Evolutionary walks through flower color space driven by gene expression in Petunia and allies (Petunieae)

Lucas C. Wheeler[1,*], Amy Dunbar-Wallis[1], Kyle Schutz[1], Stacey D. Smith[1]

1. Department of Ecology and Evolutionary Biology, University of Colorado, 1900 Pleasant Street 334 UCB, Boulder, CO, USA, 80309-0334

lwheeler9@gmail.com

Abstract

The structure and function of biochemical and developmental pathways determine the range of accessible phenotypes, which are the substrate for evolutionary change. Accordingly, we expect that observed phenotypic variation across species is strongly influenced by pathway structure, with different phenotypes arising due to changes in activity along pathway branches. Here we use flower color as a model to investigate how the structure of pigment pathways shapes the evolution of phenotypic diversity. We focus on the phenotypically diverse Petunieae clade in the nightshade family, which contains nearly 200 species of *Petunia* and related genera, as a model to understand how flavonoid pathway gene expression maps onto pigment production. We use multivariate comparative methods to estimate co-expression relationships between pathway enzymes and transcriptional regulators, and then assess how expression of these genes relates to the major axes of variation in floral pigmentation. Our results indicate that coordinated shifts in gene expression predict transitions in both total anthocyanin levels and pigment type, which, in turn, incur trade-offs with the production of UV-absorbing flavonol compounds. These findings demonstrate that the intrinsic structure of the flavonoid pathway and its regulatory architecture underlies the accessibility of pigment phenotypes and shapes evolutionary outcomes for floral pigment production.

Keywords

flavonoids, flower color, canonical correlation analysis, pathway evolution, phylo-transcriptomics, Petunieae, Solanaceae, molecular evolution, phenotypic evolution

Introduction

Biologists have long observed that species are not uniformly distributed across the space of

possible phenotypes, but are clustered in certain regions of the space, leaving gaps in others. One explanation for this pattern is natural selection, where the clusters represent phenotypes associated with some adaptive optimum (e.g. Whibley et al. 2006; Mahler et al. 2013). Another contributing factor may be developmental bias, where some phenotypes are more likely outcomes given the underlying genetic and developmental pathways and others are inaccessible (J. M. Smith et al. 1985; Uller et al. 2018). As selection acts upon the products of development, these forces may also act in concert and jointly contribute to the patchiness of phenotype space (Wagner 2011).

While much of our understanding of the factors shaping phenotype space come from experimental work (e.g. (Beldade, Koops, and Brakefield 2002; Braendle, Baer, and Félix 2010)), macroevolutionary approaches can also provide unique insights. For example, macroevolutionary trends may mirror ontogenetic trajectories, suggesting that phenotypic evolution is biased by developmental processes (Watanabe 2018). Comparative studies can also be used to estimate the degree of phenotypic integration, which is tied to stronger developmental bias (Jablonski 2020). Beyond purely morphological studies, the field of evo-devo has uncovered numerous instances of the same genes and pathways underlying independent origins of complex traits in distantly related lineages (e.g. (Xavier-Neto et al. 2007; Kozmik et al. 2008), highlighting the central role of genetic and developmental pathways in shaping evolutionary trajectories.

Here we use flower color as a model system to interrogate the relationship between pathway structure and phenotypic diversity at a macroevolutionary scale. The developmental basis for flower pigmentation, in particular through anthocyanin production, is arguably one of the best understood pathways in plants and is widely conserved across species (Grotewold 2006; Albert et al. 2014). With an extensive foundation in the genetics of anthocyanin biosynthesis, the mechanisms responsible for flower color evolution have been dissected in a diverse and growing list of taxa (e.g., (Des Marais and Rausher 2010; Yuan et al. 2013; Gates et al. 2018). Together these studies suggest that while changes in enzyme function can contribute to flower color transitions (e.g., (Ishiguro, Taniguchi, and Tanaka 2012; S. D. Smith, Wang, and Rausher 2013), differences in gene expression are by far the predominant mode of color macroevolution (Wessinger and Rausher 2012; Sobel and Streisfeld 2013). Nevertheless, we lack a broader understanding of how the structure of the pathway combines with differential gene expression to give rise to the range of observed flower pigment phenotypes and possibly explain those that are not observed (Ng and Smith 2018).

In order to explore the role of variation in gene expression and color diversity, we focus on the Petunieae, a clade of roughly 180 species comprising the South American genus *Petunia* and eight allied genera. This group is widely known for its tremendous diversity in flower colors, including white, yellow, pink, purple and red. Moreover, the cultivated petunia has long served as the premier system for studying the genetics and regulation of flower color (Koes, Verweij, and Quattrocchio 2005). Importantly, studies in petunia as well as other taxa have demonstrated that many steps in the anthocyanin pathway are jointly regulated by a complex comprising R2R3 MYB, basic-helix-loop-helix (bHLH) and WD40 transcription factors (Mol, Grotewold, and Koes 1998), allowing for coordinated expression of enzymes and the compounds they produce. In addition to anthocyanin pigments, *Petunia* flowers also produce UV-absorbing flavonols, which share biochemical precursors with anthocyanins but appear to be independently regulated by different R2R3 MYBs (Sheehan et al. 2016). Changes in the expression of these transcription factors and in turn their downstream targets (pathway enzymes) underlie the gain of floral UV

patterning (Sheehan et al. 2016), the loss of floral anthocyanins (Quattrocchio et al. 1999), and the shift to red coloration (Berardi et al. 2021) in different *Petunia* species. We predict that this connection between pathway gene expression and pigment variation holds across the broader Petunieae clade and may explain its diversity of colors, including those beyond the range of variation observed in *Petunia* itself.

Our study encompasses the broadest quantitative analysis of anthocyanin pigment production for any flowering plant clade to-date along with pathway-wide measures of expression from petal transcriptomes. Using these data, we first estimate patterns of co-expression between pathway enzymes and the previously characterized classes of transcriptional regulators in *Petunia*. Next, we apply morphospace approaches to characterize the pigmentation space of Petunieae and identify clusters within that space. Finally, we combine these datasets to determine how changes in gene expression associate with the major axes of variation in pigment production. Our results demonstrate that coordinated shifts in gene expression strongly predict repeated transitions from pale to intensely pigmented phenotypes and from the production of the common blue pigments to the less common red and purple pigments. These coordinated changes in gene expression also mediate sharp trade-offs between anthocyanins and flavonols, implicating an underappreciated role of these colorless compounds in shaping visible color diversity. Overall, these findings show that the structure of the pathway plays a fundamental role determining the accessibility of pigment phenotypes and in turn shapes the evolutionary trajectories taken to reach distinct floral pigmentation phenotypes.

Results

Flower color diversity is matched by diversity of pigment profiles

Species of Petunieae produced all six types of anthocyanidins, the base molecules that are modified to form glycosylated anthocyanins, and all three classes of the flavonol co-pigments. Delphinidin and its two methylated forms (petunidin and malvidin), commonly associated with blue and purple flowers (Wessinger and Rausher 2012), are the most commonly produced pigments while the other three classes of pigments are only found in a few species (Fig. 1,(Ando et al. 1999). The total quantity of anthocyanin pigments varies widely across species, with the many white-flowered species, like *Nierembergia rigida*, producing little to no anthocyanins and the deep purple and pink-flowered species, like *Calibrachoa caesia*, producing over 3 mg/g petal tissue (Fig. 1; see also (Lucas C Wheeler et al. 2022)). Petunieae flowers of all colors produce abundant flavonols, often at levels that are orders of magnitude higher than the anthocyanins (Fig. 1, Table S1). These compounds may act as co-pigments, altering hue or intensifying the color ((Holton, Brugliera, and Tanaka 1993) 3) and/or contributing to UV-patterning involved in pollinator attraction (Sheehan et al. 2016).

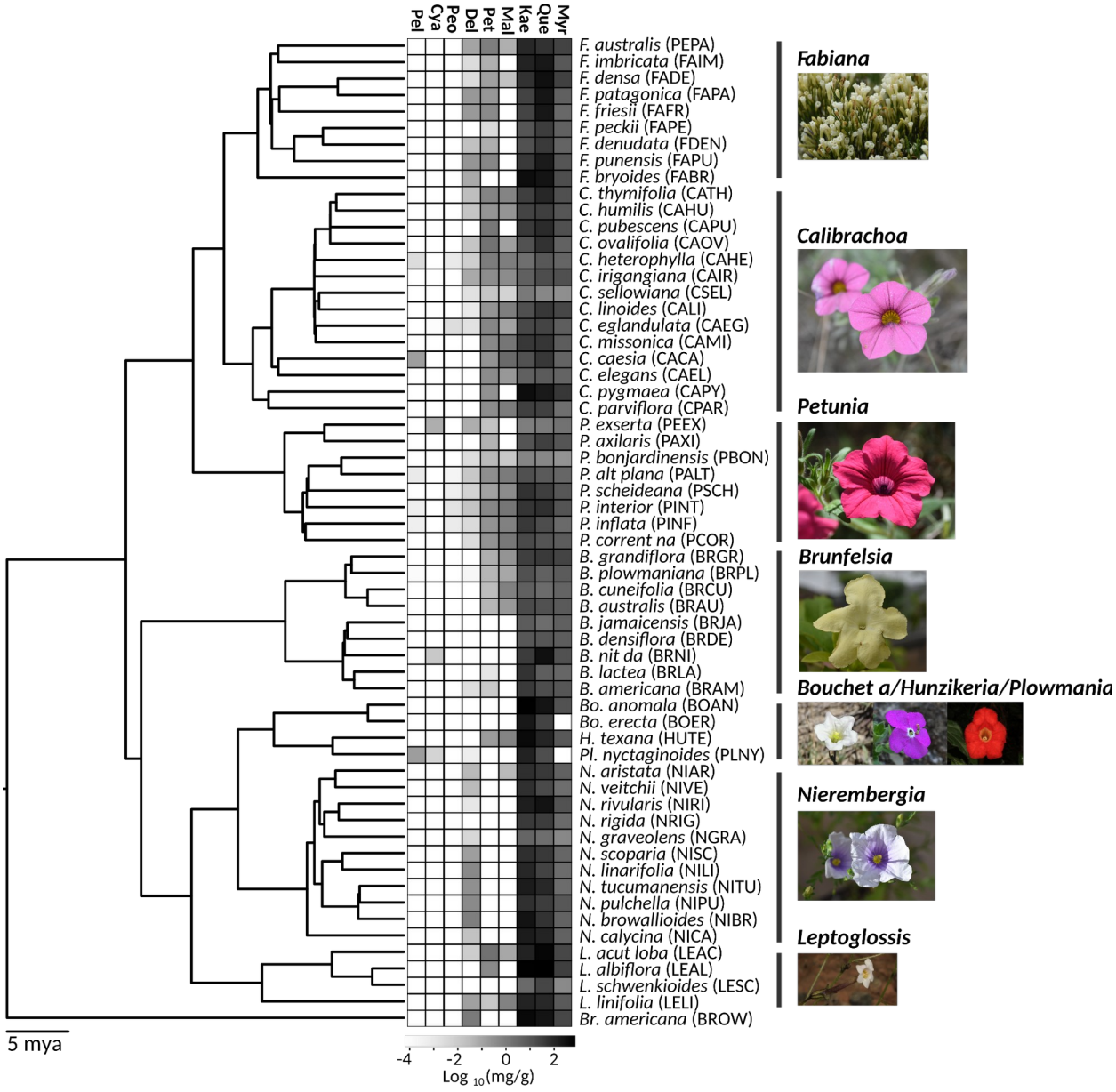

Fig. 1. Flavonoid pigmentation varies across the Petunieae clade. Species tree for 60 taxa from Astral analysis of 3672 gene trees. Tree is rooted with *Browallia americana* as the outgroup. Heatmap shows the mean $Log_{10}(mg/g)$ pigment mass fraction for the six anthocyanidins: Pelargonidin (Pel), Cyanidin (Cya), Peonidin (Peo), Delphinidin (Del), Petunidin (Pet), and Malvidin (Mal); and the three flavonols: Kaempferol (Kae), Quercetin (Que), and Myricetin (Myr). Raw values are in Table S1. Pigment level distributions are in Fig. S1. Flower images for each clade from top to bottom and left to right are as follows (with credits): *Fabiana punensis*, *Calibrachoa eglandulata*, *Petunia reitzii*, *Brunfelsia lactea, Nierembergia scoparia* (all by L. C. Wheeler), *Bouchetia erecta* (Edith Bergquist), *Hunzikeria texana* (Karla M. Benítez), *Plowmania nyctaginoides* (R. Deanna), *Nierembergia scoparia* (Lucas C. Wheeler), *Leptoglossis albiflora* (R. Deanna).

Phylogenetic correlation structure reveals co-expression relationships across the flavonoid pathway

We used petal transcriptomic data for 59 Petunieae species to examine clade-wide patterns of co-expression among nine enzymes and seven transcription factors of the flavonoid pathway. For this and subsequent analyses, we grouped two sets of genes, the methyl-transferases (MTs) and R2R3 MYB subgroup 6 activators, which vary in copy number across taxa but carry out similar functions (see Supplemental Text). We computed correlation coefficients, accounting for phylogenetic structure, and found two clusters of correlated structural genes, a flavonol module (F3'H and FLS) and an anthocyanin module, comprising the remaining steps of the pathway (Fig. 2). The 'late' anthocyanin biosynthesis (F3'5'H, DFR, ANS, and the MTs) form a tight cluster while the other core pathway genes (CHS and CHI) are more loosely connected. As expected, the components of the MBW complex (the SG6 MYBs, the bHLH AN1 and the WD40 AN11) are mostly strongly associated with the anthocyanin module, while the flavonol regulator MYB12 (Wang et al. 2018) is co-expressed with the flavonol module. Another flavonol regulator, MYB-FL, was not co-expressed with the flavonol module, suggesting its role may be specific to the clade of *Petunia* in which it was studied (Sheehan et al. 2016). We also found the repressor MYB27 is most associated with DFR expression, consistent with the notion that it is upregulated after the late steps in the pathway to provide feedback inhibition (Albert et al. 2014). The tighter connection of AN1 to anthocyanin biosynthesis compared to the other bHLH transcription factor (JAF13) may relate to the relatively late bud stage sampled; the two bHLH genes are functionally similar but AN1 acts later in floral development (Spelt et al. 2000; Albert et al. 2014).

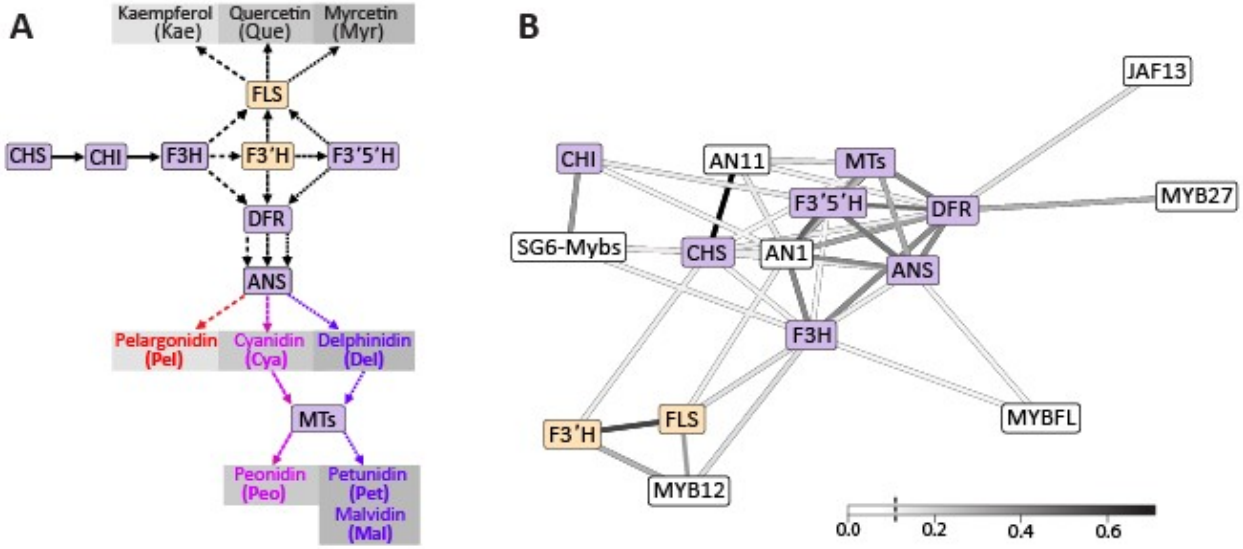

Fig. 2. Two clusters of co-expressed pathway genes and transcription factors. A) Simplified flavonoid pigment pathway, focusing on the compounds found in Petunieae (the three flavonols and six anthocyanidins). Enzymes with multiple input/output arrows can act on multiple substrates (as indicated by the different dashed lines). Gray boxes around products indicate increasing levels of hydroxylation (left to right, mono-, di- and tri-hydroxylated). Structural genes are colored by their cluster in (B); see Table S2 for full

gene names. B) Correlation structure from the phylogenetic PCA of expression values for structural genes (colored boxes) and transcription factors (white boxes). Values above the median (R^2>0.124 *, indicated with a vertical ❑ the inset scale* were visualized with a force-directed spring layout representation. Edge weights (R^2) are colored by magnitude. See Fig. S2 for full matrix of correlation coefficients. Distributions of gene expression levels are shown in Fig. S3.

Pigment phenotypes are divided by hydroxylation, methylation and flavonoid content

A phylogenetic principal component analysis (pPCA) of pigment production (Fig. 1) revealed sharp trade-offs among pathway branches, as manifested in the pigment profiles across species. The first PC axis, which accounts for 26% of the variation, is driven by the level of hydroxylation and the amount of flavonol production (Fig. 3, Table S3). It separates pale-flowered species, which produce the tri-hydroxylated delphindin and high amounts of flavonols, from those which produce the less hydroxylated cyanidin and pelargondin and lower amounts of flavonols, including the bright red-flowered *Plowmania nyctaginoides* and *Petunia exserta* (PLNY, PEEX). The intensely colored purple and pink-flowered species characteristic of *Petunia* and *Calibrachoa* are intermediate along this axis, with mostly tri-hydroxylated anthocyanins and a range of flavonol concentrations. The second PC axis reflects the level of methylation and divides the taxa that produce the unmethylated anthocyanidins (delphindin, cyanidin, pelargonidin) from those that produce mostly or entirely methylated compounds (peonidin, petunidin, malvidin). We used a k-means clustering to group to the taxa in this pigment profile space and recovered three clusters, the pale-flowered taxa making large amounts of flavonols, the deeply pigmented taxa making methylated anthocyanidins, and the taxa making less hydroxylated anthocyanidins and lower flavonols. While the first two clusters are fairly uniform in color (white to light purple and deep pink to deep purple, respectively), the cluster containing the diverse less hydroxylated anthocyanins and low flavonols range in color from yellow (BRDE, LESC) to pink (PBON, CSEL) to red (PLNY, PEEX).

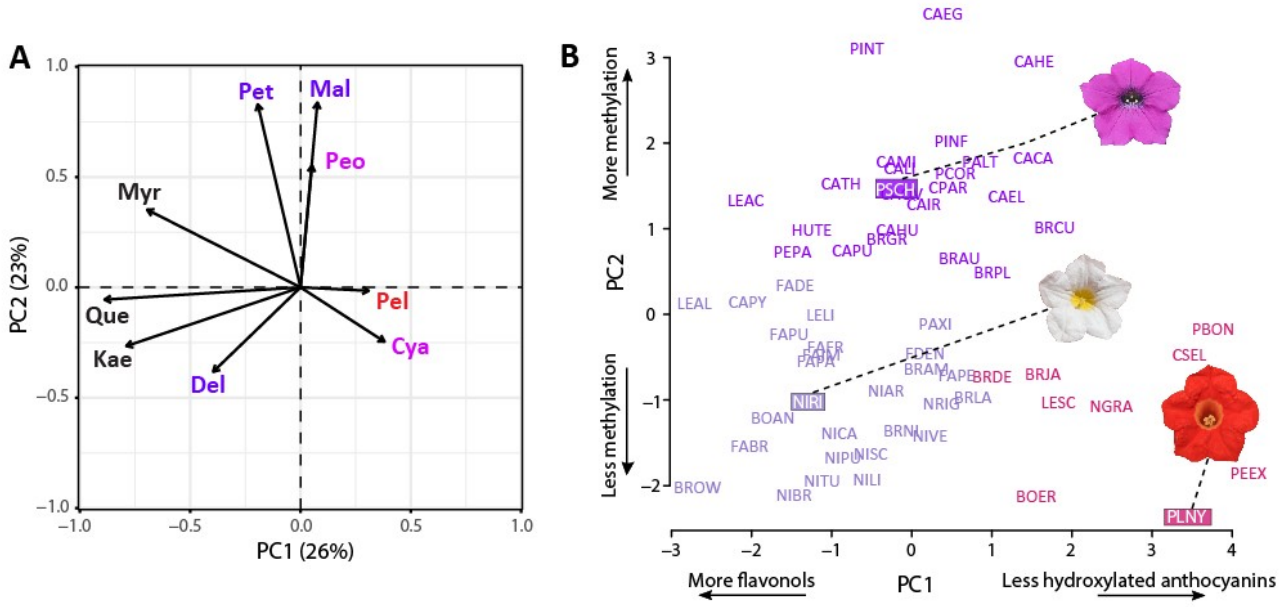

Fig. 3. Clusters in pigment space defined by pathway branches. A) Biplot from pPCA with flavonoids plotted by loading on the first two PC axes. Abbreviations follow Fig. 2. The three flavonols (quercetin, myricetin and kaempferol) plus the tri-hydroxylated delphindin load negatively onto PC1 while the less hydroxylated pelargonidin and cyanidin load positively. The three methylated anthocyanidins (petunidin, malvidin and peonidin) load positively onto PC2. B) Species of Petunieae plotted by values for PC1 and PC2. Taxon labels are colored by K-means clustering. The flower of one species from each cluster is shown; taxon abbreviations follow Fig. 1.

Pathway gene expression predicts major pigment phenotypes

Phylogenetic canonical correlation analysis (pCCA) revealed a tight relationship between the expression of flavonoid pathway structural genes and regulators, and the production of flavonoid compounds. The first three canonical variates (CVs) are statistically significant and have strong correlations between gene expression and pigment concentration variables (Fig. 4). Biplots of loadings for each gene and pigment on each CV (Table S4, S5) show similar clustering patterns as recovered in the individual analyses. For example, the flavonol module corresponding to F3'H, FLS and MYB12 (Fig. 2) emerges from the pCCA (Fig. 4B, C) and groups with the two flavonols showing correlated production, quercetin and kaempferol (Fig. 3). Similarly, the three methylated anthocyanidins (peonidin, petunidin, and malvidin) group together with several of the late pathway genes (F3'5'H, ANS, MT) that control their production (Fig. 4B). Moreover, the CVs explain the expression variation underlying the major axes of pigment variation identified in the pPCA (Fig. 3). The first CV identifies genes whose expression contributes to hydroxylation level, which distinguishes the red-flowered species from the rest. Specifically, production of the less-hydroxylated pelargonidin and cyanidin is correlated with high expression of F3'H and its regulator MYB12 and low expression of F3'5'H (Fig. 4D), which diverts production towards the tri-hydroxylated compounds (Fig. 2A). The second CV explains the production of flavonols and methylated anthocyanins (Fig. 4E). Here, high expression of the methyltransferases and other late pathway genes leads to high levels of the methylated anthocyanins responsible for the intense purples and pinks as in most *Petunia* and *Calibrachoa*. Conversely, high expression of

the flavonol module shifts production away from anthocyanins and toward the flavonols quercetin and kaempferol, as observed in the pale and white-flowered species. Finally, the third CV addresses production of the most common anthocyanidin across the species, delphinidin, and its flavonol counterpart, the trihydroxylated myricetin. Their production appears to be shaped by expression of early genes in the pathway, which control overall flux (L C Wheeler and Smith 2019).

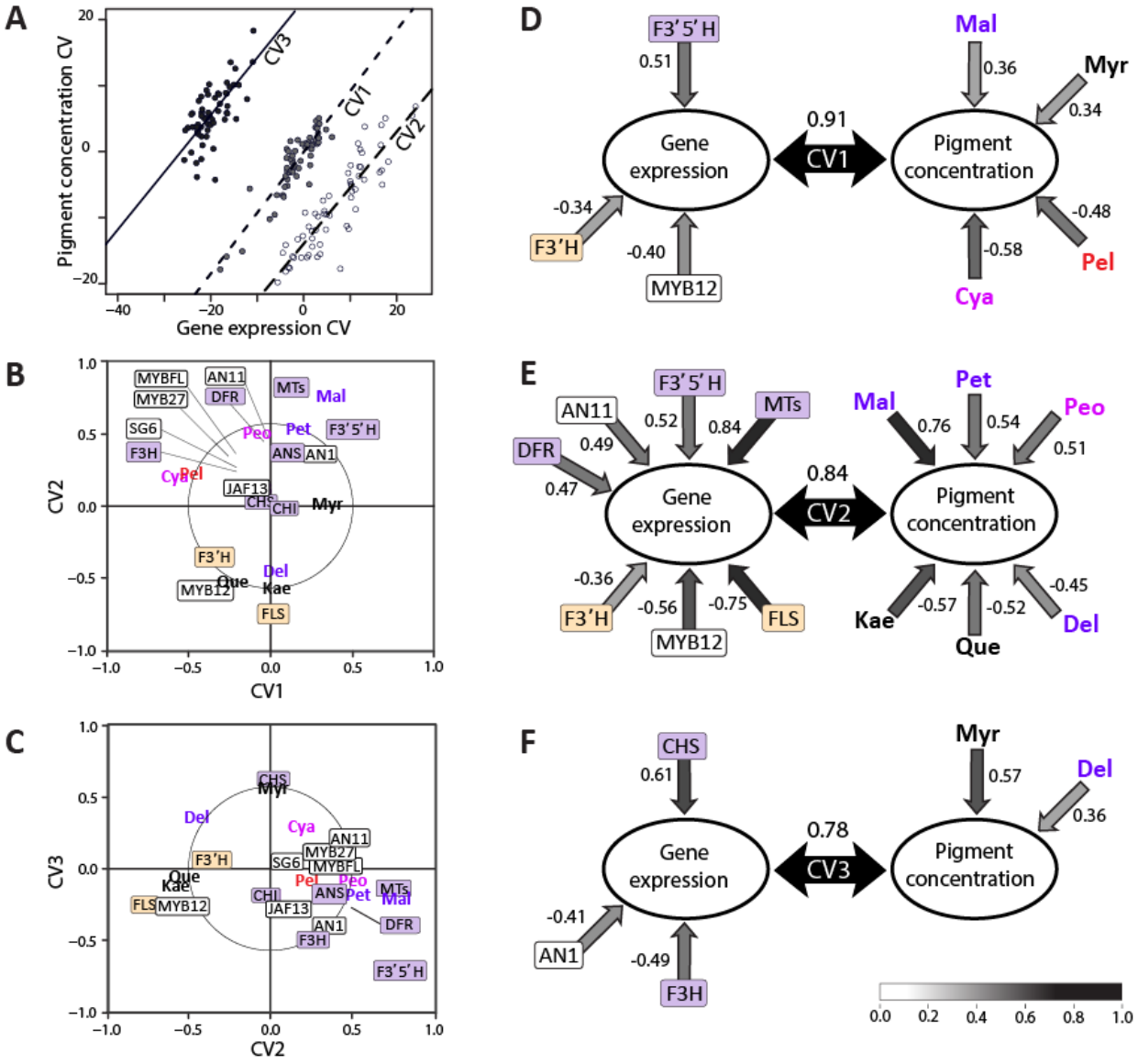

Fig. 4. Pathway gene expression correlates tightly with pigment production. A) Scatterplot of the significant canonical variates (CVs) for pigment concentration and gene expression from phylogenetic canonical correlation analysis (phylo-CCA). The correlation coefficients for each gene expression CV and pigmentation CV are shown in C-E, inset in the black arrows. B, C) Biplots of loadings of original expression and pigment variables onto

CVs. For some tightly clustered variables, the location of their point is indicated with a line. C, D, E) Variables with significant loadings onto each CV. Pearson correlation coefficients are shown for each significant variable (expression level or pigment amount) with one-way arrows. The bidirectional black arrows show the strength of the correlation between the given expression and pigment CVs.

Relationship between pigment types and genes not broadly driven by functional evolution

Changes in coding sequences may also contribute to the relationship between particular enzymes and pathway outputs (e.g. Smith et al. 2013). For example, we might expect relaxed selection on F3'5'H in lineages that have moved away from the production of tri-hydroxylated anthocyanins (Wessinger and Rausher 2015). Similarly, the methyltransferases would be predicted to experience strong purifying selection in the clades with high production of methylated anthocyanins. We tested for relationships between the rates of non-synonymous to synonymous substitutions (dN/dS) across the pathway genes and major axes of pigment variation (total anthocyanins, total flavonols, fraction methylated anthocyanins, fraction tri-hydroxylated delphinidin derivatives). Across these analyses, we recovered no significant correlations (Table S6, Supplemental Figures S5-S8), suggesting changes at the coding level are not the primary drivers of pigment variation across the species.

Nevertheless, we expect that high levels of red pelargonidin pigments should be limited by the inability of *Petunia* DFR to reduce the precursor dihydrokaempferol (Forkmann and Ruhnau 1987). Therefore, we examined the DFR sequence in *Plowmania nyctaginoides*, the only species found to produce primarily pelargonidin (Fig. 1). Compared with other sequenced Petunieae species, this species has a unique Q226K substitution (relative to *Vitis vinifera* sequence positions in crystal structure 2c29) in the active site, which would be in close contact with the substrate (Figure S4). This precise substitution has also been documented in a distantly related red-flowered pelargonidin-producing Solanaceae species and it has been shown to increase DFR activity on DHK (S. D. Smith, Wang, and Rausher 2013). Interestingly, all three sequenced *P. nyctaginoides* individuals carry both the Q (CAA) and K(AAA) codons at this position, suggesting that either all are heterozygous, or that there are two nearly-indistinguishable DFR copies in this species (Fig. S4, Supplemental Text). All individuals are fixed for a substitution Y227F, which is shared by close relatives *Bouchetia* and *Hunzikeria* (as well as *Vitis vinifera*) but absent in other Petunieae species. Given its close proximity to the Q226K substitution and its presence in the active site, it is possible that Y227F interacts with Q226K to change the active site environment and may have played a role in a shift in DFR function in *P. nyctaginoides*.

The deeply pigmented phenotypes are likely derived from the pale colors

We used the phylogeny to estimate the evolutionary history of the major pigment phenotypes in Petunieae. Using the best-fitting equal rates model and the pigment states from the pPCA (Fig. 3), we infer that the ancestor of Petunieae most likely belonged to the pale-flowered, delphinidin-producing, high flavonol phenotype (p=0.7) with multiple transitions to the other phenotypes (Fig. 5A, B). This pale-flowered state has been retained in *Fabiana* and *Nierembergia*, as well as some *Brunfelsia* and is characterized by relatively low overall pathway expression, but high FLS

expression, leading to high flavonol accumulation (Fig. 5C). The intensely colored and highly methylated pink-purple phenotype is characteristic of *Petunia* and *Calibrachoa*, while the lineages that have diverged to produce less hydroxylated anthocyanins and/or lower amounts of flavonols are scattered throughout the tree, arising from ancestors of both of the other states (Fig. 5A, B). The transition to producing high amounts of the tri-hydroxylated and methylated anthocyanins requires a shift to high expression of all pathway steps and typically comes at the expense of flavonol production (Fig. 4E, 5D). The red-flowered species producing less hydroxylated anthocyanins also tend to produce low amounts of flavonols (Fig. 5E).

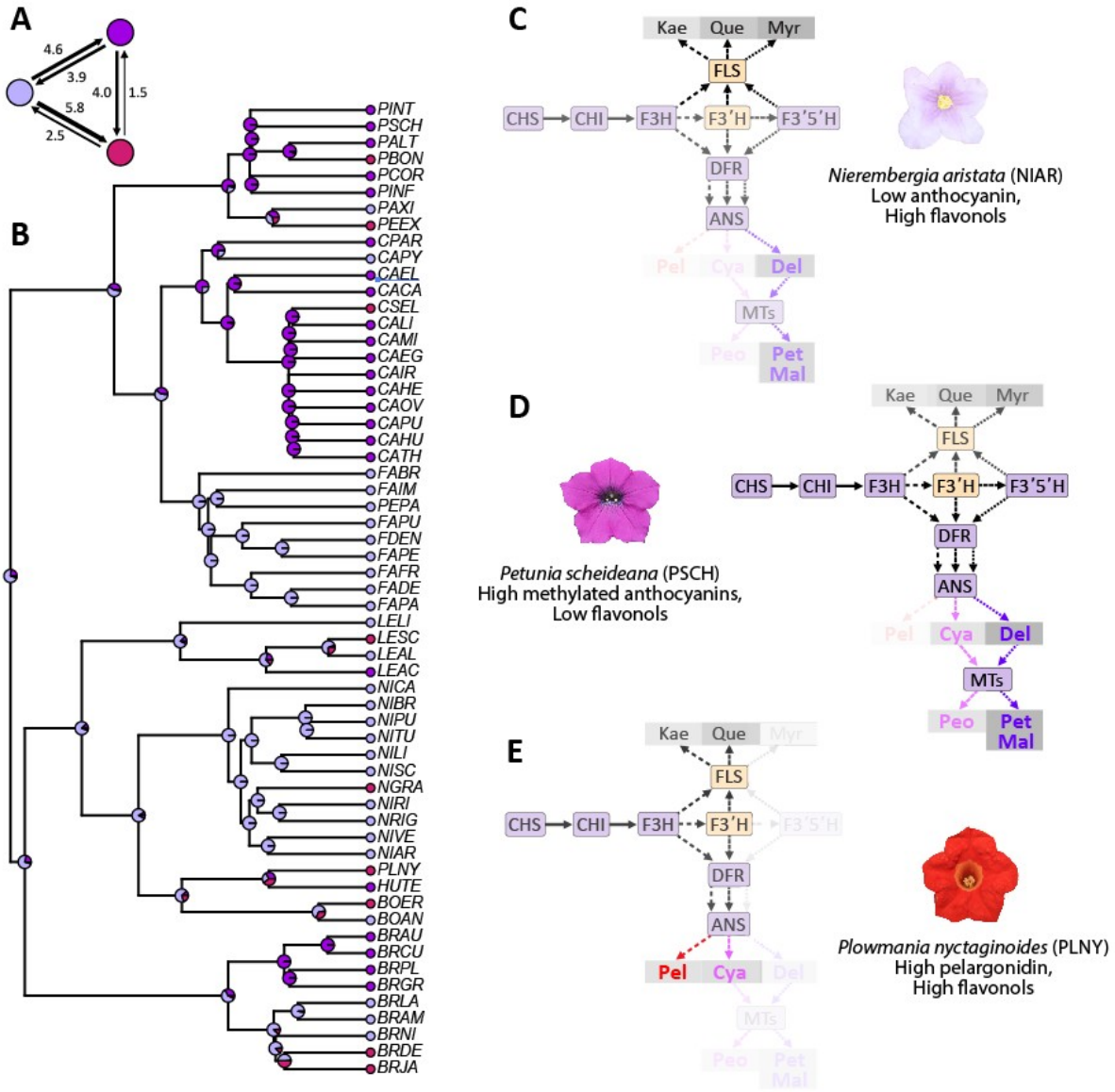

Fig. 5. Deep purple and red colors may have evolved from pale ancestors. A) Estimated numbers of transitions between each pigment phenotype from stochastic mapping. The outgroup (*Browallia americana*) was pruned from the tree to better visualize nodes inside Petunieae. B) Maximum likelihood ancestral state estimation of the three

pigmentation clusters (shown in Fig. 3B). C-E) Exemplar species from each cluster. Steps of the flavonoid pathway and pathway products (Fig. 2A) are shaded by their expression in each, with the lower expressed branches being least visible.

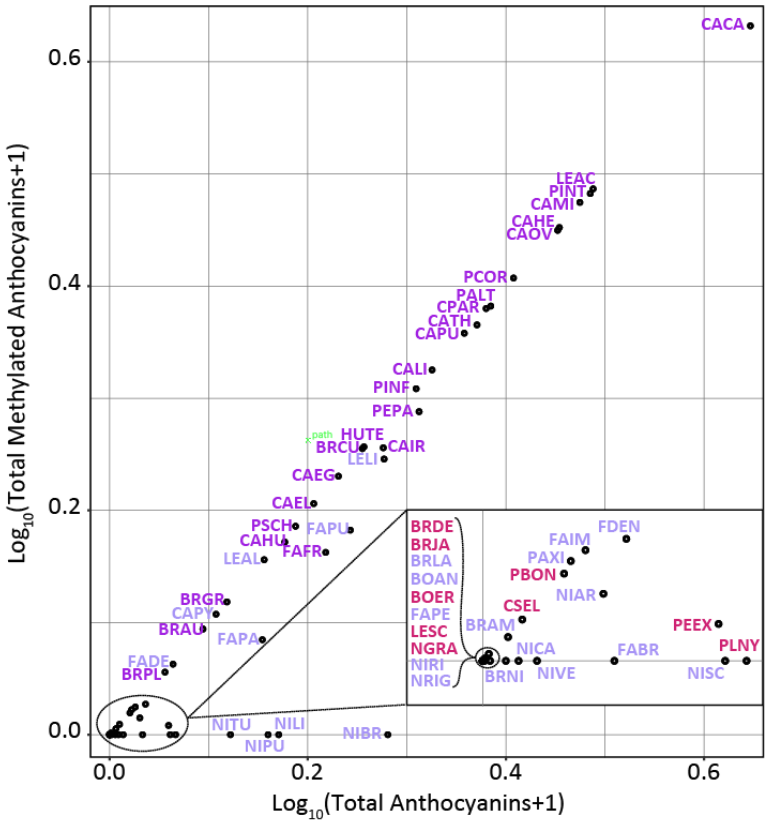

Fig. 6. Highest anthocyanin production in species making methylated anthocyanins. The concentration of methylated anthocyanins (mg/g) plotted against the concentration of all anthocyanins. Values were $\log_{10}(X+1)$ transformed for ease of visualization. Coloring of species abbreviations follows Fig. 3. Species with low anthocyanin concentrations are shown in the inset portion.

Discussion

Our study revealed that Petunieae produce all of the six classes of anthocyanidins, including three main branches (the red pelargonidin, purple cyanidin, and blue delphinidin pigments) and all three methylated derivatives (Fig. 1). Although most species present only delphinidin and its derivatives petunidin and malvidin, a few species are able to produce pigments down two or even three branches. The UV-absorbing flavonols are present in all species, but with concentrations varying over 1000-fold (Table S1, Supplemental Fig. S1). Through multivariate analyses of these biochemical profiles, we found that species are clustered in pigment space by the degree of hydroxylation and methylation of the anthocyanins and the extent of flavonol production. These

axes of variation in pigment production are tightly correlated with variation in gene expression of the corresponding branches of the pathway, supporting the notion that regulatory changes are the principal drivers of flower color evolution. Nevertheless, the relative rarity of species that have deviated from the ancestral state of making delphinidin and delphinidin-derived anthocyanins points to constraints in moving along the hue axis.

Evolutionary increases in pigment intensity coupled with higher methylation

Changes in the amount of anthocyanin production, whether associated with continuous variation in the intensity of coloration or discrete gains and losses of flower color, are common throughout angiosperms (S. D. Smith and Goldberg 2015). Our phylogenetic analysis estimates four to five transitions to the intensely pigmented purple phenotype, in the large genera *Petunia*, *Calibrachoa*, and *Brunfelsia* as well as in *Leptoglossis* and *Hunzikeria* (Fig. 5). These flowers range from hot pink, to magenta to purple, and at least for *Petunia* and *Calibrachoa* are bee-pollinated (Stehmann and Semir 2001; Ando et al. 2001). The shift to producing high amounts of delphinidin-derived anthocyanins is reversible in Petunieae, and several of these lineages have subsequently transitioned to the two other pigment composition types (Fig. 5).

One unexpected finding of this study was that these convergent transitions to intense pigmentation involve not only increasing flux down the delphinidin branch, but increasing methylation as well (Figs. 3, 6). This pattern may relate to the co-regulation of MTs with other late pathway genes (Fig. 2, (Provenzano et al. 2014). If increases in floral pigmentation often occur via trans-regulatory mutations (Sobel and Streisfeld 2013), the expression of MTs may be elevated together with F3’5’H, DFR and ANS, pulling flux toward petunidin and malvidin production. The predominance of methylated anthocyanins in highly pigmented flowers may also have effects on the color phenotype and its stability. Methylation has a reddening effect on the bluish delphinidin pigments (Tanaka, Sasaki, and Ohmiya 2008), which could contribute to the hot pink hues of many of these species. Moreover, methylation has important biochemical properties, increasing stability and water solubility (Sarni et al. 1995; Enaru et al. 2021). These factors may be particularly important as the high levels of production of anthocyanins comes at the expense of flavonols (esp. quercetin and kaempferol, Fig. 4E), which can also stabilize anthocyanins through intermolecular stacking (Trouillas et al. 2016).

Limited evolutionary transitions in anthocyanin composition likely due to ancestral preference

Shifts in floral hue (e.g. from blue to pink) are often associated with changes in the type of anthocyanin produced. Specifically, transitions from blue or purple to red commonly involve shifting from more to less hydroxylated anthocyanins (reviewed in (Wessinger and Rausher

2012). Despite the range of colors present in Petunieae (Fig. 1), we found that such changes in the level of hydroxylation are uncommon (see also (Ando et al. 1999; Ng and Smith 2018). Although 10 species make detectable amounts of pelargonidin and cyanidin (Table S1), these are generally present in trace amounts. The exceptions are *Petunia exserta*, which produces roughly half cyanidin and half delphinidin and methylated derivatives (Berardi et al. 2021), and *Plowmania nyctaginoides*, which makes 96% pelargonidin. Our phylogenetic CCA suggests that the downregulation of F3'5'H is the strongest driver of shifts away from the production of delphinidin-derived anthocyanins (Fig. 4D), a pattern observed in other empirical systems (e.g. (S. D. Smith and Rausher 2011; Hopkins and Rausher 2011; Sánchez-Cabrera et al. 2021). The fact that only two red species in Petunieae appear to have evolved red flowers via shifts to less hydroxylated anthocyanins implicates other mechanisms for diversifying color. Combining anthocyanins with carotenoid pigments to produce red color is a common strategy, both in Solanaceae (Ng and Smith 2016) and in other taxa, such as *Mimulus* (Yuan et al. 2014). Acidification of the vacuole, where anthocyanins are stored, can also shift the color to appear more red (Tanaka, Sasaki, and Ohmiya 2008). This phenomenon is known in cultivars of *Petunia* and *Calibrachoa* (Waterworth and Griesbach 2001), but not yet documented as part of an evolutionary color transition. Finally, in addition to the reddening effect of methylation mentioned above, acylation of anthocyanins has a blueing effect, so reduction in acylation can also contribute to red colors (Ando et al. 1999; Berardi et al. 2021). The most deeply red *Calibrachoa*, *C. sendtneriana*, is extremely rare (Stehmann et al. 1997), and although we were not able to obtain replicates to include the present study, previous work demonstrates that is only produces delphinidin-derivatives (Ng and Smith 2018), making it another Petunieae species to produce red flowers with blue pigments. Other Petunieae with unique shades, such as the bright salmon-colored *Petunia reitzii* and the burgundy *Leptoglossis acutifolia* also comprise candidates for using a combination of biochemical mechanisms to produce diverse colors.

The rarity of shifts from producing delphinidin-derived anthocyanins to those derived from pelargonidin also points to strong underlying constraints in moving along the hydroxylation axis. The most likely source of such constraints is substrate specificity of multi-functional pathway enzymes (e.g. DFR, ANS, Fig. 2A). The inefficiency of *Petunia hybrida* DFR in acting on pelargonidin precursors has been well documented as part of efforts to breed red horticultural varieties (e.g. (Gerats et al. 1982; Elomaa et al. 1995; Johnson et al. 1999). The prevalence of delphinidin-derived anthocyanins across the Petunieae suggests that the preference for the precursors of delphinidin is not peculiar to *P. hybrida* but likely represents the ancestral state for the clade, and perhaps for the entire Solanaceae (S. D. Smith, Wang, and Rausher 2013). In this context, it is notable that the only species of Petunieae to make predominantly pelargonidin, *Plowmania nyctaginoides*, carries the precise single amino-acid mutation found in another red-flowered lineage of Solanaceae which is known to more than double activity on the pelargonidin precursor, dihydrokaempferol (Fig. S4,(S. D. Smith, Wang, and Rausher 2013)). These patterns suggest that transitioning to pelargonidin production is accessible only through changes in the ancestral enzyme function.

Conclusions

Comparative evodevo studies have the potential to reveal commonly traversed evolutionary pathways and the mechanisms underlying those phenotypic shifts. Our study demonstrates that *Petunia* and its close relatives have repeatedly calibrated the production of blue delphinidin-derived pigments and UV-absorbing flavonols by altering levels of gene expression in the anthocyanin pathway. We posit that these axes comprise evolutionary paths of least resistance, whereby adjusting gene expression allows for a wide range of visible and UV-visible pigmentation levels. However, expression changes are probably insufficient to overcome ancestral patterns of substrate specificity in multi-functional enzymes to allow transitions along the hydroxylation axis. Thus, moving beyond the range of colors accessible by changing anthocyanin and flavonol levels alone likely requires novel mutations to enzyme activity and/or the recruitment of additional biochemical tricks, such as vacuolar acidification, to reach new color phenotypes.

Methods

Transcriptome assembly

We generated RNA-seq data for tissue from developing floral buds equivalent to *Petunia* bud stage 5 (Pollak et al. 1993), with three replicates per species. The first replicate was the data used in (Lucas C Wheeler et al. 2022), while the second and third replicates were generated using RNA extracted from the buds of additional individuals collected with the same voucher (time and location) as the first replicate. We generated RNA-seq libraries using the Illumina TruSeq kit with IDT-for-Illumina indexes and sequenced them on an Illumina NovaSeq 6000 instrument at the Weill Cornell Genomics Core Facility. For each species we combined the paired-end reads from all three replicates to increase depth of coverage. To assemble *de novo* transcriptomes for the 59 Petunieae species and the *Browallia americana* outgroup used in this study, we followed the pipeline from (Lucas C Wheeler et al. 2022). Briefly, the pipeline carries out the following steps: 1) trim the reads using IDT-for-Illumina adapter sequences, 2) perform *de novo* transcriptome assembly using Trinity, 3) detect and remove chimeric sequences using the run_chimera_detection.py script from (Yang and Smith 2014), 4) run Corset to cluster and collapse transcripts, and 5) predict CDS using TransDecoder.

Quantification of gene expression

We retrieved flavonoid pathway genes and their transcription factor regulators from transcriptomic CDS following the pipeline from (Lucas C Wheeler et al. 2022). Briefly, we used BLASTN to identify sequences matching queries (e-value cutoff = 1e-50) for the structural genes: CHS-A, CHI-A, CHI-B, F3H, FLS, F3’H, F3’5’H, DFR, ANS, MF1, MF2, and MT; the transcription factors AN2, DPL, PHZ, AN11, AN1, JAF13, MYBFL, MYB27, AN4, ASR1, ASR2, ASR3; and the housekeeping genes actin, tubulin, Rps18, Gapdh, Hprt. For downstream analyses relating gene expression to pigment production, we included only the relevant pathway-related genes and transcription factors. In contrast to the approach taken in (Lucas C Wheeler et al. 2022), we did not reduce the BLAST hits to a single best match for each gene. Instead we combined paralogous transcripts (e.g. CHS-A, CHS-J) into a single collective fasta reference file. Because the subgroup 6 MYB activators (AN2, AN4, DPL, PHZ, ASR1, ASR2, ASR3) are closely related and individual gene presence in the transcriptomes varies considerably, we also combined this set of sequences into a single group SG6-Mybs (see Supplemental Text). To

confirm the accuracy of our gene extraction pipeline we performed a reverse BLASTN search of all the resulting sequences against the annotated CDS from the *Petunia inflata* genome v1.0.1. To quantify gene expression we pseudo-mapped the reads from each individual replicate separately to the combined *de novo* transcriptome assembly of the corresponding species using Salmon v1.5.2. To extract expression levels for the flavonoid pathway genes, we used the transcript IDs from the combined fasta reference files to parse the Salmon quant.sf files and then calculated a sum of expression levels for each gene by adding together the TPM values for all corresponding transcripts (e.g. CHI-A and CHI-B). We then normalized the resulting summed TPM values to TPM10K using the approach of (Munro et al. 2022).

Quantification of anthocyanin content

We used the same high-performance liquid chromatography (HPLC) approach to quantify the mass fraction of flavonoids as in our previous Petunieae work ((Lucas C Wheeler et al. 2022), following (Berardi et al. 2021). With the exception of a few samples that were re-run for improved data quality, the anthocyanin mass fraction data is the same as that used to calculate average total pigment concentration for the species in (Lucas C Wheeler et al. 2022). However, we subsequently collected data for the flavonols (kaempferol, quercetin, and myricetin) in corolla tissue of all replicate individuals using a similar approach. To ensure exact matching between anthocyanin and flavonol samples we conducted the flavonol measurements on the flavonol-containing layer remaining from the extraction protocol used to measure anthocyanin content. We sampled flowers from three individuals per species and used these to calculate the mean anthocyanin mass fraction (mg compound per g tissue) over replicates. For each individual, we collected fresh floral corolla tissue, dried the tissue with silica gel and stored the material in 2mL tubes at -80°C. For extraction of total flavonoids, we soaked 0.0005 to 0.1g of dried tissue overnight in 1mL 2N HCL. We carried out acid hydrolysis of flavonoid glycosides and analyzed the samples using high-performance liquid chromatography (HPLC) as in Wheeler et al. (2022). Briefly, we heated samples 100-104°C for 1 hr to convert the glycosylated flavonoids into their corresponding aglycones and then performed a series of liquid phase extractions in ethyl acetate and isoamyl alcohol, before evaporating away excess solvent using an N-EVAP apparatus and eluting in 50 µL of 1% HCl in MeOH . We injected 10 µL of sample on the Agilent HPLC and separated flavonols by gradient elution on a 100-4.6 mm Chromalith Performance column at 30°C using solvents A (HPLC-grade water, 0.1% trifluoroacetic acid) and C (Methanol, 0.5% HCl). We analyzed all results using Agilent Chemstation software and peaks were compared to standards obtained from Extrasynthese (365nm for flavonols and 520nm for anthocyanidins). Resulting peak tables were individually cross-checked against chromatograms and manually corrected for slight peak shifts as needed.

Reconstruction of species phylogeny

We previously followed the approach of (Walker et al. 2018) to reconstruct the species tree for the Petunieae clade using 3,672 ortholog clusters identified from the original *de novo* transcriptome assemblies as in Wheeler et al. (2022). However, for the current study, we added an additional species; *Fabiana australis* (4-letter code = PEPA), which has recently been renamed from *Petunia patagonica* (Alaria et al. 2022). To add *F. australis* into the analysis we started with the ortholog clusters from the previous publication (downloadable from https://osf.io/b7gcp/). We identified the best-matched sequence in the new *F. australis* transcriptome using BLASTN (e-value cutoff = 1e-50), added these sequences into the clusters,

re-ran the cluster alignments using MAFFT, and then re-ran the species-tree analysis in Astral 5.7.8 using the updated clusters. We followed the TreePL smoothing approach used in (Lucas C Wheeler et al. 2022) to ultrametricize the tree, using a subset of 11 genes present in all 60 species.

Phylogenetic principal components analysis

To more closely approximate normally-distributed data, we transformed the pigment mass fraction (mg/g) values by applying a $\ln\left(\left(\left[mg/g\ pigment\right] * 100\right)+1\right)$ transformation and the gene expression (TPM10K) values by applying a $(\ln\left(TPM\ 10\,K+1\right)$ transformation. We used the *phyl*. *pca* function from the *phytools* package and the *prcomp* function from the *stats* package in R v3.6.3 to perform a phylogenetic principal components analysis (pPCA) while scaling and centering the transformed data. To obtain the underlying correlation matrix between transformed TPM10K gene expression levels from the PCA output we extracted the covariance matrix *(*the *V* attribute*)* and used the $cov\,2\,cor$ function to convert it to a matrix of correlation coefficients. To convert this matrix into the network shown in fig. 2 we selected all positive correlation coefficients larger than the median value (0.124) and used *networkx* in Python v3.8.5 to convert the matrix to a graph edge list. We generated the network figure, with edges colored according to weights (correlation coefficients) using Cytoscape v3.9.1. To generate the pigment level clusters shown in fig. 3, we performed K-means clustering on the first three principal components from the pigment pPCA using the *kmeans* function in R with three clusters, based on visual inspection of the projected data.

Phylogenetic canonical correlation analysis

To assess the relationships between expression of flavonoid pathway-related genes and flavonoid pigment levels, we performed phylogenetic canonical correlation analysis (pCCA) on the transformed data using the $phyl.cca$ function in the R *phytools* package (Revell 2012). We treated the gene expression levels as the "x" variable and pigment mass fraction as "y". We used the p-values calculated by $phyl.cca$ to determine the statistical significance of the canonical variates (CVs). We extracted the canonical coefficients from the significant CVs, which quantify the coupled associations of the original pigment mass fraction and gene expression variables with the corresponding multivariate CVs, and standardized them. We re-calculated the significant CVs, arrayed by species ID, as the linear combination of the original variables scaled by un-standardized coefficients. We then used the $cor.test$ function in R to calculate each canonical loading (correlation coefficients of original variables with their corresponding CV) and cross-loading (correlation coefficients of original variables with the CV for the other data block; e.g. pigment levels with gene expression CV1) with corresponding p-values.

Stochastic mapping and ancestral state estimation

We used the stochastic mapping tools in phytools to estimate the number of transitions between each pigment phenotype using 200 simulations of character history. We also used the ace function in phytools to estimate ancestral states across the tree. For both analyses, we used an equal rates model, as the all-rates-different model did not provide a significantly better fit to the data.

Molecular evolution

We extracted a single best-matched sequence for each gene from each species using the approach of (Lucas C Wheeler et al. 2022) and used HyPhy to fit a free-rates dN/dS model that allows a separate dN/dS ratio for each tip. We then extracted dN/dS trees from the HyPhy output and calculated a root-to-tip dN/dS ratio for each tip. We assessed the relationships between these values and the principal axes of flavonoid variation using linear regression (for details see Supplemental Text).

Acknowledgments

This work utilized the RMACC Summit and Alpine supercomputer. Summit is a joint effort of the University of Colorado Boulder and Colorado State University, supported by the National Science Foundation (awards ACI-1532235 and ACI-1532236), the University of Colorado Boulder, and Colorado State University. Alpine is jointly funded by the University of Colorado Boulder, the University of Colorado Anschutz, Colorado State University, and the National Science Foundation (award 2201538).

Funding

This work was funded by NSF-DEB 1553114 to SDS. The funders had no role in study design, data collection, analysis, decision to publish, or manuscript preparation.

Availability of data and materials

The transcriptome assemblies, scripts, and processed data files used to conduct the analyses are available in the supplementary OSF repo (https://osf.io/zg9cu/). The raw RNA-seq data files have been added to the existing SRA BioProject PRJNA746328.

Author contributions

SDS and LCW conceived the study and outlined the experimental design. LCW and SDS developed the analyses. ADW and LCW performed HPLC. LCW reconstructed the species phylogeny based on previous work. LCW built the sequencing libraries and assembled the *de novo* transcriptomes. LCW and SDS conducted the statistical analyses of the data and drafted the manuscript with revisions from ADW. KS undertook careful curation of the HPLC raw data.

Competing interests

The authors declare that they have no competing interests.

References Cited

Alaria, Alejandrina, John H. Chau, Richard G. Olmstead, and Iris E. Peralta. 2022. "Relationships among Calibrachoa, Fabiana and Petunia (Petunieae Tribe, Solanaceae) and a New Generic Placement of Argentinean Endemic Petunia Patagonica." *PhytoKeys* 194 (April): 75–93. https://doi.org/10.3897/phytokeys.194.68404.

Albert, Nick W., Kevin M. Davies, David H. Lewis, Huaibi Zhang, Mirco Montefiori, Cyril Brendolise, Murray R. Boase, Hanh Ngo, Paula E. Jameson, and Kathy E. Schwinn. 2014. "A Conserved Network of Transcriptional Activators and Repressors Regulates Anthocyanin Pigmentation in Eudicots." *The Plant Cell*, March, tpc.113.122069. https://doi.org/10.1105/tpc.113.122069.

Ando, Toshio, Masashi Nomura, Jun Tsukahara, Hitoshi Watanabe, Hisashi Kokubun, Tatsuya Tsukamoto, Goro Hashimoto, Eduardo Marchesi, and Ian J. Kitching. 2001. "Reproductive Isolation in a Native Population of Petunia Sensu Jussieu (Solanaceae)." *Annals of Botany* 88 (3): 403–13. https://doi.org/10.1006/anbo.2001.1485.

Ando, Toshio, Norio Saito, Fumi Tatsuzawa, Tomoko Kakefuda, Keiko Yamakage, Etsuko Ohtani, Maya Koshi-ishi, et al. 1999. "Floral Anthocyanins in Wild Taxa of Petunia (Solanaceae)." *Biochemical Systematics and Ecology* 27 (6): 623–50. https://doi.org/10.1016/S0305-1978(98)00080-5.

Beldade, PatrÍcia, Kees Koops, and Paul M. Brakefield. 2002. "Developmental Constraints versus Flexibility in Morphological Evolution." *Nature* 416 (6883): 844–47. https://doi.org/10.1038/416844a.

Berardi, Andrea E, Korinna Esfeld, Lea Jäggi, Therese Mandel, Gina M Cannarozzi, and Cris Kuhlemeier. 2021. "Complex Evolution of Novel Red Floral Color in Petunia." *The Plant Cell*, no. koab114 (April). https://doi.org/10.1093/plcell/koab114.

Braendle, Christian, Charles F. Baer, and Marie-Anne Félix. 2010. "Bias and Evolution of the Mutationally Accessible Phenotypic Space in a Developmental System." *PLOS Genetics* 6 (3): e1000877. https://doi.org/10.1371/journal.pgen.1000877.

Des Marais, David L., and Mark D. Rausher. 2010. "PARALLEL EVOLUTION AT MULTIPLE LEVELS IN THE ORIGIN OF HUMMINGBIRD POLLINATED FLOWERS IN *IPOMOEA*." *Evolution*, March. https://doi.org/10.1111/j.1558-5646.2010.00972.x.

Elomaa, Paula, Yrjö Helariutta, Mika Kotilainen, Teemu H. Teeri, Robert J. Griesbach, and Pauli Seppänen. 1995. "Transgene Inactivation InPetunia Hybrida Is Influenced by the Properties of the Foreign Gene." *Molecular and General Genetics MGG* 248 (6): 649–56. https://doi.org/10.1007/BF02191704.

Enaru, Bianca, Georgiana Drețcanu, Teodora Daria Pop, Andreea Stănilă, and Zorița Diaconeasa. 2021. "Anthocyanins: Factors Affecting Their Stability and Degradation." *Antioxidants* 10 (12): 1967. https://doi.org/10.3390/antiox10121967.

Forkmann, G., and B. Ruhnau. 1987. "Distinct Substrate Specificity of Dihydroflavonol 4-Reductase from Flowers of Petunia Hybrida." *Zeitschrift Für Naturforschung C* 42 (9–10): 1146–48. https://doi.org/10.1515/znc-1987-9-1026.

Gates, Daniel J., Bradley J. S. C. Olson, Tom E. Clemente, and Stacey D. Smith. 2018. "A Novel

R3 MYB Transcriptional Repressor Associated with the Loss of Floral Pigmentation in Iochroma." *New Phytologist* 217 (3): 1346–56. https://doi.org/10.1111/nph.14830.

Gerats, A. G. M., P. de Vlaming, M. Doodeman, B. Al, and A. W. Schram. 1982. "Genetic Control of the Conversion of Dihydroflavonols into Flavonols and Anthocyanins in Flowers of Petunia Hybrida." *Planta* 155 (4): 364–68. https://doi.org/10.1007/BF00429466.

Grotewold, Erich. 2006. "The Genetics and Biochemistry of Floral Pigments." *Annual Review of Plant Biology* 57: 761–80. https://doi.org/10.1146/annurev.arplant.57.032905.105248.

Holton, Timothy A., Filippa Brugliera, and Yoshikazu Tanaka. 1993. "Cloning and Expression of Flavonol Synthase from Petunia Hybrida." *The Plant Journal* 4 (6): 1003–10. https://doi.org/10.1046/j.1365-313X.1993.04061003.x.

Hopkins, Robin, and Mark D. Rausher. 2011. "Identification of Two Genes Causing Reinforcement in the Texas Wildflower *Phlox* Drummondii." *Nature* 469 (7330): 411. https://doi.org/10.1038/nature09641.

Ishiguro, Kanako, Masumi Taniguchi, and Yoshikazu Tanaka. 2012. "Functional Analysis of Antirrhinum Kelloggii Flavonoid 3′-Hydroxylase and Flavonoid 3′,5′-Hydroxylase Genes; Critical Role in Flower Color and Evolution in the Genus Antirrhinum." *Journal of Plant Research* 125 (3): 451–56. https://doi.org/10.1007/s10265-011-0455-5.

Jablonski, David. 2020. "Developmental Bias, Macroevolution, and the Fossil Record." *Evolution & Development* 22 (1–2): 103–25. https://doi.org/10.1111/ede.12313.

Johnson, Eric T., Hankuil Yi, Byongchul Shin, Boung-Jun Oh, Hyeonsook Cheong, and Giltsu Choi. 1999. "Cymbidium Hybrida Dihydroflavonol 4-Reductase Does Not Efficiently Reduce Dihydrokaempferol to Produce Orange Pelargonidin-Type Anthocyanins." *The Plant Journal* 19 (1): 81–85. https://doi.org/10.1046/j.1365-313X.1999.00502.x.

Koes, Ronald, Walter Verweij, and Francesca Quattrocchio. 2005. "Flavonoids: A Colorful Model for the Regulation and Evolution of Biochemical Pathways." *Trends in Plant Science*, Special Issue: Plant model systems, 10 (5): 236–42. https://doi.org/10.1016/j.tplants.2005.03.002.

Kozmik, Zbynek, Jana Ruzickova, Kristyna Jonasova, Yoshifumi Matsumoto, Pavel Vopalensky, Iryna Kozmikova, Hynek Strnad, et al. 2008. "Assembly of the Cnidarian Camera-Type Eye from Vertebrate-like Components." *Proceedings of the National Academy of Sciences* 105 (26): 8989–93. https://doi.org/10.1073/pnas.0800388105.

Mahler, D. Luke, Travis Ingram, Liam J. Revell, and Jonathan B. Losos. 2013. "Exceptional Convergence on the Macroevolutionary Landscape in Island Lizard Radiations." *Science* 341 (6143): 292–95. https://doi.org/10.1126/science.1232392.

Mol, Joseph, Erich Grotewold, and Ronald Koes. 1998. "How Genes Paint Flowers and Seeds." *Trends in Plant Science* 3 (6): 212–17. https://doi.org/10.1016/S1360-1385(98)01242-4.

Munro, Catriona, Felipe Zapata, Mark Howison, Stefan Siebert, and Casey W Dunn. 2022. "Evolution of Gene Expression across Species and Specialized Zooids in Siphonophora." *Molecular Biology and Evolution* 39 (2): msac027.

https://doi.org/10.1093/molbev/msac027.
Ng, Julienne, and Stacey D. Smith. 2016. “How to Make a Red Flower: The Combinatorial Effect of Pigments.” *AoB PLANTS* 8 (January). https://doi.org/10.1093/aobpla/plw013.
———. 2018. “Why Are Red Flowers so Rare? Testing the Macroevolutionary Causes of Tippiness.” *Journal of Evolutionary Biology* 31 (12): 1863–75. https://doi.org/10.1111/jeb.13381.
Pollak, P. E., T. Vogt, Y. Mo, and L. P. Taylor. 1993. “Chalcone Synthase and Flavonol Accumulation in Stigmas and Anthers of Petunia Hybrida.” *Plant Physiology* 102 (3): 925–32. https://doi.org/10.1104/pp.102.3.925.
Provenzano, Sofia, Cornelis Spelt, Satoko Hosokawa, Noriko Nakamura, Filippa Brugliera, Linda Demelis, Daan P. Geerke, et al. 2014. “Genetic Control and Evolution of Anthocyanin Methylation.” *Plant Physiology* 165 (3): 962–77. https://doi.org/10.1104/pp.113.234526.
Quattrocchio, F, J Wing, K van der Woude, E Souer, N de Vetten, J Mol, and R Koes. 1999. “Molecular Analysis of the Anthocyanin2 Gene of Petunia and Its Role in the Evolution of Flower Color.” *The Plant Cell* 11 (8): 1433–44.
Revell, Liam J. 2012. “Phytools: An R Package for Phylogenetic Comparative Biology (and Other Things).” *Methods in Ecology and Evolution* 3 (2): 217–23. https://doi.org/10.1111/j.2041-210X.2011.00169.x.
Sánchez-Cabrera, Mercedes, Francisco Javier Jiménez-López, Eduardo Narbona, Montserrat Arista, Pedro L. Ortiz, Francisco J. Romero-Campero, Karolis Ramanauskas, Boris Igić, Amelia A. Fuller, and Justen B. Whittall. 2021. “Changes at a Critical Branchpoint in the Anthocyanin Biosynthetic Pathway Underlie the Blue to Orange Flower Color Transition in Lysimachia Arvensis.” *Frontiers in Plant Science* 12. https://www.frontiersin.org/articles/10.3389/fpls.2021.633979.
Sarni, Pascale, Hélène Fulcrand, Véronique Souillol, Jean-Marc Souquet, and Véronique Cheynier. 1995. “Mechanisms of Anthocyanin Degradation in Grape Must-like Model Solutions.” *Journal of the Science of Food and Agriculture* 69 (3): 385–91. https://doi.org/10.1002/jsfa.2740690317.
Sheehan, Hester, Michel Moser, Ulrich Klahre, Korinna Esfeld, Alexandre Dell’Olivo, Therese Mandel, Sabine Metzger, Michiel Vandenbussche, Loreta Freitas, and Cris Kuhlemeier. 2016. “MYB-FL Controls Gain and Loss of Floral UV Absorbance, a Key Trait Affecting Pollinator Preference and Reproductive Isolation.” *Nature Genetics* 48 (2): 159–66. https://doi.org/10.1038/ng.3462.
Smith, J. Maynard, R. Burian, S. Kauffman, P. Alberch, J. Campbell, B. Goodwin, R. Lande, D. Raup, and L. Wolpert. 1985. “Developmental Constraints and Evolution: A Perspective from the Mountain Lake Conference on Development and Evolution.” *The Quarterly Review of Biology* 60 (3): 265–87. https://doi.org/10.1086/414425.
Smith, Stacey D., and Emma E. Goldberg. 2015. “Tempo and Mode of Flower Color Evolution.” *American Journal of Botany* 102 (7): 1014–25. https://doi.org/10.3732/ajb.1500163.
Smith, Stacey D., and Mark D. Rausher. 2011. “Gene Loss and Parallel Evolution Contribute to Species Difference in Flower Color.” *Molecular Biology and Evolution* 28 (10): 2799–2810. https://doi.org/10.1093/molbev/msr109.
Smith, Stacey D., Shunqi Wang, and Mark D. Rausher. 2013. “Functional Evolution of an

Anthocyanin Pathway Enzyme during a Flower Color Transition." *Molecular Biology and Evolution* 30 (3): 602–12. https://doi.org/10.1093/molbev/mss255.
Sobel, James M., and Matthew A. Streisfeld. 2013. "Flower Color as a Model System for Studies of Plant Evo-Devo." *Frontiers in Plant Science* 4: 321. https://doi.org/10.3389/fpls.2013.00321.
Spelt, Cornelis, Francesca Quattrocchio, Joseph N. M. Mol, and Ronald Koes. 2000. "Anthocyanin1 of Petunia Encodes a Basic Helix-Loop-Helix Protein That Directly Activates Transcription of Structural Anthocyanin Genes." *The Plant Cell* 12 (9): 1619–31. https://doi.org/10.1105/tpc.12.9.1619.
Stehmann, João Renato, and João Semir. 2001. "Biologia reprodutiva de Calibrachoa elegans (Miers) Stehmann & Semir (Solanaceae)." *Brazilian Journal of Botany* 24 (March): 43–49. https://doi.org/10.1590/S0100-84042001000100005.
Stehmann, João Renato, João Semir, Joao Renato Stehmann, and Joao Semir. 1997. "A New Species and New Combinations in Calibrachoa (Solanaceae)." *Novon* 7 (4): 417. https://doi.org/10.2307/3391775.
Tanaka, Yoshikazu, Nobuhiro Sasaki, and Akemi Ohmiya. 2008. "Biosynthesis of Plant Pigments: Anthocyanins, Betalains and Carotenoids." *The Plant Journal* 54 (4): 733–49. https://doi.org/10.1111/j.1365-313X.2008.03447.x.
Trouillas, Patrick, Juan C. Sancho-García, Victor De Freitas, Johannes Gierschner, Michal Otyepka, and Olivier Dangles. 2016. "Stabilizing and Modulating Color by Copigmentation: Insights from Theory and Experiment." *Chemical Reviews* 116 (9): 4937–82. https://doi.org/10.1021/acs.chemrev.5b00507.
Uller, Tobias, Armin P Moczek, Richard A Watson, Paul M Brakefield, and Kevin N Laland. 2018. "Developmental Bias and Evolution: A Regulatory Network Perspective." *Genetics* 209 (4): 949–66. https://doi.org/10.1534/genetics.118.300995.
Wagner, Andreas. 2011. *The Origins of Evolutionary Innovations: A Theory of Transformative Change in Living Systems*. OUP Oxford.
Walker, Joseph F., Ya Yang, Tao Feng, Alfonso Timoneda, Jessica Mikenas, Vera Hutchison, Caroline Edwards, et al. 2018. "From Cacti to Carnivores: Improved Phylotranscriptomic Sampling and Hierarchical Homology Inference Provide Further Insight into the Evolution of Caryophyllales." *American Journal of Botany* 105 (3): 446–62. https://doi.org/10.1002/ajb2.1069.
Watanabe, Junya. 2018. "Clade-Specific Evolutionary Diversification along Ontogenetic Major Axes in Avian Limb Skeleton." *Evolution* 72 (12): 2632–52. https://doi.org/10.1111/evo.13627.
Waterworth, Rebeccah A., and Robert J. Griesbach. 2001. "The Biochemical Basis for Flower Color in Calibrachoa." *HortScience* 36 (1): 131–32. https://doi.org/10.21273/HORTSCI.36.1.131.
Wessinger, Carolyn A., and Mark D. Rausher. 2012. "Lessons from Flower Colour Evolution on Targets of Selection." *Journal of Experimental Botany* 63 (16): 5741–49. https://doi.org/10.1093/jxb/ers267.
———. 2015. "Ecological Transition Predictably Associated with Gene Degeneration." *Molecular Biology and Evolution* 32 (2): 347–54. https://doi.org/10.1093/molbev/msu298.
Wheeler, L C, and S D Smith. 2019. "Computational Modeling of Anthocyanin Pathway Evolution: Biases, Hotspots, and Trade-Offs." *Integrative and Comparative Biology*,

May, icz049. https://doi.org/10.1093/icb/icz049.
Wheeler, Lucas C, Joseph F Walker, Julienne Ng, Rocío Deanna, Amy Dunbar-Wallis, Alice Backes, Pedro H Pezzi, et al. 2022. “Transcription Factors Evolve Faster Than Their Structural Gene Targets in the Flavonoid Pigment Pathway.” *Molecular Biology and Evolution* 39 (3): msac044. https://doi.org/10.1093/molbev/msac044.
Whibley, Annabel C., Nicolas B. Langlade, Christophe Andalo, Andrew I. Hanna, Andrew Bangham, Christophe Thébaud, and Enrico Coen. 2006. “Evolutionary Paths Underlying Flower Color Variation in Antirrhinum.” *Science* 313 (5789): 963–66. https://doi.org/10.1126/science.1129161.
Xavier-Neto, J., R. A. Castro, A. C. Sampaio, A. P. Azambuja, H. A. Castillo, R. M. Cravo, and M. S. Simões-Costa. 2007. “Cardiovascular Development: Towards Biomedical Applicability.” *Cellular and Molecular Life Sciences* 64 (6): 719. https://doi.org/10.1007/s00018-007-6524-1.
Yang, Ya, and Stephen A. Smith. 2014. “Orthology Inference in Nonmodel Organisms Using Transcriptomes and Low-Coverage Genomes: Improving Accuracy and Matrix Occupancy for Phylogenomics.” *Molecular Biology and Evolution* 31 (11): 3081–92. https://doi.org/10.1093/molbev/msu245.
Yuan, Yao-Wu, Janelle M. Sagawa, Laura Frost, James P. Vela, and Harvey D. Bradshaw Jr. 2014. “Transcriptional Control of Floral Anthocyanin Pigmentation in Monkeyflowers (Mimulus).” *New Phytologist* 204 (4): 1013–27. https://doi.org/10.1111/nph.12968.
Yuan, Yao-Wu, Janelle M Sagawa, Riane C Young, Brian J Christensen, and Harvey D Bradshaw Jr. 2013. “Genetic Dissection of a Major Anthocyanin QTL Contributing to Pollinator-Mediated Reproductive Isolation Between Sister Species of Mimulus.” *Genetics* 194 (1): 255–63. https://doi.org/10.1534/genetics.112.146852.
543