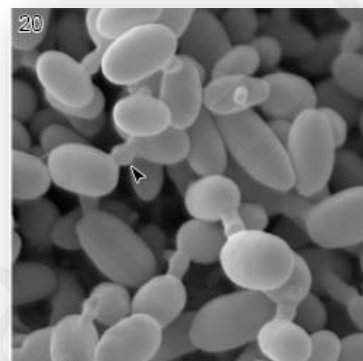


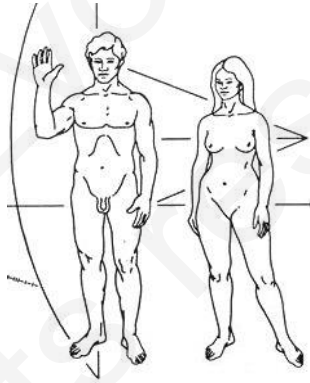
# Multiple independent events of stepwise recombination suppression on fungal mating-type chromosomes despite the lack of sexual antagonism



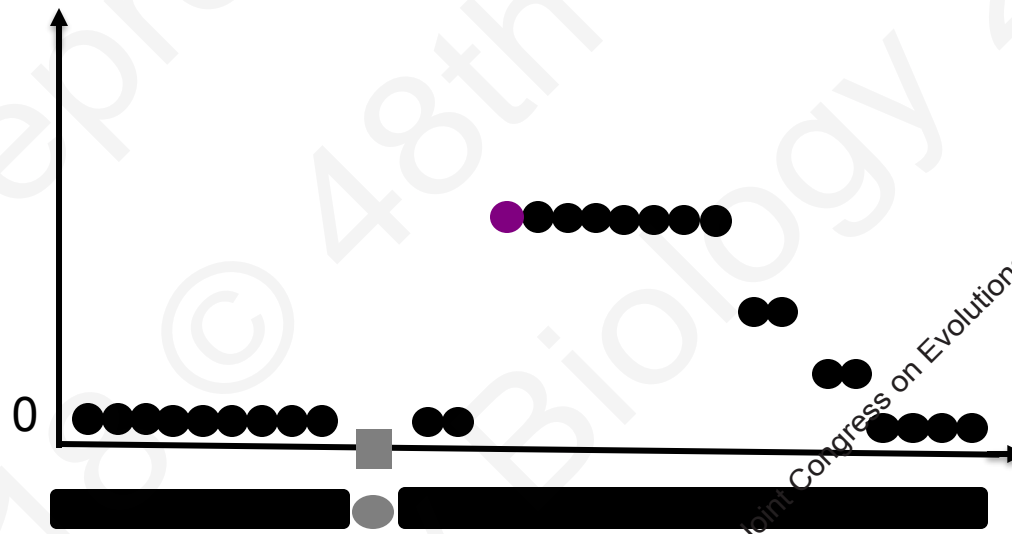
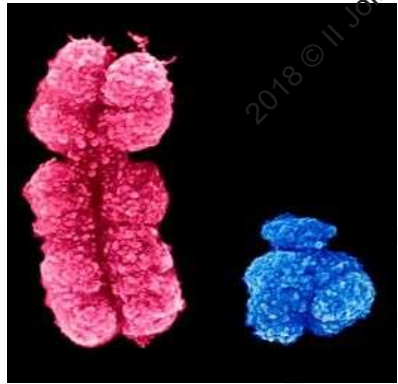
*Microbotryum* anther smut fungi

**Tatiana Giraud**  
**CNRS - Paris Sud University - France**

# Stepwise extension of recombination suppression in sex chromosomes - Evolutionary strata



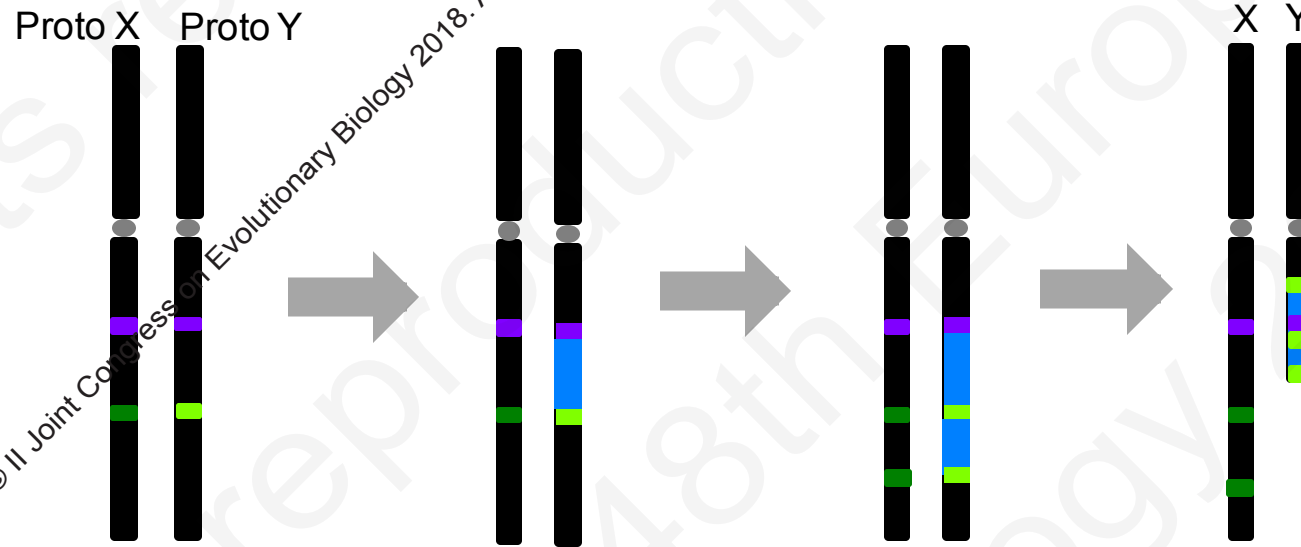
Per gene divergence between X and Y  
(proxy for time since recombination suppression)






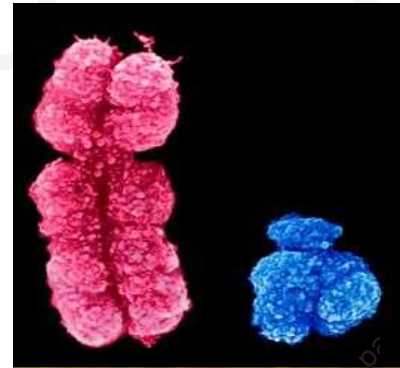
● Sex-determining gene

X chromosome gene order

# Stepwise extension of recombination suppression : Due to sexual antagonism?



-  Sex-determining gene
-  Male-specific advantageous allele
-  Recombination suppression



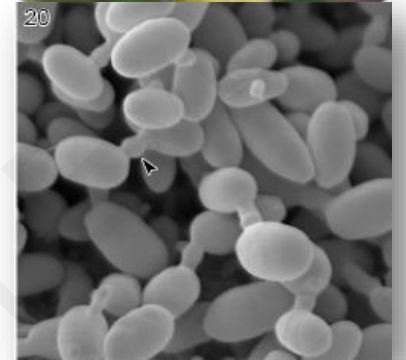
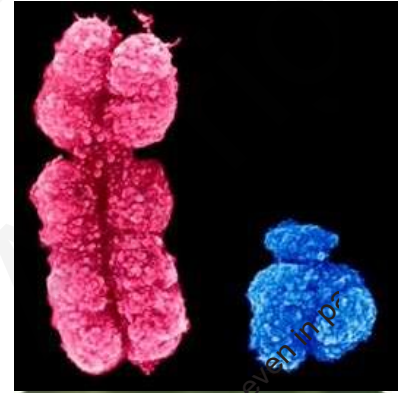
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# Stepwise extension of recombination suppression : Due to sexual antagonism?

Very little evidence for sexual antagonism  
generating evolutionary strata

Alternative explanations for stepwise extension  
of suppressed recombination (little considered)

→ Study organisms showing suppressed  
recombination but no sexual antagonism



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# Basidiomycete fungi

Mating types defined by two gene clusters:

**PR** - Pheromone precursor and receptor genes

**HD** - Homeodomain genes

**Unlinked mating-type loci**



*Coprinopsis*



Corn smut fungus  
*Ustilago maydis*

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# Basidiomycete fungi

Mating types defined by two gene clusters:

**PR** - Pheromone precursor and receptor genes

**HD** - Homeodomain genes

## Unlinked mating-type loci



## Linked mating-type loci (beneficial under selfing)



Barley smut fungus  
*Ustilago hordei*



*Microbotryum* anther smuts

# Basidiomycete fungi

Mating types defined by two gene clusters:

**PR** - Pheromone precursor and receptor genes

**HD** - Homeodomain genes

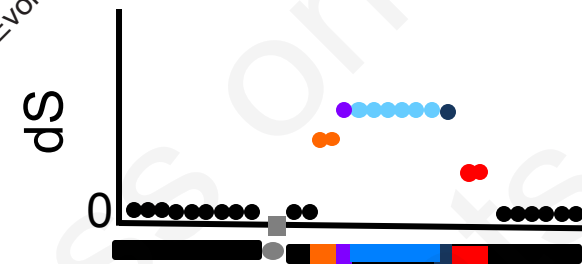
## Unlinked mating-type loci



## Linked mating-type loci (beneficial under selfing)

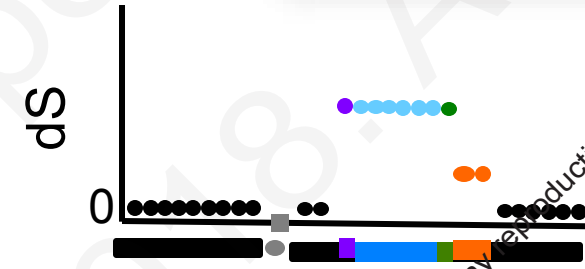
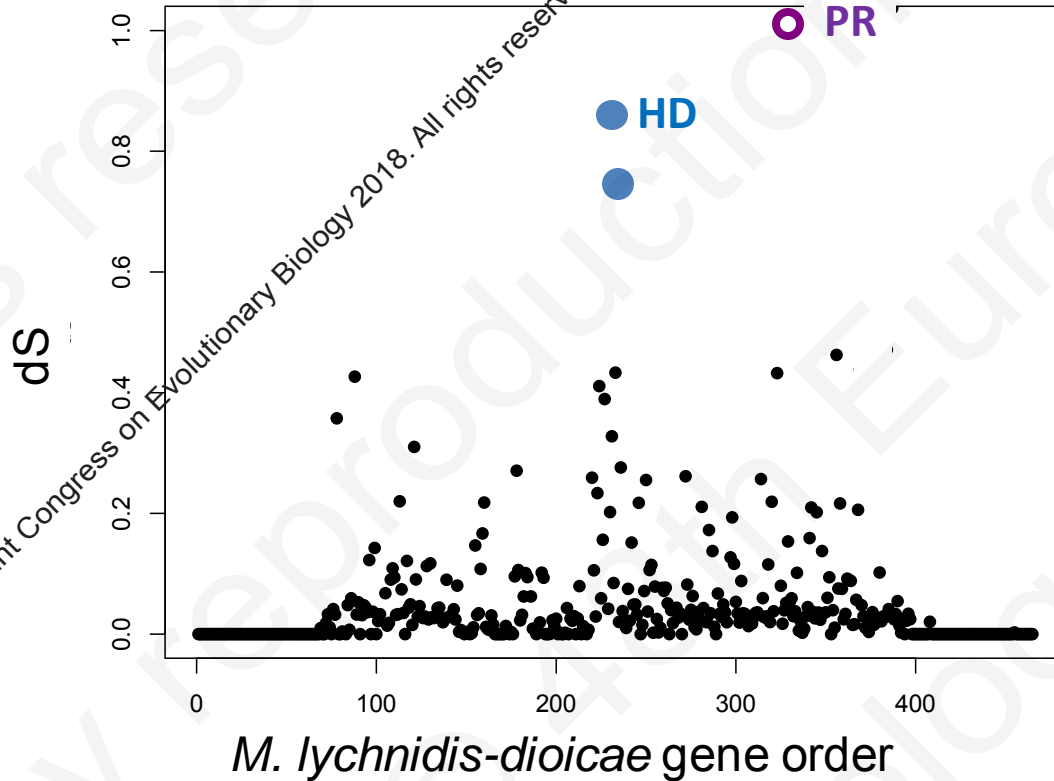


**Strata beyond  
mating-type genes?**



# Strata in *Microbotryum lychnidis-dioicae*?

Divergence between alleles associated with alternative mating types



No evidence for evolutionary strata

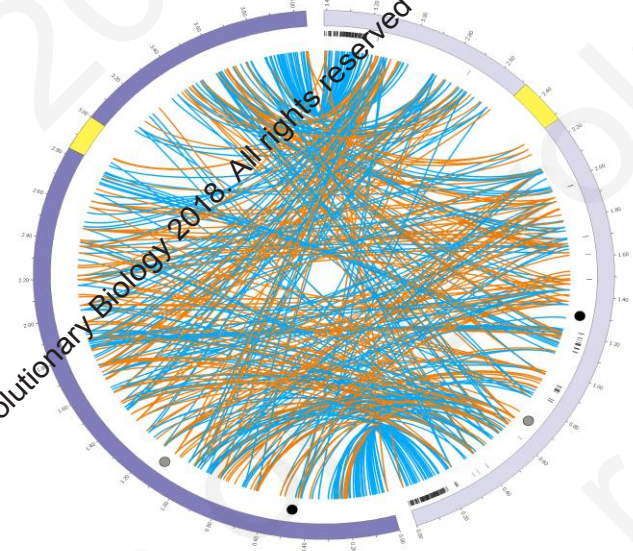
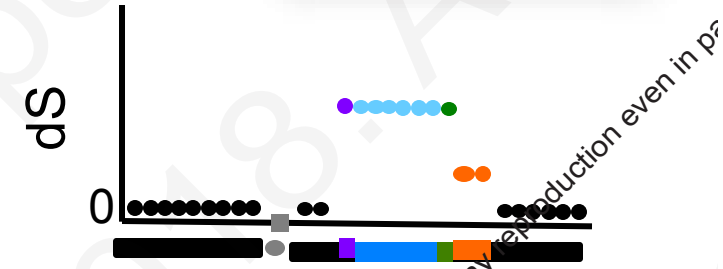
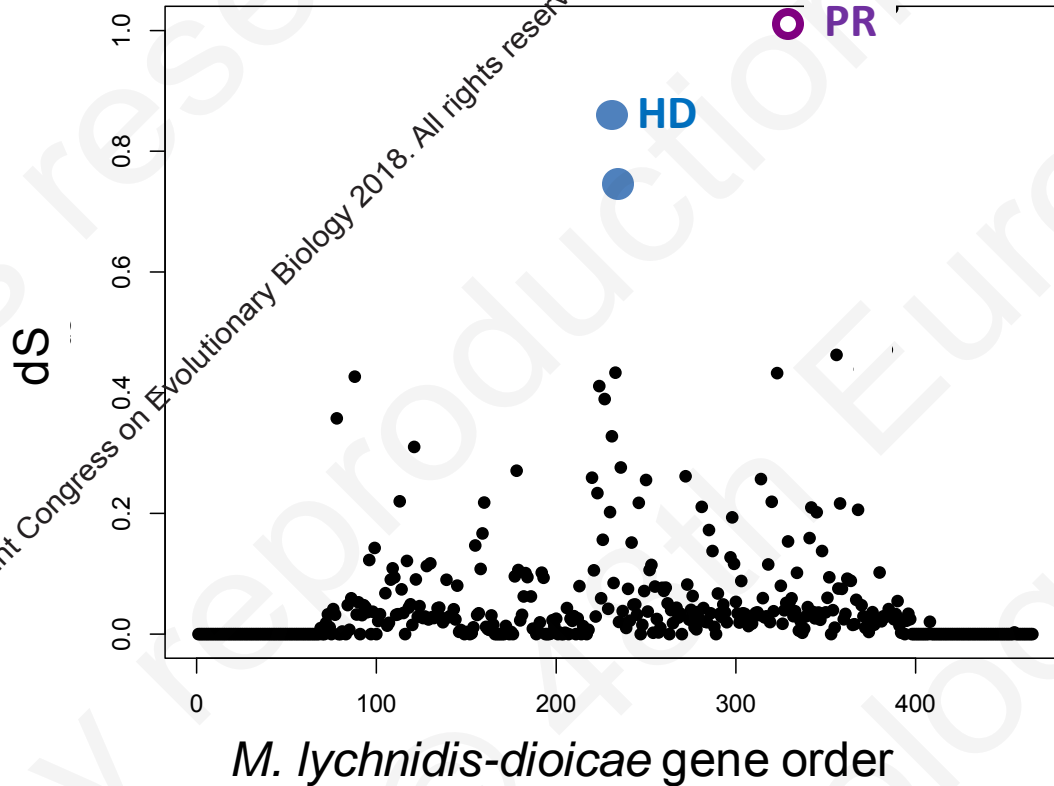
(Badouin *et al.* 2015 Genetics)

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# Strata in *Microbotryum lychnidis-dioicae*?

Divergence between alleles associated with alternative mating types

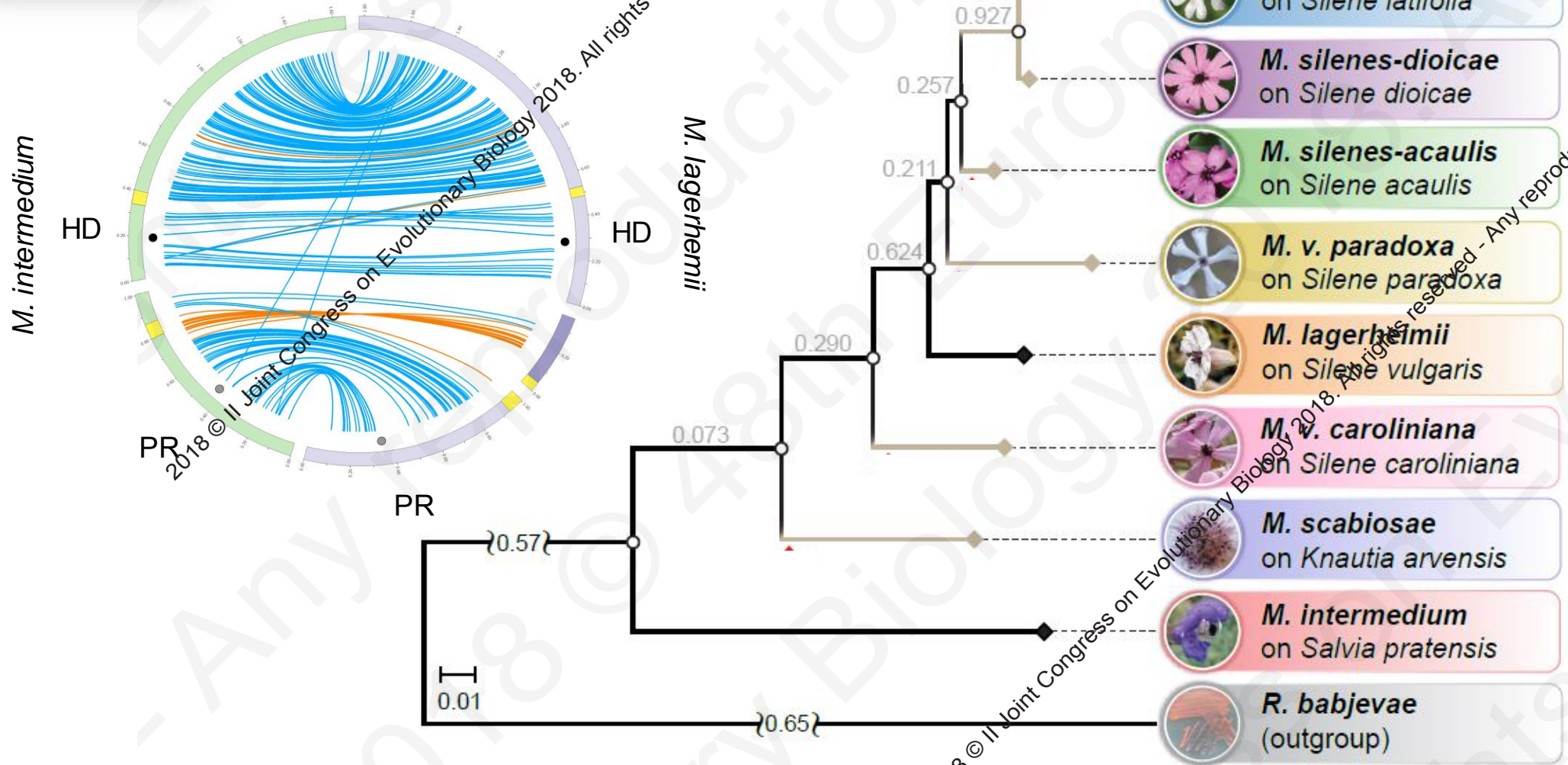


No evidence for evolutionary strata  
Mating-type chromosomes too rearranged? (neither is recombining)  
Loss of ancestral gene order...

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# Use the ancestral gene order maintained in *M. lagerhemii* ?



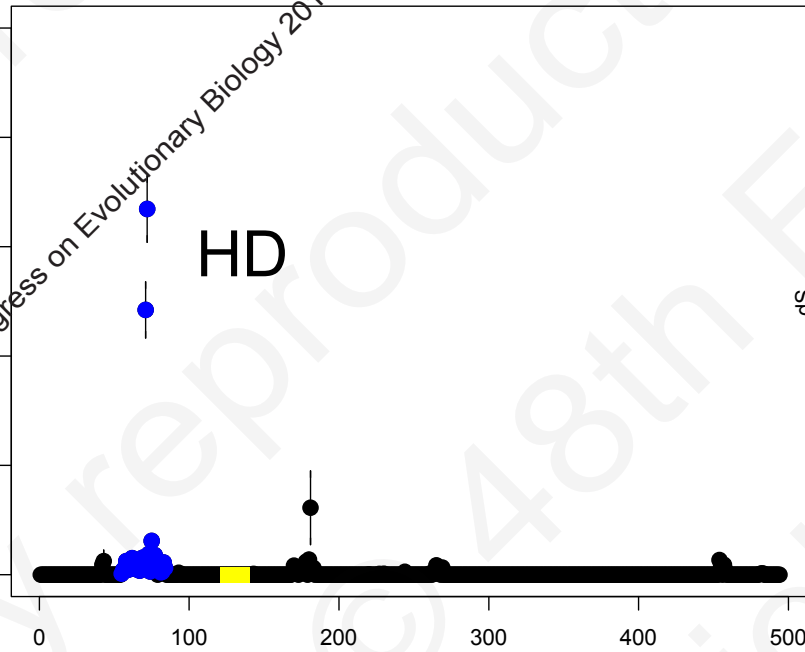
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# *Microbotryum lagerhemii*: evolutionary strata strata around HD and PR loci, not involving mating-type genes

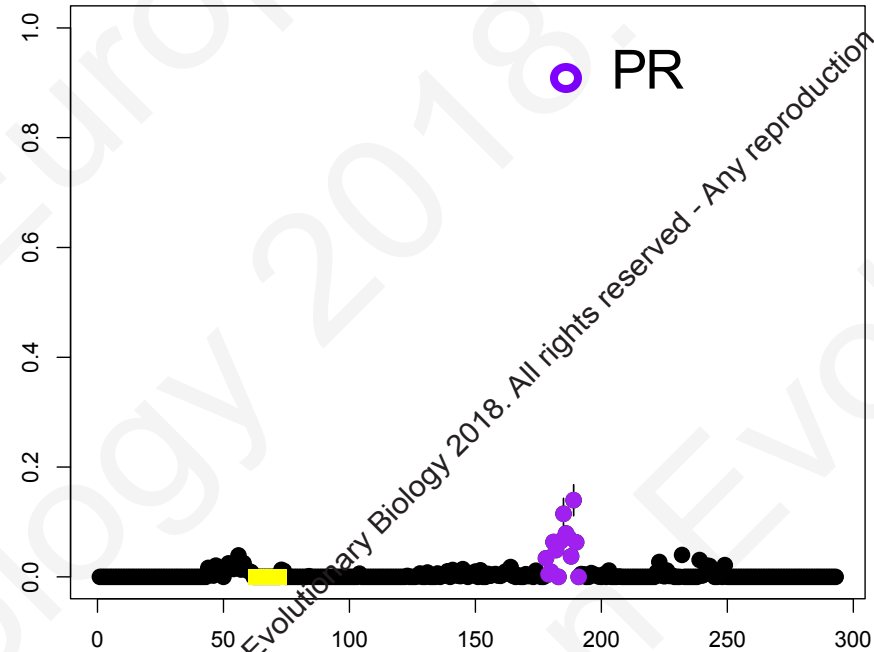


Divergence between alleles associated  
with alternative mating types

HD chromosome



PR chromosome

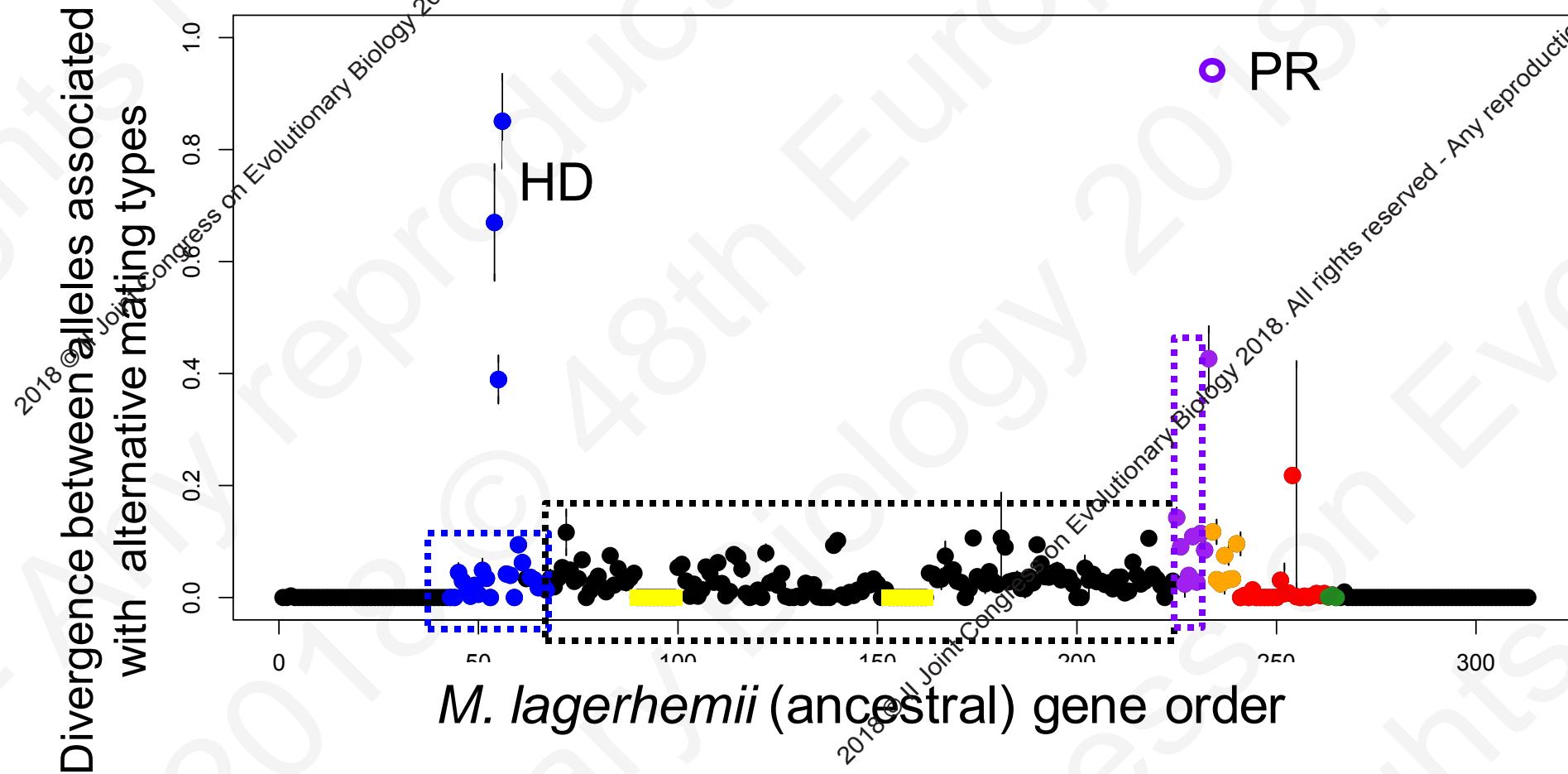


*M. lagerhemii* gene order

# Evolutionary strata in *Microbotryum lychnidis-dioicae*



- Blue and purple strata (shared, ancestral)
- HD/PR linkage creating a large non-recombining region



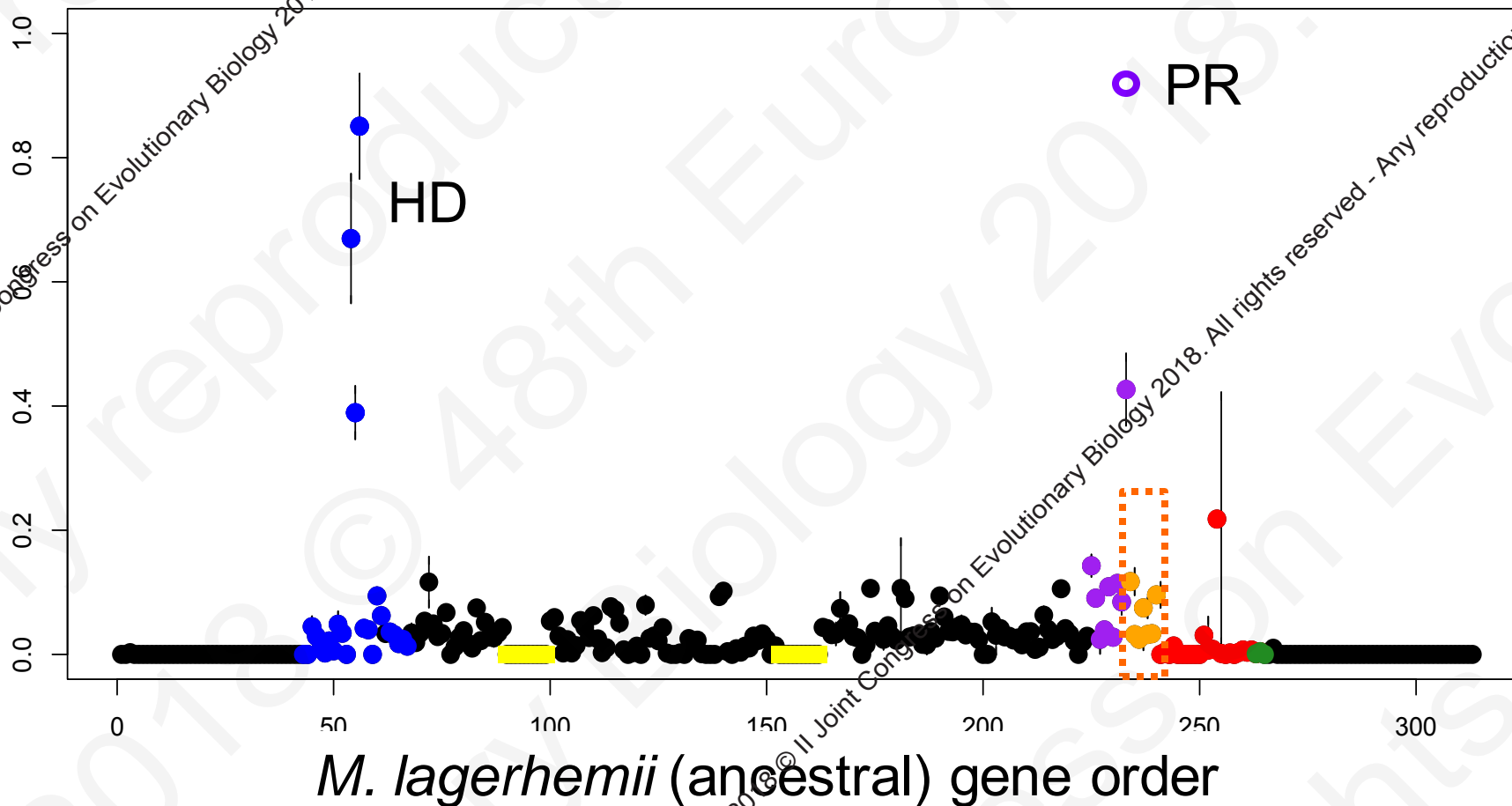
# Evolutionary strata in *Microbotryum lychnidis-dioicae* not involving mating-type genes



-A more recent (orange) stratum

MvSI MAT A1xA2 (in MvSv order) filtered

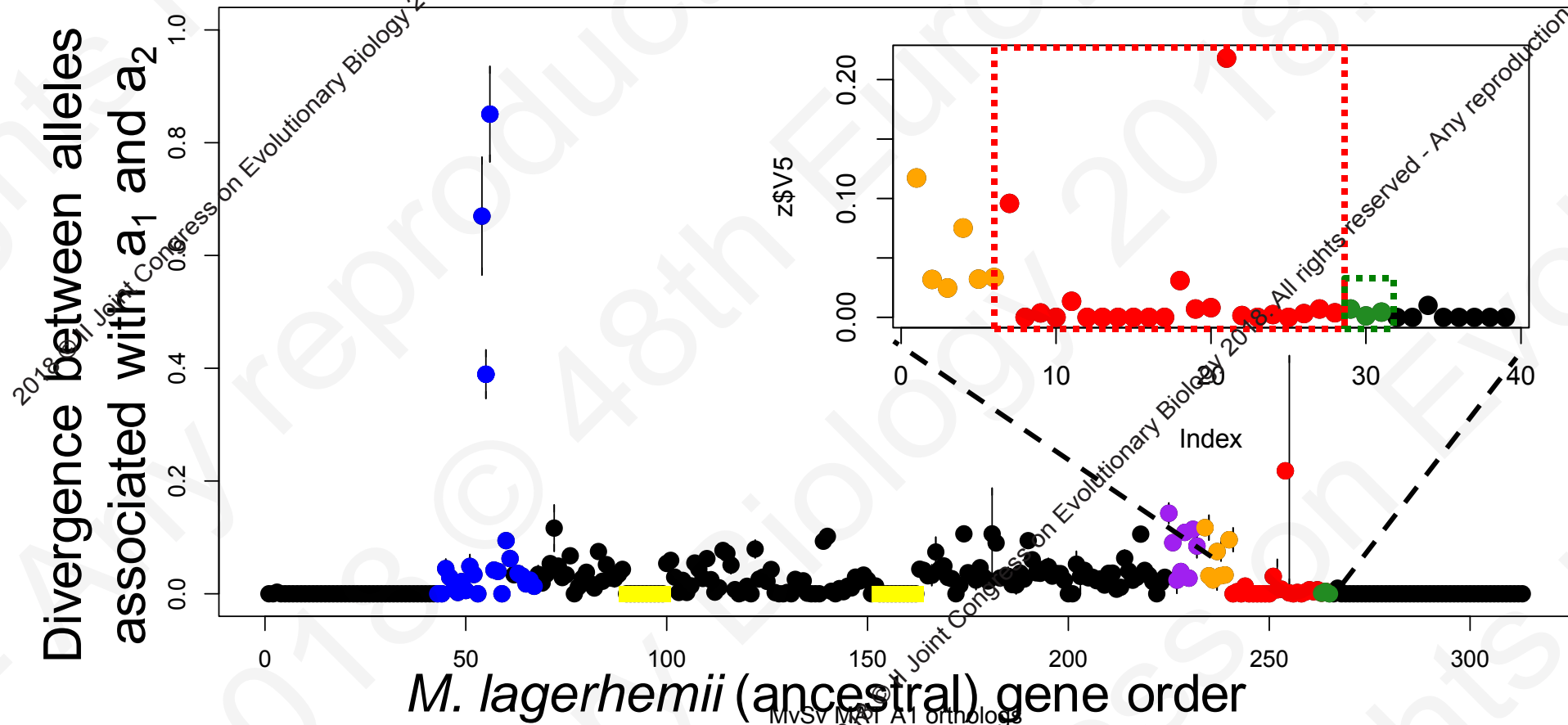
Divergence between alleles associated  
with alternative mating types



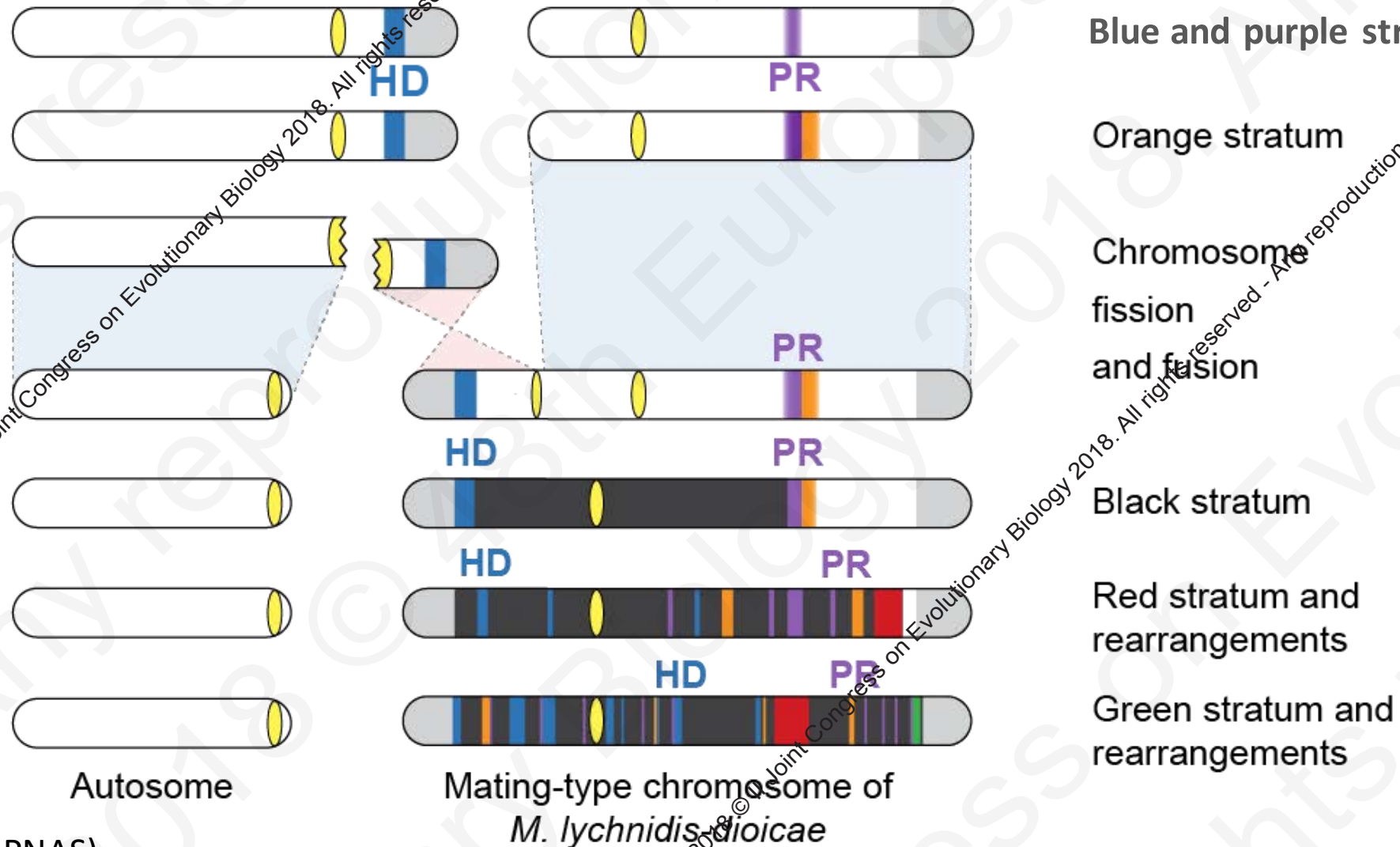
# Evolutionary strata in *Microbotryum lychnidis-dioicae* not involving mating-type genes



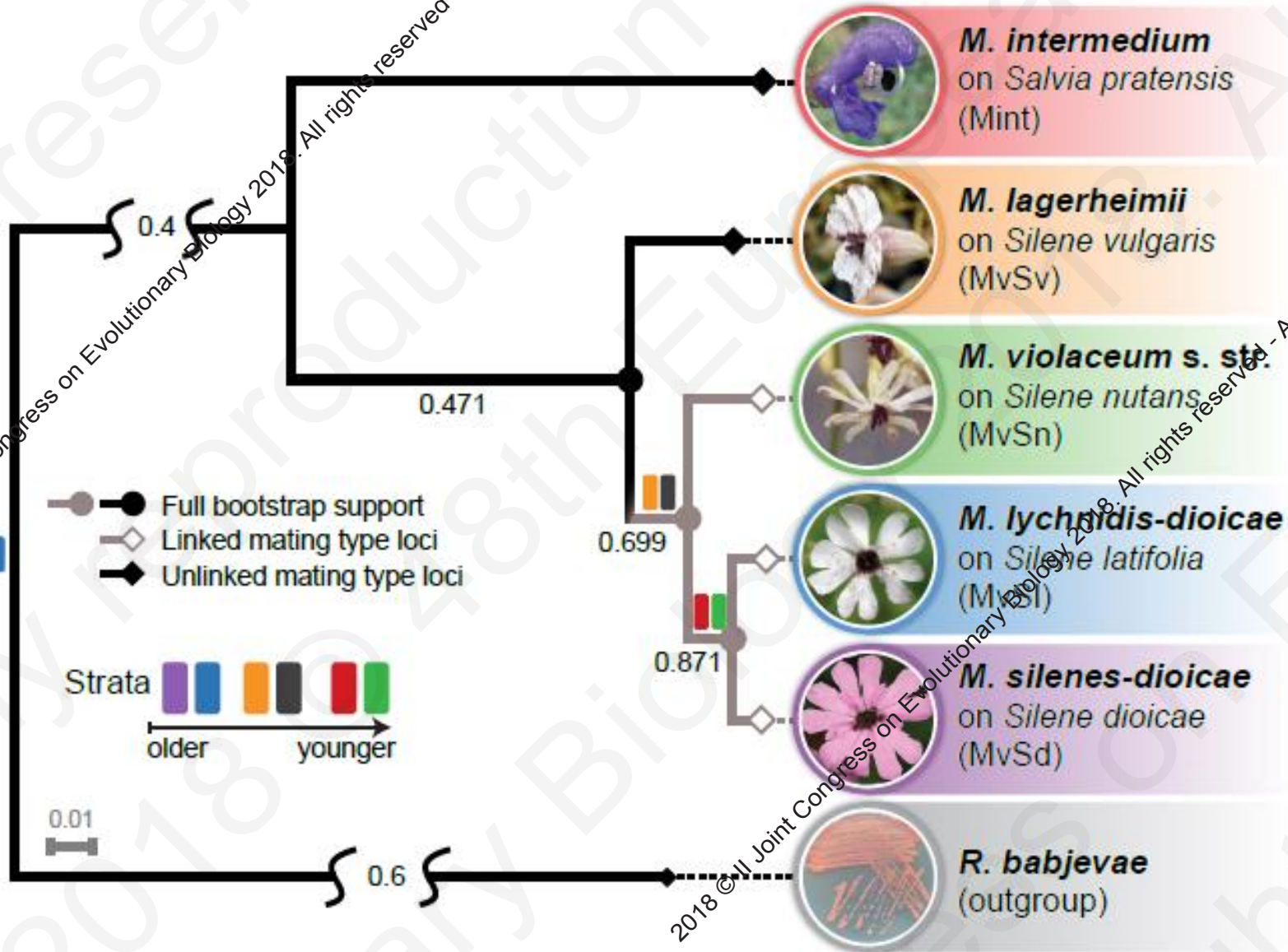
- Further very recent extension of suppressed recombination
- Currently located between the PR and HD loci



# Evolution of *Microbotryum lychnidis-dioicae* mating-type chromosomes



# Multiple evolutionary strata of different ages beyond mating-type genes

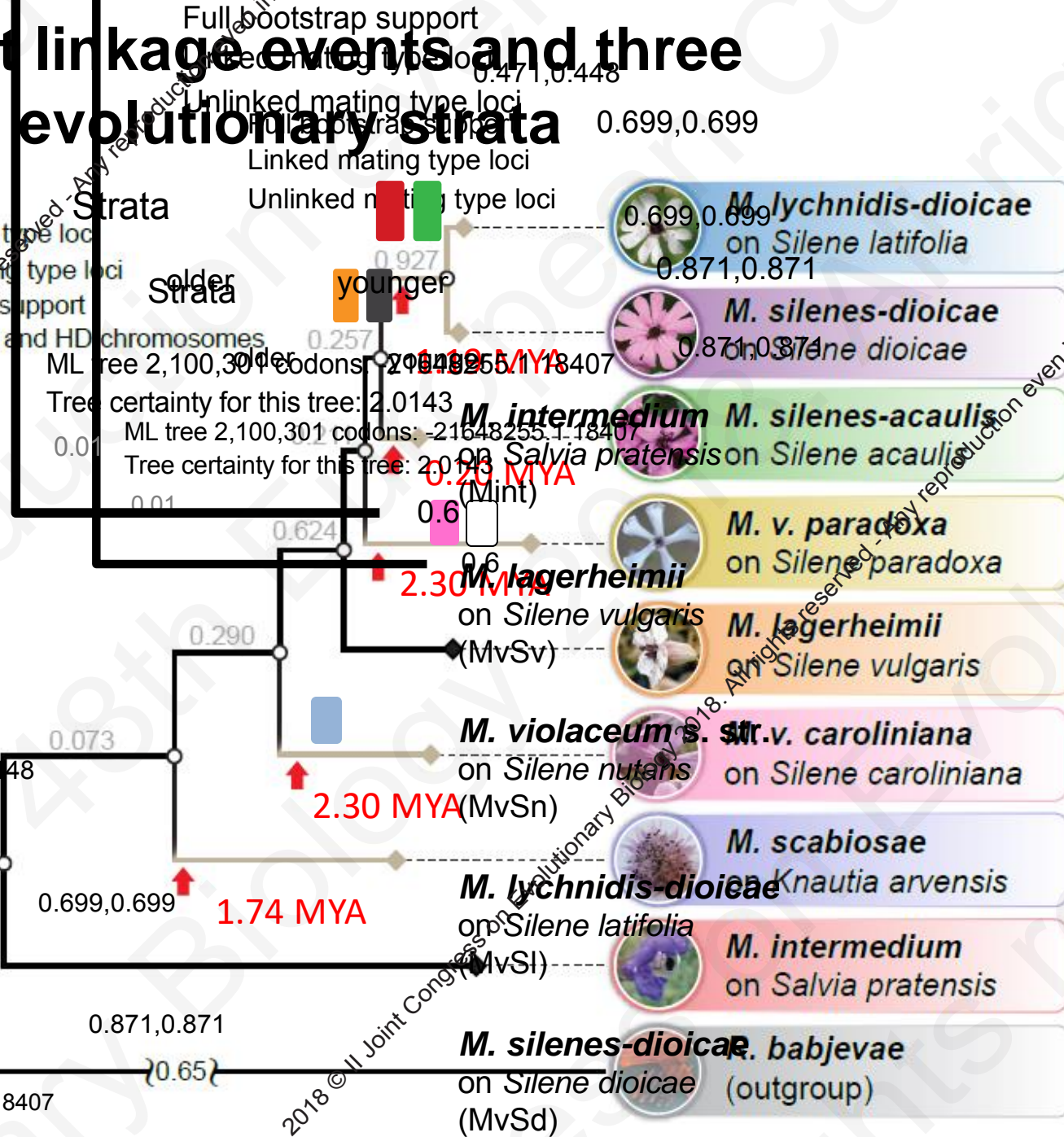




# At least five convergent linkage events and three additional young evolutionary strata

A

- Linked mating type loci
- Unlinked mating type loci
- Full bootstrap support
- Linkage of PR and HD chromosomes



B  
Different genomic rearrangements linking HD and PR loci

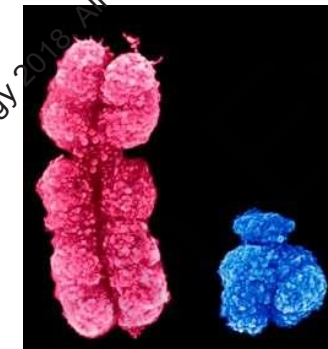
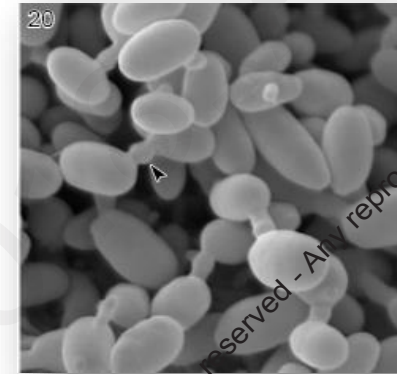
- Full bootstrap support
  - Linked mating type loci
  - Unlinked mating type loci
- Strata  
older  
younger

ML tree 2,100,301 codons: -21648255.1 18407  
Tree certainty for this tree: 2.0143

# Repeated evolution of stepwise recombination suppression beyond mating-type genes without antagonistic selection

Other mechanisms than sexual antagonism can generate evolutionary strata, which may also act on sex chromosomes

- neutral inversions
- sheltering of deleterious mutations
- spread of transposable elements and their silencing



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# Acknowledgements



Sara Branco



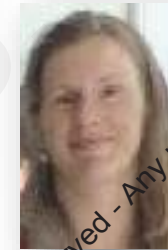
H el ene Badouin



Michael Hood



Fantin Carpentier



Sophie Siguenza



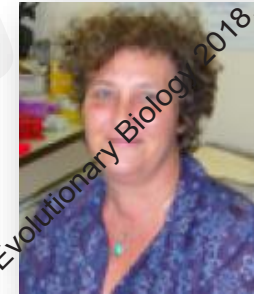
Ricardo Rodriguez de la Vega



Alodie Snirc



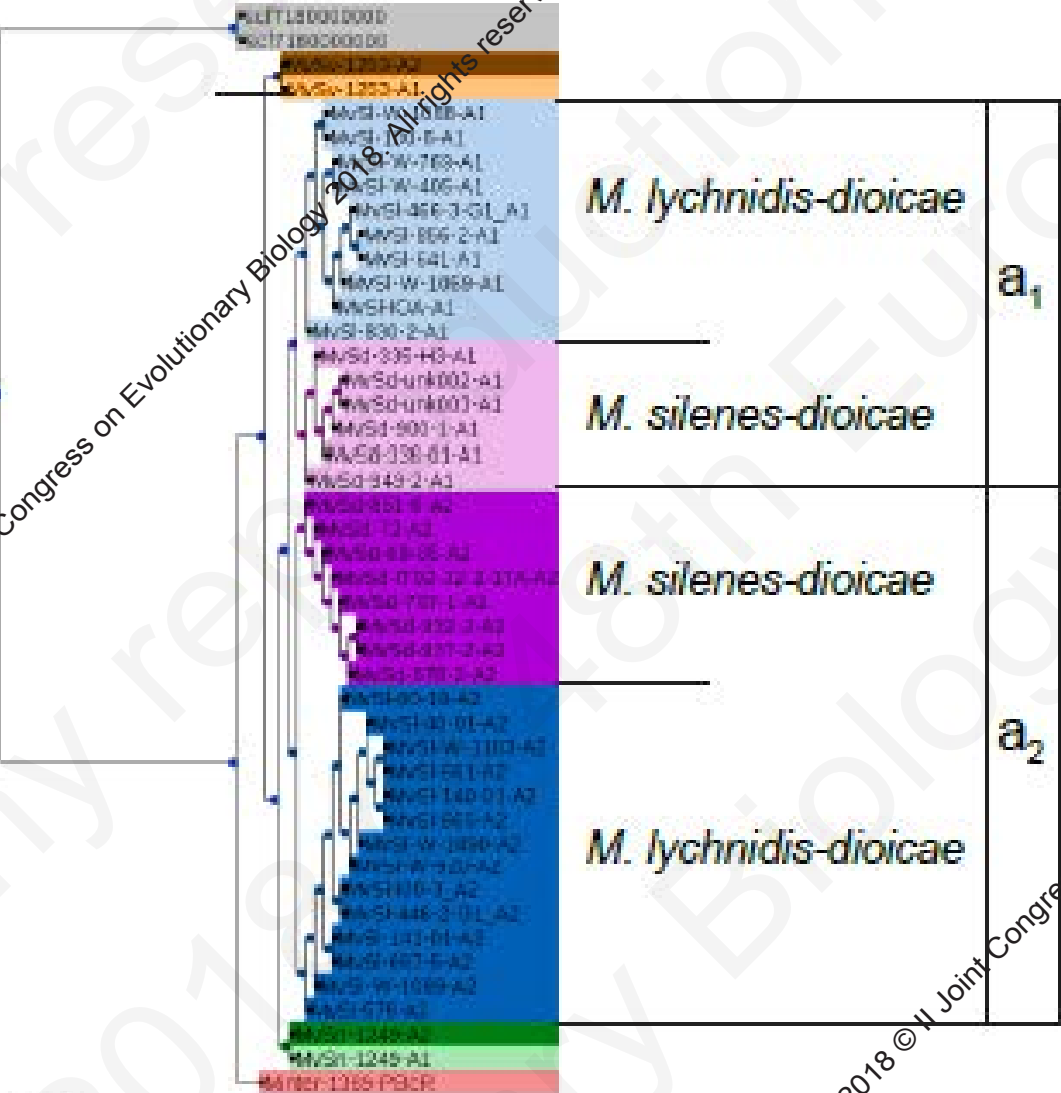
J er ome Gouzy  
St ephanie Le Prieur



C ecile Fairhead



# Trans-specific polymorphism in the red evolutionary stratum

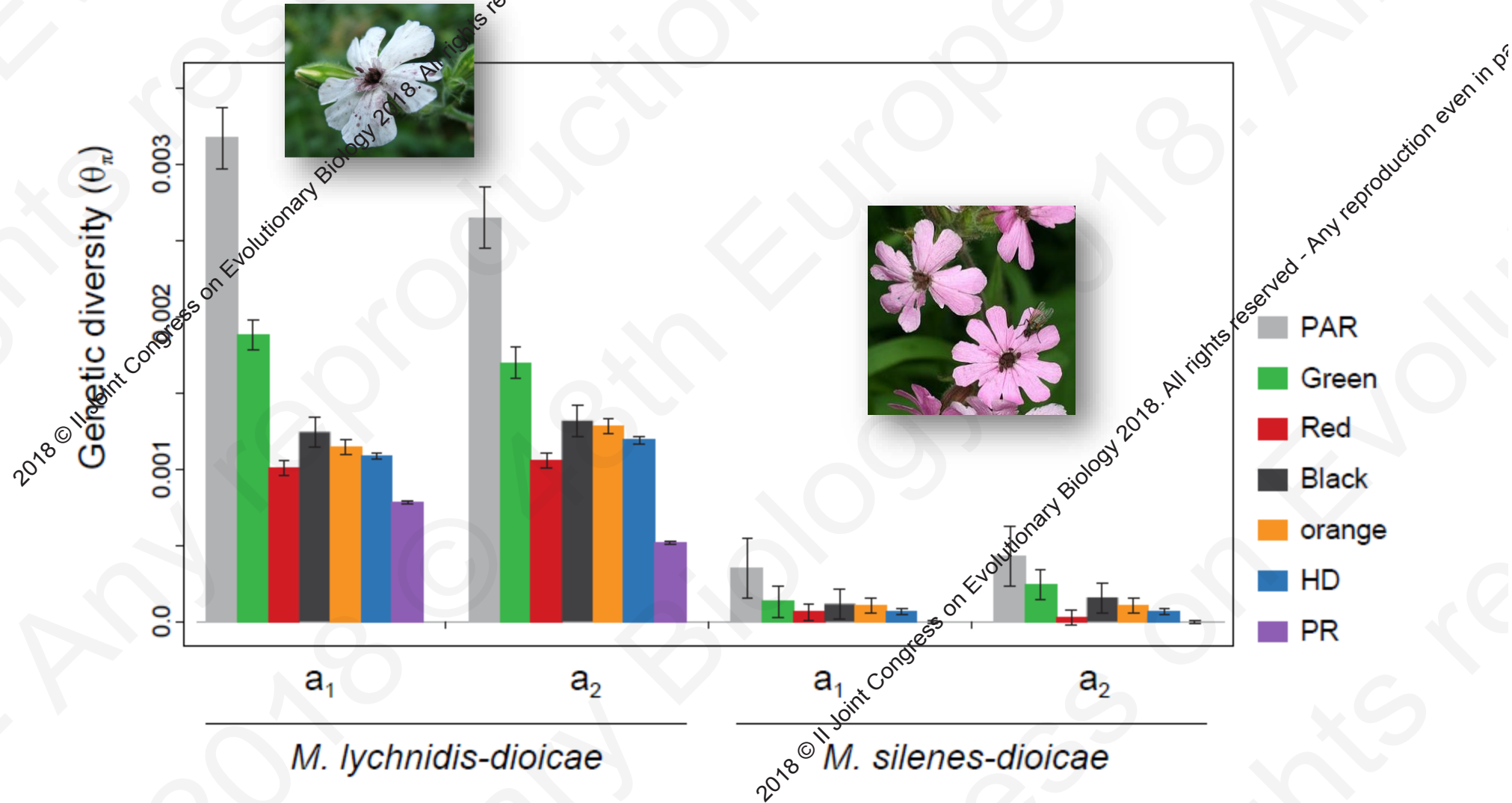


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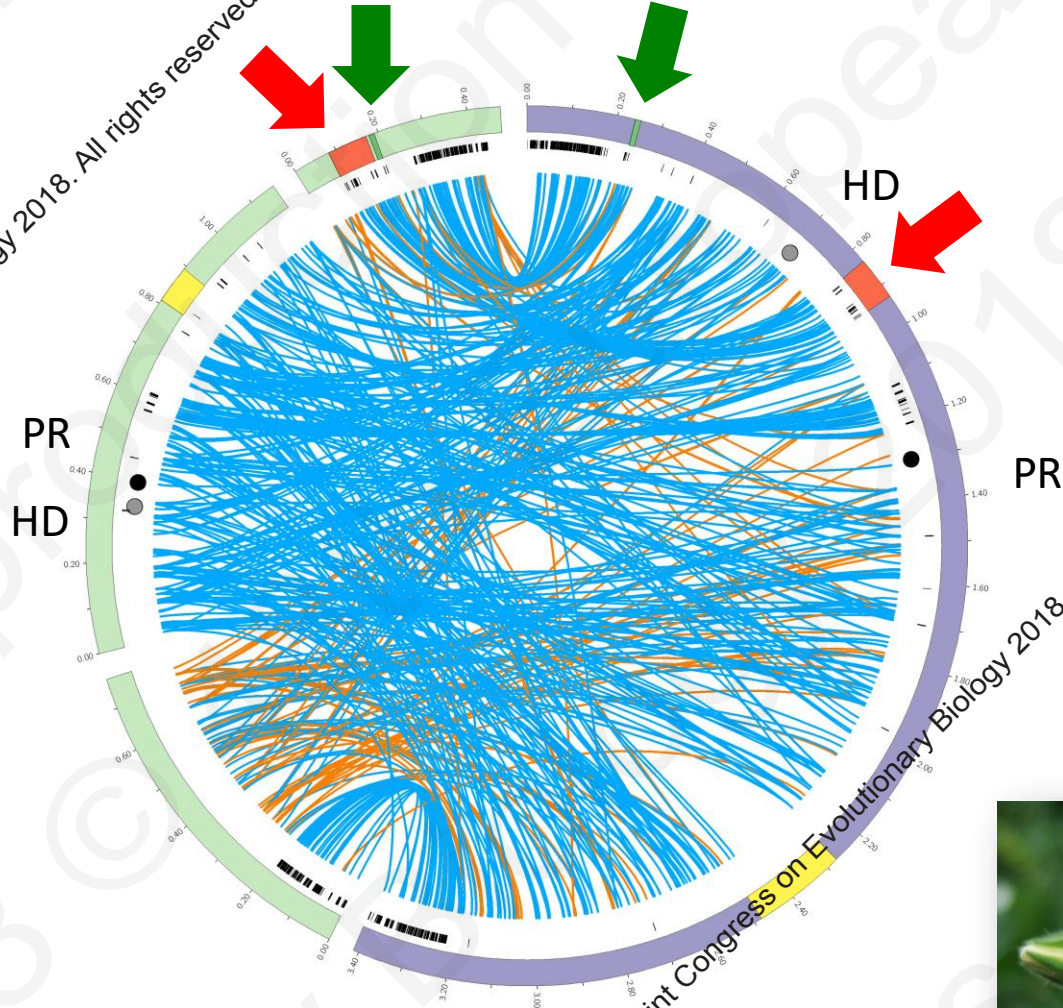
# Lower genetic diversity in the red and green evolutionary strata, as expected in non-recombining regions



# Red stratum between HD and PR in *M. lychnidis-dioicae*, but not in *M. violaceum*



*M. violaceum* s. str.



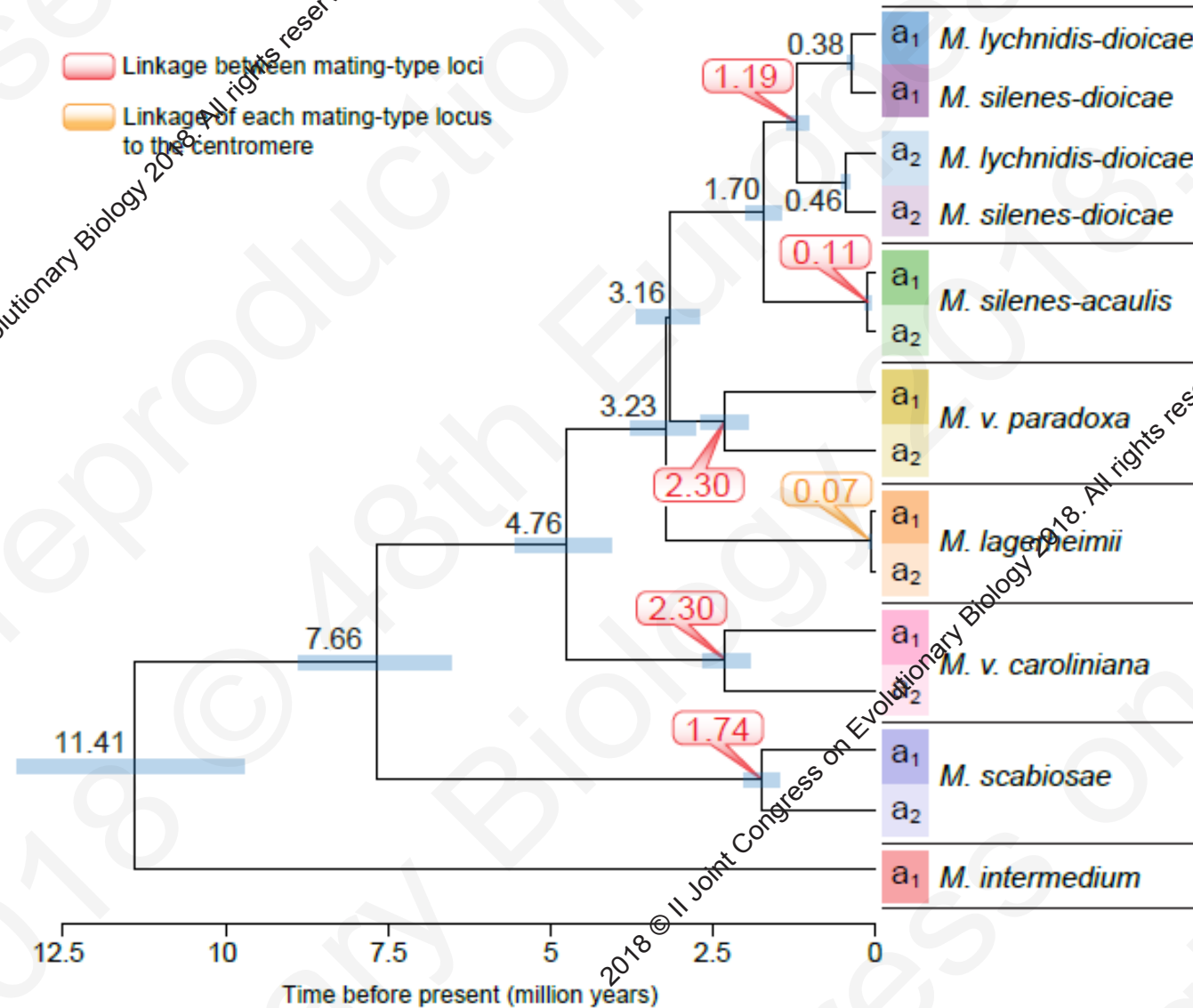
*M. lychnidis-dioicae*



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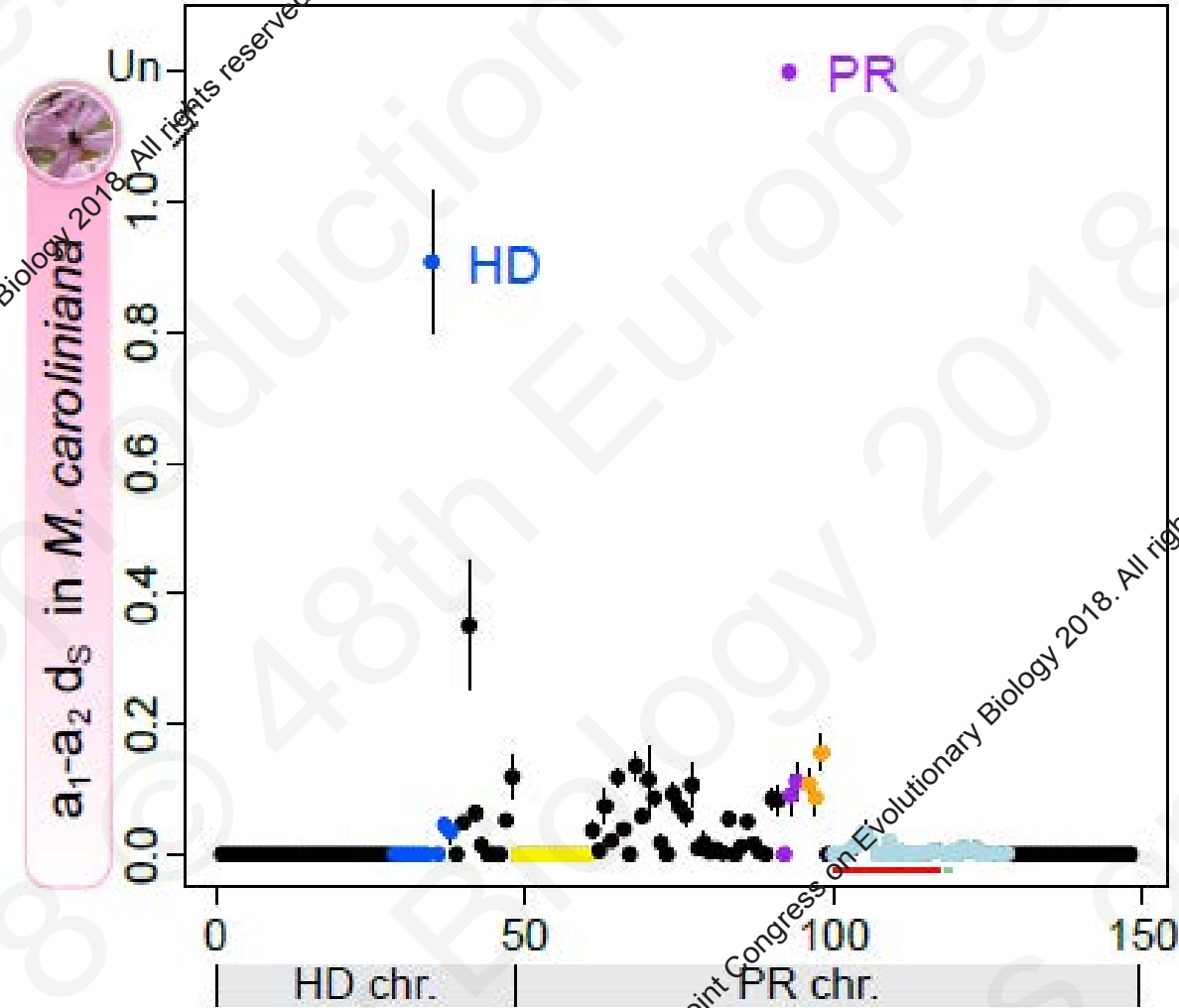
# At least five independent linkage events: convergent evolution of supergenes

Recombination suppression events younger than speciation events



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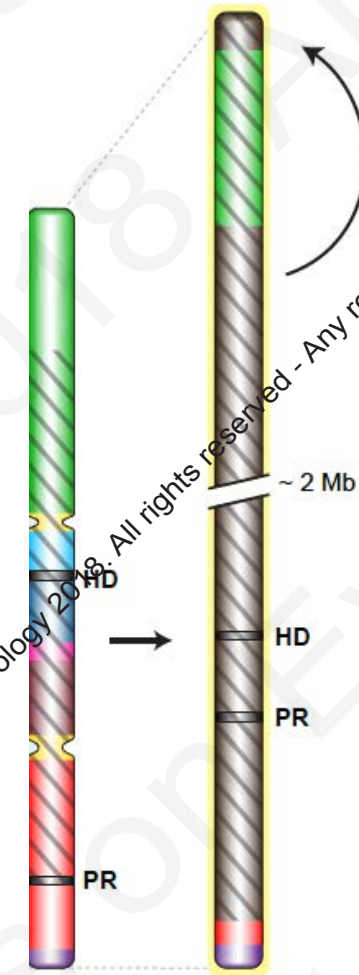
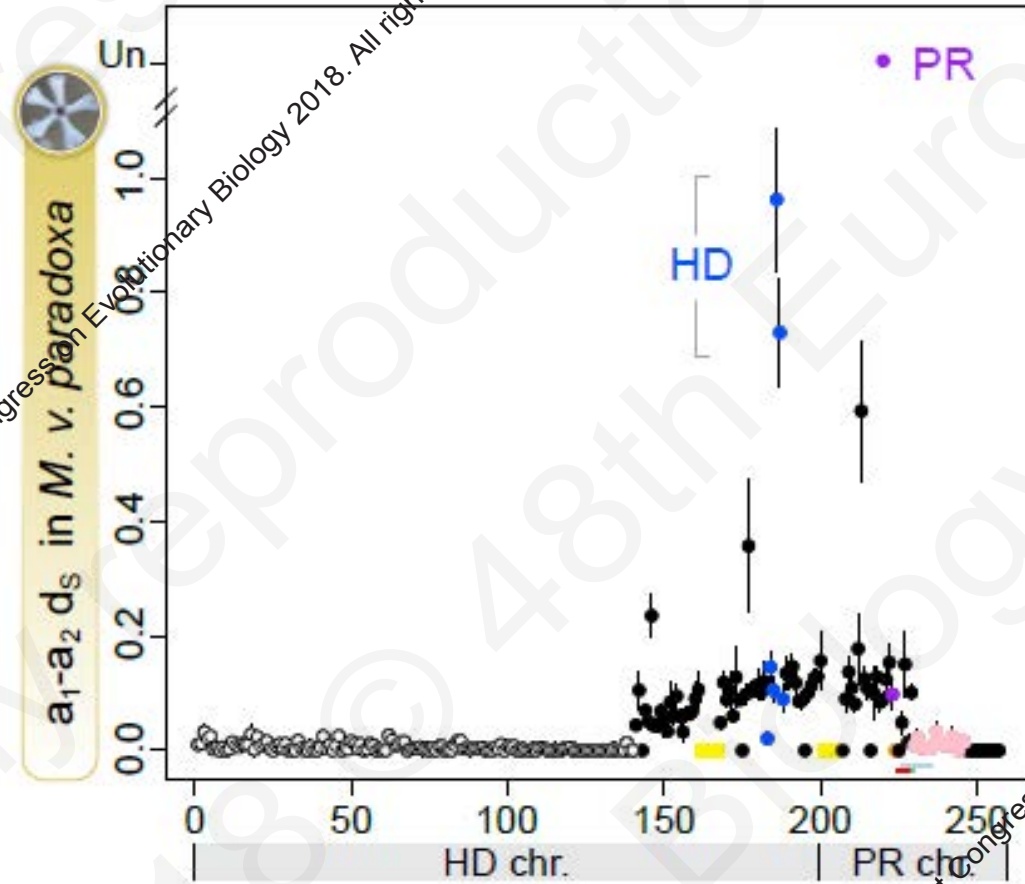
# Independent stratum in *M. v. caroliniana* devoid of mating-type genes



Gene order along the mating-type  
chromosomes of *M. lagerheimii*

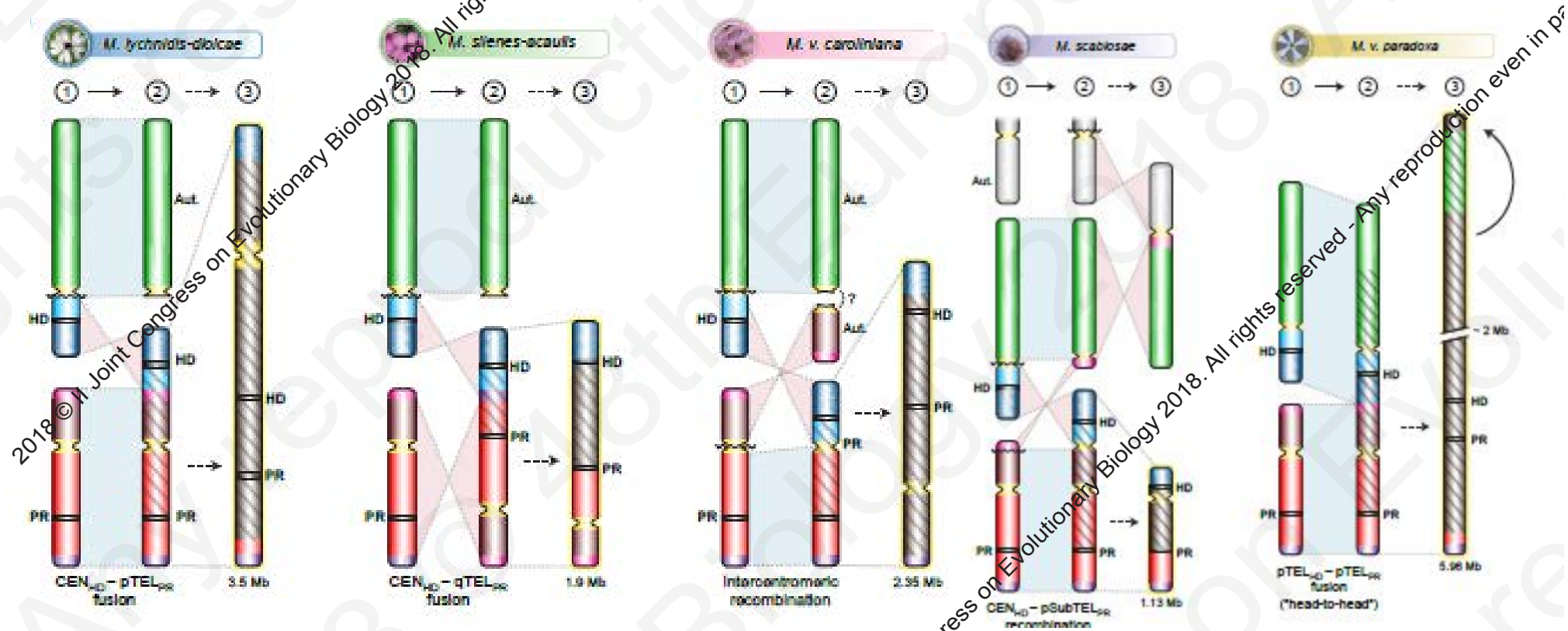


# Two independent strata in *M. v. paradoxa* devoid of mating-type genes



Gene order along the mating-type chromosomes of *M. lagerheimii*

# Genomic decay increasing with time since recombination suppression: transposable element accumulation

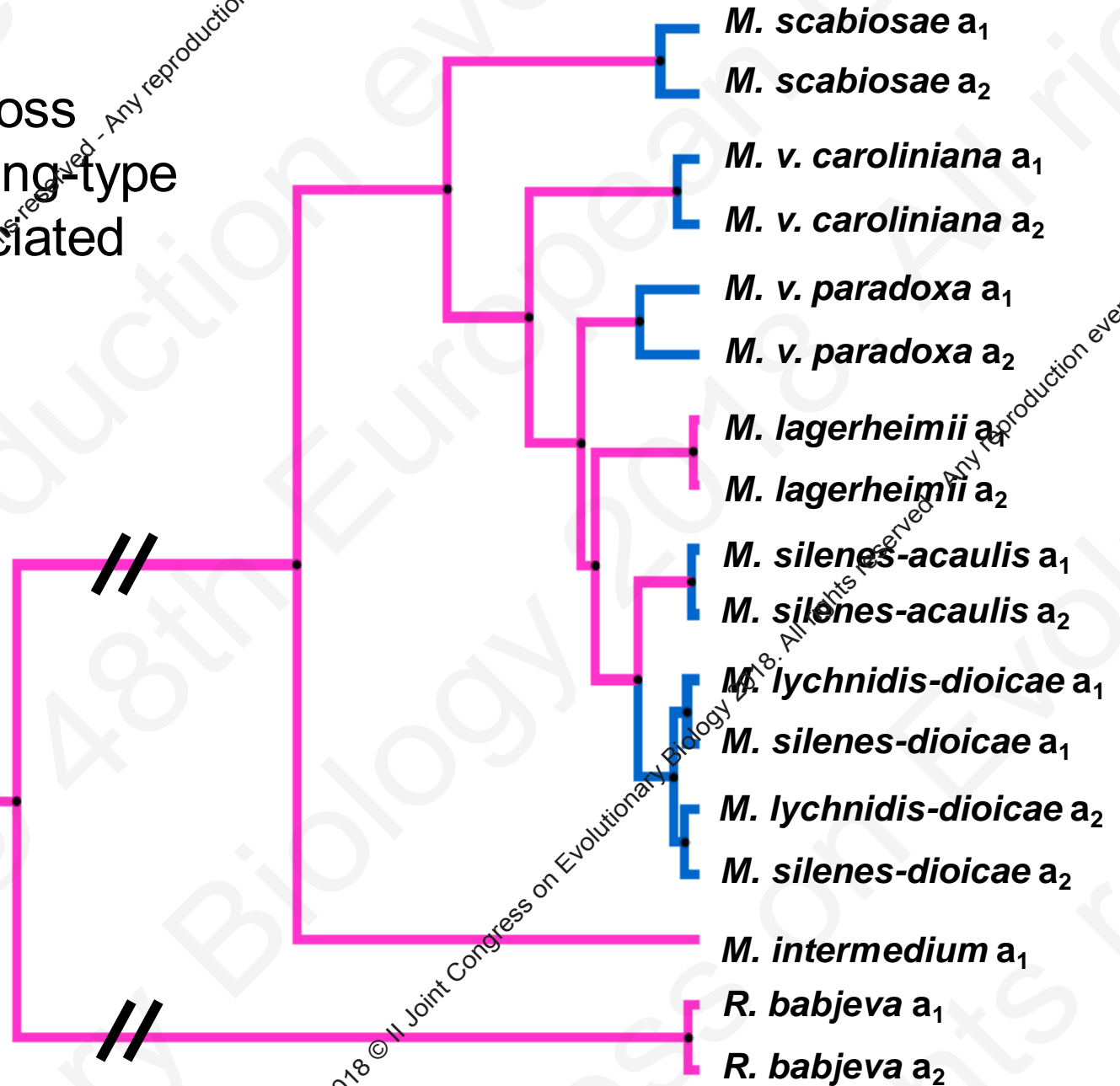


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No transpecific polymorphism across alleles in non mating-type black genes associated with  $a_1$  and  $a_2$

Tetrapolar species

Bipolar species



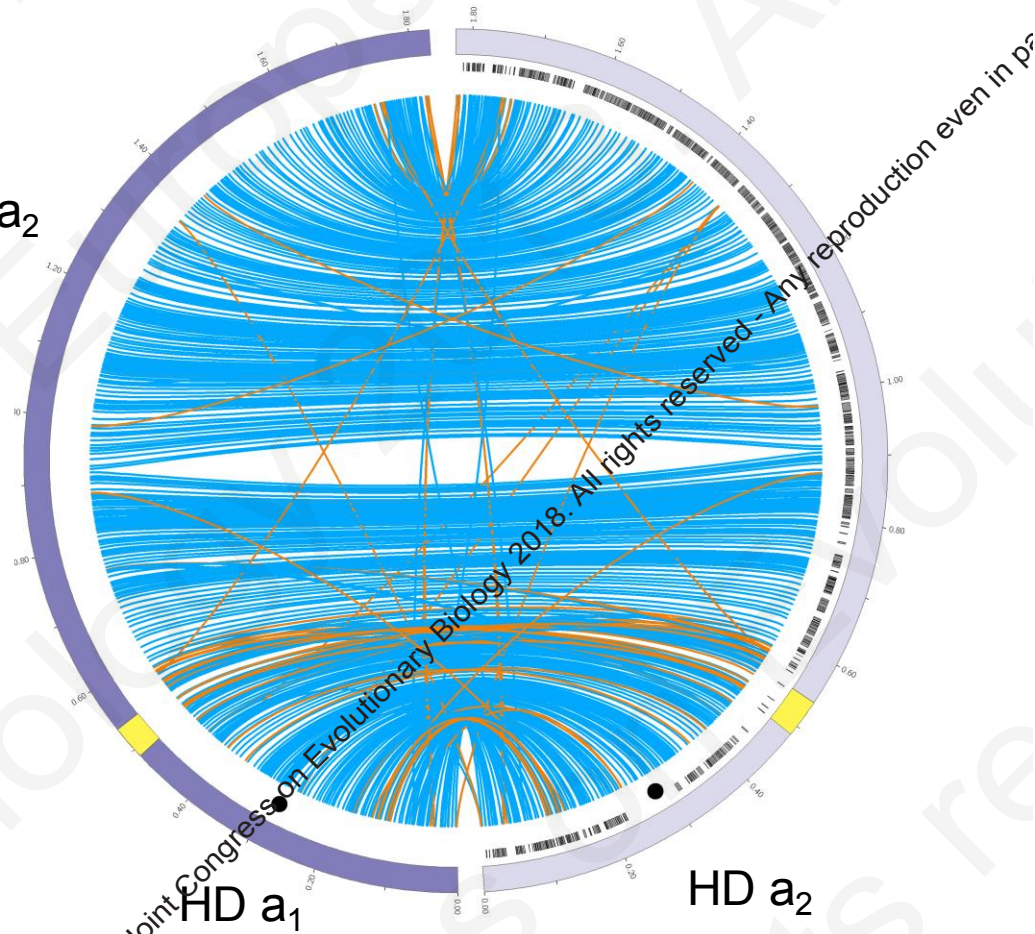
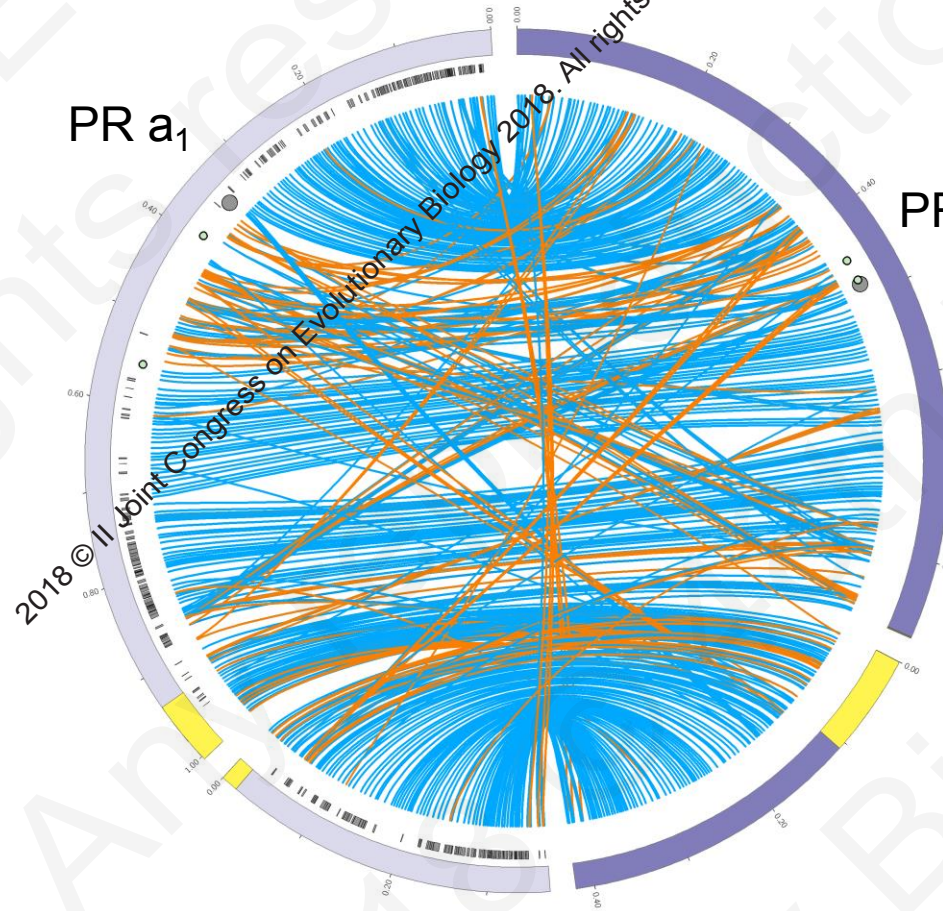
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# *M. lagerhemii*



PR chromosomes

HD chromosomes



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