



# Atlantic cod stock structure in US waters: Genetic Markers

**The Atlantic Cod Stock Structure Working Group (ACSSWG)**

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**New England Fishery Management Council Peer Review**

ACSSWG peer review, May 18-19, 2020

# Outline

## Genetic Variation & Genetic Markers

- Types of inference that can be made from different markers

## Summary of Genetic Studies

- Studies 1998-2018
- New research conducted during this process

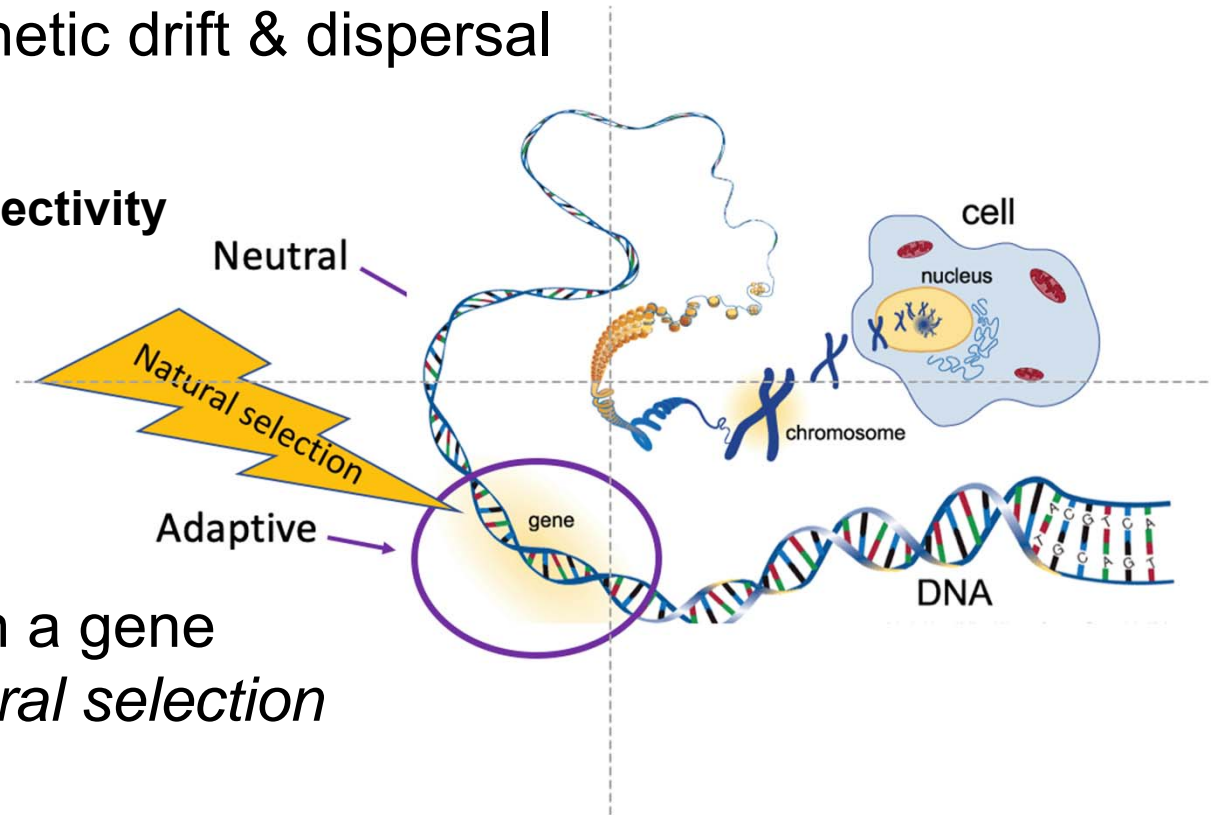
## Conclusion

- Perspective from neutral & adaptive variation
- Highlights of findings
- Resolution & remaining uncertainties

# Two kinds of genetic variation

**Neutral** – influenced by genetic drift & dispersal (gene flow)

- **Indicate demographic connectivity**



**Adaptive** – associated with a gene *under the influence of natural selection*

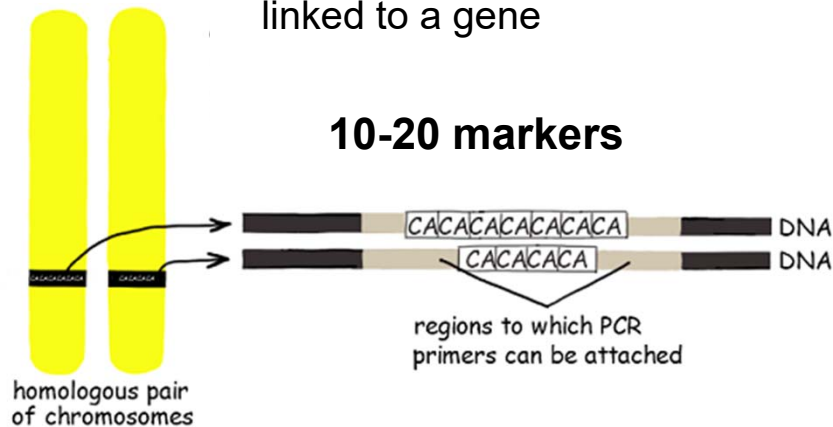
- **Ecological adaptation to local environmental conditions**

# Genetic Markers

## Microsatellites

Typically neutral unless linked to a gene

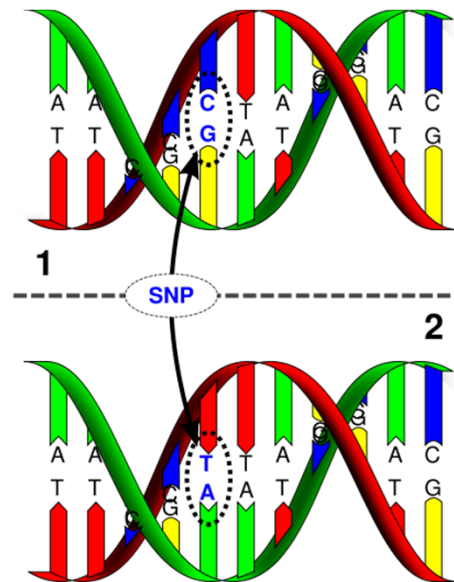
**10-20 markers**



## Single Nucleotide Polymorphisms (SNPs)

Adaptive & neutral

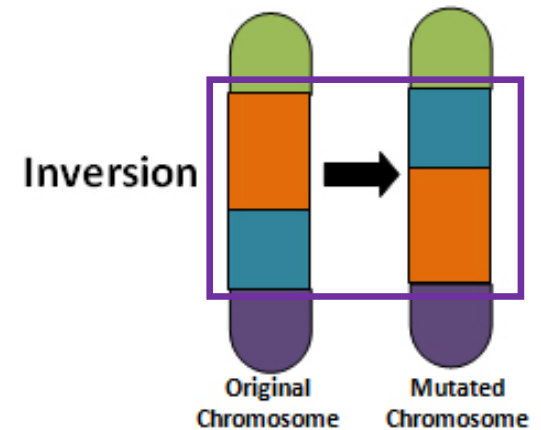
**1000s - millions**



## Chromosomal Rearrangement

Adaptive

Inverted region is inherited as a linked block



# Summary of Population Genetic Studies 1998-2018

## Comprehensive Review

### **Studies with Microsatellite Markers & Pan I**

Western Gulf of Maine, Southern New England & NE Georges Bank

- Wirgin et al. 2007, Kovach et al. 2010

Western Georges Bank/Great South Channel – eastern Georges Bank

- Weiss et al. (2005 unpublished report)

Georges Bank – Browns Bank

- Lage et al. 2004, Ruzzante et al. 1998

### **Studies with SNP markers (single nucleotide polymorphisms)**

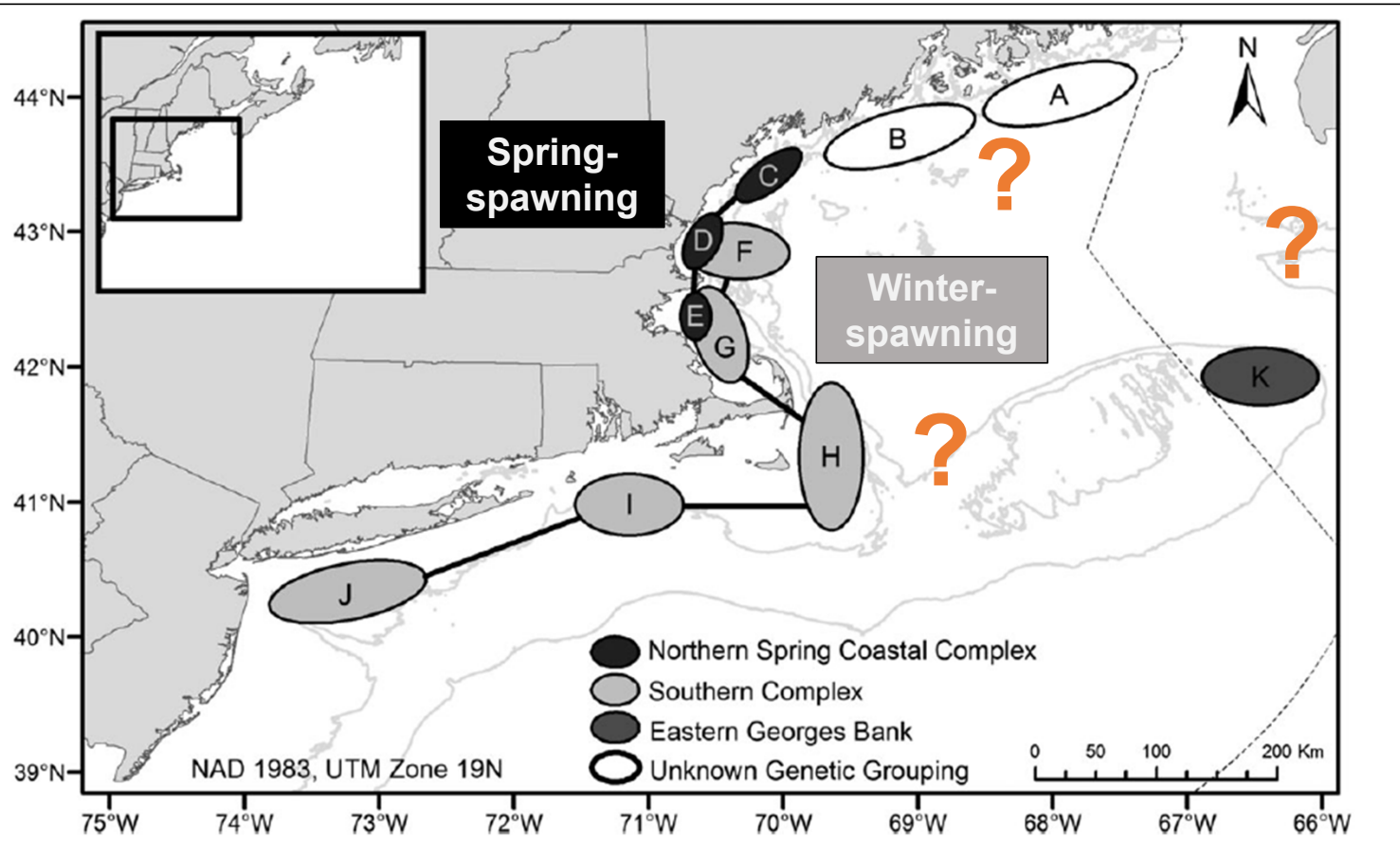
wGoM + Georges Bank – whole genomes (3 chromosomes)

- Barney et al. 2017

Western GoM, eastern GoM, NE Georges Bank – SNP (& microsat) markers

- unpublished NOAA report - Kerr, Cadrin, Kovach et al

# State of Knowledge Prior to ACSSWG Effort

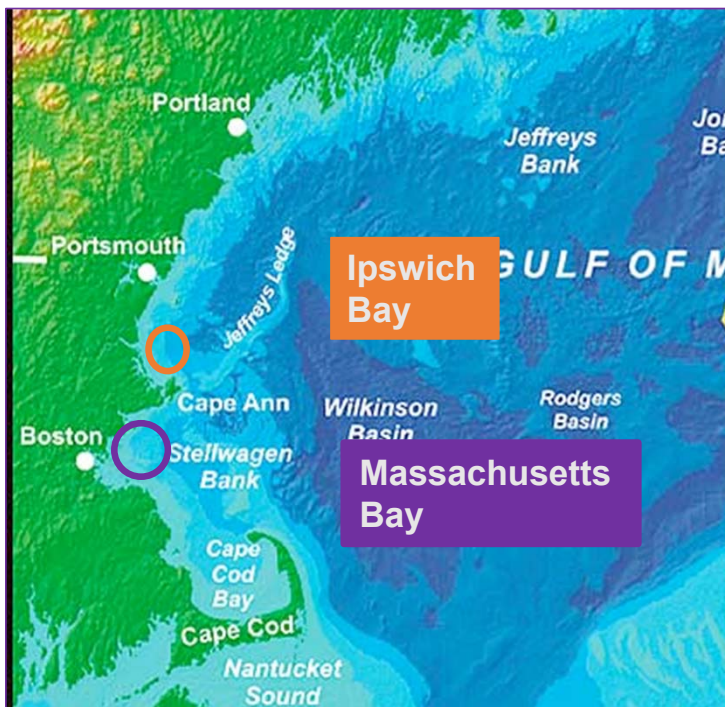


1. wGoM has 2 groups: winter & spring
2. Connectivity of wGoM winter & Nantucket & southern New England
3. NE peak of GB distinct

*Kovach et al. 2010; Zemeckis et al. 2014*

# Focus on western Gulf of Maine – Spring vs. Winter

Adaptive genetic variation drives the difference



Dec -Jan



April -May

- Temporal stability of differentiation across 10 years
- Corroborates Otoliths & Morphometrics
- Genetic assignments are robust
- Working hypothesis: winter and spring are distinct ecological units with adaptive life history differences

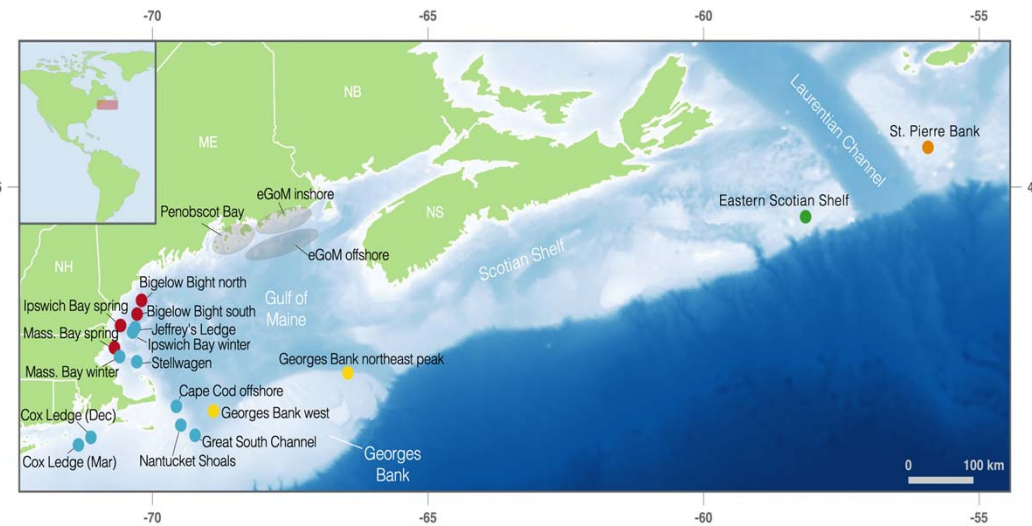


# New Studies Yield New Information

Clucas et al. 2019

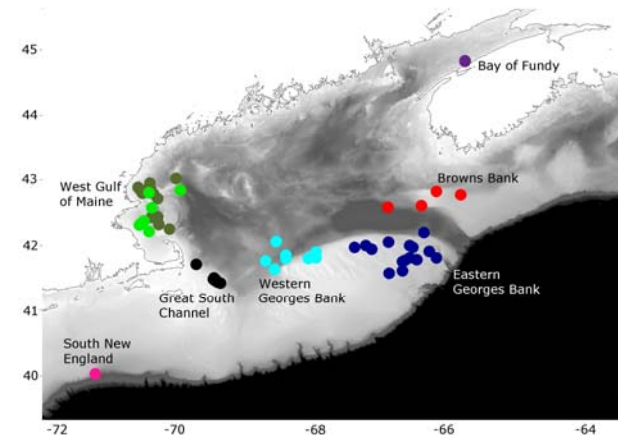
- whole genome sequencing
- 11 million SNPs
- 306 cod from 20 pops
- 11-24 fish per pop
- spawning except eGoM = Sentinel Fishery

- 3 *a priori* US groups and
- 2 Canadian pops



*Puncher, et al. in prep.*

10,000+ genome-wide SNPs



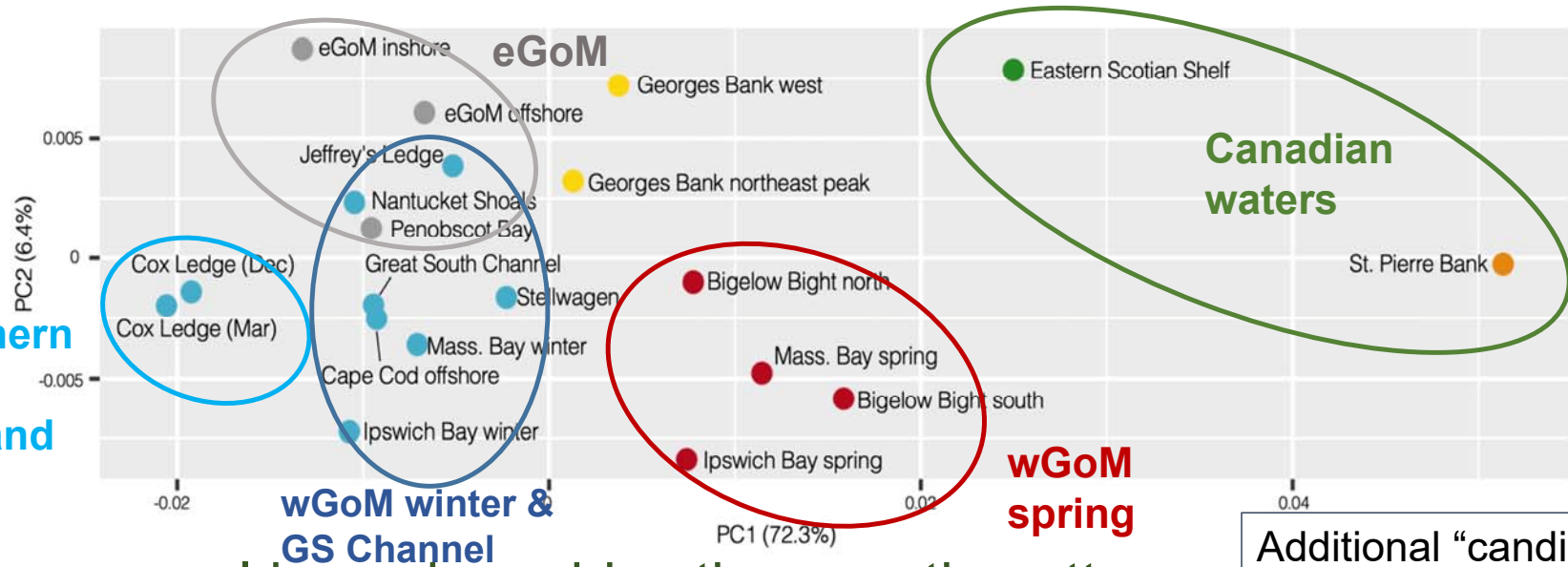


# Genome-wide Genetic Differentiation

Clucas et al. 2019

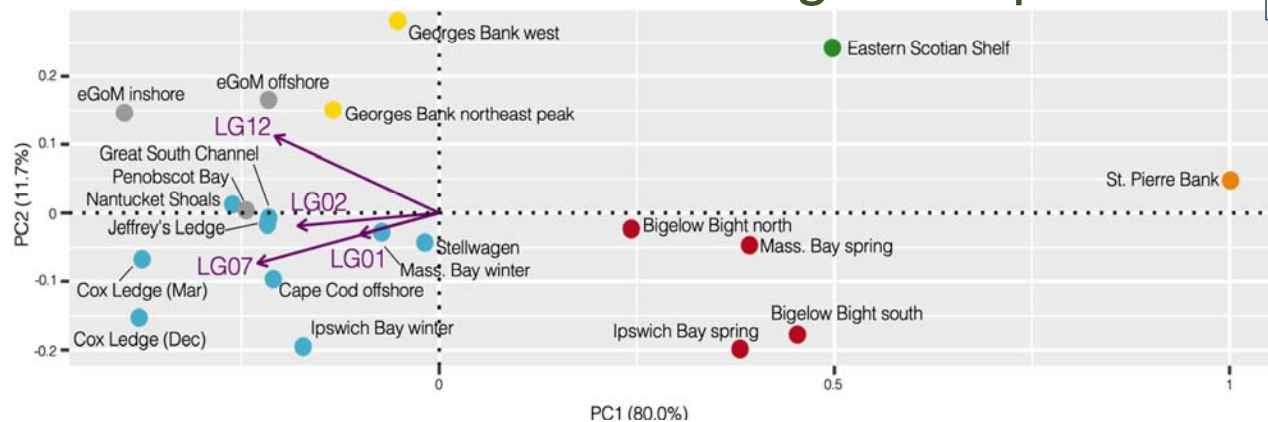
ALL LOCI  
11 million  
SNPs

Southern  
New  
England

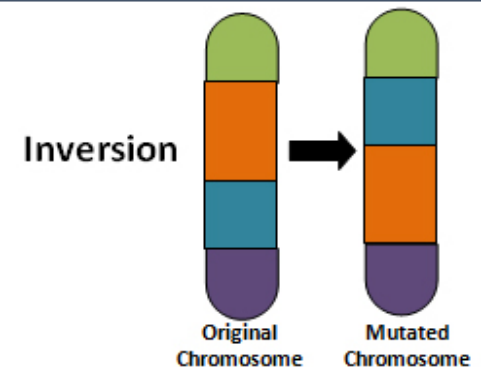


Chromosomal inversions drive the genetic patterns

LGs 1, 2, 7,  
12 only

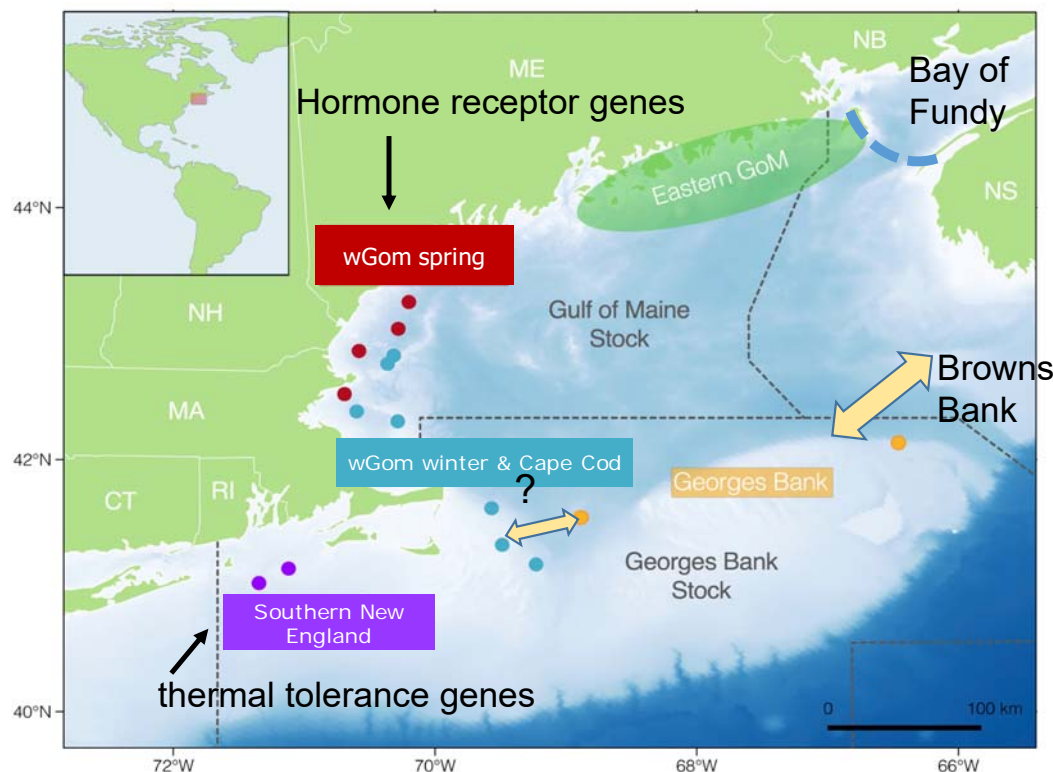


Additional "candidate genes" influence structure

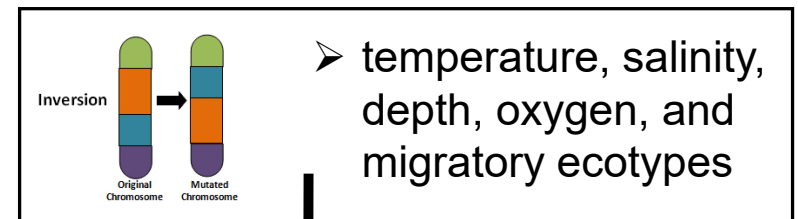


# Summary of Genomic Results

Four genetically distinct groups in US waters + eastern GoM



Gene flow across GS Channel?



- **wGoM spring** shares similarity with northern Canadian waters
- unique component of biodiversity

- Reproductive genes separate wGoM spring
- Thermal genes separate southern New England

Connections to Canadian Waters

# Conclusions

Genetic studies provide perspectives from neutral and adaptive variation

Adaptive variation largely drives the patterns of genetic differentiation, suggesting ecological, life history, physiological or behavioral differences.

- different portions of genome reveal different patterns of divergence
- biocomplexity of cod population structure

Neutral variation among populations is slight, suggesting adaptation in the face of some ongoing or recent gene flow.

- challenges of interpretation weak neutral differentiation
- demographic independence can occur with weak differentiation

# Highlights from Genetic Markers Studies

Heterogeneity within wGoM: 2 genetically distinct groups of cod spawn in 513 & 514 in spring and winter

Cod spawning in wGoM in spring are different from all cod spawning in US waters and more similar to Canadian cod in 4VsW and 3PS

Eastern GoM has some connectivity with wGoM winter and Georges Bank; may be an area of mixing. Unresolved.

High connectivity between western GoM (winter) and Cape Cod/Nantucket Shoals

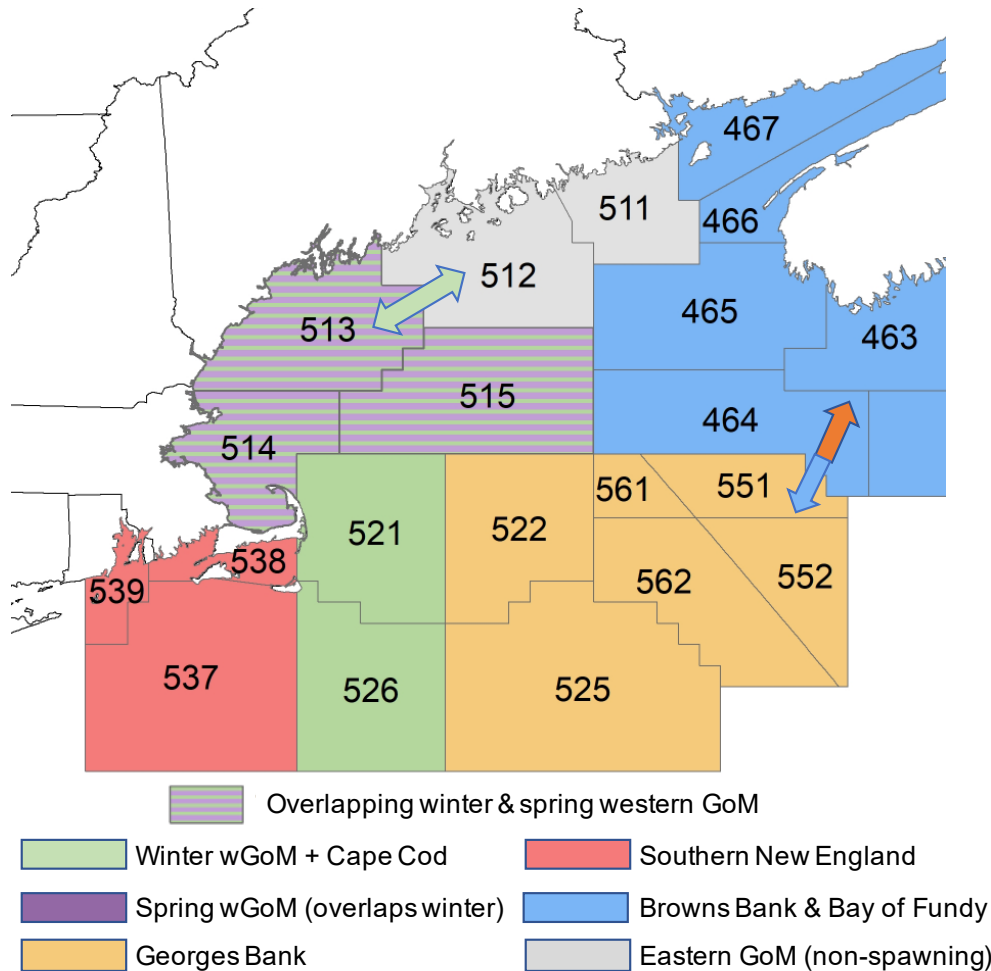
Differentiation of Southern New England from other areas

Differentiation of Georges Bank from Cape Cod and Southern New England

Connectivity between Georges Bank and Browns Bank & Bay of Fundy

# Resolution of Stock Structure from Genetic Markers

5 stocks



## Remaining Uncertainties

- Where is the geographic separation of Cape Cod from western Georges Bank (68 or 69 W boundary)?
- Was the eastern GoM a genetically distinct spawning location? What is the composition of the mixed stock in eGoM today?
- How much connectivity across the transboundary area (GB – BB)?

# Acknowledgments

## Genetics Working Group

Nina Therkildsen

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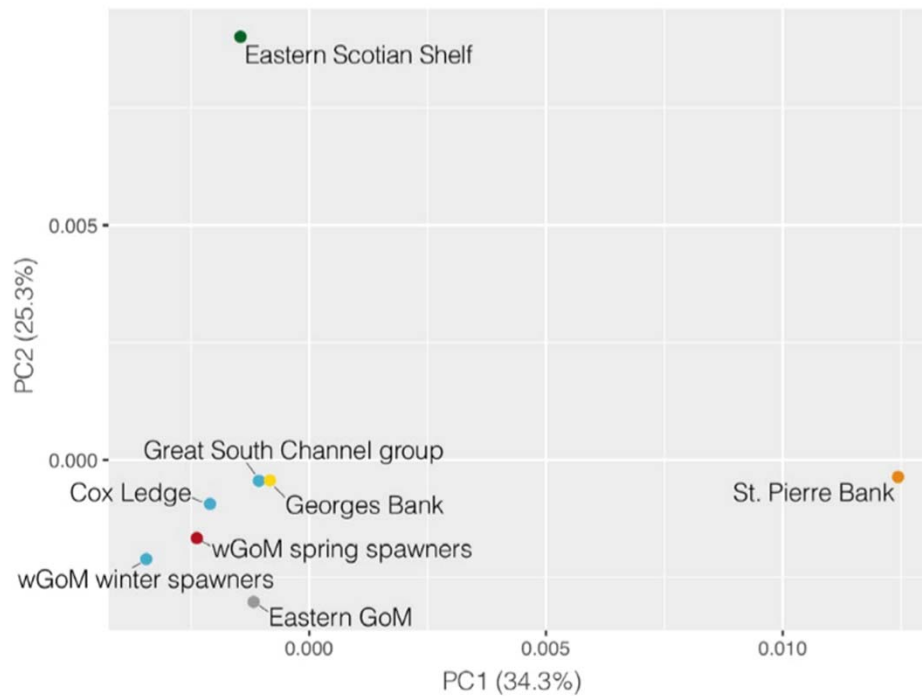
Steve Cadrin (internal review)



Backpocket slide(s)



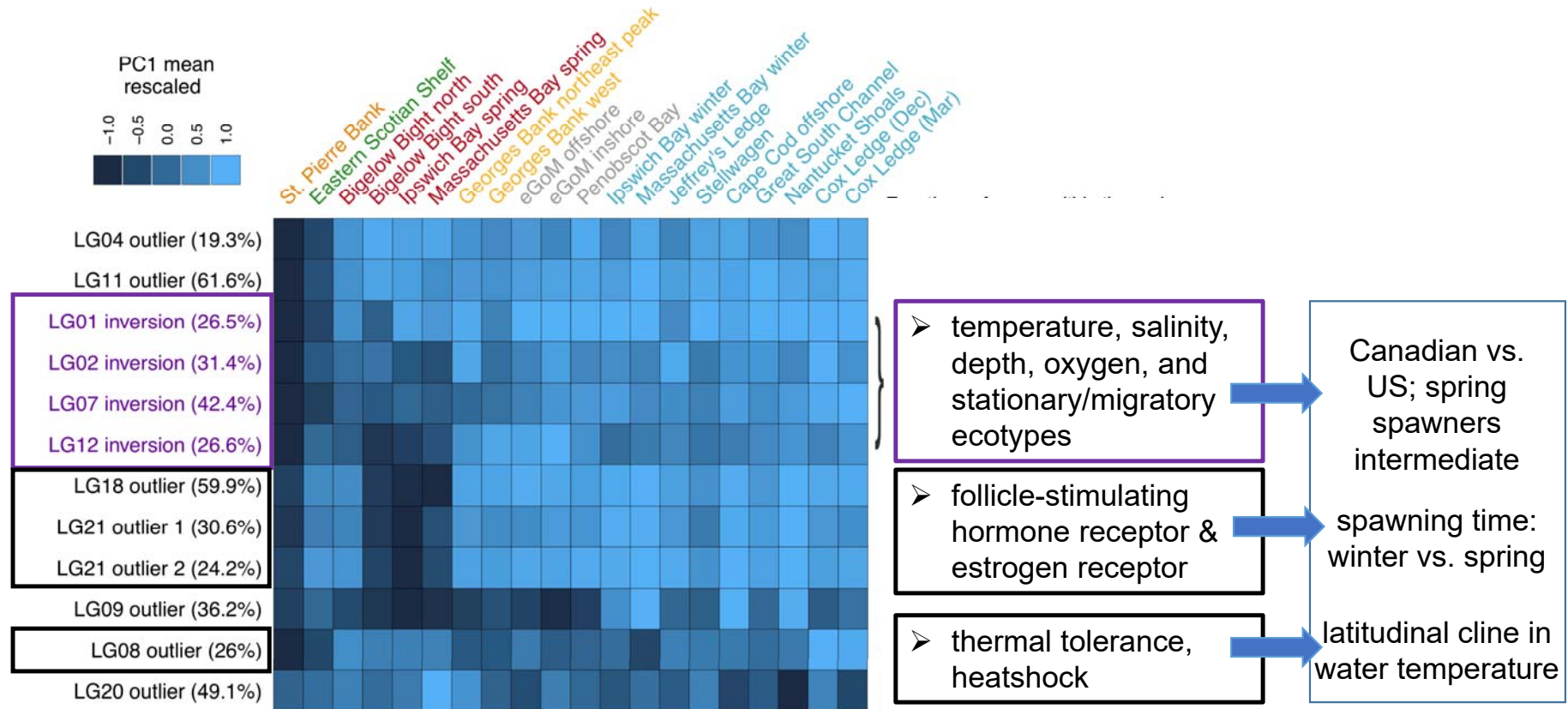
# Neutral differentiation is weak



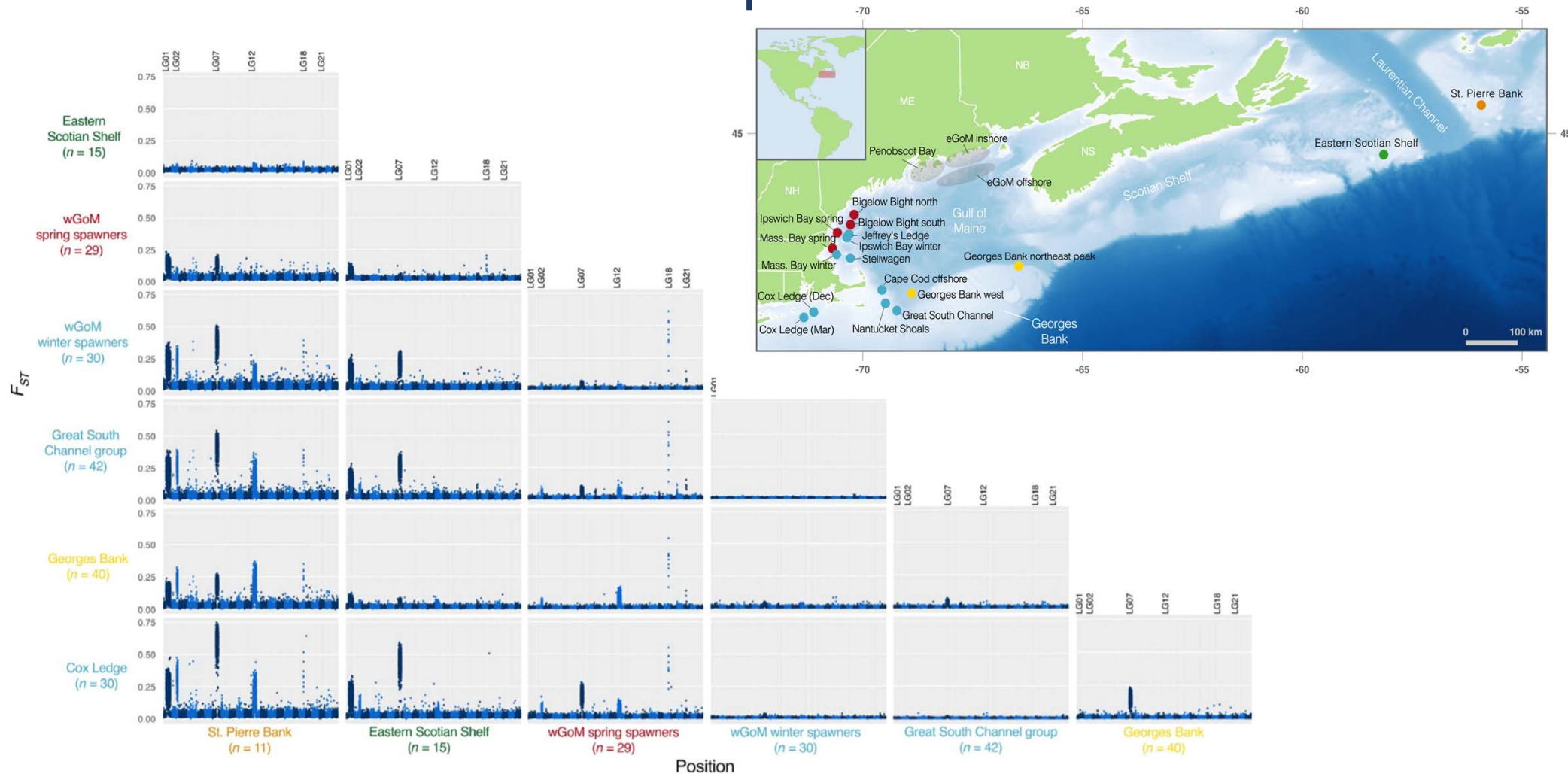
- Adaptation despite high gene flow is common in marine systems
- Challenge of interpreting low neutral  $F_{ST}$

# Complex patterns of biocomplexity

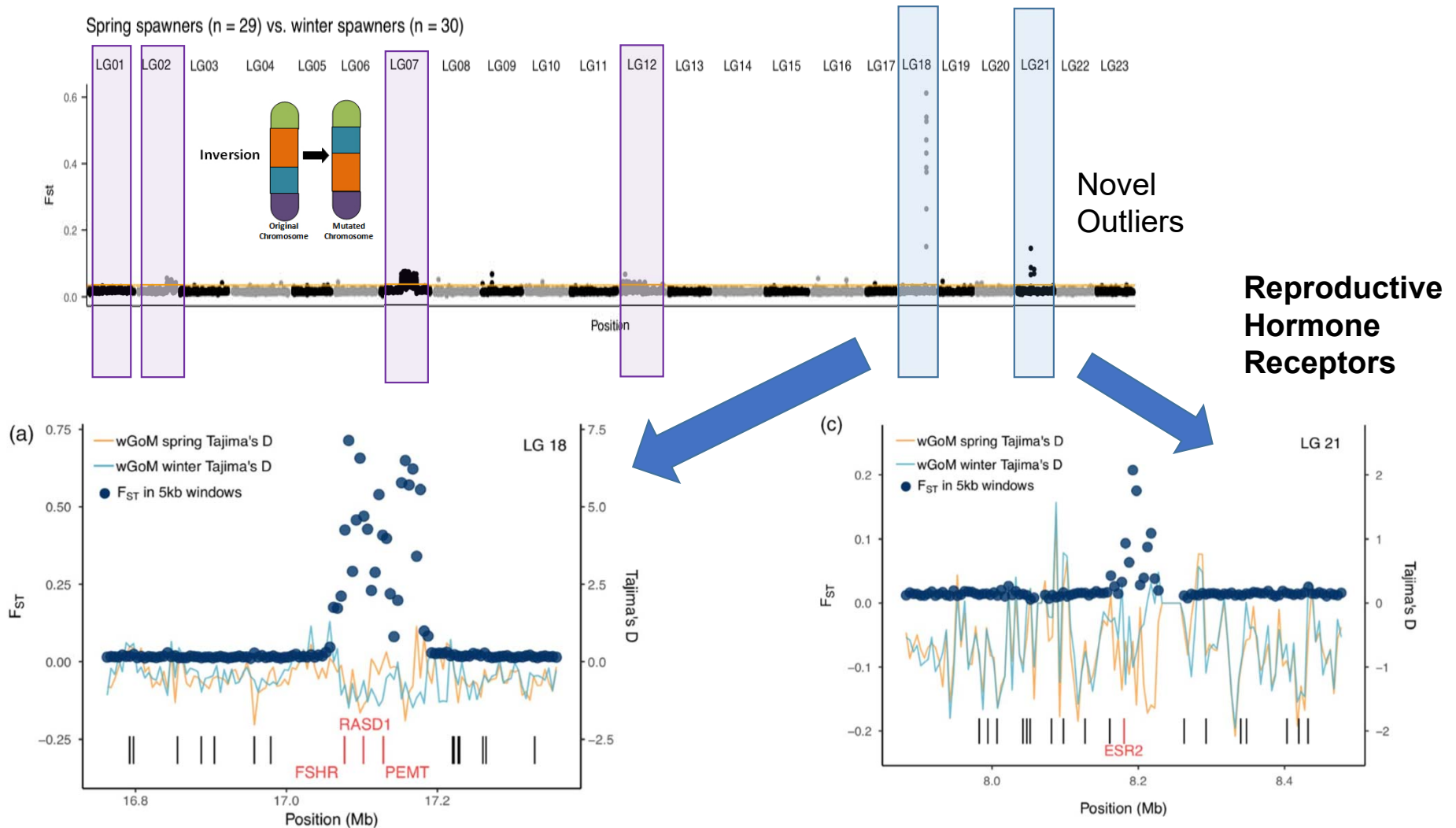
- 4 chromosomal inversions + outlier regions on other LGs (adaptive)



# Genome-wide $F_{ST}$ comparisons reveal outlier loci

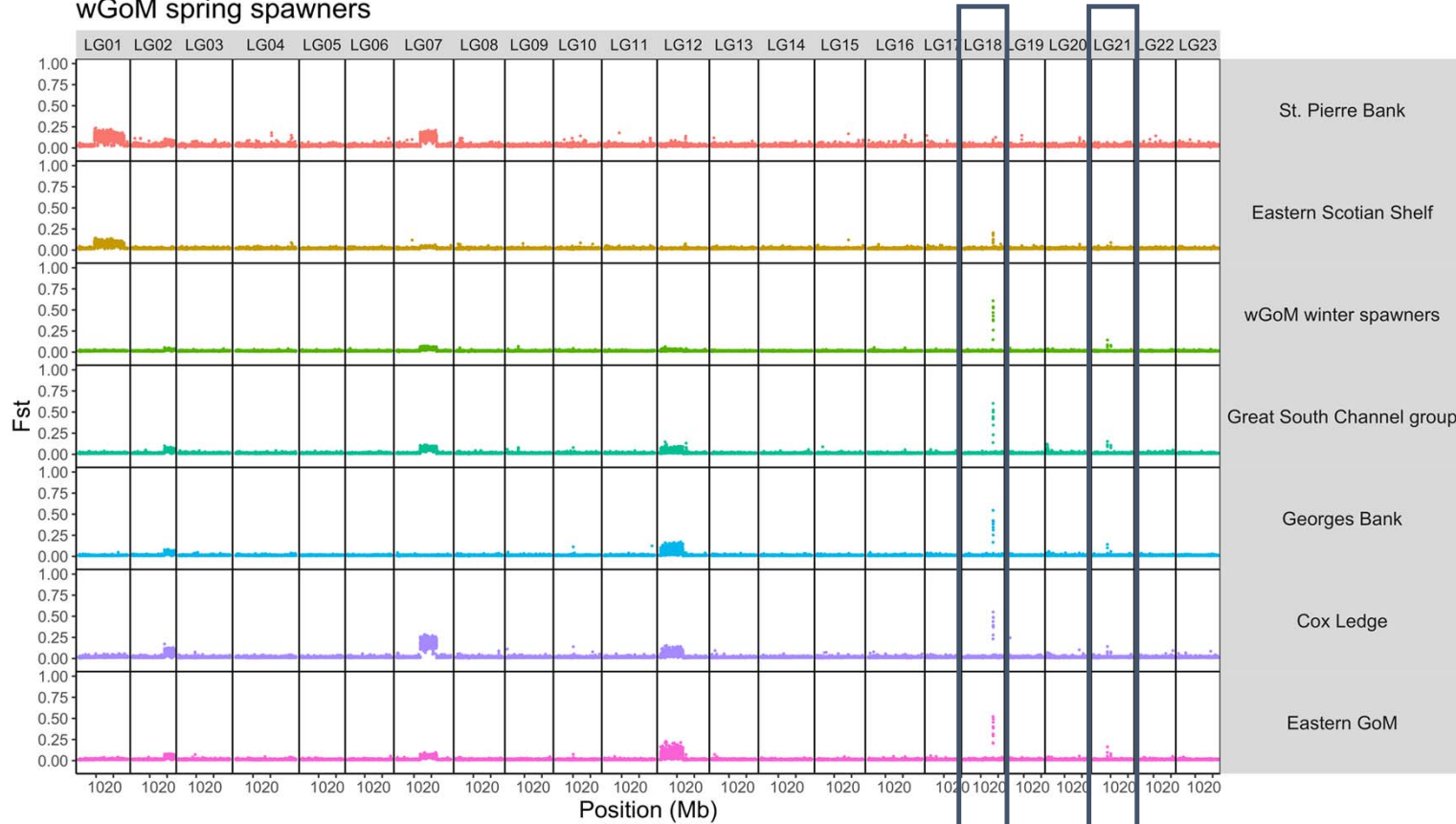


# Adaptive Divergence in winter and spring spawners



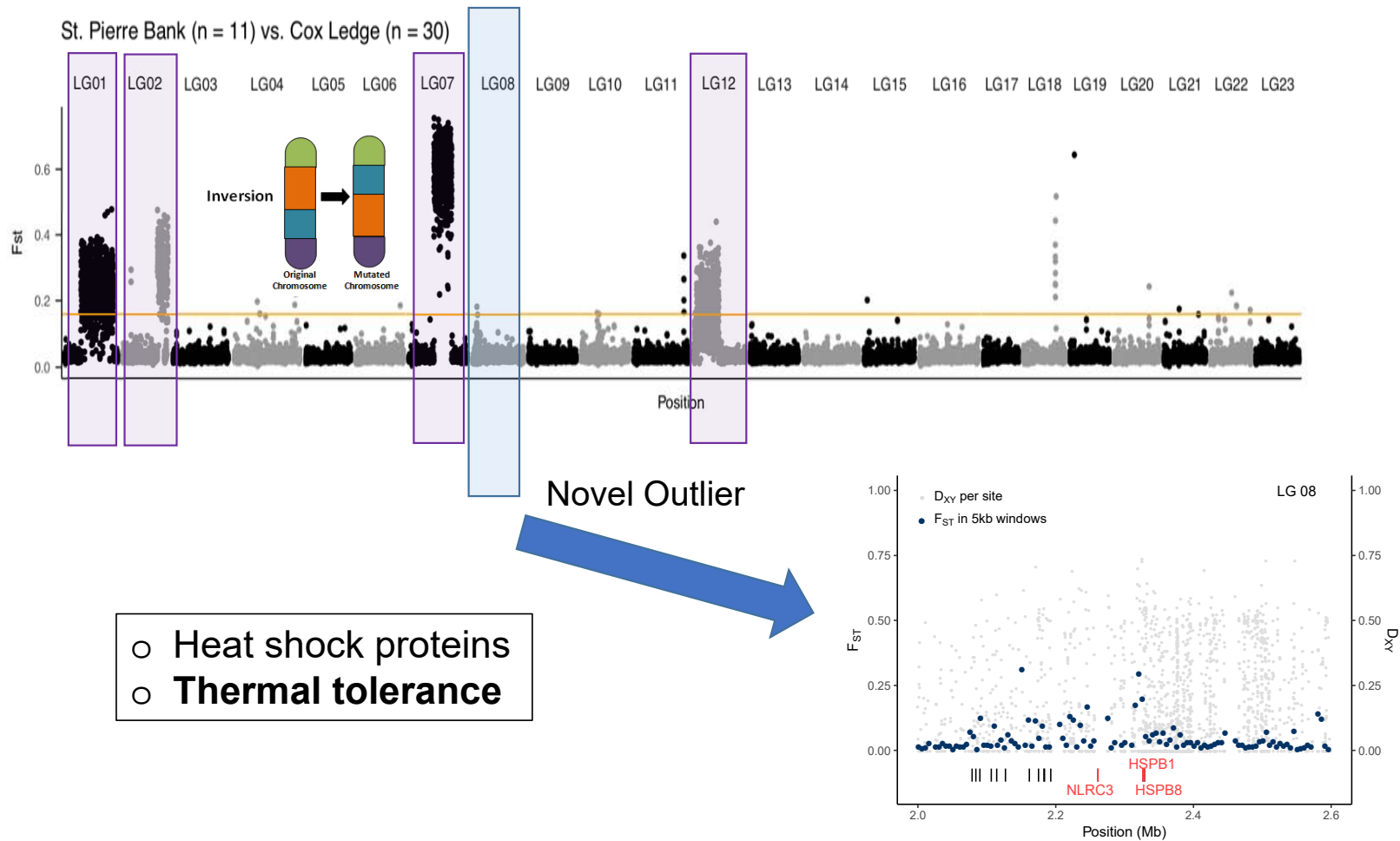
# Genetic underpinnings of spawning time

wGoM spring spawners



- **Thermal history** influences spawning time
- Temperature during **vitellogenesis** influence ovarian processes

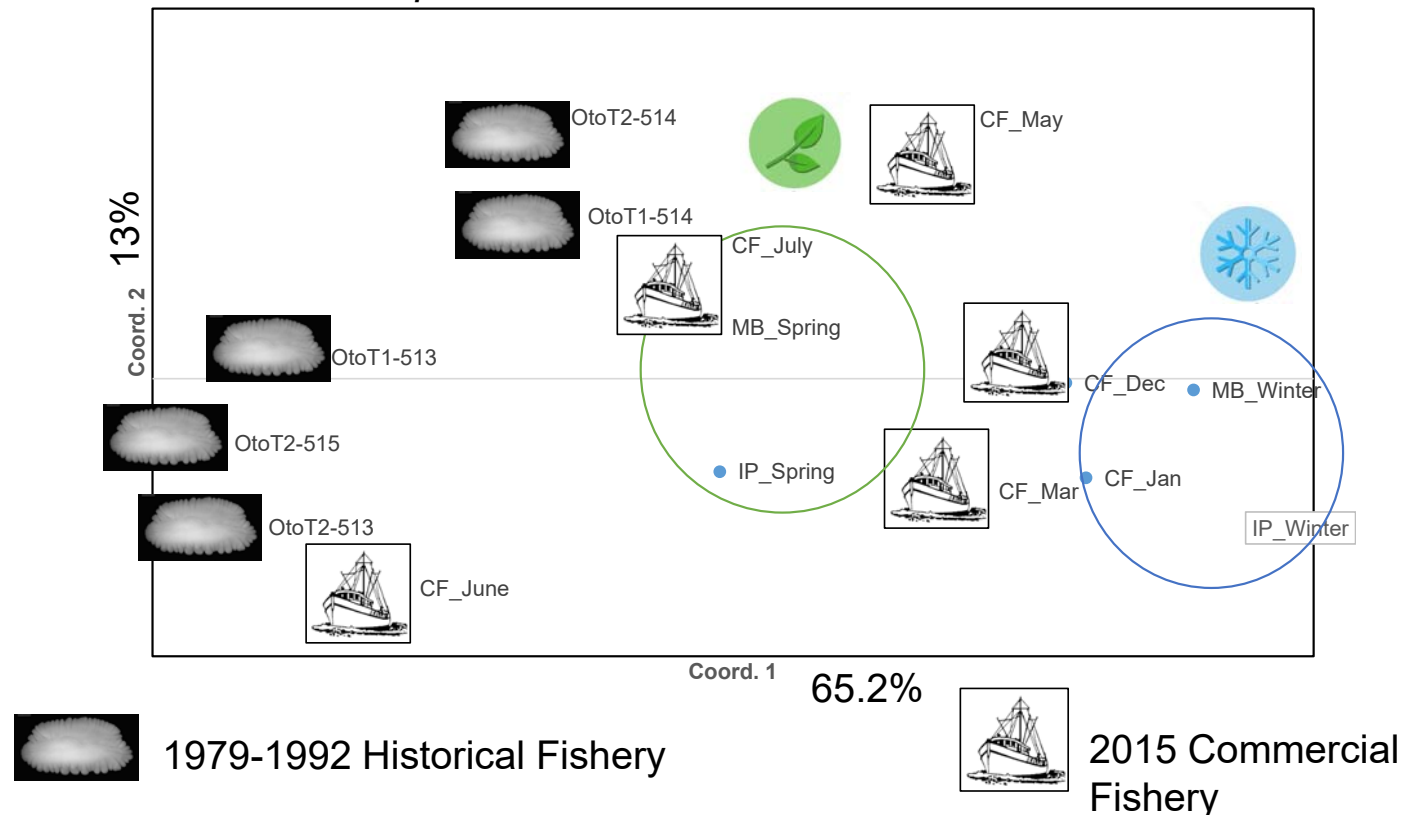
# Latitudinal thermal cline



- Comparison of Historical & Modern Fishery with Spawning Populations
  - Shift in population components comprising the fishery
    - away from spring-spawning types

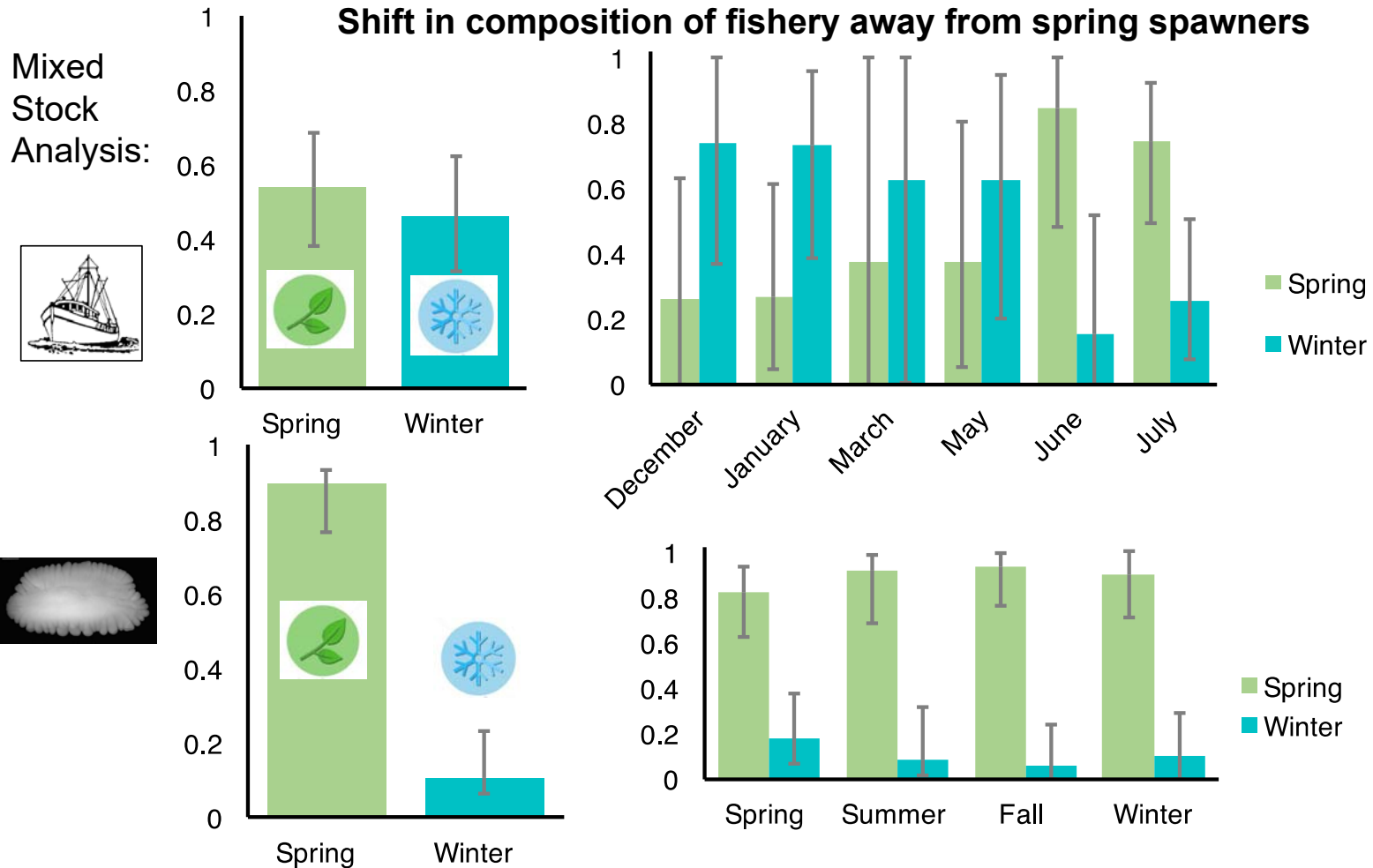
*Kerr et al. NOAA Report 2017*

Microsatellite & Pan I dataset



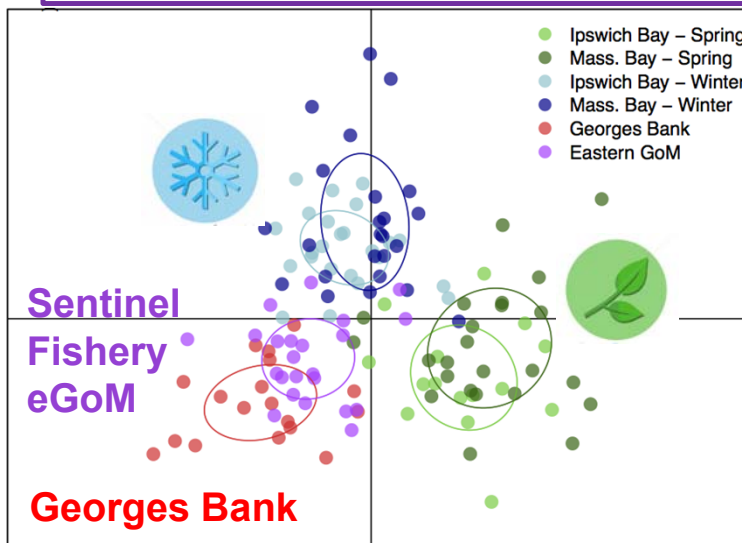


- Spring spawners (or populations similar to them) dominated the historical fishery vs. a mix today

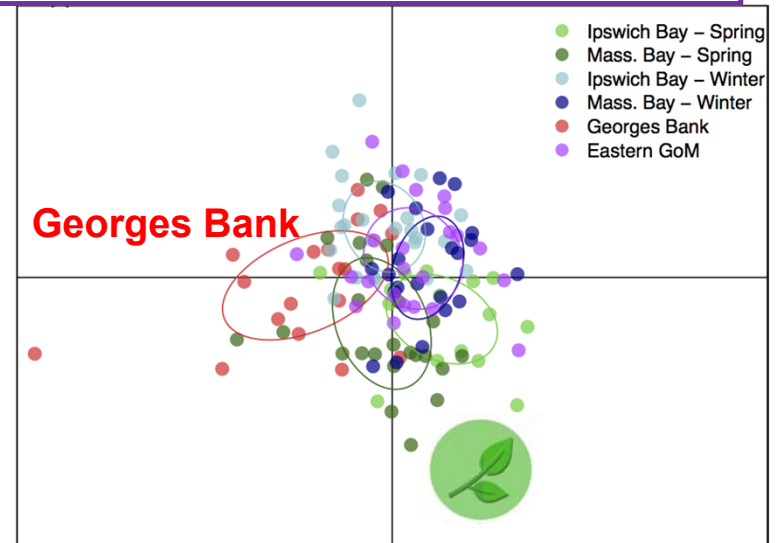


- Adaptive vs. Neutral Markers

- Differences primarily driven by **adaptive markers**
  - On 2 of the 4 chromosomes differentiated in other studies
- Weak neutral differentiation as well.



All 3128 SNP markers



2689 neutral SNP markers  
(adaptive markers removed)