Physalia

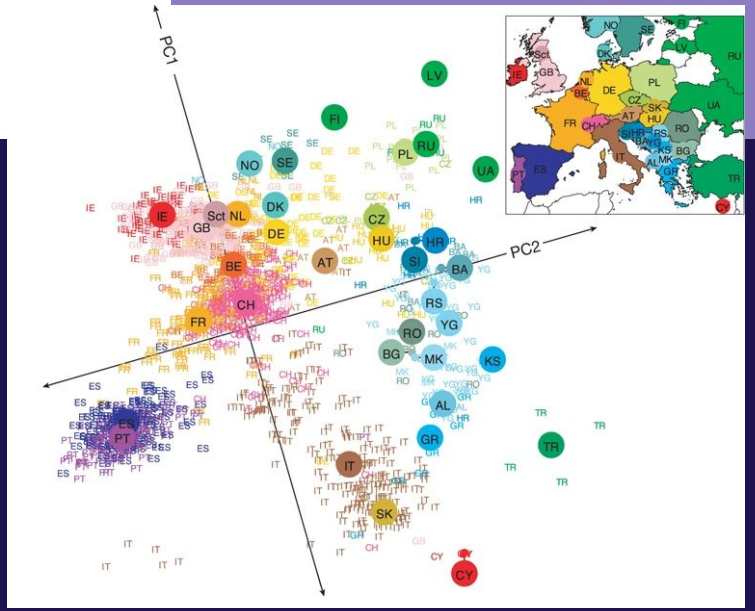
Courses

(Intro to) Demographic modeling methods

27/11/2024

Physalia course

Thibault Leroy, Yann Bourgeois



Goals for today's lecture

- Understand the importance of coalescence rates in demographic modeling
- Reconstruct past population sizes from one or a few genomes
- Introduce the interest of more complex methods based on likelihood & ABC algorithms
- Identify which method should be preferred regarding the dataset/research question
- Introduce pros and cons of each method

Current genetic diversity = long-term processes and past history

Genetic diversity is highly variable among the tree of life!

π = *the average number of nucleotide differences per site between pairs of sequences*

1:AAATACCAACAAC
2:AAATACCATCAAC
3:AAATACCATCAAG
4:AAATACCATCAAC
5:AAATACCATCGAC

Between two sets of human chromosomes, one SNP in every 1,000 nucleotides on average (human genome size ~3.1 Gb, which means that your own genome contains roughly 3 million heterozygous sites)

~1x10^{-3}

Leffler et al. Plos Biol 2012

(autosomal nucleotide diversity)

Current genetic diversity = long-term processes and past history

Genetic diversity is highly variable among the tree of life!

Between two sets of chromosomes, one SNP in every 12.5 nucleotides on average, which means 80 heterozygous sites per Kb in a single diploid individual
(genome size: 180 Mb => 14.4 million hz sites)

Ciona savignyi

$\pi \sim 8 \times 10^{-2}$

Between two sets of human chromosomes, one SNP in every 1,000 nucleotides on average (human genome size ~3.1 Gb, which means that your own genome contains roughly 3 million heterozygous sites)

$\sim 1 \times 10^{-3}$

Leffler et al. Plos Biol 2012

Current genetic diversity = long-term processes and past history

Can we understand why some species are more genetically diverse than some others?

Leffler et al. Plos Biol 2012

Current genetic diversity = long-term processes and past history

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At mutation-drift equilibrium = ***assuming constant population sizes***

$\theta = 2^* \text{ploidy} * N_e * \mu$

(*i.e.* θ (diploid species) = $4N_e\mu$)

At equilibrium $\theta = \pi$

Leffler et al. Plos Biol 2012

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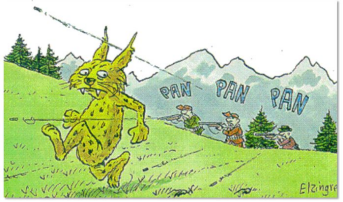

How to explain this low present-day diversity? Is it linked to the past history of the species?

Lynx lynx
~2.0x10^{-4}

Lynx pardinus (Iberian)
~1.0x10^{-4}

Leffler et al. Plos Biol 2012

(autosomal nucleotide diversity)

Current genetic diversity = long-term processes and past history

Can we understand why some species are more genetically diverse than some others?

Deviations from mutation-drift equilibrium (Genome-wide deviations from Tajima's D = 0)

π = *the average number of nucleotide differences per site between pairs of sequences*

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2:AAATACCATCAAC
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θ = # polym. sites/harmonic num. $= \sum_{i=1}^{n-1} \frac{1}{i}$

$\theta = 3 / 2.083 = 1.44$ (0.11 per bp)

Tajima's D $= \frac{\pi - \theta}{\sqrt{var(\pi - \theta)}}$

At mutation-drift equilibrium: Tajima's D~0

D>0: Deficit of rare alleles = population contraction

D<0: Excess of rare alleles = population expansion

Leffler et al. Plos Biol 2012

(autosomal nucleotide diversity)

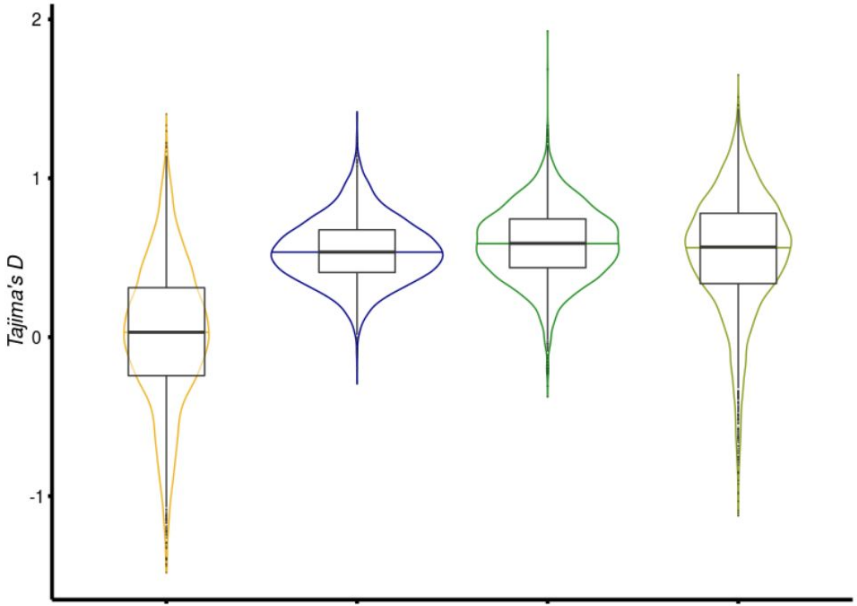

Figure S13: Distributions of the Tajima's D estimates across the four focal groups based on all 100-kb sliding windows spanning the genome. Ancient Asian, ancient European, early Asian x European and hybrid tea roses are shown in yellow, blue, dark green and khaki, respectively.

Leroy *et al.* 2023 bioRxiv

θ = # polym. sites/harmonic num.

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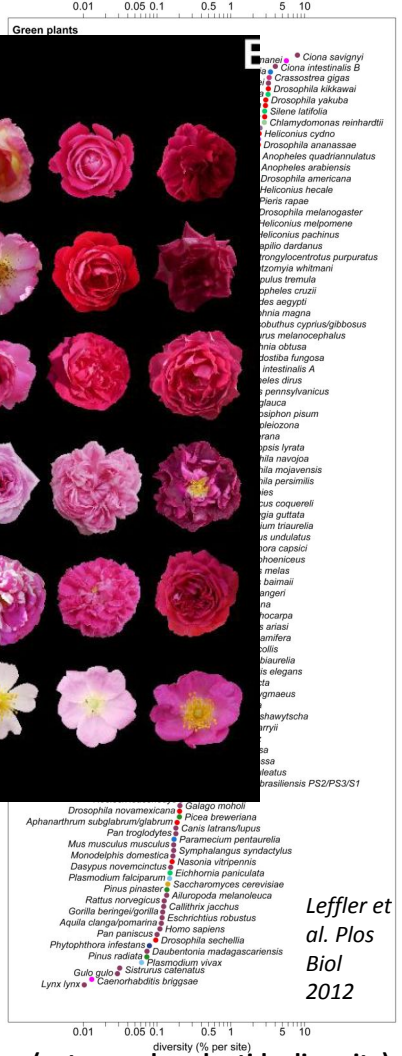

Leffler et al. Plos Biol 2012

(autosomal nucleotide diversity)

Current genetic diversity = long-term processes and past history

Can we understand why some species are more genetically diverse than some others?

Deviations from mutation-drift equilibri
(Genom
deviatio
Tajima's

π = *the average number of nucleotide differences per site between pairs of sequences*

1:AAATACCAACAAC

How can we (try to) precisely reconstruct the evolutionary history of a given species?

→ Demographic modelling

lleles

= population contraction

$$= \sum_{i=1}^{n-1} \frac{1}{i}$$

θ = 3 / 2.083 = 1.44
(0.11 per bp)

Tajima's D

At mutation-drift equilibrium:
Tajima's D~0

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Leffler et al. Plos Biol 2012

(autosomal nucleotide diversity)

All (demographic) models are wrong, but can still be informative!

Demographic modeling approaches require openness to the fact that, by definition, a model intentionally simplifies reality!

> **"…all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind …" — George Box —**

Effective population size: a crucial parameter

Census population size (*Nc*) : the number of individuals in a population that you can observe

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≠

Effective population size (*Ne*): the number of individuals in a Wright-Fisher model (*i.e.* the size of an idealized population) that would produce the same amount of genetic drift as in the real population

***Ne* captures the effects of the genetic drift** and is therefore a key parameter in population genetics!

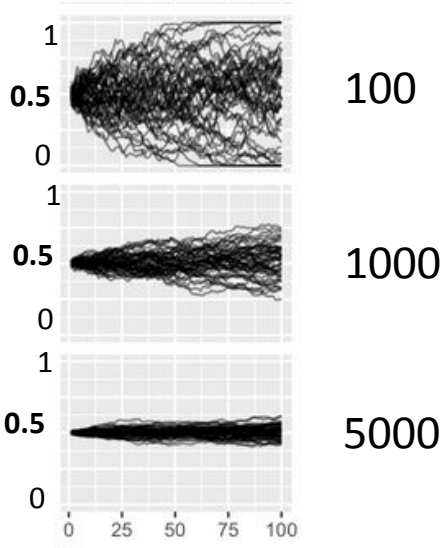
Effective population size: a crucial parameter

Effective population size (*Ne*): the number of individuals in a Wright-Fisher model (*i.e.* the size of an idealized population) that would produce the same amount of genetic drift as in the real population

Sewall Wright

Ronald A. Fisher

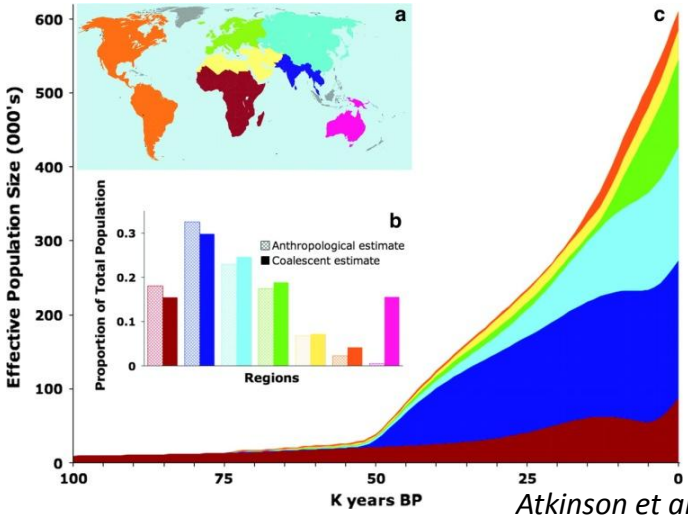
WF model:
- *non-overlapping generations*
- *no selection*
- *no mutation*
- *no migration*
- *random mating*



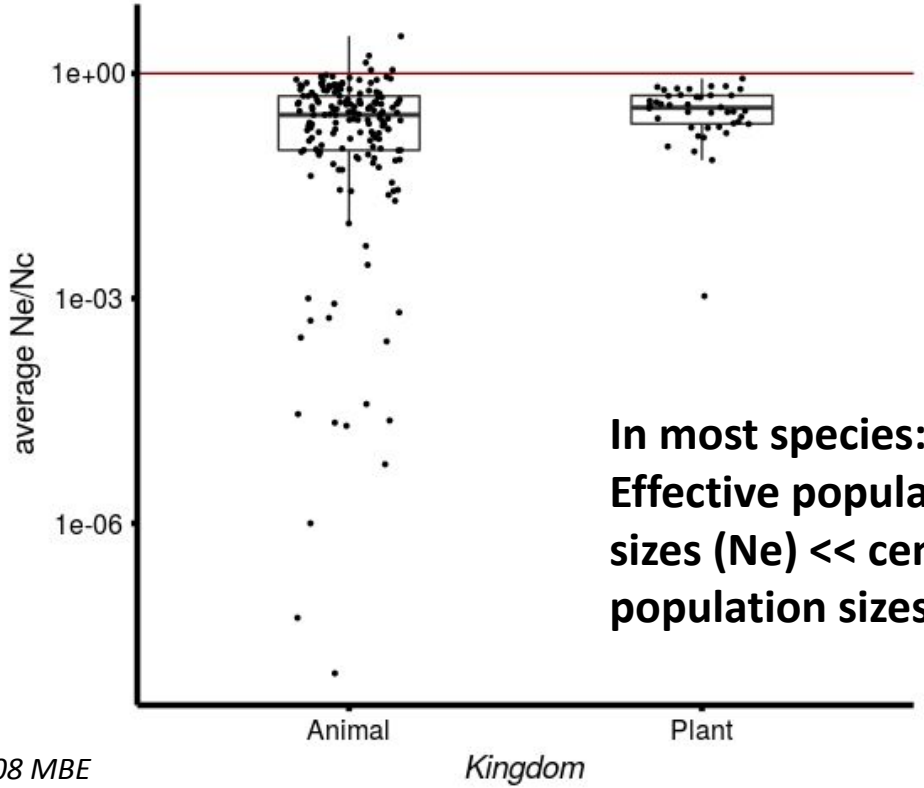
WF: a model for the allele frequency dynamics

Effective population size: a crucial parameter

Census size (N_c) ~ 8.1 *10^9 (2024)
Effective size (N_e): ~6.2* 10^5 ?
N_e/N_c = 7.6*10^{-5}



Atkinson et al. 2008 MBE



In most species: Effective population sizes (Ne) << census population sizes (Nc)

Data from Hoban et al. 2020 BiolCons

Introducing the coalescent theory through N_e

Coalescence: a stochastic process that describes how population genetic processes determine the shape of the genealogy of sampled gene sequences

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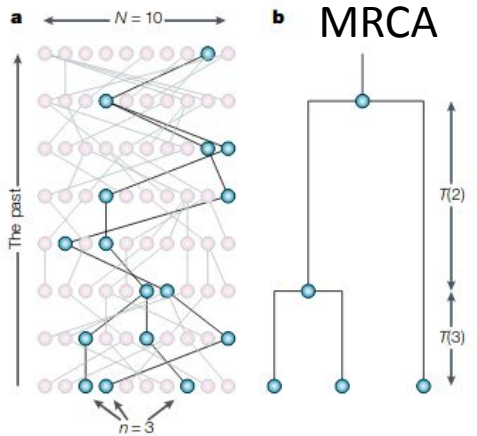
n individuals sampled from a population of:

- Size N (constant & large, well-mixed population)
- New (neutral) mutations
- No selection, no subdivision, no migration



e.g. Rosenberg & Nordborg, 2002

Introducing the coalescent theory through N_e

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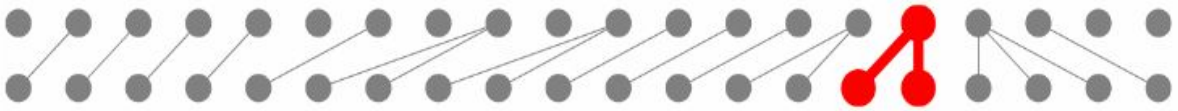
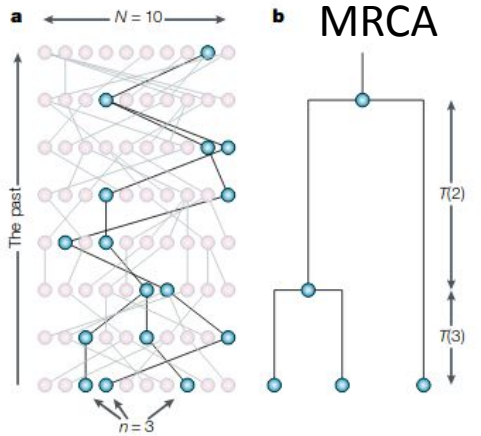


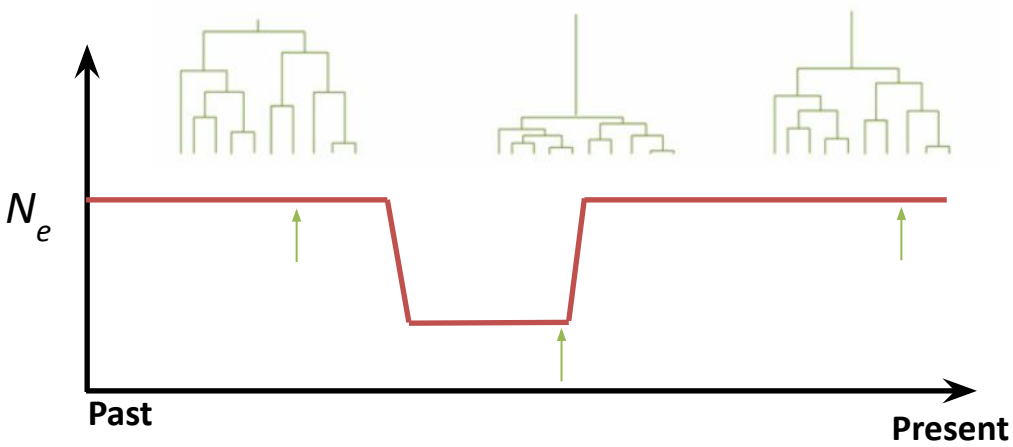


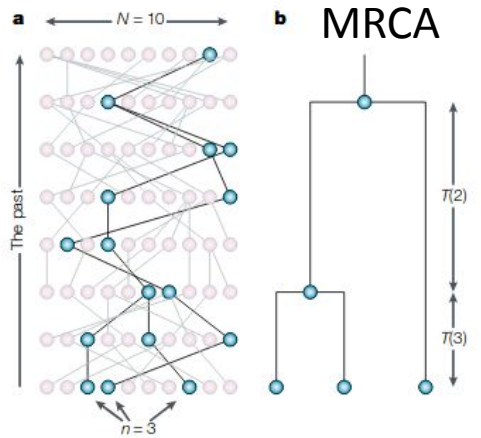
e.g. Rosenberg & Nordborg, 2002

The probability of 2 alleles in generation *t* coalesce in *t-1* is $\frac{1}{2Ne}$

⟶ A direct relationship between time and N_e

Introducing the coalescent theory through N_e





e.g. Rosenberg & Nordborg, 2002

The rates of coalescence are informative about population size because ***coalescence events are more likely to occur when the population is small****.*

For example, if we select a few people at random from a small, isolated village, they are likely to share an ancestor in recent generations.

Population decline: shorter coalescence times ("shorter branches")
Population expansion: longer coalescence times ("longer branches")

Full likelihood inferences and limitations

"The variable population size" coalescent model (Griffiths & Tavaré, 1994; Donnelly & Tavaré, 1995)

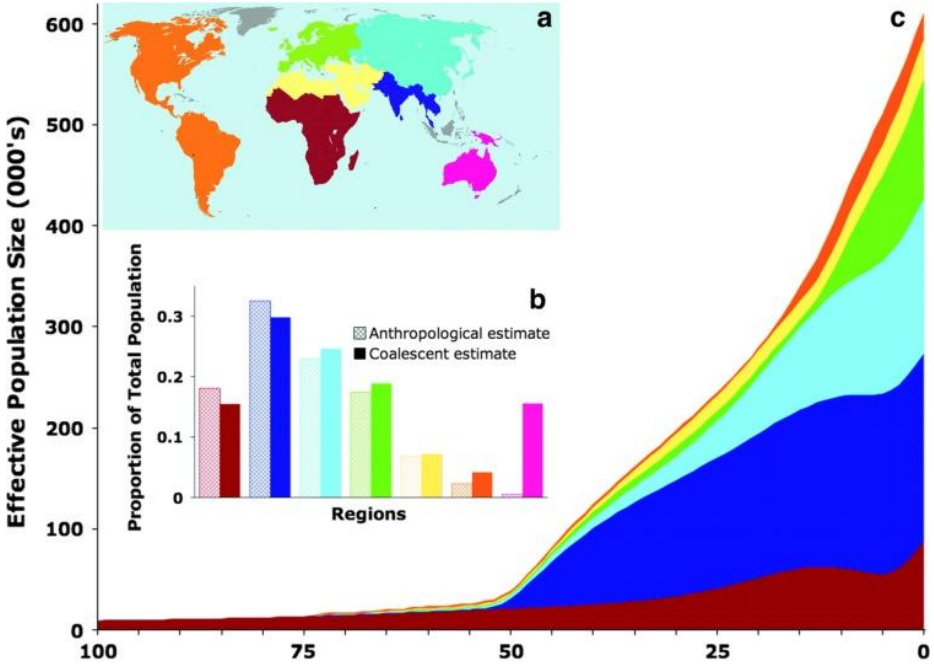
⟶ Maximum likelihood estimates of parameters (pop expansions/bottlenecks)

Full likelihood computation for one locus, *e.g.* mtDNA

While sometimes informative, statistical resolution of inferences from only one locus (here, the mtDNA) is generally poor…

Why? Power diminishes rapidly as we move further back in time, primarily because there are few independent lineages that explore such deep time depths. For example, in humans, mitochondrial DNA provides no information beyond approximately 200,000 years ago, when all humans trace back to a common maternal ancestor.

⟶ Need more loci, complete genomes?



(Atkinson et al. 2008 MBE)

Approximations to overcome scalability challenges

Ideally, we would like to estimate the full likelihood of observing all these variants along the genome

⟶ Full likelihood methods are however not applicable to genome-scale datasets (yet) because of two main limitations:
1) Methods do not scale well with the number of loci being analyzed
2) Methods are not well suited for handling recombination (modeling genomic linkage is particularly challenging)

We need to find a way to **approximate** this…

⟶ Approximating the coalescent with recombination

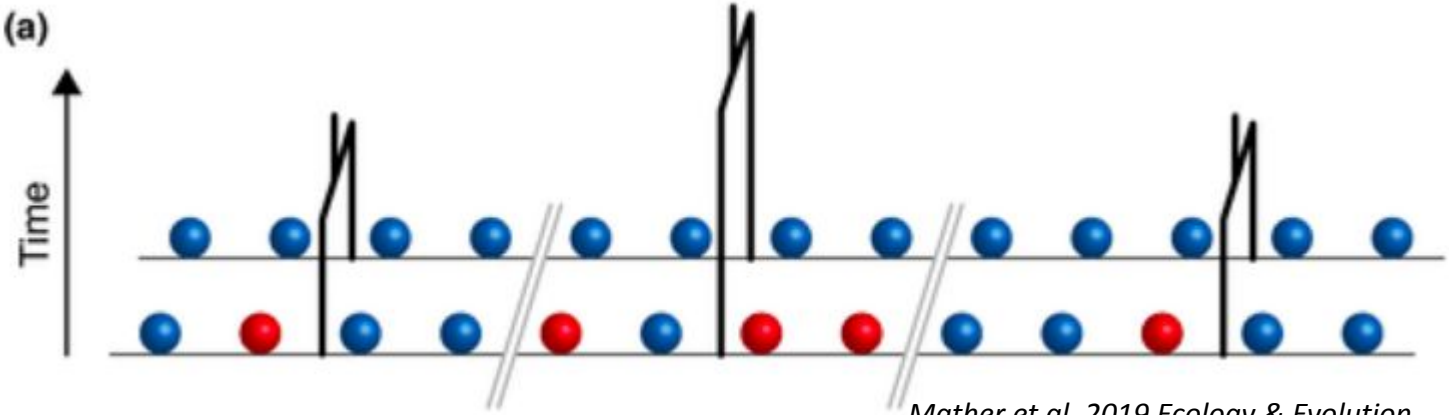
e.g. McVean & Cardin, 2005
SMC (sequential Markov coalescent)

Many demographic inference methods are based on the SMC (or SMC') approximation:
=> PSMC, MSMC, SMC++, …

Pairwise Sequentially Markovian Coalescent (PSMC)

PSMC (Li & Durbin, 2011): local time to the most recent common ancestor (TMRCA) on the basis of the local density of heterozygotes in short genomic blocks

TMRCA between the two alleles carried by an individual



Mather et al. 2019 Ecology & Evolution

Despite being a remarkably simple likelihood model for analyzing the pattern of genetic mutations in a single diploid individual, a decade of empirical applications has demonstrated the unexpectedly high power of PSMC to infer the population/species history of that individual.

Pairwise Sequentially Markovian Coalescent (PSMC)

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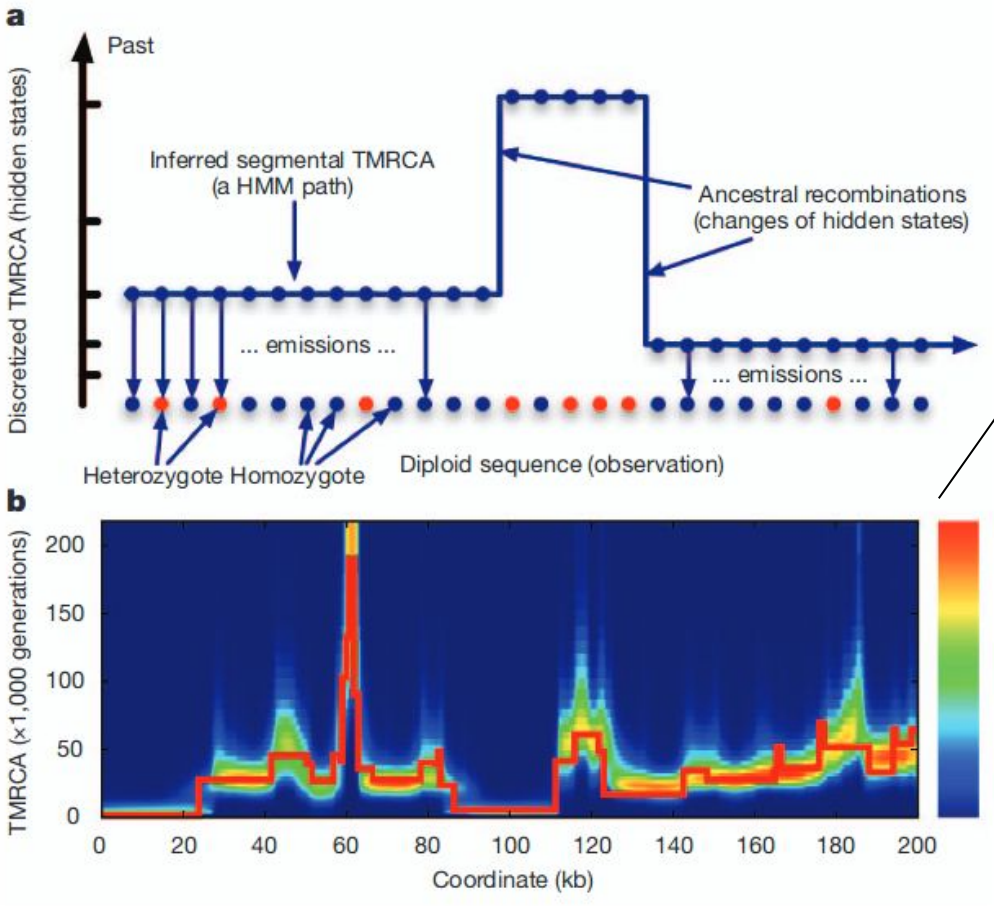
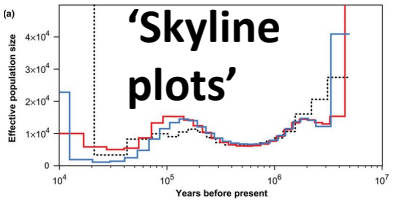


Estimating TMRCA of the two alleles at each locus is used to create a **TMRCA distribution across the whole genome**.

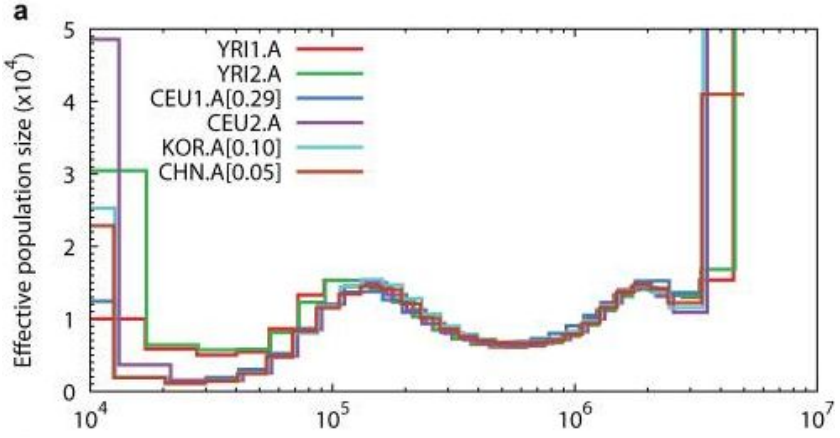
Since the rate of coalescent events is inversely proportional to N_e, PSMC identifies periods of N_e changes. For example, **when many loci coalesce at the same time, it is (assumed to be) a sign of small N_e at that time.**



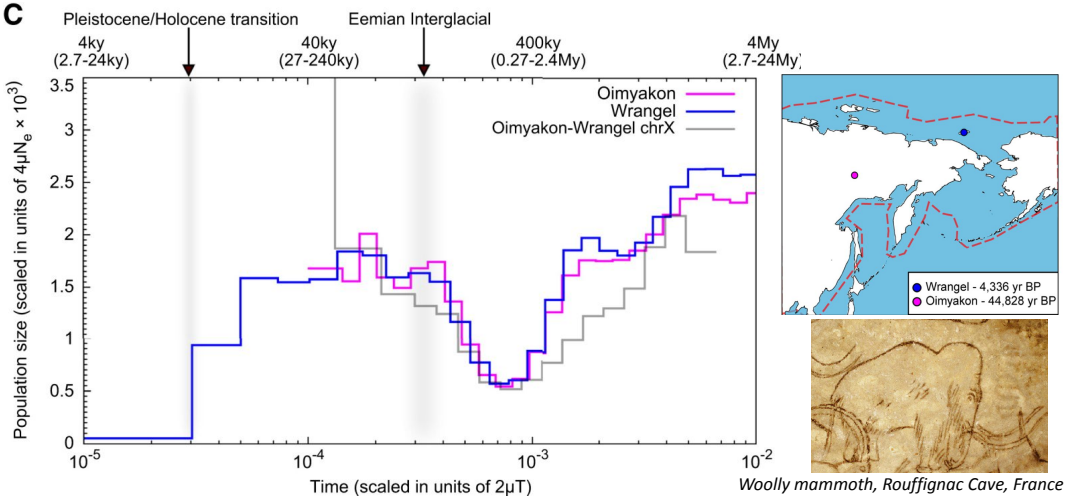
Pairwise Sequentially Markovian Coalescent (PSMC)

Example of applications:

(*e.g.* Li & Durbin, 2011 Nature)



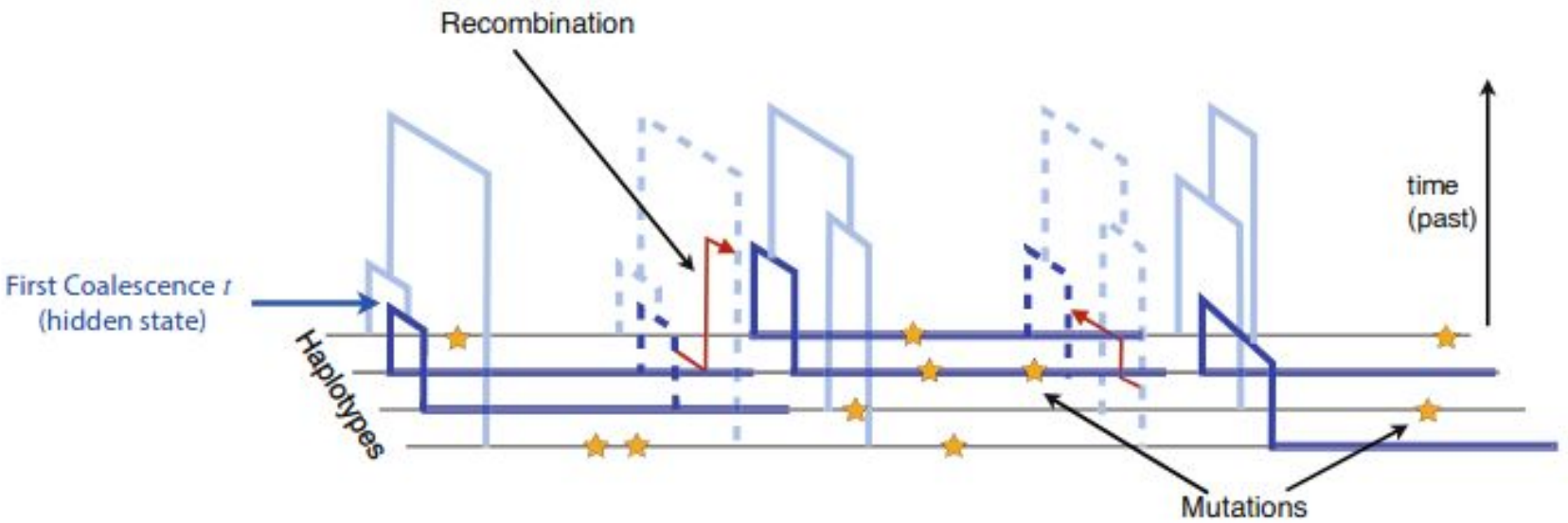
Palkopoulou et al. 2015, Current Biol



Woolly mammoth, Rouffignac Cave, France

Multiple Sequentially Markovian Coalescent (MSMC)

MSMC has better power than PSMC to resolve recent changes in effective population size, because of its use of >2 sequences. Adding alleles increase the probability for two of the copies to coalesce in the recent past.



Mather et al. 2019 Ecology & Evolution; Schiffels & Wang, 2021 Springer Protocols

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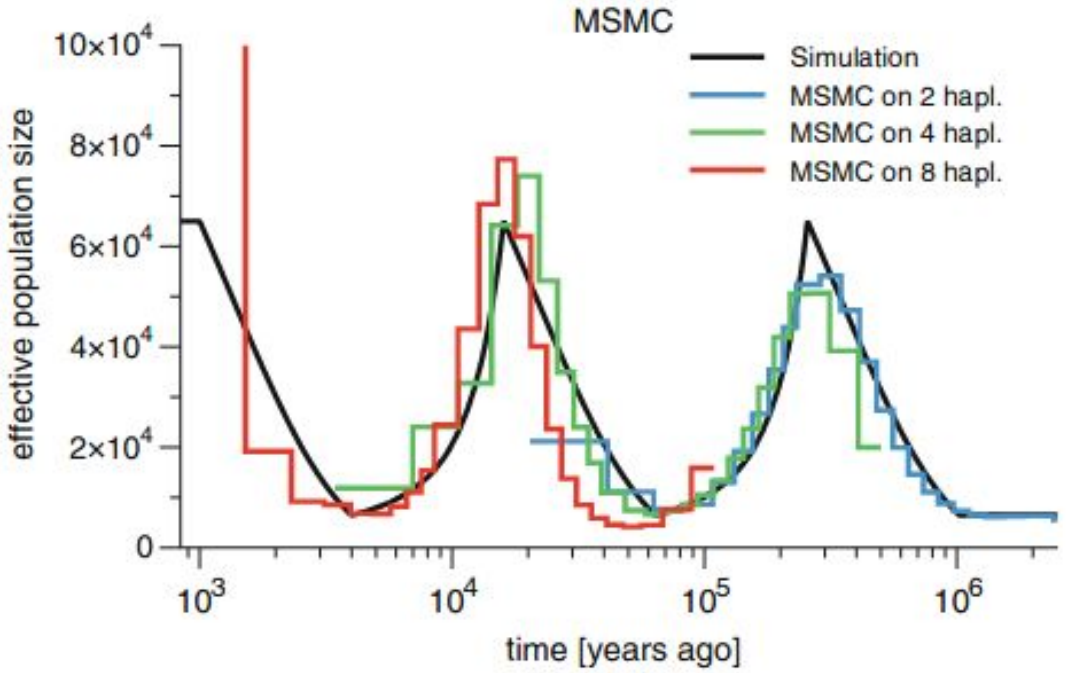
More recent estimates with more individuals (because of more recent first events of coalescence)



Schiffels & Wang, 2021 Springer Protocols

SMC++ development to overcome MSMC limitations

A main issue with MSMC is that this method requires phased genomes (or at least with unphased data the MSMC estimation accuracy is low)

Genotypes

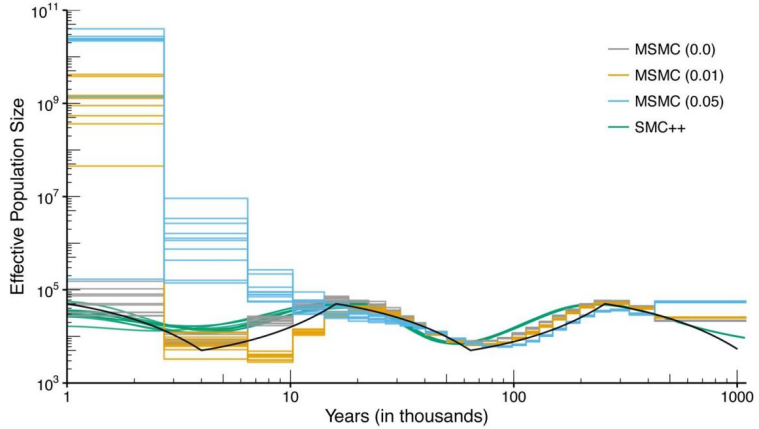
A	T/G		G	C/G	A/G	G

vs.

Haplotypes

>all1
ATGCGG
>all2
AGGGAG

Computational haplotype phasing (*i.e.* identify the alleles that are co-located on the same chromosome) represents a hard task to achieve…



Some other methods using unphased data are becoming popular to overcome this problem (*e.g.* SMC++, PopSizeABC, …) but requires tens of whole-genome sequences.

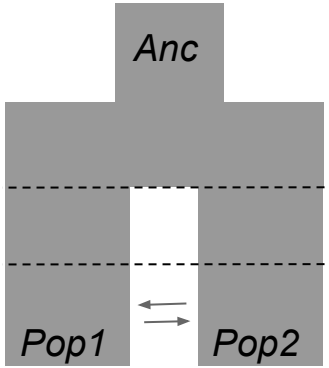
PSMC-like methods: pros and cons

Advantages:

- Rapid, simple, extremely popular
- Only one individual needed (for PSMC at least)
  => 'Genome papers' + Phylogenomic-oriented papers+ aDNA

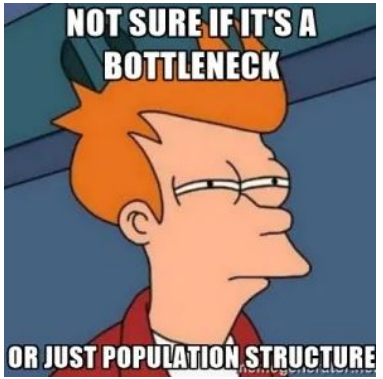
Limitations (1/2):

- Simplistic approach (assumes a panmictic population, *i.e.* drift-only)
  => change in *Ne* in a PSMC plot can be actually caused by other factors
  e.g. population structure



This past history induced population structure at many loci

Contemporary population structure associated with this past history will be artifactually considered as a period of low N_e



molecularecologist.com

PSMC-like methods: pros and cons

Limitations (2/2):

- PSMC estimates for recent times (<10kyrs) are rarely accurate (more sequences needed to use the other PSMC-like methods (MSMC, SMC++, …)!)

- Sensitive to the quality of the genome assembly and sequencing data (coverage)
  Nadachowska-Brzyska et al. (2016) suggested filters :
  e.g. A mean coverage of at least 18X, <25% of missing data, …

- Doesn't recover sudden changes in N_e or very ancient changes (>5-10 N_e generations)

- Problem of rescaling coalescent times to real time for non-model species (incorrect mutation rates or knowledge about generation times)

Site Frequency Spectrum (SFS)-based approaches

Full-likelihood methods = not adapted to WGS because of big data & recombination events

One way to circumvent this problem is to use summary statistics to describe the dataset
e.g. compute the likelihood only based on the SFS (*i.e.* a "composite" likelihood)

```
Ind1-A1: A..C..G..A..T..G..A..A..T..G
Ind1-A2: A..G..G..A..T..G..T..A..C..G
Ind2-A1: T..G..G..T..T..C..T..A..T..G
Ind2-A2: A..G..G..A..G..C..T..A..C..G
Ind3-A1: A..G..A..A..T..G..T..A..T..G
Ind3-A2: A..C..G..A..T..C..T..G..T..A
Ind4-A1: A..G..G..T..G..G..T..A..T..G
Ind4-A2: A..G..G..T..T..C..T..A..T..G
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Ind3-A1: A..G..A..A..T..G..T..A..T..G
Ind3-A2: A..C..G..A..T..C..T..G..T..A
Ind4-A1: A..G..G..T..G..G..T..A..T..G
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Ind3-A1: A..G..A..A..T..G..T..A..T..G
Ind3-A2: A..C..G..A..T..C..T..G..T..A
Ind4-A1: A..G..G..T..G..G..T..A..T..G
Ind4-A2: A..G..G..T..T..C..T..A..T..G

Minor allele   1  2  1  3  2  4  1  1  2  1
frequency      /  /  /  /  /  /  /  /  /  /
(MAF)          8  8  8  8  8  8  8  8  8  8
```

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e.g. compute the likelihood only based on the SFS (*i.e.* a "composite" likelihood)

```
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Ind1-A2: A..G..G..A..T..G..T..A..C..G
Ind2-A1: T..G..G..T..T..C..T..A..T..G
Ind2-A2: A..G..G..A..G..C..T..A..C..G
Ind3-A1: A..G..A..A..T..G..T..A..T..G
Ind3-A2: A..C..G..A..T..C..T..G..T..A
Ind4-A1: A..G..G..T..G..G..T..A..T..G
Ind4-A2: A..G..G..T..T..C..T..A..T..G
```
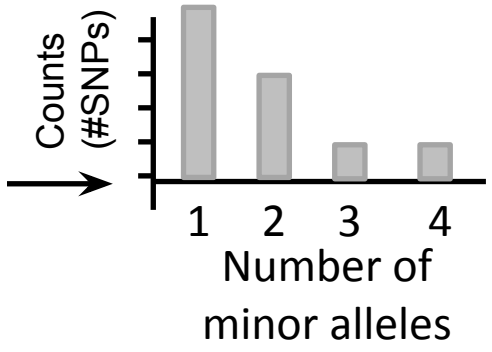

Minor allele frequency (MAF)	1/8	2/8	1/8	3/8	2/8	4/8	**1/8**	1/8	2/8	1/8

« Folded 1D-Site Frequency Spectrum » (folded 1D-SFS)



Site Frequency Spectrum (SFS)-based approaches

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Ind4-A2: A..G..G..T..T..C..T..A..T..G
```

Derived allele frequency (DAF)

1/8	2/8	1/8	5/8	2/8	4/8	7/8	1/8	6/8	1/8

Site Frequency Spectrum (SFS)-based approaches

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Ind3-A2: A..C..G..A..T..C..T..G..T..C
Ind4-A1: A..G..G..T..G..G..T..A..T..C
Ind4-A2: A..G..G..T..T..C..T..A..T..C
```
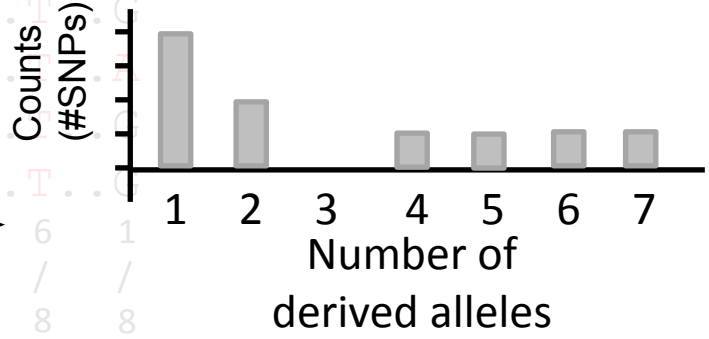
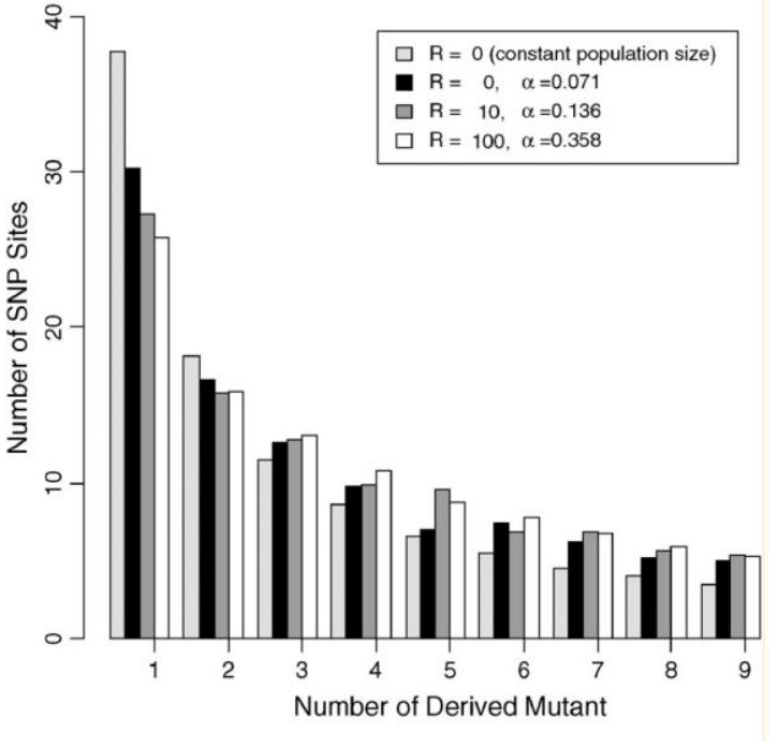

Derived allele frequency (DAF)

1/8 2/8 1/8 5/8 2/8 4/8 7/8 1/8 6/8 1/8

« Unfolded 1D-Site Frequency Spectrum » (unfolded 1D-SFS)



Site Frequency Spectrum (SFS)-based approaches



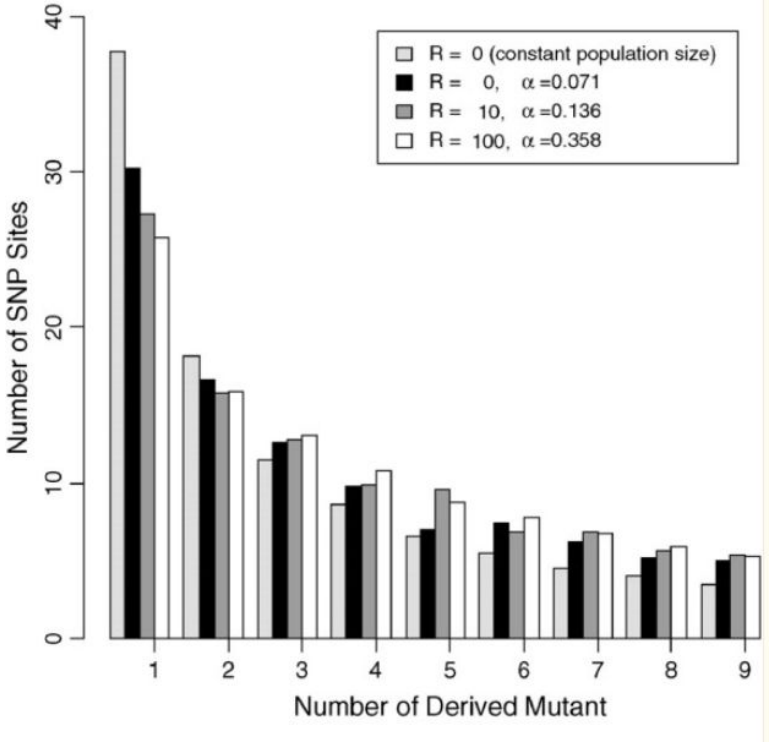
Zhu & Bustamante, 2005

Sudden population contraction (bottleneck) -> deficit of rare alleles

//Pop expansion -> excess

⟶ SFS are therefore informative about *Ne* changes

Site Frequency Spectrum (SFS)-based approaches



Zhu & Bustamante, 2005

Sudden population contraction (bottleneck) -> deficit of rare alleles

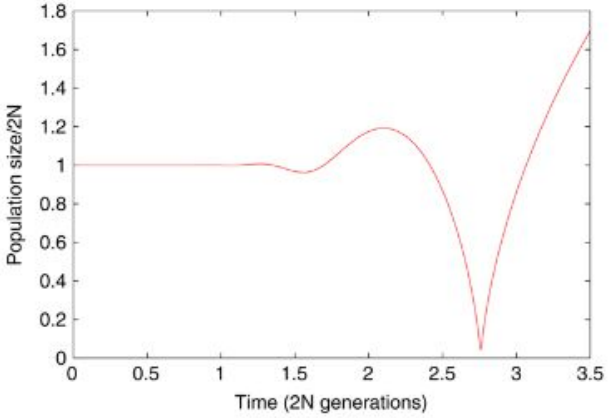
//Pop expansion -> excess

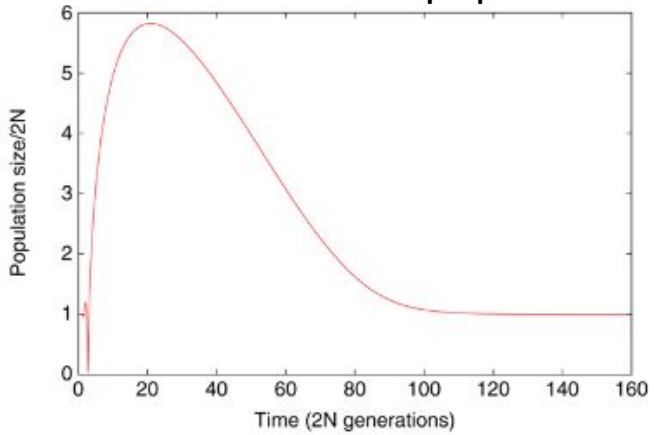
⟶ SFS are therefore informative about *Ne* changes

Site Frequency Spectrum (SFS)-based approaches

However, a single-dimensional SFS provides only limited information !

Here, two demographic histories with the same spectrum as a constant size populations!

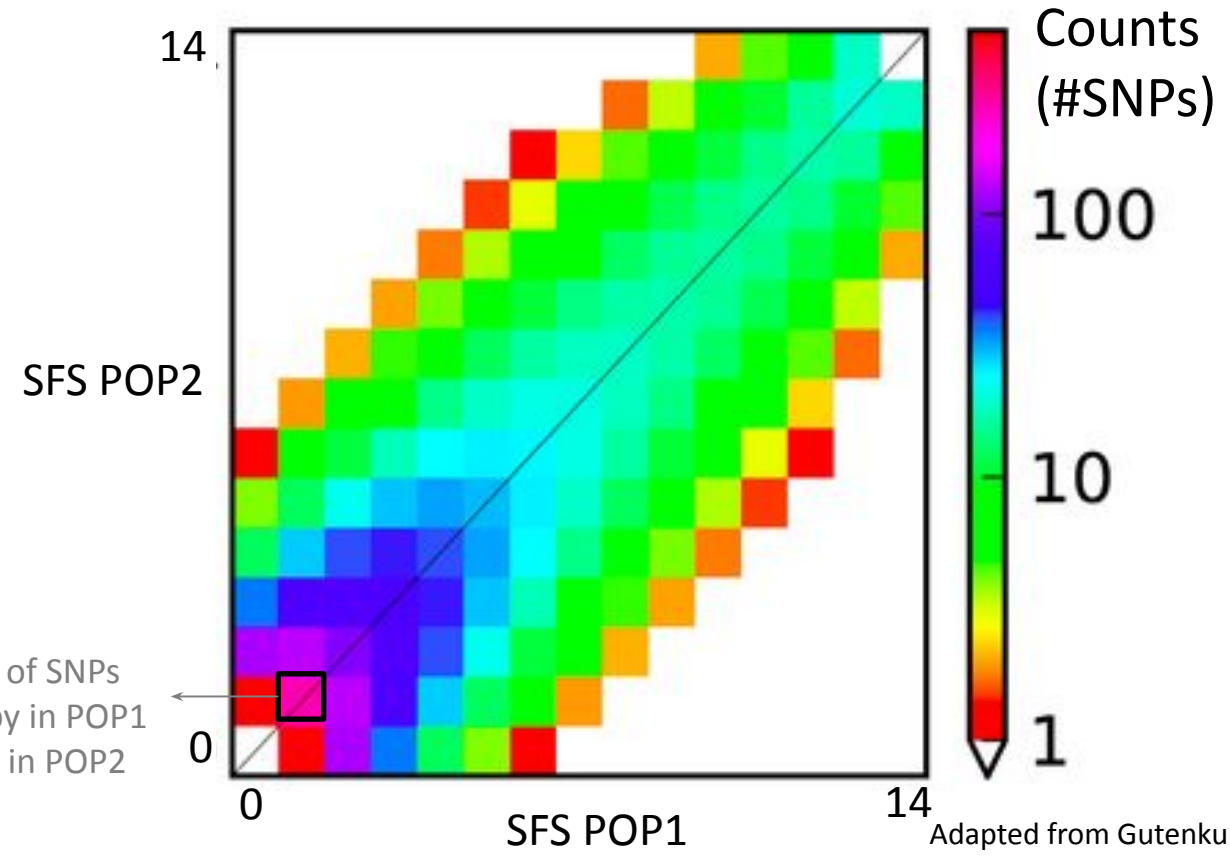




Myers et al. 2008 "Can one learn history from the allelic spectrum?"

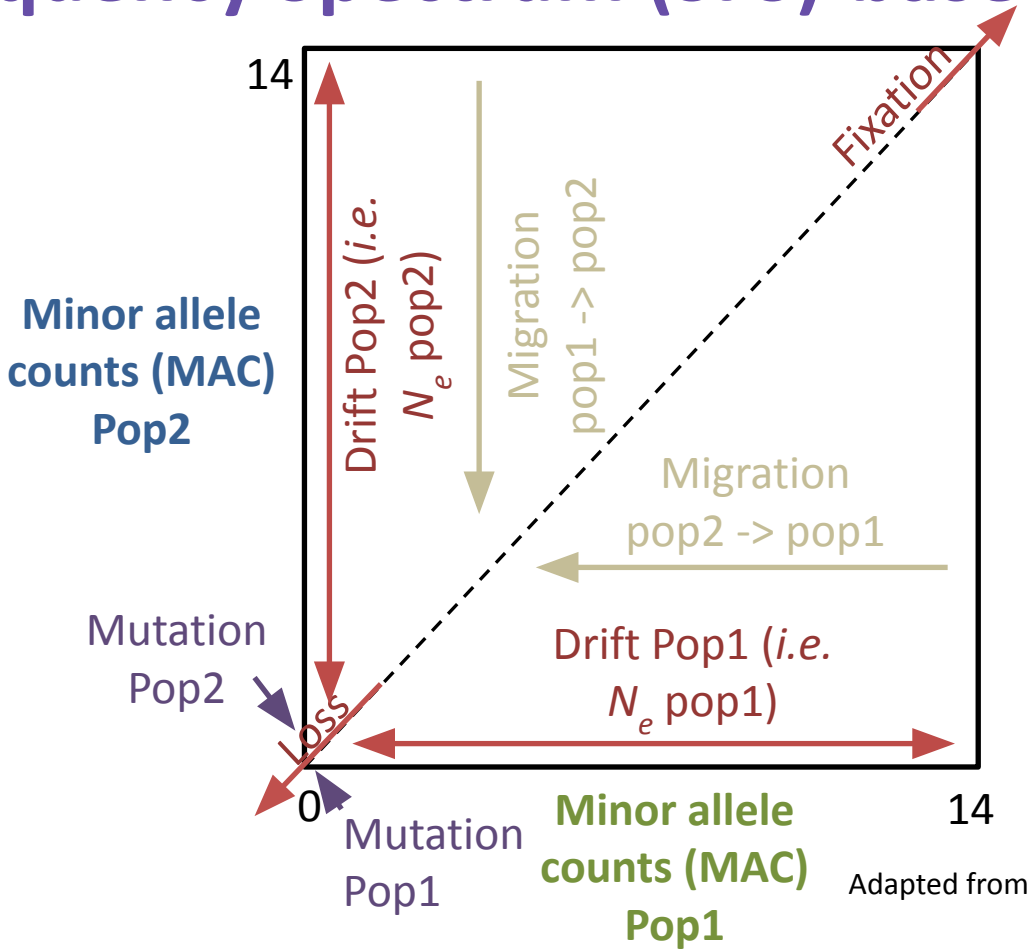
-> 2-dimensional site frequency spectrum (2D-SFS)
(use of polymorphism data from 2 populations)

Site Frequency Spectrum (SFS)-based approaches



Adapted from Gutenkunst et al. 2009 Plos Genet

Site Frequency Spectrum (SFS)-based approaches



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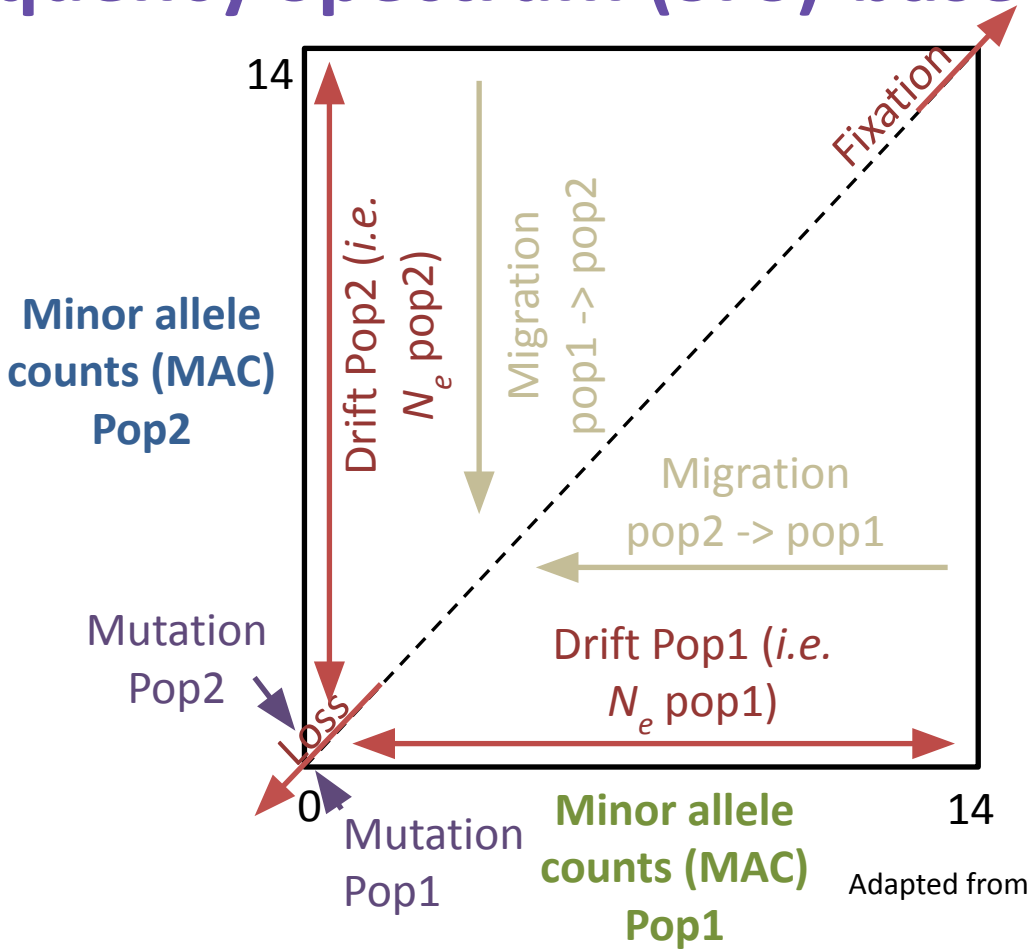
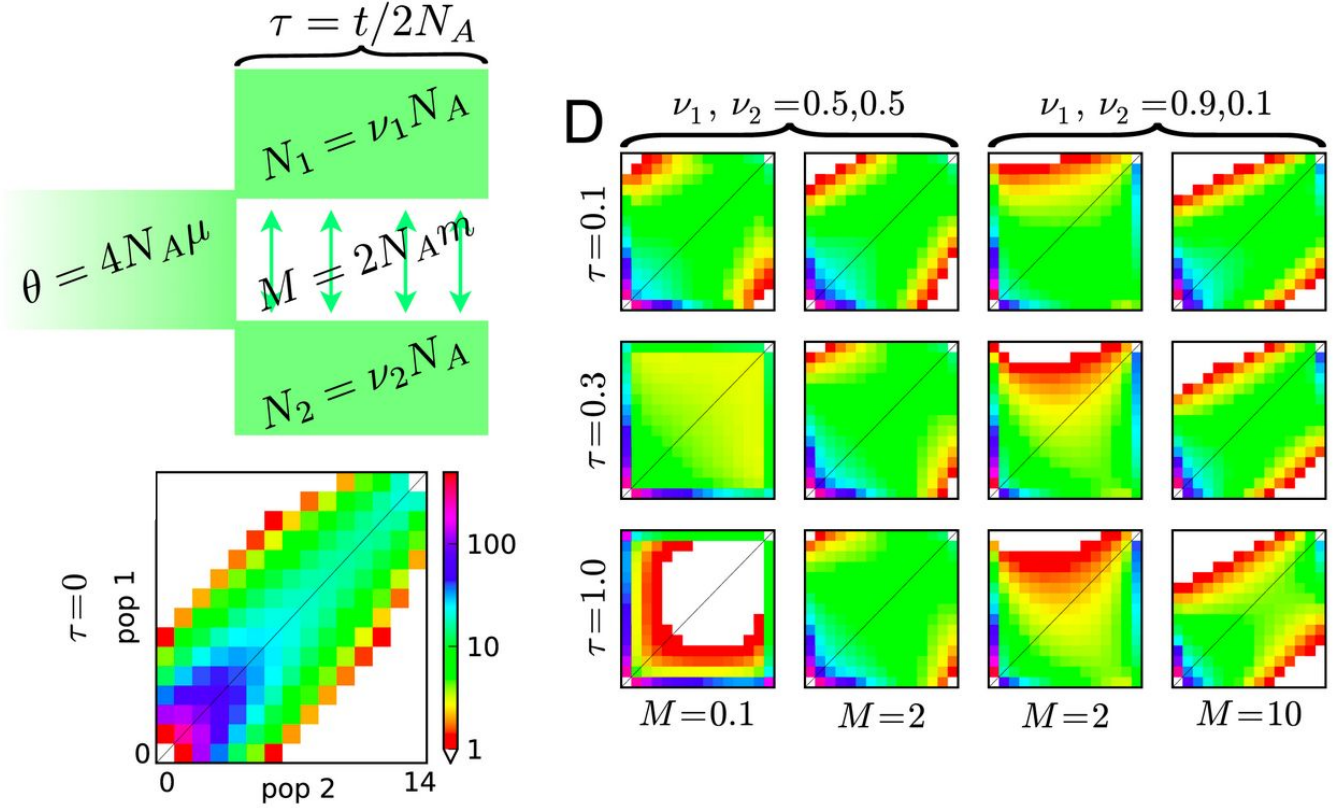
Site Frequency Spectrum (SFS)-based approaches



Recombination is not taken into account!
-> All sites are assumed to be independent

Adapted from Gutenkunst et al. 2009 Plos Genet

Composite likelihood approach : ∂a∂i



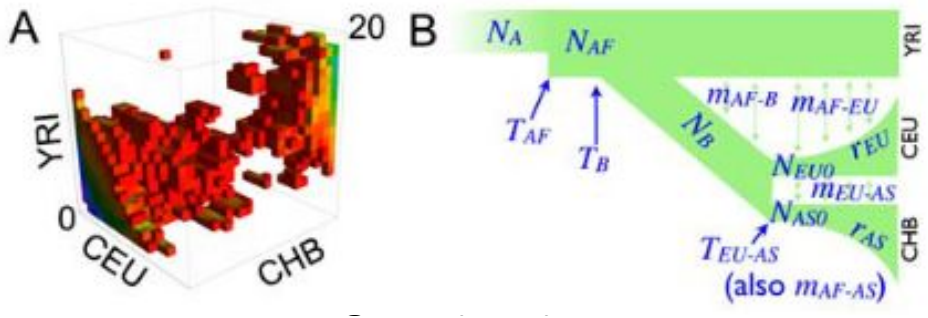
Gutenkunst et al. 2009 Plos Genet

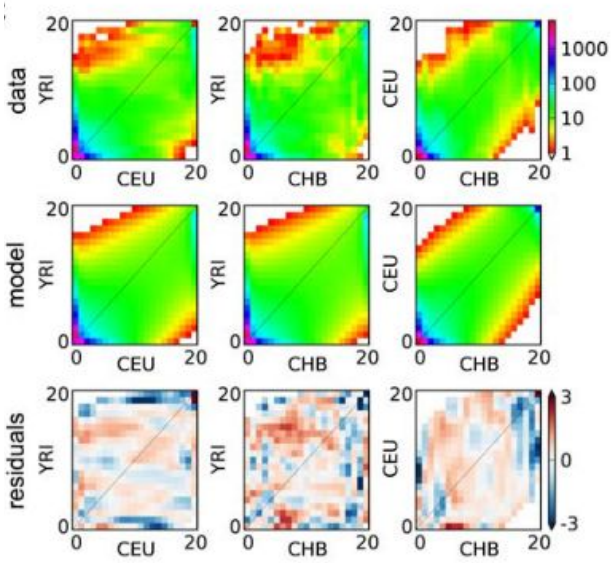
Composite likelihood approach : ∂a∂i

3-dimensional SFS

The implementation (∂a∂i program) is quite flexible. It was initially able to handle up to three simultaneous populations

Data: 1000 genomes project (human)





CEU: US with Northern or Western European Ancestry (EUR)

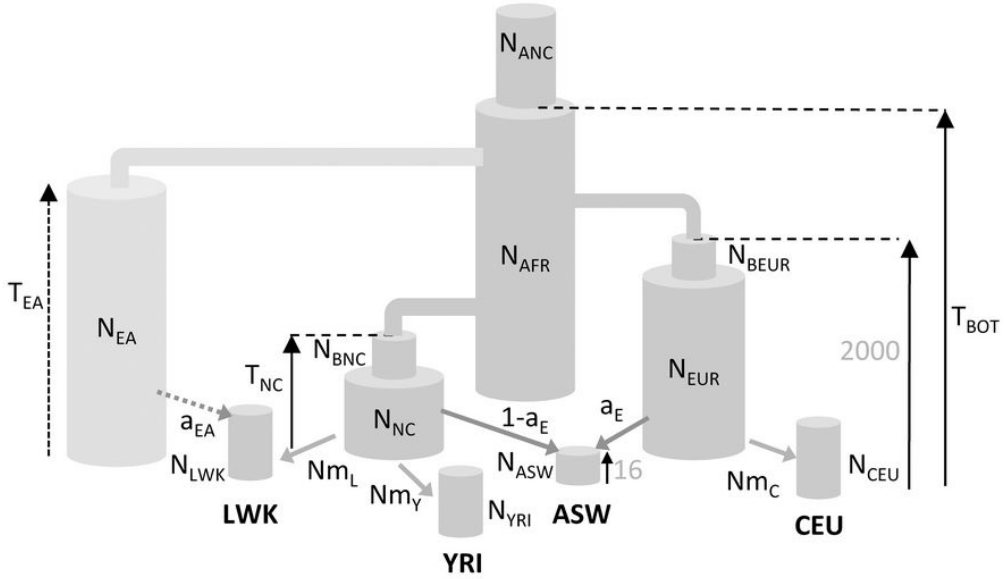
CHB: Han Chinese, Beijing, China (EAS)

Improvements to extend the ∂a∂i strategy to 4-populations (MULTIPOP, Lukic & Hey 2012 Genetics) & 5-populations (*Moments*, Jouganous et al. 2017 Genetics)

Gutenkunst et al. 2009 Plos Genetics, 2010 Nature Precedings

Composite likelihood approach : fastsimcoal

fastsimcoal2 is another very popular tool
Using a multiple pairwise joint SFS strategy, fastsimcoal2 is (in theory) be able to infer demography of an arbitrary number of populations



Excoffier *et al*. 2013 Plos Genetics

LWK : Luhya, Kenya (AFR)
YRI: Yoruba, Nigeria (AFR)
ASW: African Ancestry in SW USA (AFR)
CEU: Northern & Western European Ancestry USA (EUR)

Composite likelihood approach : pros & cons

Advantages:

Computationally efficient :

- accuracy of the inferences increase with the number of SNPs, without increasing the computational load
- Several order of magnitude faster than ABC (even more for full-likelihood methods)
- Can be used to infer complex scenarios

Limitations:

Computational issues

- Convergence problems are possible (computation of the likelihood)

Biological problems

- All sites are assumed to be independent
- Assume that the 2D-SFS is correct (can be an isssue if only few individuals were sequenced or in case of low coverage data)
- Risk of not including the true model (as for any other model-based approaches!)
- Correct parameter estimates are challenging
- Limitations on how informative allelic spectra can be

An intro to approximate Bayesian computation…

Likelihood-free demographic inferences

- No need for an explicit likelihood function
- No convergence issues associated with the computation of the likelihood
- High flexibility in model complexity

...

An intro to approximate Bayesian computation…

The rationale:

1/ Observed dataset

Ind1-A1: ATCCACATGCA…
Ind1-A2: ATCGACATGCA…
Ind2-A1: TTCGACATGCT…
Ind2-A2: ATCGACATGCA…
Ind3-A1: ATCGACATACA…
Ind3-A2: ATCCACATGCA…
Ind4-A1: ATCGACATGCT…
Ind4-A2: ATCGACATGCT…

→

Summary statistics (e.g. mean number of alleles, F_{ST} between pairs of populations, nucleotide diversity, Tajima's D, SFS, etc…)

The choice and the number of summary statistics to use for the ABC analysis are crucial (e.g. Beaumont et al 2002)

An intro to approximate Bayesian computation…

The rationale:

1/ Observed dataset

Ind1-A1: ATCCACATGCA…
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Ind2-A1: TTCGACATGCT…
Ind2-A2: ATCGACATGCA…

→ Summary statistics

The choice and the number of summary statistics to use for the ABC analysis are crucial (e.g. Beaumont et al 2002)

2/ Demographic models & simulations

A set of candidate models are hypothesized and simulations are performed using a coalescent sampler (e.g. ms)

→ Same summary statistics are computed for all simulated datasets

3/ Model Choice

Euclidian distance between summary statistics from the observed dataset and simulations

→ Identify the « best model »: simulations with the closest summary statistics

4/ Estimation of parameters under the best model

An intro to approximate Bayesian computation…

The rationale:

Real Data

100 loci x 1kb

↓

Summary statistics of pop genomics (or SFS) e.g. Fst, Tajima's D…

Simulations

Model 1

(e.g. 1 million multilocus simulations, *i.e.* 1 million with 100 loci x 1kb)

For each simulation, we repeatedly sample a parameter value from **prior** distribution e.g.

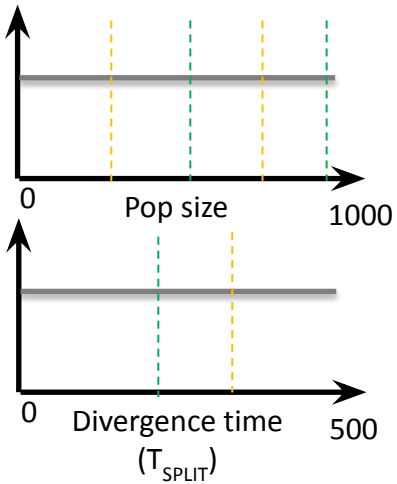
POP SIZE1: uniform[0-1000]
POP SIZE2: uniform[0-1000]
TSPLIT : uniform[0-500]

e.g.

Simul1:
PopSize1=763
PopSize2=261
Tsplit = 330

Simul2:
PopSize1=493
PopSize2=921
Tsplit = 234

… x i simulations



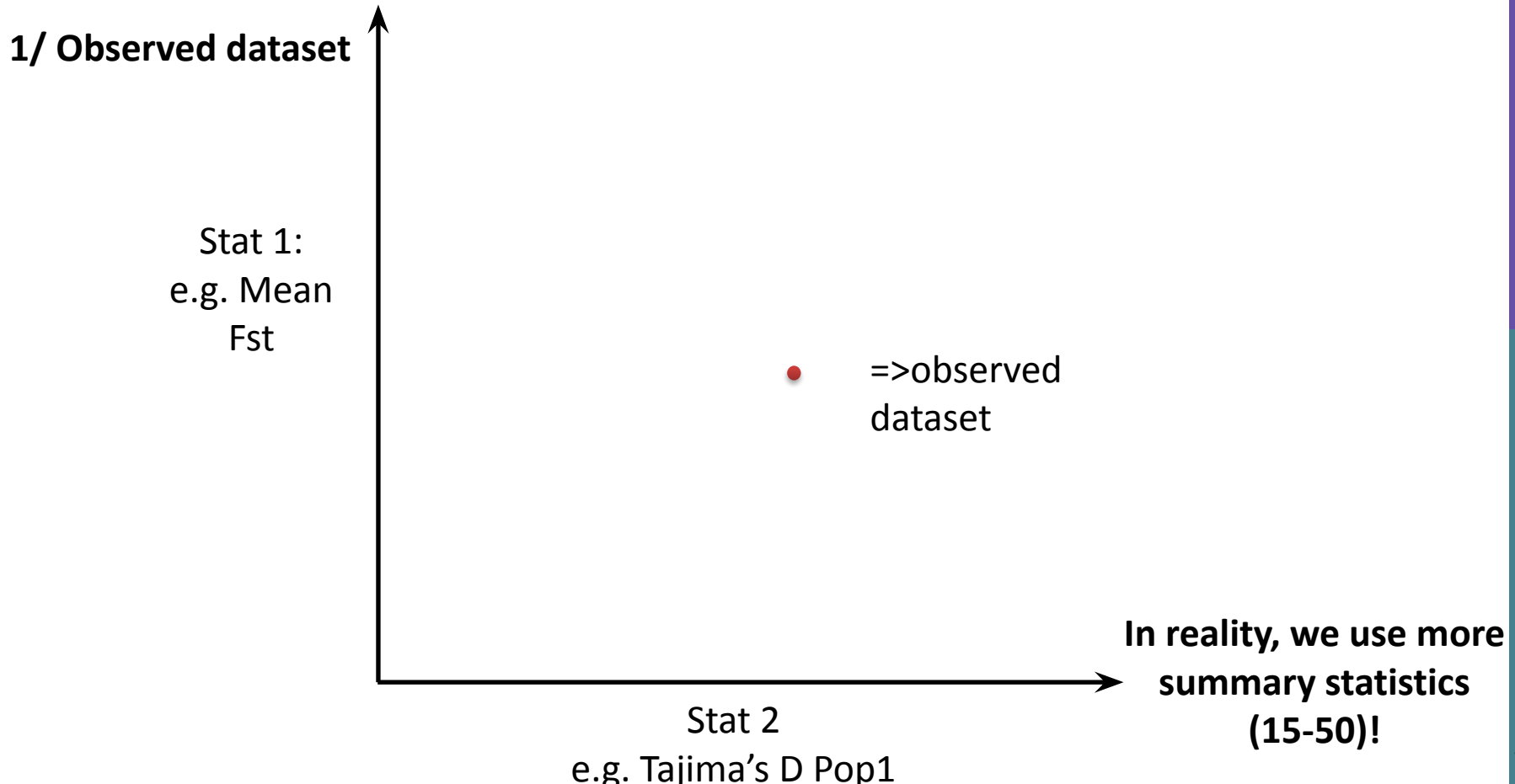
Same summary statistics than for the real data

Model 2

…

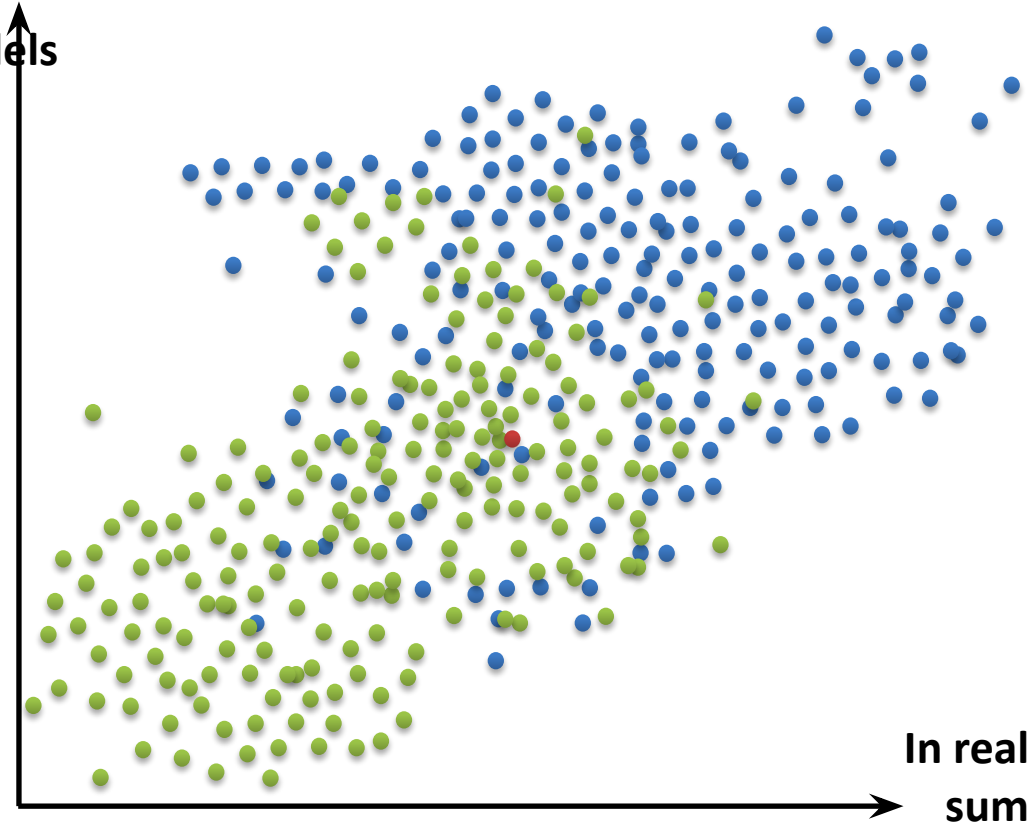
Same summary statistics

ABC in practice (very simplified)…



ABC in practice (very simplified)…

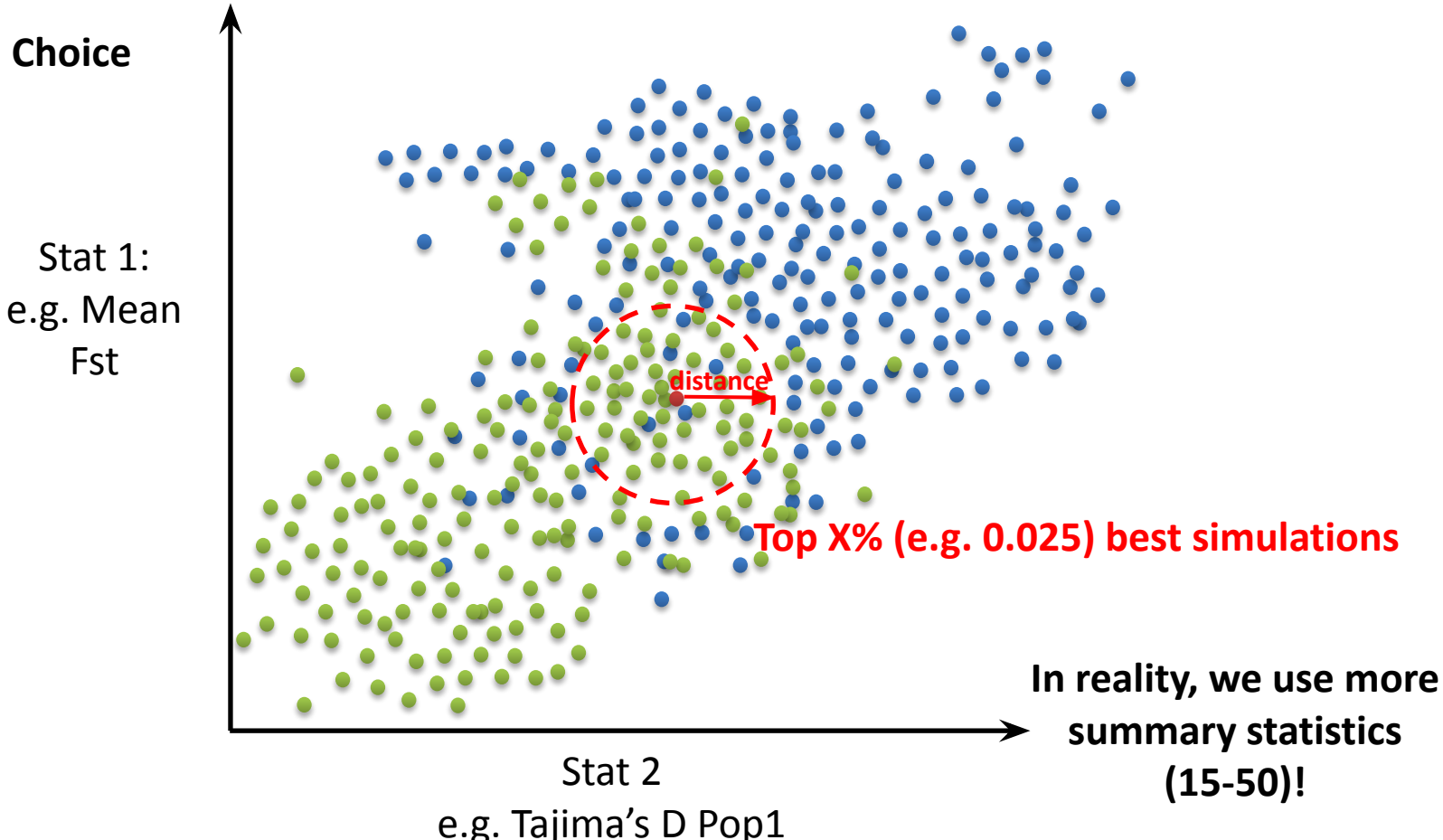
2/ Demographic models & simulations



In reality, we use more summary statistics (15-50)!

ABC in practice (very simplified)…

3/ Model Choice



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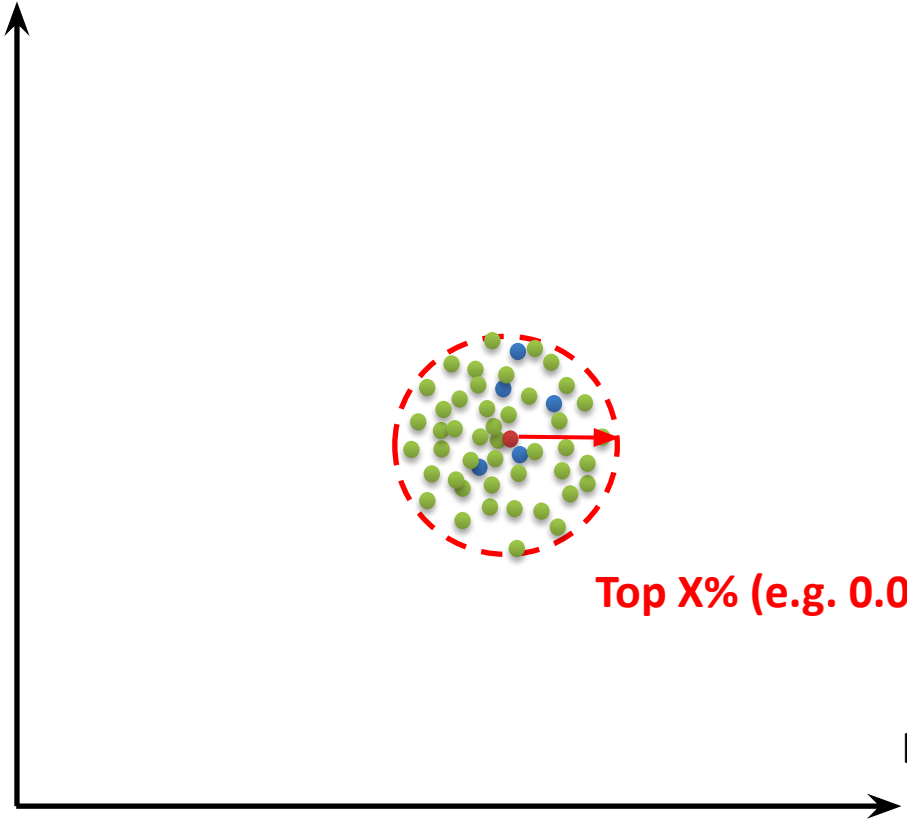
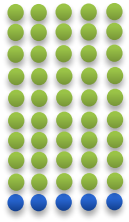


Top X% (e.g. 0.025) best simulations

In reality, we use more summary statistics (15-50)!

ABC in practice (very simplified)…

3/ Model Choice



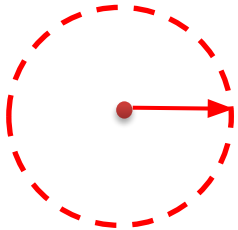
45

5

Posterior probability (green model) =90%

PostProb(blue)=10%

Stat 1:
e.g. Mean Fst



Top X% (e.g. 0.025) best simulations

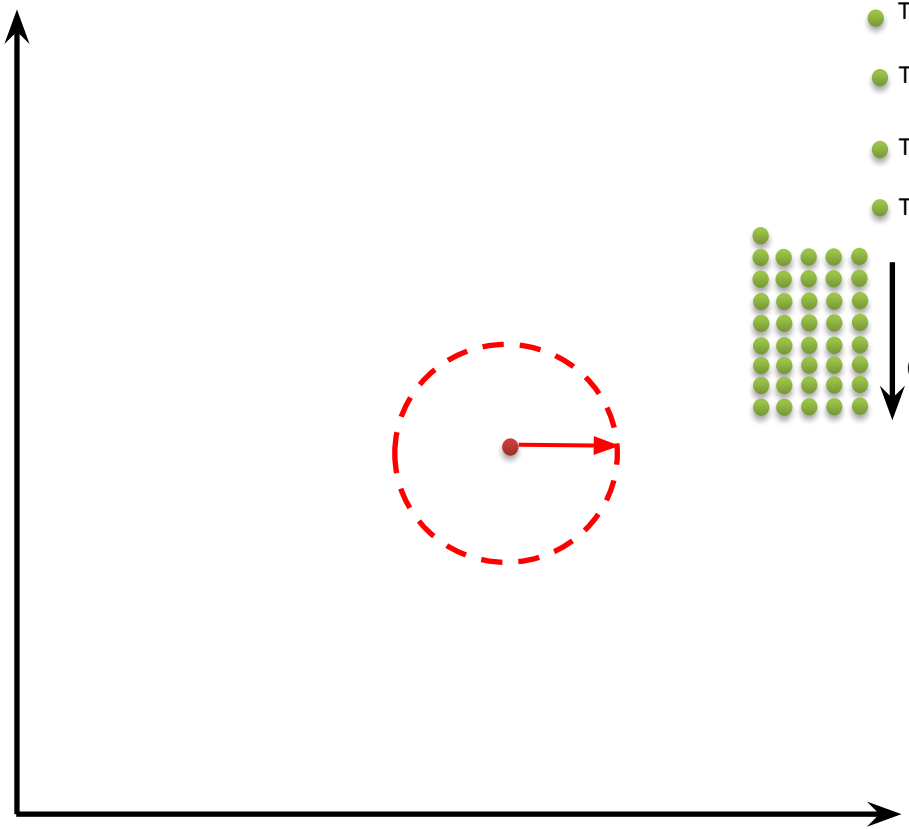
Stat 2
e.g. Tajima's D Pop1

In reality, we use more summary statistics (15-50)!

ABC in practice (very simplified)…

4/ Estimation of parameters under the best model

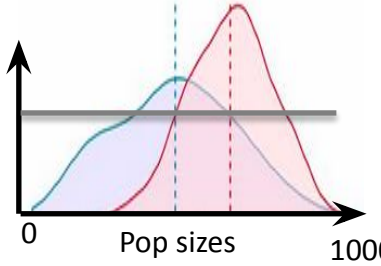
Stat 1:
e.g. Mean Fst

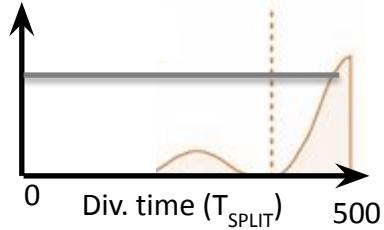


Stat 2
e.g. Tajima's D Pop1

- T_{SPLIT} = XXX ; PopSize1= YYY; PopSize2=ZZZ
- T_{SPLIT} = XXX ; PopSize1= YYY; PopSize2=ZZZ
- T_{SPLIT} = XXX ; PopSize1= YYY; PopSize2=ZZZ
- T_{SPLIT} = …

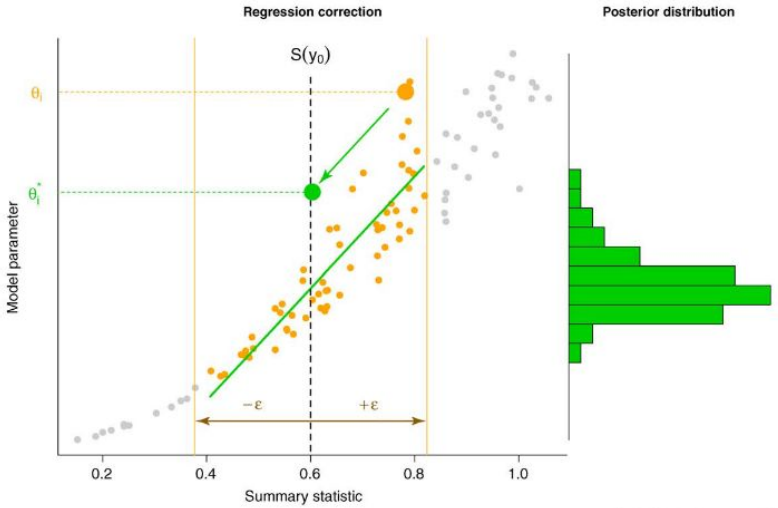
Posterior distributions of the parameters





ABC nowadays (very complex)…

In reality, ‘standard’ ABC algorithms use more complex strategies, potentially including a local regression adjustment (linear or not) before to generate the posterior distribution



Csillery et al. 2010 TREE (Trends in Ecol Evol)

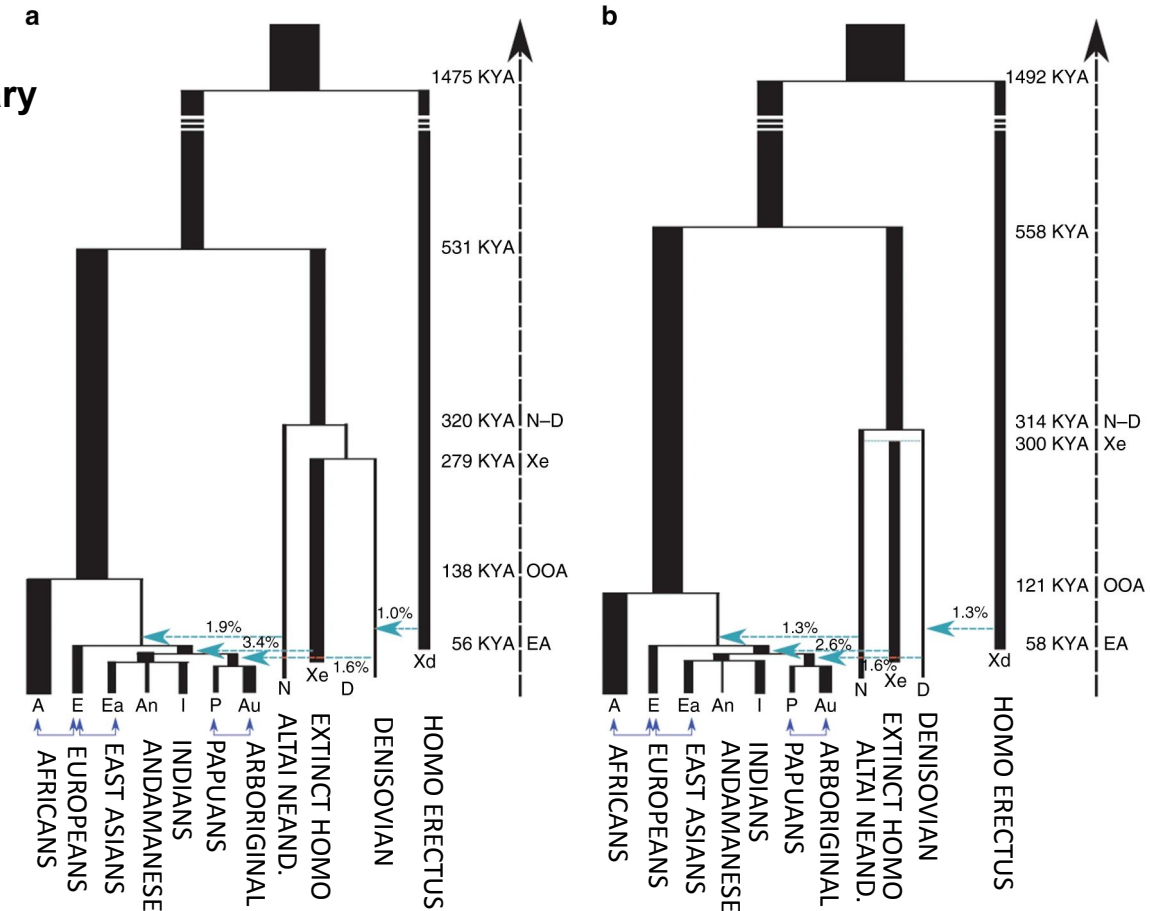
These traditional rejection/regression methods remain popular

but more and more recent ABC algorithms use complex machine learning tools (e.g. neural network (NN) or regression random forest (RF) parameter estimation in relying on the machine-learning tool to automate the inclusion of summary statistics in ABC algorithms)

-> methods learn patterns and relationships between parameter values and summary statistics across many simulations: enhancing efficiency, robustness and parameters estimation accuracy (however this comes at the cost of an increasing ‘black box’ nature)

Examples of applications

Evolutionary history of humans



ABC with deep learning to infer extremely complex demographic scenarios involving 'ghost' populations

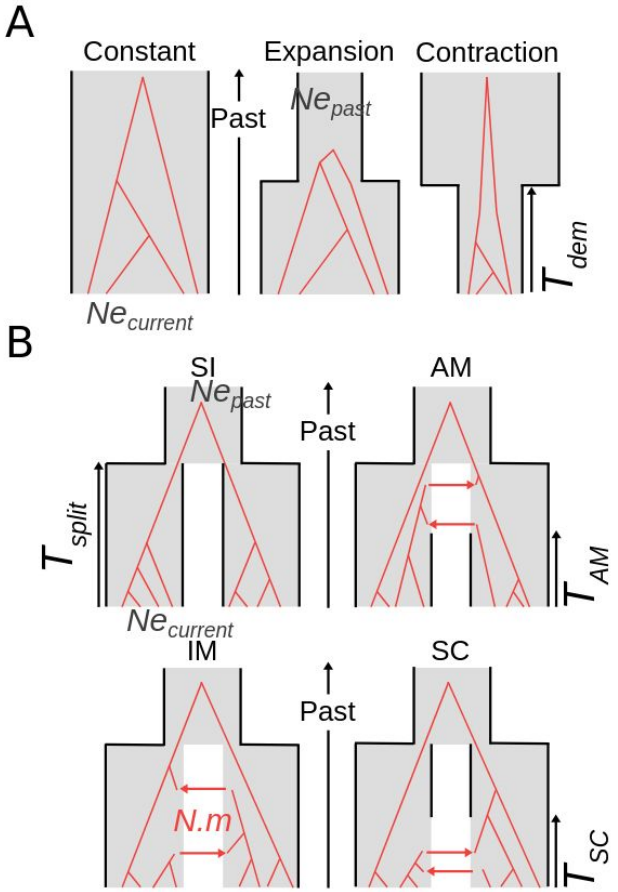
Mondal et al. 2019 Nature Communications (among many!)

Examples of applications

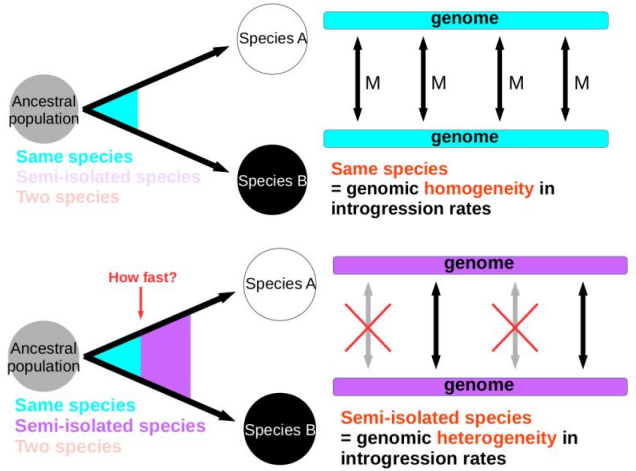
Simpler approaches: demographic simulations in single or pairs of populations (DILS, cf Camille Roux et al.)

Physalia "Model-based demographic inference from population genomics"

Fraïsse et al. 2021 Mol Ecol Res



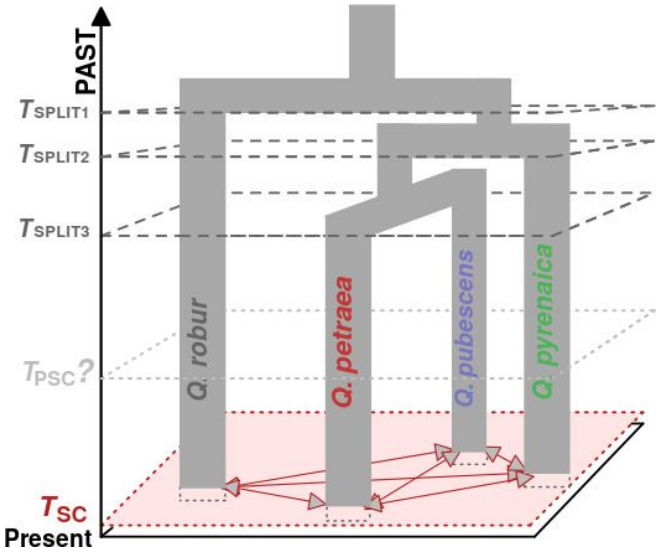
Although the number of populations is very limited, DILS accounts for many confounding factors in demographic modelling: presence of linked selection (background selection + selective sweeps), as well as the presence of barriers to gene flow



Examples of applications

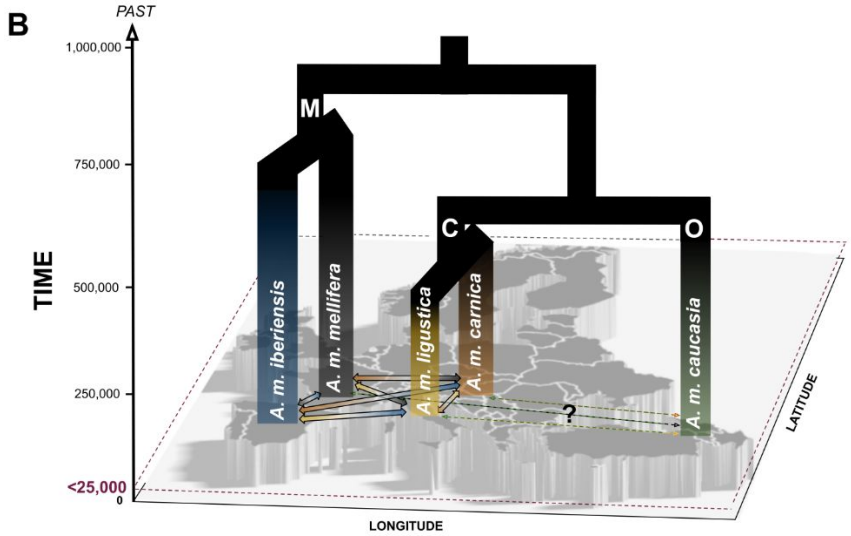
Inferences based on all pairs of pops/subspecies/species to built a general hypothetical model

Evidence for post-glacial secondary contacts in European white oaks (*Quercus*)



Leroy et al. 2017; 2020; New Phytologist

Evidence for post-glacial secondary contacts in Eurasian honey bees (*Apis mellifera*)

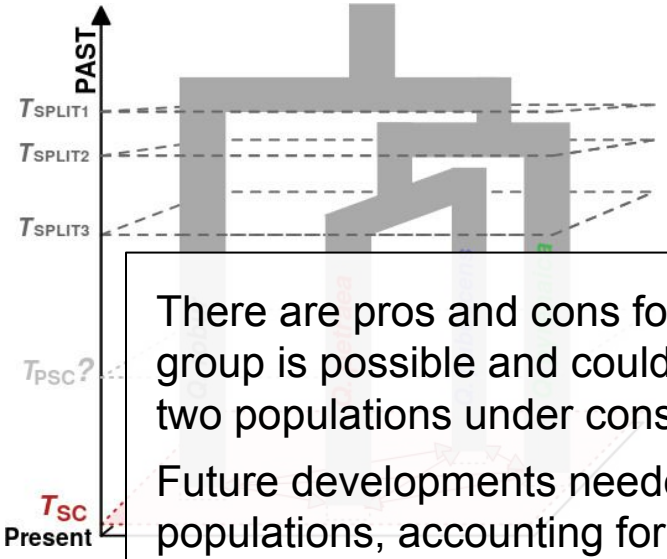


Leroy et al. 2024 bioRxiv

Examples of applications

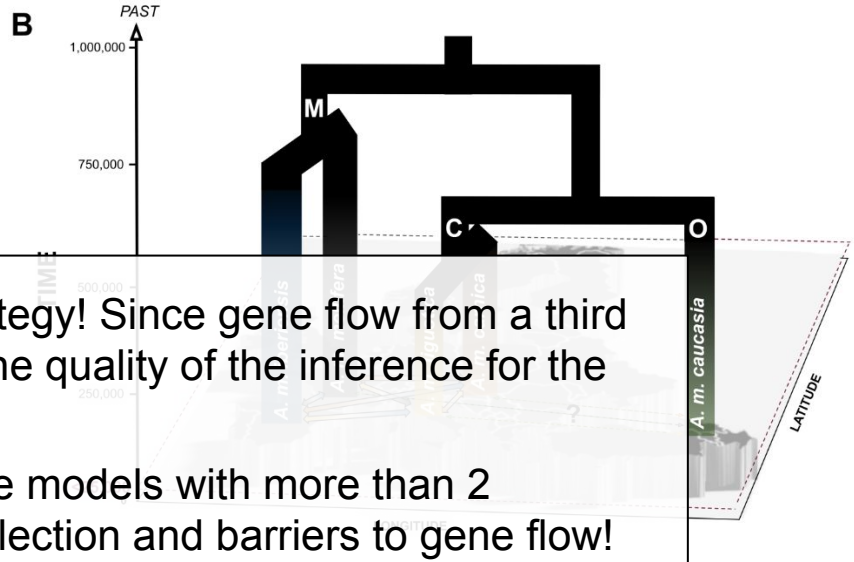
Inferences based on all pairs of pops/subspecies/species to built a general hypothetical model

Evidence for post-glacial secondary contacts in European white oaks (*Quercus*)



Leroy et al. 2017; 2020; New Phytologist

Evidence for post-glacial secondary contacts in Eurasian honey bees (*Apis mellifera*)



Leroy et al. 2024 bioRxiv

There are pros and cons for this strategy! Since gene flow from a third group is possible and could impact the quality of the inference for the two populations under consideration.

Future developments needed to have models with more than 2 populations, accounting for linked selection and barriers to gene flow!

Approximate Bayesian Computation : pros & cons

Advantages:

- Likelihood-free
- Flexible framework

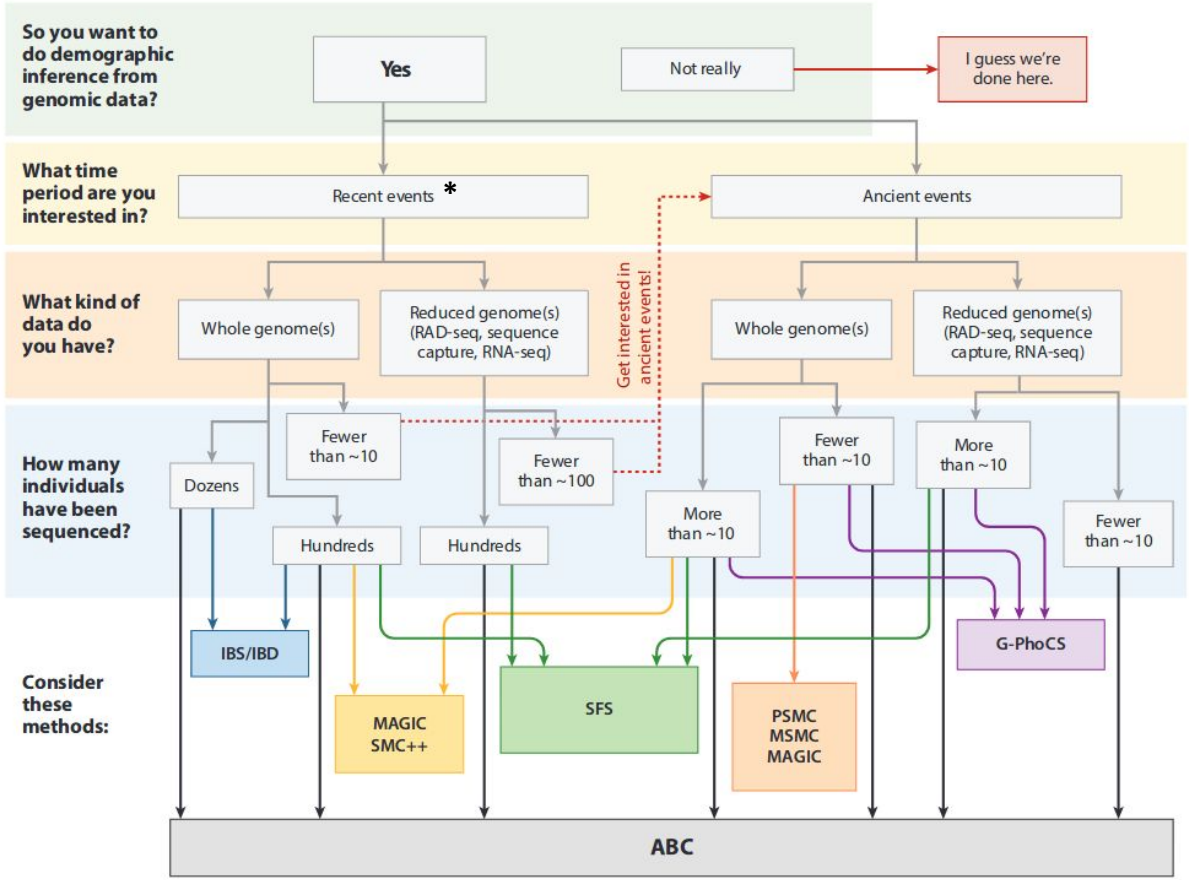
e.g. including possibility to modelize complex genome-wide processes such as heterogeneity in migration rates or effective population sizes (-> DILS)

- Both model choice and estimation of parameters are relatively straightforward
- Convenient statistical model checking based on the SFS / summary statistics

Limitations:

- Considerable computational load (still true, but now becoming less and less the case)
- Human time (especially for newbies, ABC often considered as highly complex)
- Risk of not including the true model (as for any model-based methods!)

Demographic methods: which one to prefer?



* 'Recent events' here: <1000 generations ago

Beichman et al. 2018 Nat Rev Ecol Evol Syst

To finish, back to the low diversity of lynx…

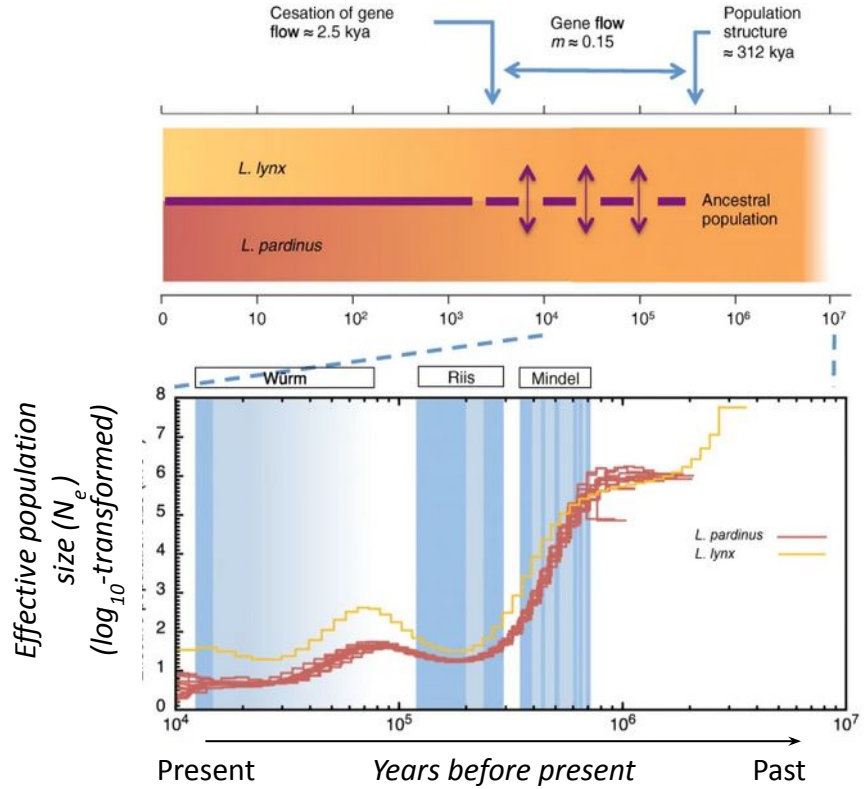
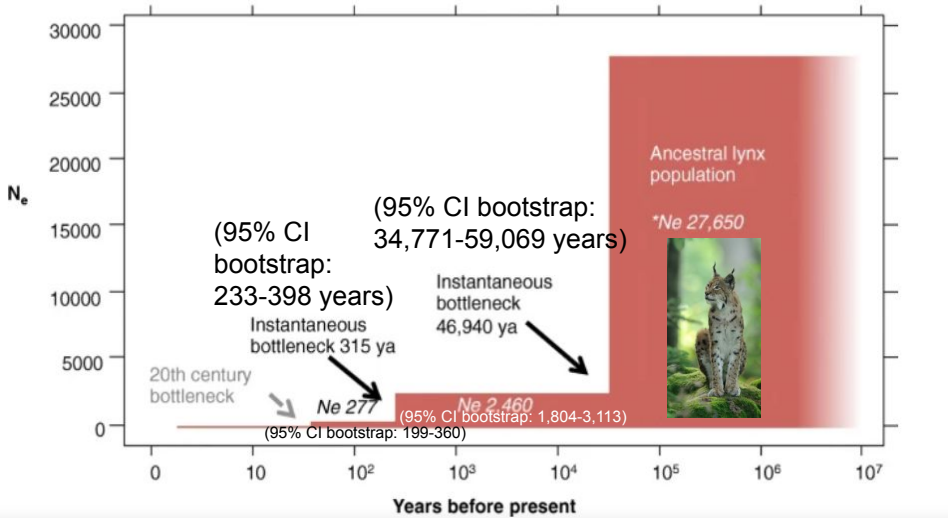


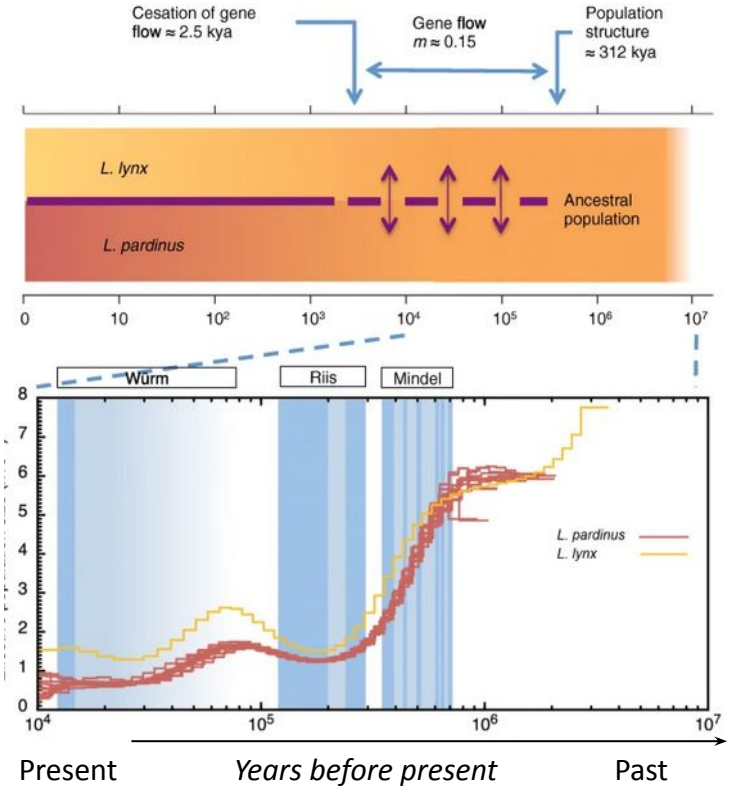
Table S20. Models considered in dadi. For each model we give the number of parameters (K), the AIC score and the AIC differences with respect to the one with the mínimum AIC (Δi).

Model	ln(L)	K	AIC	Δi
Two instantaneous changes	-3116.59	4	6241.18	0.00
One exponential change followed by an instantaneous change	-3292.73	4	6593.46	-352.28
One exponential change	-4583.89	2	9171.79	-2930.60
One instantaneous change	-4881.06	2	9766.12	-3524.94



Abascal et al. 2016 Genome Biology

To finish, back to the low diversity of lynx…



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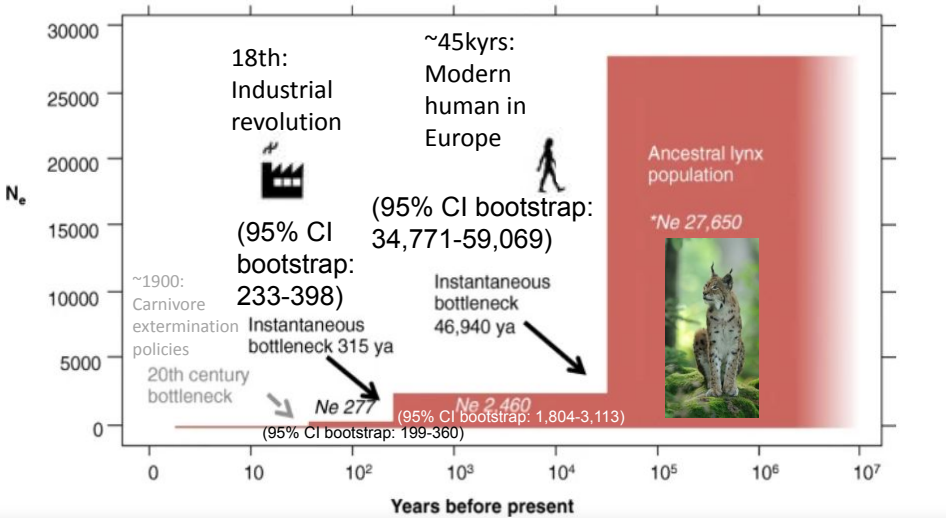
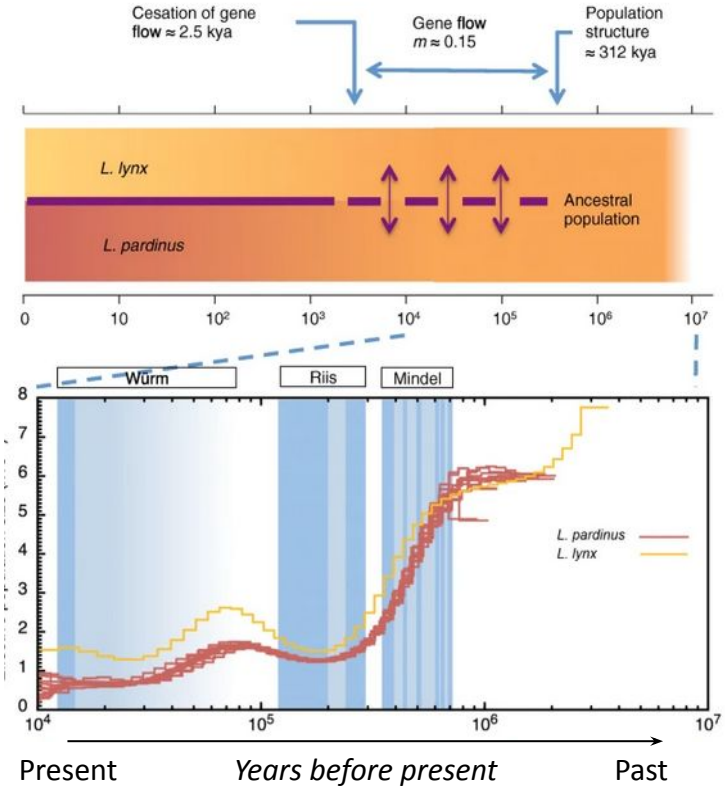


Abascal et al. 2016 Genome Biology

To finish, back to the low diversity of lynx…



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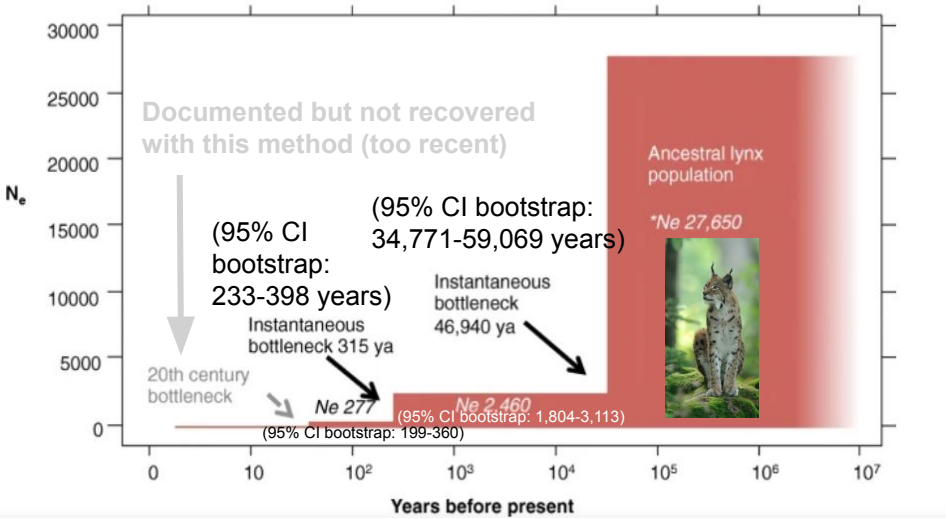


Abascal et al. 2016 Genome Biology

To finish, back to the low diversity of lynx…

+ LD-based demographic modelling

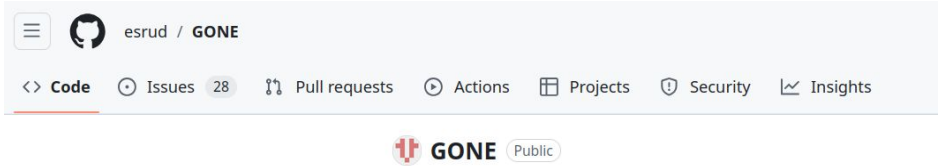
When recombination is not considered, the **mutation rate becomes the sole free parameter, guiding the timing of the coalescence process** (Hudson, 1990).
-> **Time is needed for mutations to accumulate, low resolution in the recent past.**

General idea of LD-based demographic inferences (GONE):
Inferring recent demographic history of a population (within the past 100-200 generations) **from the observed spectrum of linkage disequilibrium (LD) of pairs of loci** over a wide range of recombination rates

Recent Demographic History Inferred by High-Resolution Analysis of Linkage Disequilibrium

Enrique Santiago,*[,1] Irene Novo,[2] Antonio F. Pardiñas,[3] María Saura,[4] Jinliang Wang,[5] and Armando Caballero[2]

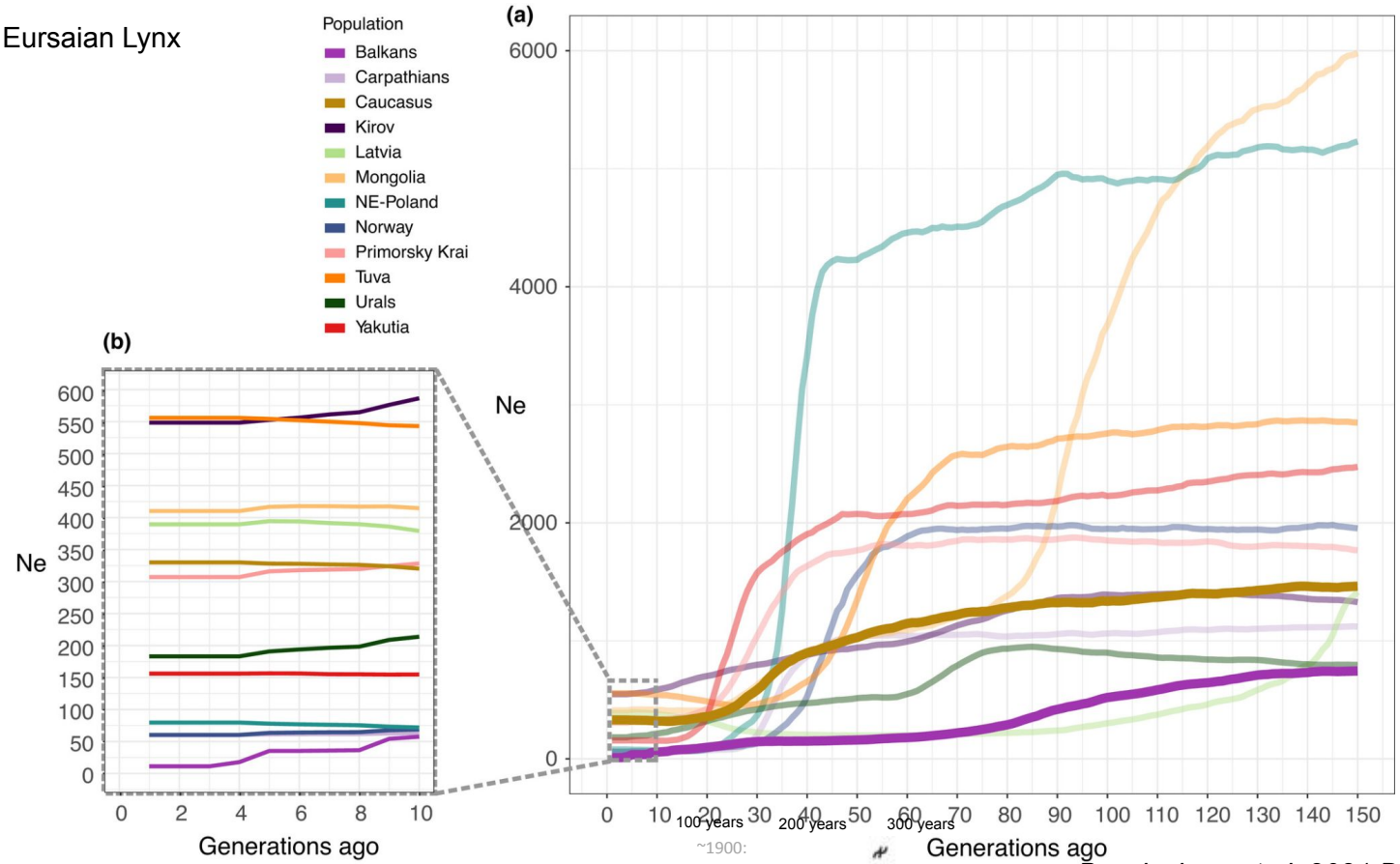
[1]Departamento de Biología Funcional, Facultad de Biología, Universidad de Oviedo, Oviedo, Spain
[2]Centro de Investigación Mariña, Departamento de Bioquímica, Genética e Inmunología, Edificio CC Experimentais, Campus de Vigo, Universidade de Vigo, Vigo, Spain
[3]MRC Centre for Neuropsychiatric Genetics and Genomics, Division of Psychological Medicine and Clinical Neurosciences, School of Medicine, Cardiff University, Cardiff, United Kingdom
[4]Departamento de Mejora Genética Animal, INIA, Madrid, Spain
[5]Institute of Zoology, Zoological Society of London, London, United Kingdom
***Corresponding author:** E-mail: esr@uniovi.es.
Associate editor: Yuseob Kim



→ If you are interested by evolution of N_e over recent time (<100 generations), LD-based modelling approaches could be of high interest (see the practical for more details)

To finish, back to the low diversity of lynx…

Eursaian Lynx



generation time (~5 years)

Bazzicalupo et al. 2021 Diversity and Distributions

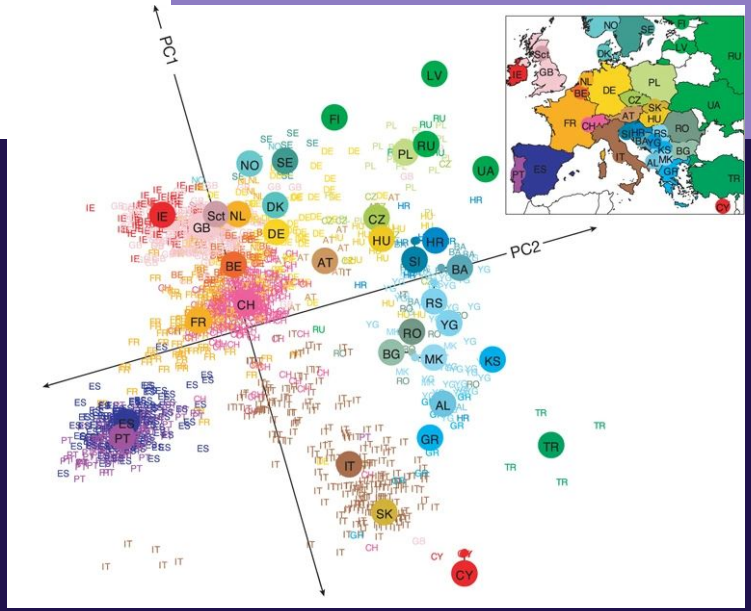
Physalia
Courses

(Intro to) Demographic modeling methods Recap Practical

27/11/2024

Physalia course

Thibault Leroy, Yann Bourgeois



Working with compressed vcf files

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz

```
##fileformat=VCFv4.2
##ALT=<ID=NON_REF,Description="Represents any possible alternative allele at this location">
##FILTER=<ID=LowQual,Description="Low quality">
##FILTER=<ID=hiDP,Description="DP > 2200">
##FILTER=<ID=hiFS,Description="FS > 60.0">
##FILTER=<ID=hiSOR,Description="SOR > 3.0">
##FILTER=<ID=indel6,Description="Overlaps a user-input mask">
##FILTER=<ID=loAN,Description="AN < 178">
##FILTER=<ID=loBaseQRankSum,Description="BaseQRankSum < -8.0">
##FILTER=<ID=loDP,Description="DP < 800">
##FILTER=<ID=loMQ,Description="MQ < 40.0">
##FILTER=<ID=loMQRankSum,Description="MQRankSum < -3.0">
##FILTER=<ID=loQD,Description="QD < 8.0">
##FILTER=<ID=loReadPosRankSum,Description="ReadPosRankSum < -1.5">
##FILTER=<ID=repmask,Description="Overlaps a user-input mask">
##FORMAT=<ID=AD,Number=R,Type=Integer,Description="Allelic depths for the ref and alt alleles in the order listed">
##FORMAT=<ID=DP,Number=1,Type=Integer,Description="Approximate read depth (reads with MQ=255 or with bad mates are filtered)">
##FORMAT=<ID=GQ,Number=1,Type=Integer,Description="Genotype Quality">
##FORMAT=<ID=GT,Number=1,Type=String,Description="Genotype">
##FORMAT=<ID=MIN_DP,Number=1,Type=Integer,Description="Minimum DP observed within the GVCF block">
##FORMAT=<ID=PGT,Number=1,Type=String,Description="Physical phasing haplotype information, describing how the alternate alleles are phased in relat
##FORMAT=<ID=PID,Number=1,Type=String,Description="Physical phasing ID information, where each unique ID within a given sample (but not across samp
##FORMAT=<ID=PL,Number=G,Type=Integer,Description="Normalized, Phred-scaled likelihoods for genotypes as defined in the VCF specification">
##FORMAT=<ID=RGQ,Number=1,Type=Integer,Description="Unconditional reference genotype confidence, encoded as a phred quality -10*log10 p(genotype ca
##FORMAT=<ID=SB,Number=4,Type=Integer,Description="Per-sample component statistics which comprise the Fisher's Exact Test to detect strand bias.">
##GATKCommandLine.GenotypeGVCFs=<ID=GenotypeGVCFs,Version=3.7-0-gcfedb67,Date="Fri Aug 04 15:34:38 EDT 2017",Epoch=1501875278990,CommandLineOptions=
=null read_filter=[] disable_read_filter=[] intervals=null excludeIntervals=null interval_set_rule=UNION interval_merging=ALL interval_padding=0 re
--More--
```

Press “q” to leave

Working with compressed vcf files

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep "#CHROM"

```
#CHROM  POS  ID  REF  ALT  QUAL  FILTER  INFO  FORMAT  Abel  Abouman  Ajwa
Alig  Amir_haj  Aseel  Atlantica_CAP1_POPMAL1  Atlantica_CAP50_BOA1  Aziza  Azraq_azraq  Barmel
Began  Besser_halooBiddajaj  Boufkouss_Rarass  BouslKhine  Braim  Canariensis_93115  Canariensis_93116
Canariensis_93121  Canariensis_DP6A  Canariensis_JBMPL_P3  Canariensis_JBMPL_P9  Chichi  Dajwani
Dedhi  Deglet_noor  Dibbas  Ebrahimi  Ewent_ayob  Fagous  Fard4  Faslee  Gajar  Halawy
HamriaHawawiri  Hayany  Helwa  Hilali  Hiri  Horra  Jao  Jihl  Kabkab  Kamla  Karbali
Kashoowari  Khadrawy  Khalte  Khastawi  Khenezi  Khisab  KuprooLulu  Maktoumi  Manjouma
Mazafati  Medjool  Nagal  Naquel_khuh  Nebeit_seif  Otaquin  Piavom  Rabee  Raslatmar
Reclinata_DP18  Rhars  RothanSaidiSamany  Shagri  Silani  Sultana  Sylvestris_P59
Sylvestris_RIV_2248_PL_F  Sylvestris_RIV_2249_PL_M  Sylvestris_RIV_2256_PL_F  Sylvestris_RIV_7394_PI_M
Sylvestris_RIV_7395_PL_M  Sylvestris_SYL87_JCP_651  Tagiat  Theophrasti_02a  Theophrasti_05a
Theophrasti_A1  Theophrasti_A5  Theophrasti_B1  Theophrasti_B3  Theophrasti_B5
Theophrasti_C1  Theophrasti_C4  Theophrasti_D1  Theophrasti_D3  Theophrasti_D5
Theophrasti_E1  Theophrasti_E2  Theophrasti_F1  Theophrasti_F2
Theophrastis_GOLK_001_91020  Theophrastis_THE83_91051  Thory  Um_al_blaliz  Um_al_hamam  Zagloul
Zahidi
```

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep "#CHROM" | awk '{print NF-9}'

105 individuals in the dataset

Working with compressed vcf files

```
zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep "PASS" | wc -l
419628

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep -v “#” | grep "PASS" | wc -l
419628

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | awk '$7 == "PASS" {print $0}' | wc -l
419628
```

OPTIONAL: Can you estimate a variant density (# high quality SNPs / length of the first scaffold on the VCF)?

```
zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep -v "#" | head -1
NW_008246507.1   6801  .   C   A   2072.27   PASS   (continued…)

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep "NW_008246507.1" | tail -1
NW_008246507.1   4532558   .   A   G   20425.49   PASS   (continued…)

zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep "NW_008246507.1" | awk '$7 == "PASS" {print $0}' | wc -l
142392
```

142392 / **4532558** = 0.0314 -> 1/0.0314 On average, **one variant every 31.8 bases** in the vcf (1st scaff)

Limits: rough estimate, it doesn’t take into account the some regions of the scaff completely uncovered

Step 1: identify non-admixed individuals

head -3 samples_Qvalues.txt

```
IID     Species Cluster_outgroups    Cluster_Pdac       Cluster_Ptheo    Note
Canariensis_93115       P._canariensis  0.99998 1E-05    1E-05    'Pure'
Canariensis_93116       P._canariensis  0.99998 1E-05    1E-05    'Pure'
```

grep "**P._dactylifera_ME**" samples_Qvalues.txt | **awk '$4 > 0.90** {print $0}' > samples_Qvalues.PdactyliferaME.txt

head -2 samples_Qvalues.PdactyliferaME.txt

```
Abouman   P._dactylifera_ME        1E-05   0.99998 1E-05   'Pure'
Ajwa  P._dactylifera_ME        1E-05   0.99998 1E-05   'Pure'
```

grep "P._dactylifera_NAfr" samples_Qvalues.txt | awk '$4 > 0.90 {print $0}' > samples_Qvalues.PdactyliferaNAfr.txt
grep "P._theophrasti" samples_Qvalues.txt | awk '$5 > 0.90 {print $0}' > samples_Qvalues.Ptheophrasti.txt

awk '{print $1}' samples_Qvalues.PdactyliferaME.txt > samples_Qvalues.PdactyliferaME.list
head -2 samples_Qvalues.PdactyliferaME.list

```
Abouman
Ajwa
```

awk '{print $1}' samples_Qvalues.PdactyliferaNAfr.txt > samples_Qvalues.PdactyliferaNAfr.list
awk '{print $1}' samples_Qvalues.Ptheophrasti.txt > samples_Qvalues.Ptheophrasti.list

Step 1: identify non-admixed individuals

How many individuals are identified as "relatively pure" in each population or species based on this criterion?

```
less samples_Qvalues.PdactyliferaME.list | wc -l
45

less samples_Qvalues.PdactyliferaNAfr.list | wc -l
9

less samples_Qvalues.Ptheophrasti.list | wc -l
16
…

wc -l samples_Qvalues.PdactyliferaME.list
45 samples_Qvalues.PdactyliferaME.list
…

for i in *list; do wc -l $i; done
45 samples_Qvalues.PdactyliferaME.list
9 samples_Qvalues.PdactyliferaNAfr.list
16 samples_Qvalues.Ptheophrasti.list
```

Remember to:

- infer population structure (PCA, Structure, …)

- remove individuals with footprints of recent admixture

- remove individuals with very recent family relationships (if any)

… before to start inferring past demography!

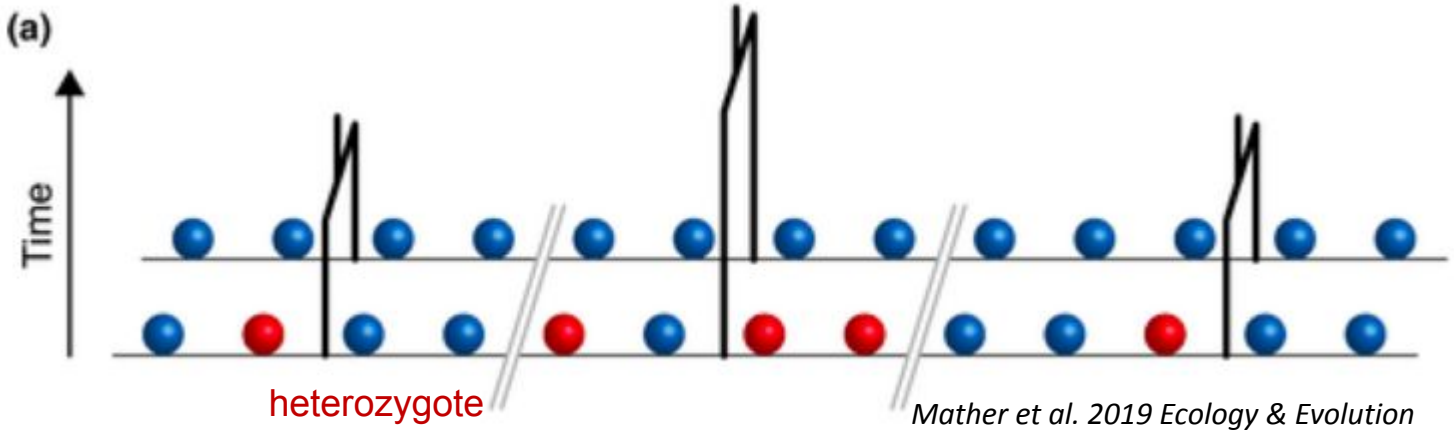
To recap, here:
45 “pure” individuals from *Phoenix dactylifera* (Middle East)

9 “pure” individuals from *P. dactylifera* (North Africa)

16 “pure” individuals from P. theophrastii

Step 2: Perform inferences of N_e with SMC++

TMRCA between the two alleles carried by an individual



Mather et al. 2019 Ecology & Evolution

Before

```
zmore Flowers_et_al_2019.SNPs.tronq.vcf.gz | grep "NW_008246507.1" | awk '$7 == "PASS" {print $0}' | wc -l
```

142392

After

```
less ./Calling/Flowers_et_al_2019.SNPs.bialleliconly.tronq.vcf | grep "NW_008246507.1" | awk '$7 == "PASS" {print $0}' | wc -l
```

142392

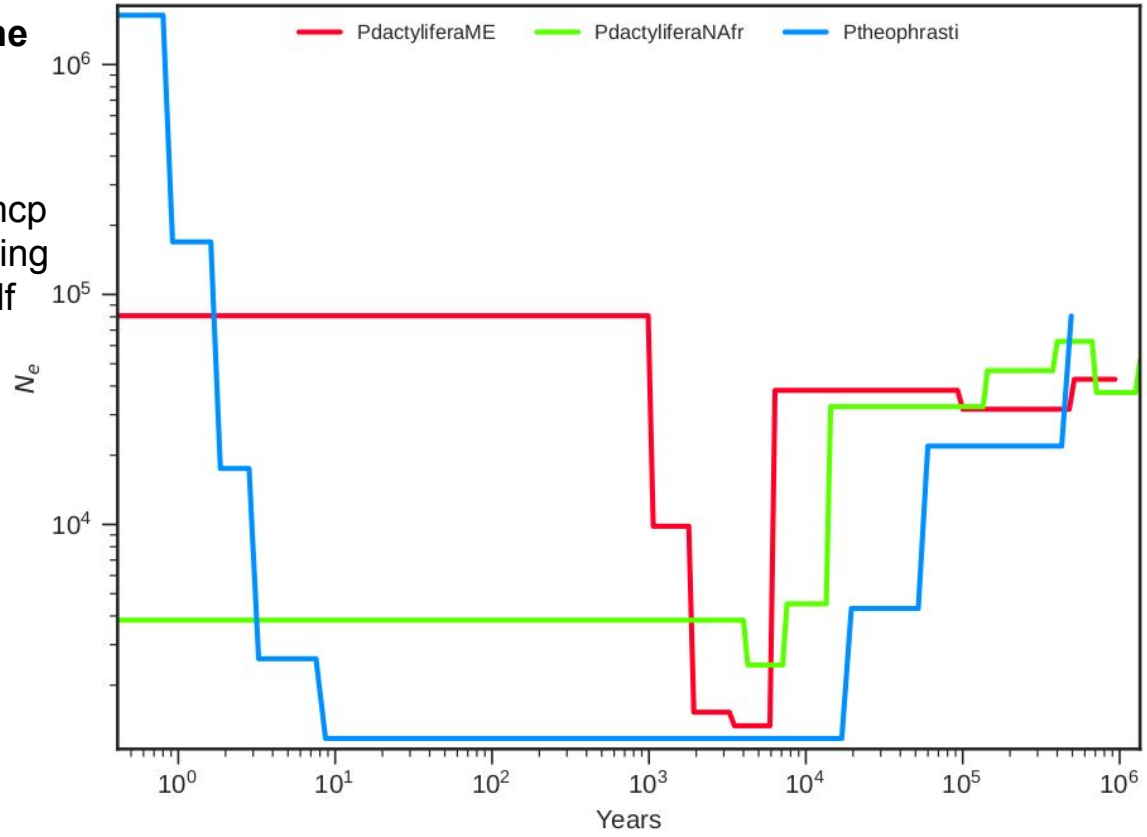
No changes! What does it mean?
Flowers et al. only deposited variants corresponding to biallelic SNPs!

Step 2: Perform inferences of N_e with SMC++

smc++ plot -g 10 -c physalia_smcpp_plot_missingcutoff500.pdf PdactyliferaMe/model.final.json PdactyliferaNAfr/model.final.json Ptheophrasti/model.final.json

output of the smc++ plot function

physalia_smcpp_plot_missingcutoff500.pdf

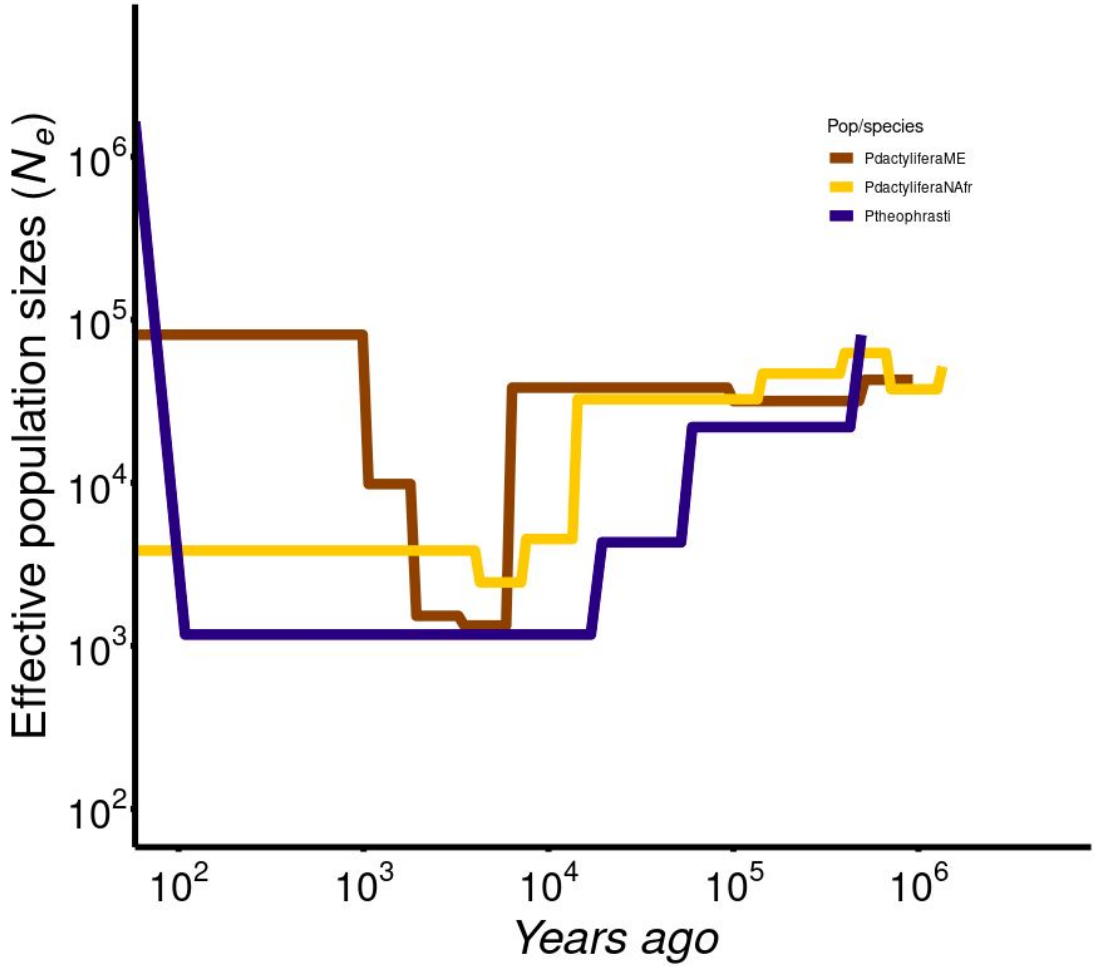


Step 2: Perform inferences of N_e with SMC++

```
inferredNe500=read.csv("physalia_smcpp_plot.csv",header=TRUE,sep=",")
colnames(inferredNe500)<-c("Population","Years","Ne","plot-type","plot-num")
My_colors <-
c("PdactyliferaME"="chocolate4","PdactyliferaNAfr"="goldenrod1","Ptheophrasti"="navyblue")

ggplot(inferredNe500, aes(x=Years, y=Ne)) +
  geom_line(aes(colour=Population),size=3)+
  scale_colour_manual("Pop/species",values=My_colors)+
  xlab("Years ago")+ ylab(expression(paste("Effective population sizes (",italic(N[e]),")")))+
  scale_x_log10(limits=c(100,5000000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  scale_y_log10(limits=c(100,5000000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  theme_bw()+
  theme(plot.margin = margin(1,3,1.5,1.2, "cm"))+
  theme(legend.position="none",panel.border = element_blank(), panel.grid.major = element_blank(),
panel.grid.minor = element_blank(), axis.line = element_line(colour = "black"))+
  theme(axis.line = element_line(colour = 'black', size = 1.75), axis.ticks = element_line(colour = 'black',
size = 1.75),
        axis.text.x = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
        axis.text.y = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
        axis.title.x = element_text(colour="black",size=28,angle=0,hjust=.5,vjust=.2,face="italic"),
        axis.title.y = element_text(colour="black",size=28,angle=90,hjust=.5,vjust=.5,face="italic"))
```

Step 2: Perform inferences of N_e with SMC++



Step 2: Perform inferences of N_e with SMC++

Optional 1

cd ~/Day3_demography/data-datepalm/Res_SMCpp/**res_SMCpp_missing50kb/**

smc++ plot -g 10 -c **../**physalia_smcpp_plot_missingcutoff50000.pdf PdactyliferaMe/model.final.json PdactyliferaNAfr/model.final.json Ptheophrasti/model.final.json
= same command than before but from the **res_SMCpp_missing50kb/**

ls
PdactyliferaMe
physalia_smcpp_plot_missingcutoff50000.csv
physalia_smcpp_plot_missingcutoff500.csv_FOR_IMPATIENT_PEOPLE_ONLY.csv
Ptheophrasti
Rplot_ggplot2_smcpp_missingcutoff500.pdf
PdactyliferaNAfr
physalia_smcpp_plot_missingcutoff50000.pdf
physalia_smcpp_plot_missingcutoff500.pdf
res_SMCpp_missing50kb
script_generate_smcpp.R

Step 2: Perform inferences of N_e with SMC++

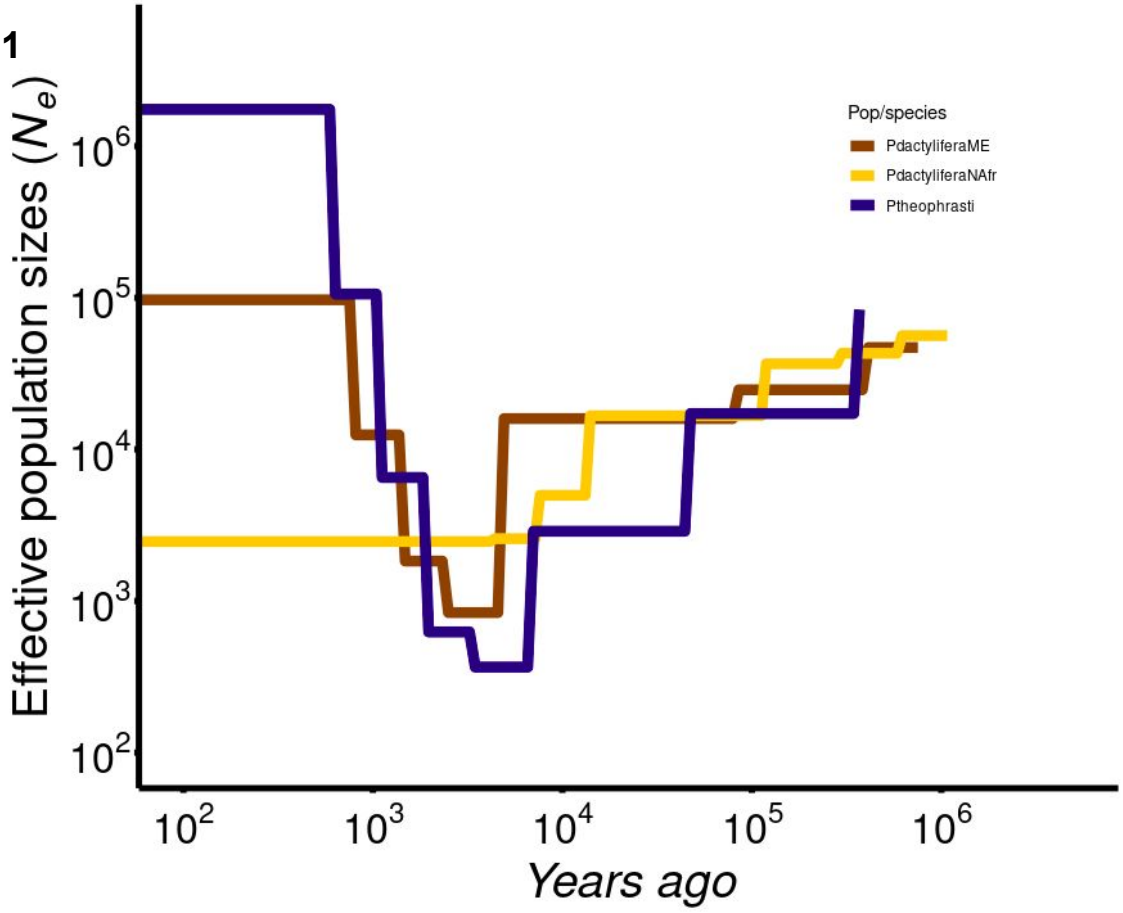
```
inferredNe50kb=read.csv("physalia_smcpp_plot_missing50kb.csv",header=TRUE,sep=",")

colnames(inferredNe50kb)<-c("Population","Years","Ne","plot-type","plot-num")

ggplot(inferredNe50kb, aes(x=Years, y=Ne)) +
  geom_line(aes(colour=Population),size=3)+
  scale_colour_manual("Pop/species",values=My_colors)+
  xlab("Years ago")+ ylab(expression(paste("Effective population sizes (",italic(N[e]),")")))+
  scale_x_log10(limits=c(100,5000000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  scale_y_log10(limits=c(100,5000000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  theme_bw()+
  theme(plot.margin = margin(1,3,1.5,1.2, "cm"))+
  theme(theme(legend.position=c(0.8, 0.8),panel.border = element_blank(), panel.grid.major =
element_blank(), panel.grid.minor = element_blank(), axis.line = element_line(colour = "black"))+
  theme(axis.line = element_line(colour = 'black', size = 1.75), axis.ticks = element_line(colour = 'black', size =
1.75),
        axis.text.x = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
        axis.text.y = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
        axis.title.x = element_text(colour="black",size=28,angle=0,hjust=.5,vjust=.2,face="italic"),
        axis.title.y = element_text(colour="black",size=28,angle=90,hjust=.5,vjust=.5,face="italic"))
```

Step 2: Perform inferences of N_e with SMC++

Optional 1



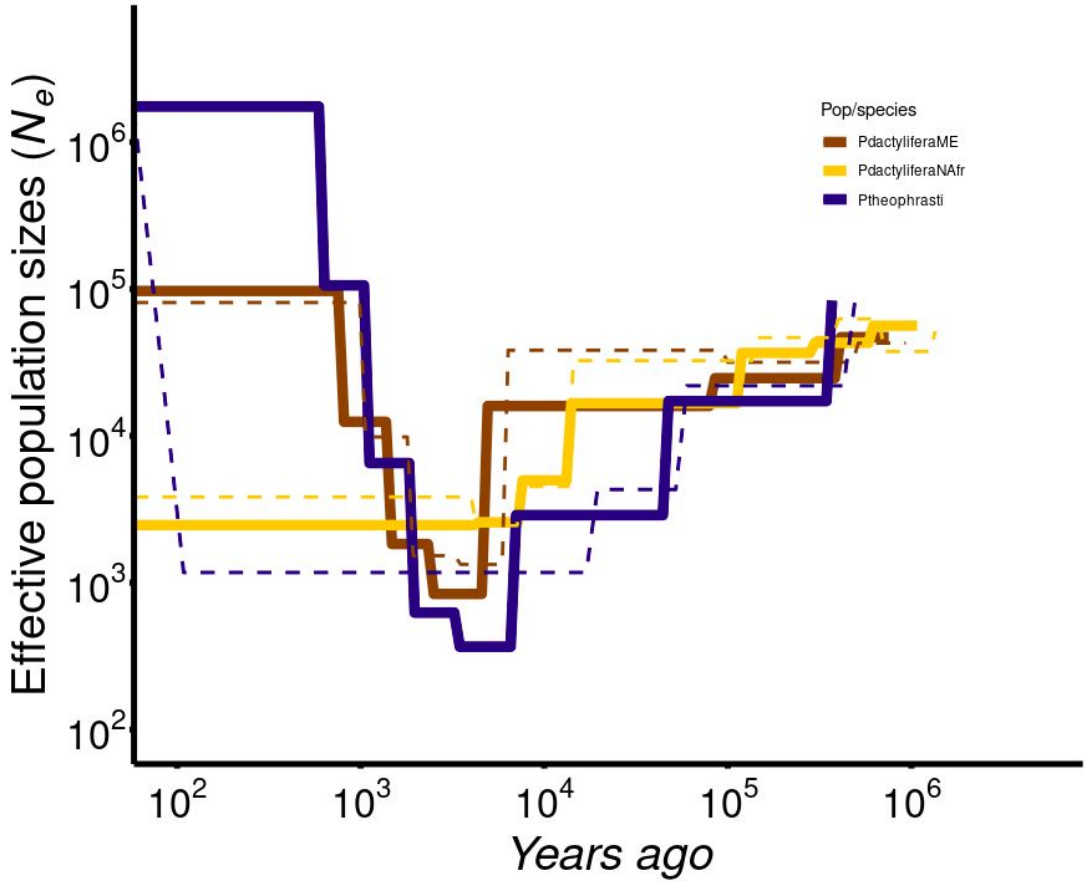
Step 2: Perform inferences of N_e with SMC++

Optional 2

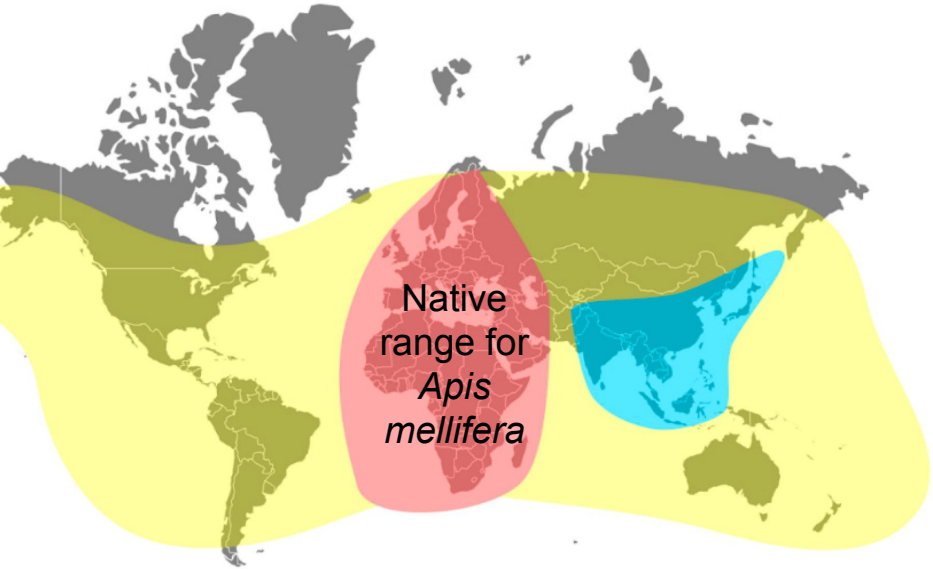
```
ggplot() +
  geom_line(data=inferredNe500,aes(x=Years, y=Ne,colour=Population),size=1,lty=2)+
  geom_line(data=inferredNe50kb,aes(x=Years, y=Ne,colour=Population),size=3)+
  scale_colour_manual("Pop/species",values=My_colors)+
  xlab("Years ago")+ ylab(expression(paste("Effective population sizes (",italic(N[e]),")")))+
  scale_x_log10(limits=c(100,5000000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  scale_y_log10(limits=c(100,5000000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  theme_bw()+
  theme(plot.margin = margin(1,3,1.5,1.2, "cm"))+
  theme(legend.position=c(0.8, 0.8),panel.border = element_blank(), panel.grid.major = element_blank(),
panel.grid.minor = element_blank(), axis.line = element_line(colour = "black"))+
  theme(axis.line = element_line(colour = 'black', size = 1.75), axis.ticks = element_line(colour = 'black', size =
1.75),
        axis.text.x = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
        axis.text.y = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
        axis.title.x = element_text(colour="black",size=28,angle=0,hjust=.5,vjust=.2,face="italic"),
        axis.title.y = element_text(colour="black",size=28,angle=90,hjust=.5,vjust=.5,face="italic"))
```

Step 2: Perform inferences of N_e with SMC++

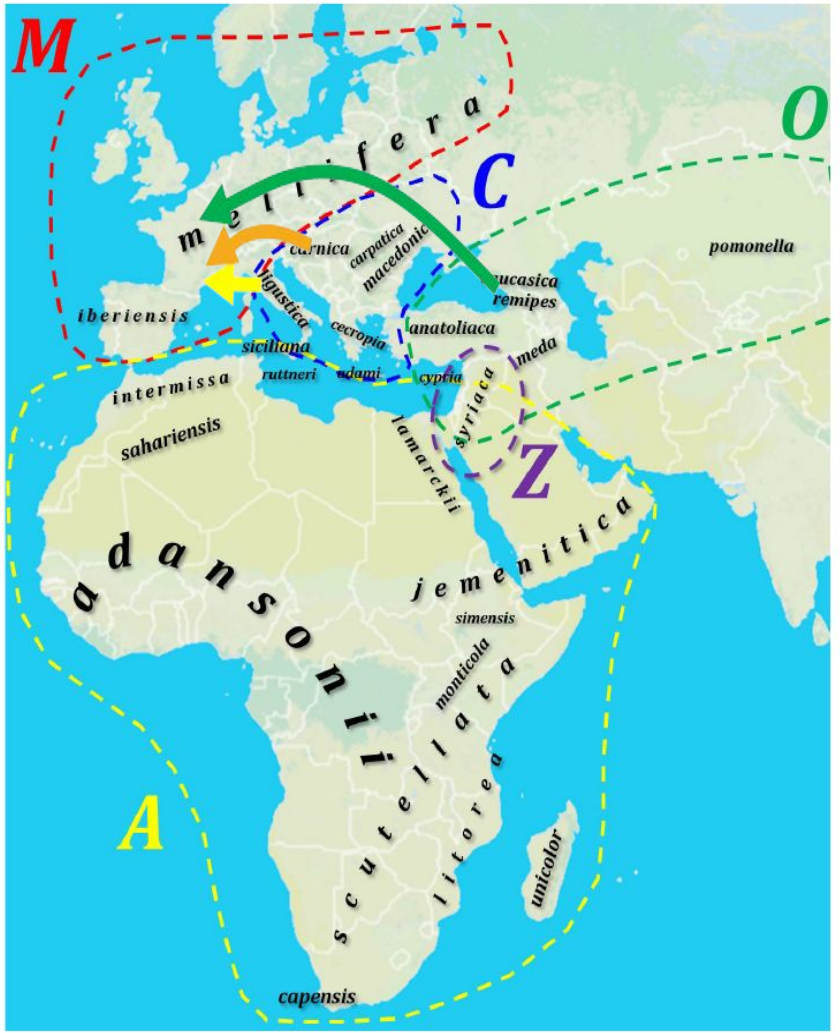
Optional 2



Apis mellifera (Western honey bee)



Beaurepaire et al. 2020

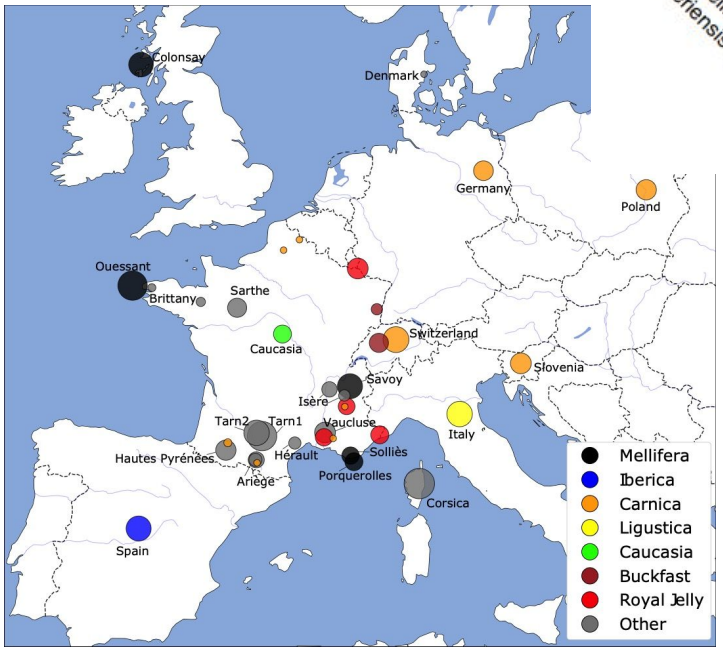


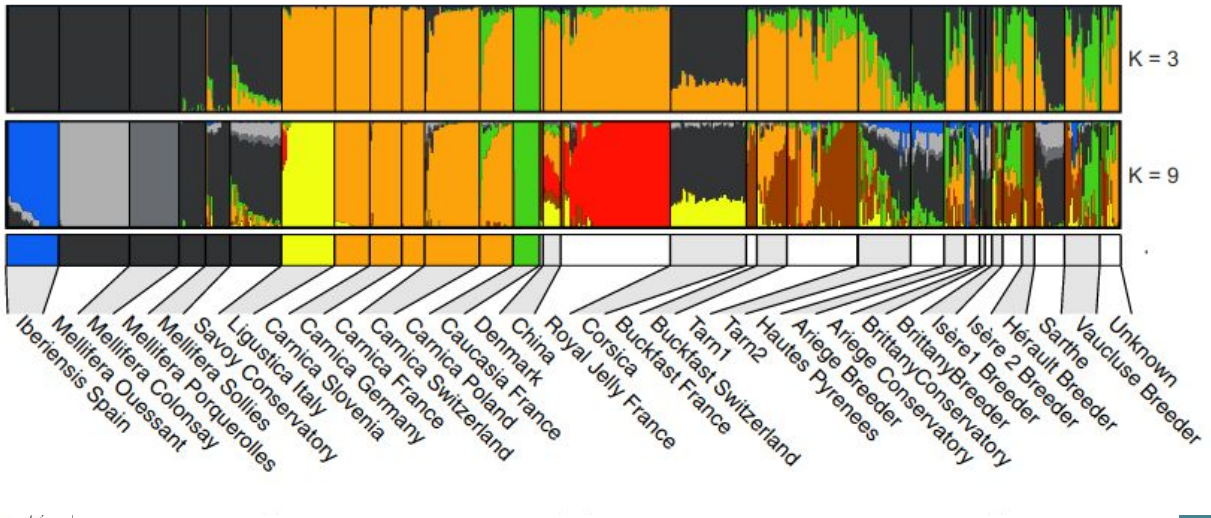
RESOURCE ARTICLE

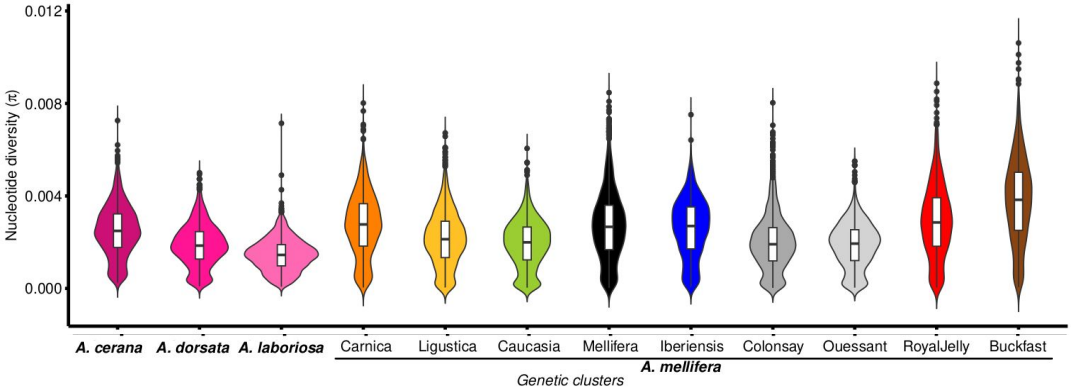
MOLECULAR ECOL RESOURCES

Complex population structure and haplotype patterns Western European honey bee from sequencing a large haploid drones

David Wragg[1] | Sonia E. Eynard[1] | Benjamin Basso[2] | Kamila Canale-Tab
Emmanuelle Labarthe[1] | Olivier Bouchez[3] | Kaspar Bienefeld[4] |
Małgorzata Bieńkowska[5] | Cecilia Costa[6] | Aleš Gregorc[7] |
Per Kryger[8] | Melanie Parejo[9] | M. Alice Pinto[10] | Jean-Pierre Bidanel[11] |
Bertrand Servin[1] | Yves Le Conte[12] | Alain Vignal[1]







Leroy et al. 2024 bioRxiv

Step 3: Perform inferences of recent N_e

less Output_Ne_seqapipop870_Ouessant_500kSNPs.withheader_FOR_IMPATIENT_PERSON_ONLY.txt

Ne averages over 40 independent estimates.

Generation	Geometric_mean
1	66.7276
2	66.7276
3	66.7276
4	66.7276
5	74.7291

head -1 Output_Ne_seqapipop870_Ouessant_500kSNPs.withheader_FOR_IMPATIENT_PERSON_ONLY.txt

Ne averages over 40 independent estimates

grep -v "independent"
Output_Ne_seqapipop870_Ouessant_500kSNPs.withheader_FOR_IMPATIENT_PERSON_ONLY.txt >
Output_Ne_Ouessant.txt

Generation	Geometric_mean
1	66.7276
2	66.7276
3	66.7276

Step 3: Perform inferences of recent N_e

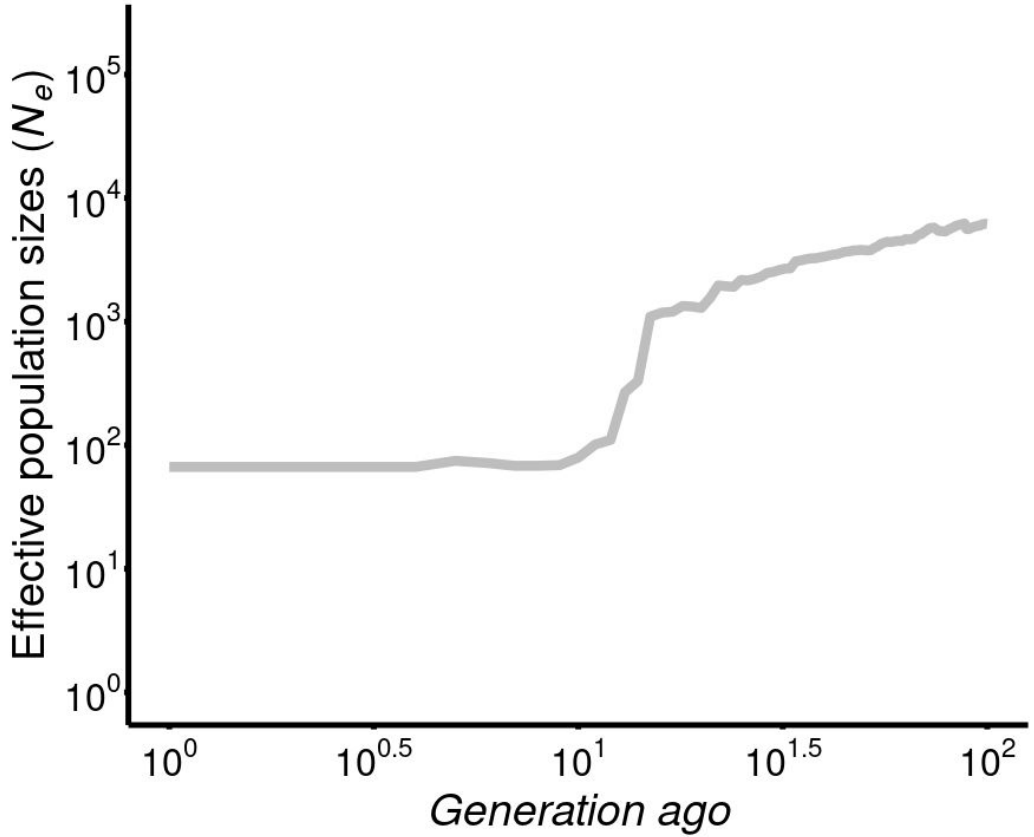
Rscript script_GONE_ggplot2.R

```
library(ggplot2)

setwd("~/Day3_demography/data-honeybees/recentNe_GONE")
GONEinferredNe=read.table("Output_Ne_Ouessant.txt",header=TRUE,sep="\t")

pdf(file="Rplot_ggplot2_Ouessant_GONE.pdf",width=10,height=10)
ggplot(GONEinferredNe, aes(x=Generation, y=Geometric_mean)) +
  geom_line(colour="grey",size=3)+
  xlab("Generation ago")+ ylab(expression(paste("Effective population sizes (",italic(N[e]),")")))+
  scale_x_log10(limits=c(1,100),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  scale_y_log10(limits=c(1,200000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
 theme_bw()+
 theme(plot.margin = margin(1,3,1.5,1.2, "cm"))+
 theme(legend.position="none",panel.border = element_blank(), panel.grid.major = element_blank(), panel.grid.minor = element_blank(), axis.line = element_line(colour = "black"))+
 theme(axis.line = element_line(colour = 'black', size = 1.75), axis.ticks = element_line(colour = 'black', size = 1.75),
            axis.text.x = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
            axis.text.y = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
            axis.title.x = element_text(colour="black",size=28,angle=0,hjust=.5,vjust=.2,face="italic"),
            axis.title.y = element_text(colour="black",size=28,angle=90,hjust=.5,vjust=.5,face="italic"))
dev.off()
```

Step 3: Perform inferences of recent N_e



Step 3: Perform inferences of recent N_e

```
ggplot() +
  geom_line(data=GONEinferredNe, aes(x=Generation, y=Geometric_mean),colour="grey",size=3)+
  geom_line(data=GONEinferredNe2, aes(x=Generation,y=Geometric_mean),colour="grey30",size=2,lty=2)+
  xlab("Generation ago")+ ylab(expression(paste("Effective population sizes (",italic(N[e]),")")))+
  scale_x_log10(limits=c(1,100),breaks = scales::trans_breaks("log10", function(x) 10^x),labels = scales::trans_format("log10",
scales::math_format(10^.x)))+
  scale_y_log10(limits=c(1,200000),breaks = scales::trans_breaks("log10", function(x) 10^x),labels =
scales::trans_format("log10", scales::math_format(10^.x)))+
  theme_bw()+
  theme(plot.margin = margin(1,3,1.5,1.2, "cm"))+
  theme(legend.position="none",panel.border = element_blank(), panel.grid.major = element_blank(), panel.grid.minor =
element_blank(), axis.line = element_line(colour = "black"))+
  theme(axis.line = element_line(colour = 'black', size = 1.75), axis.ticks = element_line(colour = 'black', size = 1.75),
        axis.text.x = element_text(colour="black",size=24,angle=0,hjust=.5,vjust=.5,face="plain"),
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        axis.title.x = element_text(colour="black",size=28,angle=0,hjust=.5,vjust=.2,face="italic"),
        axis.title.y = element_text(colour="black",size=28,angle=90,hjust=.5,vjust=.5,face="italic"))
```
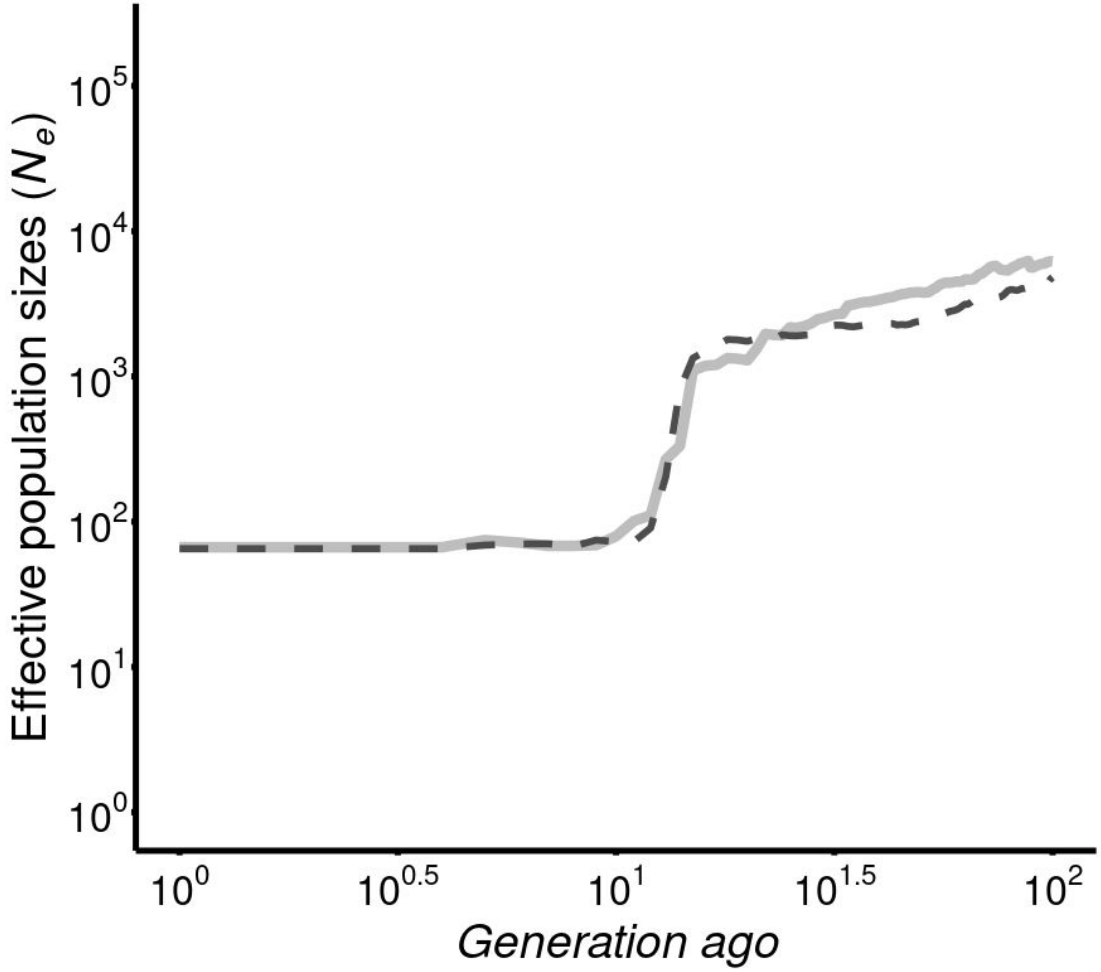
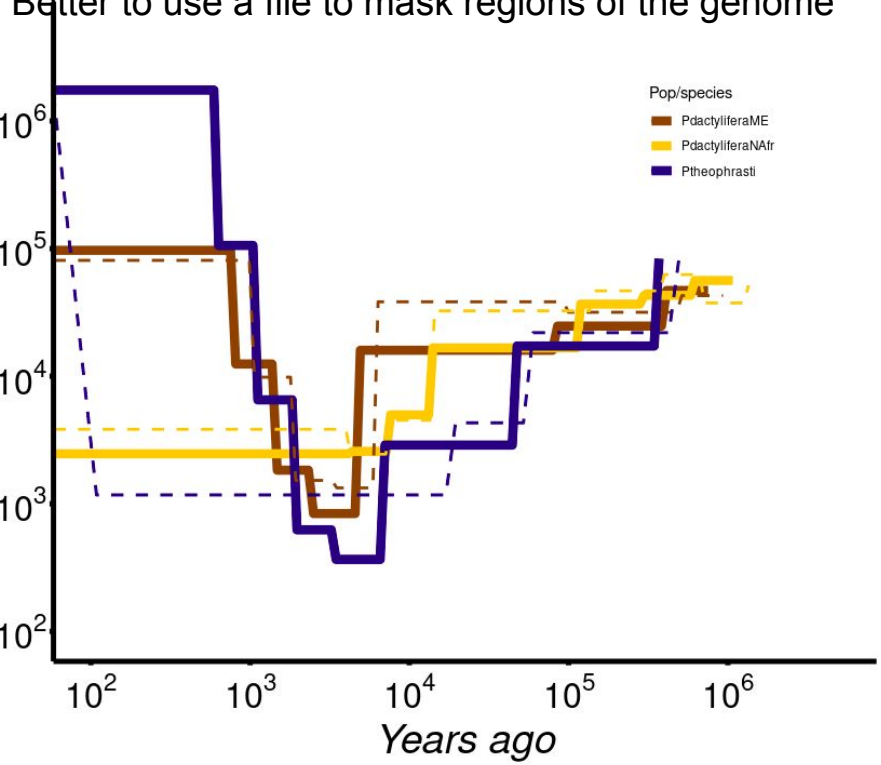

Step 3: Perform inferences of recent N_e



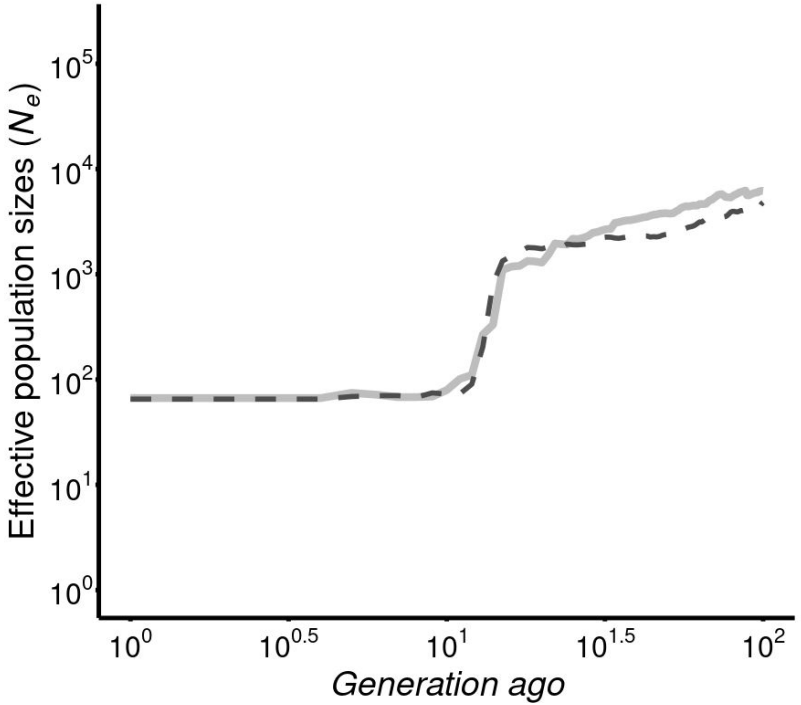
To summarize up to now

Coalescent-based approaches are good for the ancient past, but can be quite inaccurate for recent past

Better to use a file to mask regions of the genome



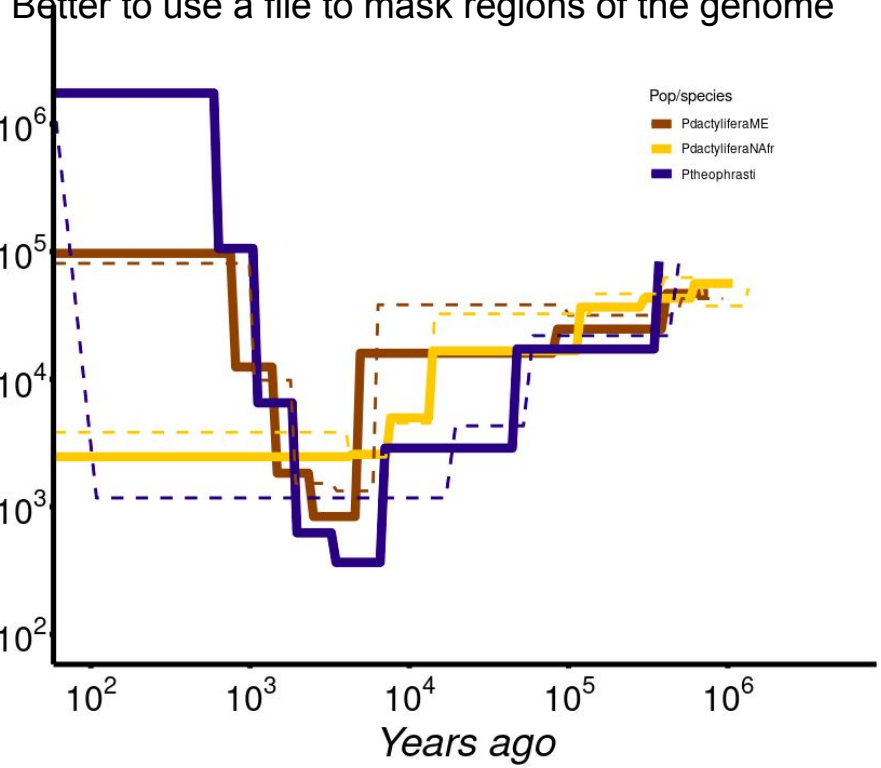
LD-based approaches are good for the recent past, but can be quite inaccurate for (a bit more) ancient past (note that here we stopped at 100 generations only)



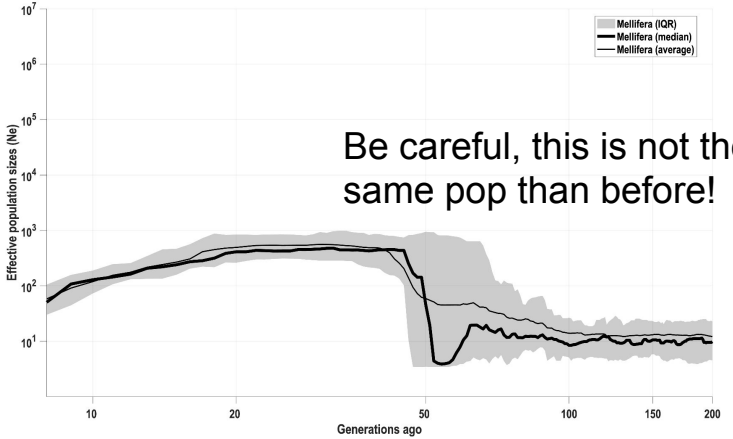
To summarize up to now

Coalescent-based approaches are good for the ancient past, but can be quite inaccurate for recent past

Better to use a file to mask regions of the genome



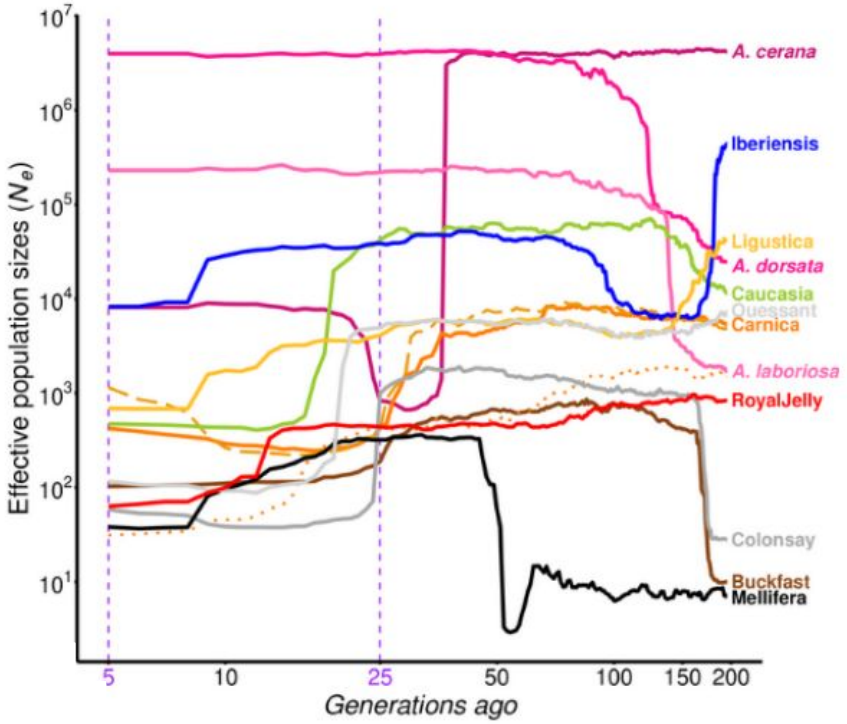
LD-based approaches are good for the recent past, but can be quite inaccurate for (a bit more) ancient past (note that here we stopped at 100 generations only)

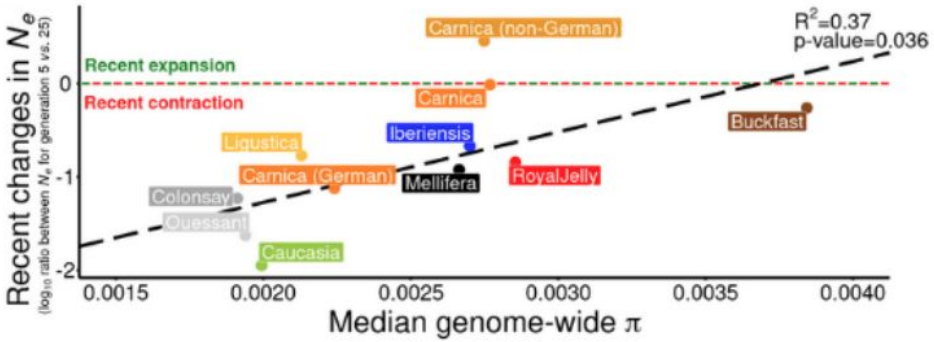


Be careful, this is not the same pop than before!

What can we learn biologically from this recent LD pattern ?

-> Human (beekeeping) impacts





The observed variable levels of diversity is explained by the variation of the intensity of the bottlenecks among the populations

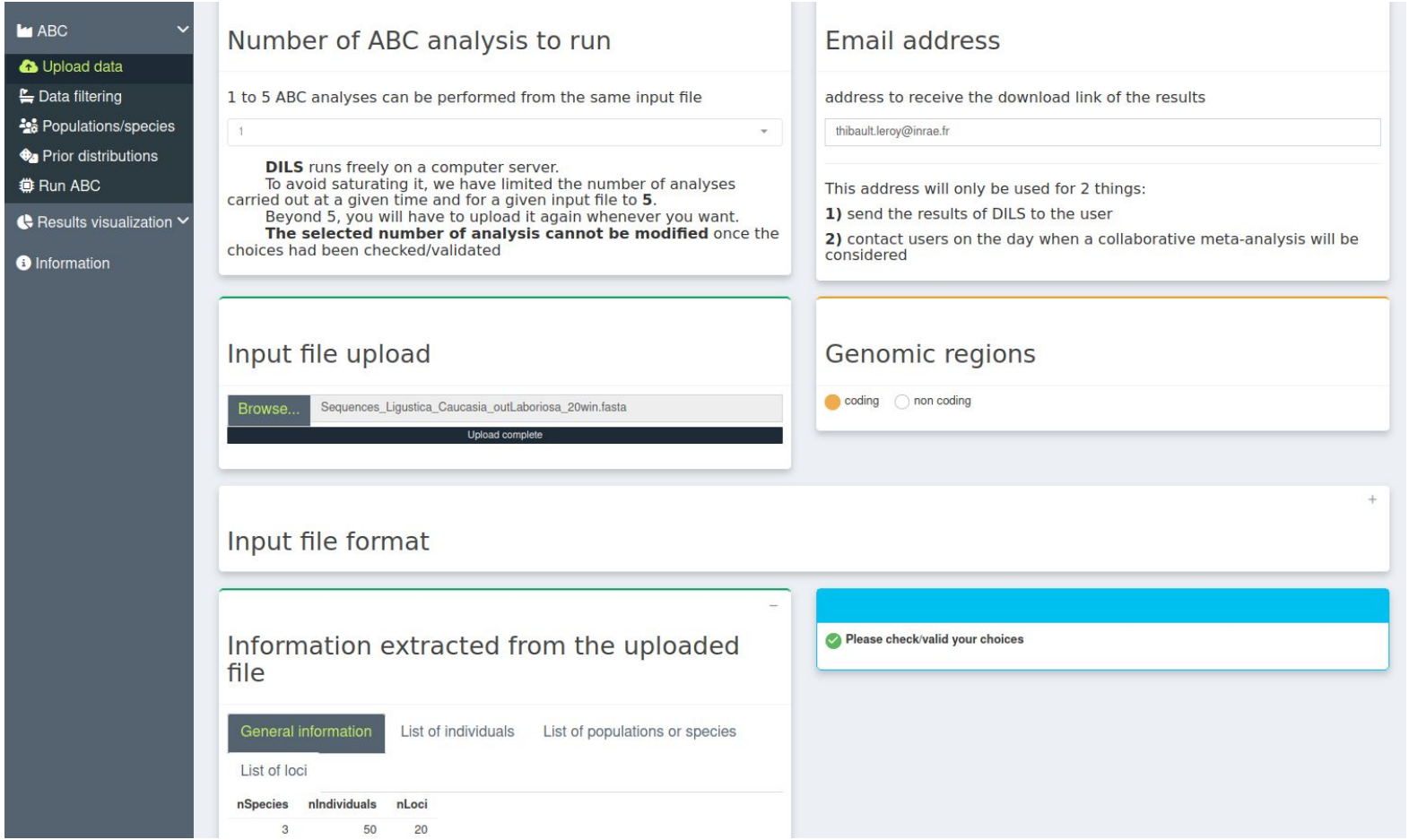
Pretty clear and strong signal for a “semi-domesticated species”

Input file:

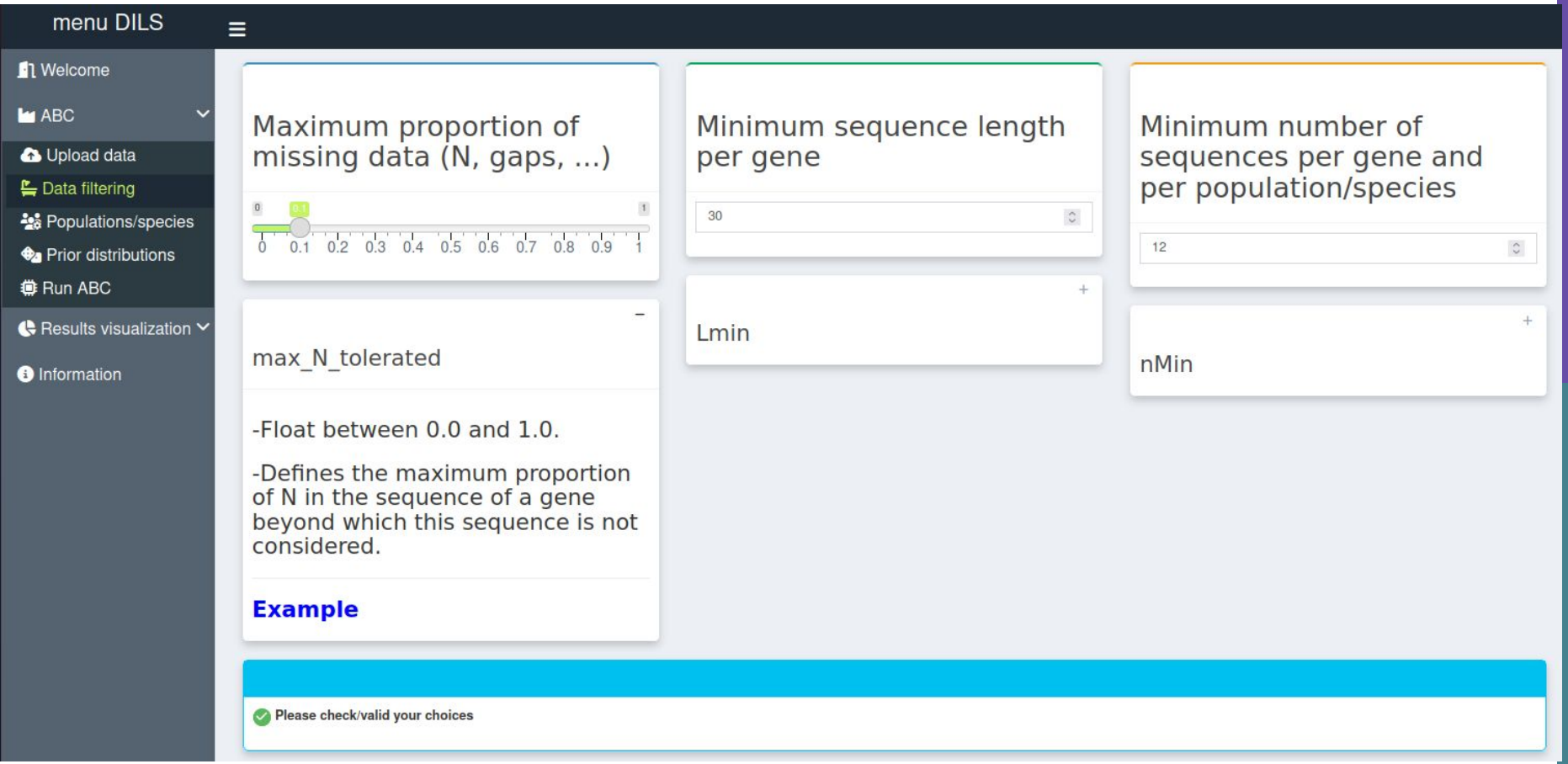
less
Sequences_Mellifera_Carnica_outLaboriosa_randomlyselected_200_genomic_regions.head200.fasta

>NC037638_1:20100001-20200000|Mellifera|POR1|Allele1
TAAATTTAAAAATGAAATCGCACTAAACACTATAACAATTTTATTTTACTTCGTCACTCTCTTACTANGC
AACTTATTCTACCGTTGATATTCACTATTGTAATTAACAAAAAAACTTCCATTTCAATCTATTTTATTTAC
AATTCGATAATATTCGATATGGTATAATAAGTAGATCGATCAAATATATTTCTAACACTCACGTTTTGAT
TTTCTATTTTTTTTNTTNTTTNTTATNGAAAAGTANATTTATCAATANATGAANCNATATACNTCNTNGAA
NTATTGNTATTAANTACATAGATTTTTATTAAATCCCAATTAATNATCAATNTATGAANATNNAATGTTG
CAATTTGATAGANGCTCGGAAAAATACTCGATGAGAGCTATATTCTTACTAATAATGATAACGTTTTAA
CTGATGCTATATTTTAACNGATNTNNNACAAACACCAGTTTTAATTTATGGTAGGTAGATAACATTCCA
TCTTTNGCAATGTTC(…)
>NC037638_1:20100001-20200000|Mellifera|POR10|Allele1
TAAATTTAAAAATGAAATCGCACTAAACACTATAACAATTTTATTTTACTTCGTCACTCTCTTACTAGGC
AACTTATTCTACCGTTGATATTCACTATTGTAATTAACAAAAAAACTTCCATTTCAATCTATTTTATTTAC
AATTCGATAATATTCGATATGGTATAATAAGTAGATCGATCAAATATATTTCTAACACTCACGTTTTGAT
TTTCTATTTTTTTTCTTATTTGTTATCGAAAAGTAAATTTATCAATACATGAACCGATATACTTCCTCGAA
ATATTGCTATTAATTACATAGATTTTTATTAAATCCCAATTAATNATCAATNTATGAANATNNAATGTTG
CAATTTGATAGANGCTCGGAAAAATACTCGATGAGAGCTATATTCTTACTAATAATGATAACGTTTTAA
CTGATGCTATATTTTAACNGATNTNNNACAAACACCAGTNTTAATTTATGGTAGGTAGATAACATTCCA
TCTTTNNNNNNNNNNNNNNNNNNNNNNNNNNN(...)

Step 4: Perform relatively simple ABC demographic modelling under DILS



Step 4: Perform relatively simple ABC demographic modelling under DILS



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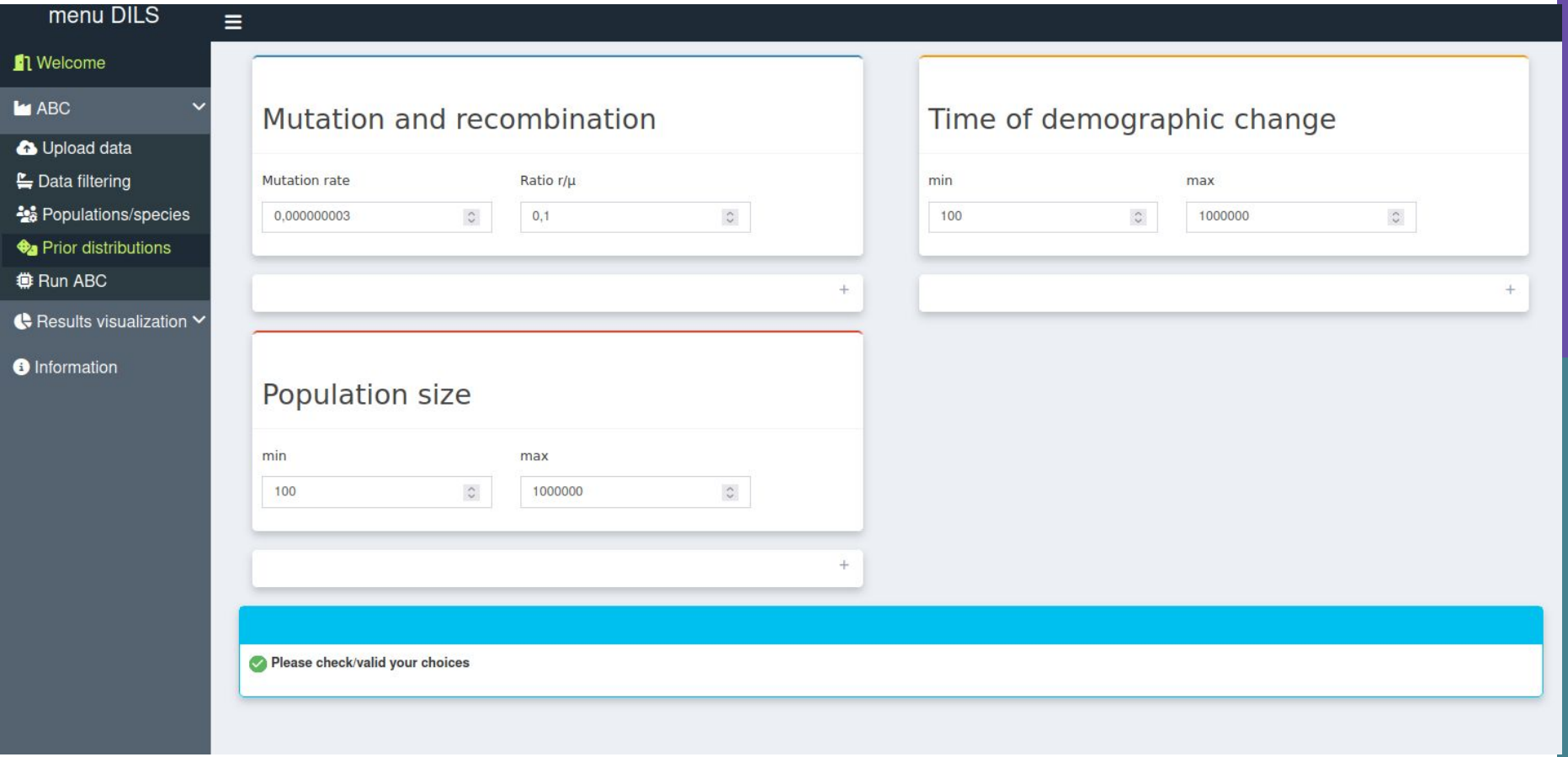

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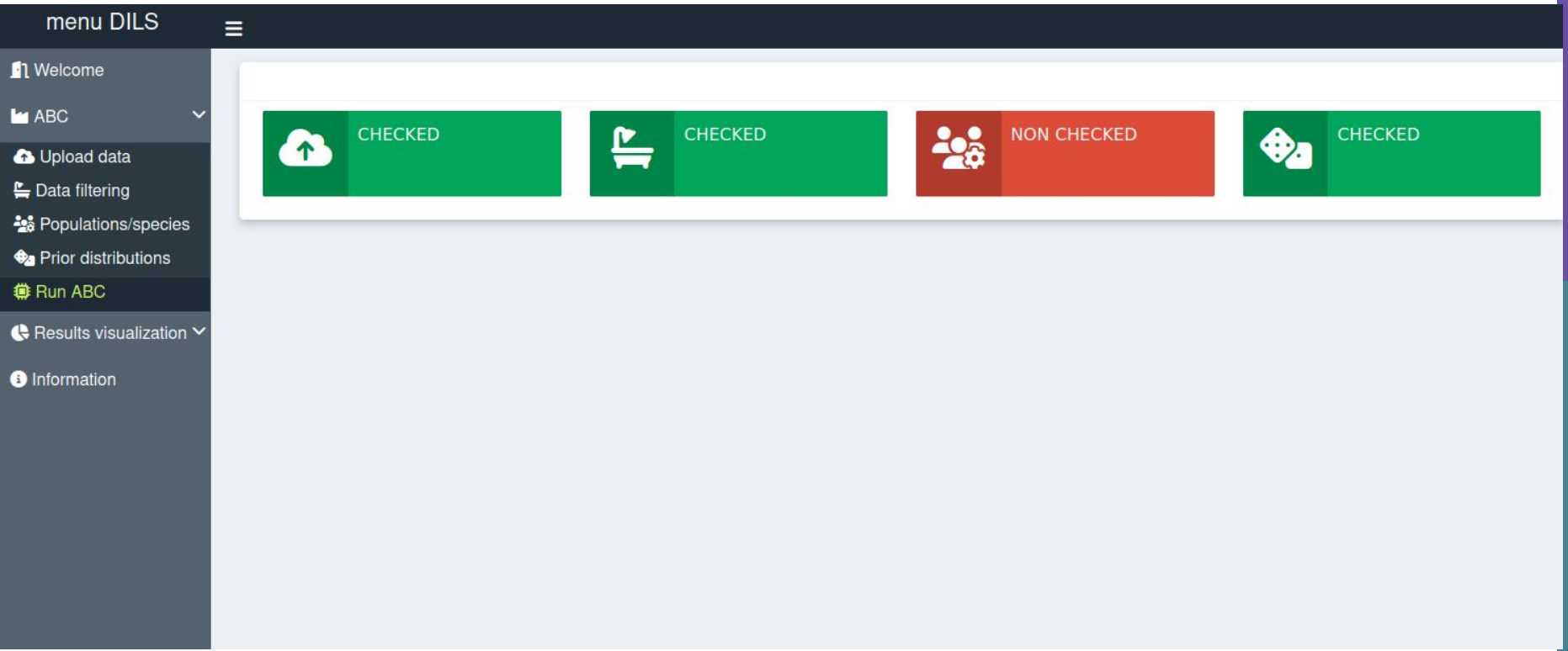
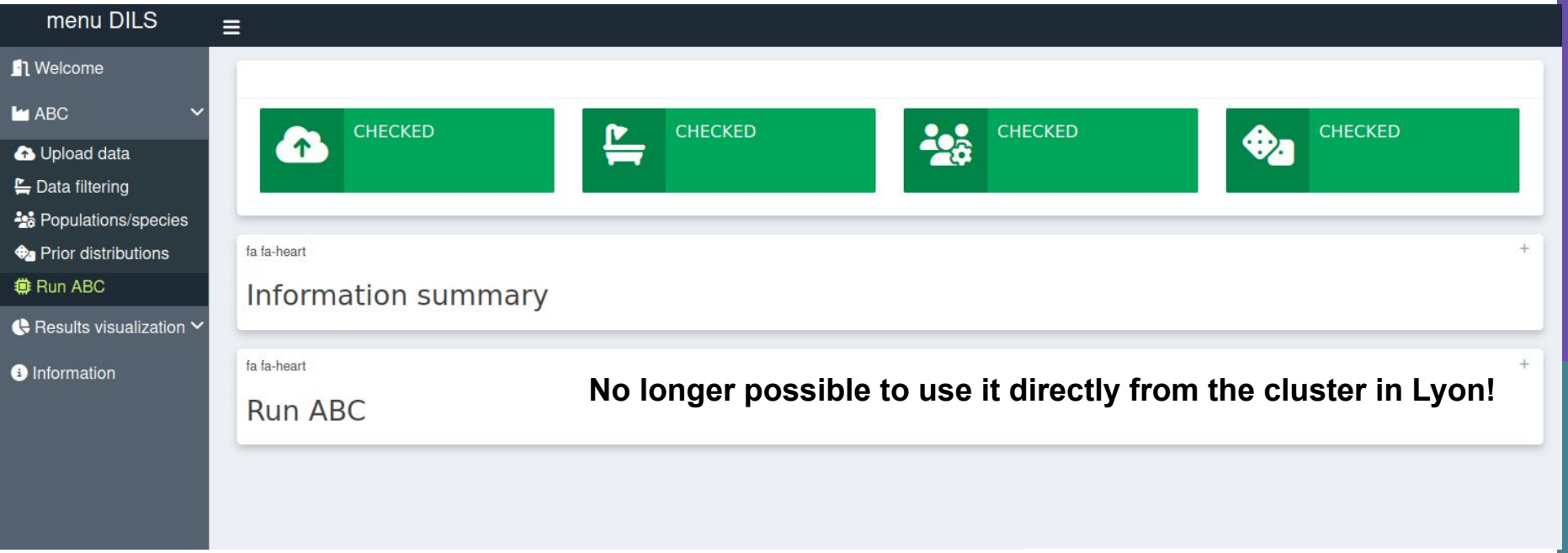


Step 4: Perform relatively simple ABC demographic modelling under DILS



But.. pretty easy to deploy on your own computer/computing cluster
See DILS Manual on github:
https://github.com/dils-popgen/dils/blob/master/manual.pdf

1. clone git repository

```
cd $HOME
git clone https://github.com/popgenomics/DILS_web
```

2. move into the DILS repertory

```
cd $HOME/DILS_web
```

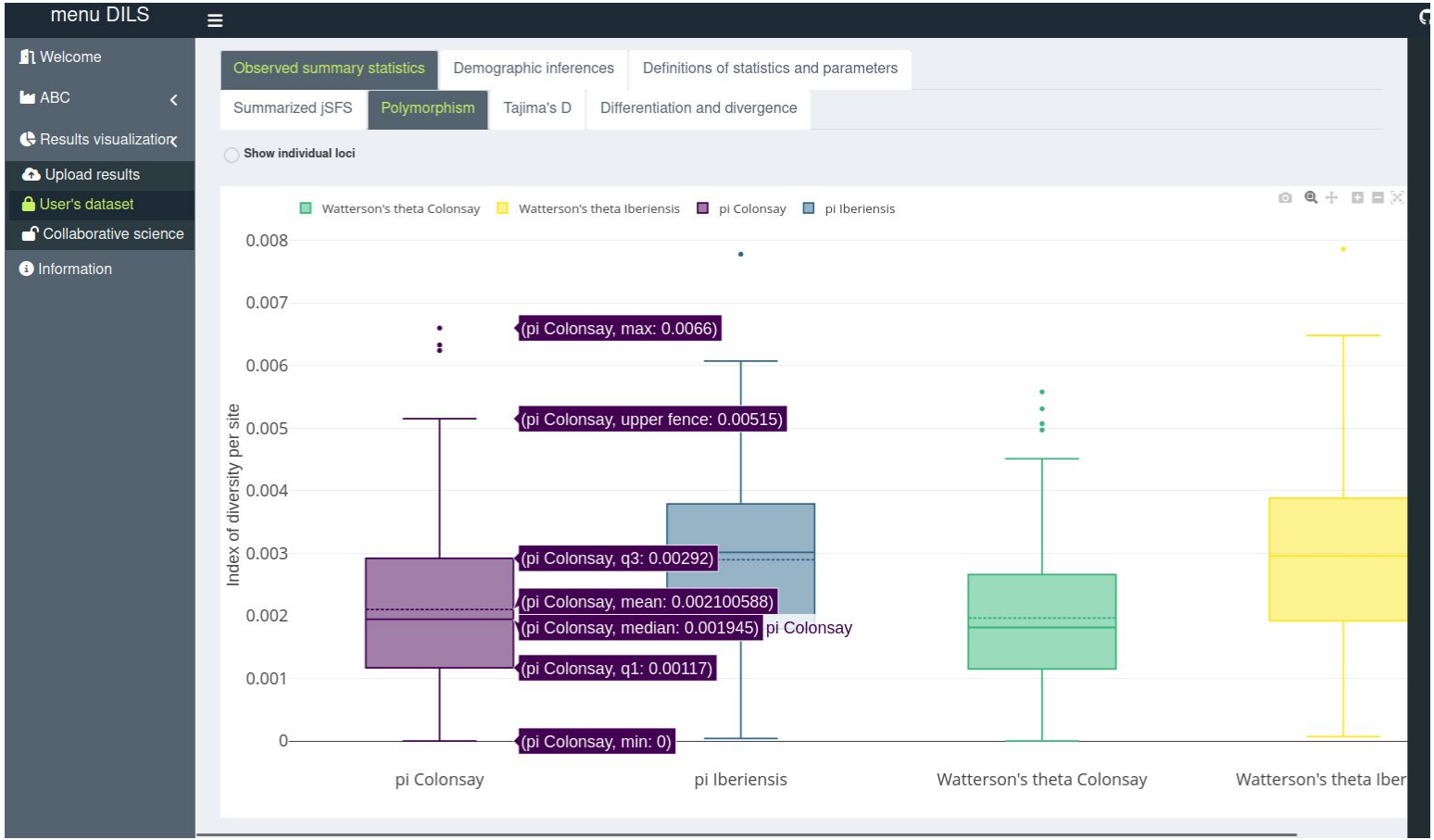
3. build singularity image (could take ≈ 20minutes)

```
sudo singularity build DILS.sif DILS.def
```

Step 5: Explore results of inferences under DILS

5.1 Observed summary statistics

Step 5: Explore results of inferences under DILS



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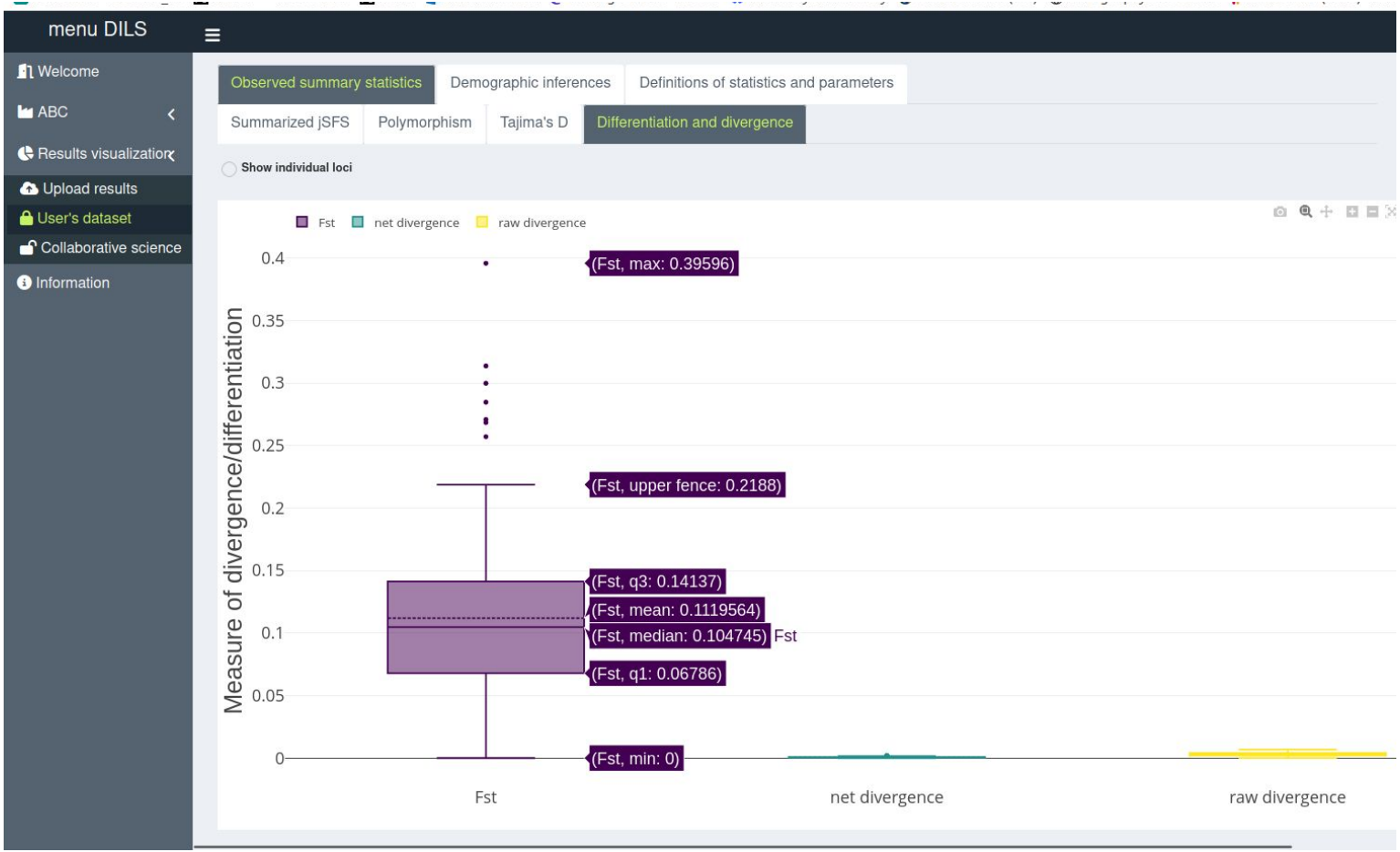
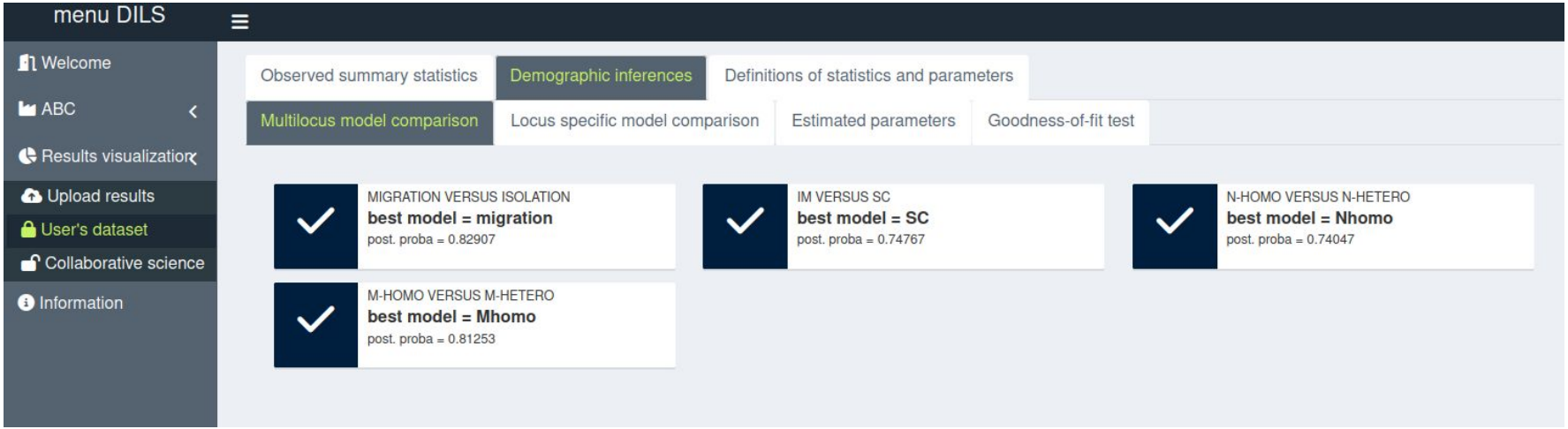
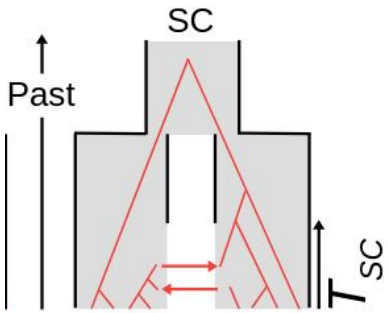
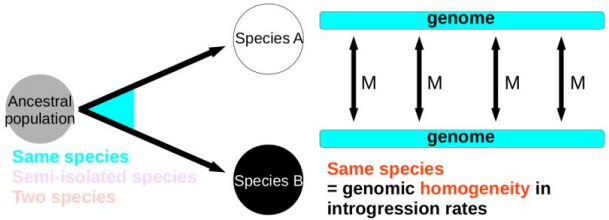


Step 5: Explore results of inferences under DILS

5.2 Model choices

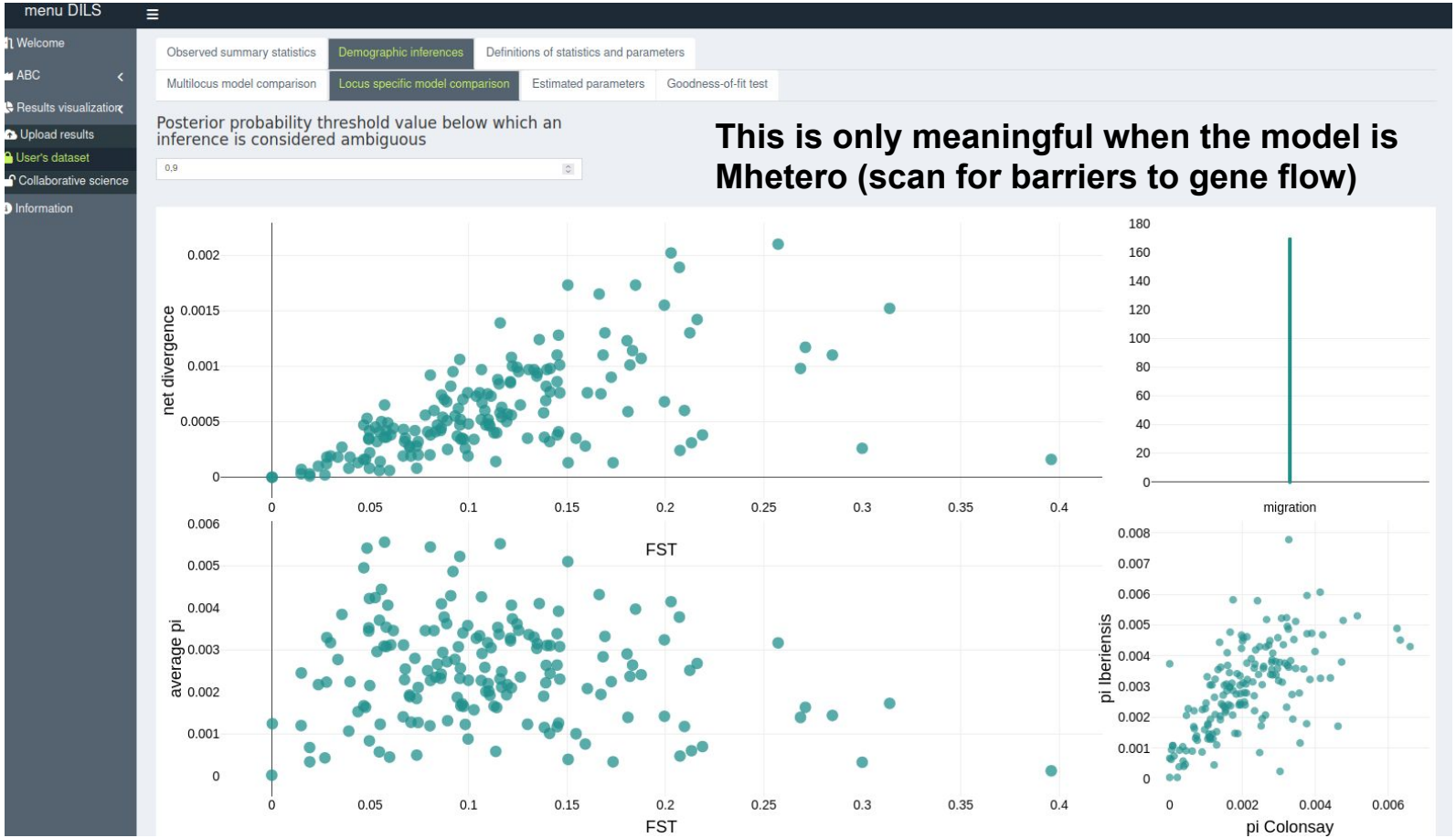






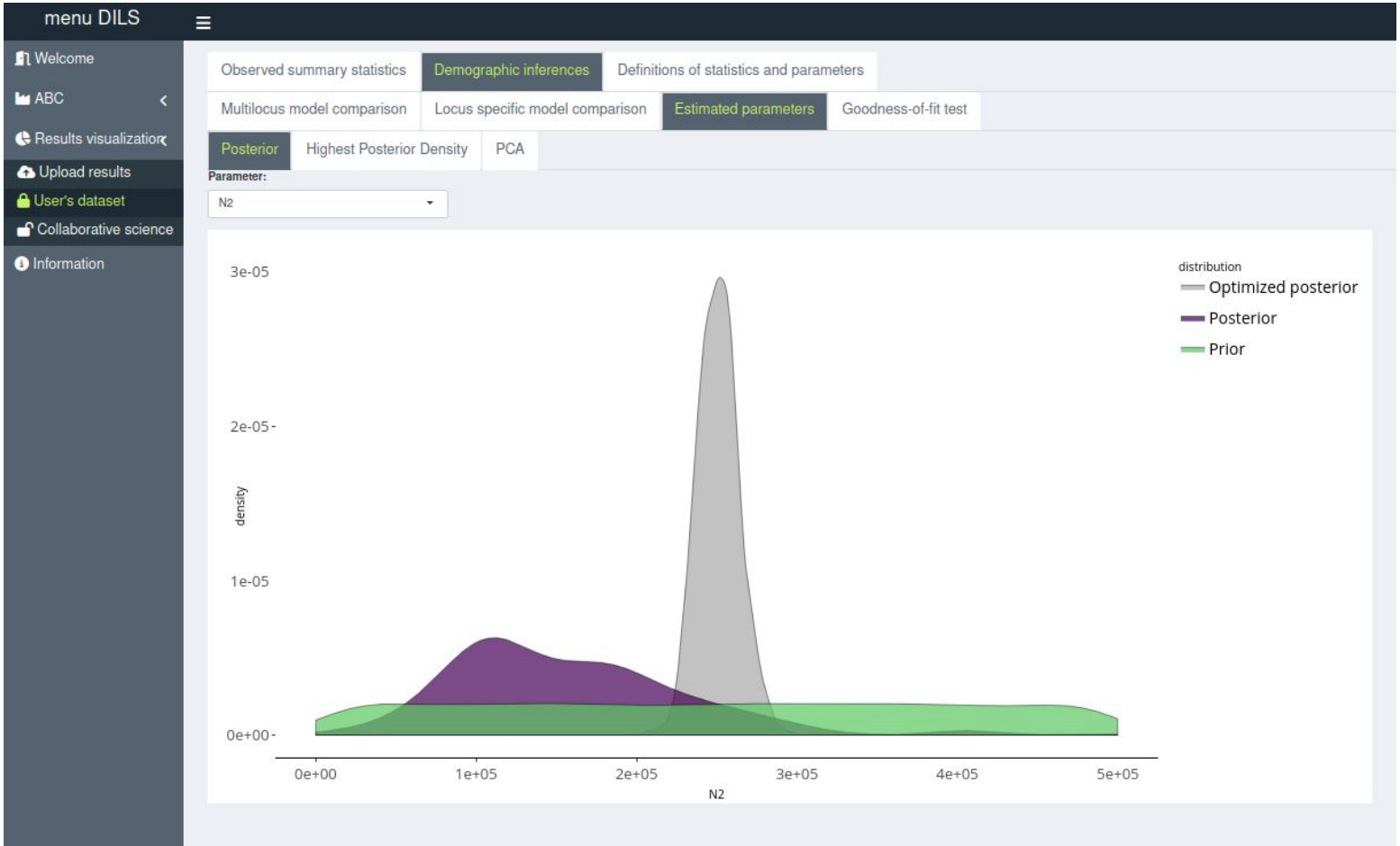
Step 5: Explore results of inferences under DILS

5.2 Model choices



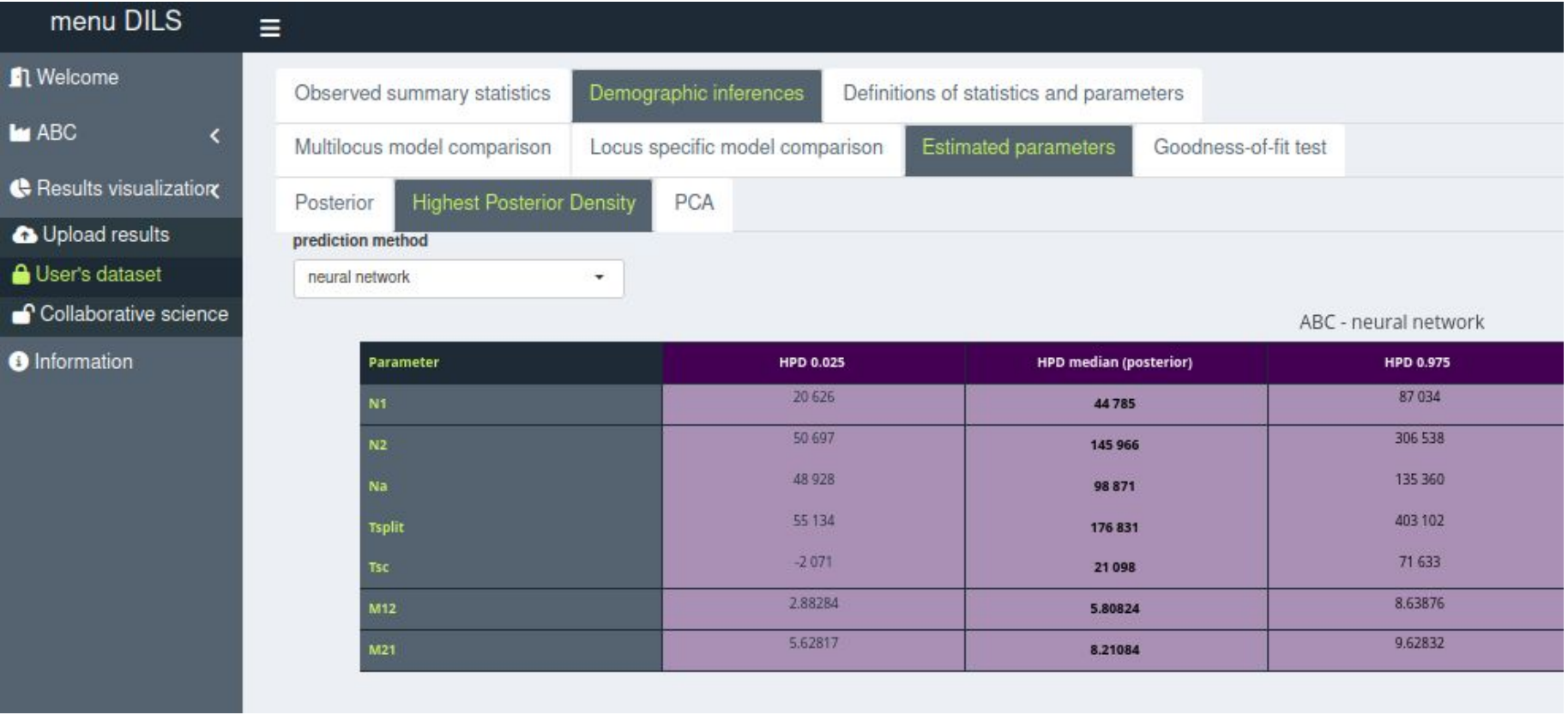
Step 5: Explore results of inferences under DILS

5.3 Estimated parameters8



Step 5: Explore results of inferences under DILS

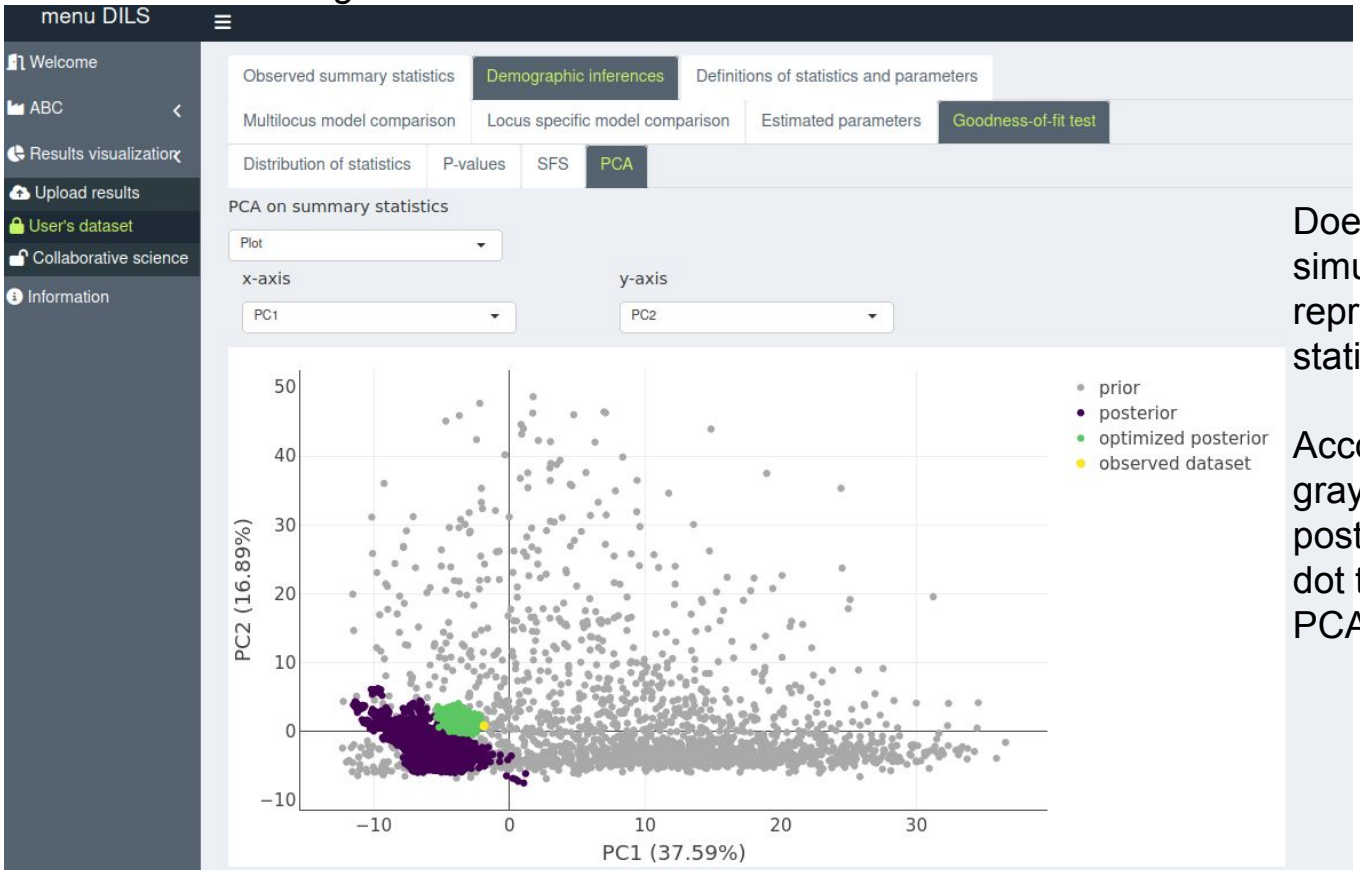
5.3 Estimated parameters



Parameter	HPD 0.025	HPD median (posterior)	HPD 0.975
N1	20 626	44 785	87 034
N2	50 697	145 966	306 538
Na	48 928	98 871	135 360
Tsplit	55 134	176 831	403 102
Tsc	-2 071	21 098	71 633
M12	2.88284	5.80824	8.63876
M21	5.62817	8.21084	9.62832

Step 5: Explore results of inferences under DILS

5.4 Model checking



Does the PCA suggest that simulations (or a subset of them) reproduce the observed summary statistics?

According to you, why might some gray points (not used for the posterior) be closer to the yellow dot than some purple points in the PCA?

Step 5: Explore results of inferences under DILS

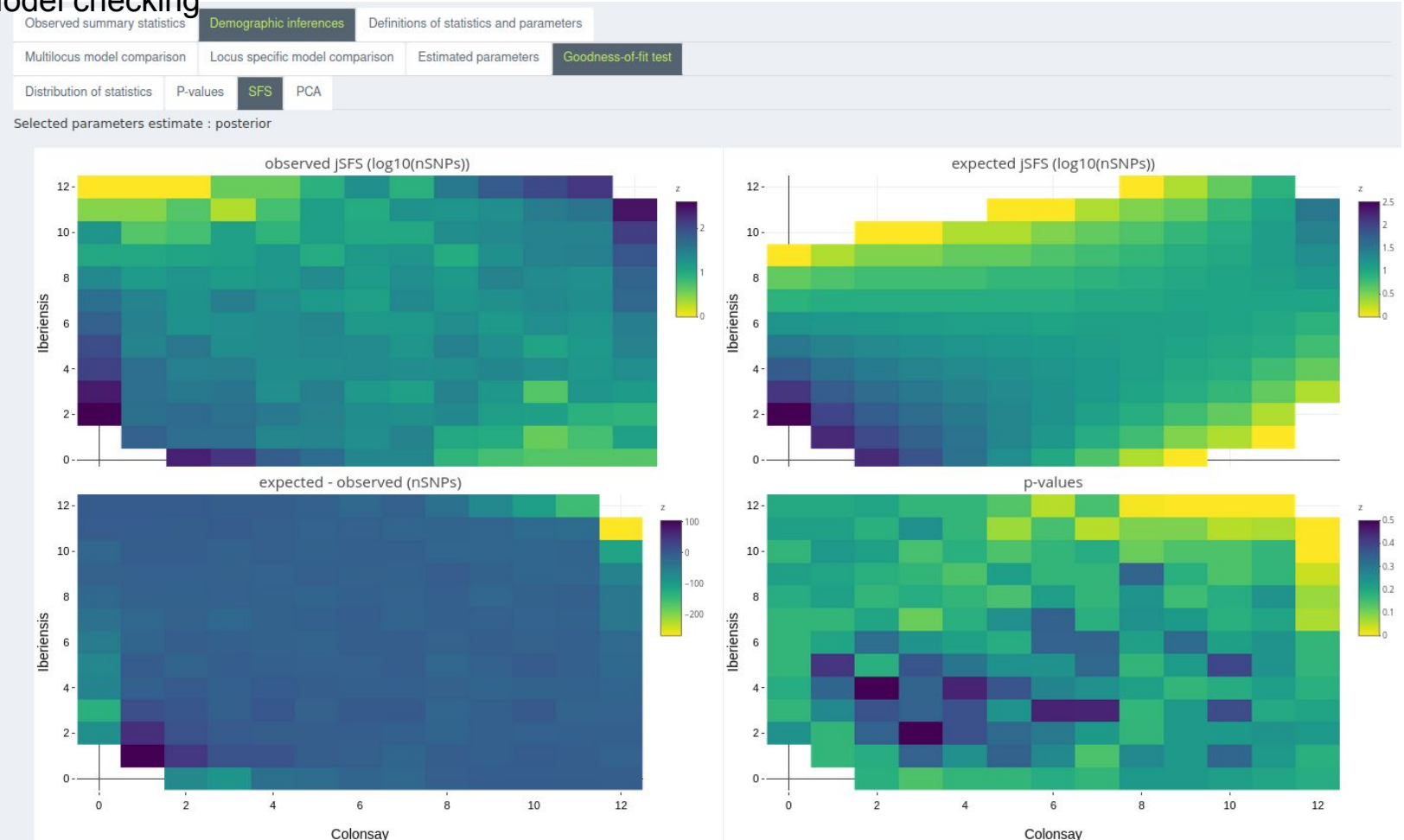
5.4 Model checking

	stats	mean_exp	mean_obs	pvals_fdr_corrected
1	bialsites_avg	27.5426	44.05882	0.0026
2	bialsites_std	13.40905	21.66556	0
3	sf_avg	0.00002	0.00001	0.13752
4	sf_std	0.00004	0.00005	0.17648
5	sxA_avg	0.00131	0.0021	0.06651
6	sxA_std	0.00102	0.00209	0.0273
7	sxB_avg	0.00283	0.0051	0.04534
8	sxB_std	0.00185	0.00256	0.12146
9	ss_avg	0.00295	0.00384	0.14349
10	ss_std	0.00202	0.00228	0.27243
11	successive_ss_avg	2.81251	2.62353	0.3822
12	successive_ss_std	2.4242	1.9065	0.1876
13	piA_avg	0.00138	0.0021	0.0286
14	piA_std	0.00089	0.00127	0.0294
15	piB_avg	0.00183	0.0029	0
16	piB_std	0.001	0.00142	0.02779
17	pearson_r_pi	0.72069	0.63213	0.19009
18	thetaA_avg	0.00141	0.00197	0.0572
19	thetaA_std	0.00083	0.00115	0.0286
20	thetaB_avg	0.00191	0.00296	0.0273
21	thetaB_std	0.00096	0.00137	0.0286
22	pearson_r_theta	0.74393	0.60166	0.12146
23	DtajA_avg	-0.09708	0.29495	0.04534
24	DtajA_std	0.9019	0.80635	0.19009
25	DtajB_avg	-0.20887	-0.17624	0.43126
26	DtajB_std	0.71777	0.51259	0.01463
27	divAB_avg	0.00188	0.0031	0.05
28	divAB_std	0.00104	0.0015	0.03
29	netdivAB_avg	0.00028	0.0006	0.13752
30	netdivAB_std	0.00036	0.00042	0.2333
31	FST_avg	0.07732	0.11196	0.19853
32	FST_std	0.07946	0.06275	0.31157
33	pearson_r_divAB_netDivAB	0.51824	0.74446	0.14502

How many summary statistics are well captured versus not well captured for the ABC analysis you have selected?

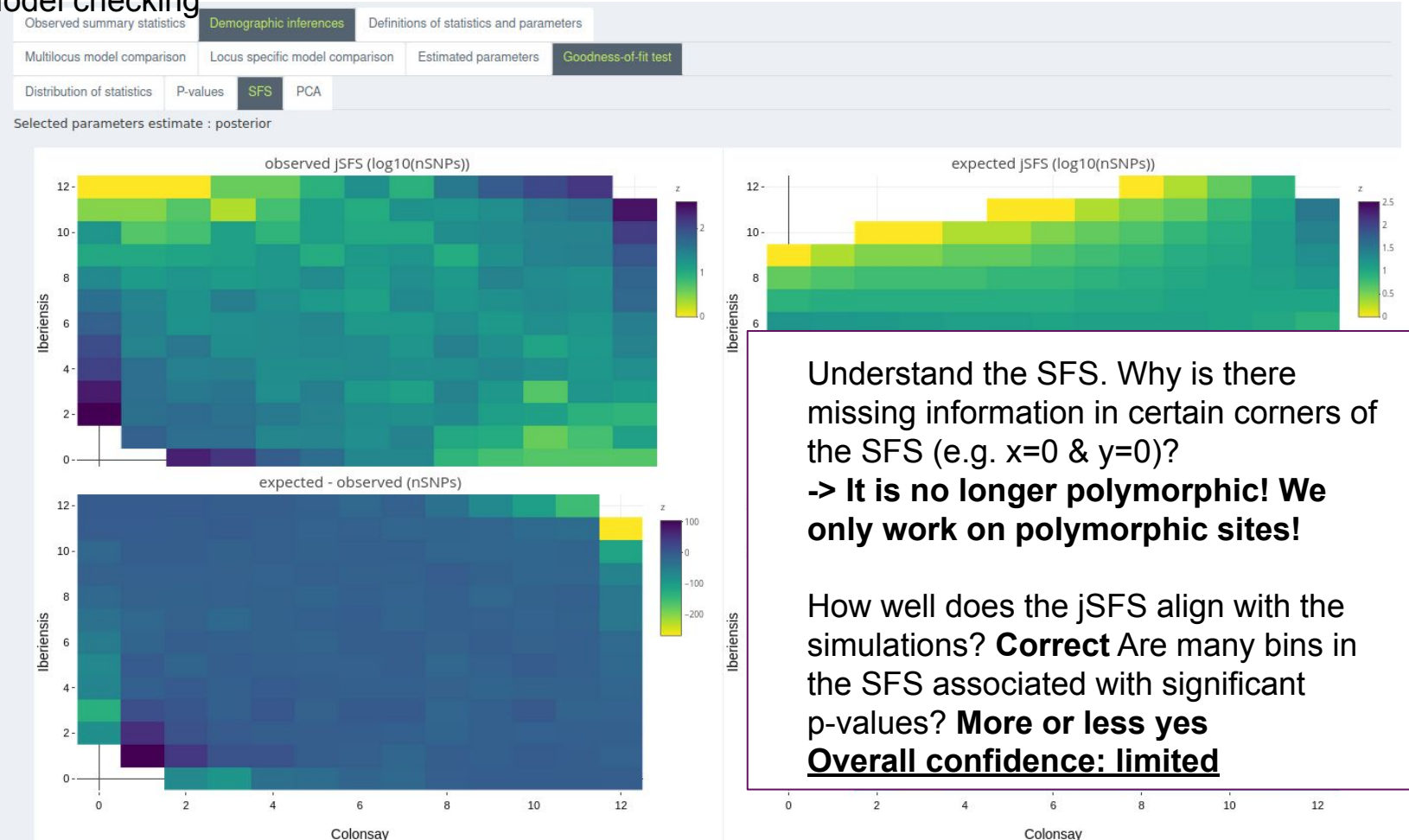
Step 5: Explore results of inferences under DILS

5.4 Model checking



Step 5: Explore results of inferences under DILS

5.4 Model checking



Understand the SFS. Why is there missing information in certain corners of the SFS (e.g. x=0 & y=0)?
-> It is no longer polymorphic! We only work on polymorphic sites!

How well does the jSFS align with the simulations? **Correct** Are many bins in the SFS associated with significant p-values? **More or less yes**
Overall confidence: limited

Overall, you have probably seen relatively good fits to the data

> "…all models are approximations. Essentially, all models are wrong, but some are useful. However, the approximate nature of the model must always be borne in mind …" — George Box —