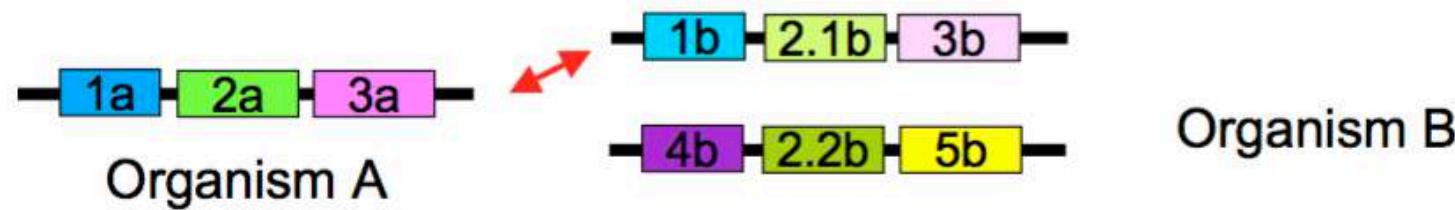
Weighted transition matrix and associated column stochastic Markov matrix for the seven proteins shown in (A).

How to detect orthologous genes?

- more rigorous: make a phylogenetic tree of the gene family

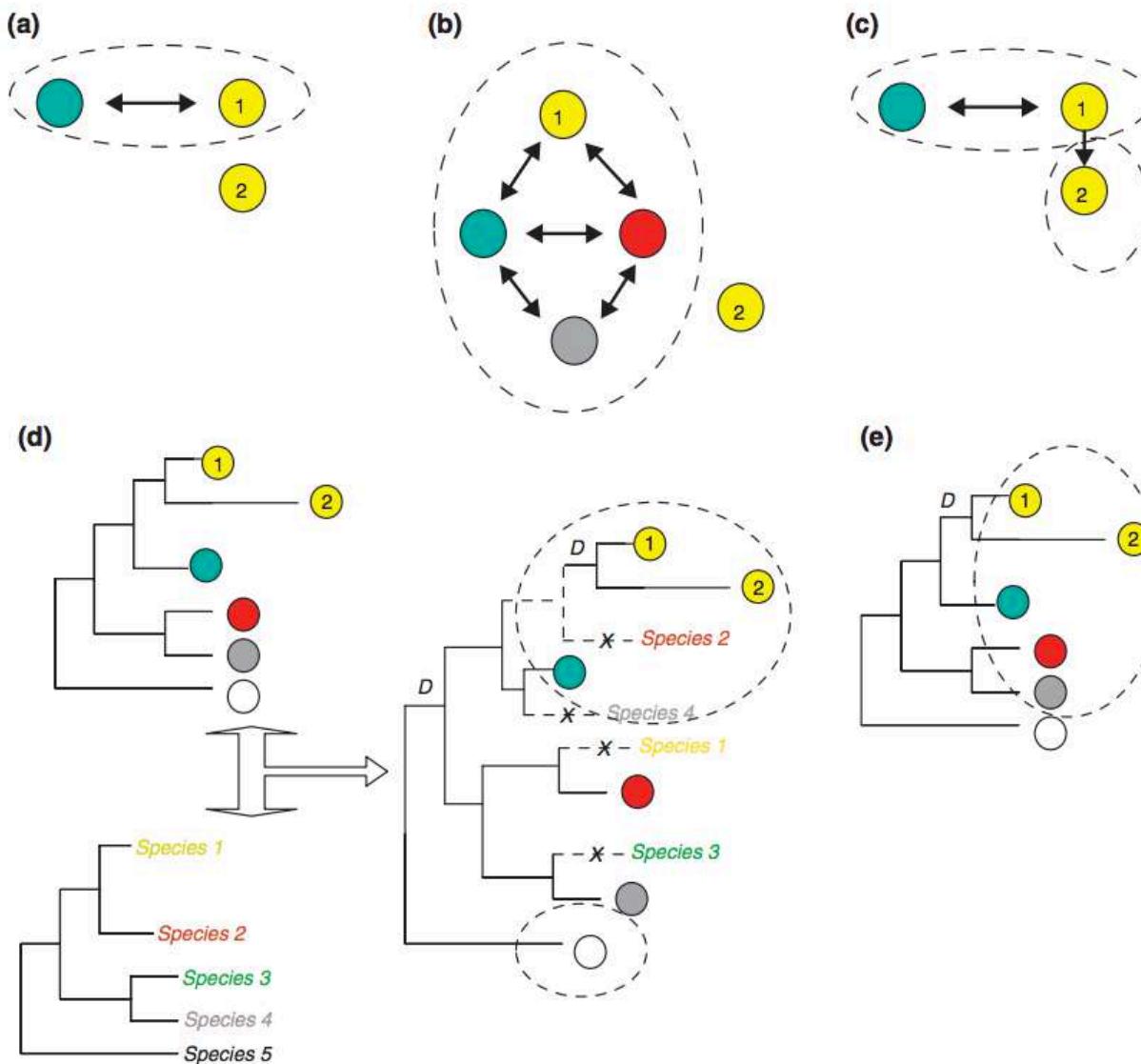


- more rigorous: look at synteny conservation



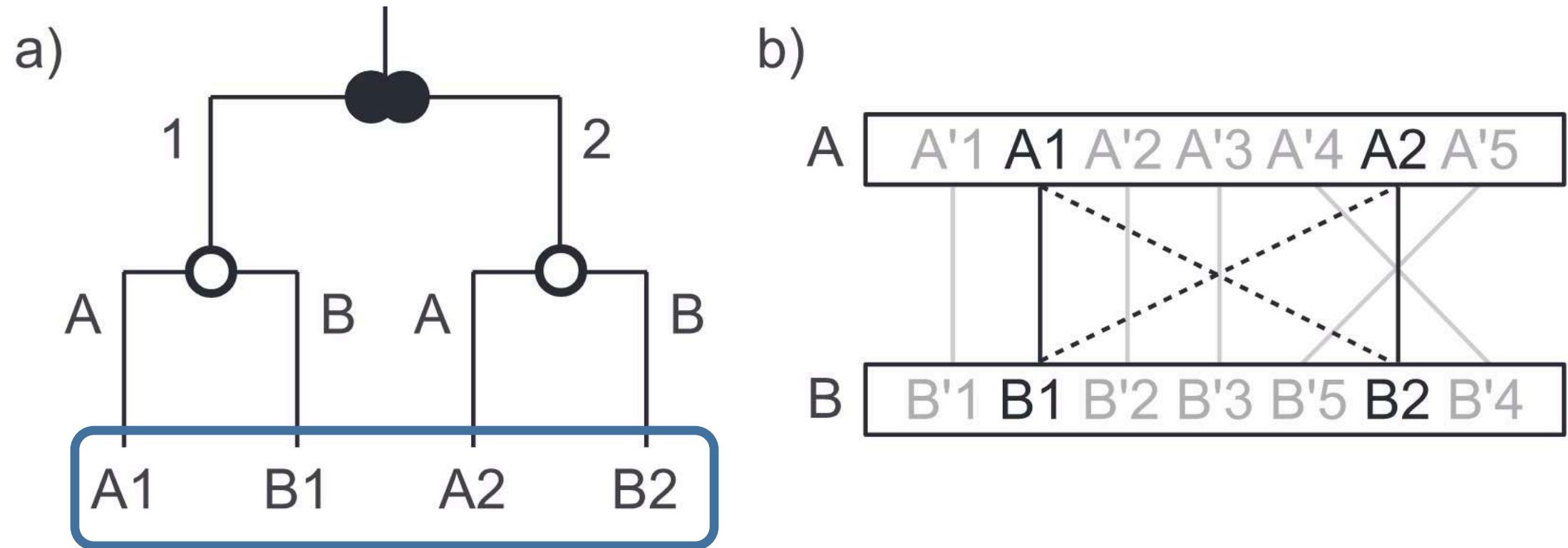
--> In fact inferring orthology is much more complicated particularly when considering more than 2 genomes!

Orthology prediction methods



- a) Best bidirectional hits
- b) COG, MCL-clustering approach
- c) InParanoid
- d) Tree reconciliation
- e) Species-overlap (PhylomeDB)

Orthology prediction methods



May be seen as a gene family (orthogroup)
with simple sequence similarity clustering methods

Figure 1. Synteny-enhanced orthology prediction. Four genes (A_1, A_2, B_1, B_2) in two species (A and B). a) The gene tree with a duplication (filled double circle) and a speciation event (empty circle). b) Gene order in the genomic context of both genes. Genes A'_x and B'_x are orthologous to each other. Lines depict suggested partners based on sequence similarity of which the dashed were neglected by the gene order algorithm.
doi:10.1371/journal.pone.0105015.g001

Methods

Similarity

Rely on genome comparisons and clustering of highly similar genes to identify orthologous groups (**suitable for large genome datasets**)

Phylogeny

use candidate gene families determined by similarity and then rely on the reconciliation of the phylogeny of these genes with their corresponding species phylogeny to determine the subset of orthologs

(Good and more interpretable for small set of genomes)

Others

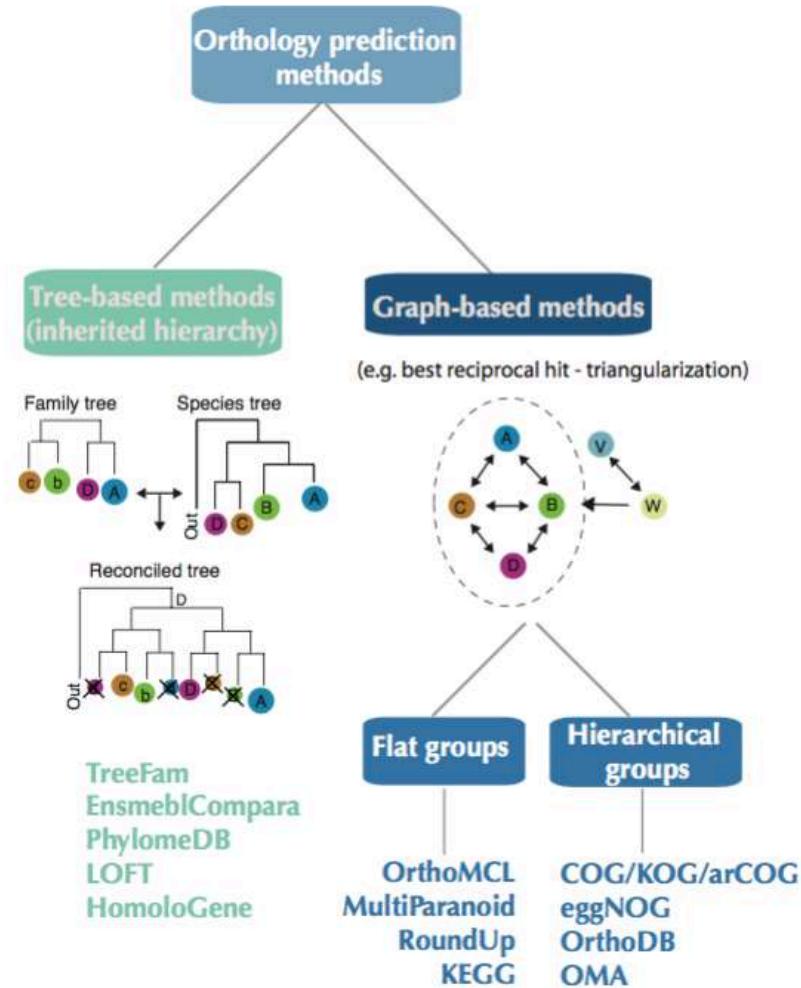
Combination of (1) and (2)

Some uses synteny

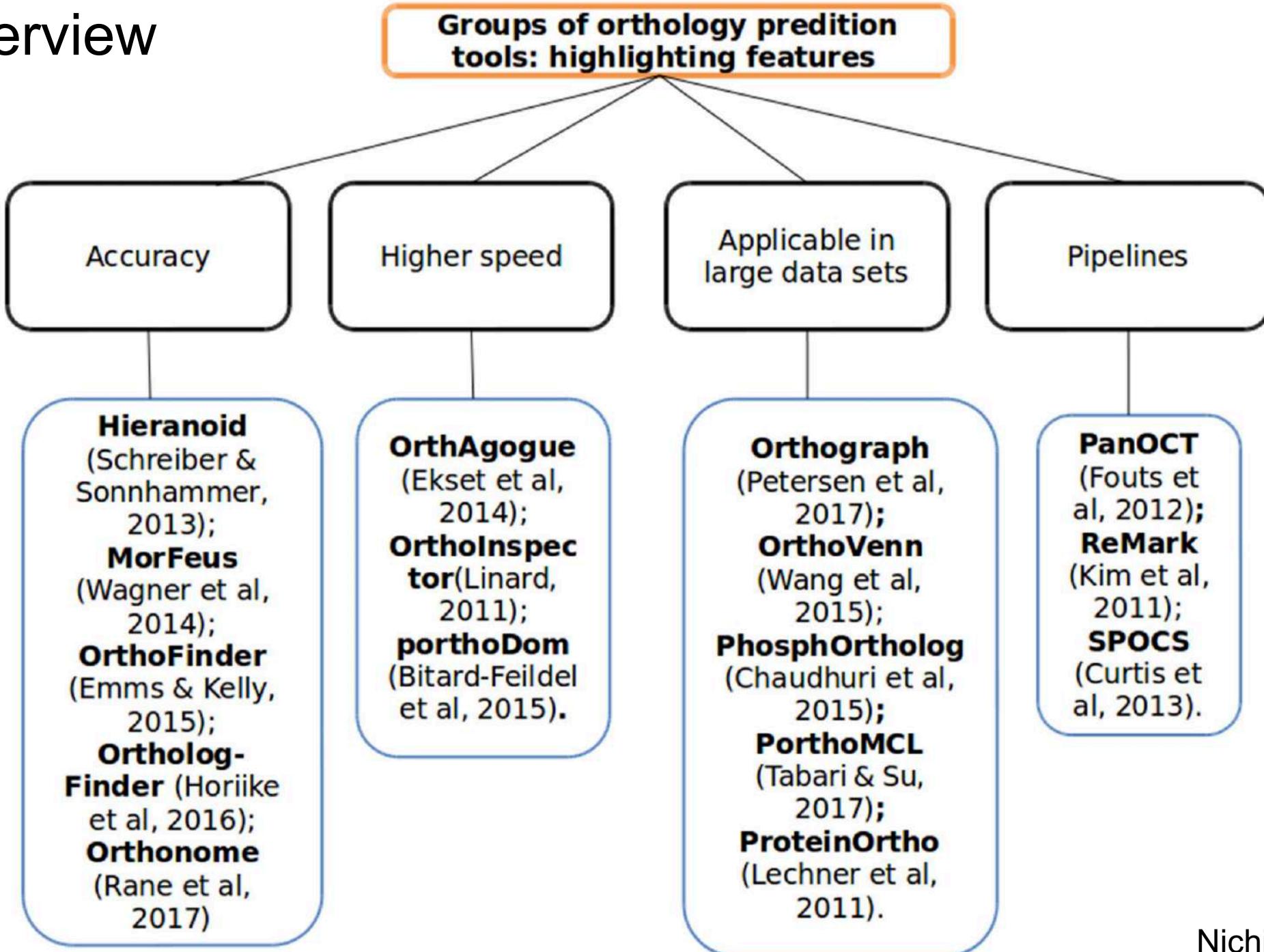
Tools

METHOD	ALGORITHM
COG ⁵⁴	Similarity—Single linkage clustering + Constraints
InParanoid/MultiParanoid ⁵⁵	Similarity (pair-wise species)/Extends to multiple species
OrthoMCL ⁵⁶	Similarity—MCL clustering algorithm
TribeMCL ⁵⁷	Similarity—MCL clustering algorithm
eggNOG ⁵⁸	Similarity—Detects false RBH due to gene fusion and protein domain shuffling
OrthoFocus ⁵⁹	Similarity—extended RBH to handle many-to-one and many-to-many relationships
OrthoInspector ⁶⁰	Similarity
SPO ⁶¹	Similarity (RBH)—Partition of orthologs includes Intra-species Partition and MCL cluster
OrthoFinder ⁶²	Similarity—Clustering
Roundup ⁶³	Reciprocal Smallest Distance
RSD ⁶⁴	Reciprocal Smallest Distance (evolutionary distance = estimated number of amino acid si
OMA ⁶⁵	Similarity—Global sequence alignment
ME ⁶⁶	Minimum Evolution Method
MSoAR ⁶⁷	Similarity—Genome rearrangement—duplication
Orthostrapper ⁶⁹	Phylogeny—bootstrap
RIO ⁷⁰	Similarity (HMMER)—bootstrap—Phylogeny
PhIGs ⁷¹	Similarity—Multiple sequence alignments—Phylogenetic trees
PhyOP ⁷²	Similarity (overlapping limits)—phylogeny based on d_s (synonymous substitution rates)
TreeFam ⁷³	Infer orthologs—paralog from the phylogenetic tree
LOFT ⁷⁴	Assigns hierarchical orthology numbers to genes based on a phylogenetic tree
EnsemblCompara GeneTrees ⁷⁵	Clustering—multiple alignment—tree generation based on TreeBeST method
SYNERGY ⁷⁶	Sequence similarity—species phylogeny—reconstruction of underlying gene evolutionary histories
PHOG ⁷⁷	Precomputed phylogenetic trees followed by identification of orthologs as sequences from different species that are each others reciprocal nearest neighbors
COCO-CL ⁷⁸	Similarity—Correlation between sequences—single linkage clustering

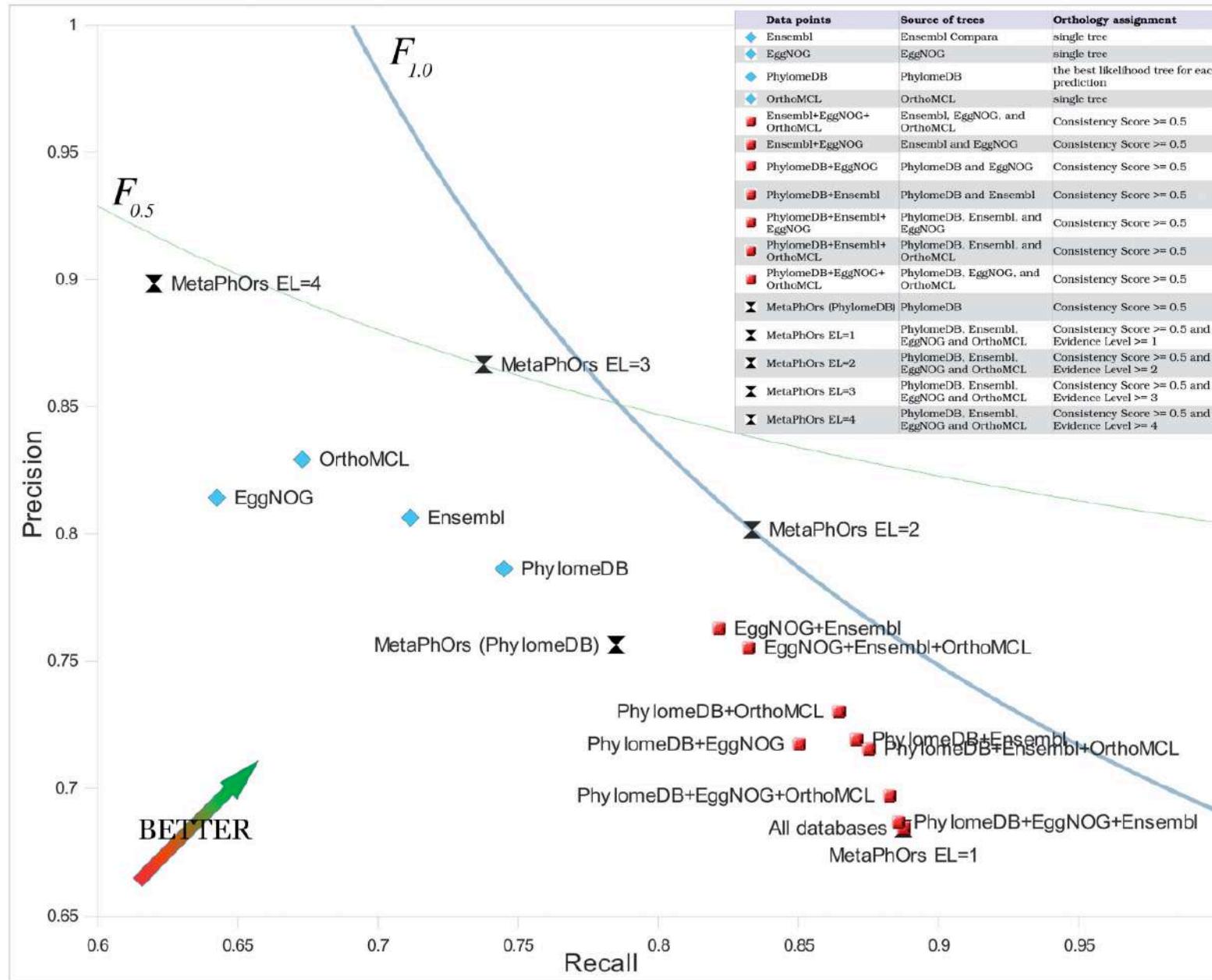
Note: This table shows some orthology inference methods with corresponding reference and a short description of their underlying algorithm.



Tools overview



Every tool kind of disagrees...



Caveats

Evolution of multi-domain proteins

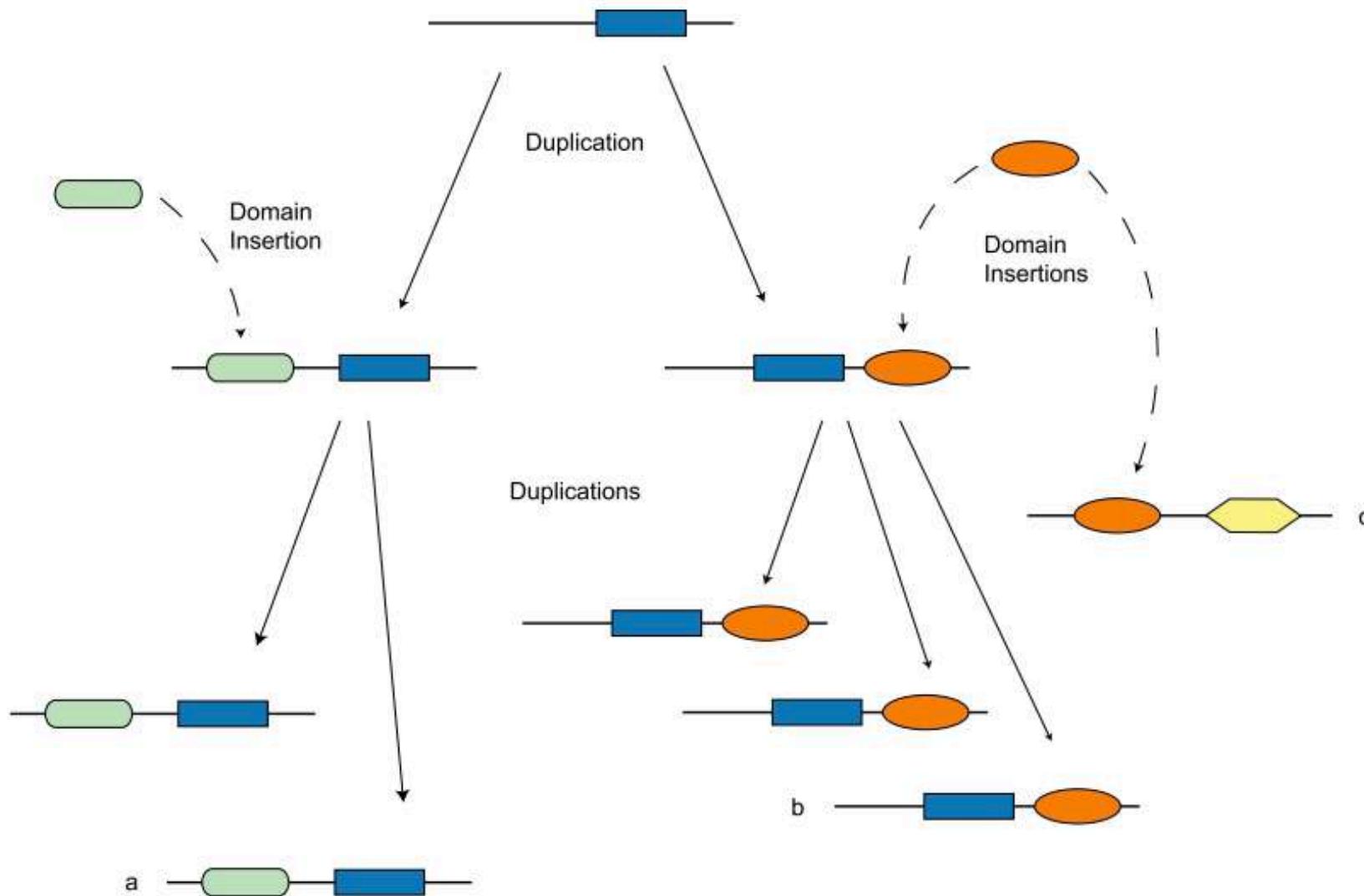
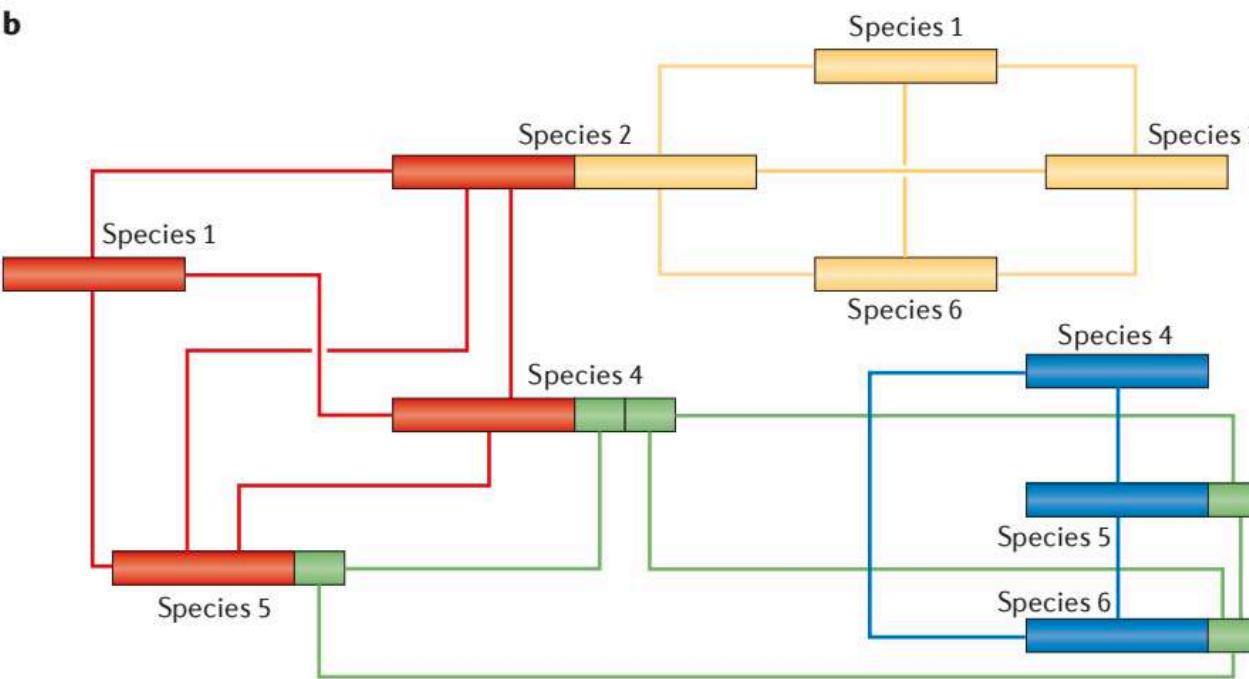
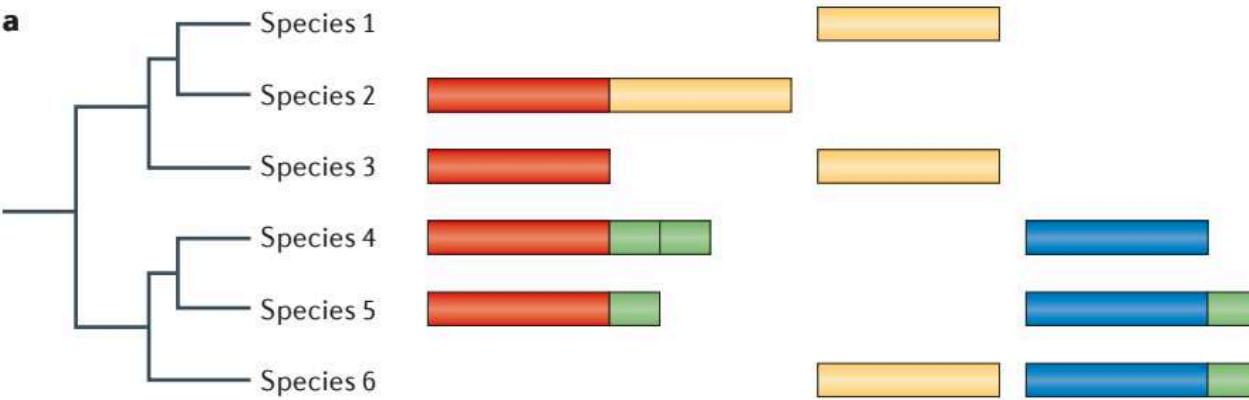


Figure 1. The evolution of a hypothetical multidomain family by gene duplication and domain insertion. Genes in the *a* and *b* subfamilies share a common ancestor but do not have identical domain composition. Gene *c* shares a homologous domain with genes in the *b* subfamily, but there is no gene that is ancestral to both *b* and *c*.

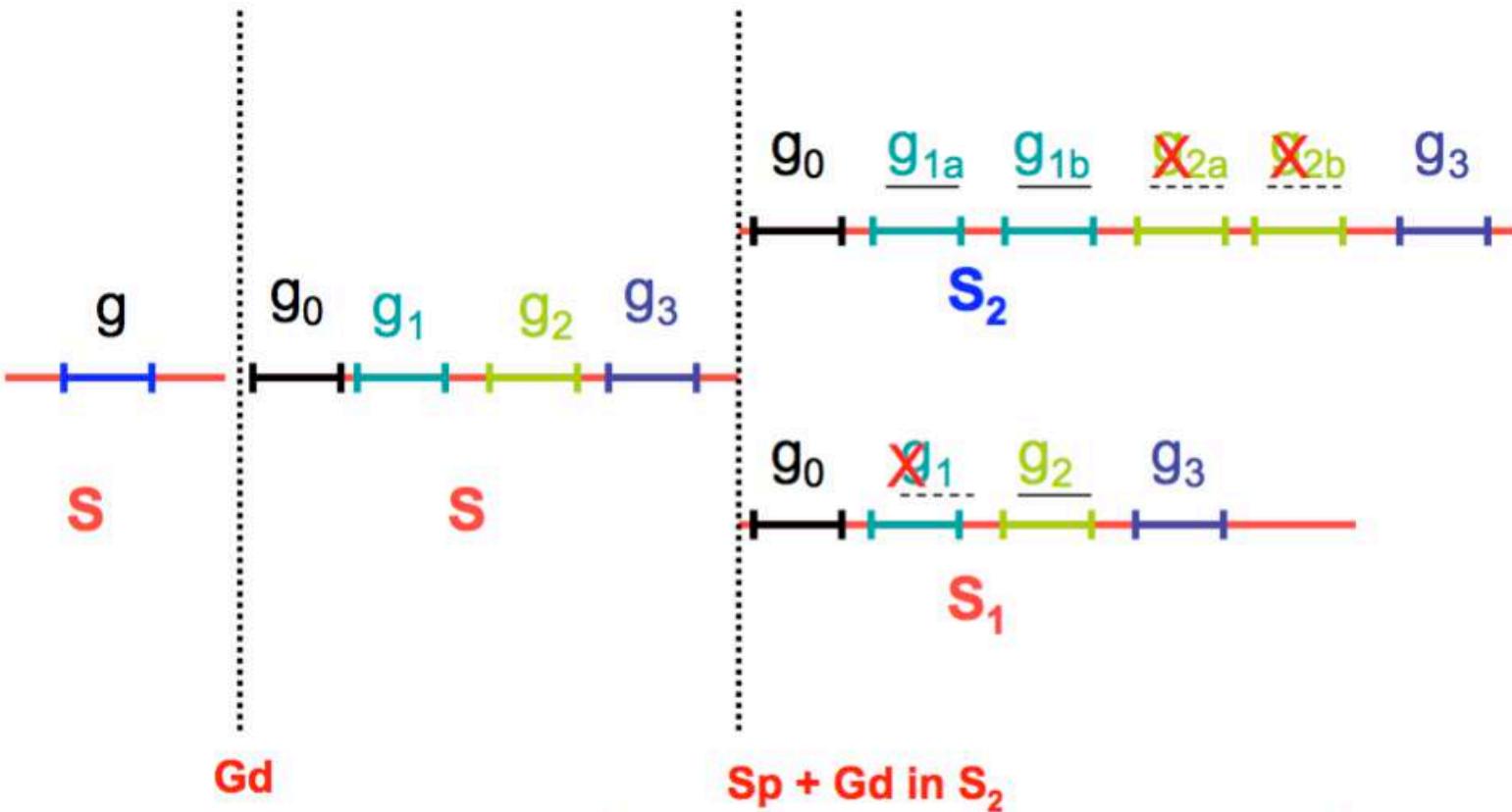
doi:10.1371/journal.pcbi.1000063.g001

Song et al (2008)

Problem of clustering to assign gene families when comes to different domain combinations



Detection can go wrong: Example of an orthology misleading situation



We assume that gene g_1 (in S_1) and genes g_{2a} and g_{2b} (in S_2) are lost, similarity and phylogenetic methods for orthology detection will assign erroneously orthology to g_2 , g_{1a} and g_{1b} . Indeed these are not orthologous, because g_2 , g_{1a} and g_{1b} do not result from the same ancestral gene after the speciation event.

In this case solely the environment conservation, will help in detecting the gene duplication and loss event, and hypothesise their non-orthology.

Effect of HGT on orthology and paralogy (If orthology is simply inferred by gene content)

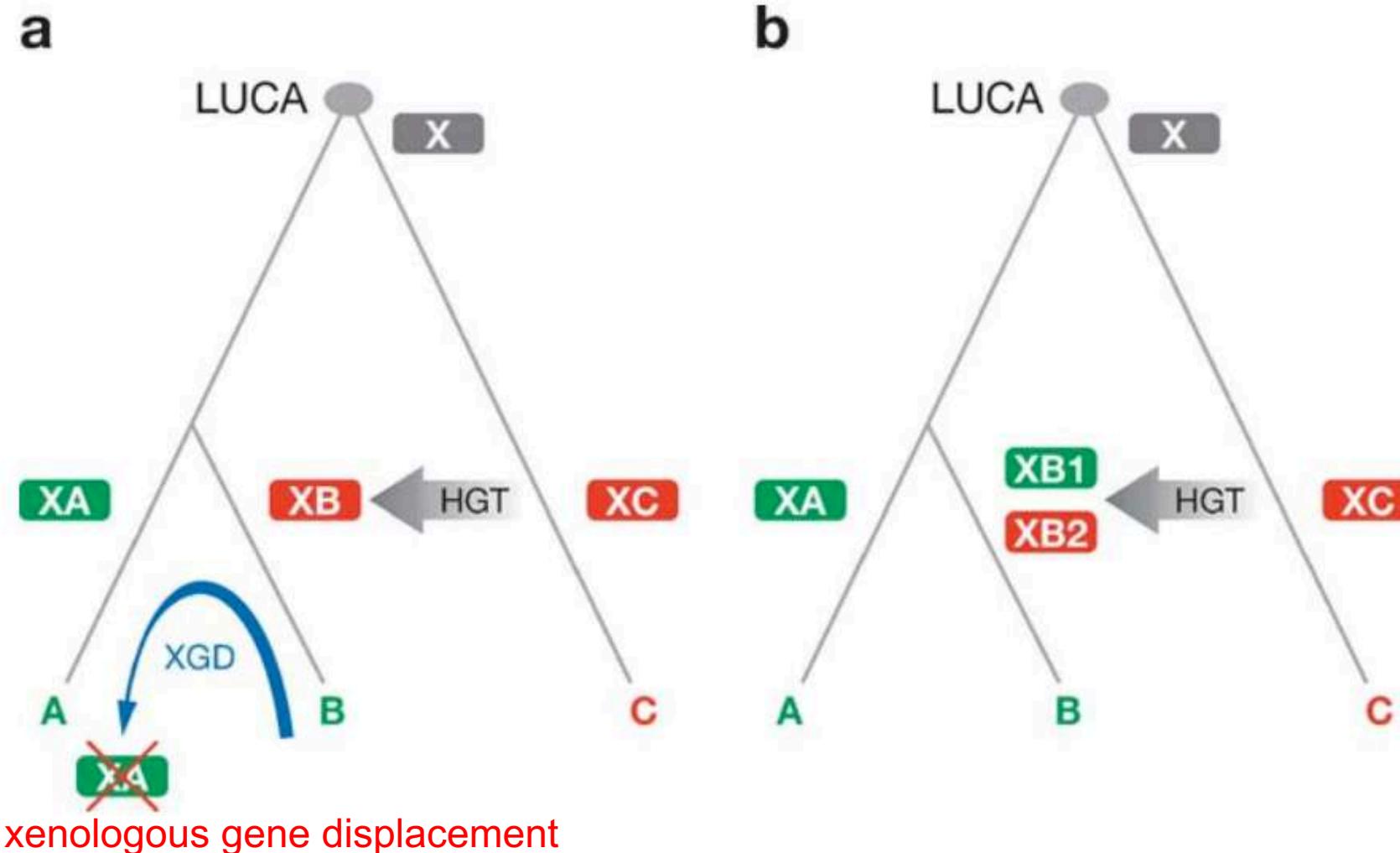


Figure 4
Effect of horizontal gene transfer on orthology and paralogy. (a) A hypothetical evolutionary scenario with HGT leading to xenology. (b) A hypothetical evolutionary scenario with HGT leading to pseudoparalogy. LUCA, Last Universal Common Ancestor (of all extant life forms).

Caveat: Do orthologs, as compared to paralogs, are more likely to share the same function?

How confident can we be that orthologs are similar, but paralogs differ?

Romain A. Studer and Marc Robinson-Rechavi

Department of Ecology and Evolution, Biophore, Lausanne University, CH-1015 Lausanne, Switzerland and Swiss Institute of Bioinformatics, CH-1015 Lausanne, Switzerland

OPEN  ACCESS Freely available online

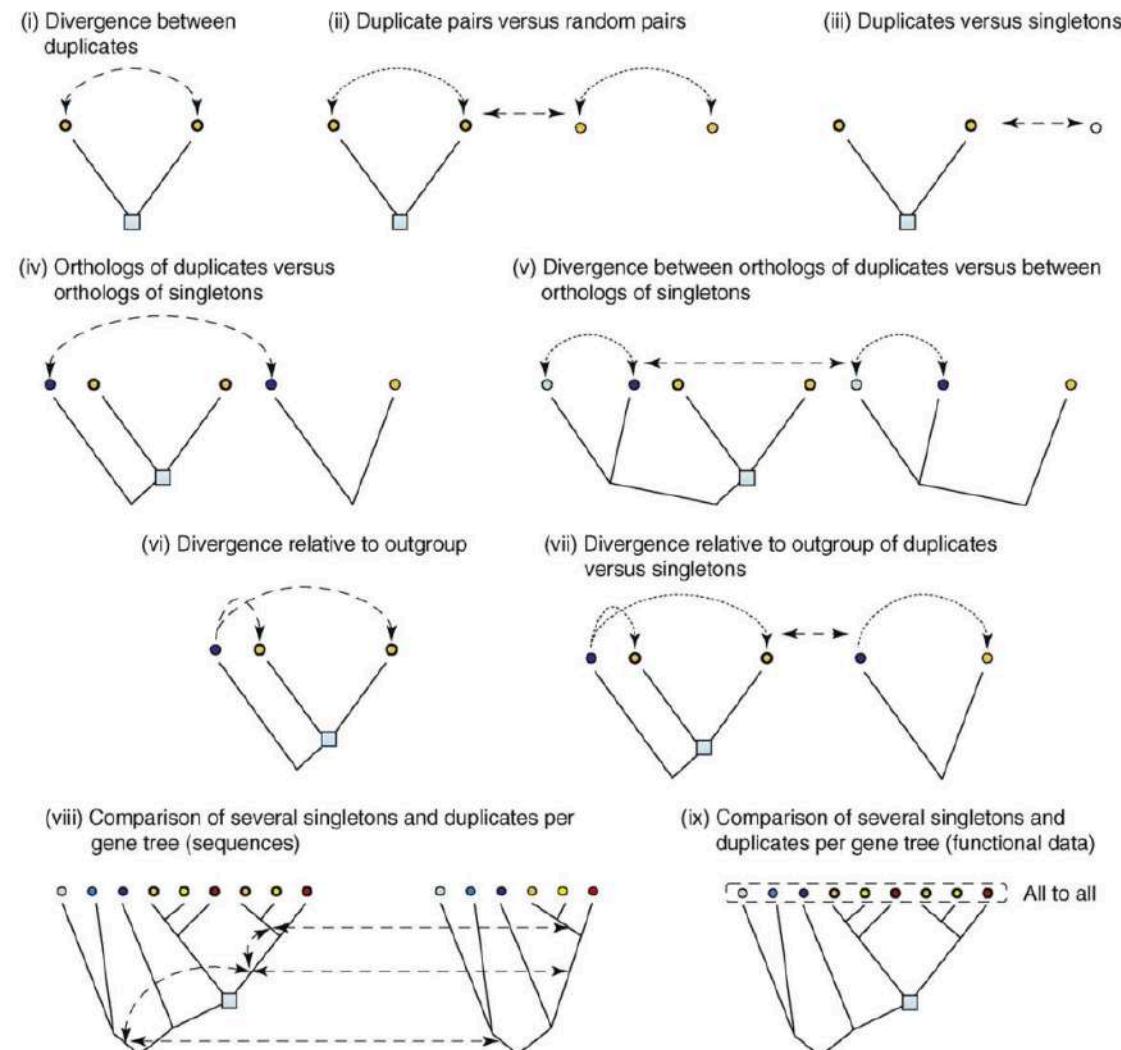
PLOS COMPUTATIONAL BIOLOGY

Resolving the Ortholog Conjecture: Orthologs Tend to Be Weakly, but Significantly, More Similar in Function than Paralogs

Adrian M. Altenhoff^{1,2}, Romain A. Studer^{2,3,4}, Marc Robinson-Rechavi^{2,3}, Christophe Dessimoz^{1,2,5*}

1 ETH Zurich, Department of Computer Science, Zürich, Switzerland, **2** Swiss Institute of Bioinformatics, Lausanne, Switzerland, **3** Department of Ecology and Evolution, University of Lausanne, Lausanne, Switzerland, **4** Institute of Structural and Molecular Biology, Division of Biosciences, University College London, London, United Kingdom, **5** EMBL-European Bioinformatics Institute, Hinxton, Cambridge, United Kingdom

Some designs for the study of gene duplication.



TRENDS in Genetics

Table 1. The impact of study design on tests of evolution after duplication

Study design ^a	Data type ^b	Predictions under simple evolutionary models		Function change after duplication or speciation	Refs
		Preferential change after duplication	Subfunctionalization ^c	Neofunctionalization	
(i) Divergence between duplicates	Functional	Differences between paralogs			[19,20,55]
(ii) Duplicate pairs versus random pairs	Functional	Paralogs more similar than random pairs, but not identical			[11,19,54]
(iii) Duplicates versus singlettons	Functional	Measure of retention bias, confused by evolution after duplication			[11,19,25]
(iv) Orthologs of duplicates versus orthologs of singlettons	Functional	Measure of retention bias			[12]
(v) Divergence between orthologs of duplicates versus between orthologs of singlettons	Sequence	Measure of retention bias			[12,53]
(vi) Divergence relative to outgroup	Sequence	No prediction relative to symmetry, relaxed purifying selection	Asymmetry between paralogs, positive selection ^e		[11,17,58]
	Functional	Two paralogs different, complementary to full outgroup function	One paralog similar to outgroup, one different		[18,21]
(vii) Divergence relative to outgroup of duplicates versus singlettons	Sequence	Higher divergence of duplicates ^d , confused by retention bias			[62]
	Functional	Two paralogs different, complementary to outgroup; singleton similar to outgroup	One paralog similar to outgroup, one different; singleton similar to outgroup		[18,24,25]
(viii) Comparison of several singlettons and duplicates per gene tree (sequences)	Sequence	Higher relaxation of purifying selection on branches after duplication	More positive selection on branches after duplication		[13,43,48,56]
(ix) <i>idem</i>	Functional	Conservation of pattern among singlettons; sub-patterns in duplicates	Conservation in most homologs; new patterns ^h in some duplicates		Positive selection in various branches of the tree ^g Variation in pattern among homologs, with gain of new patterns ^h

Testing duplication combining transcriptome dataset

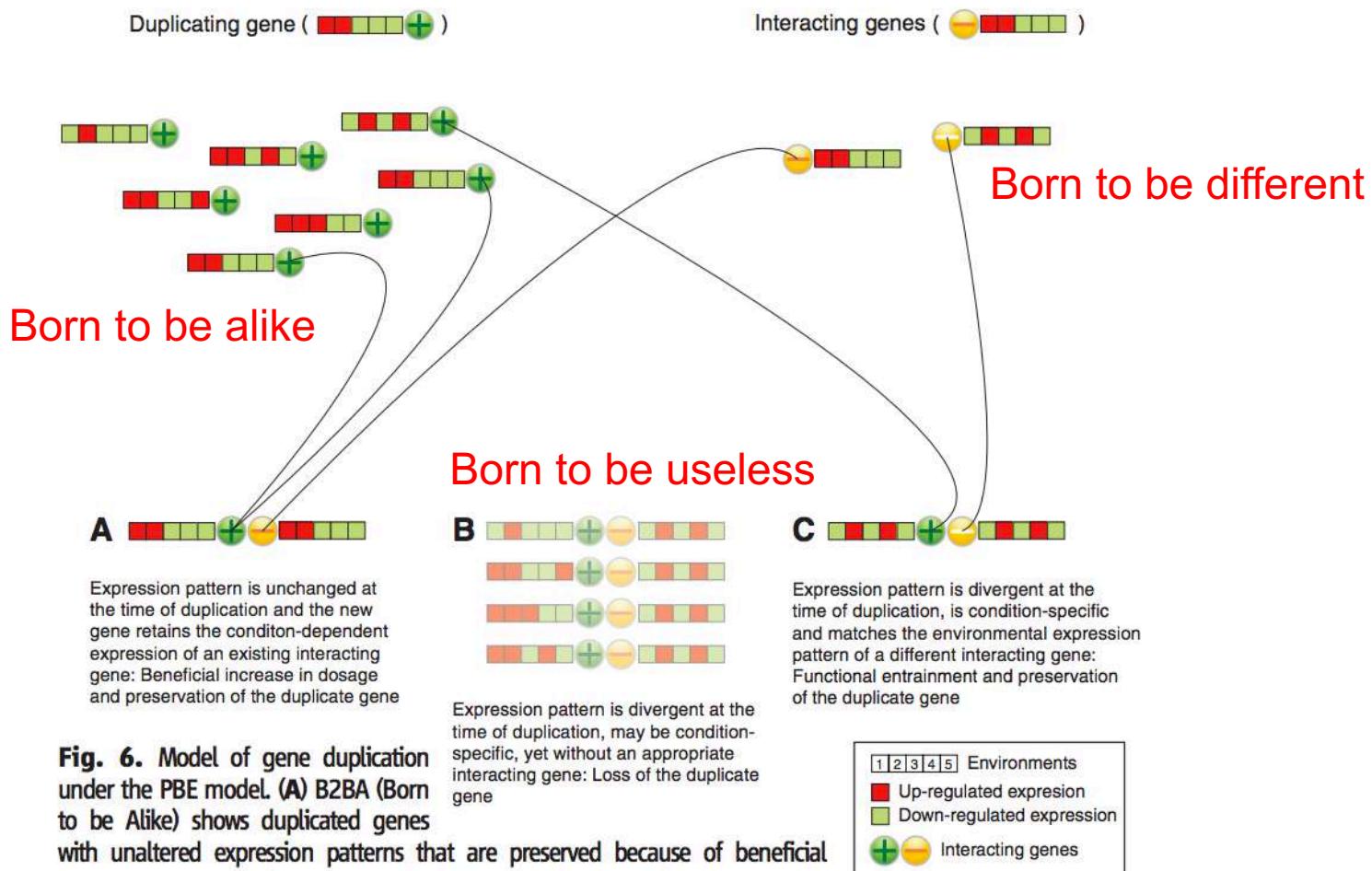


Fig. 6. Model of gene duplication under the PBE model. (A) B2BA (Born to be Alike) shows duplicated genes with unaltered expression patterns that are preserved because of beneficial increase in dosage (20) in association with the condition-dependent expression of an interacting gene. (B) B2BU (Born to be Useless) genes with initially divergent expression patterns and with inappropriate condition-dependent responses or interacting genes are most likely lost. (C) B2BD (Born to be Different). When the derived expression pattern of a paralog at the time of duplication is shared with a different interacting gene (white negative sign), and when the effect of their combined products is beneficial under a distinct environmental condition, the likelihood for preservation is increased. Color-coding represents condition-dependent expression patterns across multiple environments. Lines represent the process of functional entrainment.

Summary point

SUMMARY POINTS

1. Orthologs and paralogs are two types of homologous genes that evolved, respectively, by vertical descent from a single ancestral gene and by duplication.
2. Distinguishing between orthologs and paralogs is crucial for successful functional annotation of genomes and for reconstruction of genome evolution.
3. A finer classification of orthologs and paralogs has been developed to reflect the interplay between duplication and speciation events, and effects of gene loss and horizontal gene transfer on the observed homologous relationship.
4. Methods for identification of sets of orthologous and paralogous genes involve phylogenetic analysis and various procedures for sequence similarity-based clustering.
5. Analysis of clusters of orthologous and paralogous genes is instrumental in genome annotation and in delineation of trends in genome evolution.
6. Rearrangements of gene structure confound orthologous and paralogous relationships.
7. The gene-centered concepts of orthology and paralogy can be generalized downward, to the level of strings of nucleotides and even single base pairs, and upward, to multigene arrays.

Comparing genomes beyond gene level

Extension of homology to genomes

Gene family gains and losses in previous lecture

Comparing genomes at **different resolution**

Synteny (gene content on the same chromosome)

Colinearity (gene content + order conservation)

DNA-based alignments (base-to-base mapping)

Extension of homology to genomes: synteny

Synteny Conservation and Chromosome Rearrangements During Mammalian Evolution

Jason Ehrlich,^{*.1} David Sankoff[†] and Joseph H. Nadeau^{*.2}

^{*}Jackson Laboratory, Bar Harbor, Maine 04609 and [†]Centre de recherches mathématiques,
Université de Montréal, Montréal, Québec, H3C 3J7 Canada

Manuscript received December 13, 1996

Accepted for publication June 4, 1997

MAPS of LINKAGE and
SYNTENY HOMOLOGIES
between MOUSE and MAN

JOSEPH H. NADEAU

1989

Synteny refers to the occurrence of two or more genes on the same chromosome, whereas conserved synteny refers to two or more homologous genes that are syntenic in two or more species, regardless of gene order on each chromosome, i.e., synteny but not necessarily gene order is conserved (Figure 2; see also NADEAU 1989). Conserved linkage pertains to the conservation of both synteny and order of homologous genes between species (Figure 2; see also NADEAU 1989). A disrupted synteny refers to circumstances where a pair of genes are located on the same chromosome in one species but their homologues are located on different chromosomes in another species, i.e., the genes are syntenic in only one of the two species. Syntenic genes can be identified by examining published genetic maps and conserved segments can be identified by comparing

Synteny

conservation of gene content

A. Genetic map in reference species



Each unit is gene

Conserved synteny and linkage

Gene arrangement:



Definition: Same gene order and similar genetic distances.

Count:

One **conserved linkage** involving genes,
one **conserved synteny** involving genes A,B,C,E,F.

Possible cause:

No inter-chromosomal rearrangement.
No intra-chromosomal rearrangement.

Conserved synteny, conserved linkage, disrupted linkage

Gene arrangement:



Count:

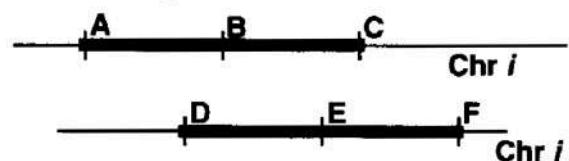
One **conserved linkage** involving genes B,C,D;
One **conserved linkage** involving genes E,F.
One **disrupted linkage** involving genes B,C,D vs E,F vs A.
One **conserved synteny** involving genes A,B,C,D,E,F.

Possible causes:

An intra-chromosomal rearrangement,
such as a paracentric inversion.

Conserved synteny, disrupted synteny, conserved linkage, disrupted linkage

Gene arrangement:



Count:

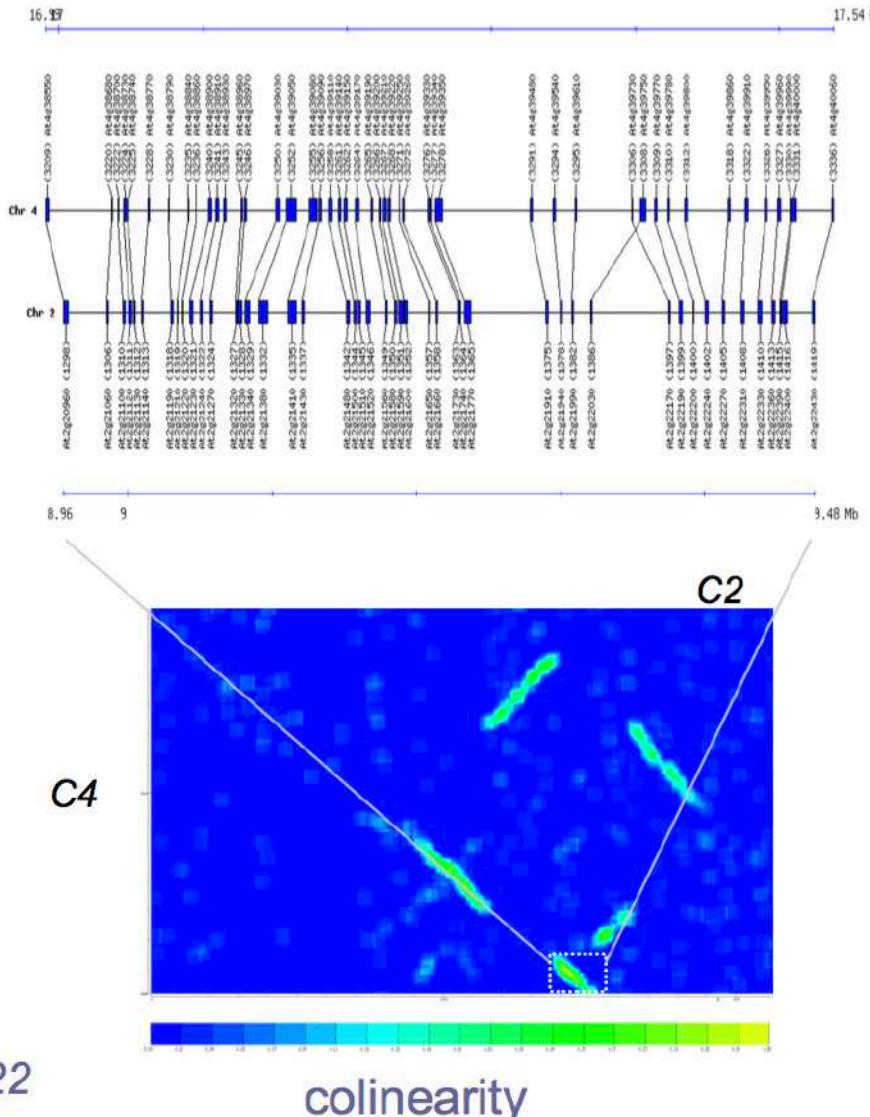
One **conserved linkage** involving genes A,B,C;
One **conserved linkage** involving genes D,E,F.
One **disrupted linkage** involving genes A,B,C vs D,E,F .
One **conserved synteny** involving genes A,B,C.
One **conserved synteny** involving genes D,E,F.
One **disrupted synteny** involving genes A,B,C vs D,E,F.

Possible causes:

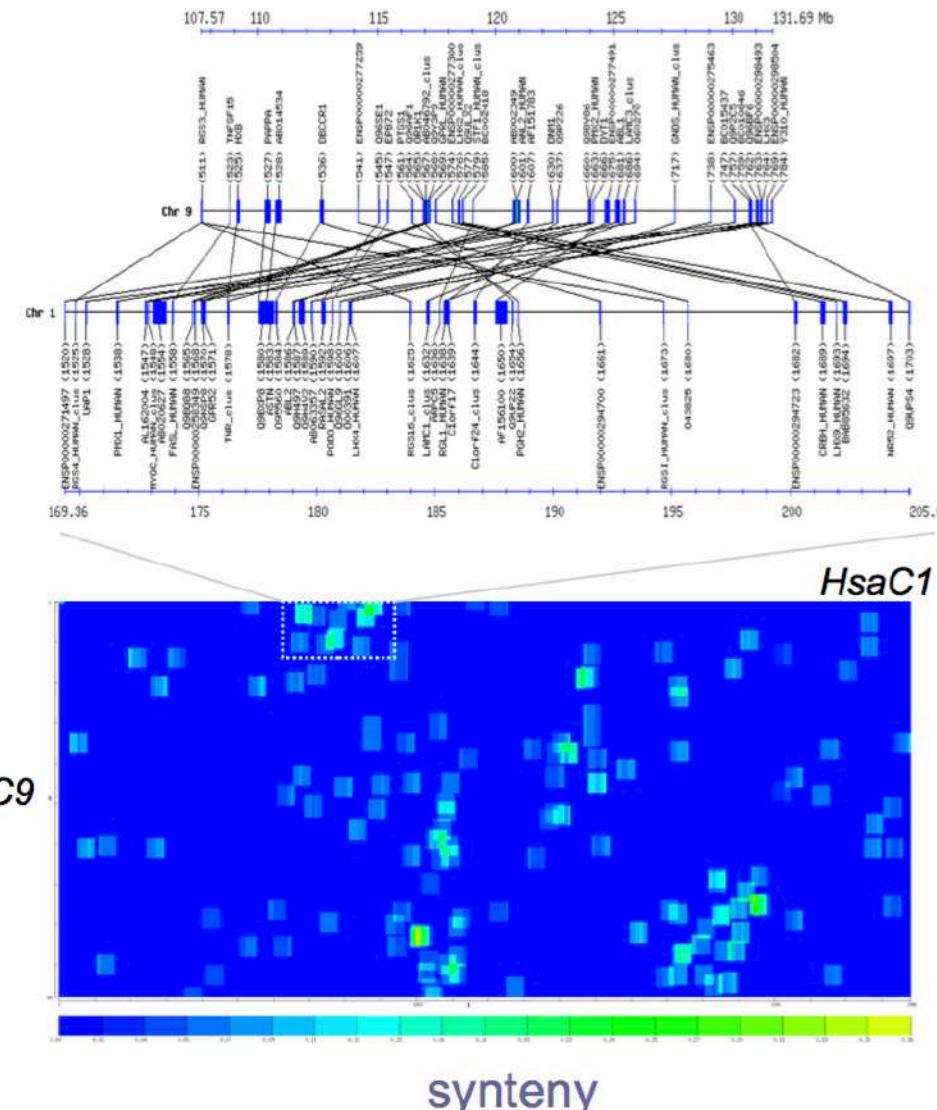
An inter-chromosomal rearrangement,
such as a reciprocal translocation.

Synteny and colinearity

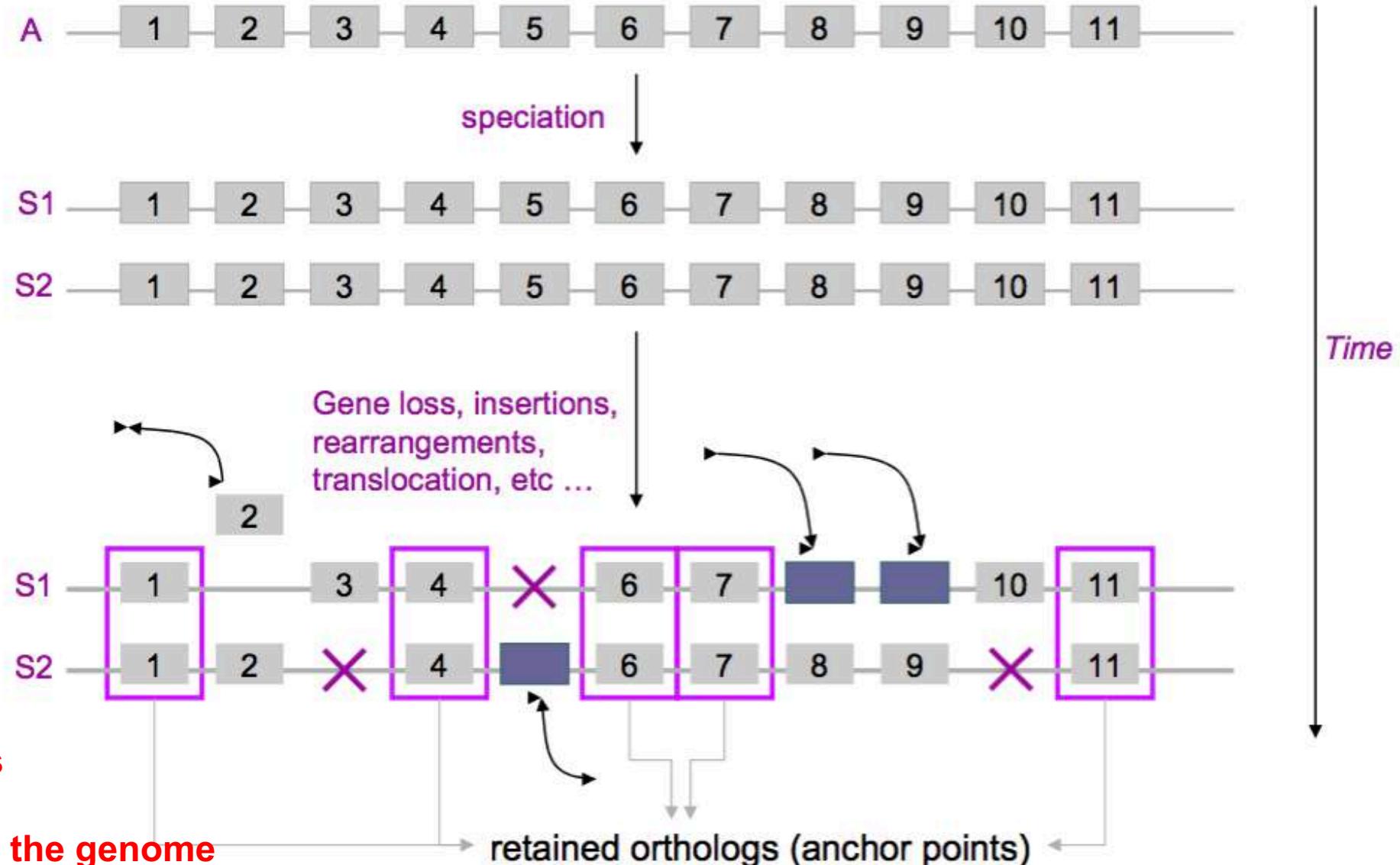
recent duplication



ancient duplication



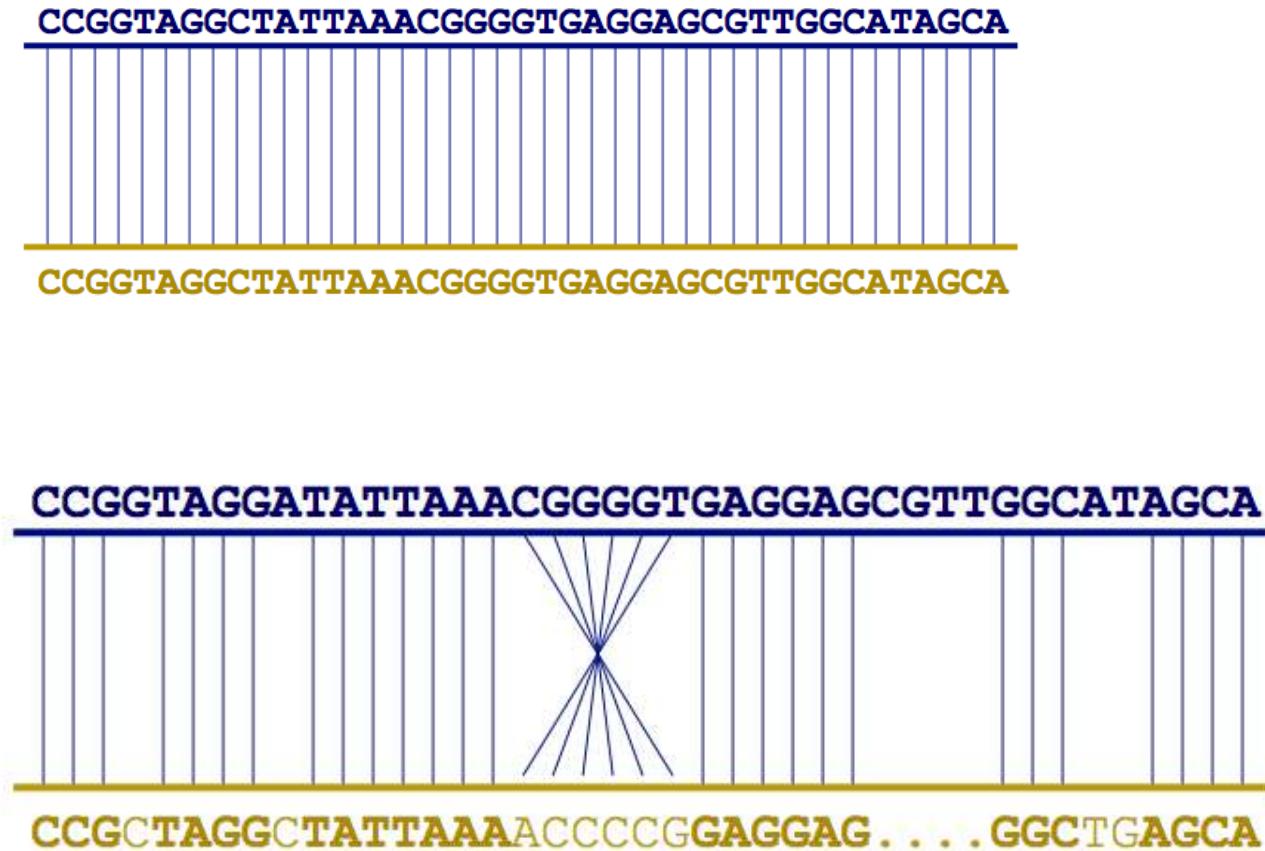
Inferring gene collinearity



Whole genome alignment

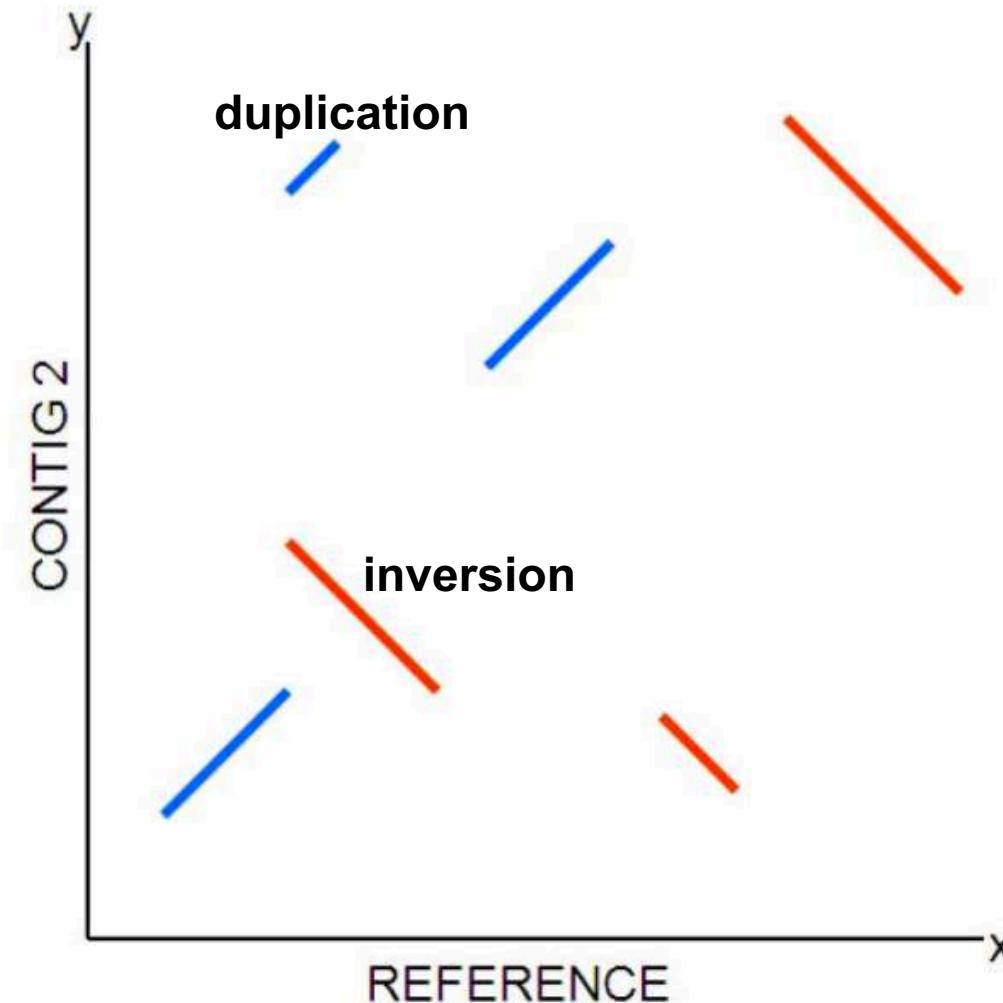
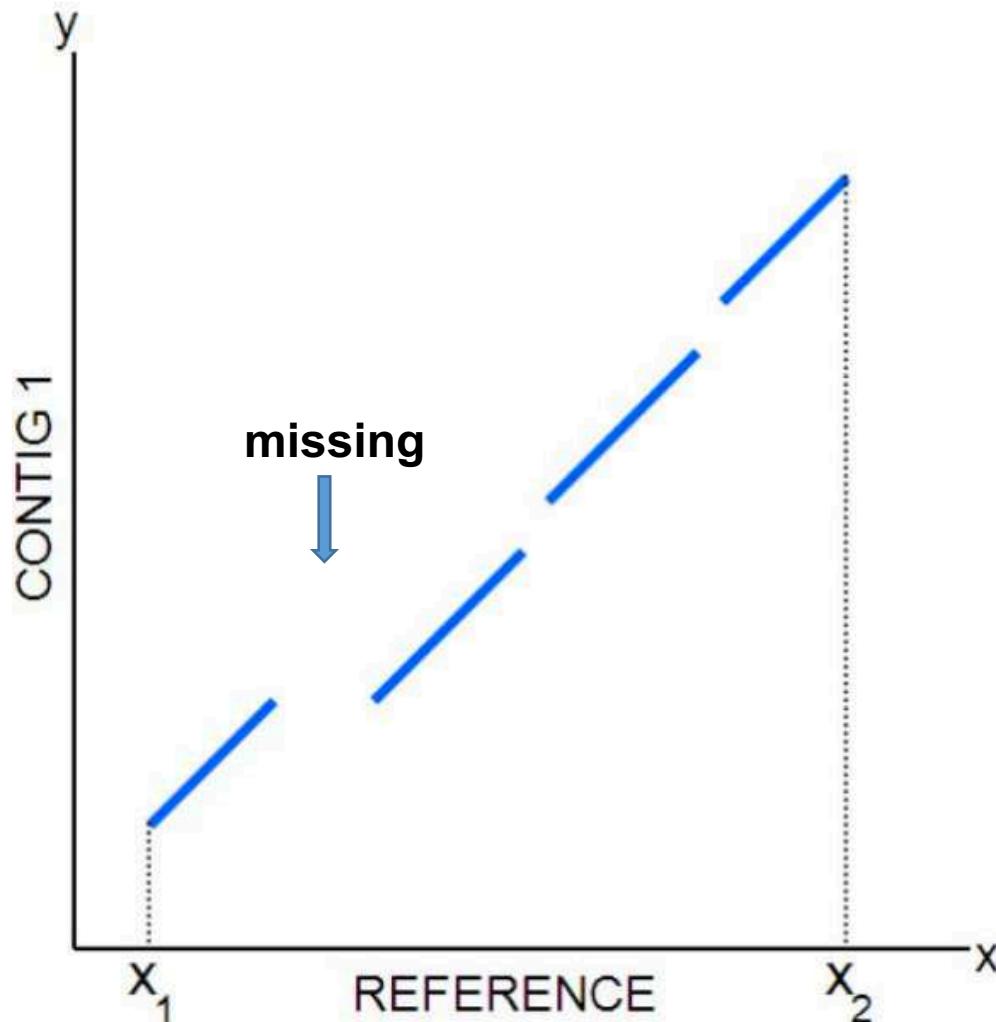
For two genomes, A and B,
find a mapping from each
position in A to its
corresponding position in B

In reality, Genome A may
have insertions, deletions,
translocations, inversions,
duplications or SNPs with
respect to B (sometimes all of
the above)



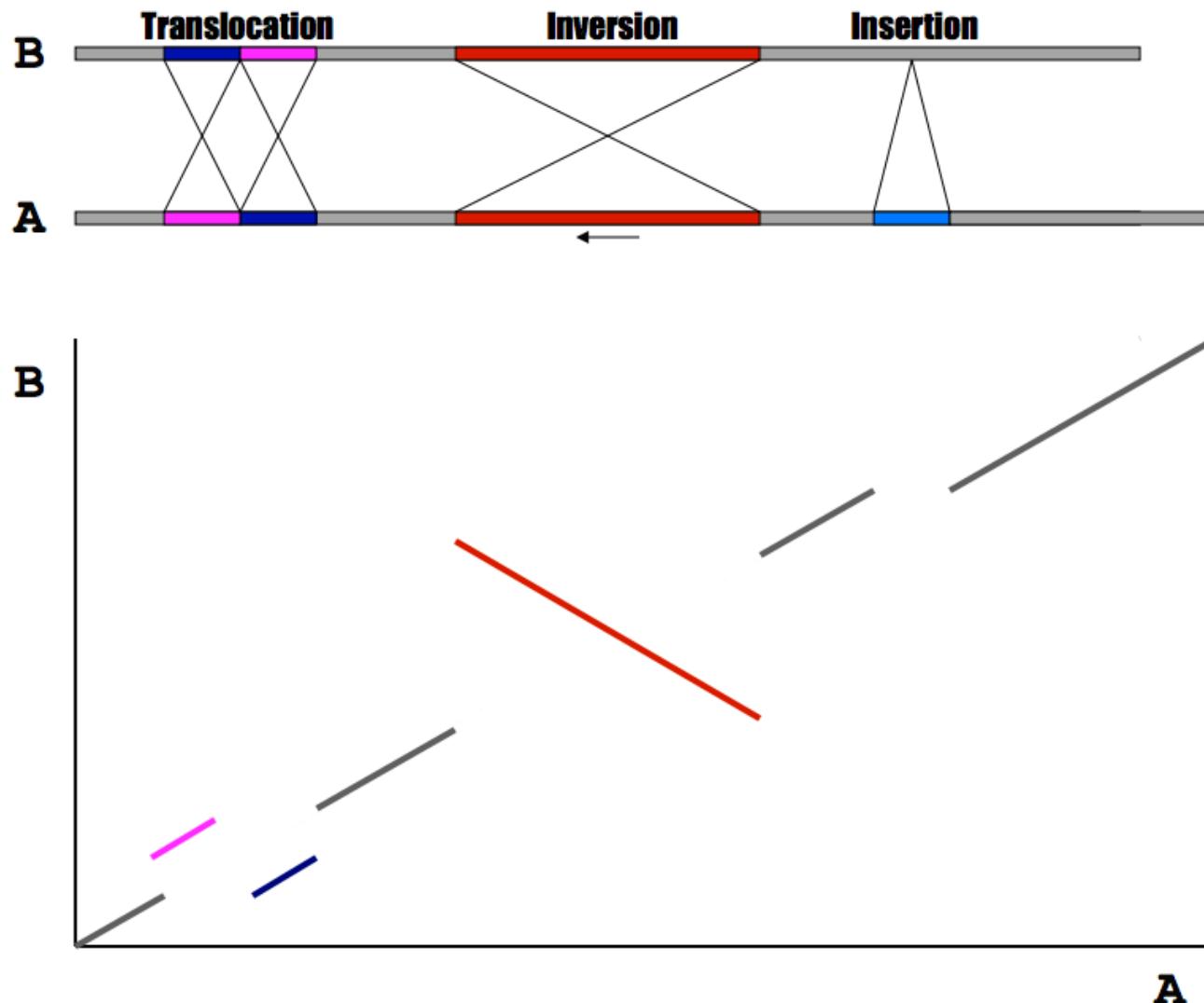
Aligning genome at nucleotide / amino acid level

Visualise through dotplot

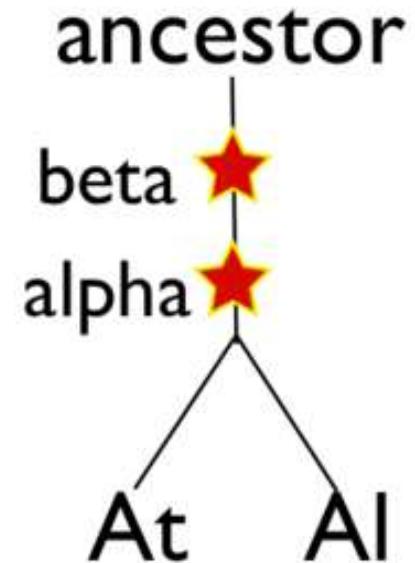
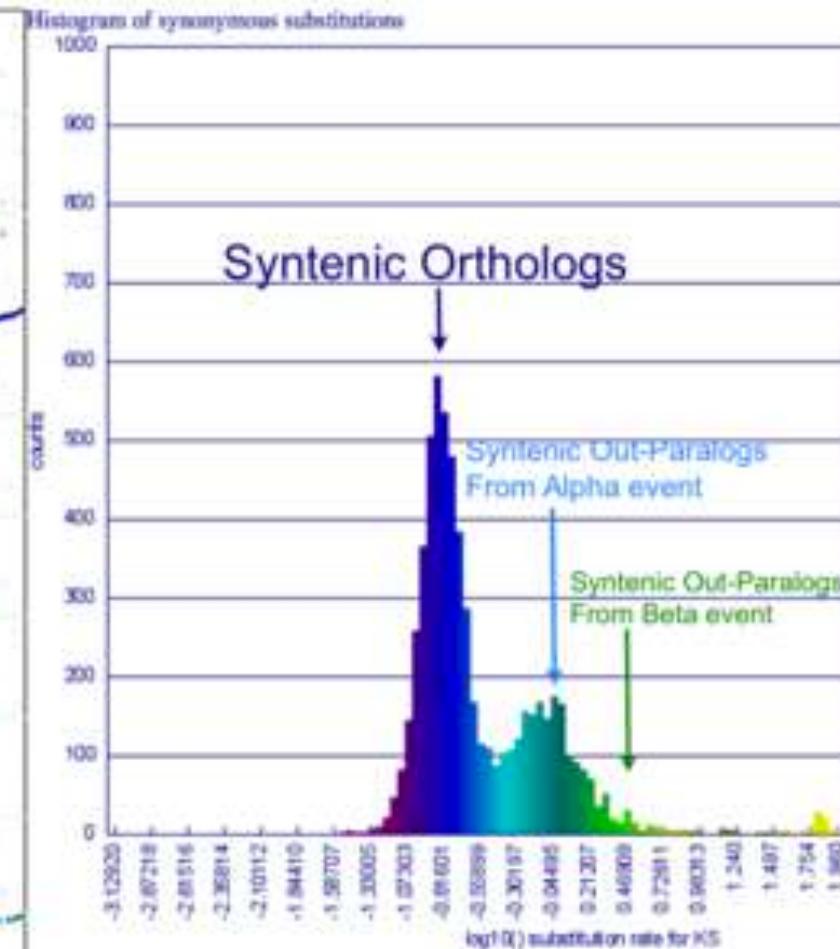
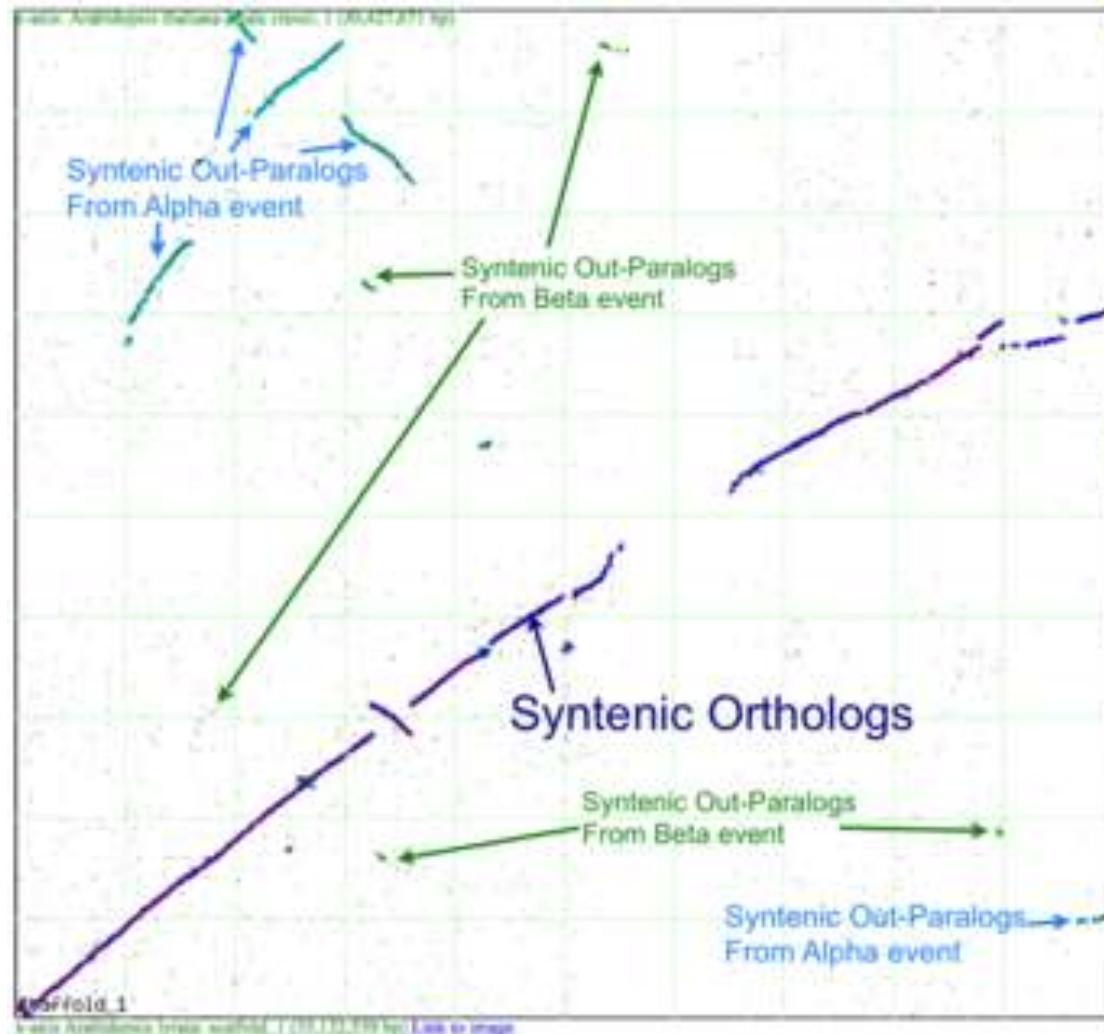


Aligning genome at nucleotide / amino acid level

Visualise through dotplot

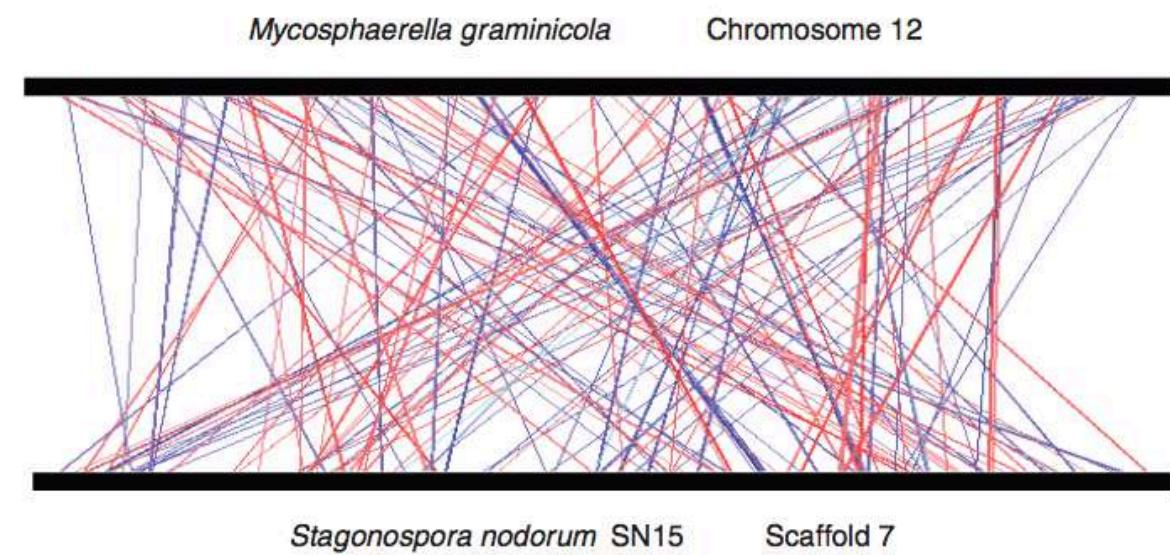
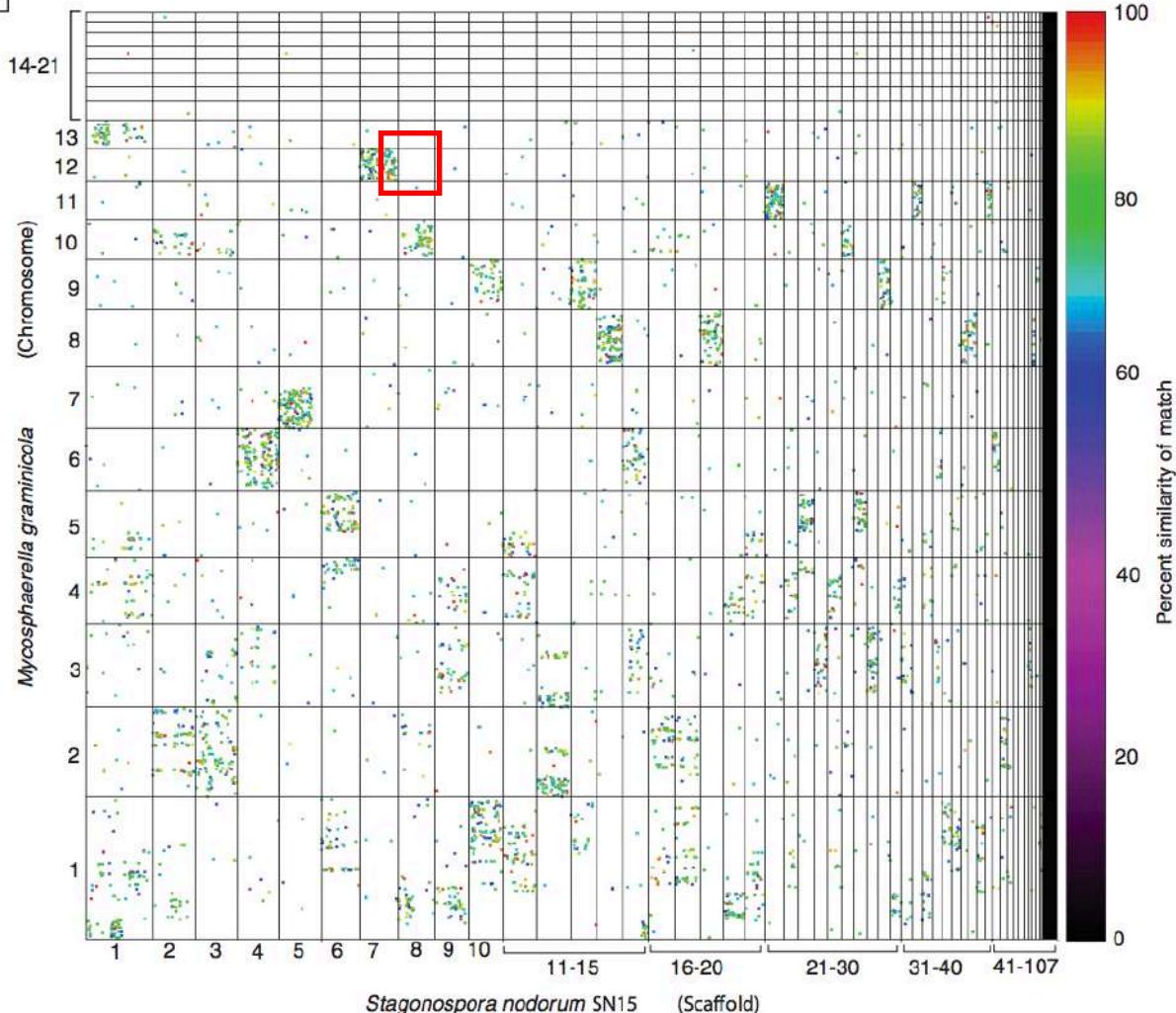


Relationship between genome synteny, syntenic orthologs and duplications



Relationship between genome synteny, syntenic orthologs and duplications

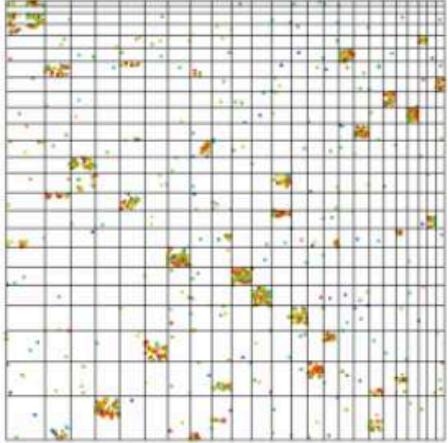
(a)



Different kinds of genome synteny

mesosynteny

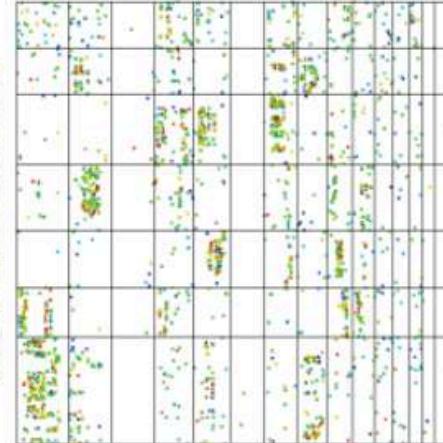
Leptosphaeria maculans



Phaeosphaeria nodorum

degraded
mesosynteny

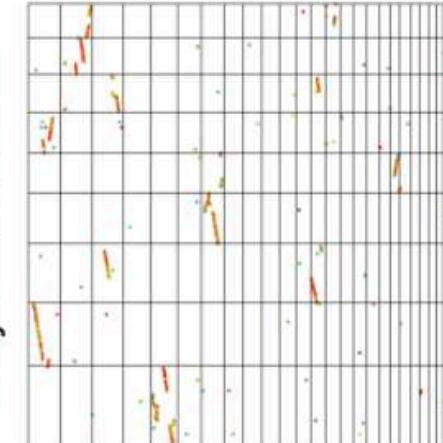
Neurospora crassa



Fusarium oxysporum

macrosynteny

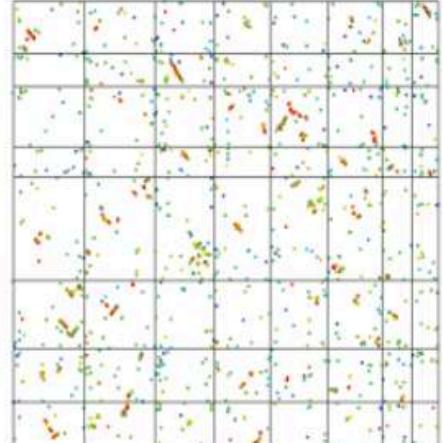
Botryotinia fuckeliana



Sclerotinia sclerotiorum

degraded
macrosynteny

Penicillium marneffei



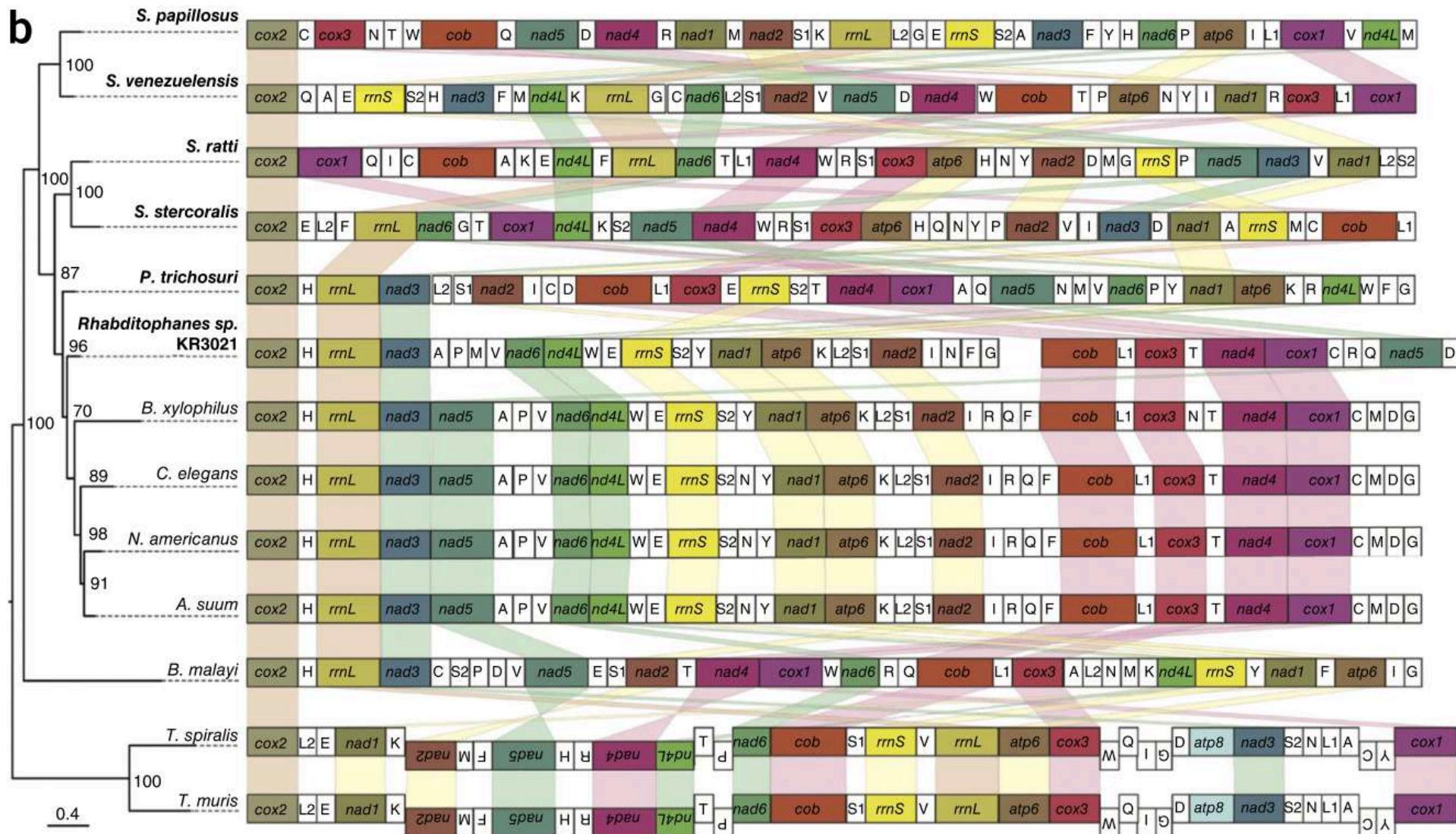
Aspergillus fumigatus

genes are conserved within homologous chromosomes,
but with randomized orders and orientations

genes are conserved within homologous chromosomes,
and with colinear gene regions

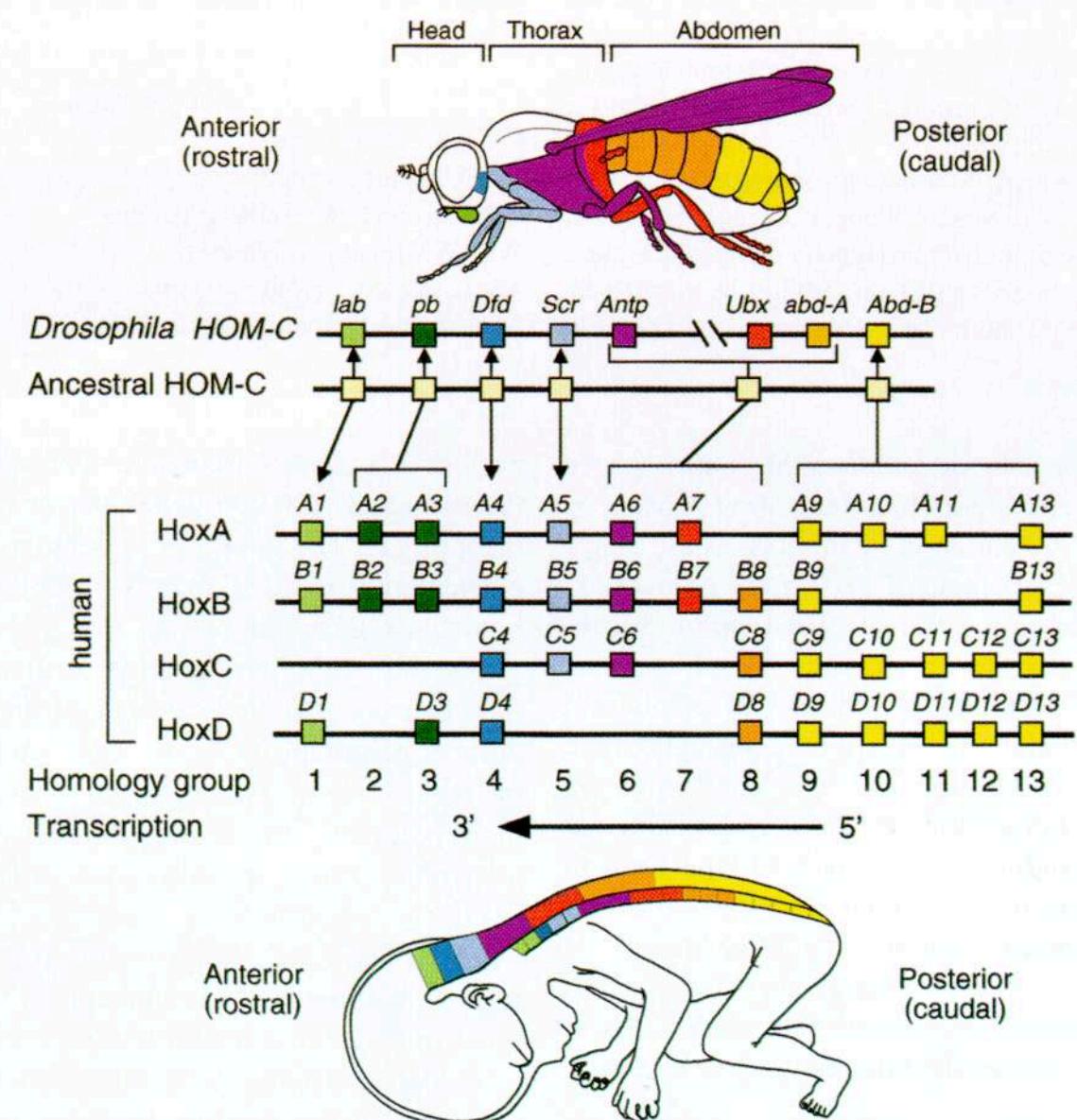
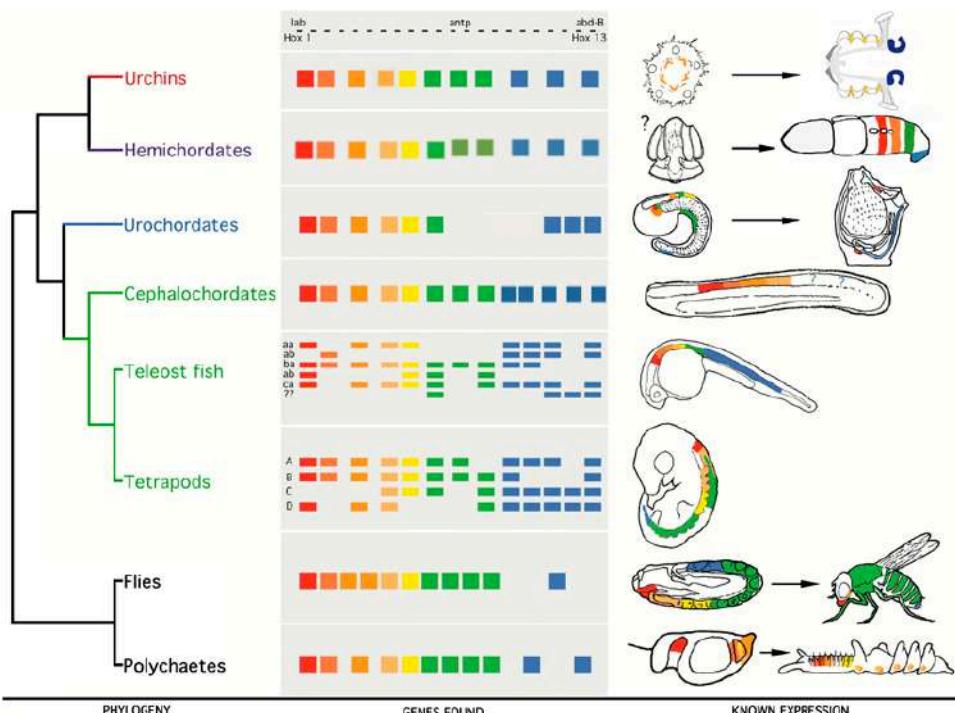
Why are we interested in synteny and collinearity?

Establish relationship between species



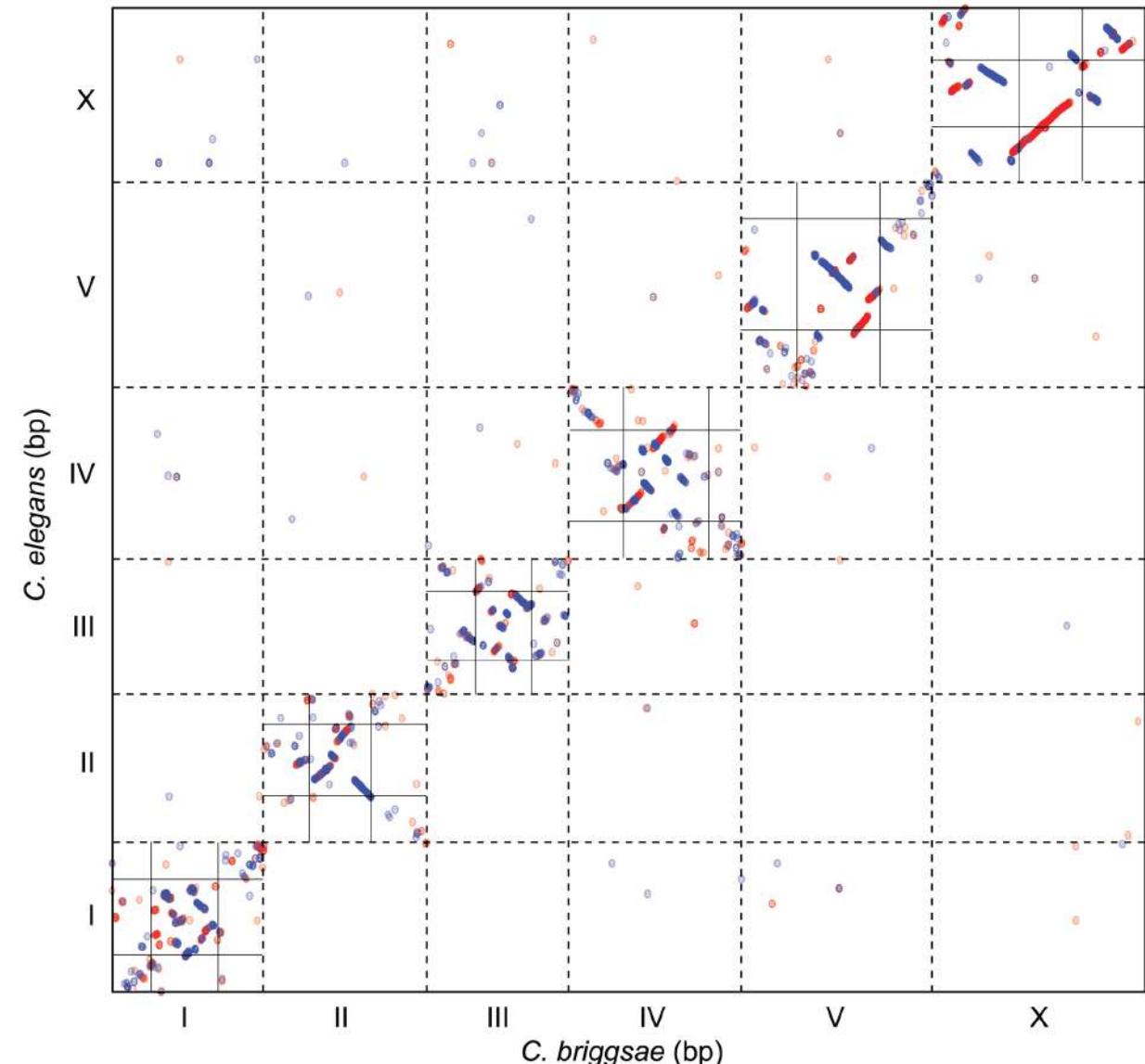
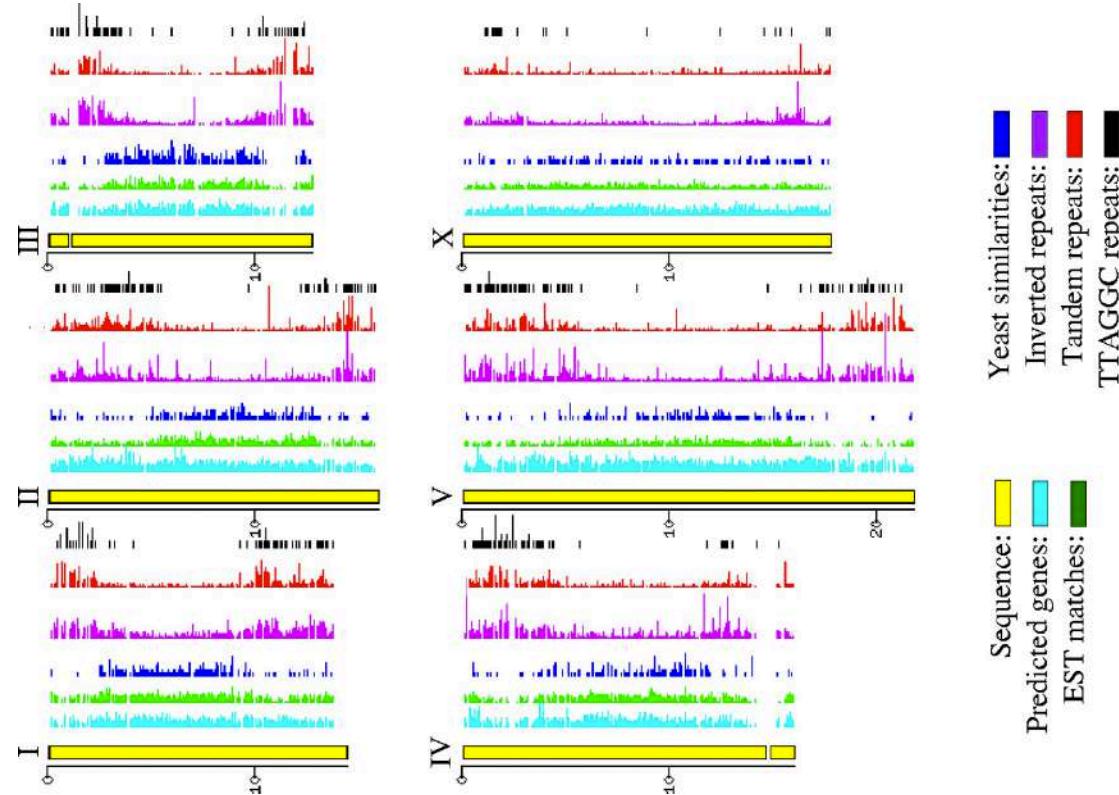
Why are we interested in synteny and collinearity?

Evolutionary conserved features
(orthologs, synteny, collinearity) are good
indicators of functionally important genome
regions



Why are we interested in synteny and collinearity?

**Evolutionary conserved features
(orthologs, synteny, collinearity) relate
to genome biology**

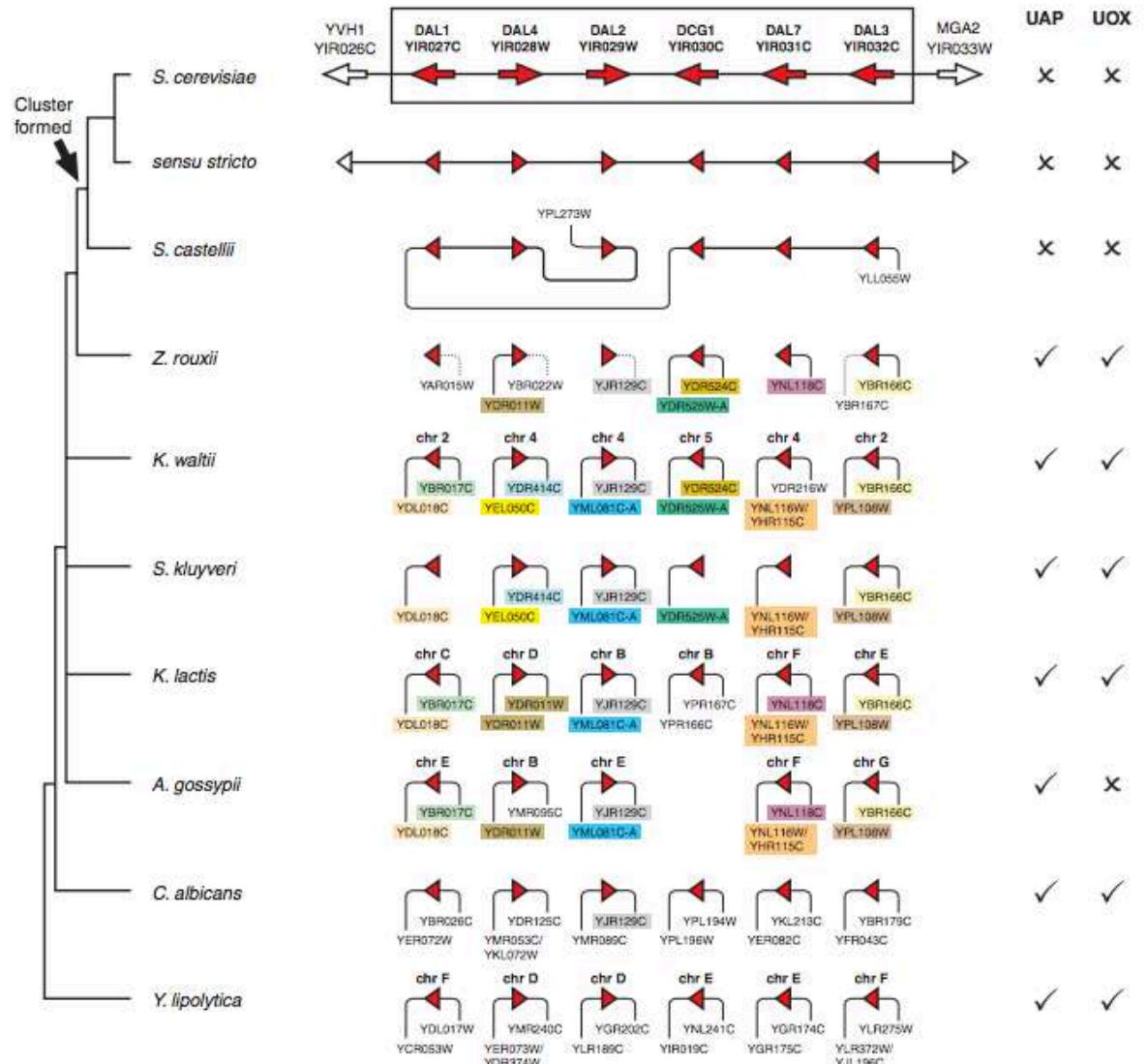


Stein et al., PLOS Biology 2003

The *C. elegans* Sequencing Consortium Science 1998

Why are we interested in synteny and collinearity?

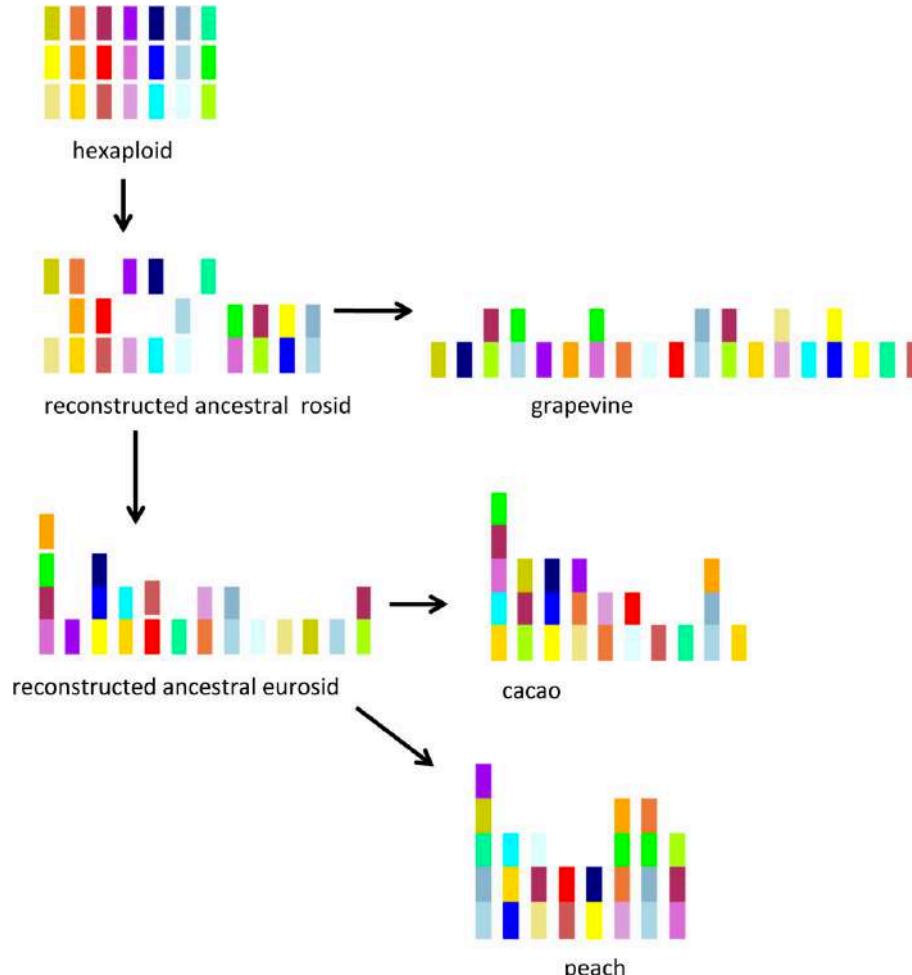
We can **reconstruct evolutionary histories of gene & gene families** and eventually lead to functioning of species



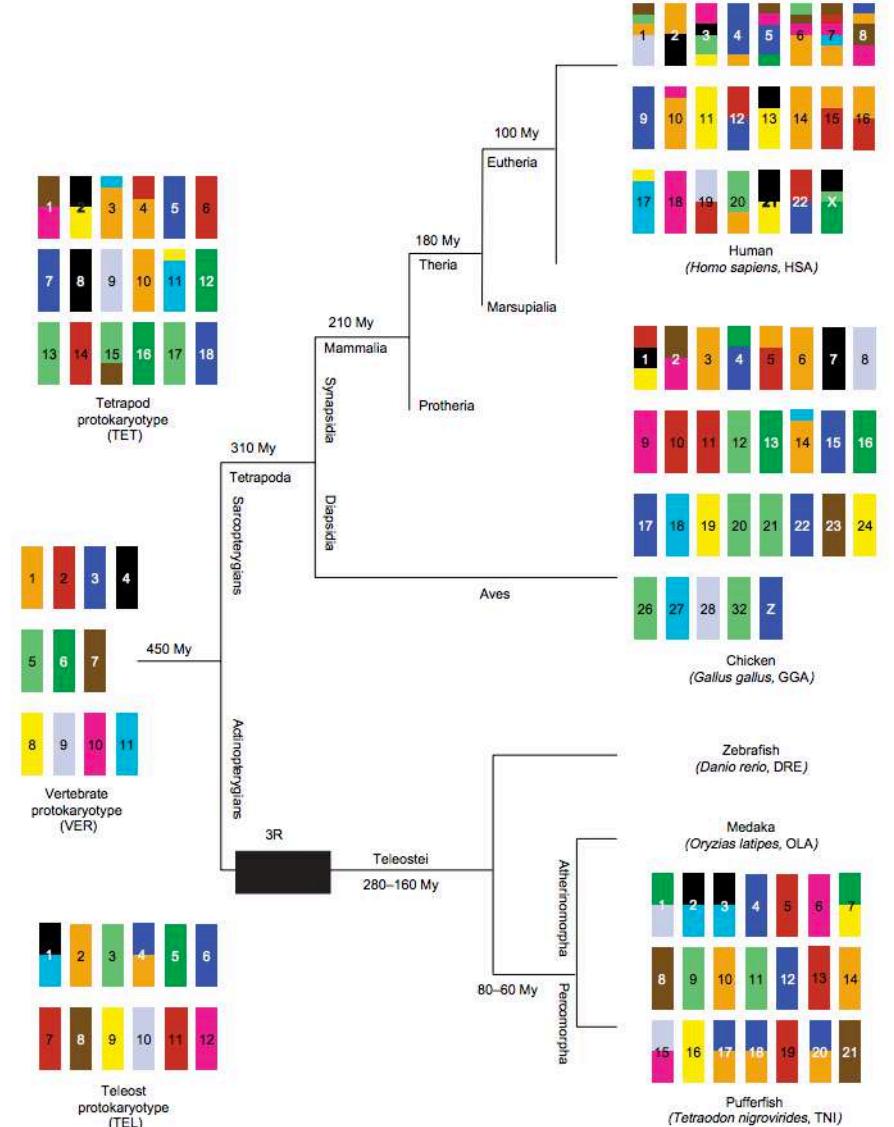
Birth of a metabolic gene cluster in yeast by adaptive gene relocation

Why are we interested in synteny and collinearity?

We can **reconstruct** ancient karyotypes that eventually lead to better understanding of evolution of species



Zheng et al (2013)

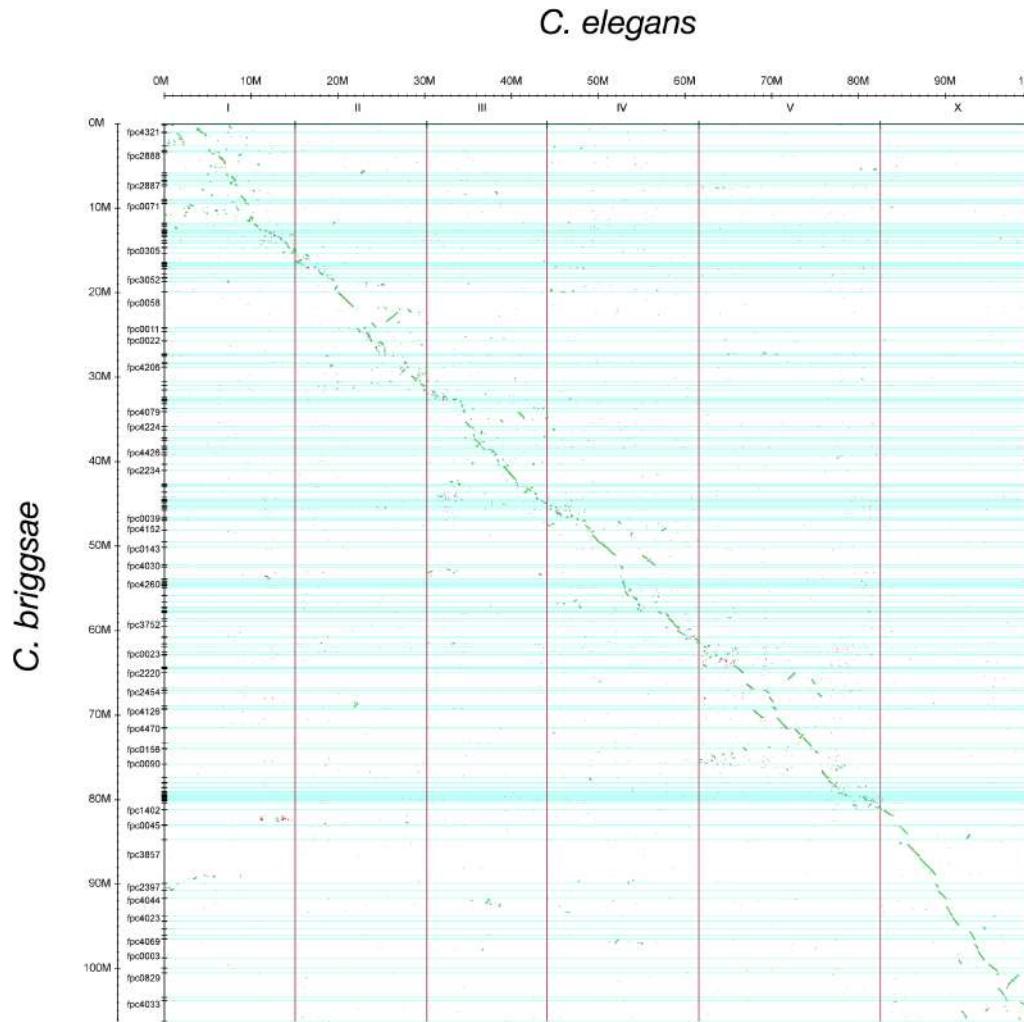


Kohn et al (2006)

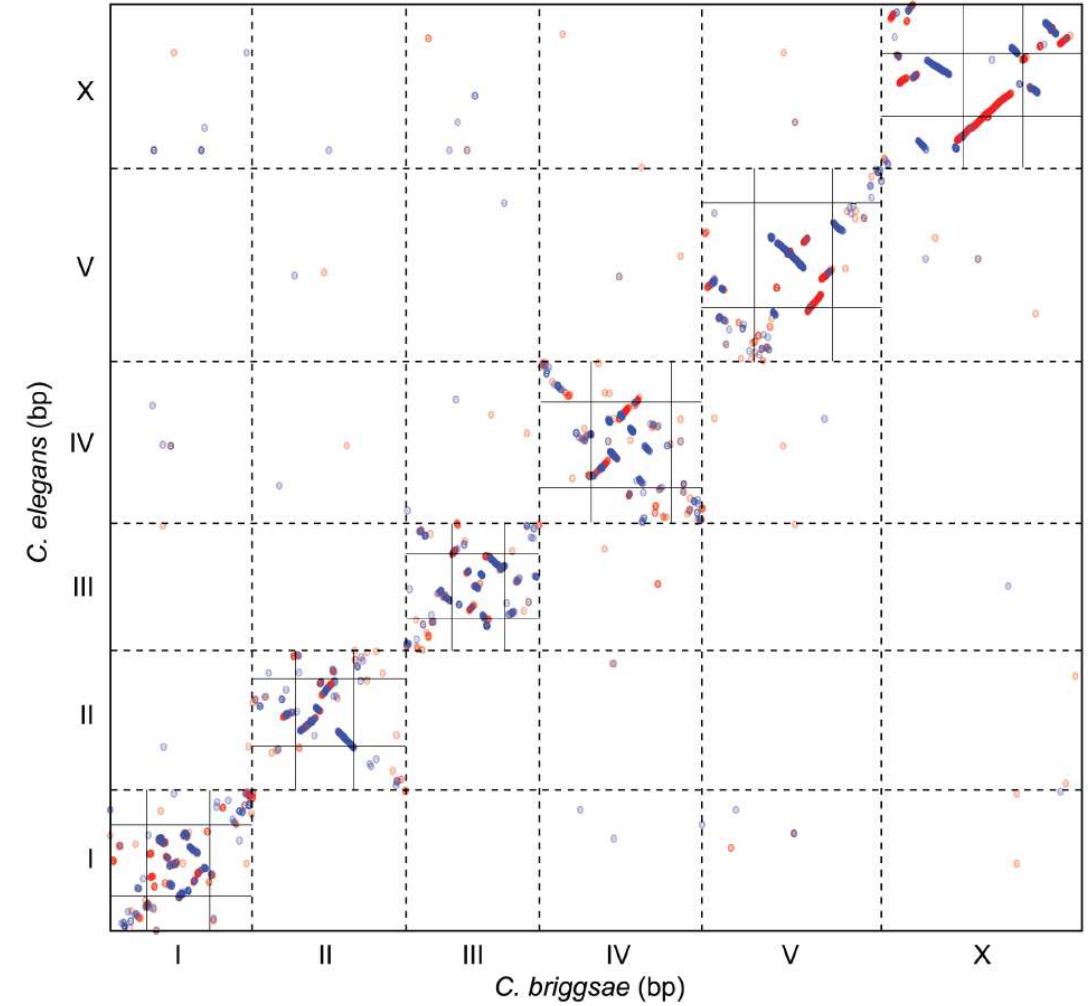
TRENDS in Genetics

Some caveats

Assembly quality likely to influence synteny observation



Stein et al., PLOS Genetics (2003)



Ross et al., PLOS Genetics (2011)

Synteny based scaffolding: use with caution

Tang et al. *Genome Biology* (2015) 16:3
DOI 10.1186/s13059-014-0573-1



METHOD

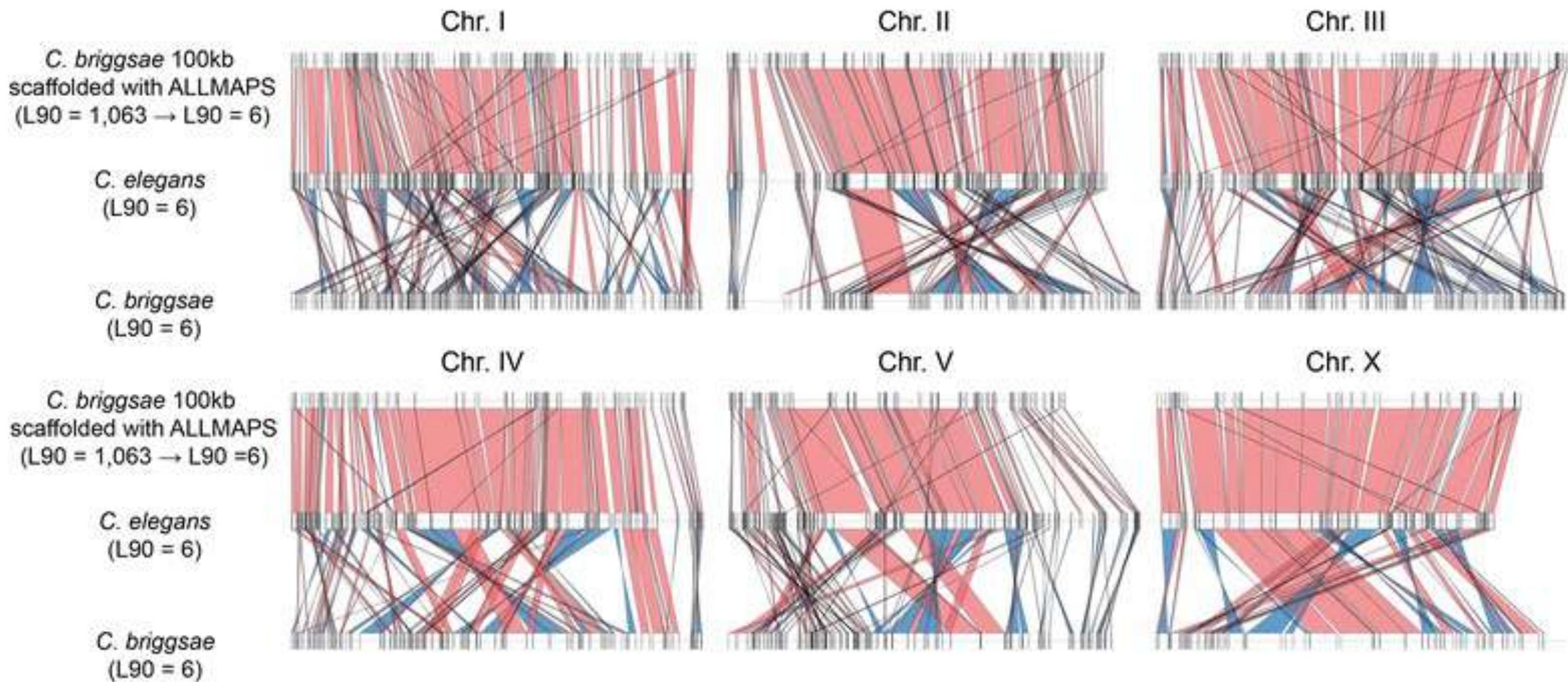
Open Access

ALLMAPS: robust scaffold ordering based on multiple maps

Haibao Tang^{1,2,3*}, Xingtian Zhang⁴, Chenyong Miao¹, Jisen Zhang¹, Ray Ming¹, James C Schnable^{3,5},
Patrick S Schnable^{3,6}, Eric Lyons² and Jianguo Lu⁷

for example, in ‘orphan’ species where there is little research investment in the past, **we can still create consensus chromosomal assemblies based on comparative maps against multiple, closely-related genomes as a collection of ‘references’ ... Correct?**

Synteny based scaffolding: use with caution



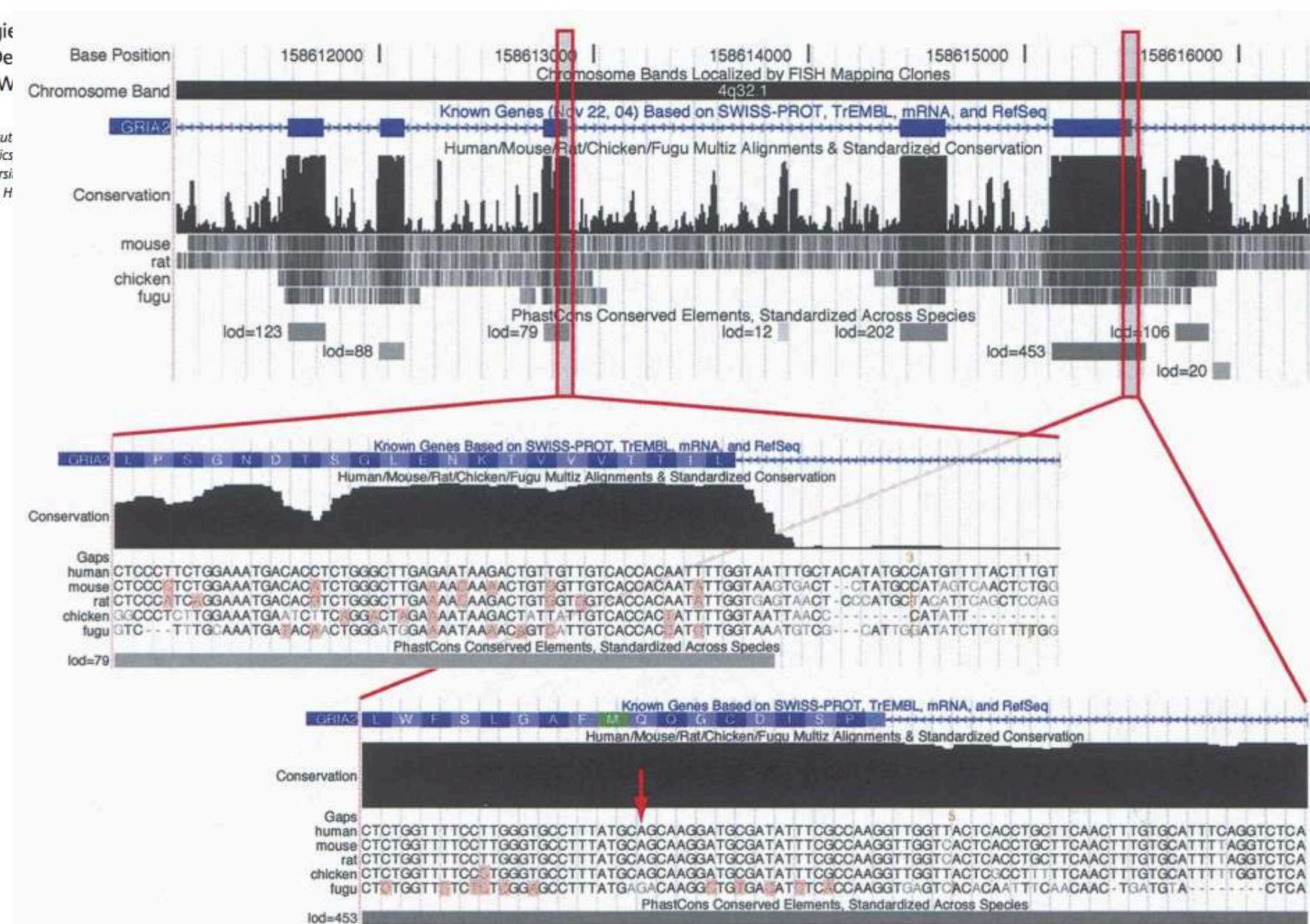
Comparing genomes beyond gene level

Evolutionarily conserved elements in vertebrate, insect, worm, and yeast genomes

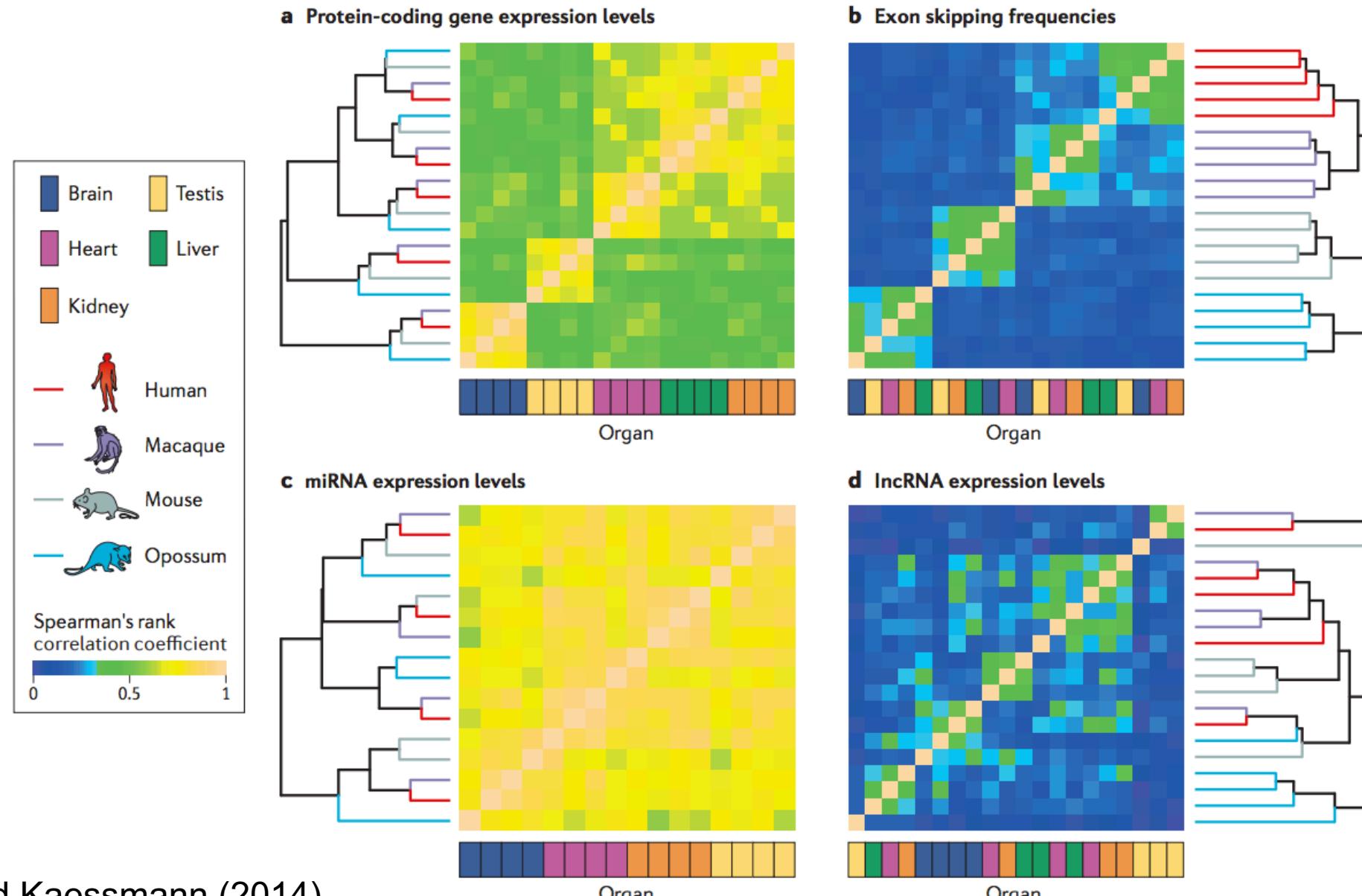
Adam Siepel,^{1,6} Gill Bejerano,¹ Jakob S. Pedersen,¹ Angie Kate Rosenbloom,¹ Hiram Clawson,¹ John Spieth,⁴ LaDe Stephen Richards,⁵ George M. Weinstock,⁵ Richard K. W W. James Kent,¹ Webb Miller,³ and David Haussler^{1,2}

¹Center for Biomolecular Science and Engineering, ²Howard Hughes Medical Institut Cruz, California 95064, USA; ³Center for Comparative Genomics and Bioinformatics Park, Pennsylvania 16802, USA; ⁴Genome Sequencing Center, Washington Universi 63108, USA; ⁵Human Genome Sequencing Center, Department of Molecular and H Houston, Texas 77030, USA

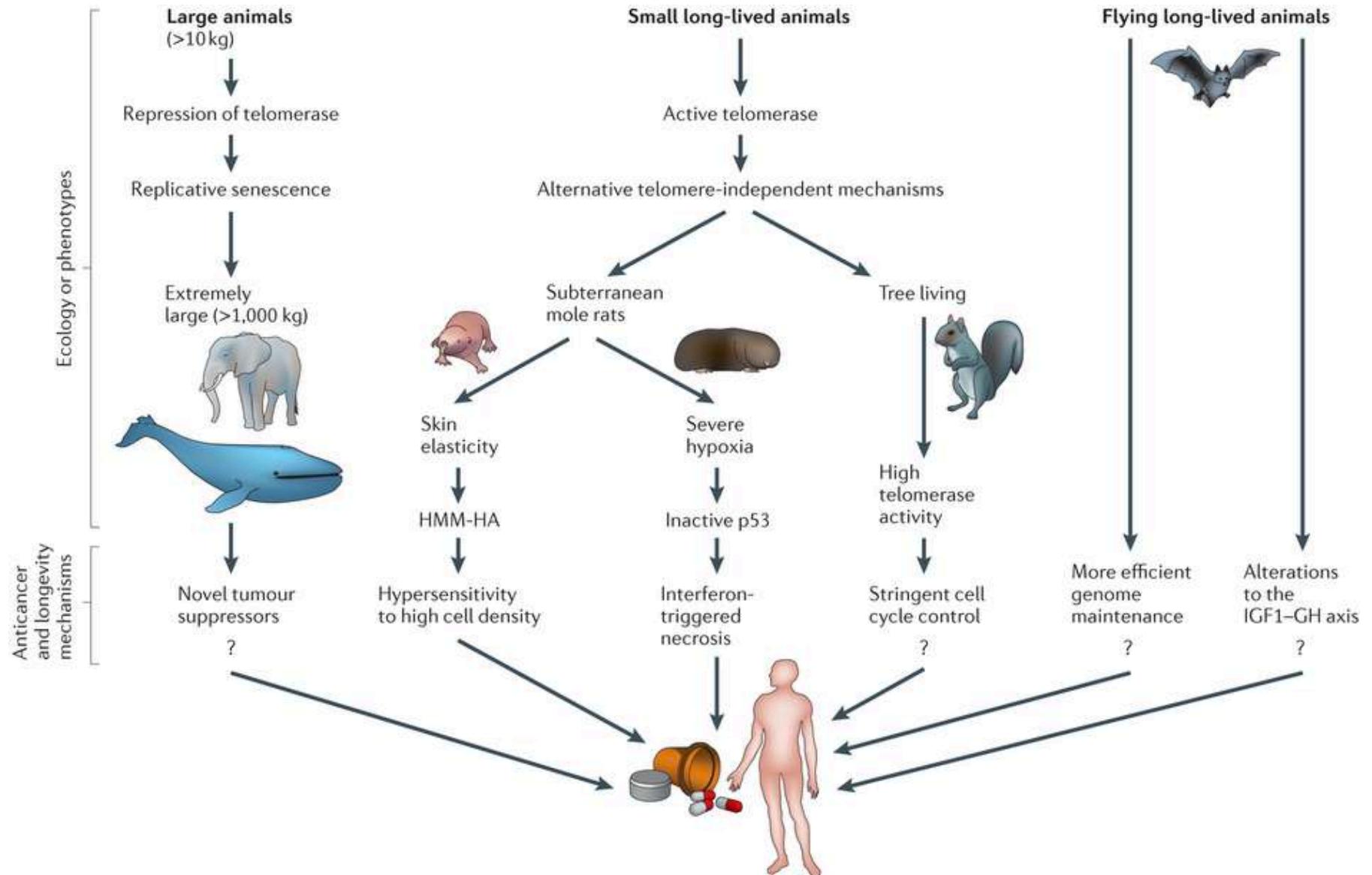
PhastCons



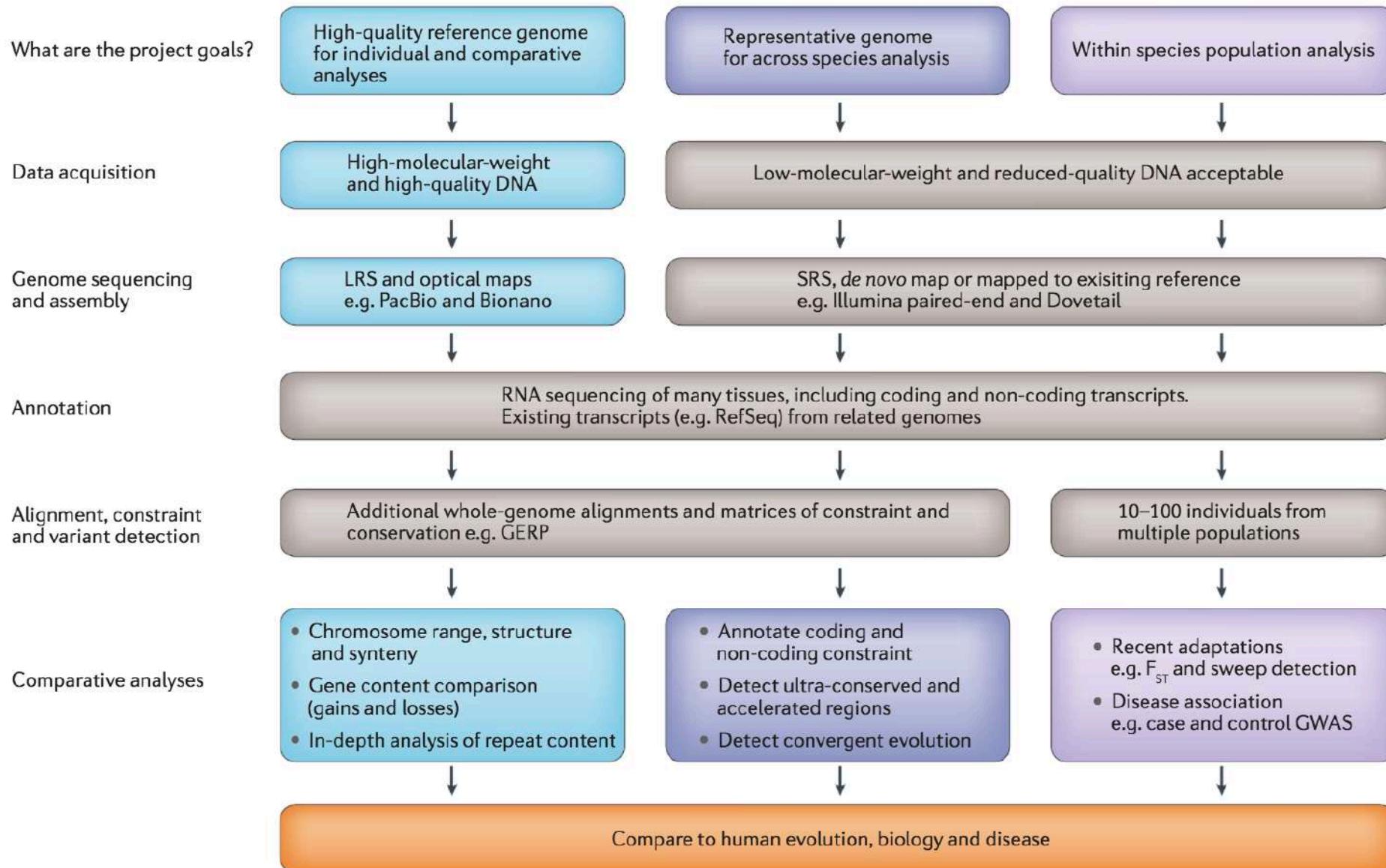
Global patterns of evolution for different aspects of the transcriptome



Comparative genomics of longevity ageing (with focus)

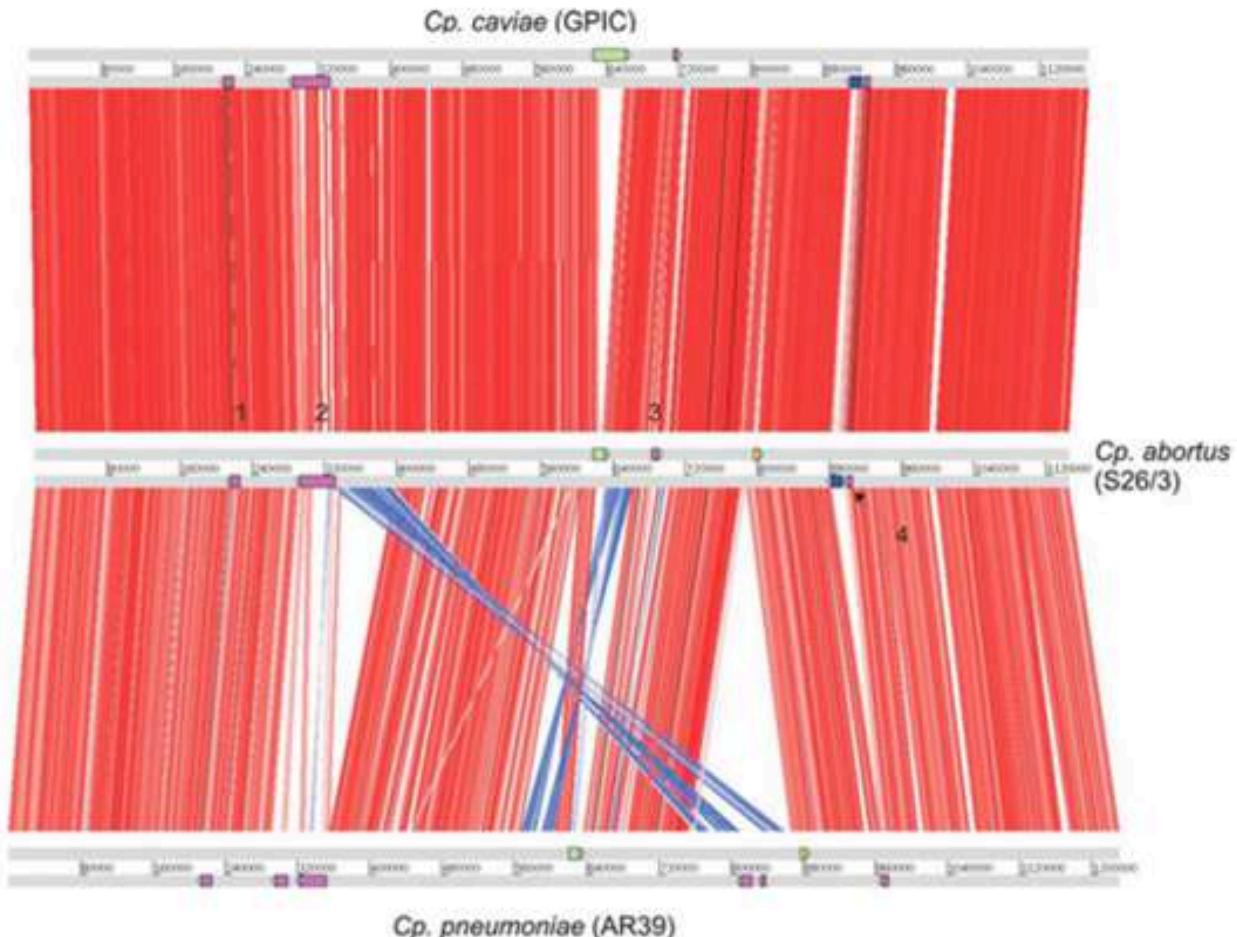


Designing a sequencing project: 2017 version



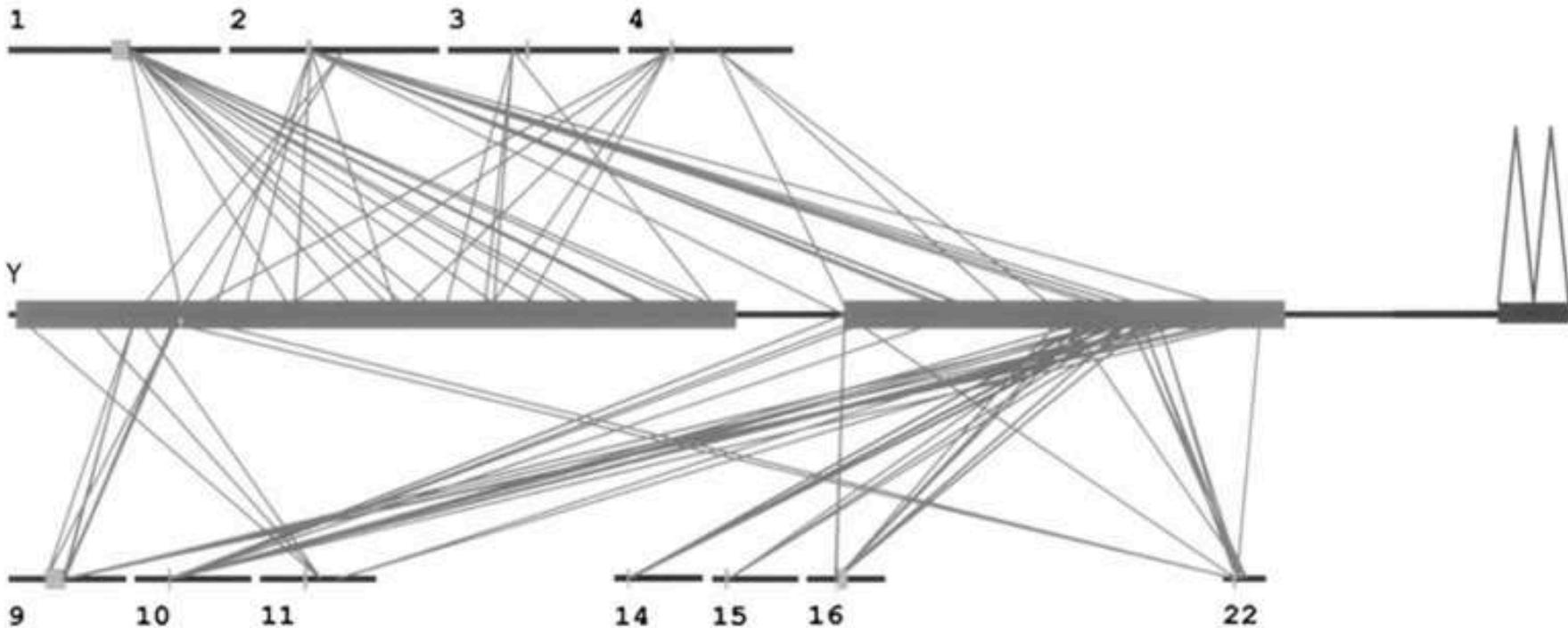
Genome visualisation

- this is the most common way to represent relationships within genomic positions
 - works when the number of cross-overs is limited



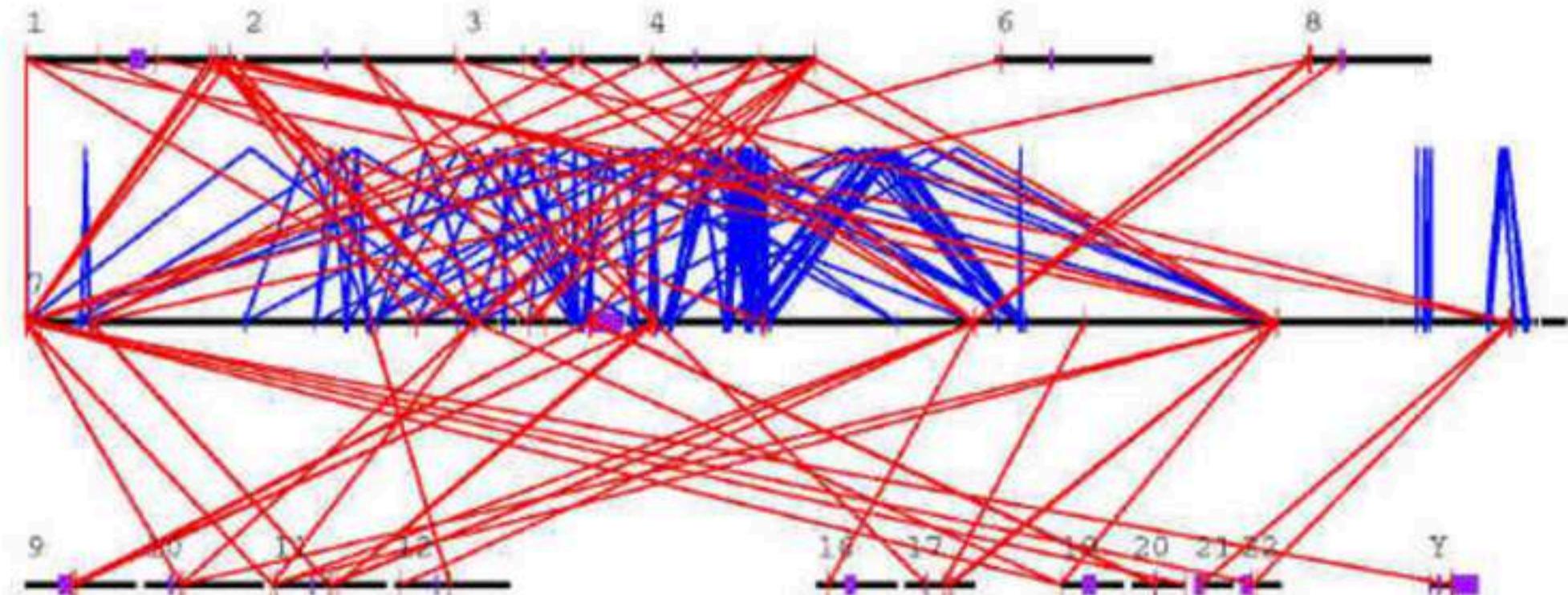
Genome Res. 2005 May;15(5):629-40

- when complexity is increased, the figure starts to lose cohesion
 - routing becomes difficult to follow
 - there is no focus point for the eye – your eye wanders over the figure



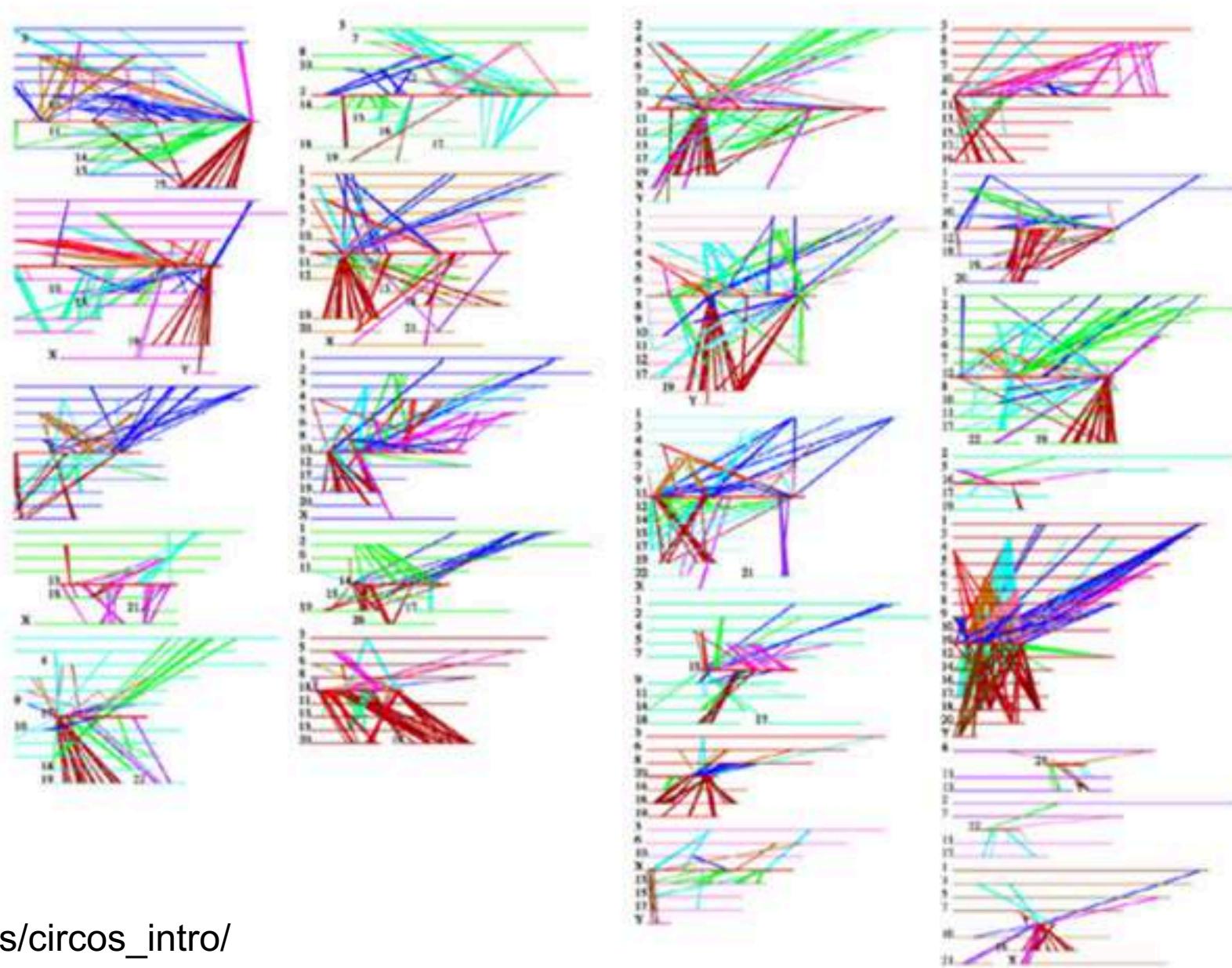
Genome Res. 2003 Jan;13(1):37-45

- things get worse and worse when mappings that link both neighbouring (blue) and distant (red) positions are shown



- you can try to fix things by partitioning your data set (somehow)

- mileage varies
 - generally poor



http://circos.ca/presentations/talks/circos_intro/

Venter, J. C., M. D. Adams, et al. (2001). "The sequence of the human genome." *Science* 291(5507): 1304-51.

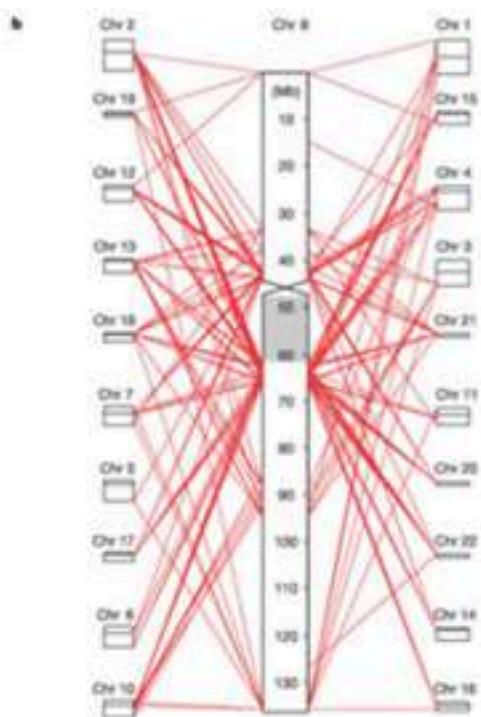
- finally, you descend into data overload and information hell
 - this is not an informative plot, although a pretty one



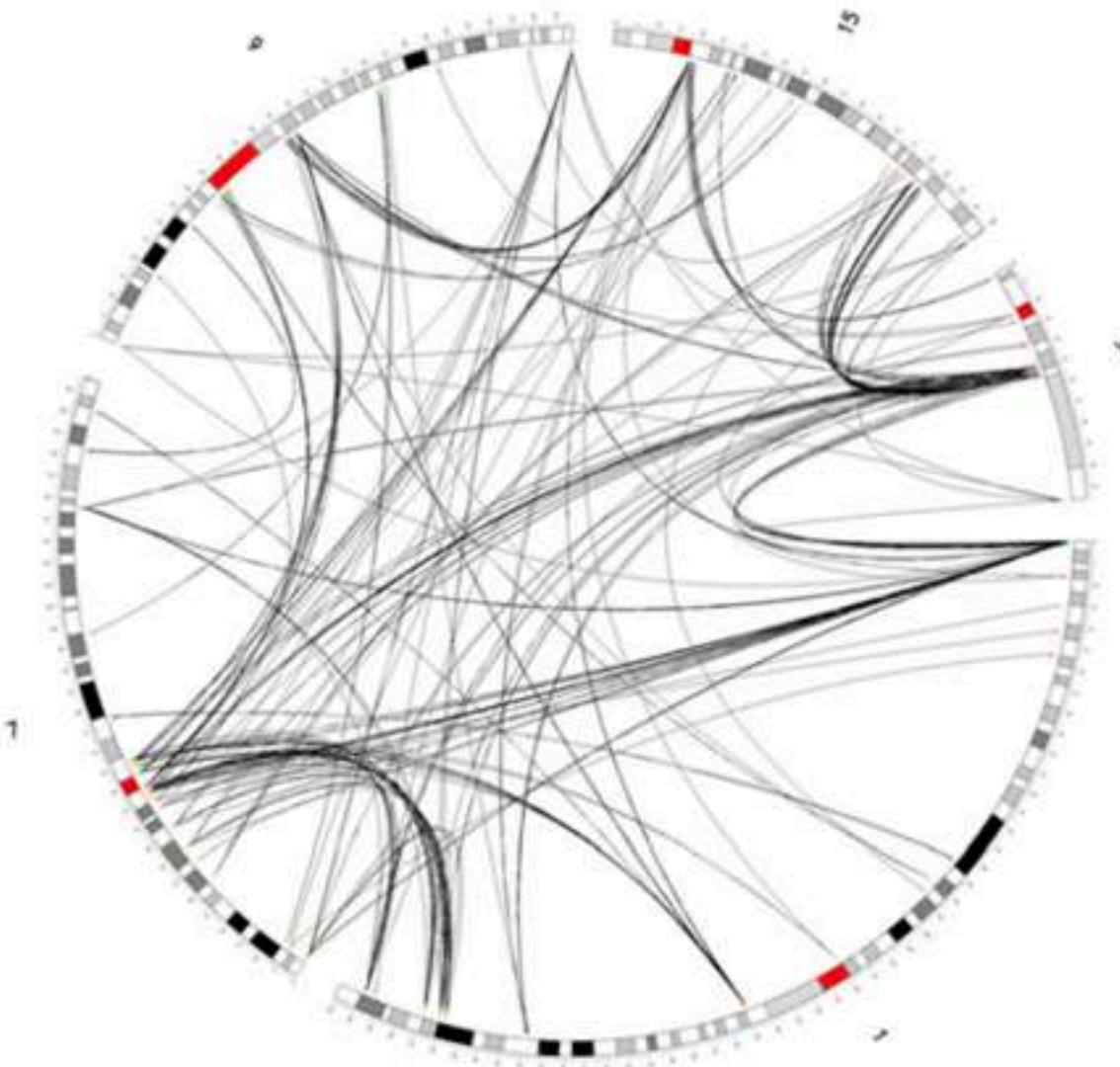
Segmental Duplications in *Arabidopsis* Genome. Alexander Kozik and Richard Michalek, UC Davis, California

Image created with GenomePixelizer

Circos

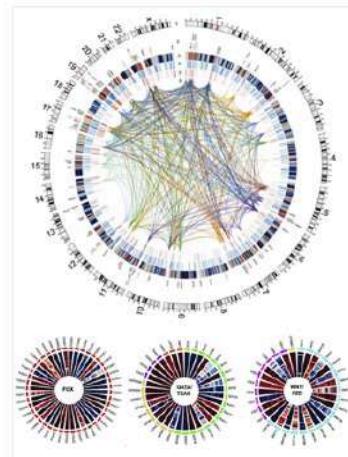


Humphray, S. J., K. Oliver, et al. (2004).
"DNA sequence and analysis of human chromosome 9."
Nature 429(6990): 369-74.

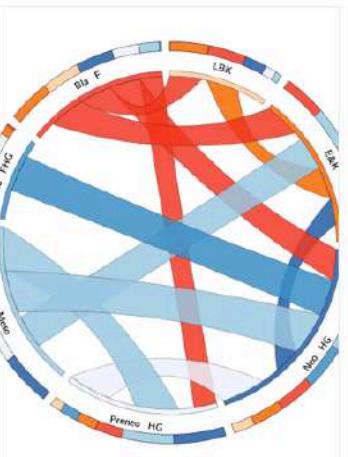


Circos image

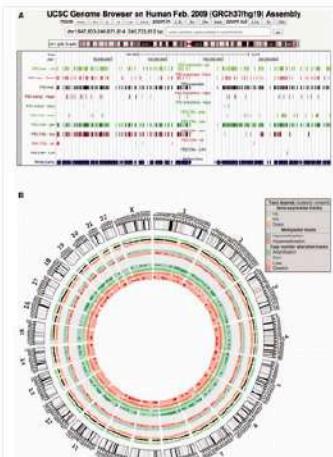
Circos



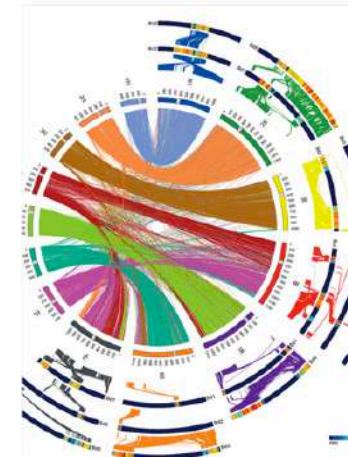
▲ 1 - 1 Dec 2013 | Saben J, Zhong Y, McKelvey S et al. (2014) A comprehensive analysis of the human placenta transcriptome. *Placenta* 35:125-131.



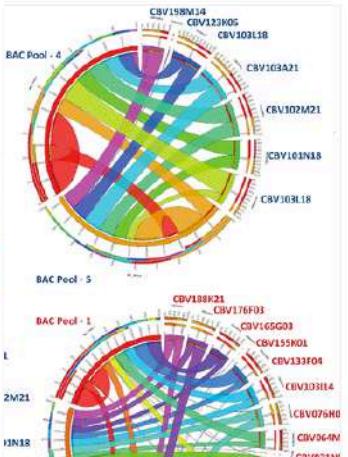
▲ 2 - 25 Oct 2013 | Bollongino R, Nehlich O, Richards MP et al. (2013) 2000 years of parallel societies in Stone Age Central Europe. *Science* 342:479-481.



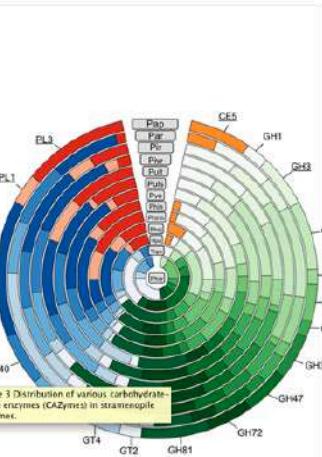
▲ 3 - 25 Oct 2013 | Dayem Ullah AZ, Cutts RI, Ghetta M et al. (2013) The pancreatic expression database: recent extensions and updates. *Nucleic Acids Res*



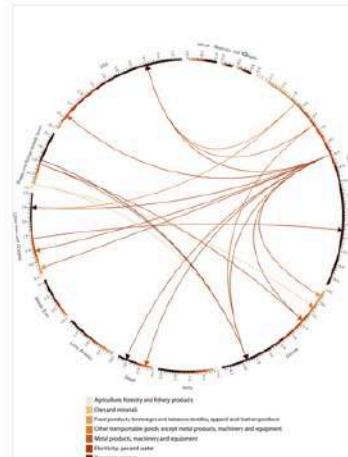
▲ 13 - 8 Oct 2013 | Martis MM, Zhou R, Haseneyer G et al. (2013) Reticulate Evolution of the Rye Genome. *Plant Cell*



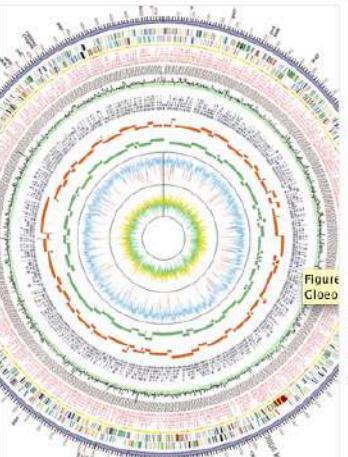
▲ 14 - 8 Oct 2013 | Buyyaparup R, Kantety RV, Yu JZ et al. (2013) BAC-Pool Sequencing and Analysis of Large Segments of A12 and D12 Homoeologous Chromosomes in Upland Cotton. *PLoS One* 8:e76757.



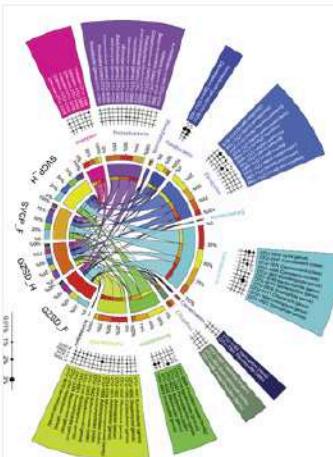
▲ 15 - 4 Oct 2013 | Adhikari BN, Hamilton JP, Zerillo MM et al. (2013) Comparative Genomics Reveals Insight Into Virulence Strategies of Plant Pathogenic Oomycetes. *PLoS One* 8:e75072.



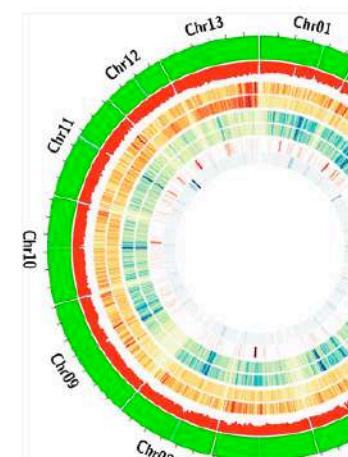
▲ 4 - 23 Oct 2013 | Kanemoto K, Moran D, Lenzen M et al. (2013) International trade undermines national emission reduction targets: New evidence from air pollution. *Global Environmental Change*



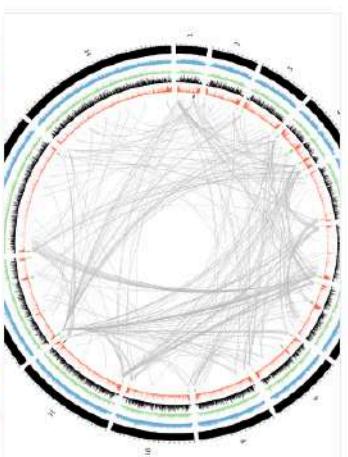
▲ 5 - 23 October 2013 | Saw JHW, Schatz M, Brown MV et al. (2013) Cultivation and Complete Genome Sequencing of Gloeobacter kilaueensis sp. nov., from a Lava Cave in Kilauea Caldera, Hawaii. *PLoS One* 8:e76376.



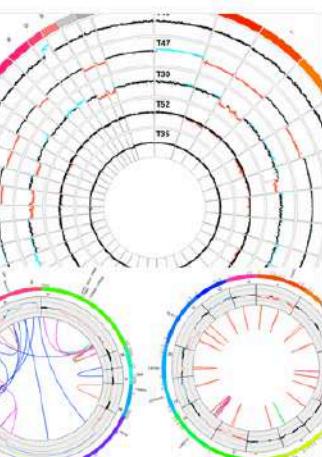
▲ 6 - 17 Oct 2013 | Ye L, Amberg J, Chapman D et al. (2013) Fish gut microbiota analysis differentiates physiology and behavior of invasive Asian carp and indigenous American fish. *The ISME Journal*



▲ 16 - 1 Oct 2013 | Page JI, Huynh MD, Liechty ZS et al. (2013) Insights into the Evolution of Cotton Diploids and Polyploids from Whole-Genome Re-sequencing G3: Genes Genomes Genetics 3:1809-1818.



▲ 17 - 30 Sep 2013 | Lemieux J-E, Kyes SA, Otto TD et al. (2013) Genome-wide profiling of chromosome interactions in Plasmodium falciparum characterizes nuclear architecture and reconfigurations associated with antigenic variation. *Molecular microbiology*



▲ 18 - 30 Sep 2013 | Beck J, Hennecke S, Bornemann-Kolatzki K et al. (2013) Genome Alterations in Canine Mammary Carcinomas and Their Detection in Cell-Free Plasma DNA. *PLoS One* 8:e75485.

Applications of comparative genomics

Phylogenomics

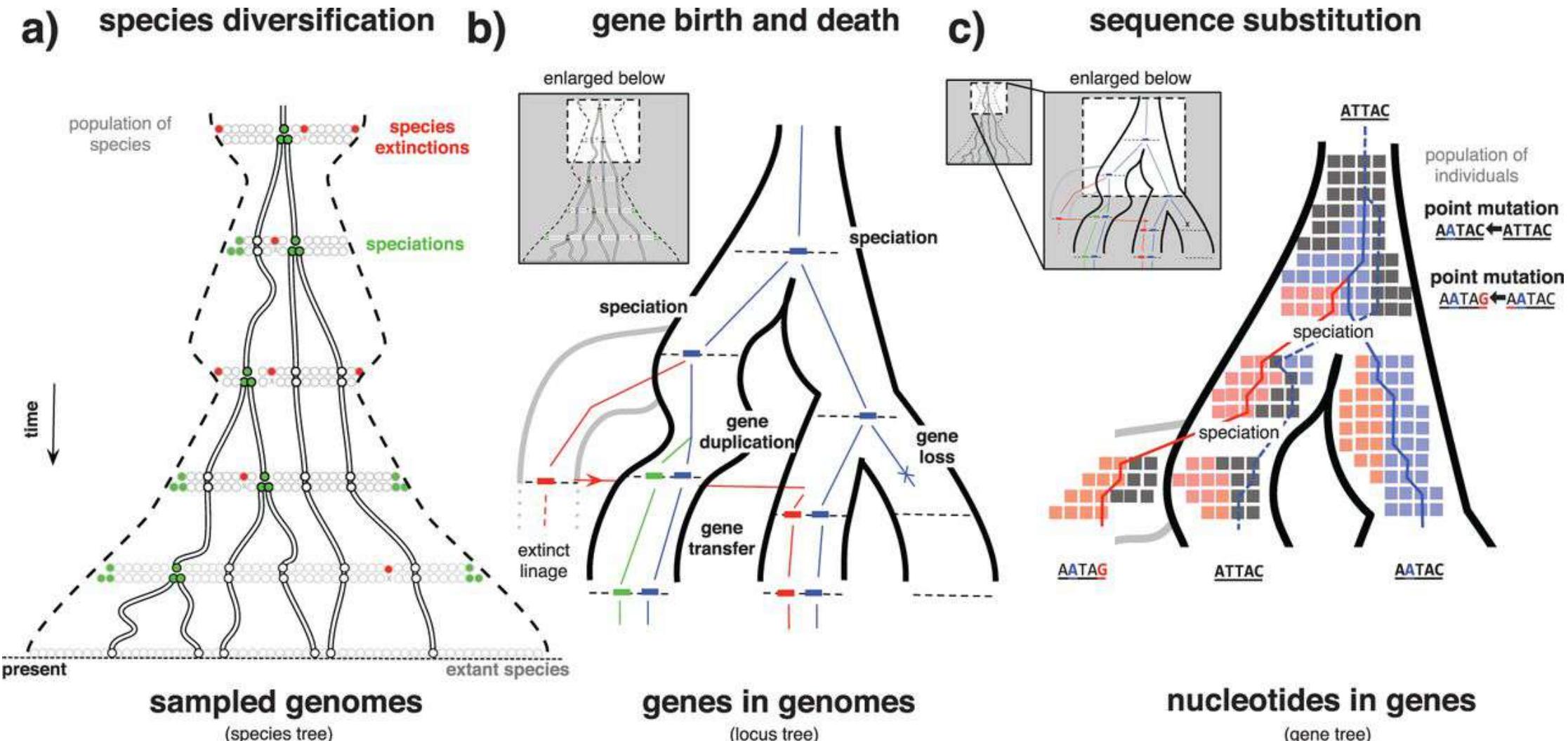
Phylogenomics aims at inferring detailed information about the evolutionary histories of organisms by using whole genomes rather than just a single gene or a few genes. The term was coined by Jonathan Eisen in the context of prediction of gene function

It would be difficult or impossible to understand the evolutionary history of an organism, even having available its whole genome sequence, in isolation. So it is always the case the phylogenomics is practiced for sets of genomes.

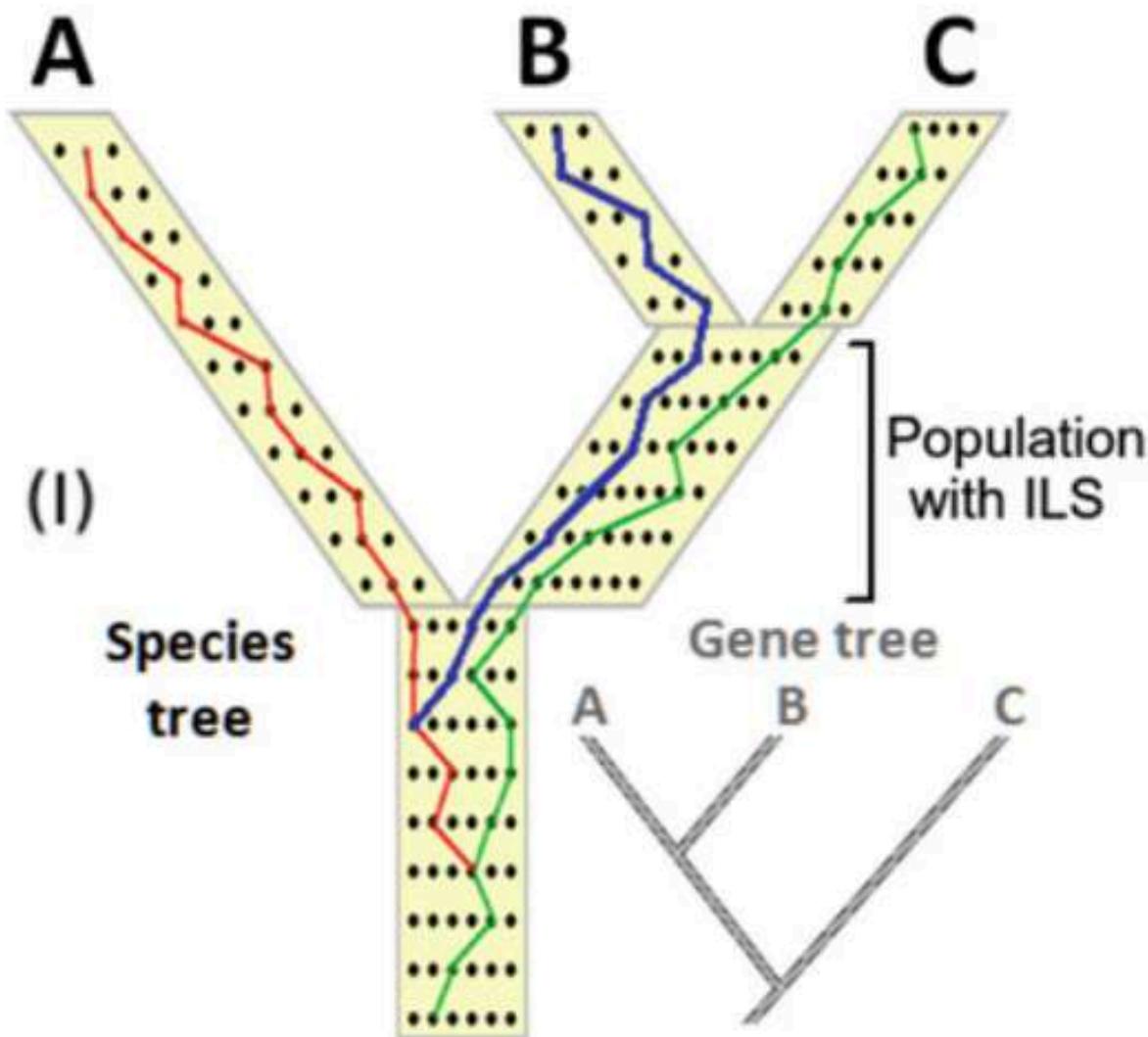
During the last 50 years, phylogeny has become more and more based on molecular data, increasingly **favoring homologous sequences over morphological characters**. This approach has been extremely fruitful, **producing constant improvement in the accuracy and resolution of phylogenetic reconstruction together with our understanding of evolutionary processes at the molecular level**.

However, we have known all along that we are barking up the wrong trees: with increasing sophistication in the models of sequence evolution, **we have been reconstructing trees describing the history of fragments of genomic sequence, which we will liberally call “gene” in this review, but never the history of species. Gene trees are not species trees** (Maddison 1997).

Each level of the hierarchy contributes to generating phylogenetic signal that can lead to differences between reconstructed gene trees.



Processes that may induce gene trees that are different than the actual species tree

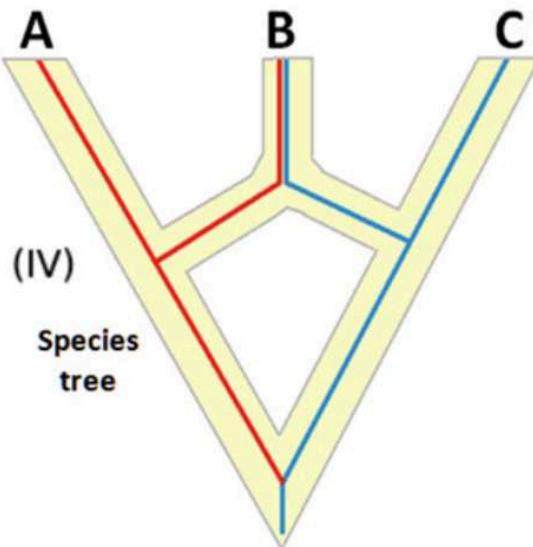
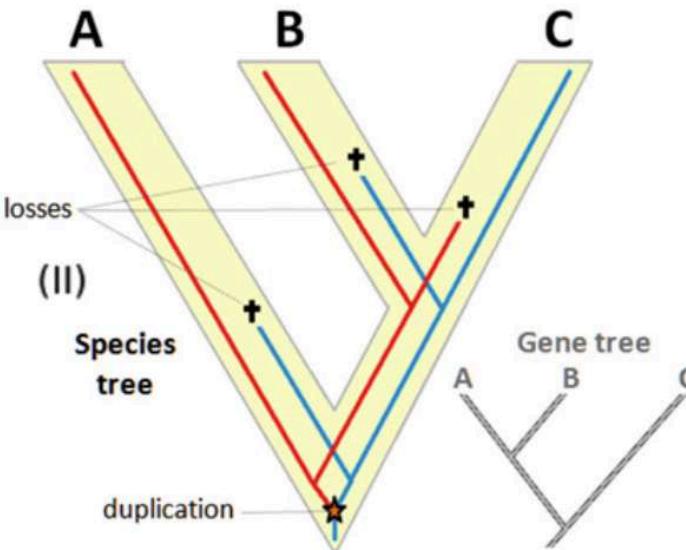
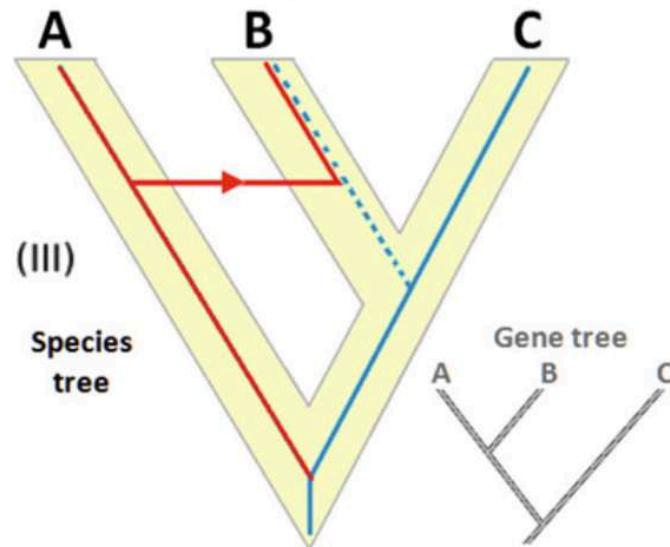


i) Incomplete lineage sorting

When a species splits in two, allelic lineages sort into the two descendant species, and this lineage sorting varies along the genome.

If speciation events are close in time, the lineage sorting process may be incomplete at the second speciation event and lead to gene genealogies that do not match the species phylogeny

Processes that may induce gene trees that are different than the actual species tree



(II) Duplication and Loss

a locus may generate a duplicate somewhere in the genome, and then both may be inherited or just a single copy is maintained in each lineage.

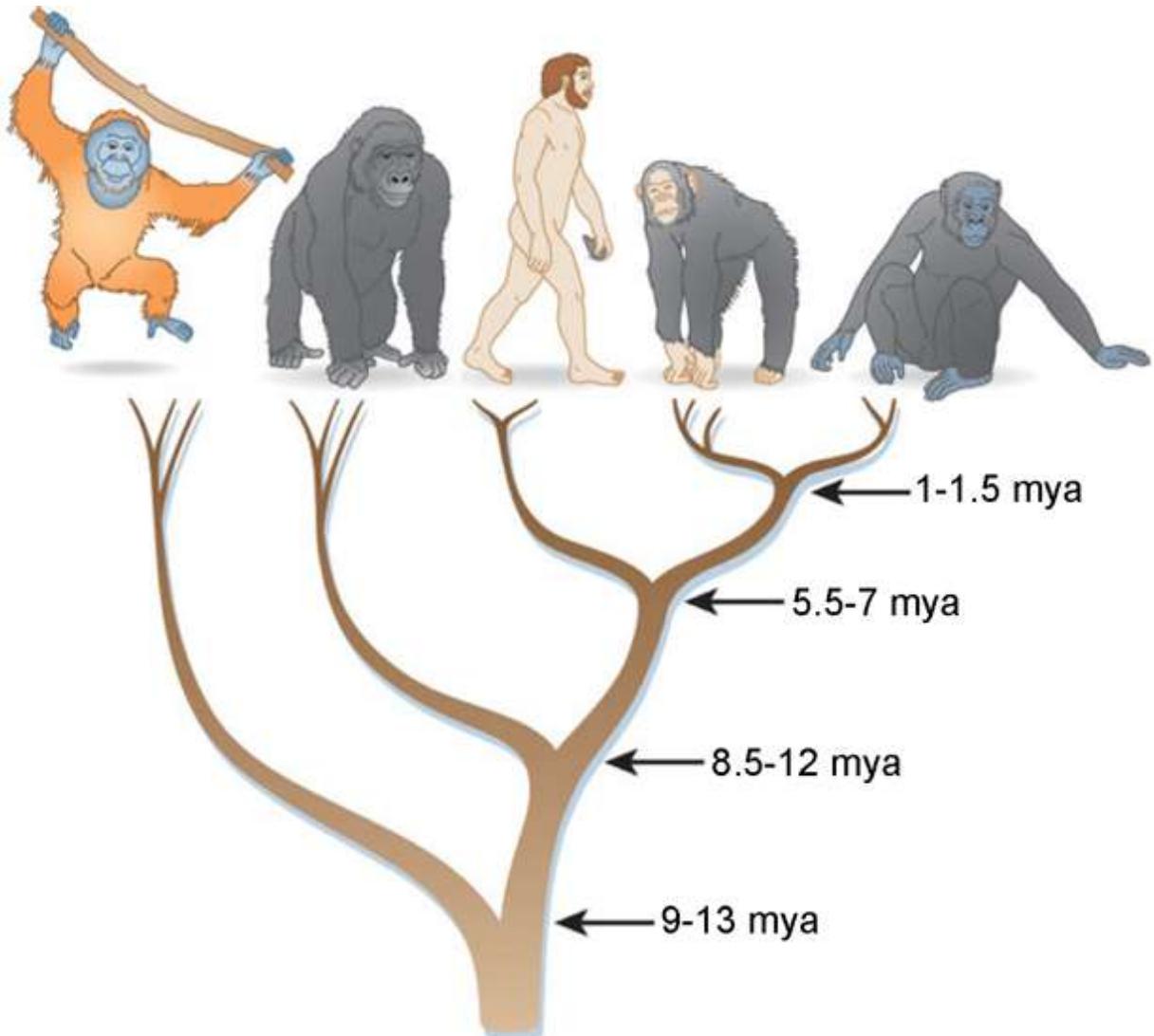
(III) Horizontal Gene Transfer

(HGT): a donor DNA segment (from taxon A) is transmitted and incorporated into the host's genome (taxon B)

(IV) Hybridization/Introgression

in extreme cases of lateral transfer, or upon mixing of related species, different regions of the genome will bear two distinct evolutionary histories;

Why is Studying (Ape) Speciation Important? (Example)

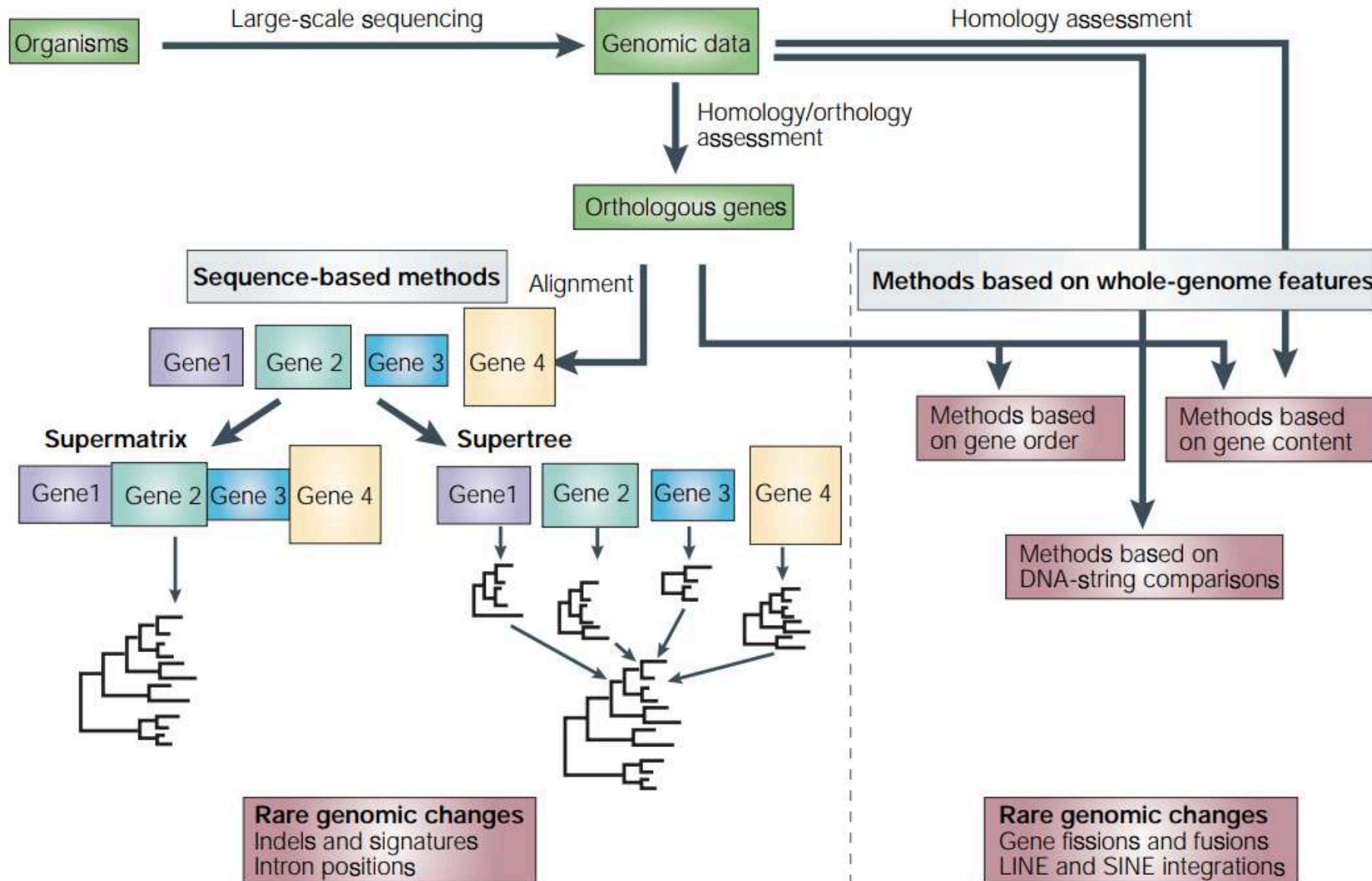


These studies also led to rich discussions about the suite of factors that may have contributed to promoting speciation in the last common ancestor of humans and African apes, as well as the factors that might have contributed to creating the amazing diversity of Hominins that co-existed with each other during the Pliocene and Pleistocene (Foley 2002).

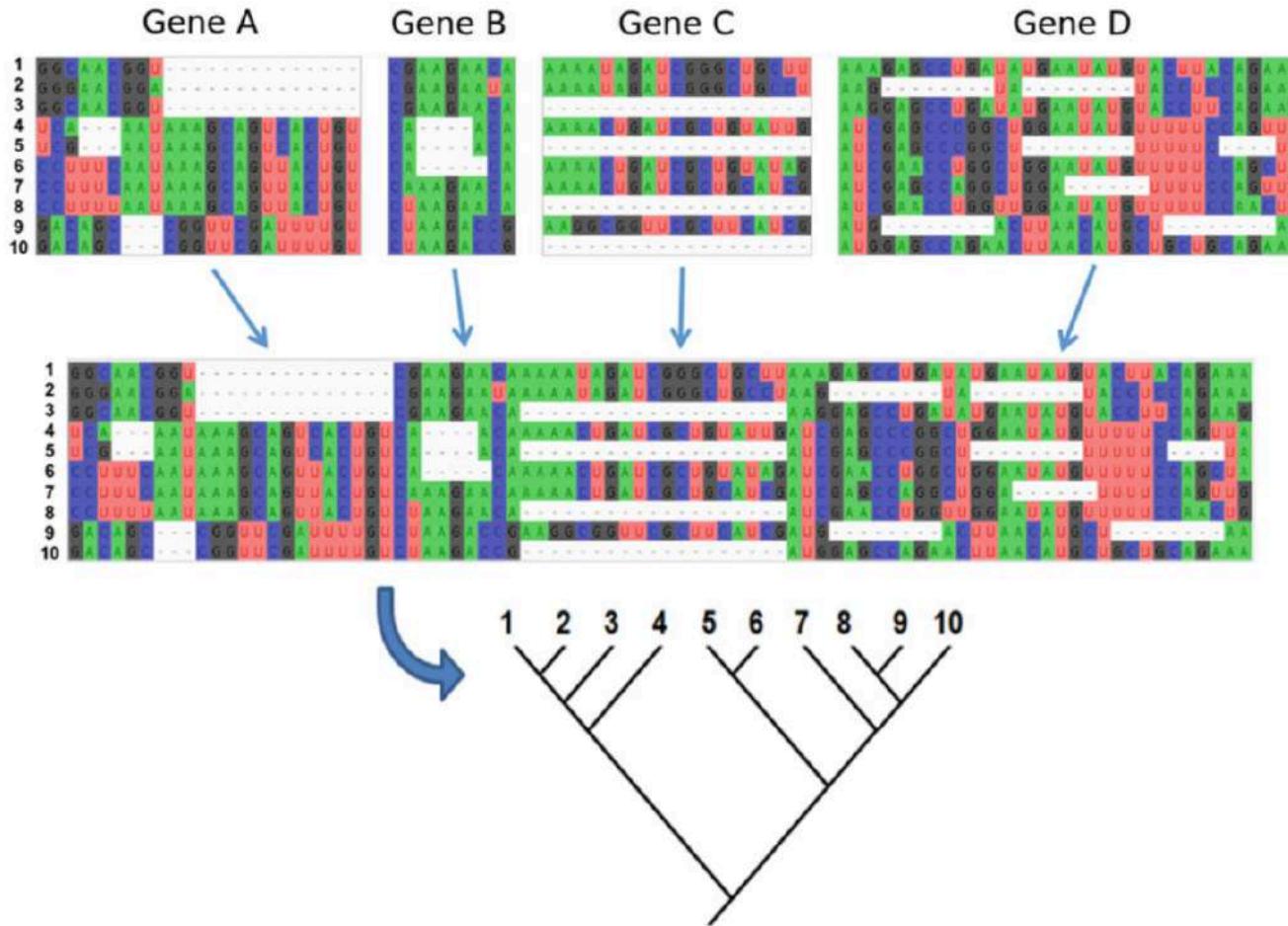
For many years, there was considerable debate about which of the African apes is our closest relative.... The general consensus that emerged is that we share a more recent relationship with chimpanzees (*Pan troglodytes*) and bonobos (*Pan paniscus*) than we do with gorillas (*Gorilla gorilla*) (Ruvolo 1997, Chen & Li 2001).

Current estimates indicate that up to 30% of the sequence of the human genome is more closely related to Gorilla than to Chimpanzee due to this process (Scally et al. 2012).

Probably the most common (easy) way to construct alignment of concatenated gene shared across all species



Probably the most common (easy) way to construct alignment of concatenated gene shared across all species (**but this is wrong**)

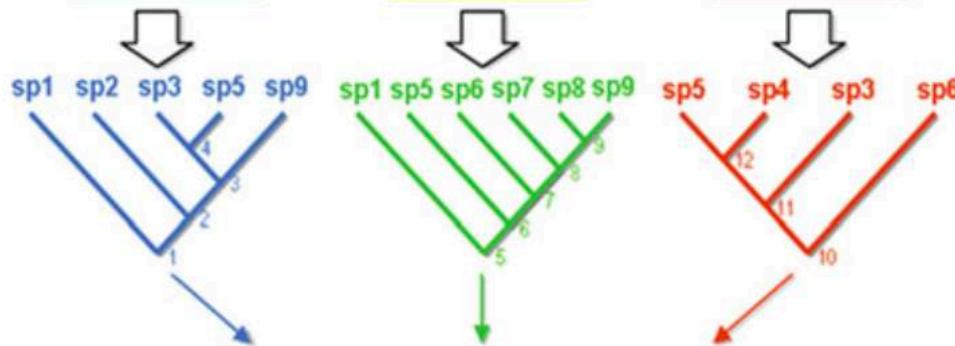


Important drawbacks:

- (1) it hinders variation among gene trees by assuming implicitly that all of them conform to a single species tree;
- (2) if sampling was heterogeneous across species there may be too much missing data, which can affect topological reconstruction; Or limited number of genes shared among all species
- (3) large data sampling effects inflate credibility in some clades;
- (4) spurious hidden support can lead to support for non-existent clades; and
- (5) in case of moderate to severe levels of ILS, supermatrix can become statistically inconsistent.

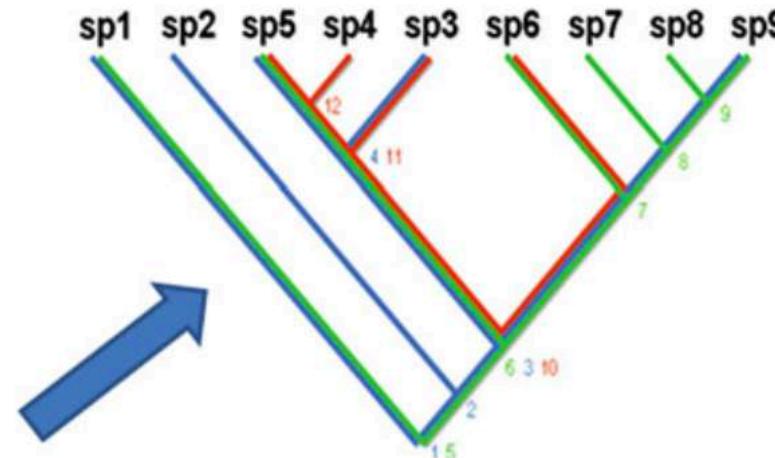
From genes to supertrees

	gene A	gene B	gene C
sp.1	aattggata	sp.1	actacgcaa
sp.2	aatttagata	sp.2	2222222222
sp.3	aatcaaata	sp.3	2222222222
sp.4	2222222222	sp.4	2222222222
sp.5	aaccaaata	sp.5	atcacaaca
sp.6	2222222222	sp.6	atcacagca
sp.7	2222222222	sp.7	atcacagca
sp.8	2222222222	sp.8	accagaaca
sp.9	agtcagtc	sp.9	2222222222

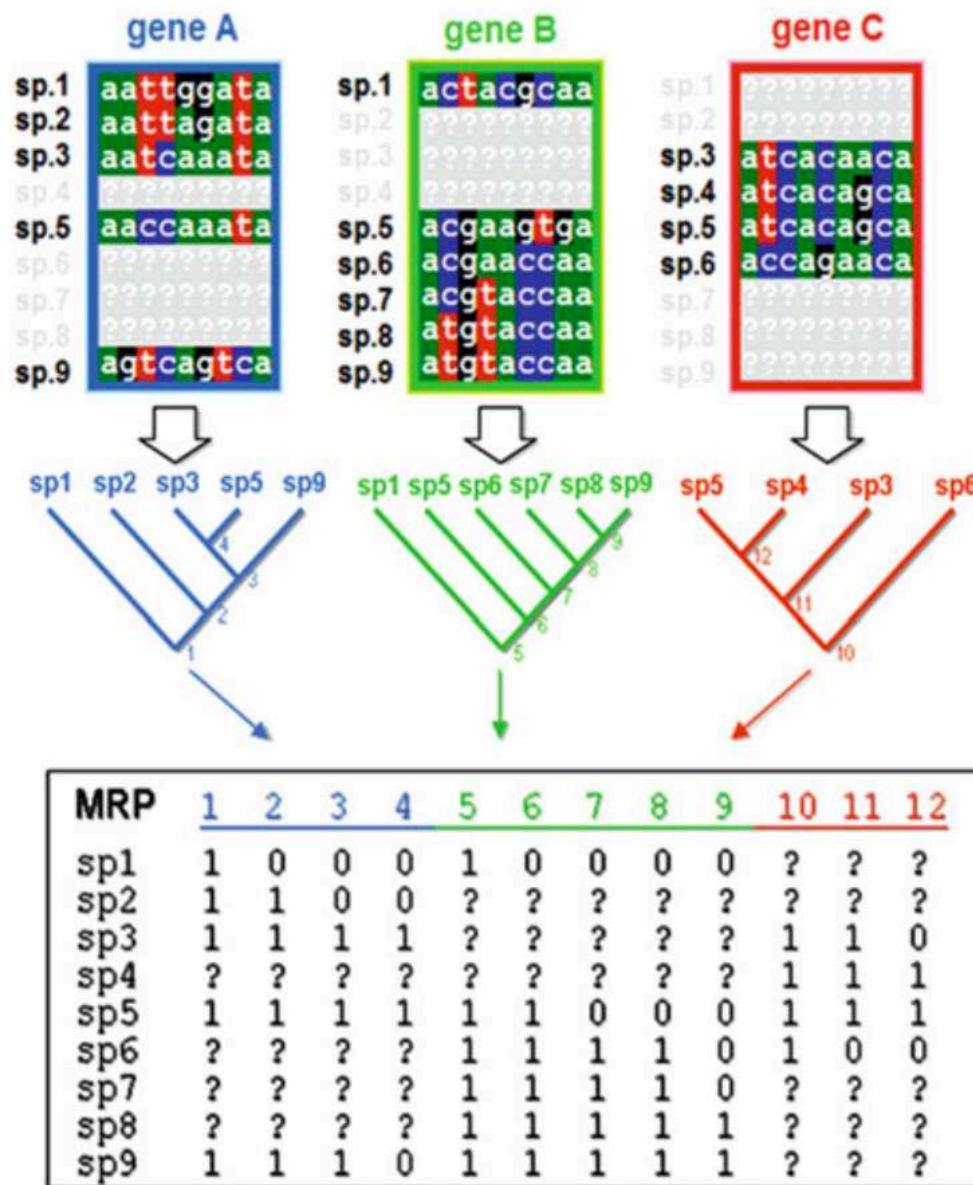


MRP	1	2	3	4	5	6	7	8	9	10	11	12
sp1	1	0	0	0	1	0	0	0	0	?	?	?
sp2	1	1	0	0	?	2	?	2	2	?	?	?
sp3	1	1	1	1	?	2	?	?	?	1	1	0
sp4	?	?	?	?	2	2	2	2	2	1	1	1
sp5	1	1	1	1	1	1	0	0	0	1	1	1
sp6	?	?	?	?	1	1	1	1	0	1	0	0
sp7	?	?	?	?	1	1	1	1	0	?	?	?
sp8	?	?	?	?	1	1	1	1	1	?	?	?
sp9	1	1	1	0	1	1	1	1	1	?	?	?

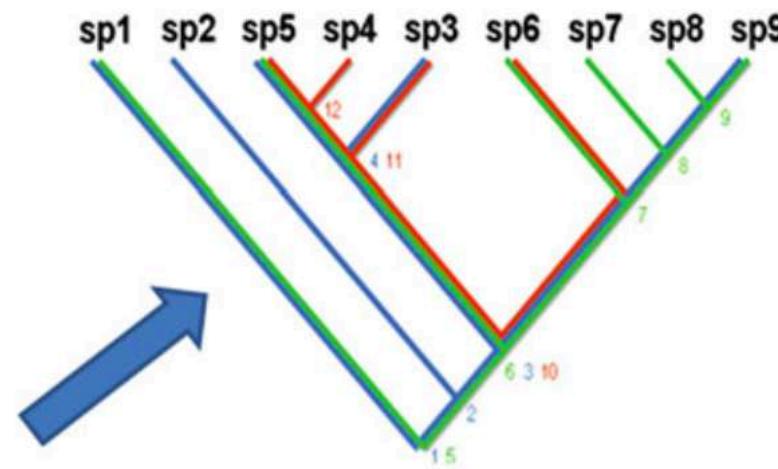
Instead of forcing all gene trees to comply to a single tree, **supertree methods infer the best topology for each gene (using the same phylogenetic method for each)**, and then a **topological consensus** is obtained. Such methods are able to make consensus trees even if the number of leaves among gene trees differs but overlaps to some extent, for example when a gene has not been sequenced for some taxa



Current methods



A step beyond supertrees is the use of methods that take into consideration specific evolutionary processes that may be responsible for differences in gene topologies, and then estimate the species tree which would most likely have generated such gene trees, under different scenarios

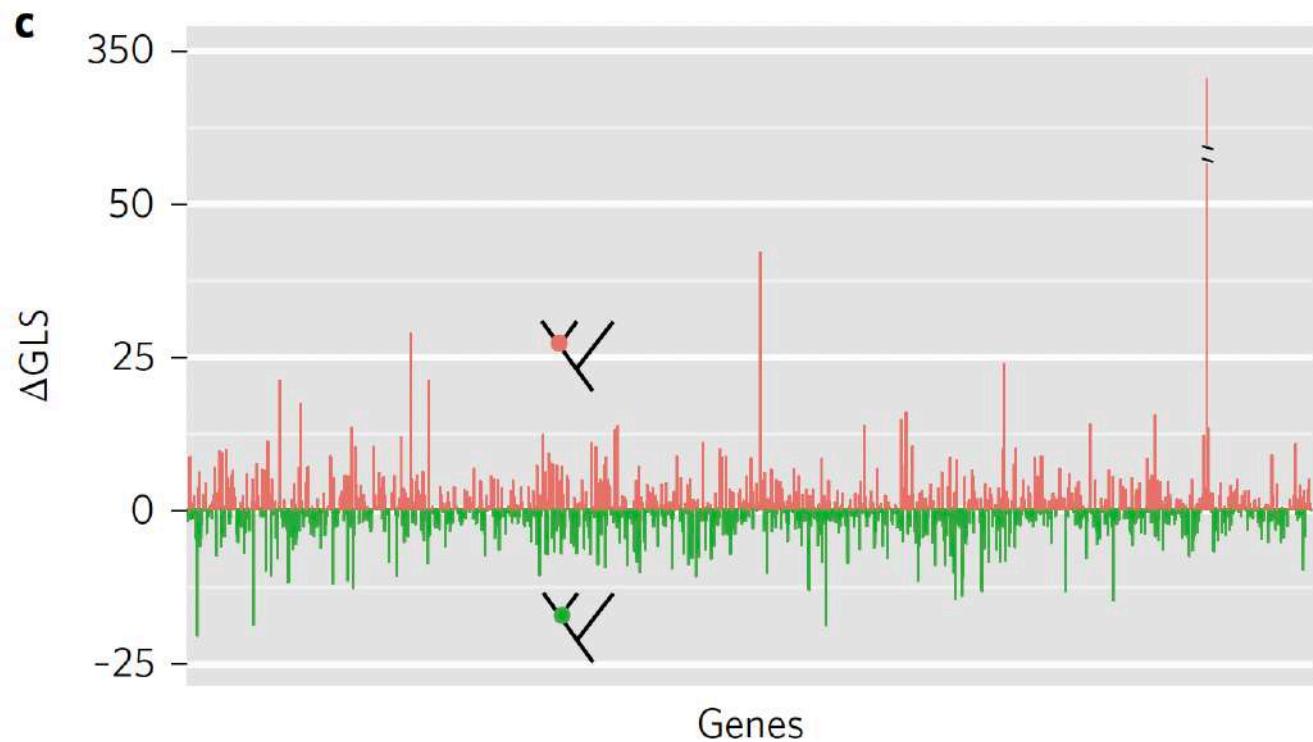
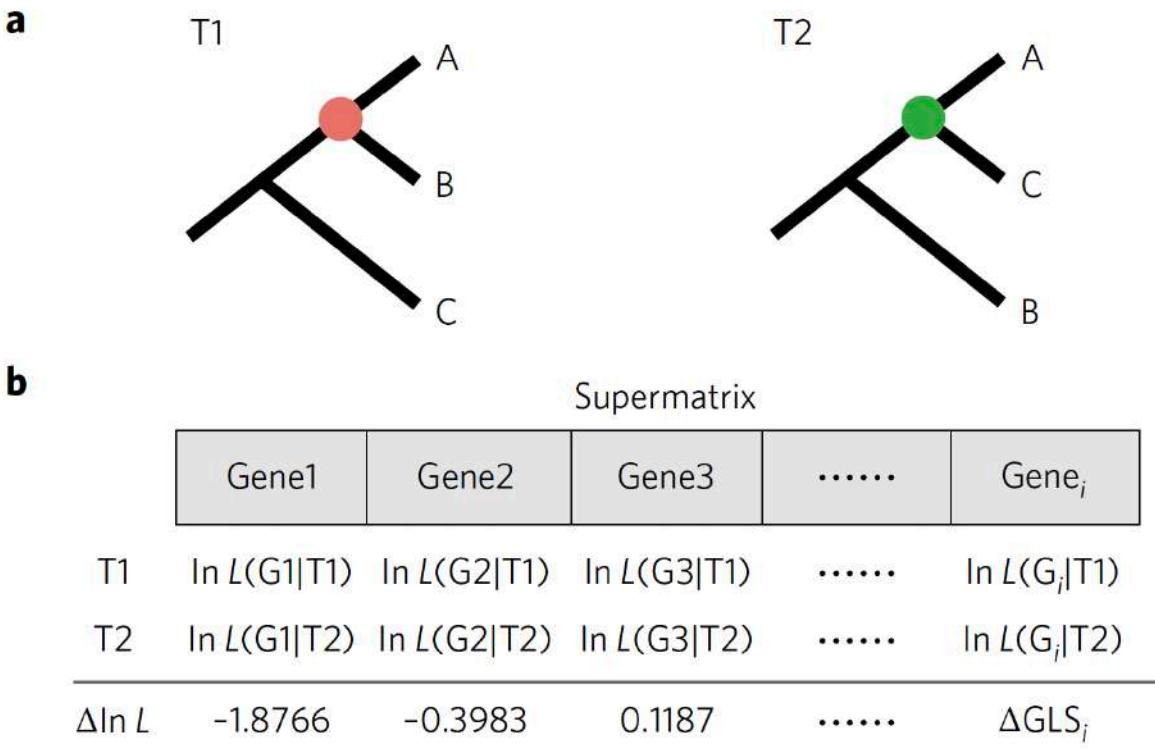


Contentious relationships in phylogenomic studies can be driven by a handful of genes

Xing-Xing Shen¹, Chris Todd Hittinger² and Antonis Rokas^{1*}

...Here, we use a maximum likelihood framework to quantify the distribution of phylogenetic signal among genes and sites for 17 contentious branches and 6 well-established control branches in plant, animal and fungal phylogenomic data matrices. **We find that resolution in some of these 17 branches rests on a single gene or a few sites, and that removal of a single gene in concatenation analyses or a single site from every gene in coalescence-based analyses diminishes support and can alter the inferred topology**

Visualizing phylogenetic signal in a phylogenomic data matrix



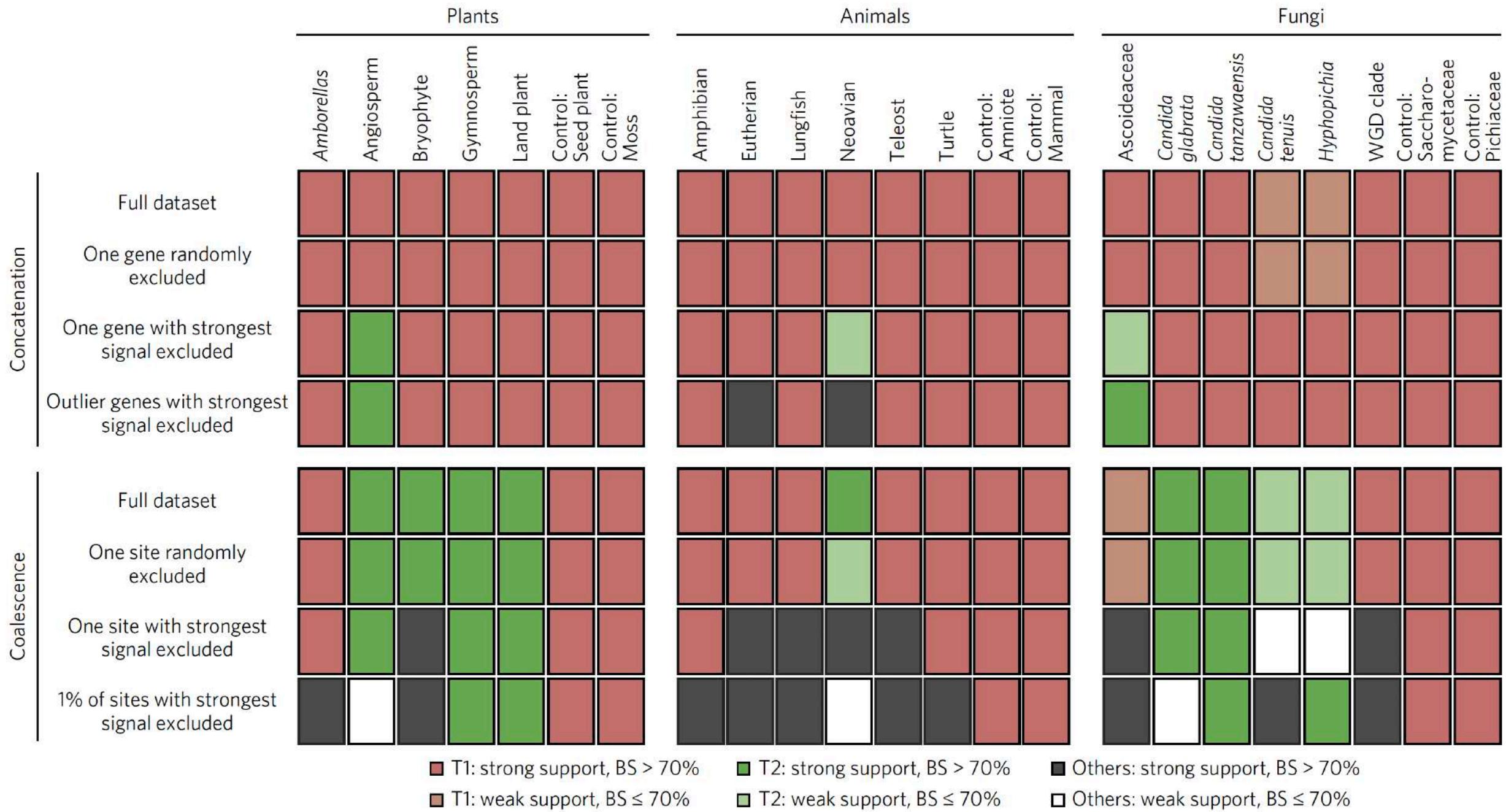
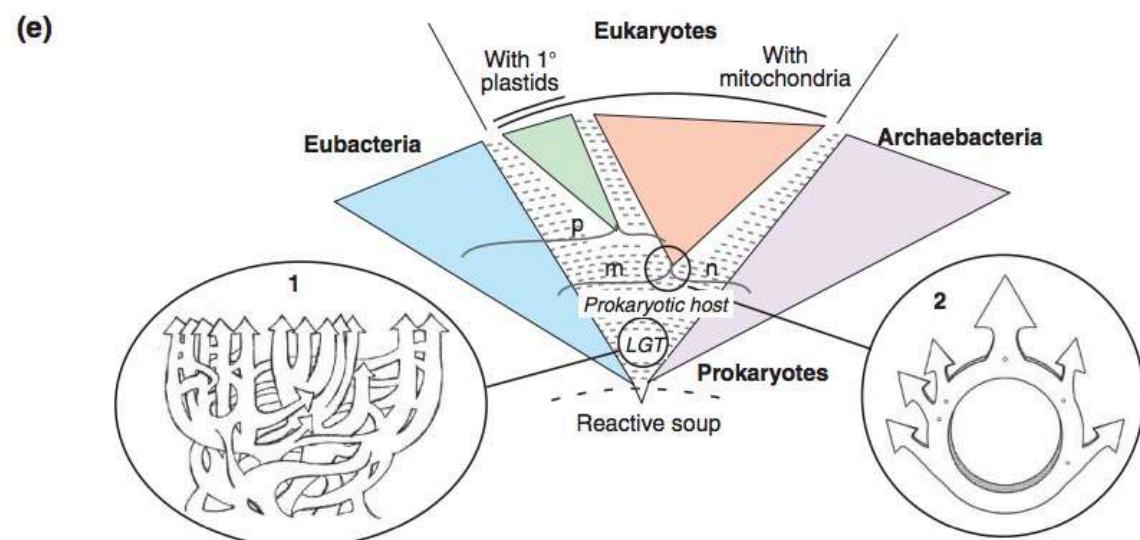
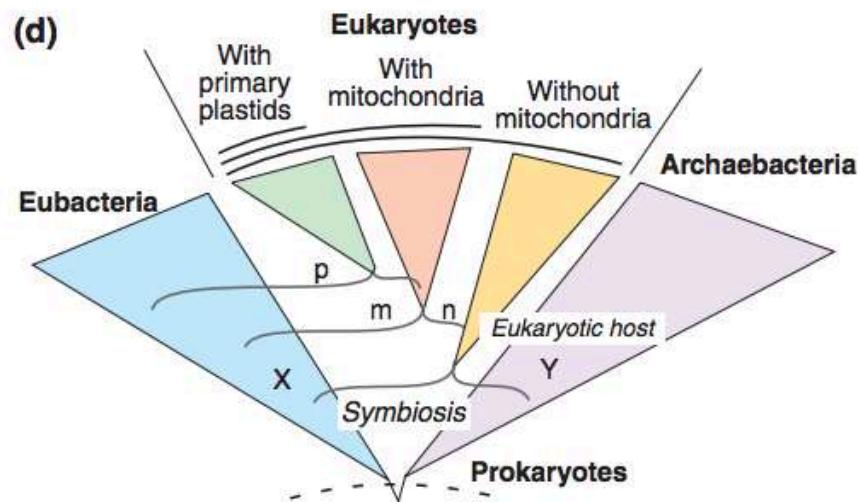
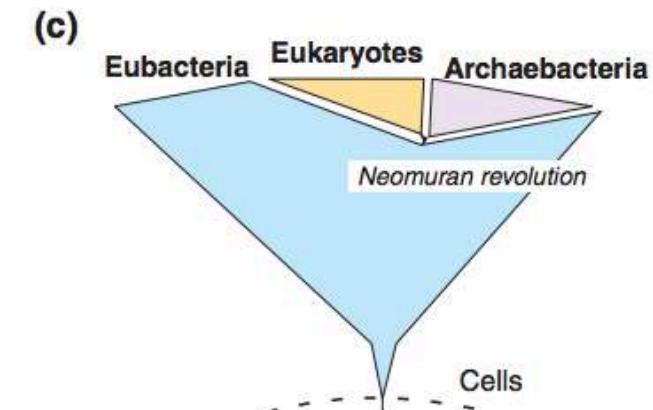
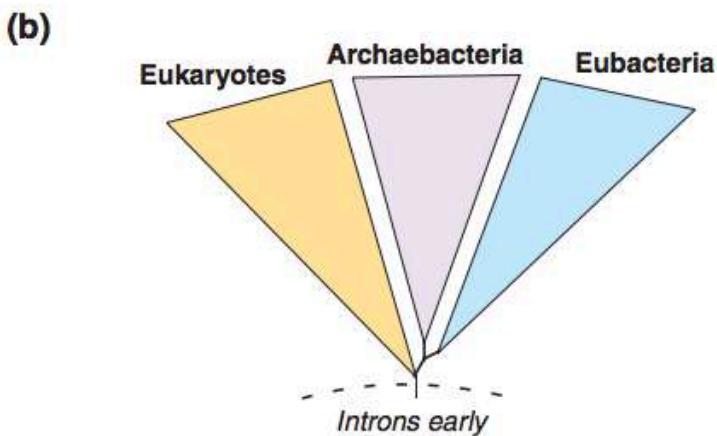
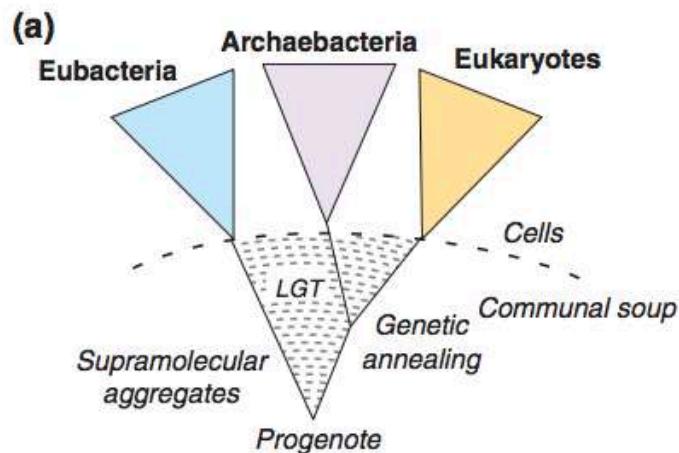
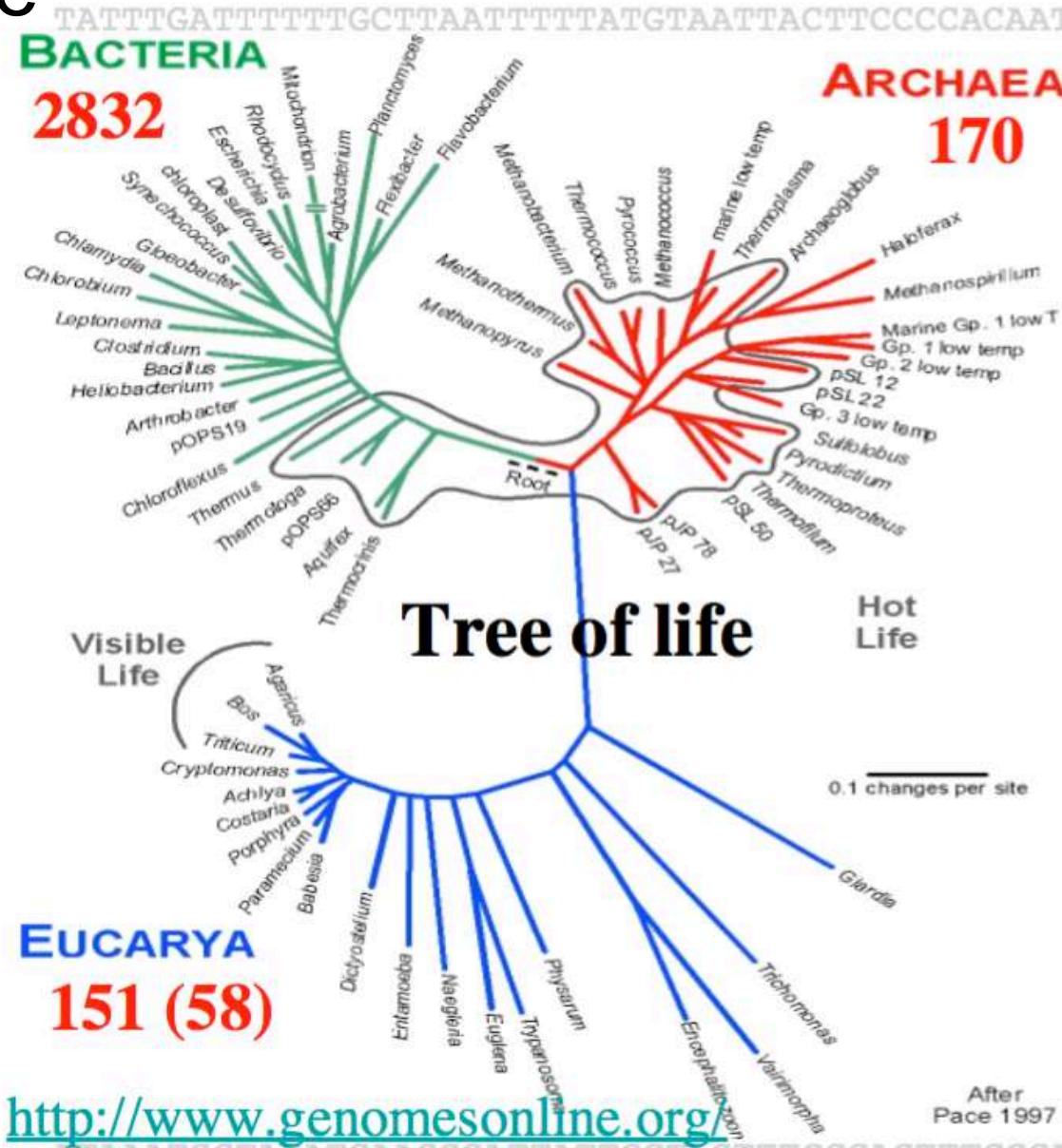


Figure 4 | Tiny amounts of data exert decisive influence in the resolution of certain contentious branches in phylogenomic studies. The effect of the

Five models models of tree of life



Tree of life



<http://www.genomesonline.org>

ATAAATGGTAGATGAAGCGATTATTGCTACCTTTCCCACTTTCCCAAC
AATAATAATTAAAAAGGGGTAAAAT

Complete finished genomes: 3060 (04/09/14)

- 2832 Bacteria
- 170 Archaea
- 58 eukaryotes

Incomplete genomes projects: 38262

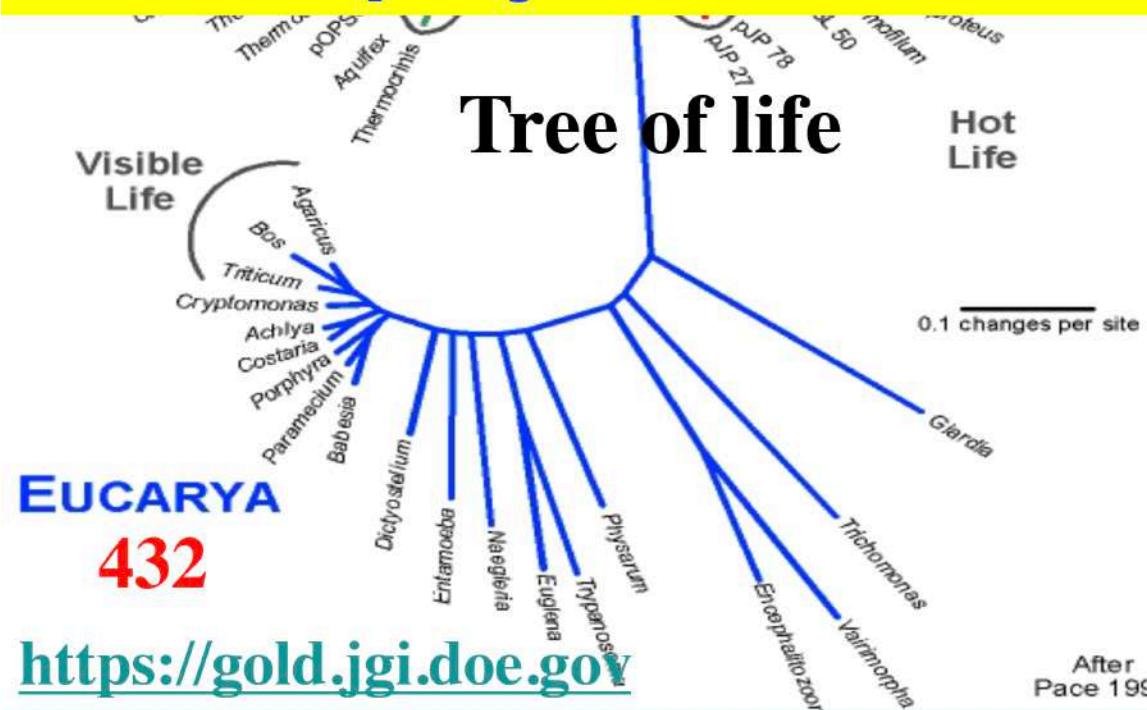
- 32068 Bacteria
- 664 Archaea
- 5530 Eukaryotes

Transcriptomes: 947

- 76 Bacteria
- 11 Archaea
- 860 Eukaryota

GAGATATACGTTCAAGTTAACCGGGA

Tree of life



Viruses: • Completed: 3503 • Permanent draft: 5079

20/05/2019

Complete sequenced genomes: 13290

- 12547 Bacteria
- 310 Archaea
- 432 Eukaryotes

Incomplete genomes: 17939

- 11159 Bacteria
- 242 Archaea
- 6538 Eukaryotes

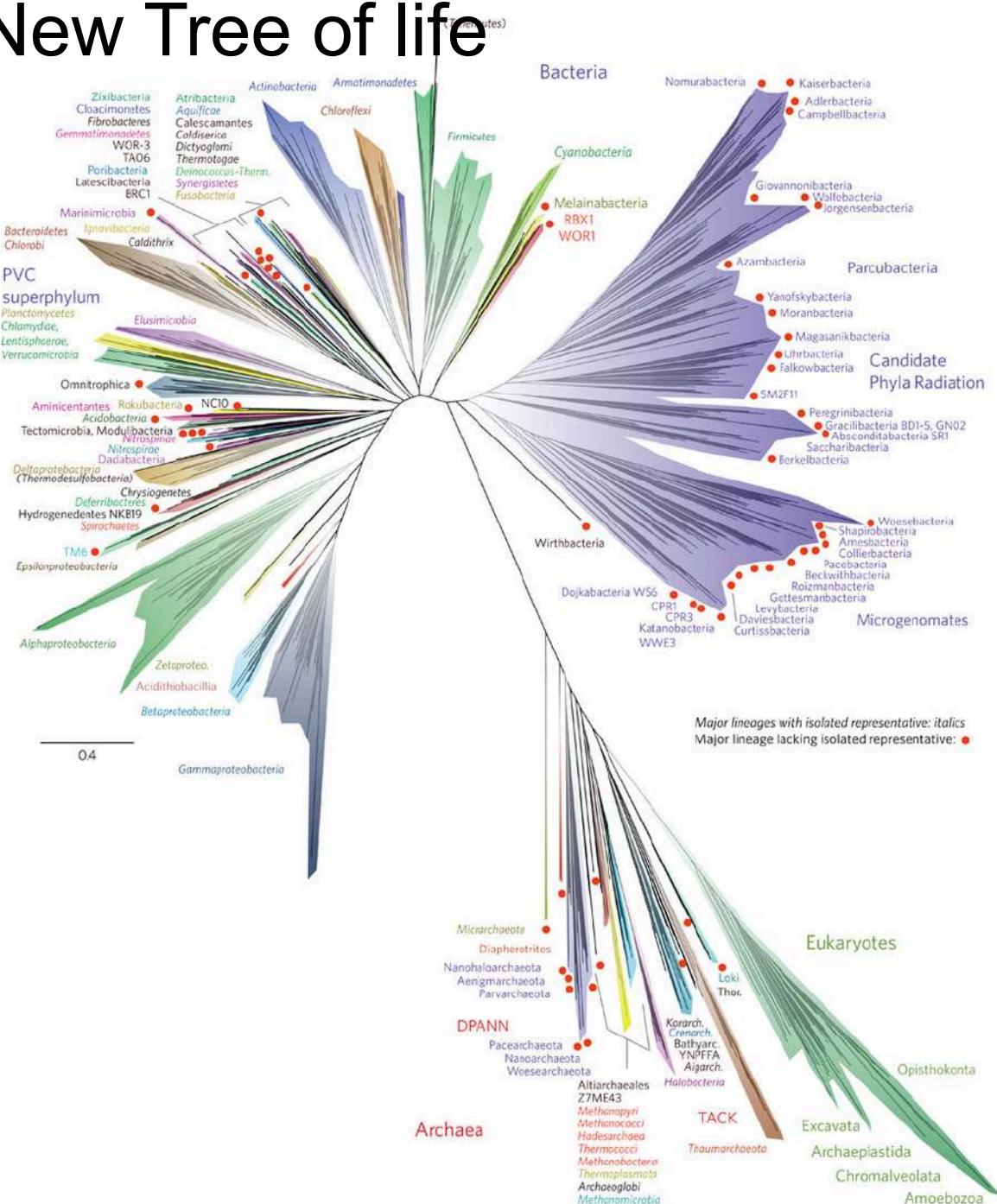
Permanent Draft genomes: 129958

- 124606 Bacteria
- 898 Archaea
- 4454 Eukaryotes

Transcriptomes: 75/25843

- 51/1763 Bacteria
- 0/162 Archaea
- 22/23926 Eukaryota

New Tree of life



The third trunk that Woese and his colleagues identified included little-known microbes that live in extreme places like hot springs and oxygen-free wetlands. Woese and his colleagues called this third trunk Archaea.

Dr. Banfield said she expected new branches to be discovered for eukaryotes, especially for tiny species such as microscopic fungi. “That’s where I think the next big advance might be found,” Dr. Banfield said.

Dr. Hug disagreed that scientists were done with bacteria. “I’m less convinced we’re hitting a plateau,” she said. “There are a lot of environments still to survey.”

Hug et al (2016)

http://www.nytimes.com/2016/04/12/science/scientists-unveil-new-tree-of-life.html?_r=0

New Tree of life

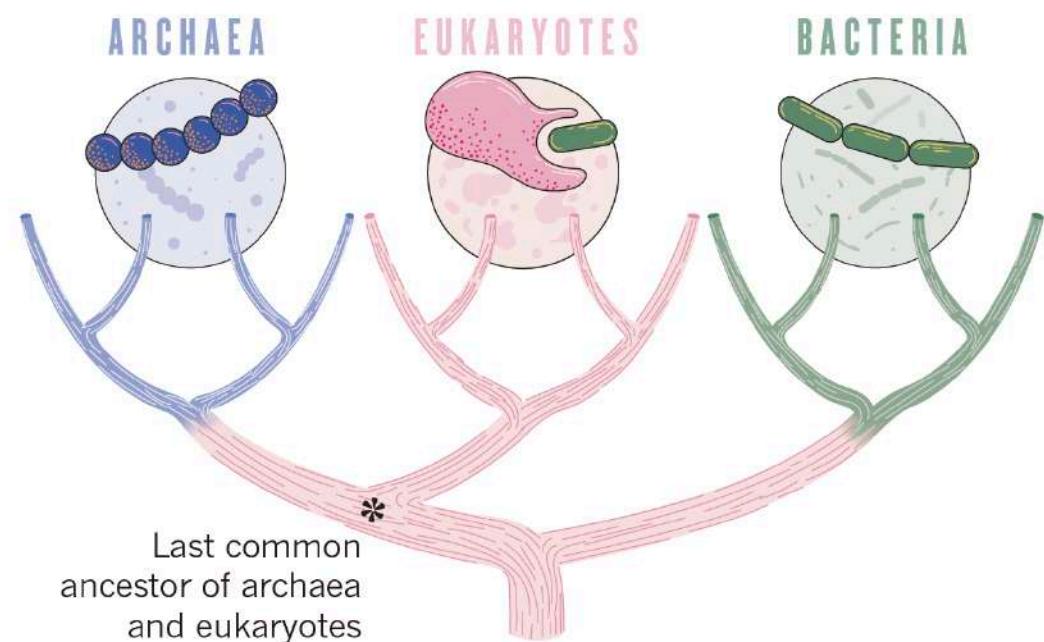


THE TRICKSTER MICROBES SHAKING UP THE TREE OF LIFE

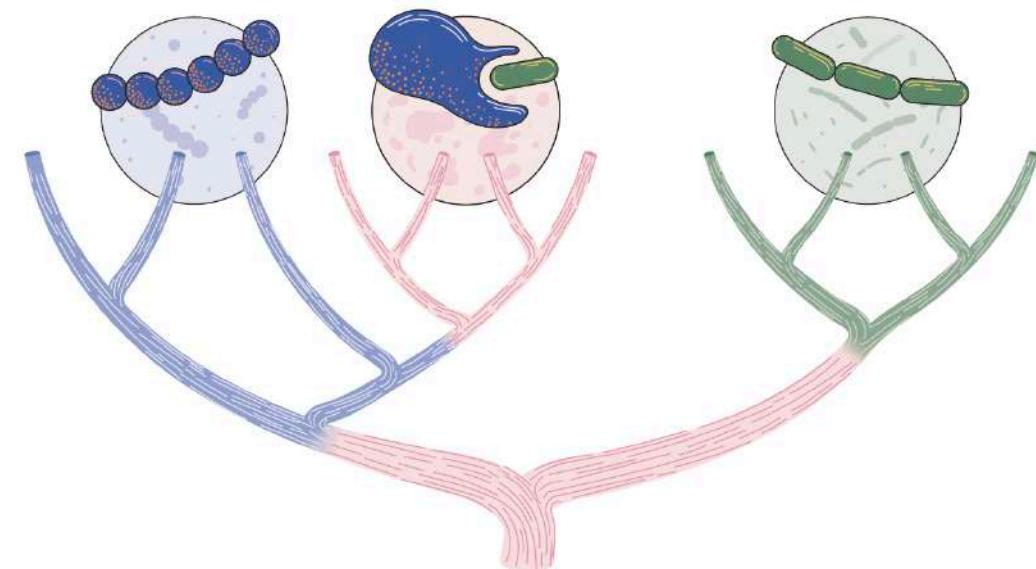
Mysterious groups of archaea – named after Loki and other Norse myths – are stirring debate about the origin of complex creatures, including humans.

Domains in debate

An organism related to archaea engulfed one related to modern bacteria eons ago, resulting in eukaryotes — complex organisms whose cells contain membrane-wrapped structures such as mitochondria. But it is unclear what the engulfing cells were. A three-domain model holds that they shared a common ancestor with archaea.



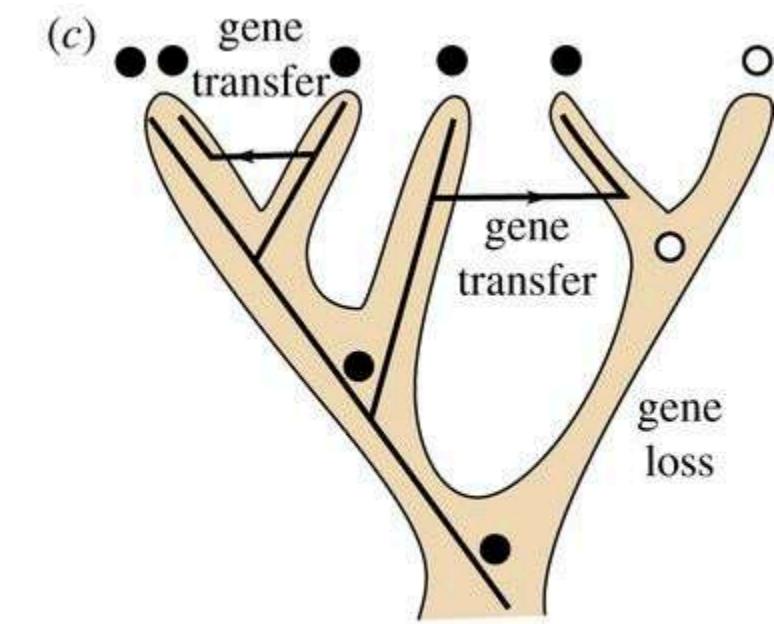
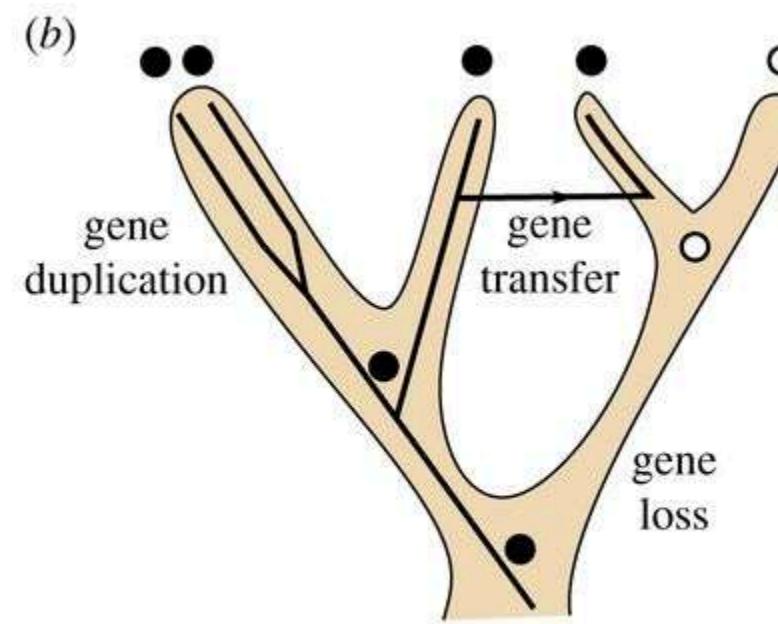
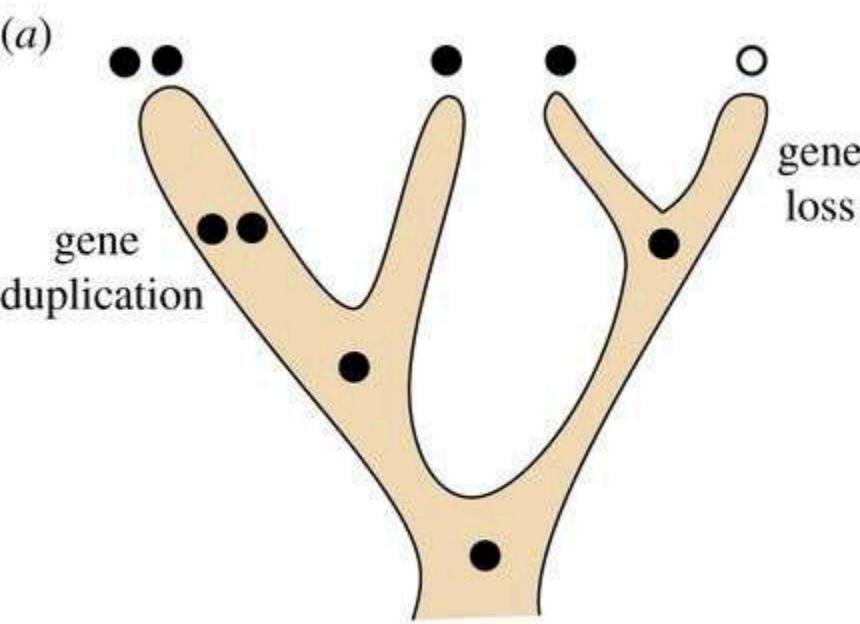
Supporters of a two-domain model argue that the engulfing cell was an archaeon and that all eukaryotes — humans included — descend from archaea.



Horizontal gene transfer (HGT)

Inferring HGT require

- 1) species phylogeny ; 2) gene phylogeny
- 3) extensive taxon sampling



● presence ○ absence

Complicated history of genes: dig into finer details

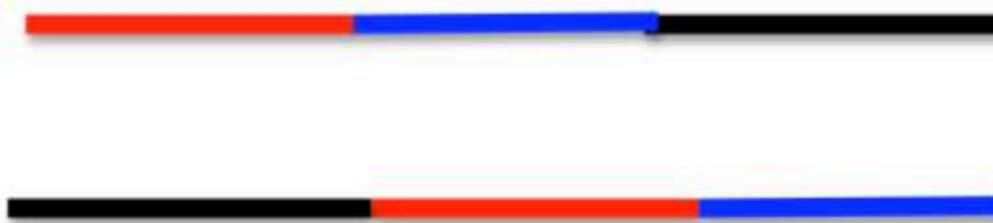
Gene fusion



Gene fission



Domains shuffling



Visualisation of gene content / families

Extensive mosaic structure revealed by the complete genome sequence of uropathogenic *Escherichia coli*

R. A. Welch*, V. Burland^{†‡}, G. Plunkett III[†], P. Redford*, P. Roesch*, D. Rasko[§], E. L. Buckles[¶], S.-R. Liou^{||}, A. Boutin^{†***}, J. Hackett^{†,††}, D. Stroud[†], G. F. Mayhew[†], D. J. Rose[†], S. Zhou^{†††}, D. C. Schwartz^{†††}, N. T. Perna^{§§}, H. L. T. Mobley[§], M. S. Donnenberg[¶], and F. R. Blattner[†]

*Department of Medical Microbiology and Immunology, University of Wisconsin
Sciences, University of Wisconsin
Department of Medicine, University of Wisconsin

Edited by John J. Mekalanos, Harvard University

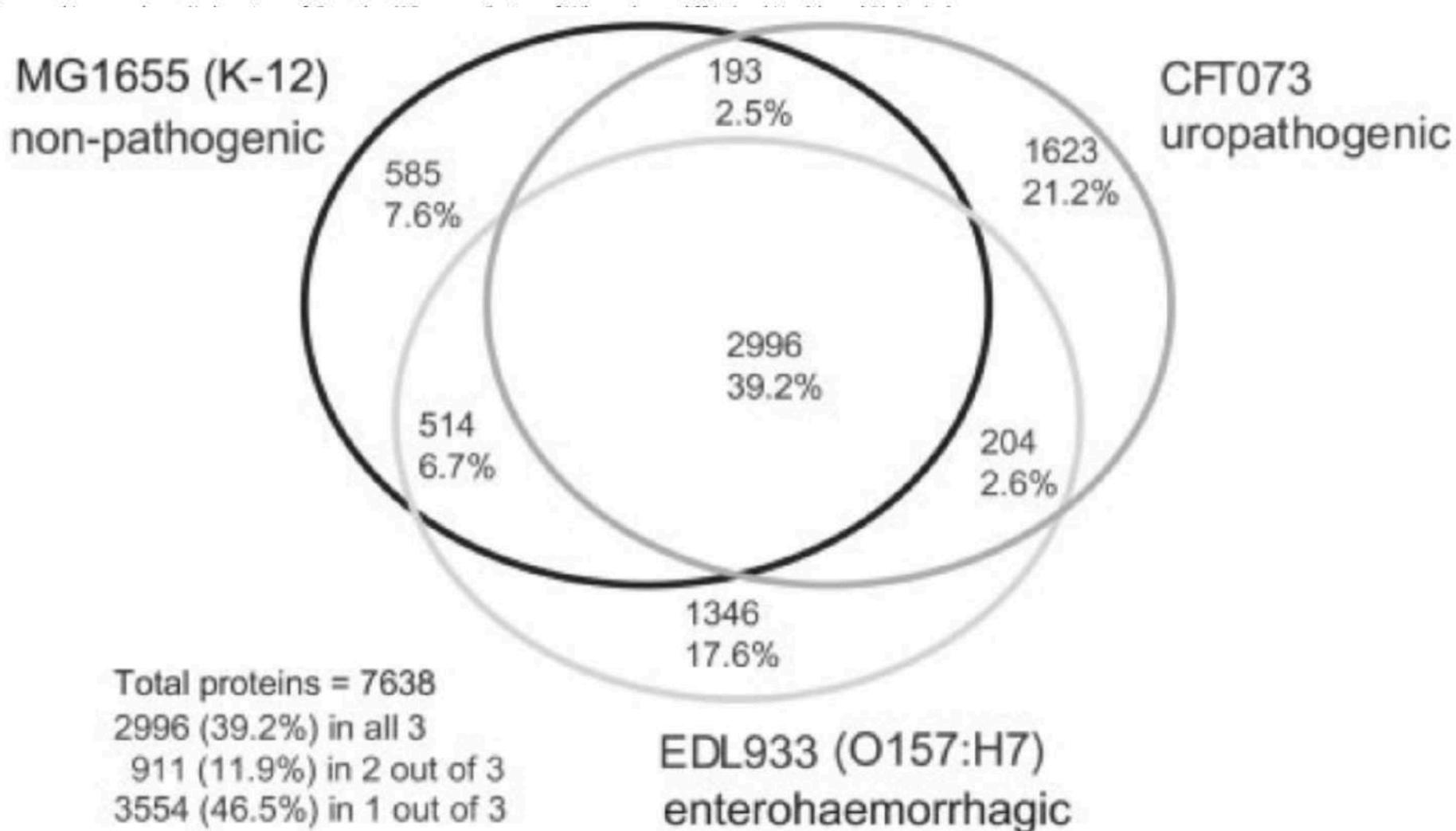


Illustration of a gene content Venn diagram for three hypothetical genomes A, B, and C

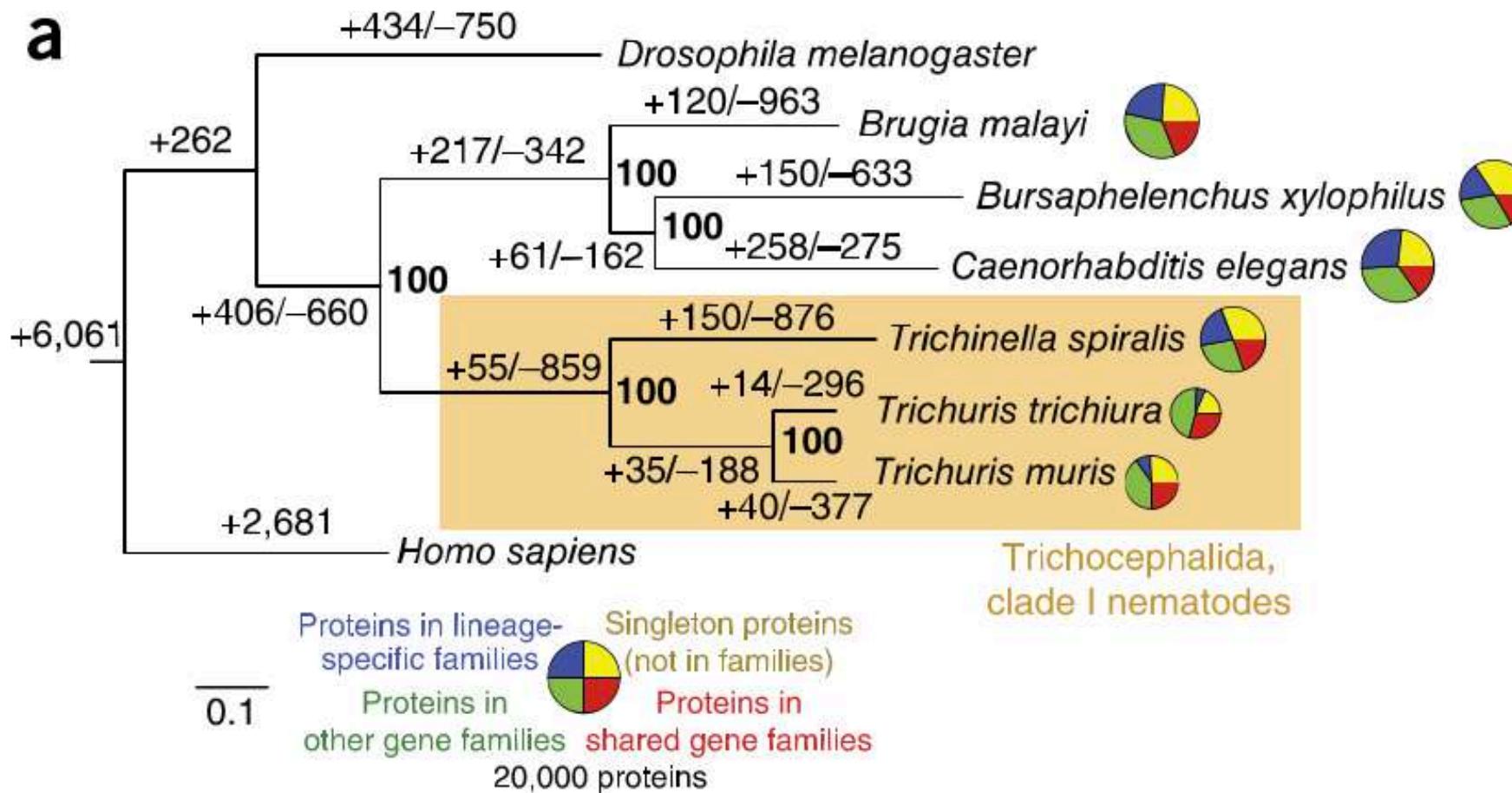
Gene	Genome						
	A	B	C	D	E	F	G
1	✓	✓			✓	✓	
2	✓		✓	✓	✓	✓	✓
3		✓		✓			
4		✓			✓		
5				✓			
6			✓		✓	✓	
7		✓		✓			✓



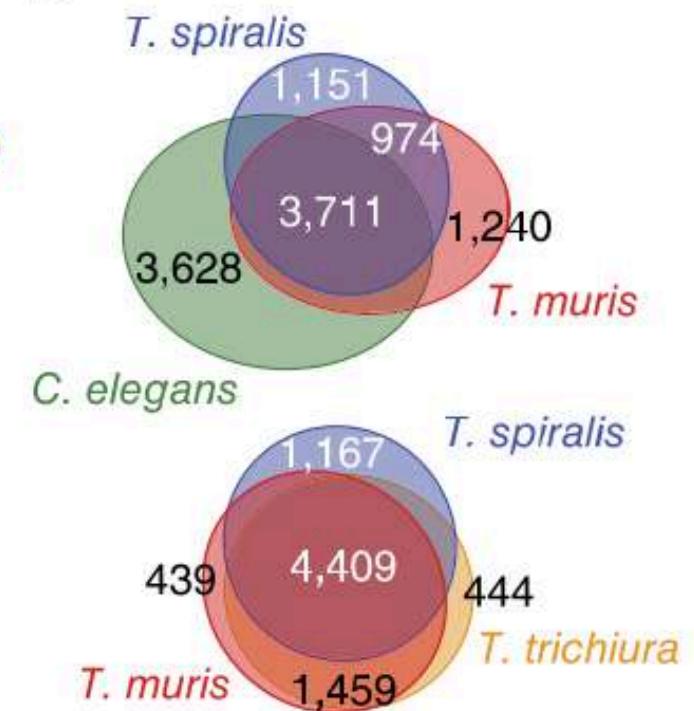
Schematic representation of a presence/absence gene matrix. Genomes are represented in columns, and gene families are represented in rows

Phylogeny + Venn diagram to show expansion/loss

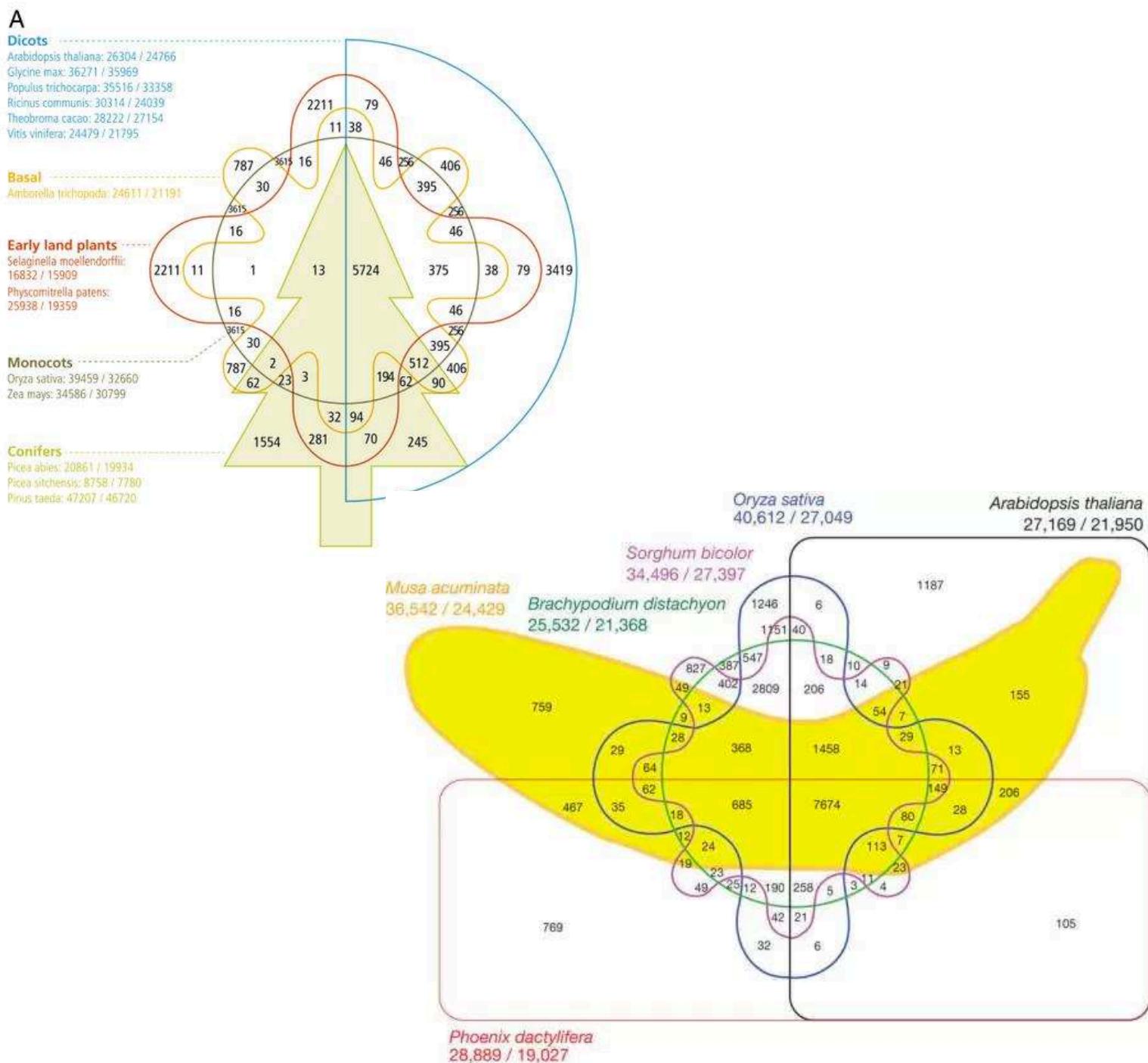
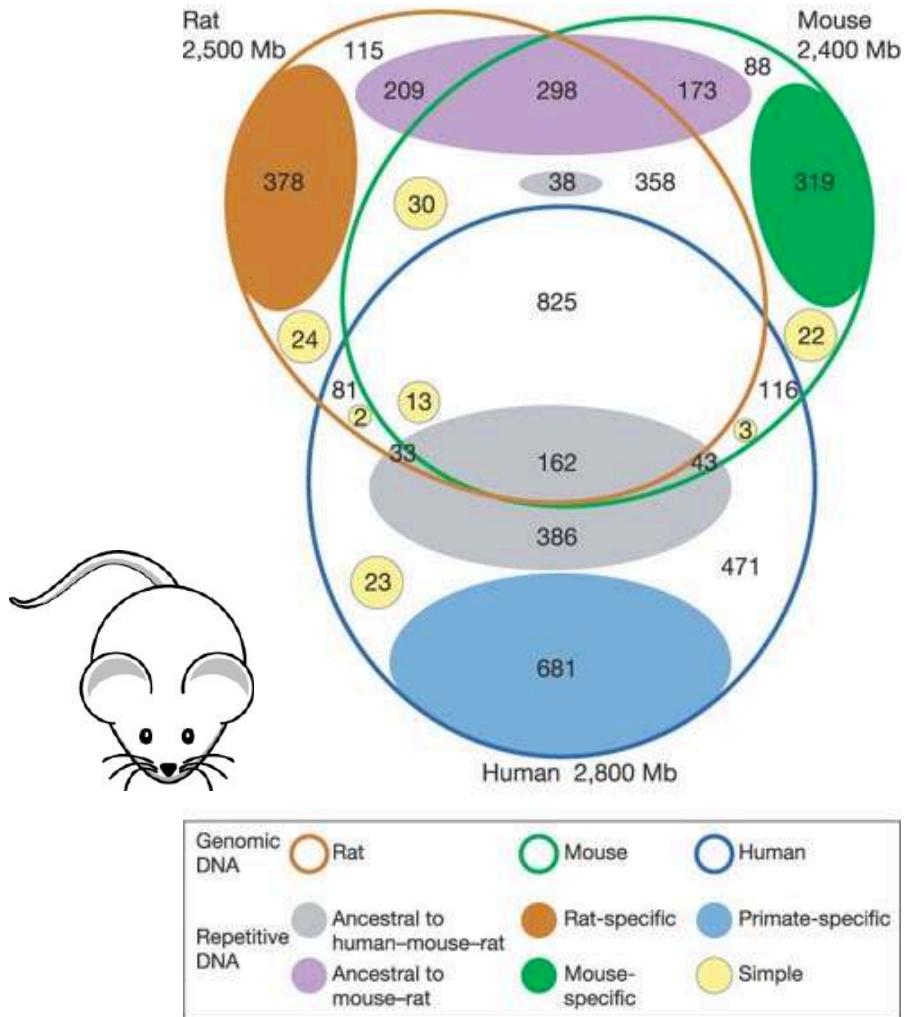
a



b



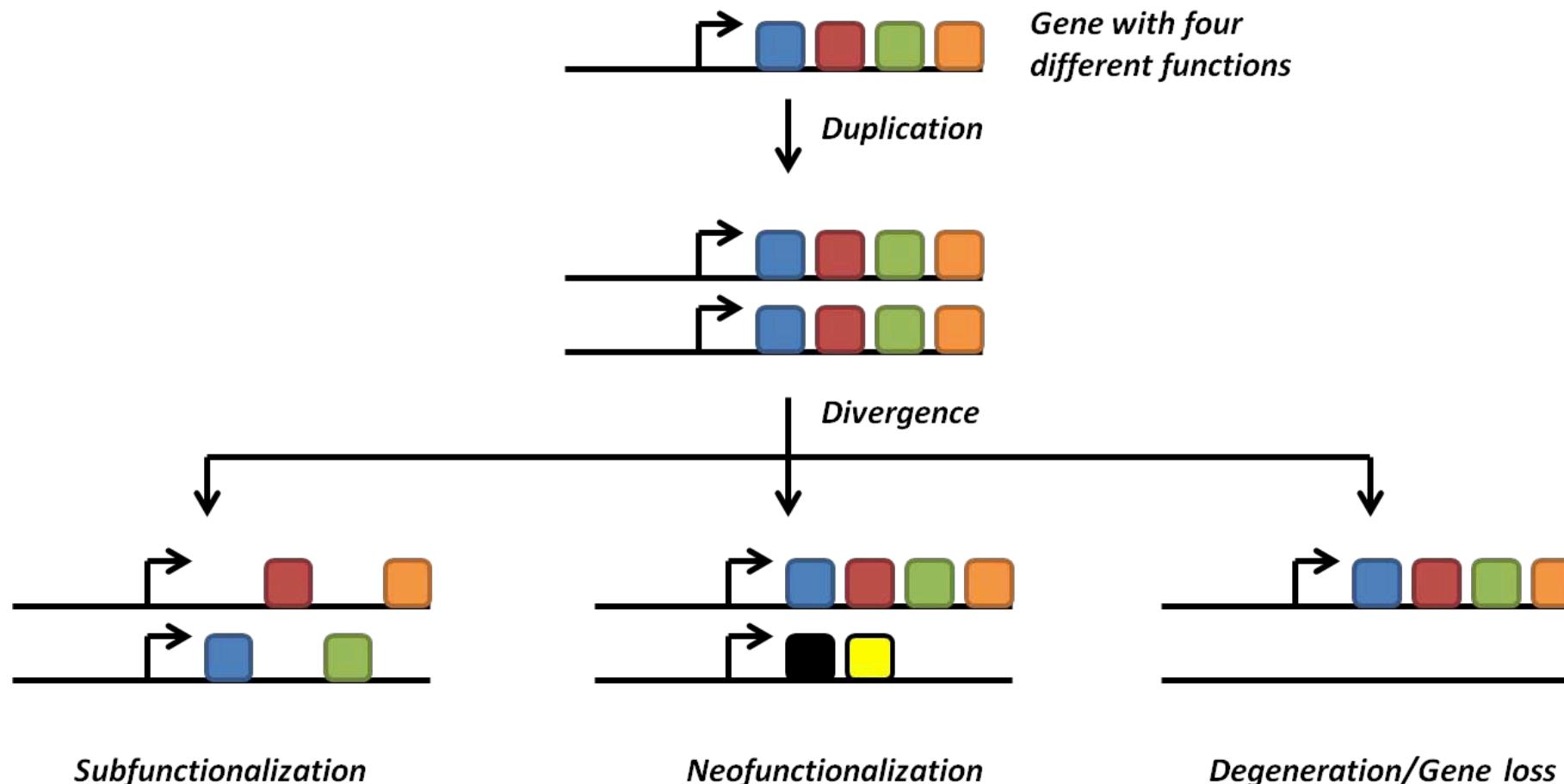
Trend of venn diagram...



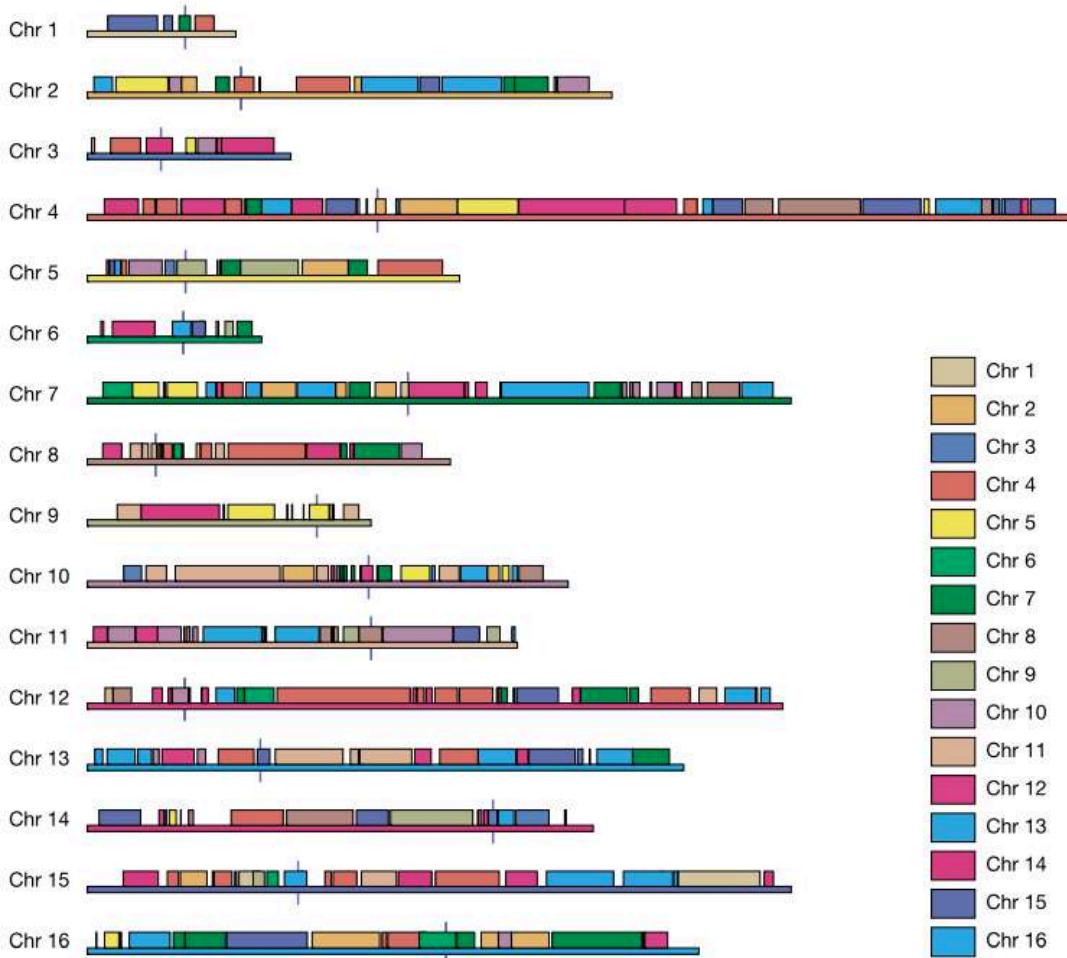
Gene and genome duplication

Why study gene duplication?

Gene duplications are traditionally considered as a major evolutionary source for protein new functions

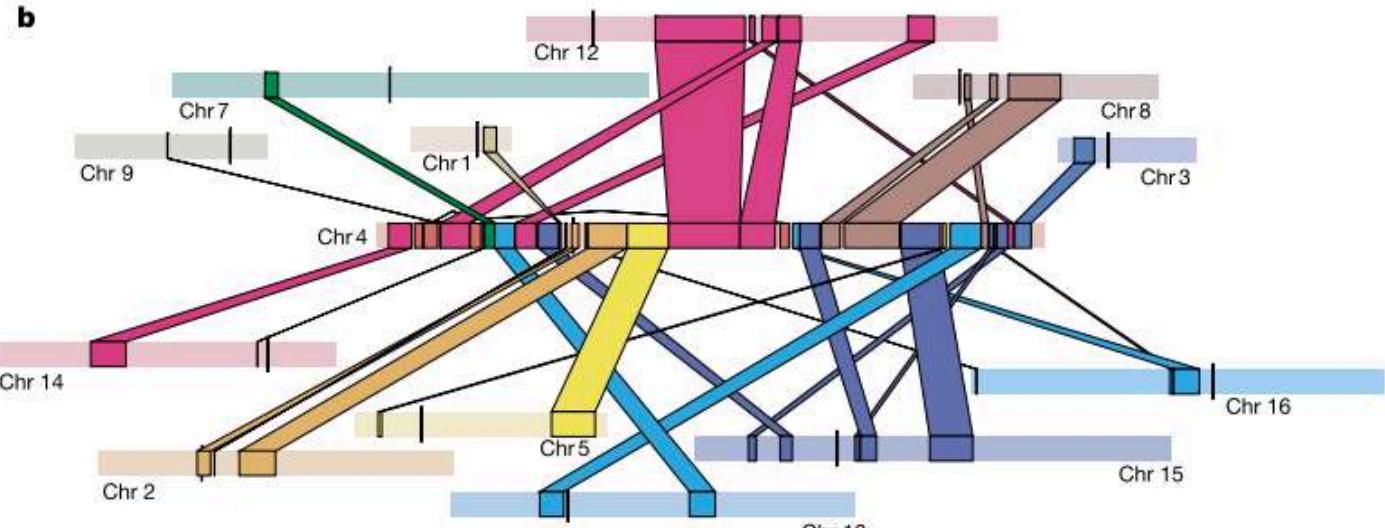


Within species

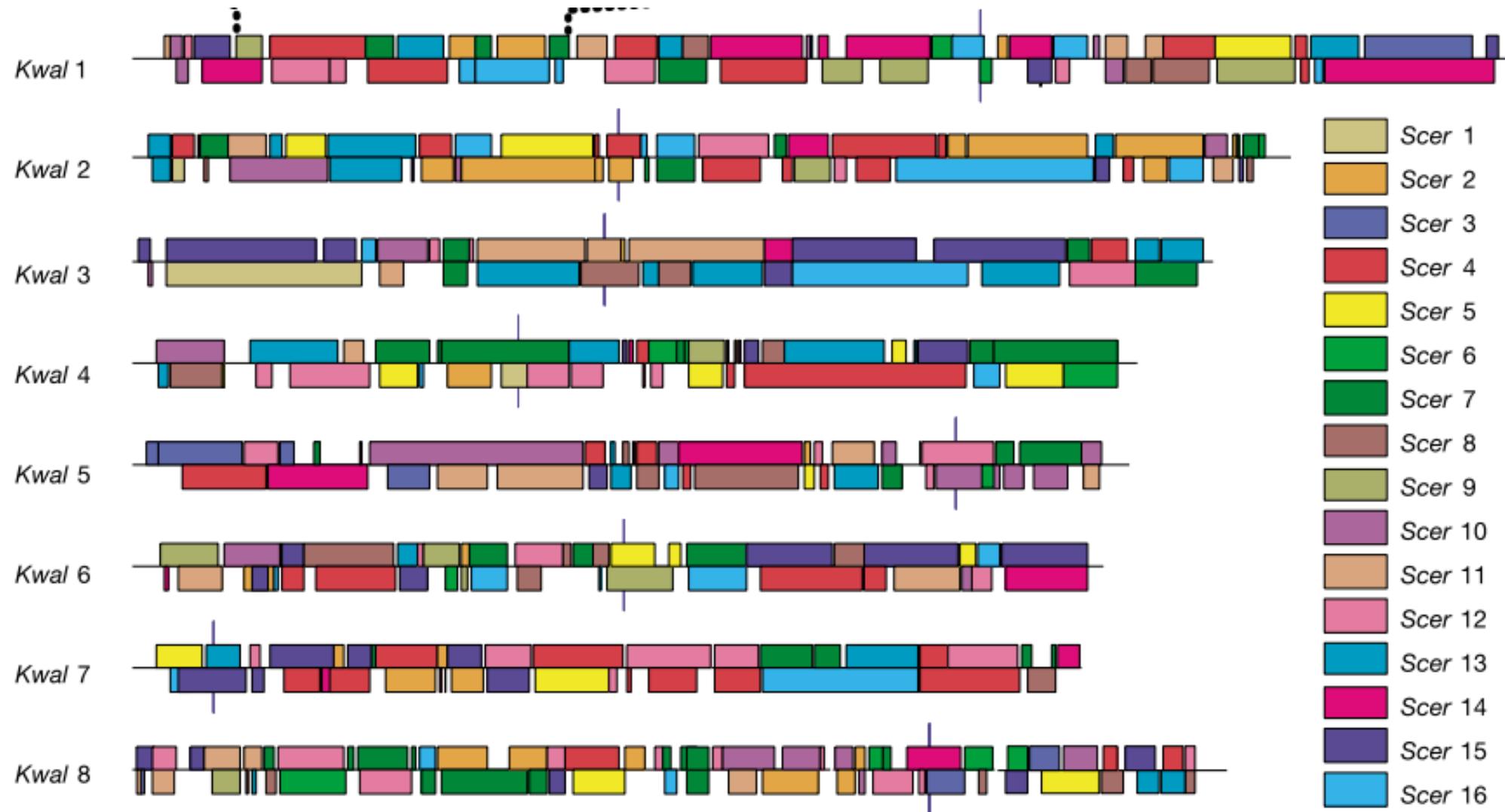


Chr 1
Chr 2
Chr 3
Chr 4
Chr 5
Chr 6
Chr 7
Chr 8
Chr 9
Chr 10
Chr 11
Chr 12
Chr 13
Chr 14
Chr 15
Chr 16

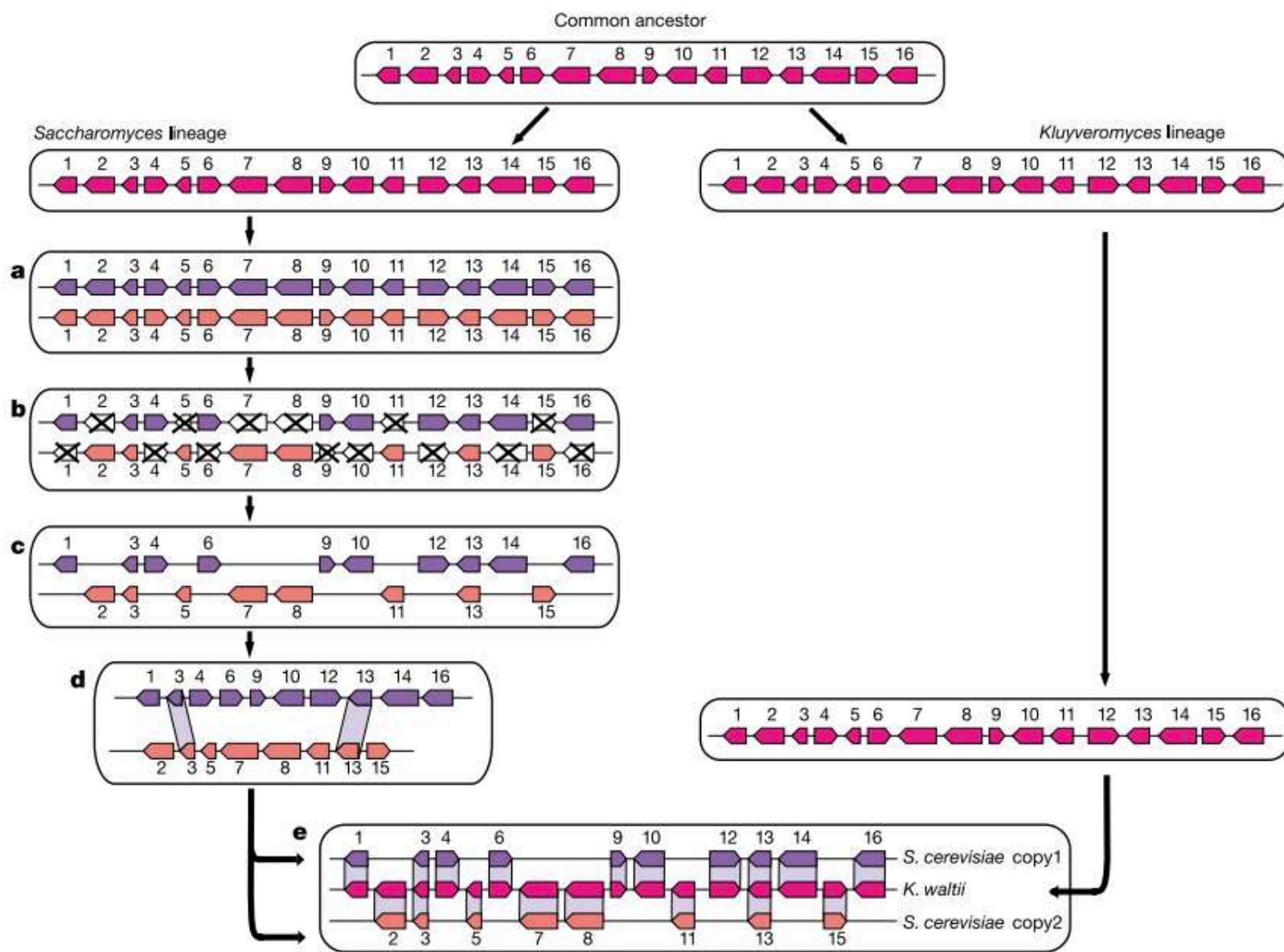
b



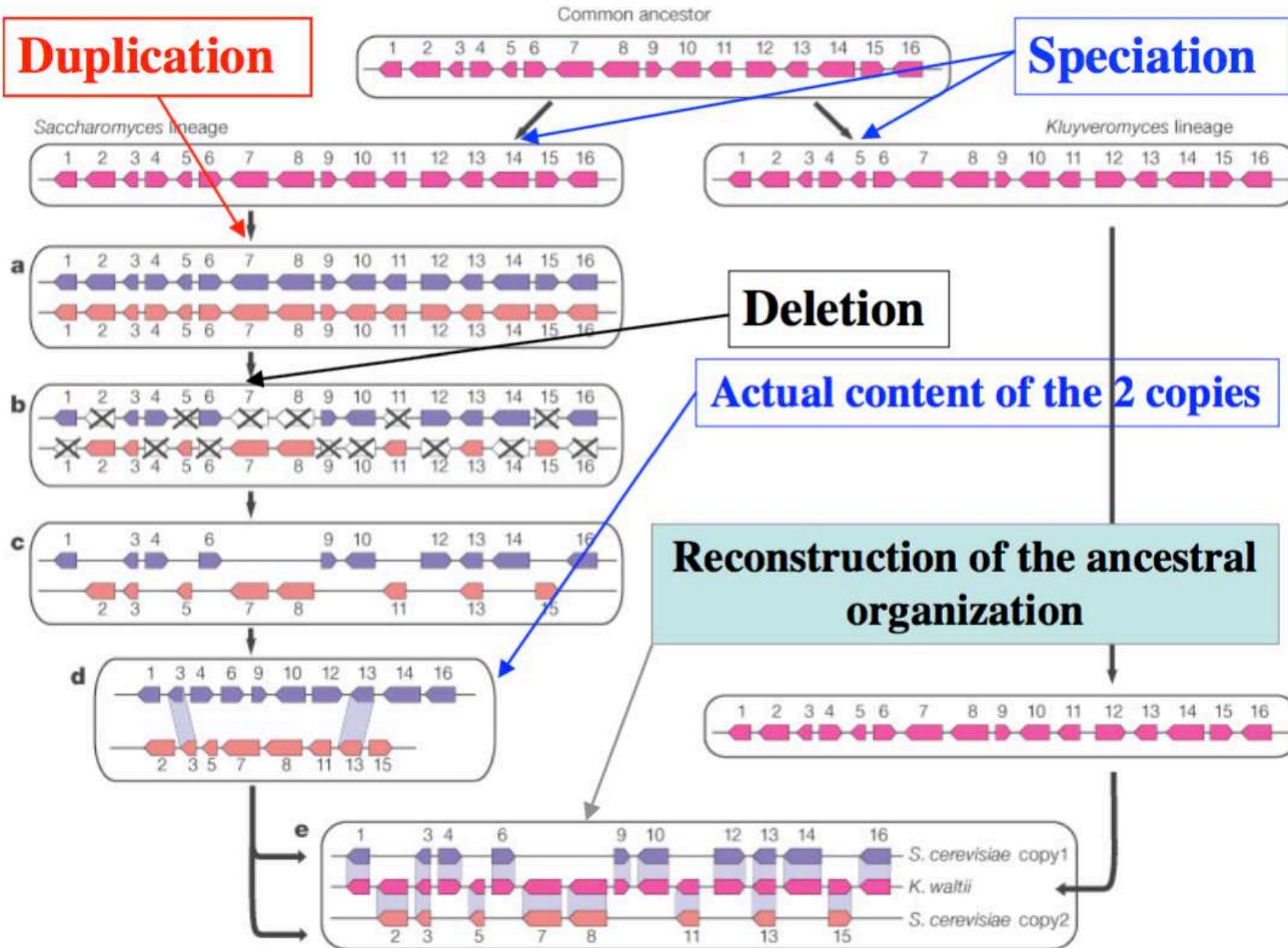
Between species



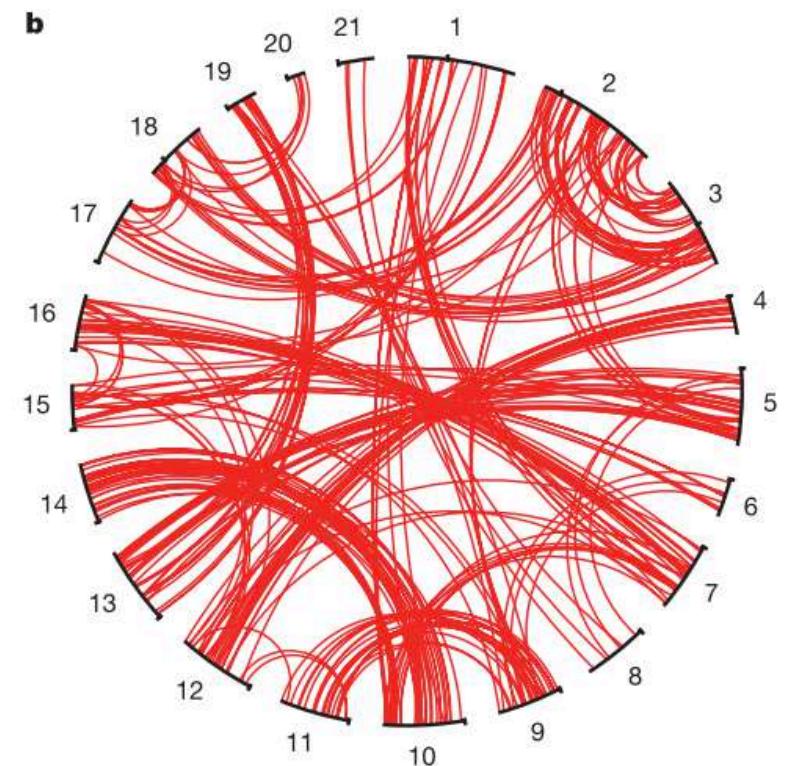
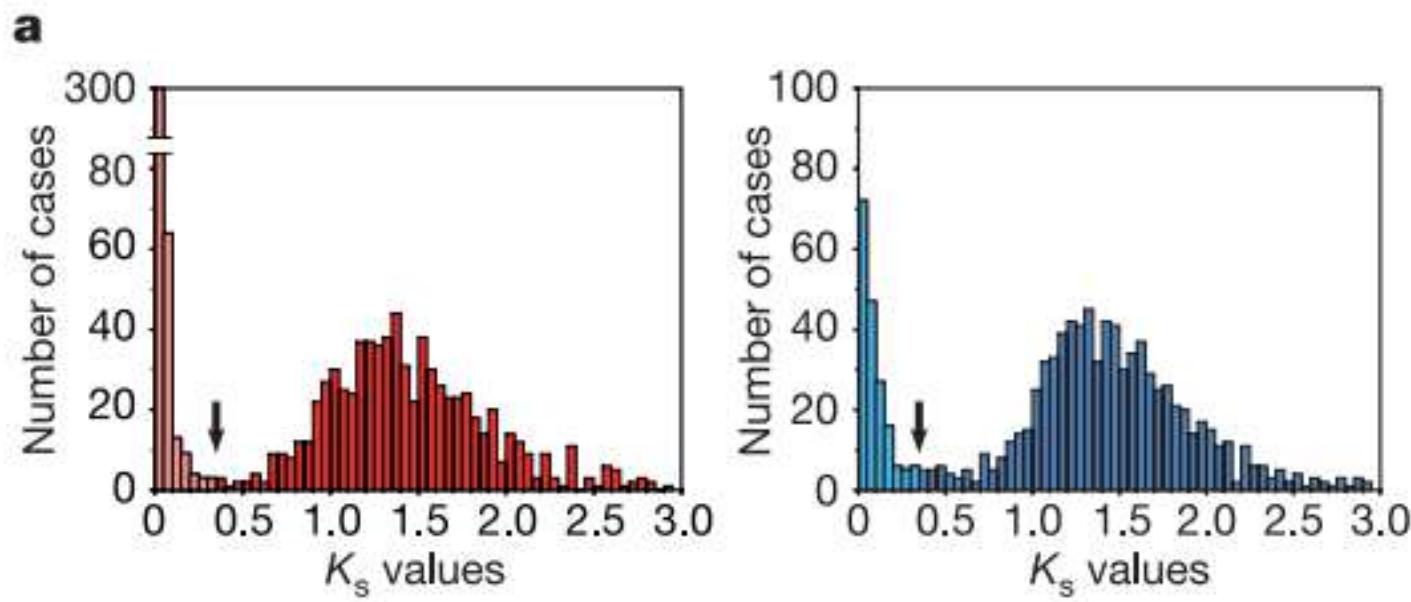
Whole genome duplication model



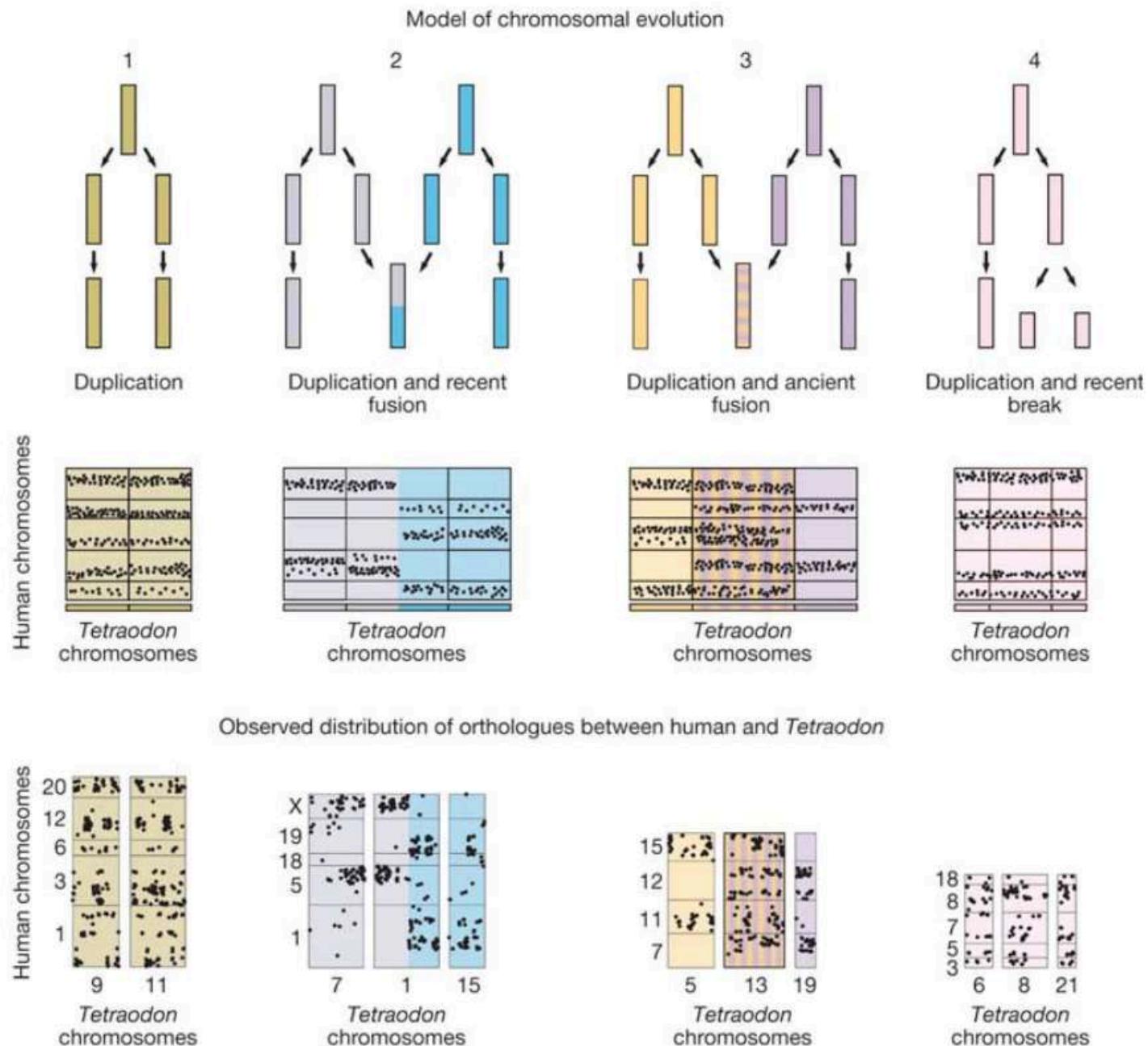
Determining ancestral conservation



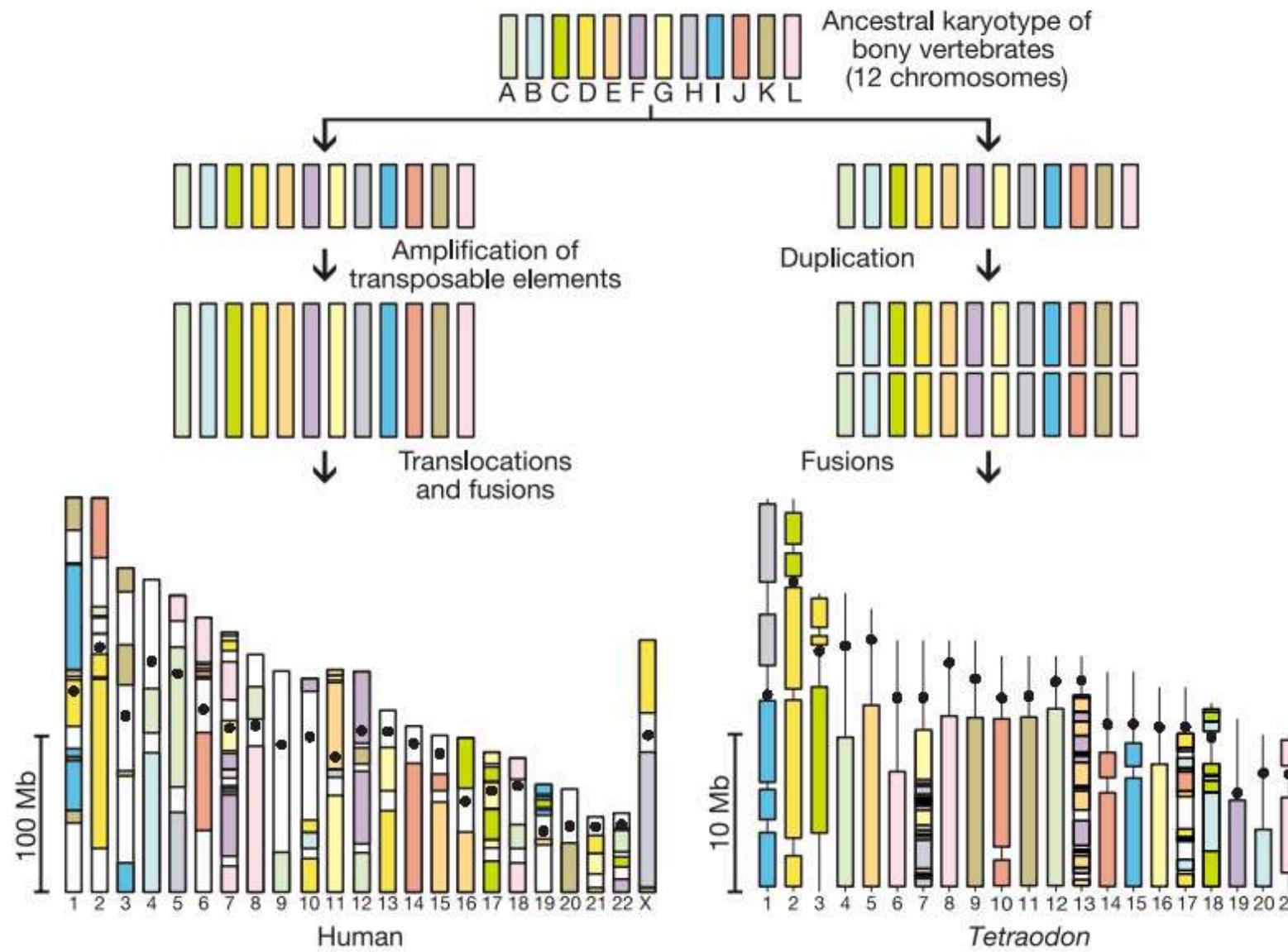
Genome duplication in the teleost fish *Tetraodon nigroviridis* reveals the early vertebrate proto-karyotype



Reconstructing ancient genome rearrangement

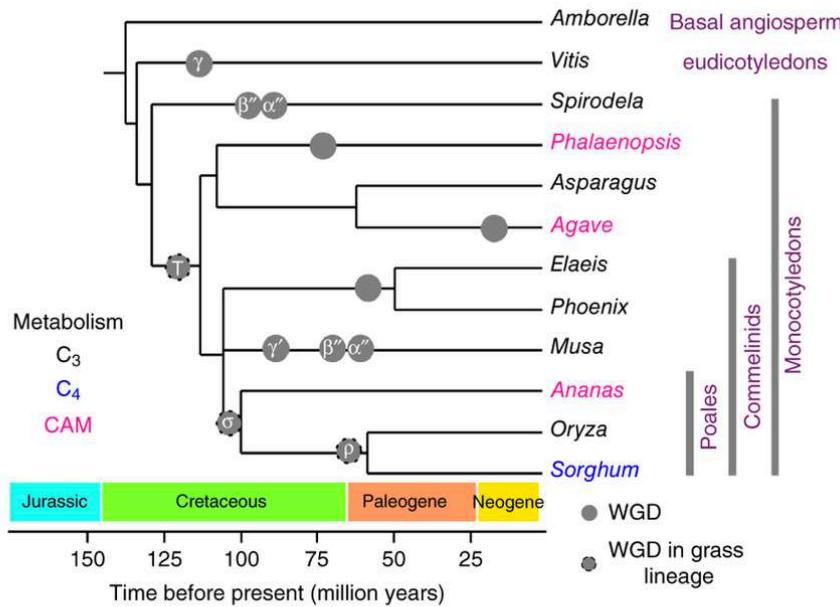


Reconstructing ancient genome rearrangement



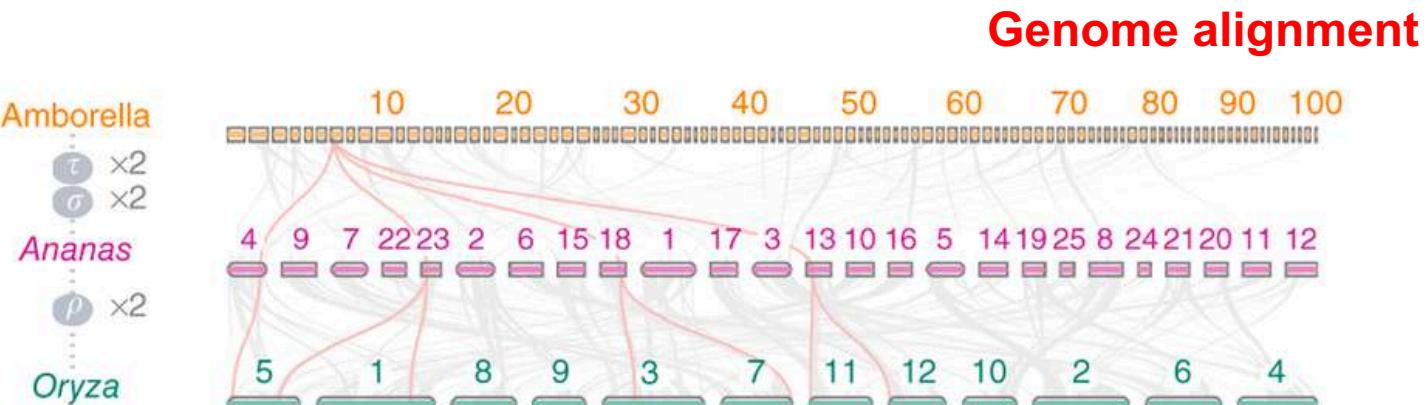
Pineapple genome

a



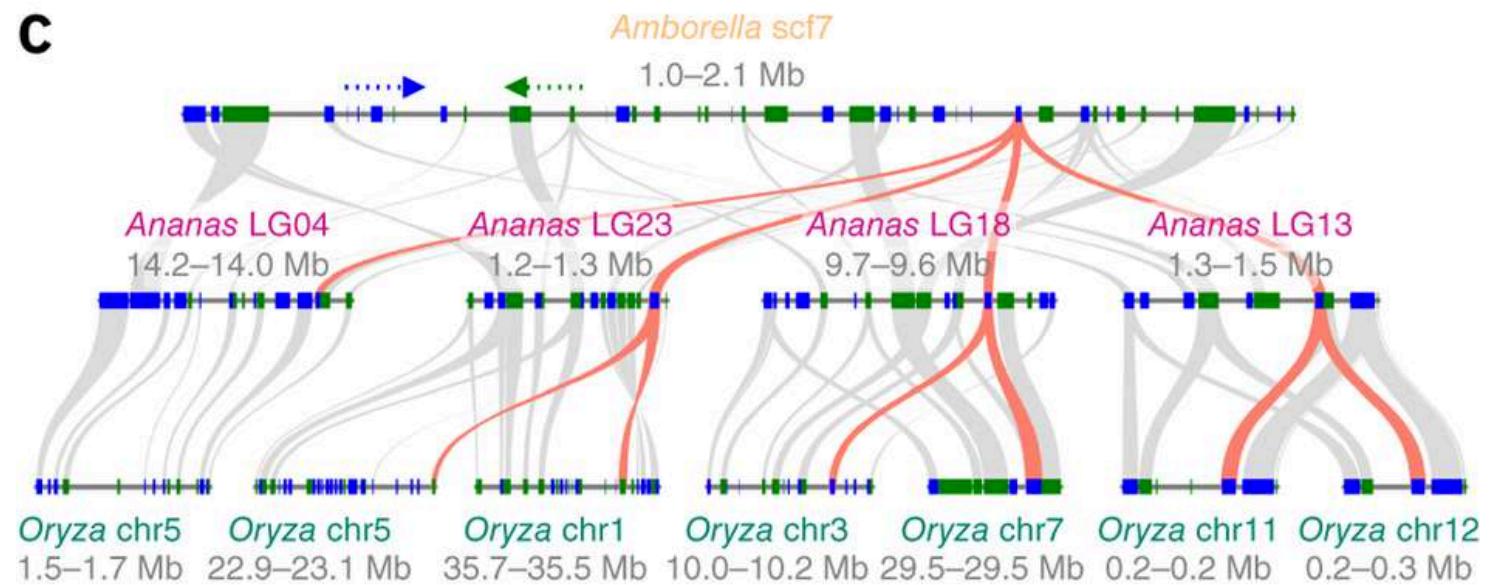
Evolution of chromosomes

b



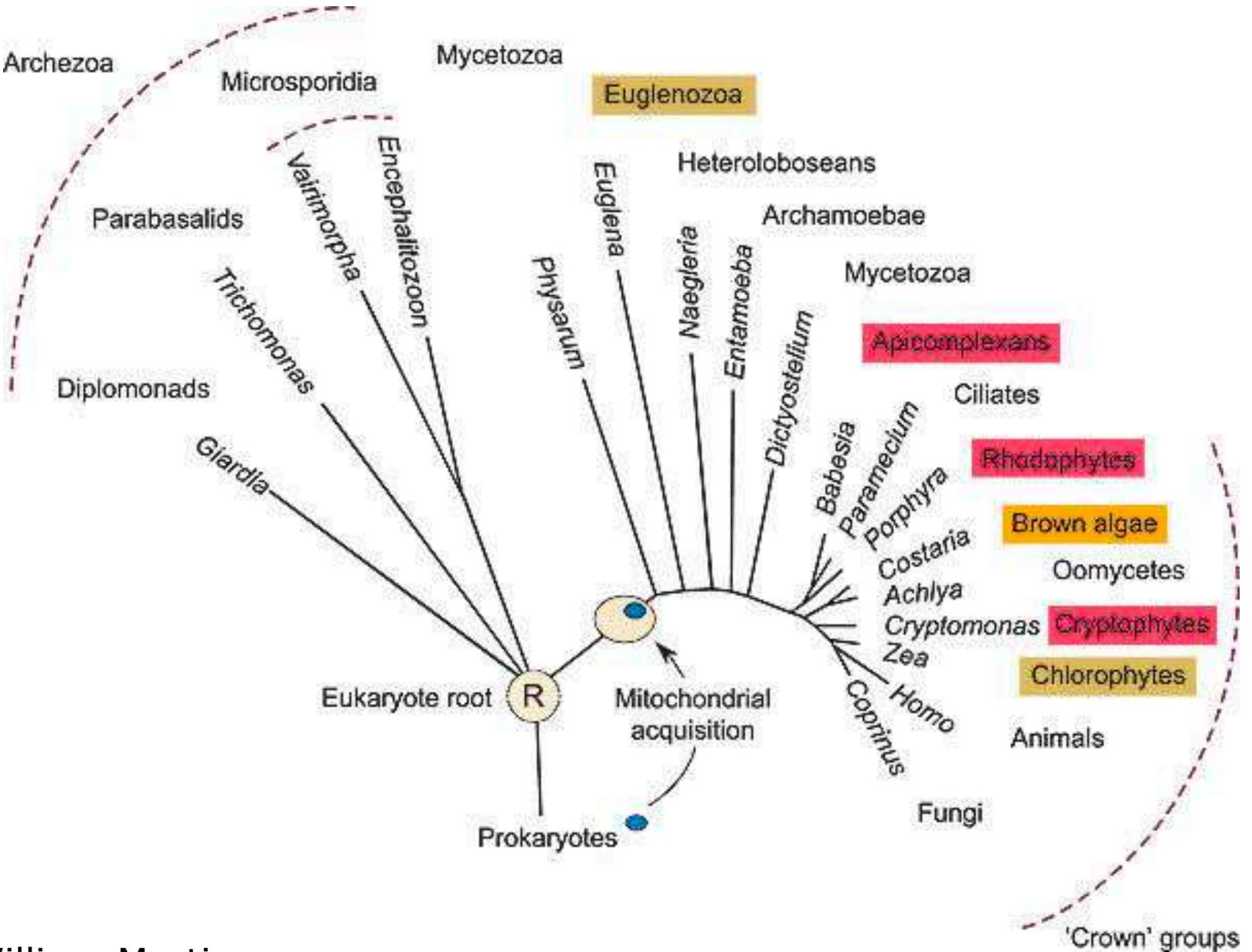
Genome alignment

c



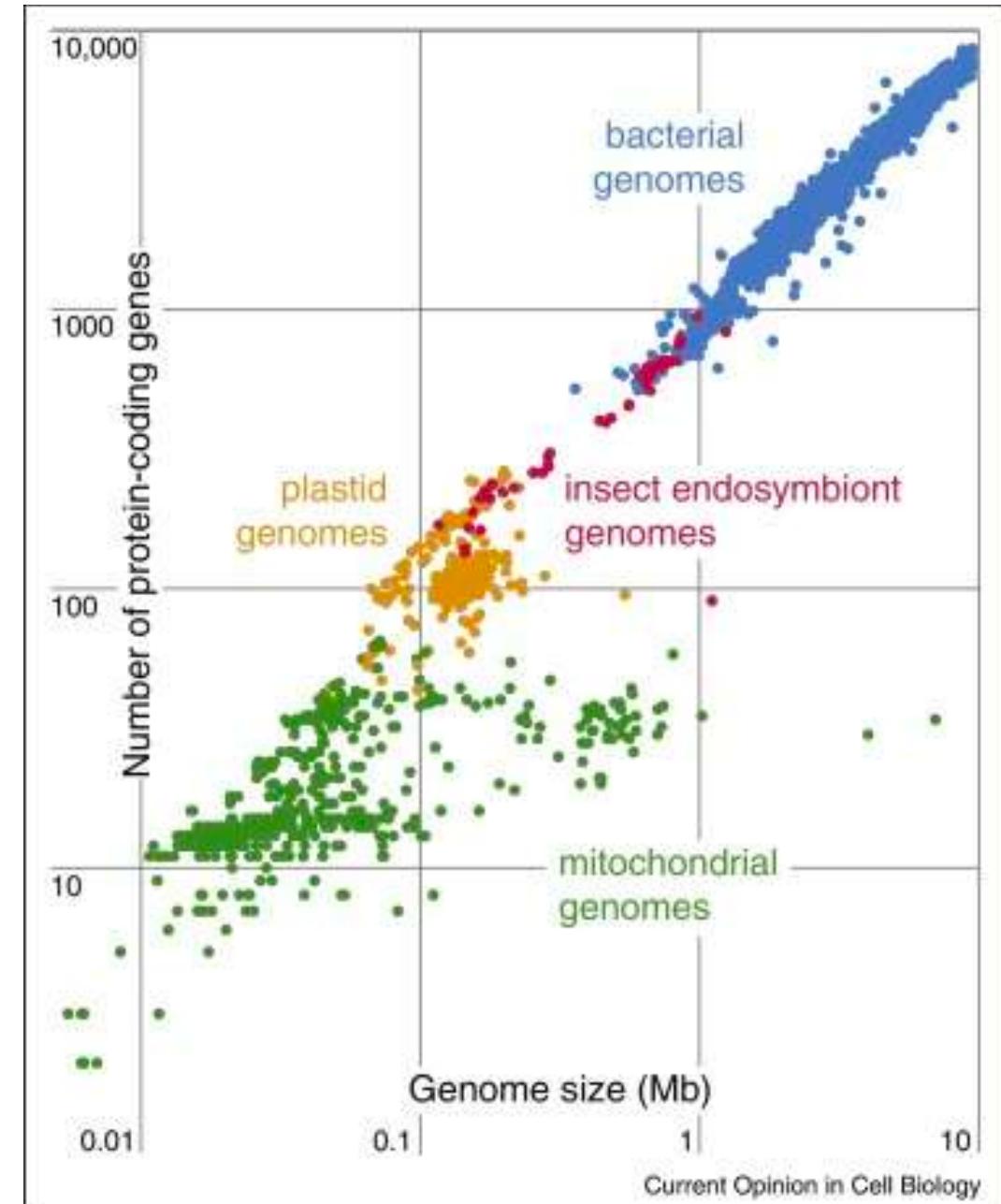
Colinearity of genes

Symbiosis



Genomes from bacteria, insect endosymbionts, chloroplasts, and mitochondria form an unbroken continuum of size and coding density. The plot is truncated at 10 Mb and 10,000 genes.

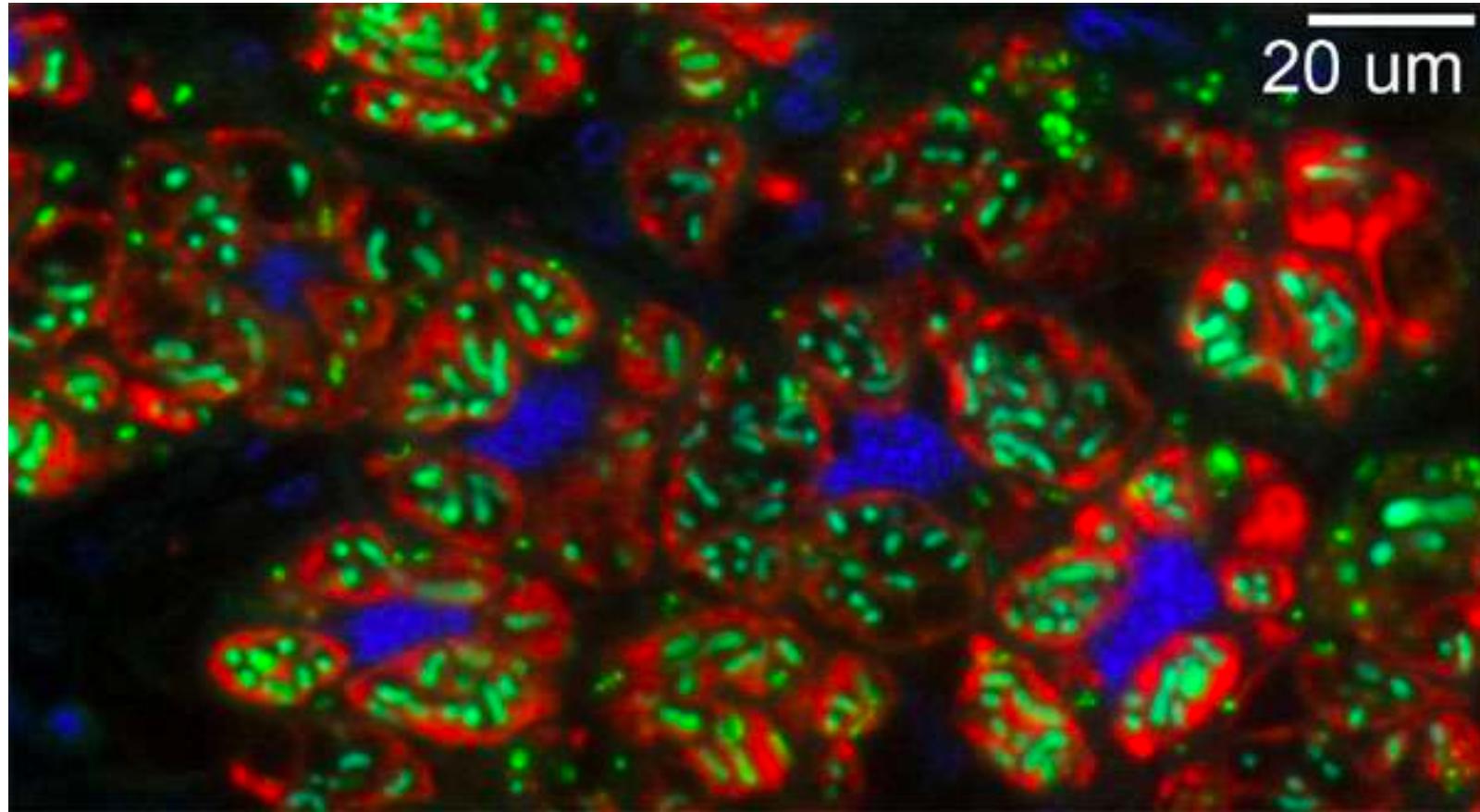
“Insect endosymbionts are missing (genomic) links between bacteria and organelles. It is now widely appreciated that all animals form symbioses with bacteria. Insects are especially interesting in this regard because they form many intracellular symbioses — that is, they allow bacteria to live inside their cells — that are not pathogenic from the host perspective”



Case study: Mealybugs

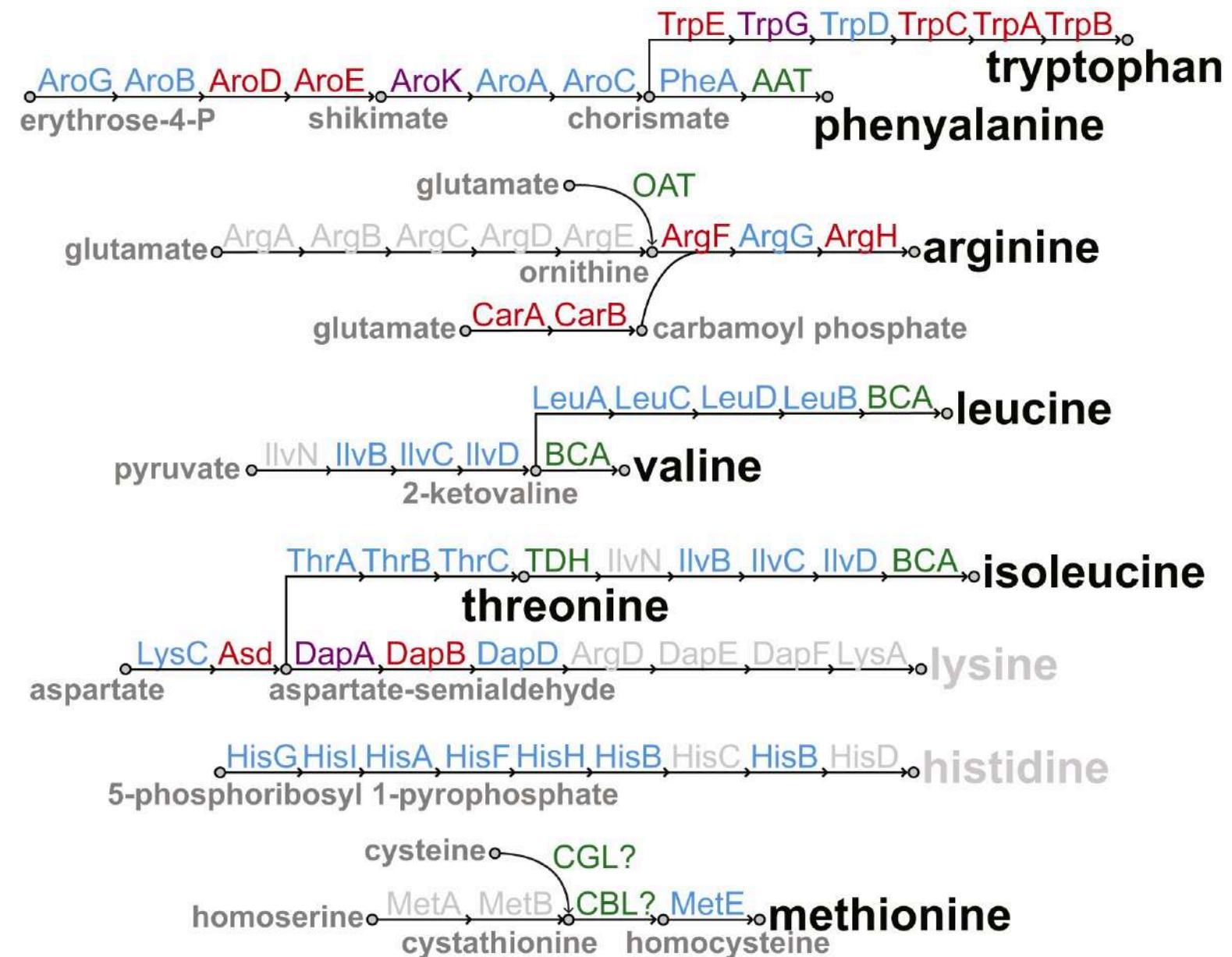


Triple Symbiotic Relationship between Mealybugs, *Tremblaya princeps*, and *Moranella endobia*



Mealybug cells, showing Tremblaya (red), Moranella (green) and mealybug nuclei (blue).
Credit: Ryuichi Koga, National Institute of Advanced Industrial Science and Technology,
Japan

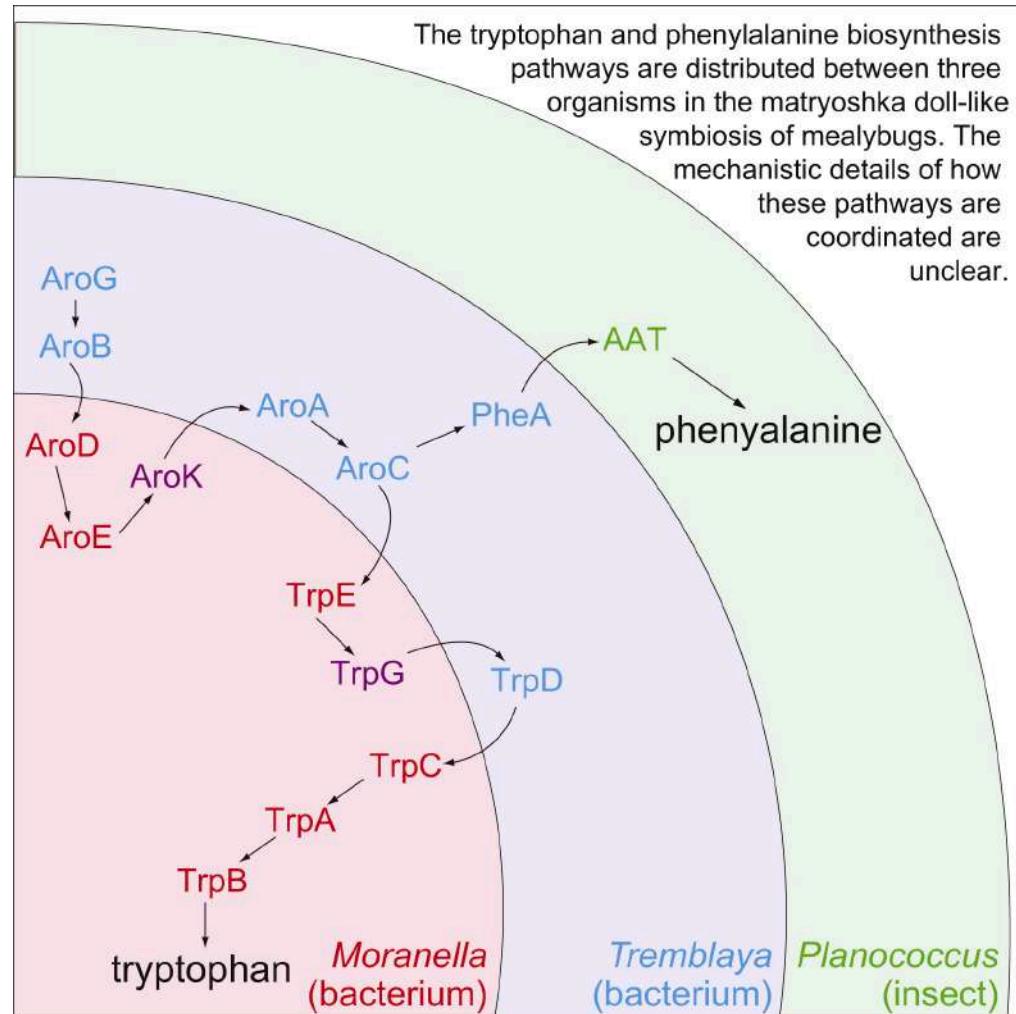
Predicted Essential Amino Acid Metabolic Contributions of the Mealybug-Tremblaya-Moranella Symbiosis



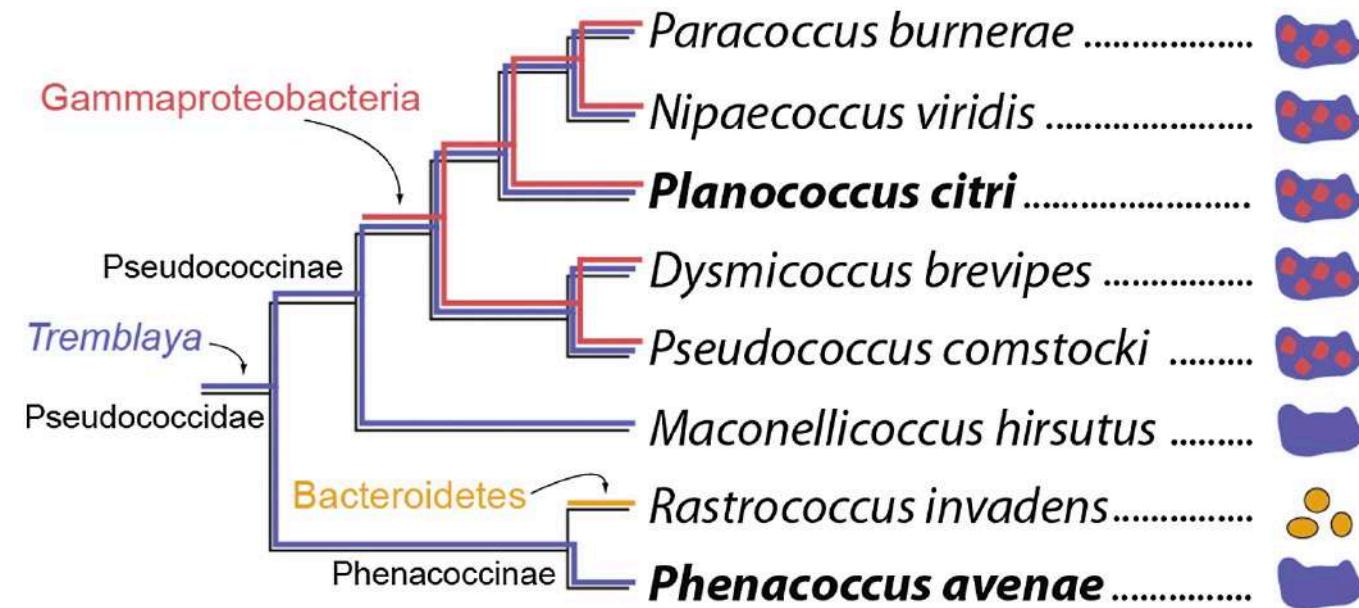
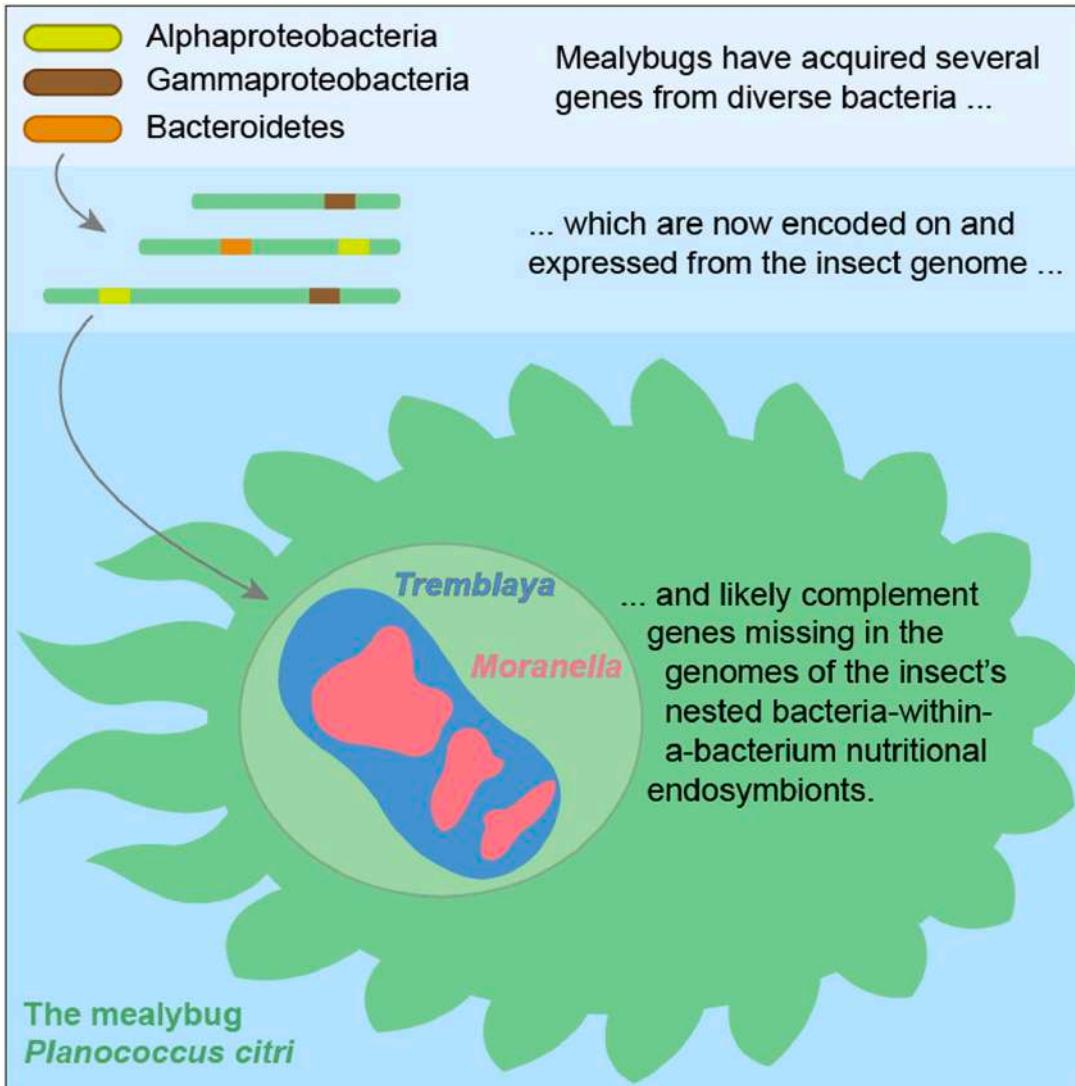
Gene homologs found in the Tremblaya genome are blue; the Moranella genome, red; both the Tremblaya and Moranella genomes, purple; neither the Tremblaya nor the Moranella genome, gray; activities not found in either bacterial genome but predicted to be encoded in the mealybug genome, green.

Genome degeneracy of a bacterial endosymbiont is driven by its own endosymbiont

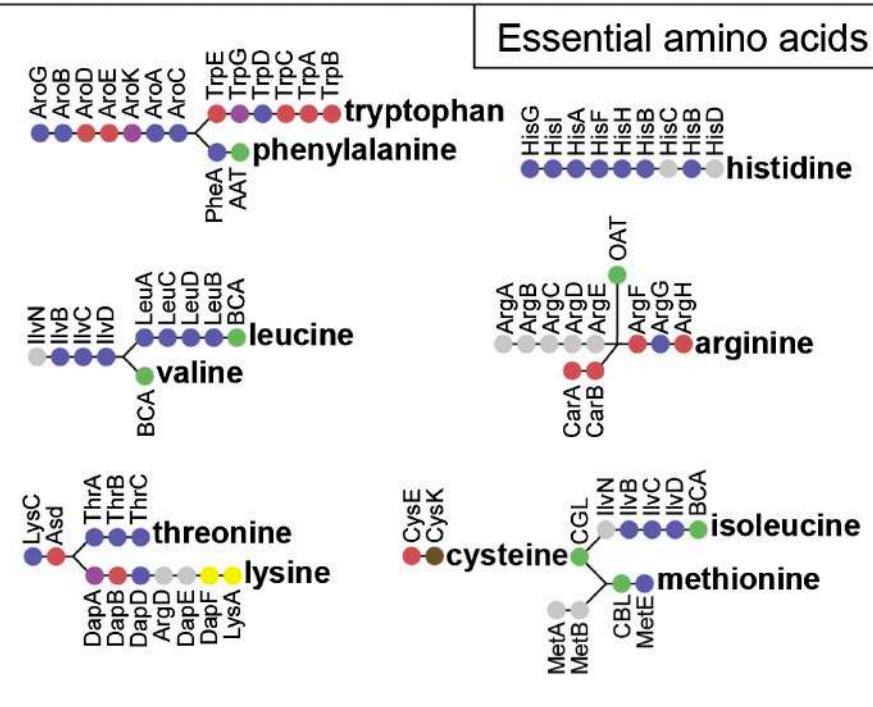
- HGT from diverse bacteria to the insect host genome support the three-way symbiosis
- Endosymbiont genomes can massively degrade without transfer of genes to the host



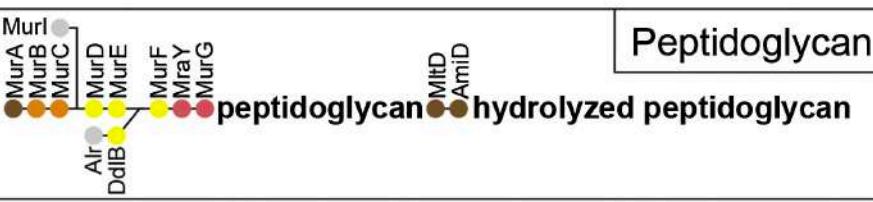
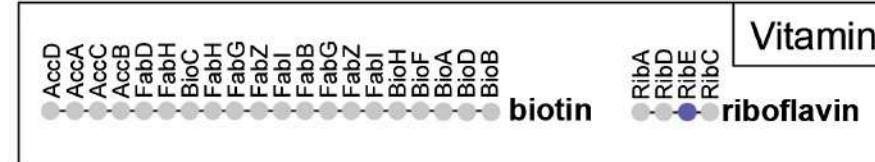
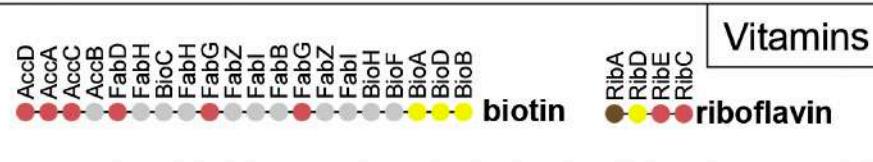
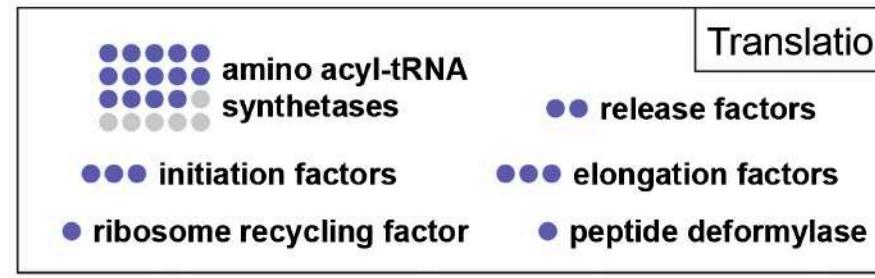
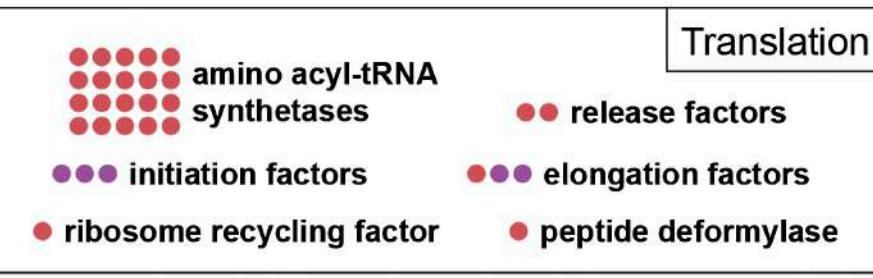
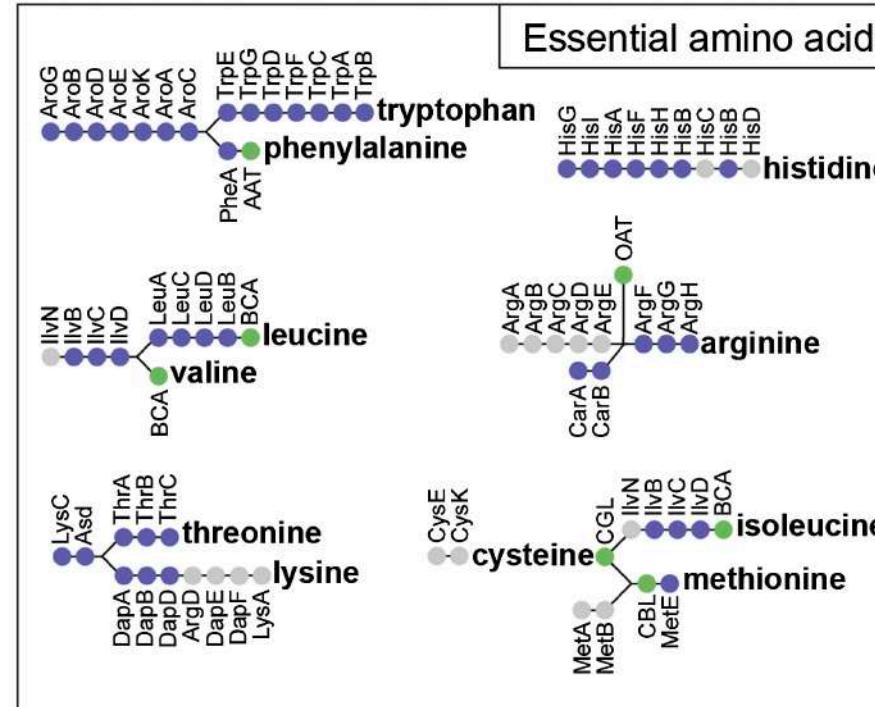
Horizontal Gene Transfer from Diverse Bacteria to an Insect Genome Enables a Tripartite Nested Mealybug Symbiosis



A *Planococcus citri*



B *Phenacoccus avenae*



- Tremblaya
- Moranella
- Tremblaya and Moranella
- Host genome, eukaryotic origin
- Missing in the system
- HGT from Alphaproteobacteria
- HGT from Gammaproteobacteria
- HGT from Bacteroidetes

Even more fascinating case

Cell

Sympatric Speciation in a Bacterial Endosymbiont Results in Two Genomes with the Functionality of One

James T. Van Leuven,¹ Russell C. Meister,² Chris Simon,² and John P. McCutcheon^{1,3,*}

¹Division of Biological Sciences, University of Montana, Missoula, MT 59812, USA

²Department of Ecology and Evolutionary Biology, University of Connecticut, Storrs, CT 06269, USA

³Canadian Institute for Advanced Research, CIFAR Program in Integrated Microbial Biodiversity, Toronto, ON M5G 1Z8, Canada

*Correspondence: john.mccutcheon@umontana.edu

<http://dx.doi.org/10.1016/j.cell.2014.07.047>

<https://www.youtube.com/watch?v=XRI2JxTzJ-0&list=UUlSV2Tk7x-wBBXP6-VCNbNw>

Some cicadas contain two bacterial symbionts, *Sulcia* and *Hodgkinia*.



Other cicadas contain three symbionts: *Sulcia* and two versions of *Hodgkinia*.



The two new *Hodgkinia* genotypes arose from an unusual speciation event.



The single *Hodgkinia* genome encodes genes needed for the production of histidine and methionine.



The new *Hodgkinia* genotypes partition these pathways, requiring both species for the production of histidine and methionine.

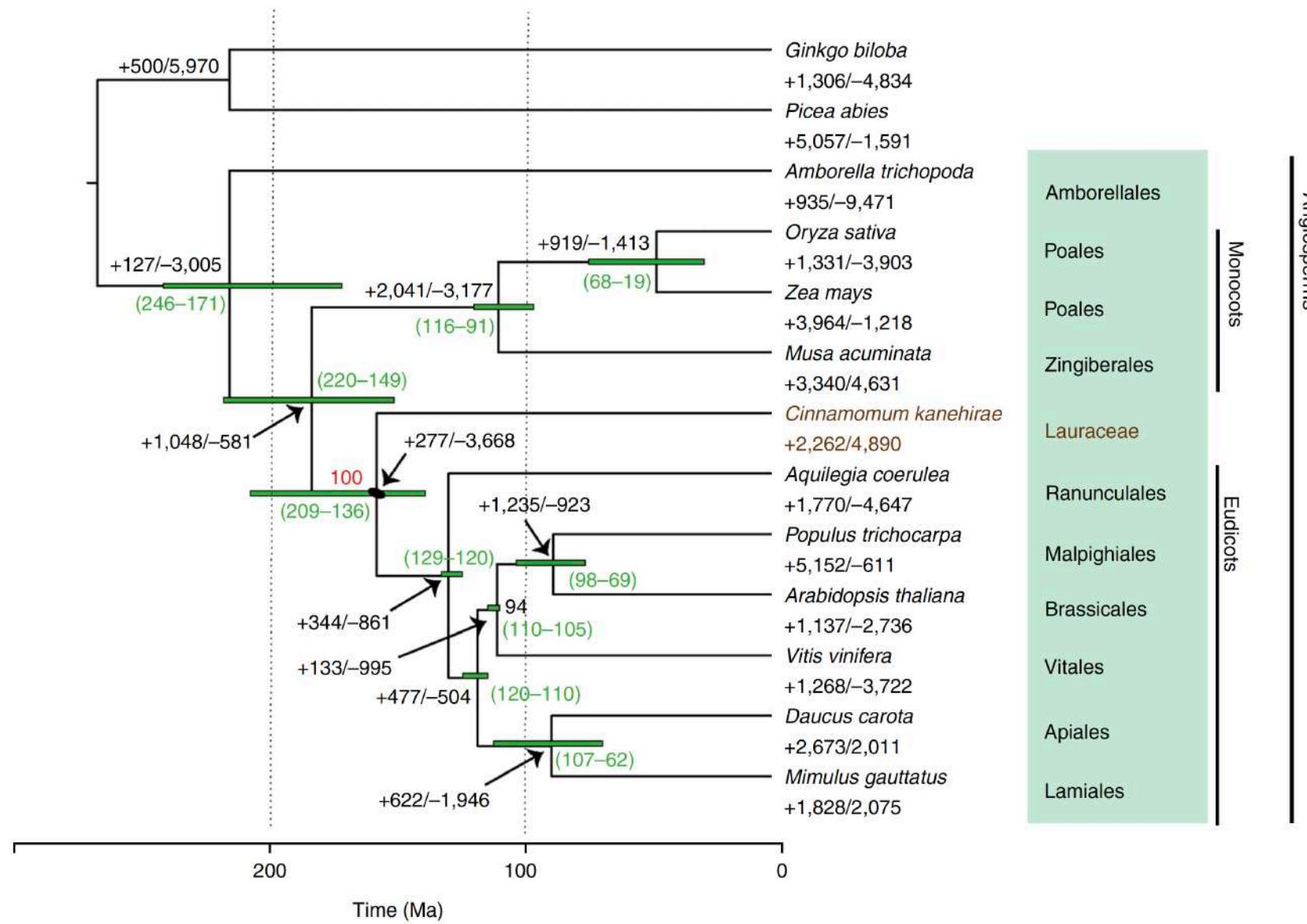
More case studies:

Stout camphor tree genome fills gaps in understanding of flowering plant genome evolution

Shu-Miaw Chaw  ^{1,6*}, Yu-Ching Liu¹, Yu-Wei Wu², Han-Yu Wang¹, Chan-Yi Ivy Lin¹, Chung-Shien Wu¹, Huei-Mien Ke¹, Lo-Yu Chang^{1,3}, Chih-Yao Hsu¹, Hui-Ting Yang¹, Edi Sudianto  ¹, Min-Hung Hsu^{1,4}, Kun-Pin Wu⁴, Ling-Ni Wang¹, James H. Leebens-Mack⁵ and Isheng J. Tsai  ^{1,6*}

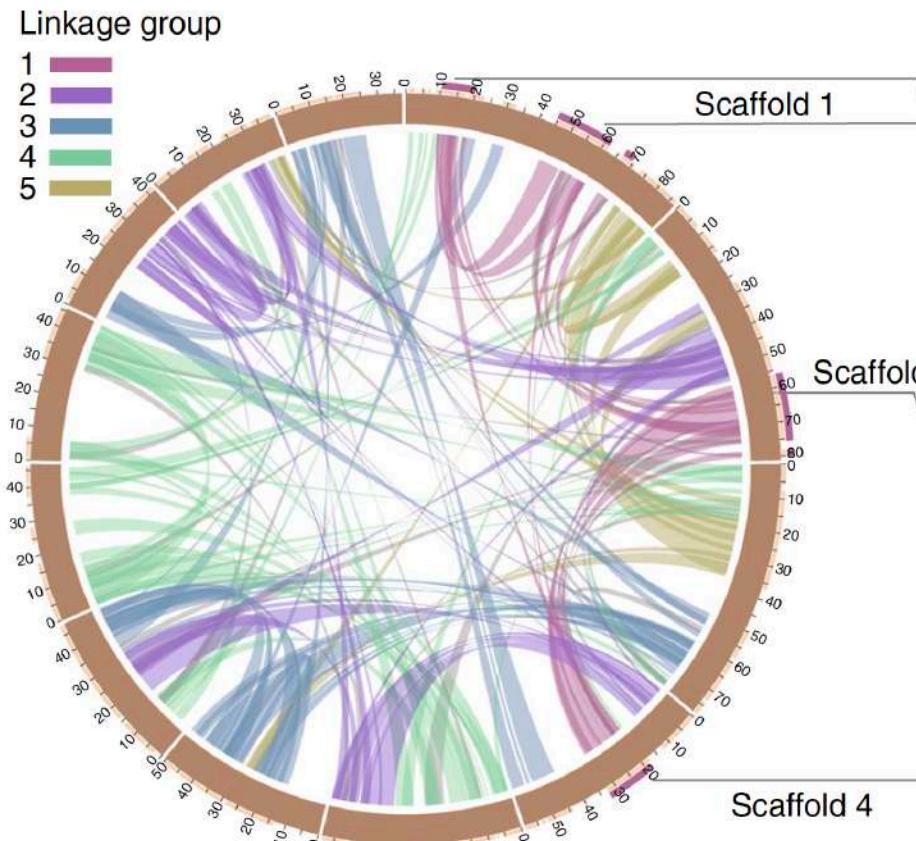
We present reference-quality genome assembly and annotation for the stout camphor tree (*Cinnamomum kanehirae* (Laurales, Lauraceae)), the first sequenced member of the Magnoliidae comprising four orders (Laurales, Magnoliales, Canellales and Piperales) and over 9,000 species. **Phylogenomic analysis of 13 representative seed plant genomes indicates that magnoliid and eudicot lineages share more recent common ancestry than monocots.** Two whole-genome duplication events were inferred within the magnoliid lineage: one before divergence of Laurales and Magnoliales and the other within the Lauraceae. Small-scale segmental duplications and tandem duplications also contributed to innovation in the evolutionary history of *Cinnamomum*. For example, expansion of the terpenoid synthase gene subfamilies within the Laurales spawned the diversity of *Cinnamomum* monoterpenes and sesquiterpenes.

Stout camphor tree genome



Stout camphor tree genome

a



b

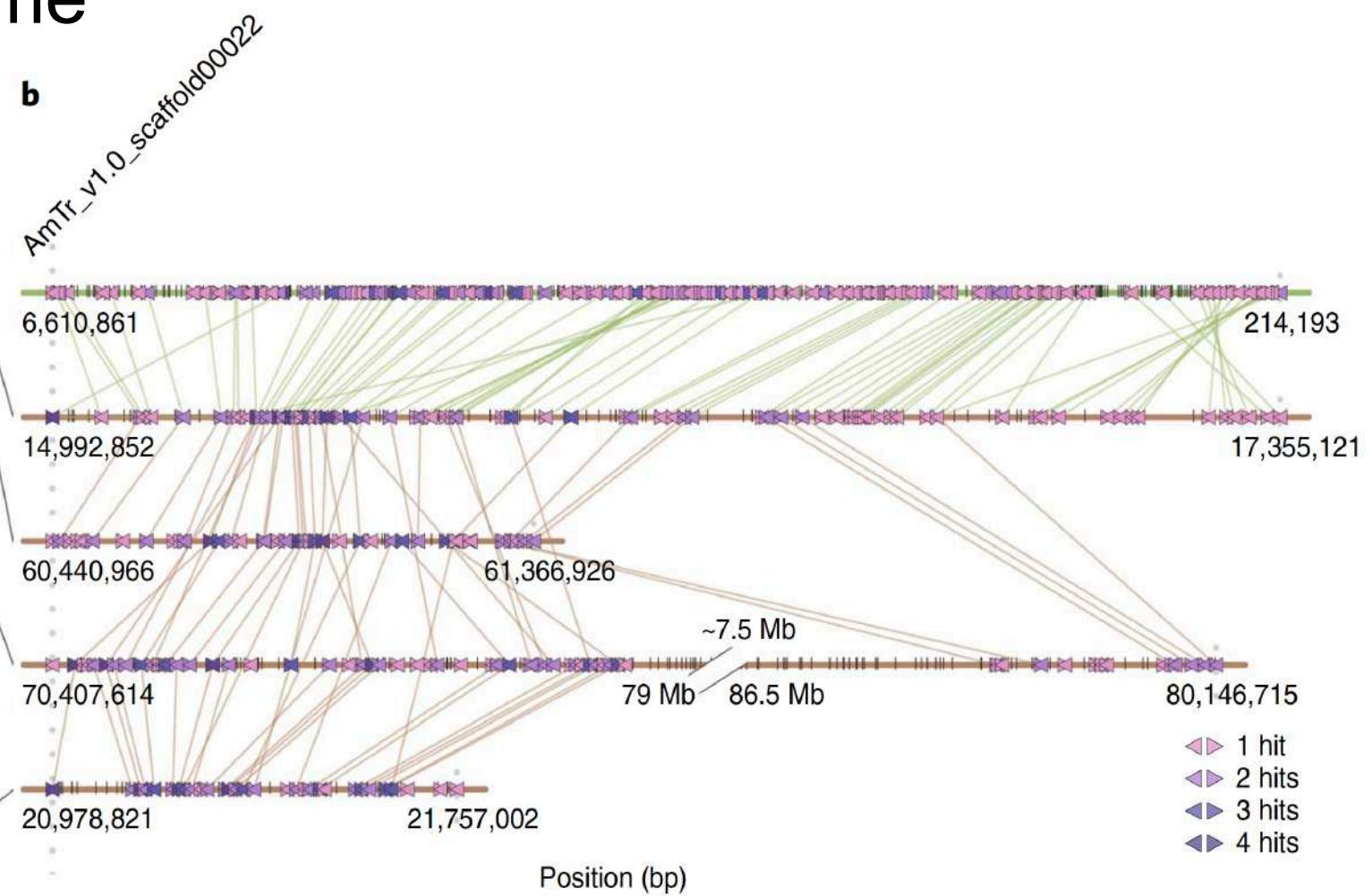


Fig. 3 | Evolutionary analysis of the SCT genome. a, Schematic representation of the intragenomic relationship among the 637 synteny blocks in the SCT genome. Synteny blocks (denoted by peach blocks) were assigned unambiguously into five linkage clusters representing ancient karyotypes and are colour coded. Purple blocks denote the synteny block assigned in the first linkage group (see also Supplementary Fig. 13). **b,** Schematic representation of the first linkage group within the SCT genome and their corresponding relationship in *A. trichopoda*.

Stout camphor tree genome

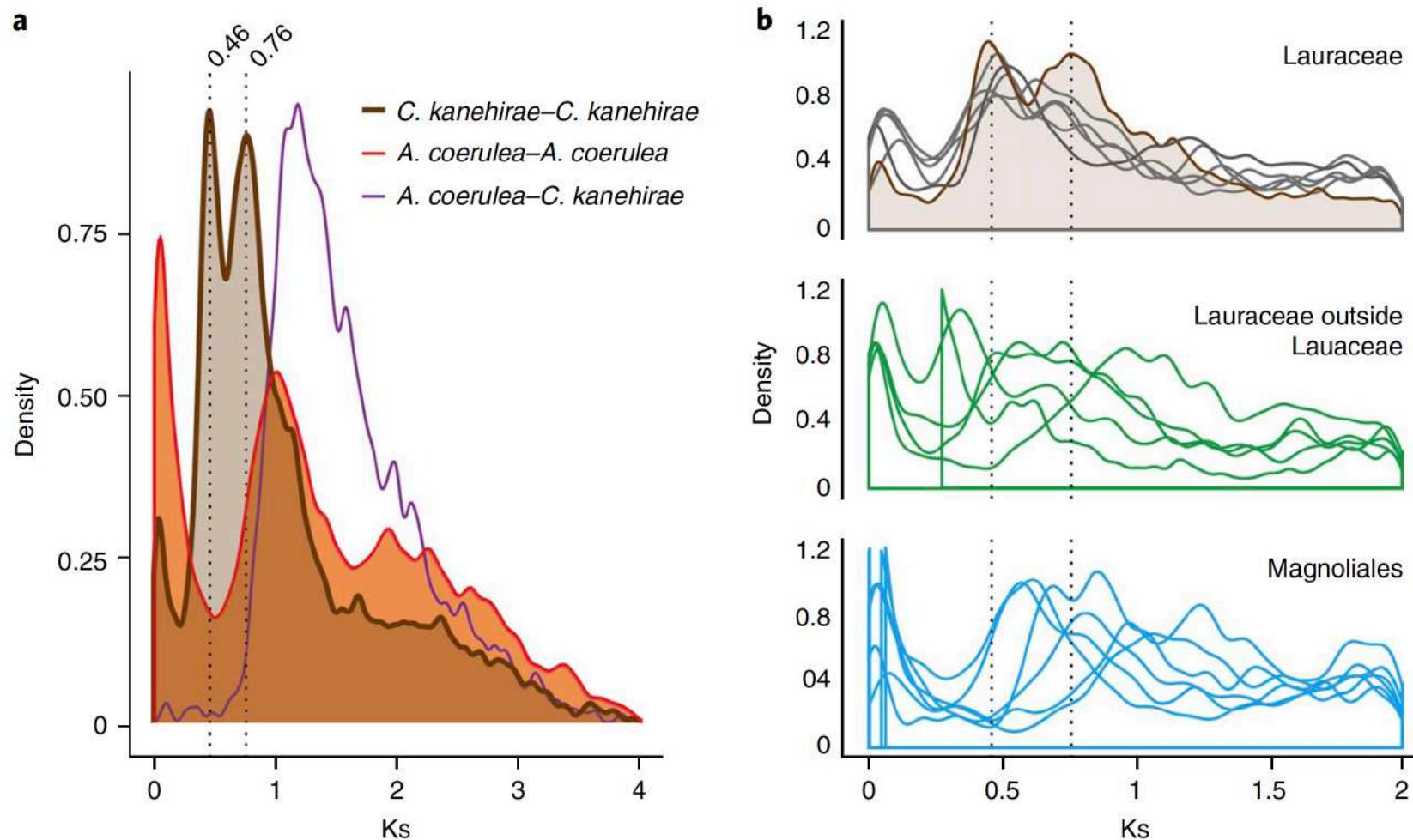
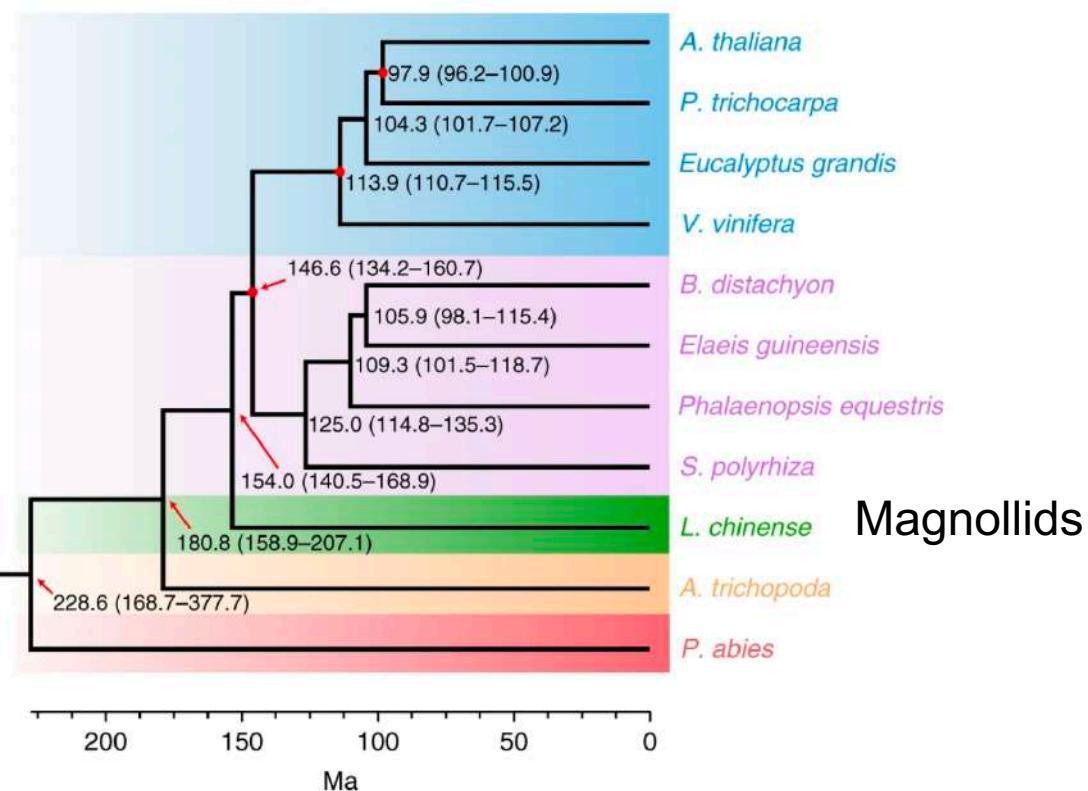


Fig. 4 | Density plots of synonymous substitutions (Ks) of the SCT genome and other plant species. a, Pairwise orthologue duplicates identified in synteny blocks within SCT, *A. coerulea* and between SCT and *A. coerulea*. **b,** Ks of intragenomic pairwise duplicates of the Lauraceae and the Magnoliales in the 1KP project²⁹. Dashed lines denote the two Ks peaks observed in SCT. Brown and grey lines denote SCT and other Lauraceae's Ks distribution, respectively.

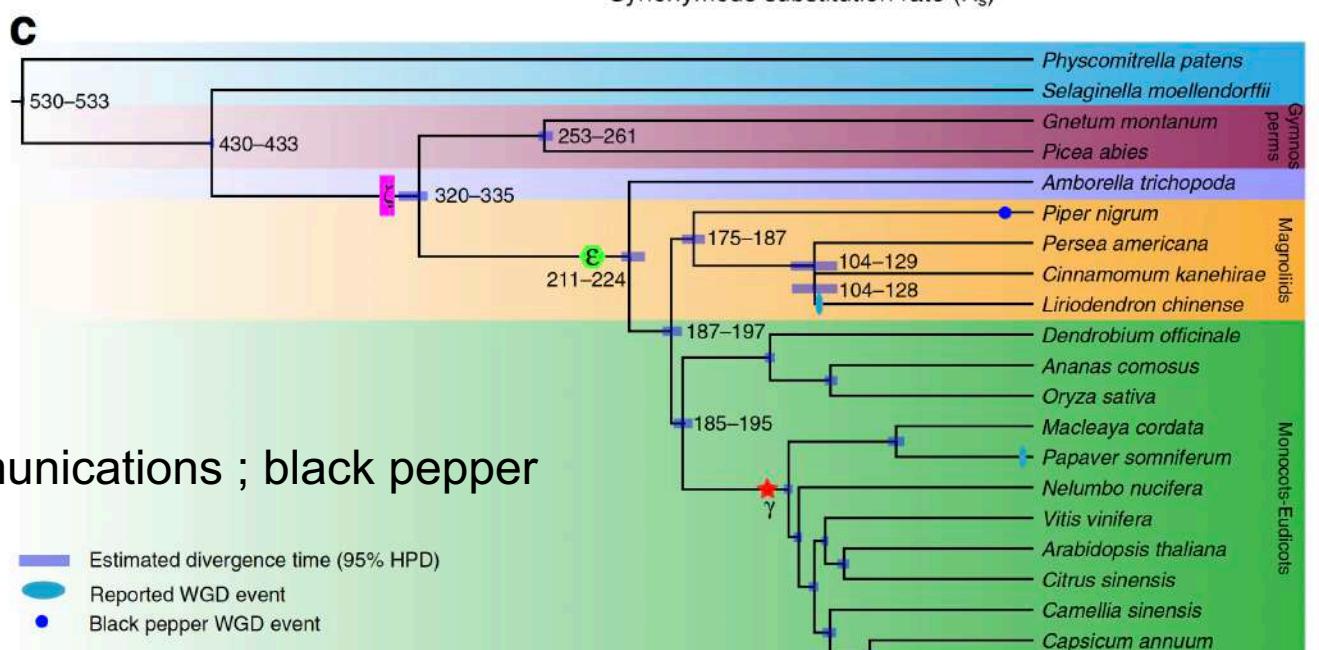
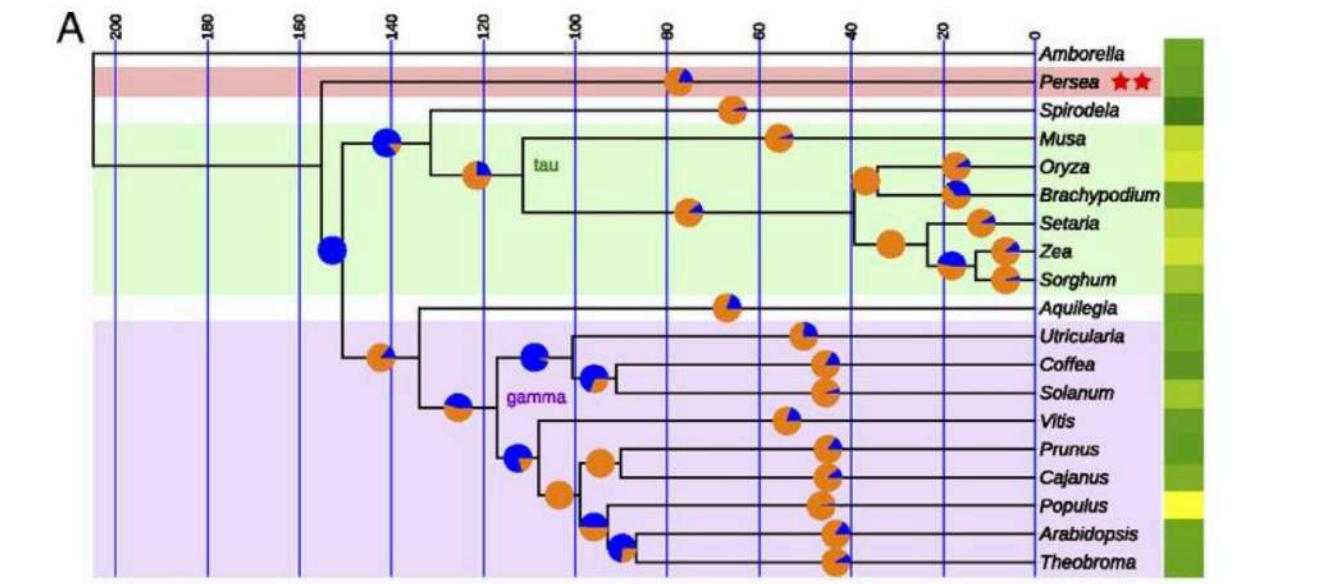
Still unresolved...



Hu et al (2019) Nature communications ; black pepper

- Estimated divergence time (95% HPD)
- Reported WGD event
- Black pepper WGD event

C O S D C P T J K Pg N Q Million years ago (MYA)

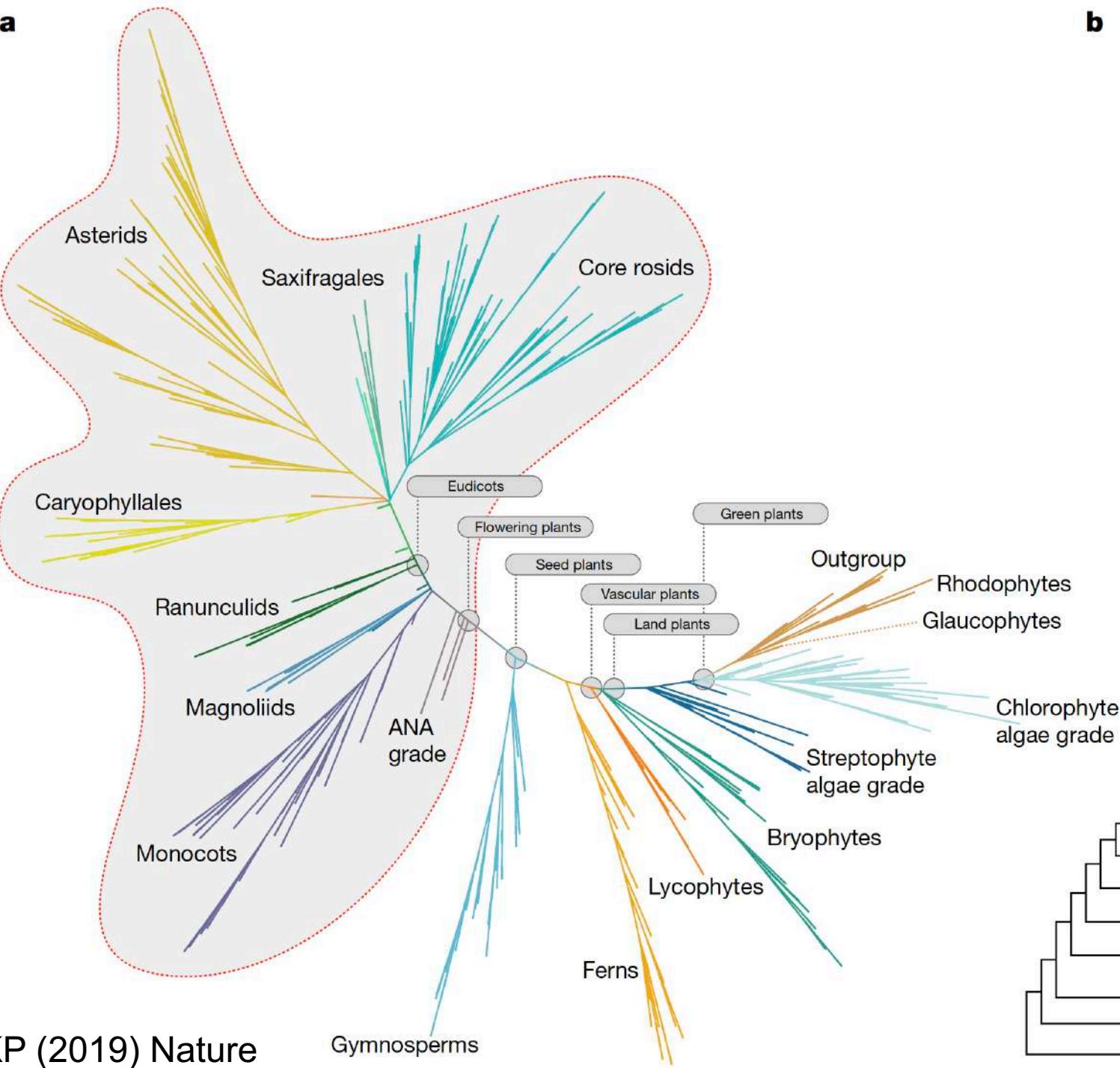
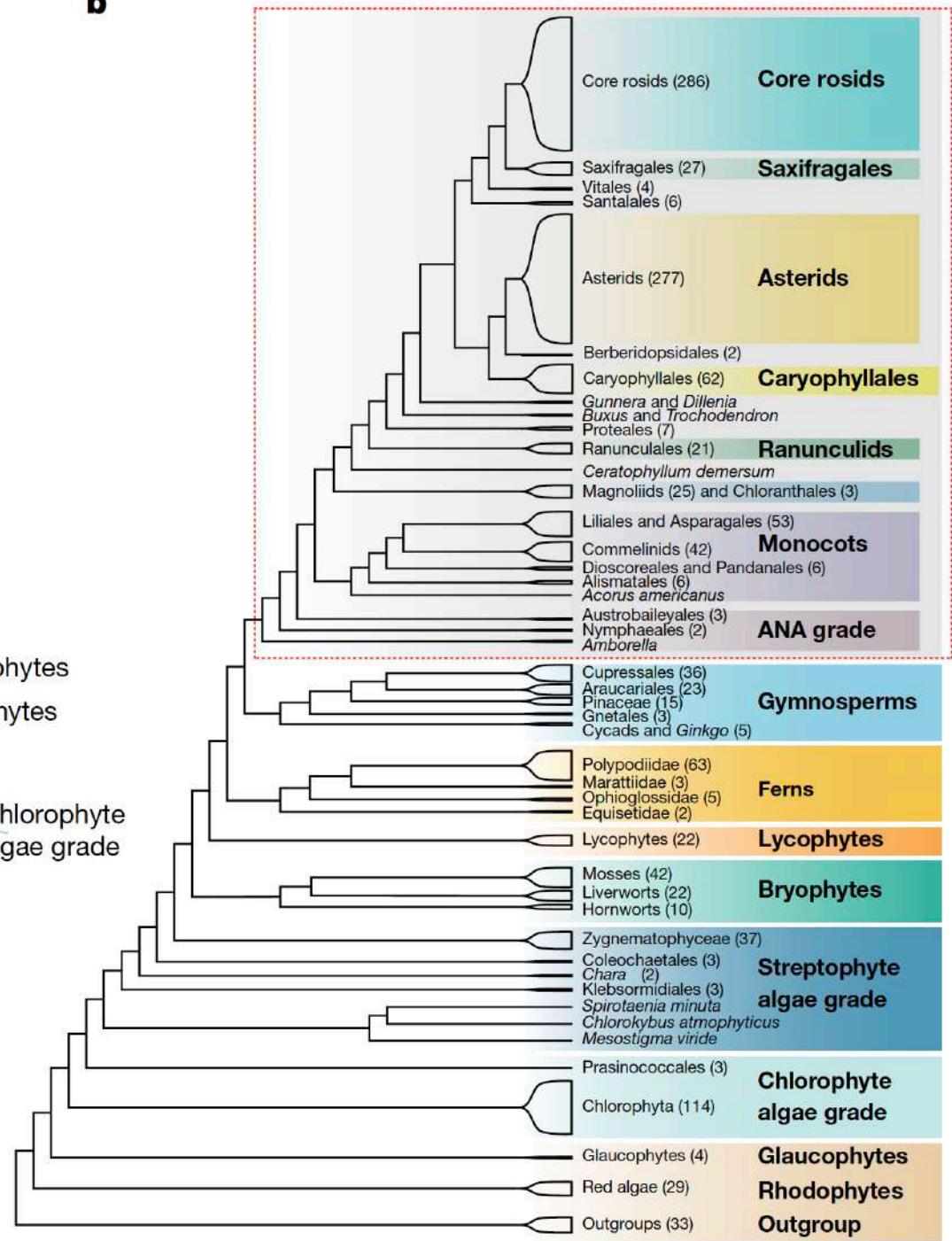


One thousand plant transcriptomes and the phylogenomics of green plants

<https://doi.org/10.1038/s41586-019-1693-2>

One Thousand Plant Transcriptomes Initiative

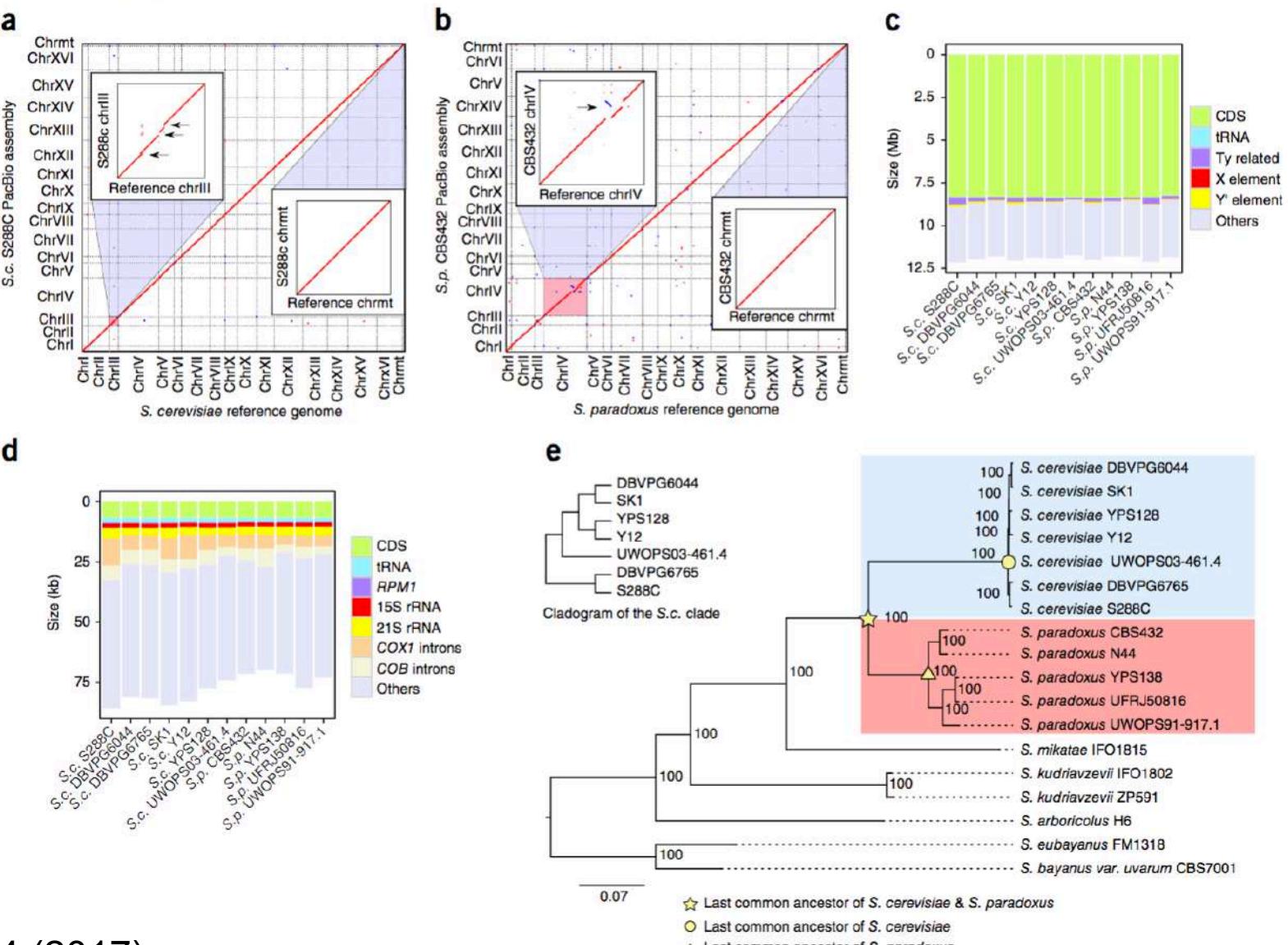
Green plants (*Viridiplantae*) include around 450,000–500,000 species^{1,2} of great diversity and have important roles in terrestrial and aquatic ecosystems. **Here, as part of the One Thousand Plant Transcriptomes Initiative, we sequenced the vegetative transcriptomes of 1,124 species that span the diversity of plants in a broad sense (Archaeplastida), including green plants (*Viridiplantae*), glaucophytes (*Glaucophyta*) and red algae (*Rhodophyta*).** Our analysis provides a robust phylogenomic framework for examining the evolution of green plants. Most inferred species relationships are well supported across multiple species tree and supermatrix analyses, but discordance among plastid and nuclear gene trees at a few important nodes highlights the complexity of plant genome evolution, including polyploidy, periods of rapid speciation, and extinction. Incomplete sorting of ancestral variation, polyploidization and massive expansions of gene families punctuate the evolutionary history of green plants. Notably, we find that large expansions of gene families preceded the origins of green plants, land plants and vascular plants, whereas whole-genome duplications are inferred to have occurred repeatedly throughout the evolution of flowering plants and ferns. The increasing availability of high-quality plant genome sequences and advances in functional genomics are enabling research on genome evolution across the green tree of life.

a**b**

Contrasting evolutionary genome dynamics between domesticated and wild yeasts

Jia-Xing Yue¹, Jing Li¹, Louise Aigrain², Johan Hallin¹, Karl Persson³, Karen Oliver², Anders Bergström², Paul Coupland^{2,5}, Jonas Warringer³, Marco Cosentino Lagomarsino⁴, Gilles Fischer⁴, Richard Durbin² & Gianni Liti¹

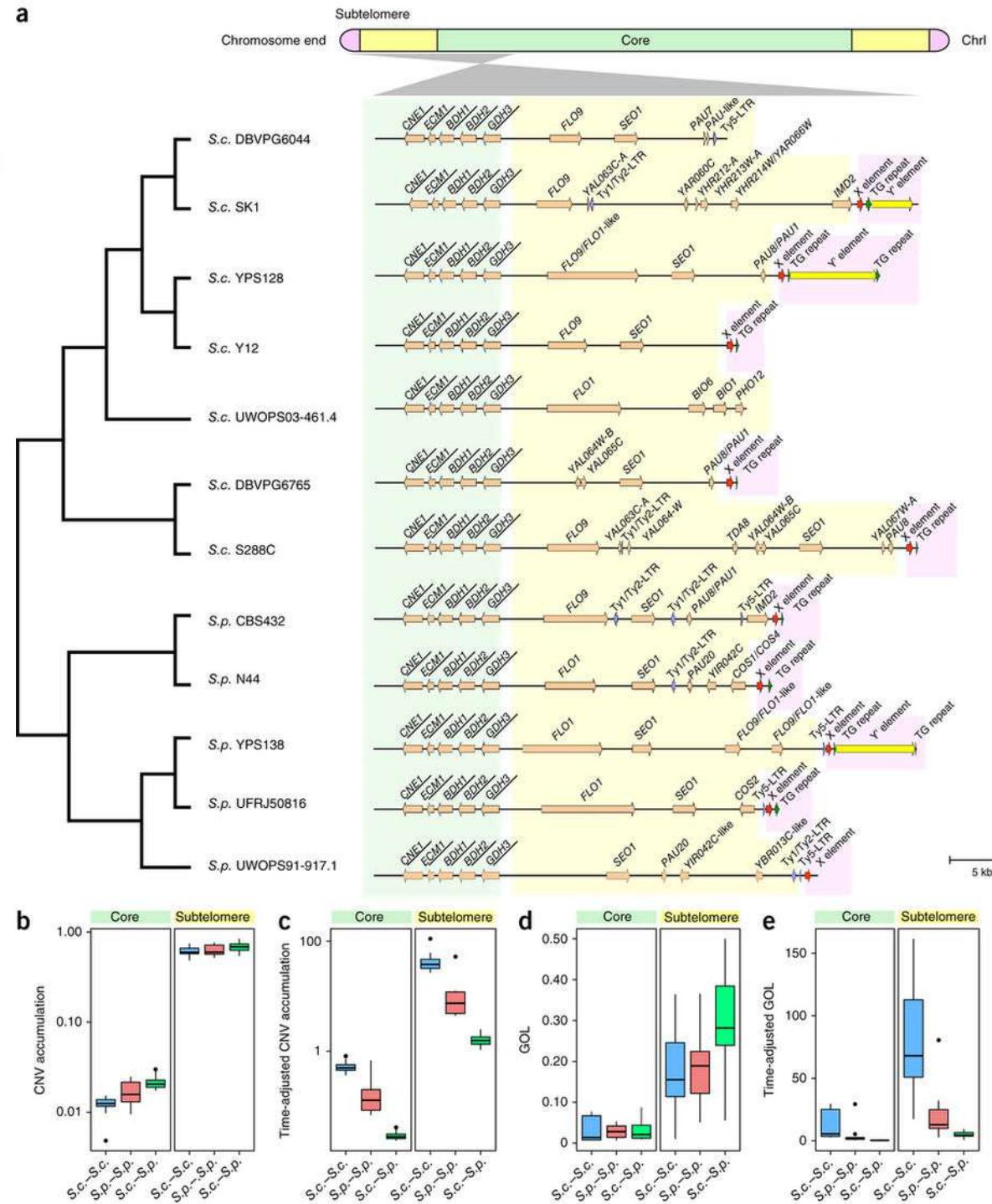
- long-read sequencing to generate **end-to-end genome assemblies** for **12 strains** representing major subpopulations of the partially domesticated yeast *Saccharomyces cerevisiae* and its wild relative *S. paradoxus*.



Contrasting evolutionary genome dynamics between domesticated and wild yeasts

Jia-Xing Yue¹ , Jing Li¹, Louise Aigrain², Johan Hallin¹ , Karl Persson³ , Karen Oliver², Anders Bergström², Paul Coupland^{2,5}, Jonas Warringer³ , Marco Cosentino Lagomarsino⁴, Gilles Fischer⁴, Richard Durbin² & Gianni Liti¹

- enable precise definition of chromosomal boundaries between cores and subtelomeres
- S. paradoxus* shows faster accumulation of balanced rearrangements (inversions, reciprocal translocations and transpositions), *S. cerevisiae* accumulates unbalanced rearrangements (novel insertions, deletions and duplications) more rapidly.
- Such striking contrasts between wild and domesticated yeasts are likely to reflect the influence of human activities on structural genome evolution.

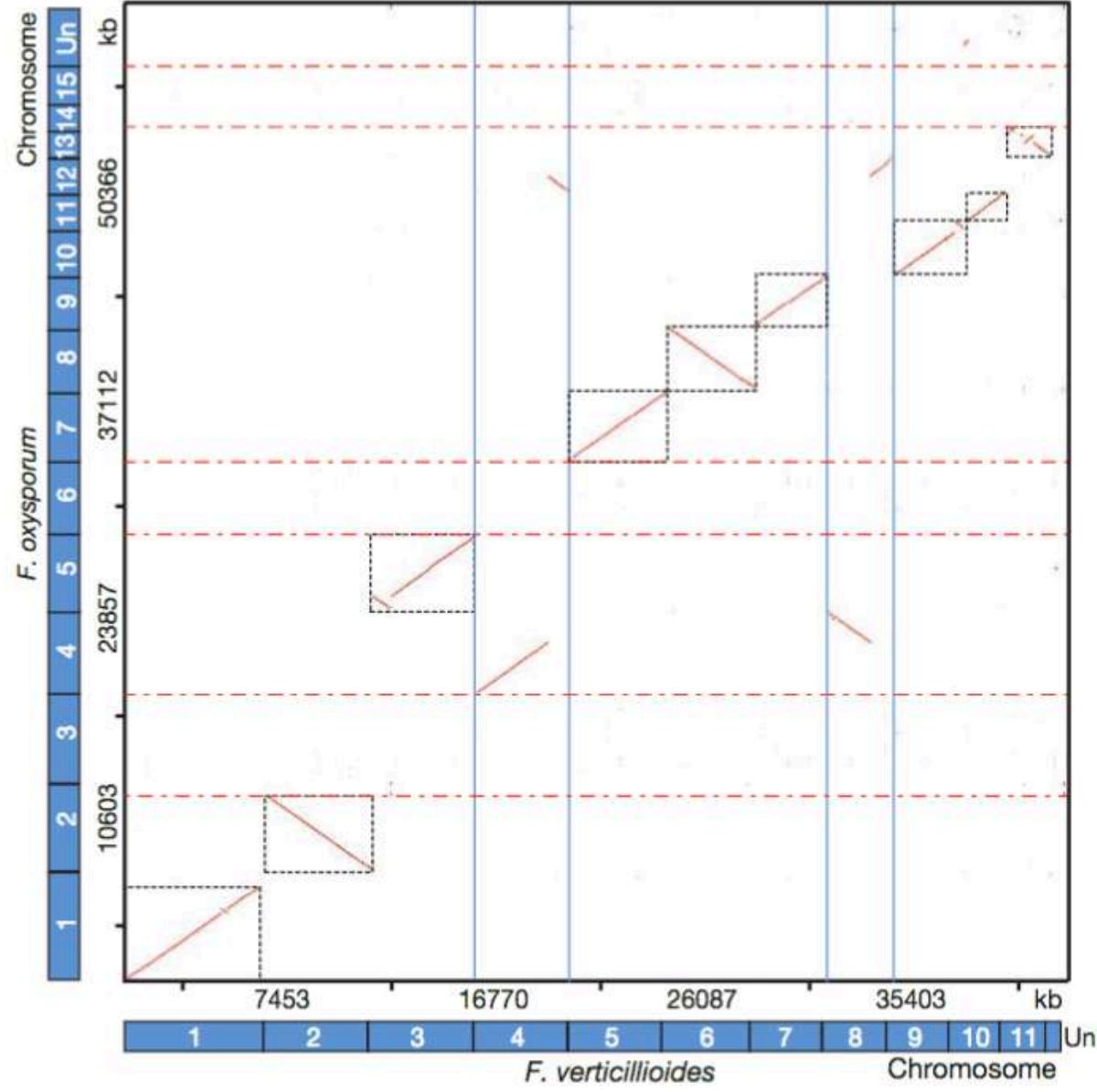
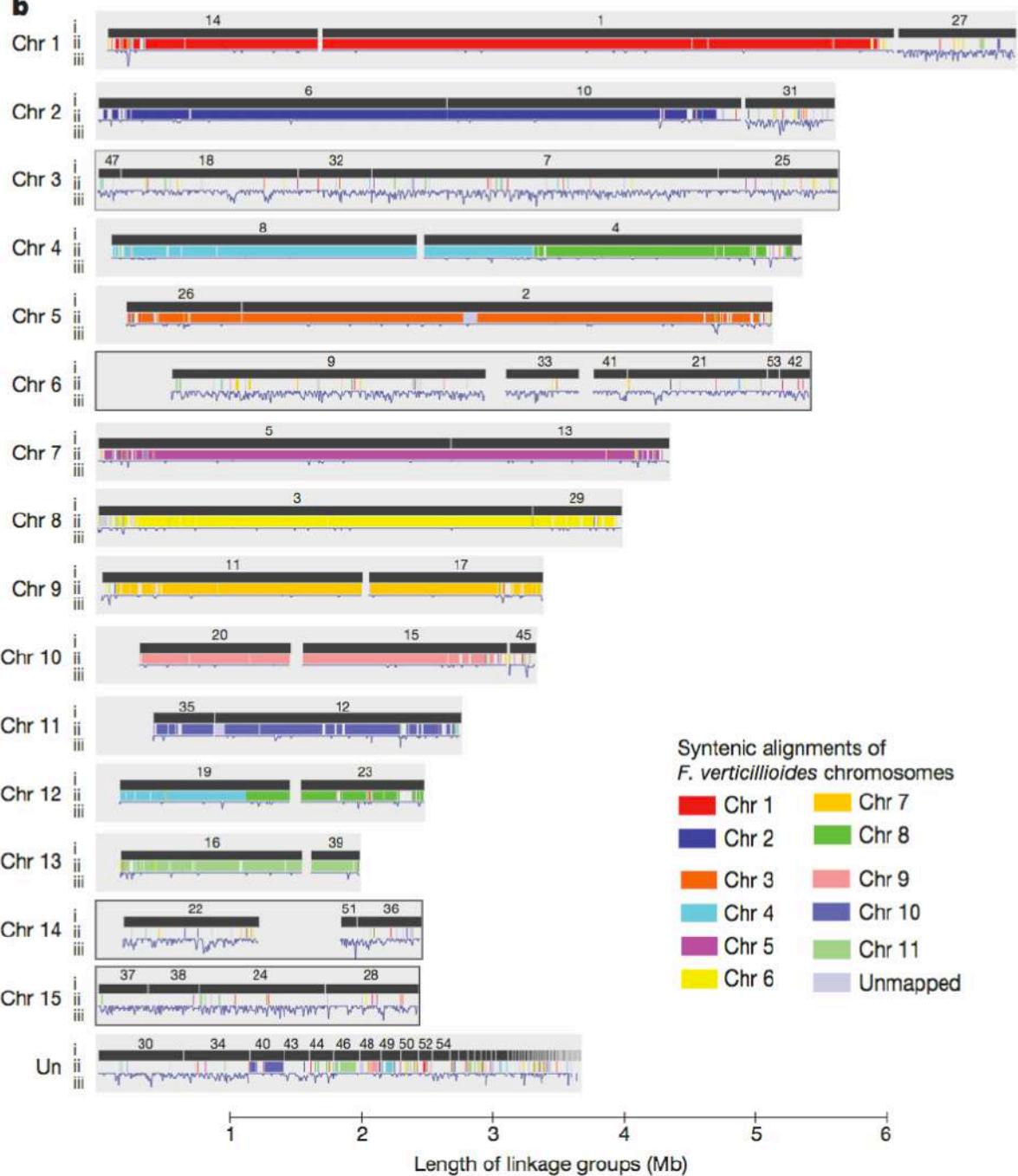


ARTICLES

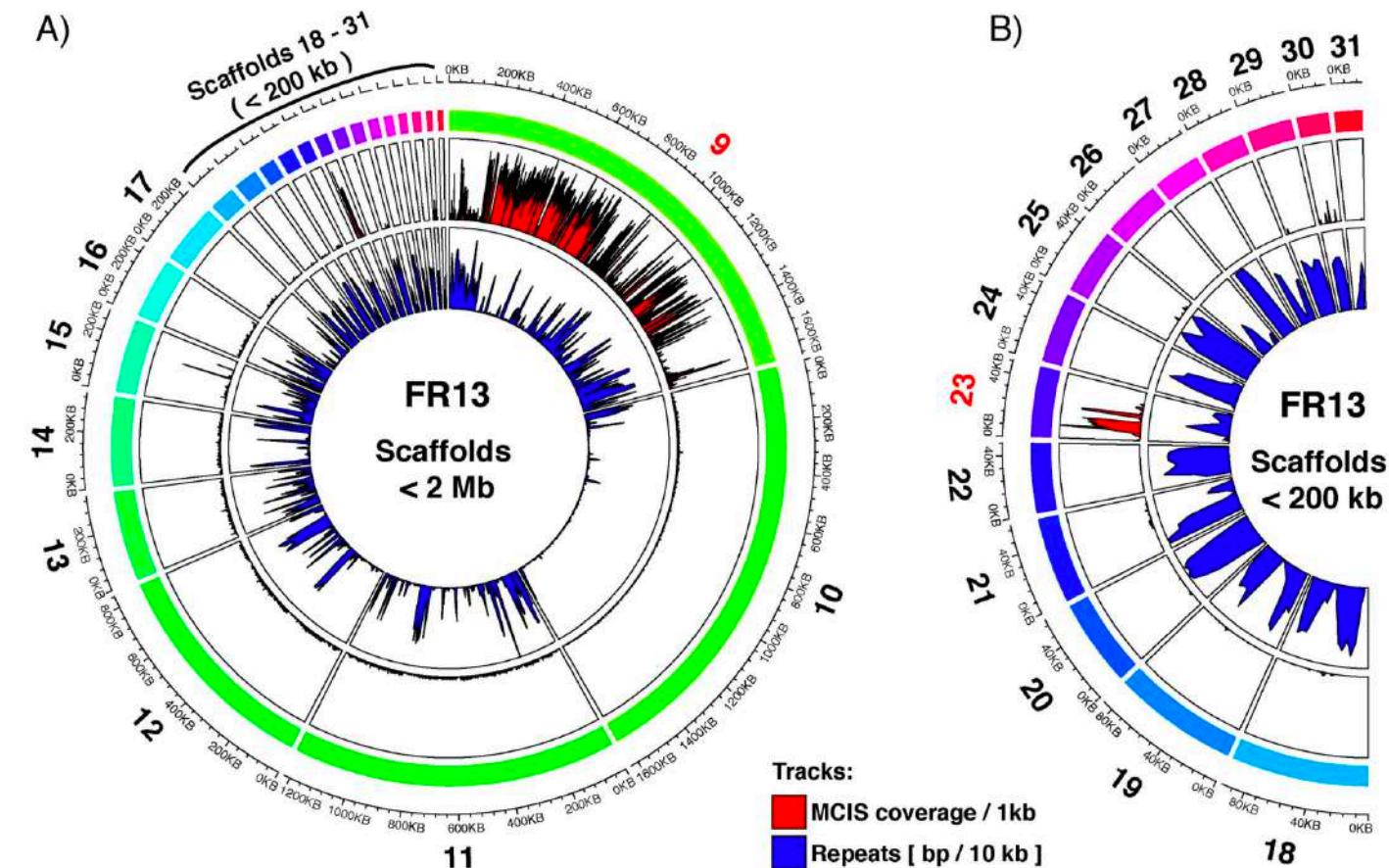
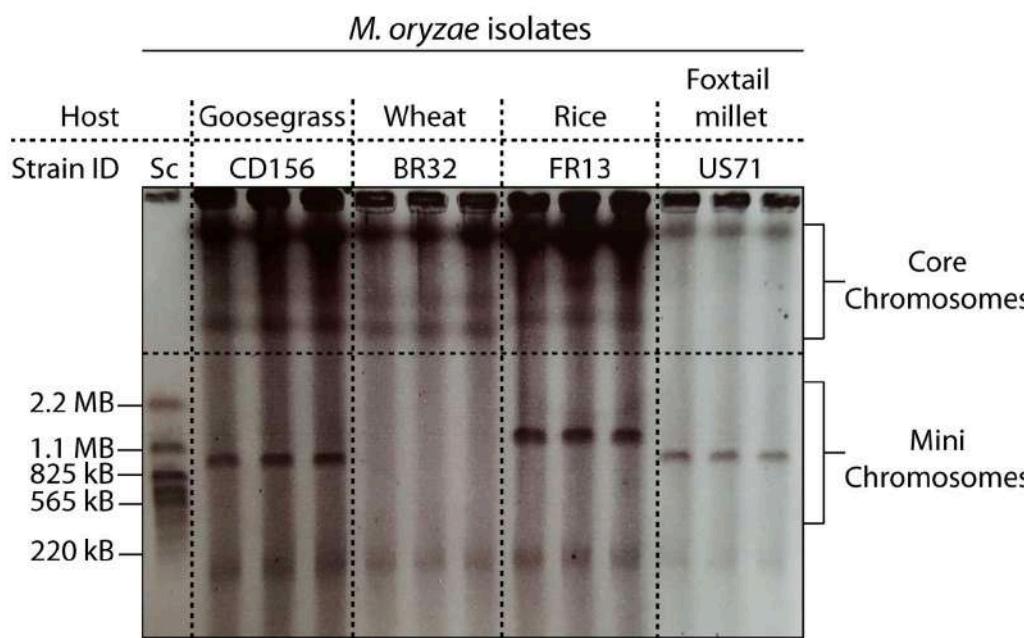
Comparative genomics reveals mobile pathogenicity chromosomes in *Fusarium*

Li-Jun Ma^{1*}, H. Charlotte van der Does^{2*}, Katherine A. Borkovich³, Jeffrey J. Coleman⁴, Marie-Josée Daboussi⁵, Antonio Di Pietro⁶, Marie Dufresne⁵, Michael Freitag⁷, Manfred Grabherr¹, Bernard Henrissat⁸, Petra M. Houterman², Seogchan Kang⁹, Won-Bo Shim¹⁰, Charles Woloshuk¹¹, Xiaohui Xie¹², Jin-Rong Xu¹¹, John Antoniw¹³, Scott E. Baker¹⁴, Burton H. Bluhm¹¹, Andrew Breakspear¹⁵, Daren W. Brown¹⁶, Robert A. E. Butchko¹⁶, Sinead Chapman¹, Richard Coulson¹⁷, Pedro M. Coutinho⁸, Etienne G. J. Danchin^{8†}, Andrew Diener¹⁸, Liane R. Gale¹⁵, Donald M. Gardiner¹⁹, Stephen Goff²⁰, Kim E. Hammond-Kosack¹³, Karen Hilburn¹⁵, Aurélie Hua-Van⁵, Wilfried Jonkers², Kemal Kazan¹⁹, Chinnappa D. Kodira^{1†}, Michael Koehrsen¹, Lokesh Kumar¹, Yong-Hwan Lee²¹, Liande Li³, John M. Manners¹⁹, Diego Miranda-Saavedra²², Mala Mukherjee¹⁰, Gyungsoon Park³, Jongsun Park²¹, Sook-Young Park^{9†}, Robert H. Proctor¹⁶, Aviv Regev¹, M. Carmen Ruiz-Roldan⁶, Divya Sain³, Sharadha Sakthikumar¹, Sean Sykes¹, David C. Schwartz²³, B. Gillian Turgeon²⁴, Ilan Wapinski¹, Olen Yoder²⁵, Sarah Young¹, Qiandong Zeng¹, Shiguo Zhou²³, James Galagan¹, Christina A. Cuomo¹, H. Corby Kistler¹⁵ & Martijn Rep²

Our analysis revealed lineage-specific (LS) genomic regions in *F. oxysporum* that include four entire chromosomes and account for more than one-quarter of the genome. LS regions are rich in transposons and genes with distinct evolutionary profiles but related to pathogenicity, indicative of horizontal acquisition. Experimentally, we demonstrate the transfer of two LS chromosomes between strains of *F. oxysporum*, converting a non-pathogenic strain into a pathogen.

a**b**

Genomic rearrangements generate hypervariable mini-chromosomes in host-specific isolates of the blast fungus



Reversal of an ancient sex chromosome to an autosome in *Drosophila*

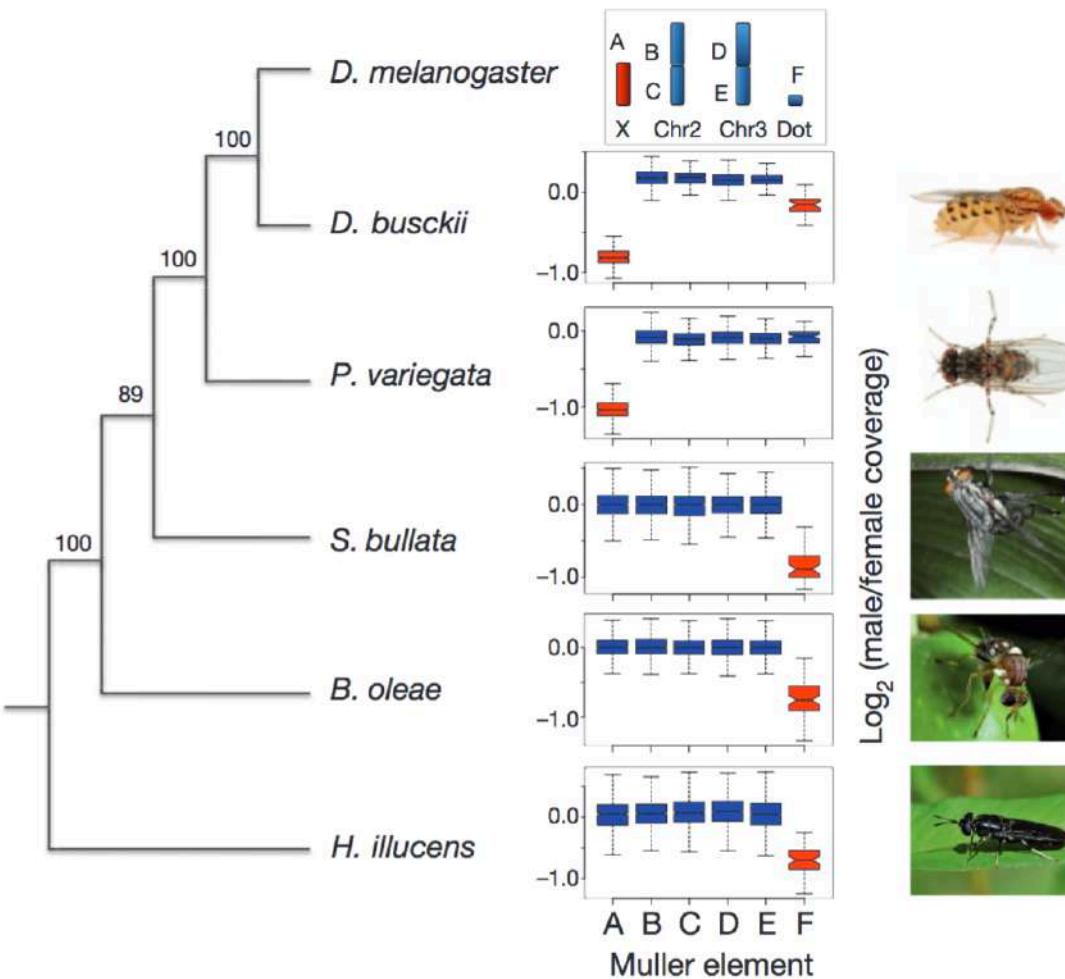
Beatriz Vicoso¹ & Doris Bachtrog¹

Figure 1 | Sex chromosomes in higher Diptera revealed by genome analysis. Evolutionary relationship inferred from 185 conserved protein-coding genes (93,134 amino acids) using PhyML (with bootstrap values indicated at the nodes), and male-to-female coverage ratio across chromosome elements (Muller elements A–F) in the Diptera species studied. X chromosomes (red) have only half the read coverage in males versus females. Boxes extend from the first to the third quartile and whiskers to the most extreme data point within 1.5 times the interquartile range.

Why comparative genomics? – A summary

- Duplication (genes, chromosomes, whole genomes)
- Conservation
- Specificity
- Inferring Paralogs, orthologs
- Families (clusters) of paralogs, of orthologs
- Gene Transfer, introgression between species
- Origin of genes

**How genome evolved;
How genome functions**

Why comparative genomics? – A summary

Compare multiple genomes now a norm

Similarity and differences between genomes

Use genomes to study evolution of these species:

- At various resolution (whole genome, chromosomes, regions, genes, base pairs)
- Identify the genomic basis of key phenotypes

Reference

<https://www.notion.so/References-papers-links-in-start-learning-genomics-b7e57b28e9194bb29a02f483e0b894ad>