Introduction to Plant Epigenetics

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HIGHLIGHTED ARTICLE
GENETICS | PERSPECTIVES

What Do You Mean, “Epigenetic”?

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Genetics (2015), Vol. 199, 887–896

„Epigenetics“ is not a precisely defined term – it has evolved with time and it has been used to describe very different concepts

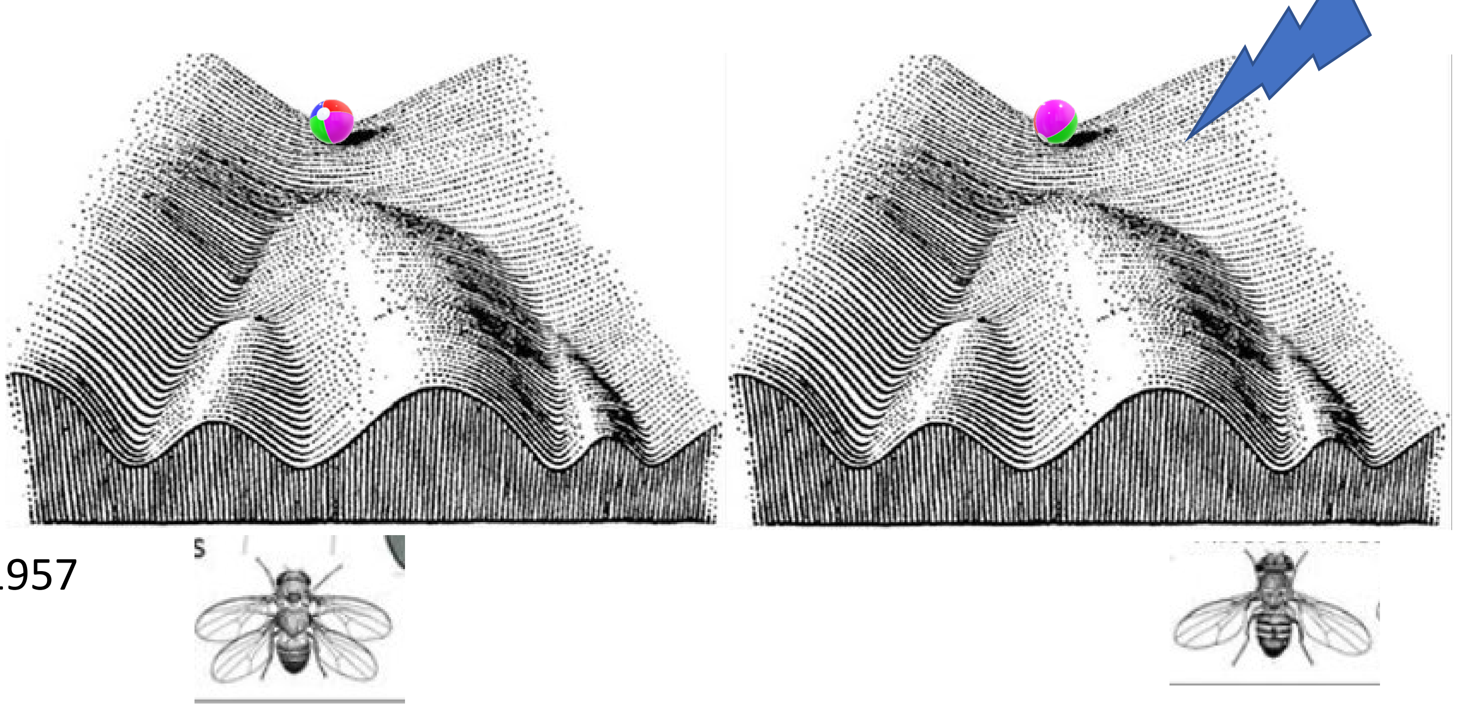
Some researchers attribute „epigenetics“ to genetic observations, others more to mechanisms

Waddingtons definition of epigenetics

Canalization of developmental processes

Conrad Hal Waddington
(1905 -1975)

Perturbation



Waddington, 1957

normal

altered

1.) Developmental processes are canalized
2.) Developmental processes are sometimes more sensitive to perturbations
3.) Developmental processes are directional

The term “epigenetic” was coined in 1940, when C. H. Waddington fused “Genetic” und“Epigenesis”.

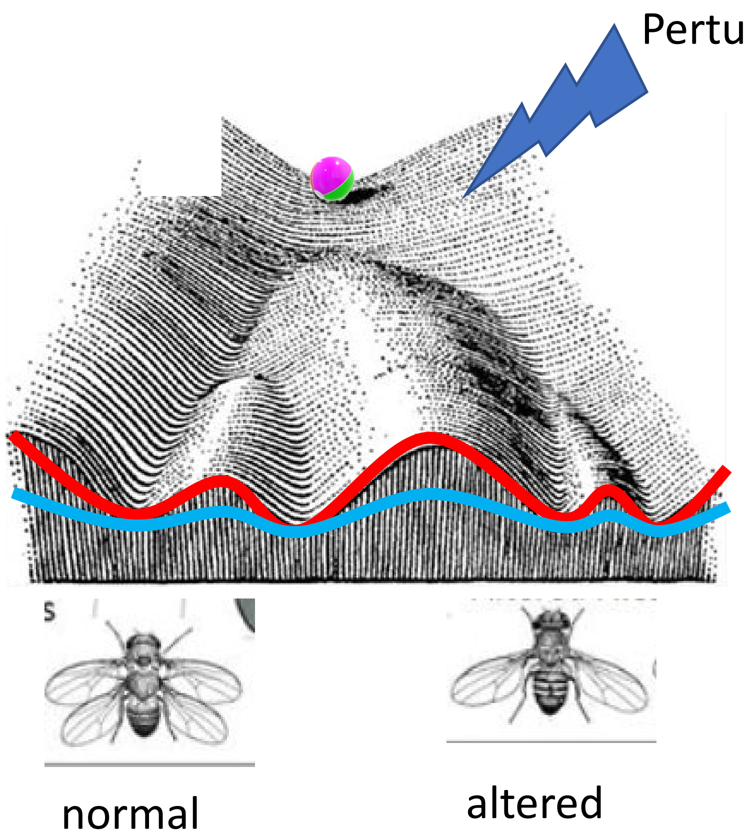
Waddingtons Definition of Epigenetics

’’…the branch of biology which studies the causal interactions between genes and their products which bring the phenotype into being.”

=> which is basically „regulation of gene expression“

=> Note absence of terms “heritable”, “memory”,...

Epigenetics and genetic assimilation



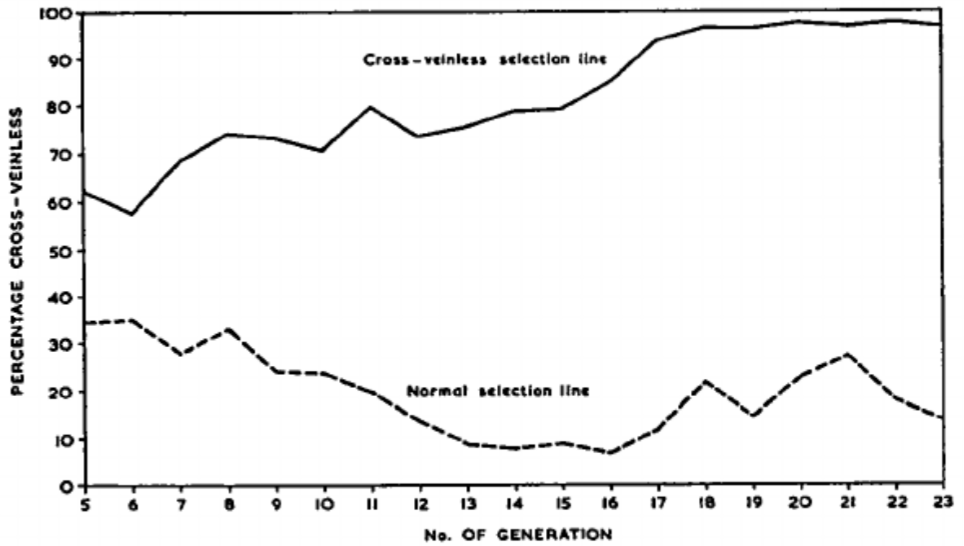


FIG. 2. The response to selection, from generation 5 onwards, for crossveinless wings ("upward" selection) and normal wings ("downward" selection).

Waddington, C. H. (1956). The genetic assimilation of the bithorax phenotype. *Evolution* 10, 1-13
. https://doi.org/10.2307/2406091

Summary on genetic assimilation

⇒ Developmental processes are canalized through the converging action of many gene networks

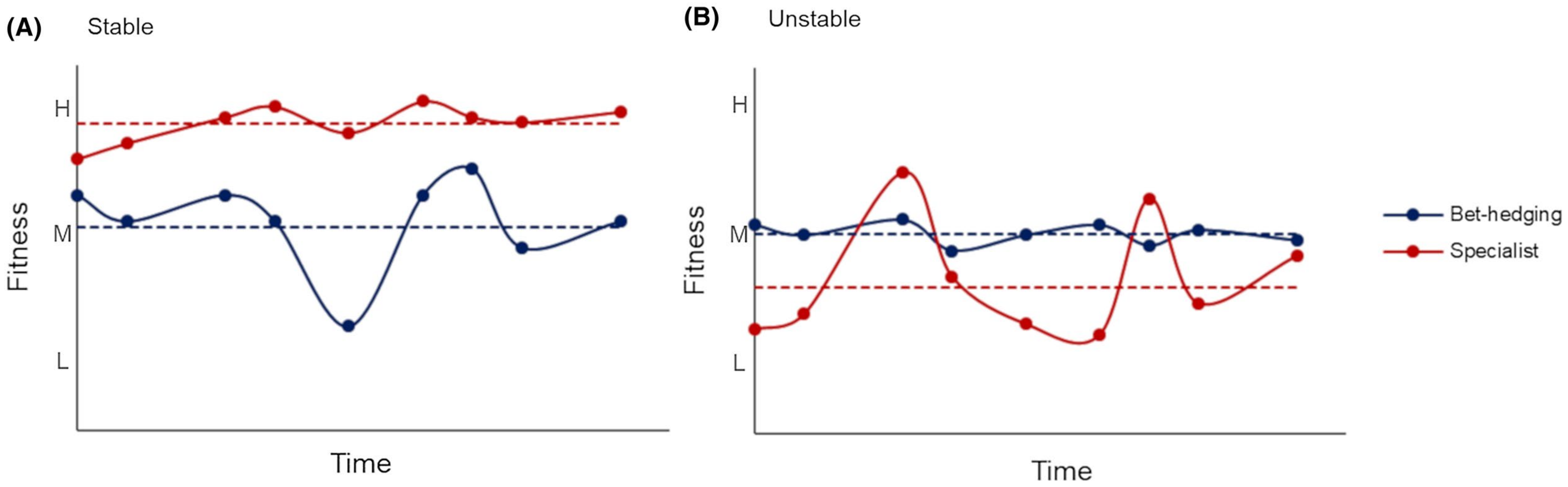
⇒ changes in the epigenetic landscape affect the frequency of possible outcomes but not canalization

⇒ A population can respond rapidly to selection within the possible fates determined by canalization

Further reading: **Conrad Waddington and the origin of epigenetics**
Denis Noble *J Exp Biol* (2015) 218 (6): 816–818.
https://doi.org/10.1242/jeb.120071

Epigenetic trait regulation and „bet hedging“

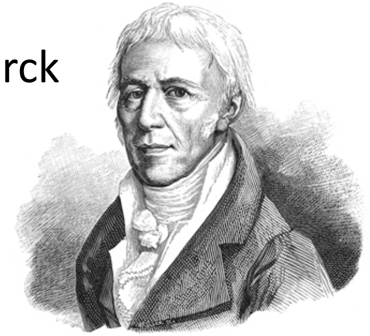
Core hypothesis: For a population it may be advantagous to keep several trait ourcomes, in particular if the environment is unstable

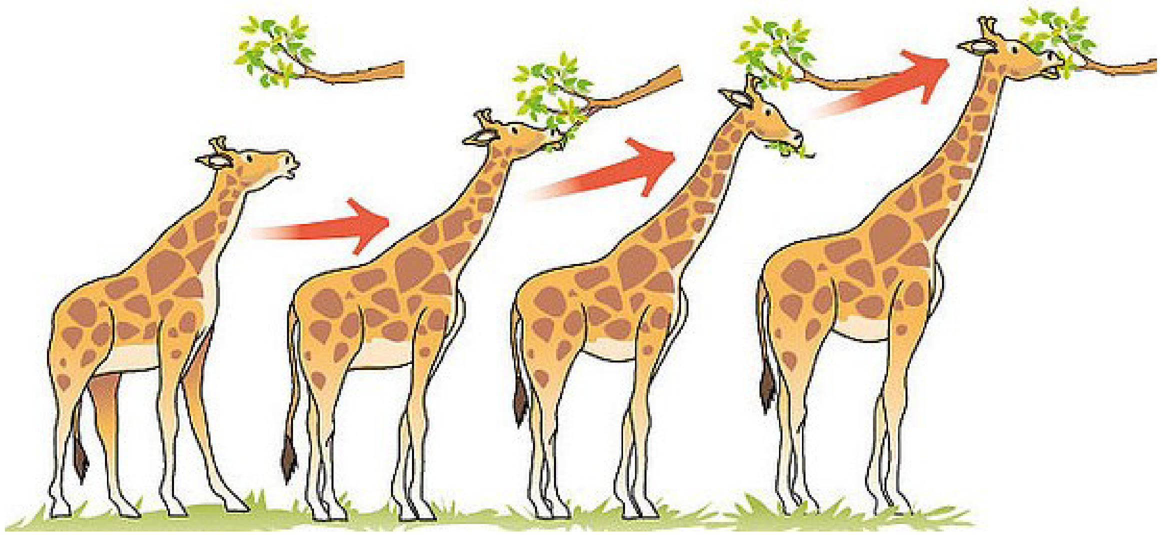


Gianella, M., er.al.*Plant Reprod* **34**, 21–36 (2021).

Lamarckism and Neo-Lamarckism

Jean_Baptiste Lamarck
1744-1826





1809 *Philosophie Zoologique*.

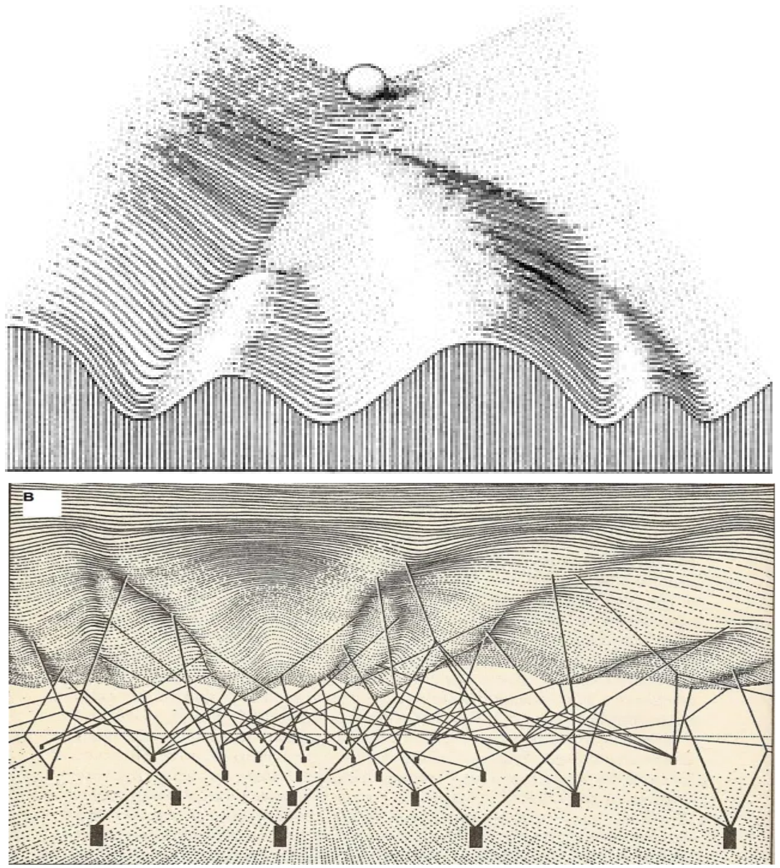
According to his theory, two laws govern the origin of species:

1. law: usage of traits results in degeneration or formation
2. law: experiences are inherited across generations

Neo-Lamarckism postulates that trait usage within „canalized“ options can contribute to adaptation.

Further reading: Eva Jablonka, Marion J. Lamb. (2008). *Soft Inheritance: Challenging the Modern Synthesis*. Genetics and Molecular Biology. 31: 393.

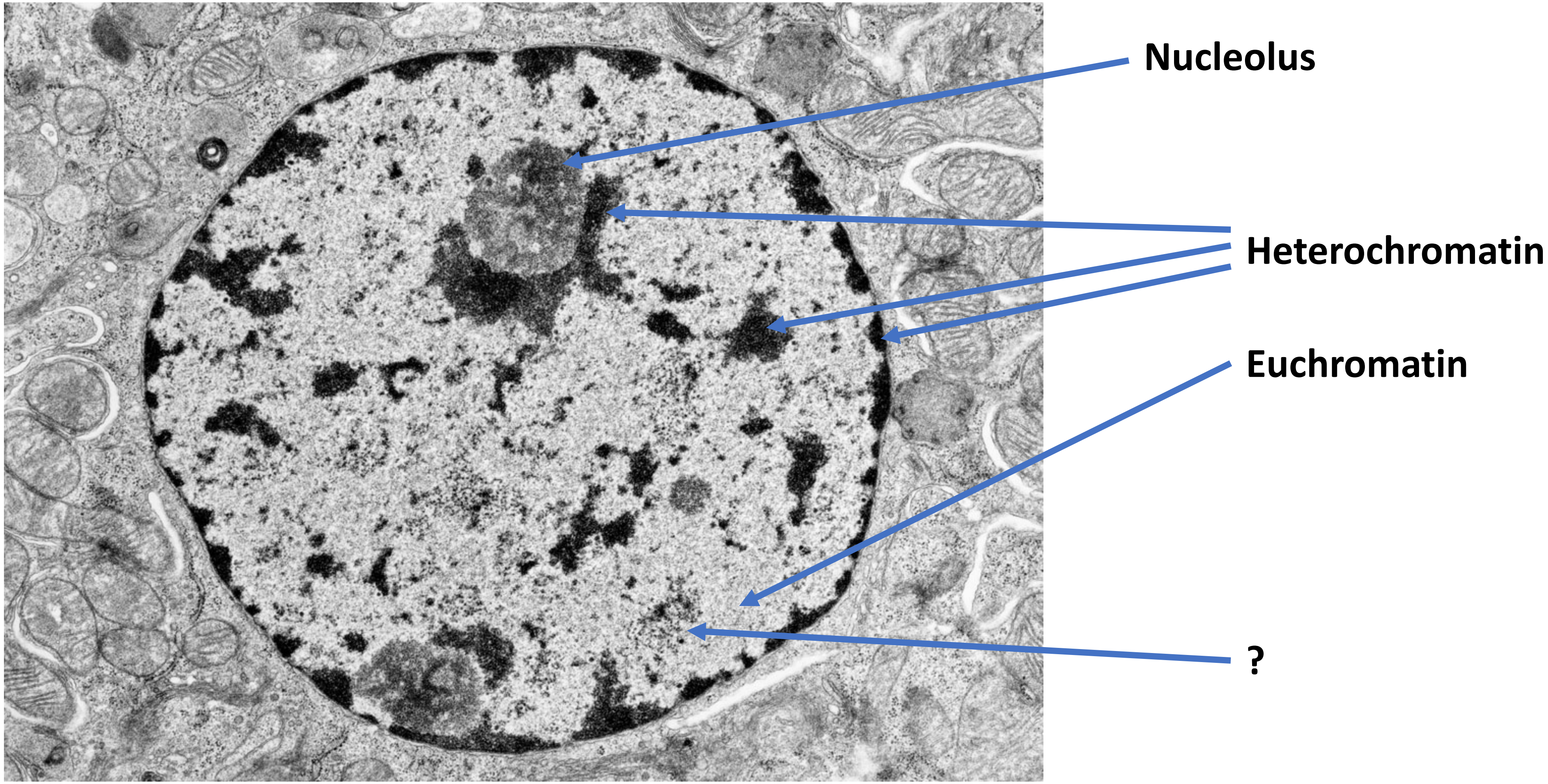
What are the mechansims behind epigenetic landscapes?



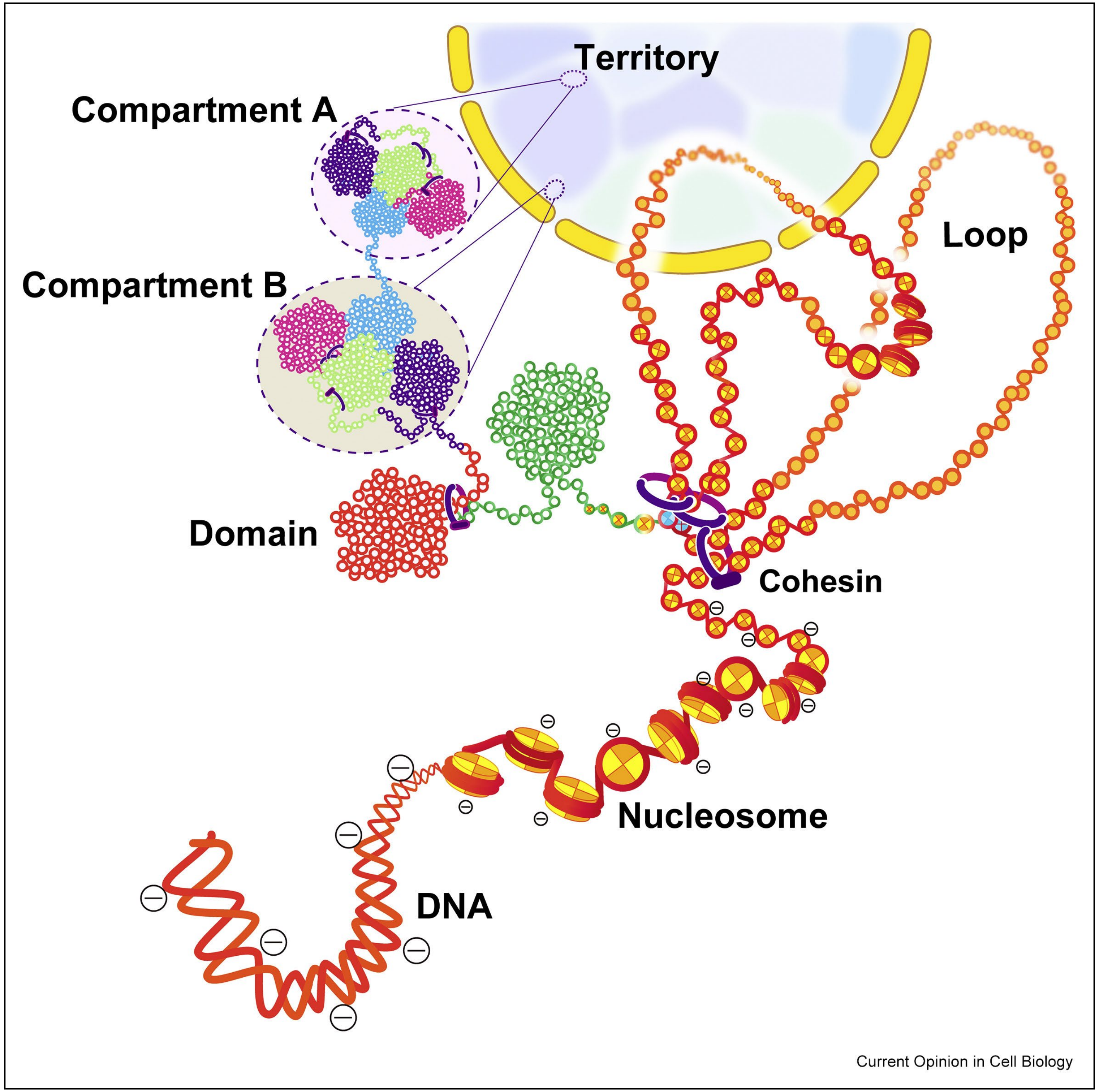
Waddington‘s concept of „Underpinning“

Epigenetic mechanisms are tightly connected to chromatin packaging

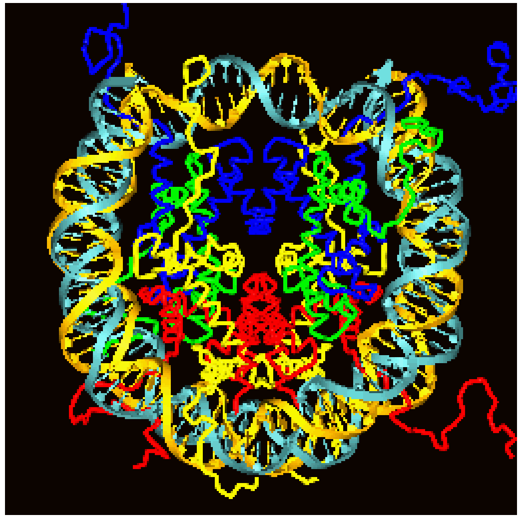
Heterochromatin and Euchromatin



Cell nucleus in transmission electroscopic image



Volume 64, June 2020, Pages 77-89



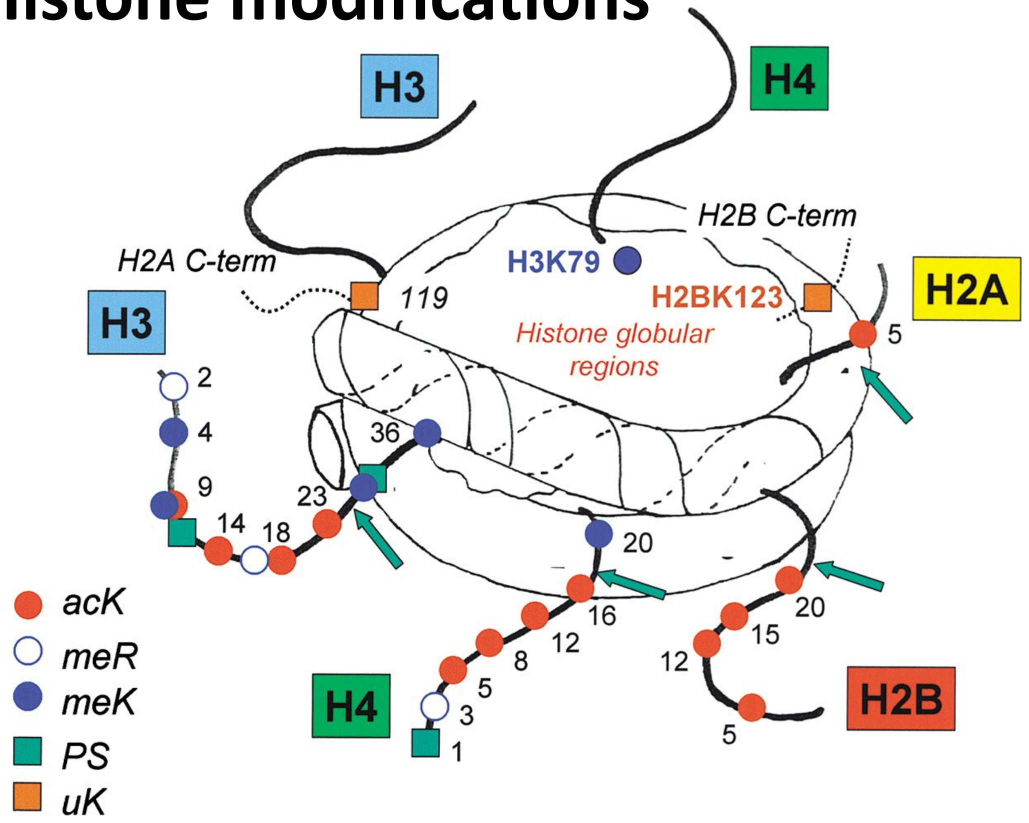
Rhodes, 1997

=> Packaging of nuclear DNA in a chromatin sturcture allowed evolution of larger genomes
=> Chromatin and is a formidable barrier to transcription and replication
With chromatin, eukaryotes have co-evolved a zoo of chromatin-associated protein complexes that regulated packaging and gene expression

Modifications of DNA- and histones extend the genetic by an epigenetic code

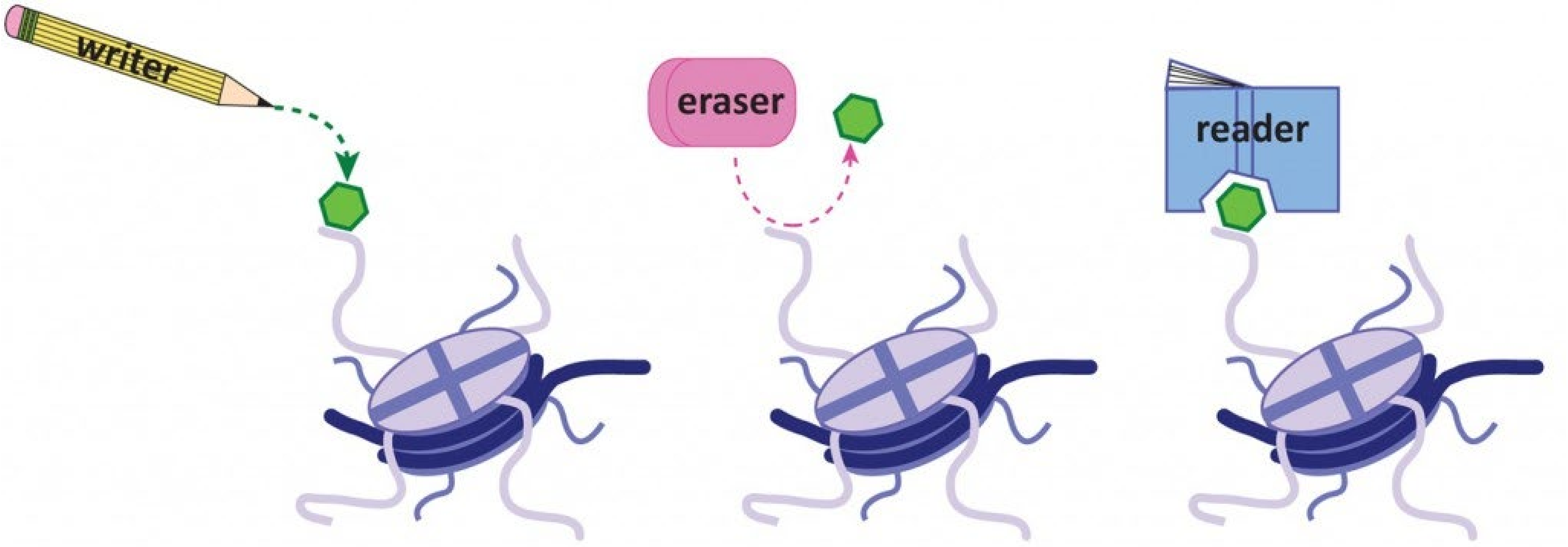
DNA methylation => Part II

Histone modifications



Turner, 2002

Concept of writers/readers/erasers



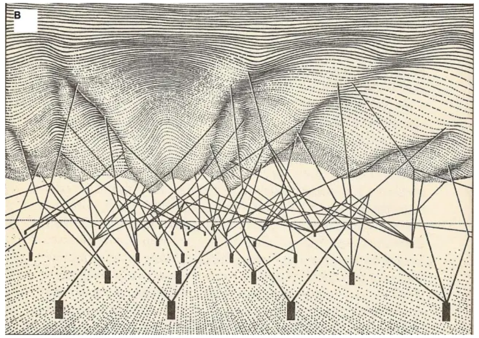
Examples of protein domains

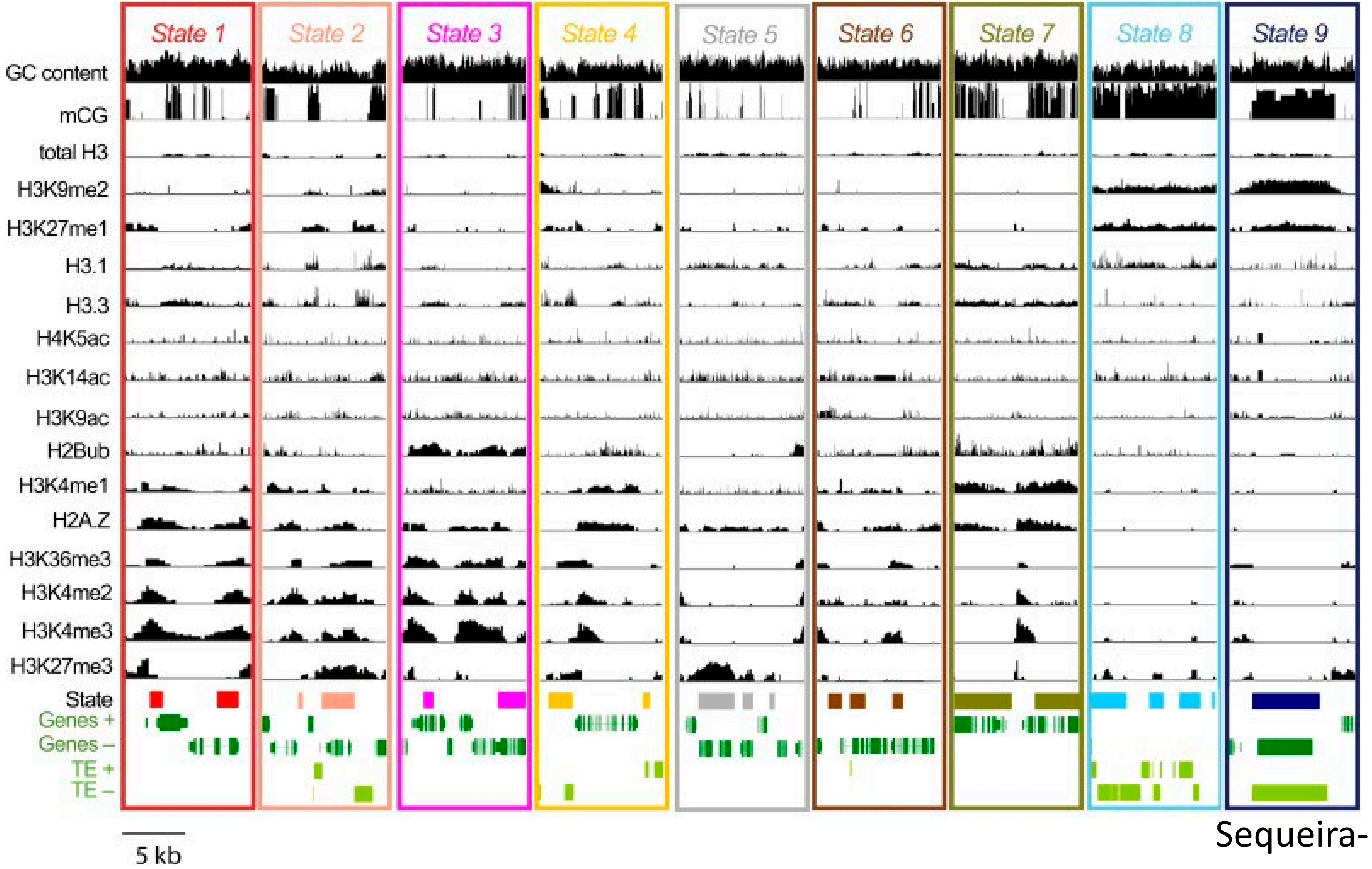
Su(Var)3-9, Ez,Trx (SET)
Histone Acetylase (HAT)

Jumonji
Histone Deacetylase (HDA)

Chromo
Bromo
Tudor
PHD

Classification of chromatin in different „colors“





Some chromatin colors contain expressed others repressed genes

Sequeira-Mendes et al. TPC 2014

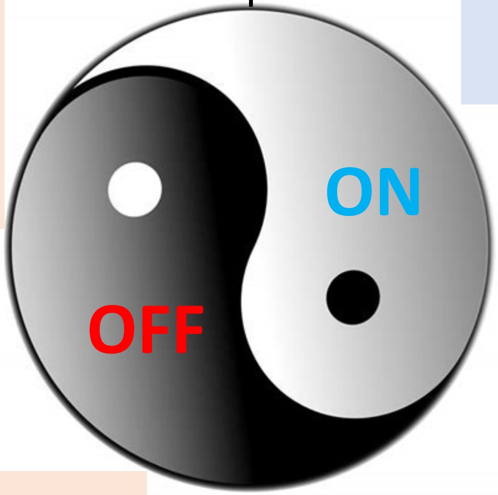
Chromatin states can antagonize or confirm each other – generation of bistable states

Polycomb Group modifications

H3K27me3
H2AK121ub1

High H1
absence of Histone acetylation

Gene expression

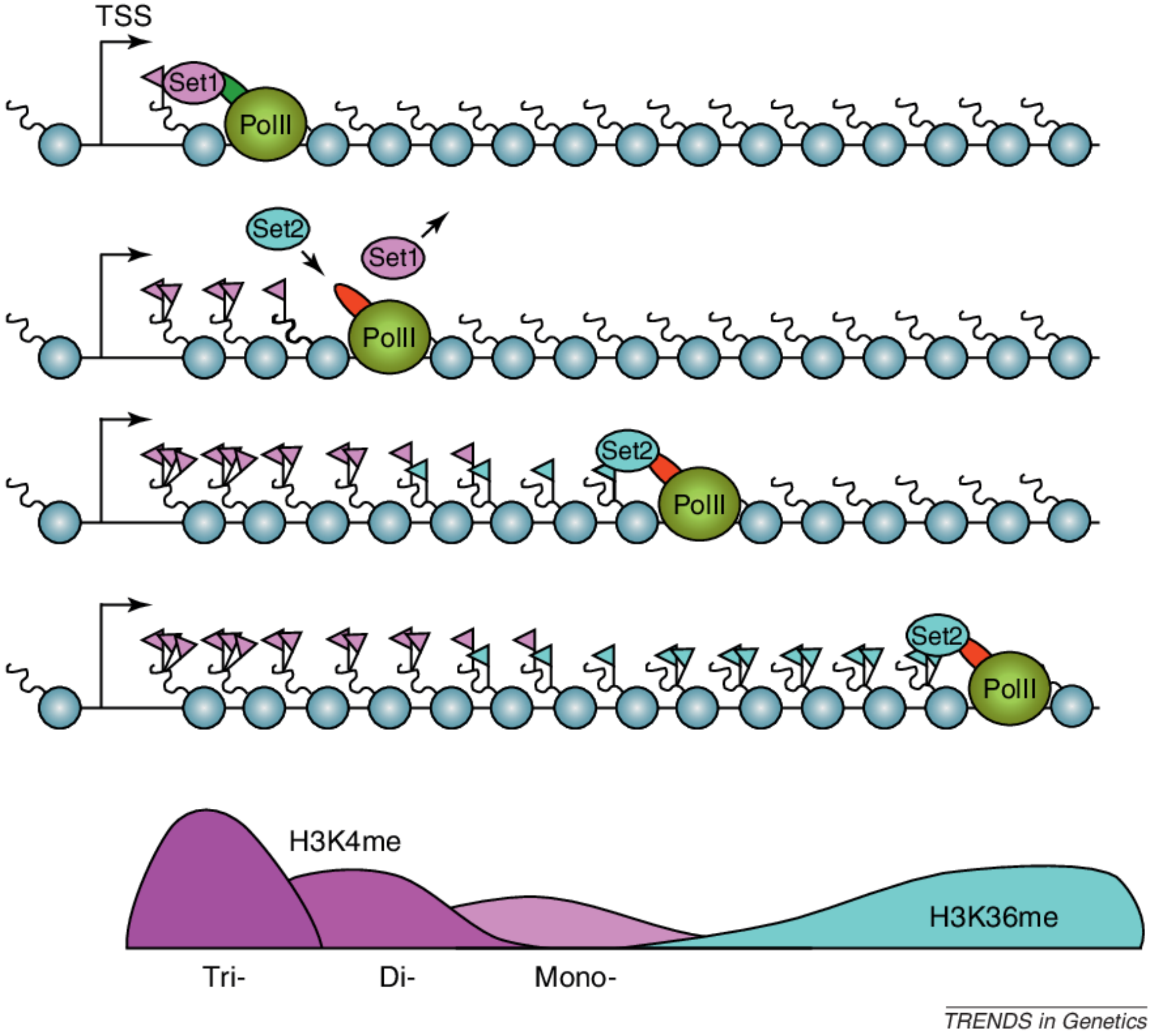


Transcription cycle modifications
- RNAPII S5, S2 phosphorylation
- Histone acetylation
- H2Aub1

Trithorax Group modifications

H3K4me3/me2
H3K36me2/me3
H3K27ac?

Transcription of genes is linked to changes in „epigenetic“ modifications



Steven Henikoff, Ali Shilatifard, 2011

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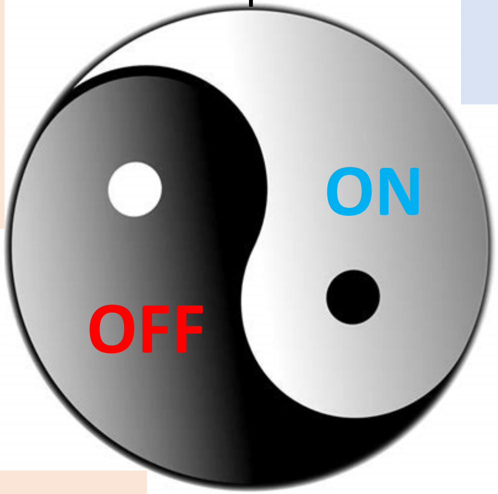

Transcription cycle modifications
RNAPII S5, S2 phosphorylation
Histone acetylation
H2Aub1

Trithorax Group modifications

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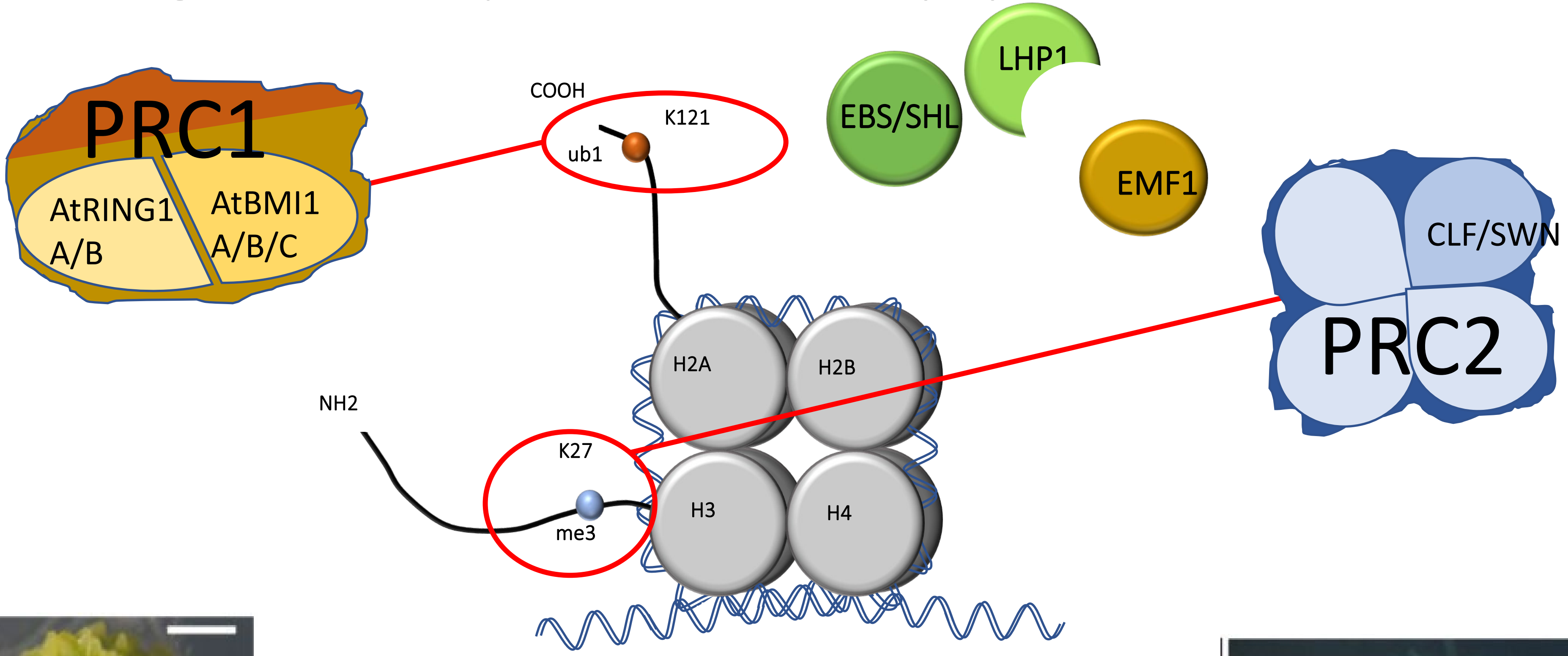
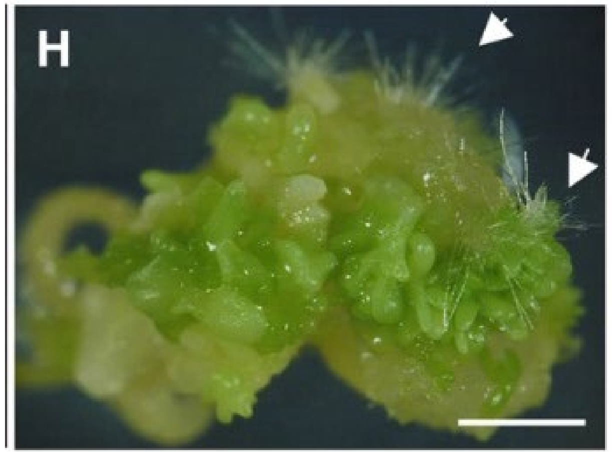
H3K36me2/me3
H3K27ac?

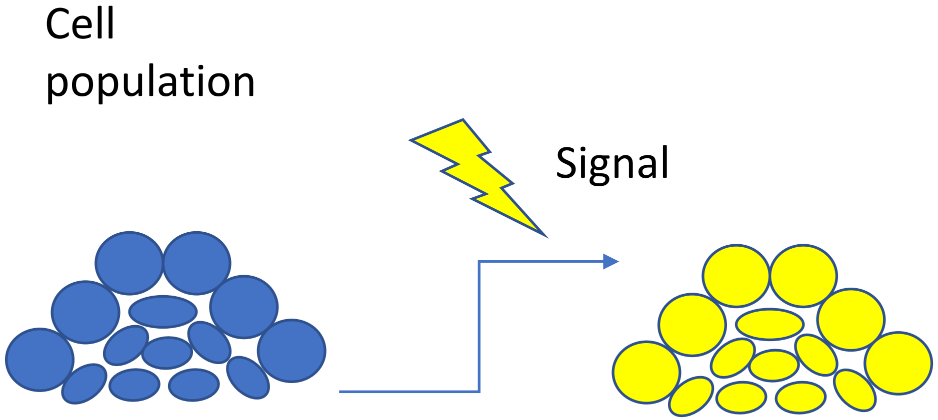
Introducing the Polycomb Group proteins in detail





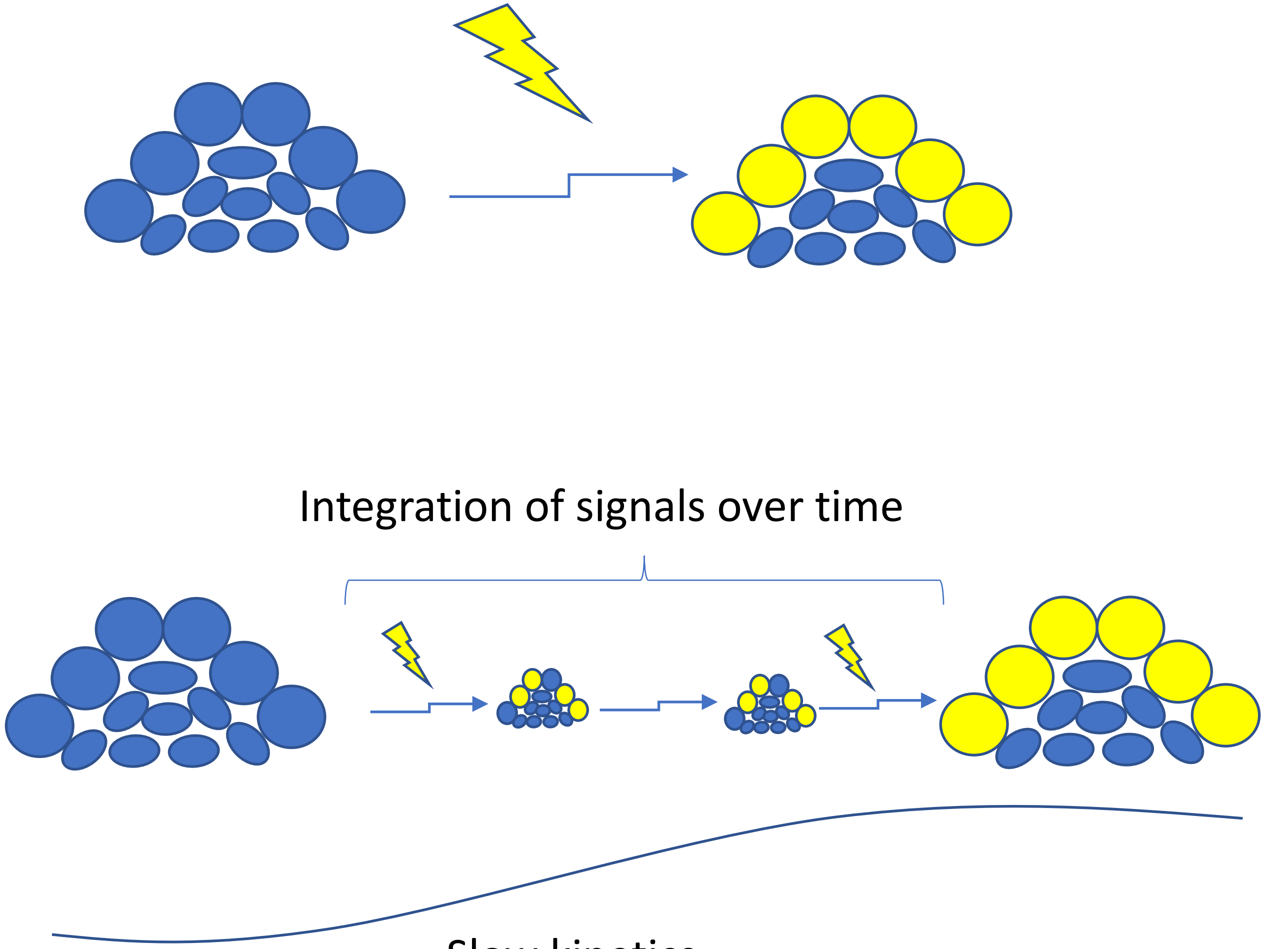
Bistable chromatin states explain gene memories

Without bistability



Fast kinetics, limited control

With bistability

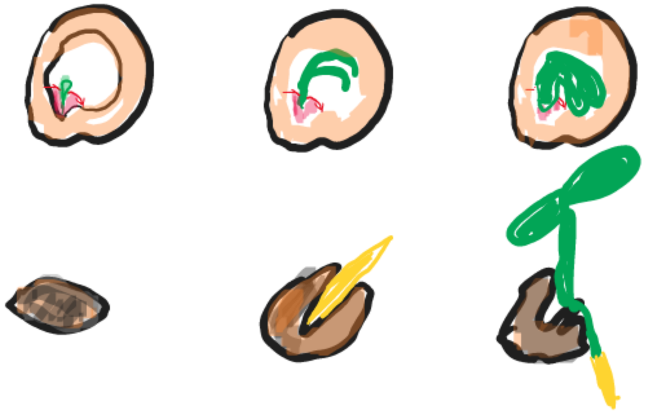


Examples of developmental processes under epigenetic control in plants

1. Switching OFF the seed maturation programm during seedling establishment
2. The memory of winter in Brassicaceae
3. Switching ON floral organ identitiy genes after the floral transition

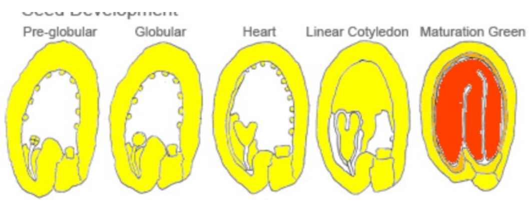
Genes expressed during seed maturation must be stably repressed during seedling establishment

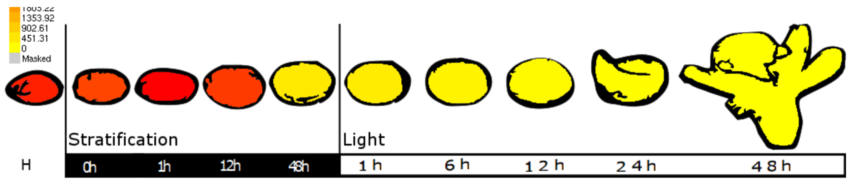
Developing seed



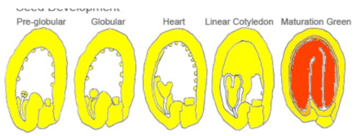
Seed germination and seedling establishment

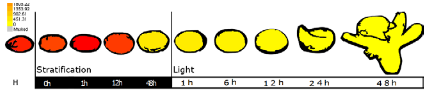
LATE EMBRYO ACTIVATED (LEA) expression

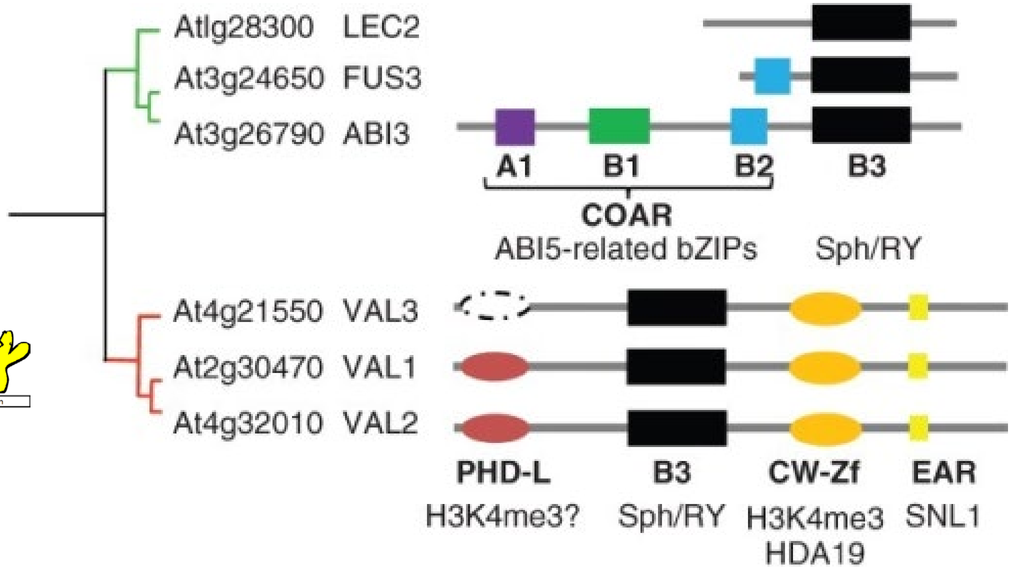




Regulation of seed maturation genes is dependent on „AFL“ and „VAL“ transcription factors

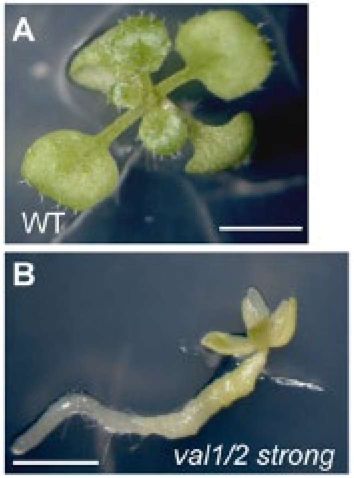






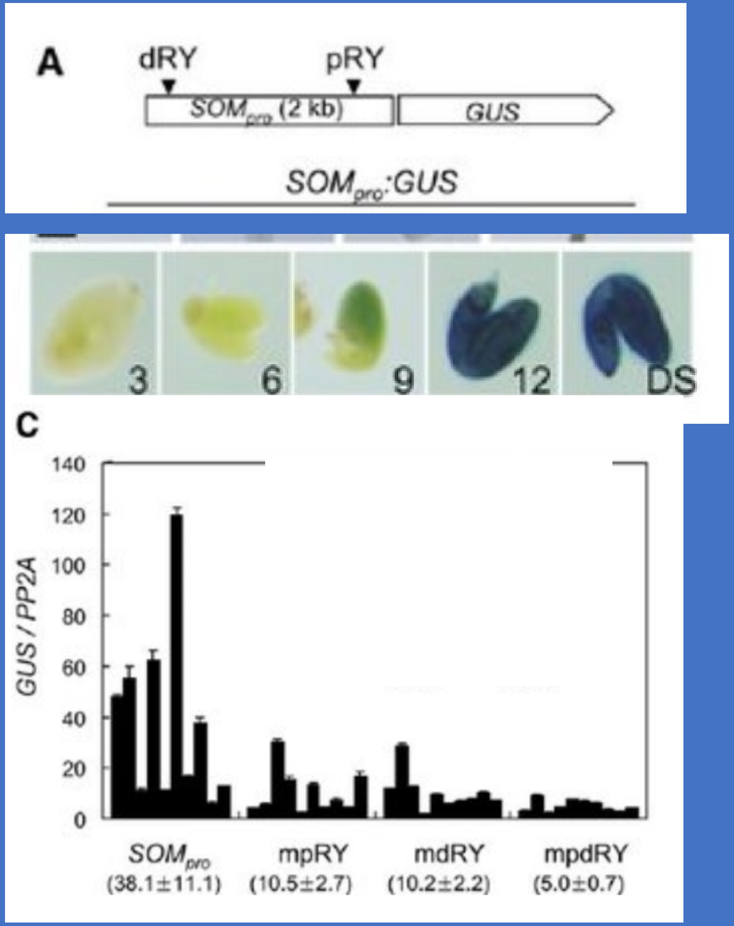
Jia H, Suzuki M, McCarty DR - Wiley Interdiscip Rev Dev Biol (2013)

Delms et al., PNAS. 2013



Yang et al., Current Biol. 2013

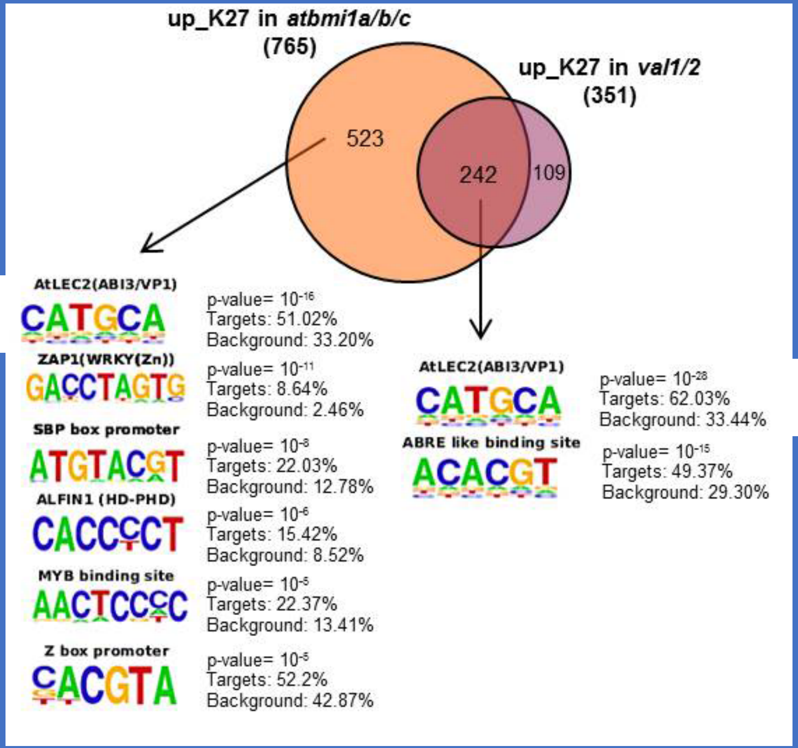
AFL and VAL proteins bind RY-motifs which are necessary for gene activation in maturing seed but also for stable repression during seedling establishment



Modifed from Park et al. TPC, 2011

Transcriptome data

RY-motif

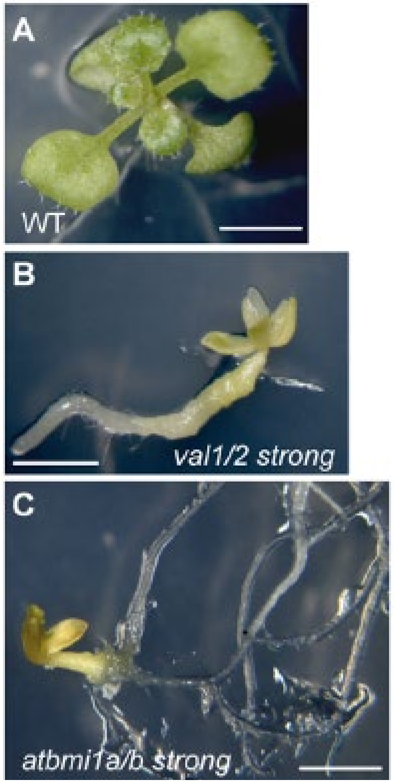


RY-motif

Transcriptome indicates a failure to shut down embryo- and seed-specific genes

Merini et al. Plant Phys, 2016

Mutations in VAL1/2 and PRC1 components cause similar phenotypic changes in seedlings; furthermore, VAL proteins interact with PRC1 components, Histone de-acetylases and PRC2 associated proteins



Wild type

val1 val2

atbmi1a
atbmi1b

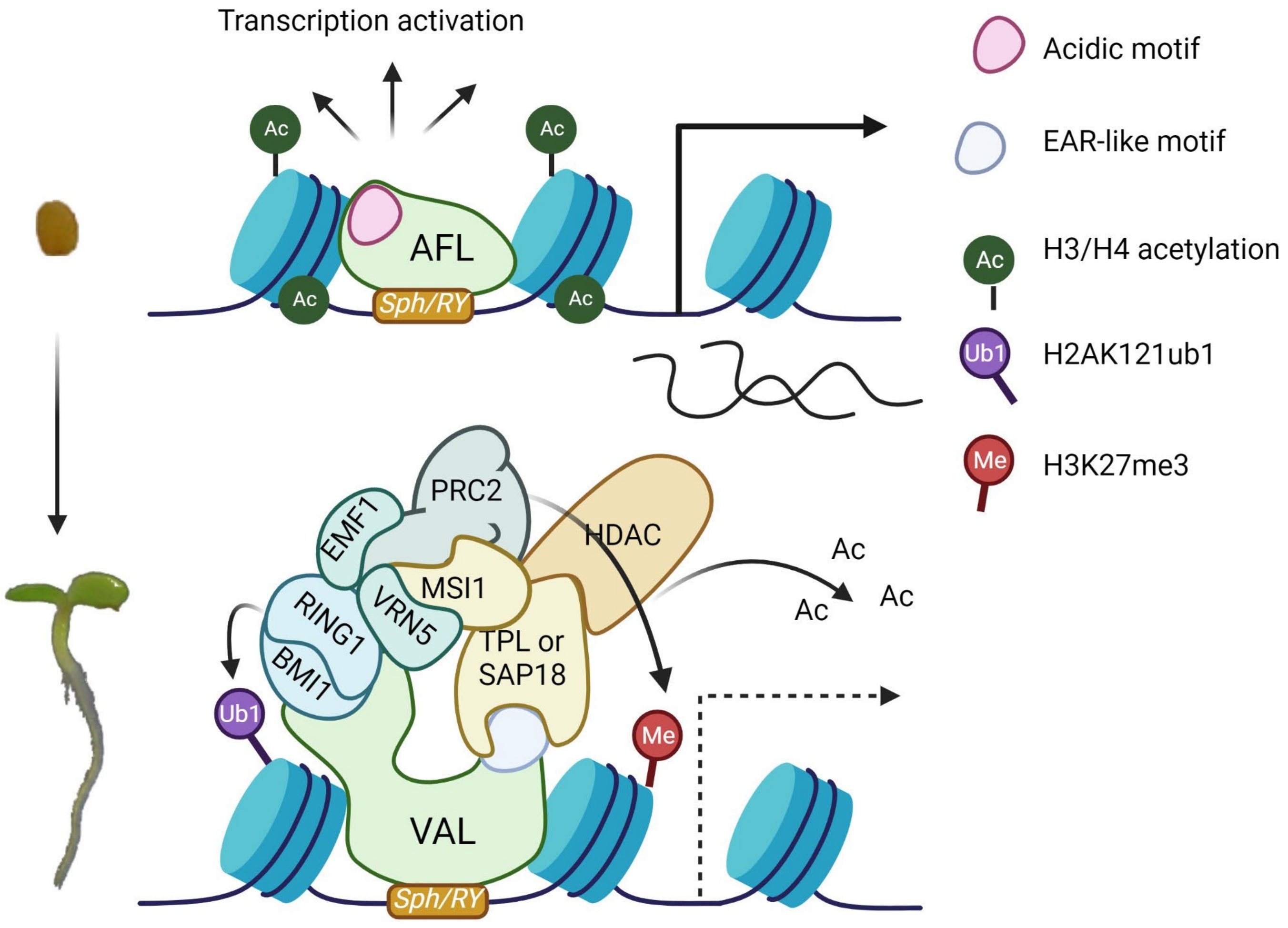
Yang et al., Current Biol. 2013

A

Identified Protein	Accession no.	Mol. Mass (kDa)	No. of Protein Matched Peptides				Sequence Coverage (%)			
			IP1	IP2	IP3	IP4	IP1	IP2	IP3	IP4
VAL1	At2g30470	87	34	29	15	14	48	39	20	20
AtBMI1A	At2g30580	47	10	8	6	5	13	12	7	7
AtSAP18	At2g45640	17	10	0	8	6	60	0	43	36
ACINUS	At4g39680	69	0	11	13	10	0	15	28	15
AtSR45	At1g16610	45	0	0	5	3	0	0	7	8

Qüesta et al. Science 2016

Graphic summary



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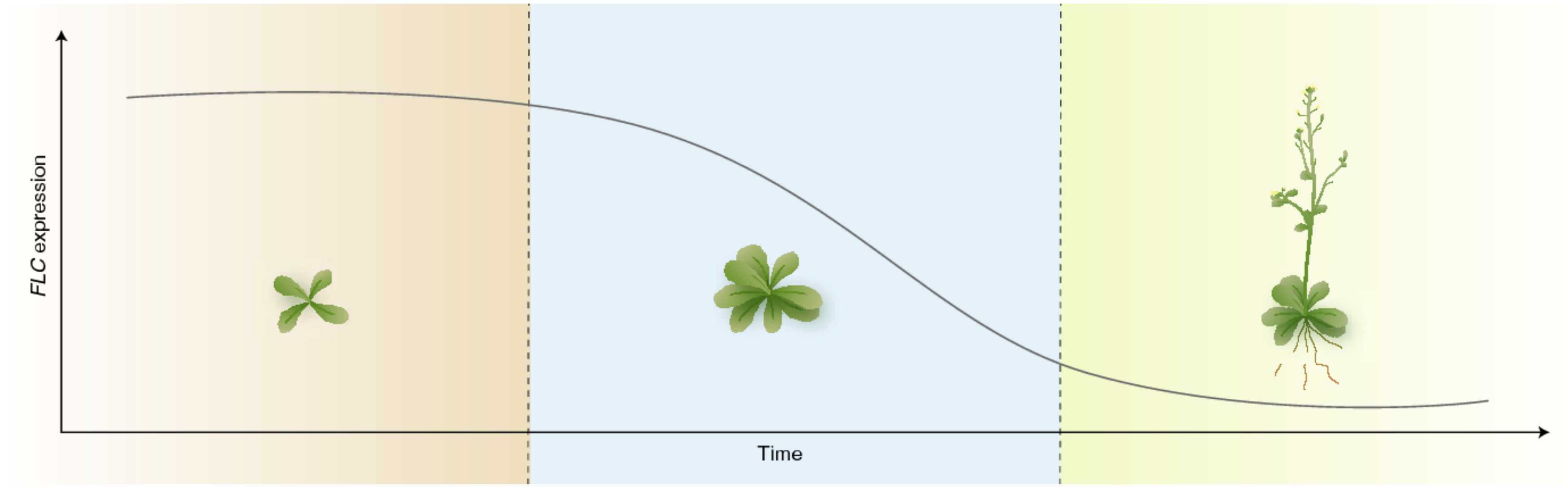
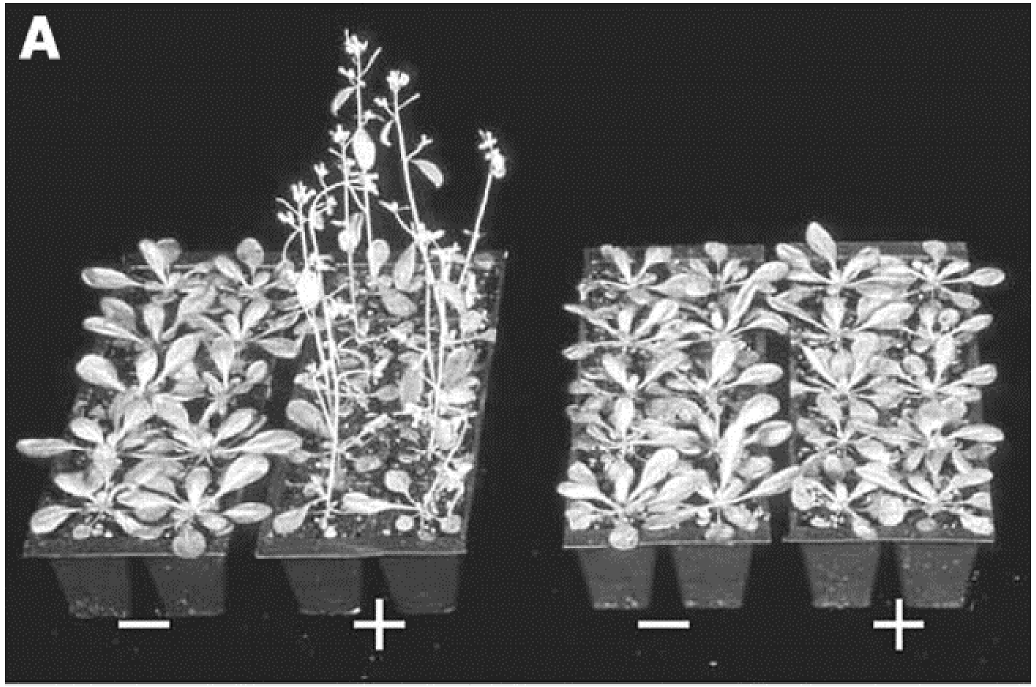
What is the memory of winter in the Brassicaceae



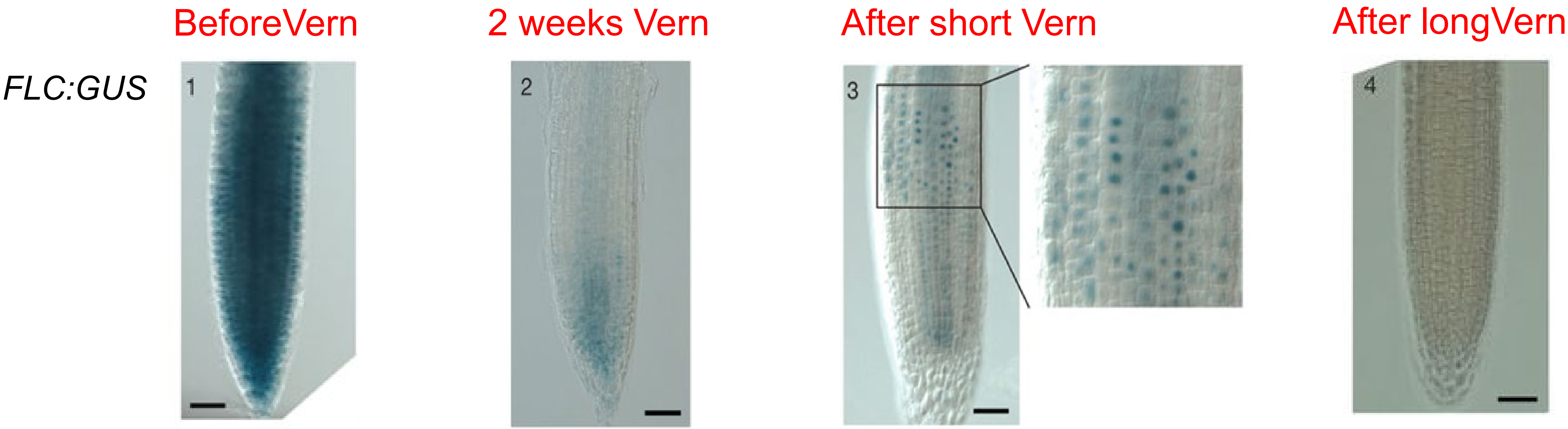
FLC repression is unstable in PRC2 mutants

VERNALIZATION INSENSITIVE 3	VIN3	does not downregulate *FLC* in 4°C
VERNALIZATION 1	VRN1	does not downregulate *FLC* in 4°C
VERNALIZATION 2	VRN2	does not maintain *FLC* down-regulation
LIKE HETEROCHROMTIN PROTEIN 1 (also called TERMINAL FLOWER 2)	LHP1 TFL2	does not maintain *FLC* downregulation

LHP1, VRN2 and VIN3 are PcG Group or associated proteins



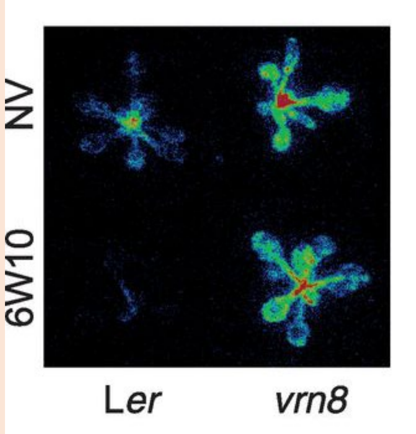
PcG-mediated memory is cell autonomous

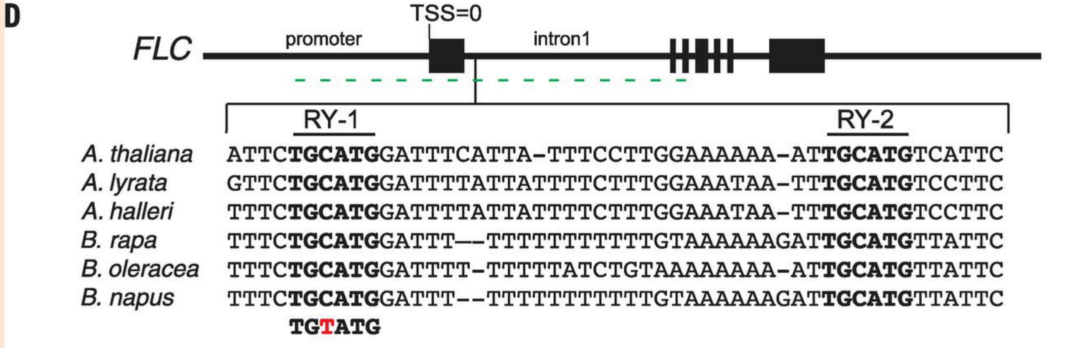


Angel et al. (2011) Nature 476: 105-108

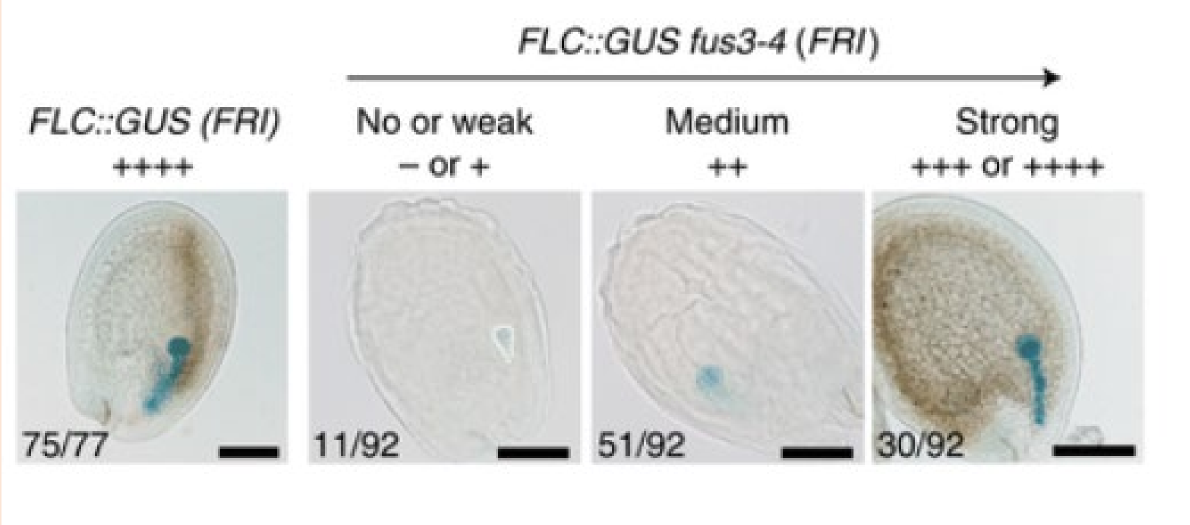
Downregulation of *FLC* in the cold is dependent on RY motifs and VAL1. *FLC* activation during seed development requires AFL proteins

FLC-LUC



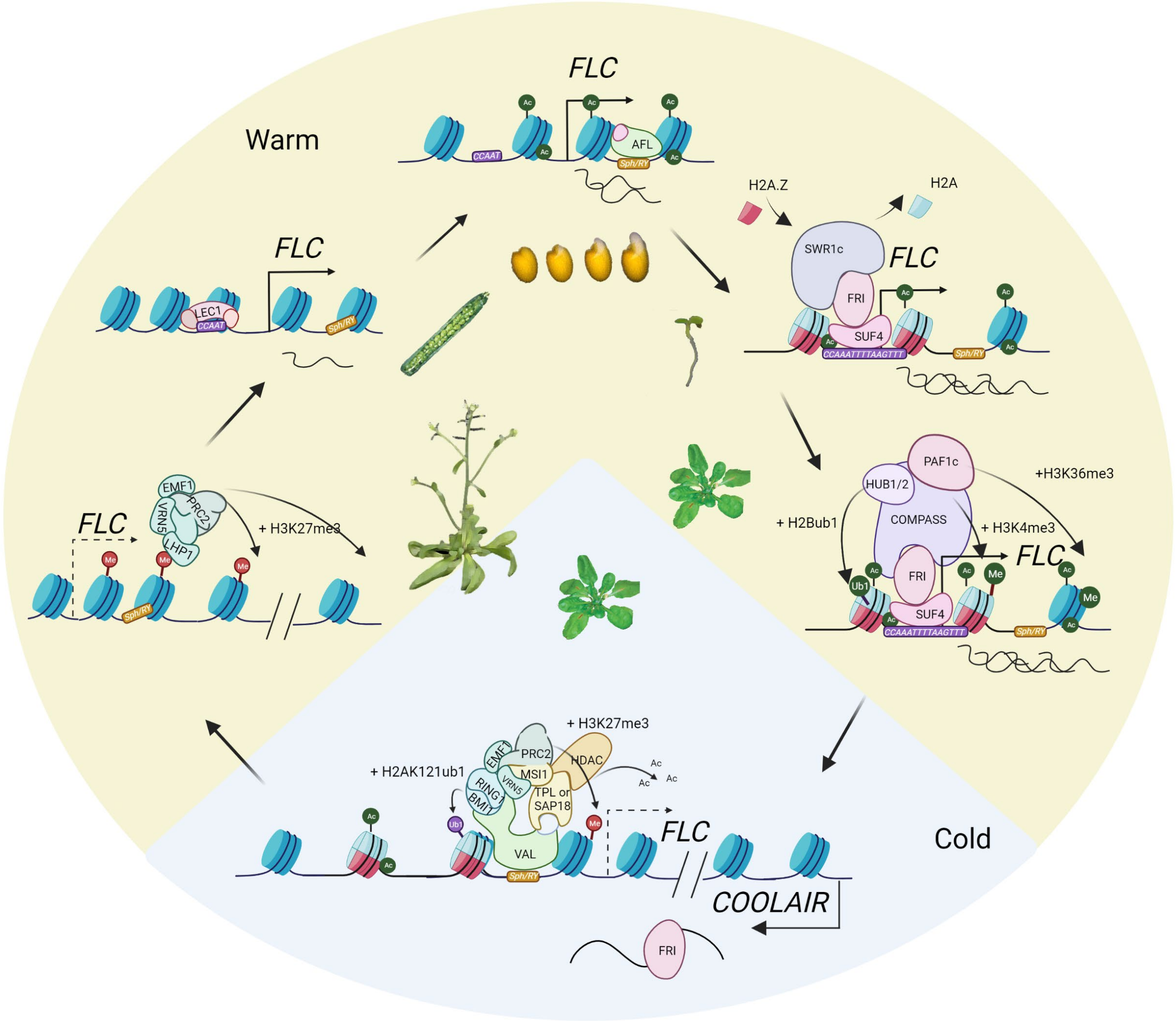


Qüesta et al. Science 2016
Yuan et al. Nature Genetics 2016



Tao et al. Nature Plants 2019

Presence of *FRI* prevents *FLC* downregulation during seedling establishement – but how?



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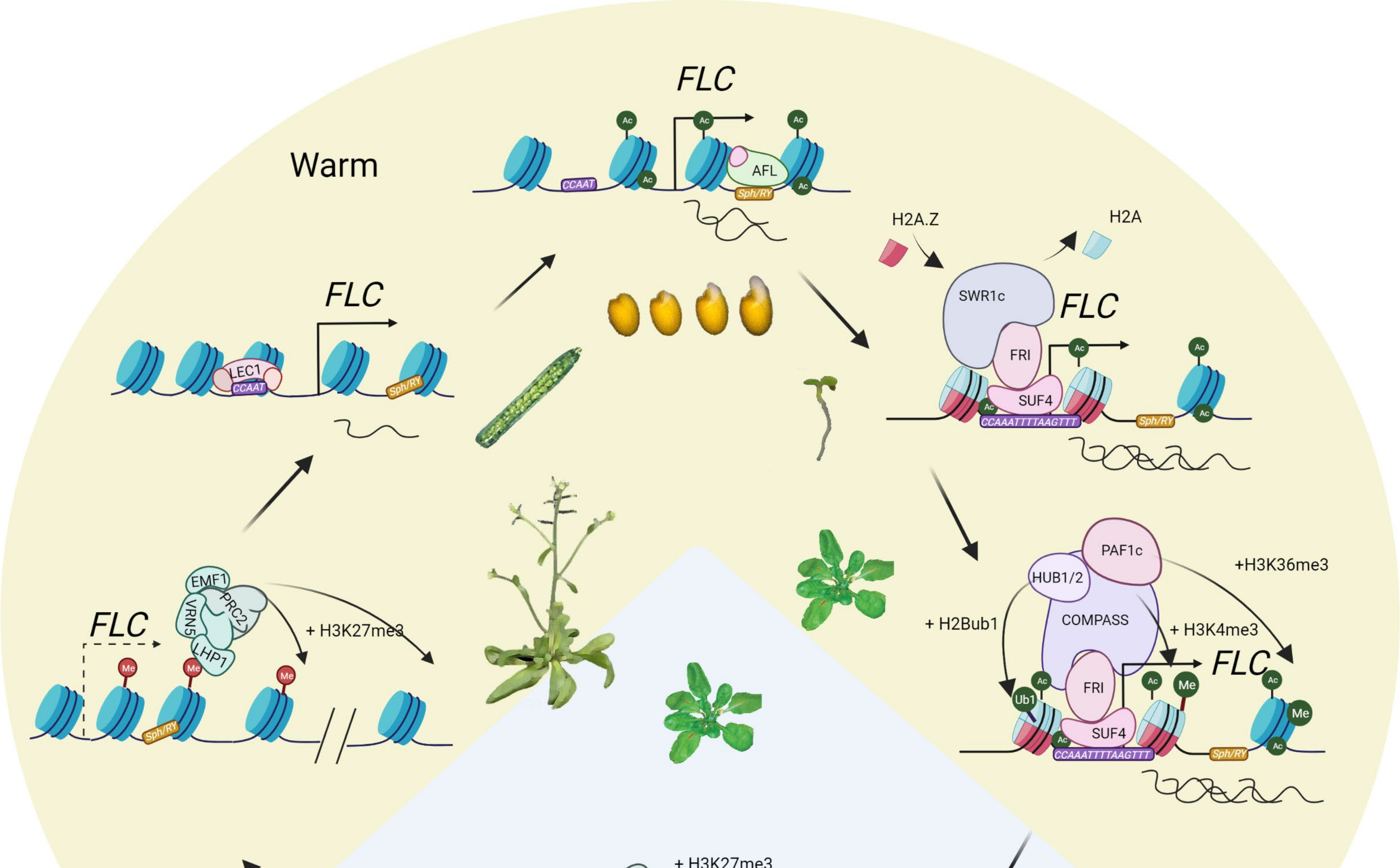

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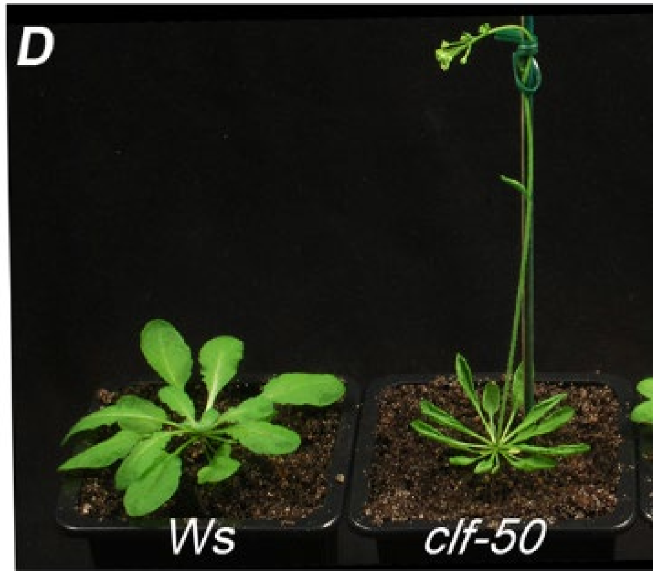
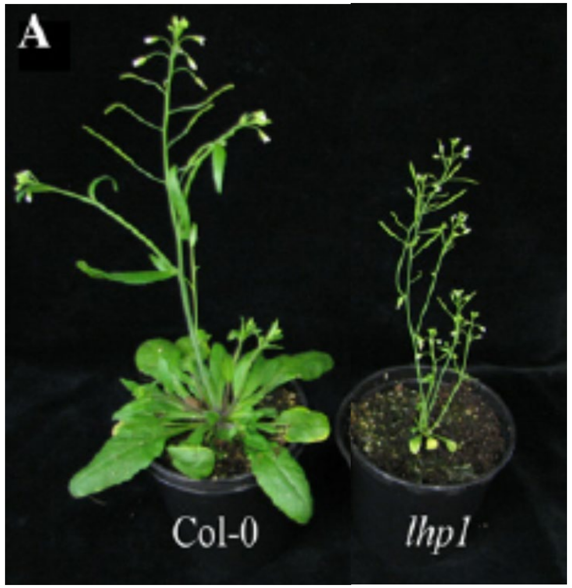
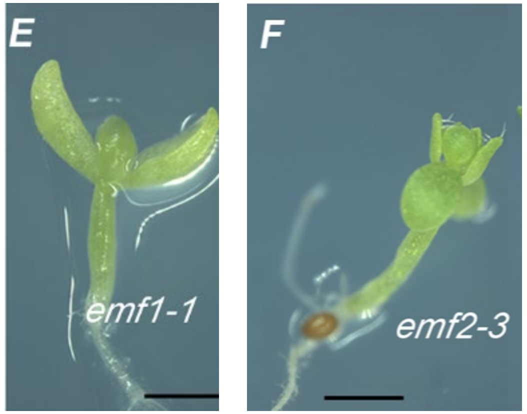
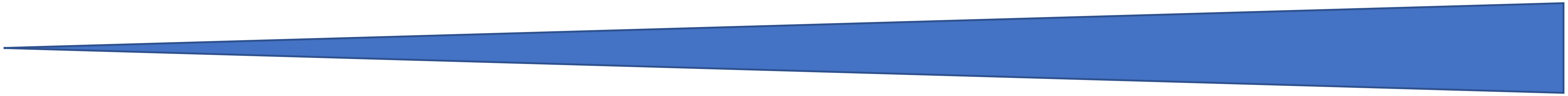
PRC2 holds back the reproductive transition







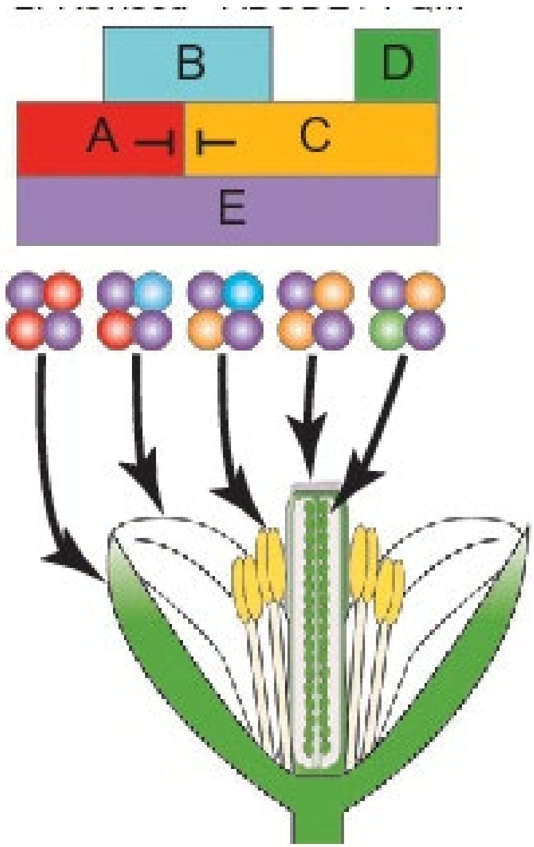


Early flowering mostly in SD

Early flowering in SD and LD

Embryonic flower

Flower organ formation requires expression of ABC(DE) genes



Overexpression of a single ABCDE gene can kick-start expression of the others

Thomson, B., & Wellmer, F. (2019). *Current topics in developmental biology, 131*, 185-210 .

PRCs repress florigen and genes regulated by florigen

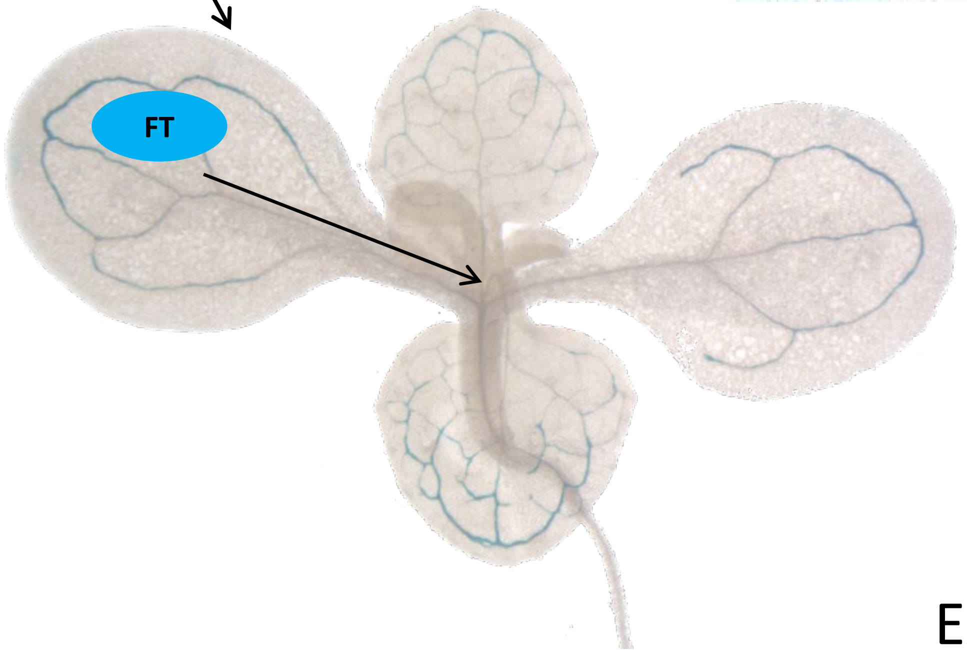
Photoperiod

Vernalization

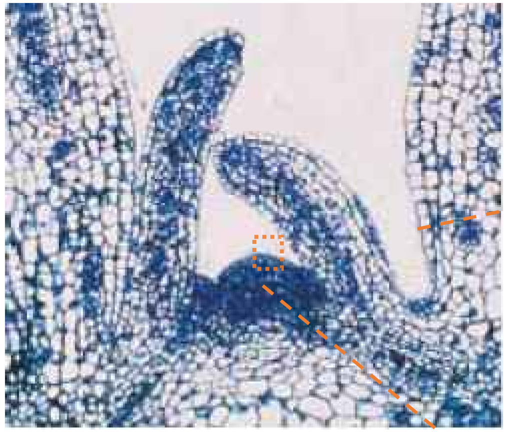
Ambient temperature

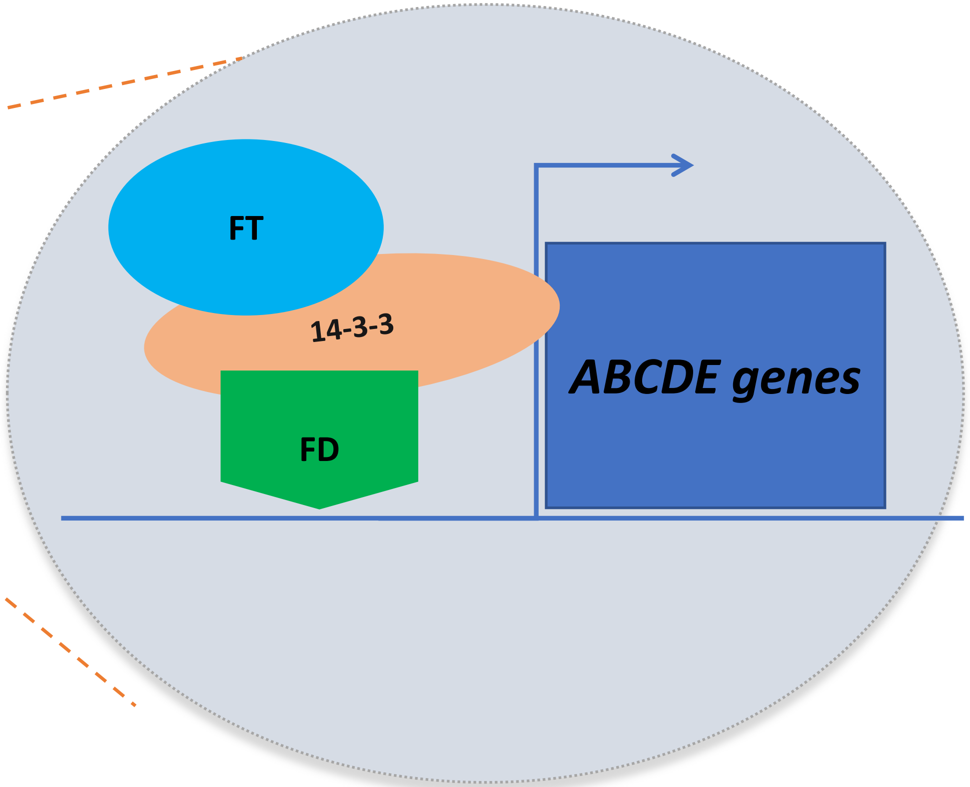
Age

Stress



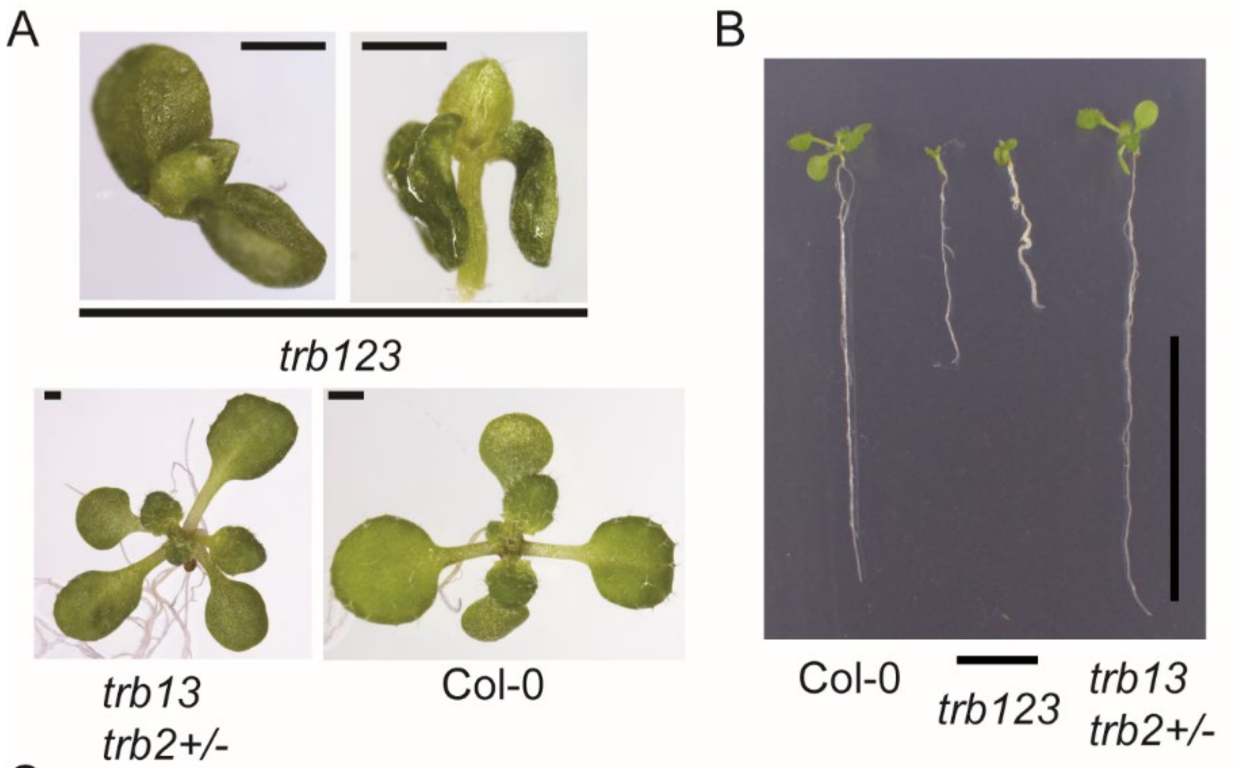
8.1kb-FTp-GUS





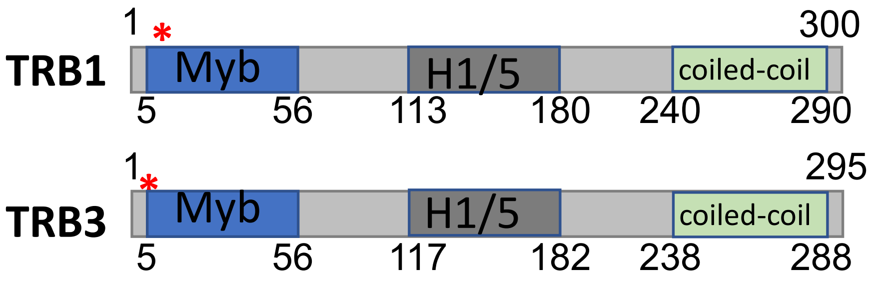
Expression occurs only in LD photoperiod

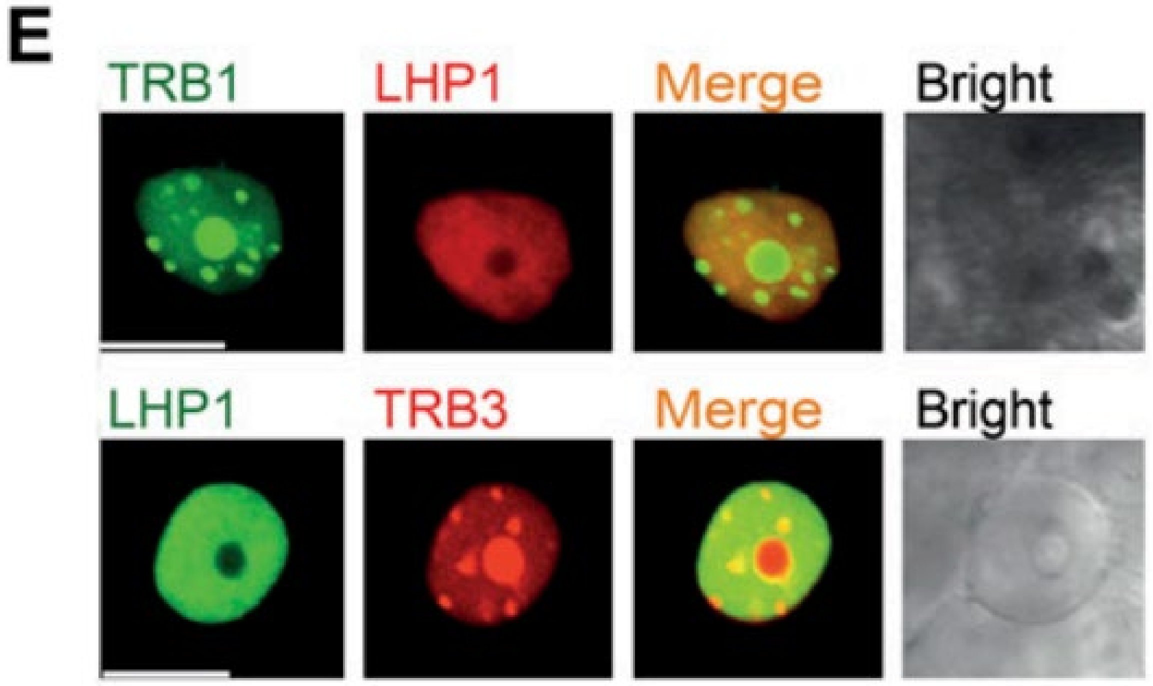
Triple mutants in TELOMERE REPEAT BINDING FACTORS show severe developmental defects and misexpression of ABCDE genes



Zhou et al., Nature Genetics 2018

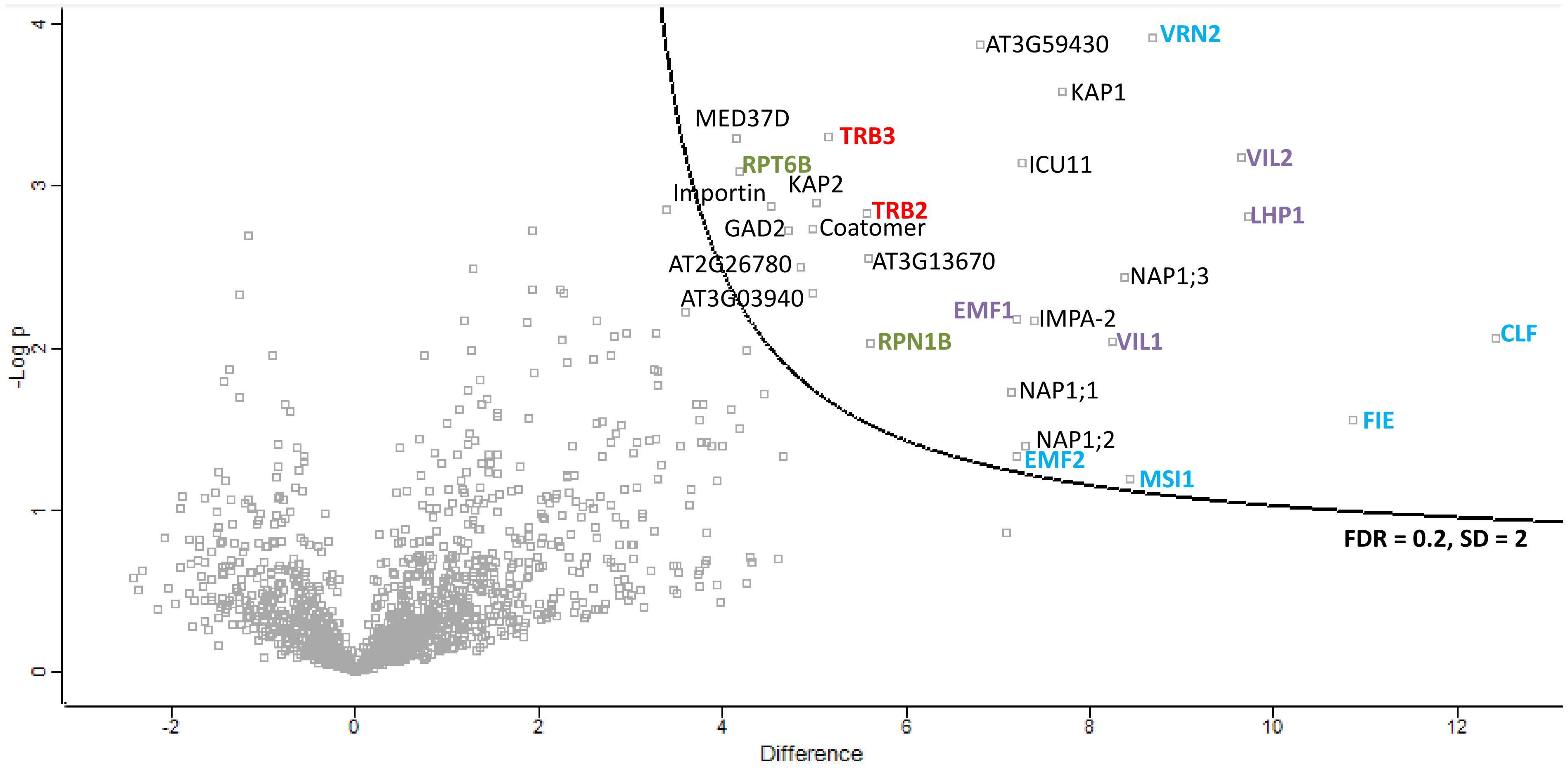
TELOMERE REPEAT BINDING FACTORS bind telomeres and motifs related to telomere repeats





Zhou et al., TPC 2016

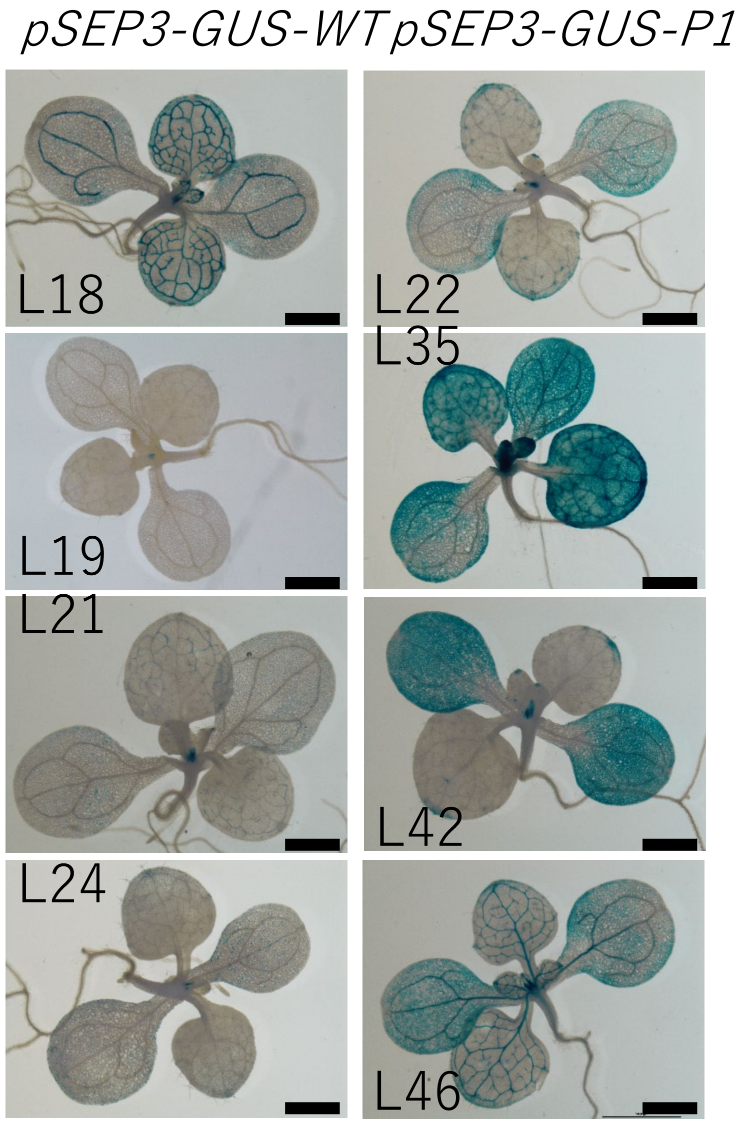
TRB2 and TRB3 are frequent accessories of PRC2

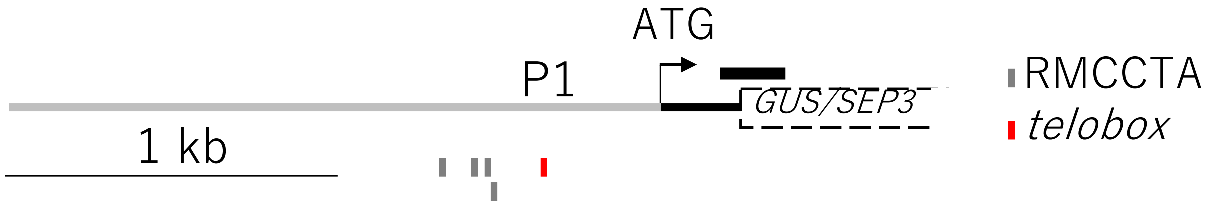


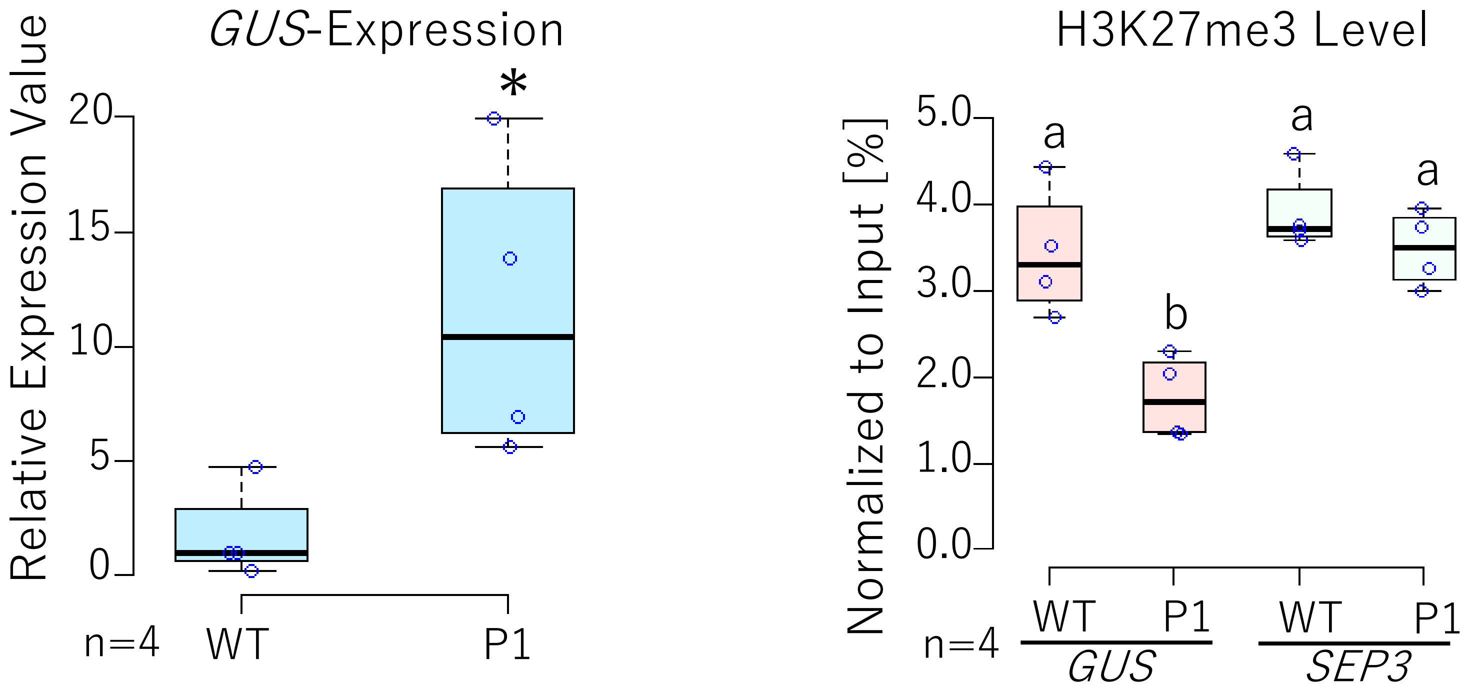
MS-MS pull-down with CLF-PRC2

Bloomer et al. 2020, PNAS

A telobox at *SEP3* participates in repression and H3K27me3 recruitment

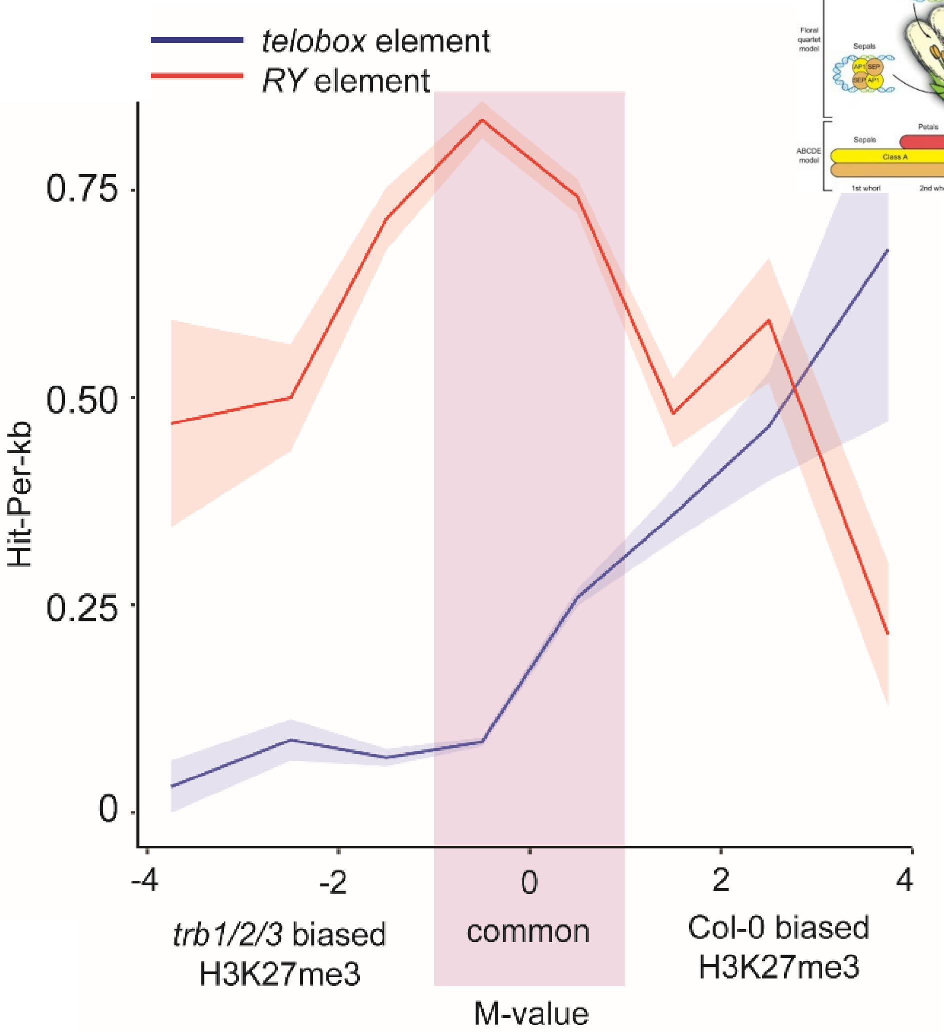


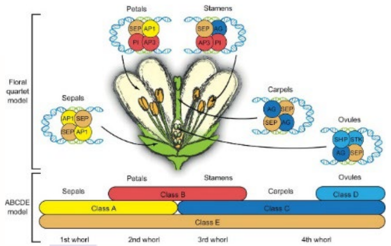


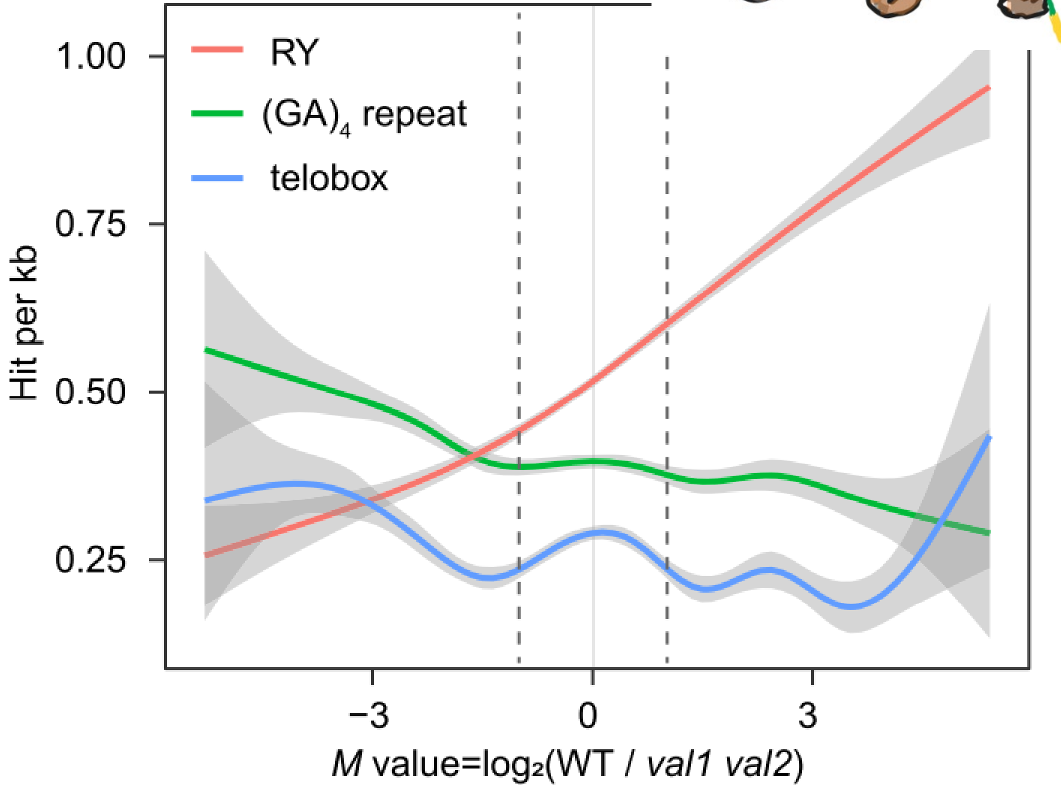


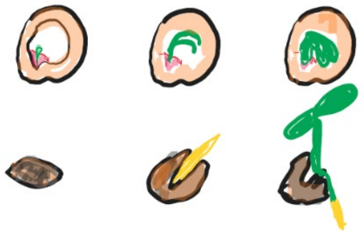
Zhou et al., Nature Genetics 2018

PcG targeting is dependent on a „barcode“



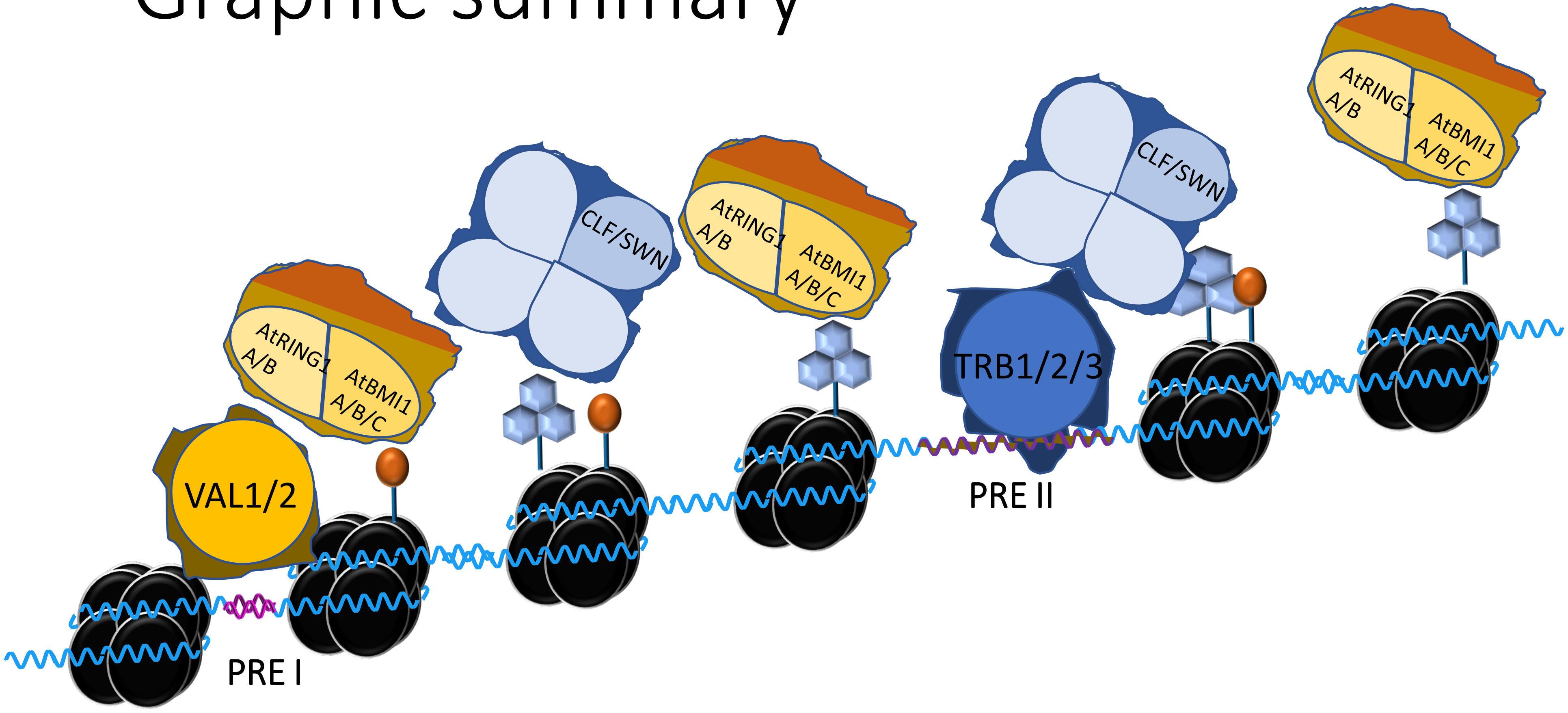






Zhou et al., Nature Genetics 2018

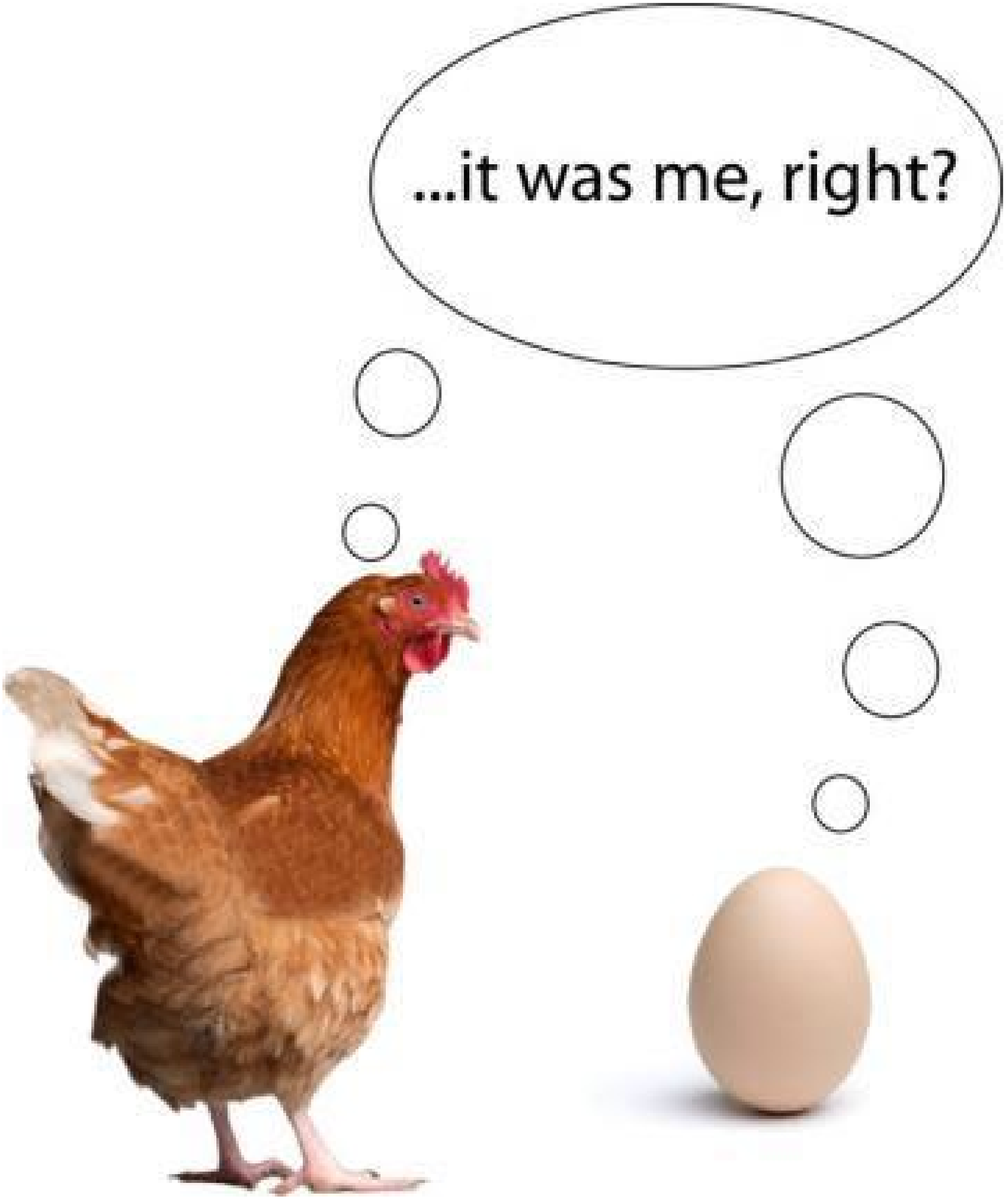
Graphic summary



H2AK121ub

H3K27me3

PRE Polycomb Responsive Element


...it was me, right?