Lies, damn lies, and .... genomics

you, your data, your perceptions and reality

Christopher West Wheat

Goal of this lecture

- Present a critical view of ecological genomics
- Make you uncomfortable by sharing my nightmares
- Encourage you to critically assess findings and your expectations in light of publication biases

Disclaimer

I'm a positive person

I love my job and the work we all do

I'm just sharing scrumptious food for thought

What if .....

50% of your favorite studies had conclusions that were just wrong?

How would that affect your expectations and work?

If the biomedical science has the most money and oversight, then ....

Their findings should be robust:

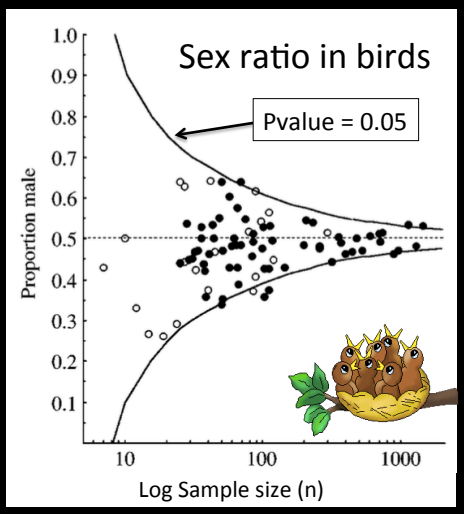
- Repeatable effect sizes
- The same across different labs
- The same across years

Publication replication failures

- Biomedical studies
  - Of 49 most cited clincal studies, 45 showed intervention was effective
  - Most were randomized control studies (robust design)
- Mouse cocaine effect study, replicated in three cities
  - Highly standardized study

Ioannidis 2005 *JAMA;* Lehrer 2010

Assessing reality using funnel plots



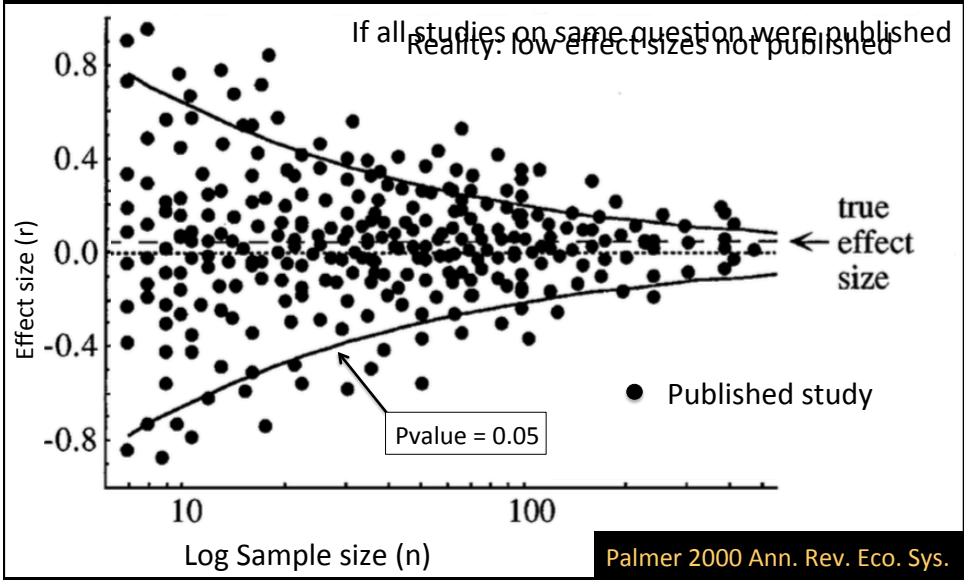
Small sample sizes affect measurement accuracy

Each dot = a study and has error

Study estimates are randomly distributed about the real value

Your study is just a random estimate of some idealized value

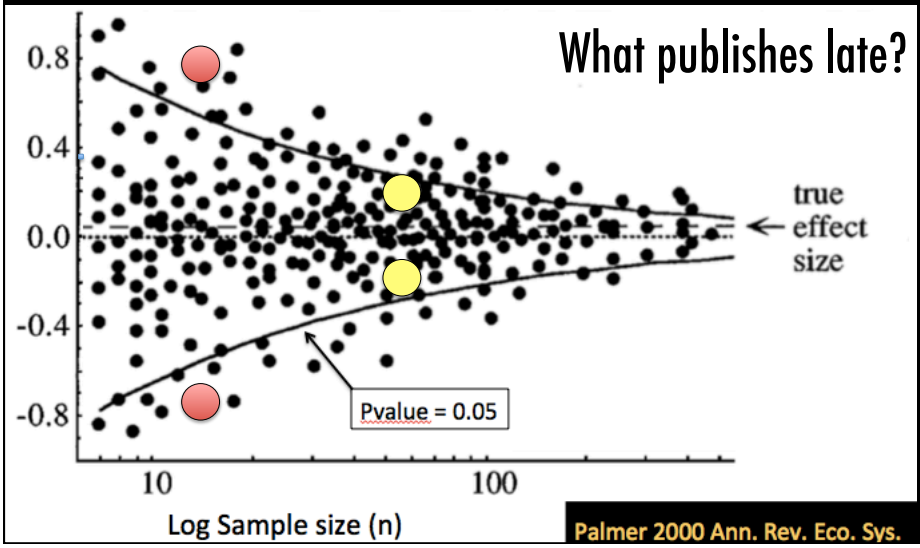
Publication bias increases effect size



Palmer 2000 Ann. Rev. Eco. Sys.

What if there is no replication?

What is most likely to publish first & where?



Palmer 2000 Ann. Rev. Eco. Sys.

Why Most Published Research Findings Are False

A research finding is less likely to be true when:

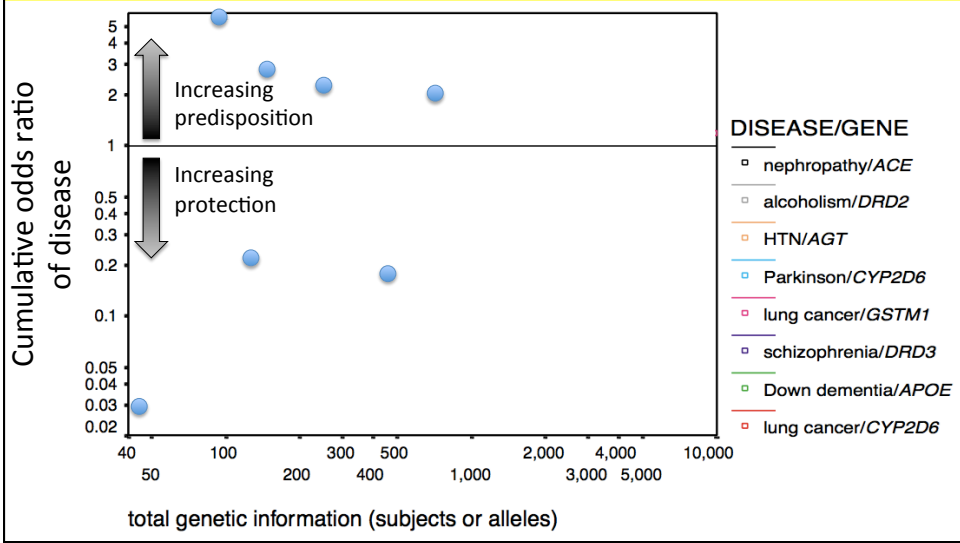
- the studies conducted in a field have a small sample size
- when effect sizes are small
- when there are many tested relationships using tests without *a priori* selection
- where there is greater flexibility in designs, definitions, outcomes, and analytical modes
- when there is greater financial and other interest and prejudice
- when more teams are involved in a scientific field, all chasing after statistical significance by using different tests

Ioannidis 2005 Plos Med.

But surely, this doesn't apply to genomics ....

Or does it?

8 topics first reported with P < 0.05



Ioannidis, J. P., E. E. Ntzani, T. A. Trikalinos, and D. G. Contopoulos-Ioannidis. 2001. Replication validity of genetic association studies. Nat Genet 29:306–309.

There are lies, damn lies, and ....

But wait, is that fair?

Are these really lies?

Where does this bias come from?

- Population heterogeneity
  - Space and time
- Publication bias
  - Large & significant effects publish fast and with high impact
  - Small & non-significant effects publish slow with low impact

Where does this bias come from?

YOU!!

And me …. All of us

Its arises from humans doing science

The way we think

The way our institutions work

Apophenia

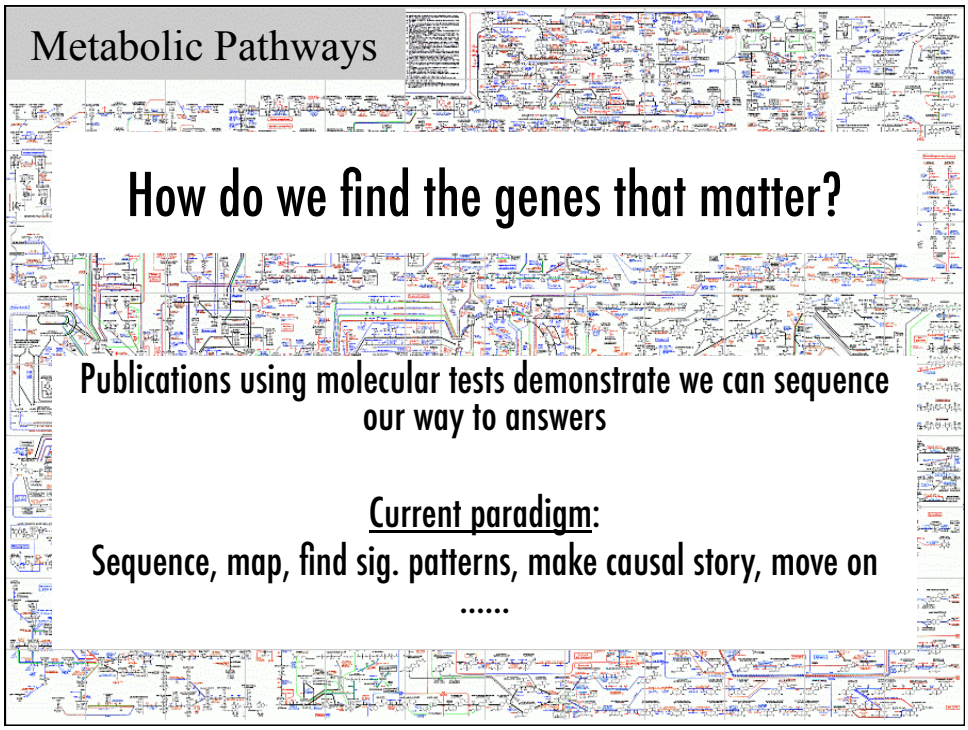
A universal human tendency to seek patterns in random information and view this as important

Story telling of Type 1 errors

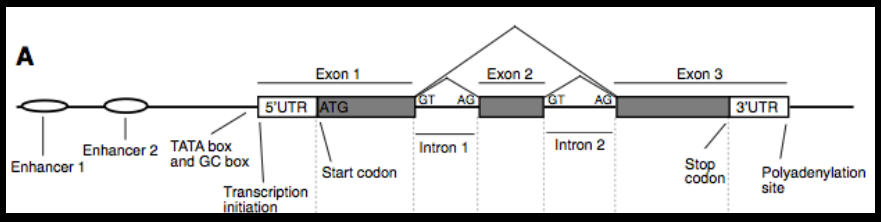
Celebration of the false positives

Outline

- Are there biases understanding the genomic architecture of adaptations?
- What is the power of molecular tests of selection?
- What does the dissection of some classic comparative genomics study reveal?

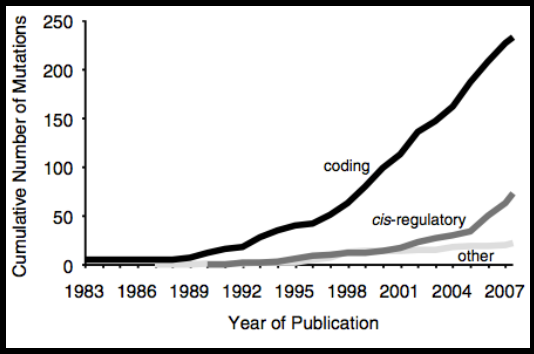


What is the architecture of a causal variant?



How predictable are adaptations?

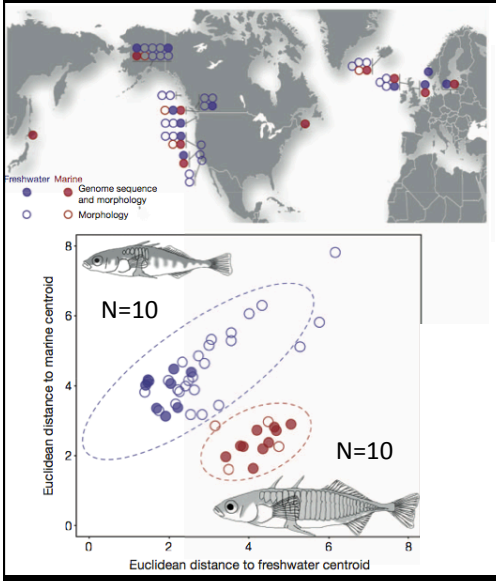
	Plants	Animals
Coding[1]	71	163
Cis-regulatory	26	48
Other[2]	16	7
Total	113	218
Null[3]	67	32



	Morphology	Physiology	Behavior
Coding[3]	62	170	2
Cis-regulatory	43	29	2
Other[4]	3	20	0
Total	108	219	4
Null[5]	41	58	0

Stern & Orgogozo 2008 Evolution

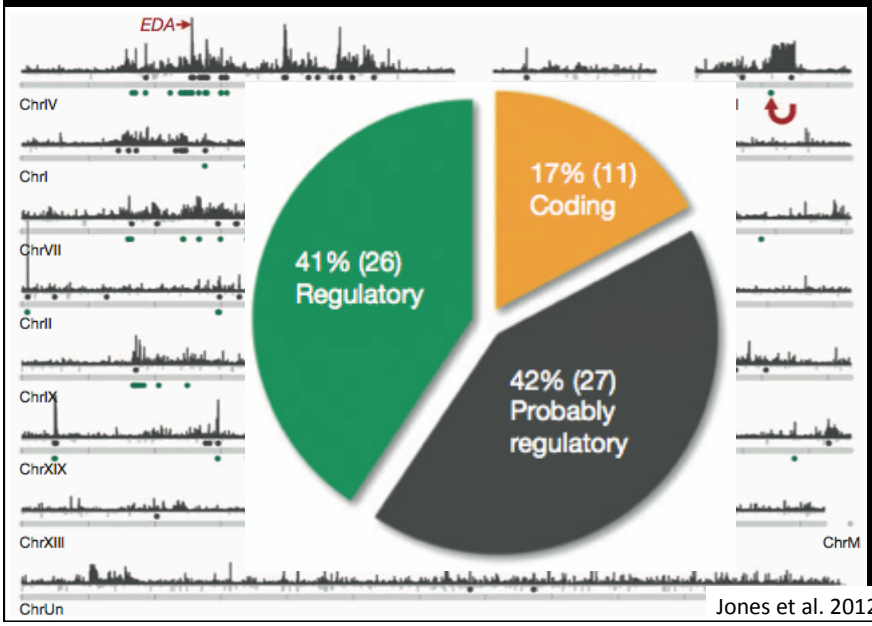
Individual genome sequencing: powerful insights



2-5 X per individual, sliding 2500 bp window, 500 bp step

Jones et al. 2012 Nature

Which regions are more important? Coding or expression?

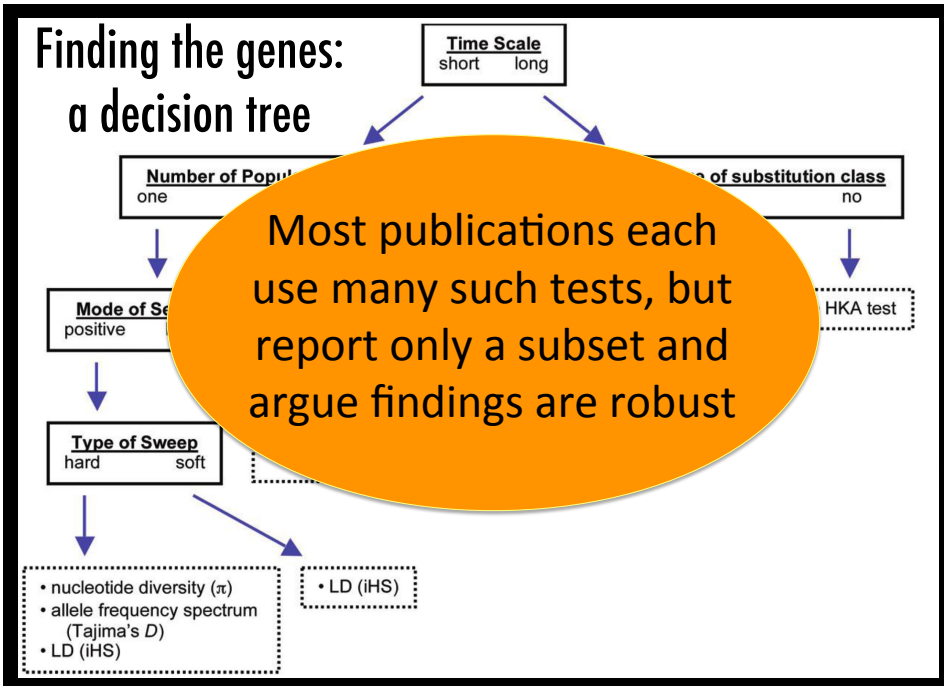


Jones et al. 2012 Nature

How do we identify the genes that matter?

- Molecular tests of selection are popular, but …
  - What are their assumptions and power?
- What are these tests detecting?
  - What is a footprint of selection?
    - How are they formed?
    - How large are they?
    - How long do the last?

Finding the genes: a decision tree



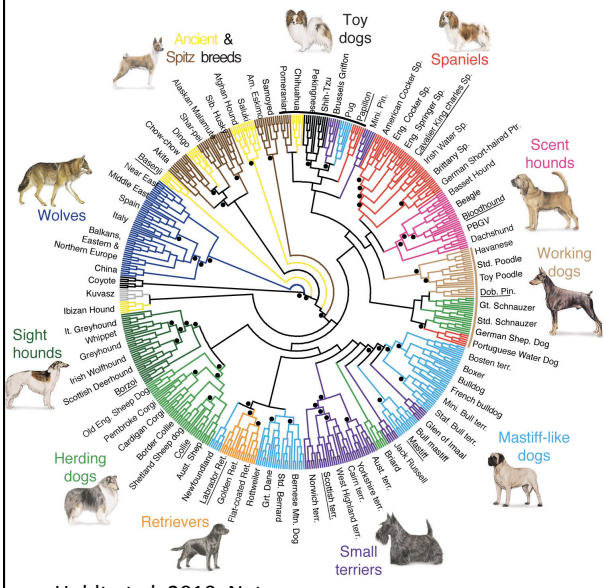
Hohenlohe et al. 2010 Int. J. Plant Science

What power do we have to detect evolution by natural selection?

What is statistical power?

Power is the probability that the test will reject the null hypothesis when the alternative hypothesis is TRUE

Using a t-test, you would want power > 90% at reasonable sample size, right?



von Holdt et al. 2010. Nature

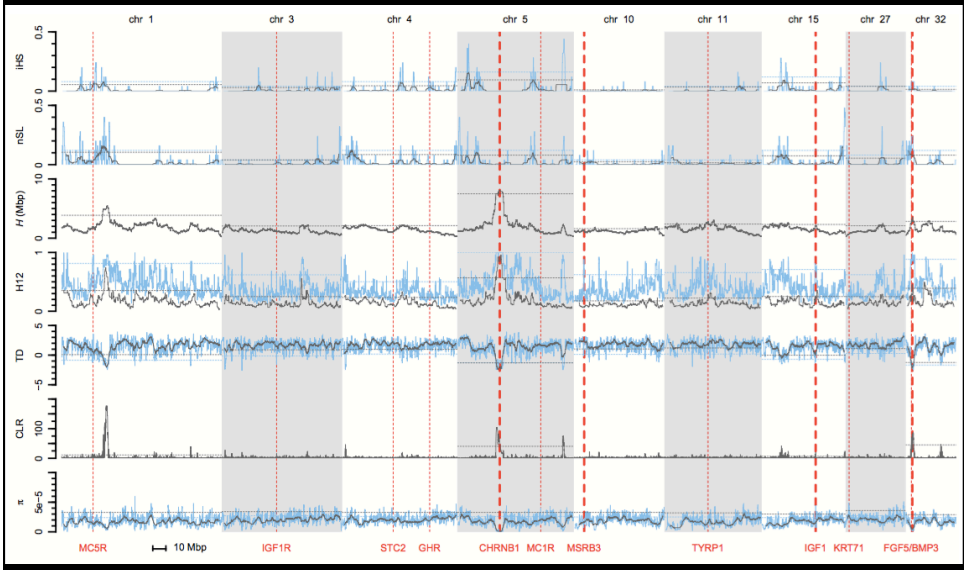
Breed specific morphologies

Test set of Schlamp et al. 2016:

- 25 breeds
- 12 causal loci identified by QTLs
- N = 25 / breed
- 7 tests of selection
  - iHS,nSL,H,TajD, etc.

How accurate are molecular tests of selection detect?

French Bulldog sample: low power (high type II error)

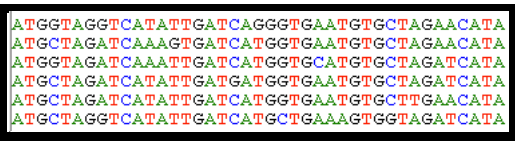


Schlamp et al. 2016. Evaluating the performance of selection scans to detect selective sweeps in domestic dogs. Molecular Ecology 25:342–356.

Why don't these these tests have much power?

Biological reality
vs.
theoretical population genetics?

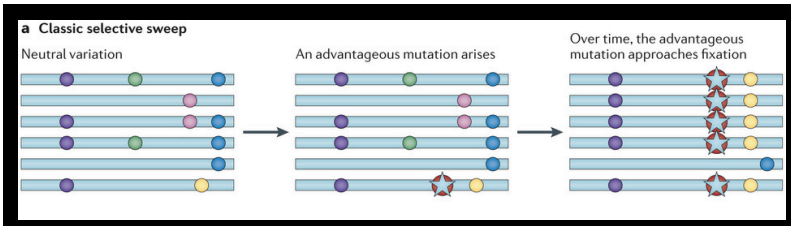
Directional selection:
an example of the expectations of hard selection

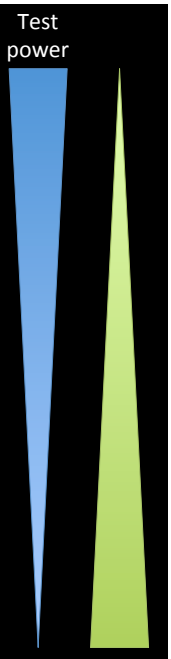


Population genomics has been dominated by developing methods to detect hard sweeps for past two decades

- But a proper 'null model' continues to be elusive, resulting in a high false positive rate since their inception

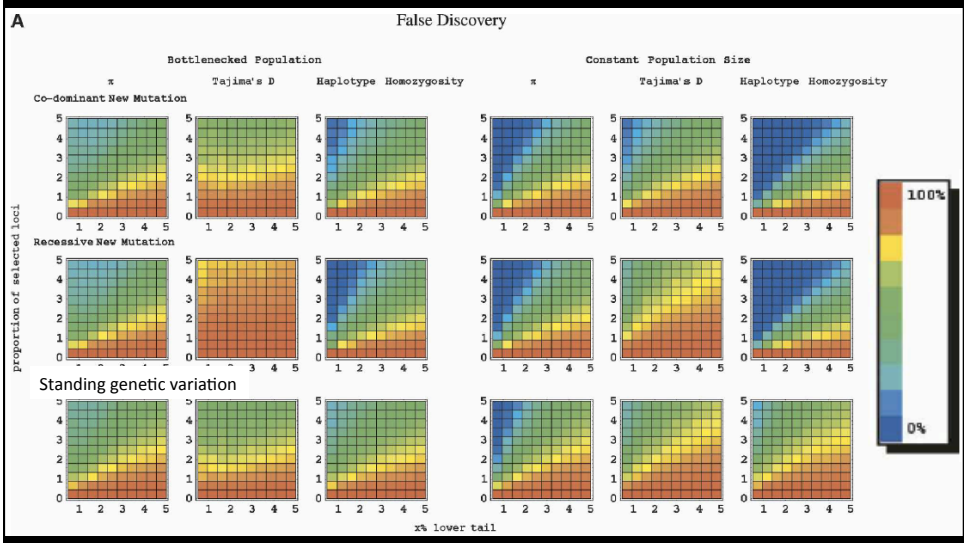
Storz 2005 Mol. Ecology





Scheinfeldt & Tishkoff. 2013. Nat Rev Genet 14:692–702.

Estimate of error rates using , Tajima's D, and haplotype homozygosity under the models for a human population



Teshima et al. 2006 Genome Research

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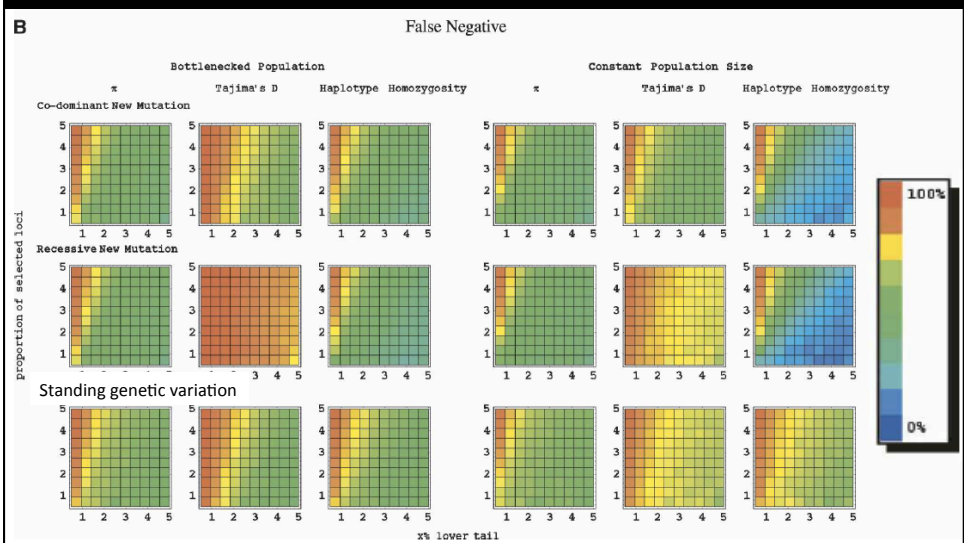


Teshima et al. 2006 Genome Research

Simulation conclusions

- Simulations suggest
  - empirical approaches will identify several interesting candidates
  - But will also miss many–in some cases, most–loci of interest
- Power is lower when
  - directional selection involves a recessive rather than a co-dominant allele
  - when it acts on a previously neutral rather than a new allele
  - Demographic changes rather than constant population size

Genomic scans yield an unrepresentative subset of loci that contribute to adaptations

Molecular tests …

BASED ON 20 YEARS OF PUBLICATIONS

- Are still chasing an elusive null model ….
  - Each performs better than previous ones under a specific set of conditions, all have poor null model
- But … under realistic biological conditions, they all
  - Have very low power (high type II error rates)
  - Have high false positive rates

How common are hard sweeps in nature?

- "we argue that soft sweeps might be the dominant mode of adaptation in many species" Messer and Petrov 2013 TREE

Certainly not everyone agrees ....

- This is an important read, critical of
  - assumptions underlying soft sweep (selection on standing variation)
  - the low power of molecular tests to detect hard & soft sweeps

How likely does natural selection use standing variation in your species?

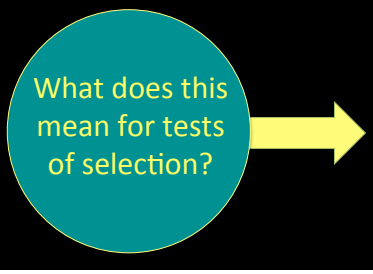
Thought experiment:

What fraction of species respond to selection in the lab?

Why?

If populations have variation, how likely is selection to use it?

What's likelihood of selection on standing variation in wild?



We have not been studying the dominant form of selection in the wild & cannot reliably detect it

Age and type of selection matters

- Novel mutation, large effect, hard sweep that goes to fixation
  - Probability of detection 20 – 90%, depending on demography, etc.
- Old mutation and / or polygenetic that does not sweep to fixation
  - Probability of detection close to 0
- Finding the causal mechanism
  - Coding > expression (but allele specific expression can be lightening rod for expression)
  - SNPs > more complex mutations (indel, TE, CNV)
  - Ongoing gene flow & grouping by phenotype across replicate populations helps a lot
- Demographic effects
  - Nearly all species have experienced a major demographic change in the past 10,000 generations
  - Demographic change significantly reduces power and increases false positive rates.
- What is the relative frequency of these?
  - What will be the architecture of your phenotype?
  - What does your method have the highest power to detect?

Get ready, here come the 1000^n genomes

- Roughly 20 arthropods sequenced to date
  - plans to sequen
- Many other larg

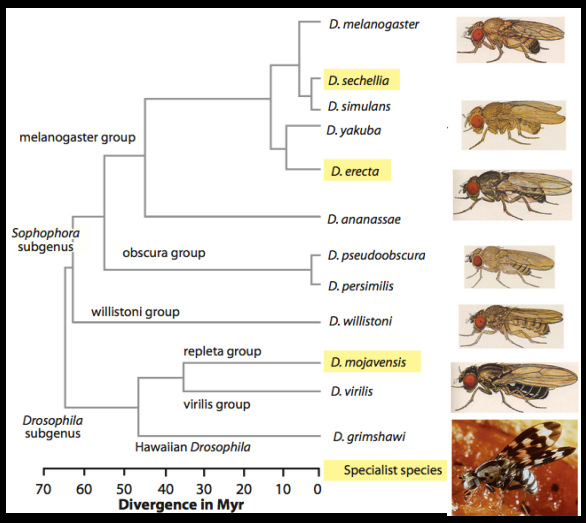
An unprecedented opportunity for large scale errors?

studying:

lationships

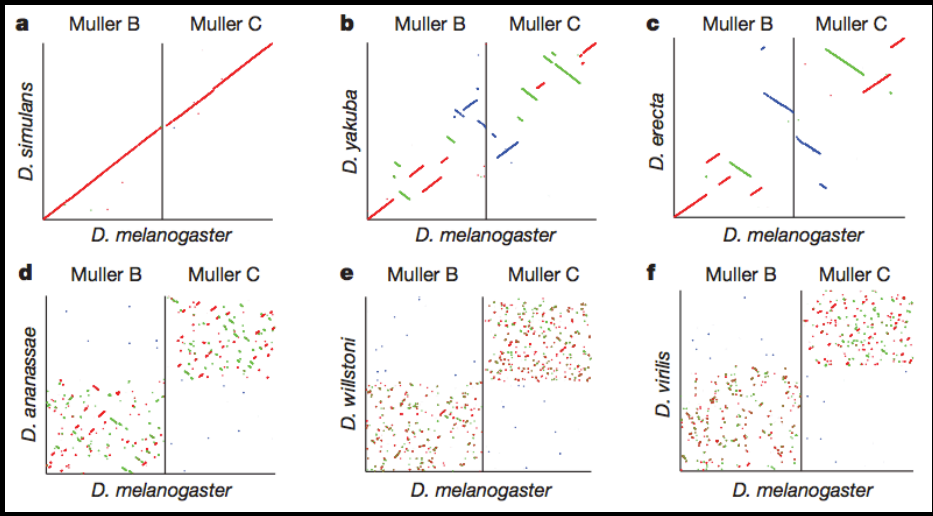
- Genome evolution
- Functional insights into genes and genomic features (e.g. regulation and inheritance)

Classic study: Evolution of genes and genomes on the *Drosophila* phylogeny



Drosophila 12 Genomes Consortium 2007 Nature

Tempo and mode of chromosome evolution



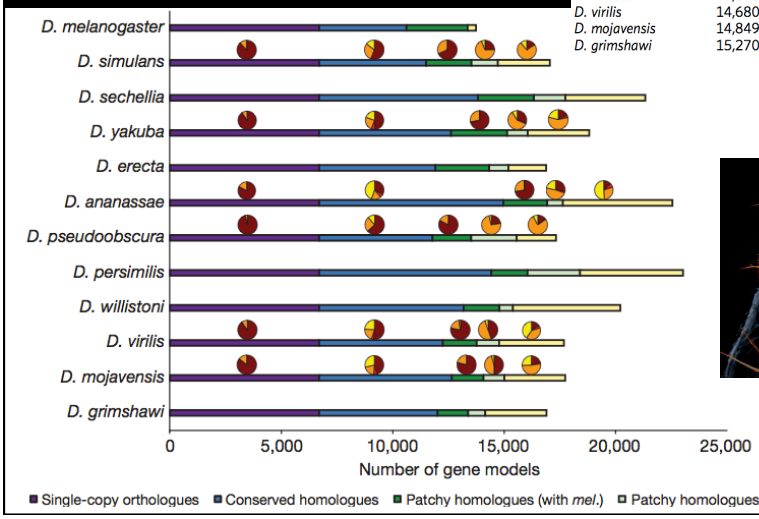
- > 20 My, chromosomal order completely reshuffled in Diptera

Drosophila 12 Genomes Consortium 2007 Nature

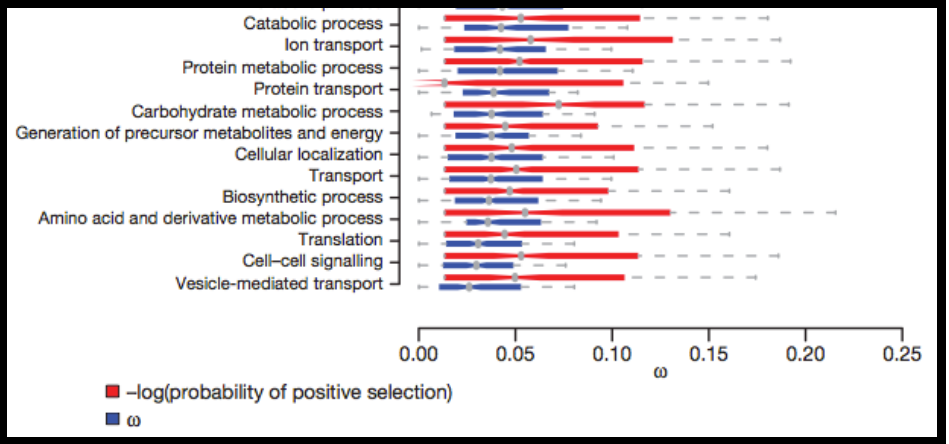
Genome evolution

Drosophila 12 Genomes Consortium 2007 Nature

	Total no. of protein- coding genes (per cent with *D. melanogaster* homologue)	Coding sequence/ intron (Mb)
D. melanogaster	13,733 (100%)	38.9/21.8
D. simulans	15,983 (80.0%)	45.8/19.6
D. sechellia	16,884 (81.2%)	47.9/21.9
D. yakuba	16,423 (82.5%)	50.8/22.9
D. erecta	15,324 (86.4%)	49.1/22.0
D. ananassae	15,276 (83.0%)	57.3/22.3
D. pseudoobscura	16,363 (78.2%)	49.7/24.0
D. persimilis	17,325 (72.6%)	54.0/21.9
D. willistoni	15,816 (78.8%)	65.4/23.5
D. virilis	14,680 (82.7%)	57.9/21.7
D. mojavensis	14,849 (80.8%)	57.8/21.9
D. grimshawi	15,270 (81.3%)	54.9/22.5



Selection dynamics across functional categories

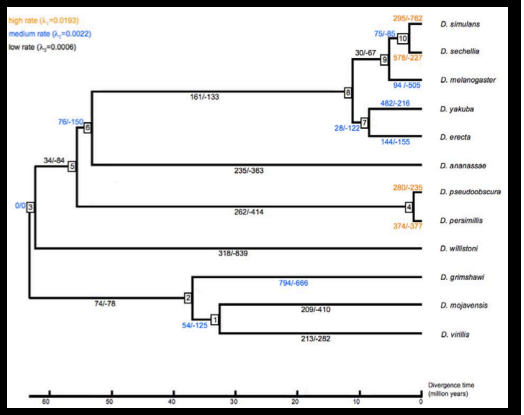


- 33.1% of single-copy orthologues have experienced positive selection on at least a subset of codons.

Drosophila 12 Genomes Consortium 2007 Nature

Gene Family Evolution across 12 Drosophila Genomes

- One fixed gene gain/ loss across the genome every 60,000 yr
- 17 genes are estimated to be duplicated and fixed in a genome every million years



Drosophila 12 Genomes Consortium 2007 Nature
Hahn et al. 2007 Plos Genetics

Comparative Genomics : a house of cards?

- Data scale is too large to thoroughly assess errors …
  - Perhaps the findings are just …. wrong

- All conclusions, at some stage, rest upon
  - Simple bioinformatics
  - Assumptions that get incorporated into seemingly unbiased methods

Lets exploring two pillars of these studies, their error and repercussions

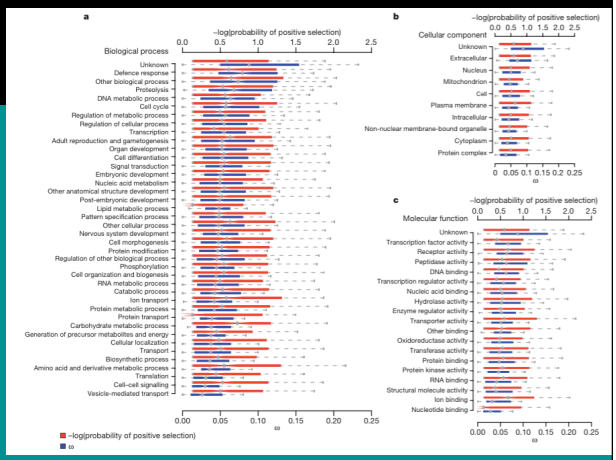
- Gene alignments in detecting positive selection
- Calibrations in temporal analysis

Published studies allow …

Follow up studies to reveal limitations

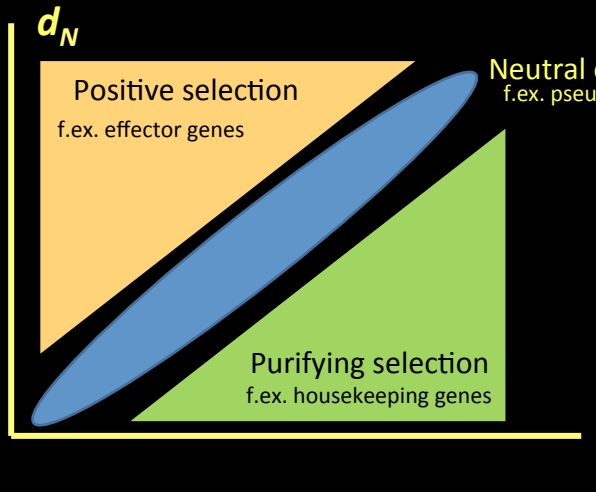
But, must have enough details to be repeatable

Genome-wide selection dynamics:



How robust are these conclusions?

Codon based tests of selection

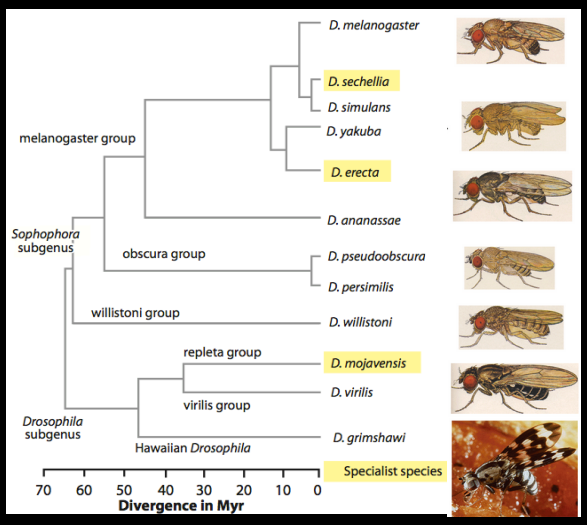


d_N / d_s ratio

```
> 1 positive sel.
= 1 neutral
< 1 purifying sel.
```

IMPRS workshop, Comparative Genomics

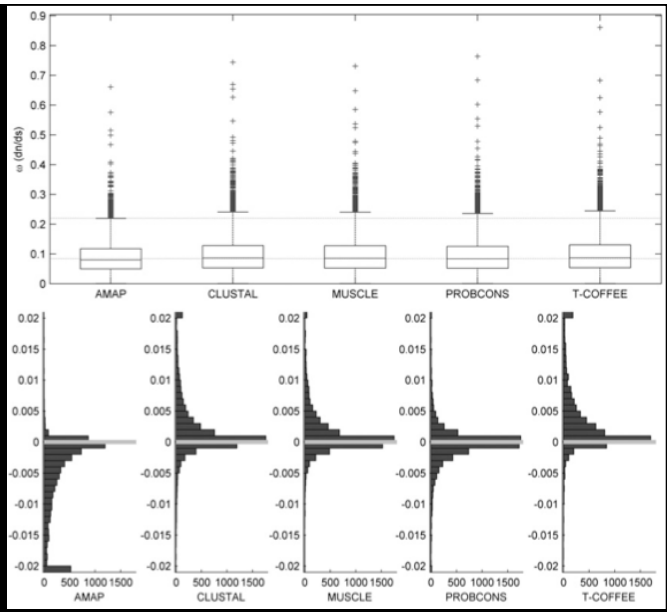
Evolution of genes and genomes on the *Drosophila* phylogeny



Drosophila 12 Genomes Consortium 2007 Nature

dN/dS estimates by aligner

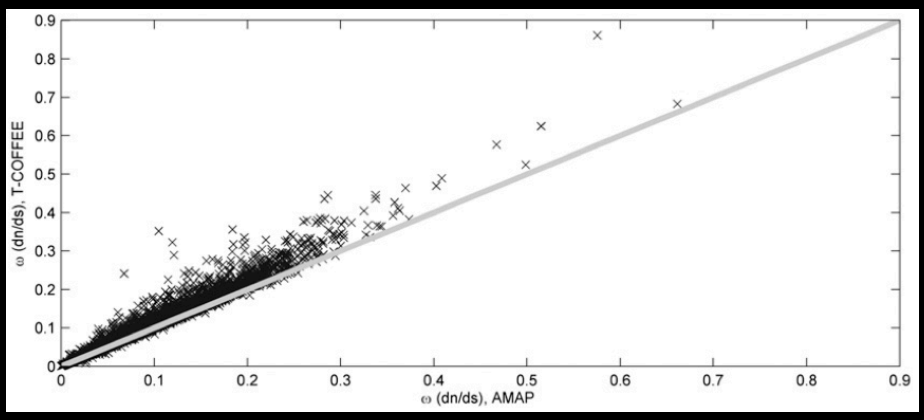
- 6690 orthologs
- 5 alignment methods
- Alignment methods affect dN/dS estimates



Markova-Raina & Petrov 2011 Genome Biology

Comparing results across methods is responsible bioinformatics!!!!!

Since we can't look at our data, we need approaches that allow 1st principal assessments



Markova-Raina & Petrov 2011 Genome Biology

Aligner has a larger effect than biological signal

	12 genomes, M7/8		12 genomes, M1a/2a		12 genomes, M7/8, with removed gaps		*Melanogaster* group, M7/8	
Aligner	95% (a)	99% (b)	95% (c)	99% (d)	95% (e)	99% (f)	95% (g)	99% (h)
AMAP	817	213	256	110	558	104	973	257
MUSCLE	1043	306	379	192	764	155	1134	366
ProbCons	1013	281	346	180	801	182	1128	371
T-Coffee	1290	479	612	353	824	173	1248 (909)	463 (218)
ClustalW	902	261	244	117	666	112	1269	453
Total in 5	1902	673	799	441	1562	384	1737 (1723)	652 (620)
PRANK	468	49	49	16	258	42	581	70

Markova-Raina & Petrov 2011 Genome Biology

Alignment results highlight importance of alignment score!

- Tcoffee finds 3 selected sites indicated by arrows
- ProbCons identifies region with low alignment score, not used

Markova-Raina & Petrov 2011 Genome Biology

What about recent genomes?

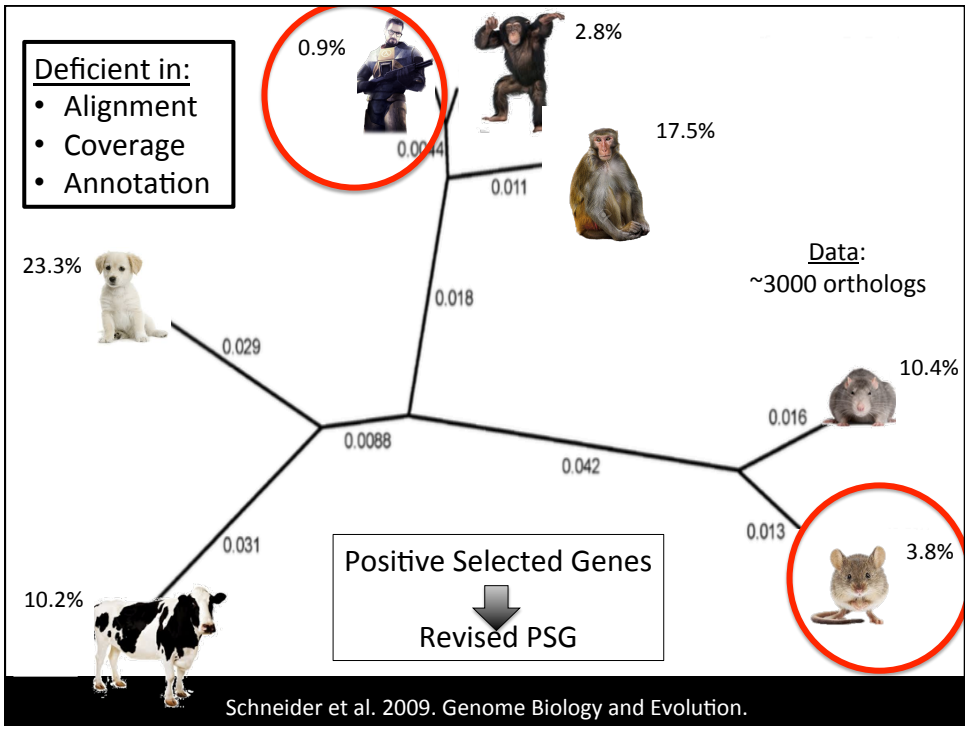
Surely they are better?

and mammals ... they have good genomes

and alignment problems rarely happen

... right?


How did I evolve to be so cute?


Deficient in:
• Alignment
• Coverage
• Annotation
0.9%
2.8%
17.5%
23.3%
10.2%
10.4%
3.8%
0.0044
0.011
0.018
0.029
0.0088
0.042
0.016
0.013
0.031
Data:
~3000 orthologs
Positive Selected Genes
Revised PSG
Schneider et al. 2009. Genome Biology and Evolution.

Post-genomics challenge

"What we can measure is by definition uninteresting and what we are interested in is by definition unmeasureable"

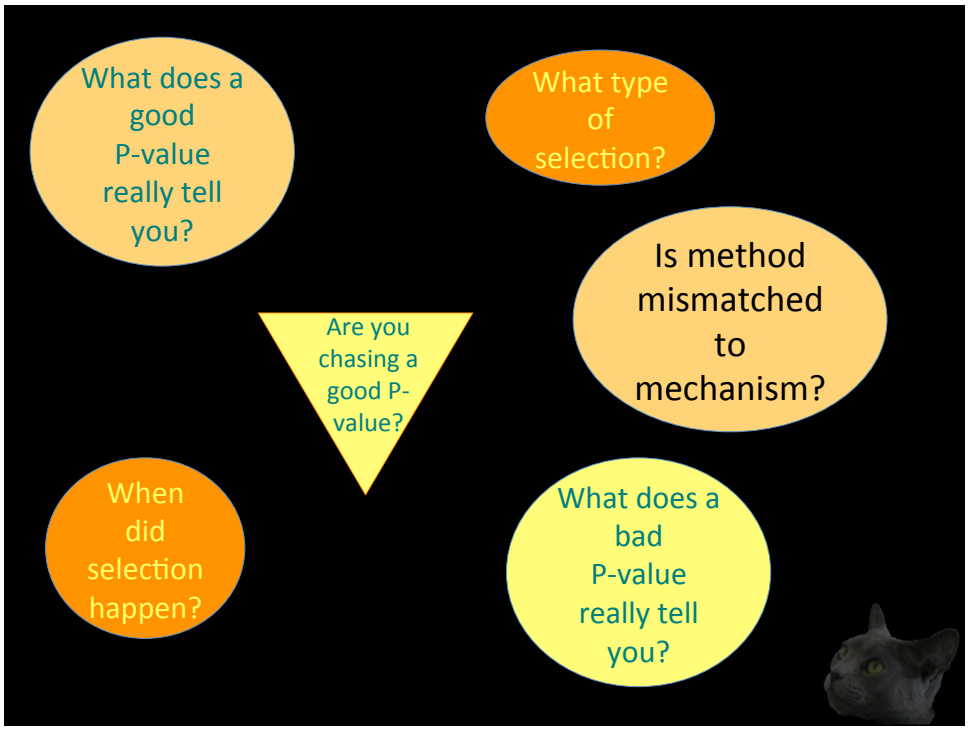
- Lewontin 1974

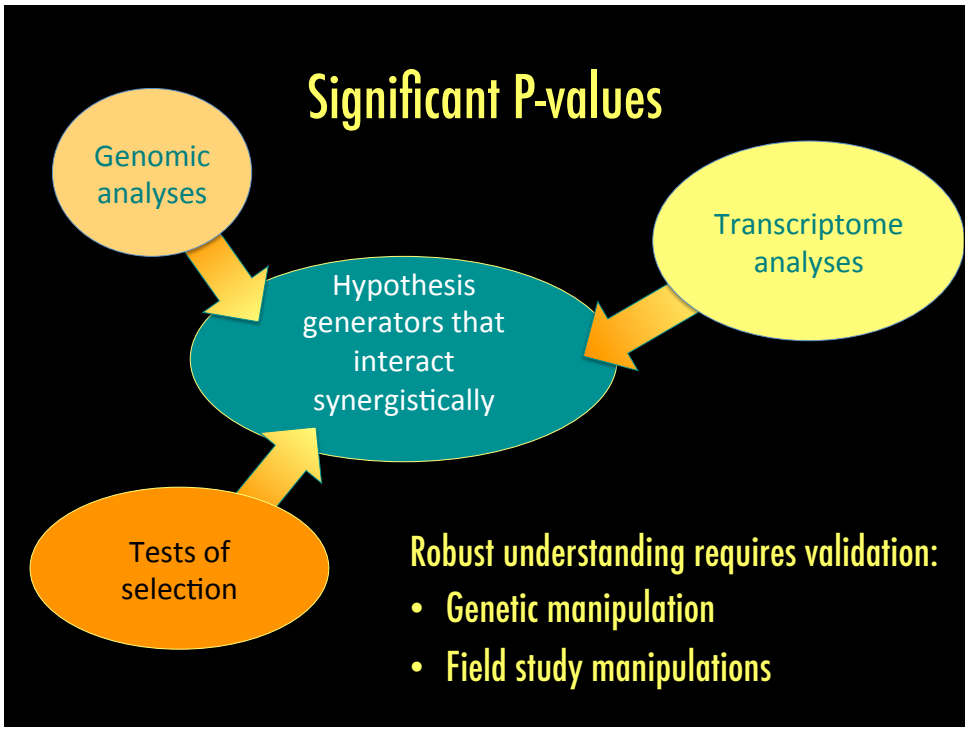
"What we understand of the genome is by definition uninteresting and what we are interested in is by definition very damn difficult to sequence and assemble and annotate and analyze at genomic scale"

- Wheat 2015

For example:

- indels & inversions
- gene family dynamics
- evolutionary dynamics





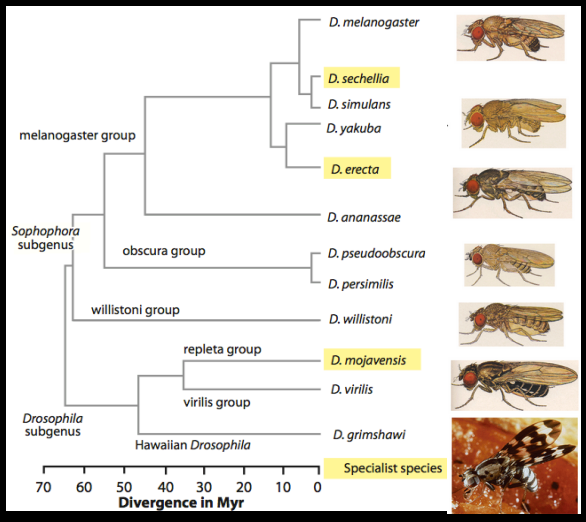
Goal of this lecture

- Present a non-typical view of ecological genomics
  - So you have a more complete view of the field
- Make you uncomfortable
  - Provide a context for understanding your results
- Encourage you to rethink the reality presented by publication biases
  - Overcoming this bias is a continual challenge

Temporal inference:

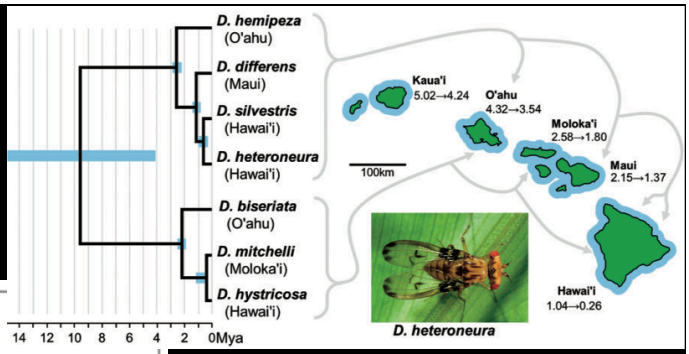
fact or fiction?

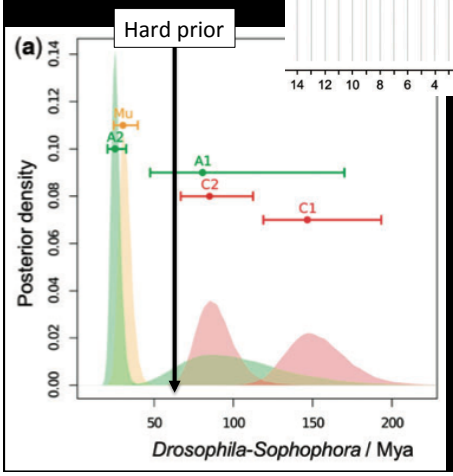
Evolution of genes and genomes on the *Drosophila* phylogeny



Drosophila 12 Genomes Consortium 2007 Nature

Determining objective priors is challenging





Priors in Bayesian rel. clock analysis:

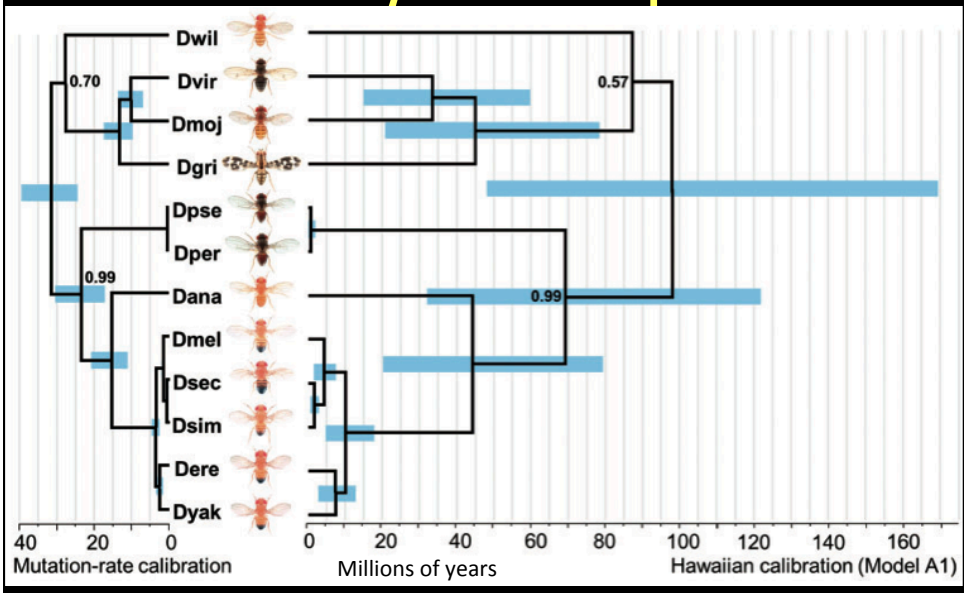
Mu = lab observed mutation rate

A1,2 = geological calibration, small Ne

C1,2 = geological calibration, large Ne

Obbard et al. 2012 Mol. Biol. Evol.

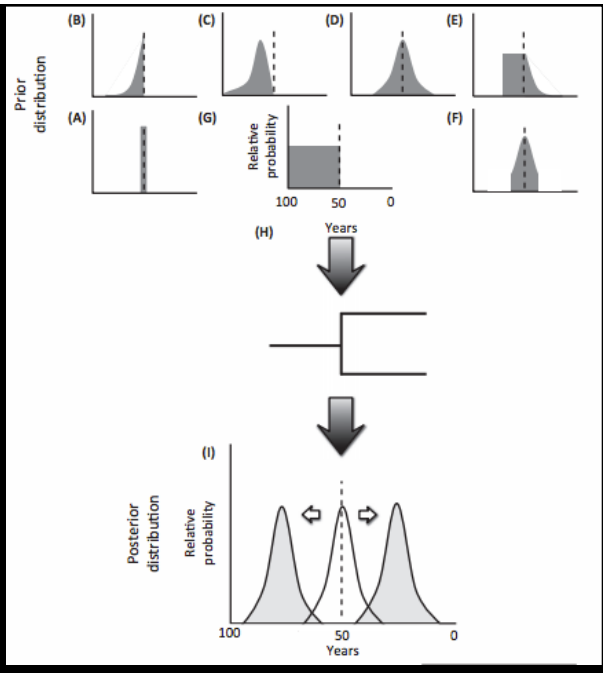
Priors directly influence posteriors



Obbard et al. 2012 Mol. Biol. Evol.

Prior distributions matter

- Integrative science is challenging
- Discuss or collaborate with experts to evaluate your approach.



Wheat and Wahlberg 2013 Trends Ecology & Evolution

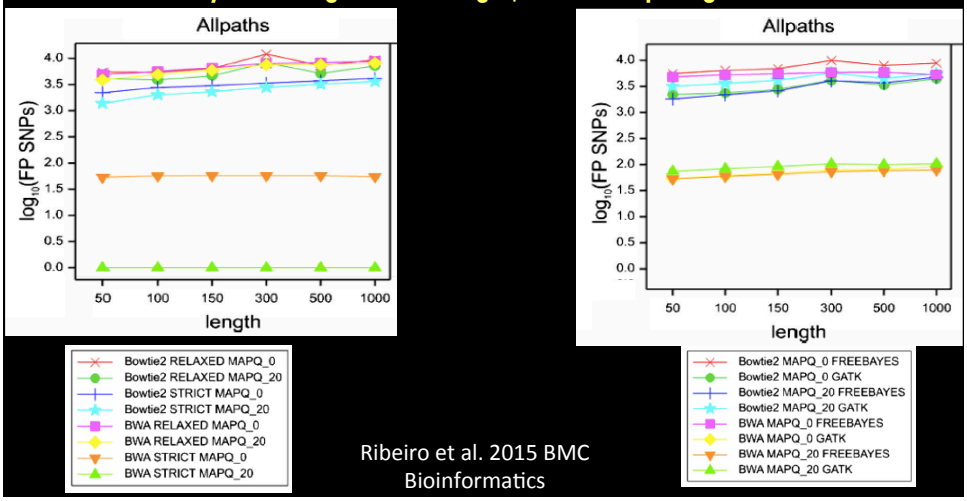
How do we gain dating confidence when we are in the dark?

- Fossils and DNA are likely to rarely agree
- How can we assess the temporal signal in the DNA in a robust manner?
  - Reducing prior biases and using lots of DNA data, while modeling likely violations of analysis models

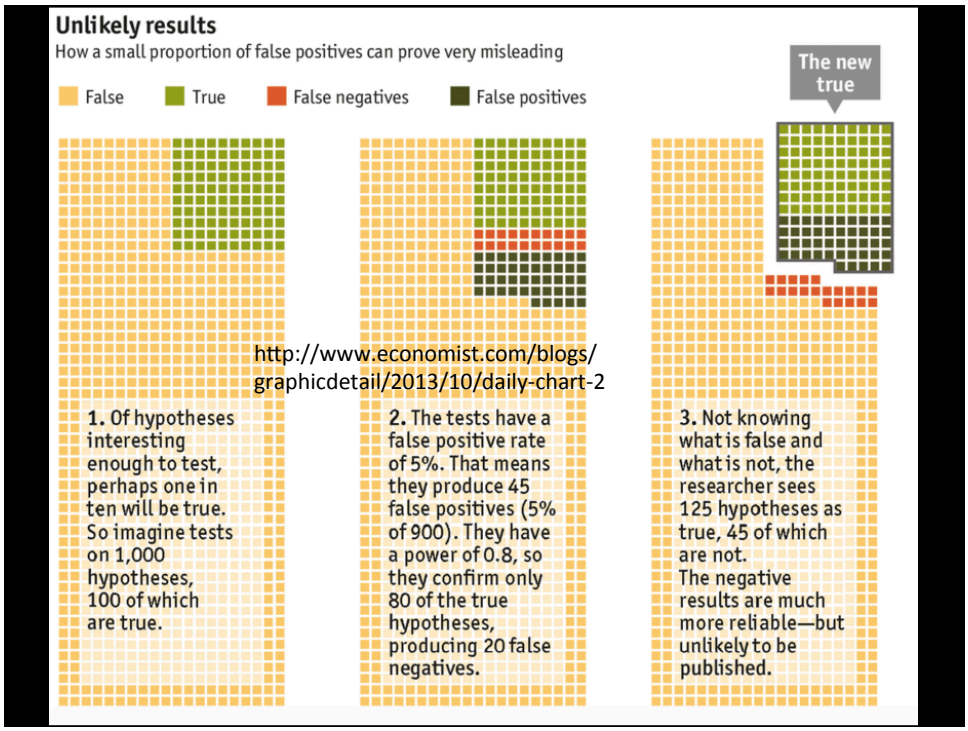
Wheat and Wahlberg 2013
Trends Ecology & Evolution

•

- 1000's of false positive SNPs (FP SNPs) result from misassembly x mapping x calling
- Genome was small (~125 Mbp) with few repeats (*Arabidopsis thaliana*)
- FP rates likely much higher with larger, more complex genomes

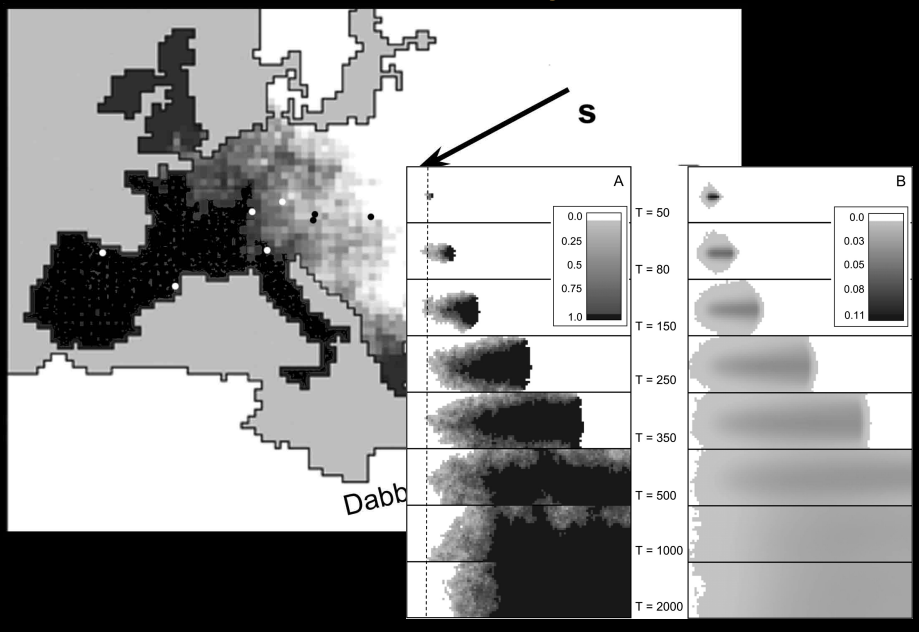


Ribeiro et al. 2015 BMC Bioinformatics


Unlikely results
How a small proportion of false positives can prove very misleading
False
True
False negatives
False positives
The new true
http://www.economist.com/blogs/graphicdetail/2013/10/daily-chart-2
1. Of hypotheses interesting enough to test, perhaps one in ten will be true. So imagine tests on 1,000 hypotheses, 100 of which are true.
2. The tests have a false positive rate of 5%. That means they produce 45 false positives (5% of 900). They have a power of 0.8, so they confirm only 80 of the true hypotheses, producing 20 false negatives.
3. Not knowing what is false and what is not, the researcher sees 125 hypotheses as true, 45 of which are not. The negative results are much more reliable—but unlikely to be published.


... and now for pt. 2
Stockholm University

The Fate of Mutations Surfing on the Wave of a

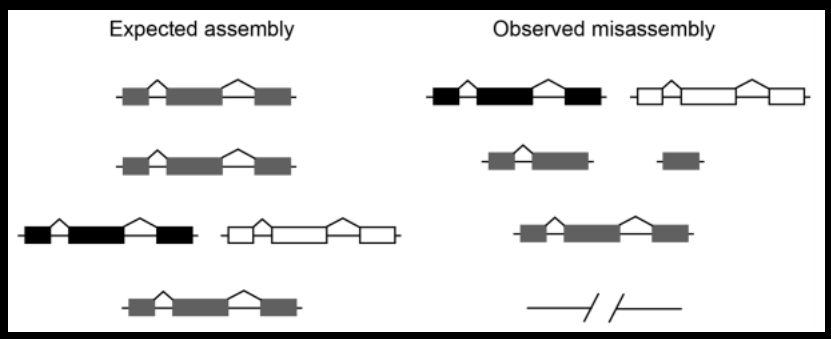


JOURNAL OF NEGATIVE RESULTS

- ECOLOGY & EVOLUTIONARY BIOLOGY -

Now handling genomic data

http://www.jnr-eeb.org/index.php/jnr



Microevolution effects

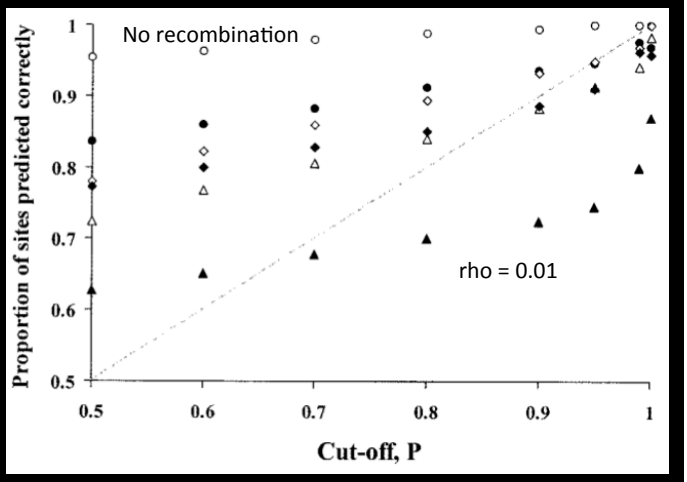
Previous examples were at deep evolutionary time scales

Surely such problems don't exist at the within genera level ..... Right?

Recombination violates dN/dS tests

Codeml inferred selection:

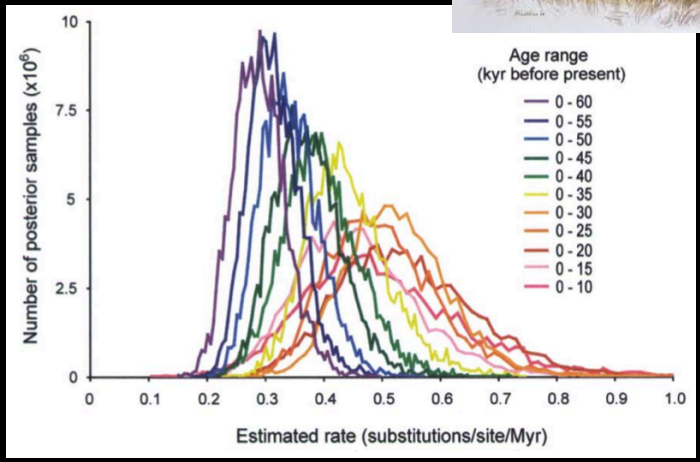
False positives can increase to over 30%



- 13% of sites simulated at omega = 2.5
- Sample size = 30 sequences

Anisimova 2003 Genetics

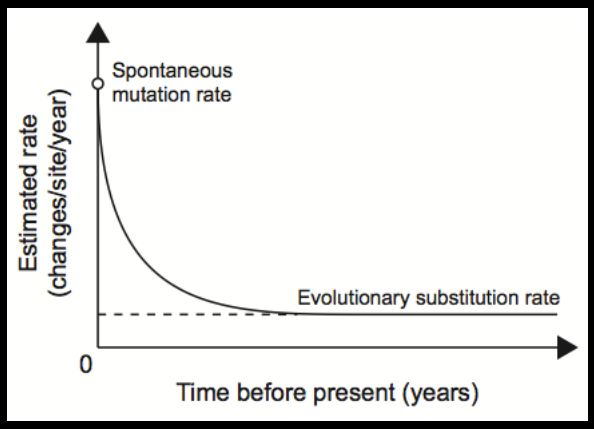
Posterior distribution estimates of substitution rates from mitochondrial control region from Beringian bison



Ho et al. 2007 Systematic Biology

Time dependent rates of molecular evolution

Significant implications for phylogeographic studies that use fixed rates to assess demographic with environmental change



Ho et al. 2011 Molecular Ecology

What power do we have to detect balancing selection?

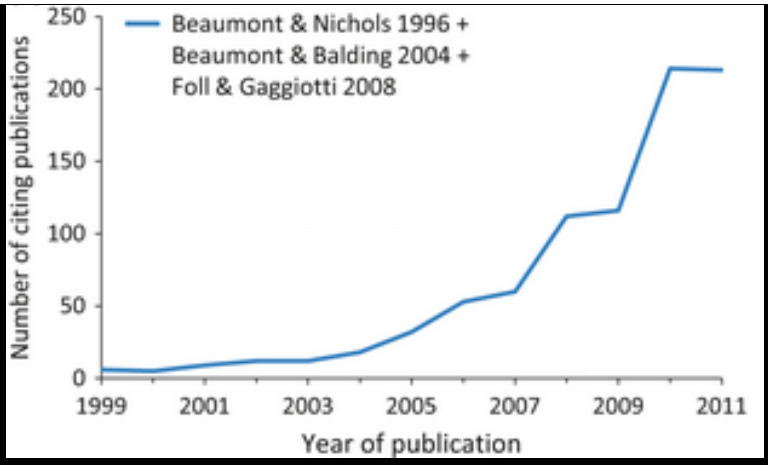
	Width of window (bp)				
ρ	25	50	100	200	1000
1	85.6	90.2	92.8	93.5	83.8
3	80.8	85.3	86.3	83.5	44.7
10	69.0	69.9	64.5	51.0	4.1
30	48.1	42.5	31.0	15.7	0.1
100	20.5	15.6	8.9	2.4	0.0

Tajima's D
% finding selection of 5000 simulations

- For *Drosophila melanogaster*, power = 50% with window size of 200 bp, using 24 diploid individuals.
- For species with larger population size, power likely lower
- Recombination and gene conversion destroy 'footprint' rather quickly

Nordborg and Innan 2003 Genetics

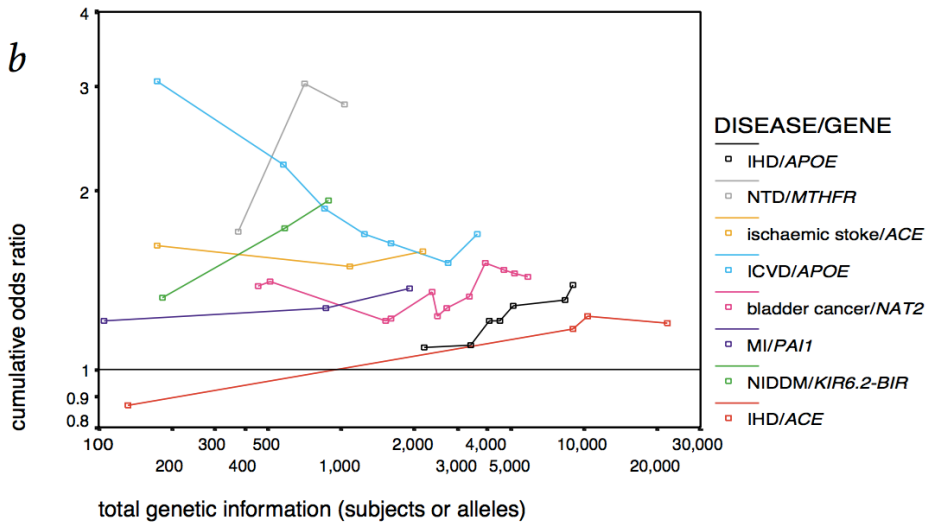
Fst outlier analyses are common



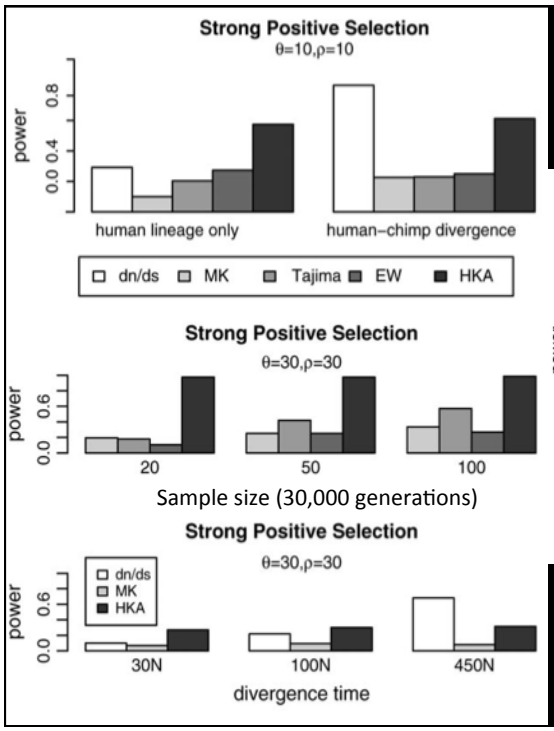
Pervasive selection or is it…? why are *F*ST outliers sometimes so frequent?

Bierne et al. Molecular Ecology 2013

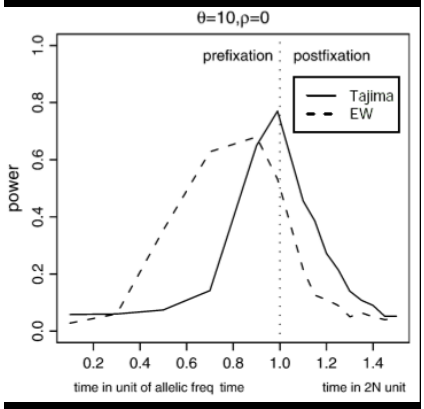
8 topics where first study P > 0.05, but became significant after meta-analyses



Ioannidis, J. P., E. E. Ntzani, T. A. Trikalinos, and D. G. Contopoulos-Ioannidis. 2001. Replication validity of genetic association studies. Nat Genet 29:306–309.



What is our power to detect hard sweeps?



When did selection act on your phenotype?

Zhai, Nielsen & Slatkin 2008 MBE

Hard vs. soft or incomplete sweeps in populations

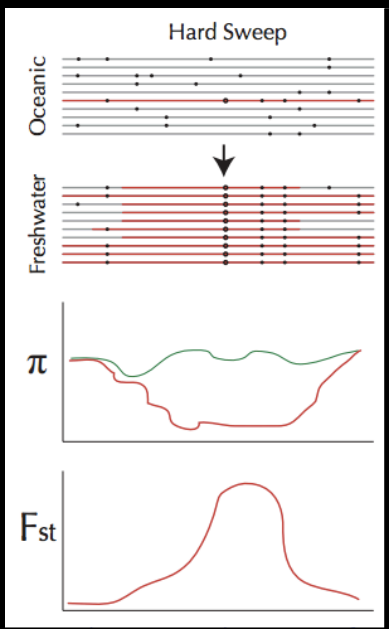
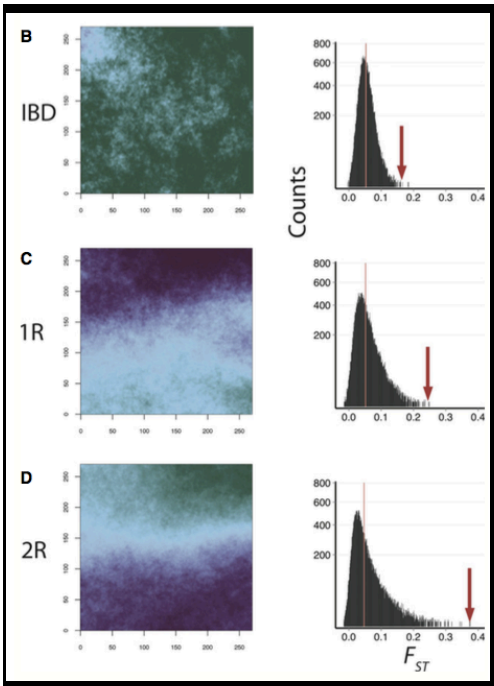


Image courtesy of W. Cresko



Fst outlier analysis

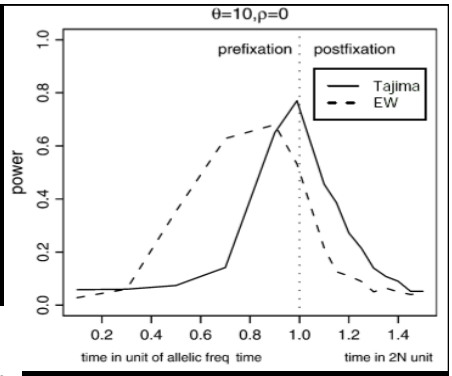
9900 Neutral, 100 selected sites

N=1500 (20 ind. per 75 populations)

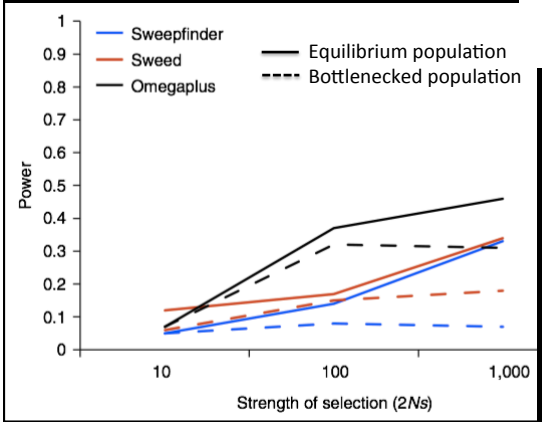
Bayescan FDIST2 FLK

Lotterhos and Whitlock. 2014. Molecular Ecology 23:2178–2192.

What is our power to detect hard sweeps within a population?



Zhai, Nielsen & Slatkin 2008 MBE



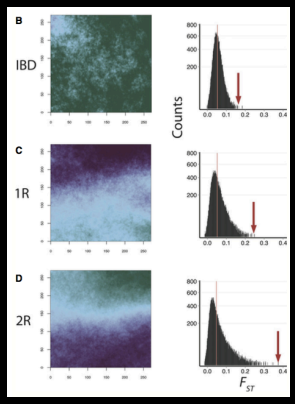
When did selection act on your phenotype?

What's the demographic history of your population?

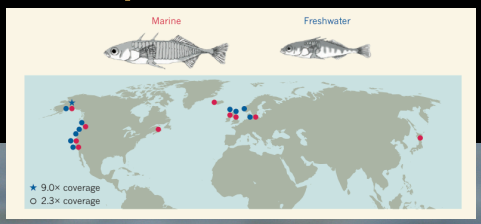
Jensen 2014. Nature Communications 5:1–10.

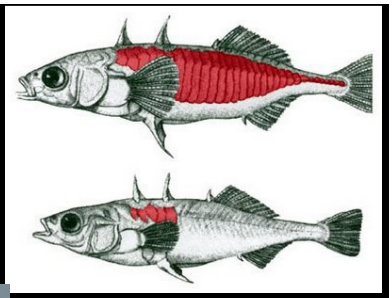
What's a good way to assess molecular tests?

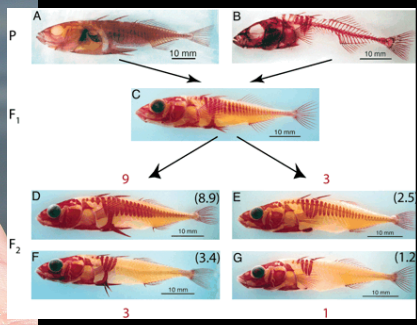
- Computer simulations of evolution
  - Across range of demographic scenarios
- What else?
- Testing them on real data where we know the targets of selection = real world validation
  - Which ones work and when
  - We could then use this to make better tests, right? (very rare)



Hard selection case example: threespine stickleback fish



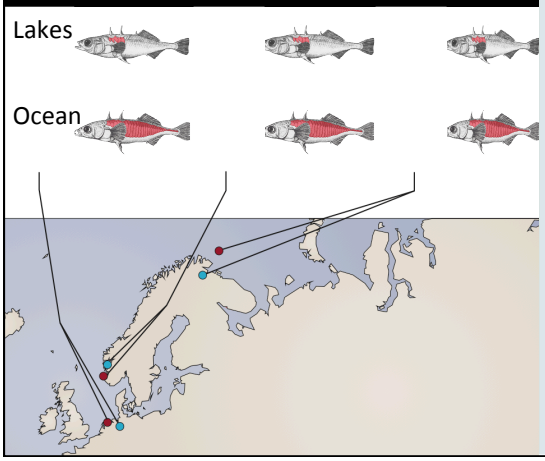


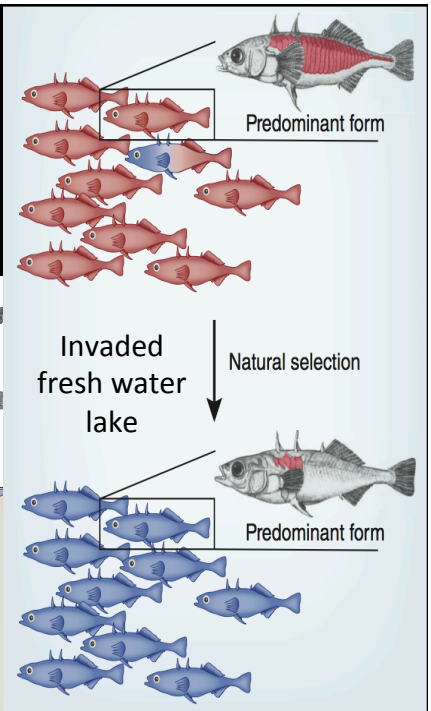


Threespine stickleback fish

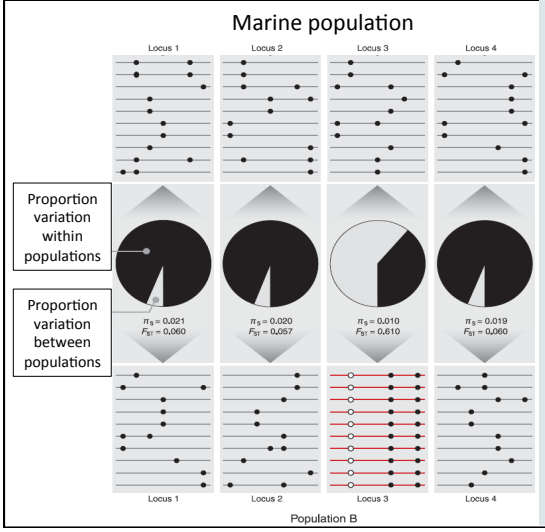
(Gasterosteus aculeatus)

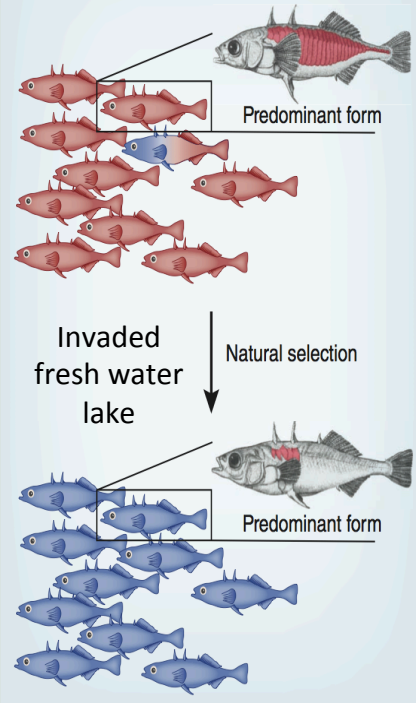
- Has body armor in the ocean
- Loses almost all armor in lakes





Parallel adaptation in fresh water lakes via hard sweeps

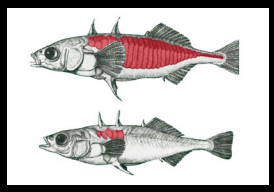




Non – adaptive

disease, aging, height, etc.

Adaptive



salinity, color, resistance, etc.

generally …

1000's of loci, each of small effect size

One or several loci of large effect

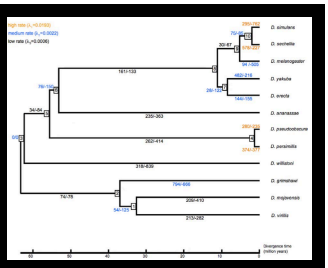
Is this a publication bias?

Will your trait have 1000's of small effect genes, or a few genes of large effect?

Sear (2010) … Is bigger always better?

Rockman (2011) … All that's gold does not glitter

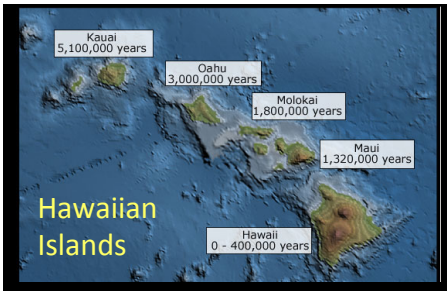
Timing of divergence



- Directly affects rate estimates
- Deriving unbiased dates from molecular data
  - Large field of software development

- Bayesian methods, while potentially informative and unbiased
  - Can be easily, and are routinely, abused

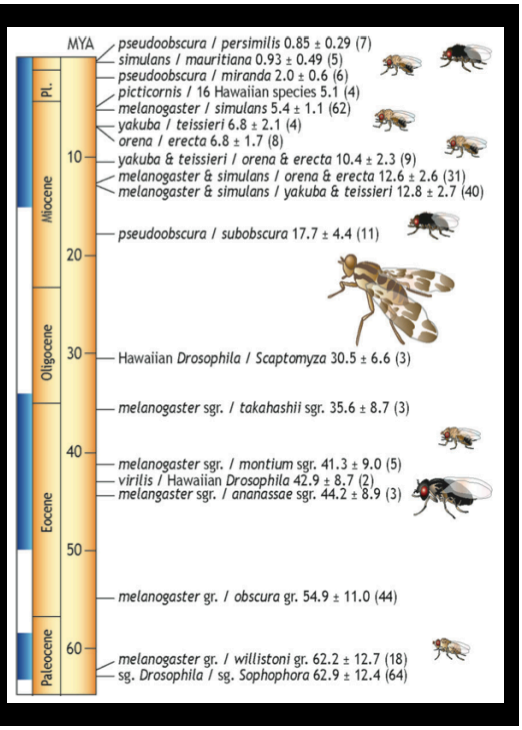
Wheat and Wahlberg 2013 TREE



Calibration: Kauai age of 5.1 my for divergence of two Hawaiian species

1. No phylogeny
2. Fixed clock rate
3. Between 3 – 64 genes in pairwise comparisons

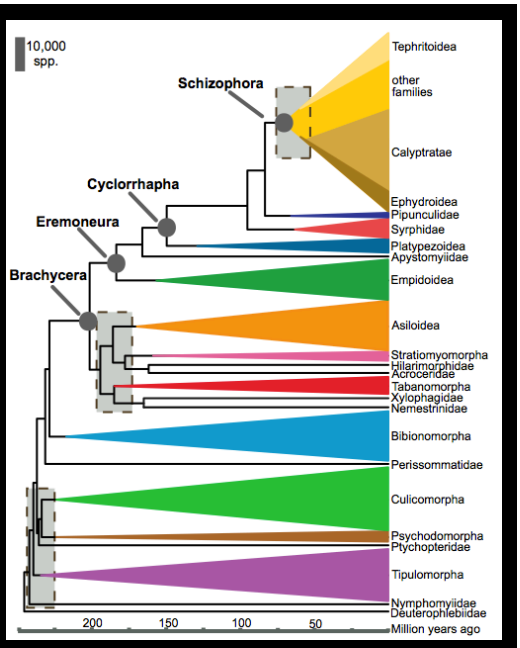
Temporal patterns in fruitflies (Tamura et al. 2004 MBE)



Drosophila clade:

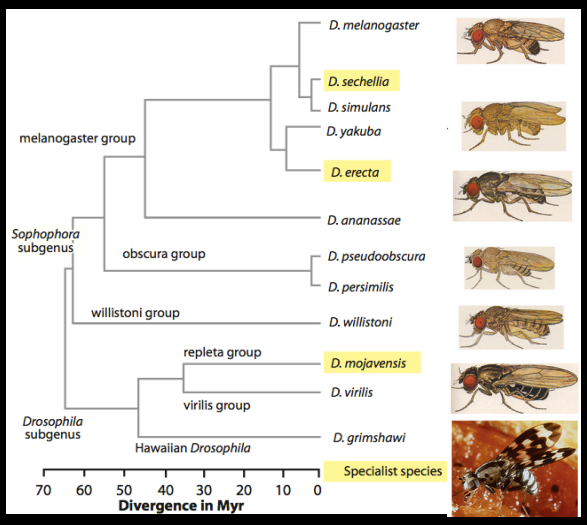
- Schizophora constrained to maximum of 70 Ma
- Without constraint, goes to 115 Ma

What is reality?



Episodic radiations in the fly tree of life (Wiegmann et al. 2011 PNAS)

Thus, the age of this clade is fiction



Drosophila 12 Genomes Consortium 2007 Nature