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# Incorporating biological information into genomic prediction models

Fanny Mollandin, Pascal Croiseau, Andrea Rau

VistaMilk

*Artificial Intelligence in Agriculture Masterclass @ Zoom*

February 8, 2023





## INRAE Research Center @ Jouy en Josas:

- ✓ 1500+ staff
- ✓ Animal biology, microbiology, data science, systems biology

## Animal Genetics & Integrative Biology (GABI) unit

- ✓ Understanding & exploiting animal genetic variability
- ✓ Construction of phenotypes and their interaction with microbial ecosystems and environments
- ✓ Agroecological transition

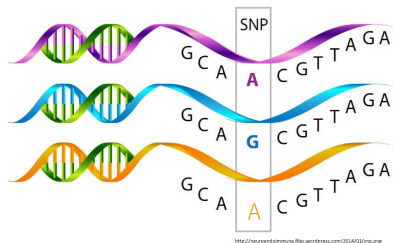


# Genomic selection overview

Objective: select the best animals for reproduction to obtain **genetic improvement** of the population on **traits of interest**

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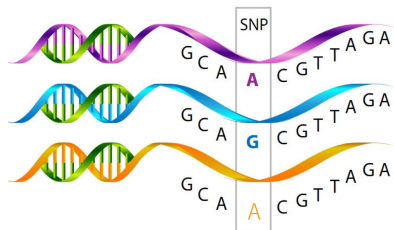
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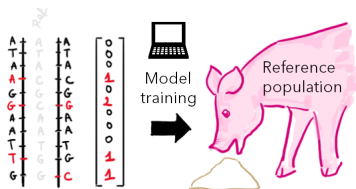
- Low- to high-density genotyping chips (10k-100k SNPs)  
→ whole genome sequencing (10MM SNPs)

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<http://neuroendocrine.wikis.wordpress.com/2014/03/npng>

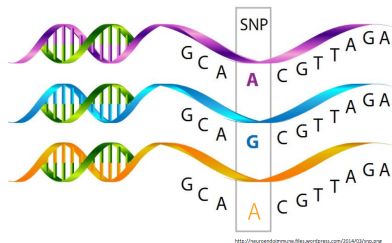


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Image: F. Mollandin

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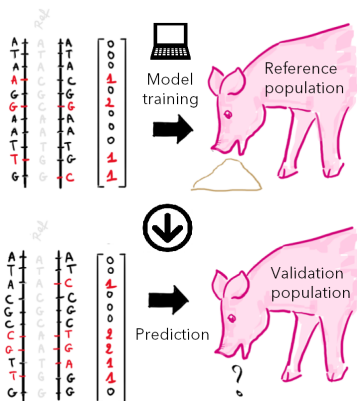


Image: F. Mollandin

# Prediction models for genomic selection

Goal: given a **training set** of data  $(Y_i, X_i, Z_i)$  for  $i = 1, \dots, n$  individuals

- $Y_i$  = trait
- $X_i$  = vector of (usually genome-wide) genotypes
- $Z_i$  = vector of covariates (age, location, sex, ...)

... **predict the unobserved trait**  $Y_*$  of a future individual with corresponding  $X_*$  and  $Z_*$



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- Introduced by Meuwissen *et al.* (2001)
- Successfully implemented in many plant/animal breeds for traits related to production, health, climate adaptation, ...
- Modest gains in predictions can have large economic impacts (reduced generation interval, reduced cost and labor for phenotyping)

# Challenges of genomic prediction models

- Non-random association between alleles at neighboring loci (aka LD)
- Polygenic nature of complex traits
- Many more SNPs (variables) than individuals (observations)  $\Rightarrow$  curse of dimensionality
  - Including too many predictors in a model risks **over-fitting**, **poor generalizability**, and **problems with model estimation**
  - ... but including only a small pre-identified subset of SNPs (e.g., significant GWAS hits) usually leads to **poor predictions**

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Can genomic prediction models be improved by better accounting for our **knowledge** about the **function** of certain regions of the genome?

# Context: H2020 GENE-SWitCH project

The regulatory GENomE of Swine & Chicken: functional annotation during development

High-quality richly annotated maps of pig and chicken genomes:

- **Development:** early/late organogenesis, new born/hatched, adult
- **Sexes:** {M,F} × 3 biological replicates
- **Tissues:** liver, skeletal muscle, small intestine, cerebellum, dorsal epidermis, lung, kidney
- **Assays:** RNA-seq, ATAC-seq, ChIP-seq, smRNA-seq, methylation, Hi-C



Integrate functional information with phenotypic + genotypic data in **genomic prediction models** for greater **power** and **interpretability**

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## But how?

# First, back to basics: the linear model

The workhorse of genomic prediction is the multiple linear regression model:

$$Y = \mathbf{Z}\theta + \mathbf{X}\beta + \varepsilon$$

- $Y = n$ -vector of traits
- $\mathbf{Z} = n \times m$  matrix of covariates
- $\theta = m$ -vector of covariate effect parameters
- $\mathbf{X} = n \times p$  matrix of (suitably coded) genotypes
- $\beta = p$ -vector of genetic effect parameters
- $\varepsilon = n$ -vector of errors representing noise, assumed to be iid and (usually) normally distributed

# Bayesian methods for genomic prediction

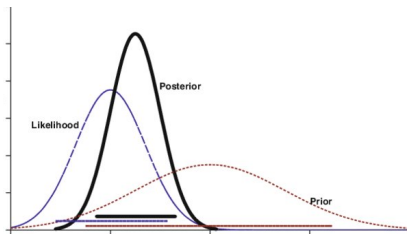


Image: 10.1007/s10681-007-9516-1

# Bayesian methods for genomic prediction

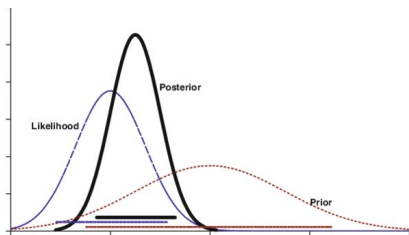


Image: 10.1007/s10681-007-9516-1

likelihood

×

prior

$$\prod_{i=1}^n N \left( Y_i \mid \left( \mu + \sum_{j=1}^p X_{ij} \beta_j \right), \sigma^2 \right) \times p(\sigma^2) \prod_{j=1}^p p(\beta_j \mid \Psi)$$

- $\sigma^2$  often assigned a  $\chi^{-2}$  prior distribution
- Choice of prior for  $\beta_j$  should ideally reflect a trait's genetic architecture (and be computationally feasible...)



# Which prior to use for $\beta_j$ ?

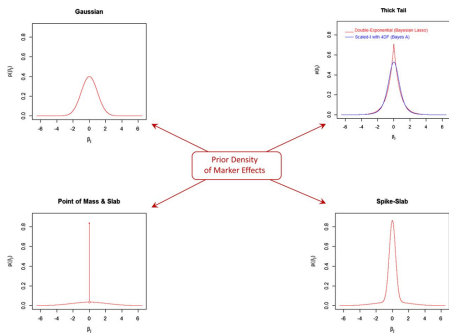


Image: 10.1543/genetics.112.143313

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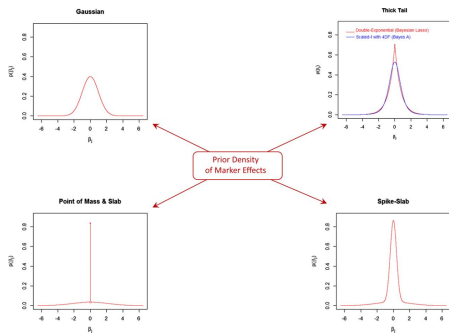


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**GBLUP:**  $\beta_i \sim N(0, \sigma_\beta^2)$

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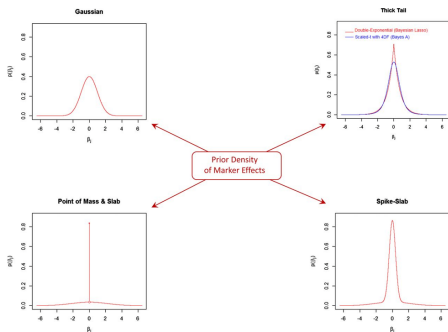


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**BayesB:**  $\beta_i \sim N(0, \sigma_{\beta_i}^2), \sigma_{\beta_i}^2 \sim \pi\delta(0) + (1 - \pi)\text{Inv } \chi^2(\nu, S^2), \pi$  fixed

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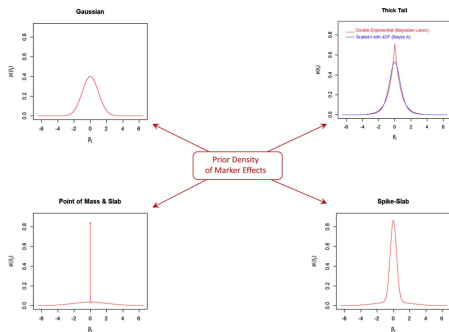


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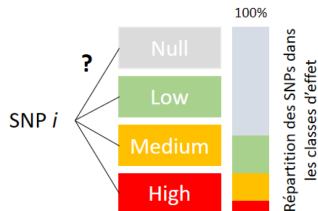
**BayesC:**  $\beta_i \sim \pi\delta(0) + (1 - \pi)N(0, \sigma_\beta^2), \sigma_\beta^2 \sim \text{Inv } \chi^2(\nu, S^2), \pi$  fixed

**BayesC $\pi$ :** BayesC with  $\pi \sim \text{Unif}(0, 1)$

# BayesR (Erbe *et al.*, 2012)

$$\beta_i \sim \underbrace{\pi_1 \delta(0)}_{\text{null}} + \underbrace{\pi_2 N(0, 0.0001\sigma_g^2)}_{\text{small}} + \underbrace{\pi_3 N(0, 0.001\sigma_g^2)}_{\text{medium}} + \underbrace{\pi_4 N(0, 0.01\sigma_g^2)}_{\text{large}}$$

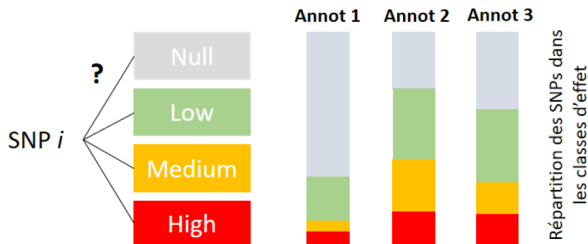
- $\pi \sim \text{Dirichlet}(\alpha)$ , with  $\alpha = (1, 1, 1, 1)$
- Gibbs sampler for estimation



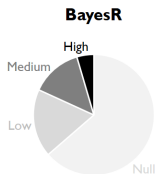
# Back to annotations: BayesRC (MacLeod *et al.*, 2016)

$$f(\beta_i | C_i = c) = \sum_{k=1}^4 \pi_{c,k} f_k(\cdot | \theta_k)$$

- SNPs assigned to disjoint **“annotations”**, model is a factorized BayesR
- $\pi_c \sim \text{Dirichlet}(\alpha)$ , with  $\alpha = (1, 1, 1, 1)$
- Gibbs sampler for estimation



# From BayesR to BayesRC ... and beyond



**Genotype** ...000001001201002100200010100001011001011110...  
 ...ACTCCGTAAGTACTAGCCTACAAAGGCTAACTTACAAAAGATTTA...

Predict →



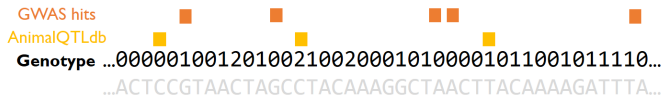
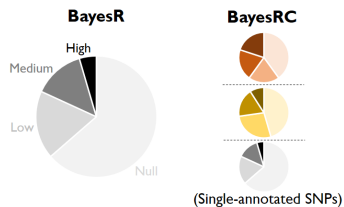
**GBV**



This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under the grant agreement n° 817998



# From BayesR to BayesRC ... and beyond

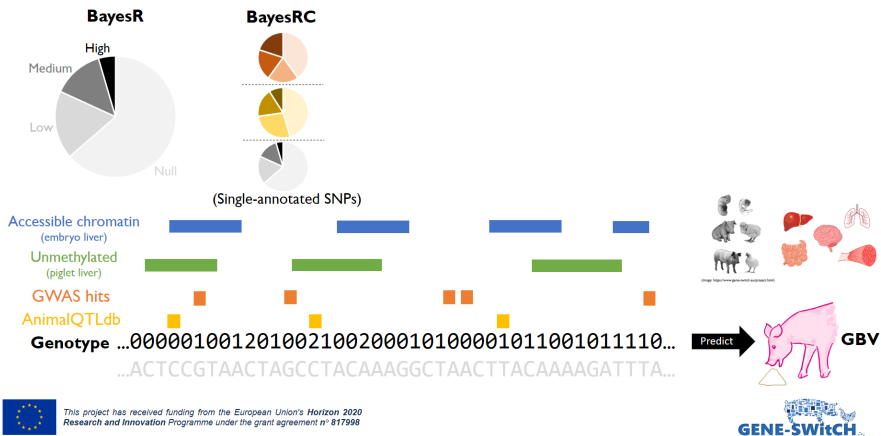


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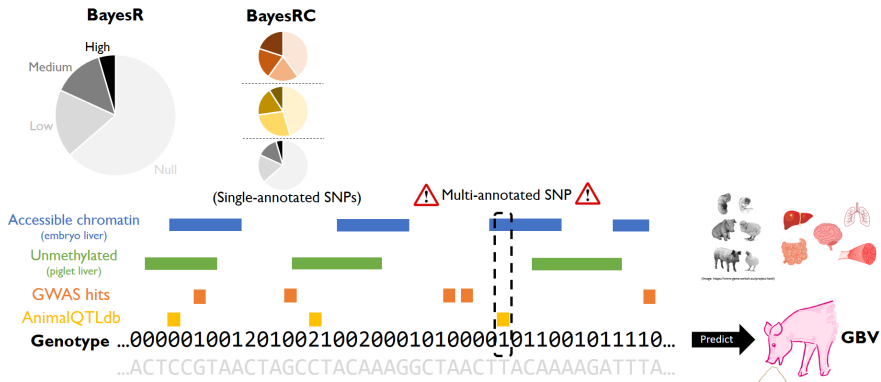
Predict →



**GBV**

**GENE-SWITCH**

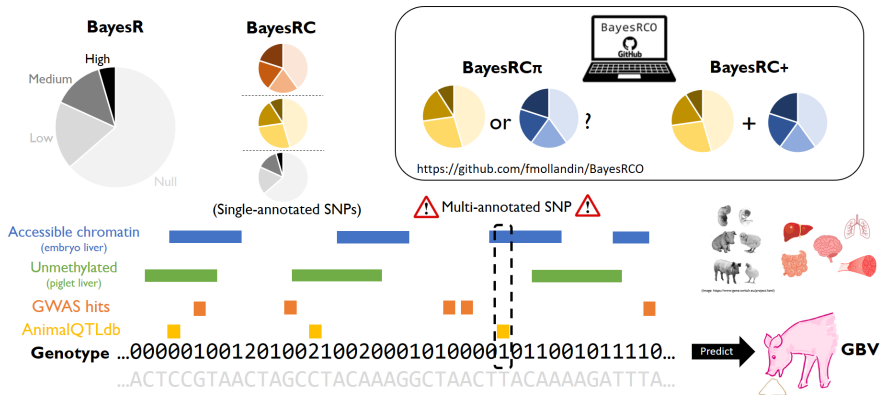
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# BayesRCO: BayesRC for Overlapping annotations

Two hypotheses = two models!

- 1 Multi-annotations represent **added confidence** → BayesRC+
- 2 Multi-annotations represent **uncertainty** → BayesRC $\pi$

$$A \in \{0, 1\} = \begin{pmatrix} & \text{Annot 1} & \text{Annot 2} & \dots & \text{Annot K} \\ \text{SNP 1} & 0 & 1 & \dots & 0 \\ & 0 & 0 & \dots & 1 \\ & \cdot & \cdot & \cdot & \cdot \\ & 1 & 0 & \dots & 0 \\ & 1 & 0 & \dots & 0 \end{pmatrix}$$

$$\sum_{i=1}^K A(i, j) = 1$$

$$A \in \{0, \beta\} = \begin{pmatrix} & \text{Annot 1} & \text{Annot 2} & \dots & \text{Annot K} \\ \text{SNP 1} & 1 & 1 & \dots & 0 \\ & 0 & 0 & \dots & 1 \\ & \cdot & \cdot & \cdot & \cdot \\ & 1 & 0 & \dots & 1 \\ & 1 & 1 & \dots & 1 \end{pmatrix}$$

$$\sum_{i=1}^K A(i, j) \geq 1$$

	Method	SNP effect prior distribution	Annotations
	BayesR	$\beta_i \sim \sum_{K=1}^4 \pi_K \mathcal{N}(0, k\sigma_g^2)$	No
	BayesRC	$\beta_i   a = A(i) \sim \sum_{K=1}^4 \pi_{K,a} \mathcal{N}(0, k\sigma_g^2)$	Yes, disjointed
Cumulative →	BayesRC+	$\beta_i   a \in A(i) \sim \sum_{a \in A(i)} \sum_{K=1}^4 \pi_{K,a} \mathcal{N}(0, k\sigma_g^2)$	Yes, overlapping
Preferential assignment →	BayesRC $\pi$	$\beta_i   a \in A(i) \sim \sum_{a \in A(i)} p_{i,a} \sum_{K=1}^4 \pi_{K,a} \mathcal{N}(0, k\sigma_g^2)$	Yes, overlapping

# Simulation strategy

Phenotypes simulated from real cattle genotypes, 2500 animals:

- $h^2 = \{0.2, 0.5\}$
- 5 **large** QTLs representing  $k = \{1\%, 2.5\%, 5\%$  of total additive variance  $\sigma_a^2$
- 300 **medium** QTLs representing 0.1% of  $\sigma_a^2$
- 450 to **6500** **low** effect SNPs representing 0.01% of  $\sigma_a^2$
- 50 datasets generated for each setting

Scenarios

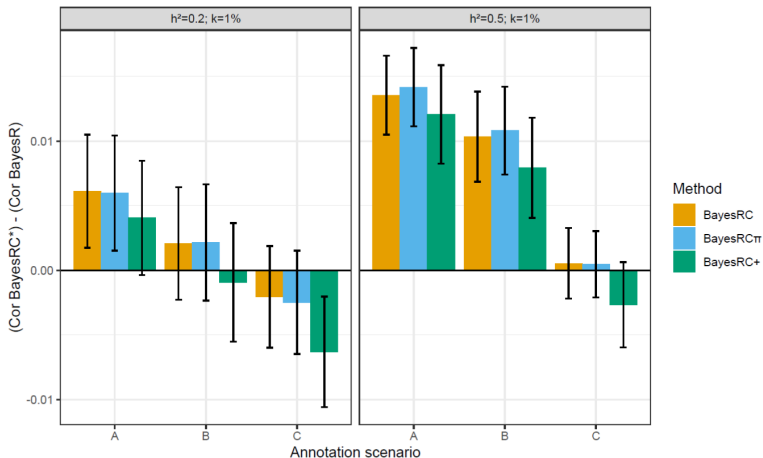
**A B C**



4 types of annotations possible:

- 1 strongly enriched:** 5 **large** QTLs + 300 **medium** QTLs + 150 **low** or null SNPs
- 2 moderately enriched:** 2 **large** QTLs + 100 **medium** QTLs + 300 **low** or null SNPs
- 3 weakly enriched:** 20 **medium** QTLs + 400 **low** or null SNPs
- 4 unenriched:** 450 **low** or null SNPs

# Evaluating impact of using annotations on validation data



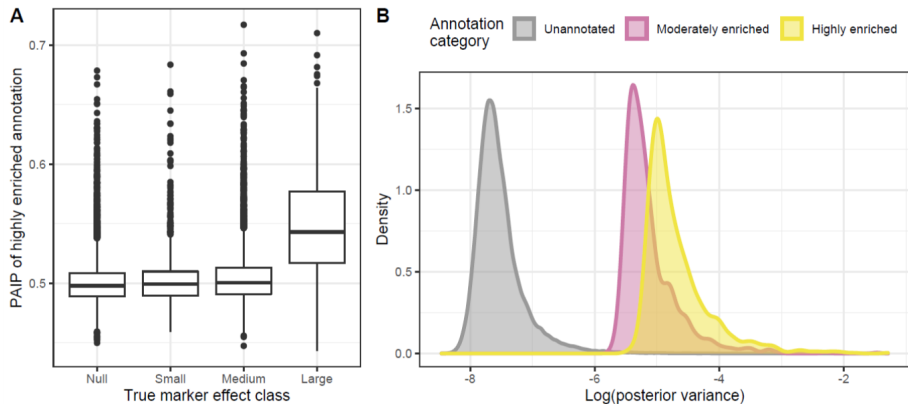
**k**= per-large QTL % of additive variance

**A**= 1 strongly enriched + 1 moderately enriched + unannotated;

**B**= 1 strongly enriched + 1 moderately enriched + 1 weakly enriched + 1 unenriched + unannotated

**C**= 2 strongly enriched + 2 moderately enriched + 3 weakly enriched + 2 unenriched + unannotated

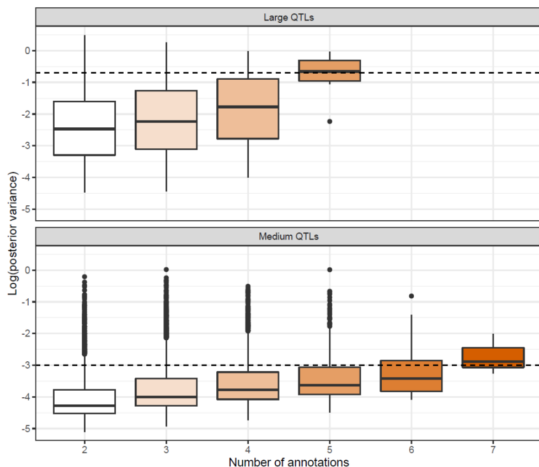
# BayesRC $\pi$ assigns informative annotations to QTLs



$h^2 = 0.5$ ,  $k = 1\%$ , scenario A

PAIP = posterior annotation inclusion probability (BayesRC $\pi$  output)

# BayesRC+ assigns more weight to multi-annotated variants



$h^2 = 0.5$ ,  $k = 1\%$ , scenario C



# Application in backcross population of growing pigs

- $n = 1297$  backcross pigs (3/4 Large-White, 1/4 Creole), genetically related sows sired with 10 boars
  - Genotyped with Illumina Porcine 60k BeadChip array
  - Sibling-structured 10-fold cross validation procedure
- Traits pre-corrected for age, sex, farm
- Focus on average daily weight gain (**ADG**) and backfat thickness (**BFT**) at 23 weeks



# Correlation of predicted traits in pig validation data

Annotations constructed using pigQTLdb for 11 trait sub-hierarchies

- Anatomy, behavioral, blood parameters, conformation, fatness, fatty acid content, feed conversion, growth, immune capacity, litter, reproductive organs
- Nearest up- and downstream neighboring markers also annotated

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	BayesR	BayesRC	BayesRC $\pi$	BayesRC+
ADG	0.21 ( $\pm 0.08$ )	+1.2 pts	+1.7 pts	+1.4 pts
BFT	0.26 ( $\pm 0.16$ )	-0.6 pts	-1 pts	+0.6 pts

# Interpreting pigQTLdb annotations with BayesRC $\pi$



# Conclusions: incorporating annotations with BayesRCO

## BayesRCO:

- **BayesRC $\pi$**  can assign informative annotations to multi-annotated SNPs to account for uncertainty in prior knowledge
- **BayesRC+** upweights multi-annotated SNPs and is robust to various annotation scenarios

- Fairly modest improvements in prediction ( $\sim 1-2$  points) observed when incorporating biological annotations
  - Improved predictions and rankings of large QTLs in simulations, especially for highly informative annotations
  - Slight improvement in predictions for some traits in real data
  - Strategies for constructing annotation categories impact results

## Take home messages

Can genomic prediction models be improved by better accounting for our **knowledge** about the **function** of certain regions of the genome?

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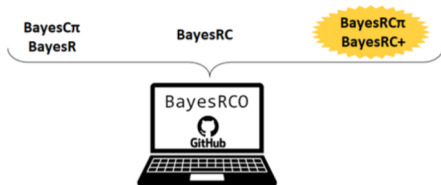
- **Models** → BayesRCO for overlapping annotation categories, extensions in progress to handle quantitative annotations
- **Genotyping data** → Capitalizing on annotation maps likely requires WGS resolution
- **Validation data** → Greater potential gains when prediction is performed on genetically distant populations
- **Traits** → Heritability, genetic architecture, link with annotations, ...
- **Annotations** → Which molecular assays, in which tissues?



# Thank you!



Mollandin *et al.* (2022) Accounting for overlapping annotations in genomic prediction models of complex traits, *BMC Bioinformatics*, 23:65.



<https://github.com/FAANG/BayesRCO>