Epigenetic Gene Regulation: Genomic Imprinting in Plants

Ueli Grossniklaus

Universität Zürich[UZH]

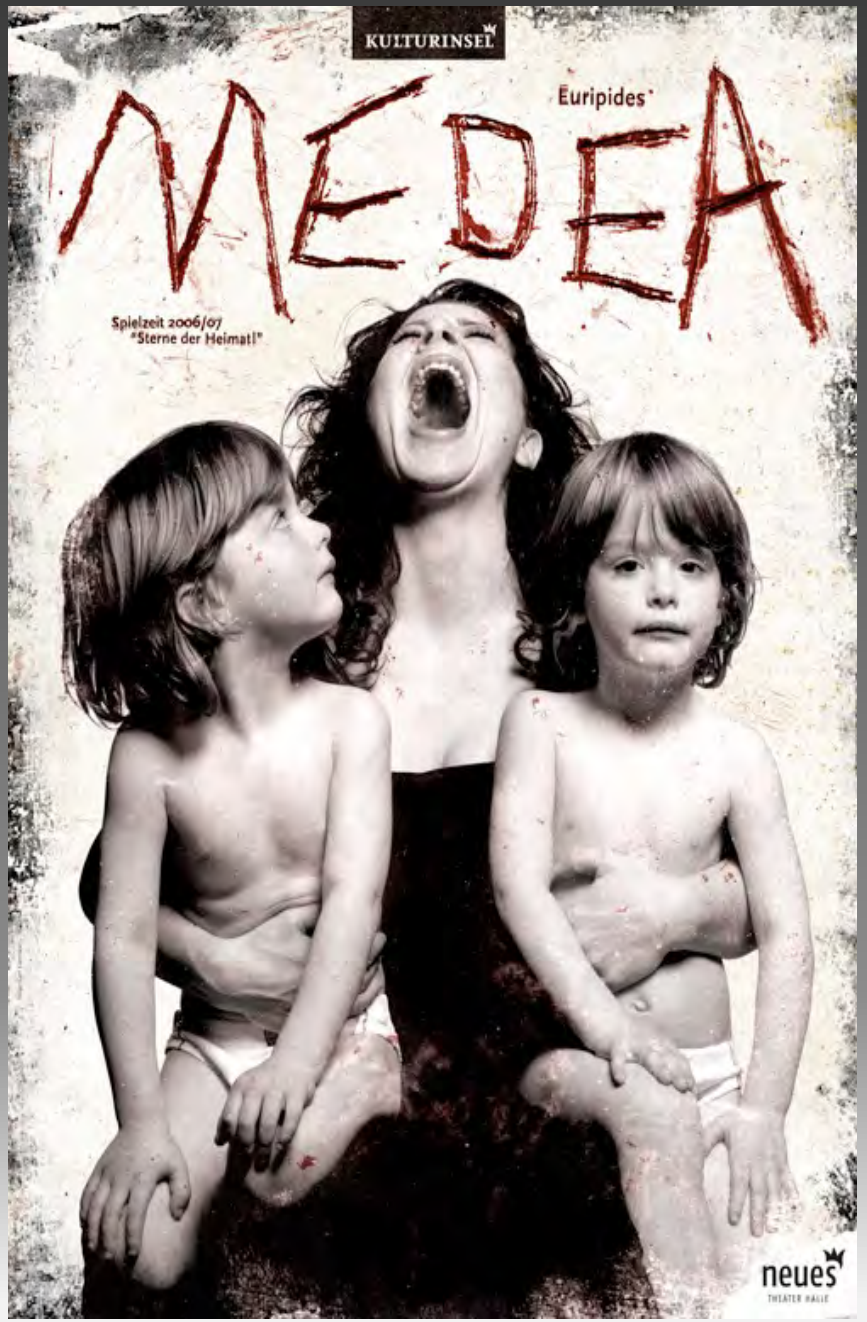
Zurich – Basel Plant Science Center

INDIAN INSTITUTE OF SCIENCE

Molecular Diagnostics 2024, Zurich, March 7th to 8th, 2024

Overview

- Introduction to plant reproduction and genomic imprinting
- Evolution of genomic imprinting
- Molecular mechanisms of genomic imprinting



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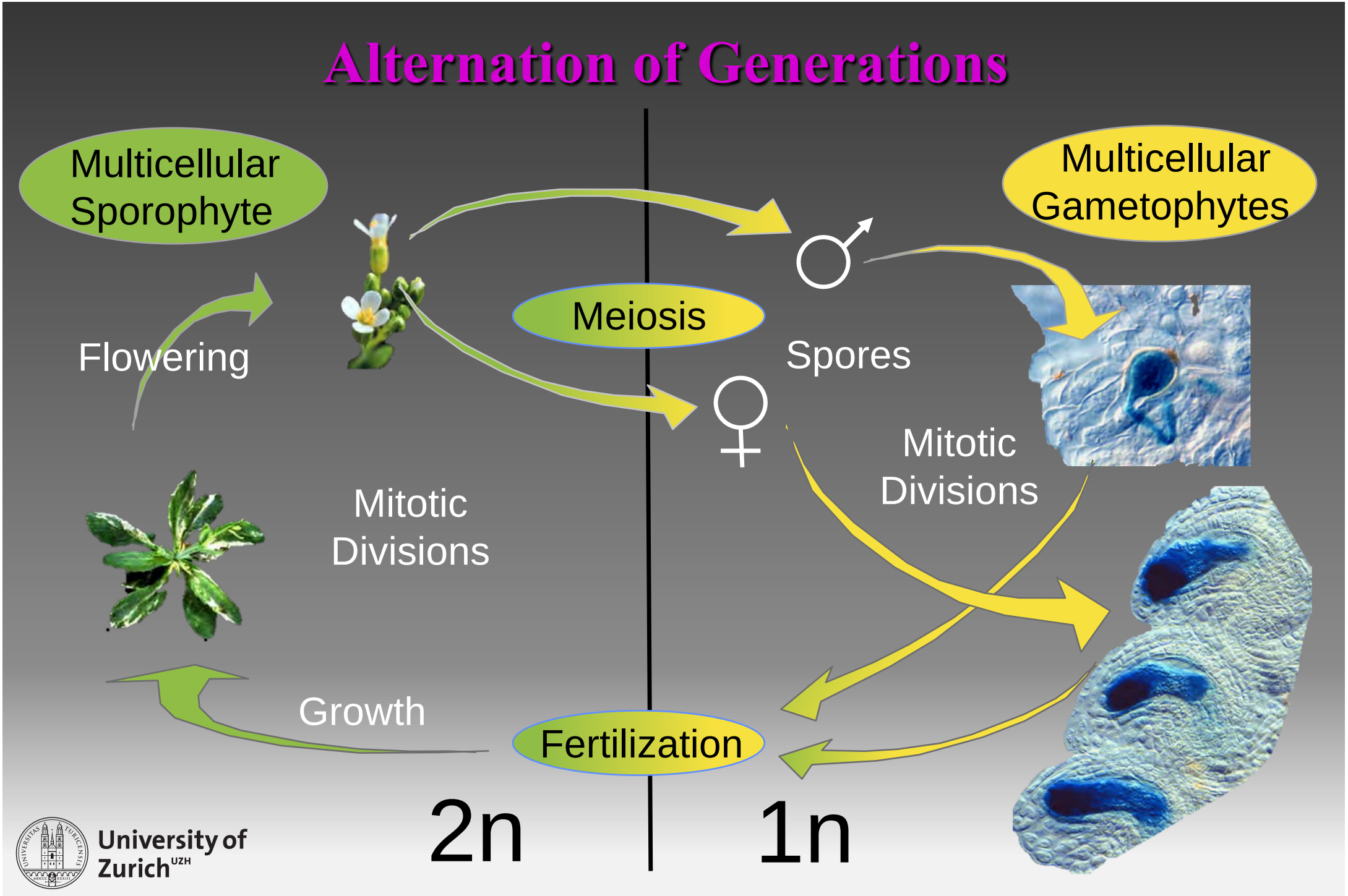
Alternation of Generations



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Double Fertilization and Seed Development

Ovule

Sporophytic Tissue

Central Cell

Egg Cell

Sperm Cells

Pollen Tube

Mature Seed

Seed Coat
(2n maternal)

Endosperm
(3n: 2m/1p)

Embryo
(2n: 1m/1p)

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Sporophytic Maternal Effects

Gametophytic Maternal Effects

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Double Fertilization and Seed Development

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Central Cell

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Mature Seed

Seed Coat
(2n maternal)

Endosperm
(3n: 2m/1p)

Embryo
(2n: 1m/1p)

Textbook view:

No Maternal Effects in Plants

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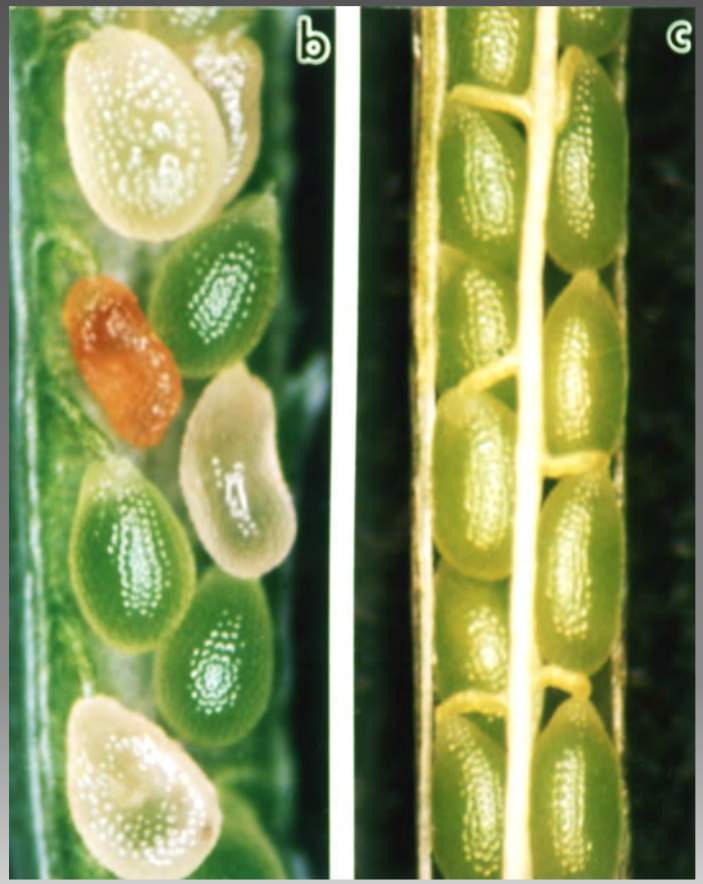
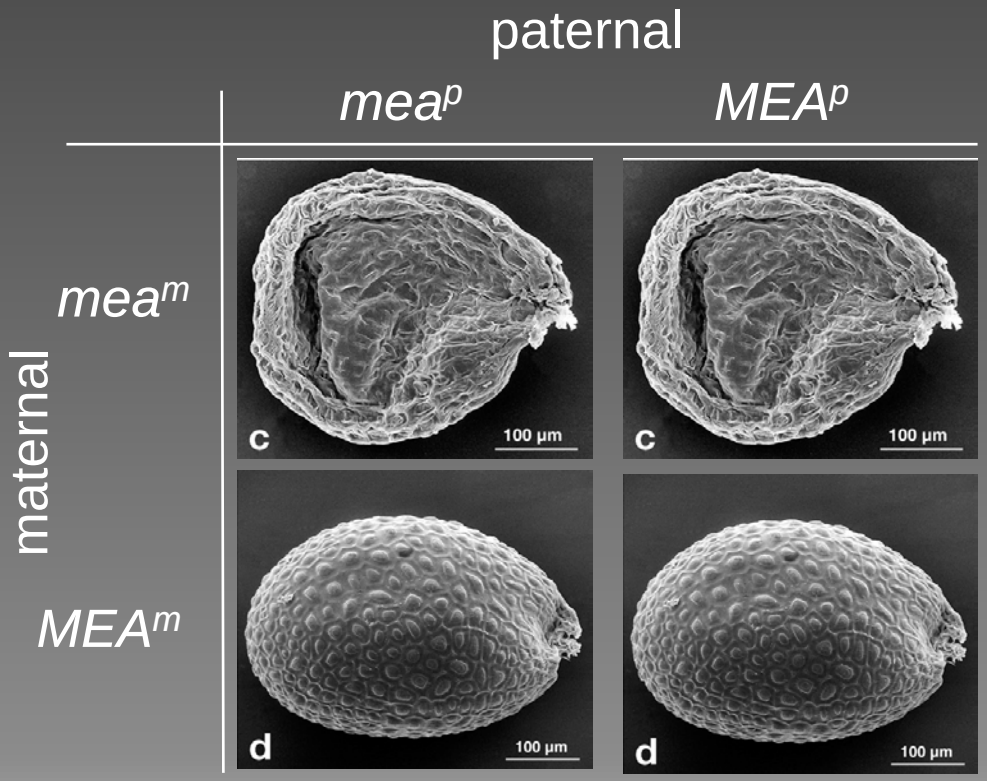
The *medea* Mutation Causes Parent-of-Origin-Dependent Seed Abortion

mea/*MEA* x wt wt x *mea*/*MEA*





seeds from *mea* embryo sacs abort
irrespective of paternal contribution

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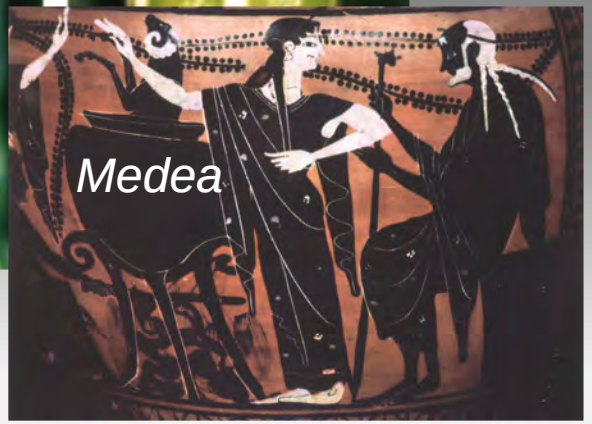
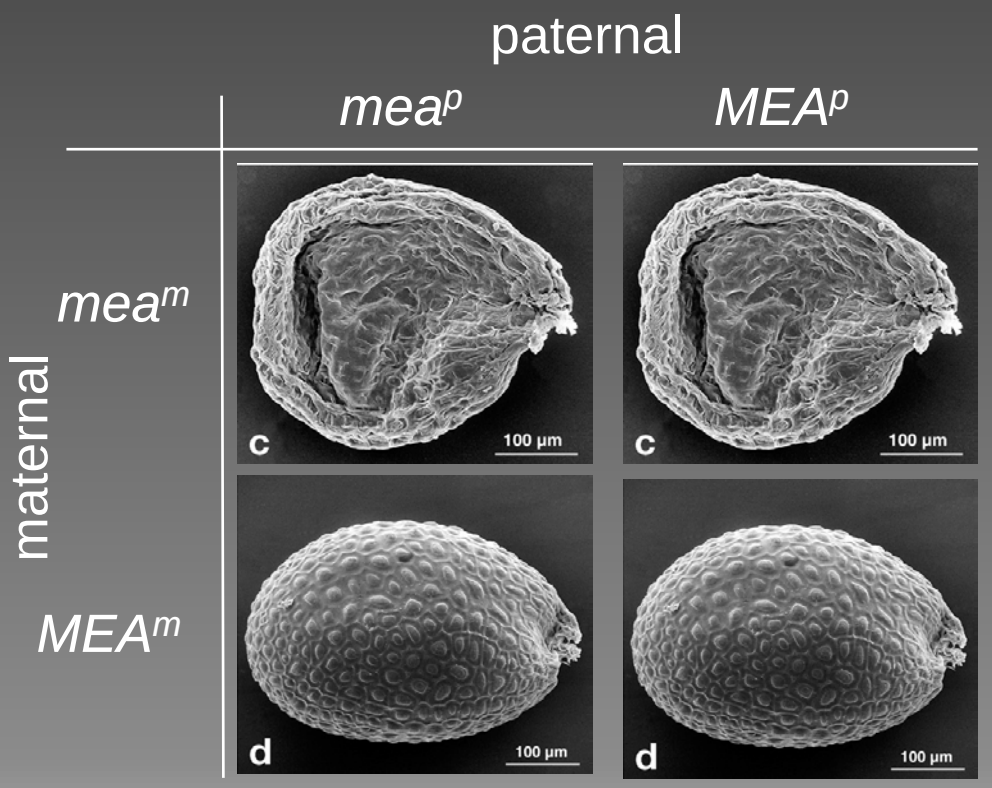
Grossniklaus *et al*.(1998) *Science* **280**, 446

The *medea* Mutation Causes Parent-of-Origin-Dependent Seed Abortion

mea/*MEA* x wt wt x *mea*/*MEA*





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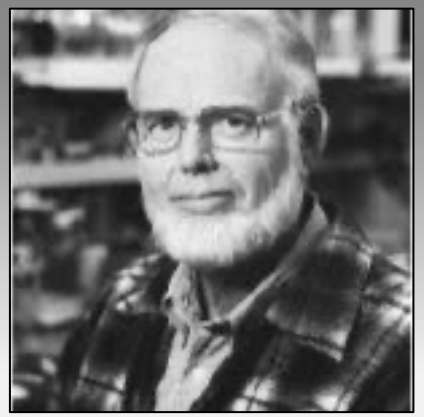
Grossniklaus *et al*.(1998) *Science* **280**, 446

Genomic Imprinting at the *R1* Locus in Maize

$R^m/R^m/r^p$

$r^m/r^m/R^p$



Jerry L. Kermicle

Genomic Imprinting at the *R1* Locus in Maize

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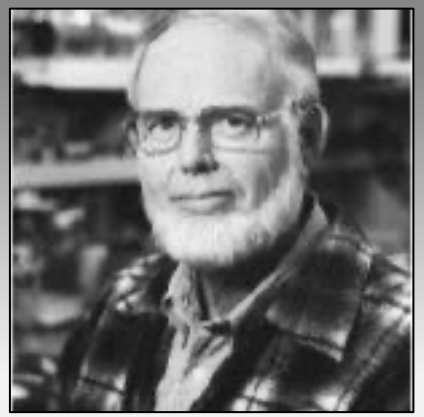


Jerry L. Kermicle

- caused by a dosage effect, not a maternal factor
- maternal effect of '**extra-chromosomal**' nature, i.e., cytoplasmicly stored factors like proteins, mRNA, sRNAs, metabolites, organelles
- '**chromosomally based**' maternal effect (genomic imprinting)

Genomic Imprinting at the *R1* Locus in Maize

$R^m/R^m/r^p$

$r^m/r^m/R^p$

DEPENDENCE OF THE *R*-MOTTLED ALEURONE PHENOTYPE IN MAIZE ON MODE OF SEXUAL TRANSMISSION[1]

J. L. KERMICLE

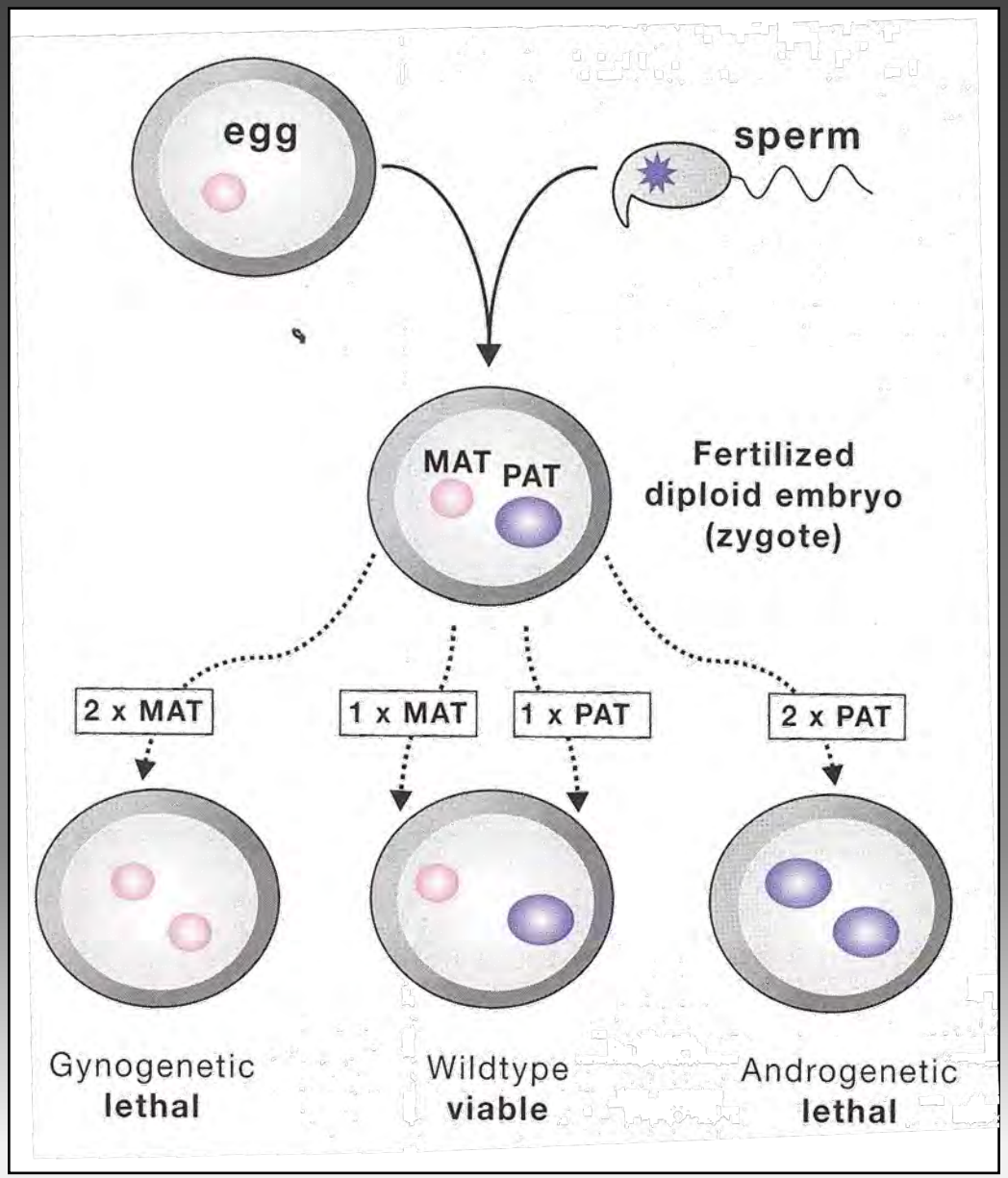
Laboratory of Genetics, University of Wisconsin, Madison 53706

Received April 13, 1970

- caused by a dosage effect, not a maternal factor
- maternal effect of '**extra-chromosomal**' nature, i.e., cytoplasmicly stored factors like proteins, mRNA, sRNAs, metabolites, organelles
- '**chromosomally based**' maternal effect (genomic imprinting):

" … that the **differential expression of *R* according to sexual origin** is chromosomal."

Genomic Imprinting at the *R1* Locus in Maize



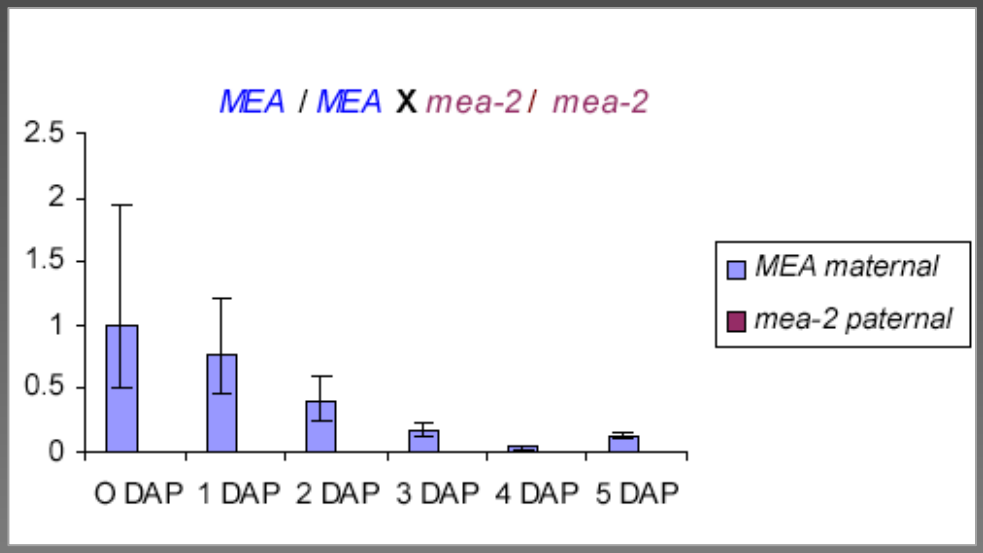
Azim Surani

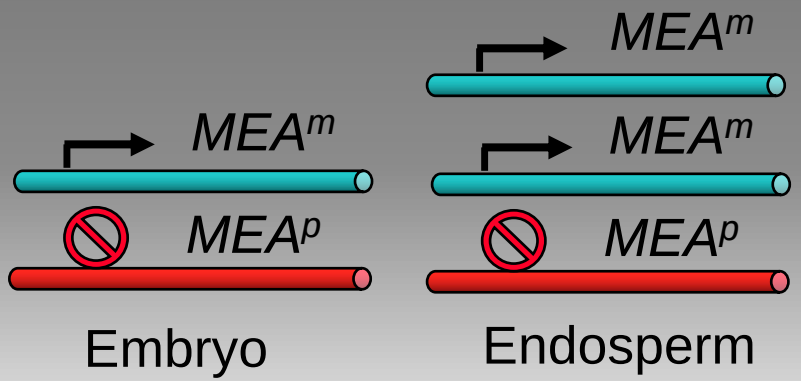
Davor Solter

In 1984, imprinting was discovered in mice and studied extensively at the mechanistic level

McGrath & Solter (1984) *Cell* **37**, 170
Surani et al. (1984) *Nature* **308**, 548

The *MEDEA* Locus Is Regulated by Genomic Imprinting





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Vielle-Calzada *et al.* (1999) *Genes Dev* **13**, 2971; Baroux et al. (2006) *Genes Dev* **20**, 1081

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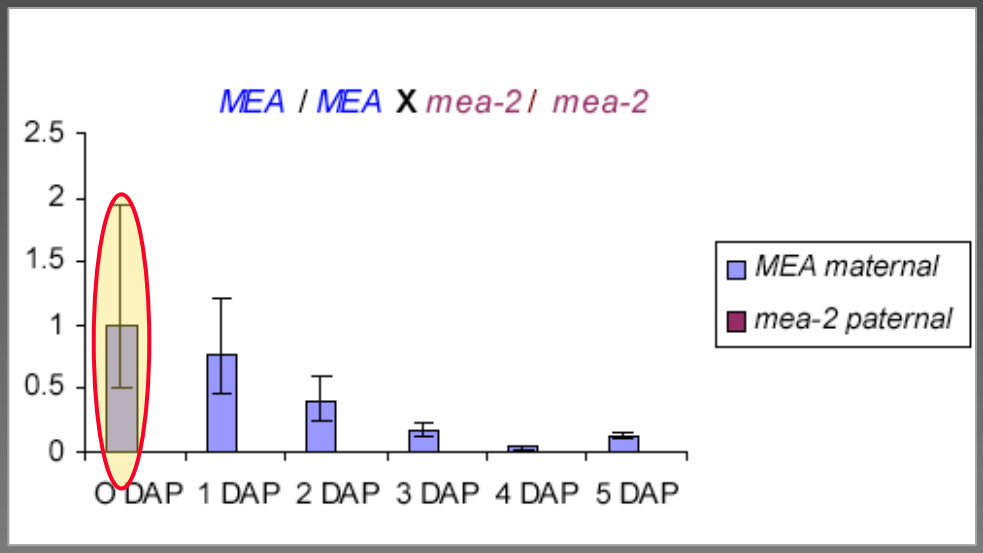

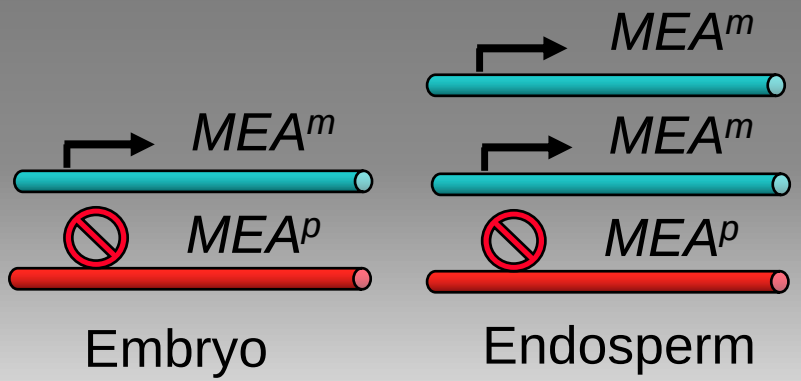

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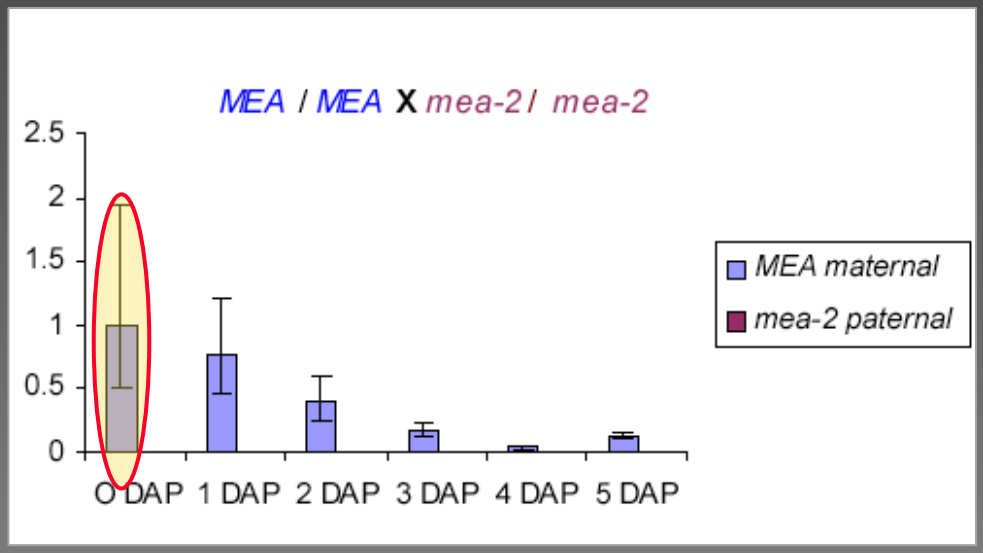
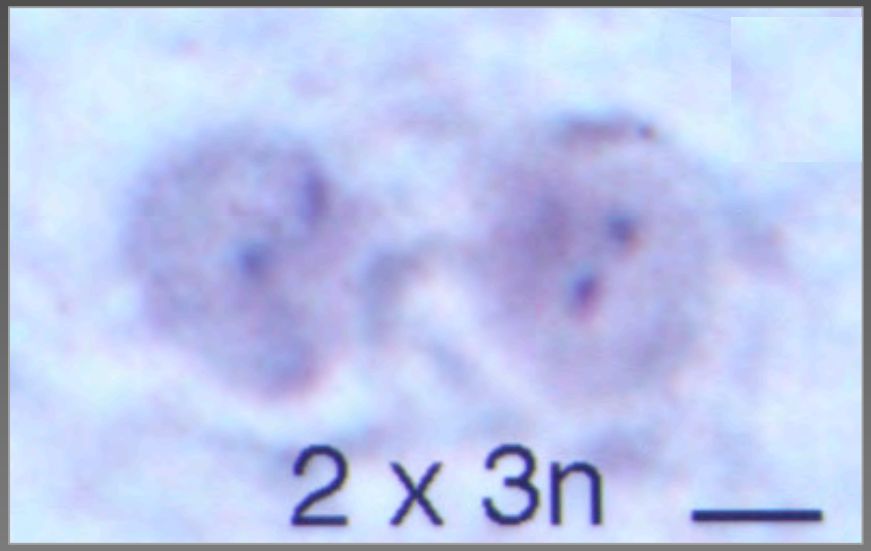
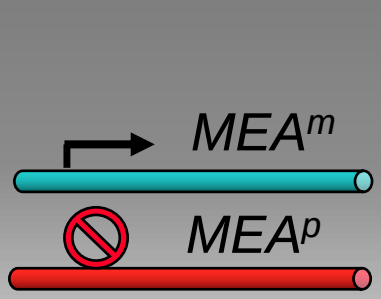
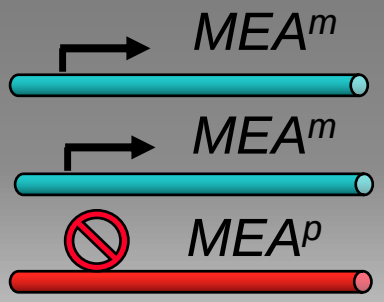


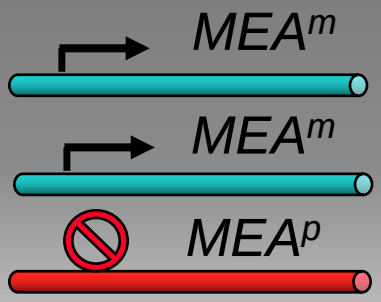




Embryo



Endosperm



Endosperm

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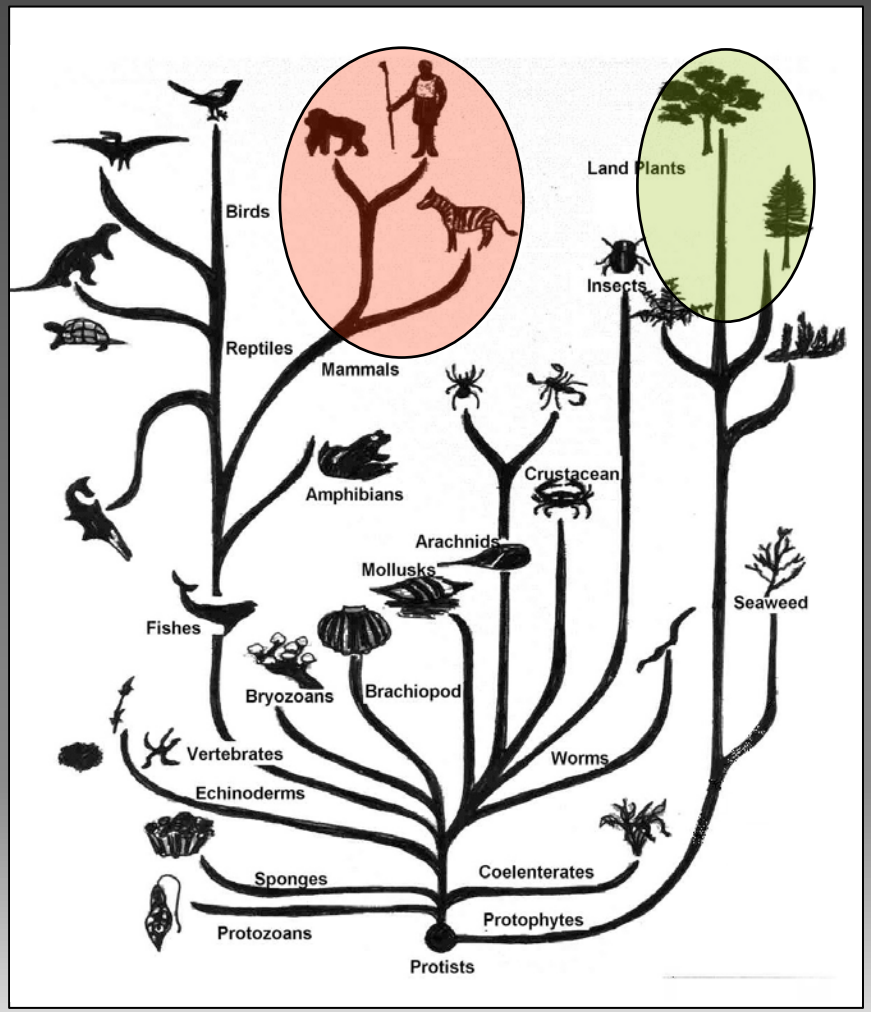
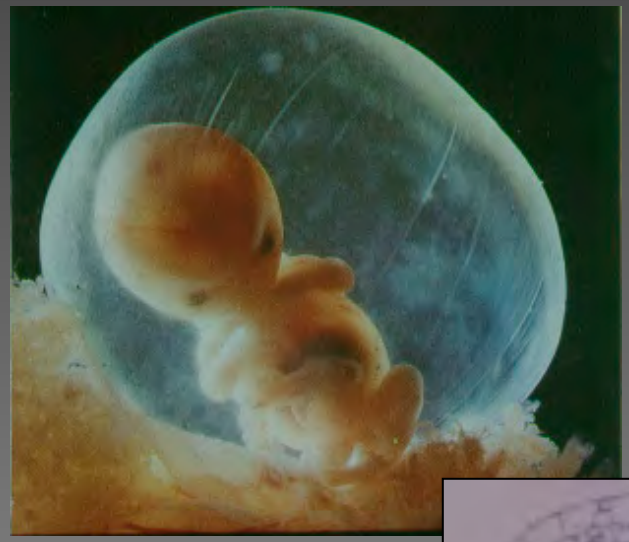
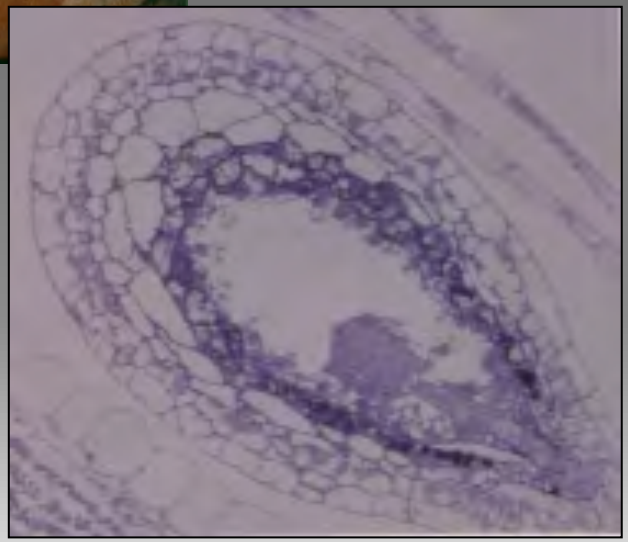
Vielle-Calzada *et al.* (1999) *Genes Dev* **13**, 2971; Baroux et al. (2006) *Genes Dev* **20**, 1081

Mammals and Seed Plants Share a Placental Habit





The mother provides all nutrients for embryo or seed development



Parental Conflict Theory for the Evolution of Imprinting


David A. Haig

- Hypothesis:

  In polygamous organisms with a placental habit imprinting evolved as a consequence of a conflict between maternal and paternal interests over the allocation of nutrients from mother to offspring

- Predictions:
  - Paternal expression should tend to increase offspring size
  - Maternal expression is expected to restrict growth of the embryo or seed

Haig & Westoby (1989) *Am. Nat.***134**, 147

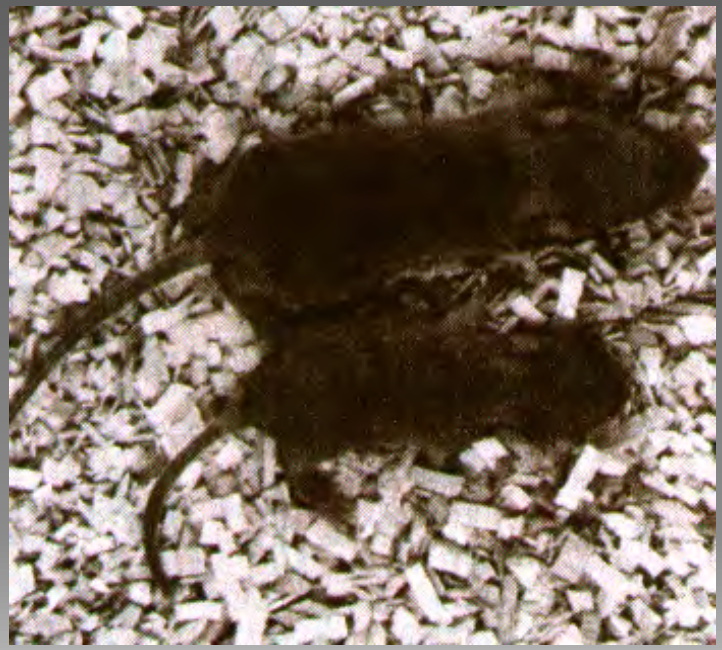
The *medea* Phenptype Is Consistent with the Parental Conflict Theory

MEA: maternally expressed
mutant: embryonic overgrowth

IGF-II: paternally expressed
mutant: small (40% less weight)

wild-type

mea^{m}/*MEA*^{p}



+/+

+/-

IGF-II ^{m}/*Igf-II* ^{p}

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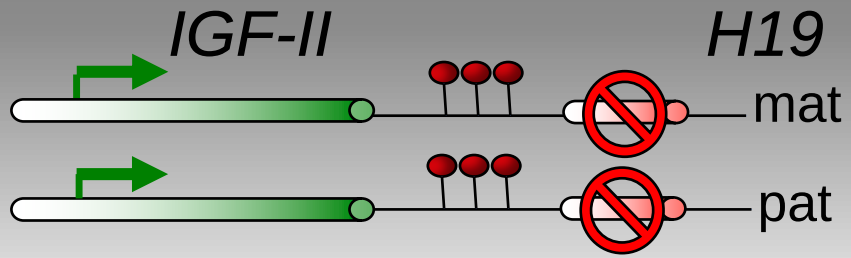
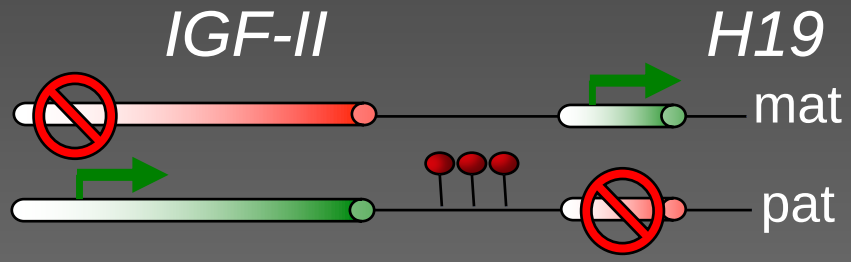
Grossniklaus *et al*. (1998) *Science* **280**, 446; Wang et al. (1994) *Nature* **372**, 464

In Beckwith-Wiedemann (BWS) and Russell-Silver Syndromes (RSS) Imprinting Is Affected

BWS

5-10%

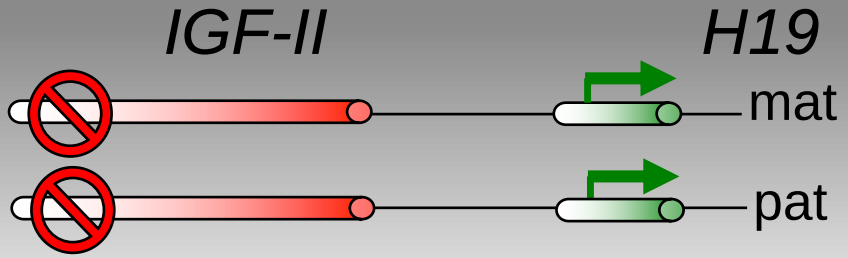




Chromosome 11p15.5

RSS

37-63%



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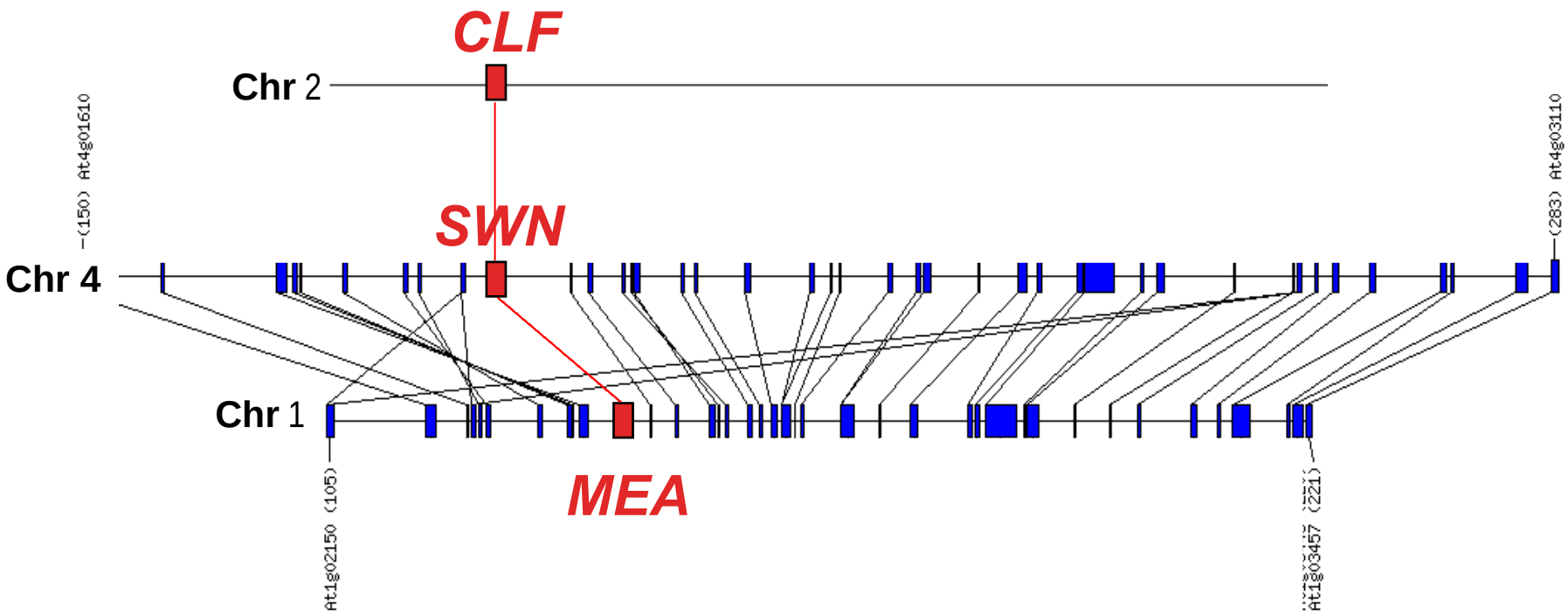
Õunap (2016) *Mol Syndromol* **7**, 110

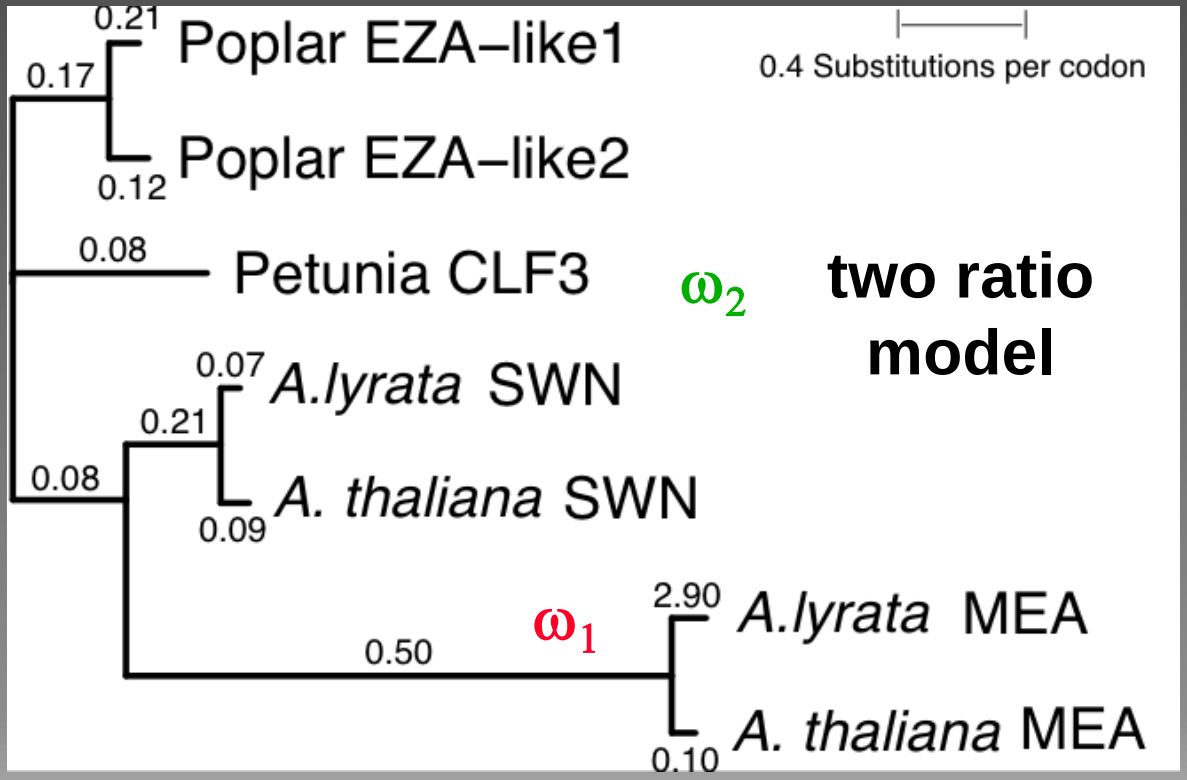
MEDEA Is A Paralog of *SWINGER* (*SWN*) that Arose 35-85 mya



Arabidopsis MEA & SWN are paralogs that arose by an ancestral segmental duplication which occured ~35-85 Mya (Blanc *et al*. (2003) *Genome Res* **13**, 137)

Spillane *et al.* (2007) *Nature* **448**, 349

Branch Models (PAML) Provide Support for Positive Darwinian Selection at *MEDEA*



Tree topology was obtained with protml, and branch lengths were calculated with codeml using Model M0. The numbers above branches indicate ω-ratios, which were calculated with the free-ratio model.

- *MEA* evolved more rapidly than *SWN* in the branch before *A. lyrata* and *A. thaliana* split
- This could be due to neofunctionalization and/or genomic conflict
- Within *A. thaliana*, *SWN* and *MEA* evolve similarly

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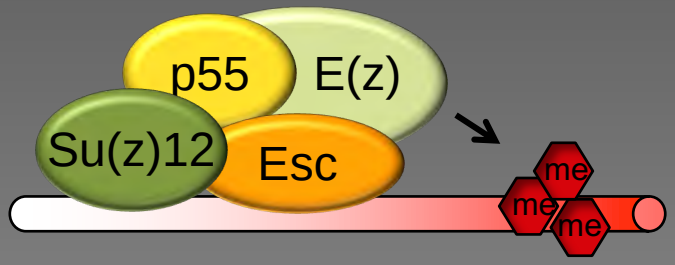
Spillane *et al.* (2007) *Nature* **448**, 349

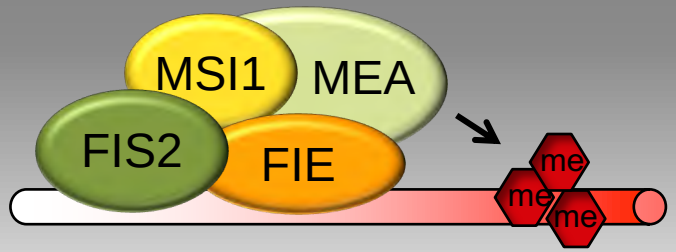
MEDEA Encodes the Methyltransferase of Plant *Polycomb* Repressive Complex 2 (PRC2)

PRC2 silences its target genes
by H3K27me3

Drosophila PRC2



Arabidopsis FIS-PRC2



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Grossniklaus *et al*.(1998) *Science* **280**, 446; Köhler *et al.* (2003) *EMBO J* **22**, 4804

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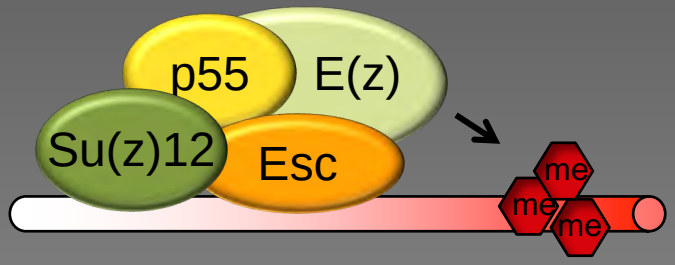

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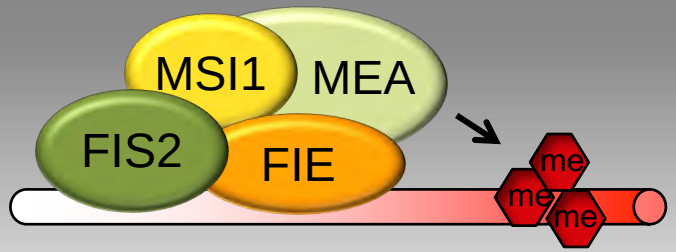
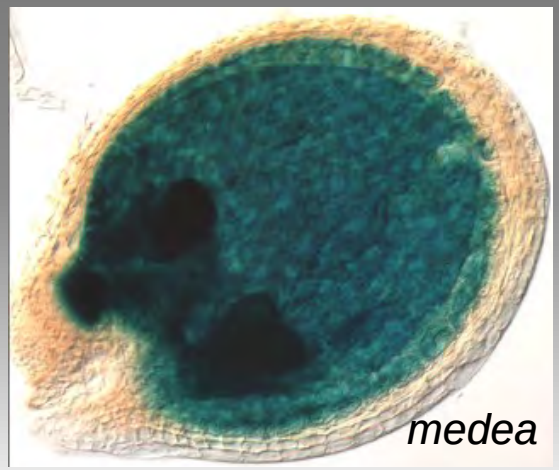


PHERES1 is a MEA target



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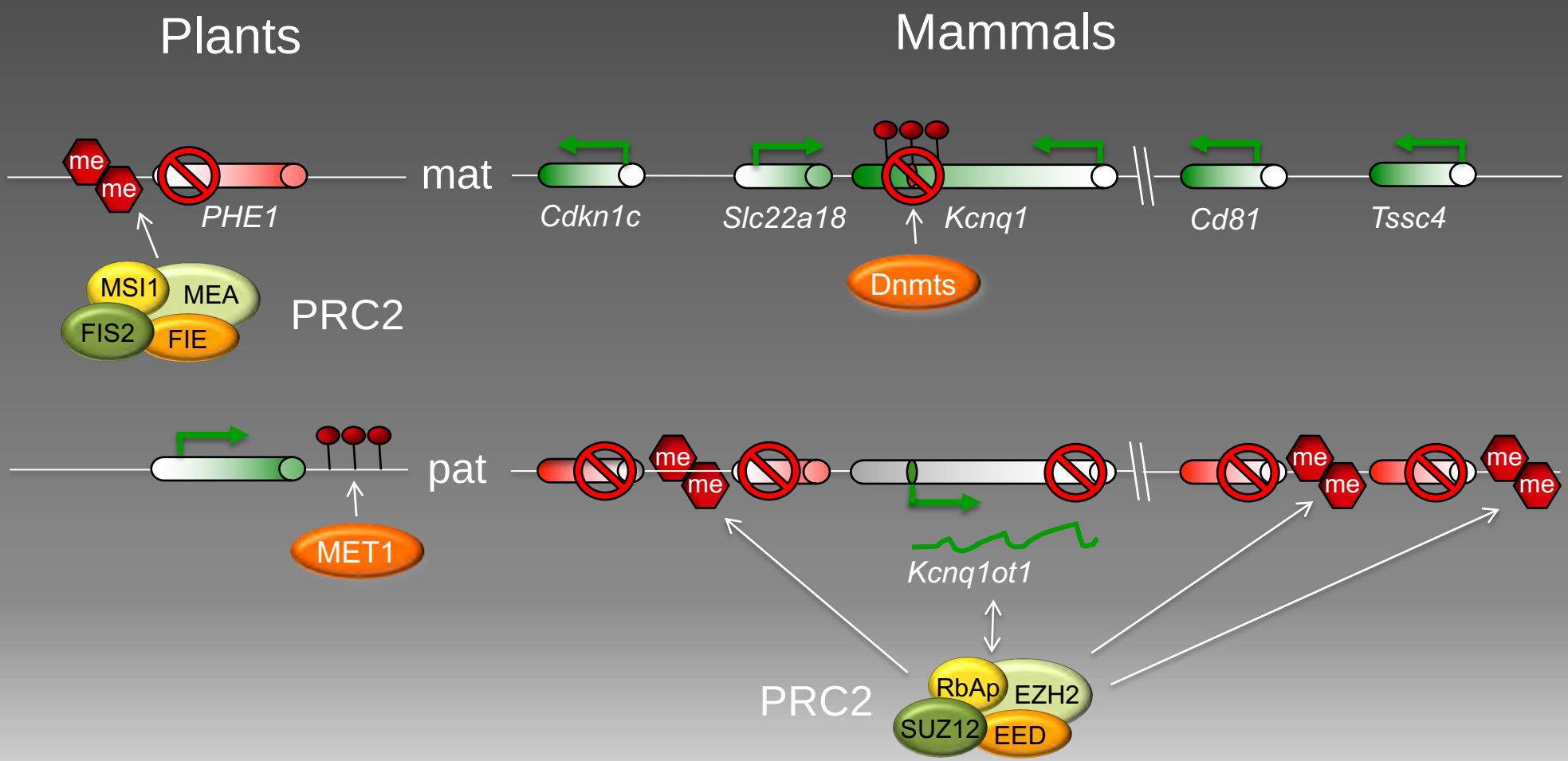
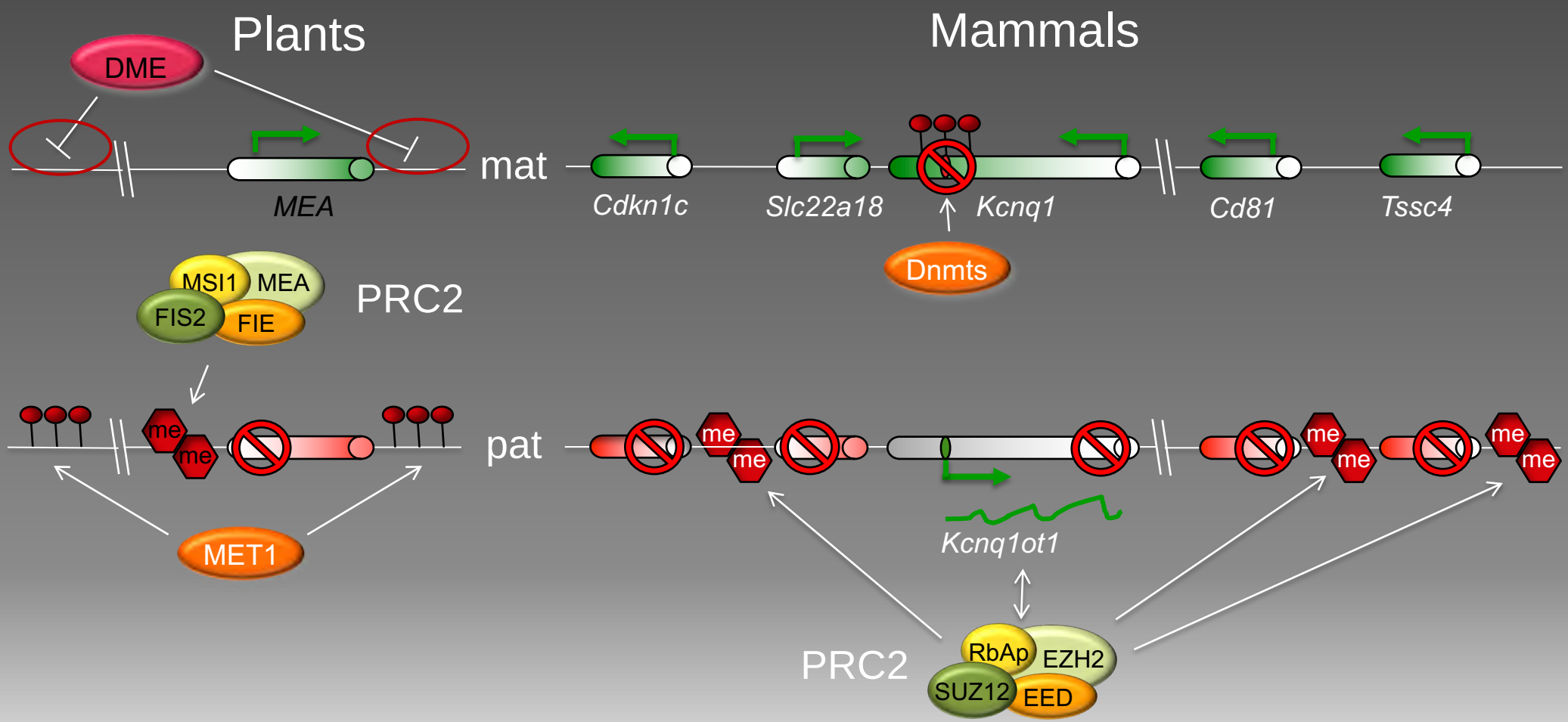
Köhler *et al.* (2003) *Genes Dev* **17**, 1540; Köhler *et al.* (2005) *Nature Genet* **37**, 28

DNA Methylation and PRC2 Contribute to Imprinting in Mammals and Plants



Köhler *et al. Genes Dev* (2003), Köhler *et al. Nat Genet* (2005), Makarevich *et al. J Cell Sci* (2008), Gehring *et al. Cell* (2006) Jullien *et al. Curr Biol* (2006); Baroux *et al. Genes Dev* (2006); Umlauf *et al. Nat Genet* (2004), Terranova *et al. Dev Cell* (2008)

DNA Methylation and PRC2 Contribute to Imprinting in Mammals and Plants



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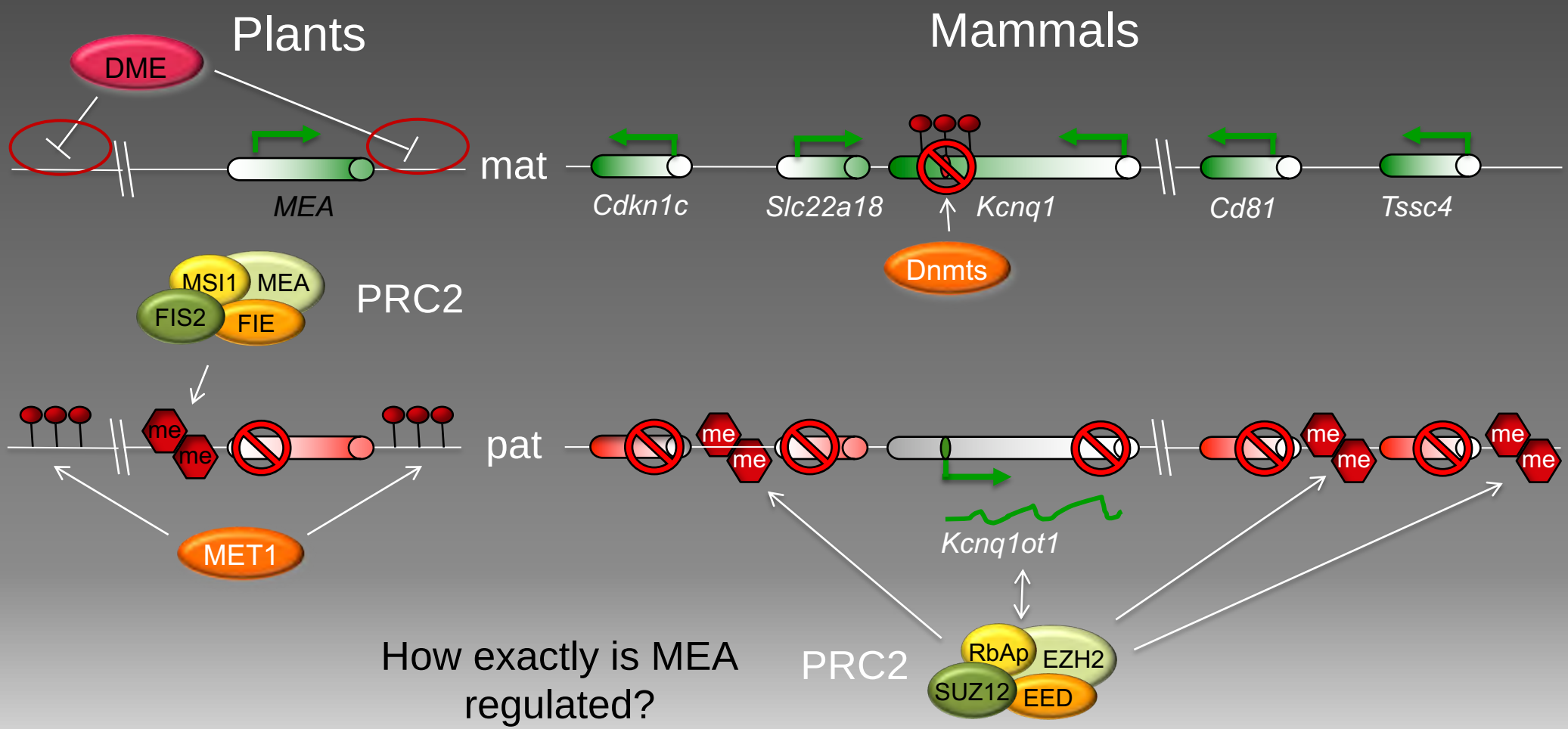
DNA Methylation and PRC2 Contribute to Imprinting in Mammals and Plants



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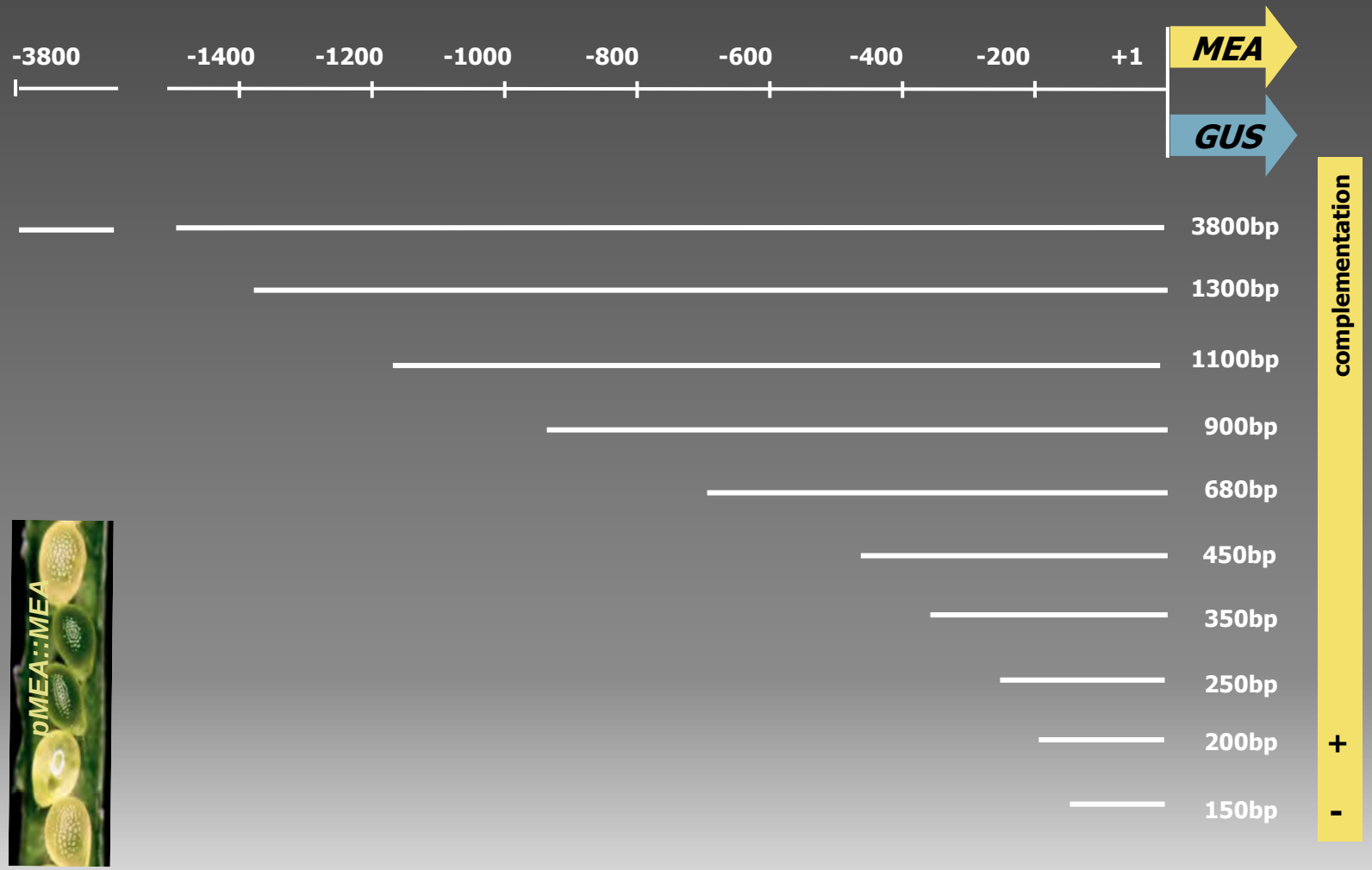
A 200 bp Region in the Promoter Is Required for *MEDEA* Expression and Function



University of Zurich[UZH]

Wöhrmann *et al*. (2012) *Genes Dev* **26**, 1837

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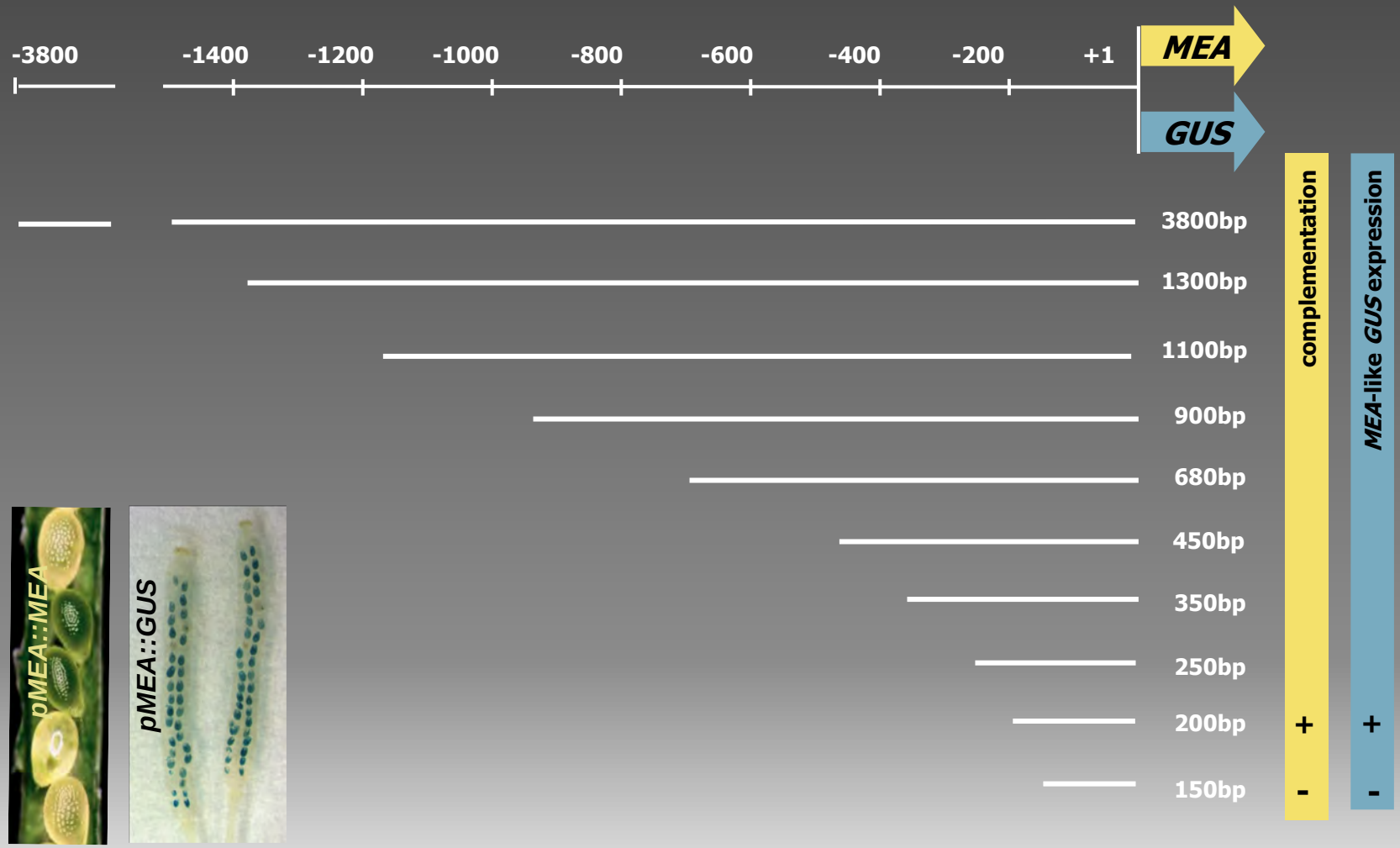

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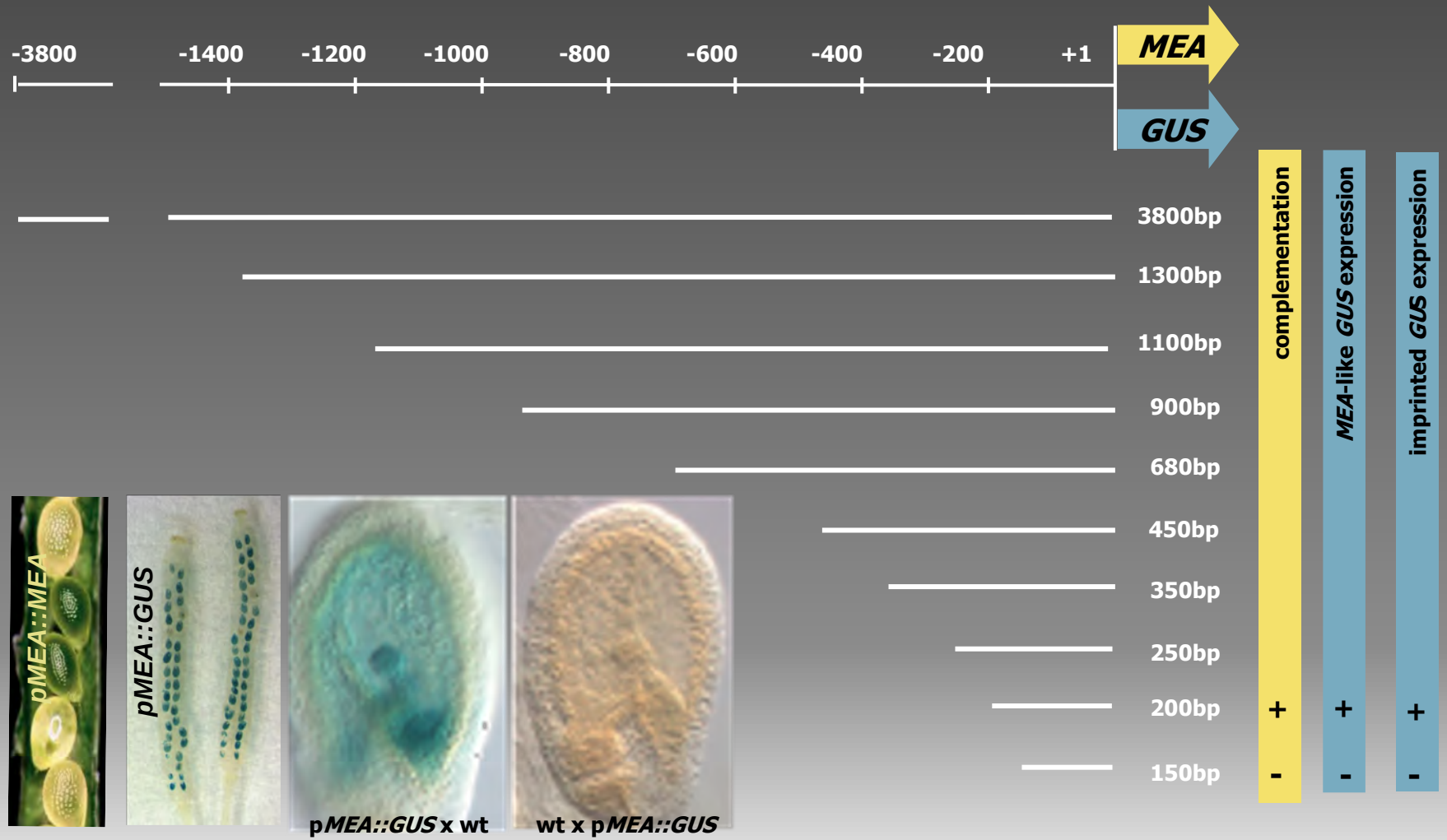
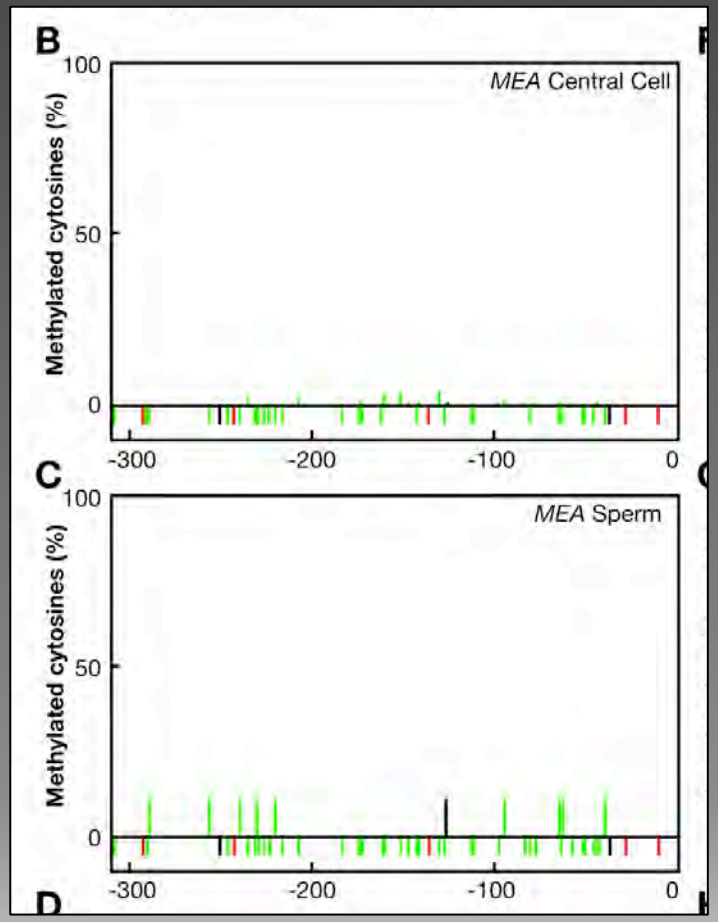


University of Zurich[UZH]

Wöhrmann *et al*. (2012) *Genes Dev* **26**, 1837

DNA Methylation is NOT the Primary Imprint

MEA-ICR



Wendelin Wehrle, Anja Schmidt
Julia Arand, Sascha Tierling, Jörn Walter

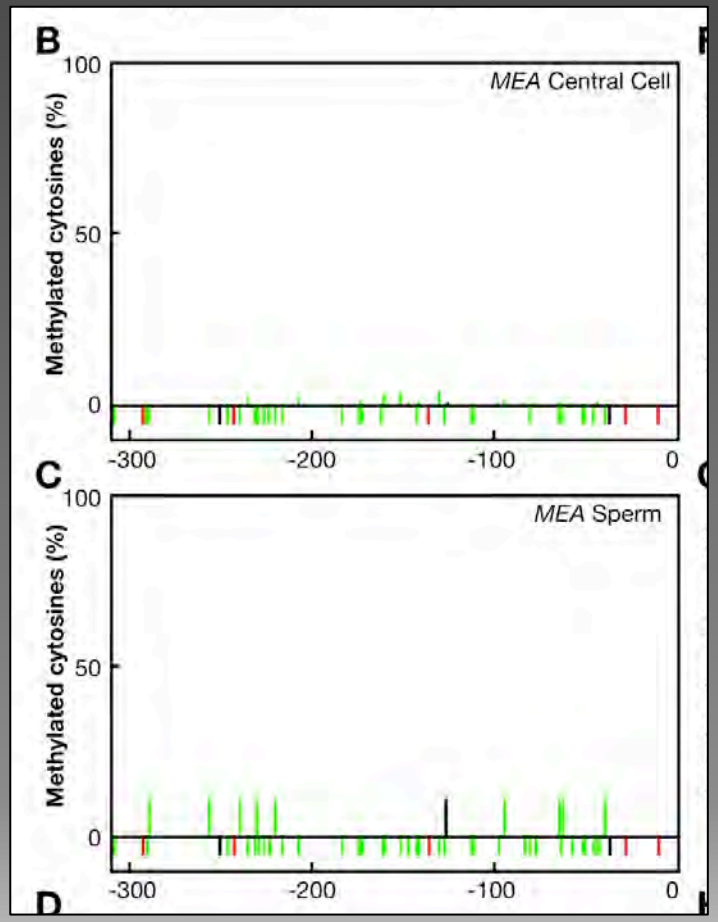
- First ICR without a DNA methylation mark in gametes

University of Zurich[UZH]

Wöhrmann *et al*. (2012) *Genes Dev* **26**, 1837

DNA Methylation is NOT the Primary Imprint

MEA-ICR



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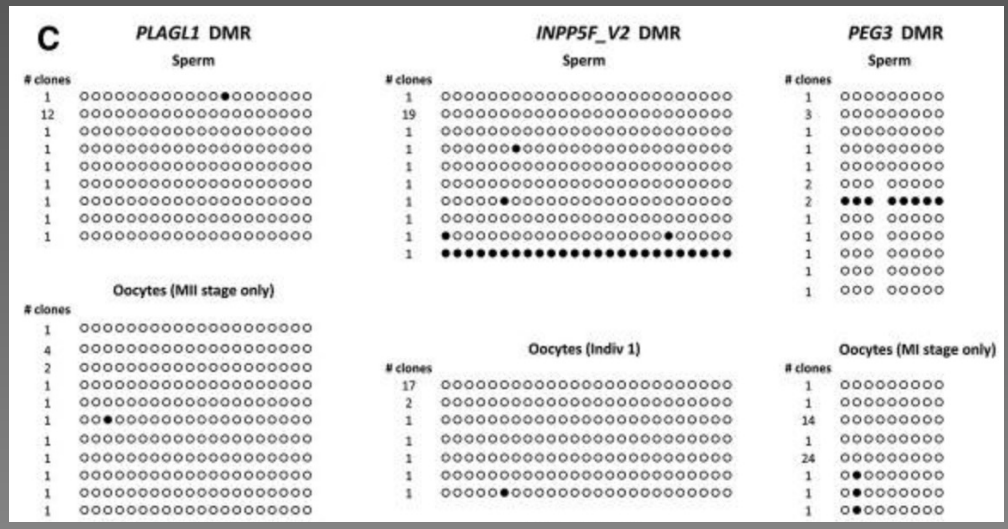
- First ICR without a DNA methylation mark in gametes



ICR w/o DNA methylation also exist in mice (Cheong et al. (2015) *Genome Res* **25**, 611)

Maternal H3K27me3 controls DNA methylation-independent imprinting

Azusa Inoue[1,2,3]*, Lan Jiang[1,2,3]*, Falong Lu[1,2,3]†*, Tsukasa Suzuki[1,2,3] & Yi Zhang[1,2,3,4,5]

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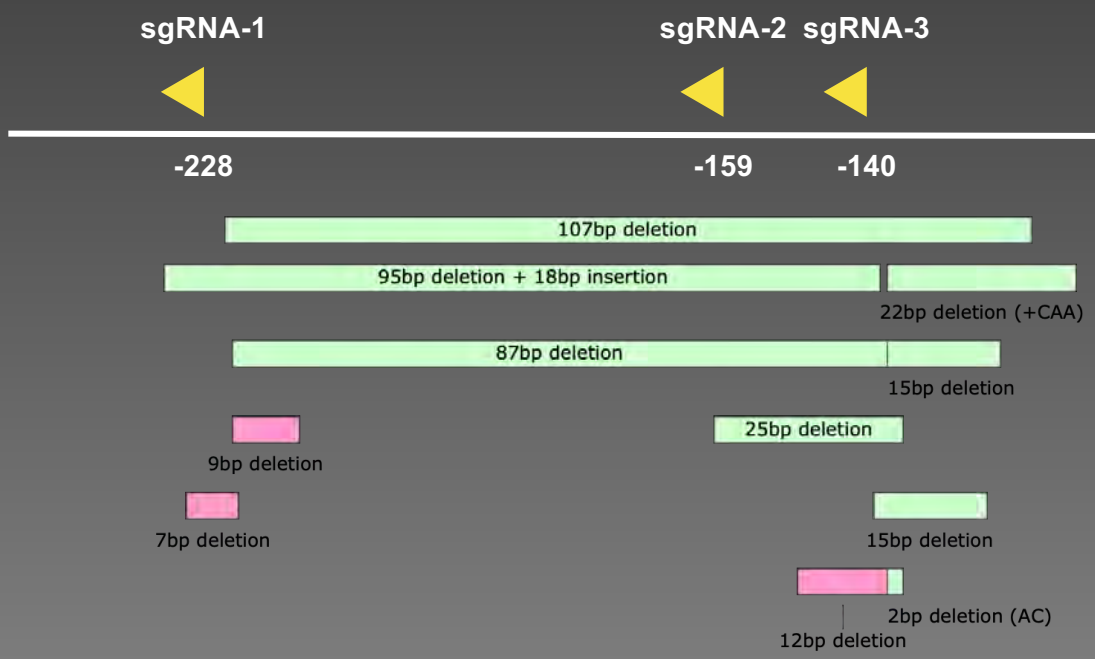
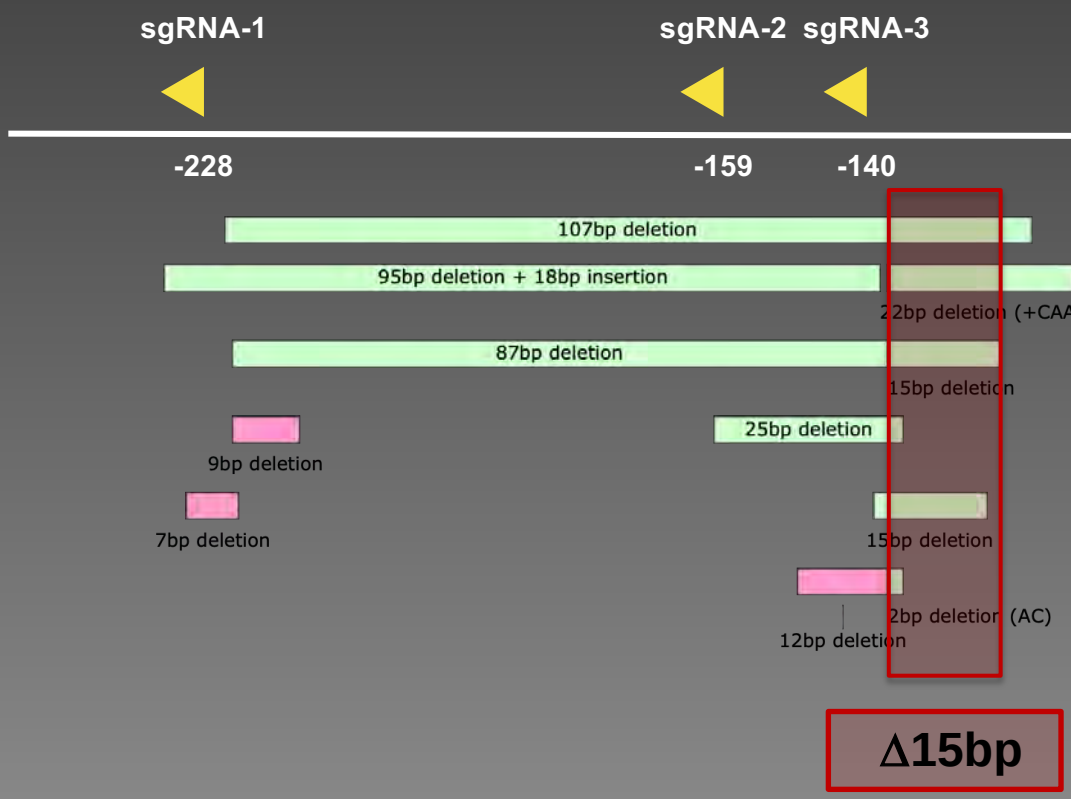
Wöhrmann *et al*. (2012) *Genes Dev* **26**, 1837

cis-Regulatory Mutagenesis by CRISPR/Cas9



- Mutations in *MEA* promoter causing maternal effect seed abortion
- Mutations are not fully penetrant

cis-Regulatory Mutagenesis by CRISPR/Cas9



- Mutations in *MEA* promoter causing maternal effect seed abortion
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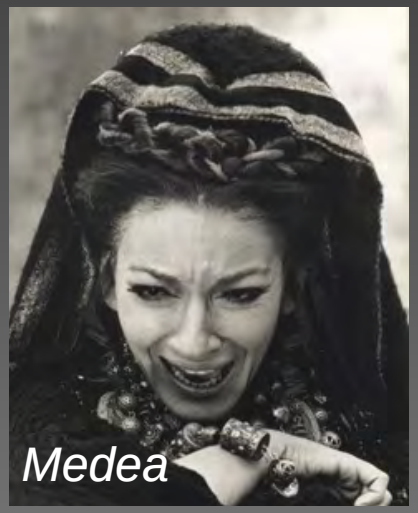
Summary

- *MEDEA* is regulated by **genomic imprinting** which likely evolved due to a parental conflict similar to the situation in mammals (convergent evolution)
- For some imprinted loci in both mammals and plants, **DNA methylation** and **PRC2 repression** are key regulators, but for many imprinted plant genes, they are not
- The molecular nature of the primary imprint at *MEDEA* is unknown; **DNA-methylation is NOT the primary imprint**
- A **15bp *cis*-element** is required for imprinting; deletions lead to seed abortion due to loss of imprinting
  → Imprinting Control Region (ICR)

Acknowledgements: Imprinting



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erc European Research Council

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Thank you for your Attention!