Laboratorio de
Sistemas Dinámicos

Lecture 3

The neuroethology perspective in neuroscience. Case of study: models of vocal production in birds.

Ana Amador

Lab. Sistemas Dinámicos – Universidad de Buenos Aires

& INFINA – CONICET, ARGENTINA

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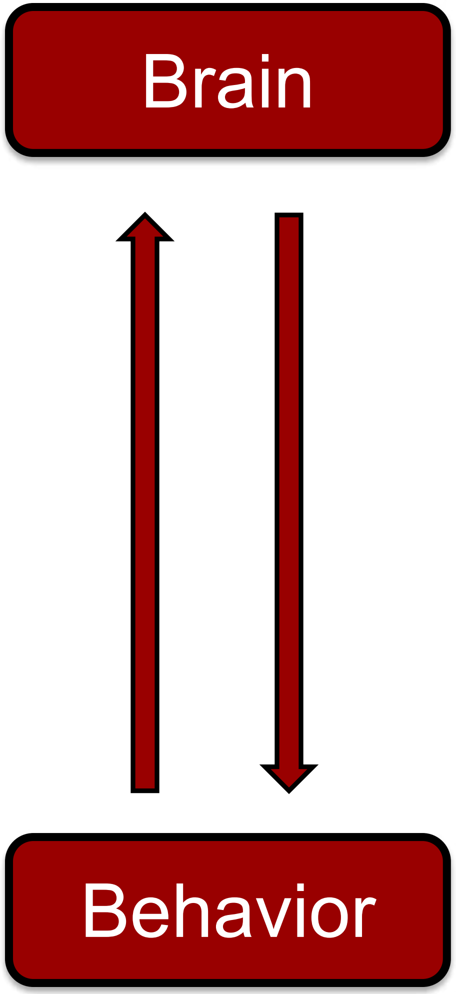
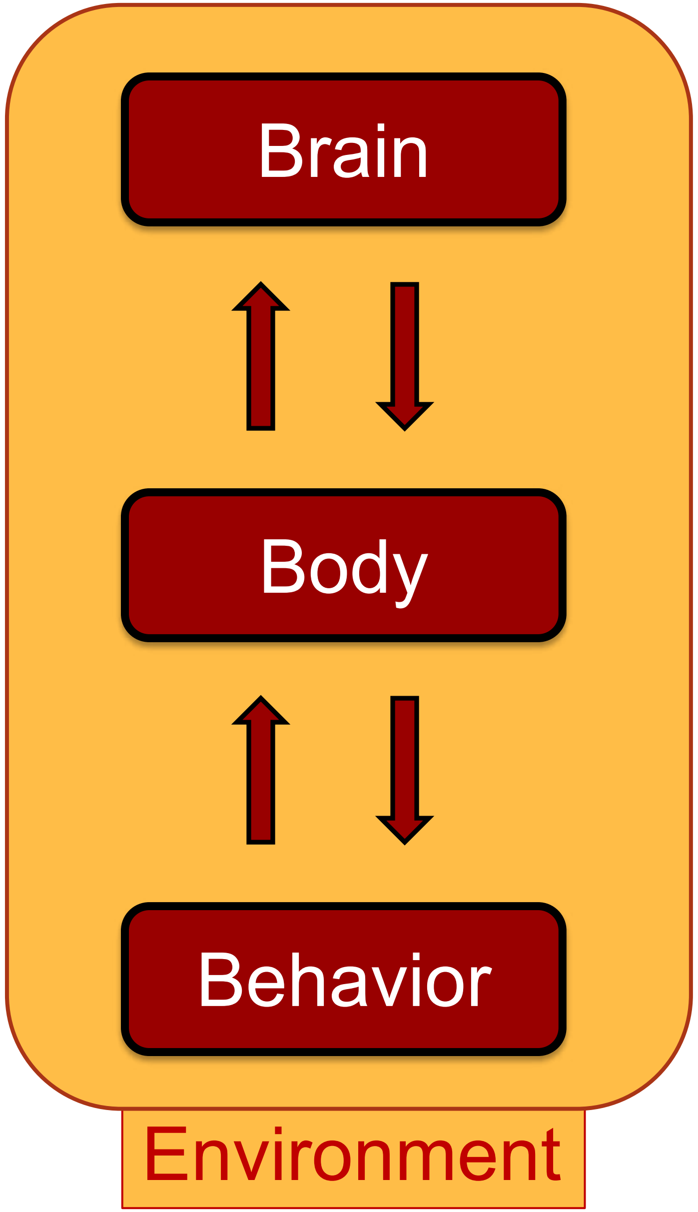
SCHOOL ON NONLINEAR DYNAMICS, COMPLEX NETWORKS, INFORMATION THEORY AND MACHINE LEARNING IN NEUROSCIENCE
ICTP-SAIFR - São Paulo, Brasil – May 22 - 26, 2023

Neuroethological approach

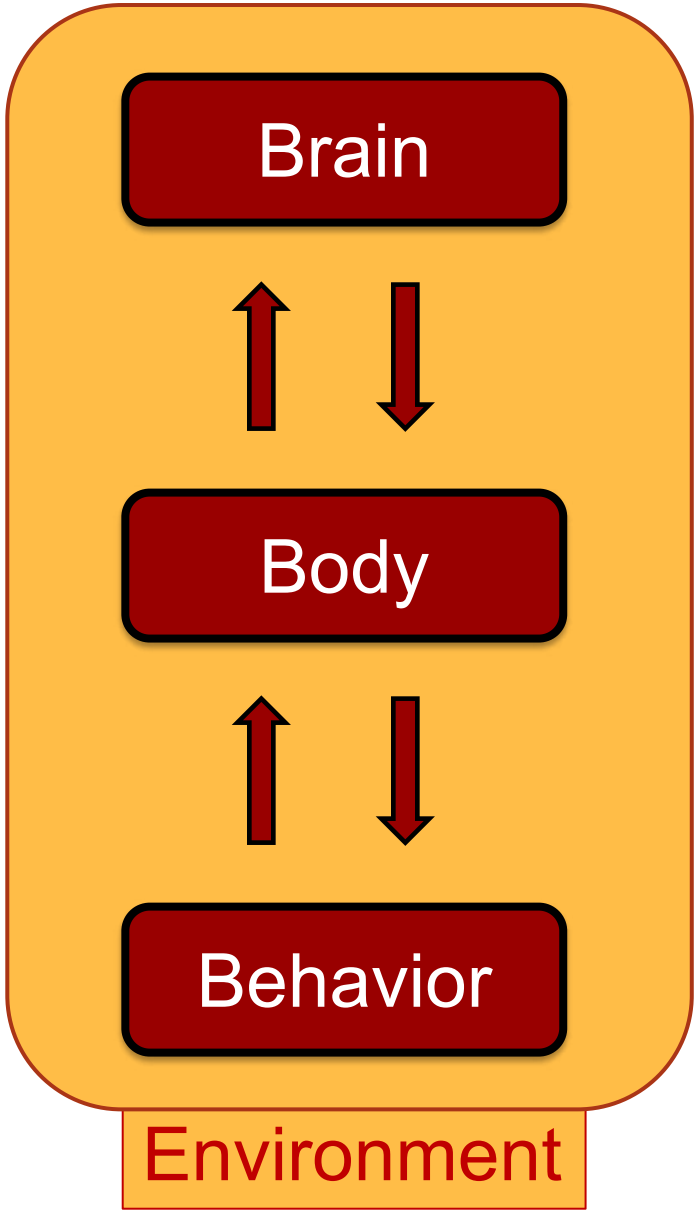


Neuroethological approach



Neuroethology:
interdisciplinary science that combines **neuroscience** and **ethology** (study of animal behavior in natural conditions)

Neuroethological approach

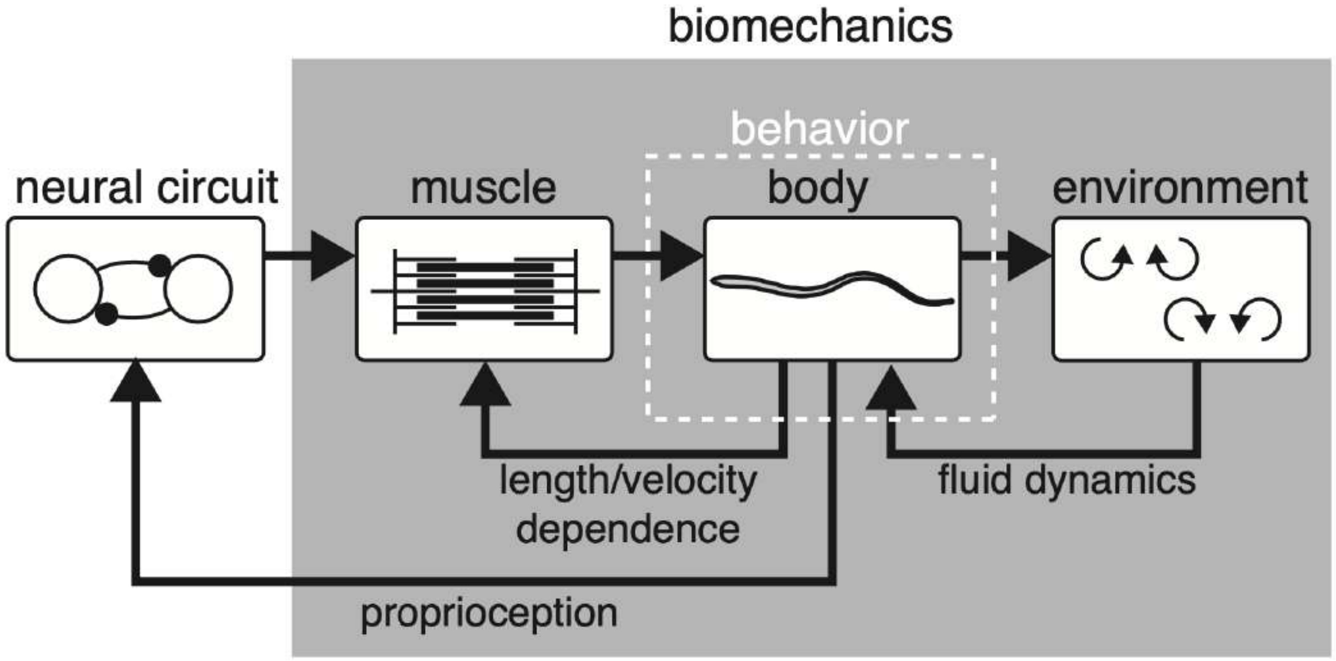


Available online at www.sciencedirect.com
ScienceDirect
Current Opinion in Neurobiology

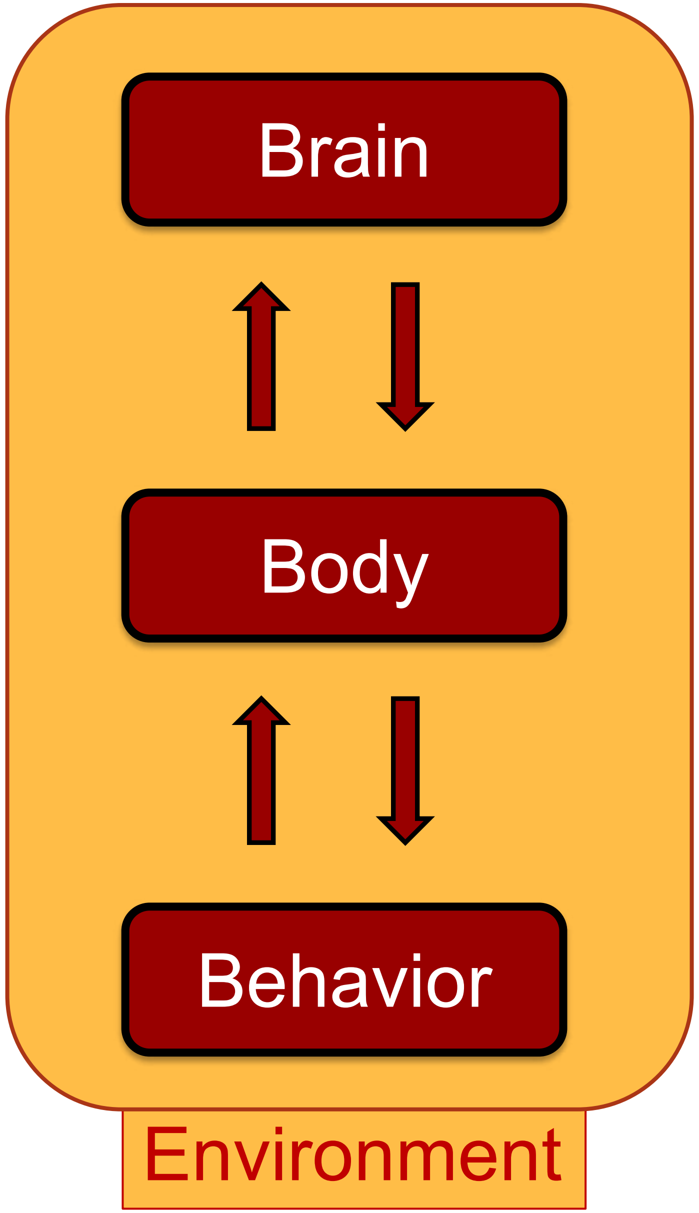
Spikes alone do not behavior make: why neuroscience needs biomechanics

ED Tytell[1], P Holmes[2] and AH Cohen[3]

Current Opinion in Neurobiology 2011, **21**:816–822 www.sciencedirect.com



Neuroethological approach



Case of study: birdsong production

The vocal organ and the brain are nonlinear devices

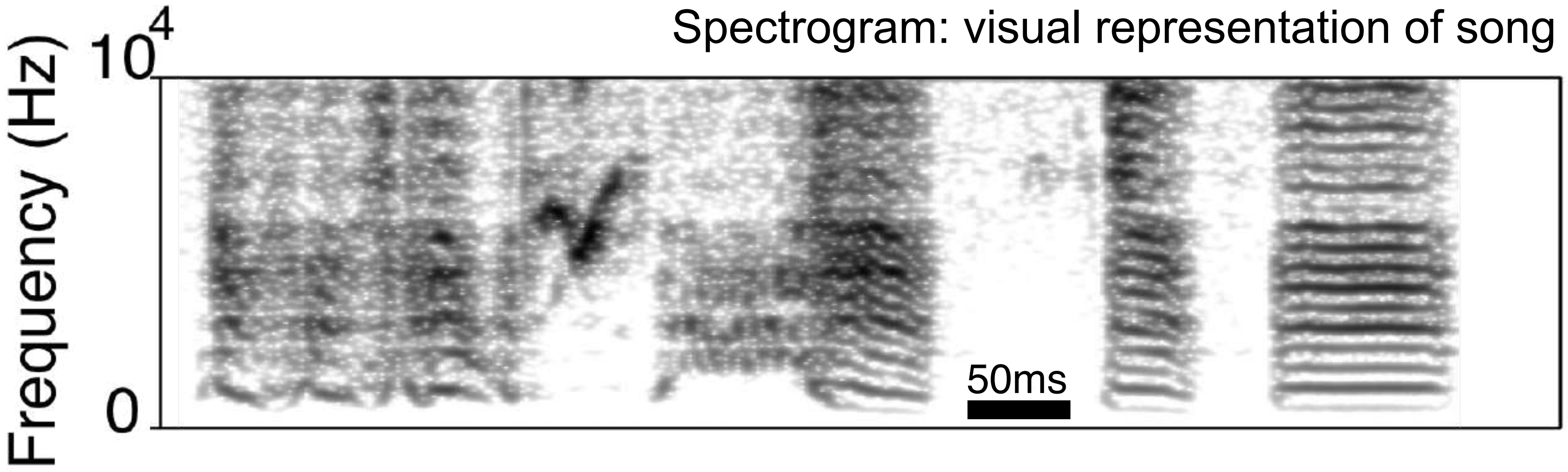
Why songbirds?

- Well-stablished animal model to study:
  - mechanisms of vocal learning (not common in mammals).
  - complex motor control.

- Shared properties with humans:
  - Similar learning stages.
  - Similar sound production mechanisms.

The behavior: birdsong

Zebra Finch song

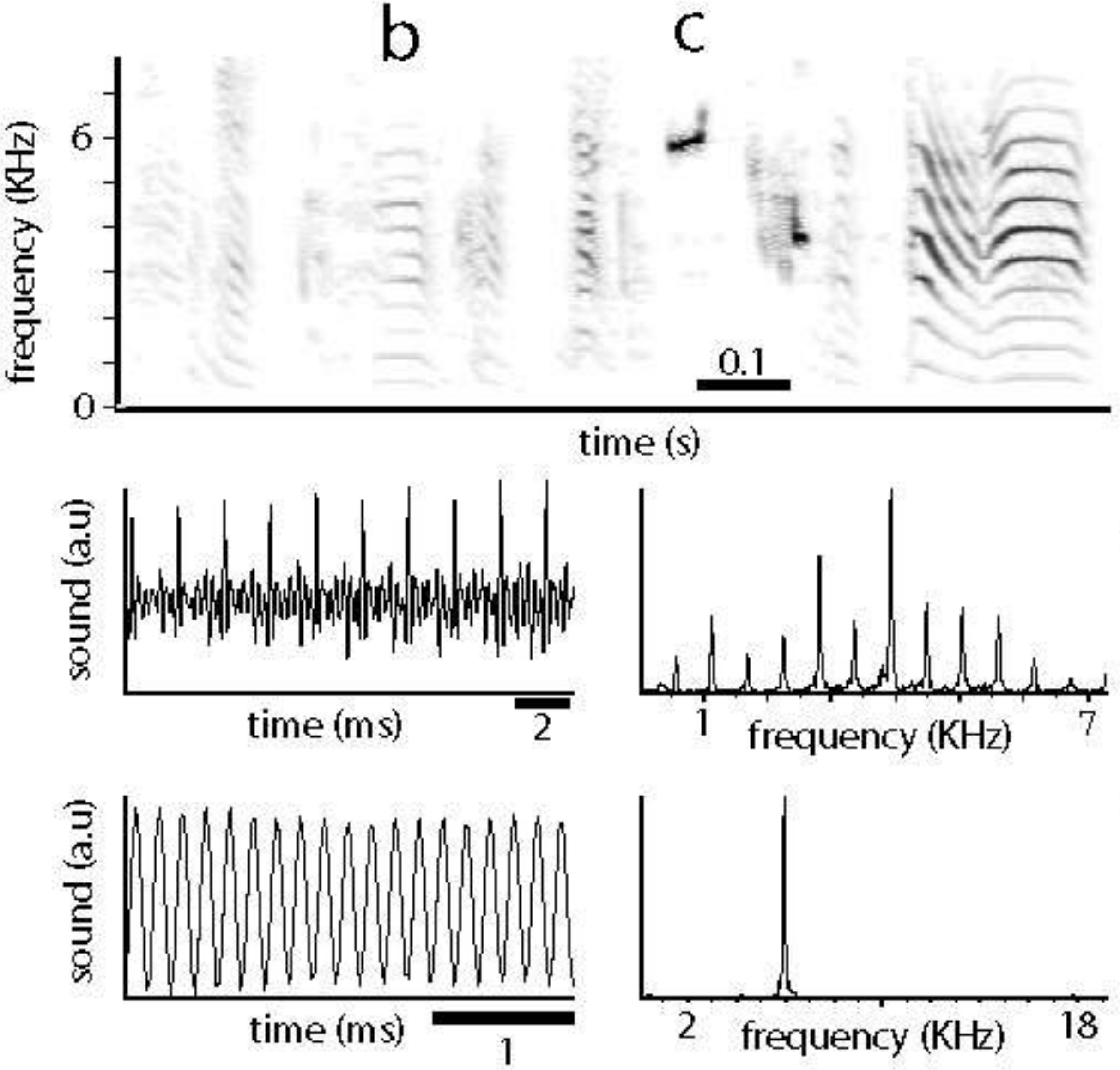


- ✓Complex sounds
- ✓Spectrally rich
- ✓Highly repetitive

The song is like a fingerprint:
Every individual has its Own Song (BOS)

The behavior: zebra finch song

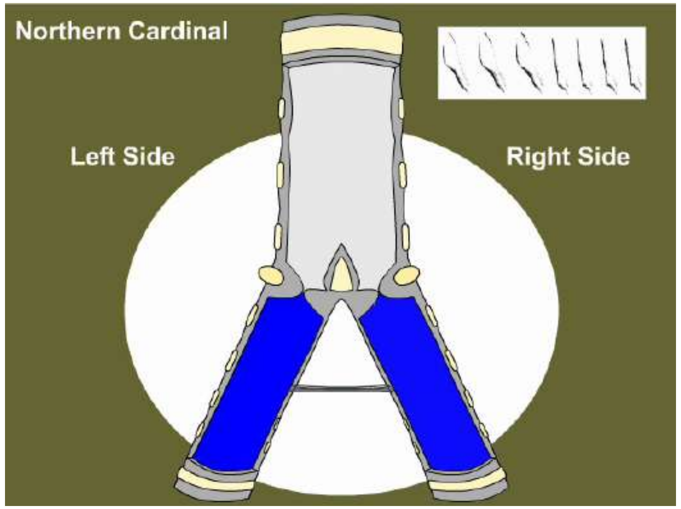
Complex and stereotyped song



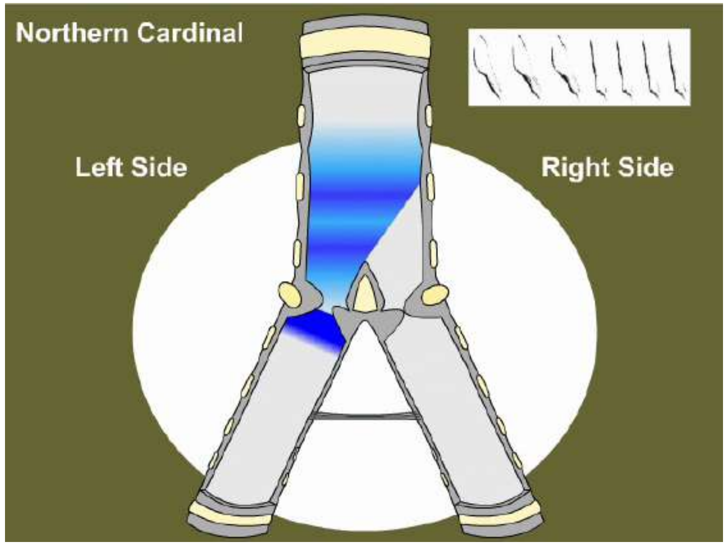
b Spectrally rich notes

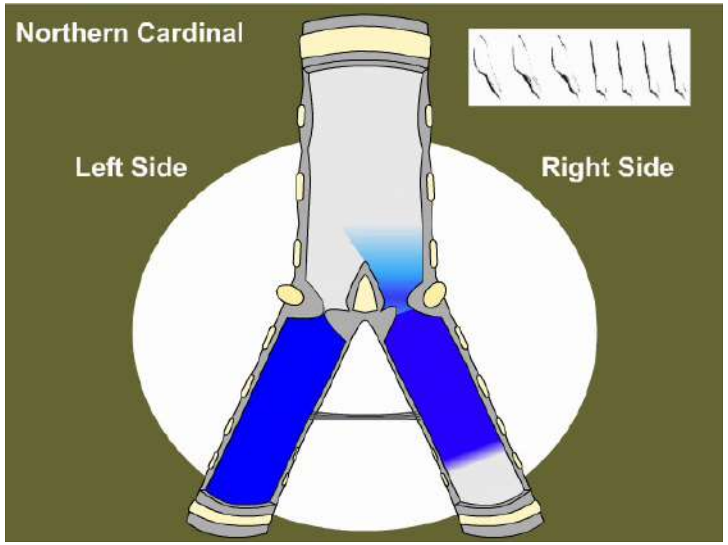
c Almost tonal notes

Avian vocal organ



Syringeal muscles
+
respiratory muscles

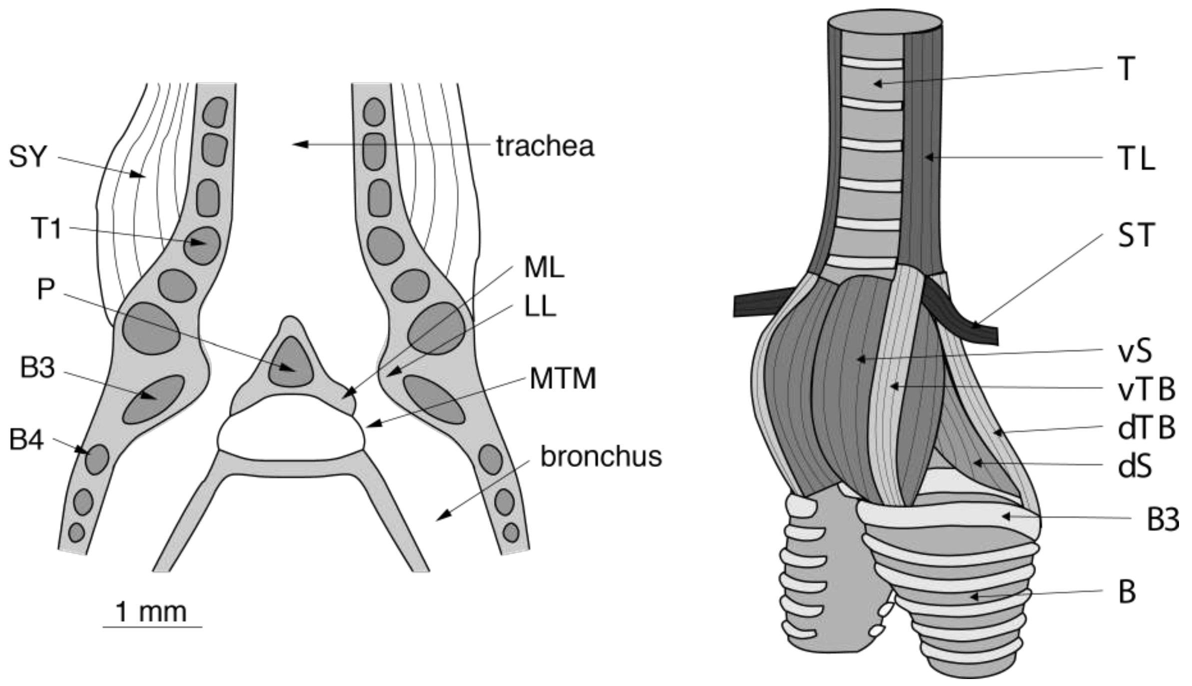


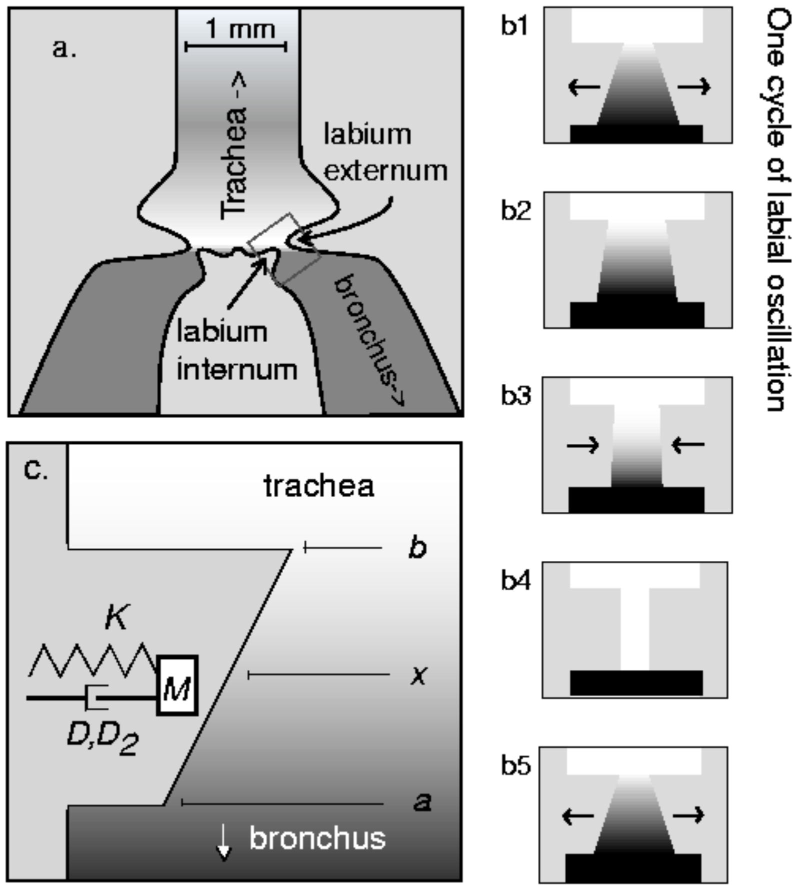


Credits: Rod Suthers

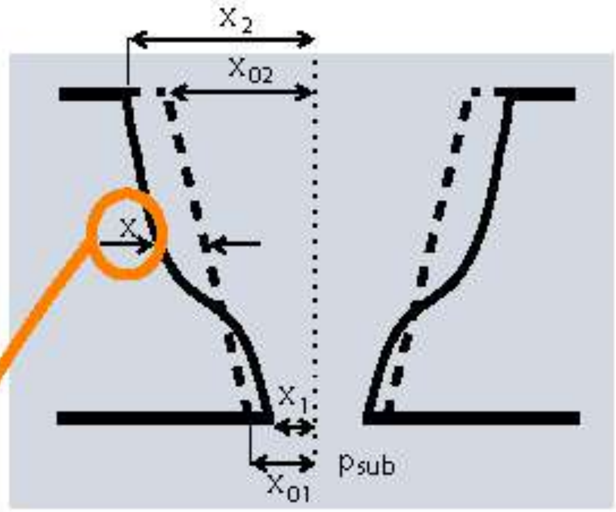
When physics and biology meet…

- Biology is used to complexity
- Physics is obsessed with simplicity





Dynamical system model for the syrinx



Sound is generated by modulations of the airflow passing through the syrinx.

The motion of the oscillating labia is represented as a surface wave propagating in the direction of the airflow

$$k(x)x = k_1 x + k_3 x^3$$

$$\beta(\dot{x})\dot{x} = \beta_1 \dot{x} + \beta_3 \dot{x}^3$$

Equation of motion:

$$m\ddot{x} + \underbrace{\beta(\dot{x})\dot{x}}_{\text{nonlinear dissipative force}} + \underbrace{\kappa(x)x}_{\text{nonlinear restitution force}} + \underbrace{cx^2\dot{x}}_{\text{collision force}} + f = P_s a_{lab} \frac{\Delta x + 2\tau\dot{x}}{x_{01} + x + \tau\dot{x}}$$

active gating

subsyringeal pressure

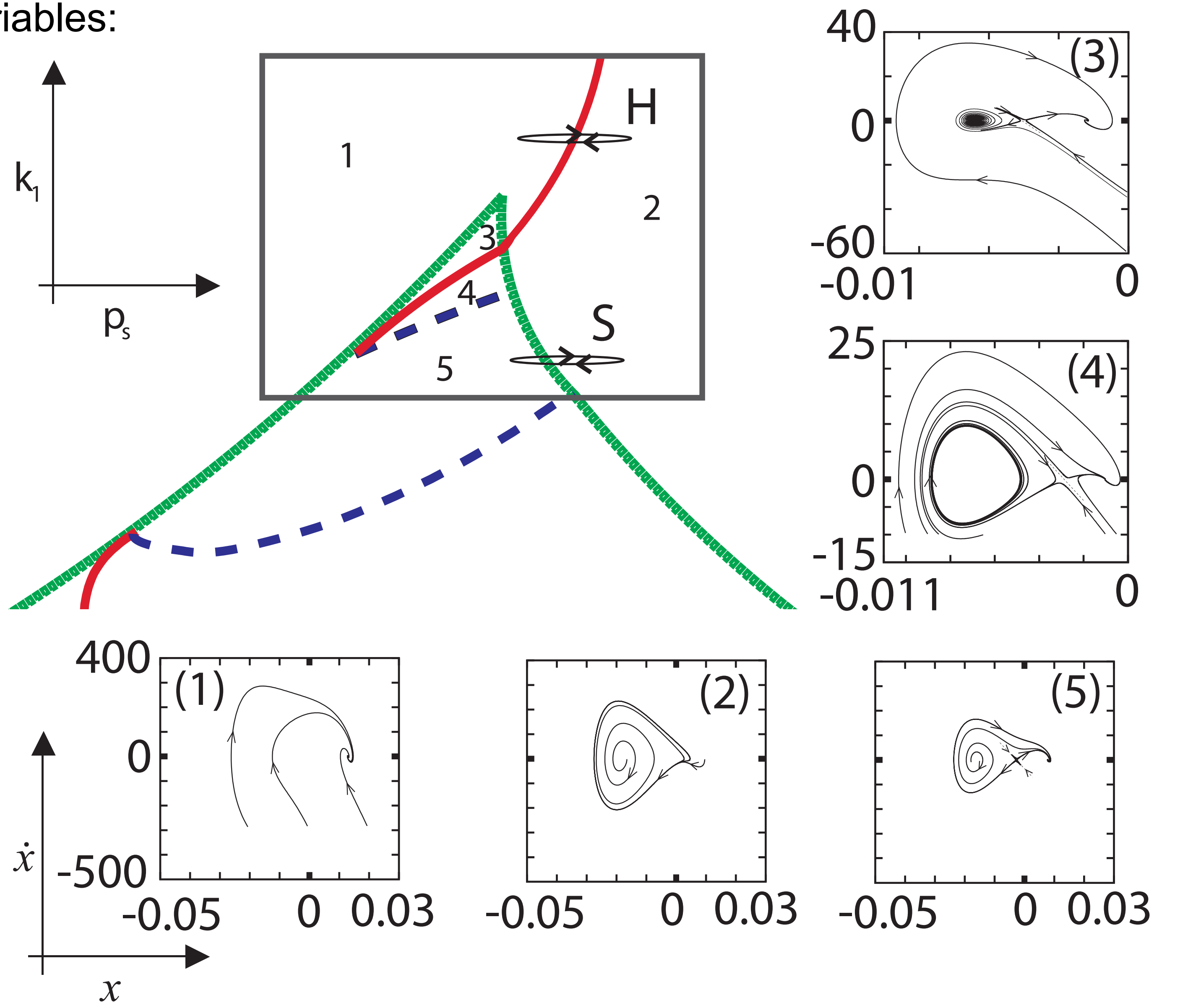
Dynamical analysis of the model

Parameters ***k1*** y ***Ps*** are related to physiological variables:
k1 ∝ activity of vS syringeal muscle
Ps ∝ subsyringeal pressure

<u>**Bifurcations:**</u>

H: Hopf:
✓almost tonal
✓frequency defined by k_1

S: SNILC:
✓ spectrally rich
✓fundamental frequency defined by pressure



Numbers indicate regions of the parameter space with qualitative similar outputs

Dynamical analysis of the model

Parameters ***k1*** y ***Ps*** are related to physiological variables:
k1 ∝ activity of vS syringeal muscle
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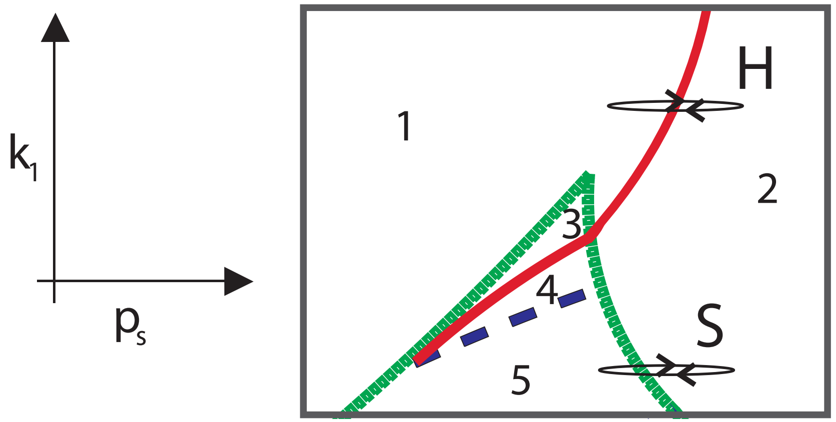

Bifurcations:

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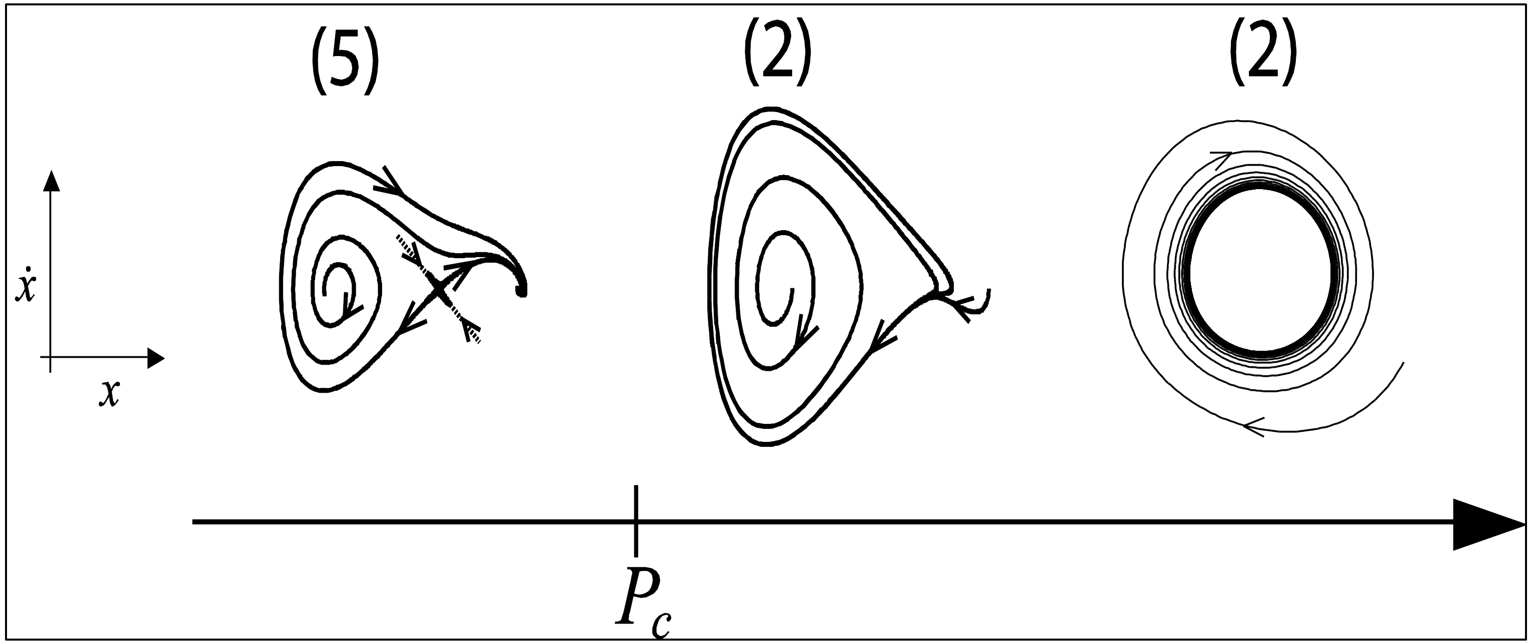
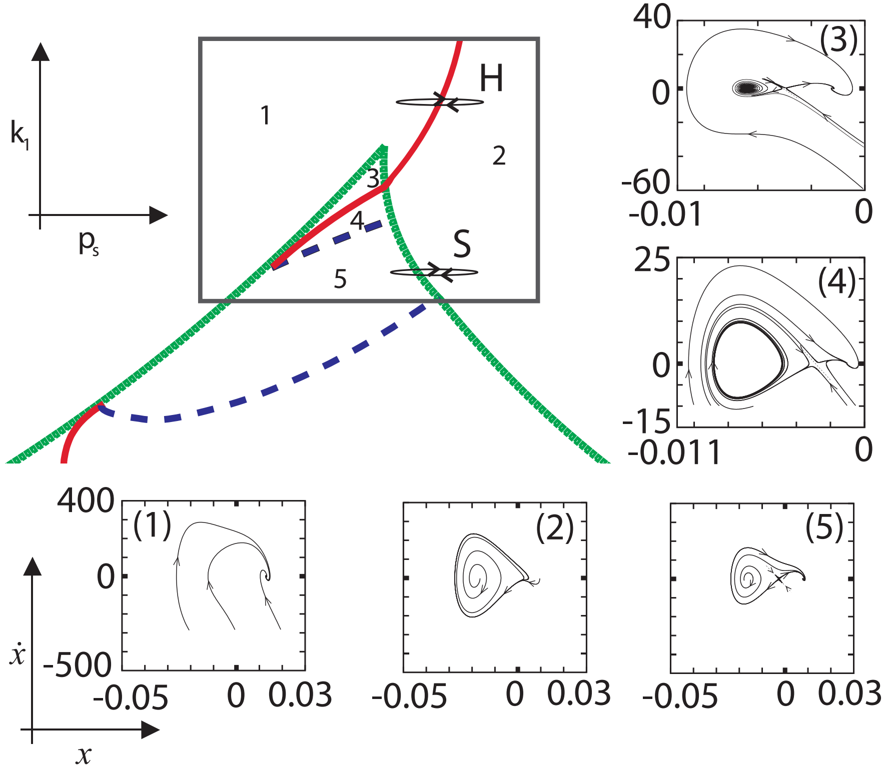
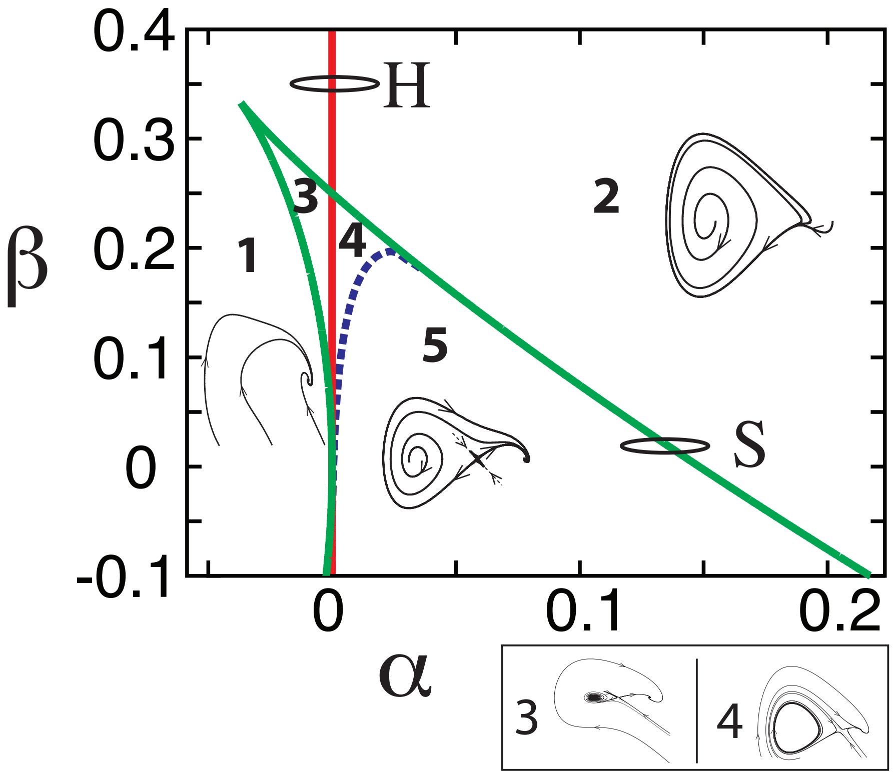


Normal form reduction

Complete model



Normal form



$$\frac{dx}{dt} = y$$

$$\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y$$

Generating synthetic songs: source

Dynamical system model of the sound source

$$\frac{dx}{dt} = y$$

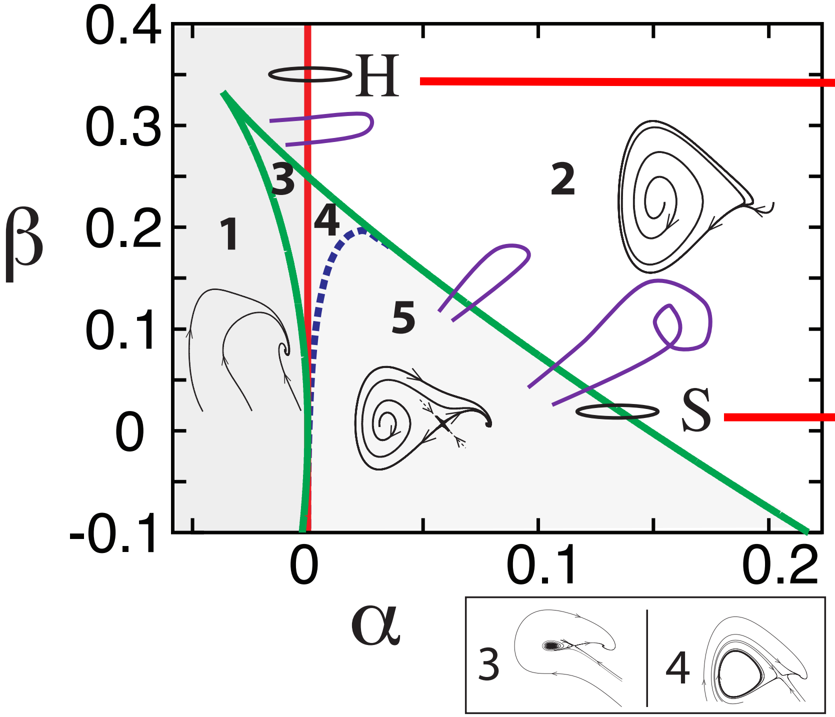
$$\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y$$

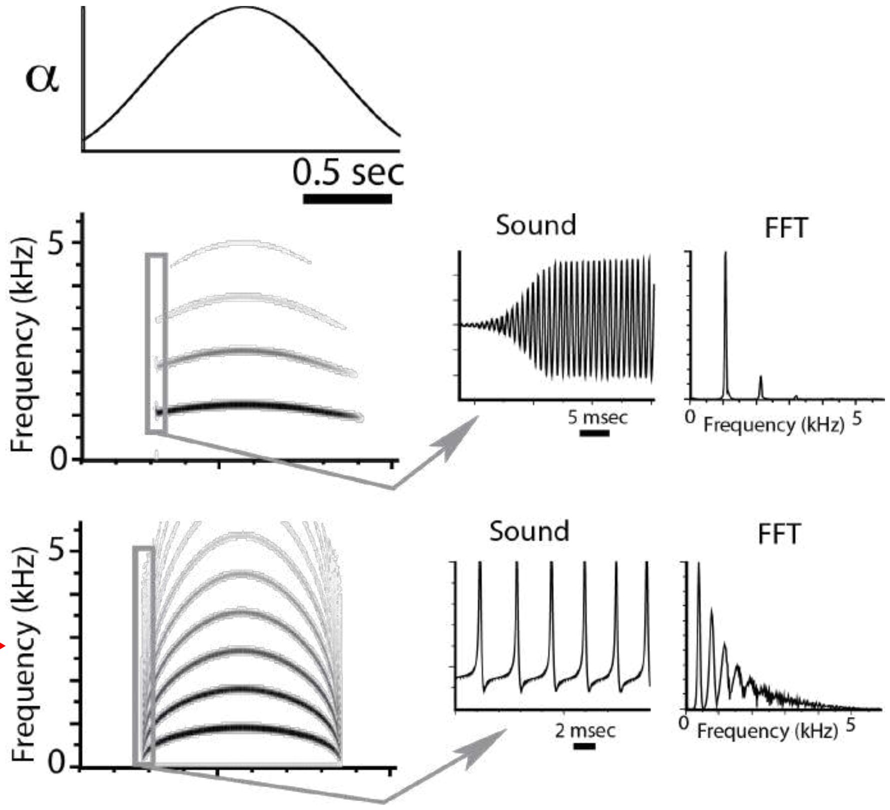
x: medial position of a labium

α: **pressure** of the air sac system, β: **tension** of the syringeal labia

Dynamical analysis of the sound source

Numbers indicate regions of the parameter space with qualitative similar outputs





Generating synthetic zebra finch songs

$$\frac{dx}{dt} = y$$

$$\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y$$

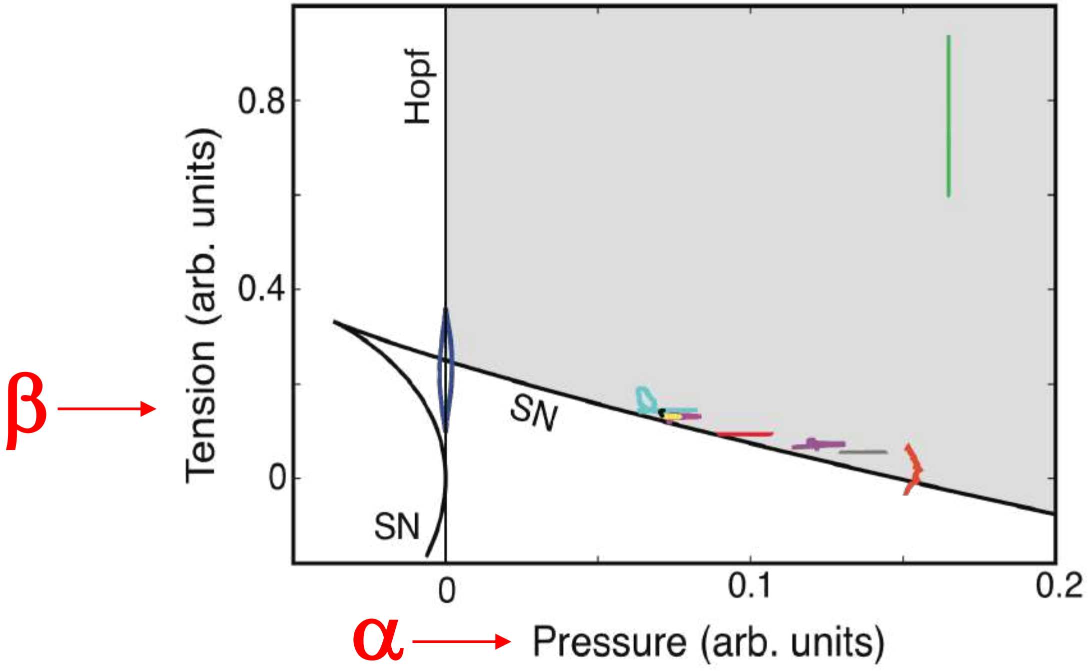
x: medial position of a labium

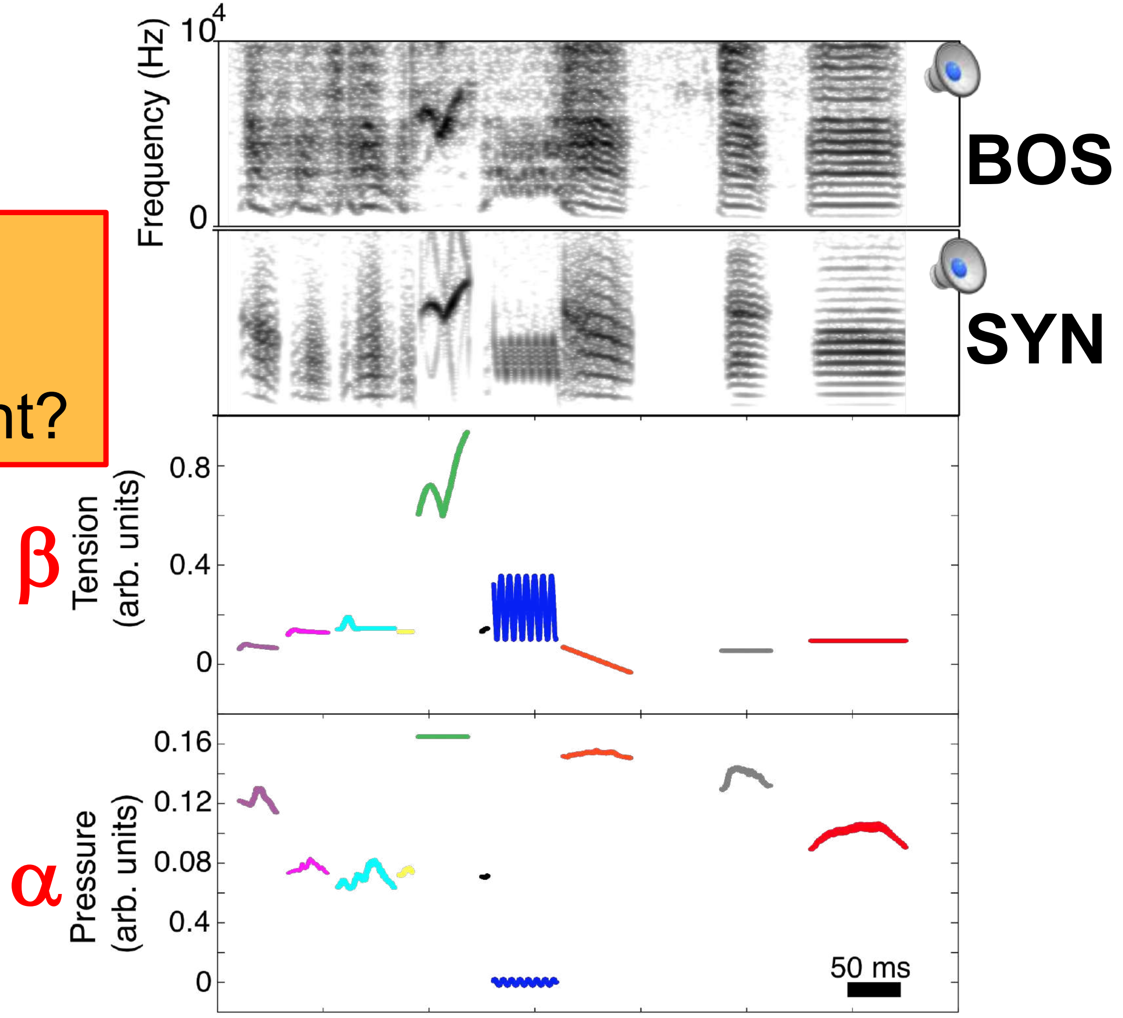
α : **pressure** of the air sac system

β : **tension** of the syringeal labia

γ : scale factor

Looks good!
Sounds good!
But is this relevant?



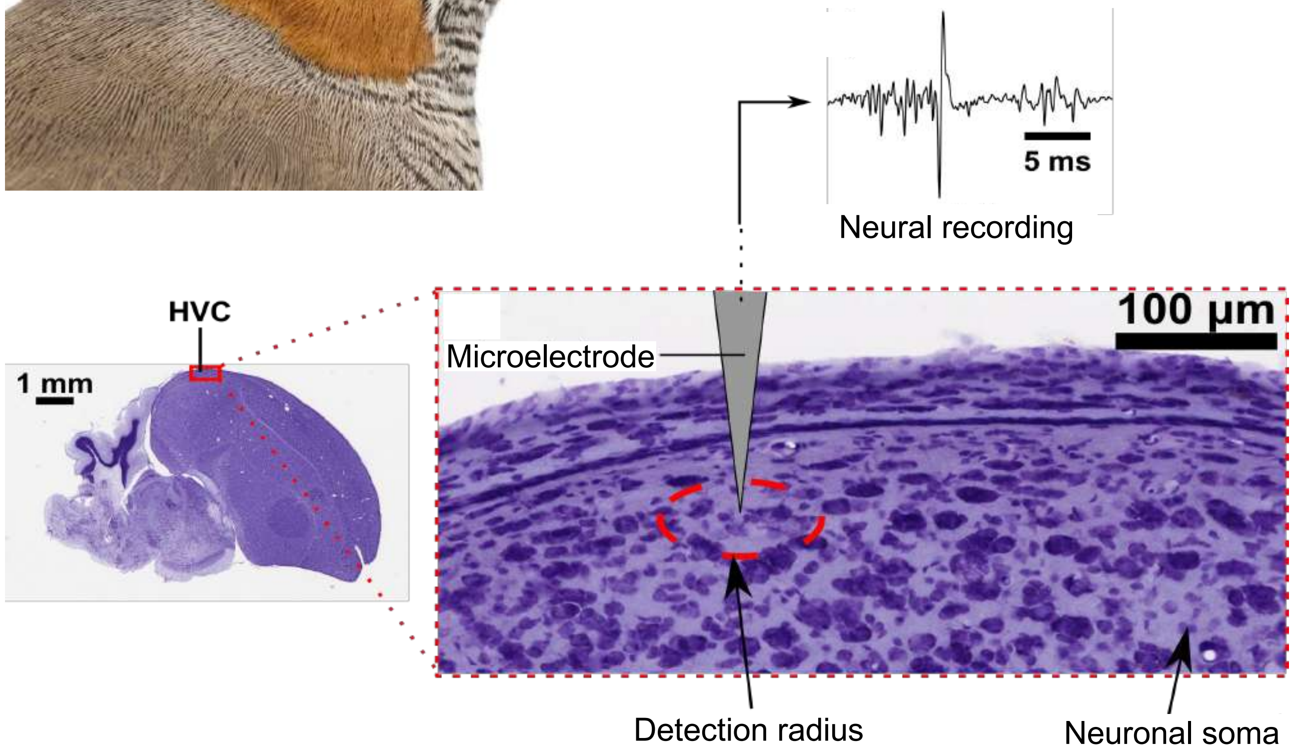


Synthetic copies of zebra finch song

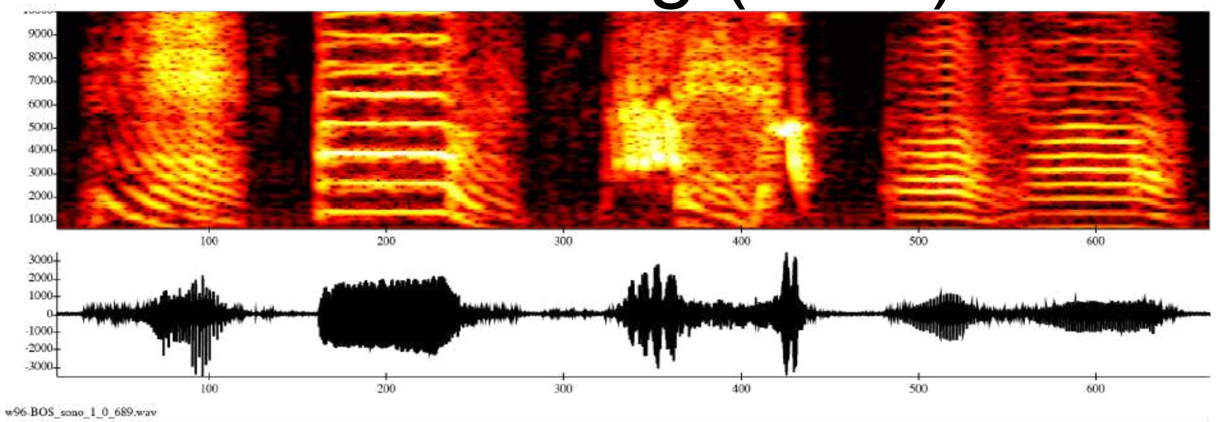
Neural recordings to validate the model

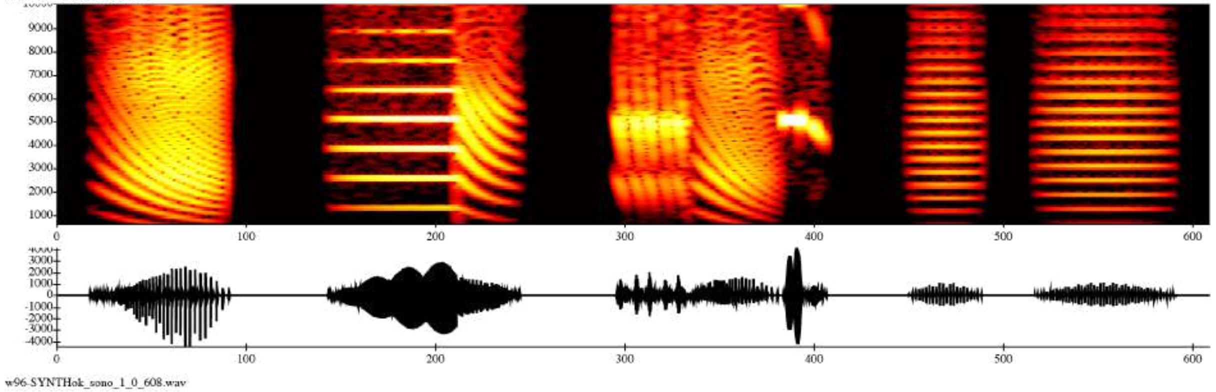
Ask the bird!

Extracellular recordings



Bird´s Own Song (BOS)

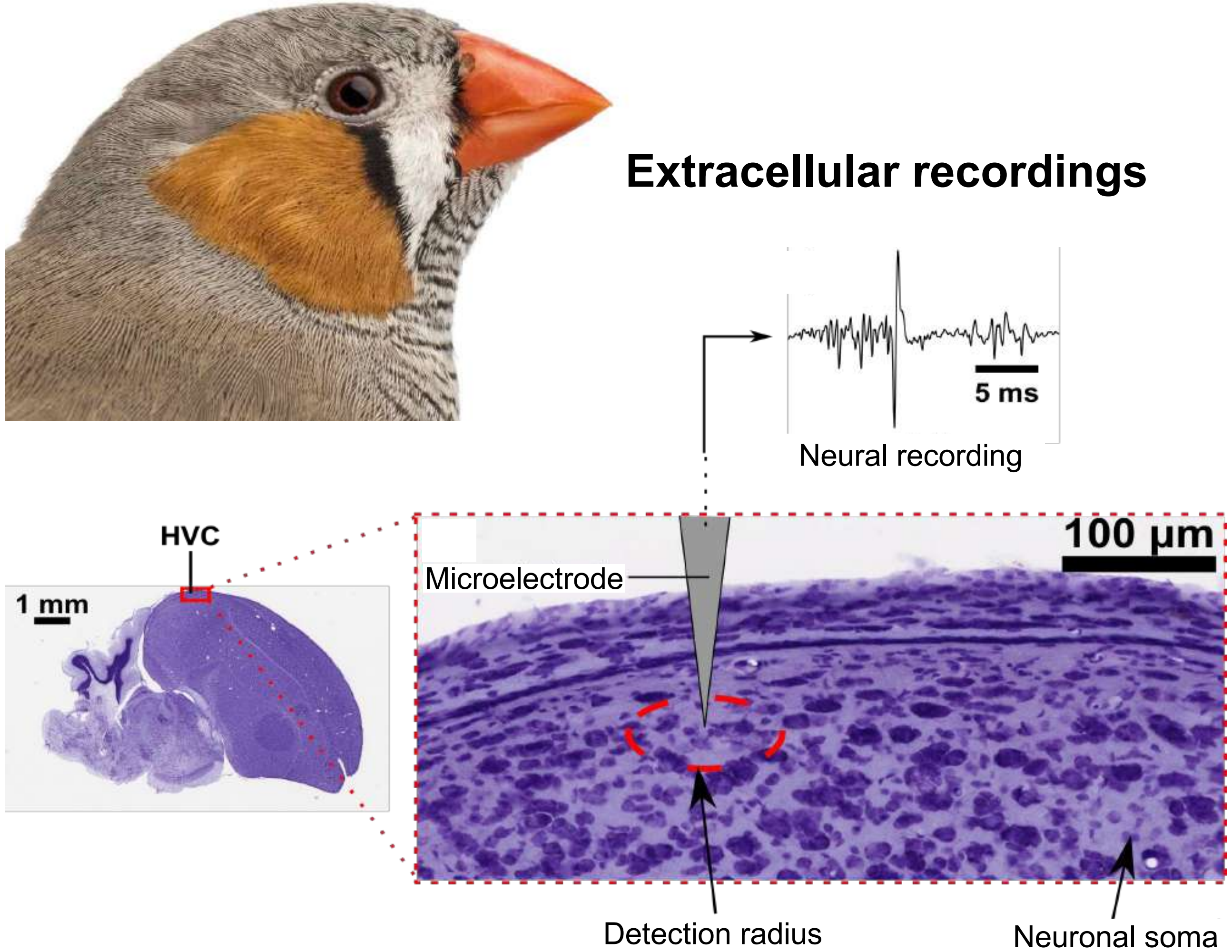




Synthetic copy (SYN)

Testing the model

Neural recordings to validate the model



Neural selectivity in the song system

Neurons respond to the **auditory presentation** of the bird's own song (BOS) with a **distinctive pattern**.

No other auditory stimulus elicits any response.

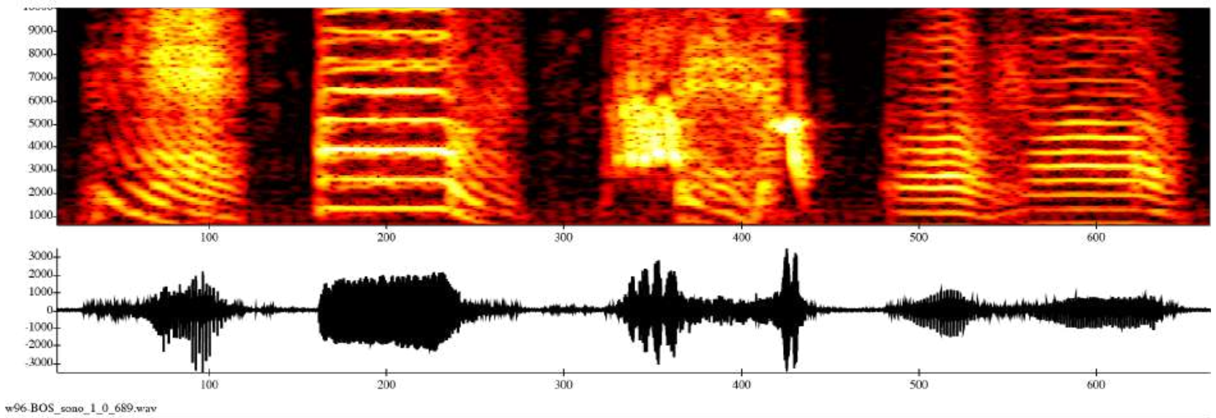
Synthetic copies of zebra finch song

$$\frac{dx}{dt} = y$$

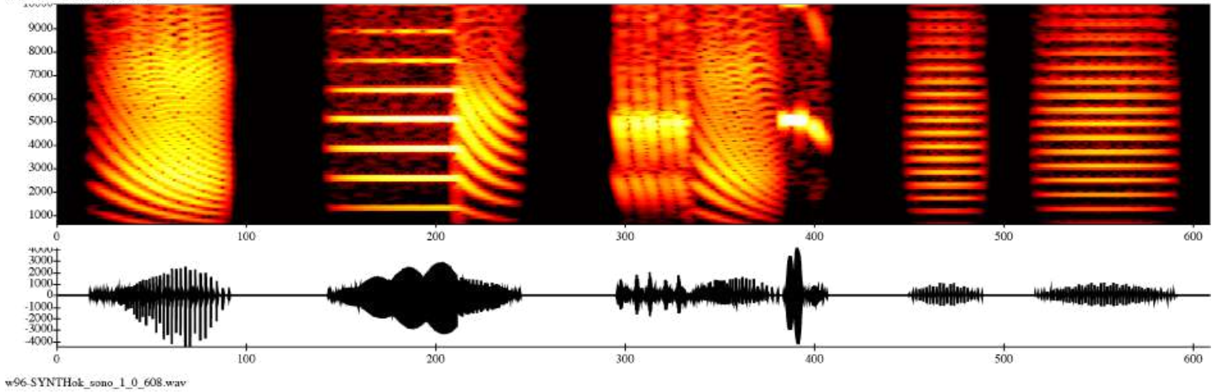
$$\frac{dy}{dt} = -\alpha(t)\gamma^2 - \beta(t)\gamma^2 x - \gamma^2 x^3 - \gamma x^2 y + \gamma^2 x^2 - \gamma x y$$

x: medial position of a labium
α : pressure of the air sac system
β : tension of the syringeal labia
γ : scale factor

Zebra finch song



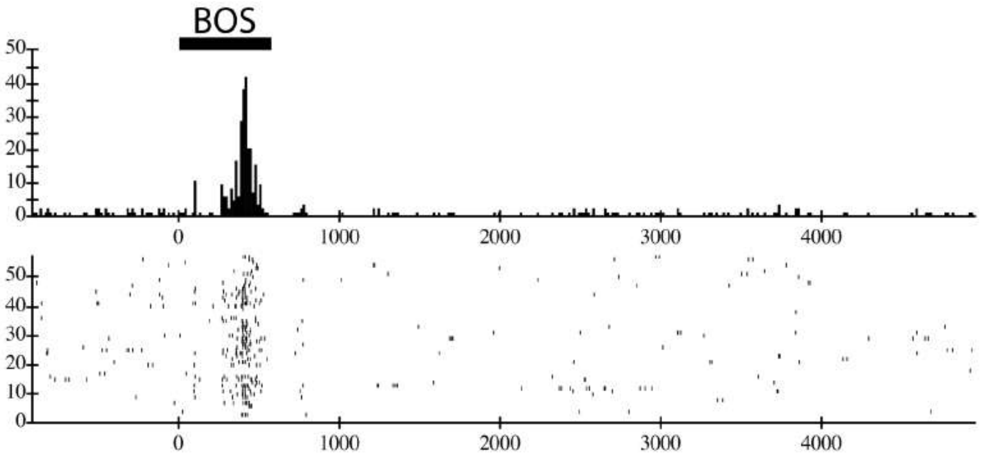
BOS

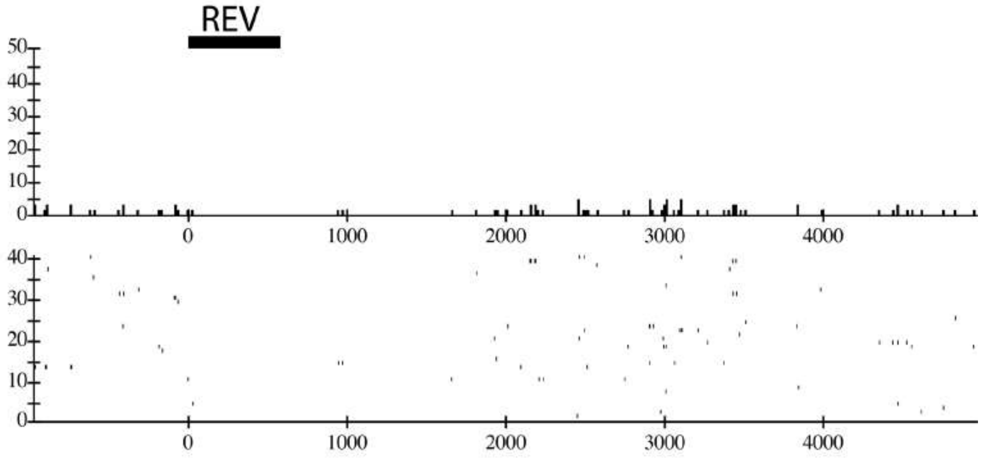


SYN

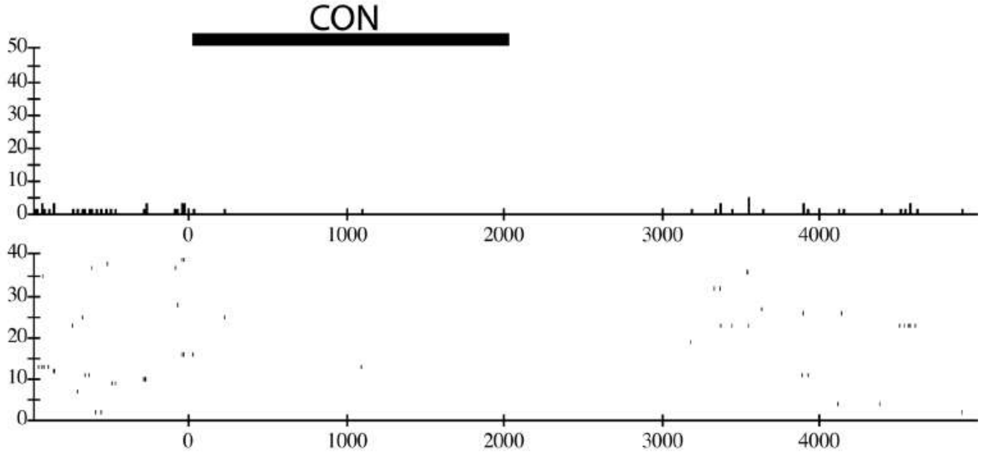
Testing the model

Neurons in HVC respond selectively to the Bird's Own Song (BOS)





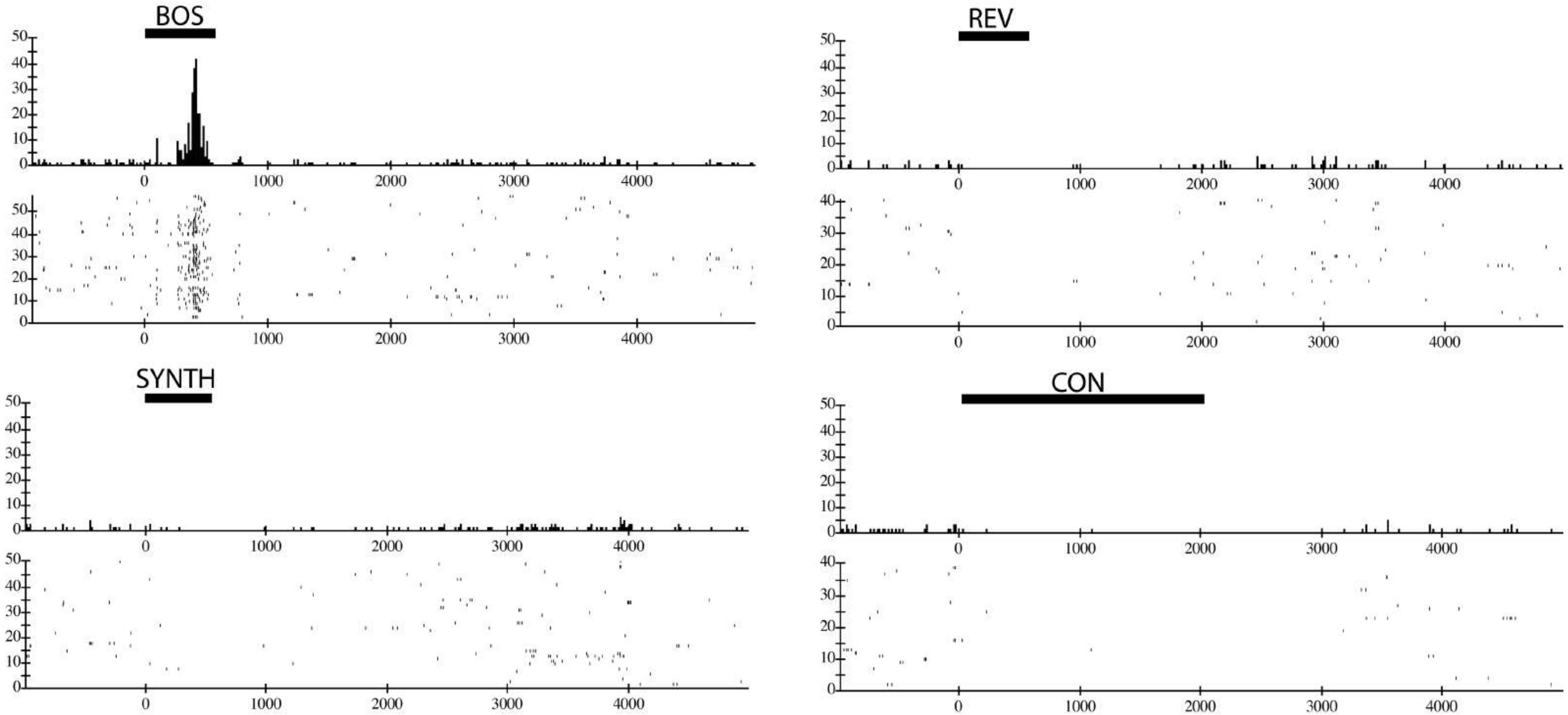
Guess what happens when testing the model in this way



Sound presentation during sleep

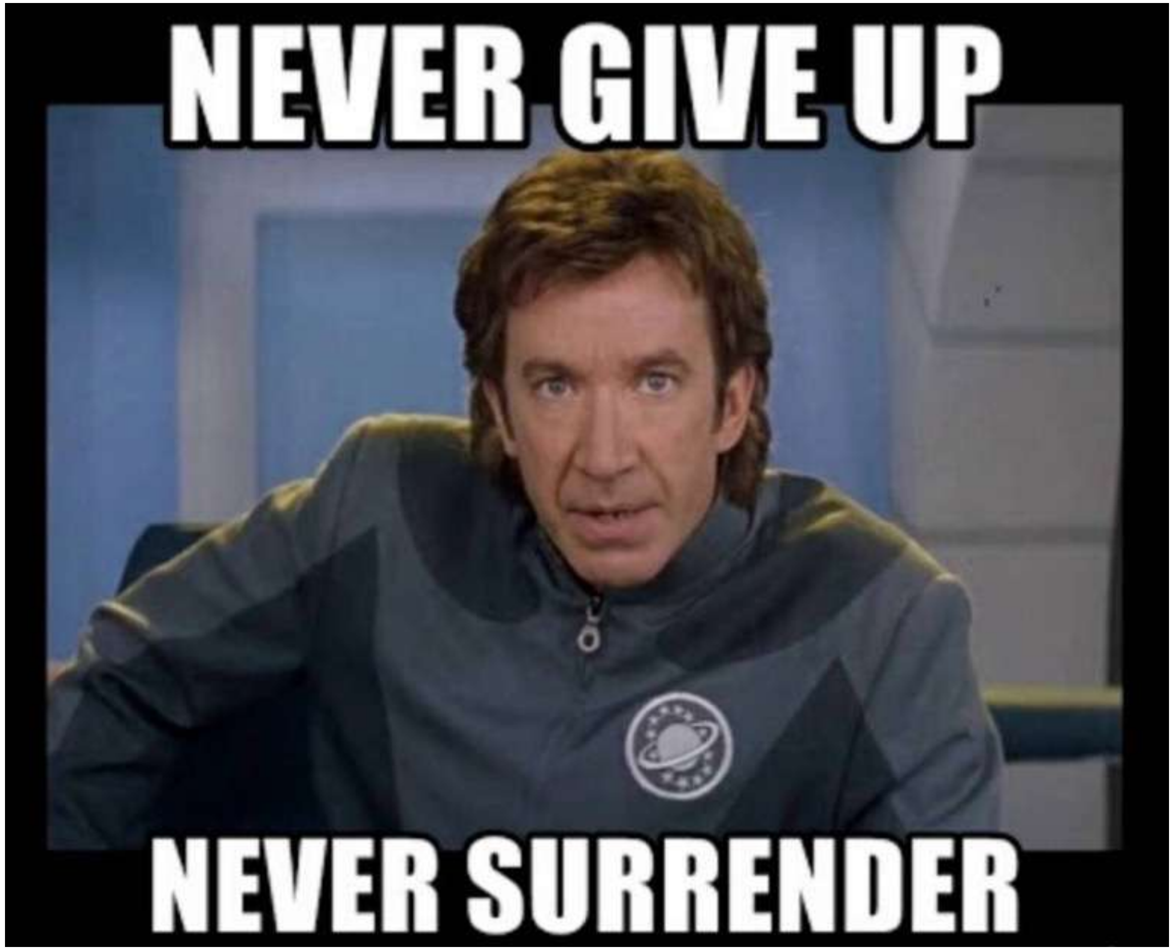
Testing the model

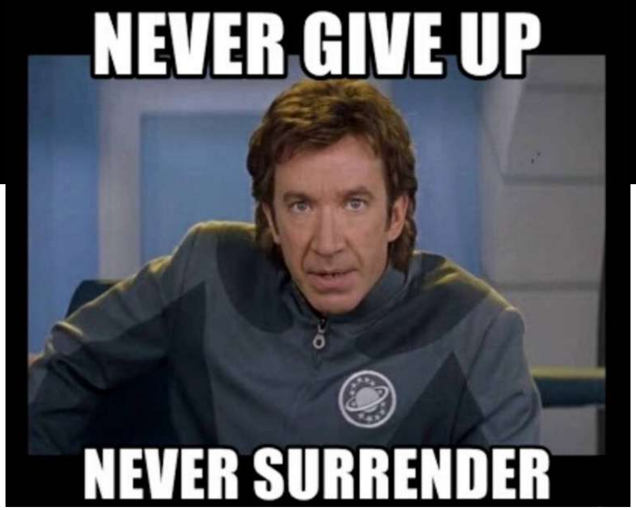
Neurons in HVC respond selectively to the Bird's Own Song (BOS)



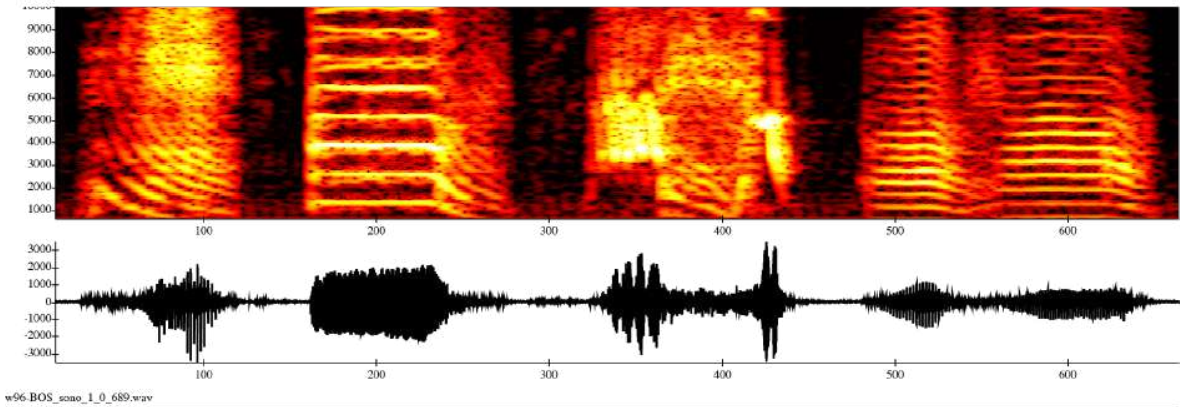
Sound presentation during sleep

What do we do now ???

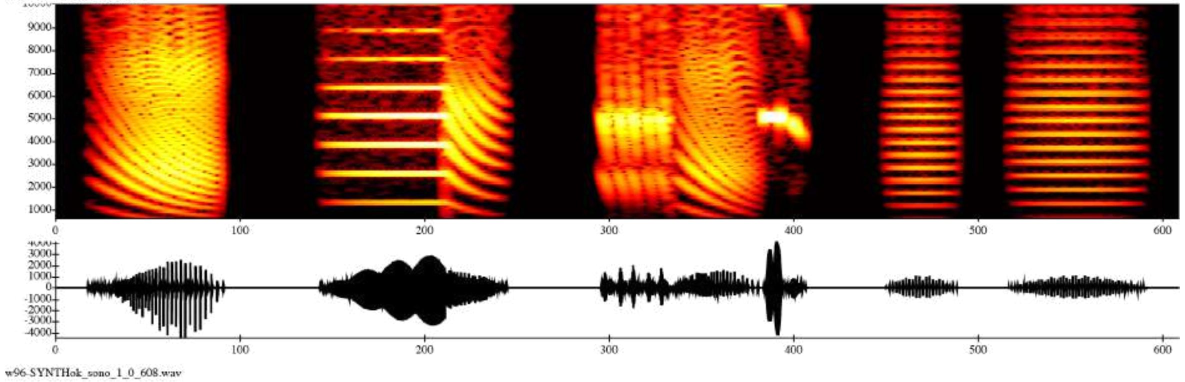




BOS



SYN



The challenge is
to remain simple!

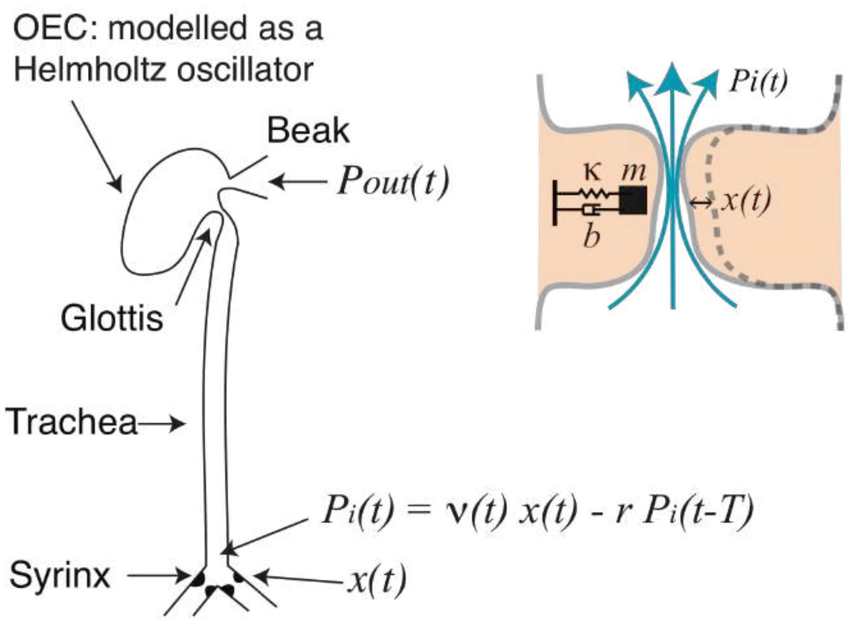
This is not working

A more detailed modeling

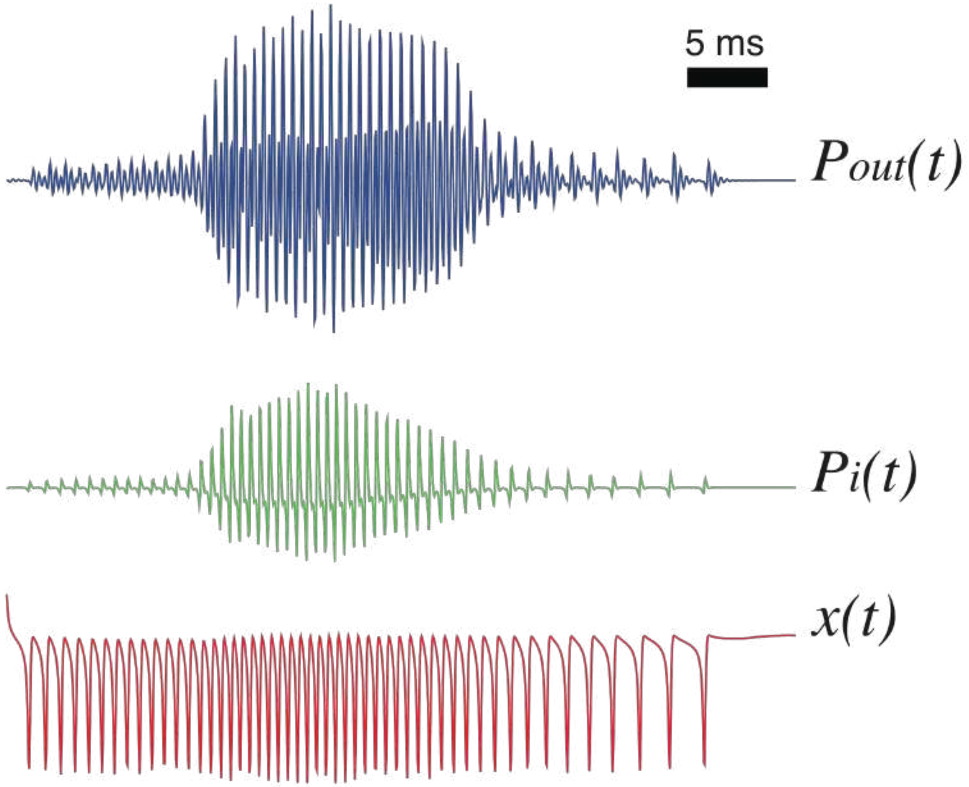
- ✓ More detailed modeling of the vocal tract (before: 3 tubes).

Oropharyngeal cavity as a resonator

- ✓ Noise in the labial tension (controlled by syringeal muscles)



Filter action



Same source

$$\frac{dx}{dt} = y$$

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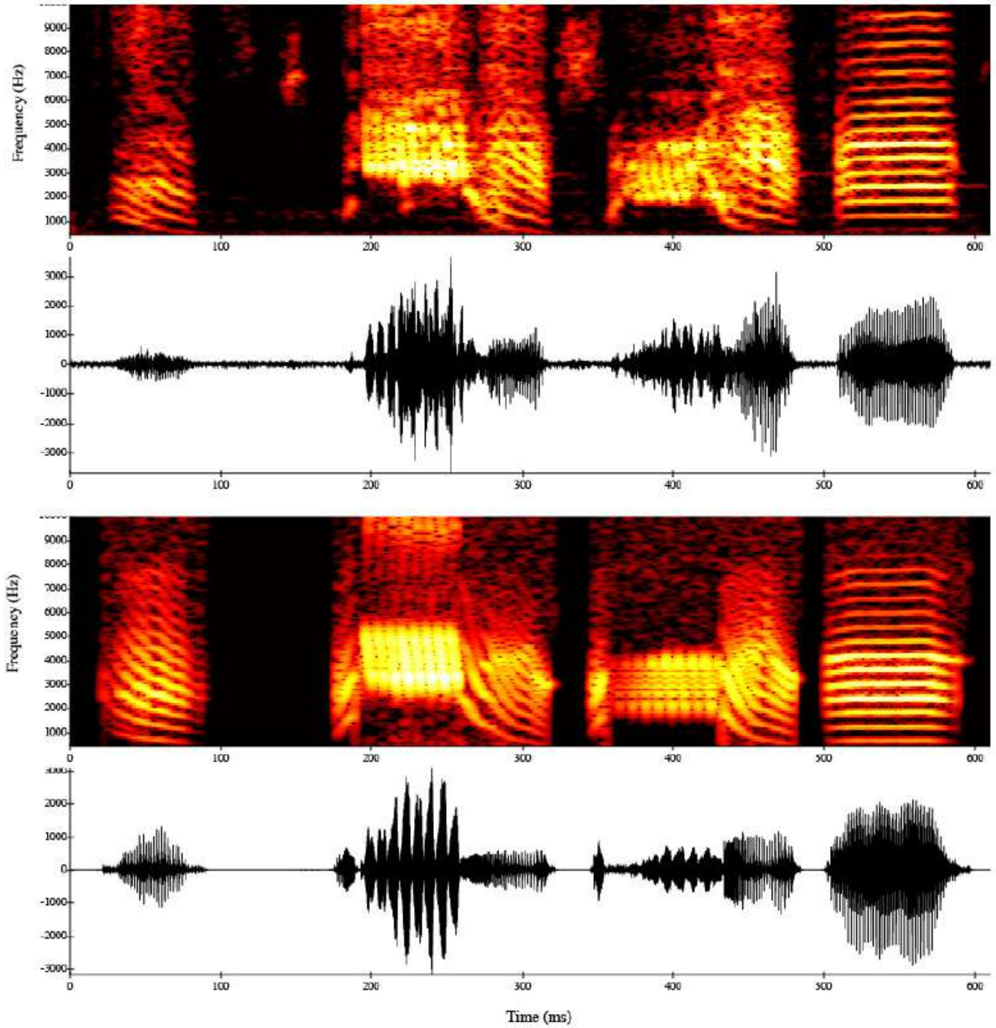
Amador et al, Nature 2013

A more detailed modeling



BOS

SYN

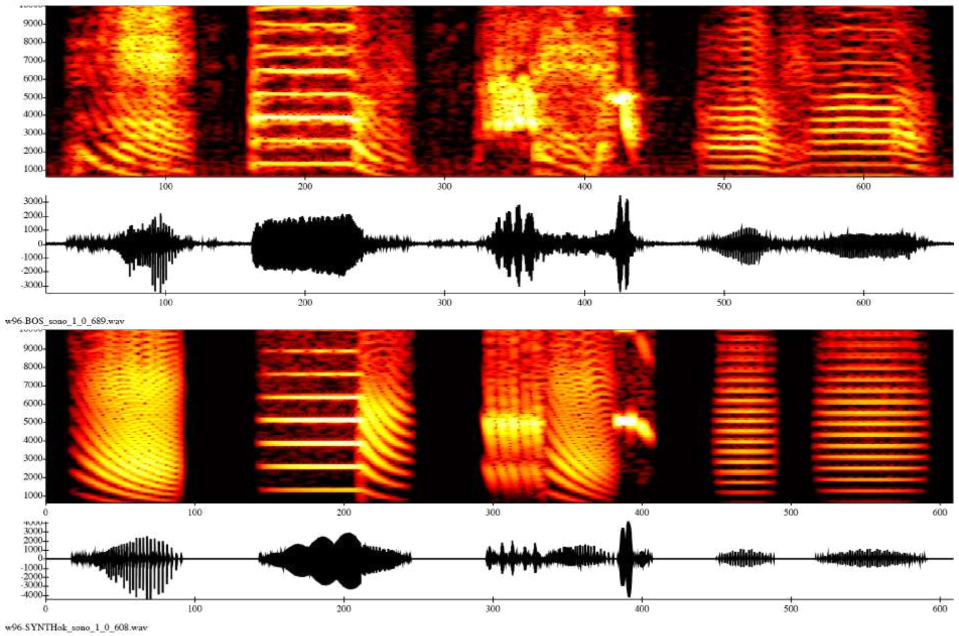
Amador et al., Nature 2013

A more detailed modeling

Before

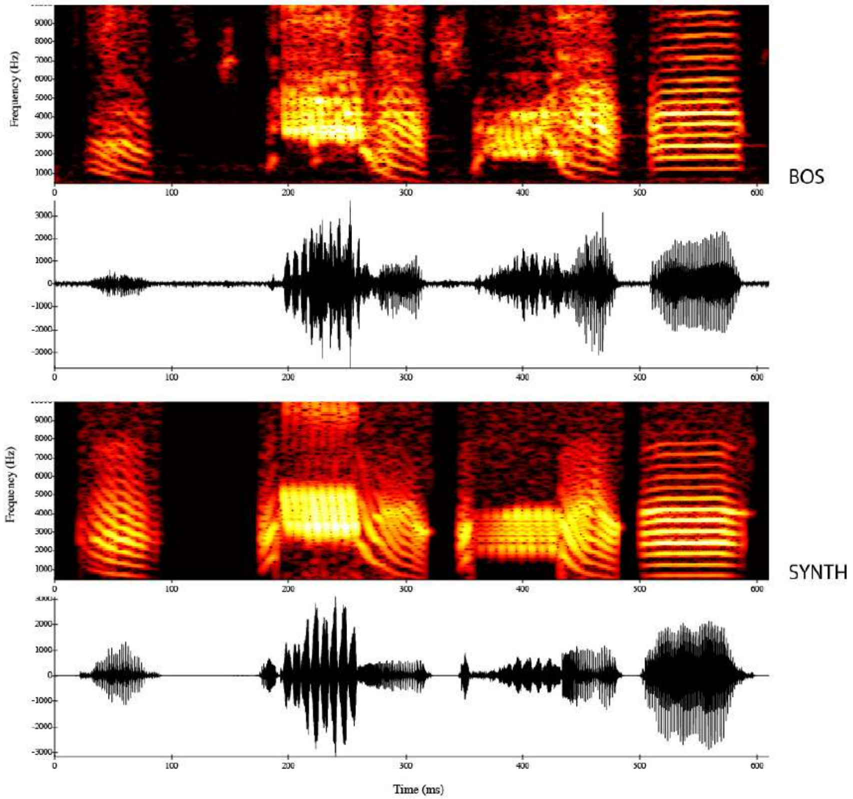
BOS

SYN



- No noise in Vs activity
- No oropharingeal cavity

After



BOS

SYN

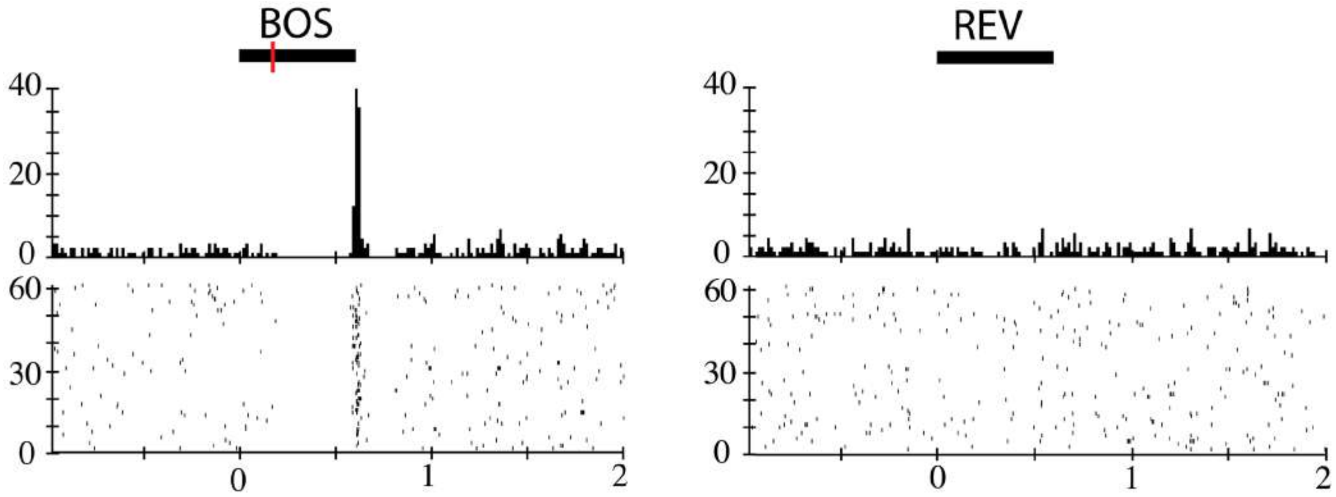
✓ Noise in Vs activity

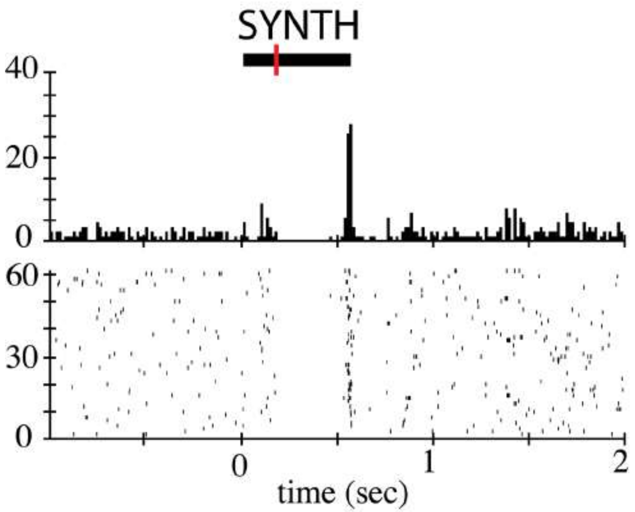
✓ Oropharingeal cavity

Synthetic copies of zebra finch song

Neural selectivity in the song system

Extracellular recordings in HVC (sensorimotor nucleus)

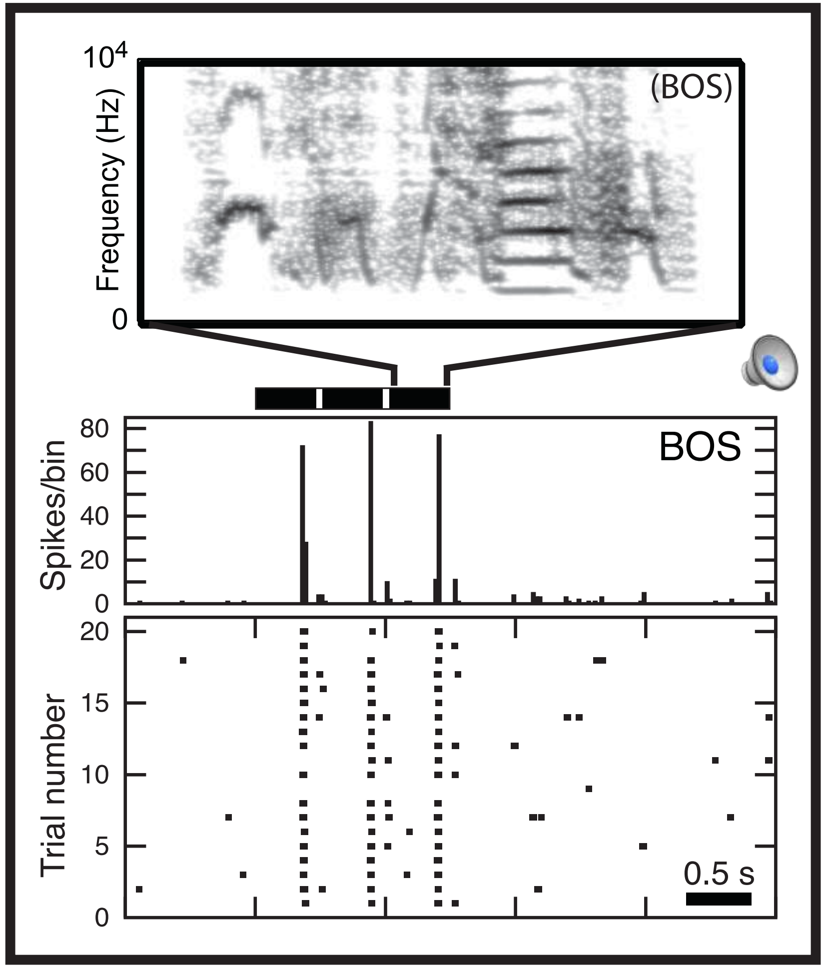


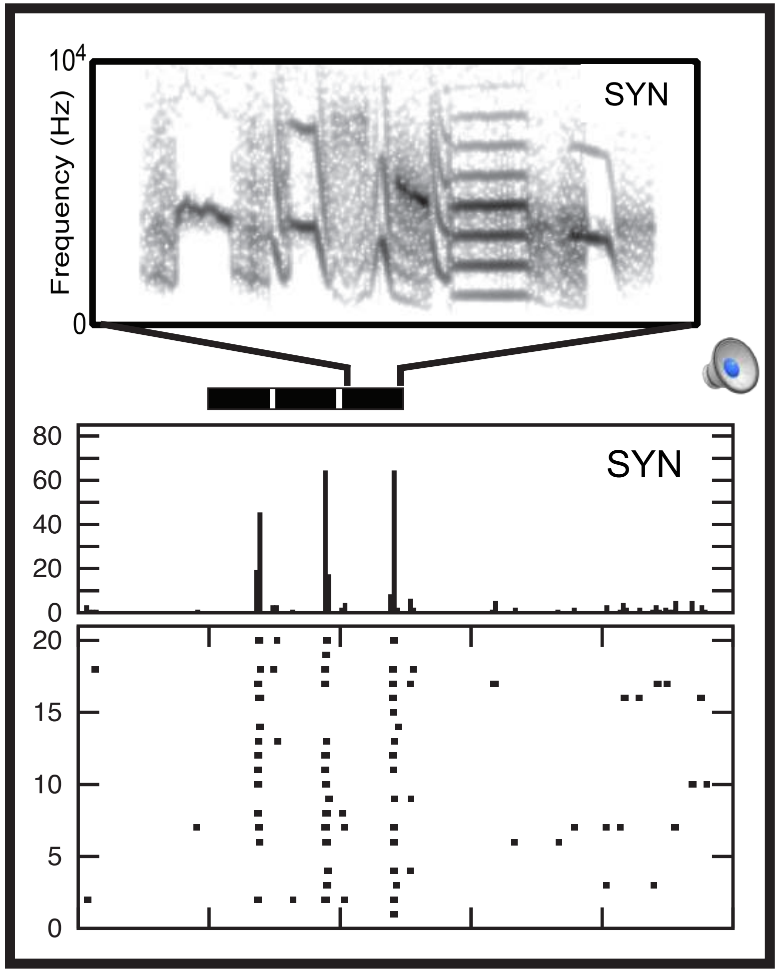


The synthetic song elicits the same neural response than the bird's own song

Amador et al. (2013) Nature

A more detailed modeling



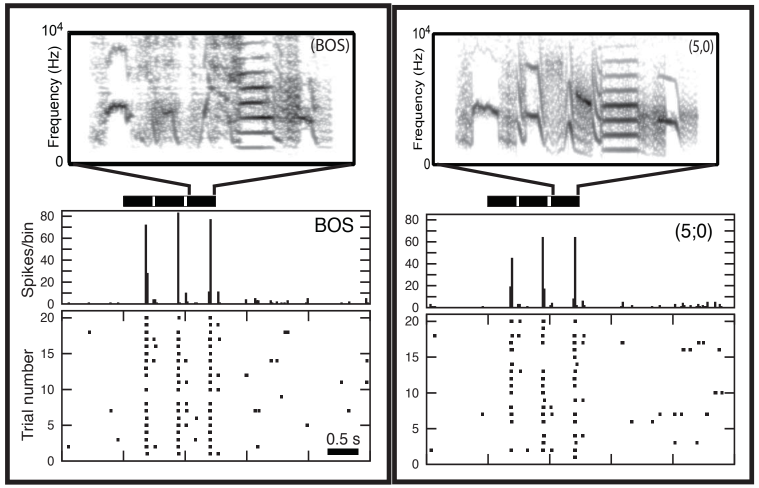


The synthetic song elicits the same neural response than the bird's own song

Amador et al, Nature 2013

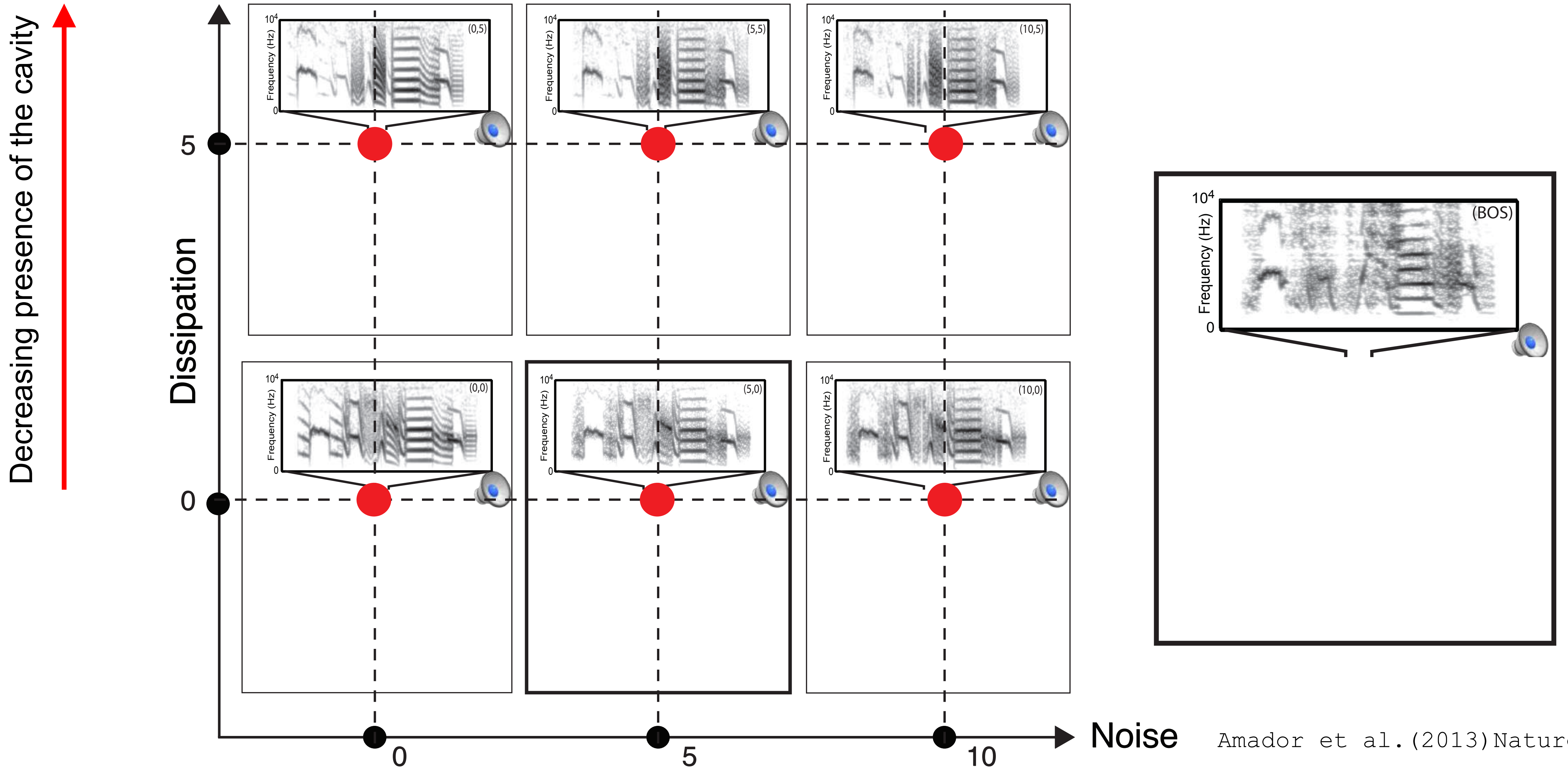
Partial summary

- A **minimal model** is able to generate **complex behavior** that is coded by neurons in the same way as natural behavior.



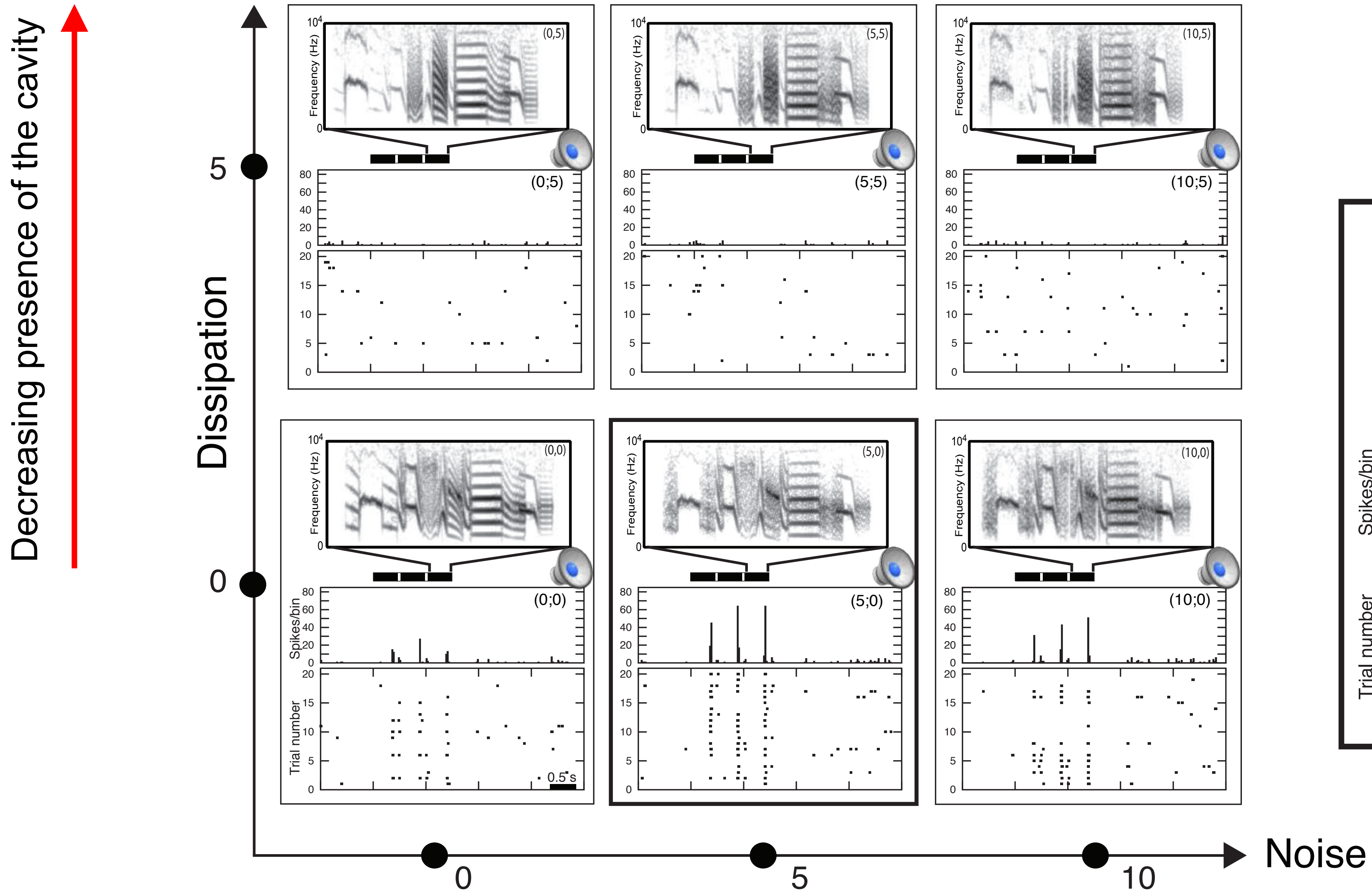
- We can now use the mathematical model as a **tool** to **study motor control**, **auditory perception** and **neural coding in songbirds**.

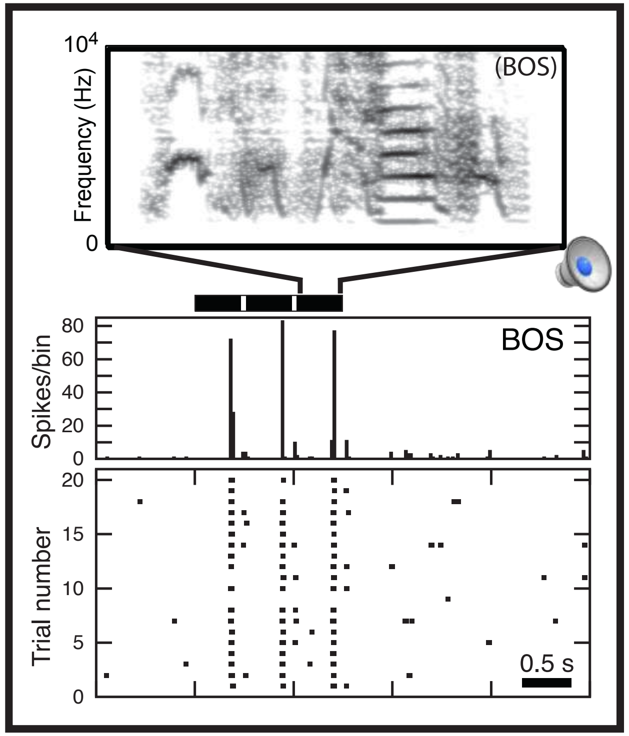
Studying relevance of static parameters



Amador et al.(2013)Nature

Studying relevance of static parameters





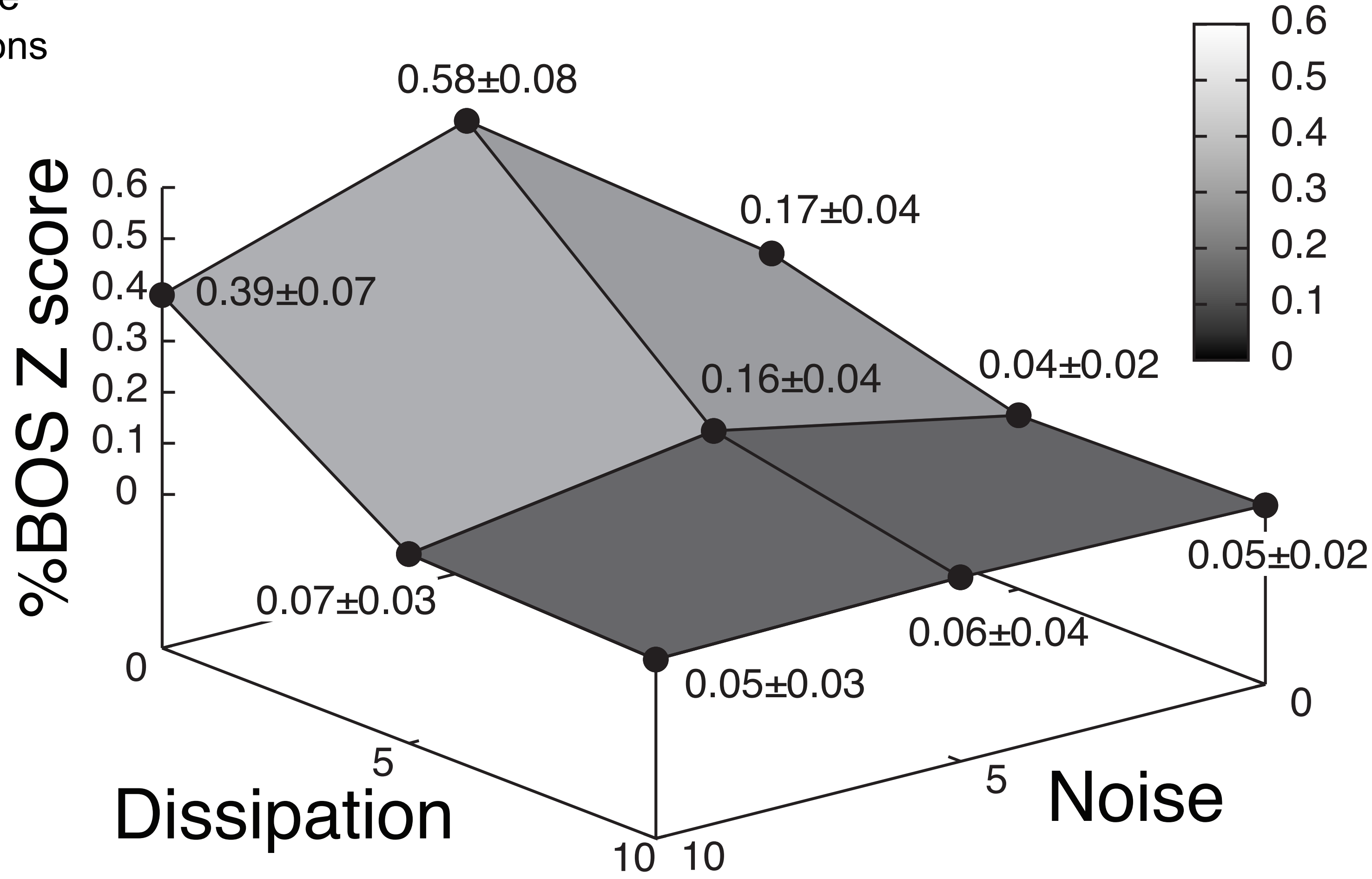
Amador et al.(2013)Nature

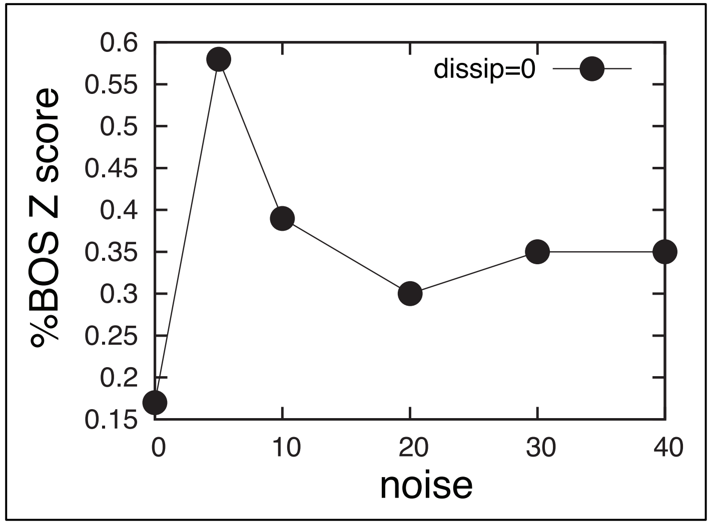
Hierarchy of static parameter relevance

Grouped data:

- 4 birds
- 30 selective HVC neurons

The resonant cavity is a relevant feature (can be controlled by the birds while singing)





The noise has a specific value that maximizes the neural responses.

Amador et al.(2013)Nature

Gracias por su atención!

Collaborators

✧ Gabriel B. Mindlin (UBA, CONICET)

✧ Daniel Margoliash (Univ. of Chicago)

PhD Students

✧ Cecilia T. Herbert (UBA, Biology)

✧ Javier N. Lassa Ortiz (UBA, Biology)

✧ Fiamma L. Leites (UBA, Biology)

Postdocs

✧ Santiago Boari (UBA, Physics)

Thanks for the support

✧ National Institute of Health (NIH, USA)

✧ University of Buenos Aires (Argentina)

✧ National Council for Science and Technology (CONICET, Argentina)

✧ Agencia Nac. de Promoción Científica y Tecnológica (ANPCyT, Argentina)

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Autor	Gabriel B. Mindlin
Colecciones	Nuevos enfoques en ciencia y tecnología
Año de edición	2018
ISBN	978-987-558-503-4
Páginas	248 p.
Formato	15,5 x 22,5 cm
Peso	320 g.
Tema	Física, Física cuántica, Estudios
Precio	$ 300

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