Statistical models on phylogenetic networks

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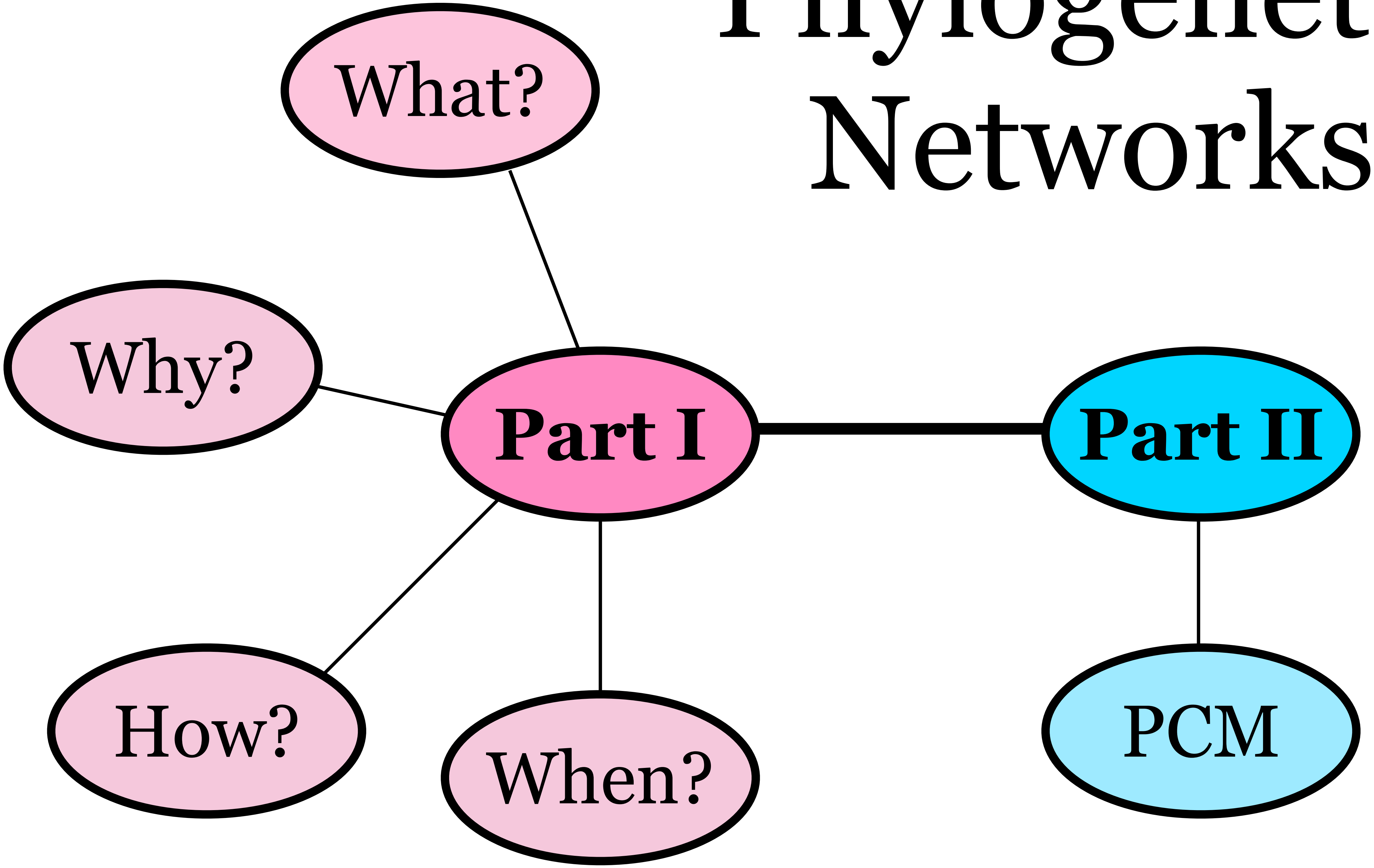
https://solislemuslab.github.io/ @solislemuslab crsl4 @thestatistician

Phylogenetic Networks



What?

Why?

Part I

Part II

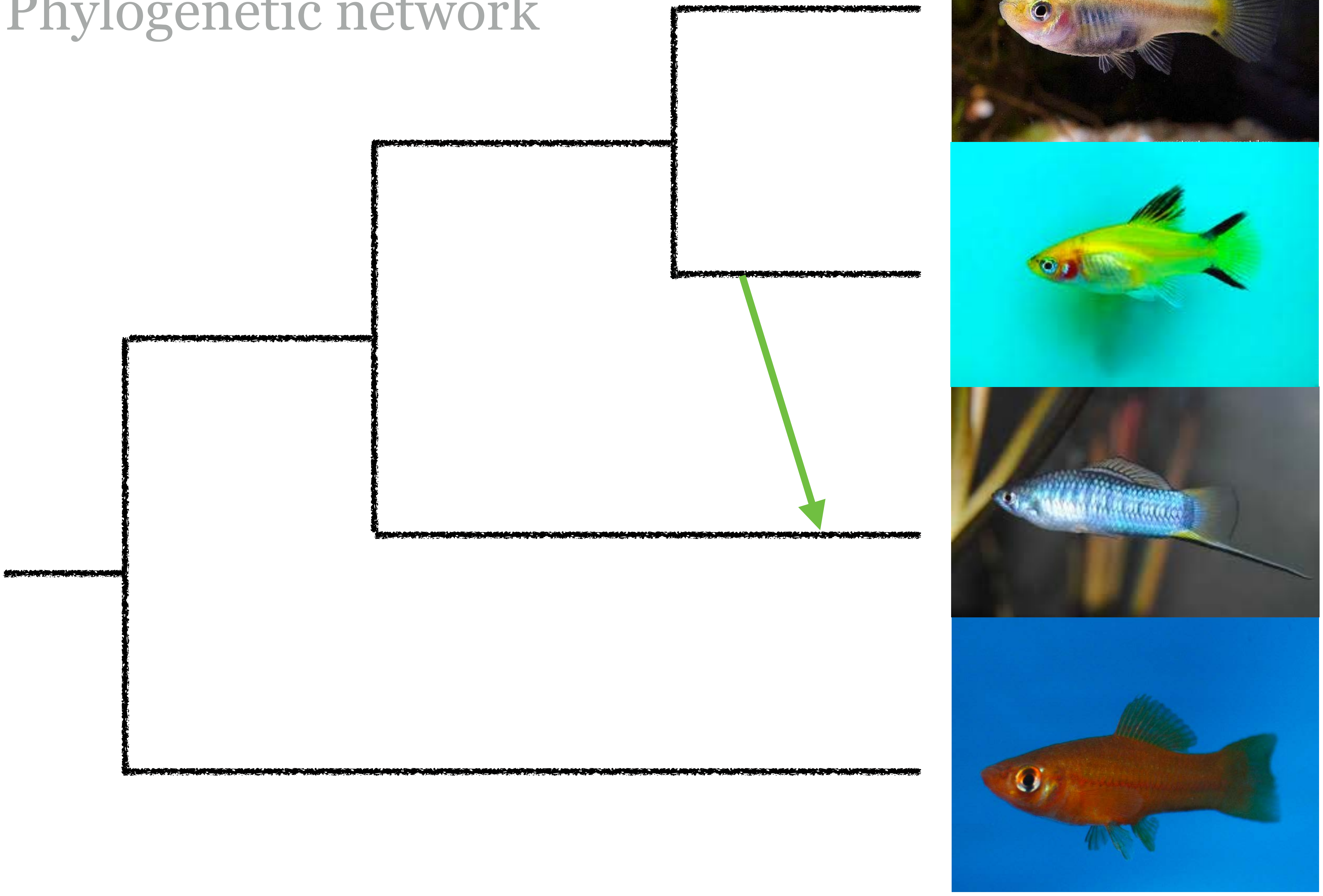
How?

When?

PCM

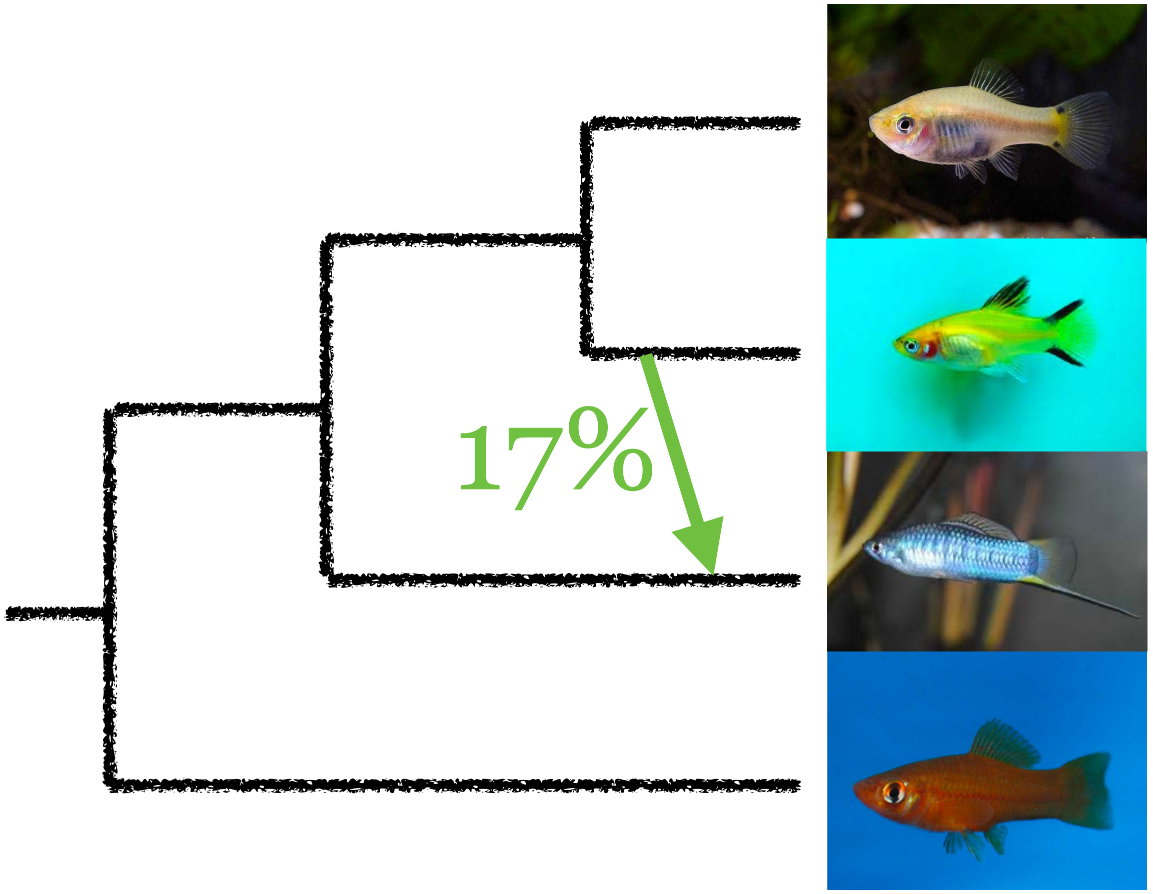
What?

Phylogenetic network

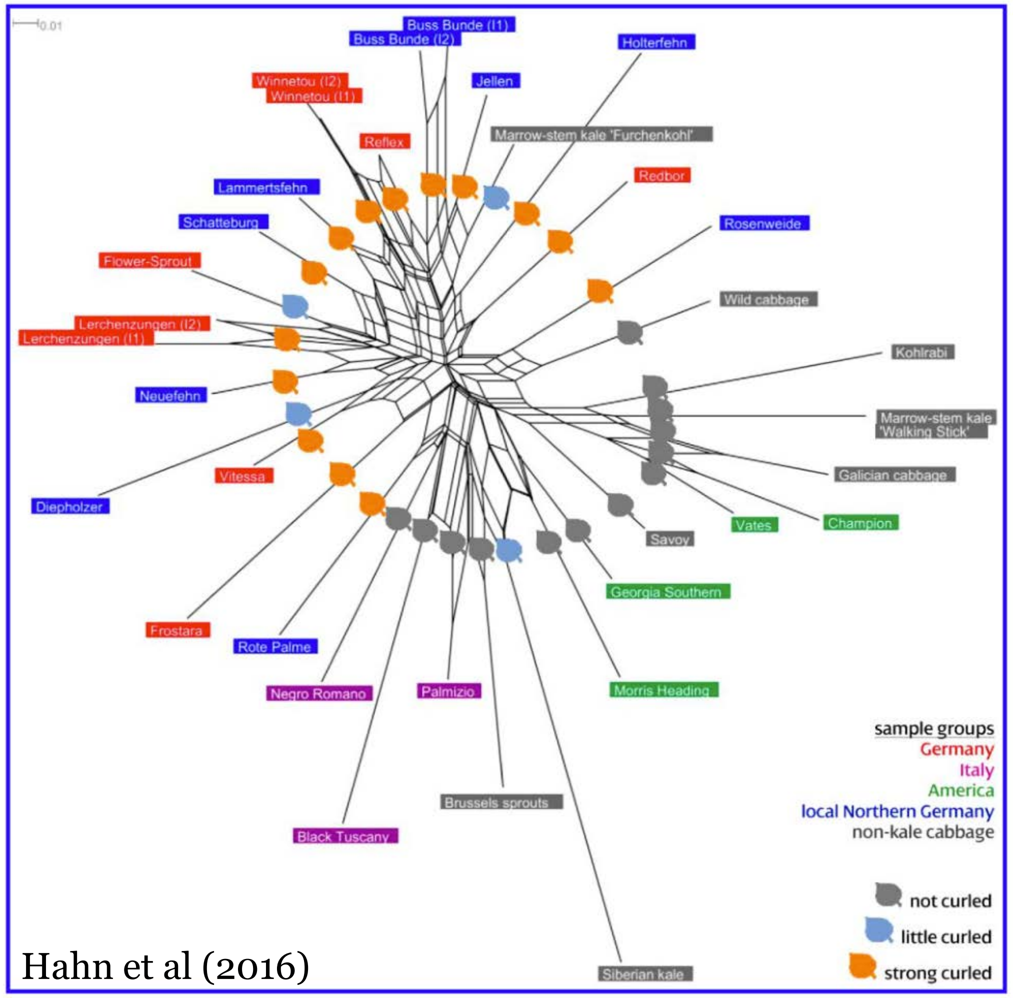


What?

Phylogenetic network



Explicit

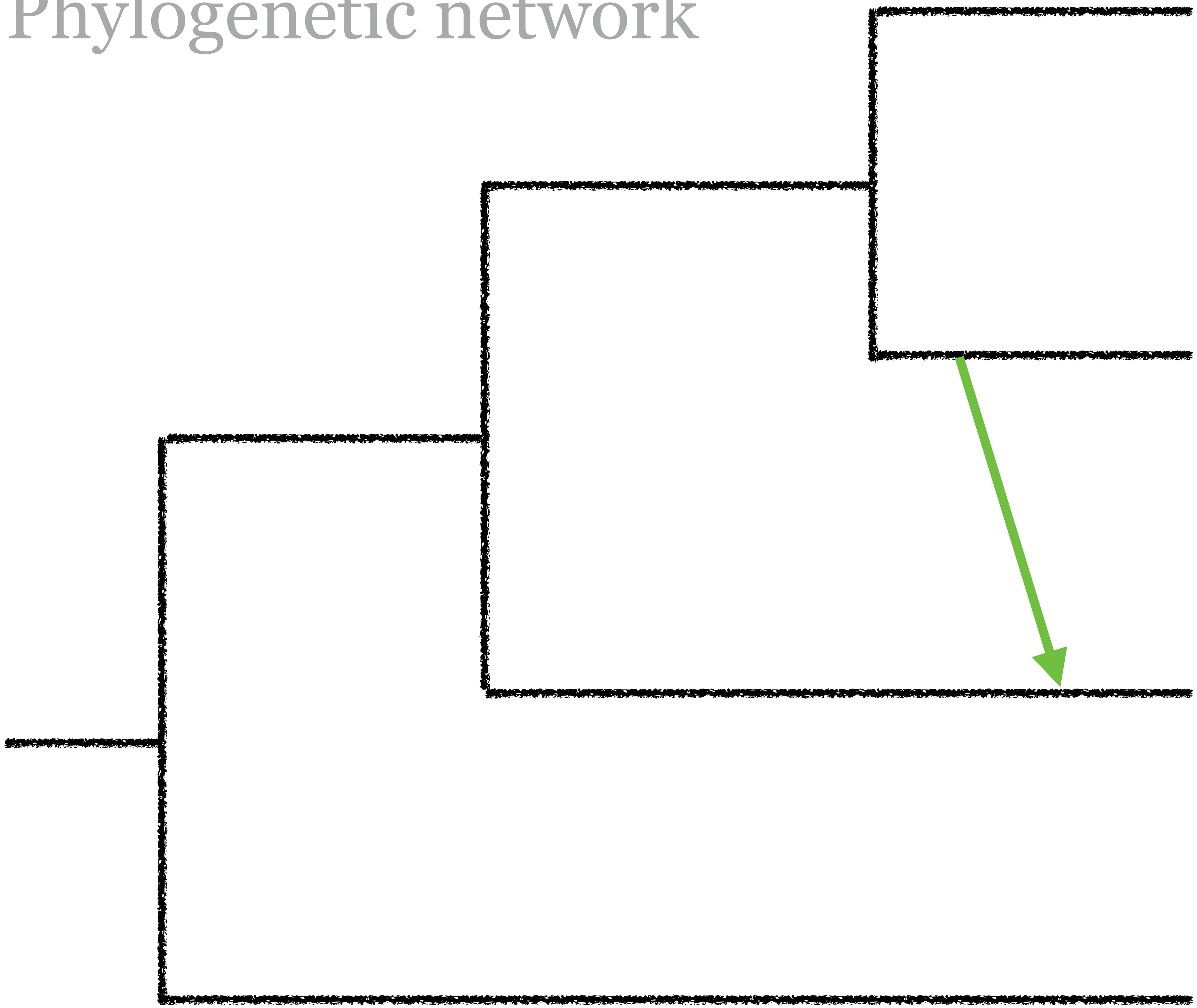


Hahn et al (2016)

Implicit

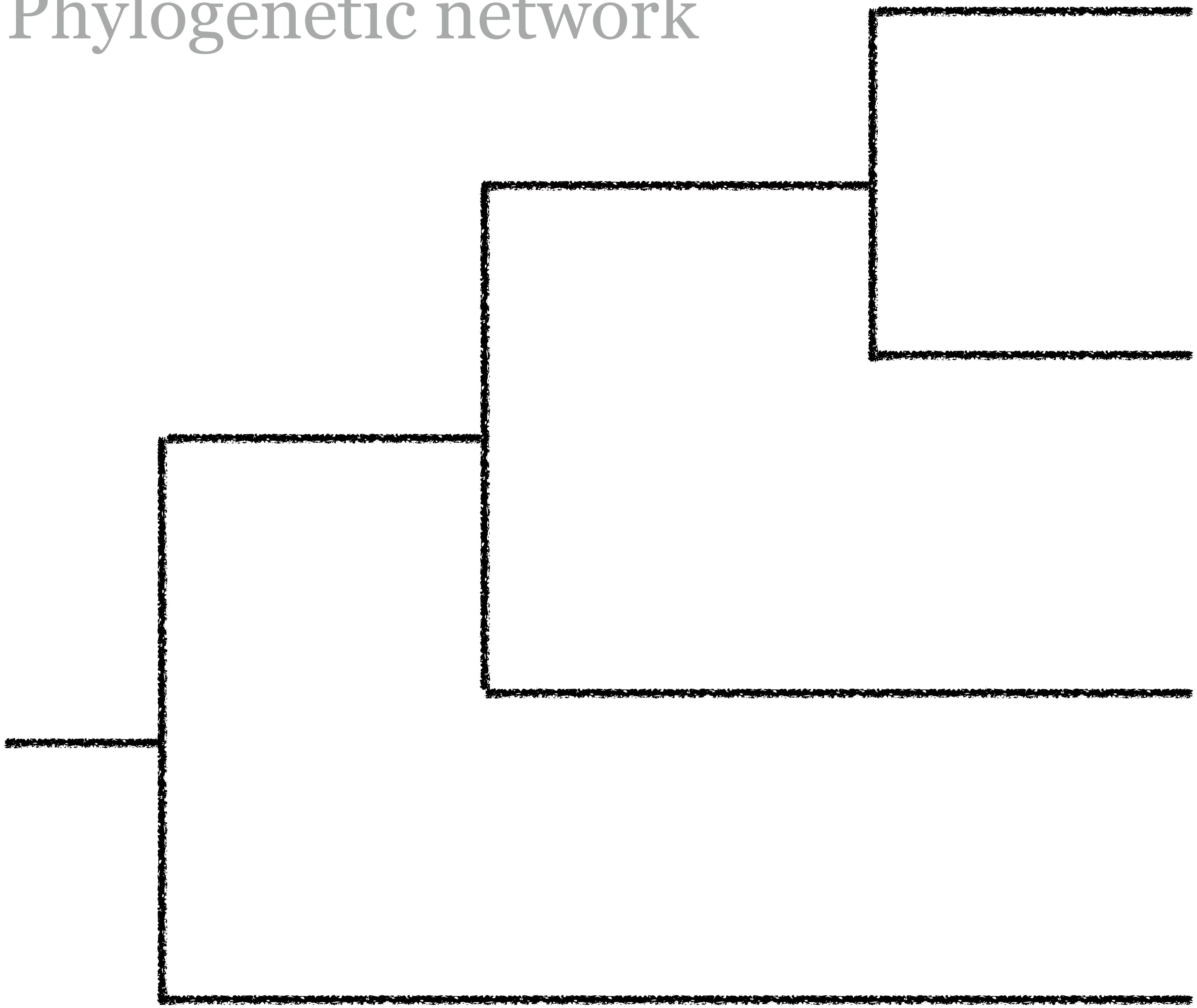
Why?

Phylogenetic network



Why?

Phylogenetic network

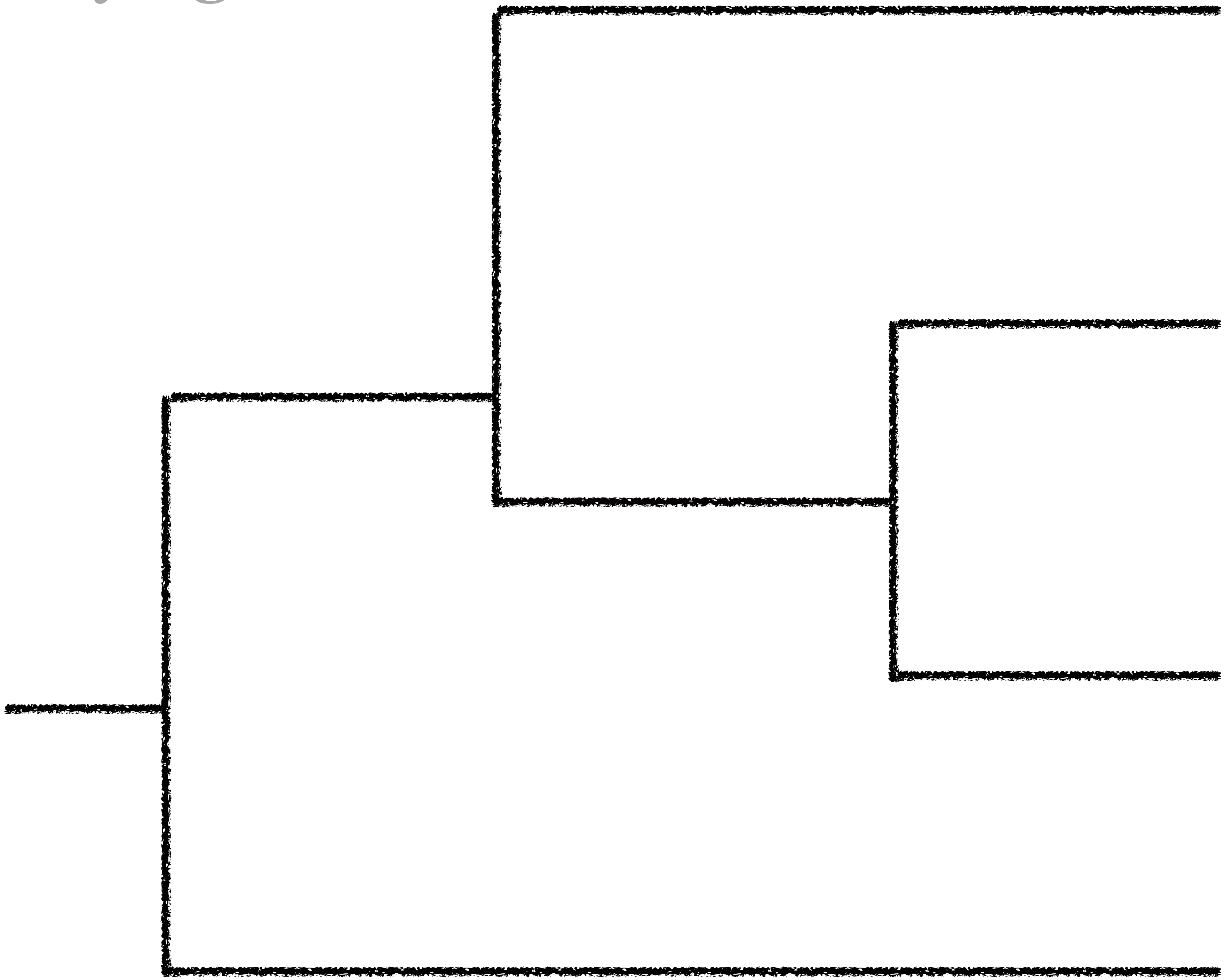


Main tree

Why?

Phylogenetic network

Ignore gene flow
=>Wrong tree!

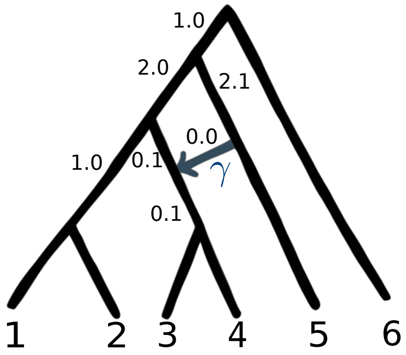


(S.-L., Yang, Ané, 2016, Syst Bio)

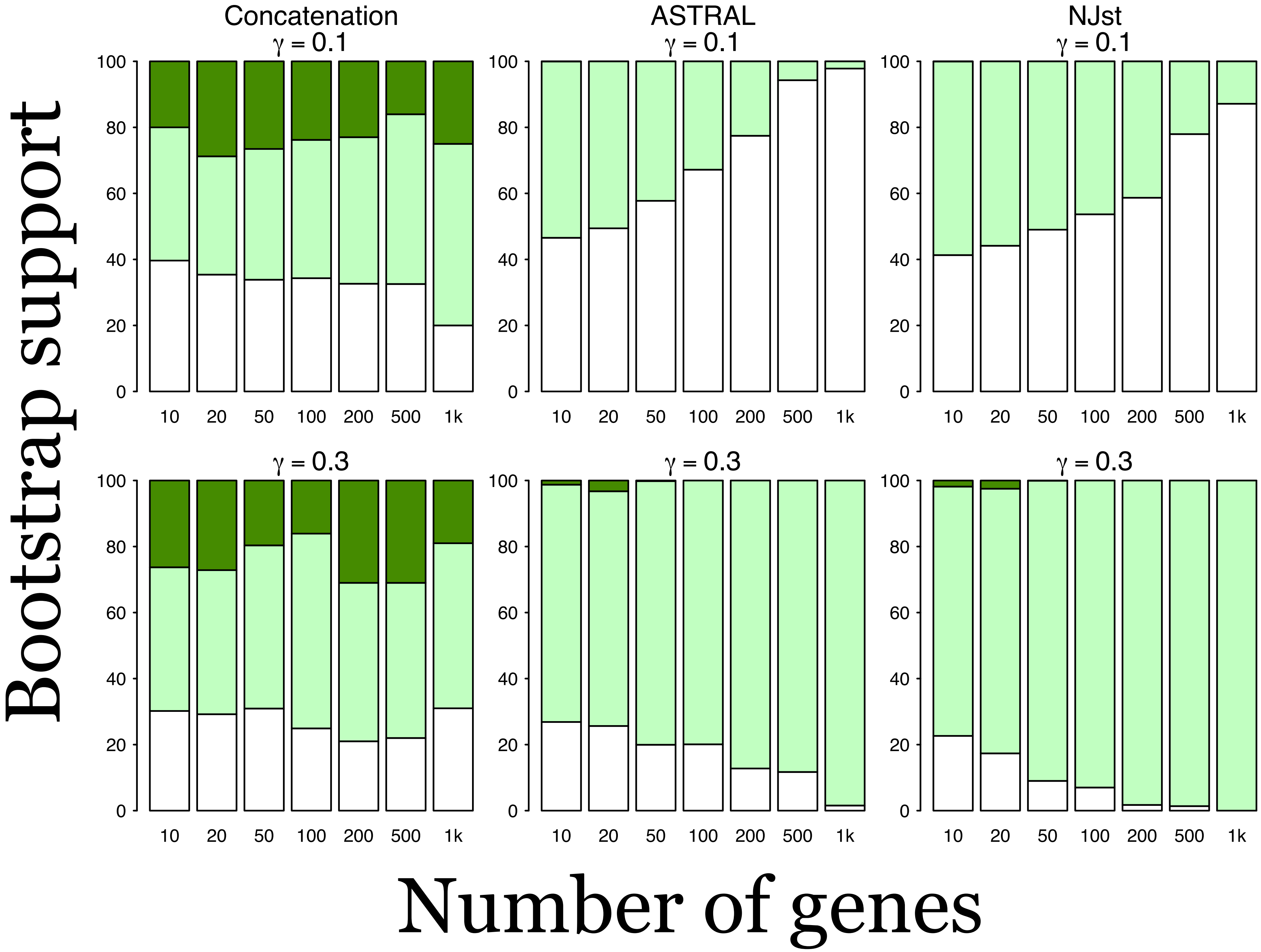
Why?

Phylogenetic network

Coalescent tree methods not robust to gene flow



White: true tree



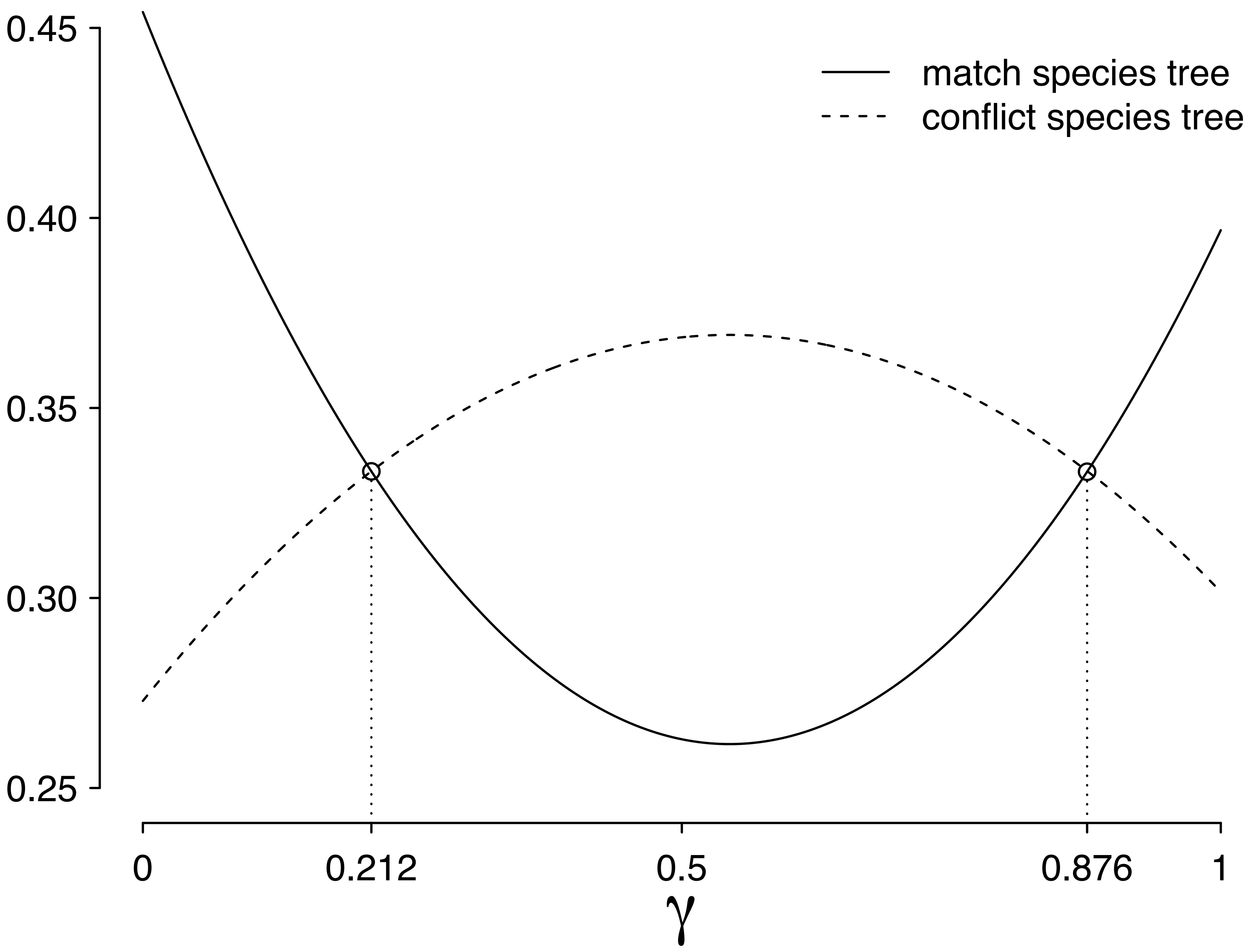
(S.-L., Yang, Ané, 2016, Syst Bio)

ASTRAL (Mirarab et al, 2014)
NJst (Liu&Yu,2011)

Why?

Phylogenetic network

Anomaly zone with gene flow

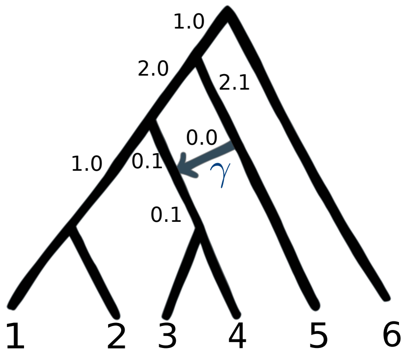


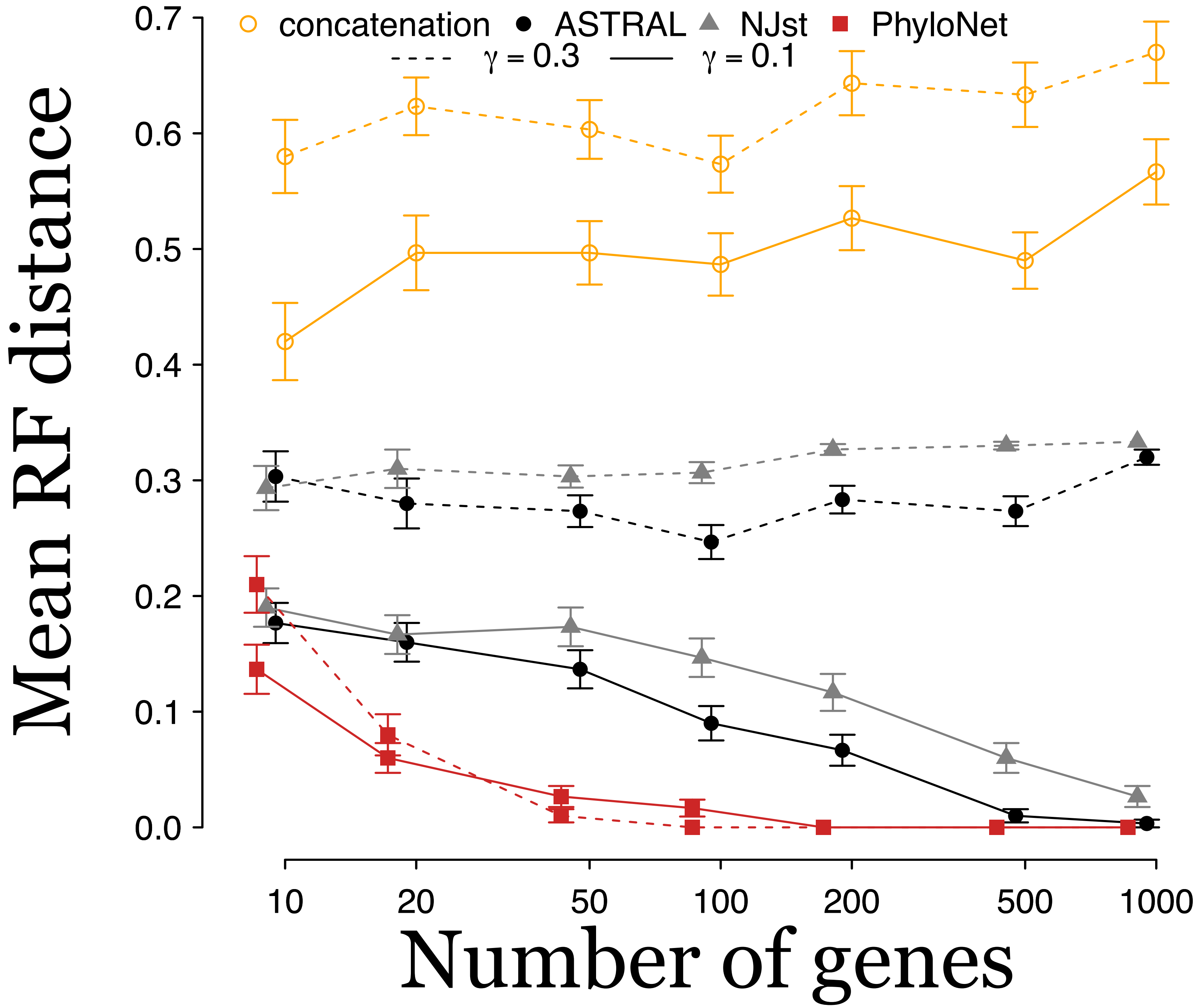
(S.-L., Yang, Ané, 2016, Syst Bio)

Why?

Phylogenetic network

Coalescent tree methods not robust to gene flow





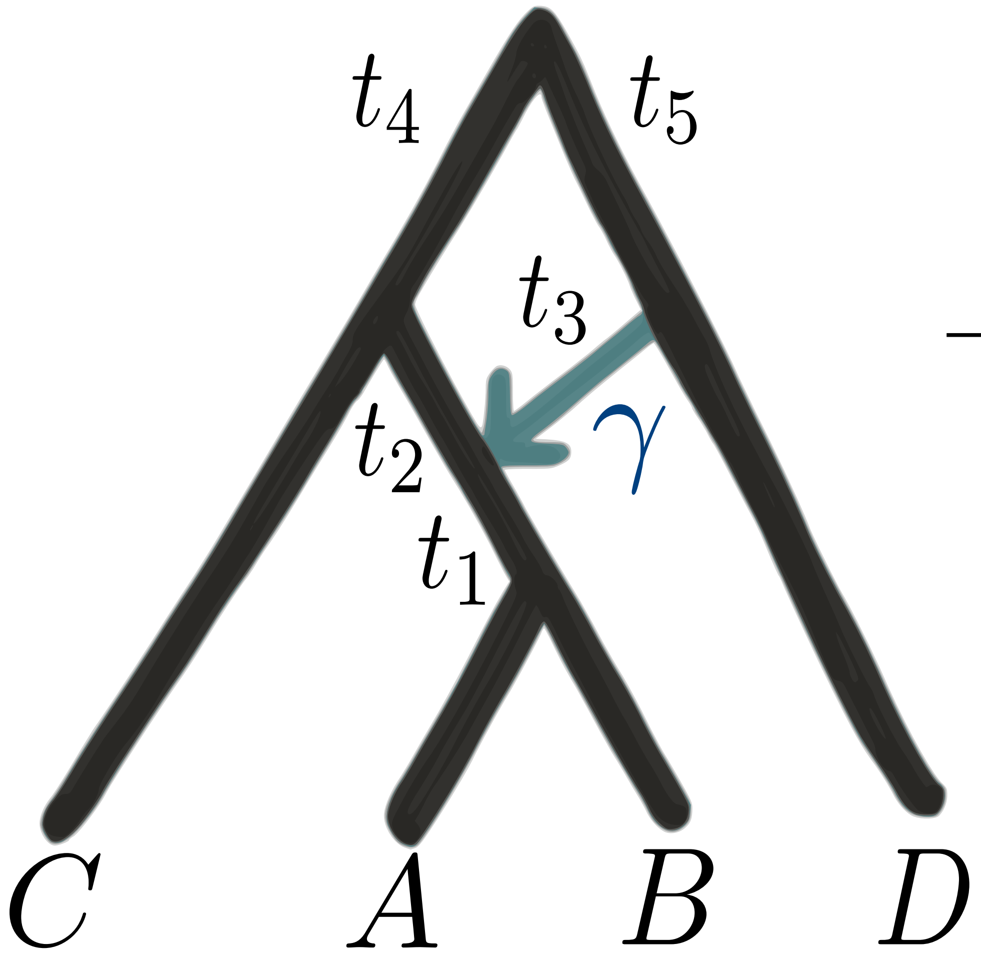
(S.-L., Yang, Ané, 2016, Syst Bio)

ASTRAL (Mirarab et al, 2014)
NJst (Liu&Yu,2011)
PhyloNet (Yu et al 2012, 2014)

Why?

Phylogenetic network

Anomalous unrooted gene trees with gene flow



Frequency among gene trees

Quartet	$\gamma = 0.0$	$\gamma = 0.1$	$\gamma = 0.3$
$AB\|CD$	**0.347**	**0.298**	**0.260**
$CA\|BD$	0.327	0.351	0.370
$CB\|AD$	0.327	0.351	0.370

$t_1 = t_2 = 0.01, t_3 = t_4 = t_5 = 1$

- **ILS**: no AUGT on 4 taxa (Degnan, 2013)
- **ILS**+**HGT**: AUGT on 4 taxa (S.-L., Yang, Ané, 2016, Syst Bio)

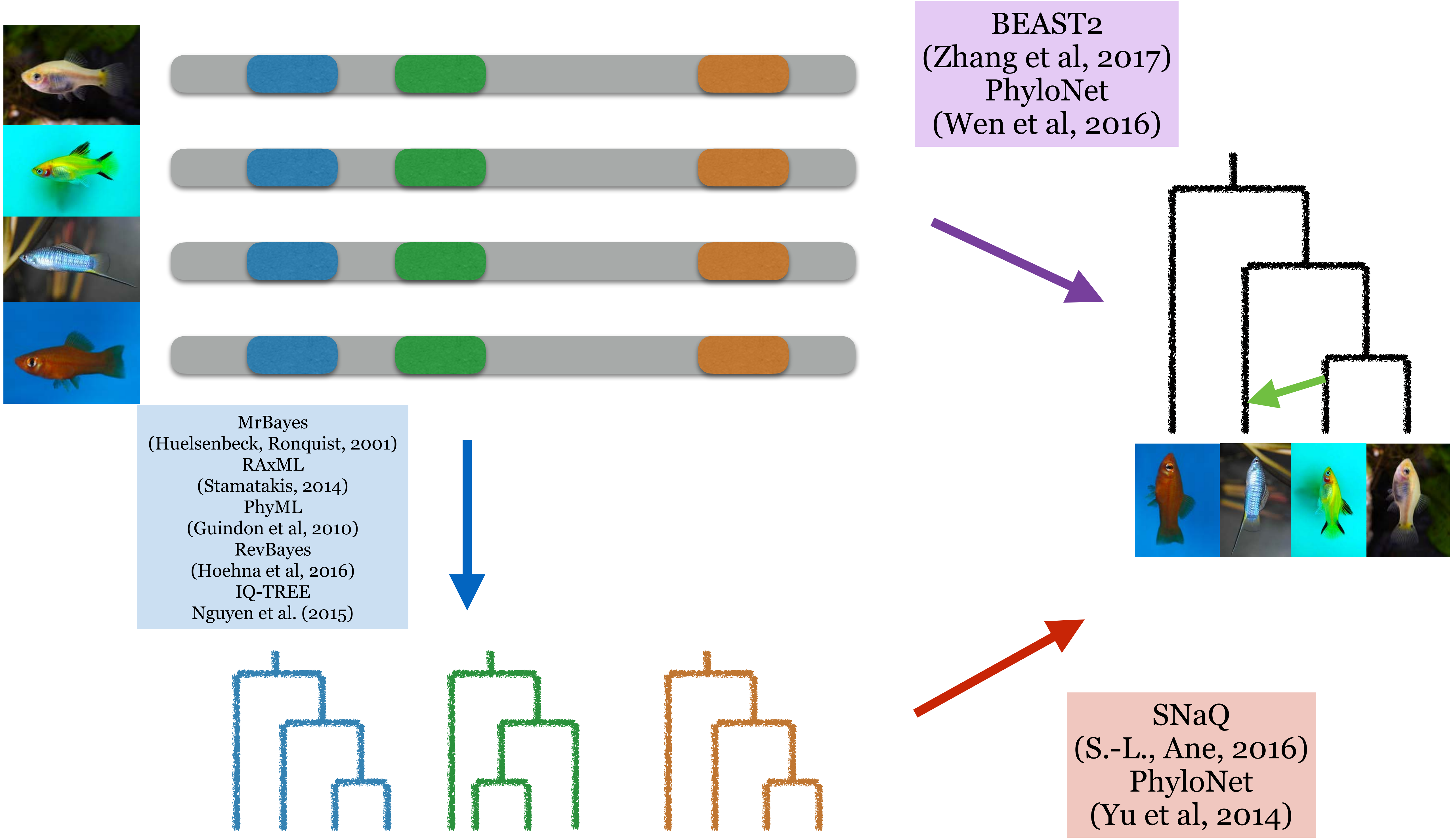
See also Long & Kubatko (2018) for AUGT under continuous gene flow between sister species

So far…

- Networks are good
- Explicit networks are better
- If you ignore gene flow, you can estimate the wrong tree

How?

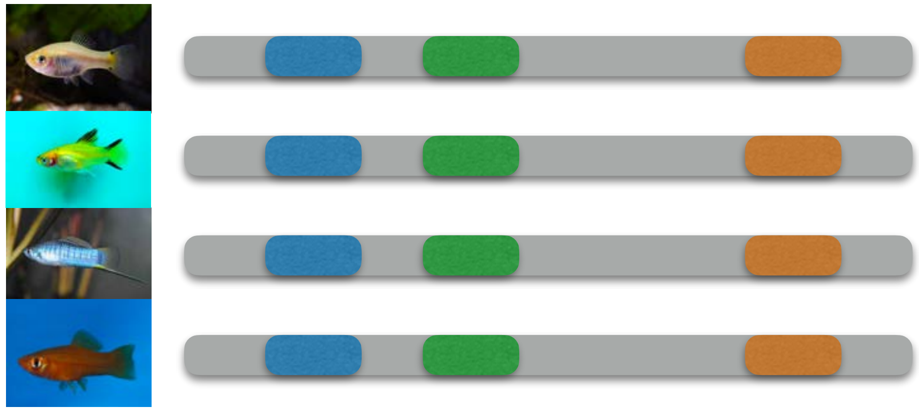
Phylogenetic network



BEAST2
(Zhang et al, 2017)
PhyloNet
(Wen et al, 2016)

MrBayes
(Huelsenbeck, Ronquist, 2001)
RAxML
(Stamatakis, 2014)
PhyML
(Guindon et al, 2010)
RevBayes
(Hoehna et al, 2016)
IQ-TREE
Nguyen et al. (2015)

SNaQ
(S.-L., Ane, 2016)
PhyloNet
(Yu et al, 2014)



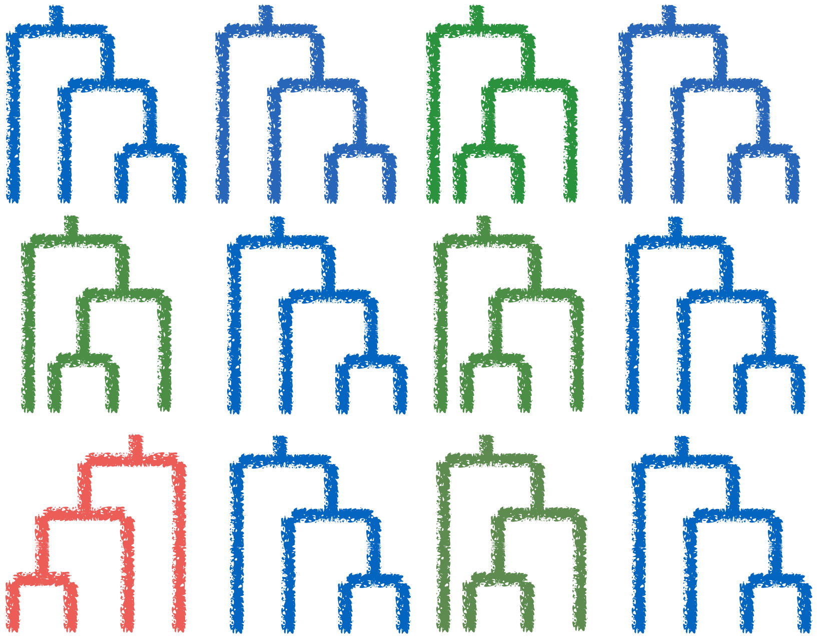
$$P(\overset{\text{network}}{N}, \underset{\text{gene trees}}{G}, \theta | \underset{\text{L loci}}{D}) \propto \underbrace{\pi(N)}_{\text{Prior Network}} \pi(\theta) \prod_{i=1}^{L} \underbrace{P(D_i|G_i)}_{\text{Substitution Model}} \underbrace{P(G_i|N)}_{\text{Multispecies Coalescent}}$$

Birth-hybridization process

BEAST2
(Zhang et al, 2017)

# reticulations, cycle diameter

PhyloNet Bayesian
(Wen et al, 2016)

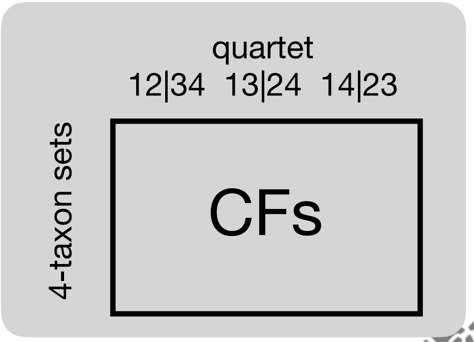


$$P(N, \theta | G) \propto \pi(N) \pi(\theta) \prod_{i=1}^{L} P(G_i | N, \theta)$$

PhyloNet Bayesian
(Wen et al, 2016)

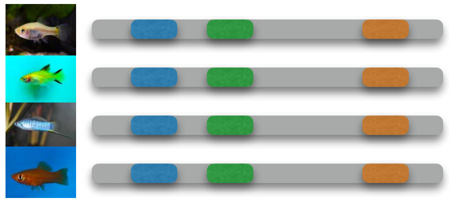
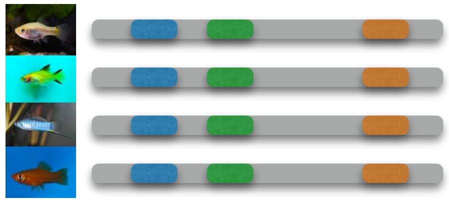
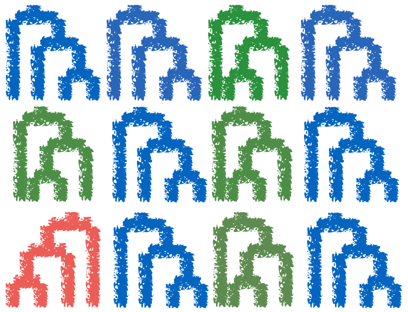
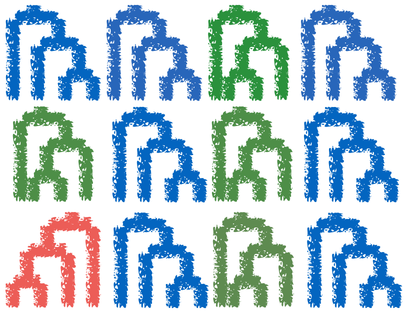
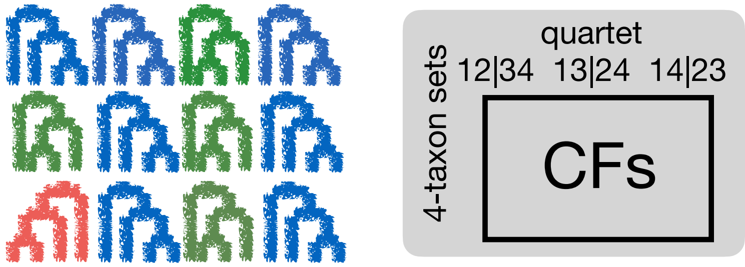
$$L(N, \theta) = \prod_{i=1}^{L} P(G_i | N, \theta)$$

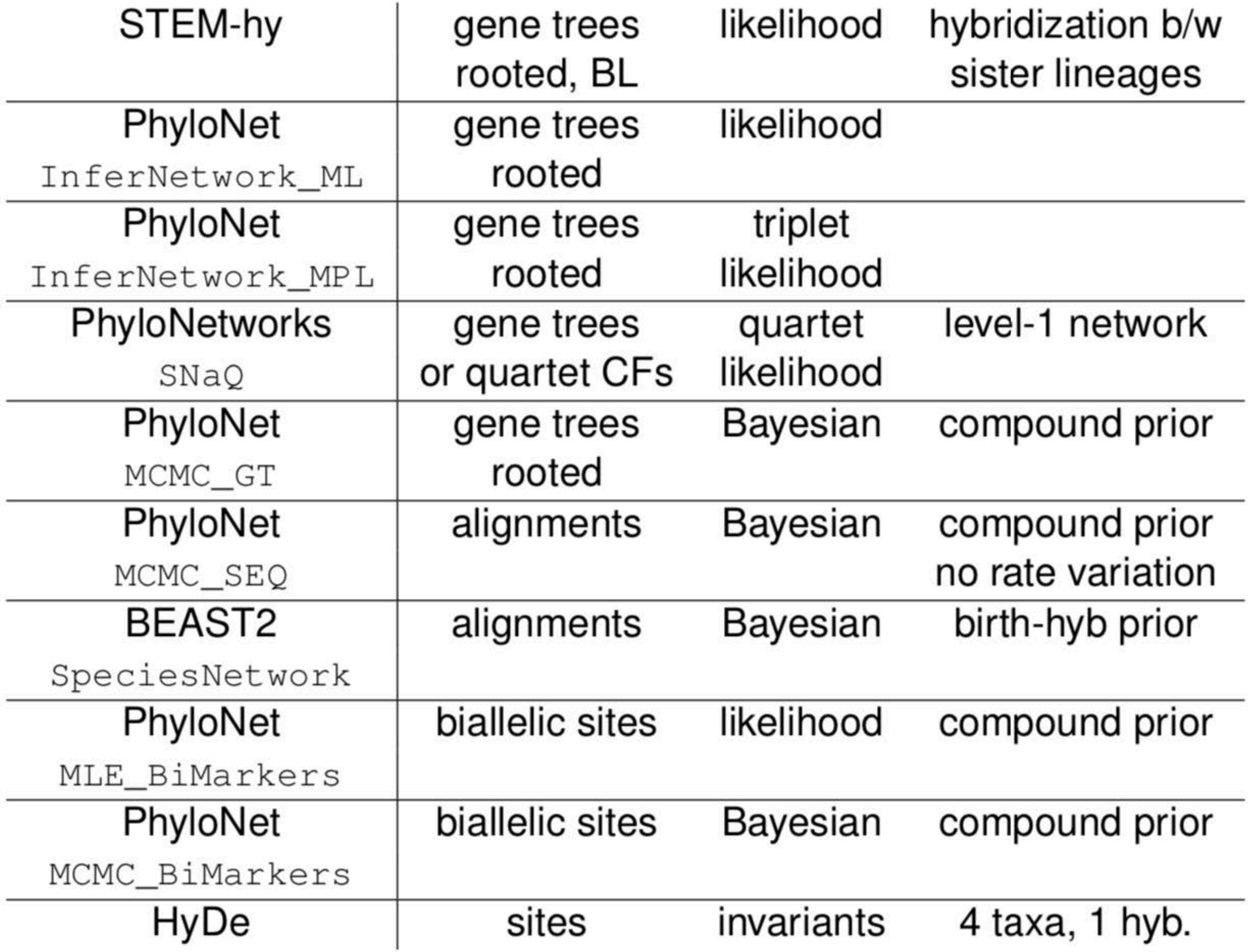
PhyloNet Likelihood
(Yu et al, 2014)



$$\tilde{L}(N, \theta) \propto \prod_{q} L(q | N, \theta)$$

SNaQ
(S.-L., Ane, 2016)

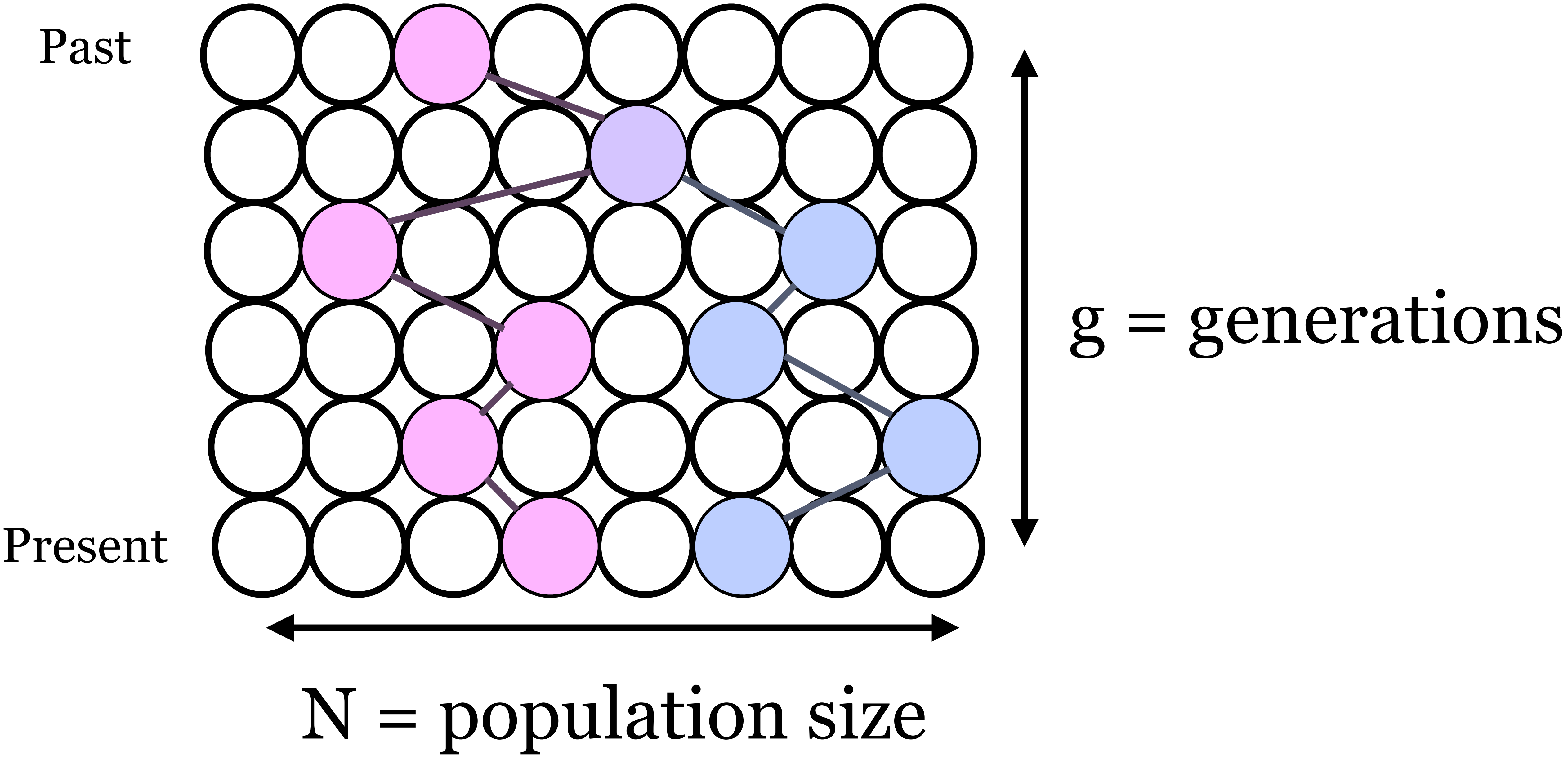
	BEAST2 (Zhang et al, 2017)	Birth-hybridization process	**MCMC:** Network moves, mixing	Most accurate, not scalable
	PhyloNet Bayesian (Wen et al, 2016)	# reticulations, cycle diameter		
 Rooted	PhyloNet Bayesian (Wen et al, 2016)			
 Rooted	PhyloNet Likelihood (Yu et al, 2014)		**Heuristic search:** Network moves	
 Unrooted	SNaQ (S.-L., Ane, 2016)	Level-1 networks		More scalable, Robust



STEM-hy	gene trees rooted, BL	likelihood	hybridization b/w sister lineages
PhyloNet InferNetwork_ML	gene trees rooted	likelihood	
PhyloNet InferNetwork_MPL	gene trees rooted	triplet likelihood	
PhyloNetworks SNaQ	gene trees or quartet CFs	quartet likelihood	level-1 network
PhyloNet MCMC_GT	gene trees rooted	Bayesian	compound prior
PhyloNet MCMC_SEQ	alignments	Bayesian	compound prior no rate variation
BEAST2 SpeciesNetwork	alignments	Bayesian	birth-hyb prior
PhyloNet MLE_BiMarkers	biallelic sites	likelihood	compound prior
PhyloNet MCMC_BiMarkers	biallelic sites	Bayesian	compound prior
HyDe	sites	invariants	4 taxa, 1 hyb.

Slide by Cecile Ane

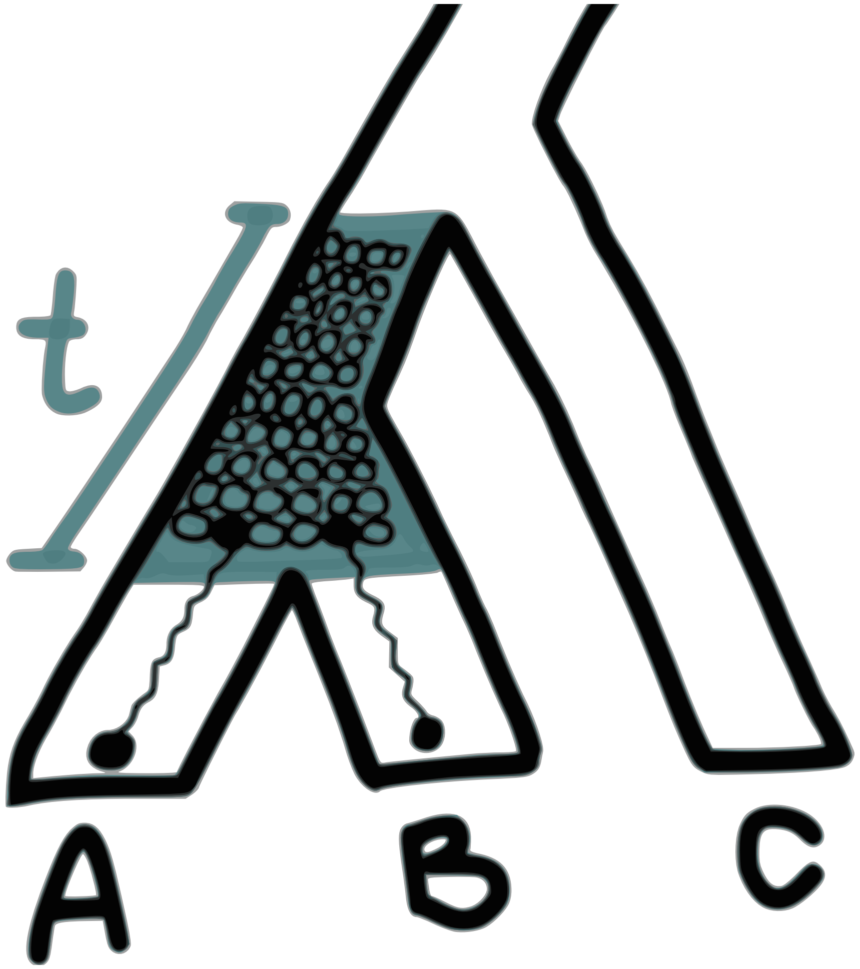
Coalescent model within 1 population



Probability of no coalescence in g generations: $\left(1 - \frac{1}{N}\right)^g$

$$t = g/N \Rightarrow \left(1 - \frac{t}{Nt}\right)^{Nt} \xrightarrow[N \to \infty]{} e^{-t}$$

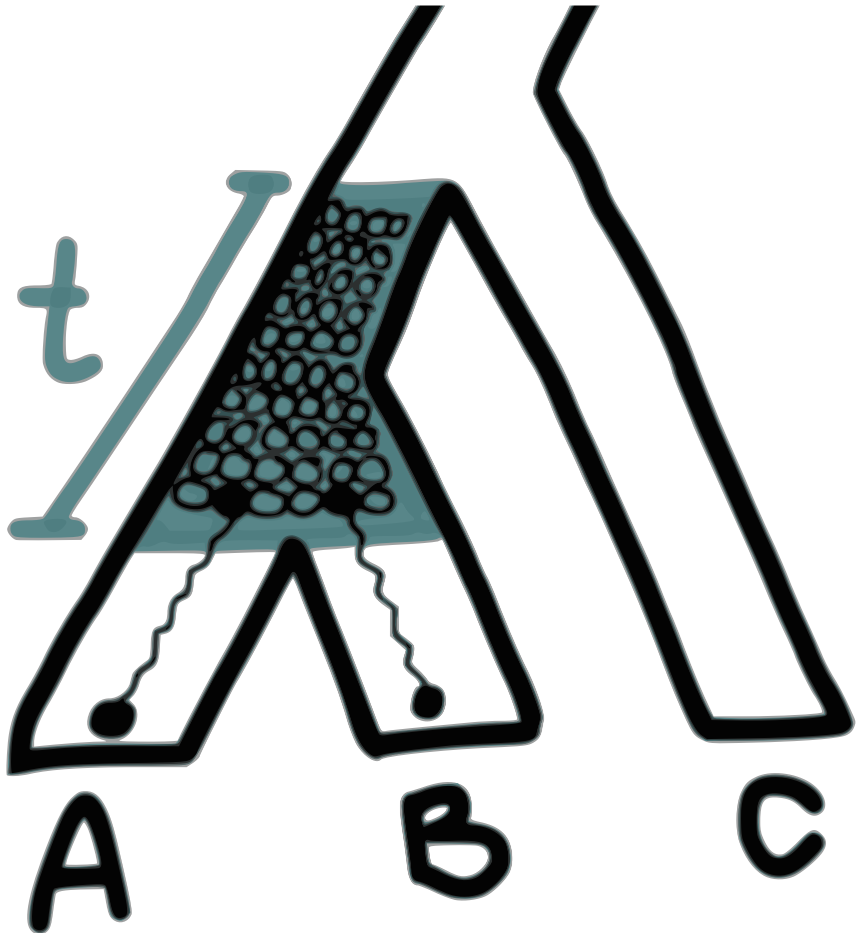
Multispecies coalescent on a tree



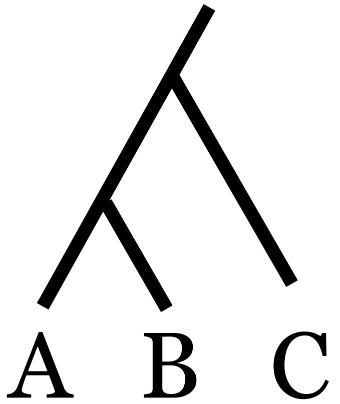
$$P(T > t) = e^{-t}$$

$$T = \frac{g}{N} \text{ coalescent units } \sim Exp(1)$$

Multispecies coalescent on a tree



$$P(T > t) = e^{-t}$$

$\mathbb{P}\Bigg($  $\Bigg) =$

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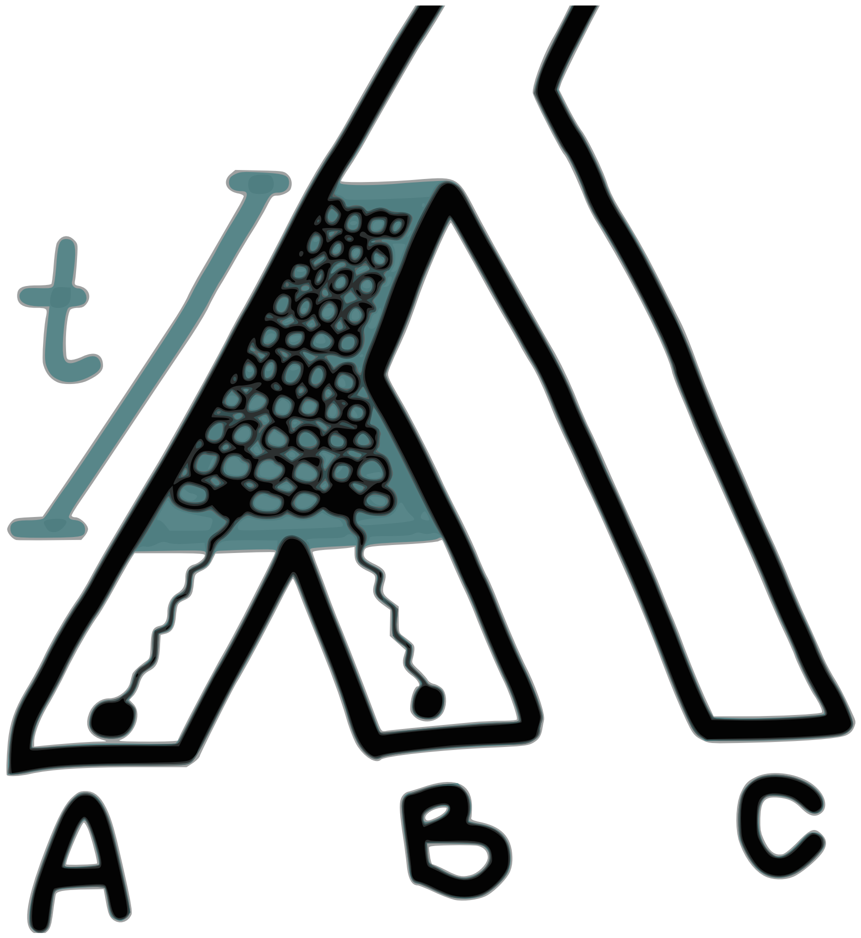
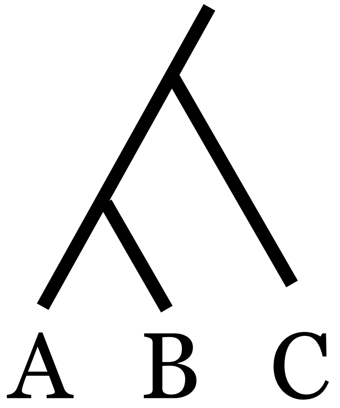
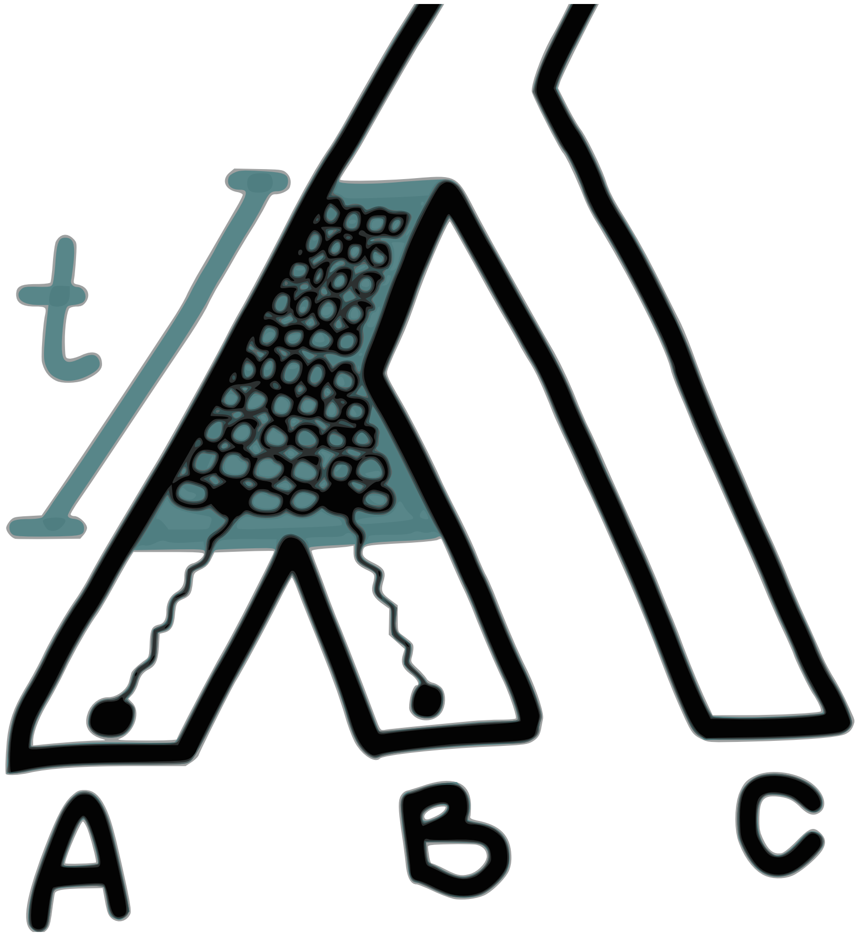


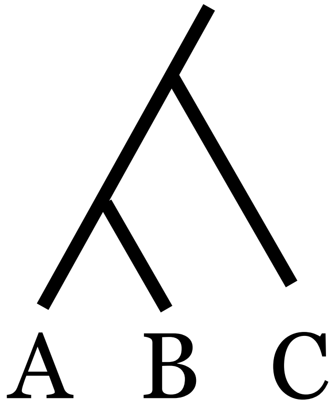
$P(T > t) = e^{-t}$

$\mathbb{P}\Bigg($  $\Bigg) =$

$$1 - e^{-t}$$

Multispecies coalescent on a tree



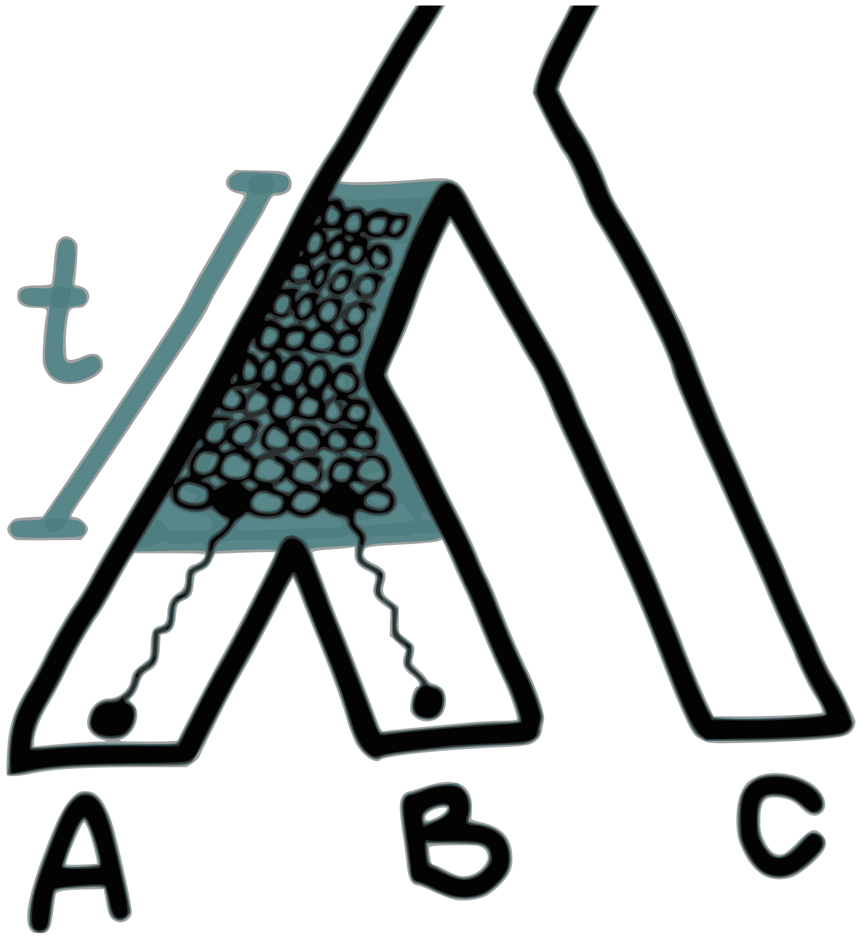
$\mathbb{P}\Big($  $\Big) =$

$$1 - e^{-t}$$

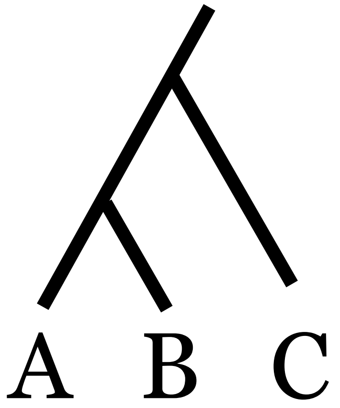
$$+$$

$$P(T > t) = e^{-t}$$

Multispecies coalescent on a tree

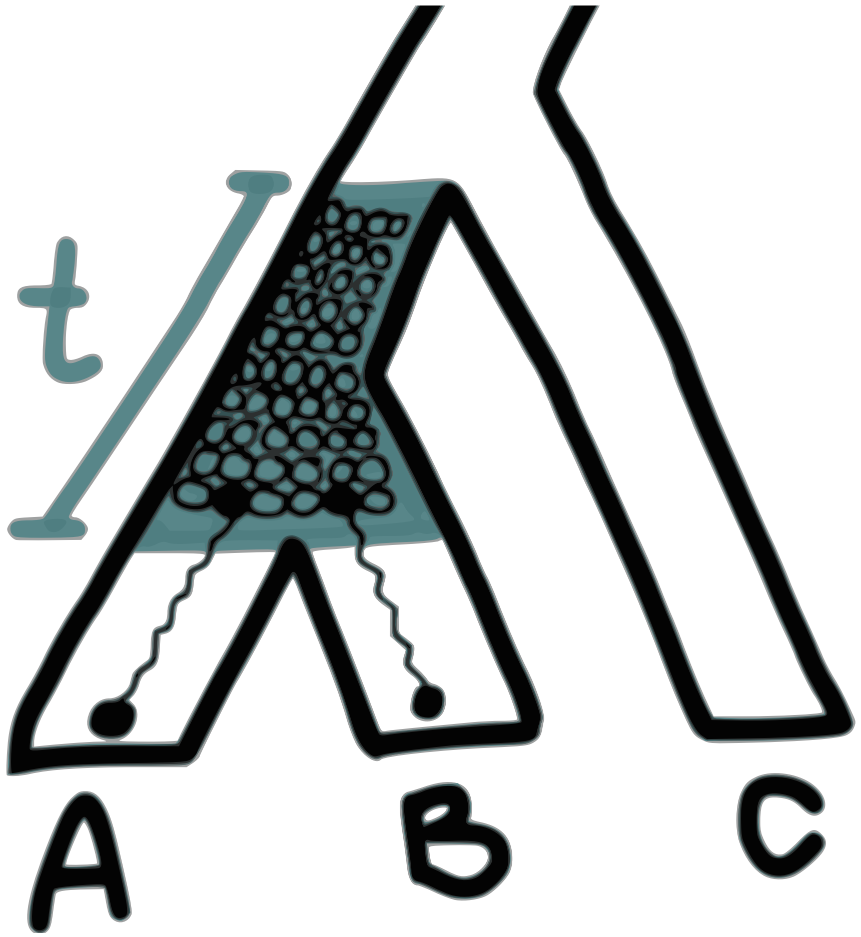


$$P(T > t) = e^{-t}$$

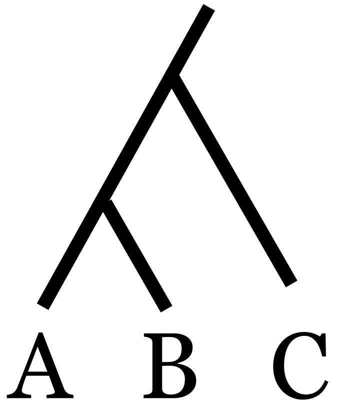
$\mathbb{P}\Big($  $\Big) =$

$$1 - e^{-t}$$
$$+$$
$$e^{-t} \times 1/3$$

Multispecies coalescent on a tree



$P(T > t) = e^{-t}$

$\mathbb{P}\Bigg($  $\Bigg) =$

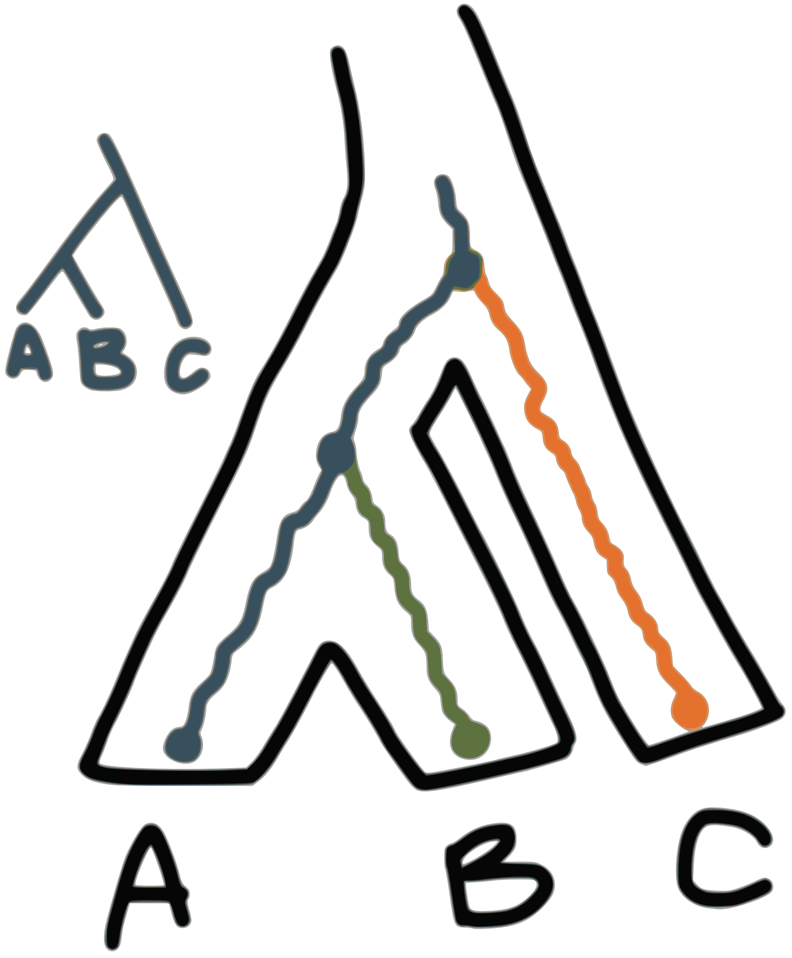
$$1 - e^{-t}$$

$$+$$

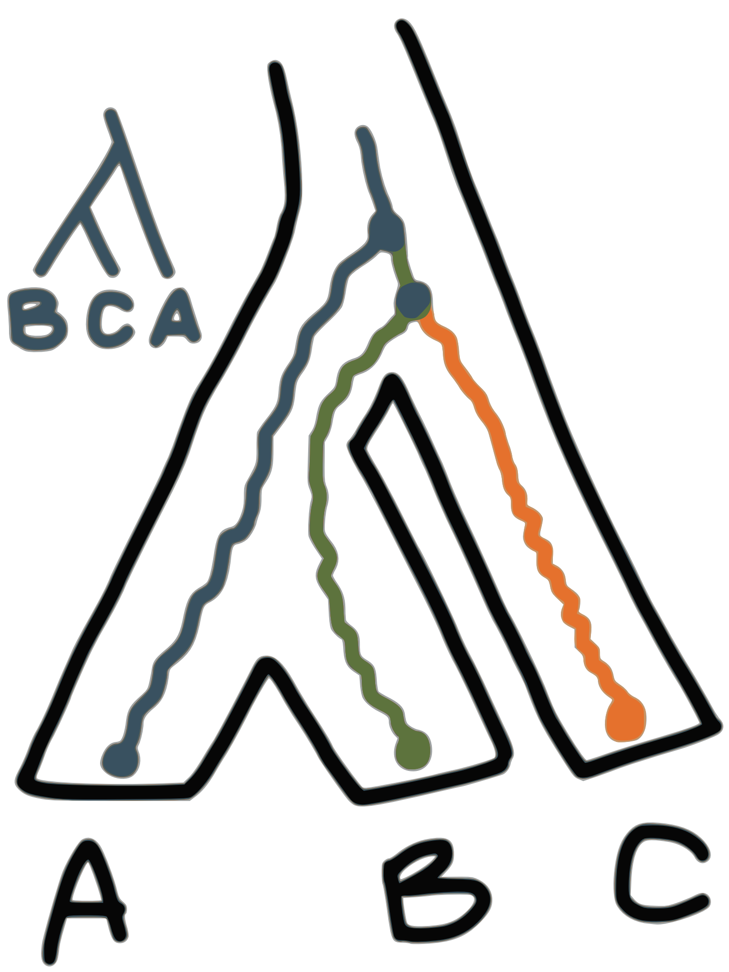
$$e^{-t} \times 1/3$$

$$= 1 - \frac{2}{3}e^{-t}$$

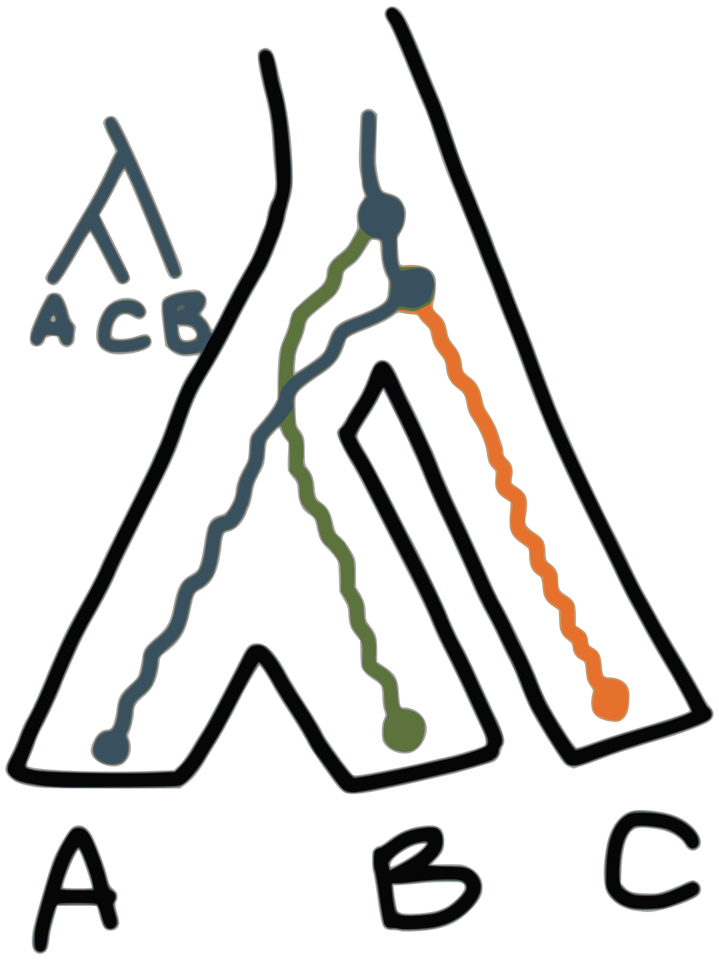
Multispecies coalescent on a tree



$$1 - \frac{2}{3}e^{-t}$$

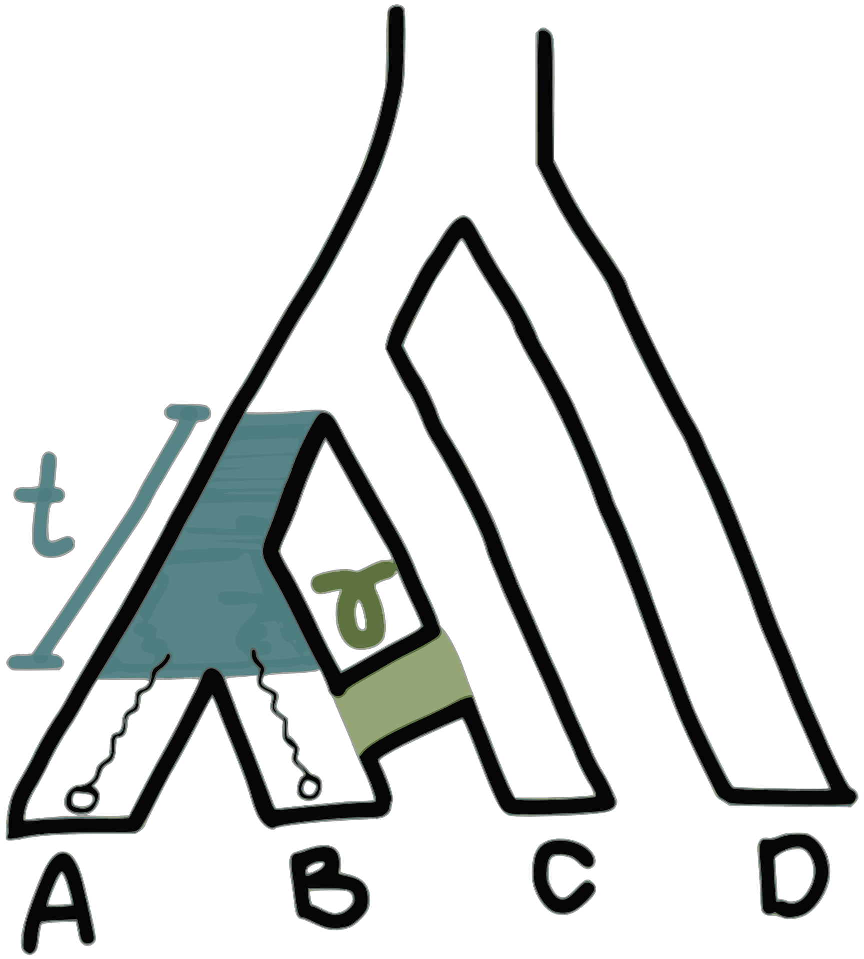


$$\frac{1}{3}e^{-t}$$



$$\frac{1}{3}e^{-t}$$

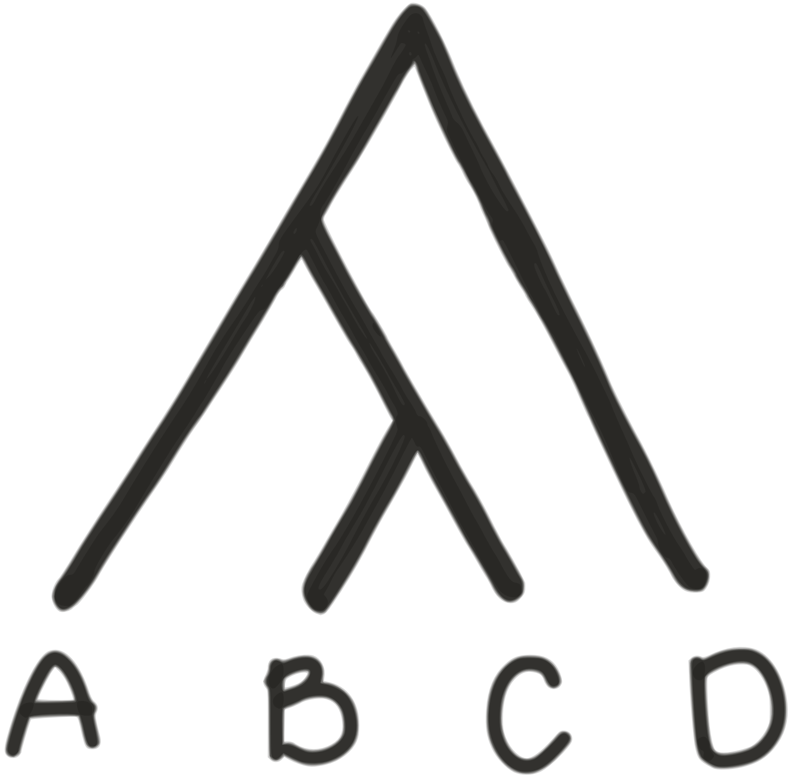
Multispecies coalescent on a network



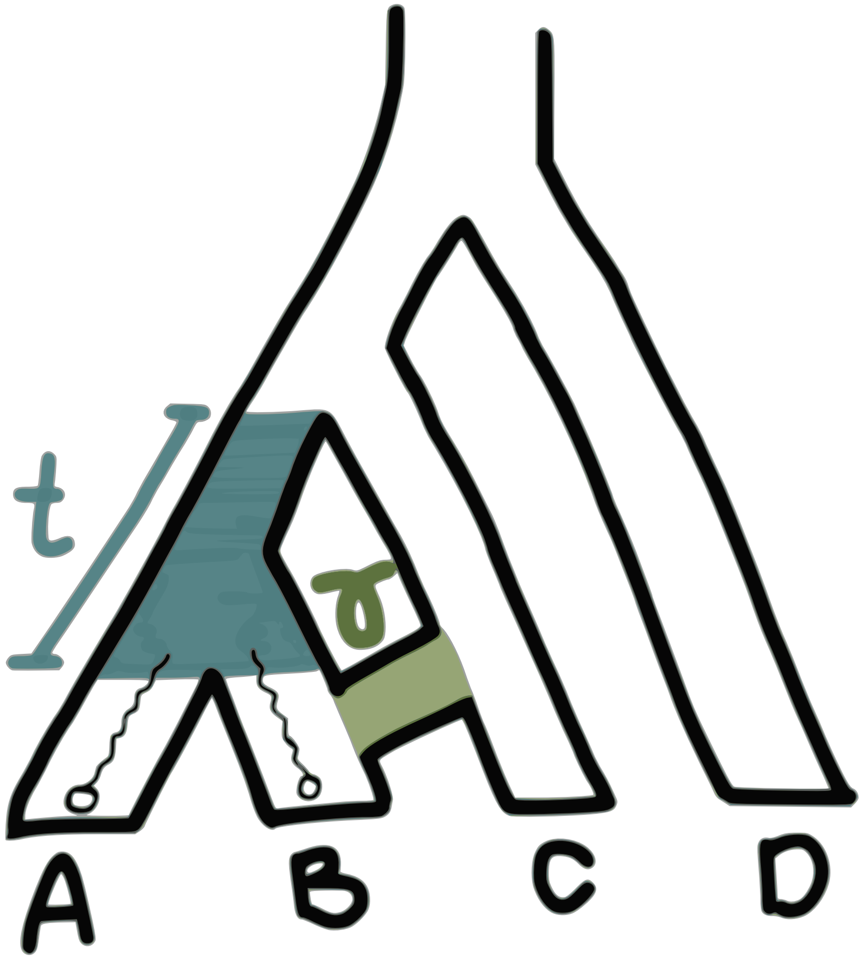
(Meng, Kubatko, 2009)
(Yu, Degnan, Nakhleh, 2012)

Multispecies coalescent on a network

$P($



$|$



$)$

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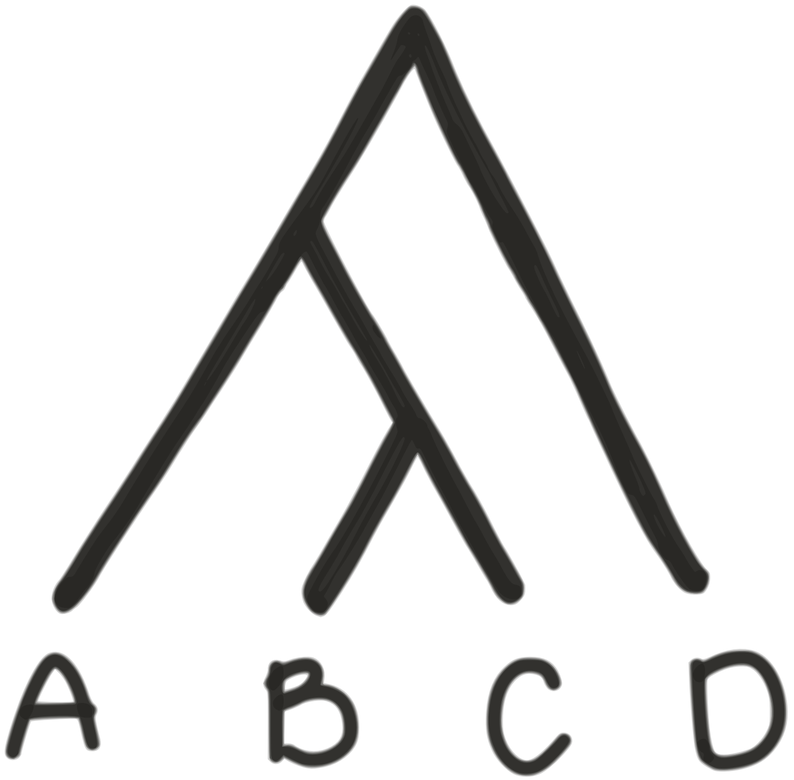
Multispecies coalescent on a network

$P($



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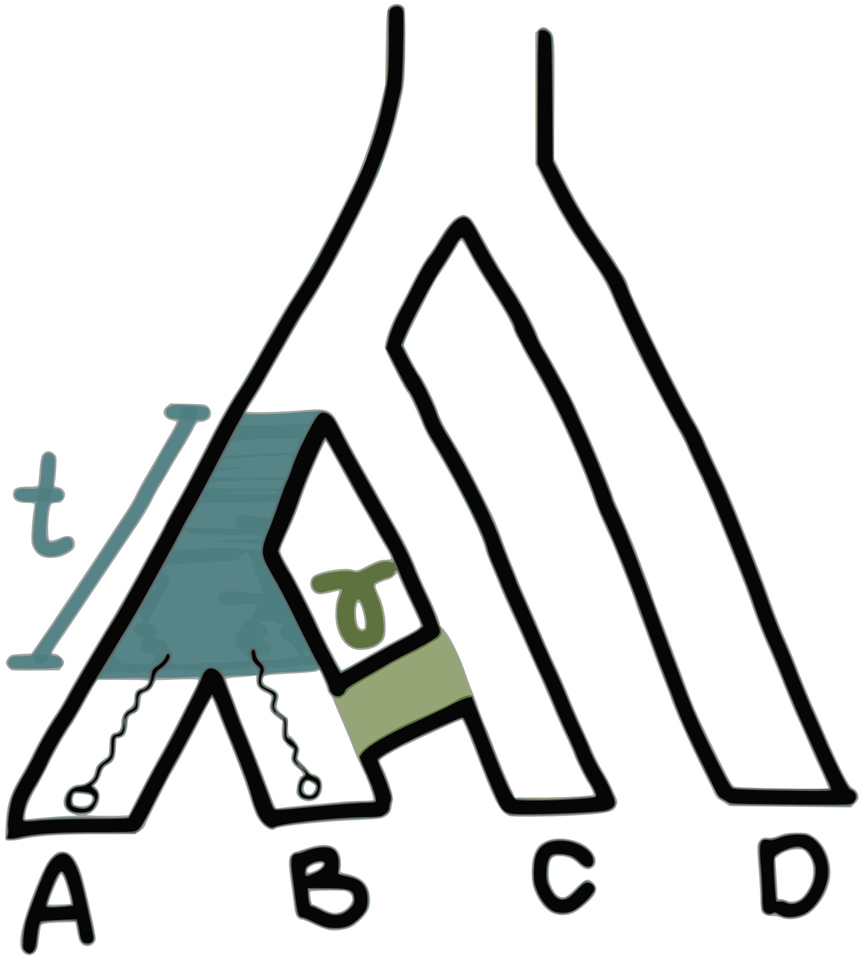

$)$

$$(1-\gamma)\frac{1}{3}e^{-t} + \gamma(1-\frac{2}{3}e^{-t_2})$$

(Meng, Kubatko, 2009)
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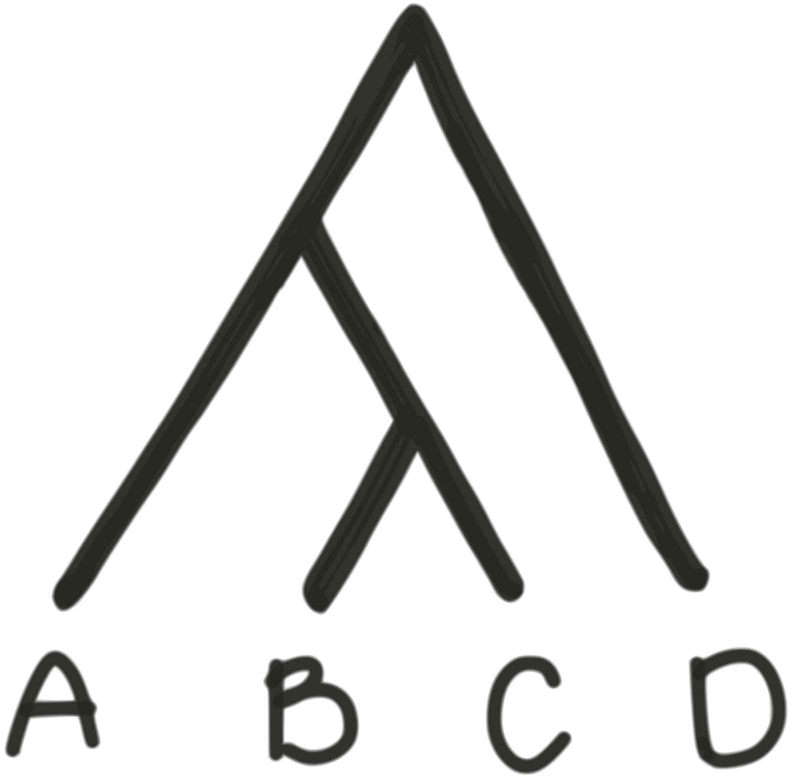
Multispecies coalescent on a network

$P($



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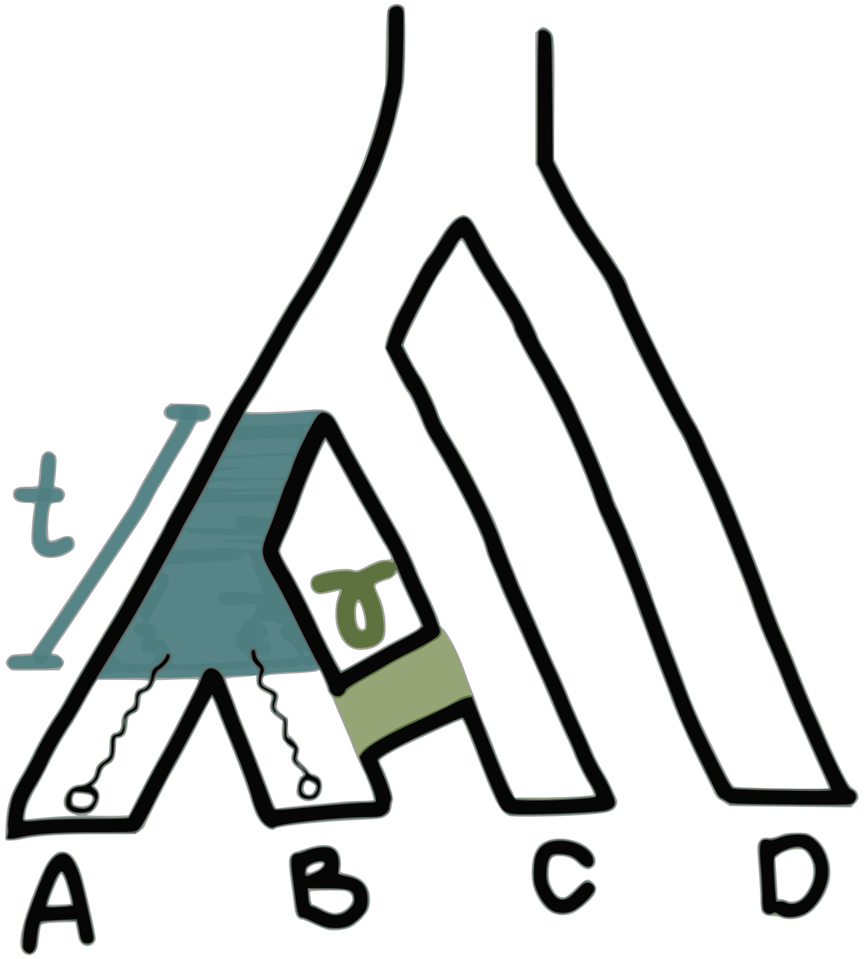
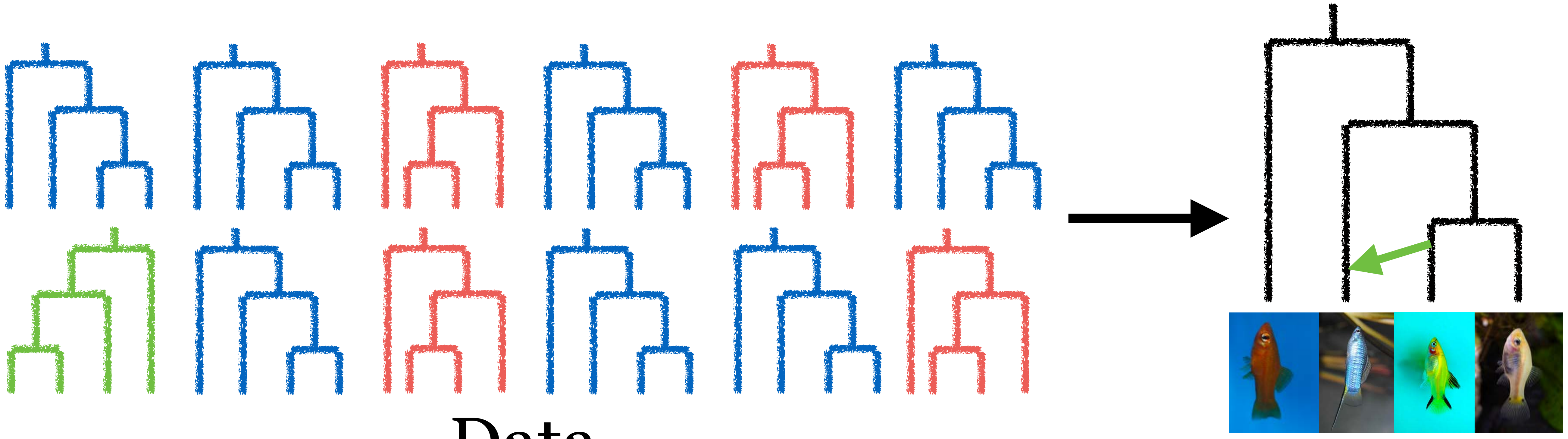


$)$

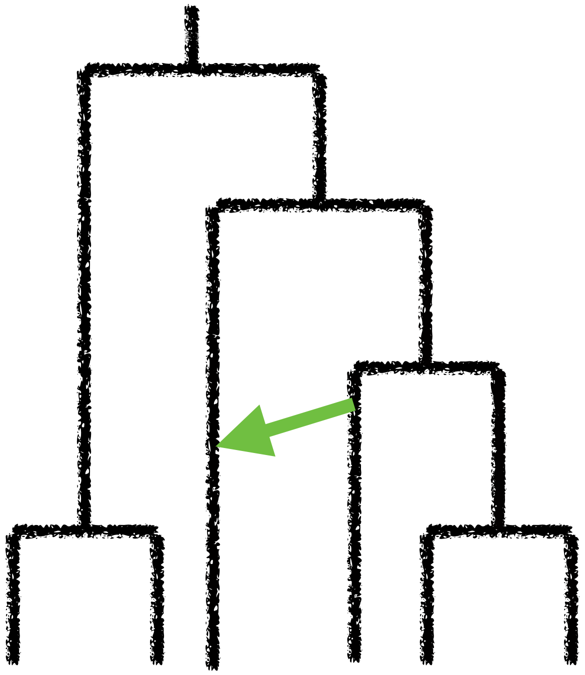
$$CF_{BC|AD}(t, t_2, \gamma) = (1-\gamma)\frac{1}{3}e^{-t} + \gamma(1 - \frac{2}{3}e^{-t_2})$$

(Meng, Kubatko, 2009)
(Yu, Degnan, Nakhleh, 2012)

Maximum **pseudo**likelihood



Data



Quartet-based inference

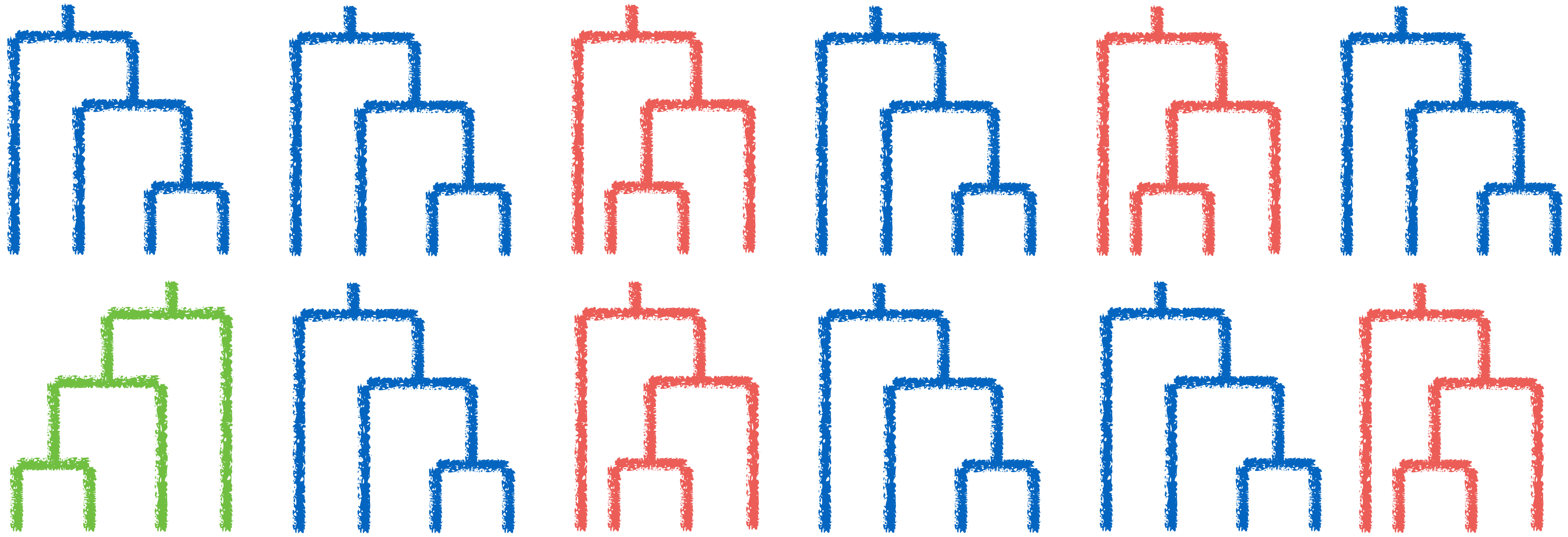
$$\tilde{L}(network) = \prod L(quartet)$$

(S-L, Ané, 2016, PLoS Genetics)

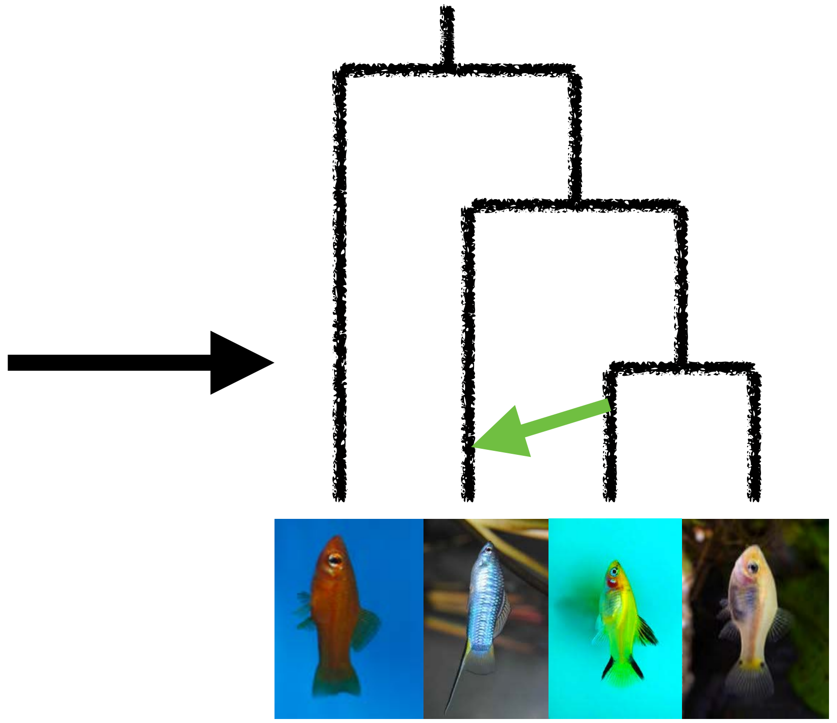
`www.github.com/CRSL4/PhyloNetworks`

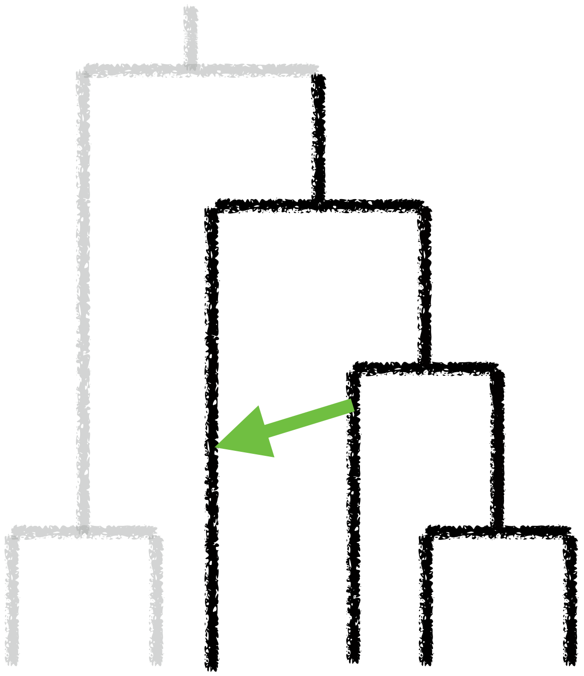
snaq julia

Maximum **pseudo**likelihood



Data





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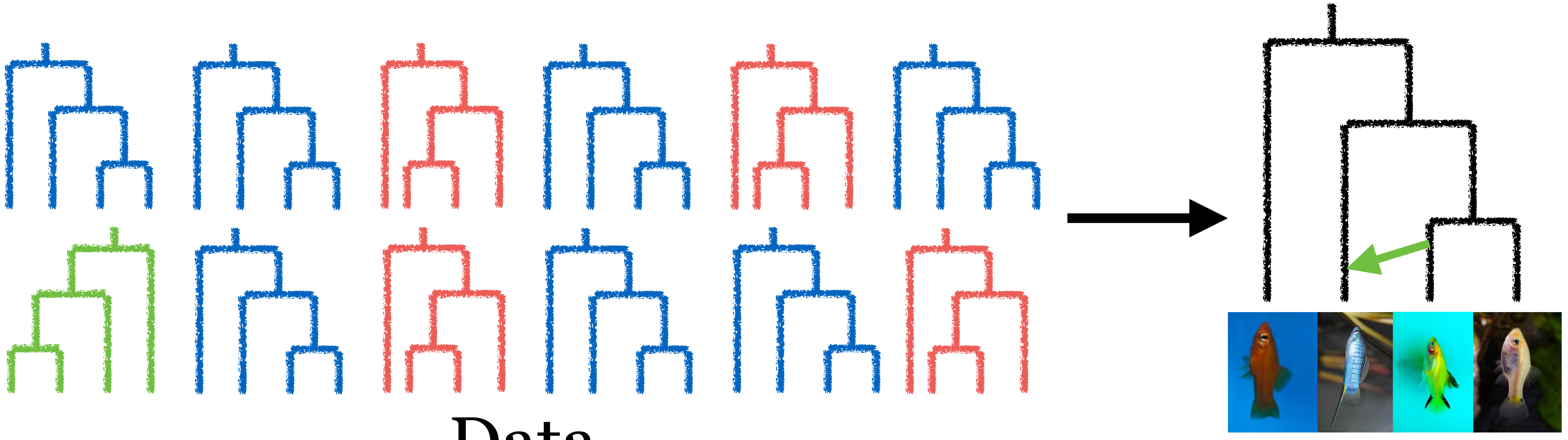

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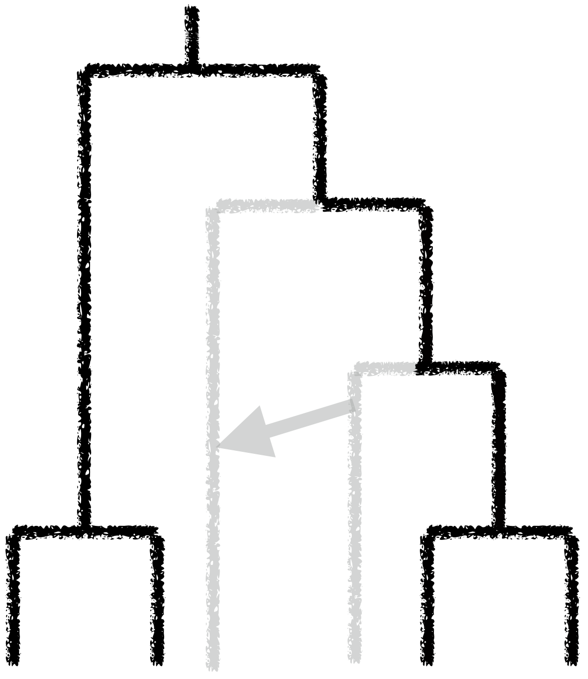

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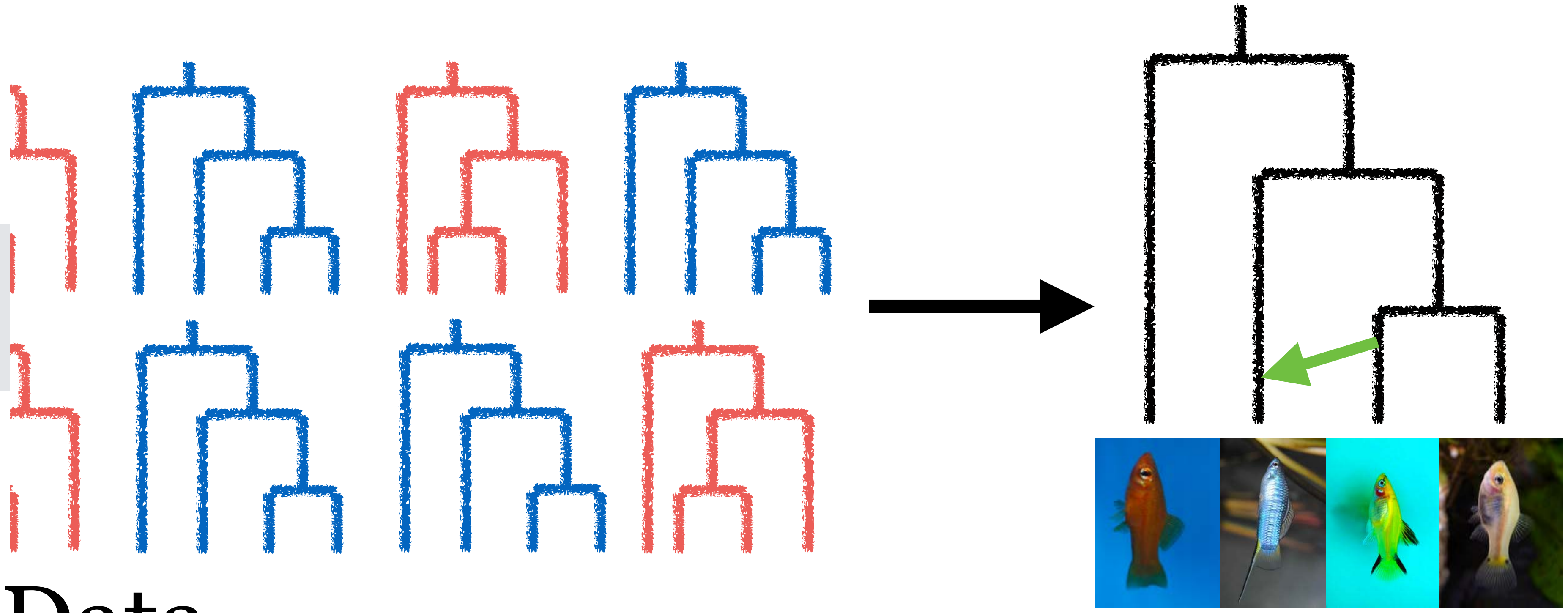
(S-L, Ané, 2016, PLoS Genetics)

www.github.com/CRSL4/PhyloNetworks

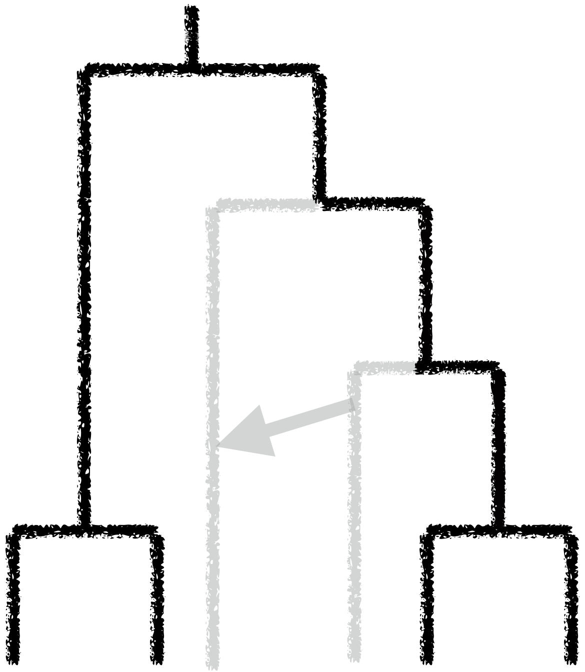
https://solislemuslab.github.io/ @solislemuslab crsl4

Maximum **pseudo**likelihood

Unrooted gene trees	No rooting error
No branch lengths	No molecular clock assumption
Concordance factors	Account for tree estimation error



Data



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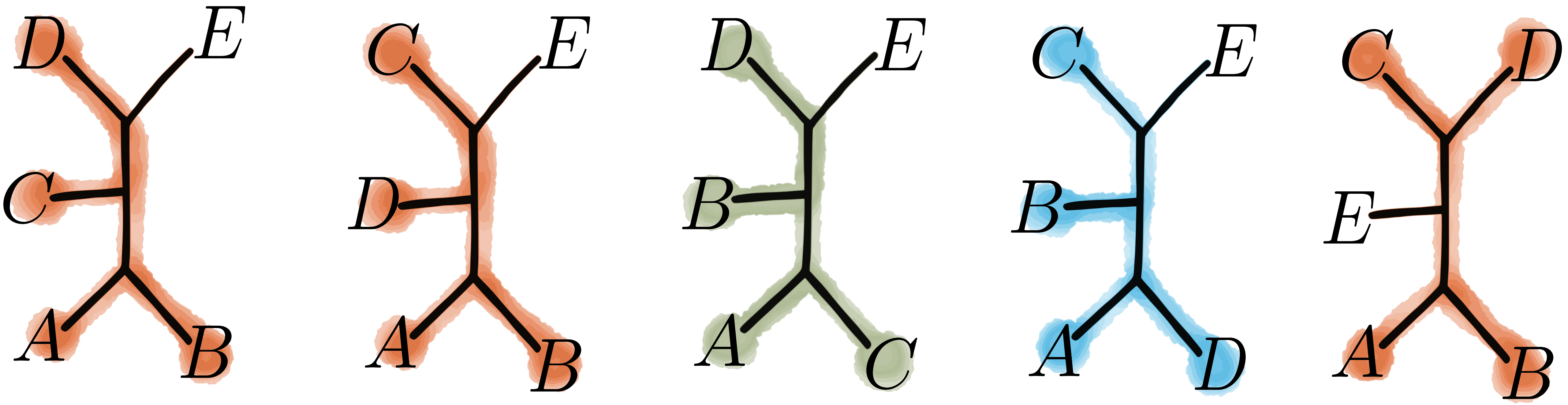
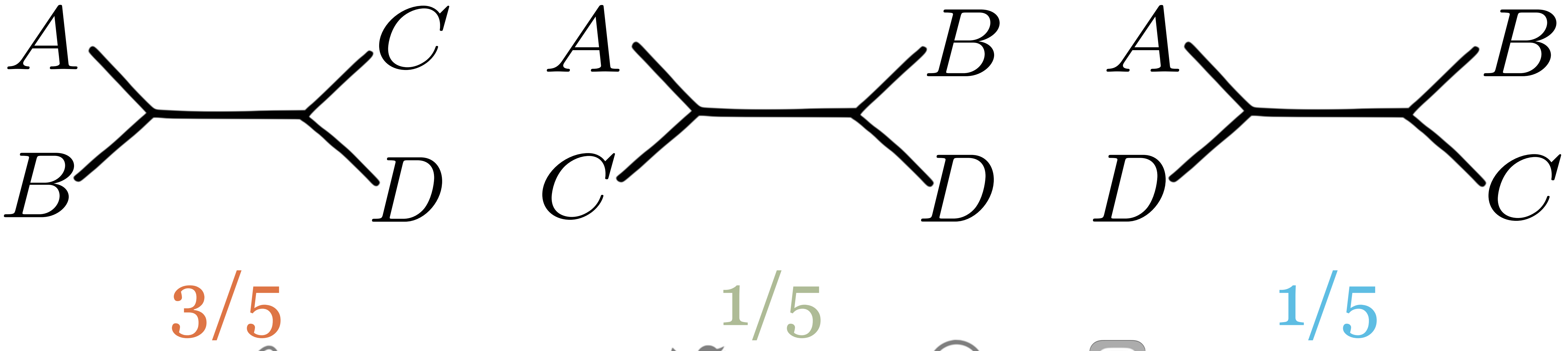
www.github.com/CRSL4/PhyloNetworks

Quartet-based inference



Concordance factors (CF):
% of genes having the quartet in their tree



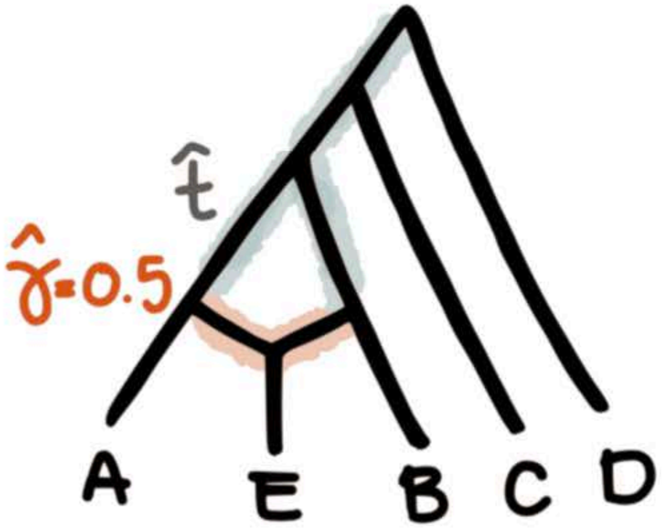
Quartet-based inference

Observed **quartet** CFs:

4 taxon set	CF_1	CF_2	CF_3
A B C D	.80	.10	.10
A B C E	.40	.40	.20
A B D E	.40	.40	.20
A C D E	.84	.08	.08
B C D E	.82	.10	.08

→

inferred network:

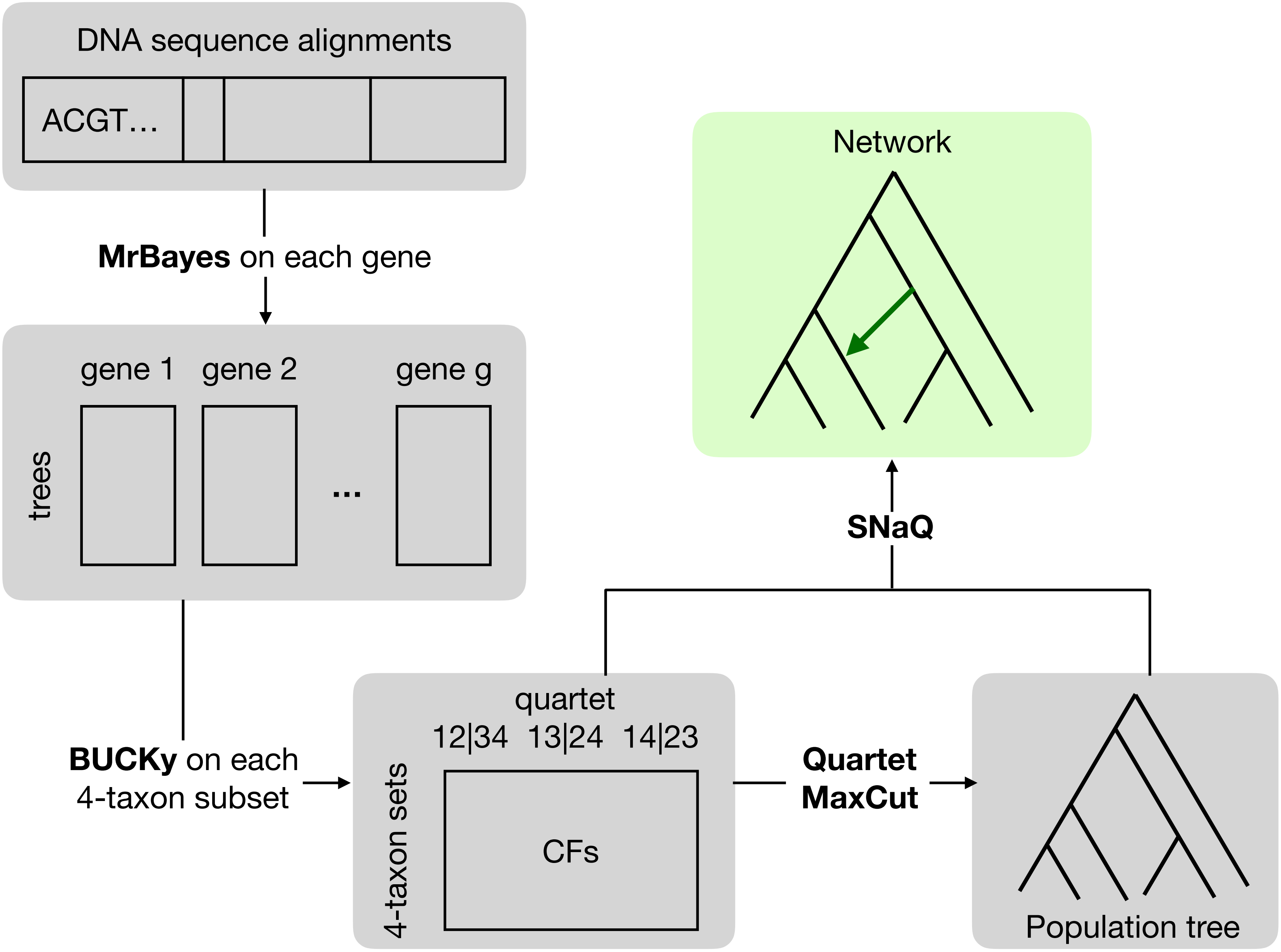


Maximum Pseudo-Likelihood:

$$\log \tilde{L} = \sum_{q \in Q(N)} \mathrm{CF}_{in,1} \log(\mathrm{CF}_{net,1}) + \mathrm{CF}_{in,2} \log(\mathrm{CF}_{net,2}) + \mathrm{CF}_{in,3} \log(\mathrm{CF}_{net,3})$$

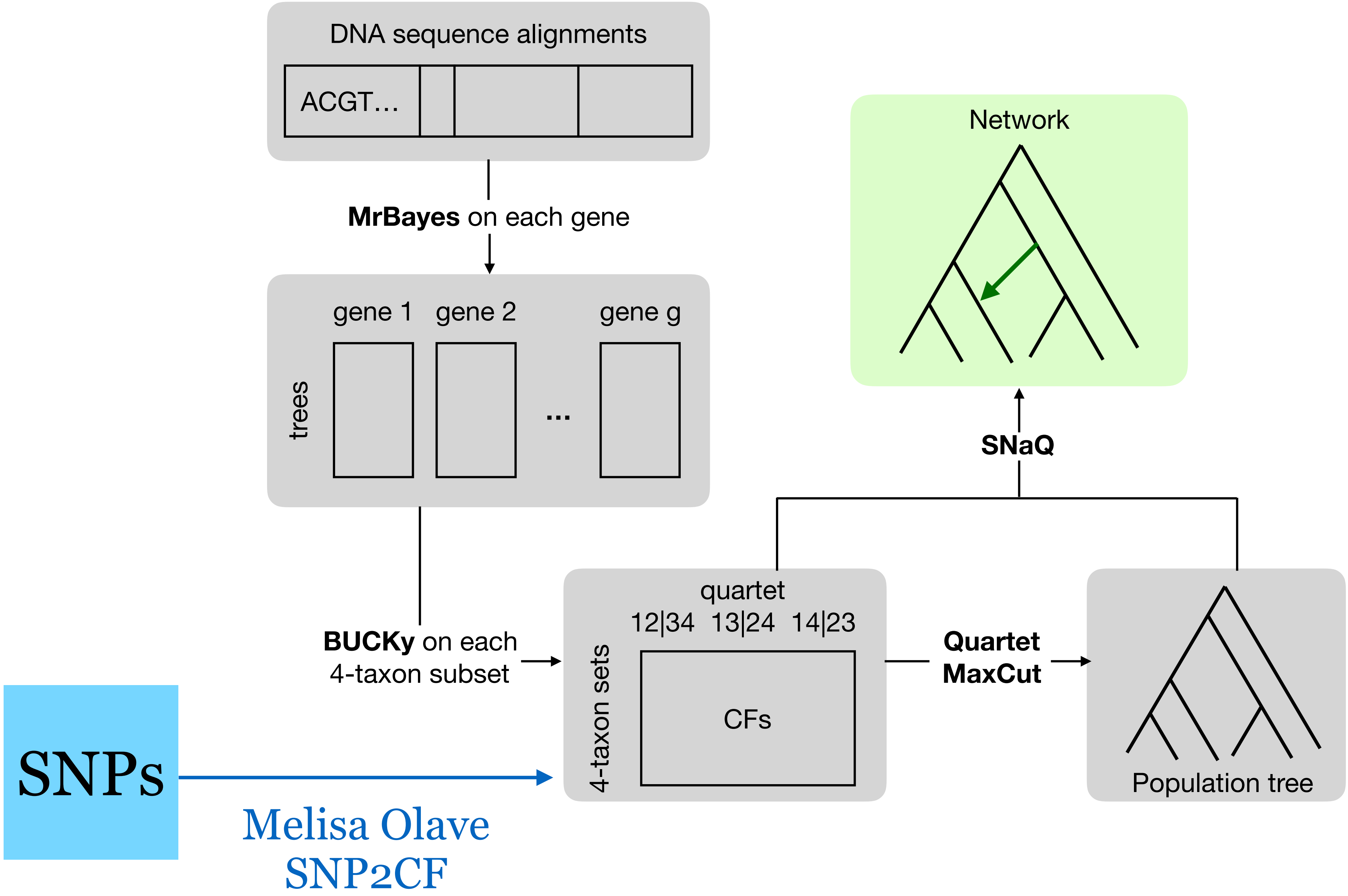
How?

Phylogenetic network



How?

Phylogenetic network



DNA sequence alignments

ACGT…

MrBayes on each gene

gene 1 gene 2 gene g

trees

…

BUCKy on each 4-taxon subset

quartet

12|34 13|24 14|23

4-taxon sets

CFs

Quartet MaxCut

Population tree

SNaQ

Network

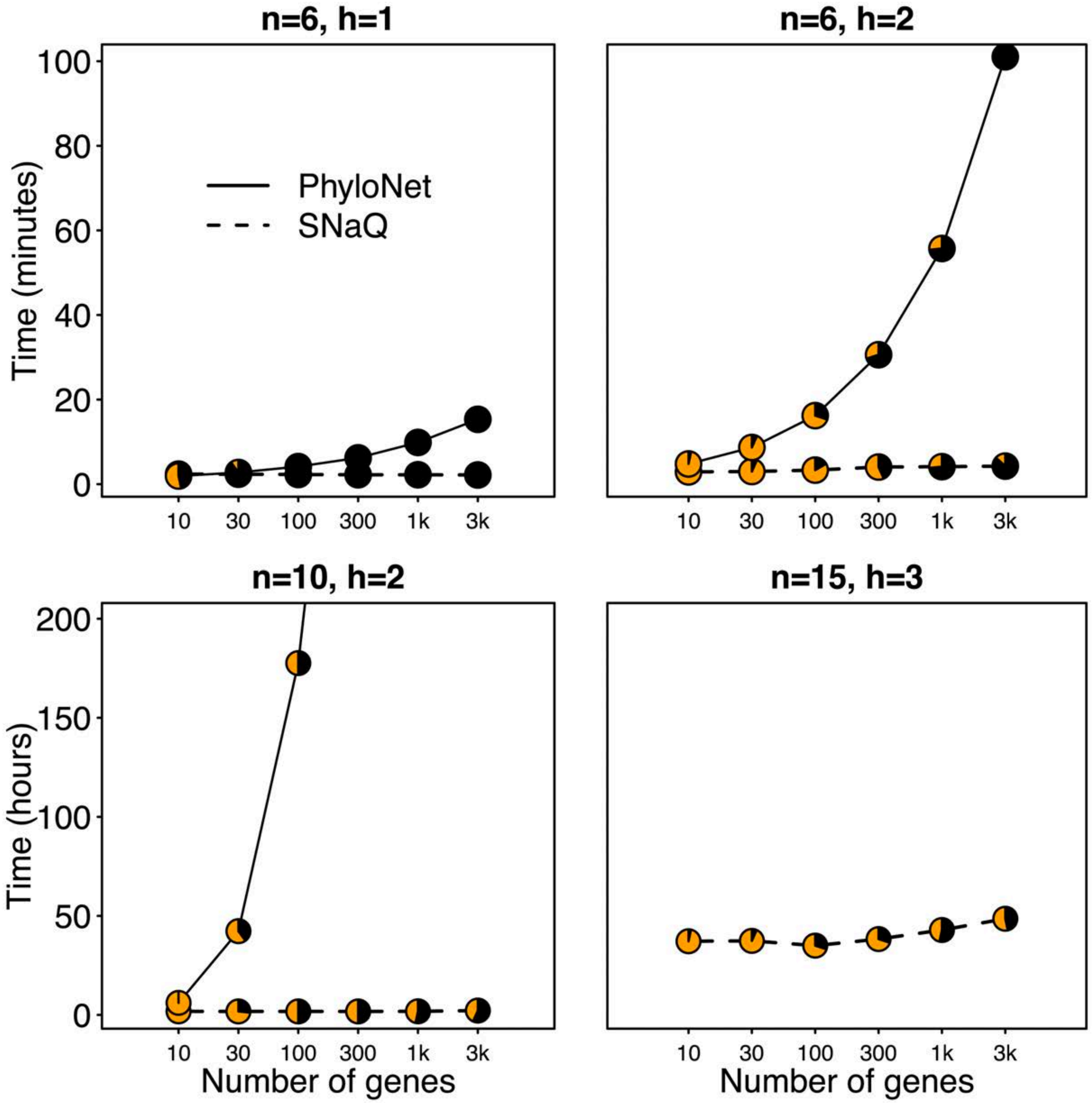
SNPs

Melisa Olave
SNP2CF

Network challenges

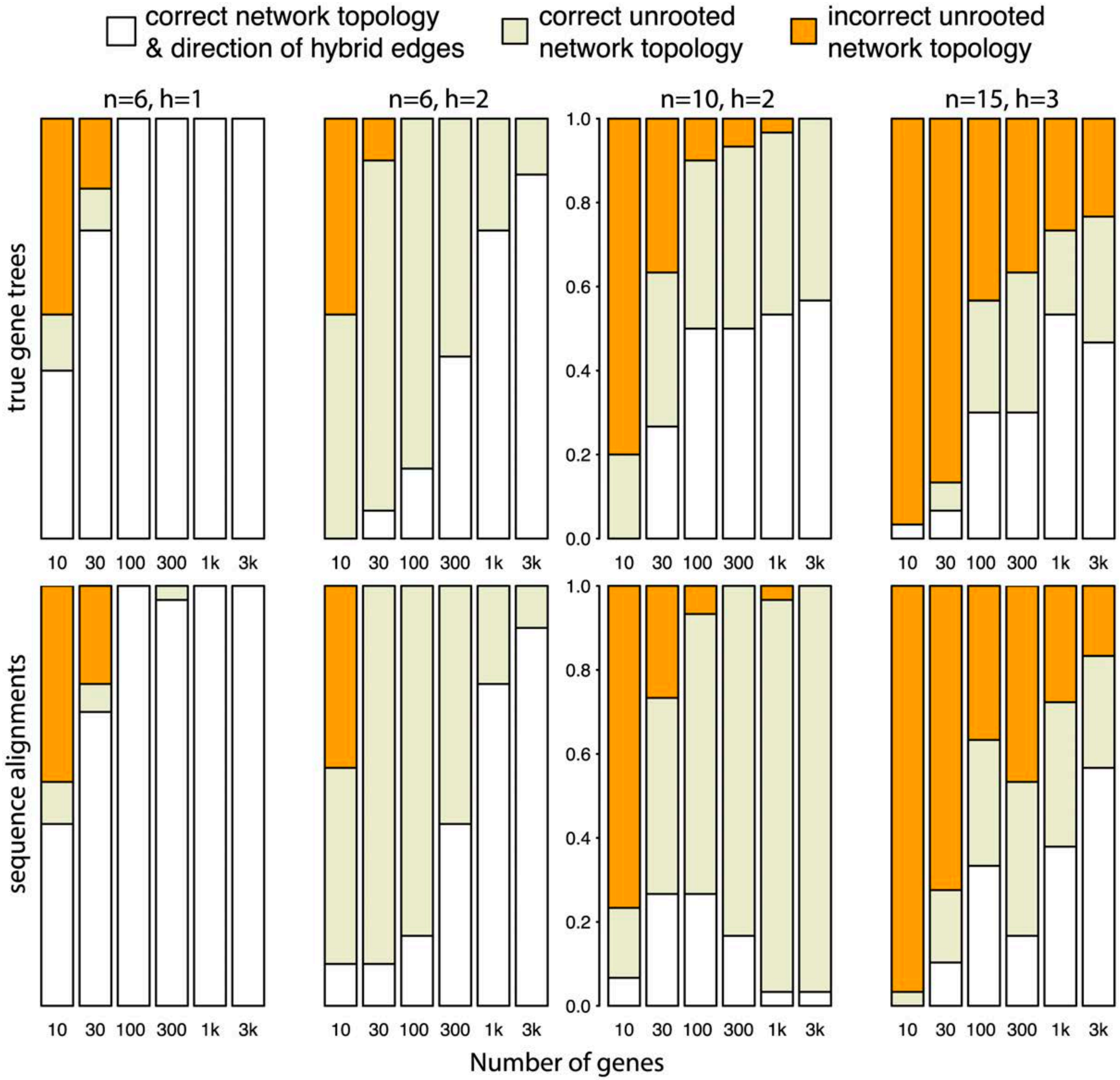
- Scalability
- Identifiability
- Network space
- Network comparison

Scalability gains



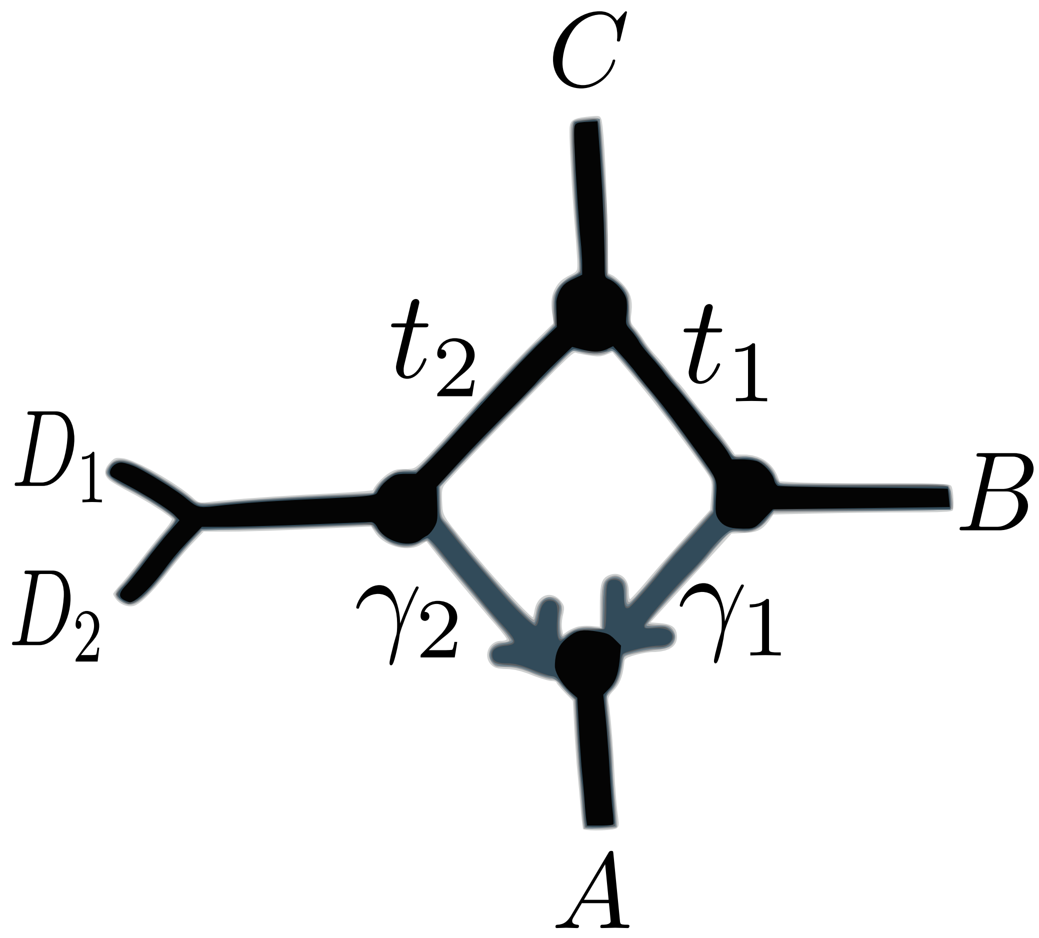
(Solís-Lemus, Ané, 2016, PLoS Genetics)

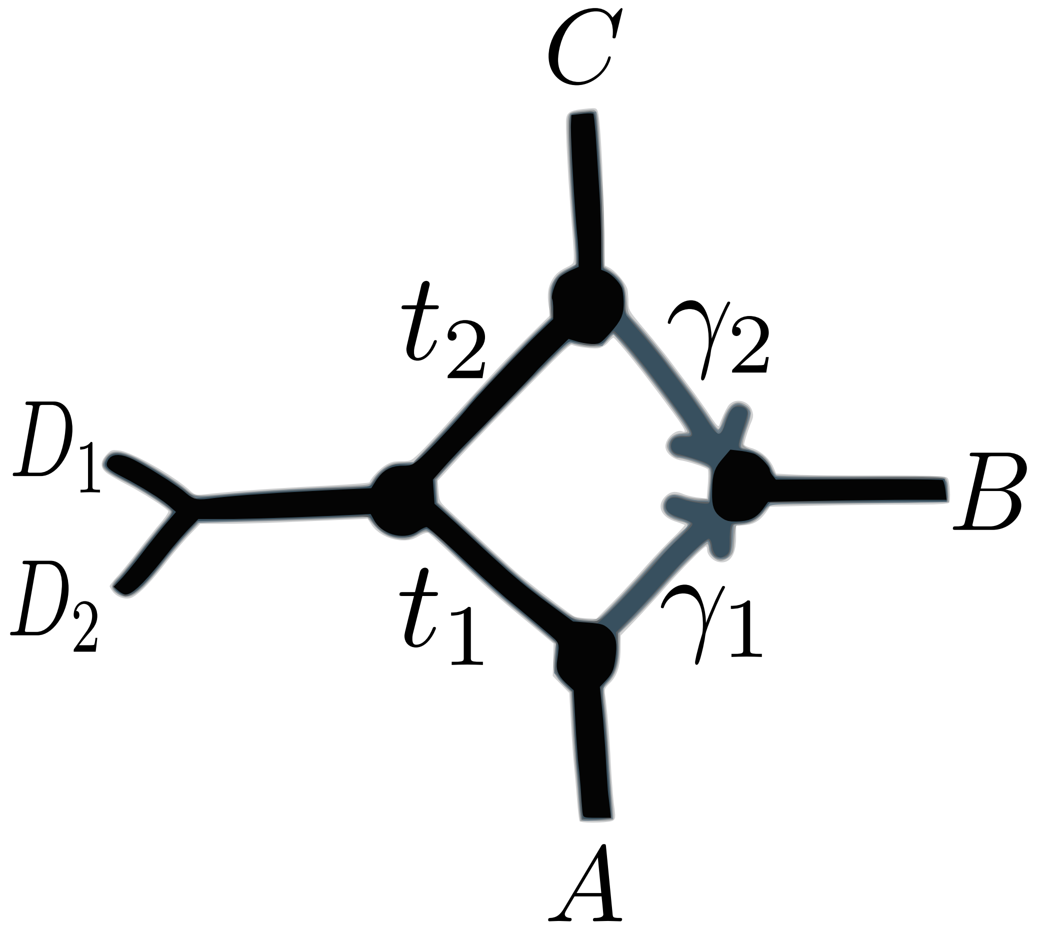
Accuracy



(Solís-Lemus, Ané, 2016, PLoS Genetics)

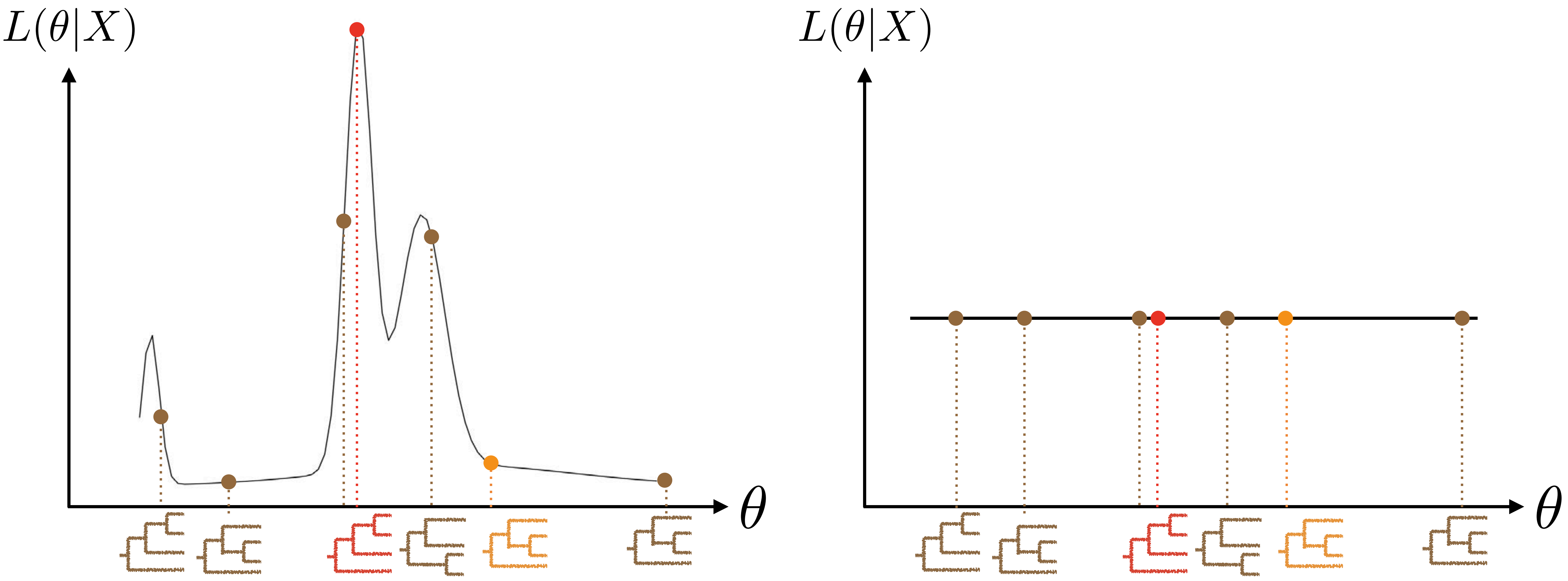
In practice: flat pseudolikelihood

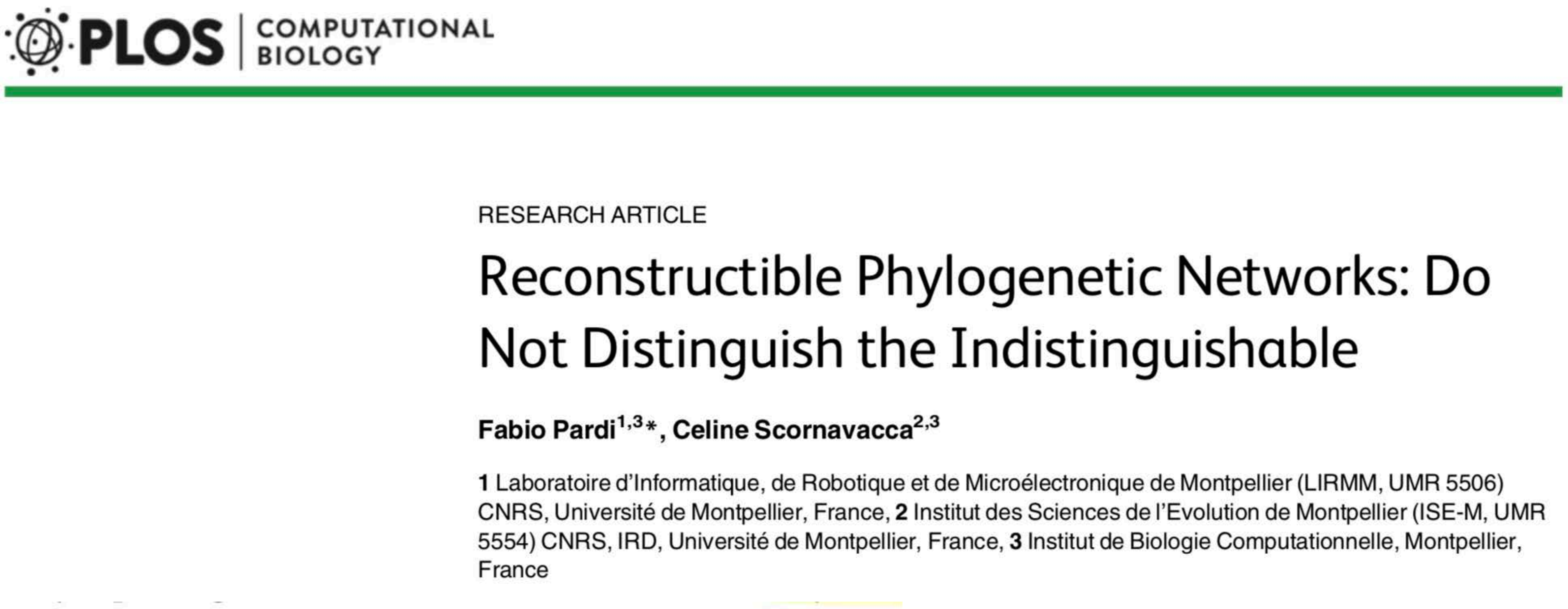




(S.-L., Ané, 2016, PLoS Genetics)

Identifiability





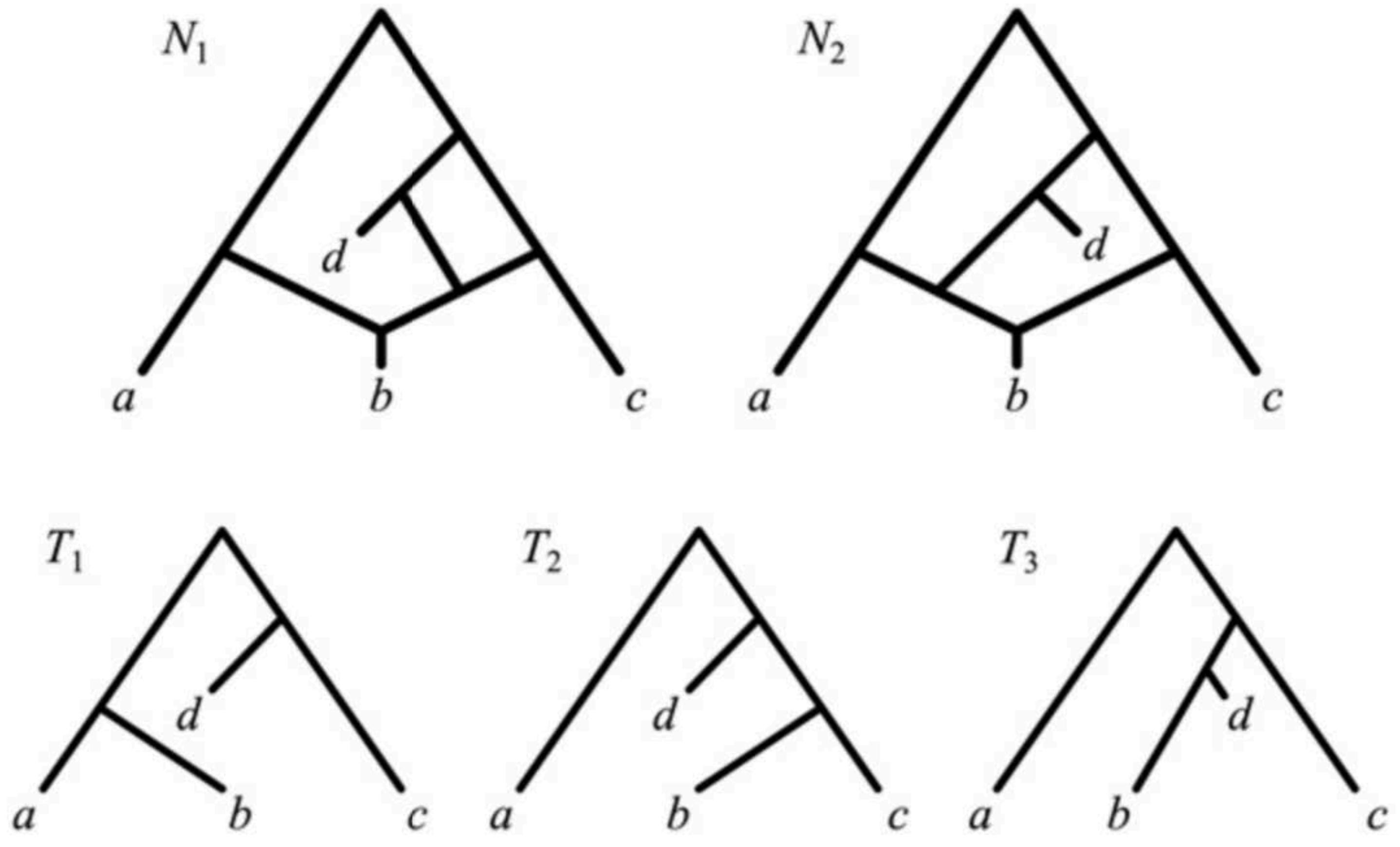
PLOS | COMPUTATIONAL BIOLOGY

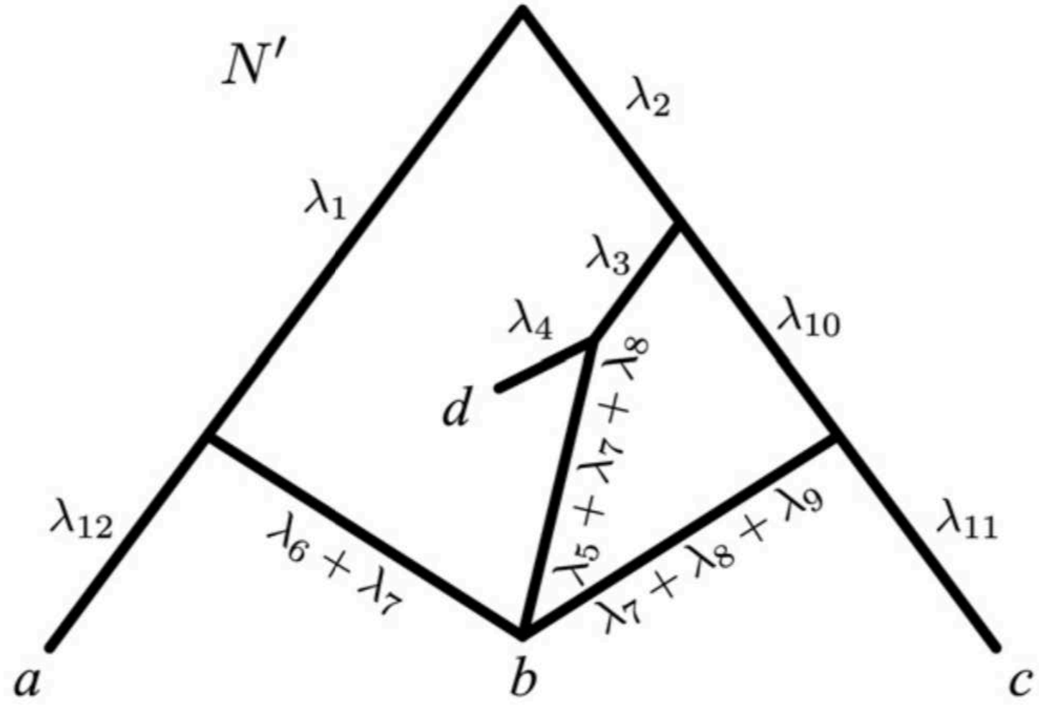
RESEARCH ARTICLE

Reconstructible Phylogenetic Networks: Do Not Distinguish the Indistinguishable

Fabio Pardi[1,3]*, Celine Scornavacca[2,3]

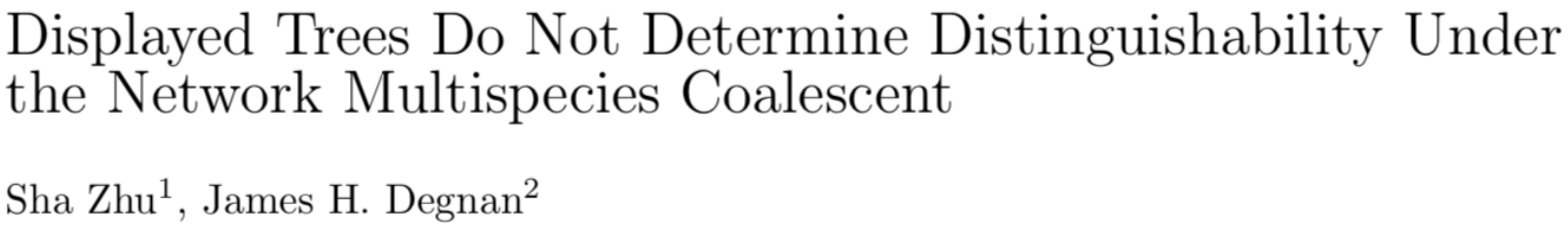
1 Laboratoire d'Informatique, de Robotique et de Microélectronique de Montpellier (LIRMM, UMR 5506) CNRS, Université de Montpellier, France, 2 Institut des Sciences de l'Evolution de Montpellier (ISE-M, UMR 5554) CNRS, IRD, Université de Montpellier, France, 3 Institut de Biologie Computationnelle, Montpellier, France





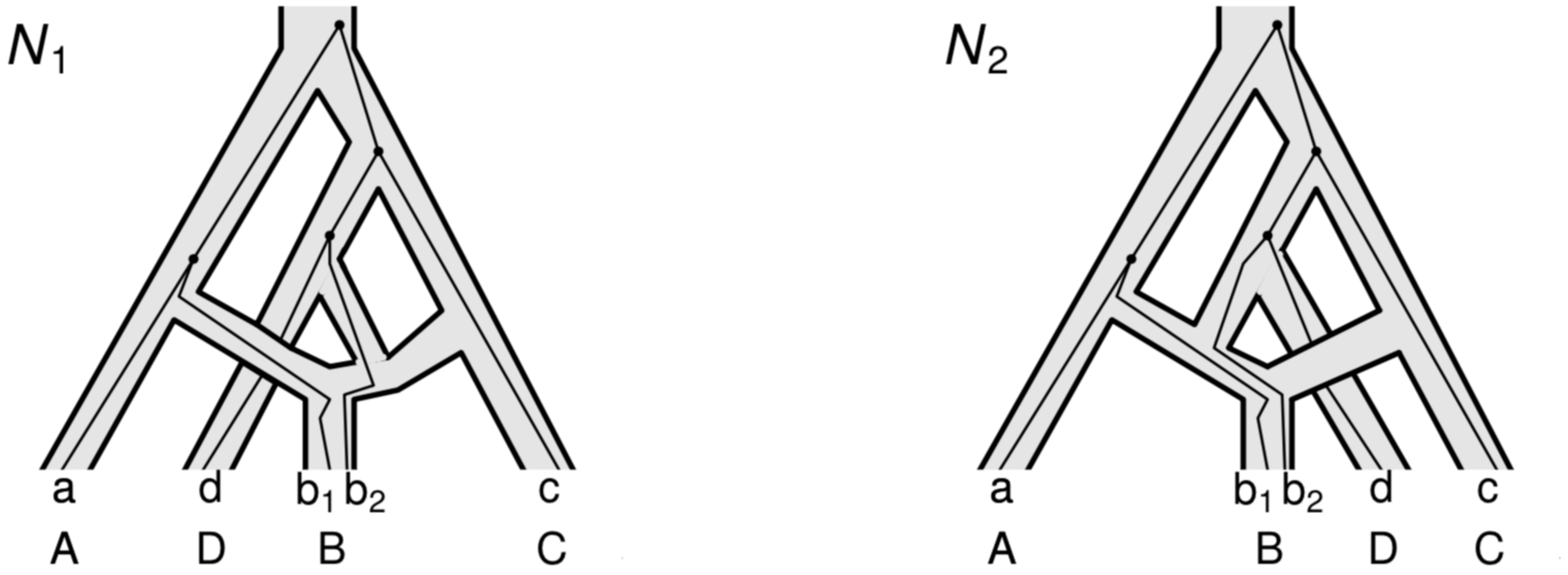
Undistinguishable with the “displayed trees” criterion

Solution: Canonical network (“unzipped”)



Displayed Trees Do Not Determine Distinguishability Under the Network Multispecies Coalescent

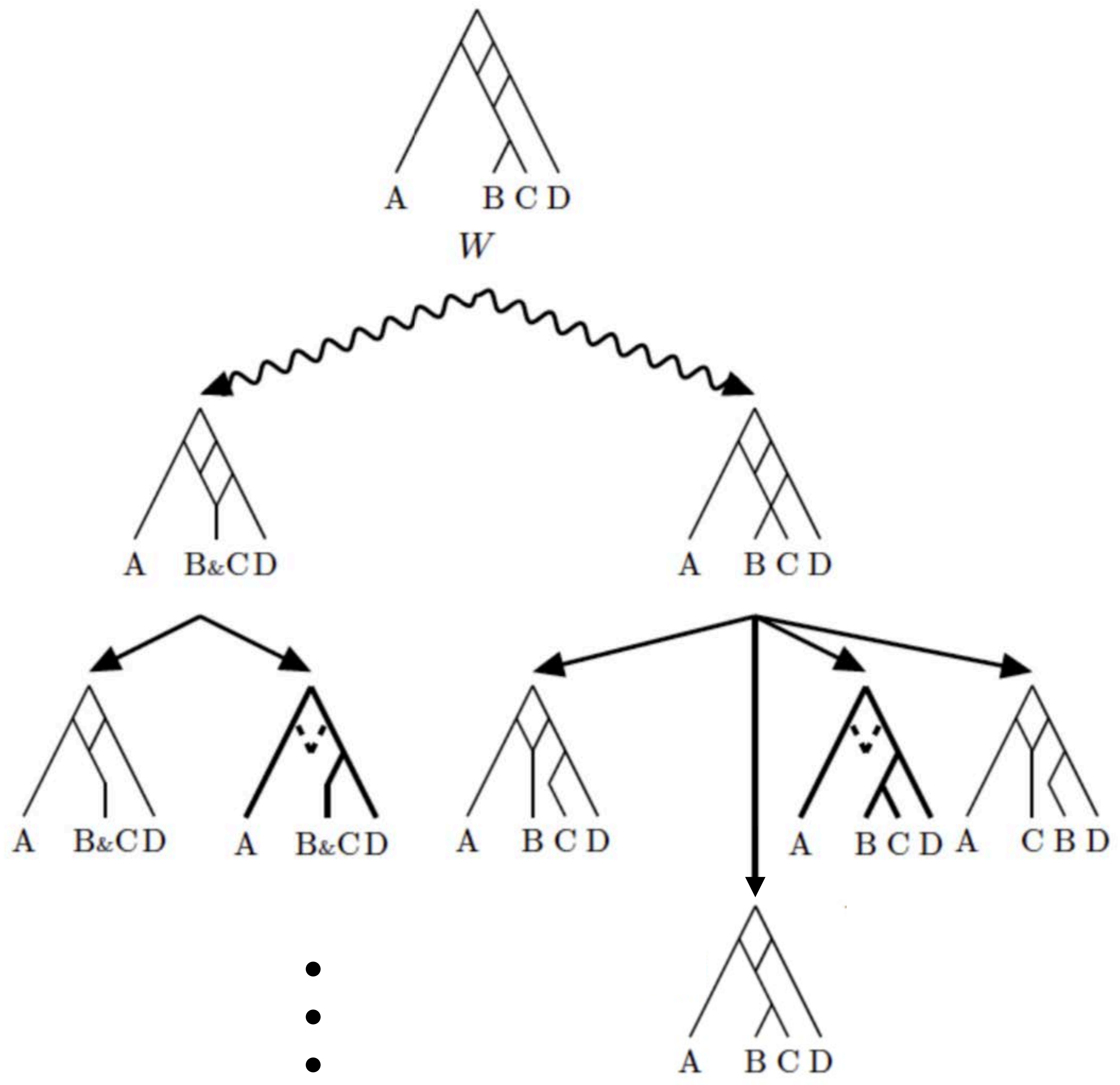
Sha Zhu[1], James H. Degnan[2]



Distinguishable under the MSC

Displayed Trees Do Not Determine Distinguishability Under the Network Multispecies Coalescent

Sha Zhu[1], James H. Degnan[2]



Decomposing network in **parental** trees

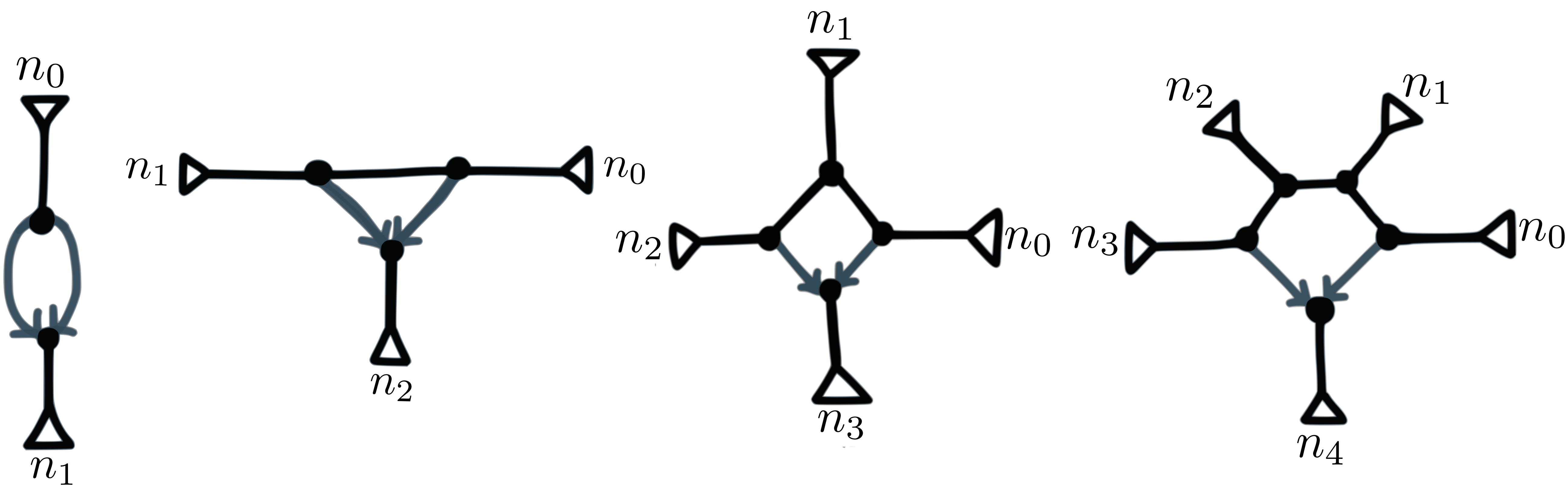
PLOS | GENETICS

RESEARCH ARTICLE

Inferring Phylogenetic Networks with Maximum Pseudolikelihood under Incomplete Lineage Sorting

Claudia Solís-Lemus[1]*, Cécile Ané[1,2]

Can we detect the presence of hybridization in level-1 networks?



No

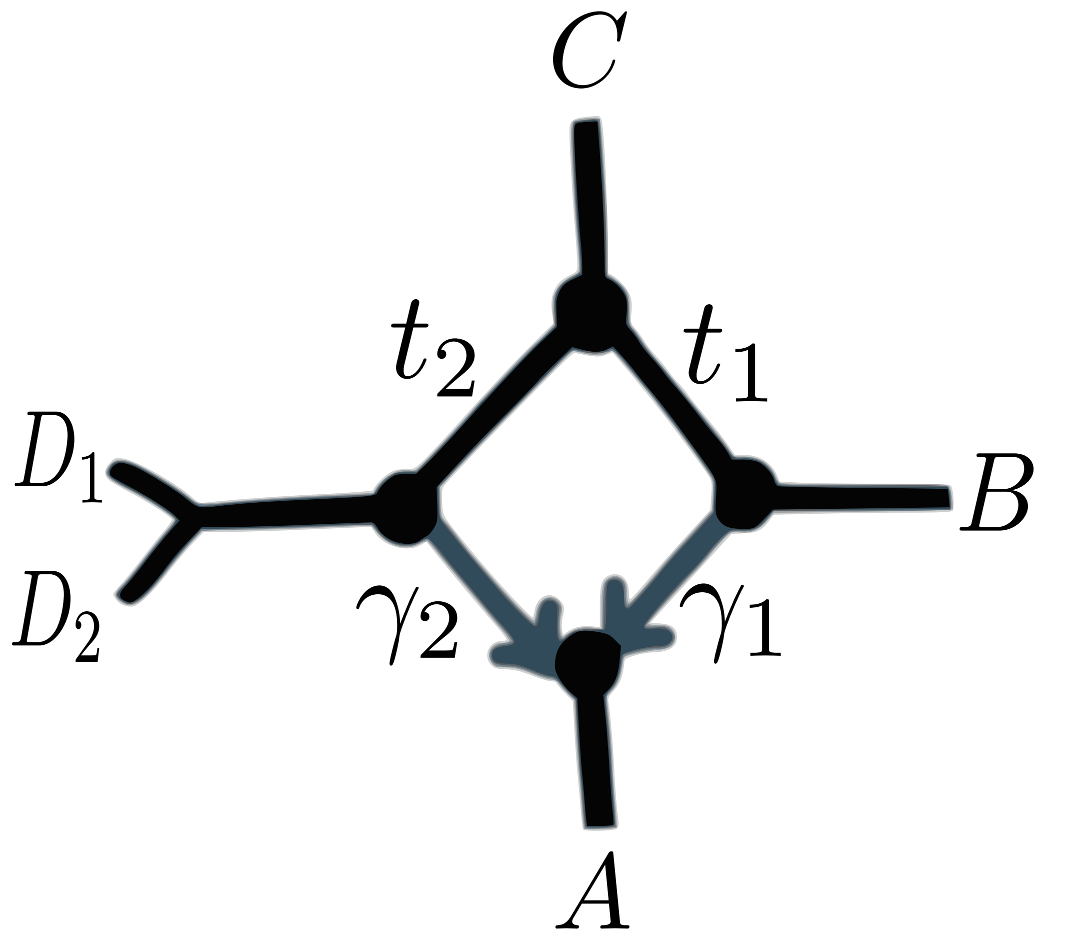
Yes $(n_i, n_j \geq 2)$

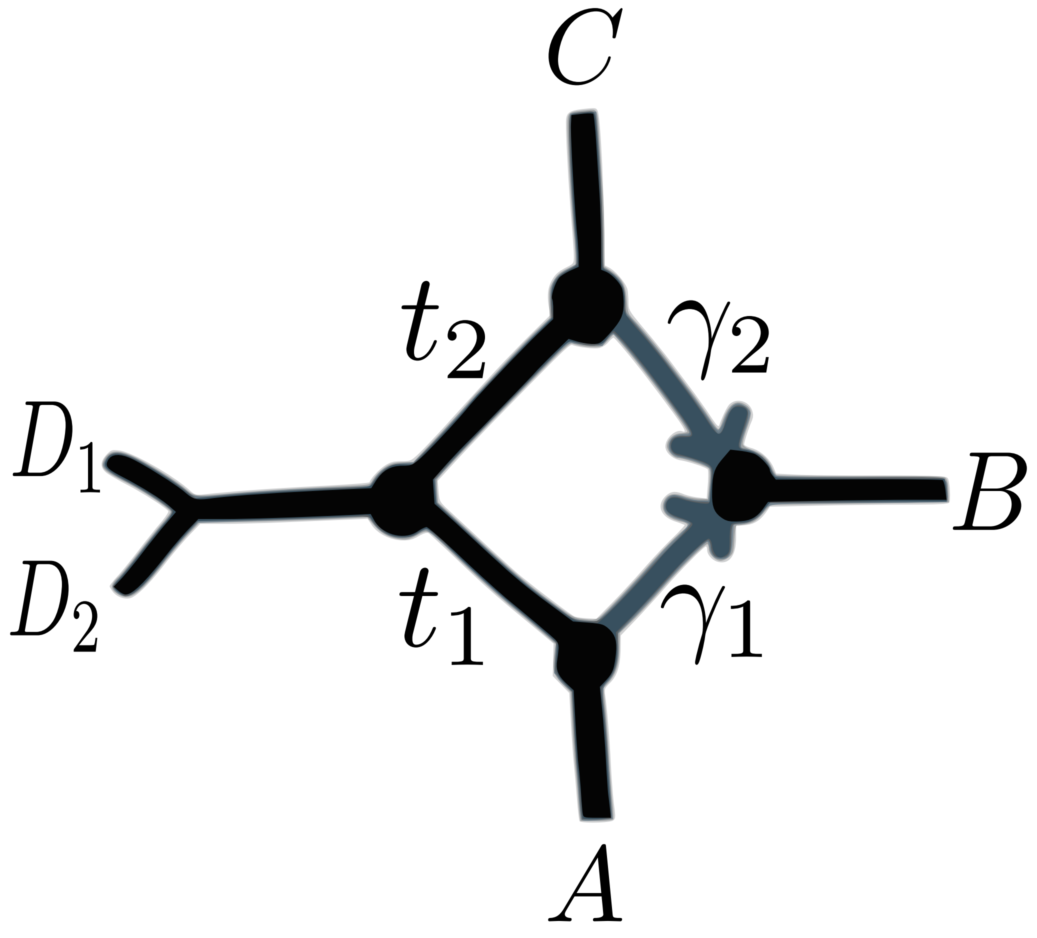
Yes $(n_i \geq 2)$

Yes

Generic Identifiability $t_i \in (0, \infty), \gamma \in (0, 1)$

In practice: flat pseudolikelihood





(S.-L., Ané, 2016, PLoS Genetics)

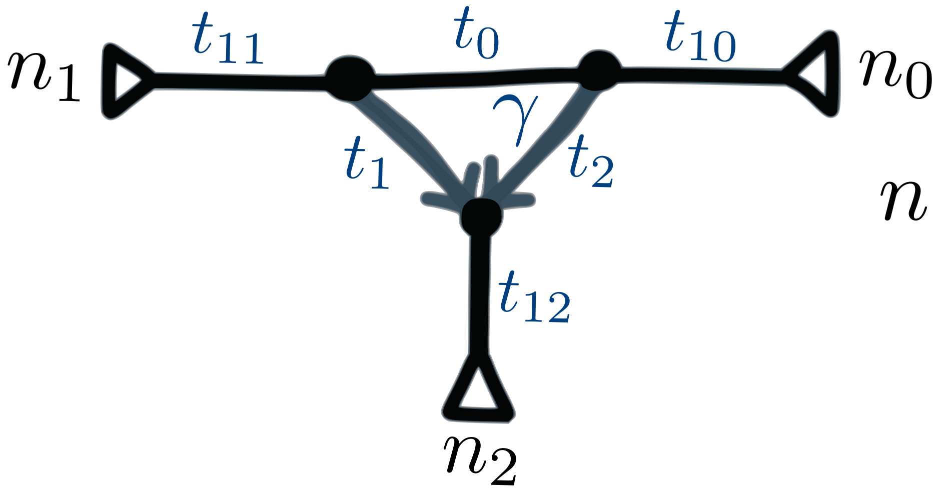
PLOS | GENETICS

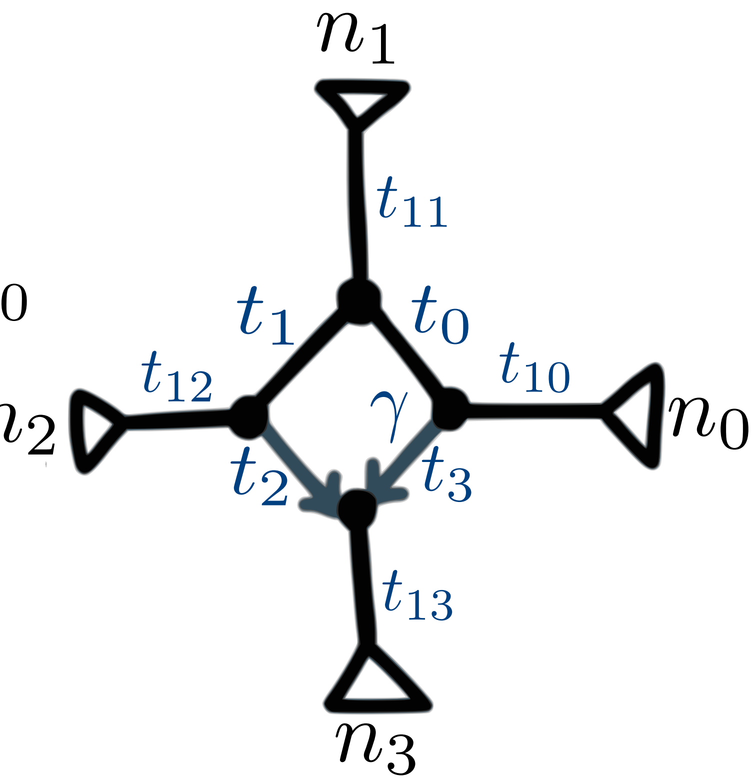
RESEARCH ARTICLE

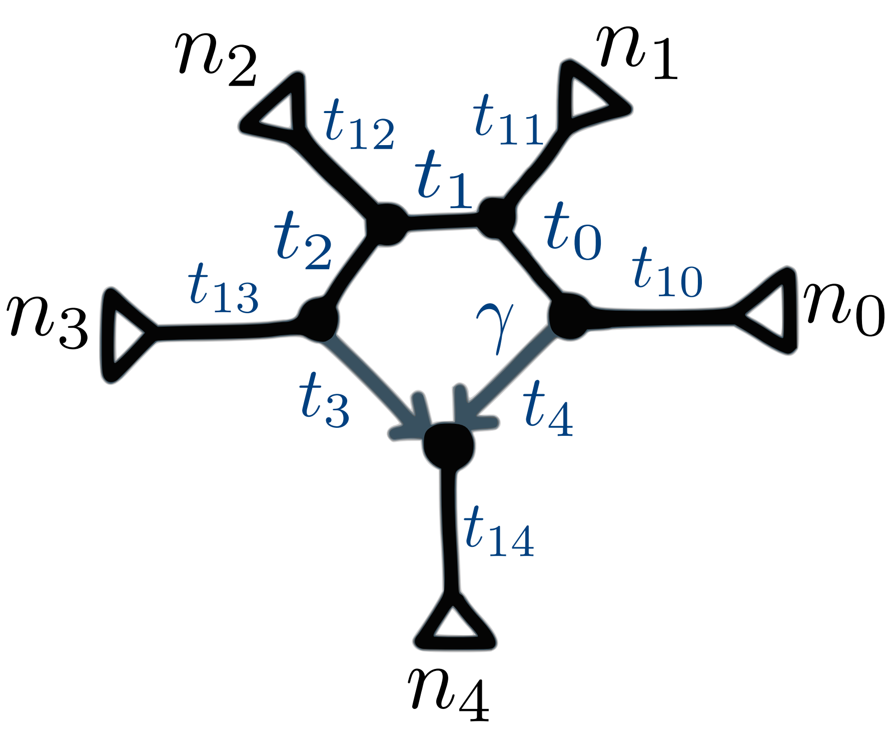
Inferring Phylogenetic Networks with Maximum Pseudolikelihood under Incomplete Lineage Sorting

Claudia Solís-Lemus[1]*, Cécile Ané[1,2]

Can we estimate numerical parameters?







No

Good triangle
($t_{12} = 0$)

Yes

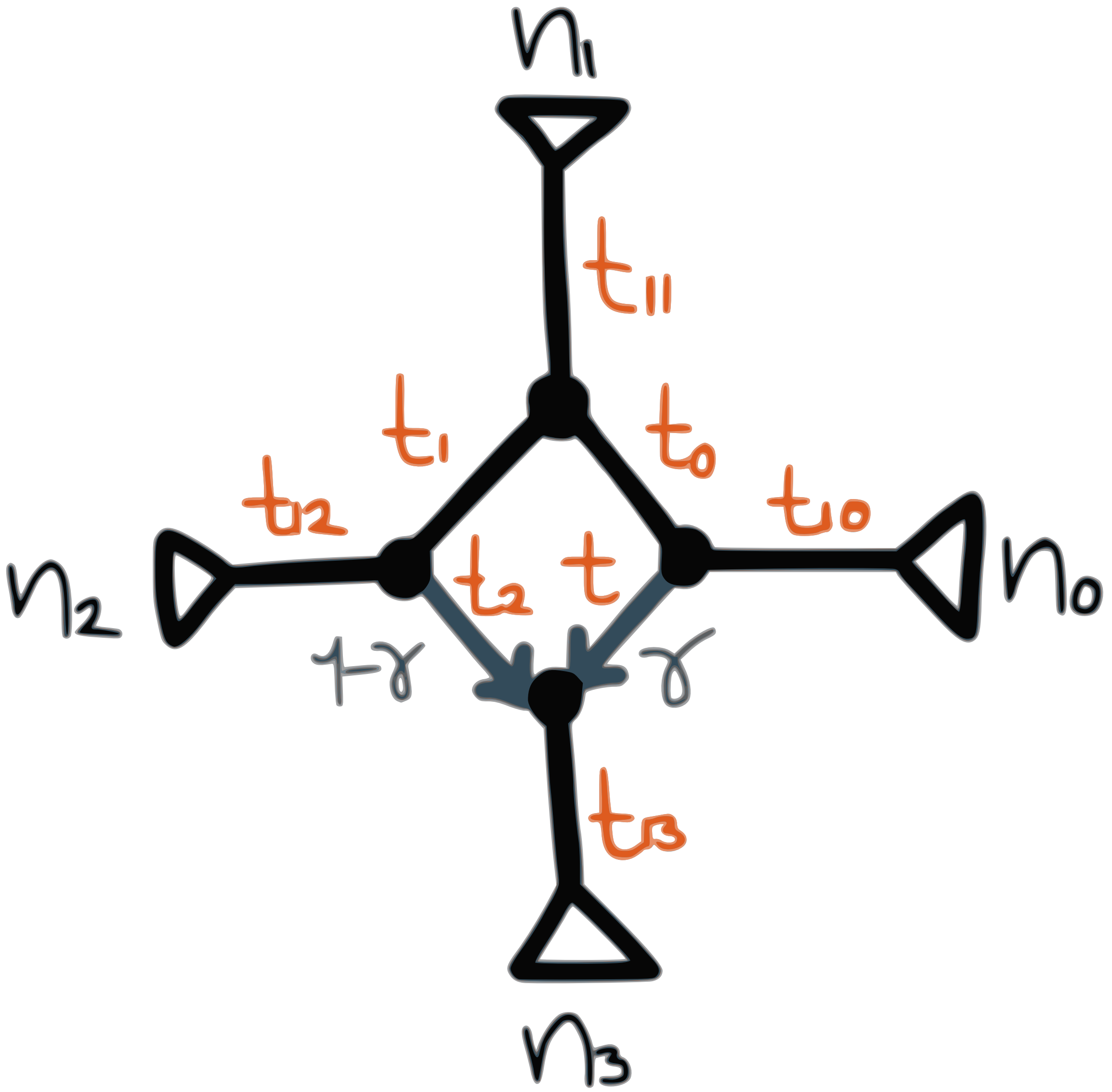
Good diamond
($n_0, n_2 \geq 2$)

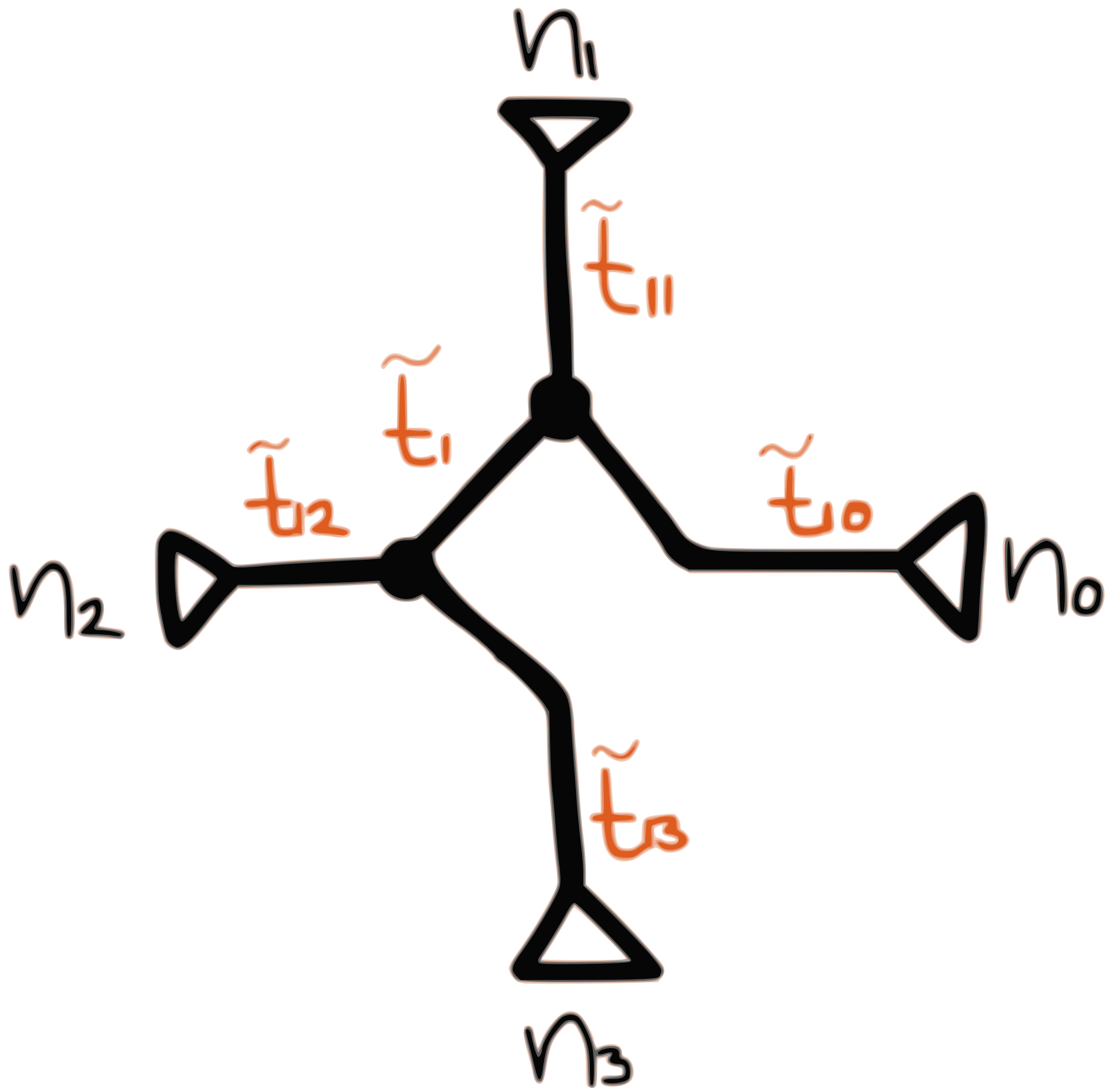
Yes

Generic Identifiability

$t_i \in (0, \infty), \gamma \in (0, 1)$

Idea of proof of identifiability: hybridization





System of equations

$\{CF_{network}\}$

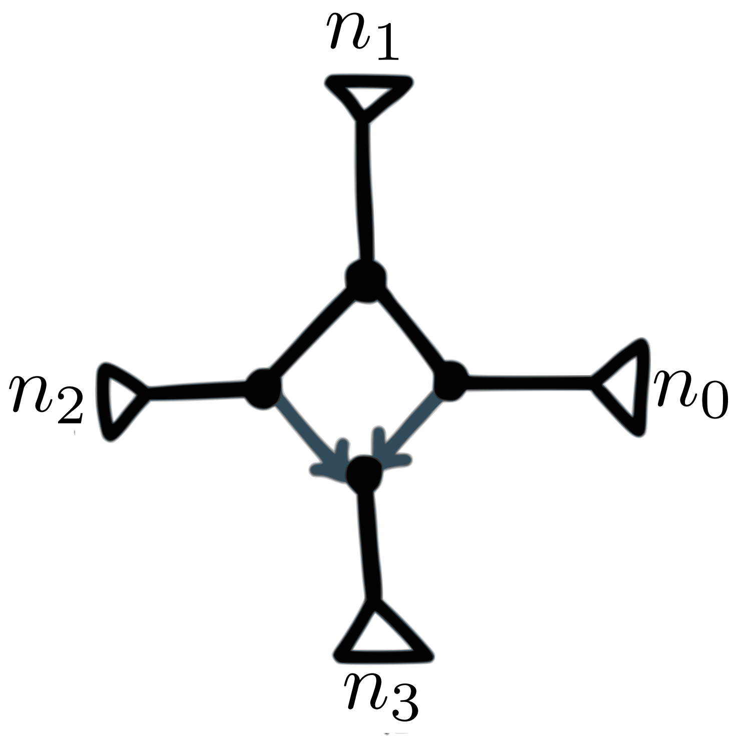
(Solís-Lemus & Ané, 2016;
Solís-Lemus et al, 2020)

System of equations

$\{CF_{tree}\}$

Can we detect the presence of hybridization in level-1 networks?

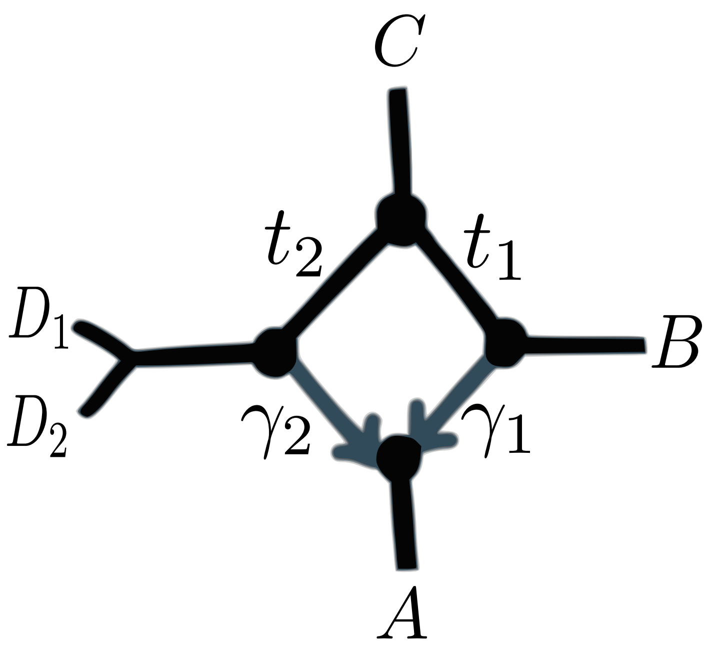
In theory

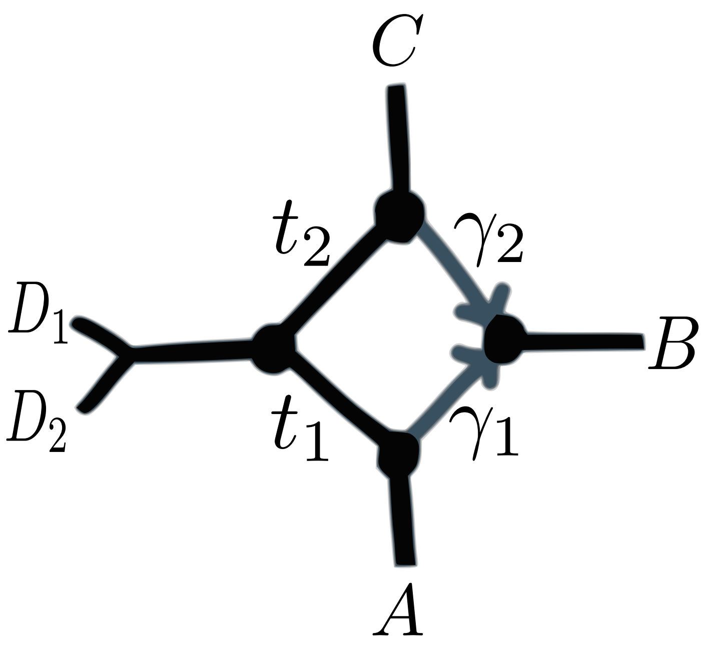


Yes

$(n_i \geq 2)$

In practice

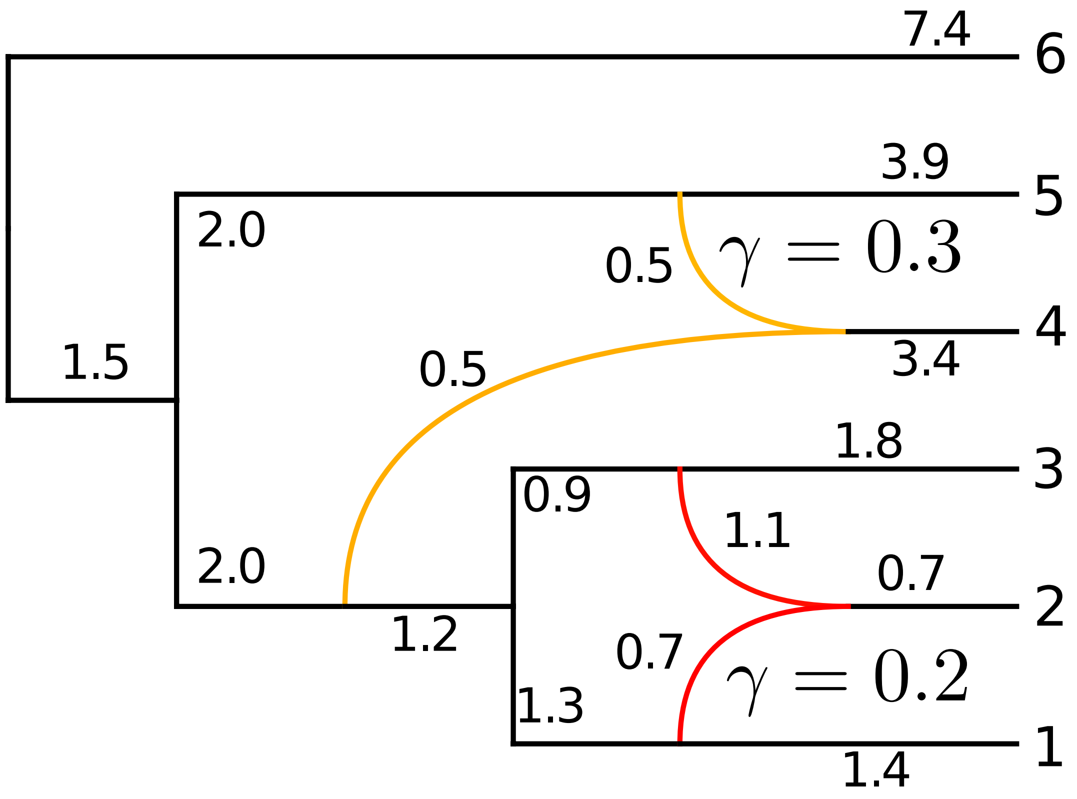




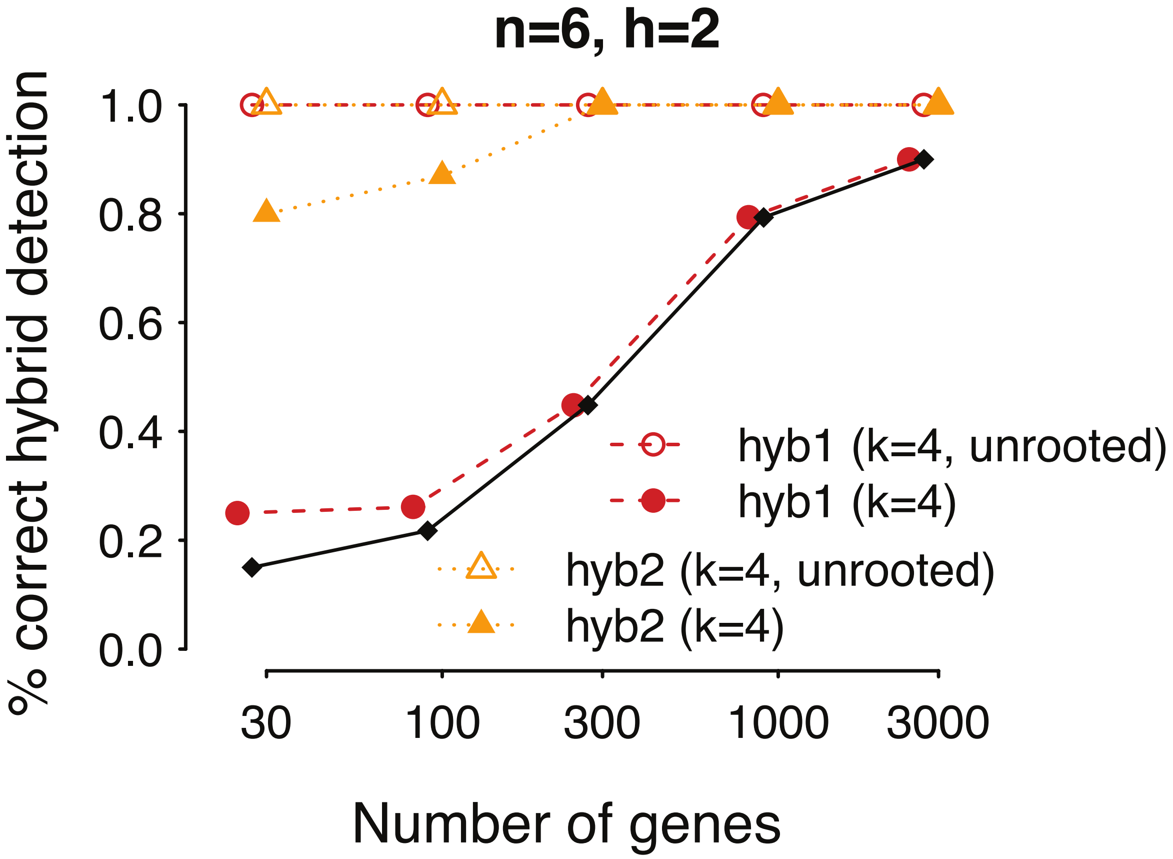
Sometimes

Identifiability matters: SNaQ performance

Good diamond



Bad diamond



(S.-L., Ané, 2016, PLoS Genetics)

Network challenges

- Scalability
- Identifiability
- Network space
- Network comparison

Displayed vs Parental trees
Level-1 semi-directed networks
Hybridizations: case by case
Missing: likelihood, level-k semi-directed

Network challenges

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Level-1 semi-directed networks
Hybridizations: case by case
Missing: likelihood, level-k semi-directed

K. Huber, V. Moulton, C. Scornavacca,…
Missing: path through tree space, semi-directed

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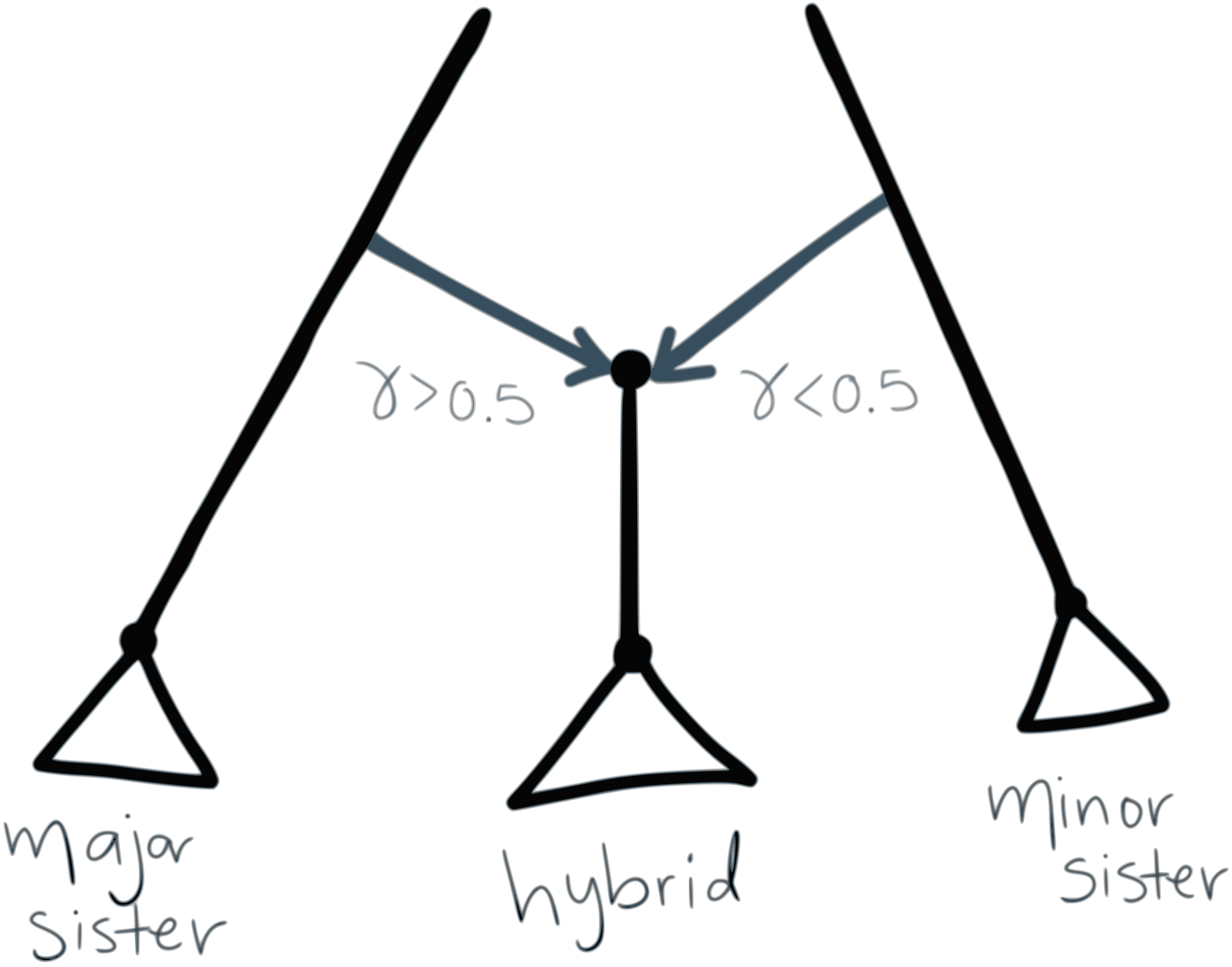
Displayed vs Parental trees
Level-1 semi-directed networks
Hybridizations: case by case
Missing: likelihood, level-k semi-directed

K. Huber, V. Moulton, C. Scornavacca,…
Missing: path through tree space, semi-directed

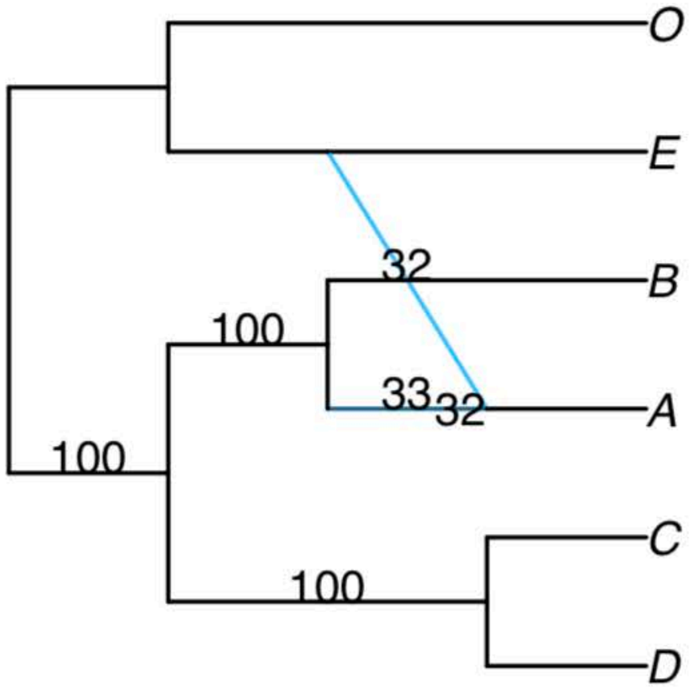
Missing: distance function
Hardwired-cluster distance only for rooted networks
Summary of networks: clades!

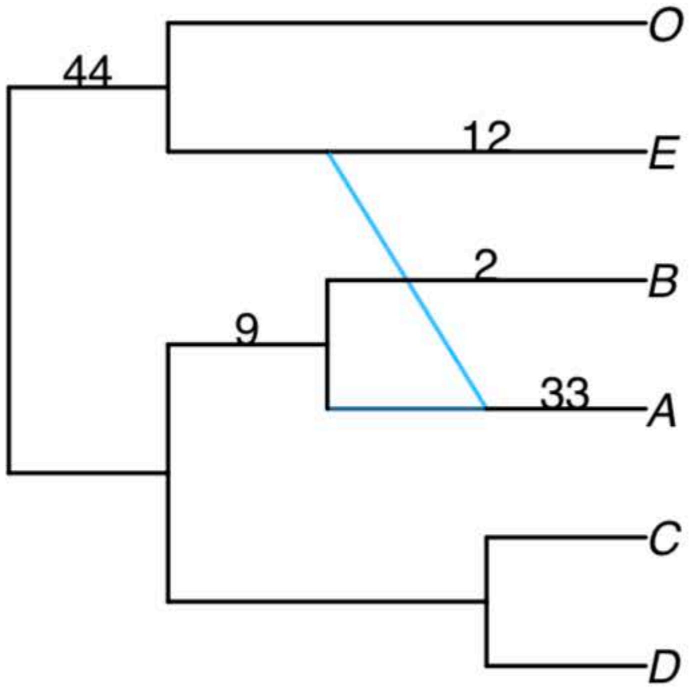
Network summary



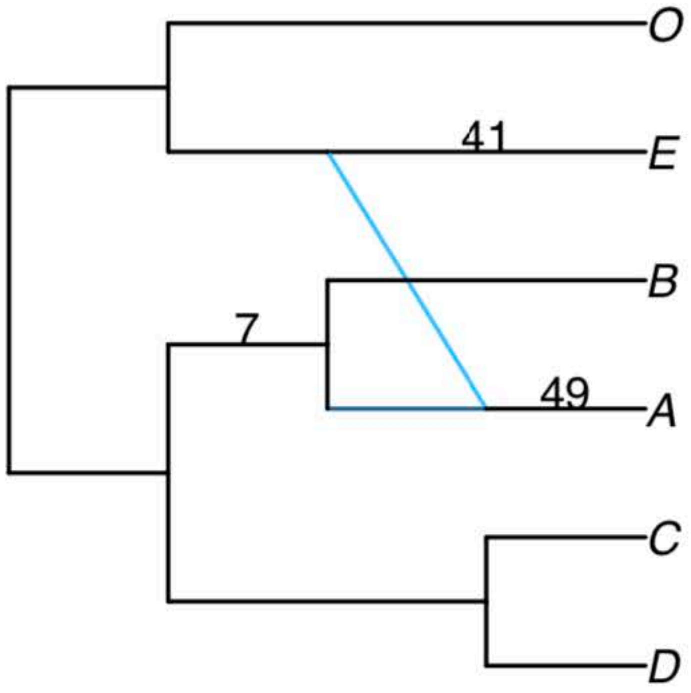
(S.-L. et al, 2017, MBE)

Network summary





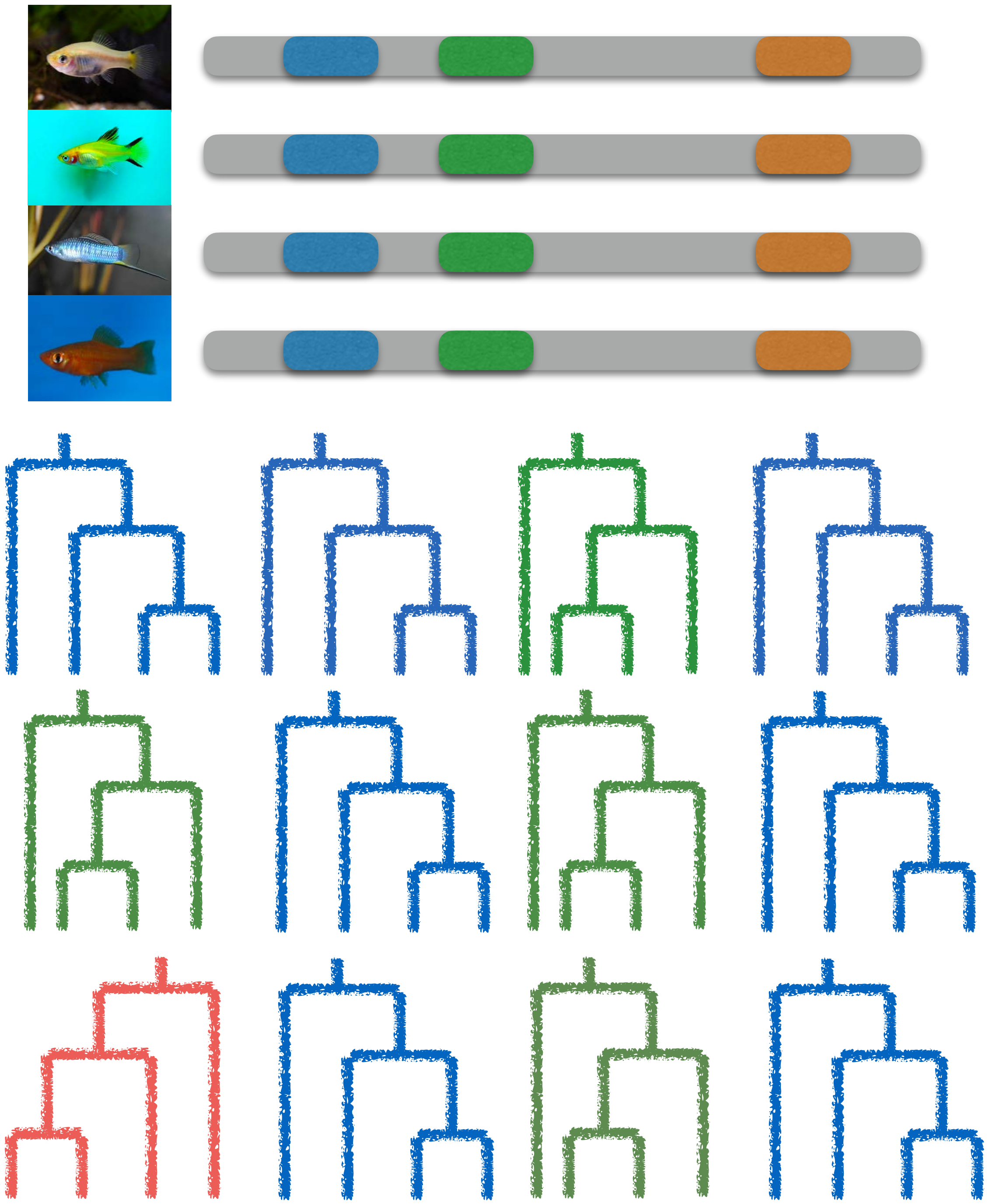
Hybrid clades



Minor sister clades

When?

Phylogenetic network



Data

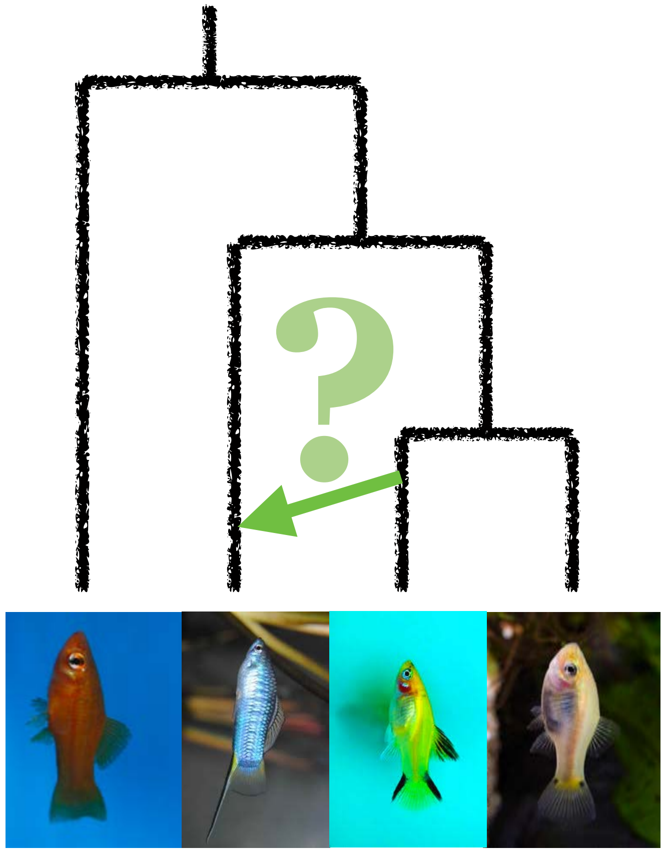
Goodness-of-fit test

Hypothesis test:

Is a tree a good fit?

TICR

GitHub



`https://github.com/nstenz/TICR`

(Stenz et al, 2015, Syst Bio)

Practical advice

- Do multiple runs
- Do bootstrap
- Check the .networks output file (especially if hybridization conflicts with outgroup)
- What is the quality of my input data (gene trees/CFs)?
- Run SNaQ sequentially: h=0, h=1, h=2,…

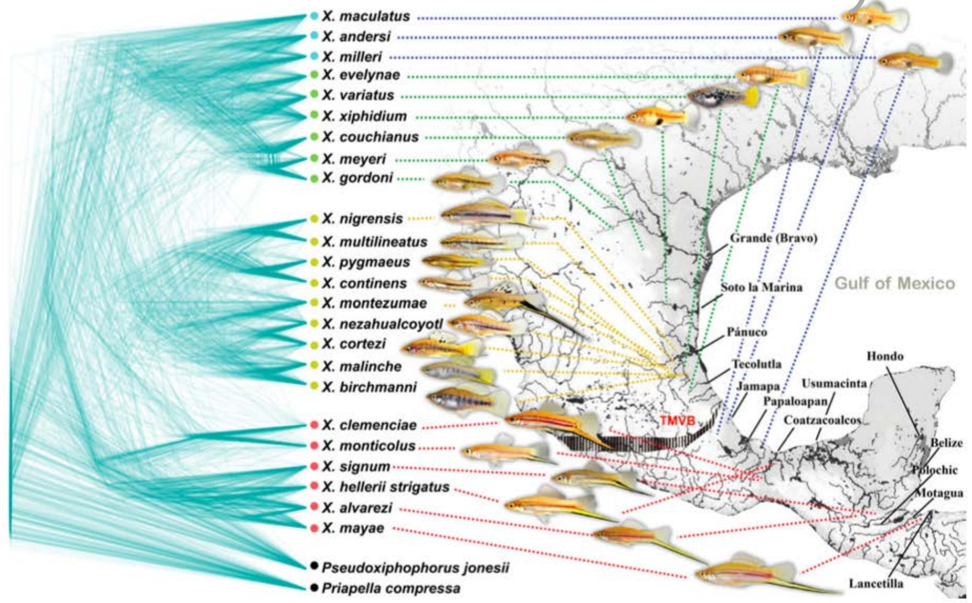
Practical advice

- Do multiple runs
- Do bootstrap
- Check the .networks output file (especially if hybridization conflicts with outgroup)
- What is the quality of my input data (gene trees/CFs)?
- Run SNaQ sequentially: h=0, h=1, h=2,…

When to stop?
(Cai and Ané, 2020)

Part II

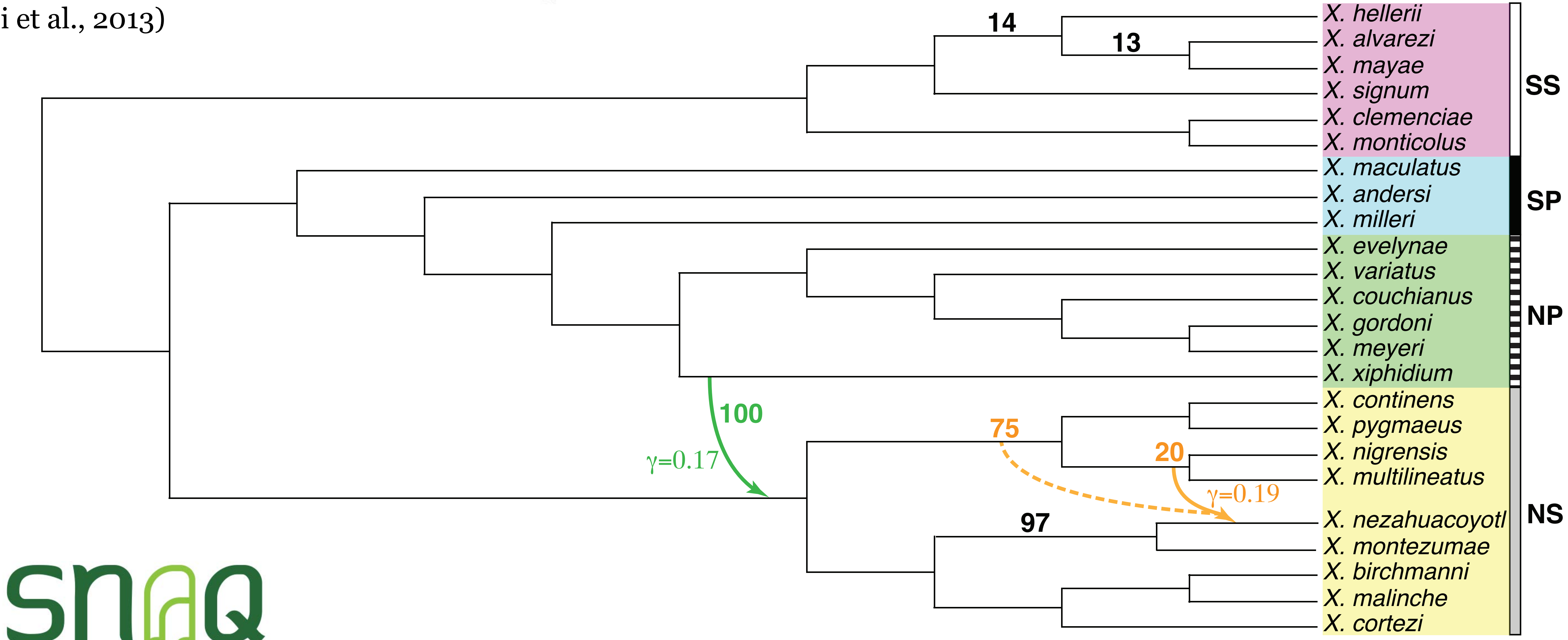
I have the network, now what?



(Cui et al., 2013)

1183 genes,
24 swordtails
and platyfish

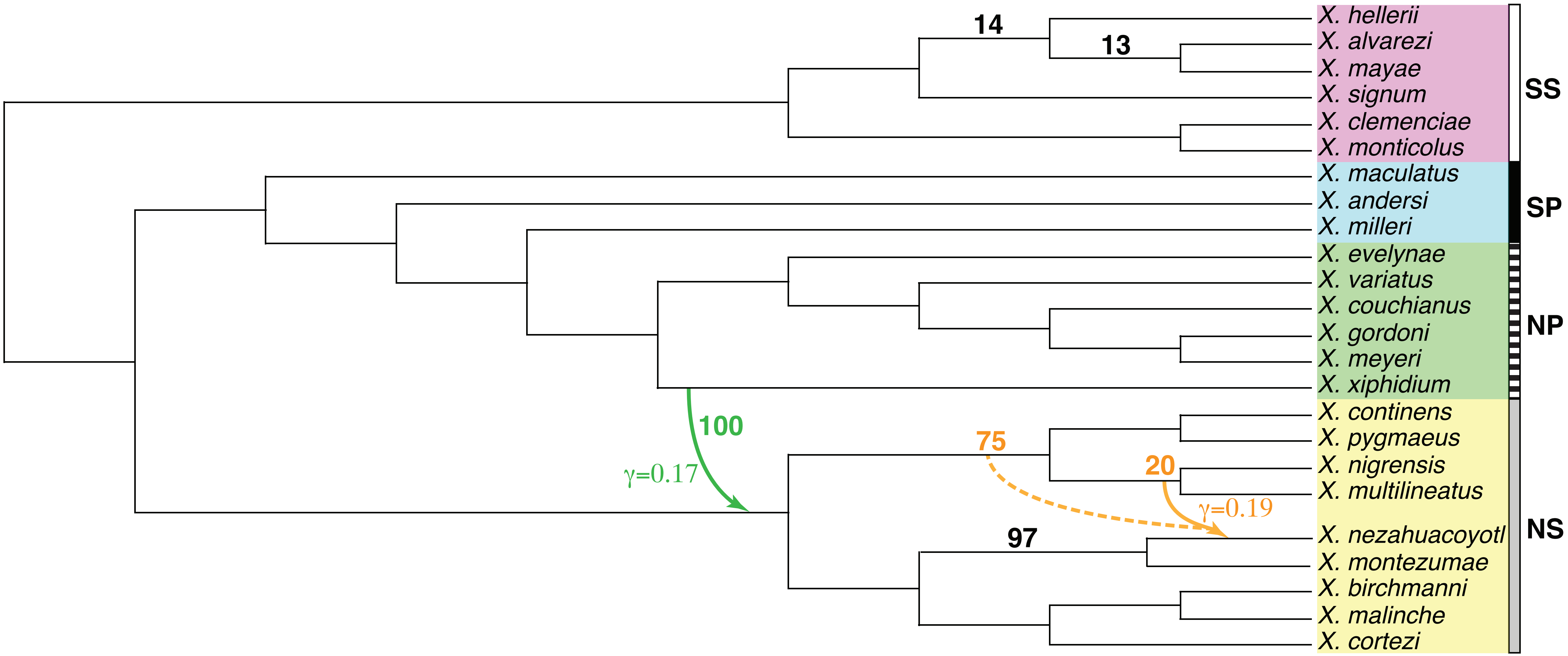
Xiphophorus fish data



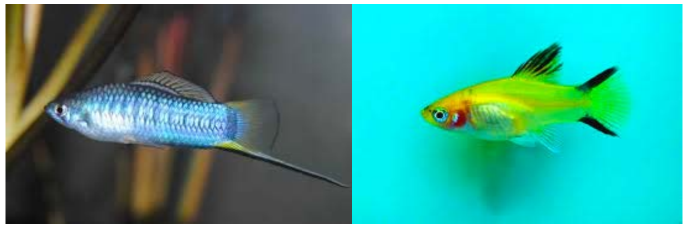
(Solís-Lemus, Ané, 2016, PLoS Genetics)

Part II

I have the network, now what?

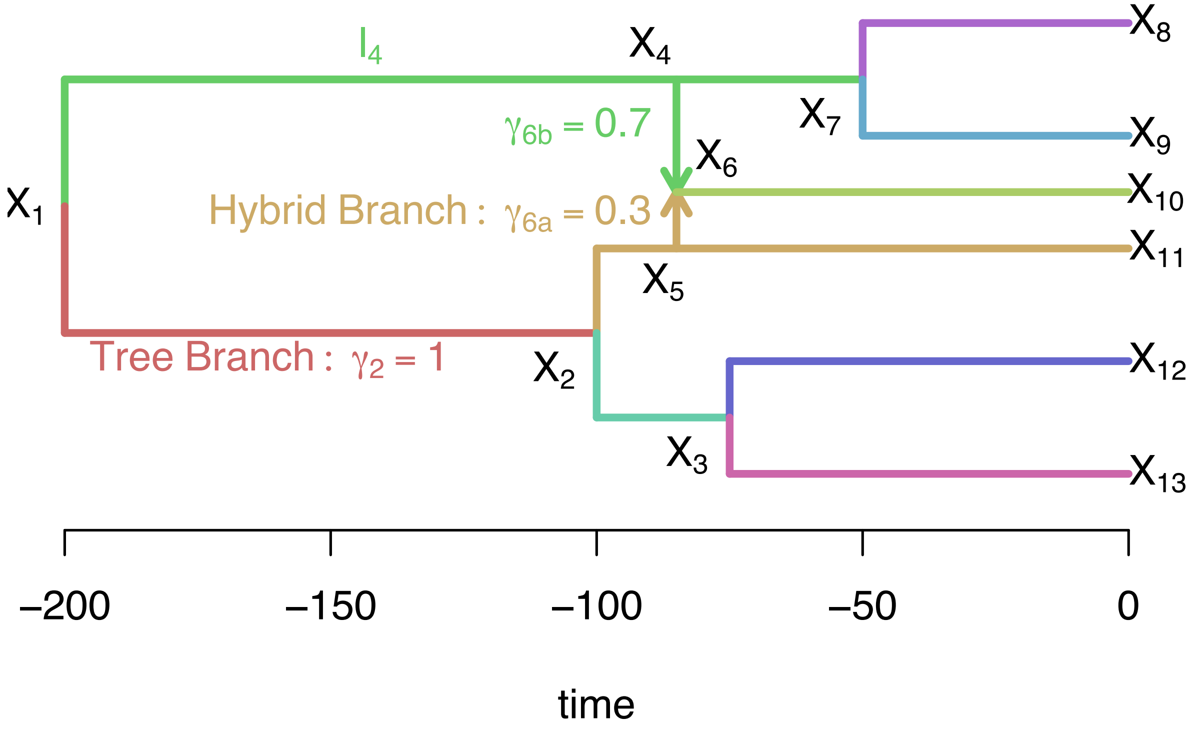


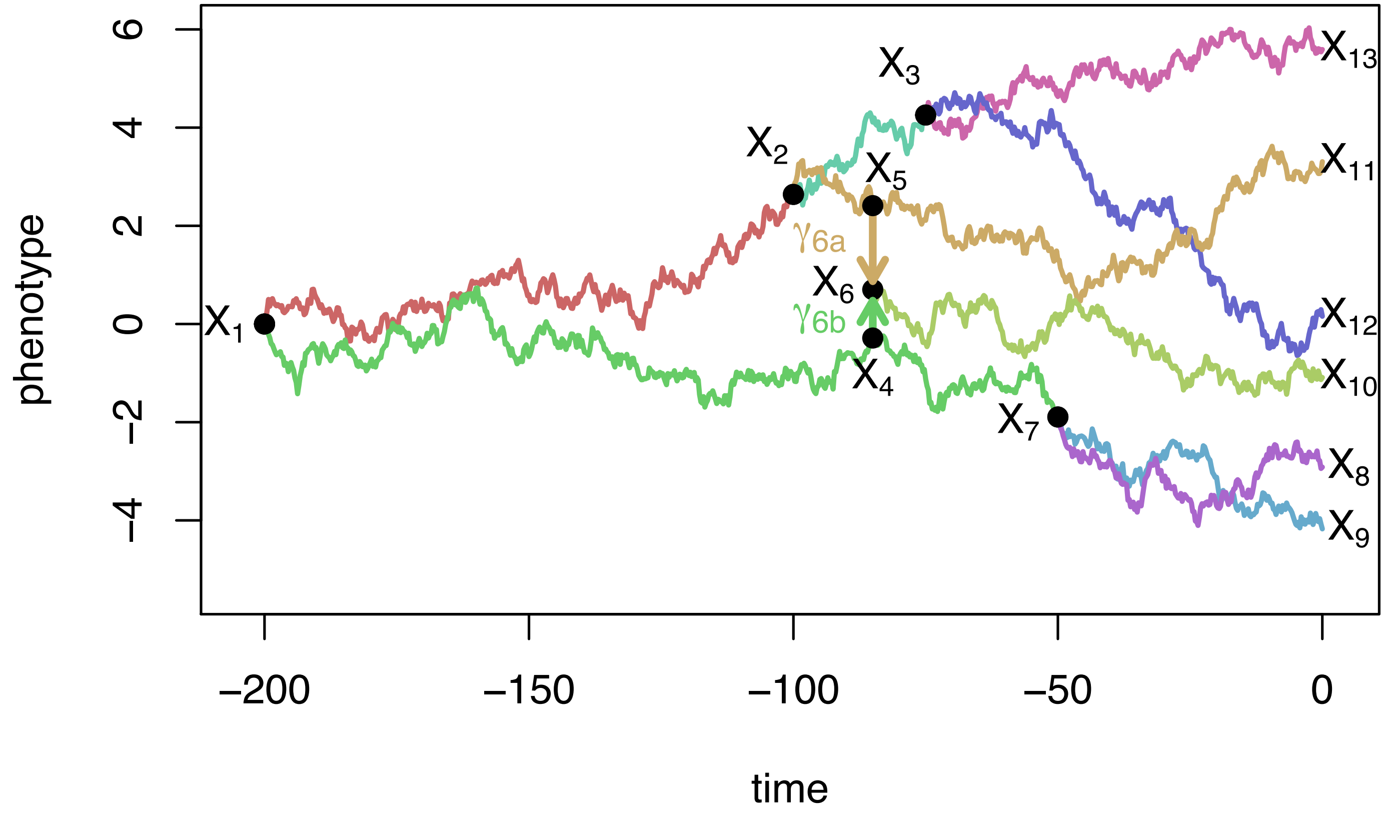
- Sword index
- Female preference



(Cui et al., 2013)
(Solís-Lemus, Ané, 2016, PLoS Genetics)

Trait models of evolution in networks





Brownian Motion
+ weighted
average in hybrid

$$X_h = \gamma_1 X_{p_1} + \gamma_2 X_{p_2}$$

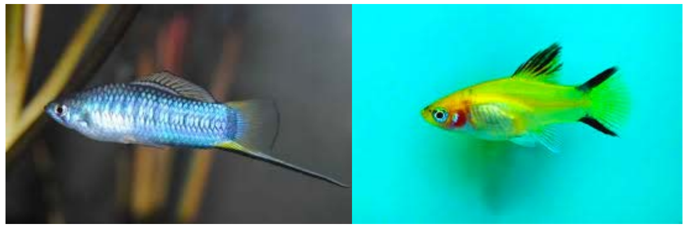
(Bastide et al, 2018, Syst Bio)

$$\mathbf{X} \sim N(X_{root}, \sigma^2 \mathbf{V})$$

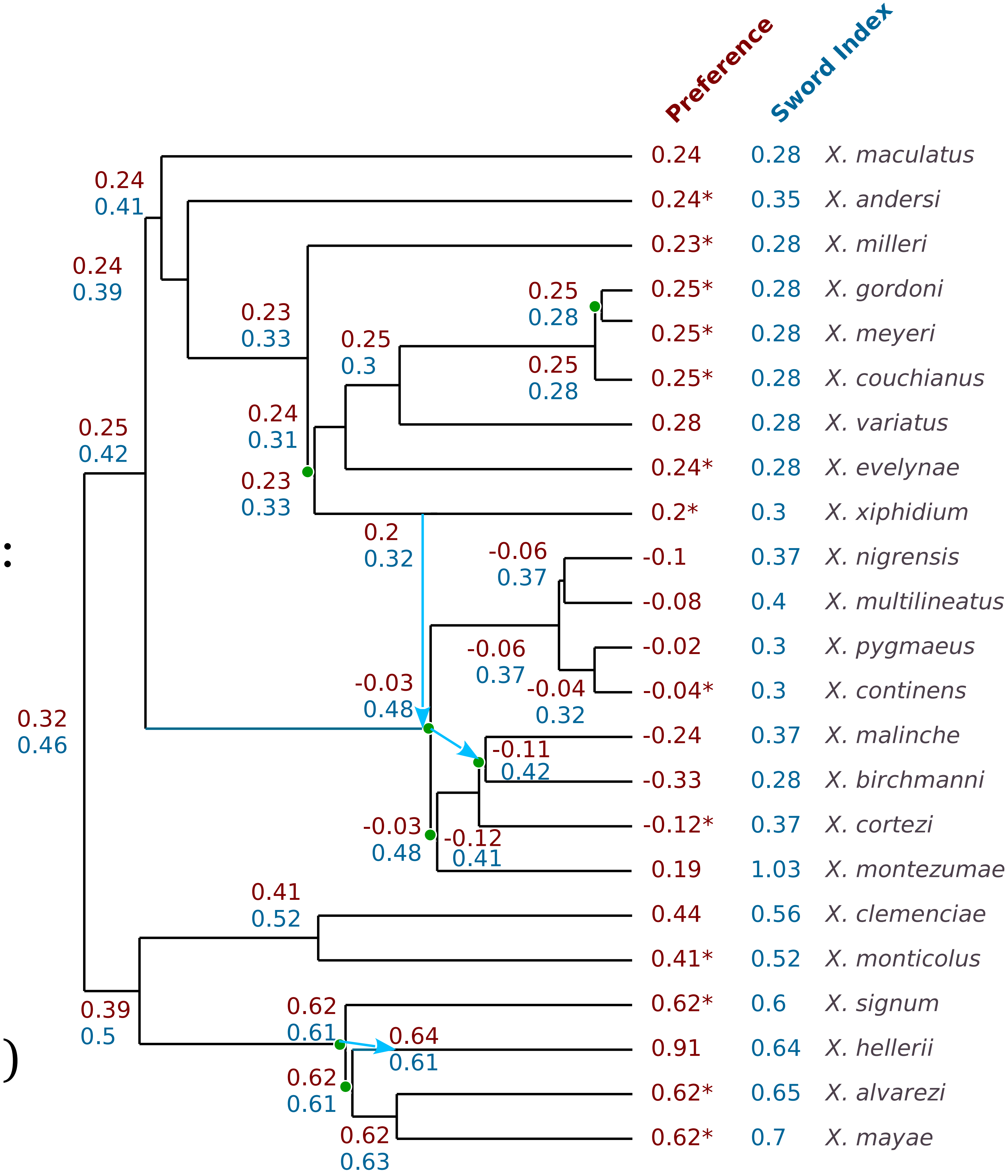
- Phylogenetic signal
- Ancestral reconstruction
- Phylogenetic regression
- Phylogenetic ANOVA

`www.github.com/CRSL4/PhyloNetworks`

- Sword index
- Female preference



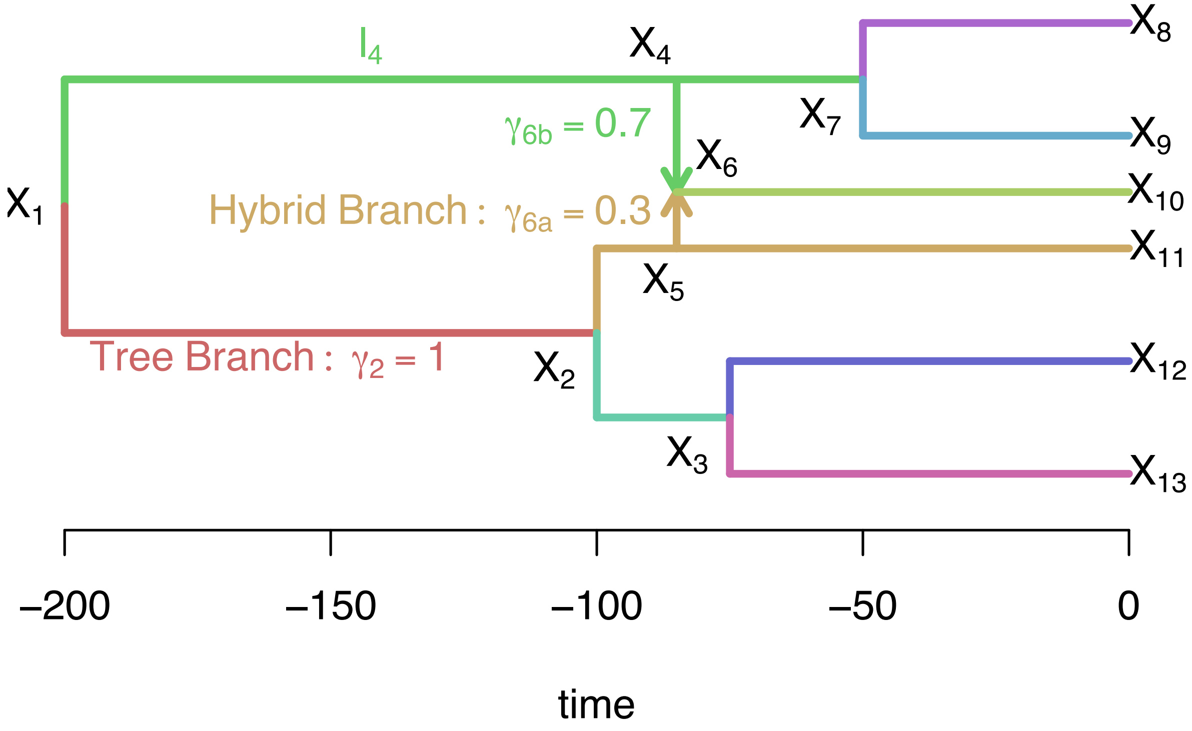
- **Ancestral reconstruction**: common ancestor likely had sword
- **Phylogenetic regression:** positive association between sword index and female preference but not significant (p = 0.106)

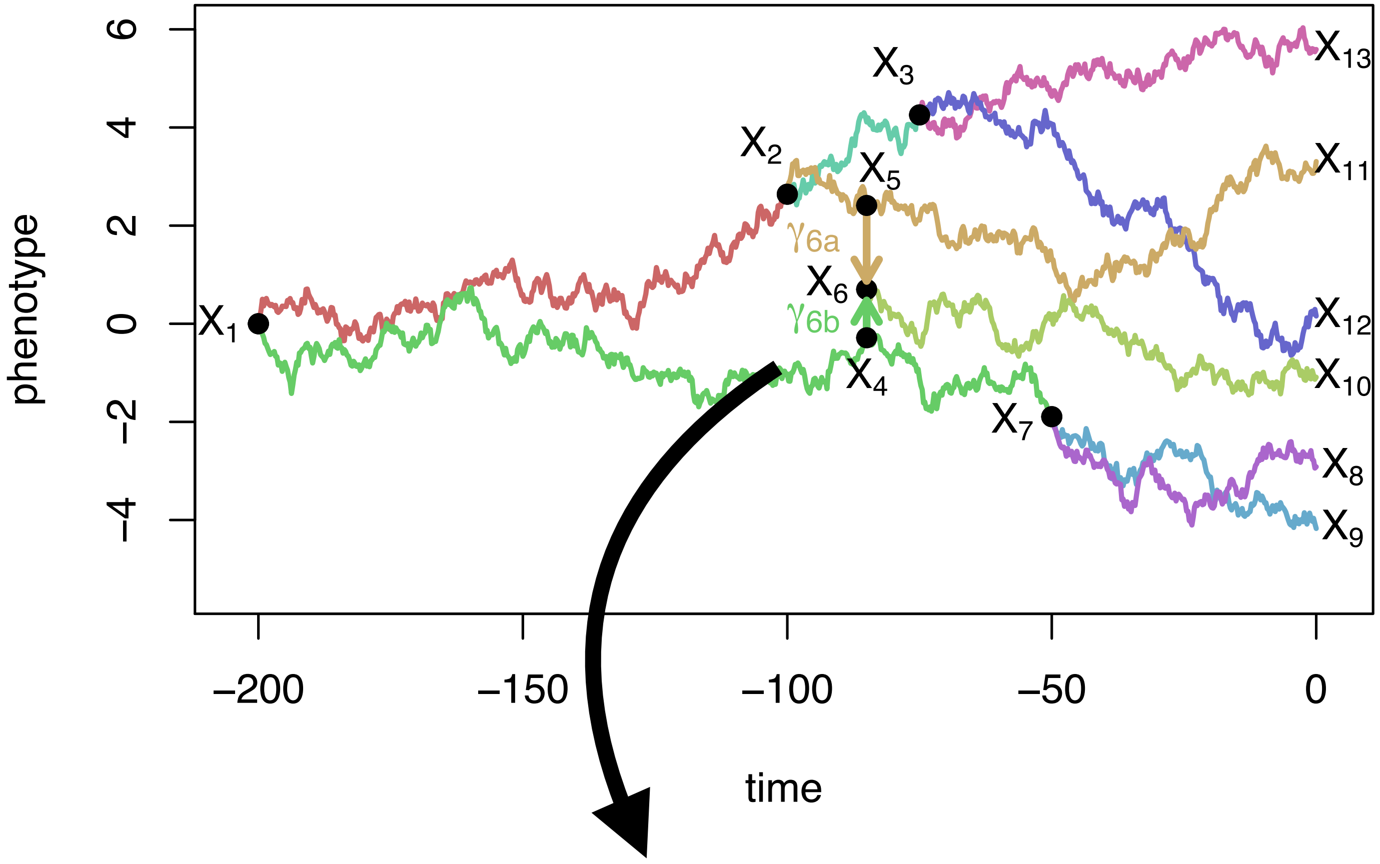


Preference	Sword Index	
0.24	0.28	*X. maculatus*
0.24*	0.35	*X. andersi*
0.23*	0.28	*X. milleri*
0.25*	0.28	*X. gordoni*
0.25*	0.28	*X. meyeri*
0.25*	0.28	*X. couchianus*
0.28	0.28	*X. variatus*
0.24*	0.28	*X. evelynae*
0.2*	0.3	*X. xiphidium*
-0.1	0.37	*X. nigrensis*
-0.08	0.4	*X. multilineatus*
-0.02	0.3	*X. pygmaeus*
-0.04*	0.3	*X. continens*
-0.24	0.37	*X. malinche*
-0.33	0.28	*X. birchmanni*
-0.12*	0.37	*X. cortezi*
0.19	1.03	*X. montezumae*
0.44	0.56	*X. clemenciae*
0.41*	0.52	*X. monticolus*
0.62*	0.6	*X. signum*
0.91	0.64	*X. hellerii*
0.62*	0.65	*X. alvarezi*
0.62*	0.7	*X. mayae*

Test for transgressive evolution

$$X_h = \gamma_1 X_{p_1} + \gamma_2 X_{p_2} + \Delta_h$$





$\Delta_h = 0$ No transgressive evolution

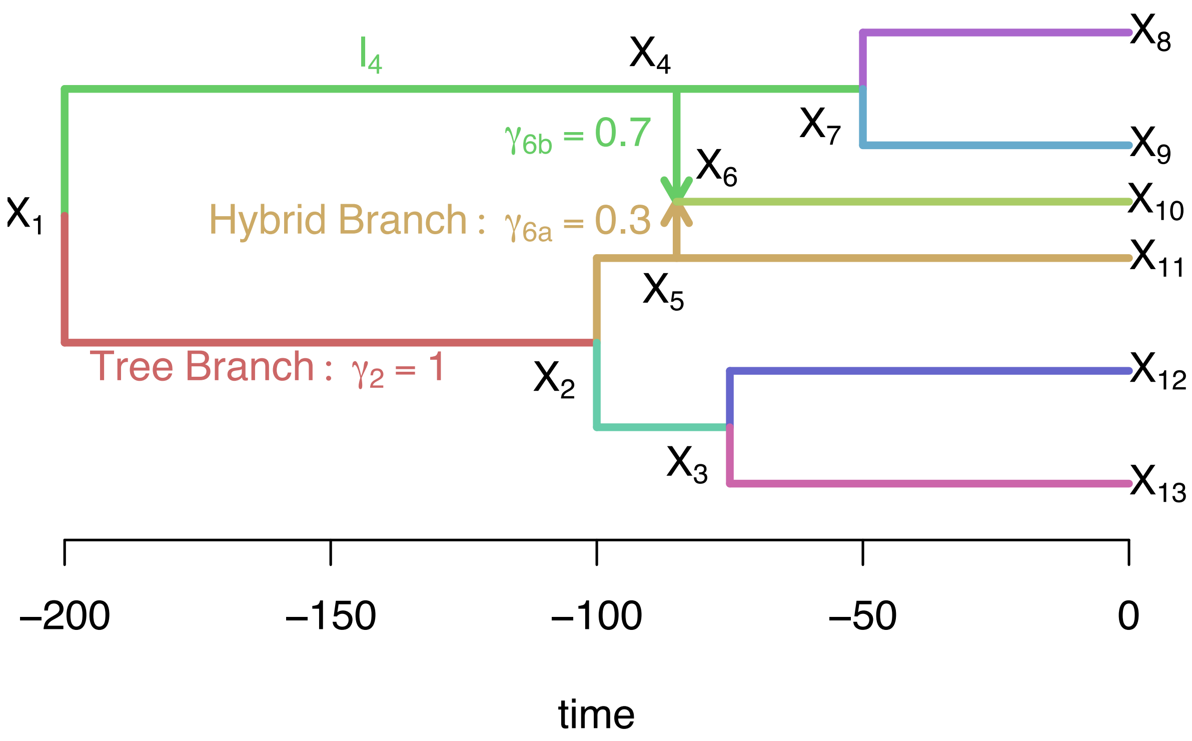
$\Delta_h = \Delta$ Single-effect transgressive evolution

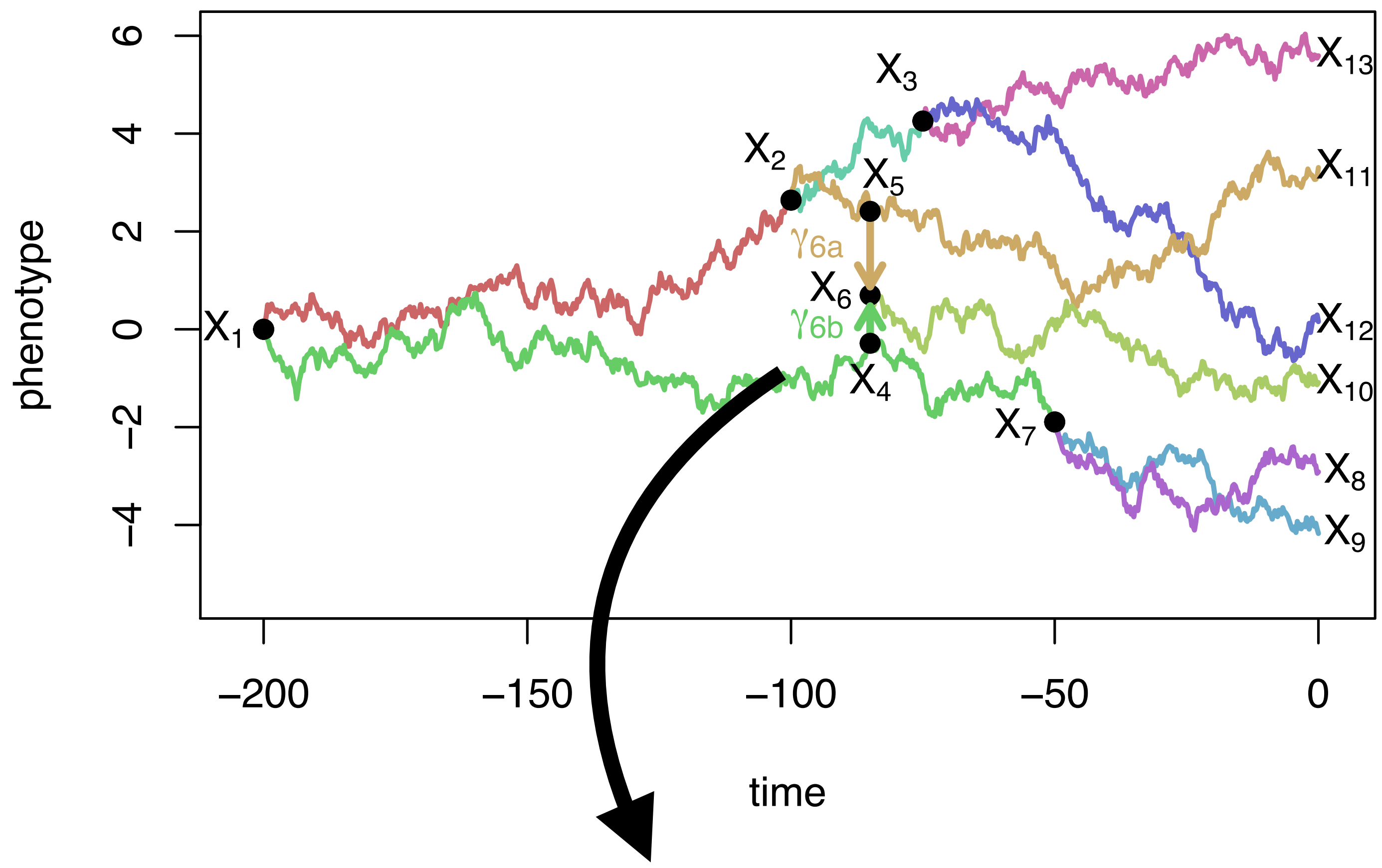
Δ_h Multi-effect transgressive evolution

F tests

Hybrid value:
shift from
parents range

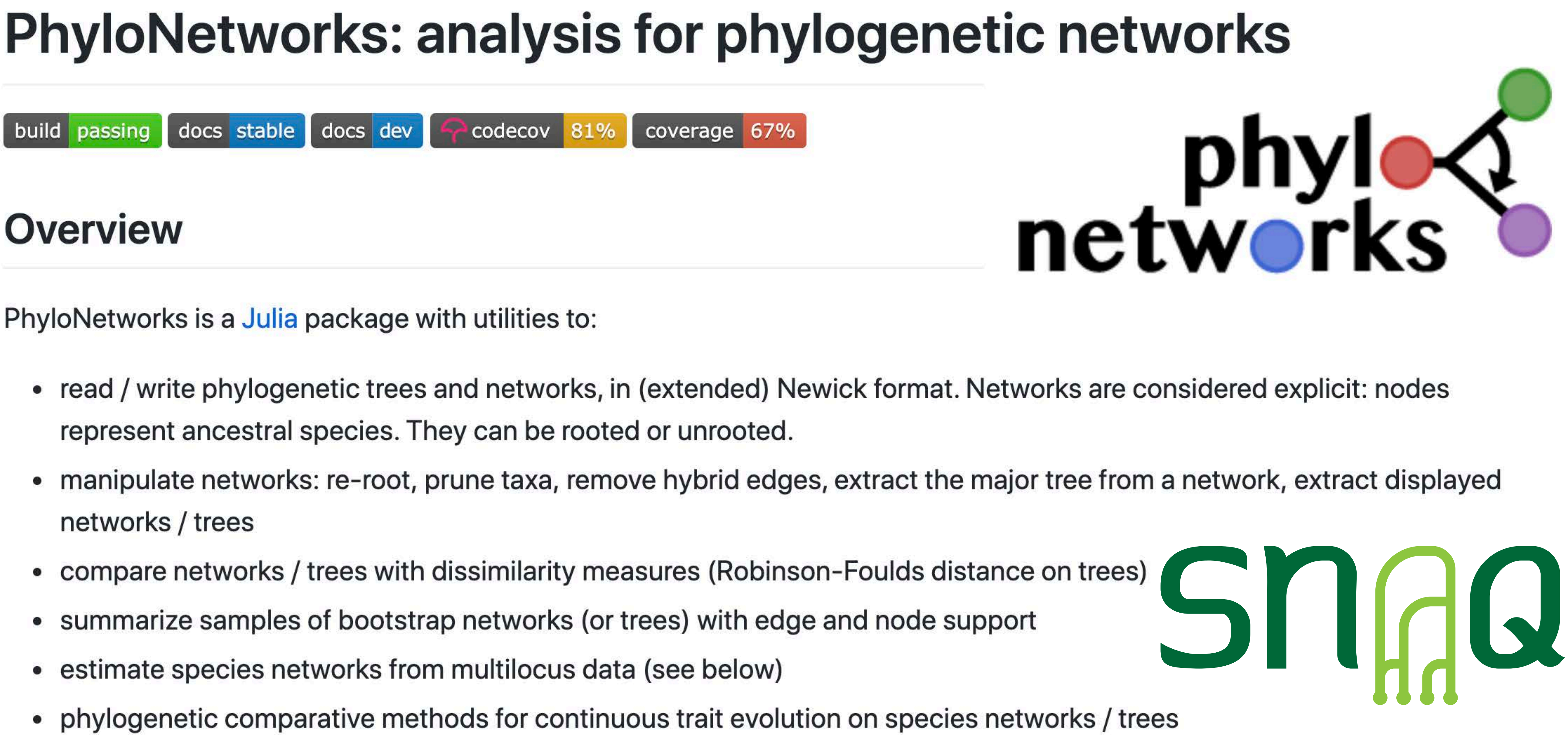
Test for transgressive evolution





- Sword index: p=0.55
- Female preference: p=0.0064

Hybrid value: shift from parents range



PhyloNetworks: analysis for phylogenetic networks

build passing | docs stable | docs dev | codecov 81% | coverage 67%

Overview

PhyloNetworks is a Julia package with utilities to:

- read / write phylogenetic trees and networks, in (extended) Newick format. Networks are considered explicit: nodes represent ancestral species. They can be rooted or unrooted.
- manipulate networks: re-root, prune taxa, remove hybrid edges, extract the major tree from a network, extract displayed networks / trees
- compare networks / trees with dissimilarity measures (Robinson-Foulds distance on trees)
- summarize samples of bootstrap networks (or trees) with edge and node support
- estimate species networks from multilocus data (see below)
- phylogenetic comparative methods for continuous trait evolution on species networks / trees

GitHub

- Step-by-step tutorial
- Online documentation
- Google user group

(Solis-Lemus & Ane, 2016; Solis-Lemus. et al, 2017)

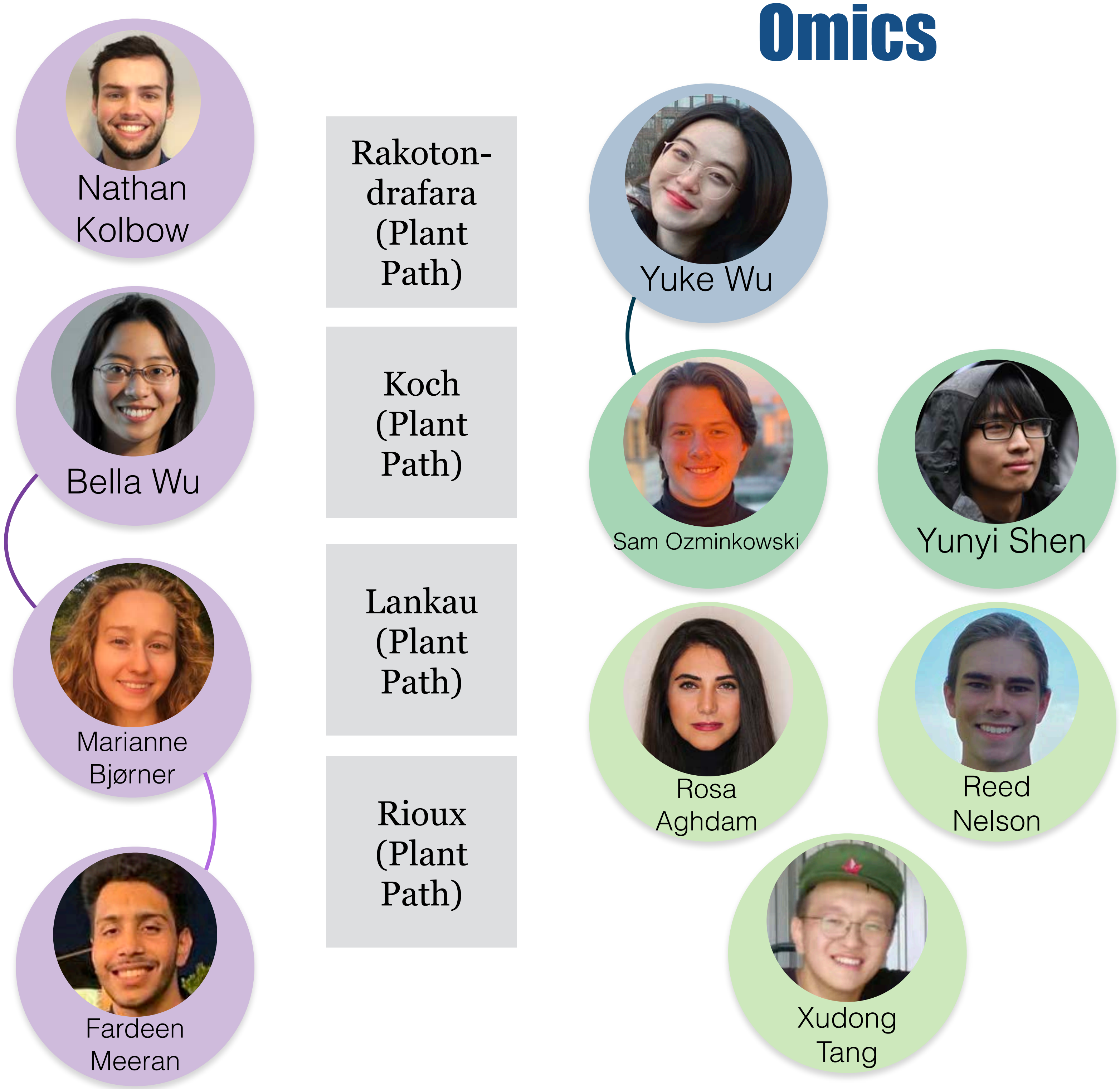
https://solislemuslab.github.io/ @solislemuslab crsl4 @thestatistician

Join us: Positions available in the lab!

New collaborations welcome!

Omics

Phylogenomics



Nathan Kolbow

Bella Wu

Marianne Bjørner

Fardeen Meeran

Rakoton-drafara (Plant Path)

Koch (Plant Path)

Lankau (Plant Path)

Rioux (Plant Path)

Yuke Wu

Sam Ozminkowski

Yunyi Shen

Rosa Aghdam

Reed Nelson

Xudong Tang

Microbiome

Thank you!

http://solislemuslab.github.io/ @solislemuslab crsl4