Pan Lab

Journal Club

Auditory system of *Drosophila*

— *Listening to singing*

Can G. *Chao G.* *Yicong J.*

2019-4-1

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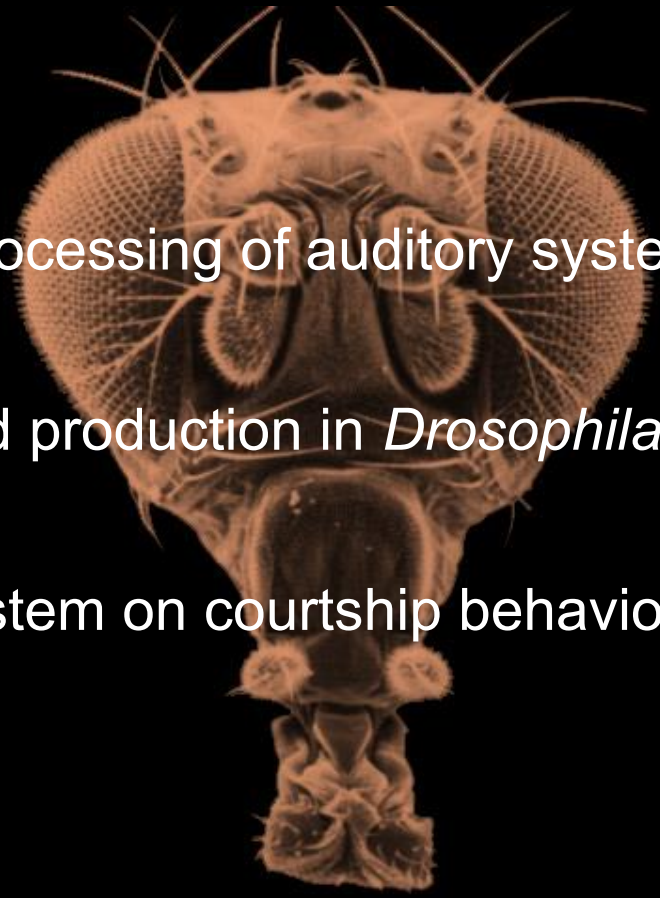
Journal Club



I. The structure & signal processing of auditory system in *Drosophila* — *Can G.*

II. The mechanism of sound production in *Drosophila* — *Chao G.*

III. The effect of auditory system on courtship behavior & other behaviors — *Yicong J.*

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The Structure and Signal Processing of Auditory System in *Drosophila*

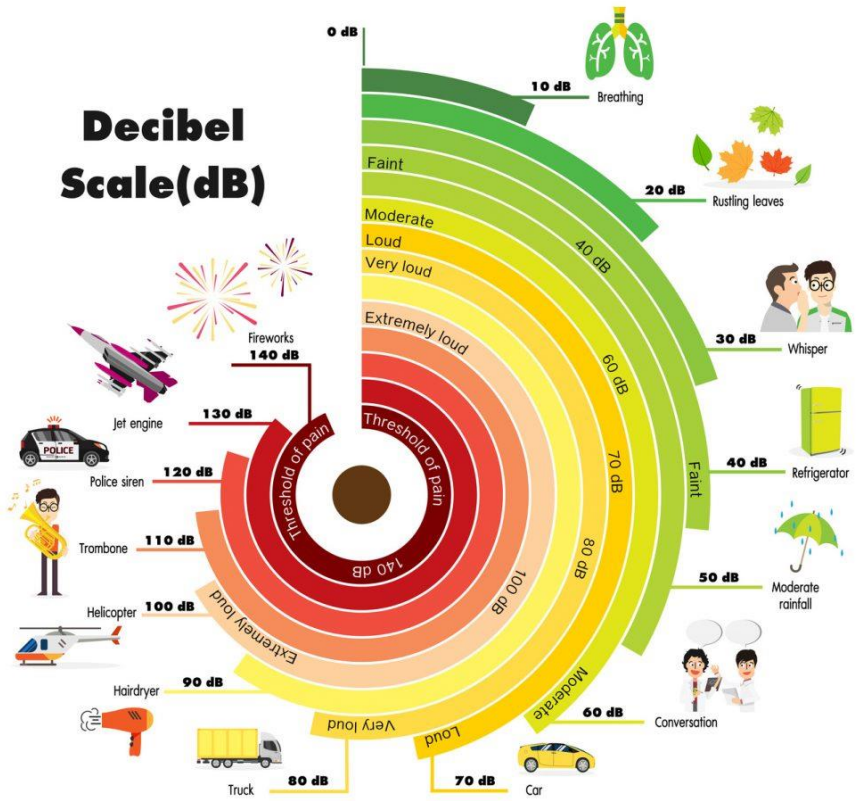
Gao Can
高灿

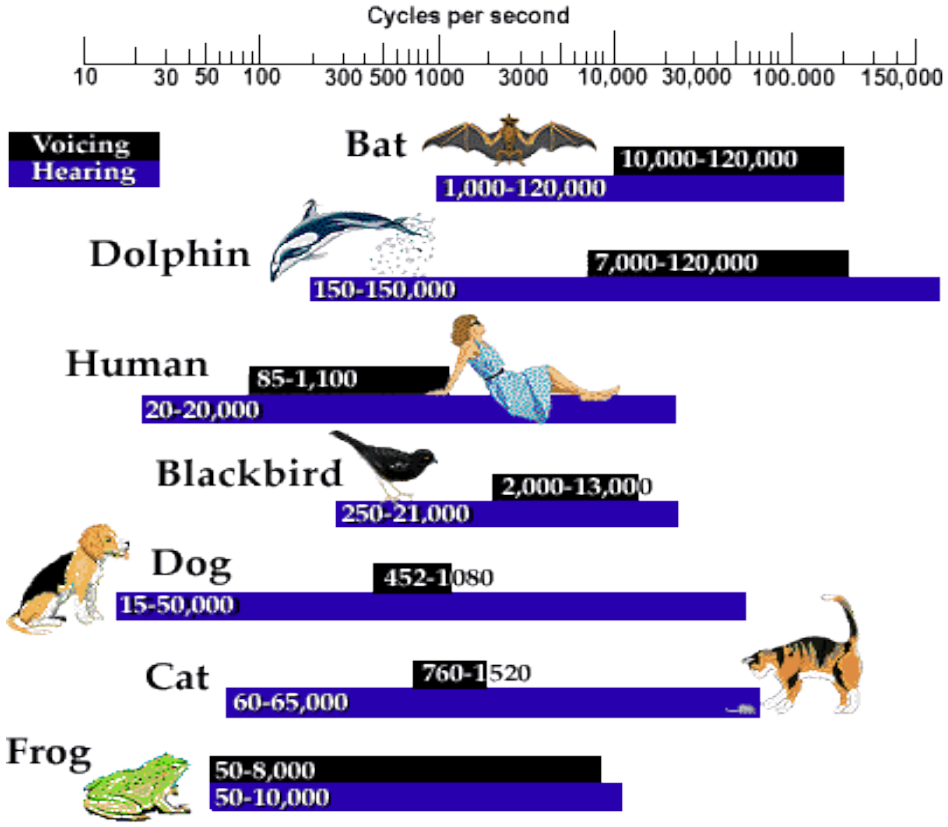
Three elements of sound

Volume (dB)

Pitch (Hz)

Timbre





AAMC

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A video in collaboration between the Association of American Medical Colleges and Khan Academy

www.khanacademy.org

Outline

- The structure of *Drosophila* hearing organ—Johnston's organ
- Mechano-electrical transduction of auditory system
- Active amplification of auditory system
- The main auditory circuit in *Drosophila*

Why so many studies on auditory system in *Drosophila*

- The structure of central projections from the fly ear to the brain is similar to that of its mammalian counterparts;

  Many properties of the hearing system of flies parallel those in the vertebrate auditory system;

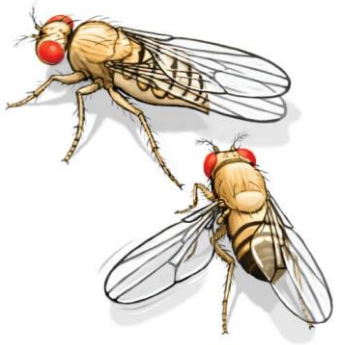
  The *Drosophila* auditory organ and vertebrate hair cells are both specified by *atonal* family genes;

  Genes such as *spalt*, *Distal-less*, and *crinkled*, whose mammalian homologs are linked to various human deafness syndromes.

- Johnston's organ serves as an excellent model

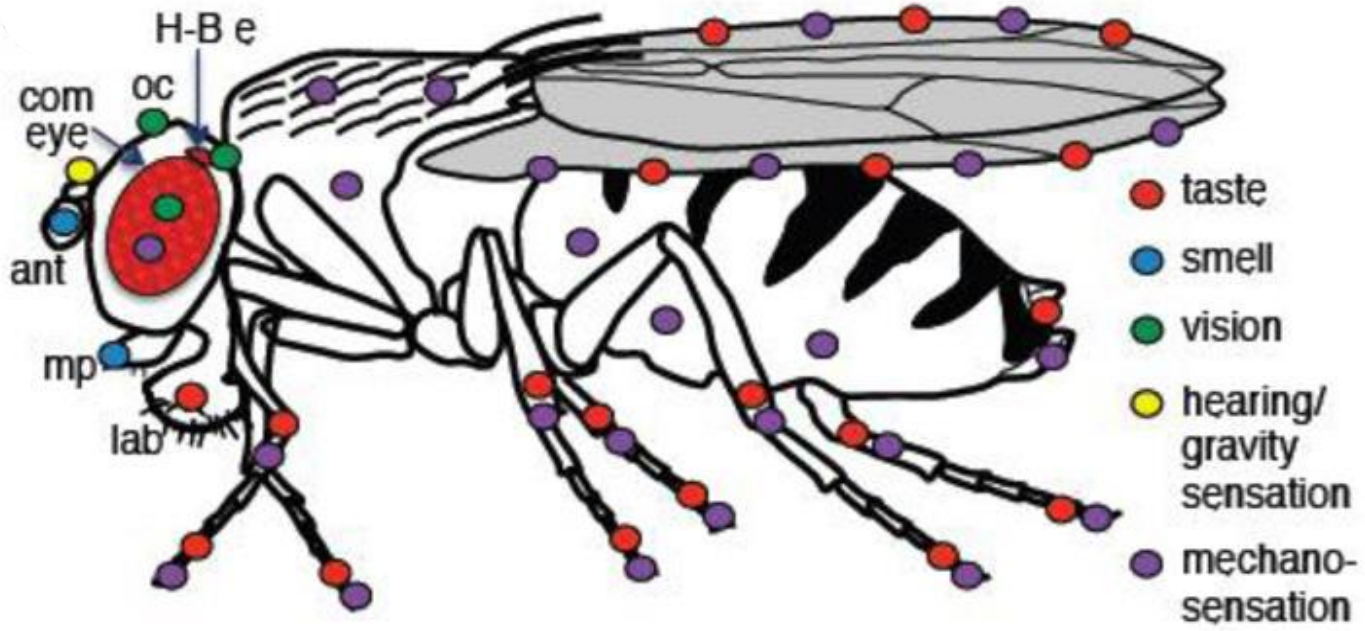
The effects of insects auditory system

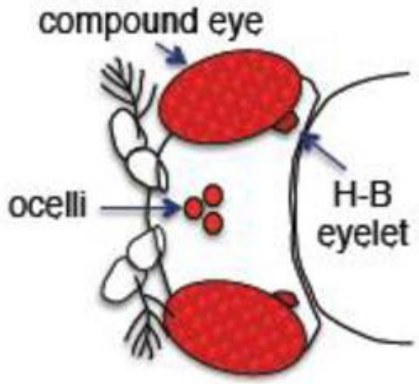
Intraspecific communication

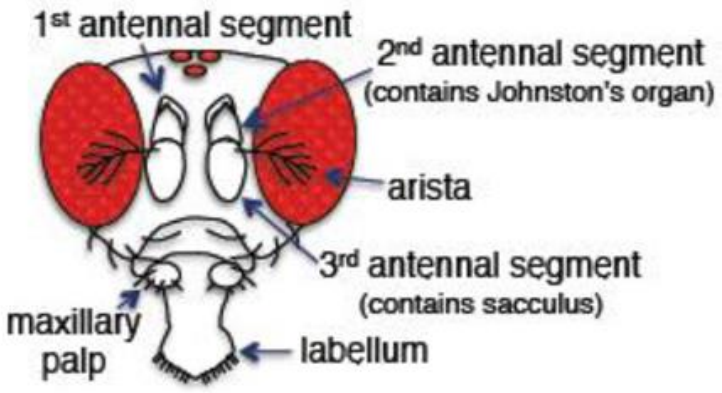


Predator detection

Sensory organs of adult *Drosophila*

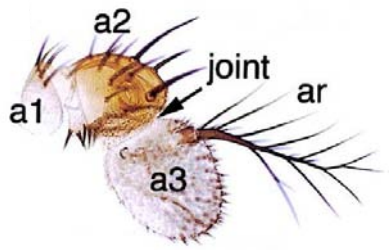


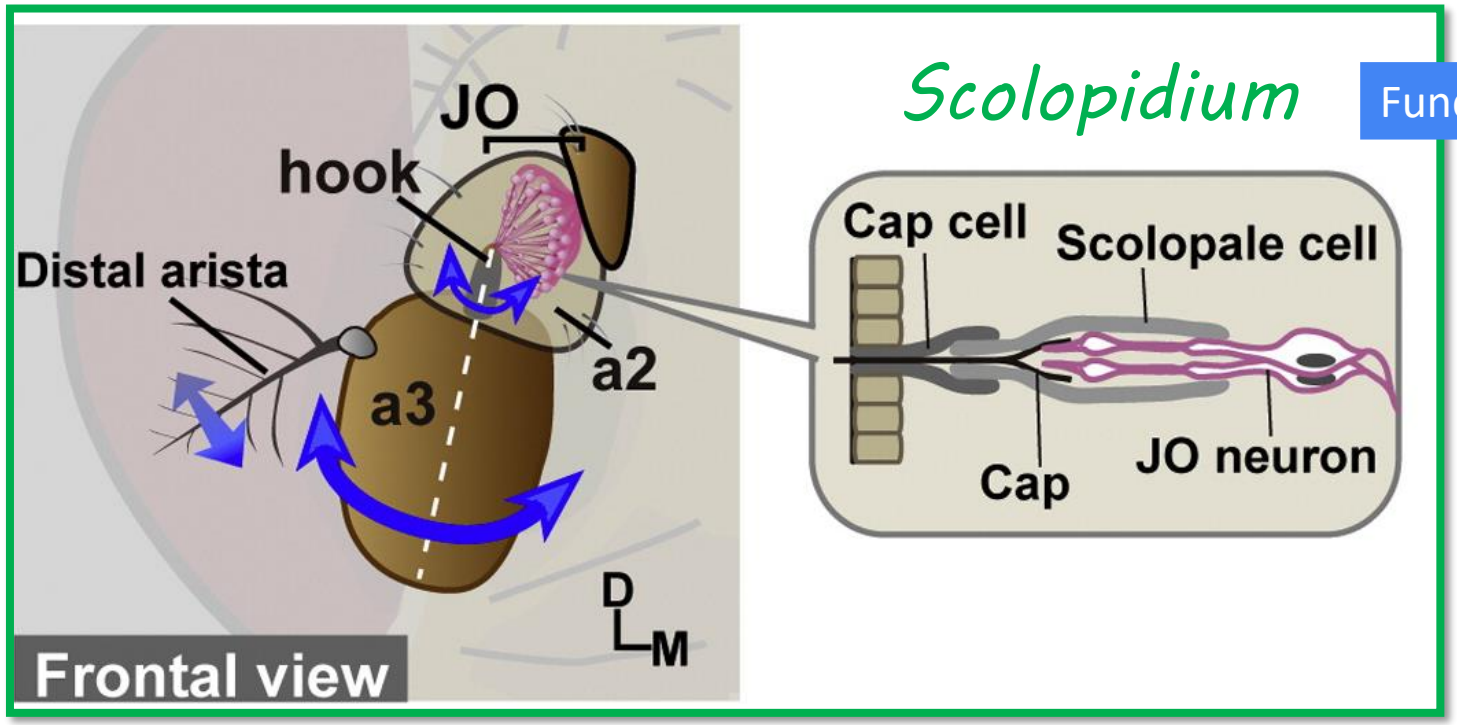




Johnston's organ (JO)——the main auditory organ of Drosophila

- Location　　the second antennal segment (a2)
- Structure & Components





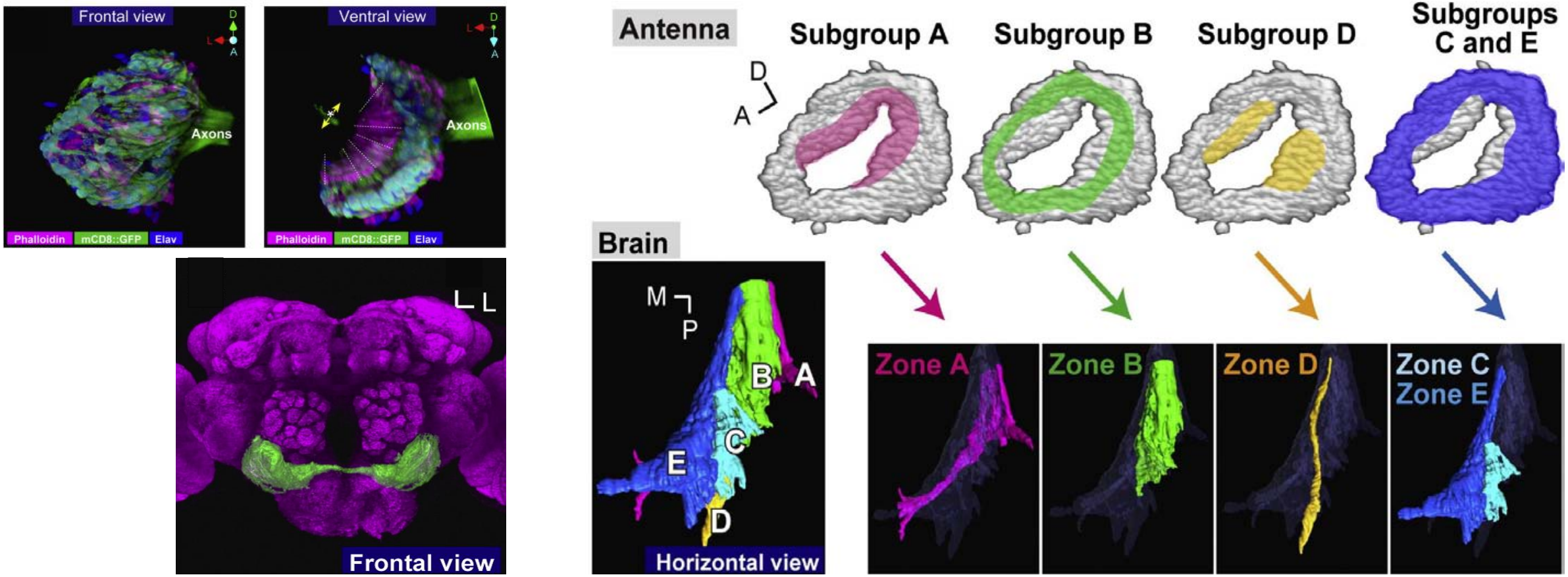
Functional sensory units of JO

JO ≈ Scolopidium x 200

bipolar JO neurons in each unit

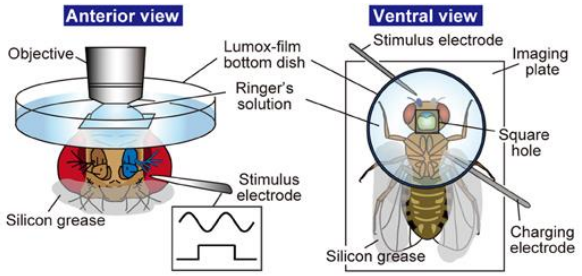
Azusa Kamikouchi.2013

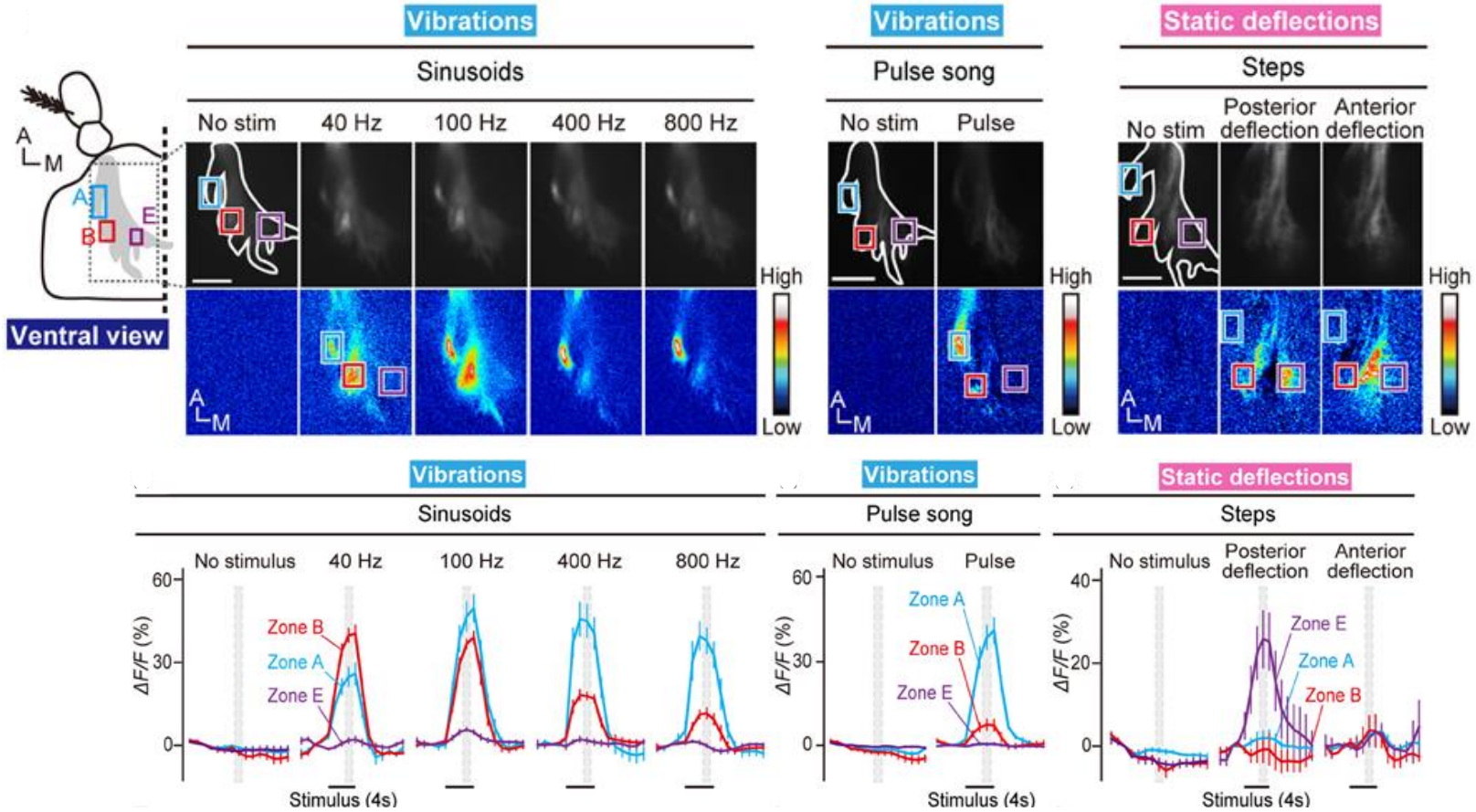
Projection and classification of JO neurons



Azusa Kamikouchi.2013

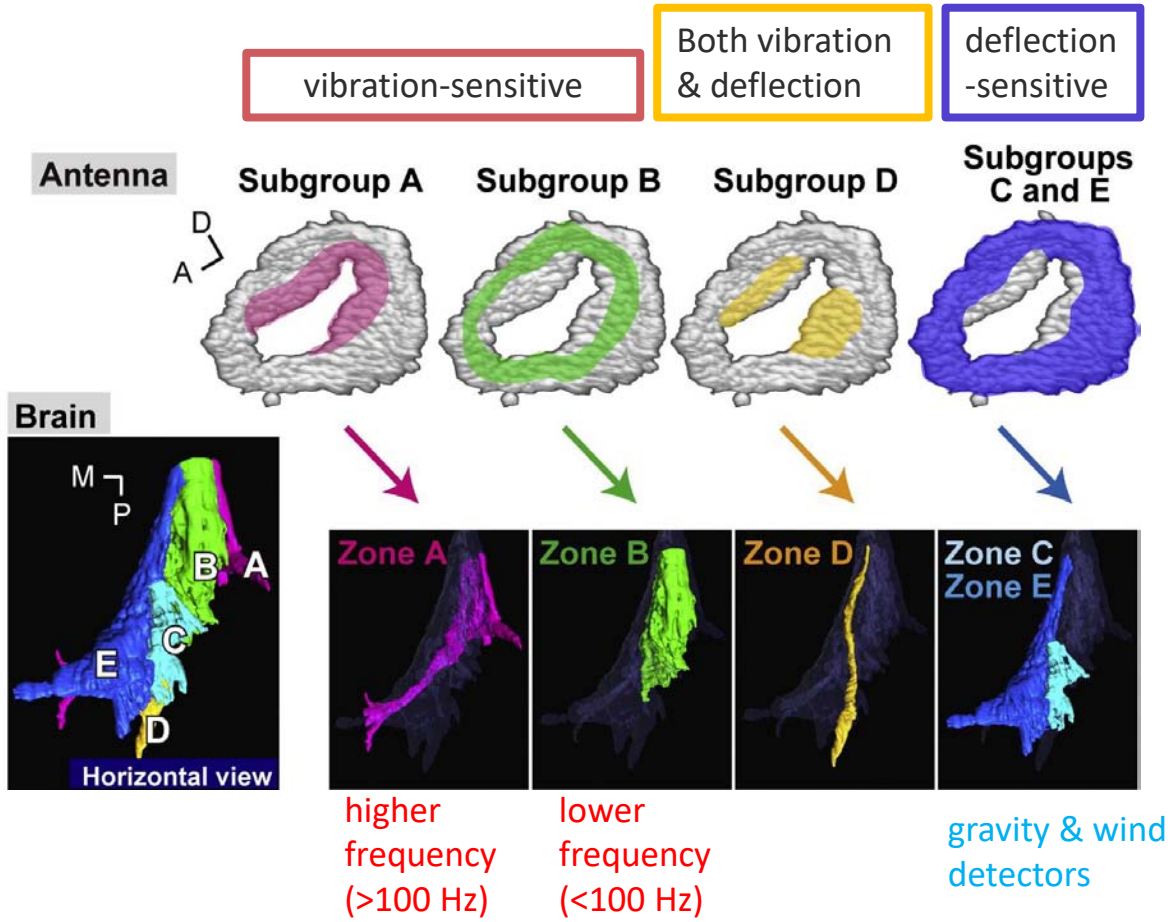
Different subtypes of JONs responsible for different function





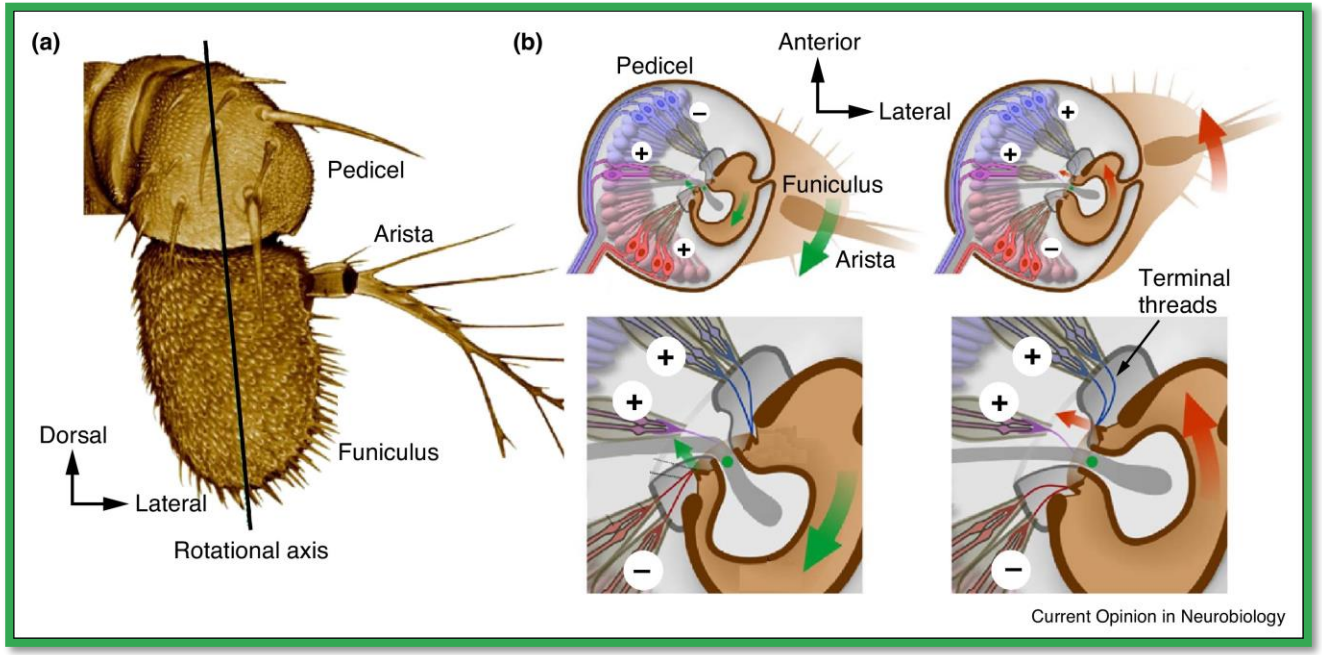
Eriko Matsuo et al.2014

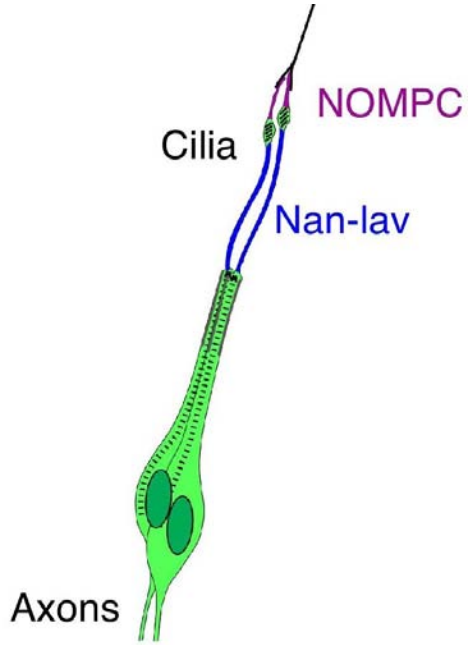
Different subtypes of JONs responsible for different function



Azusa Kamikouchi.2013

Mechano-electrical transduction of auditory system





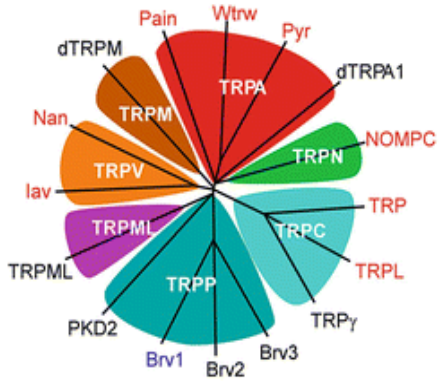
NompC（No Mechanoreceptor Potential C)

Nan-lav (Nanchung-Inactive)

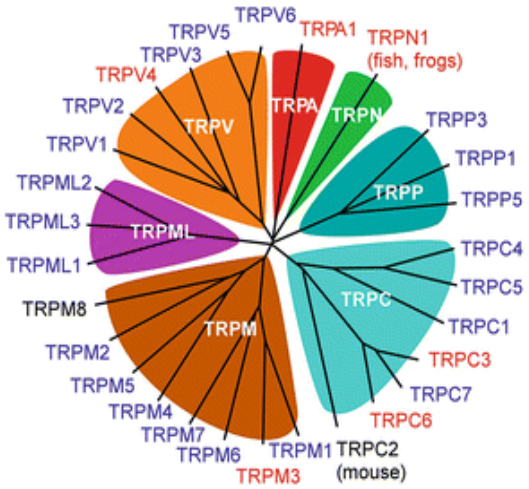
Both are transient receptor potential (TRP) channels （瞬时受体电位通道） expressed in JO neurons

Jörg Talbert et al.2015

TRP Channels

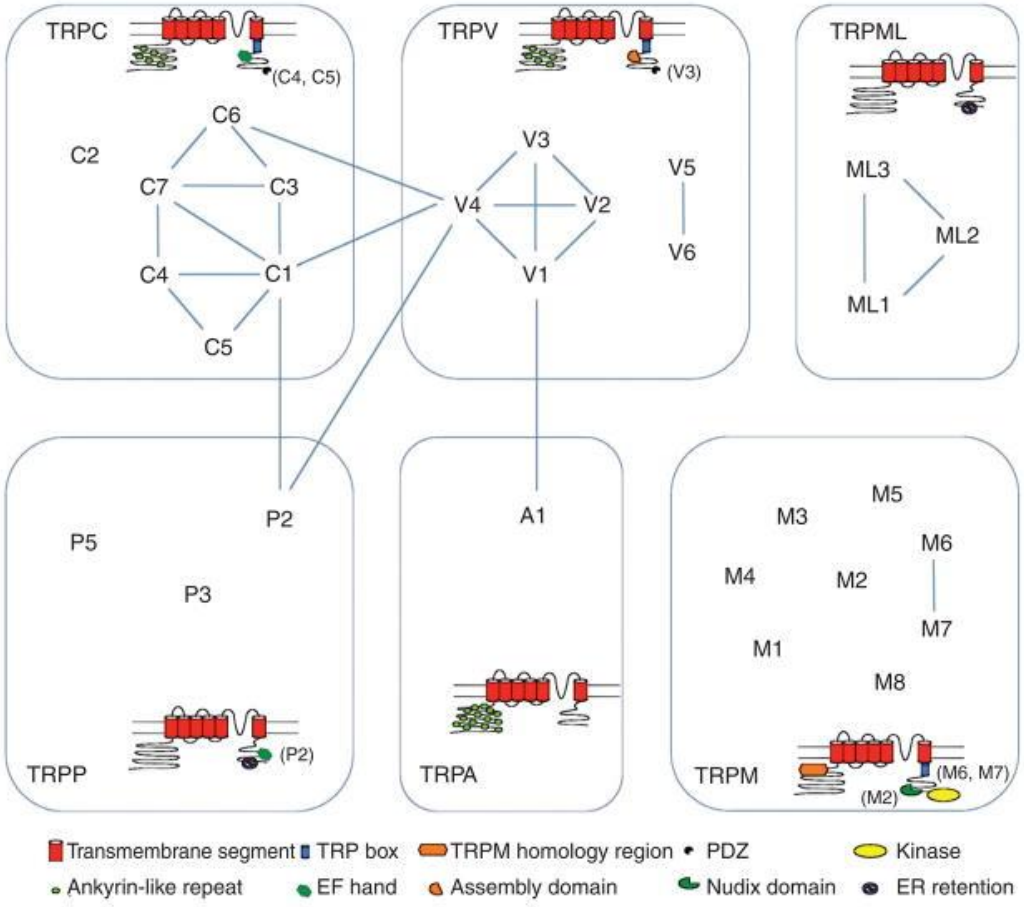


Drosophila



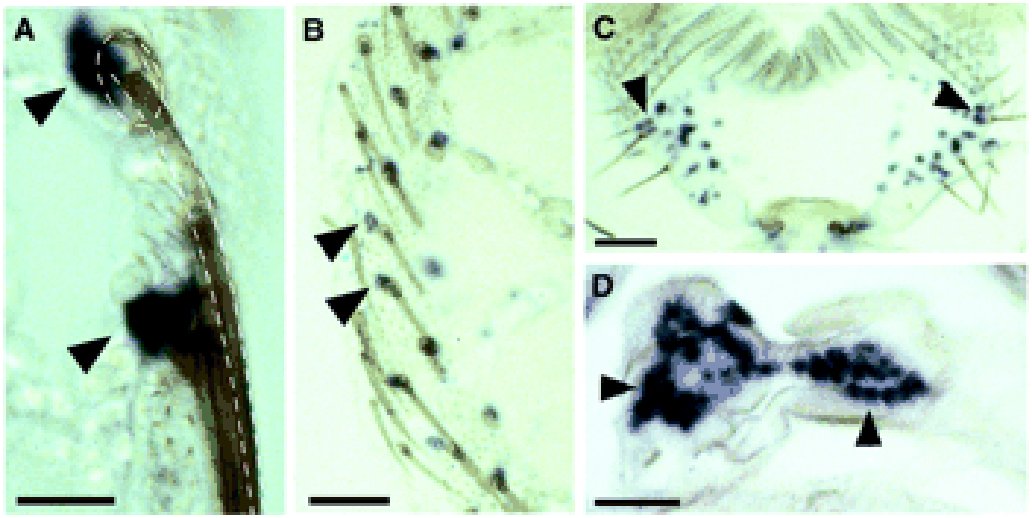
Vertebrate

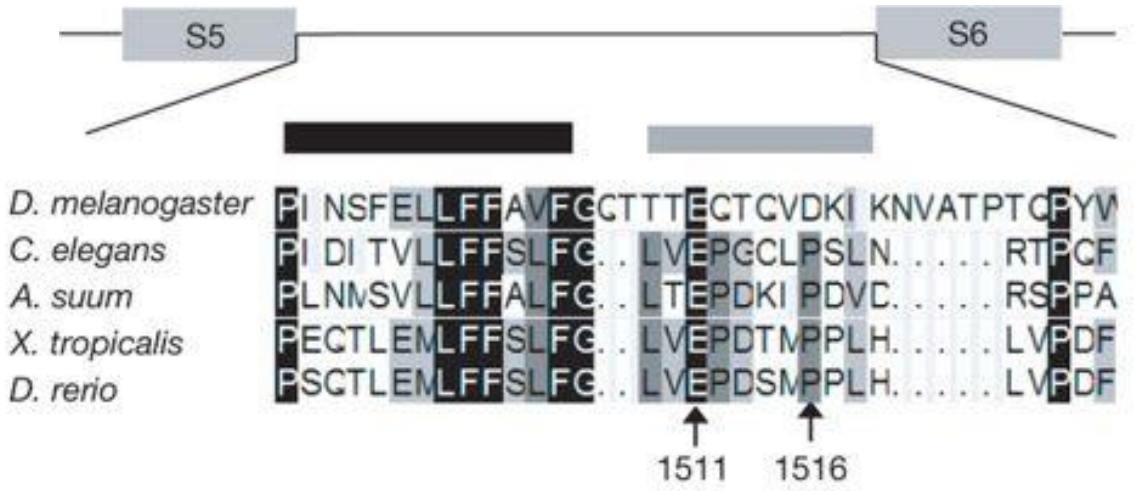
Insect TRP channels as targets for insecticides and repellents



Jie Zheng.2013

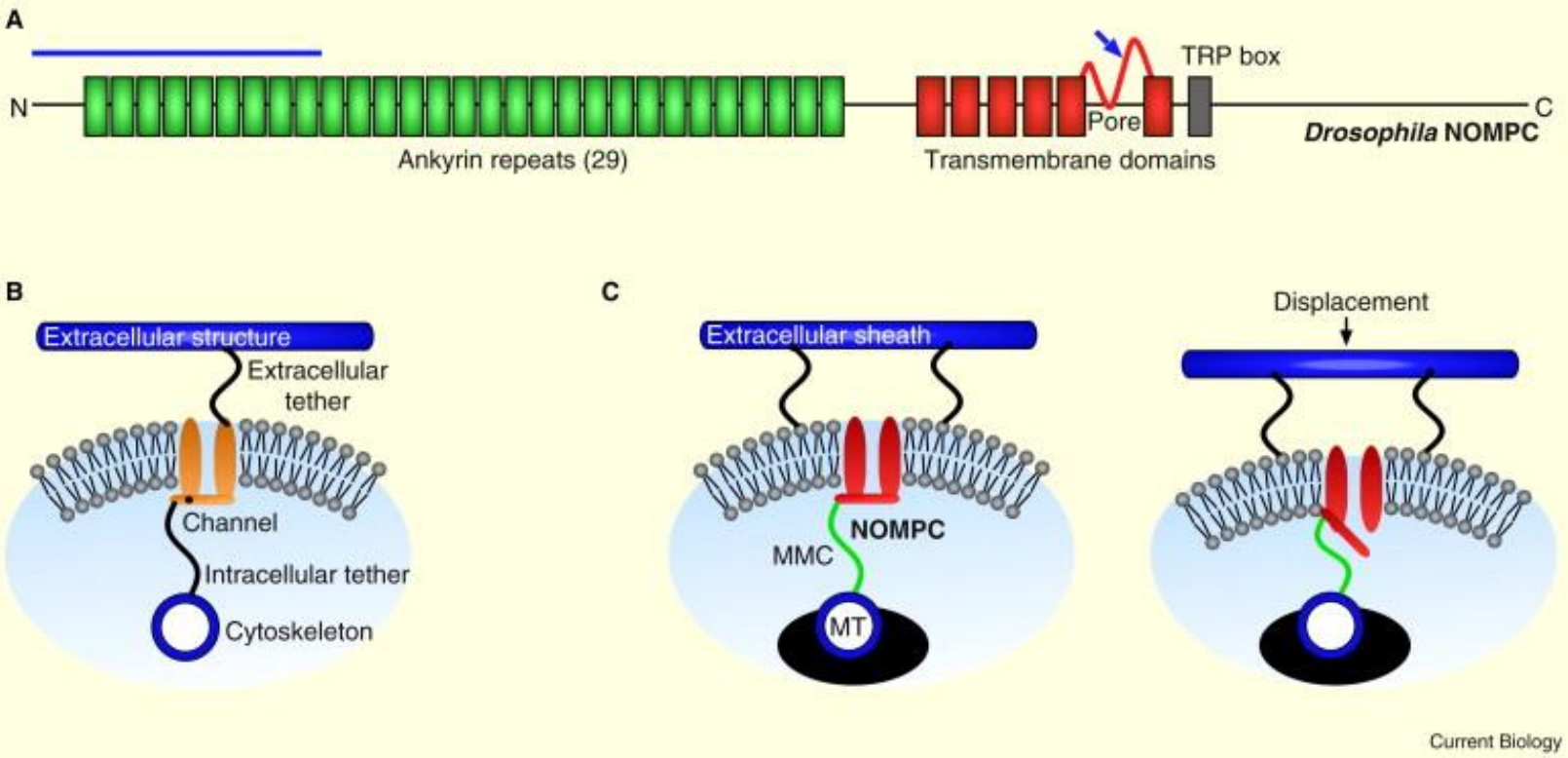
nompC is specifically expressed in mechanosensory organs and conserved in different species





Damiano Zanini et al.2013

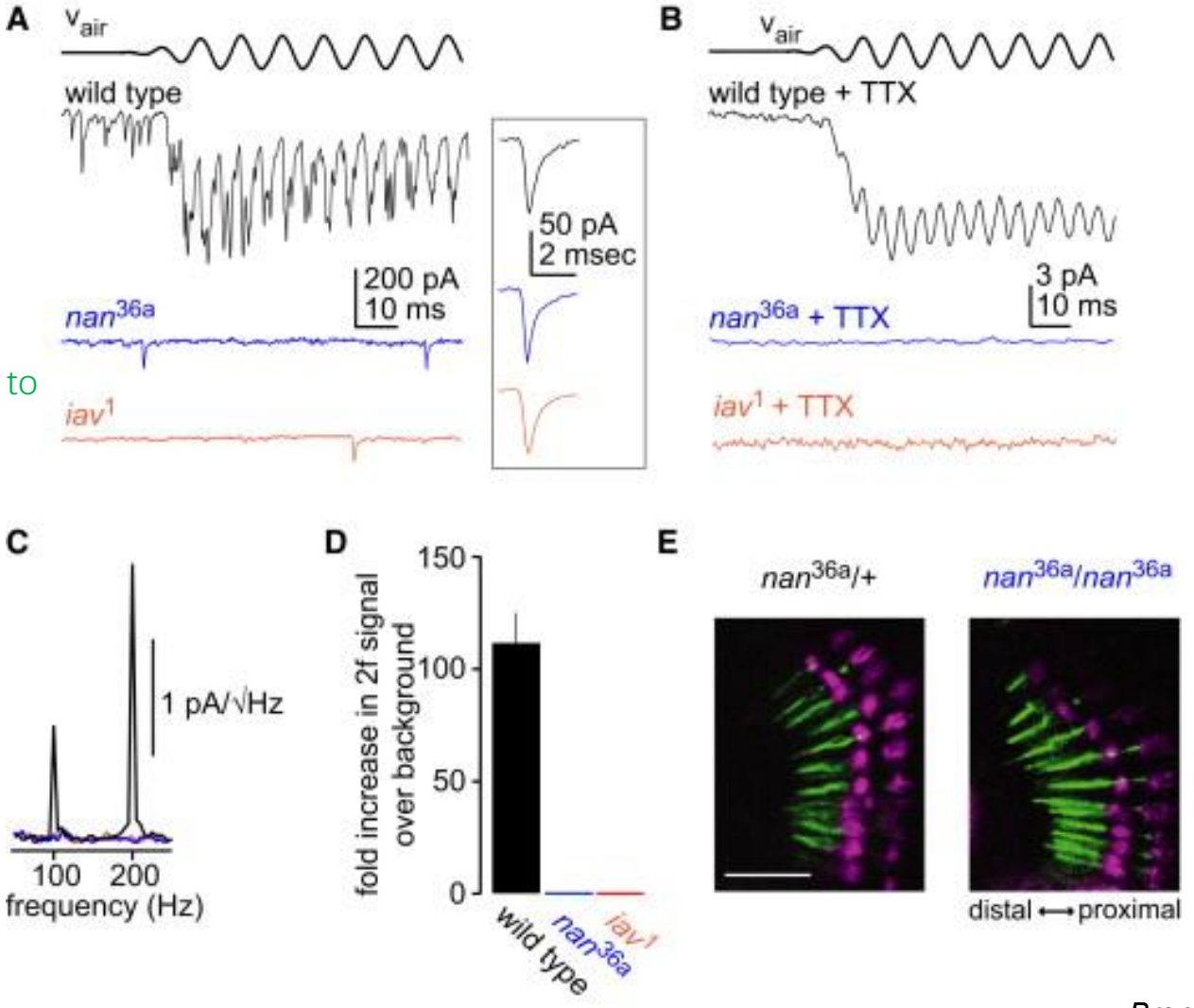
Sensing mechanical stimuli with NOMPC



Damiano Zanini et al.2013

Loss of Nanchung or Inactive Completely Abolishes Generator Currents

record in the GFN in response to a 100 Hz tone (0.0044 m/s).

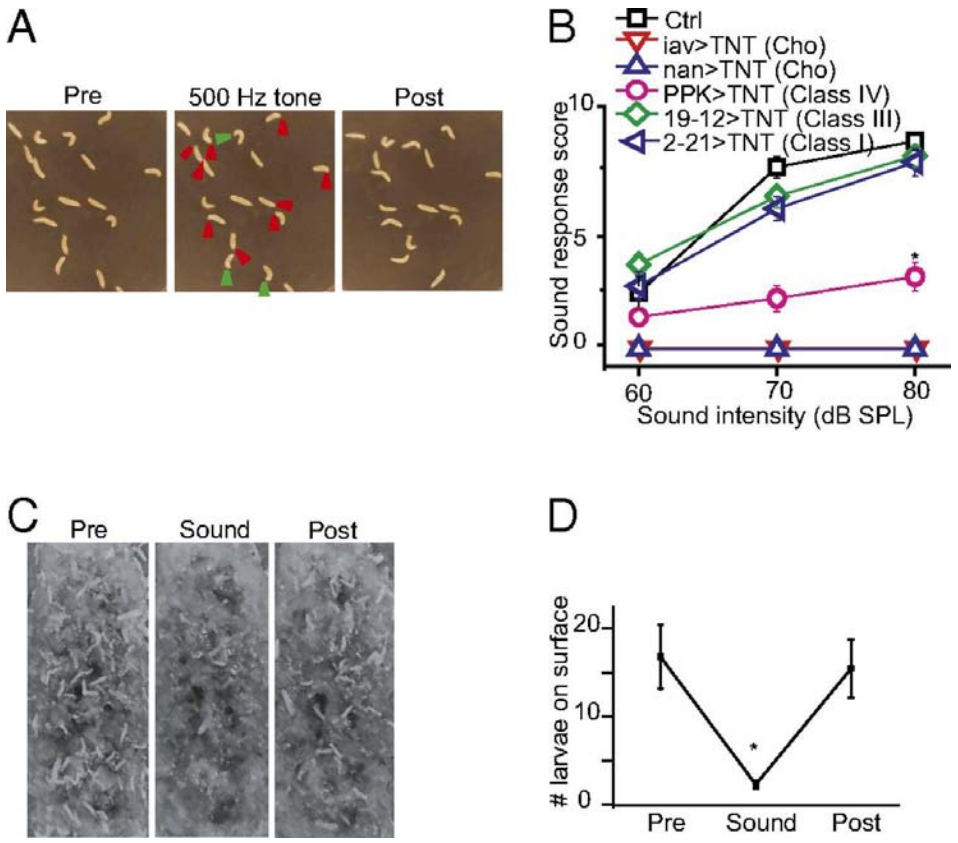


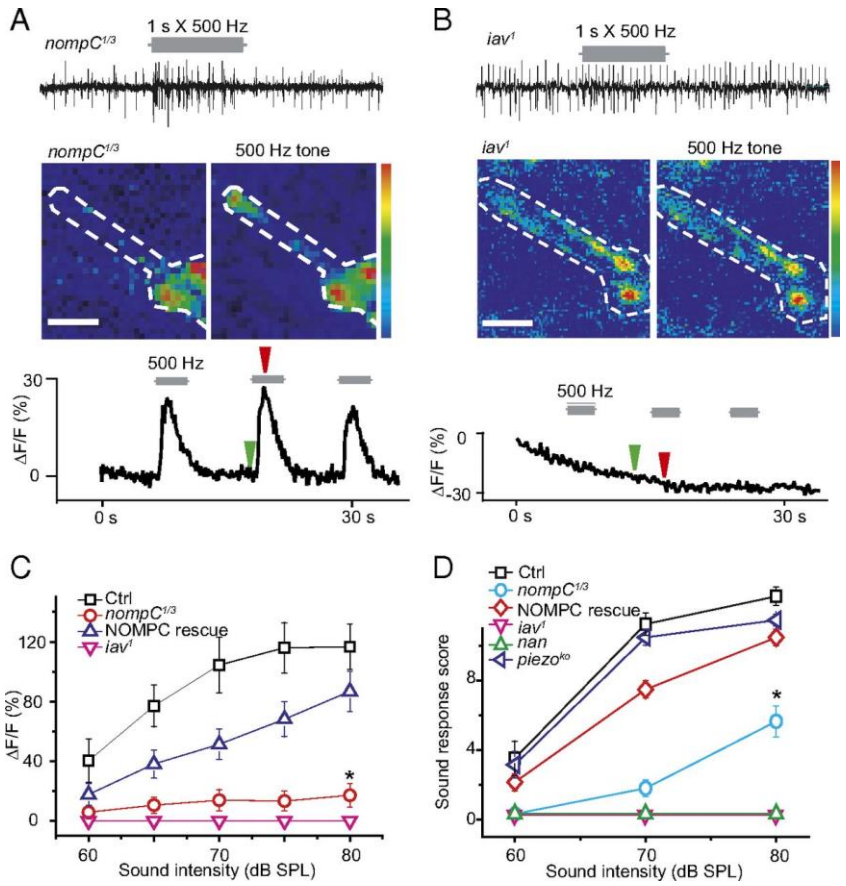
Ciliary dilation (magenta)

NompC:GFP fusion protein (green)

Brendan P. Lehnert et al.2012

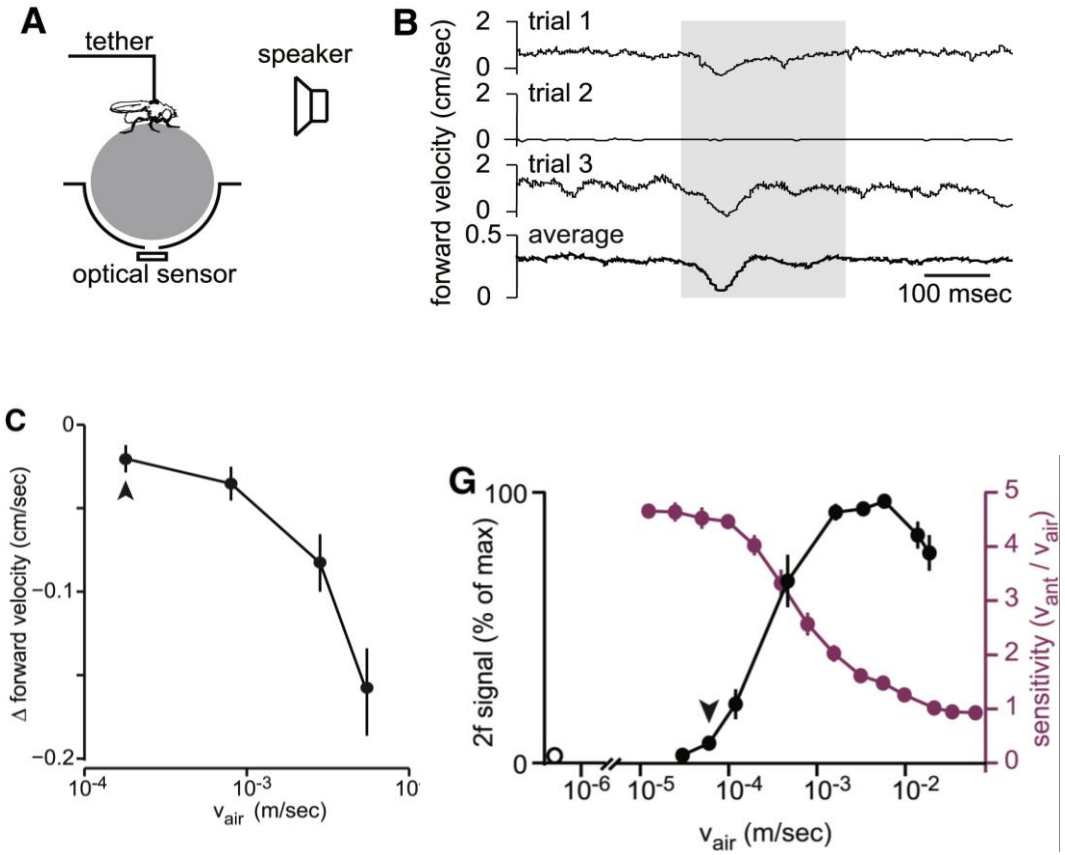
Sound response mediated by the TRP channels NOMPC, NANCHUNG, and INACTIVE in chordotonal organs of *Drosophila* larvae

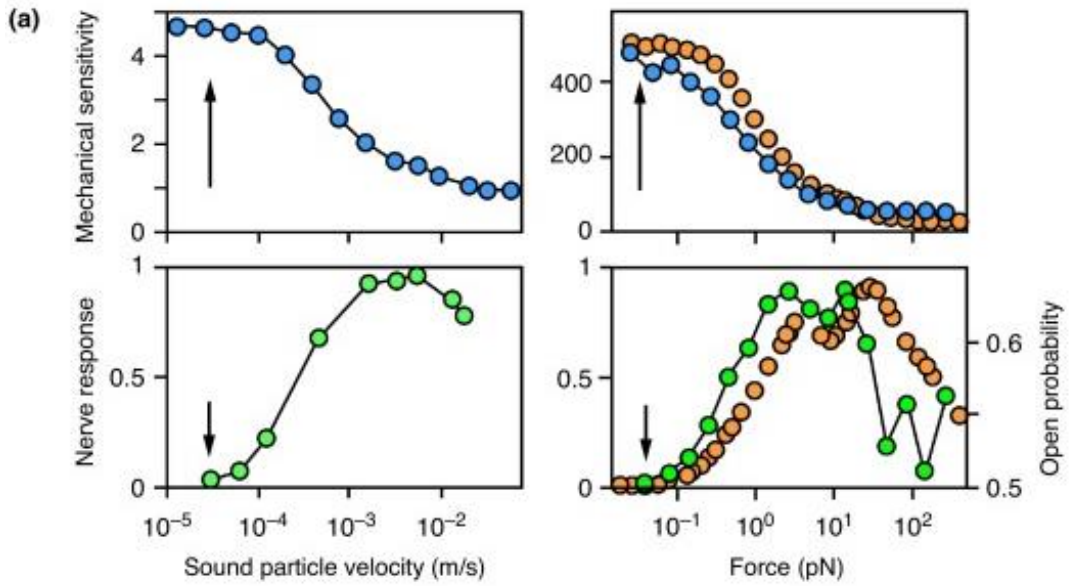




Wei Zhang et al.2013

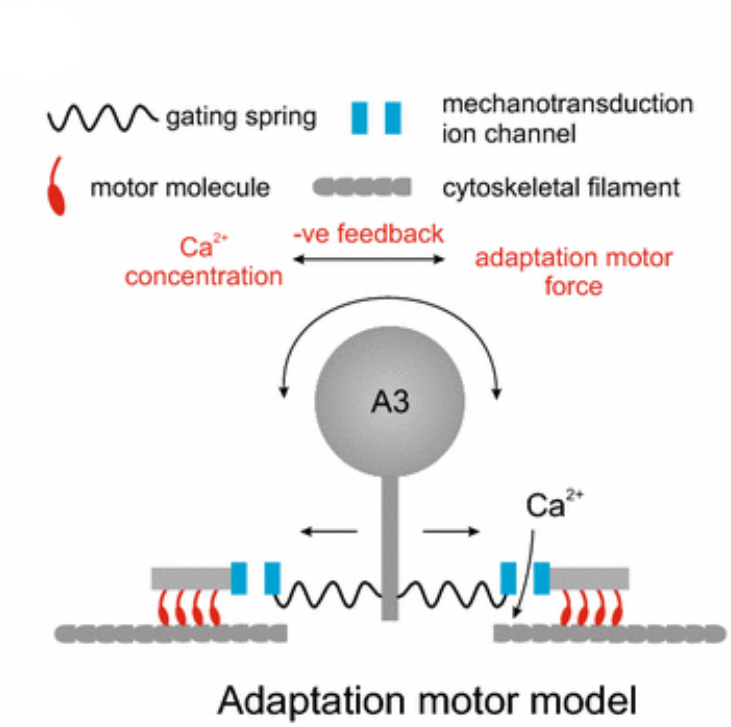
Drosophila hearing is sensitive to low-intensity sounds



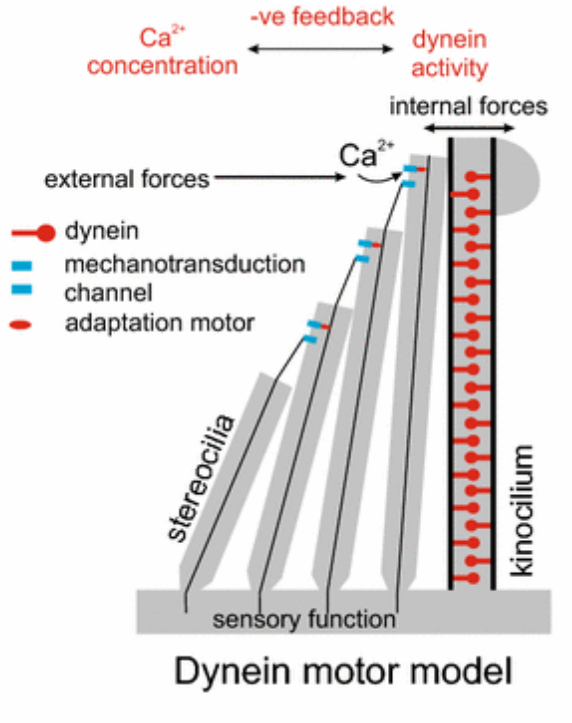


Brendan P. Lehnert et al.2012

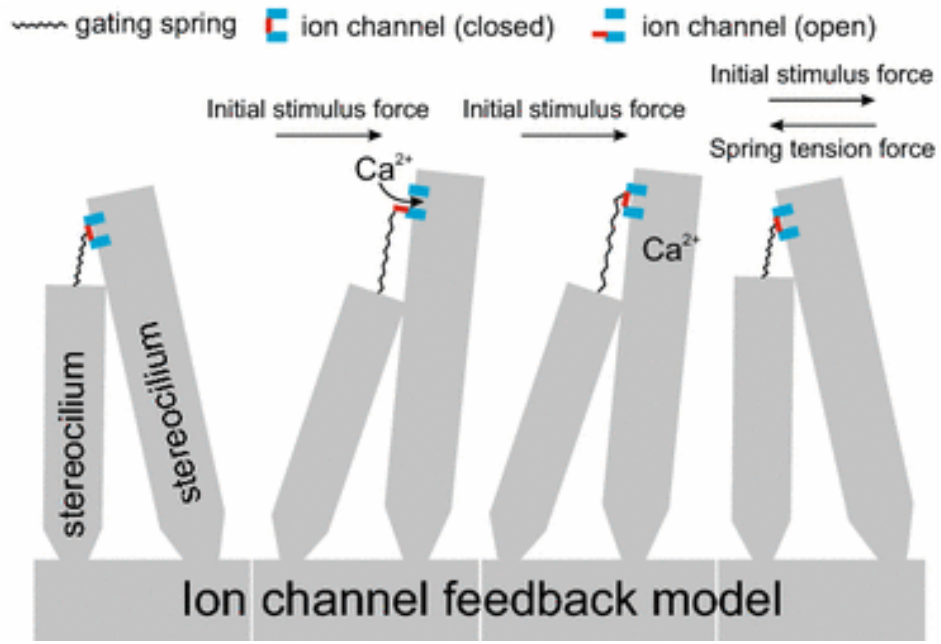
Active amplification models



Adaptation motor model



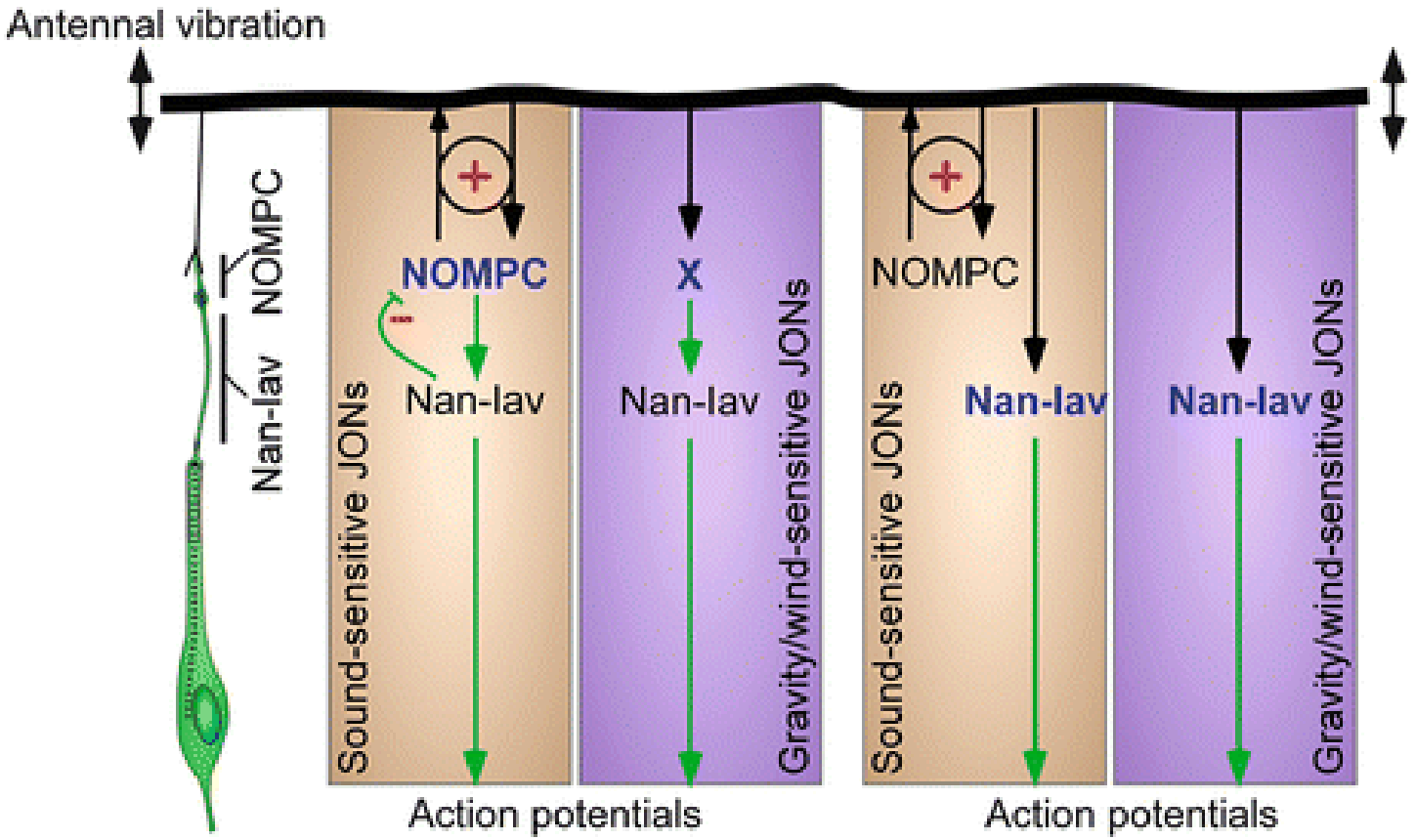
Dynein motor model



Ion channel feedback model

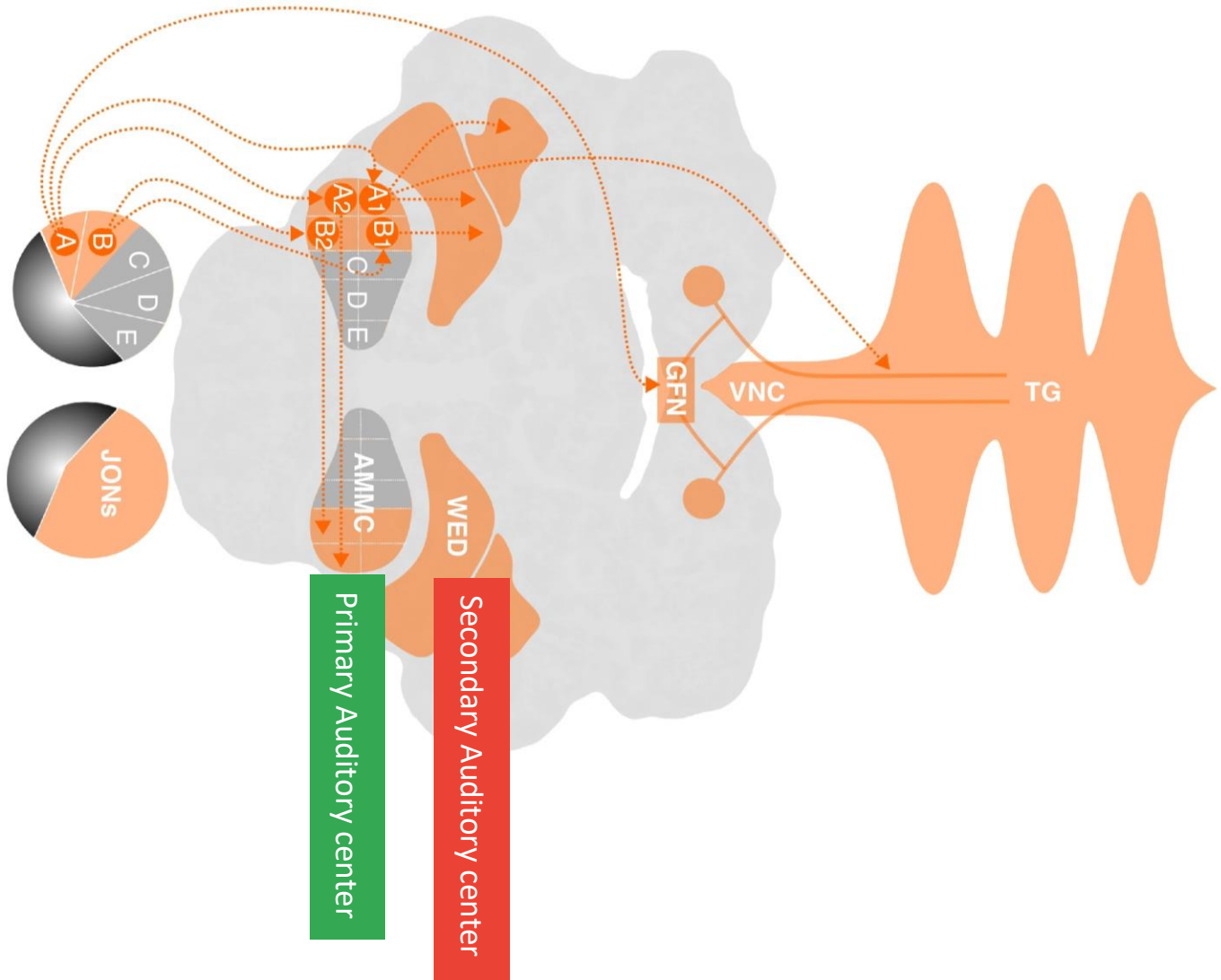
Natasha Mhatre.2014

Two models for Transduction machinery



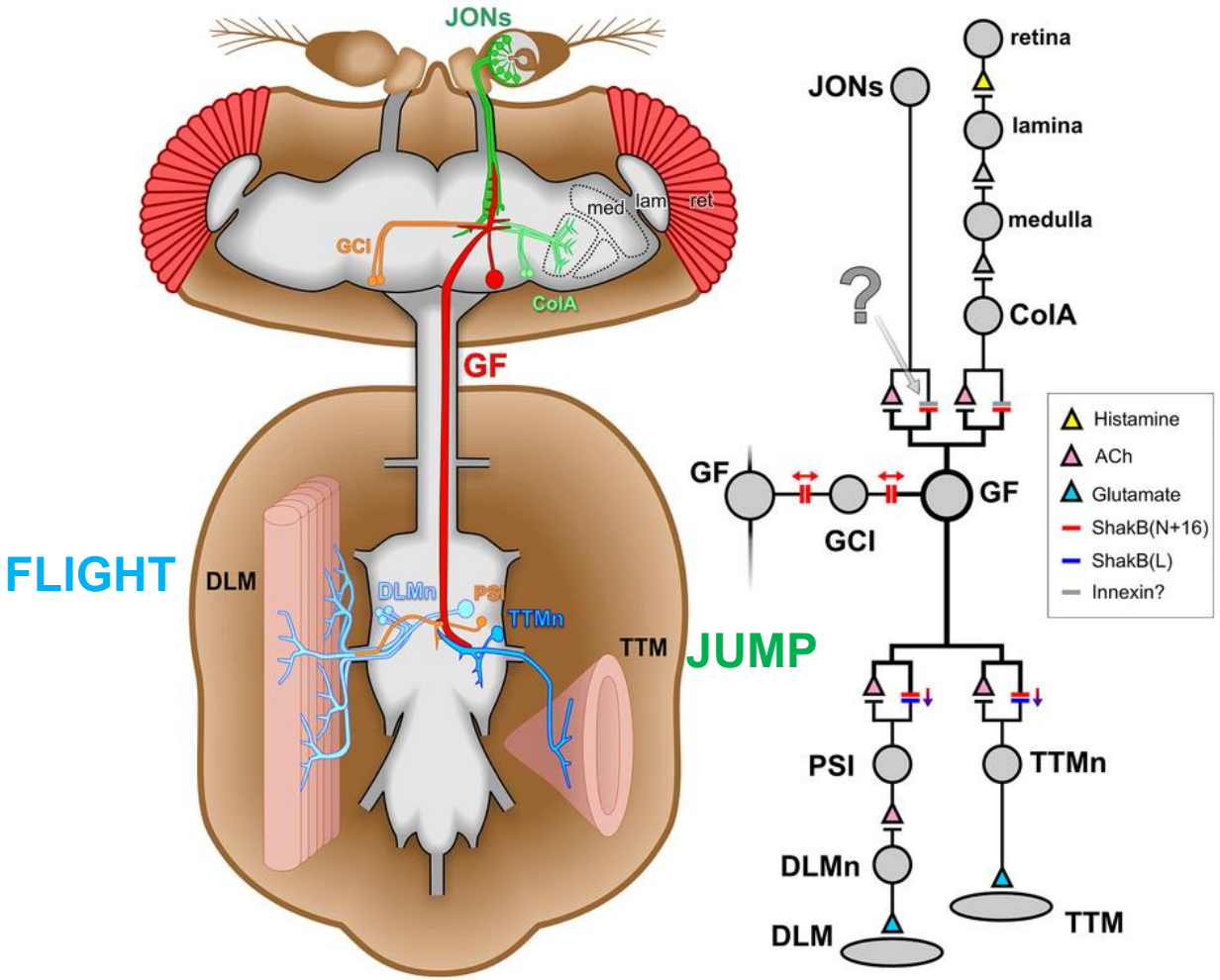
Brendan P. Lehnert et al.2012

The main auditory circuit in *Drosophila*



Jörg Talbert et al.2015

The Drosophila giant fiber (GF) escape circuit



tergotrochanteral motorneurons (TTMn)

tergotrochanteral jump muscles (TTM)

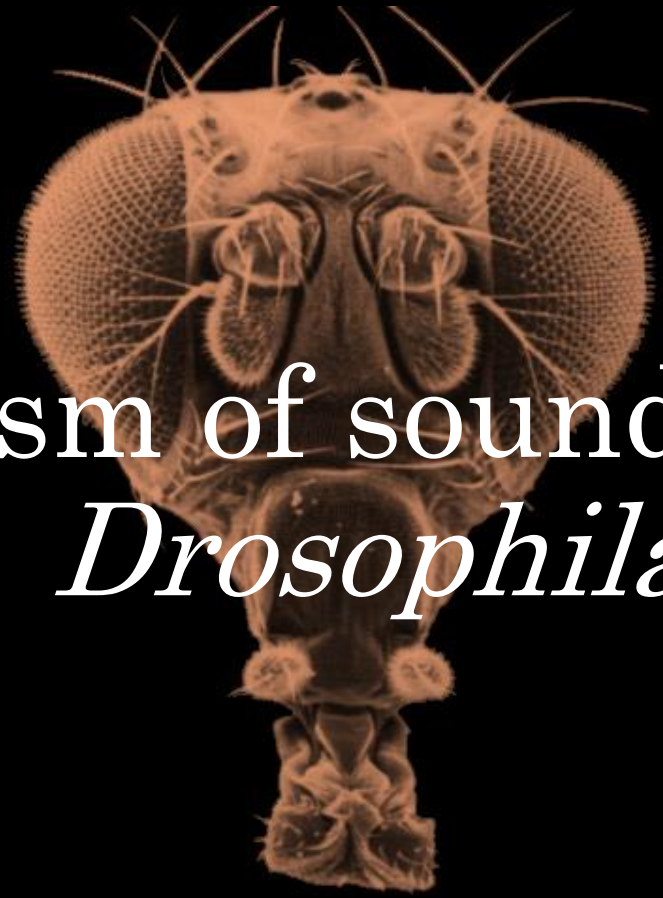
dorsal longitudinal motorneurons (DLMn)

dorsolongitudinal flight muscles (DLM)

Adeline Pezier et al.2016

Welcome to part II

Pan Lab
Journal Club



The mechanism of sound production in *Drosophila*

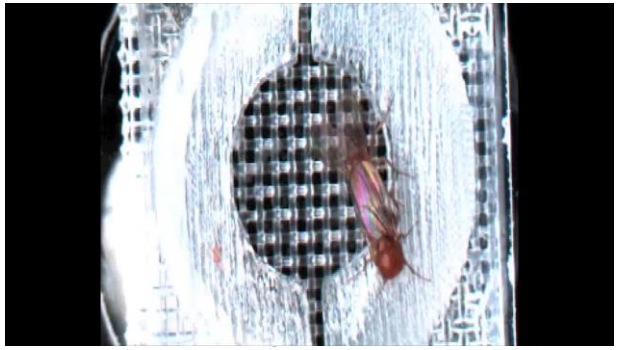
Guo Chao
郭超

Outline

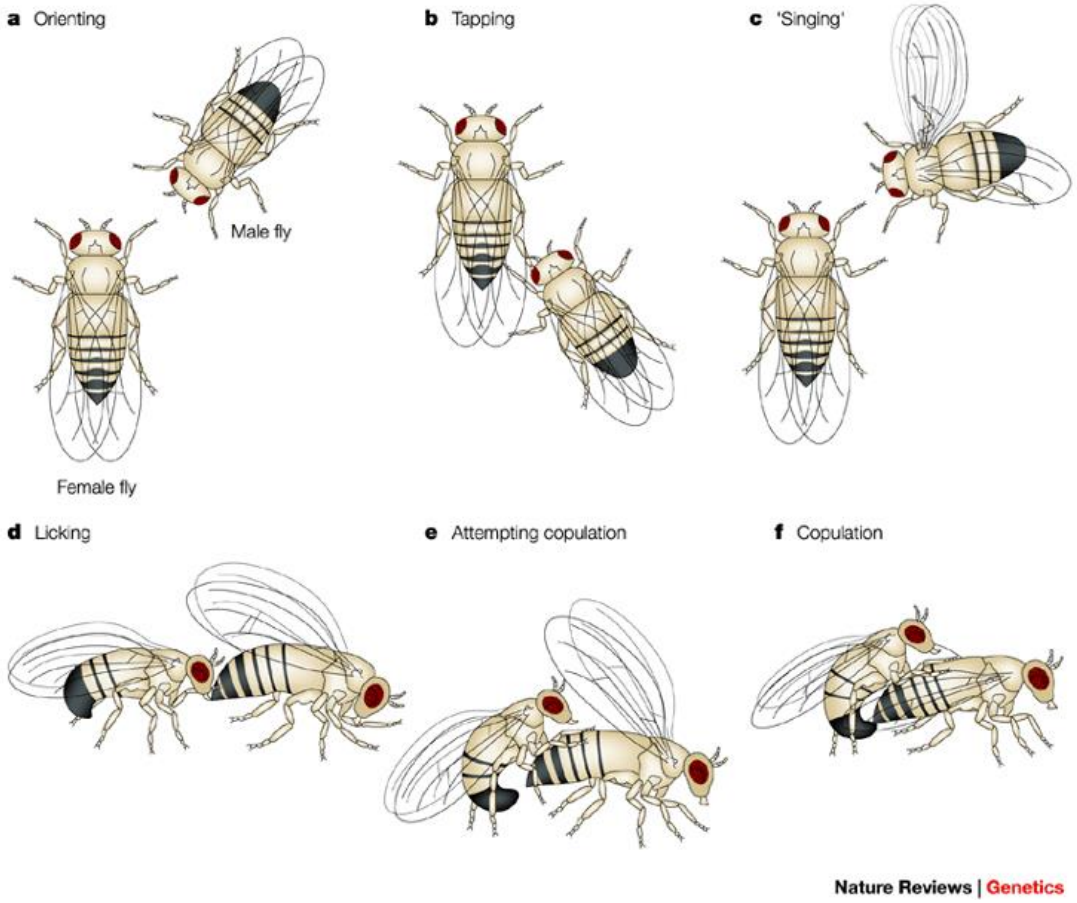
- The sound produced by Drosophila
- Genetic of courtship song
- Neuronal control of courtship song
- Motor control of courtship song
- Sensory modulation of courtship song

Sound in nature

Chirping insects

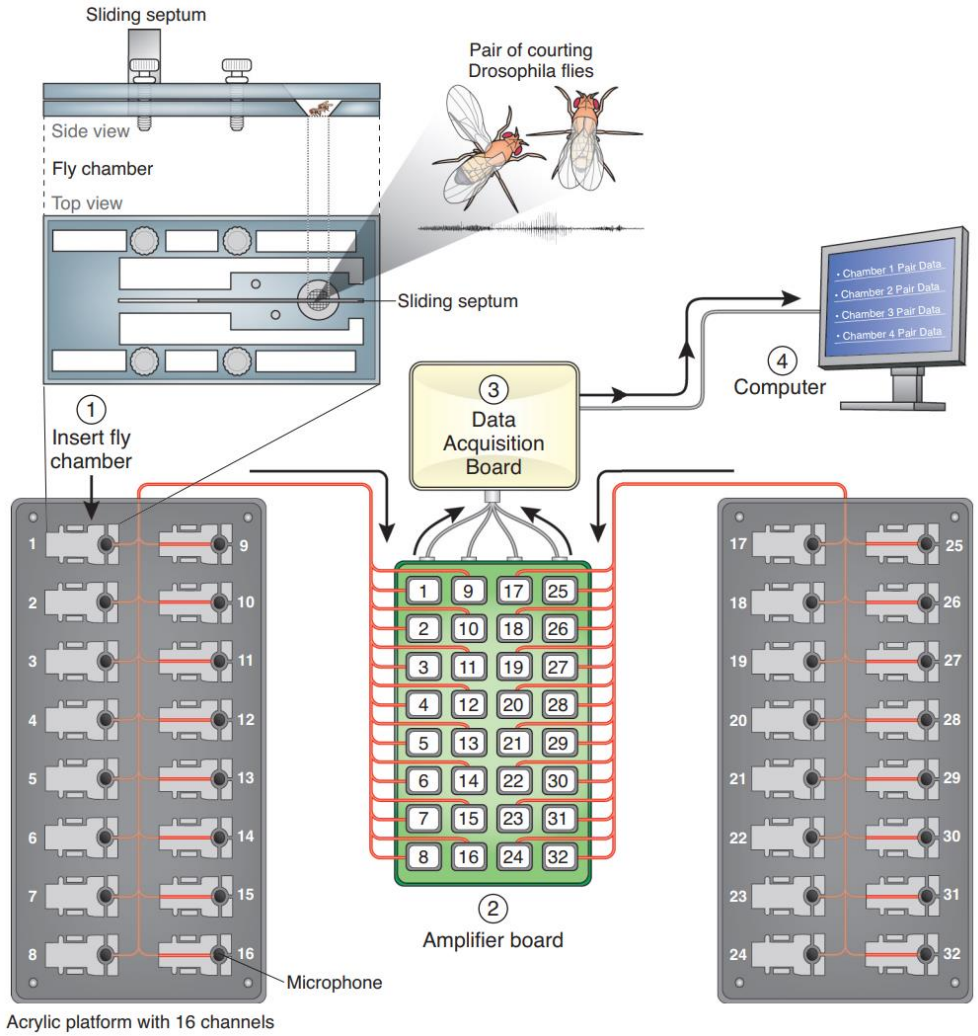


Drosophila courtship and the courtship song

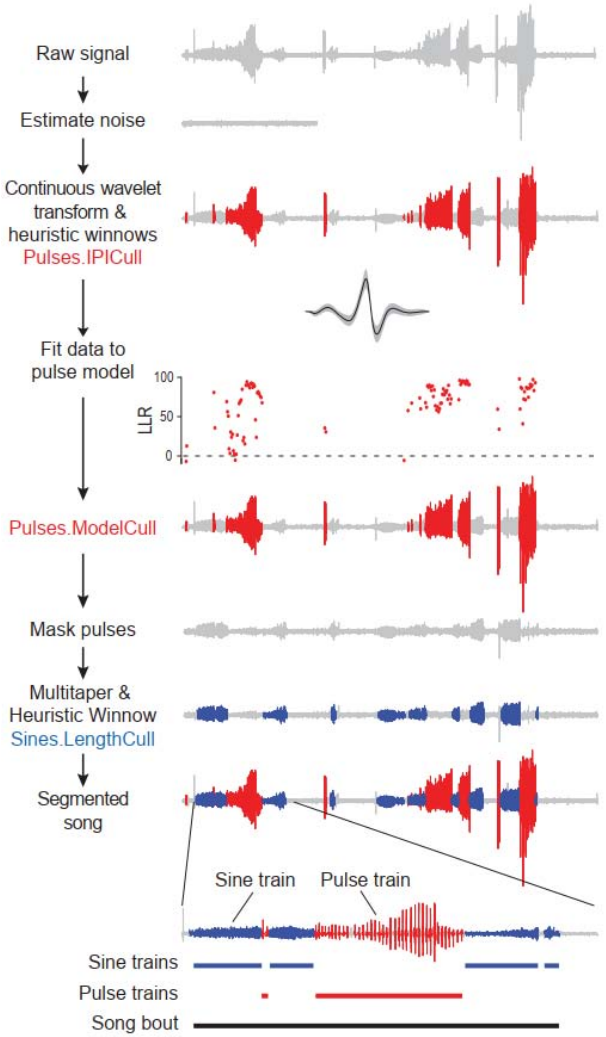


Sokolowski, M.B. 2001

Sound recording & analysis



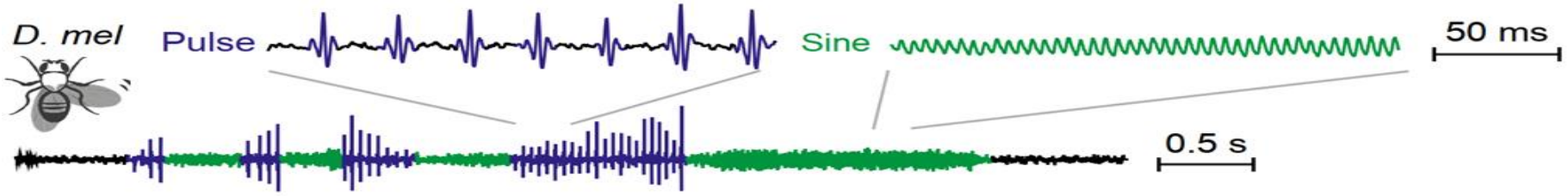
32-channel courtship song recording apparatus



Computational analysis by FlySongSegmenter

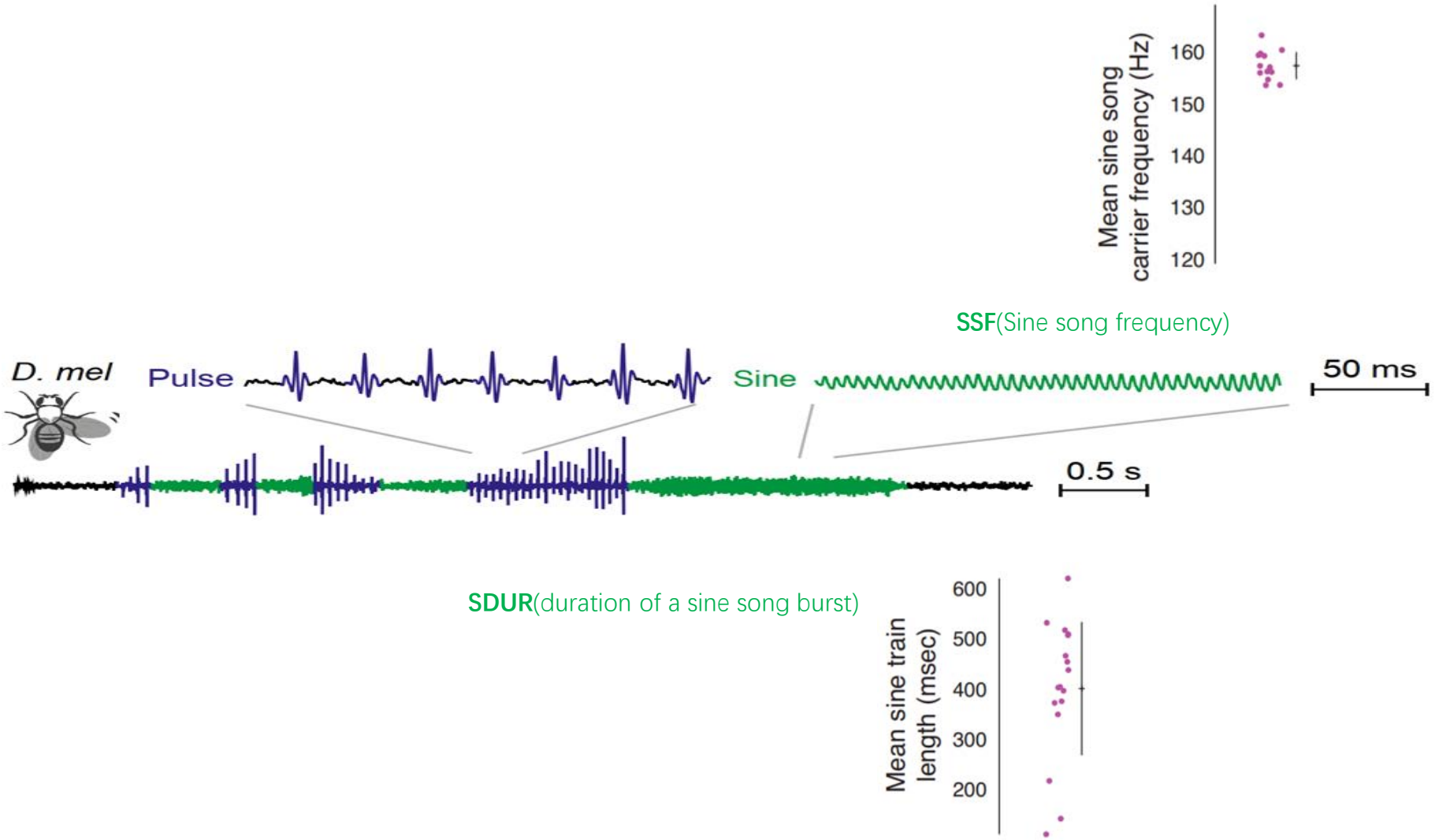
Arthur, B. J. et al. 2013

Courtship song of *Drosophila melanogaster*



Ding, Y et al. 2019; Gleason, J. M. 2005

Courtship song of *Drosophila melanogaster*



Ding, Y et al. 2019; Gleason, J. M. 2005

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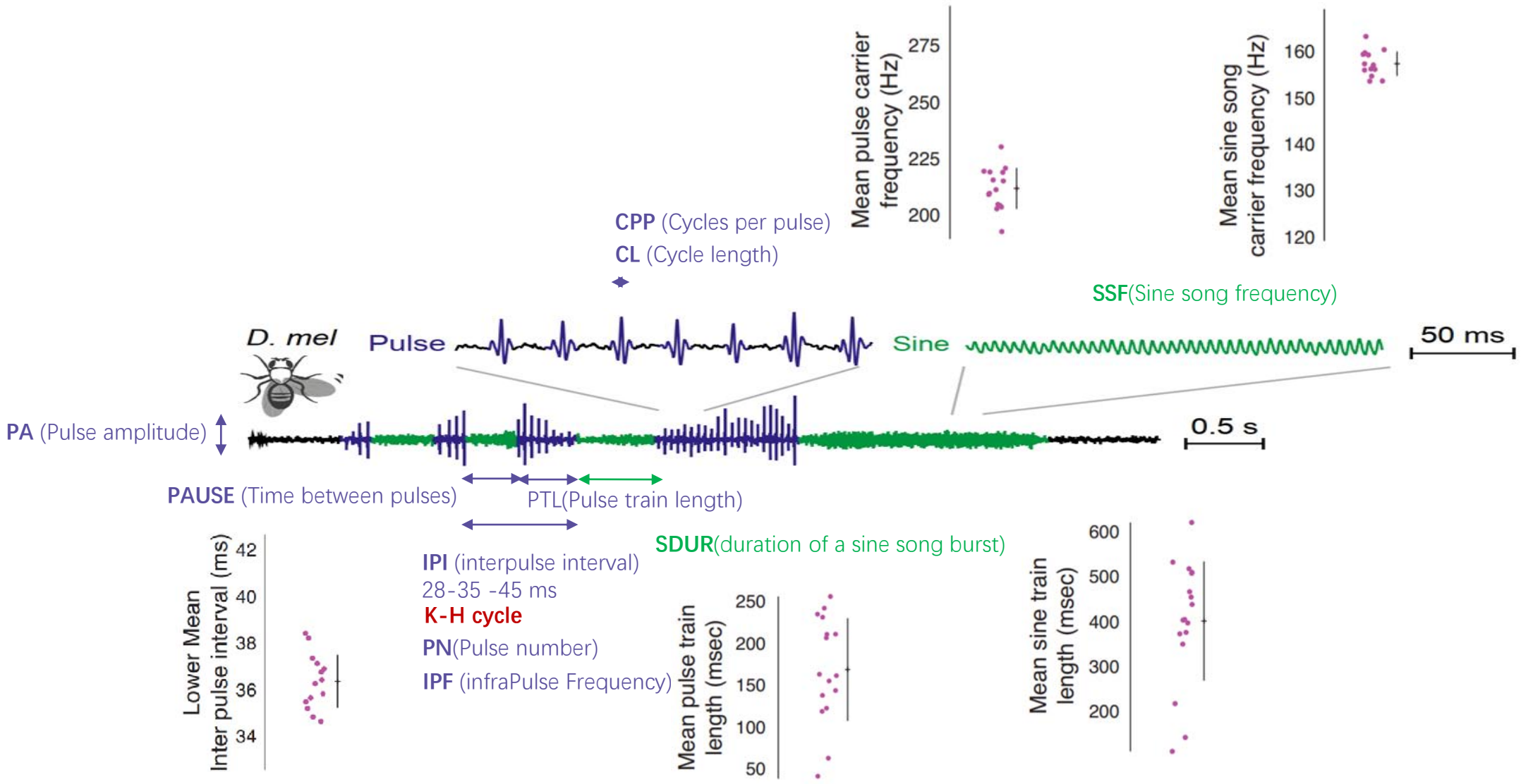
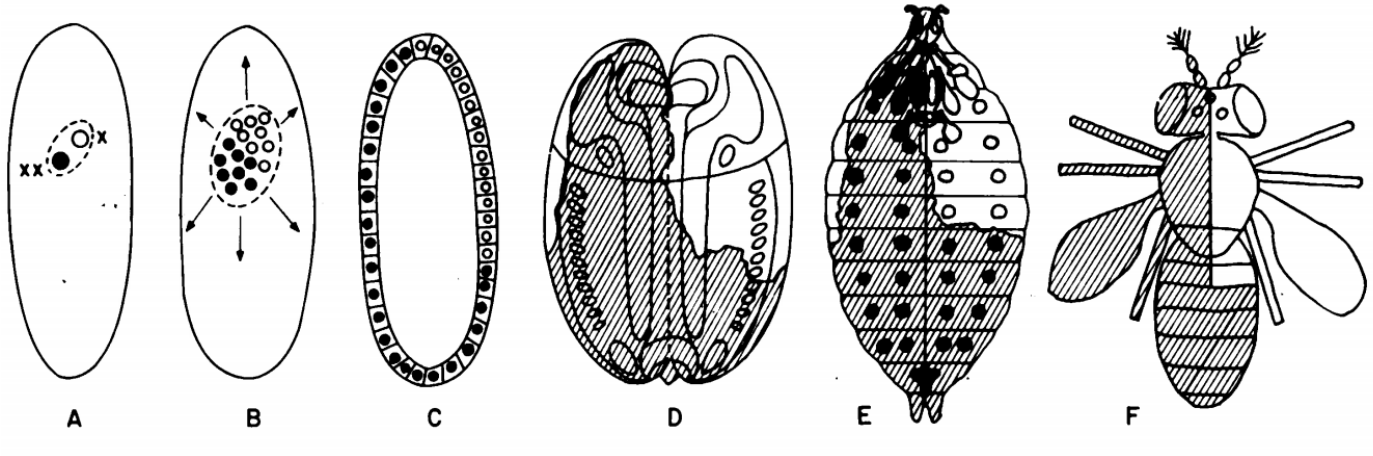


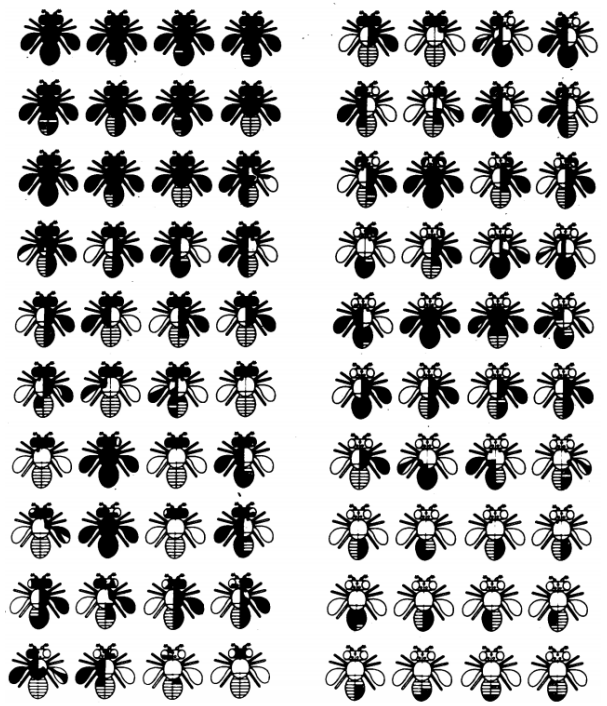
Ding, Y et al. 2019; Gleason, J. M. 2005

Foray into loci of courtship song by sex mosaics

Genetic dissection of the *Drosophila* nervous system by means of mosaics

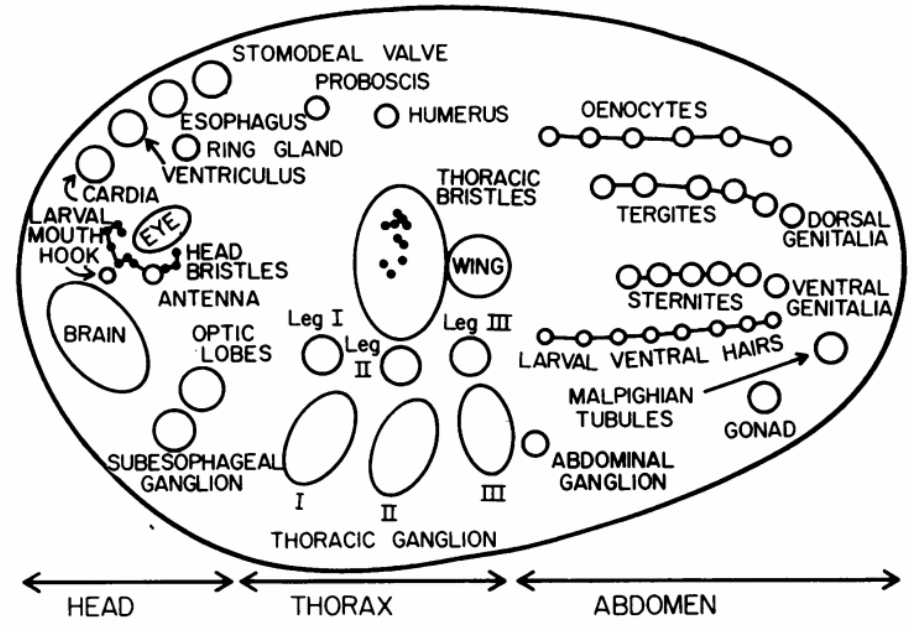


Schematic diagram illustrating formation of a gynandromorph (sex mosaics).



Hotta, Y. & S. Benzer 1970

Sex-specific foci for sequential action patterns



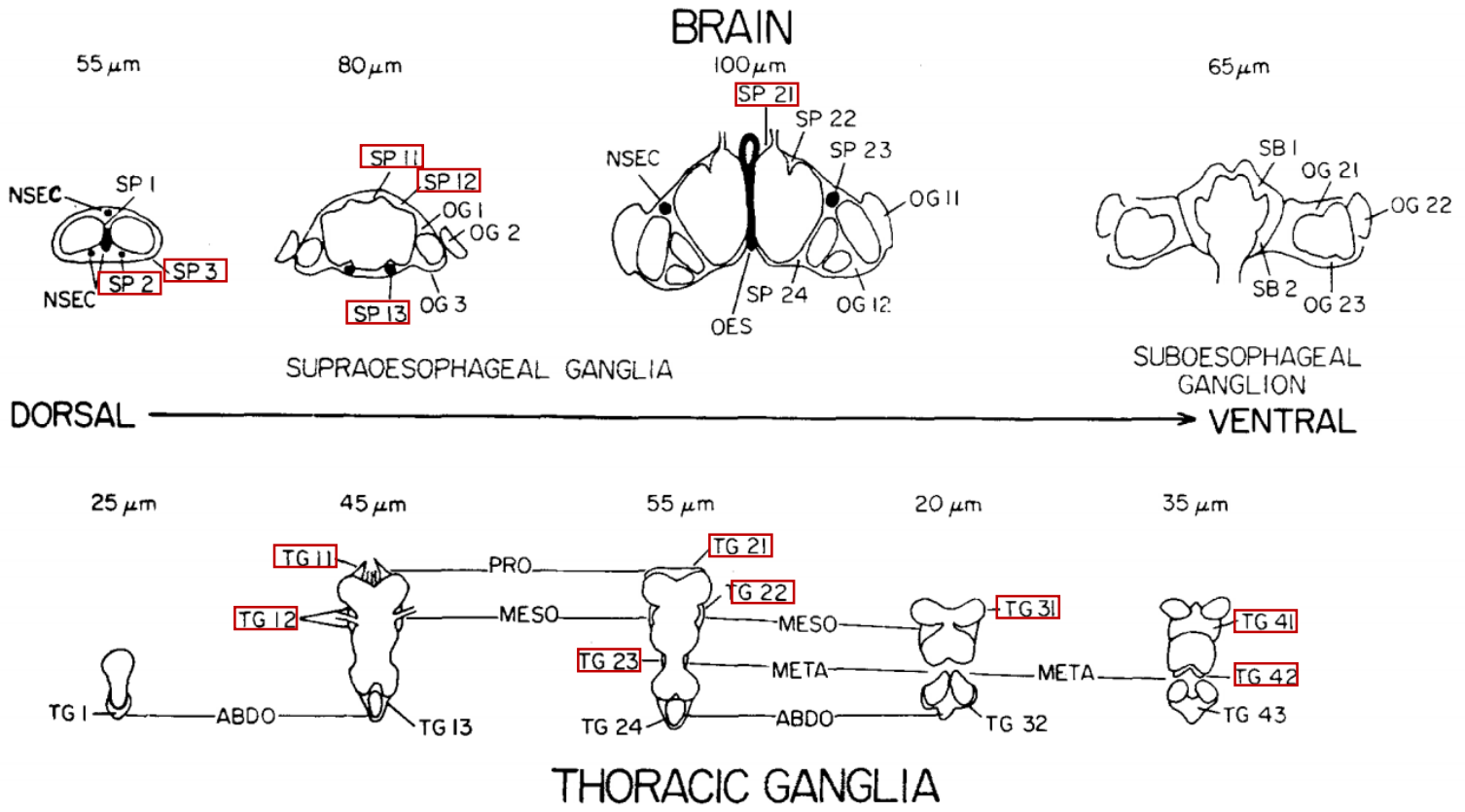
Fate map of *Drosophila* embryo,

Table 1. Male wing vibration compared with sex of cuticle

	Head		Thorax		Abdomen	
Vibrate	Male	Female	Male	Female	Male	Female
Yes	162	2	91	11	22	26
No	5	133	33	47	36	19

Hotta, Y. & S. Benzer 1976

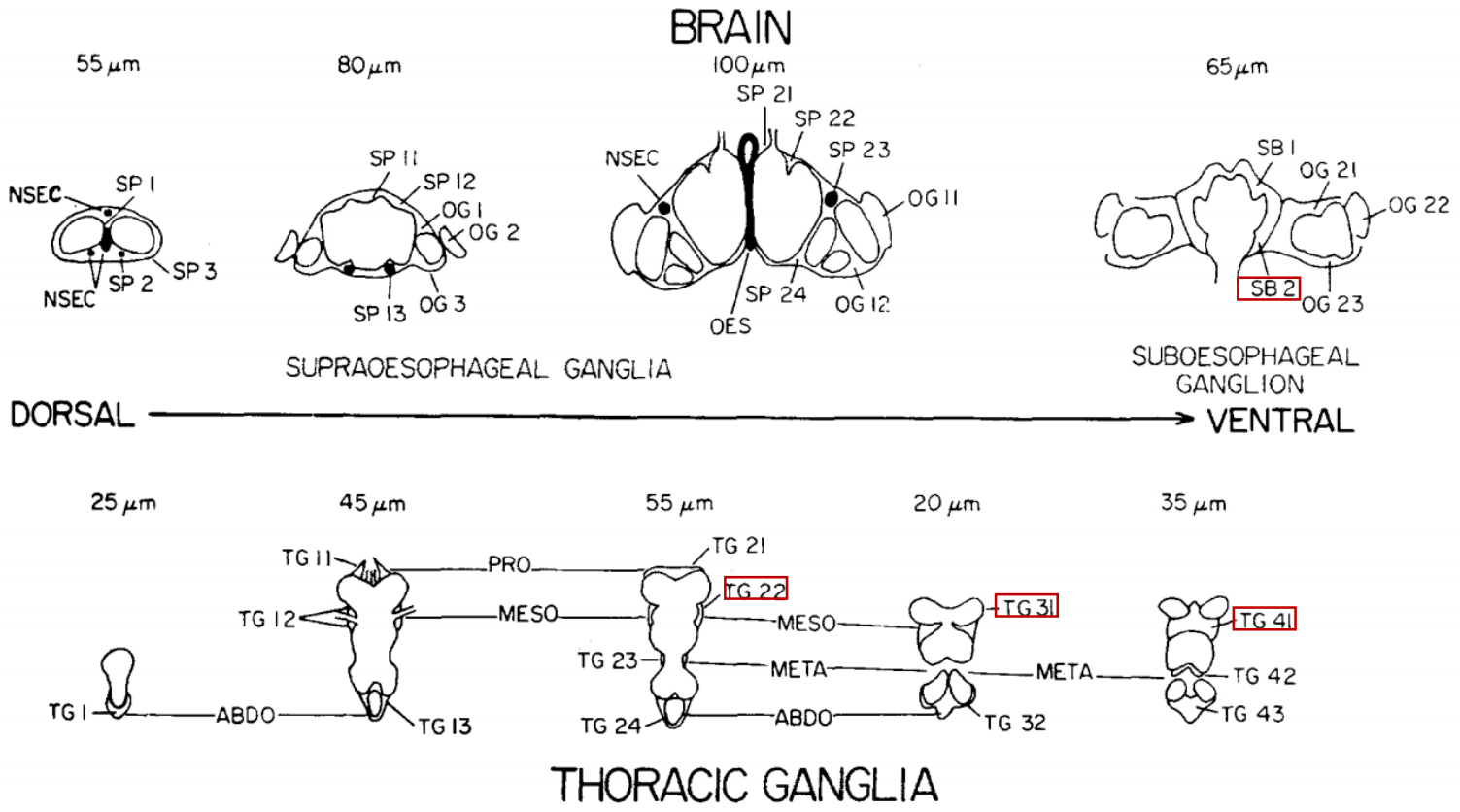
Mosaicism in the central nervous systems of male-behaving mosaics



Brain	♀♀	♂♀ ♀♂	♂♂	*P* (♀♀)
SP 1	9	37	43	0.10
SP 2	0	42	49	0.00
SP 3	0	41	52	0.00
SP 11	2	45	48	0.02
SP 12	4	52	37	0.04
SP 13	3	47	41	0.03
OG 1	9	31	56	0.09
OG 2	7	30	59	0.07
OG 3	7	30	58	0.07
SP 21	3	40	51	0.03
SP 22	6	48	41	0.06
SP 23	10	46	40	0.10
SP 24	4	41	48	0.04
OG 11	7	29	60	0.07
OG 12	7	28	61	0.07
SB 1	11	42	37	0.12
SB 2	9	52	29	0.10
OG 21	9	26	59	0.10
OG 22	7	27	61	0.07
OG 23	7	28	60	0.07
Thoracic ganglion				
TG 1	46	37	8	0.51
TG 11	13	58	21	0.14
TG 12	13	56	17	0.15
TG 13	44	38	9	0.48
TG 21	13	54	17	0.16
TG 22	13	44	13	0.19
TG 23	15	56	18	0.17
TG 24	45	37	11	0.49
TG 31	16	43	13	0.22
TG 32	43	33	11	0.49
TG 41	19	44	12	0.25
TG 42	20	49	18	0.23
TG 43	43	34	19	0.50

Vonschilcher, F. & J. C. Hall 1979

Internal mosaicism in gynandromorphs with different courtship songs



	Defective song			Normal song			Chi-square
	♀♀	♂♀ ♀♂	♂♂	♀♀	♂♀ ♀♂	♂♂	
Brain							
SP 1	4	12	11	5	25	32	1.38
SP 2	0	14	14	0	28	35	0.24
SP 3	0	15	14	0	26	38	1.00
SP 11	0	16	13	2	29	35	1.68
SP 12	0	16	12	4	36	25	1.83
SP 13	1	15	11	2	32	30	0.29
OG 1	2	9	18	7	22	38	0.39
OG 2	2	9	18	5	21	41	0.01
OG 3	2	9	17	5	21	41	0.01
SP 21	2	11	16	1	29	35	2.02
SP 22	4	14	10	2	34	31	4.50
SP 23	4	14	11	6	32	29	0.60
SP 24	2	14	13	2	27	35	1.20
OG 11	2	9	18	5	20	42	0.02
OG 12	2	9	18	5	19	43	0.02
SB 1	6	11	10	5	31	27	3.60
SB 2	6	13	7	3	39	22	6.95*
OG 21	4	7	18	5	19	41	0.97
OG 22	3	8	18	4	19	43	0.54
OG 23	3	8	18	4	20	42	0.56
Thoracic ganglion							
TG 1	21	7	0	25	30	8	10.78**
TG 11	10	15	3	3	43	18	16.43***
TG 12	11	13	1	2	43	16	24.82***
TG 13	20	8	0	24	30	9	10.14**
TG 21	10	12	2	3	42	15	18.31***
TG 22	12	4	0	1	40	13	44.14***
TG 23	12	14	0	3	42	18	26.62***
TG 24	23	5	0	22	32	11	19.01***
TG 31	13	3	0	3	40	13	41.75***
TG 32	21	5	0	22	28	11	15.48***
TG 41	15	4	0	4	40	12	39.08***
TG 42	16	9	0	4	40	18	35.50***
TG 43	21	5	0	22	29	9	14.84***

* $P < 0.05$
** $P < 0.01$
*** $P < 0.001$

Vonschilcher, F. & J. C. Hall 1979

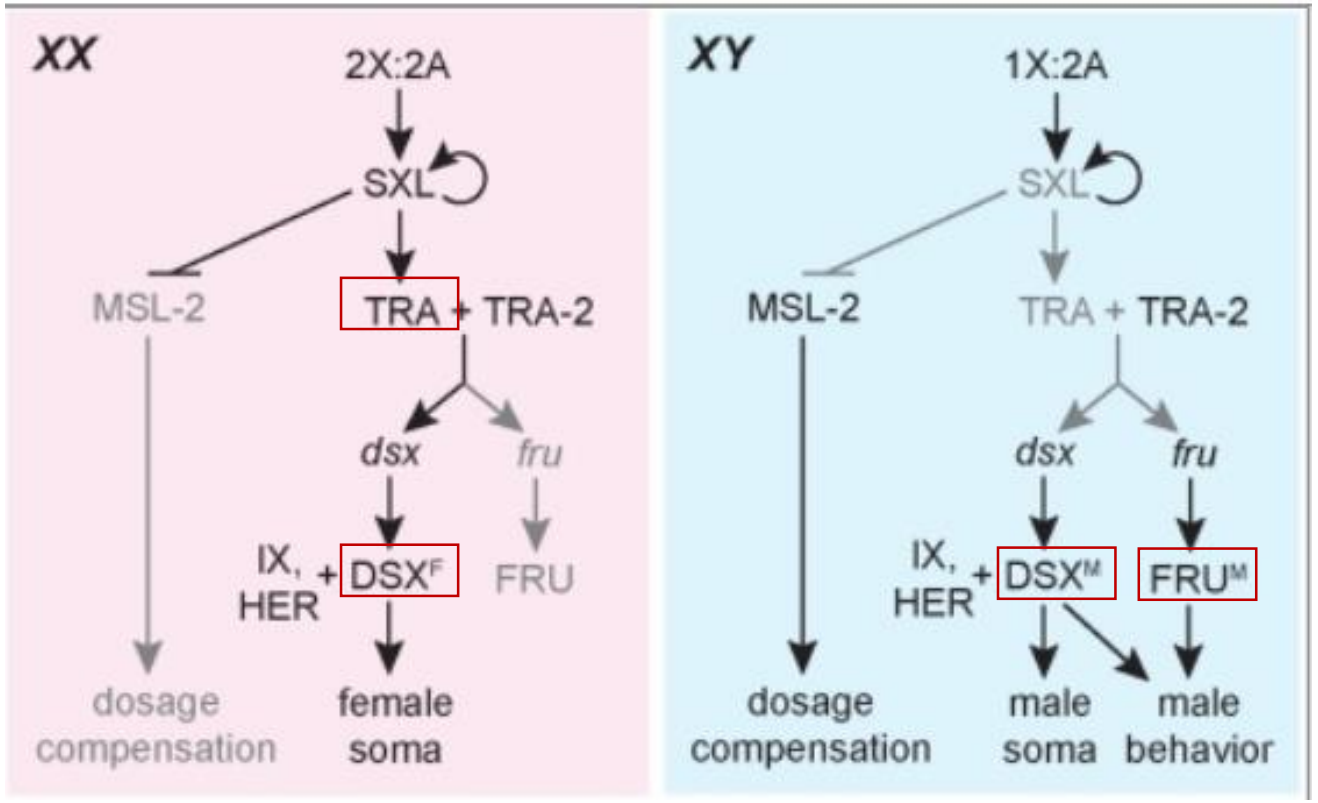
Genetic dissection of courtship song

Table II. Genes with Effects on Courtship Song in *Drososphila melanogaster*

Locus	Traits affected[a]	Molecular characterization[b]	Chromosome
period (*per*)	K& H cycle	Transcription corepressor	X
cacophony (*cac*)	CPP, FFT, IPI, PA, sine song, PA, FFT	Voltage-gated calcium channel	X
no-on transient A (*nonA*)	CPP, FFT	RNA binding protein	X
paralytic (*para*)	IPI	Voltage-gated sodium channel	X
ariadne (*ari-1*)	no song	Ubiquitin protein ligase	X
touch-insensitive-larva-B (*tilB*)	AMP-RT, SSF	Unknown	X
beethoven (*btv*)	AMP-RT, CPP, PD, SSF	ATPase activity	2L
maleless (*mle*)	IPI, enhances *cac* IPI defects	Double stranded RNA binding domain	2R
croaker	CPP, IPI	Unknown	2R
temperature-induced-paralytic-E (*tipE*)	IPF, PA	Voltage-gated sodium channel	3L
Cysteine string protein (*Csp*)	CPP, IPF, PA	ATPase activity	3R
transformer (*tra*)	CPP, FFT	Pre-mRNA splicing factor	3R
doublesex (*dsx*)	IPI, sine song	Transcription factor	3R
atonal (*ato*)	AMP-RT, CPP, PL, PN	Transcription factor	3R
fruitless (*fru*)	FFT, IPI, song production	RNA polymerase II transcription factor	3R
ebony (*e*)	IPF, sine song	Beta-alanyl-dopamine synthase	3R
slowpoke (*slo*)	CPP, IPF, IPI, PA	Calcium activated potassium channel	3R

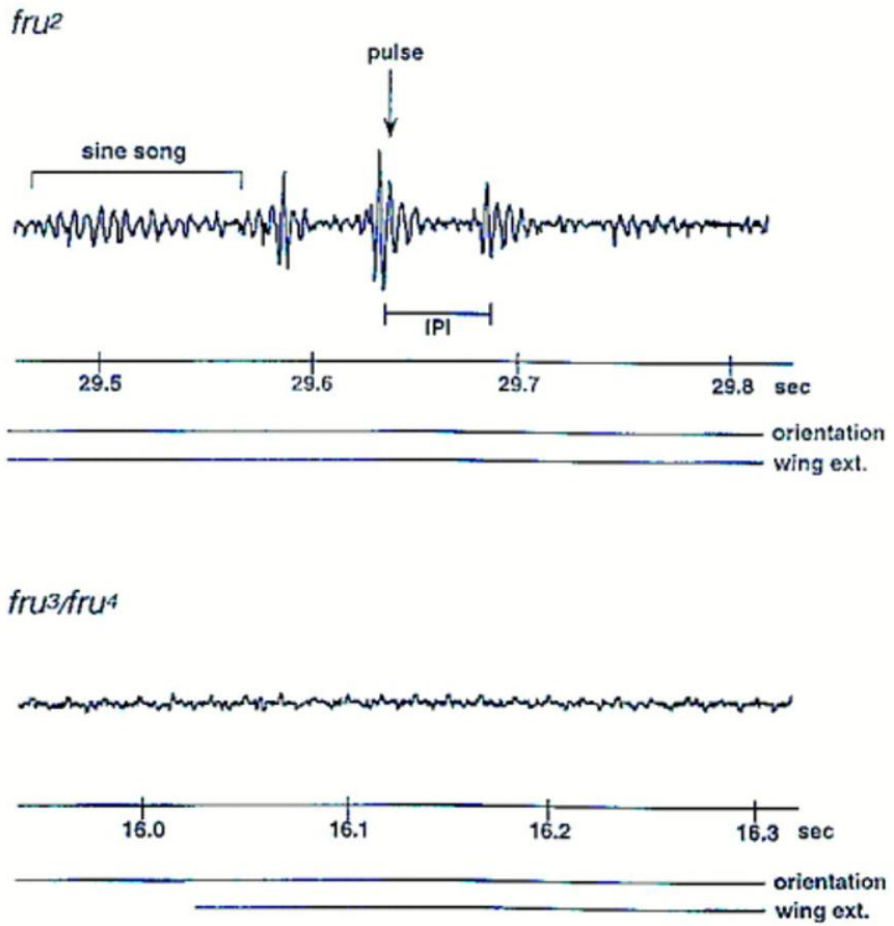
Gleason, J. M. 2005

The *Drosophila* sex hierarchy



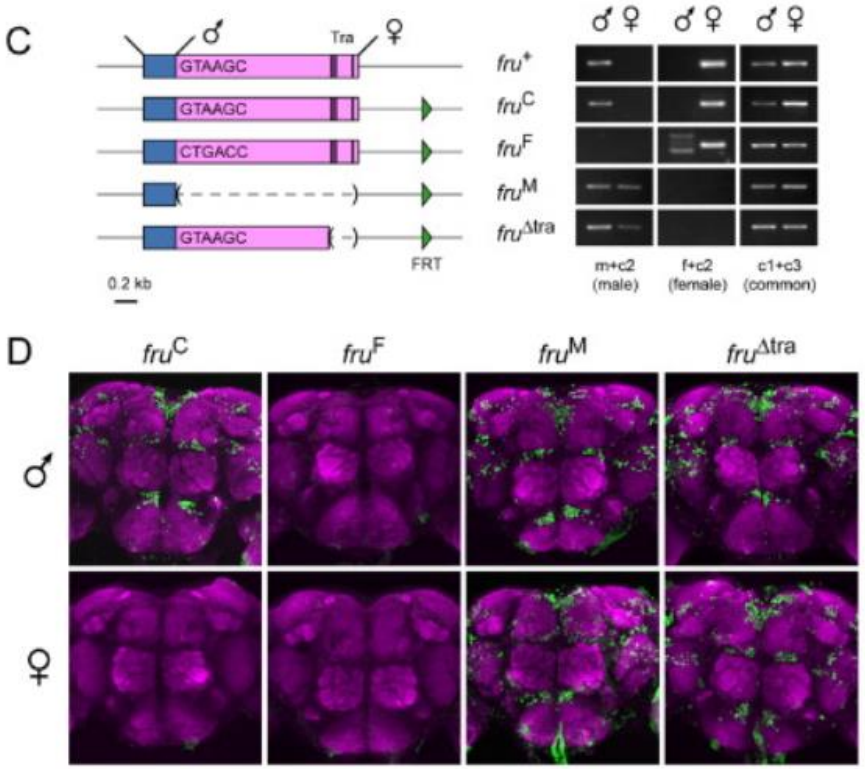
Robinett, C. C. et al. 2010

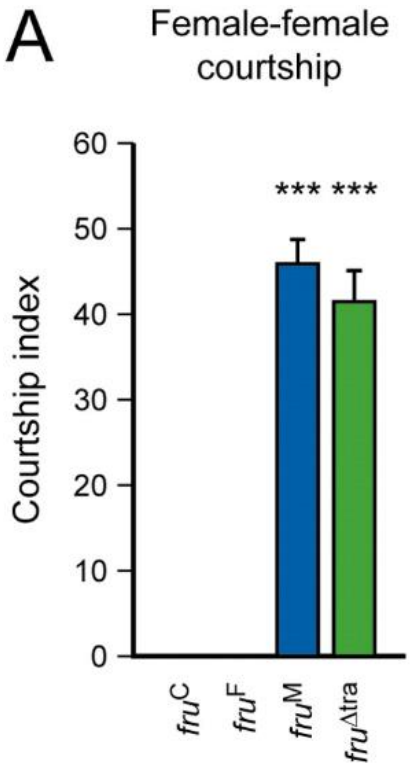
fru^M mutant males lack pulse song

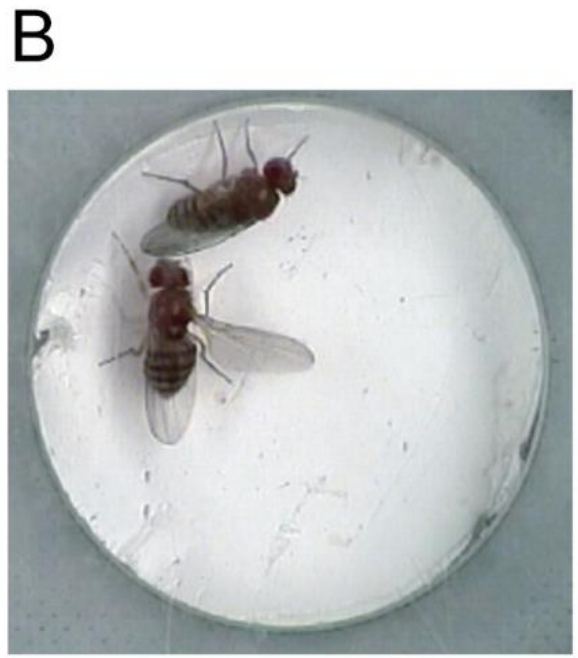


Ryner, L. C. et al. 1996

Male splicing of *fru* is sufficient for male courtship behavior







Demir, E. & B. J. Dickson 2005

Fru^M is not sufficient for courtship song

Table S1. Song Analysis of Wild-Type and Mutant Flies.

Genotype	n	WEI	SI	SBPM	PTPM	MPPT	IPI (ms)
Canton S (XY)	15	38.3 ± 2.8	87.9 ± 2.4	18.6 ± 2.2	19.9 ± 1.4	8.1 ± 0.3	31.7 ± 3
XY;;$fru^M/Df(3R)fru^{4\text{-}40}$	15	53.0 ± 2.9	90.3 ± 2.0	23.1 ± 1.9	28.5 ± 2.3	9.1 ± 0.3	32.0 ± 3
XY;;$fru^{\Delta tra}/Df(3R)fru^{4\text{-}40}$	18	54.6 ± 2.8	85.3 ± 2.2	20.6 ± 1.8	29.3 ± 1.8	9.6 ± 0.4	31.7 ± 4
XX;;$fru^M/Df(3R)fru^{4\text{-}40}$	16	37.6 ± 3.3	44.8 ± 4.7*	0*	7.1 ± 1.5*	3.0 ± 0.1*	26.5 ± 7*
XX;;$fru^{\Delta tra}/Df(3R)fru^{4\text{-}40}$	13	31.4 ± 2.9	60.1 ± 5.6*	0*	9.4 ± 1.4*	2.9 ± 0.1*	24.3 ± 5*
XX;;$tra^1/Df(3L)st\text{-}J7$	10	46.3 ± 4.5	89.7 ± 2.9	23.2 ± 1.8	19.2 ± 1.4	9.0 ± 0.2	33.0 ± 3
XY;;$In(3R)dsx^{23},fru^3/Df(3R)dsx^{15},fru^3$	11	0*	0*	N.D.	N.D.	N.D.	N.D.

WEI: wing extension index
SI: song index
SBPM: sine bouts per minute
PTPM: pulse trains per minute
MPPT: mean pulses per train
IPI: interpulse interval

Rideout, E. J. et al. 2007

dsx mutant males has abnormal courtship song

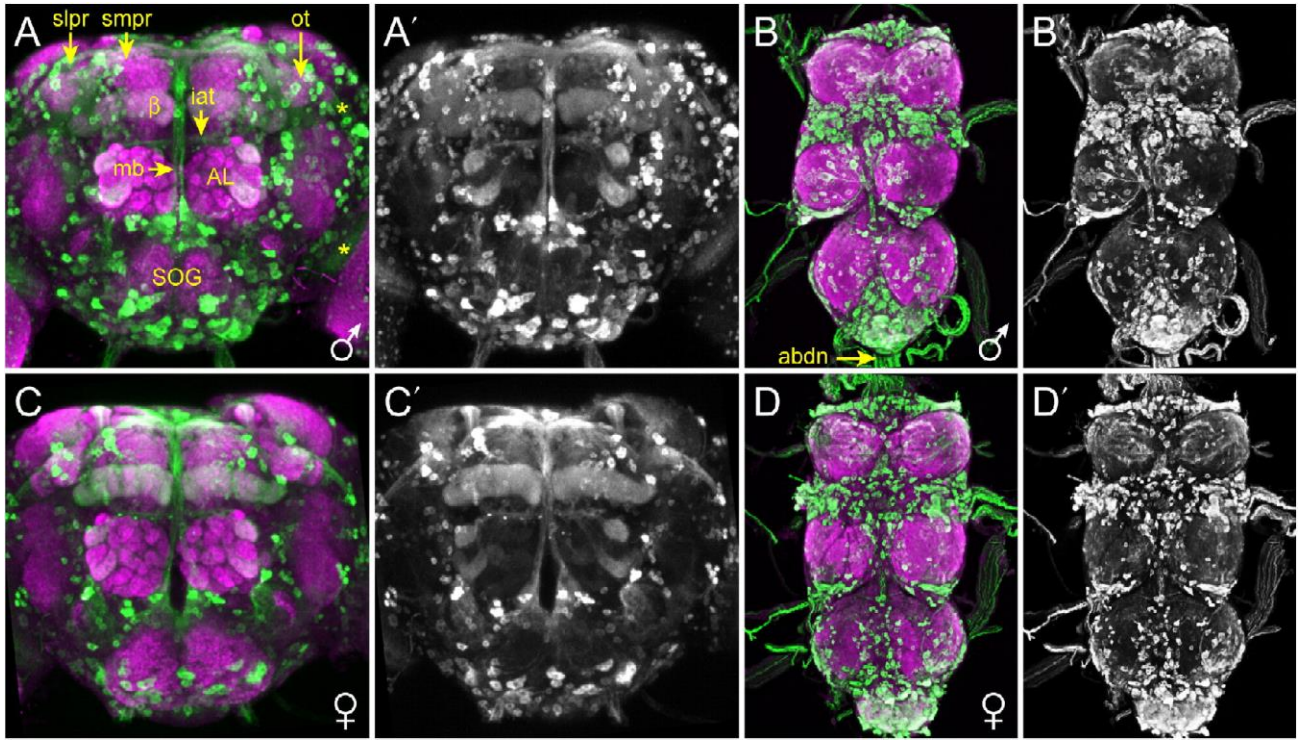
TABLE 1. Courtship Songs of *dsx*$^{-}$ Males*

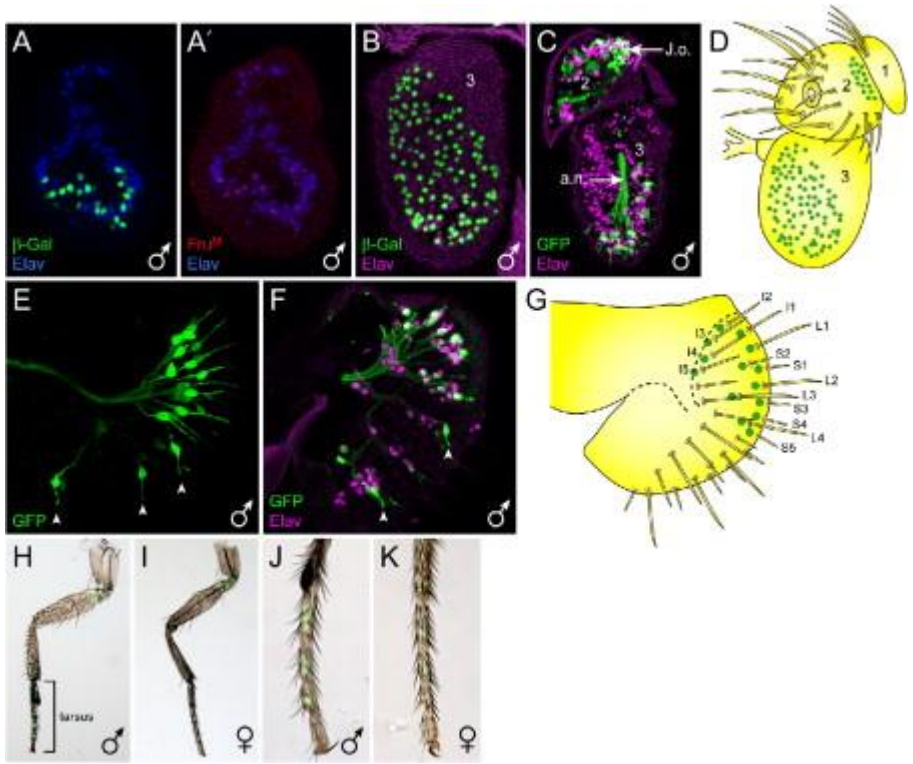
	dsx^{-} (n = 4)	Controls (n) (wild-type/ /B^{S})
Basic song performance		
Trains/min	10 ± 3	26 ± 3 (3)/ /14 ± 3 (4)
Pulses/min	138 ± 43	338 ± 20 (3)/ /210 ± 46 (4)
Train length (no. pulses)	11.8 ± 0.3	10.3 ± 0.3 (3)/ /11.6 ± 0.5 (4)
Song-pulse parameters		
Interpulse interval (ms)	38 ± 1	35 ± 1 (5)[a]
Cycles/pulse	2.48 ± 0.5	3.13 ± 0.4 (13)[b]
Intrapulse frequency(Hz)	223 ± 8	222 ± 13 (5)[a]
No. FFT peaks	1.6 ± 0.2	1.1 ± 0.0 (6)[c]
FFT peak width (Hz)	121 ± 12	174 ± 6 (13)[b]

Taylor, B. J. et al. 1994

Neuronal control of courtship song

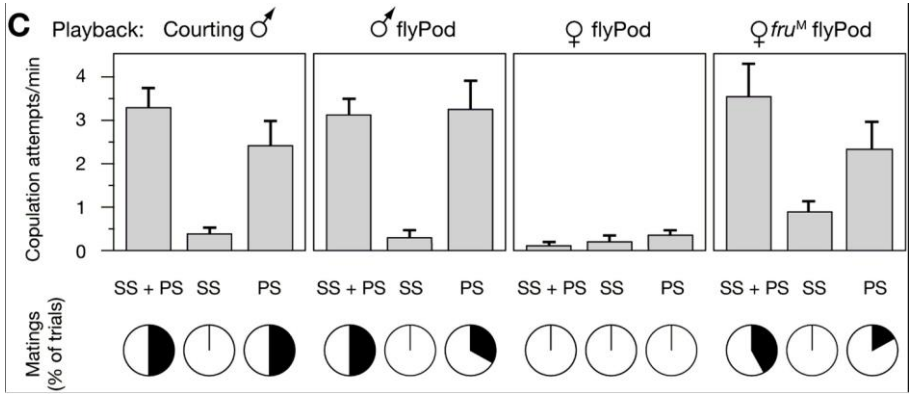
fruGAL4 projections in the CNS and PNS

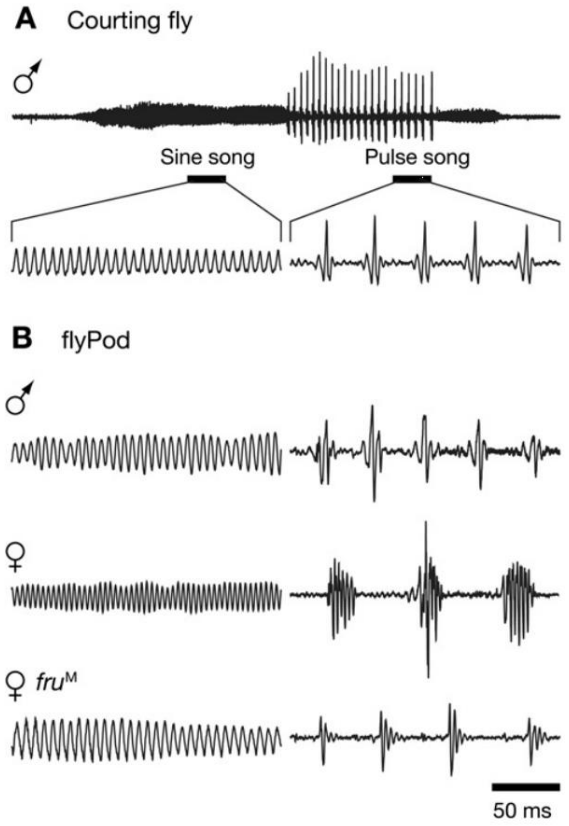


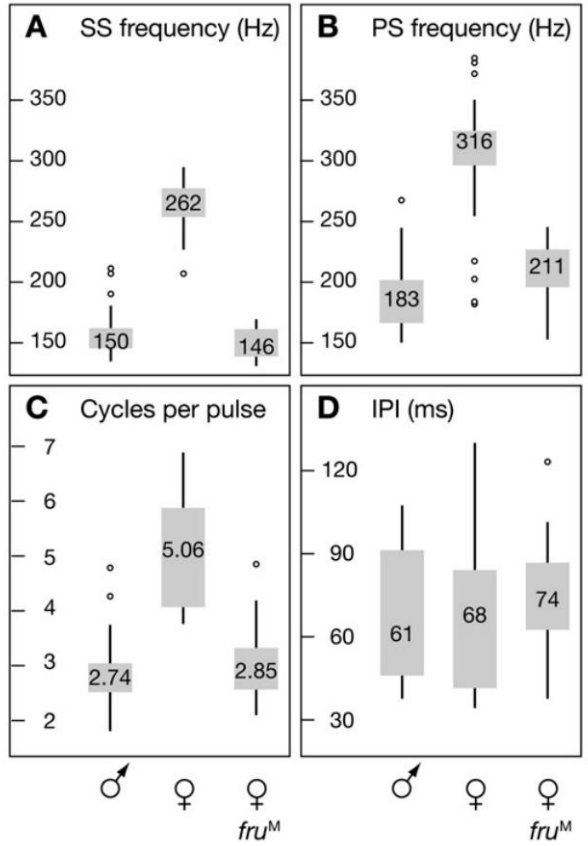


Stockinger, P. et al. 2005

The light-activation of *fru* neurons in beheaded flies generate courtship song

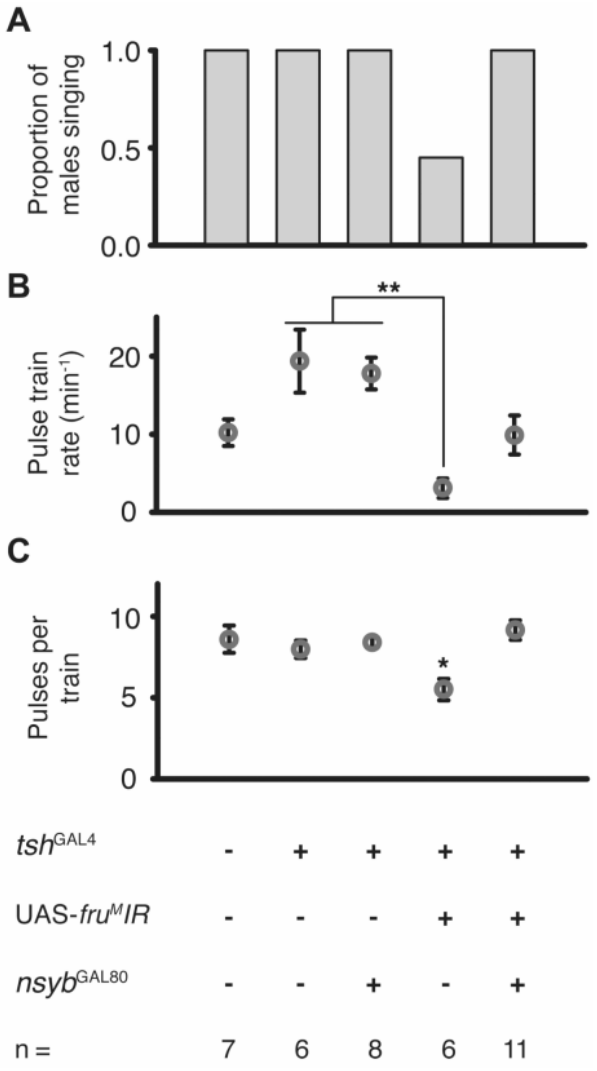






Clyne, J. D. & G. Miesenbock 2008

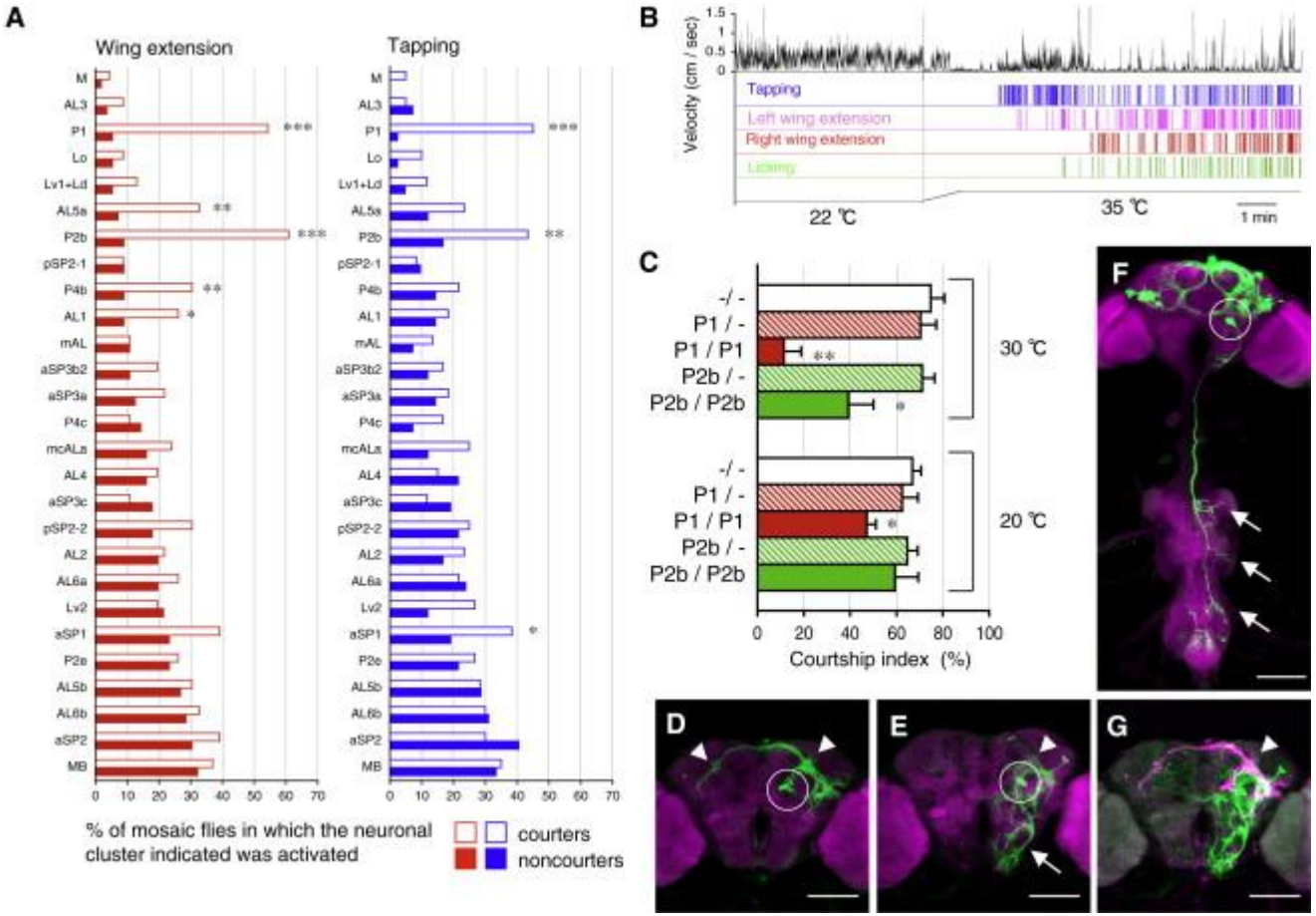
Expression of fru^{M}IR in tsh-specific pattern reduces amount of courtship song



Rubinstein, C. D. , P. K. Rivlin and R. R. Hoy 2010

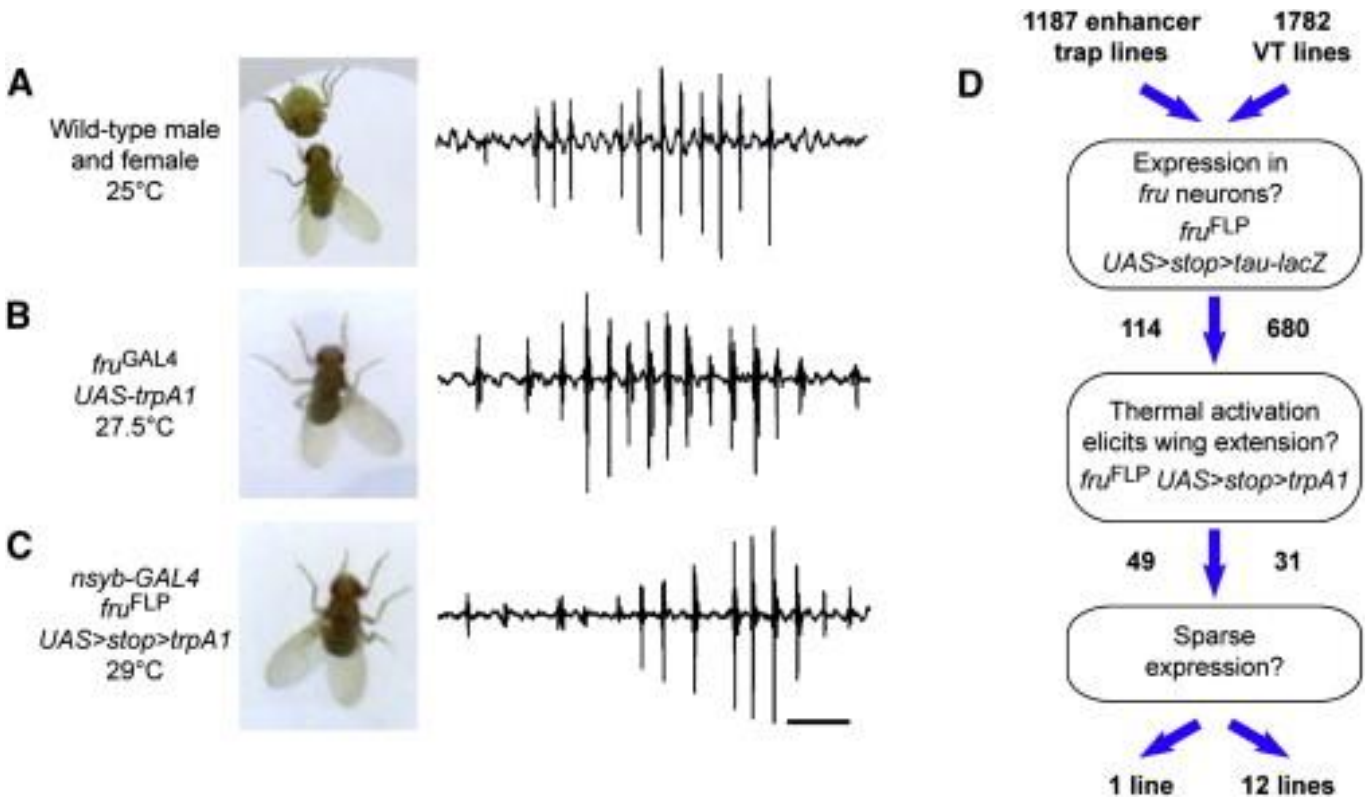
Identification of neurons, the activation of which is correlated with the generation of courtship

y hs-flp; FRTG13 tub-Gal80/FRTG13 UAS-mCD8::GFP; fru^{NP21}/UAS-dTrpA1



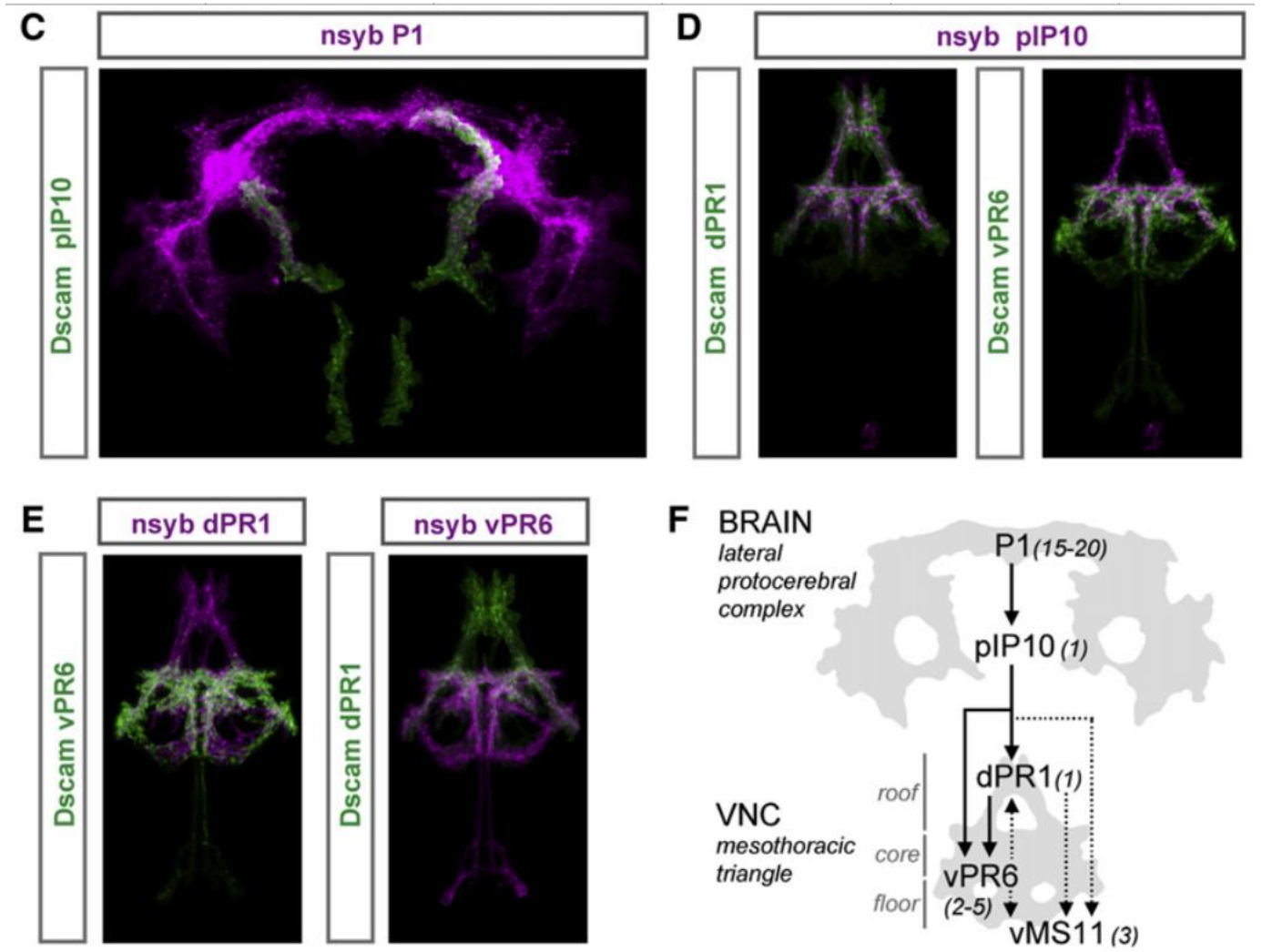
Kohatsu, S., M. Koganezawa and D. Yamamoto 2011

Thermal activation of fru neurons with TrpA1 evokes courtship song



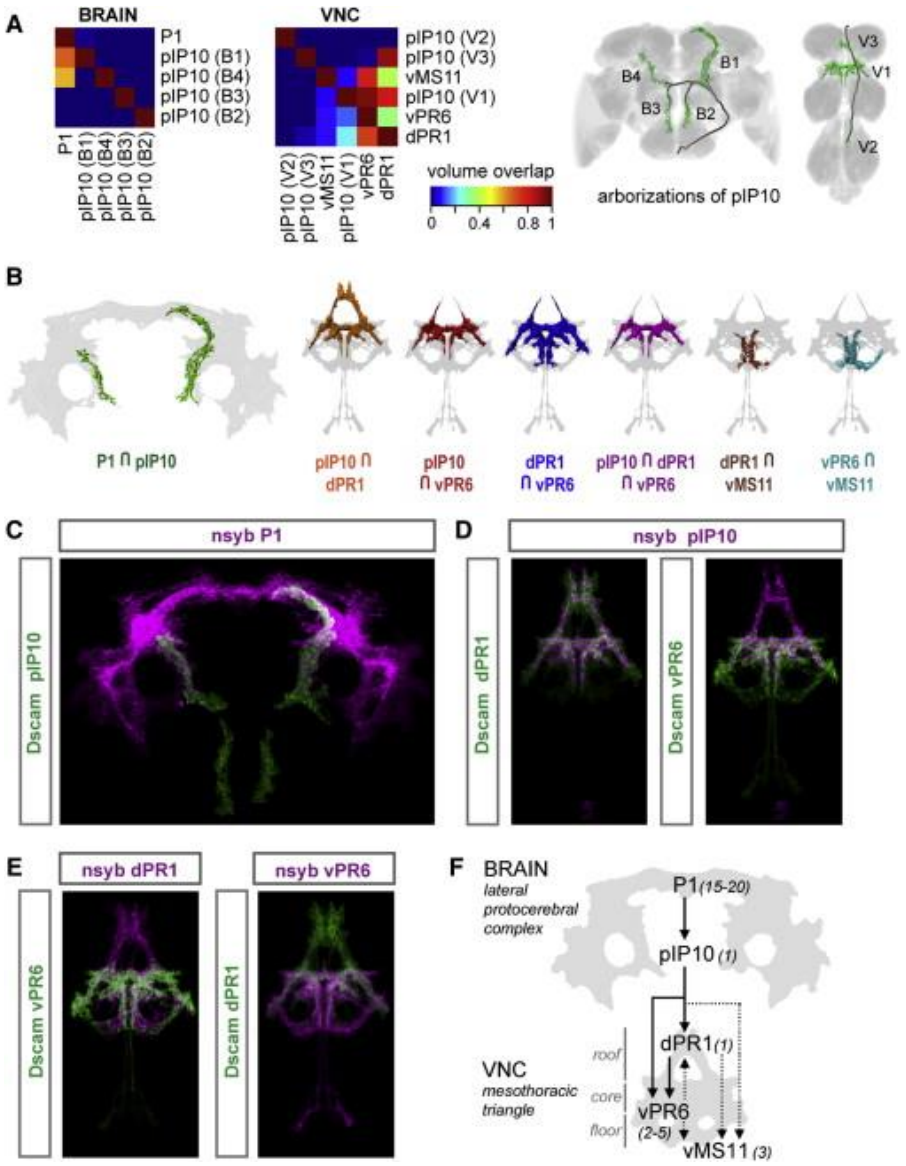
von Philipsborn, A. C. et al. 2011

Neuronal control of *Drosophila* courtship song



von Philipsborn, A. C. et al. 2011

A putative neuronal circuit for pulse song



Triggers Pulse Song

A Descending Command Neuron for Pulse Song

A Prothoracic Song Neuron

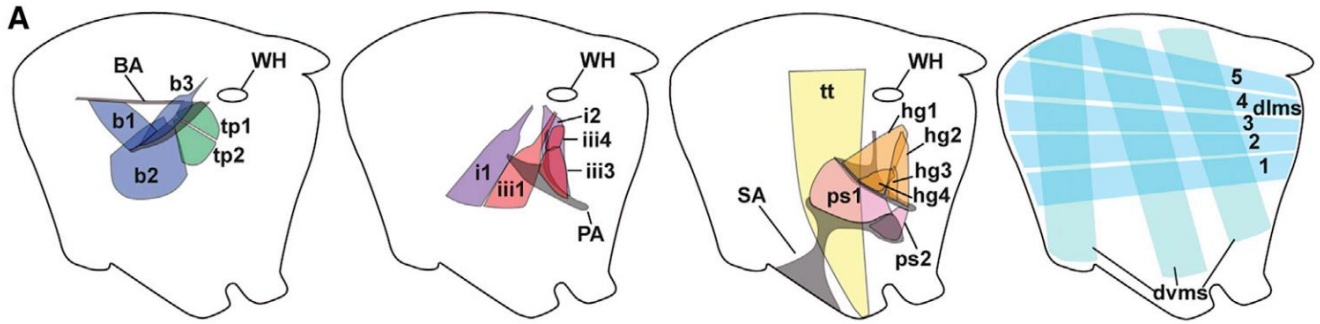
A Thoracic Neuron that Influences the IPI

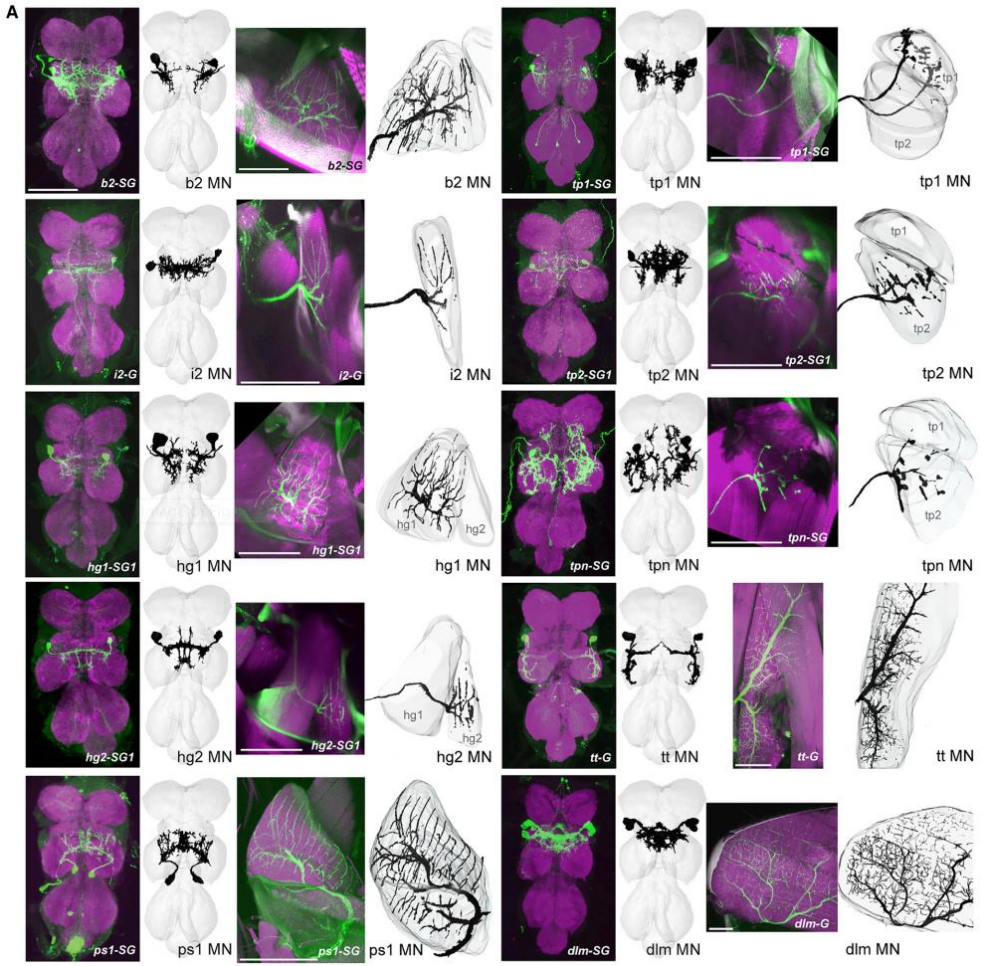
A Mesothoracic Neuron that Controls Wing Extension

von Philipsborn, A. C. et al. 2011

Motor control of courtship song

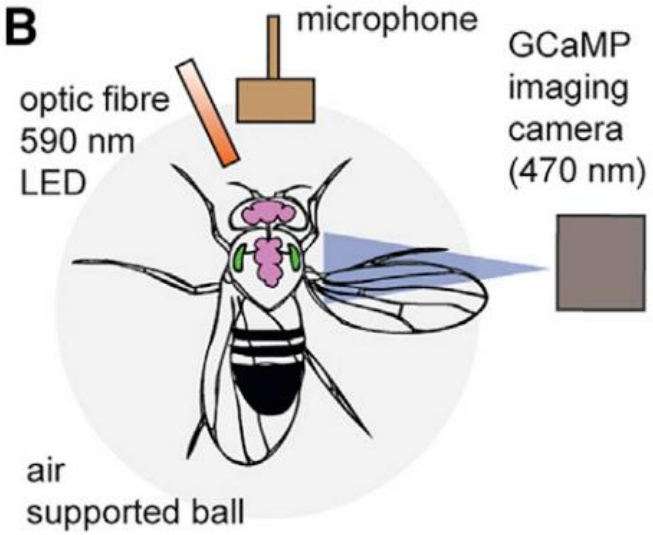
An Anatomical Map of Motor Neurons Innervating Wing Muscles

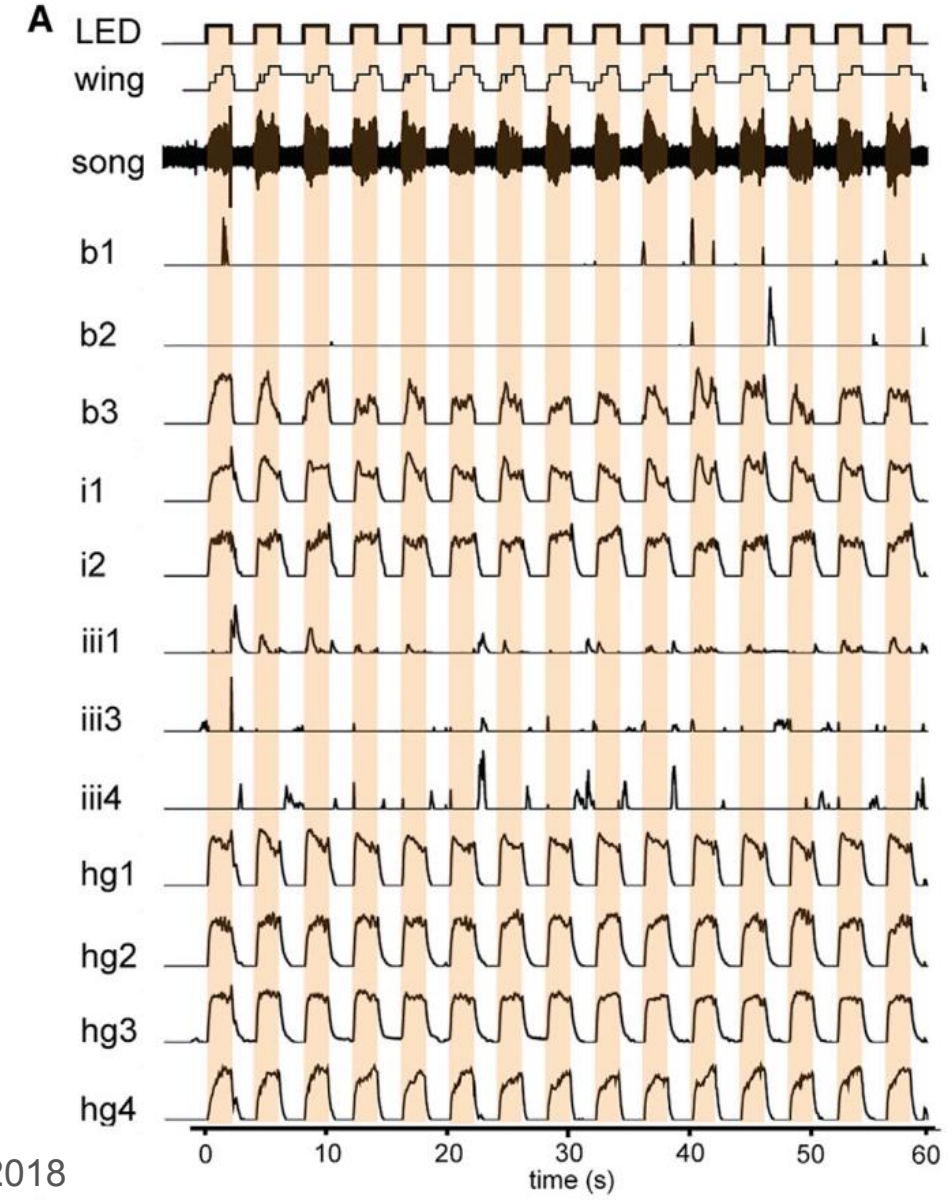




O'Sullivan, A. et al. 2018

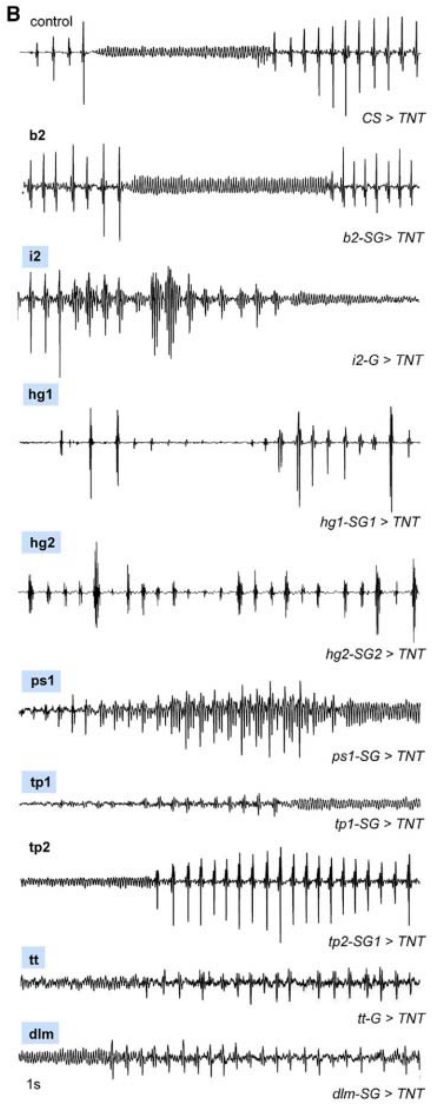
Imaging the motor neurons while singing induced by optogenetic activation of P1P10

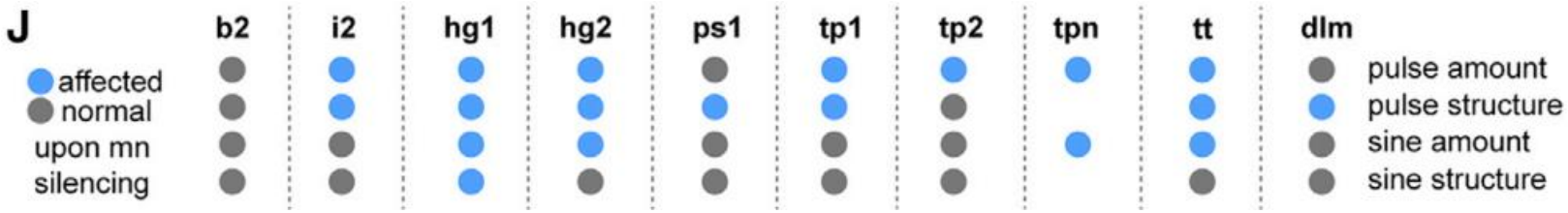




O'Sullivan, A. et al. 2018

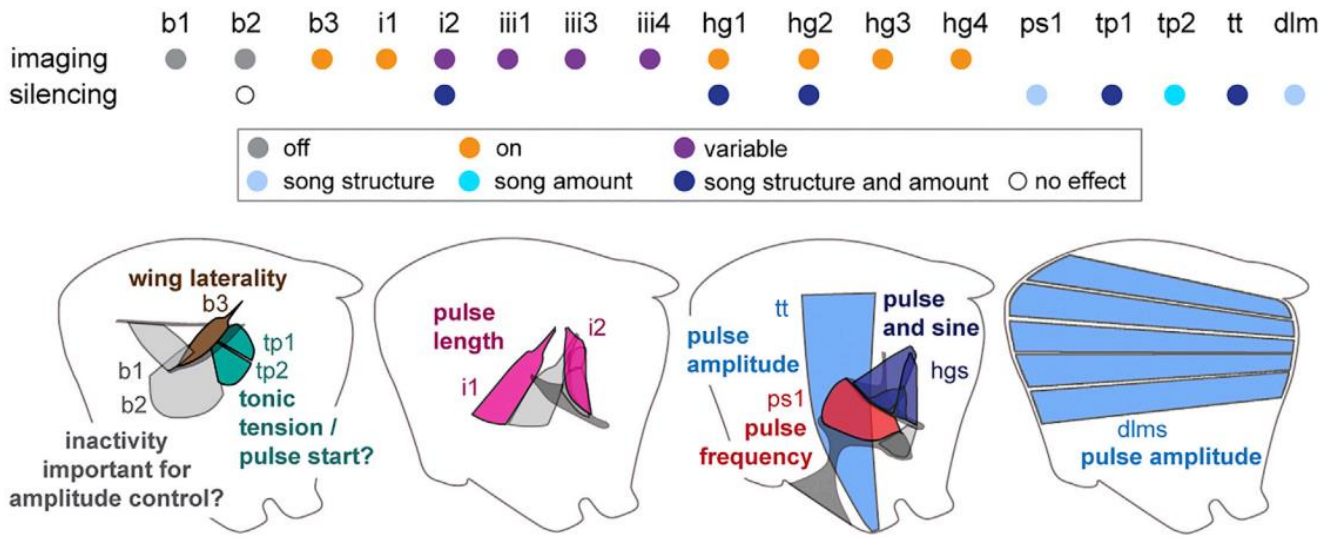
Wing motor neurons differentially pattern courtship song





O'Sullivan, A. et al. 2018

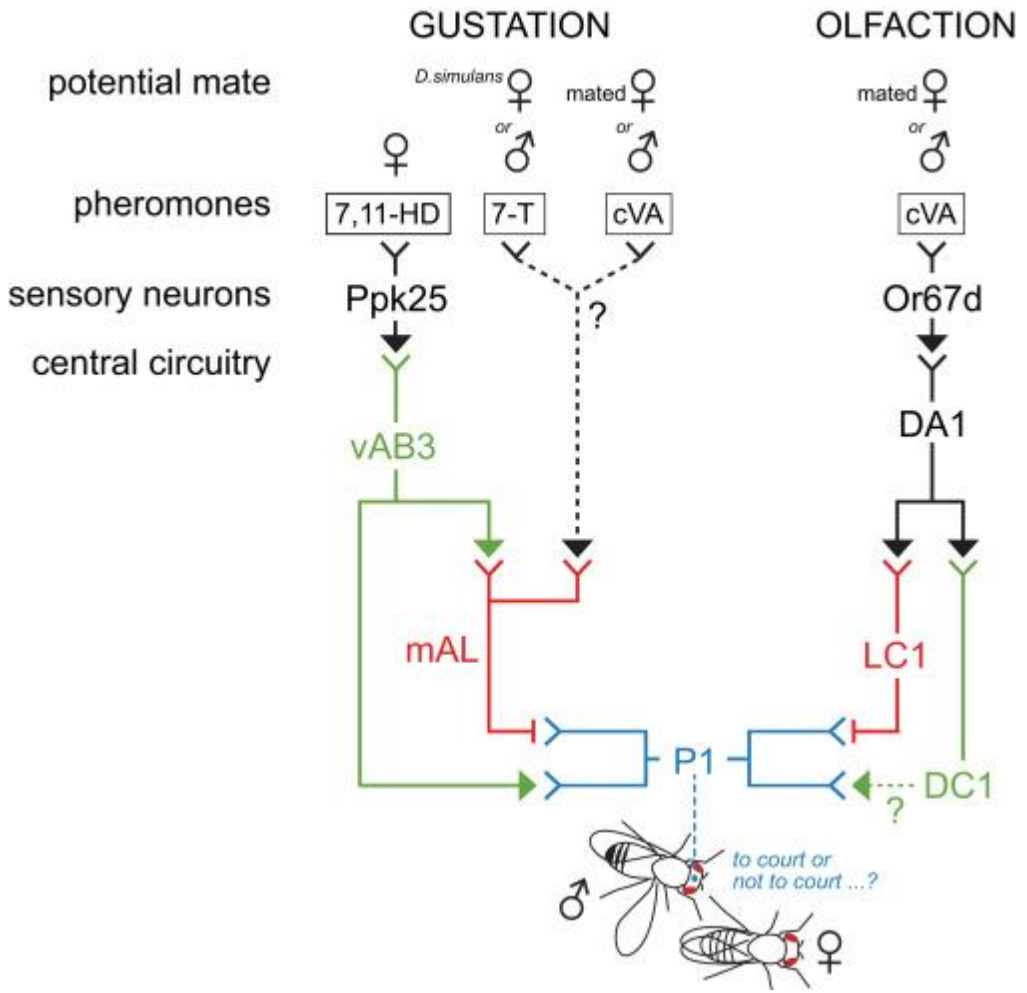
Modes of wing motor control for song



O'Sullivan, A. et al. 2018

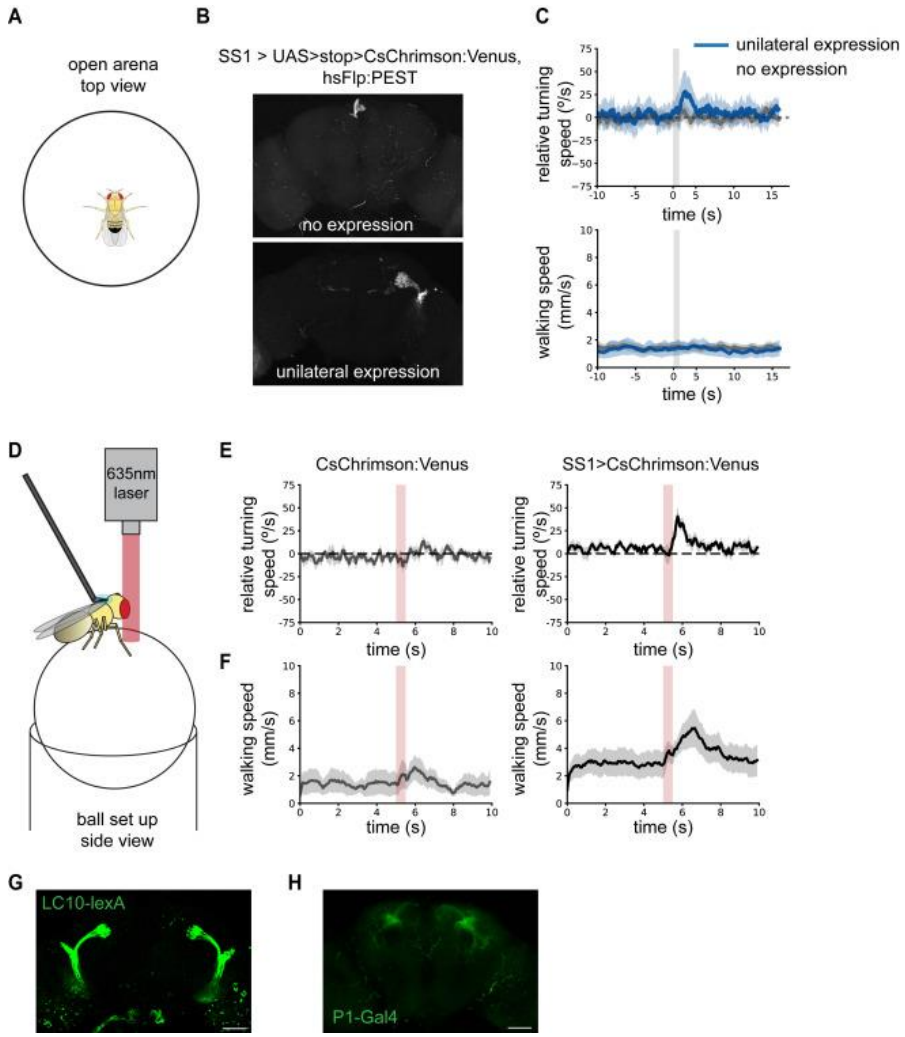
Sensory modulation of courtship song

the gustatory and olfactory pathways in male *Drosophila melanogaster* controlling the decision to court



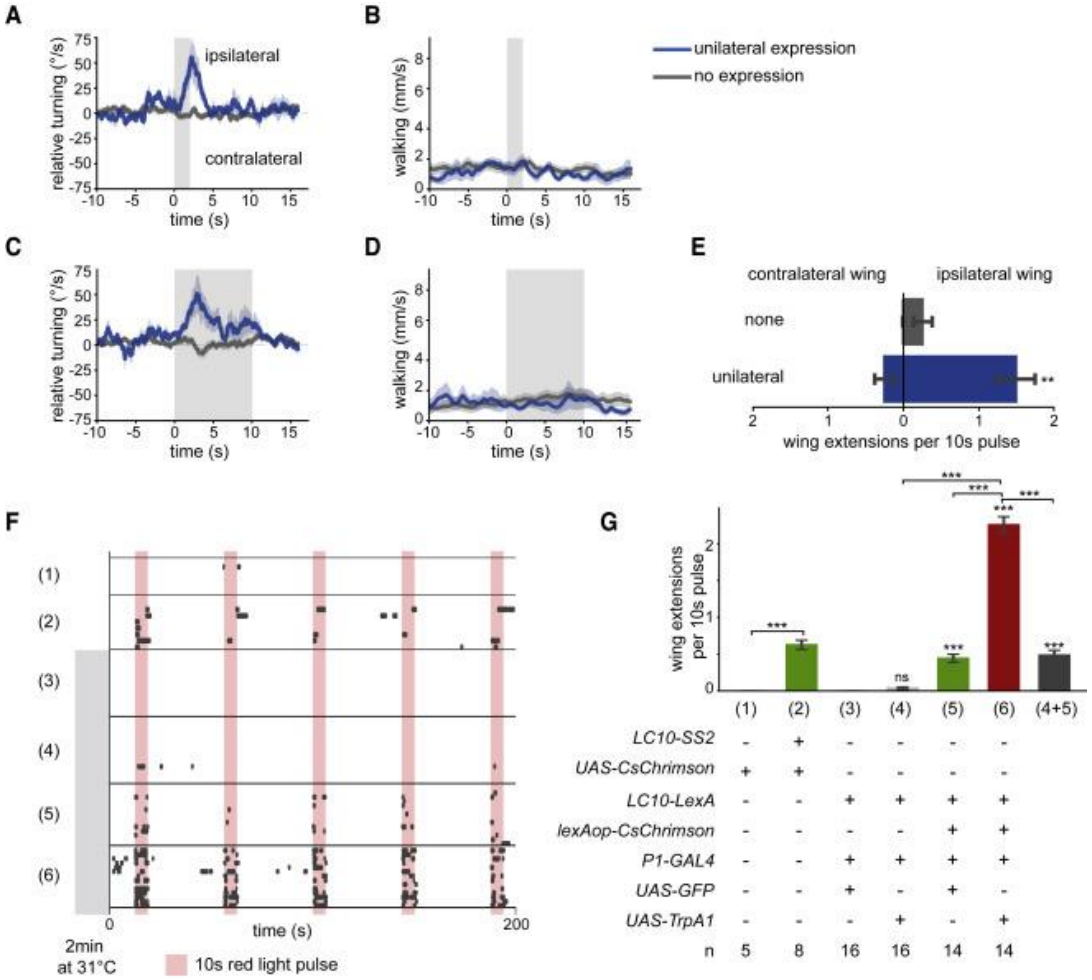
Benton, R. 2015

Unilateral activation of LC10 elicits ipsilateral turning



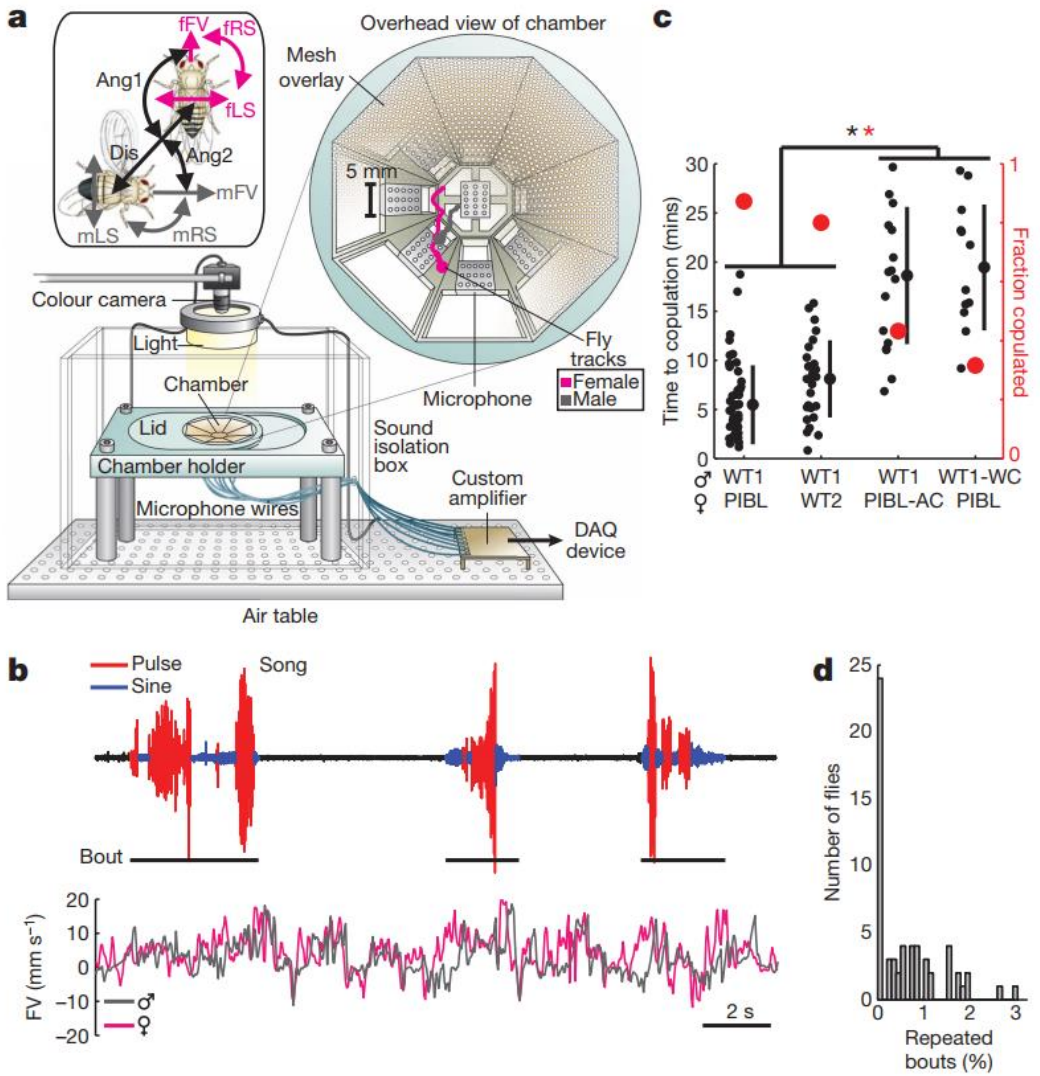
Ribeiro, I. M. A. et al. 2018

LC10 activation elicits ipsilateral turning and short wing extensions that are potentiated by pre-activation of P1 neurons



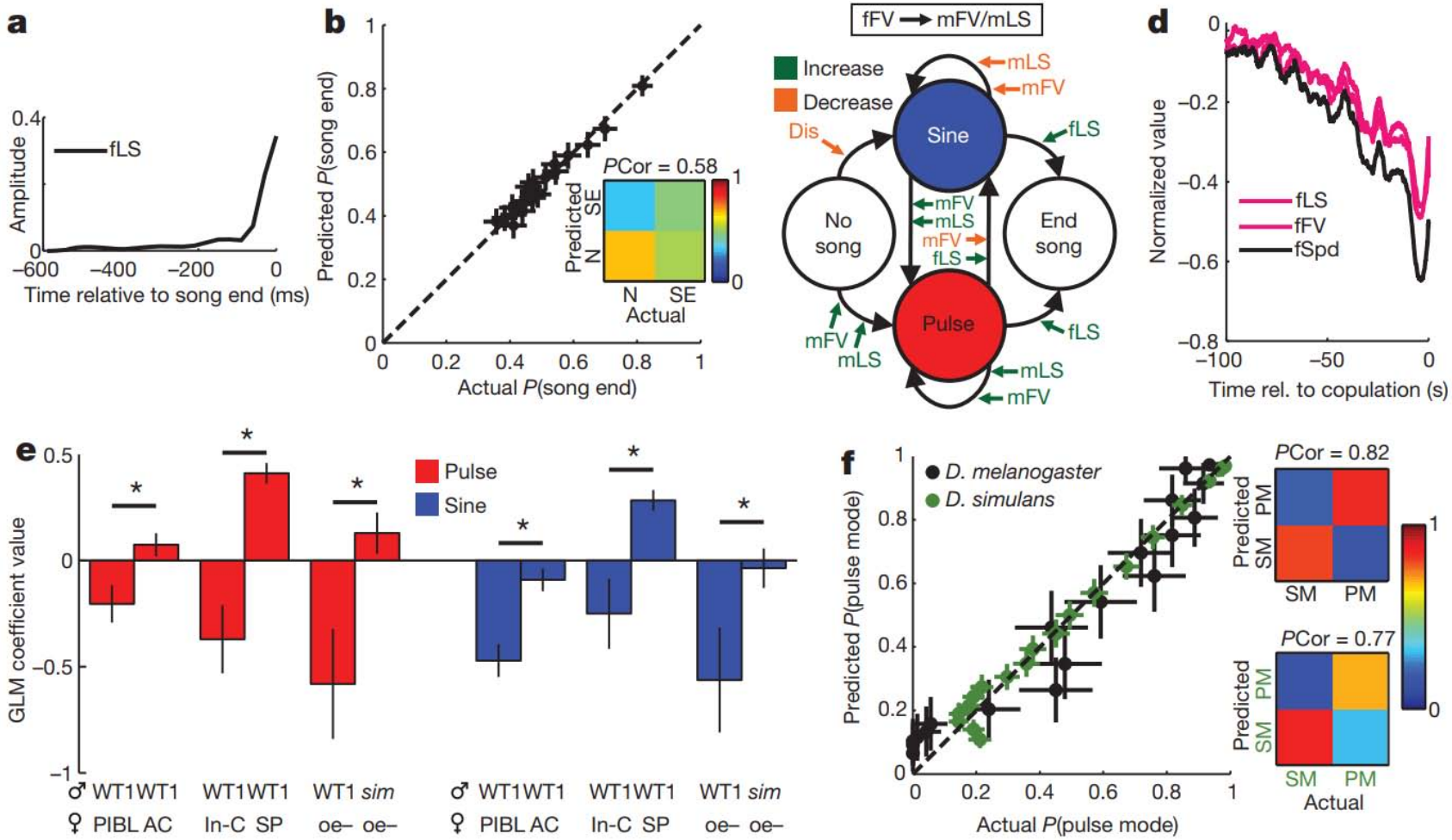
Ribeiro, I. M. A. et al. 2018

A novel assay to study *Drosophila* song behavior



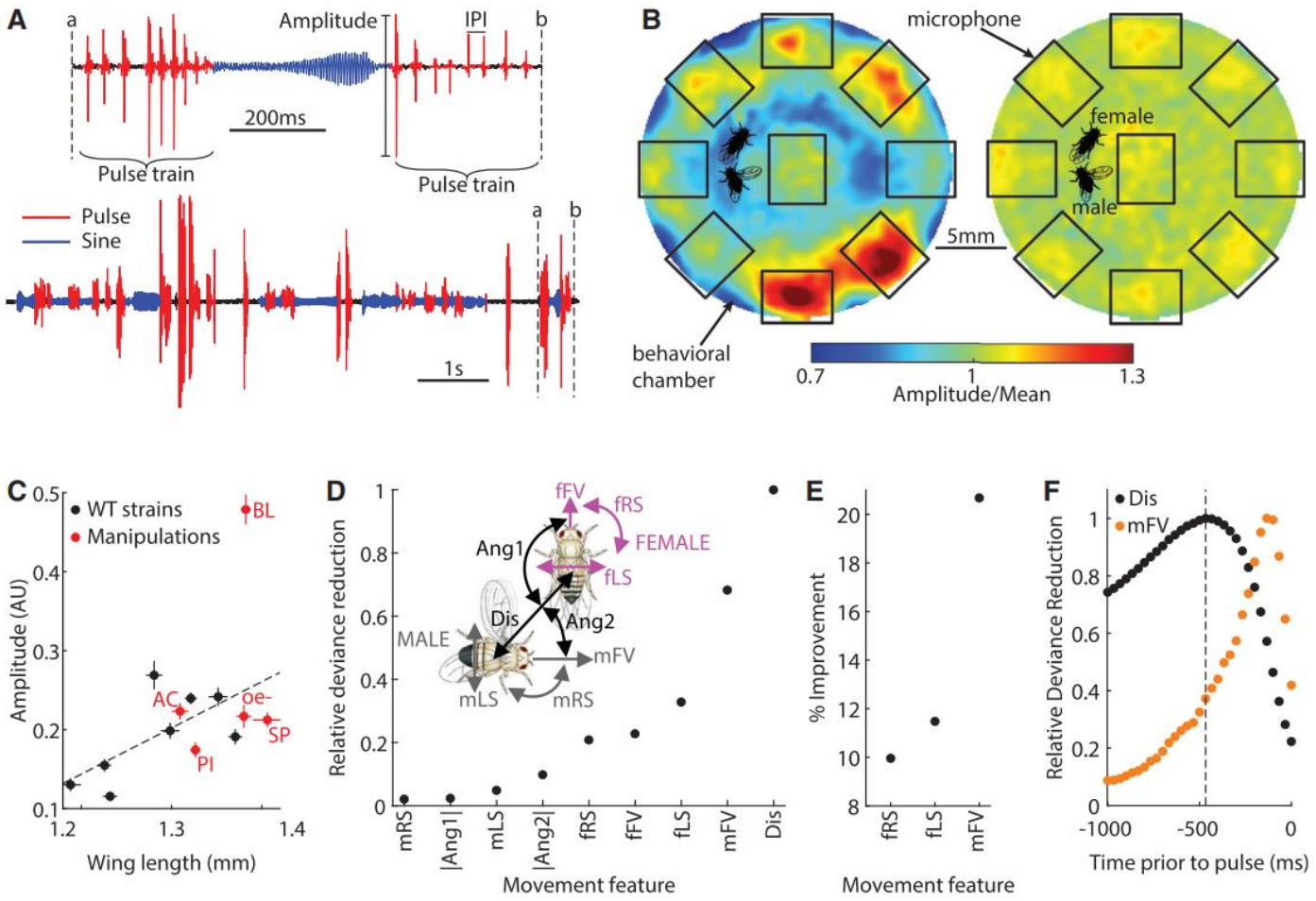
Coen, P. et al. 2014

Song patterning decisions and female responses



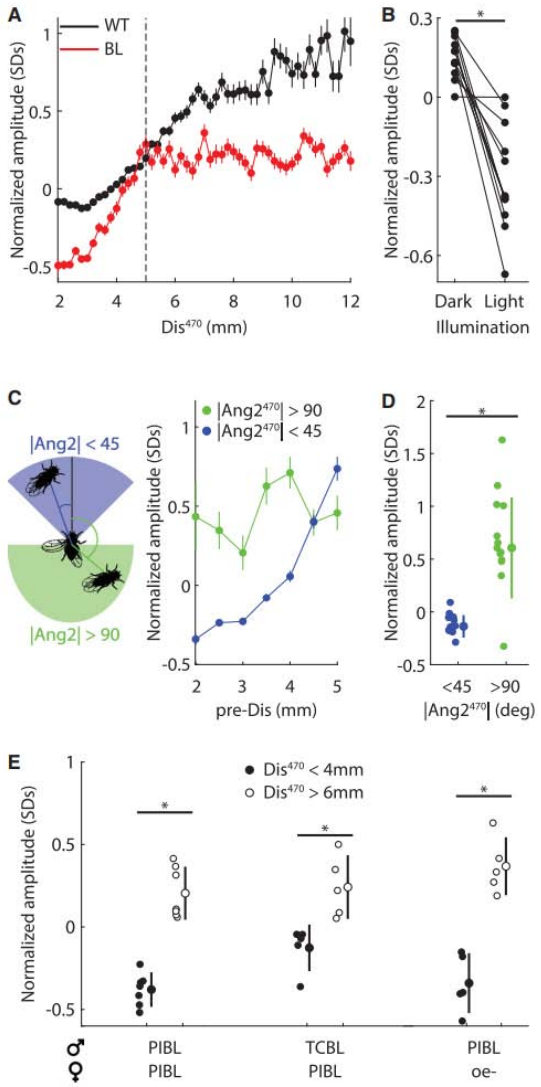
Coen, P. et al. 2014

Song amplitude modulation with distance in Drosophila



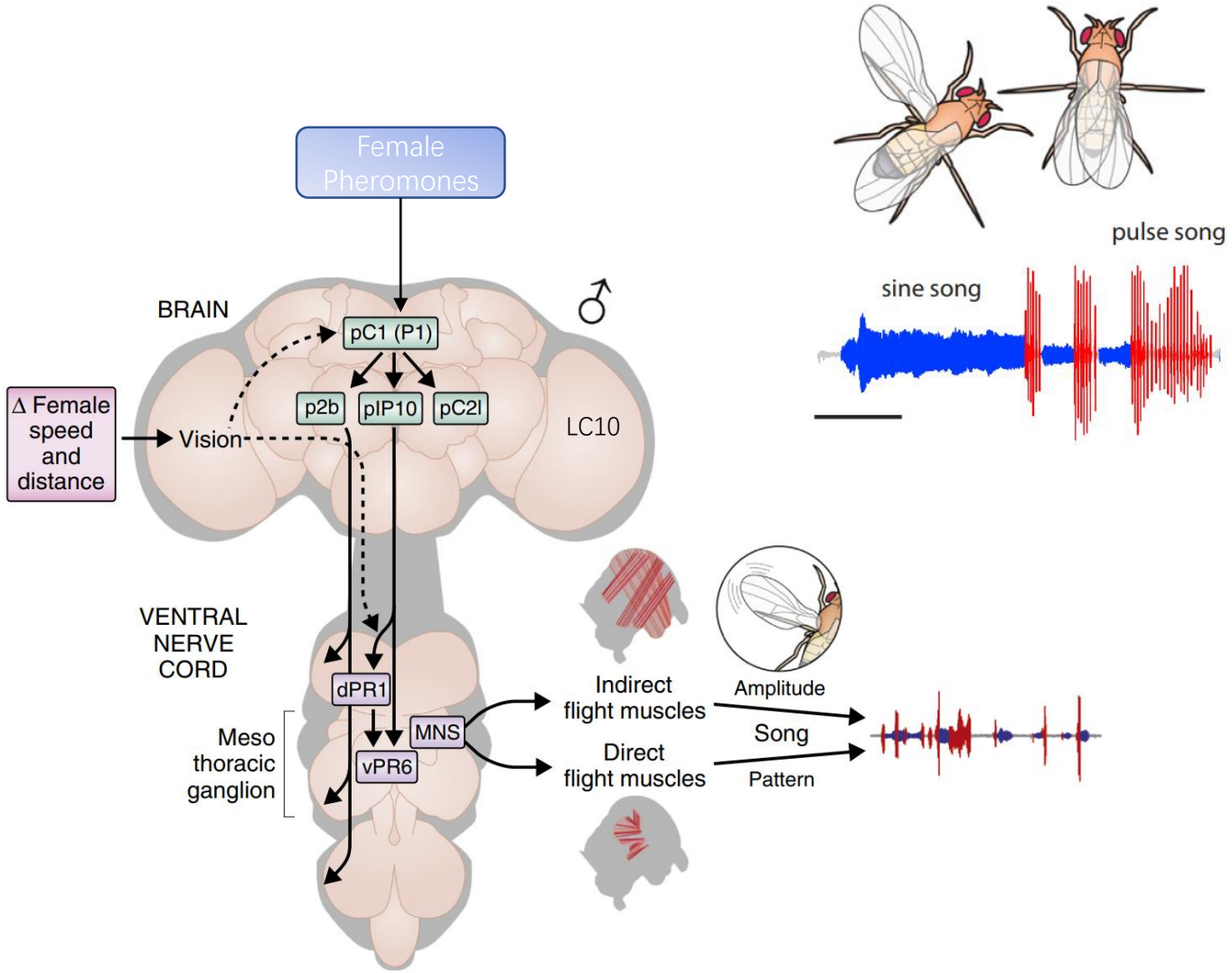
Coen, P. et al. 2016

The role of vision in AMD

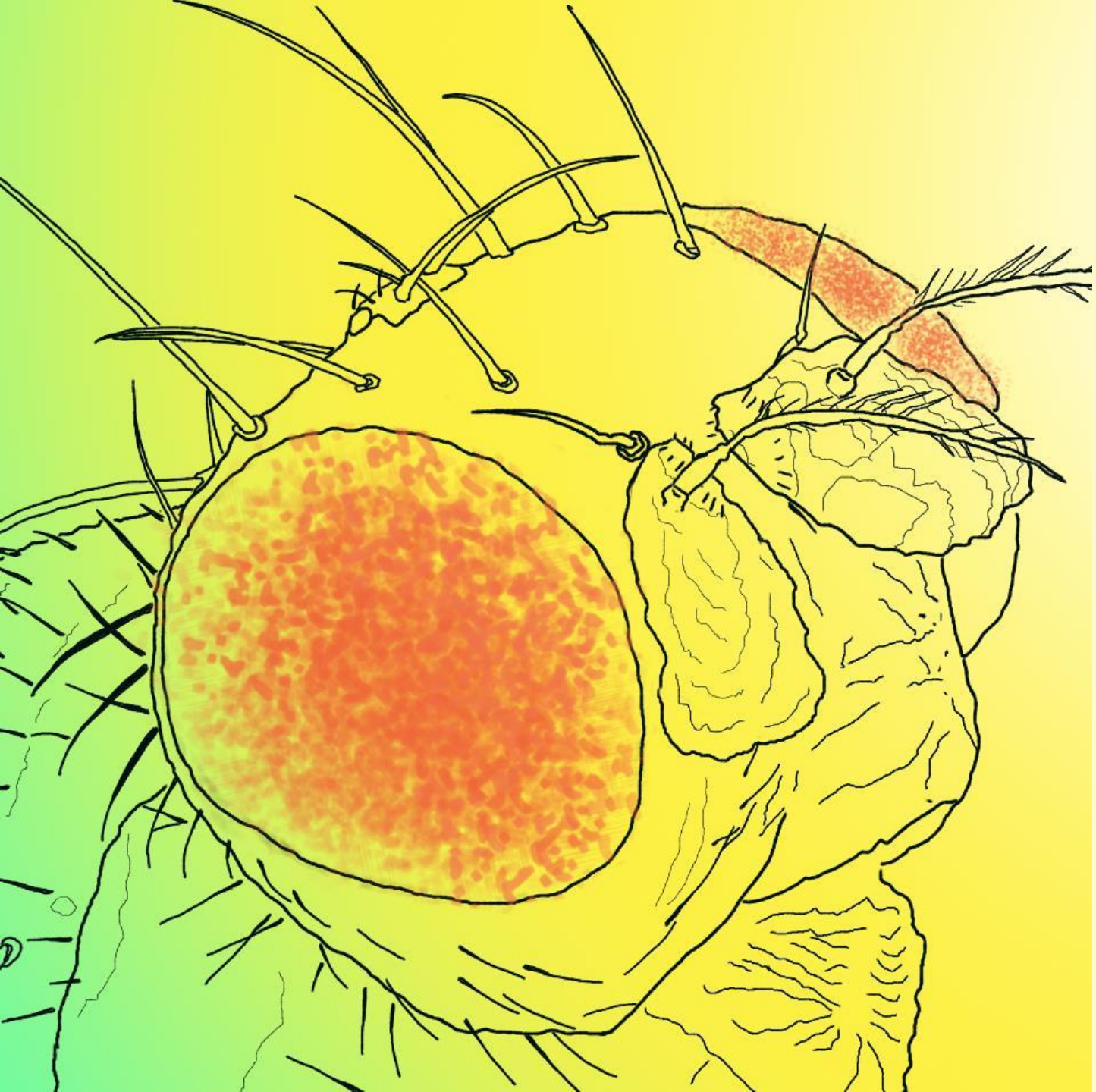


Coen, P. et al. 2016

Conclusion



Adapted from Coen, P. et al. 2016



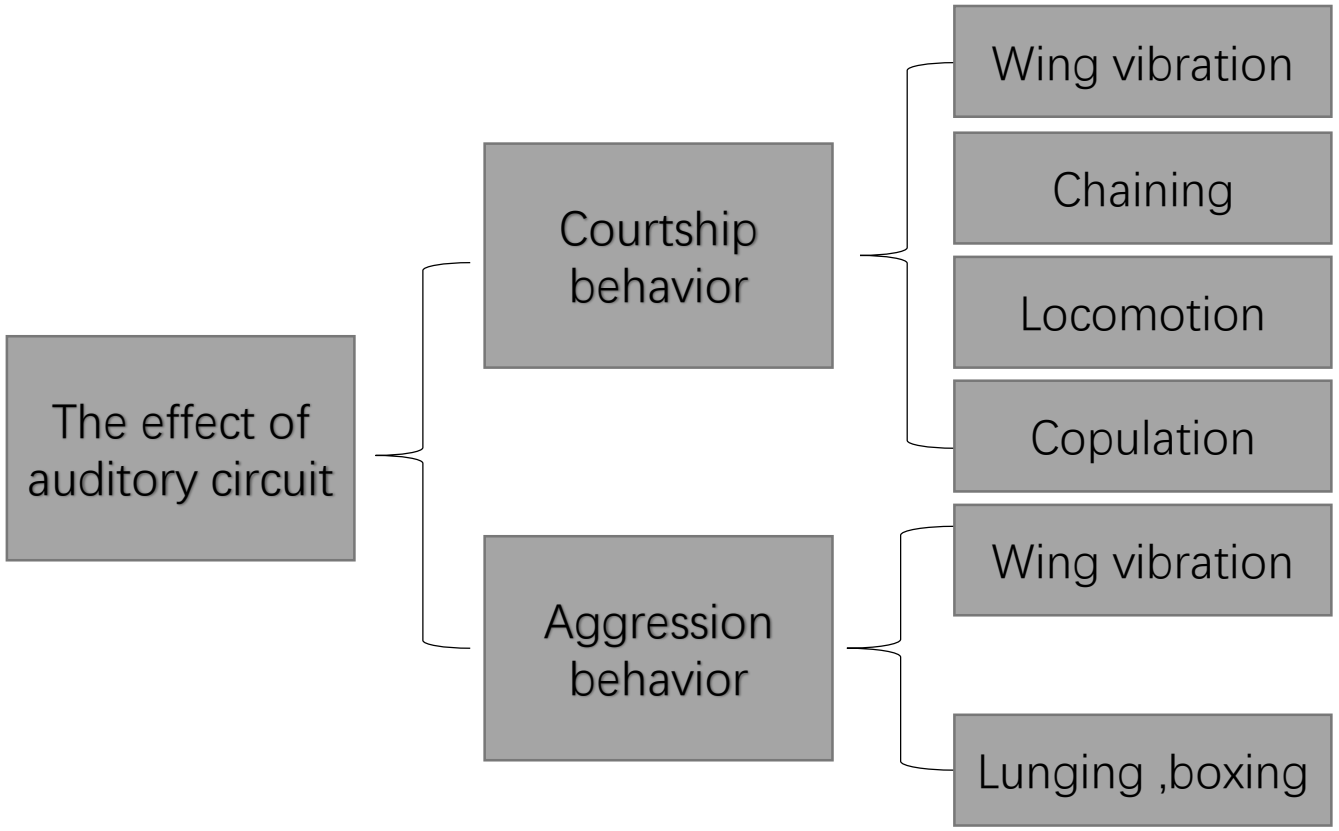
Welcome to part III

Pan Lab
Journal Club

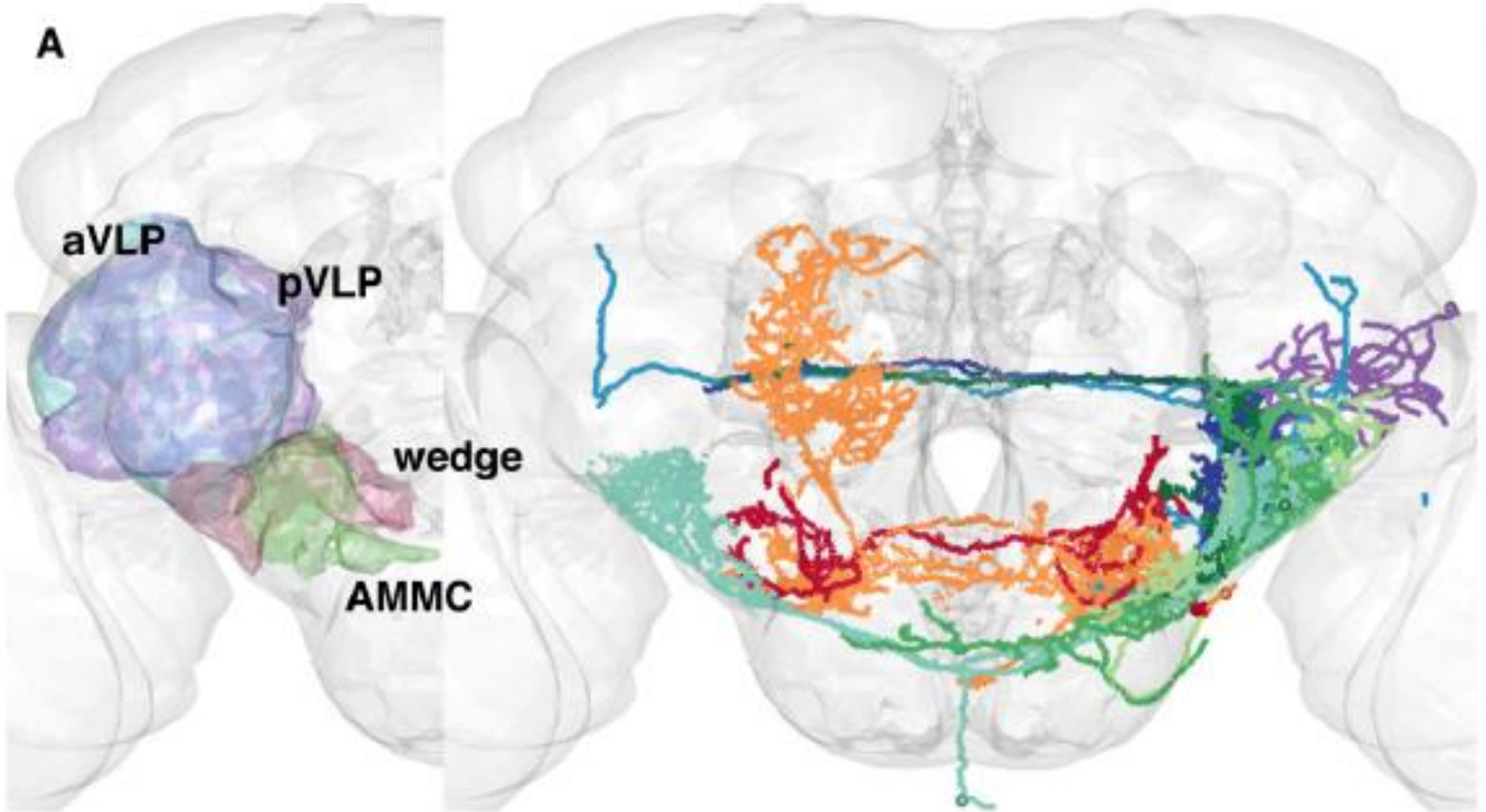
The effect of auditory system on courtship behavior & other behaviors

Jia Yi Cong
賈藝聰

Outline

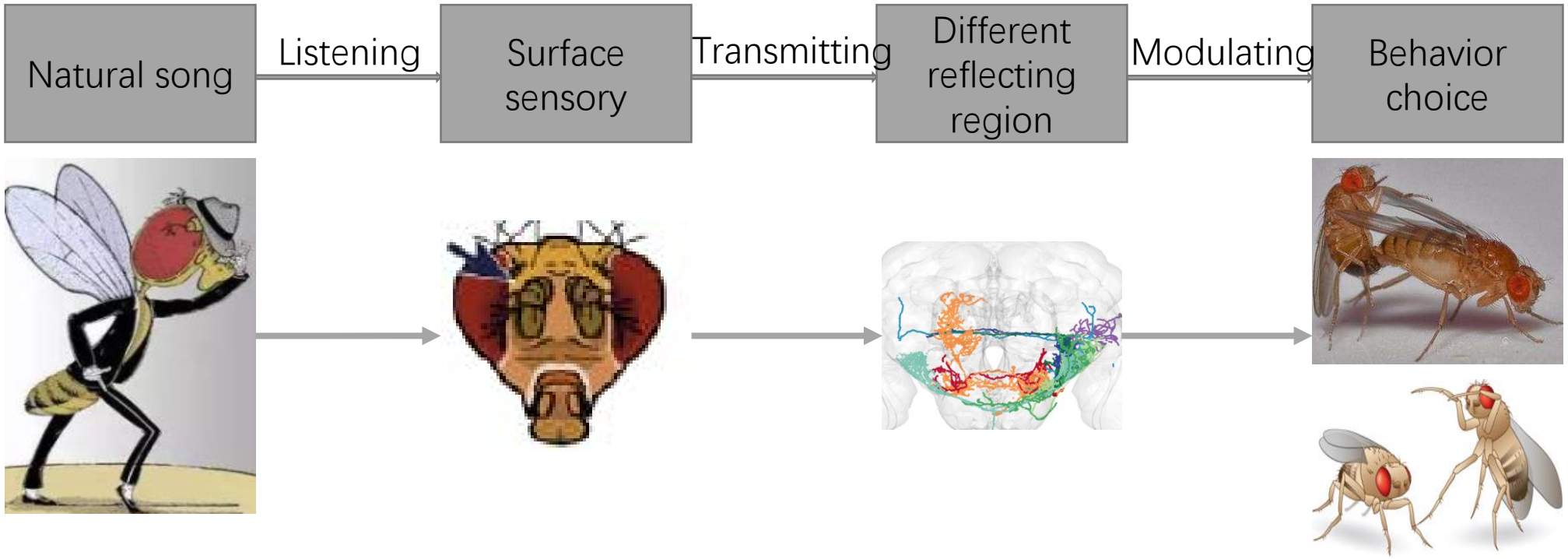

The effect of auditory circuit
Courtship behavior
Wing vibration
Chaining
Locomotion
Copulation
Aggression behavior
Wing vibration
Lunging ,boxing

The auditory reflex region in brain



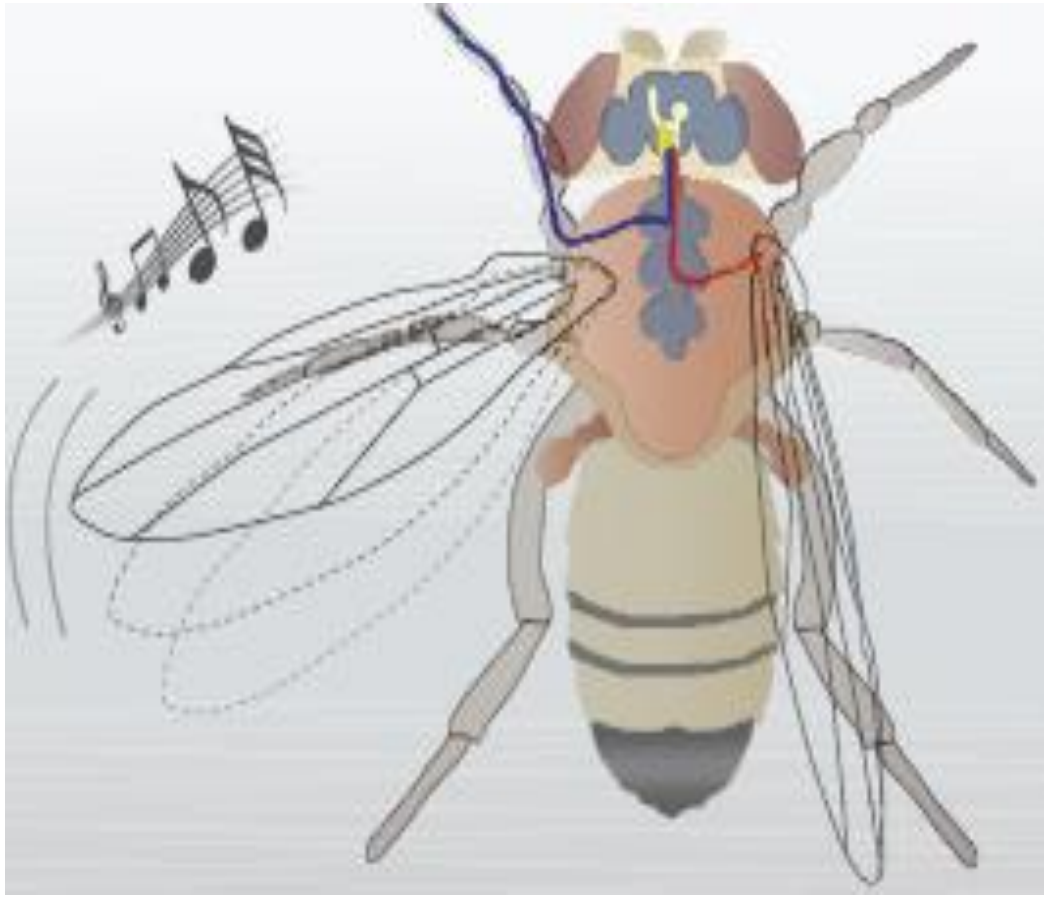
Jan Clemens et al. Neuron. 2015

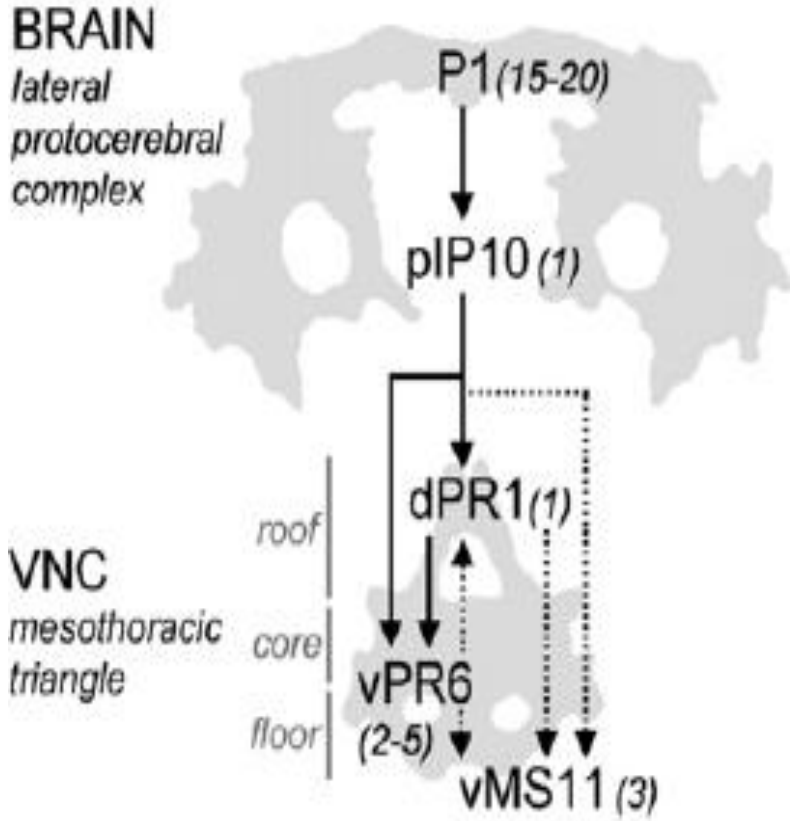
The model of song response



The effect of auditory system in courtship behavior

Pheromone input received at the foreleg in the courting male shapes courtship song pattern

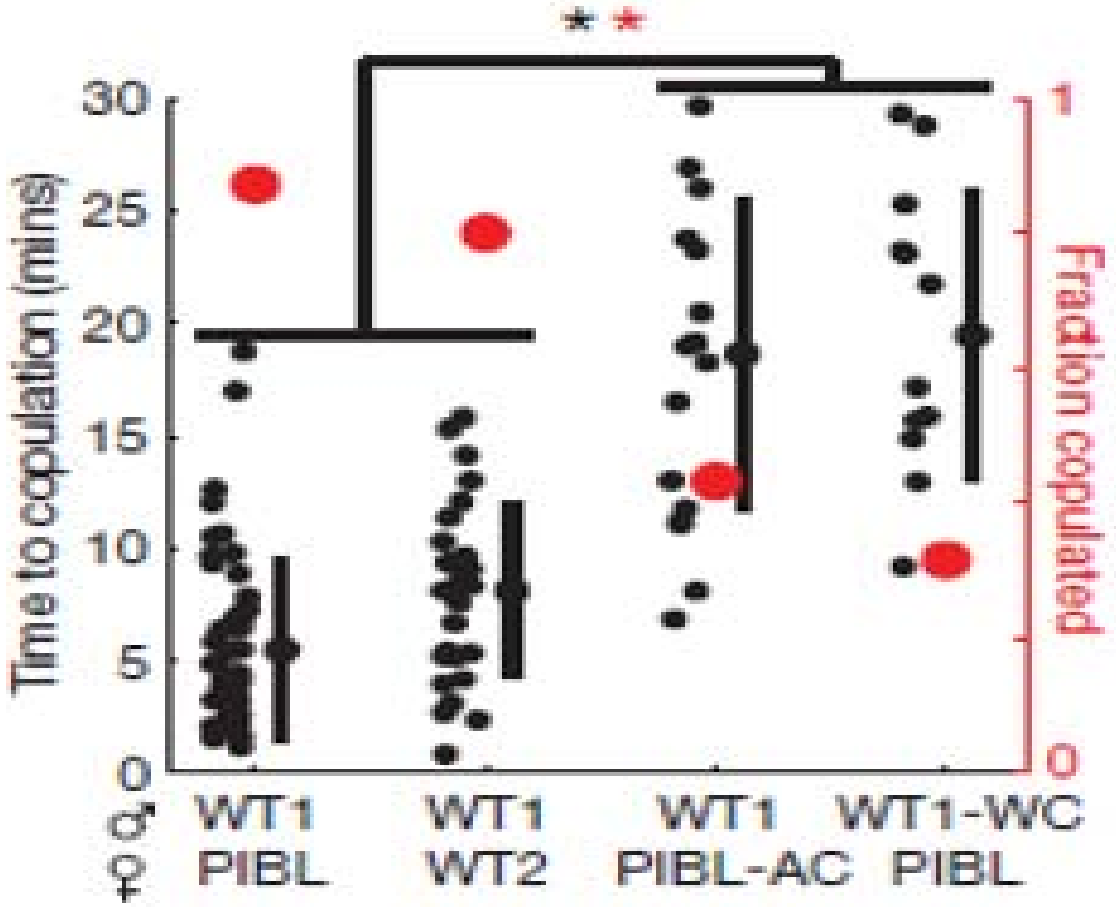




Kyung-An Han and Young-Cho Kim. Current Biology.2009

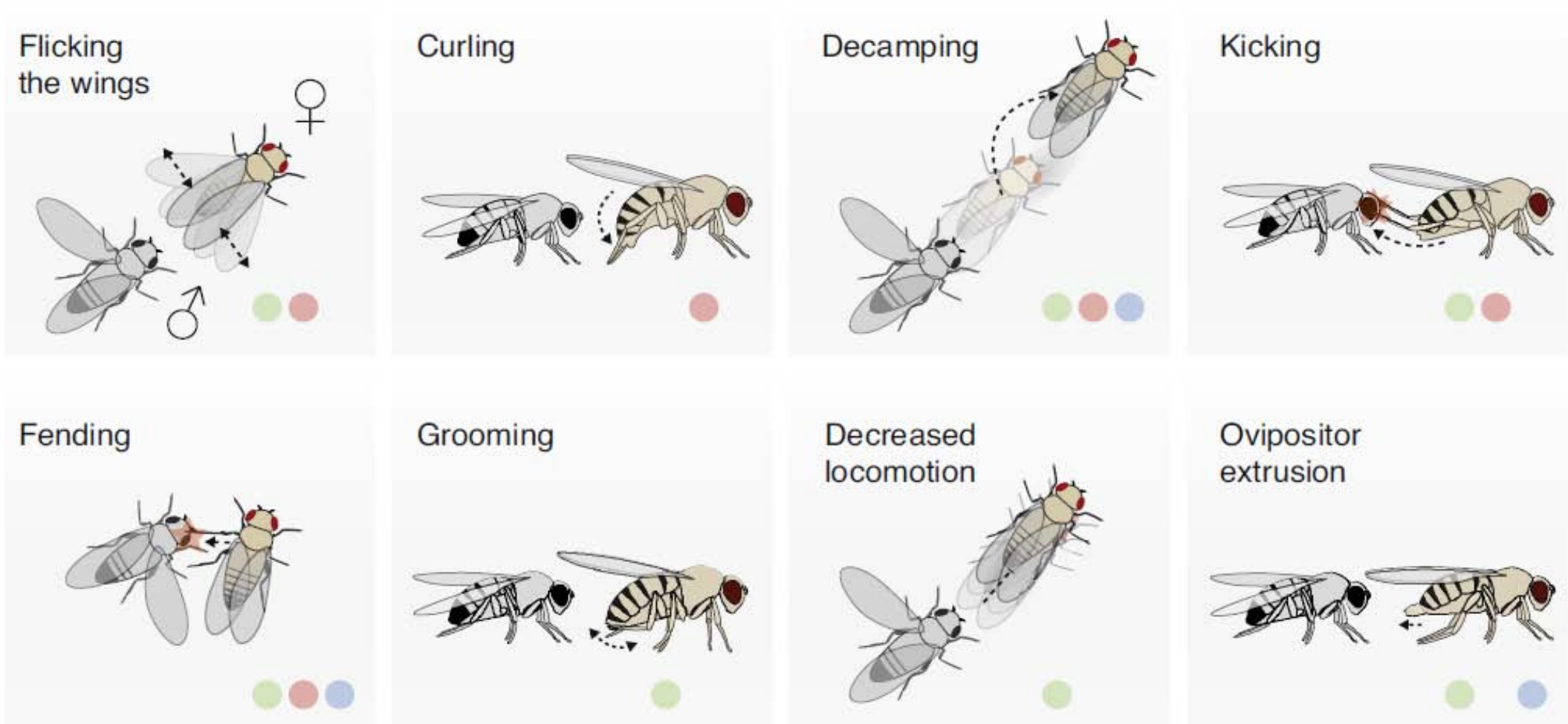
The effect of auditory system in female receptivity

Courtship song is important for copulation



Philip Coen, et al. Nature. 2014

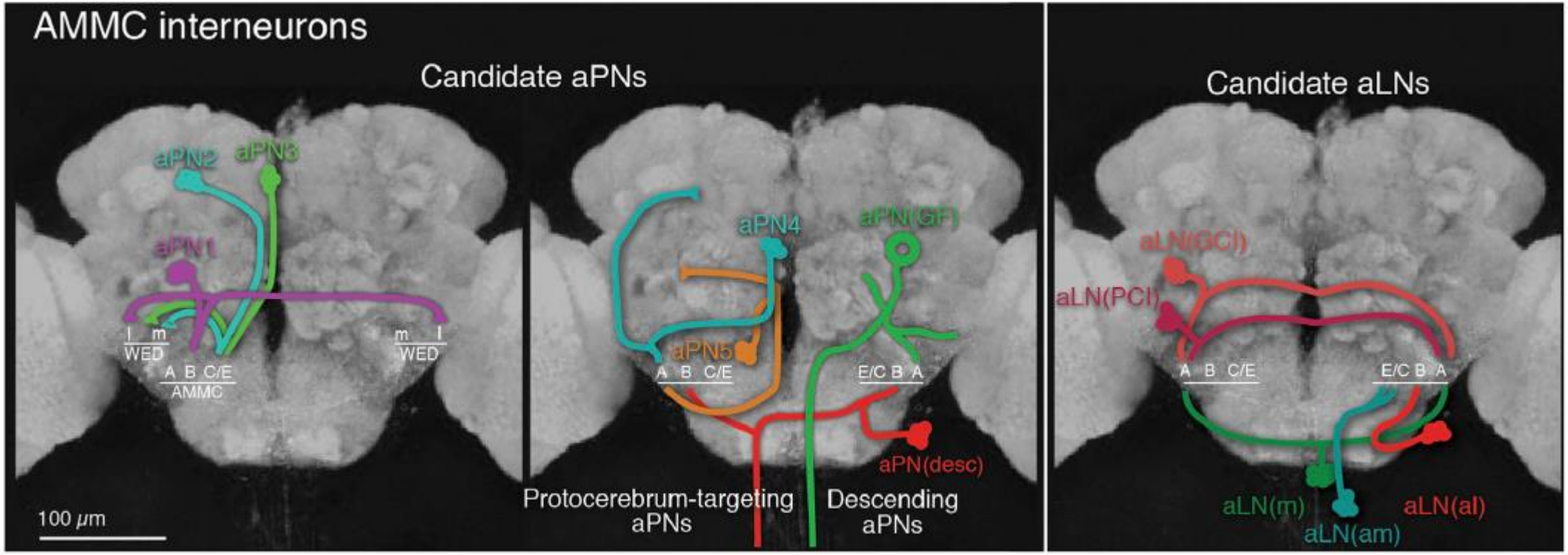
Female response to courtship song



Kyung-An Han and Young-Cho Kim. Current Biology.2009

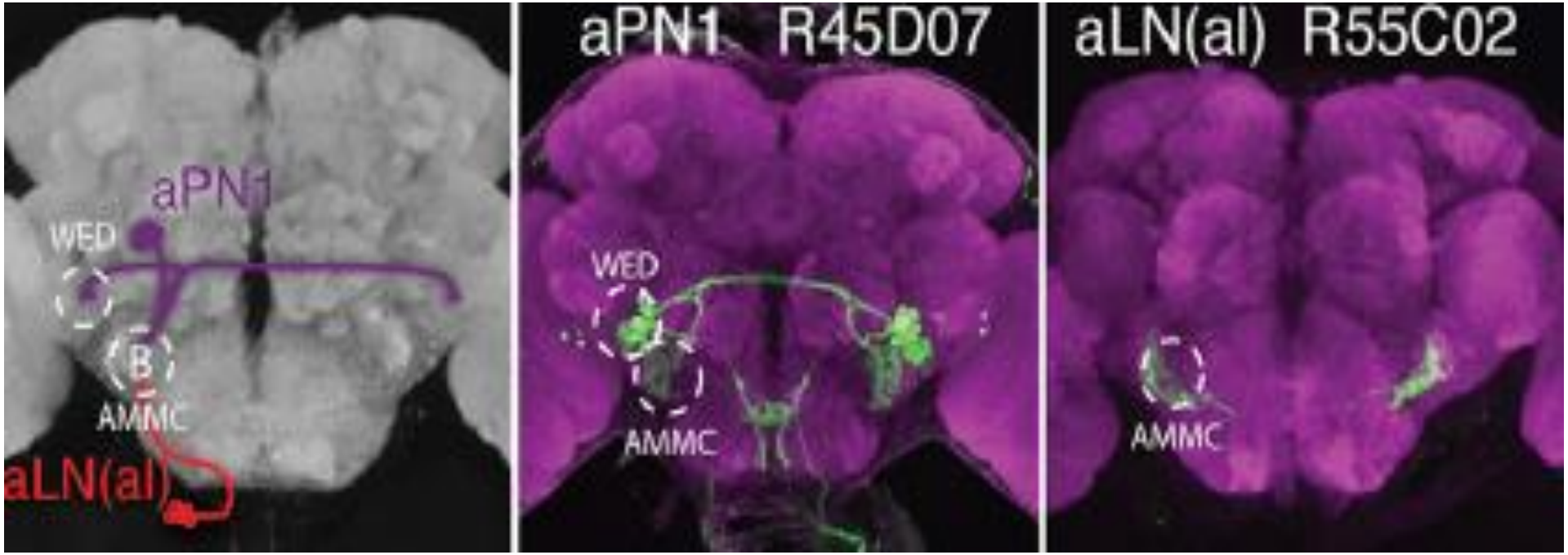
The aPN1 and aLN influence female receptivity

Schematic projections of twelve identified classes of AMMC



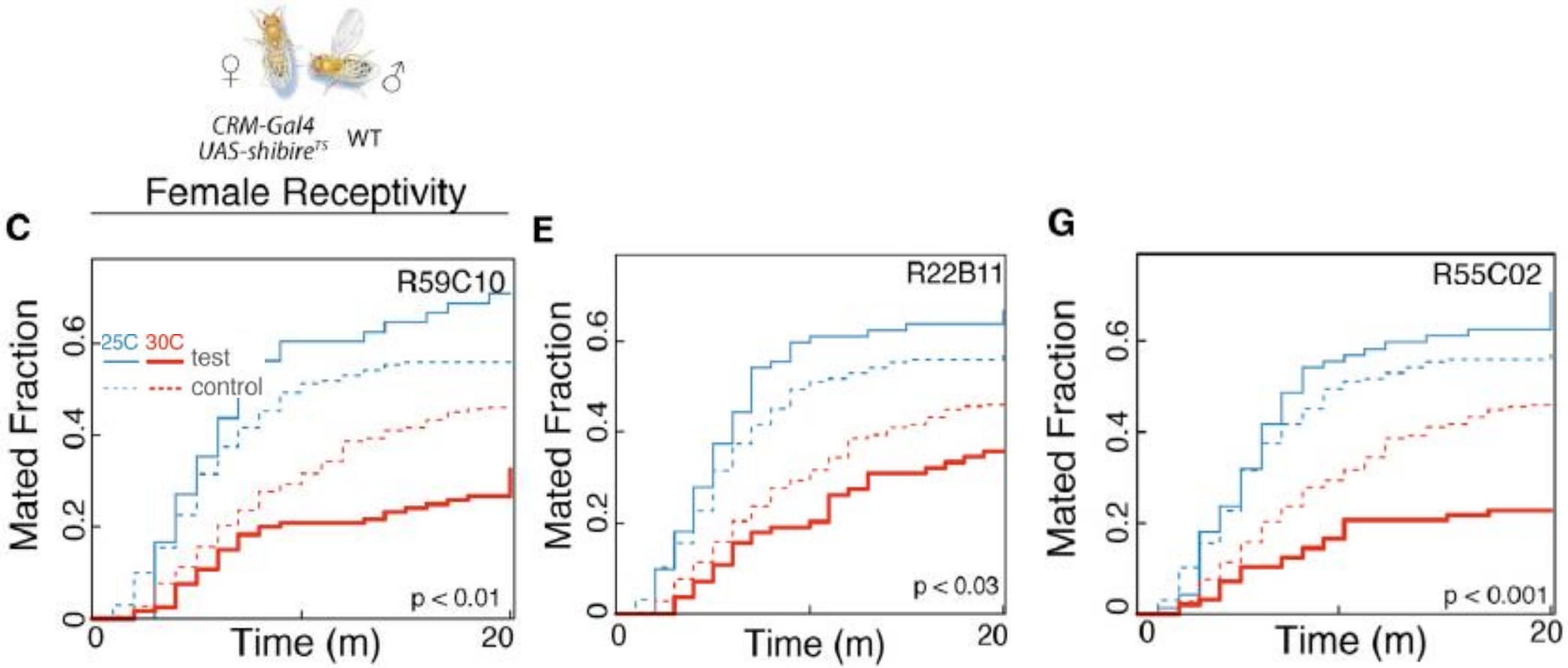
Vaughan, et al. Current Biology, 2014.

The Immunofluorescence of aPN1 and aLN



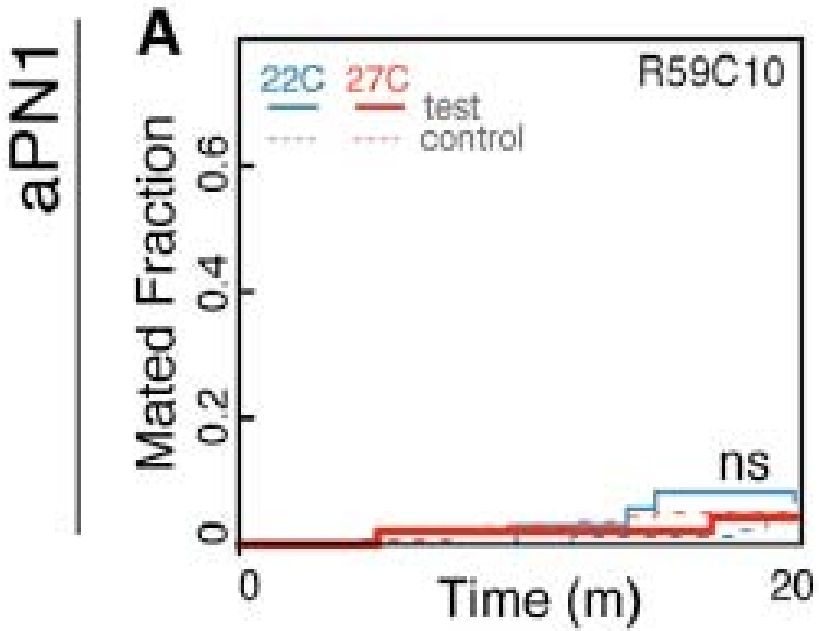
Vaughan, et al. Current Biology, 2014.

Neuronal silencing of aPN1 and aLN(al) disrupts courtship hearing



Vaughan, et al. Current Biology, 2014.

The aPN hyperactivation fails to rescue female receptivity to mute males



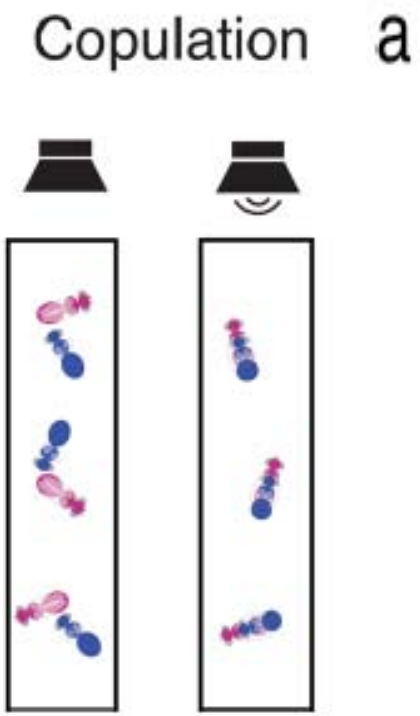
CRM-Gal4
UAS-dtrpA1

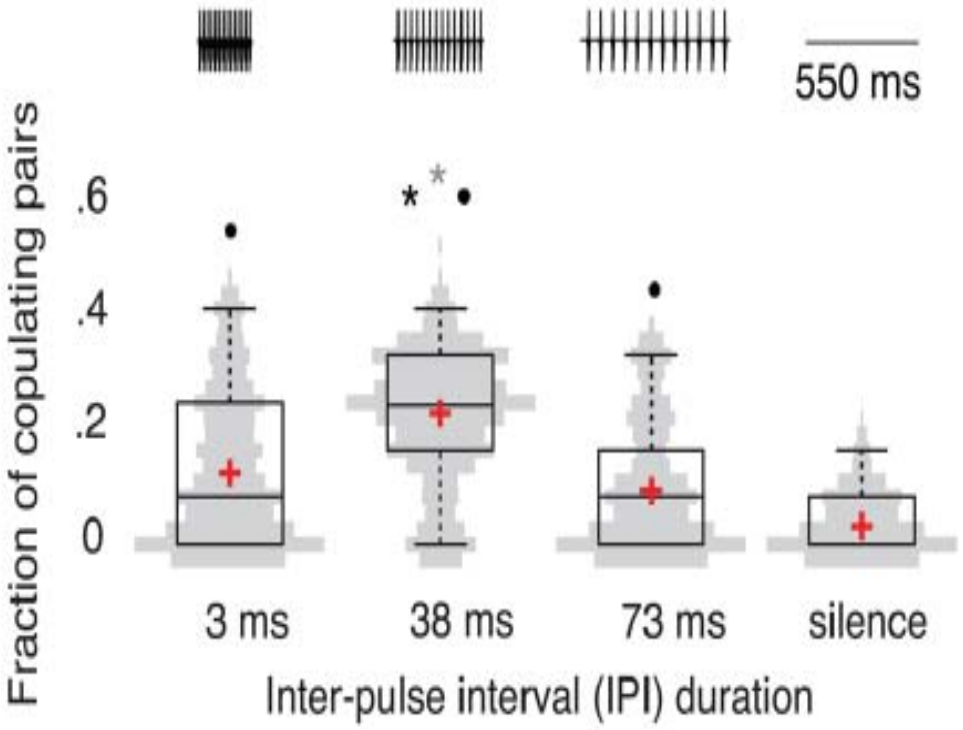
dewinged

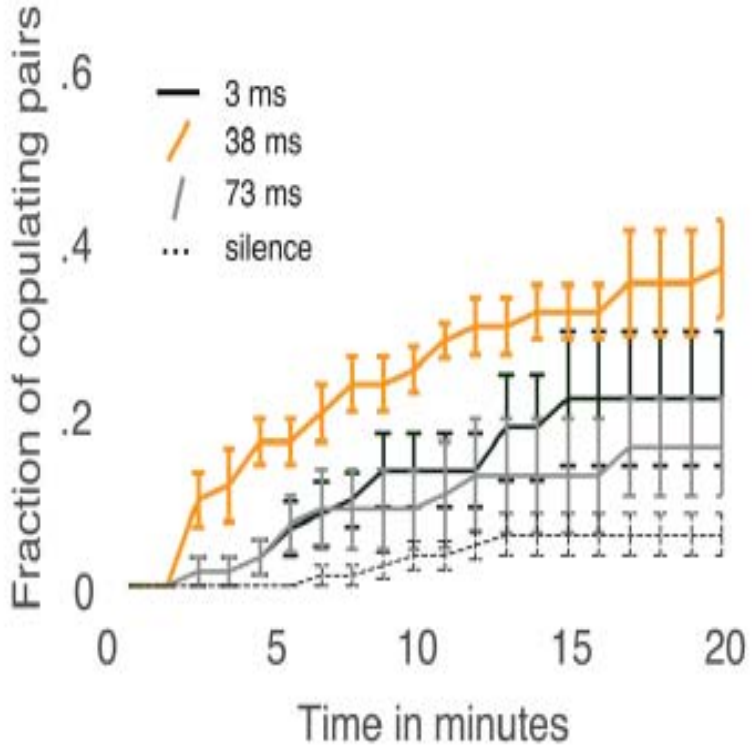
Vaughan, et al. Current Biology, 2014.

The pC1 modulates female receptivity

Courtship song promoted copulation of blinded and silenced males

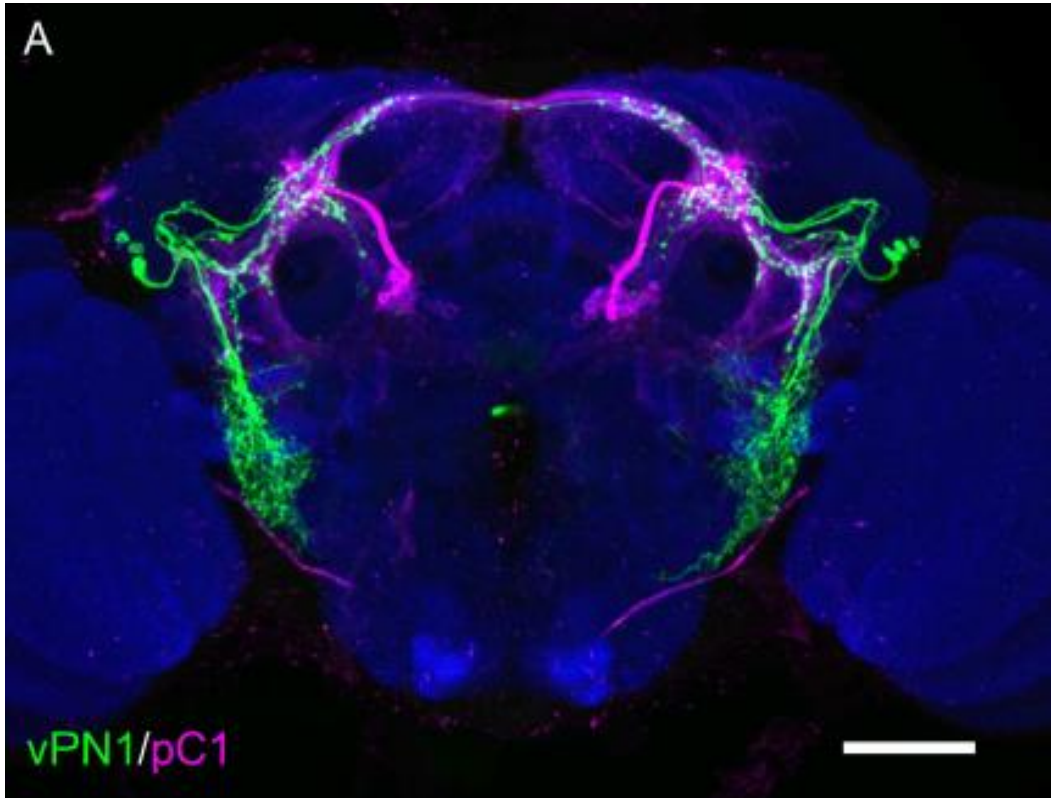


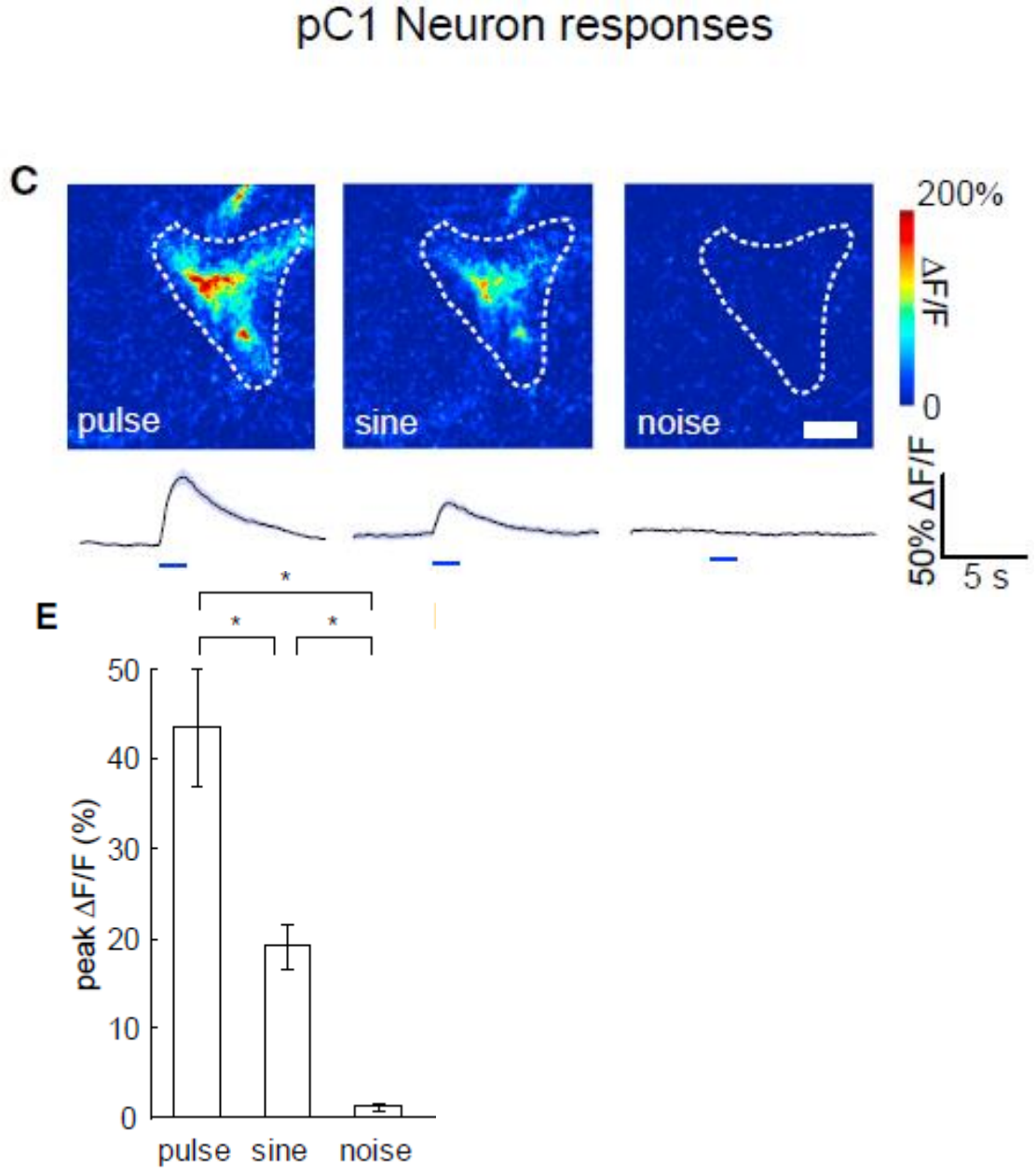




Birgit Bru¨ ggemeier, et al. Biology Open, 2018.

pC1 neurons response to courtship song

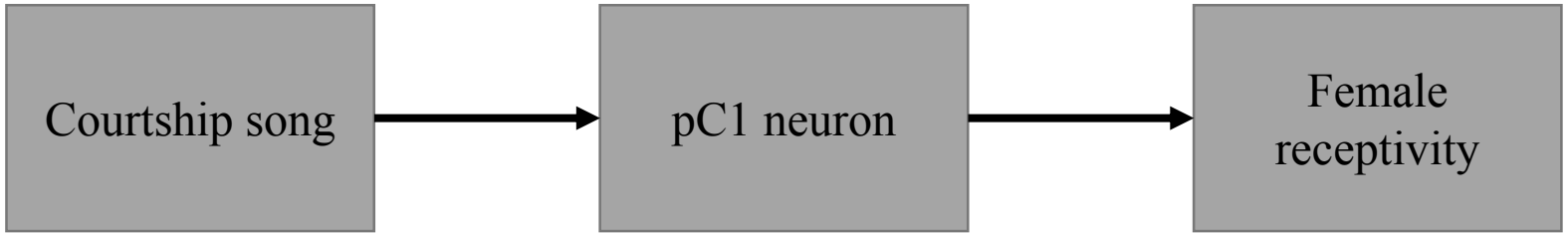




Zhou, et al. Neuron, 2014.

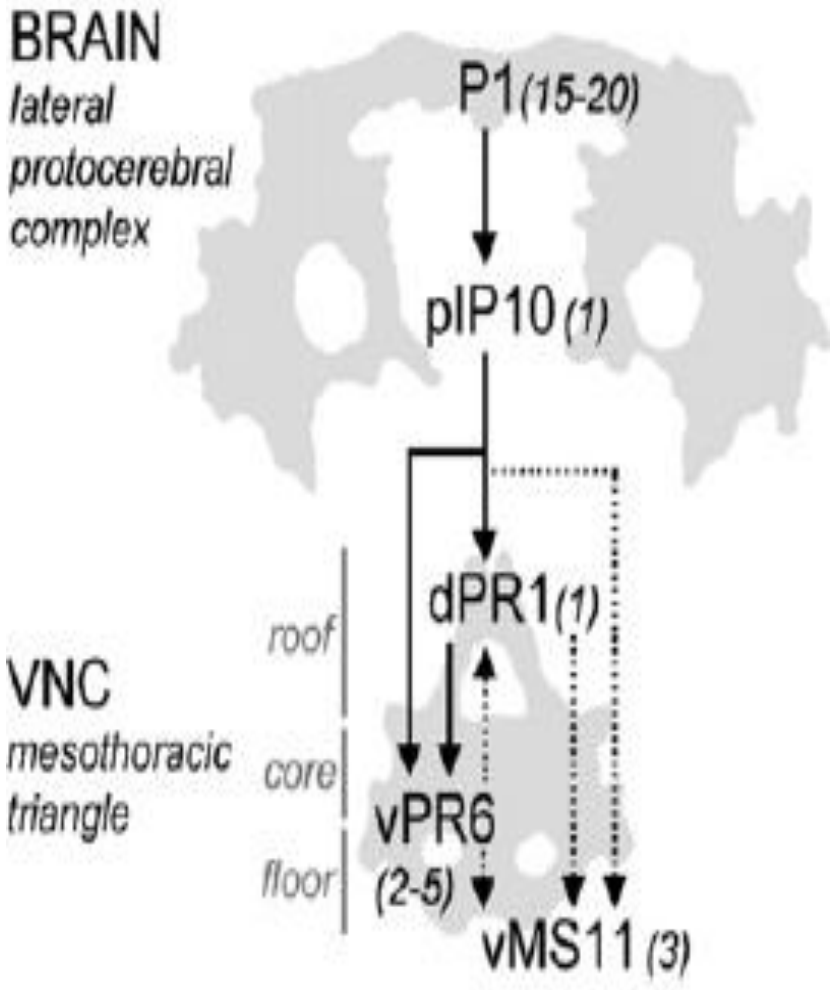
Zhou, et al. eLife, 2015.

pC1 neurons respond to courtship song

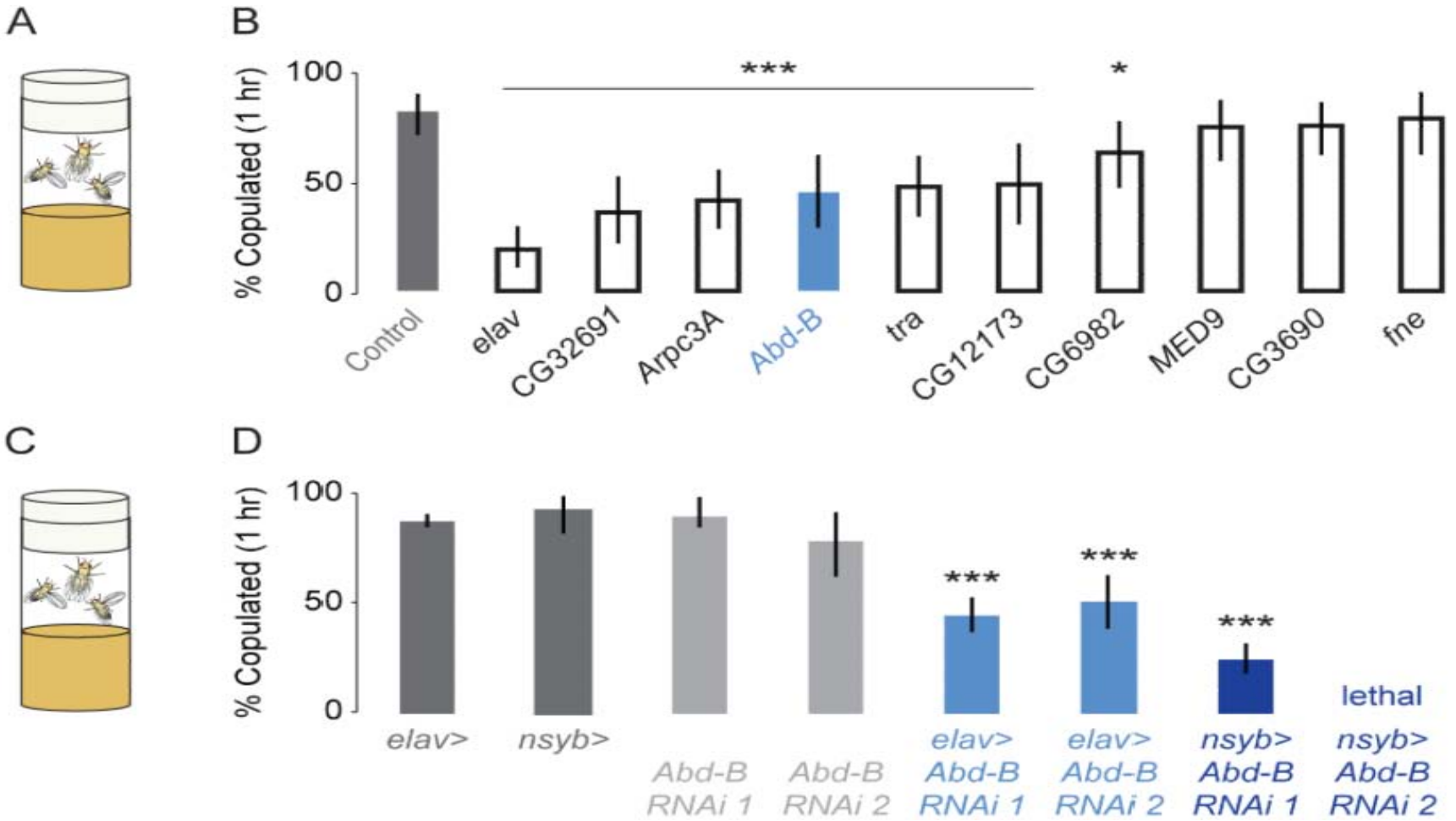


VNC neurons control of Drosophila courtship behavior

VNC neurons control of Drosophila courtship behavior

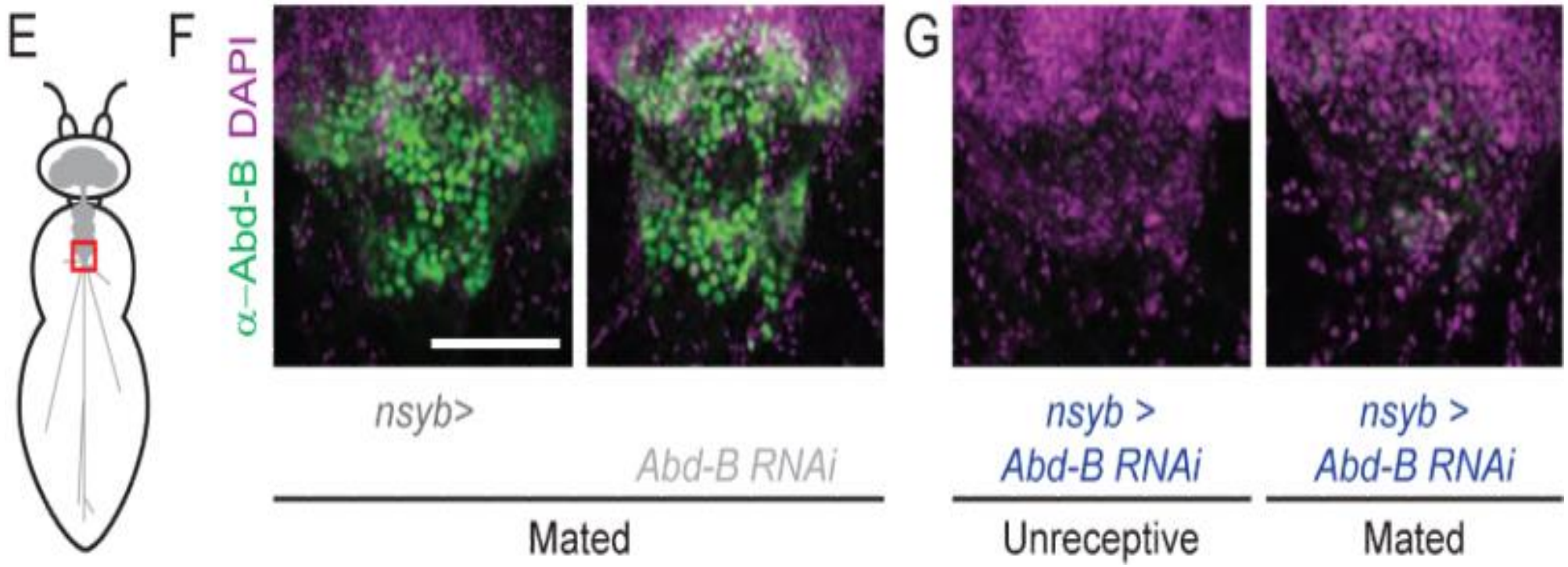


Abd-B is required in neurons for female receptivity



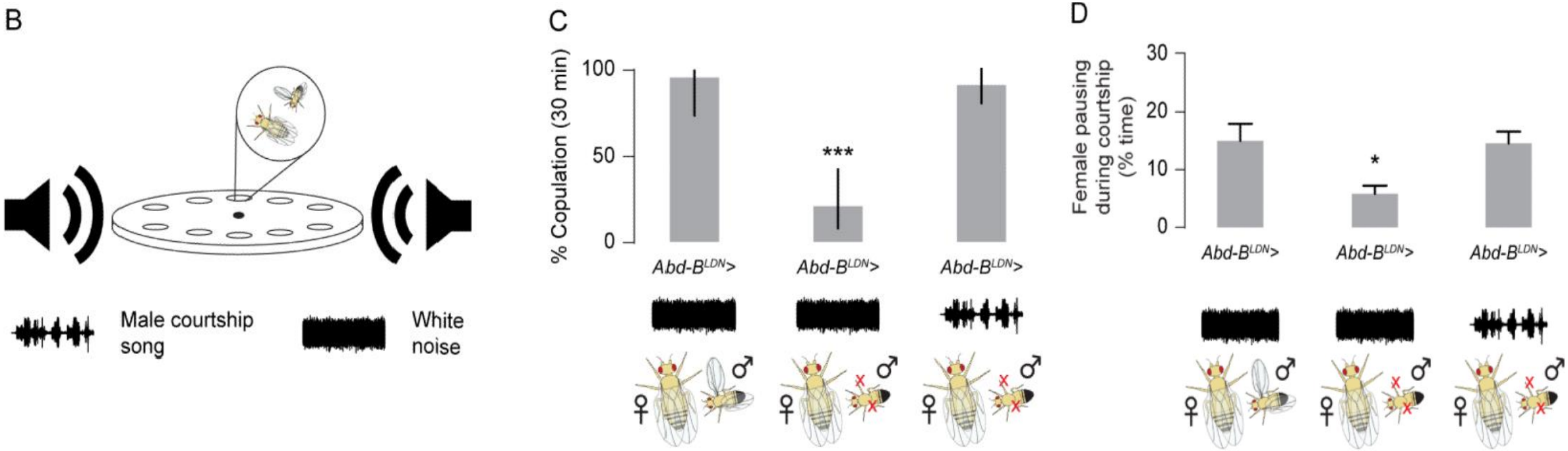
Bussell, et al. Curr Biol. 2015.

Immunofluorescence of Abd-B



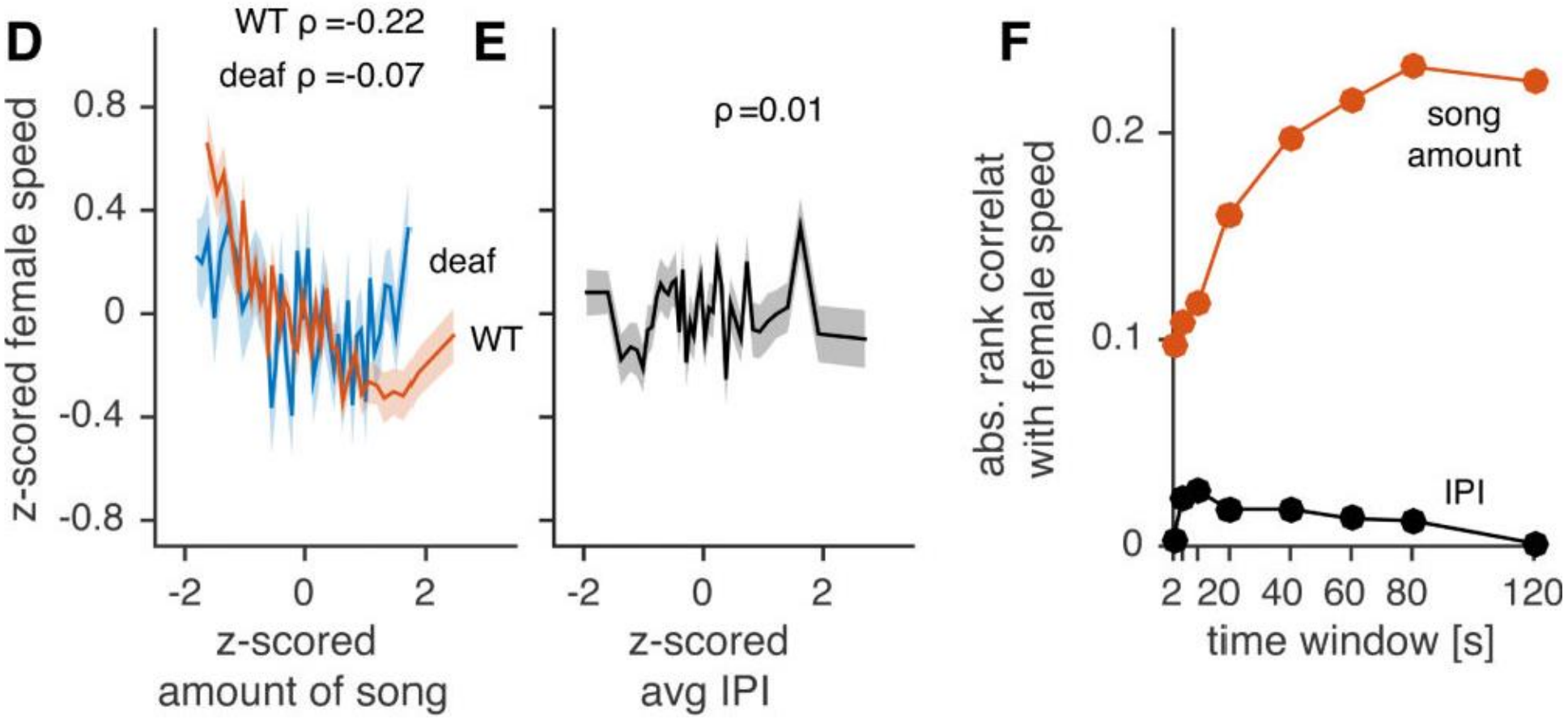
Bussell, et al. Curr Biol. 2015.

Abd-B responses to courtship song



Bussell, et al. Curr Biol. 2015.

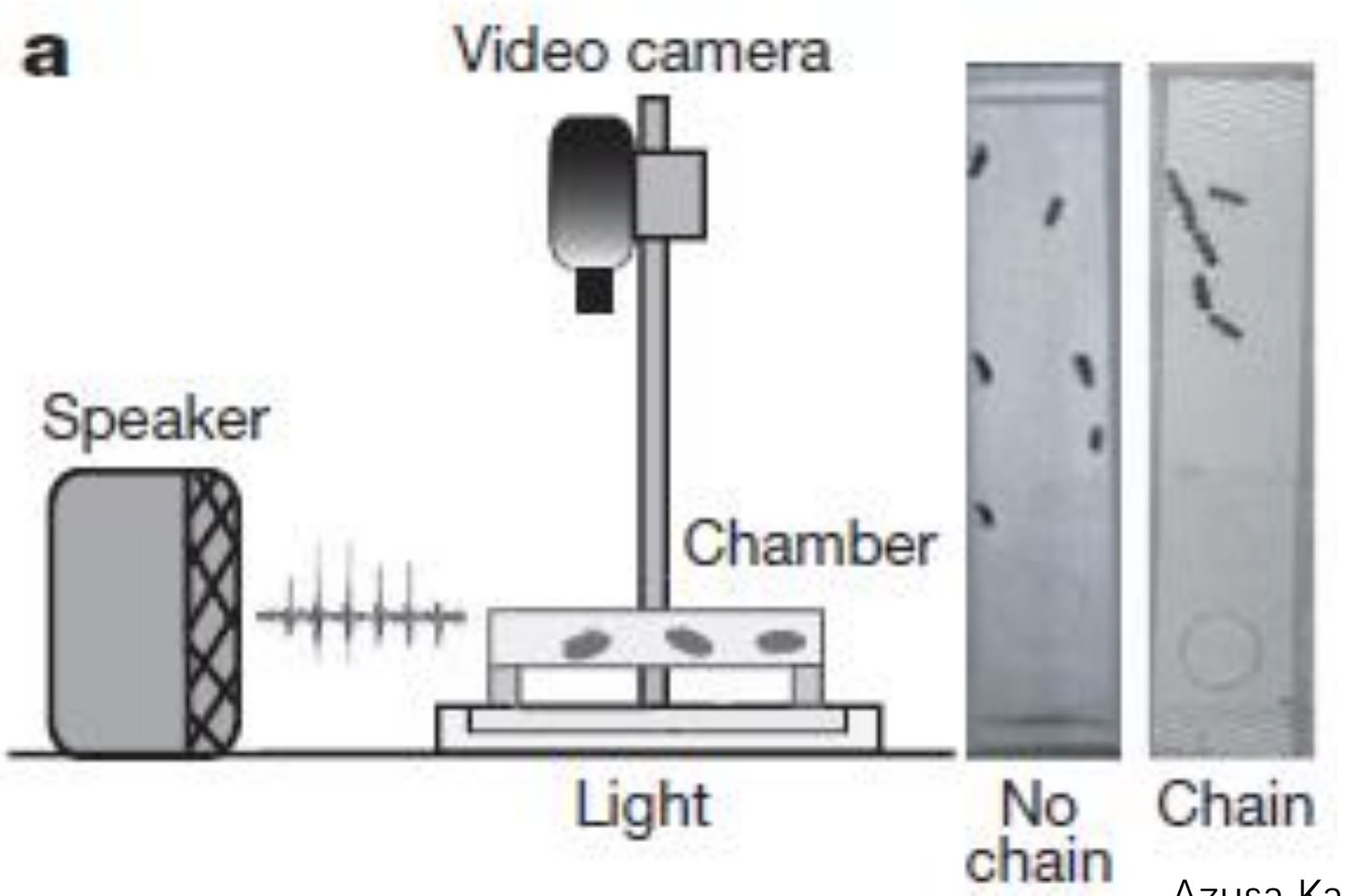
Female locomotion responses to courtship song



Clemens, et al. Neuron, 2016.

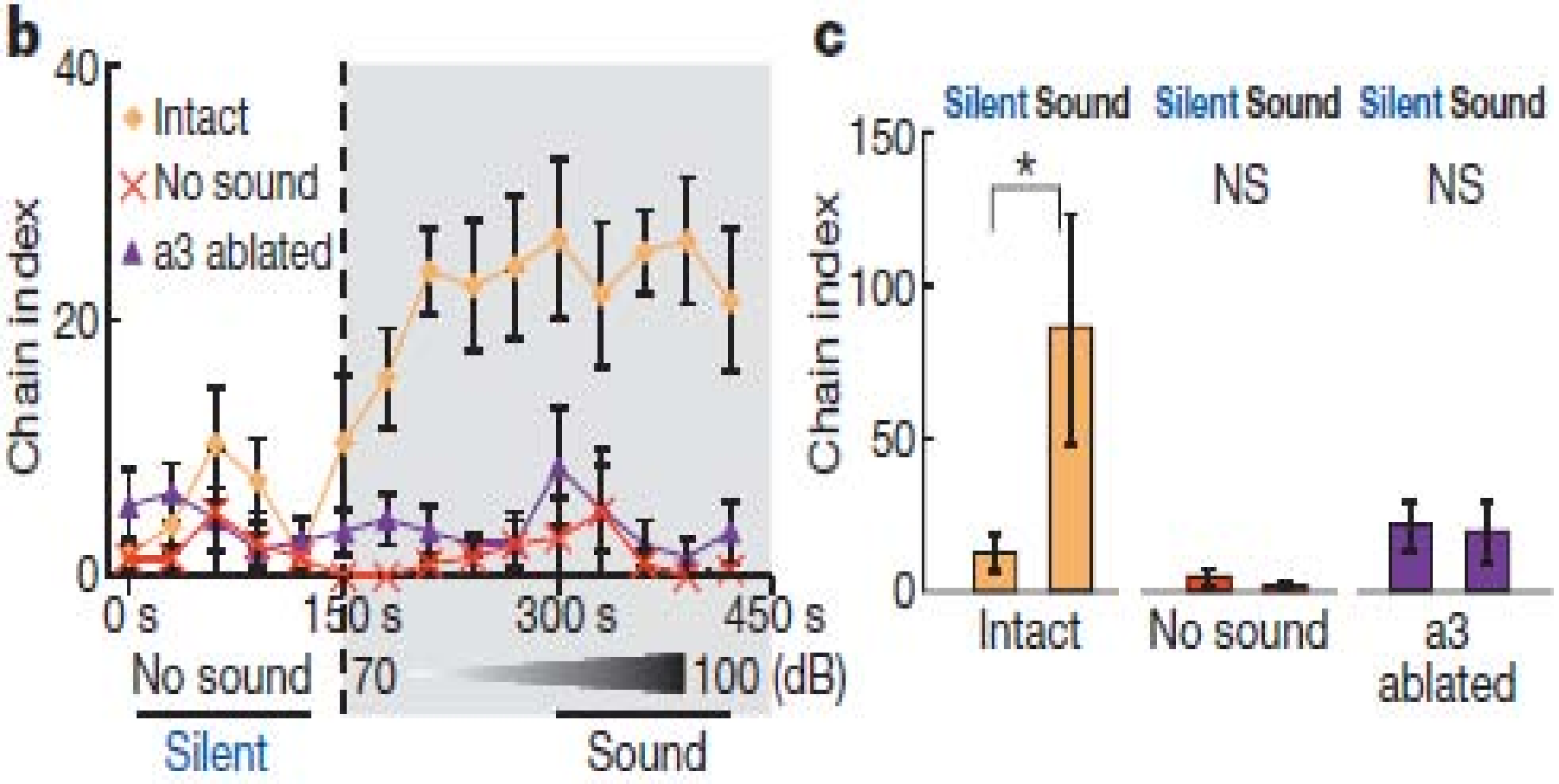
The pulse promoted male chaining behavior

The pulse component of courtship song promoted male chaining behavior



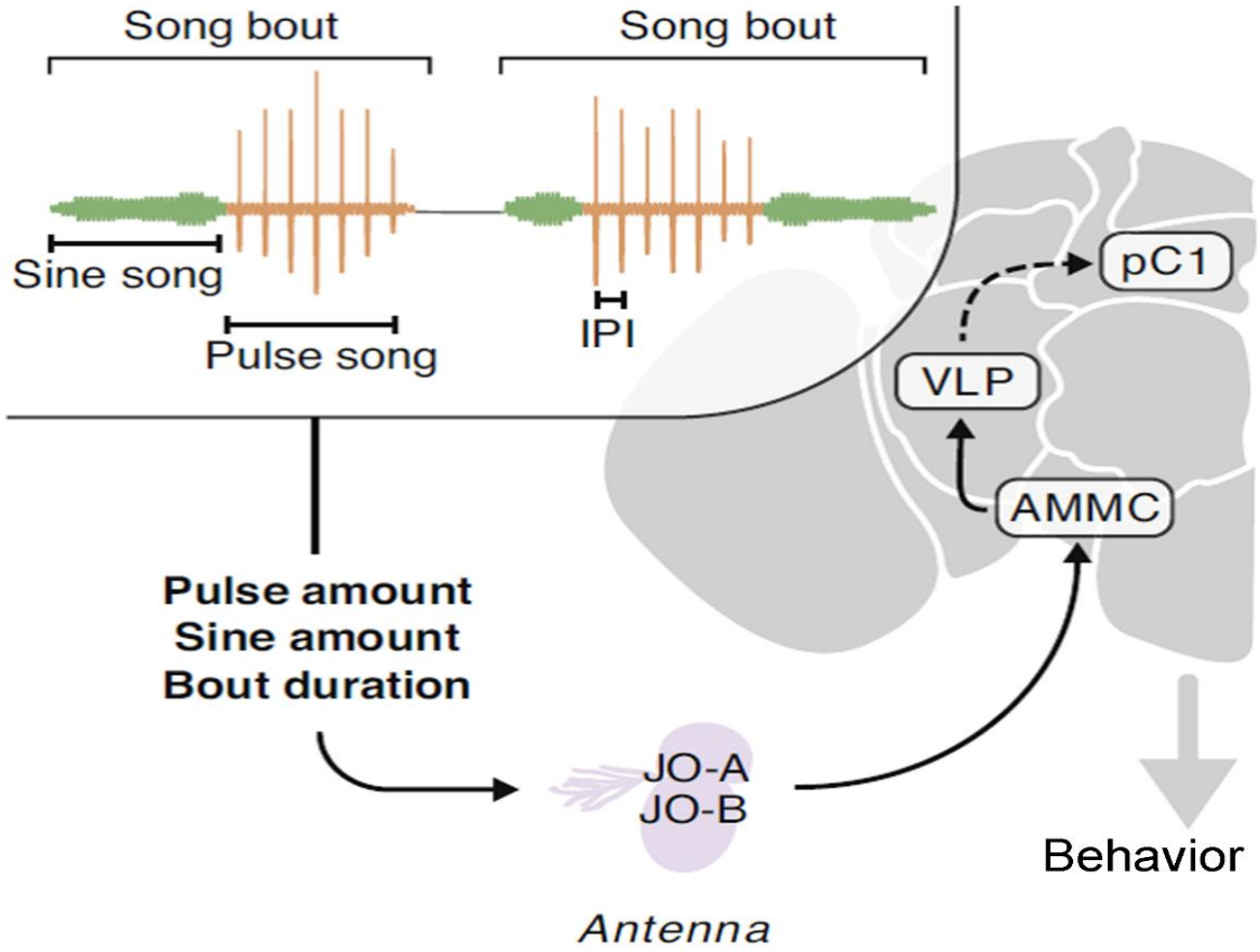
Azusa Kamikouchi, et al. *Nature*, 2009.

Courtship song is necessary for chaining behavior



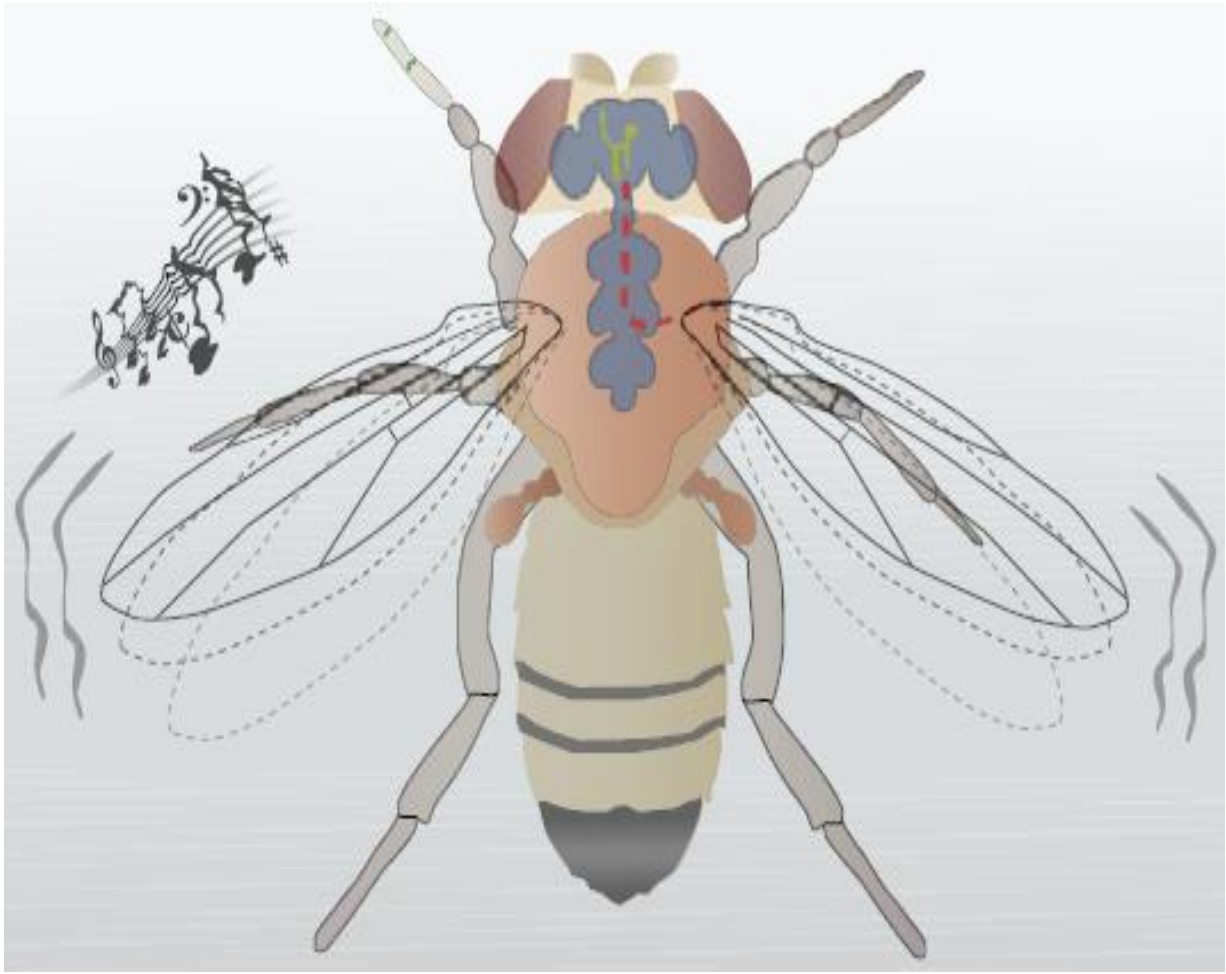
Azusa Kamikouchi, et al. Nature, 2009.

Song is a major determinant of courtship



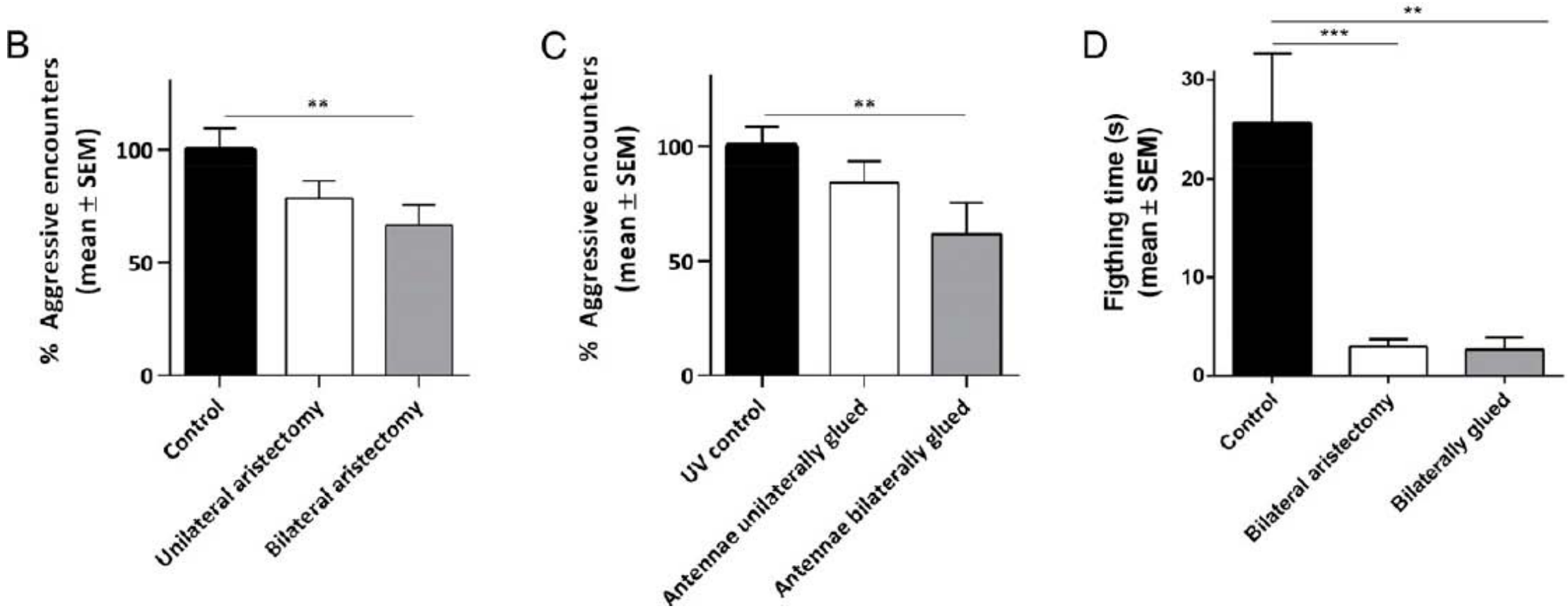
The effect of auditory system in aggression

Male forms offensive posture when feeling other males



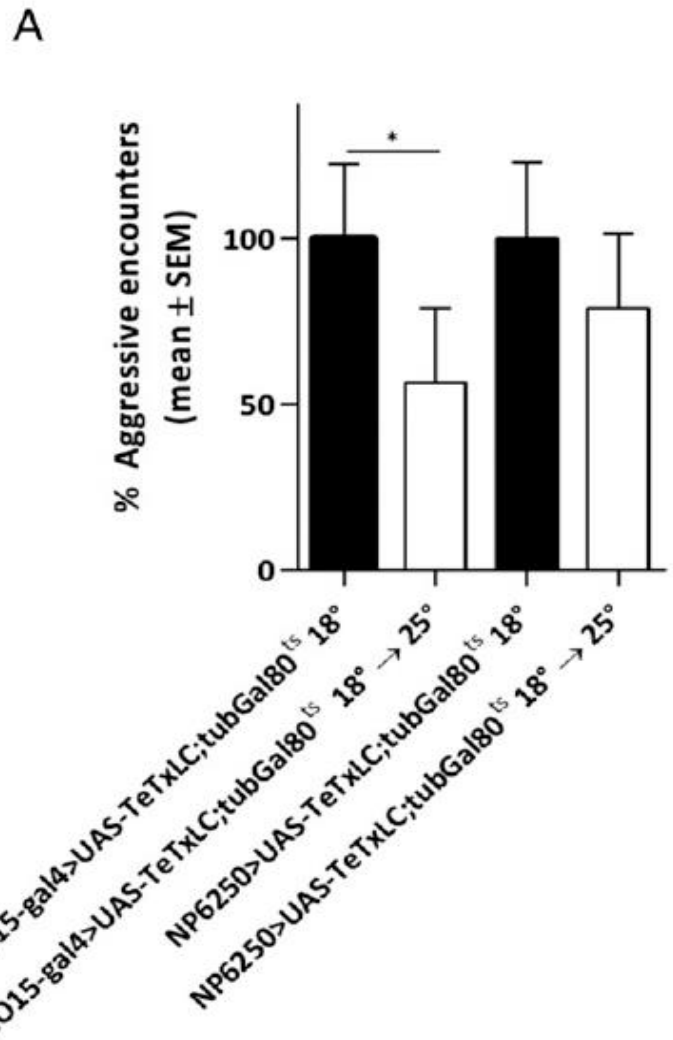
Kyung-An Han and Young-Cho Kim. Current Biology.2009

Mechanical disruption of hearing modulates aggression

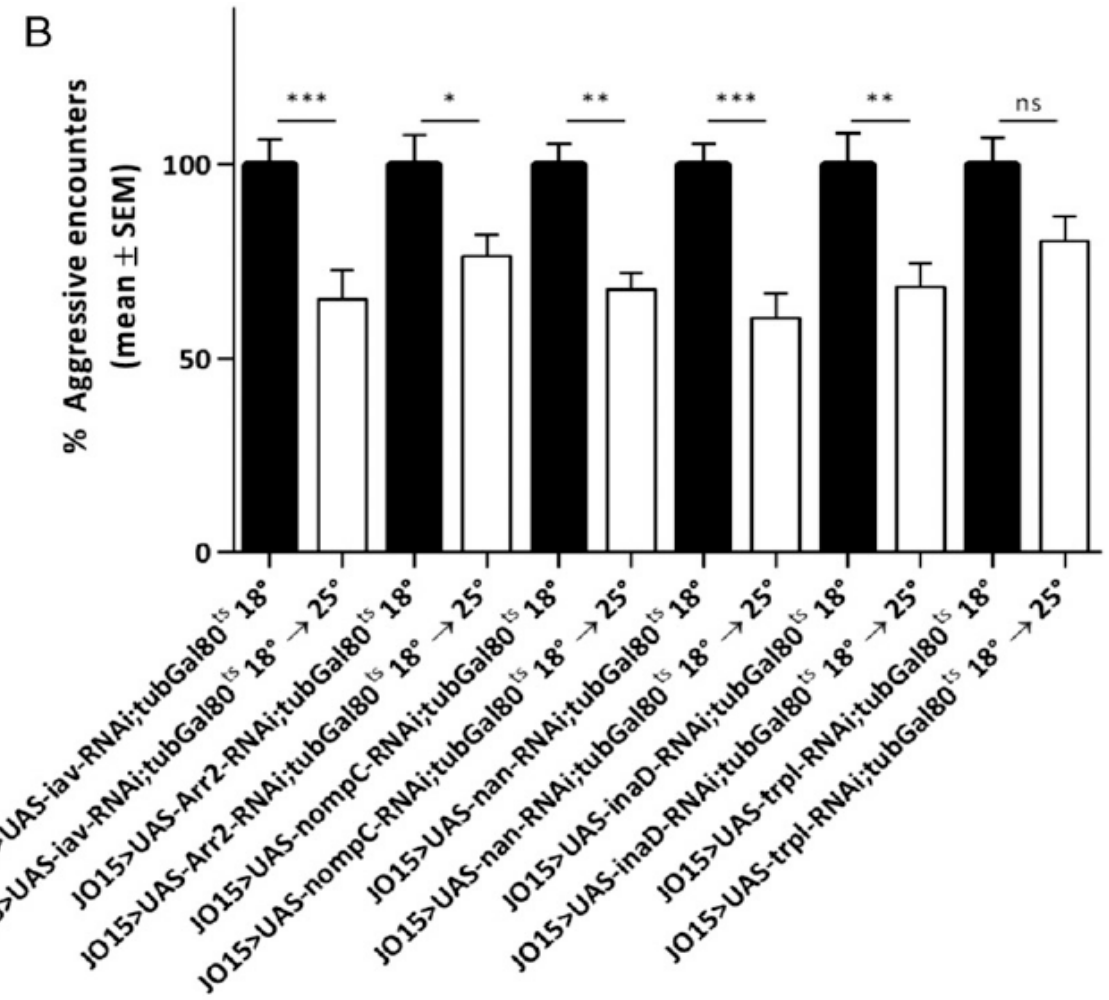


Versteven, et al. PNAS, 2017.

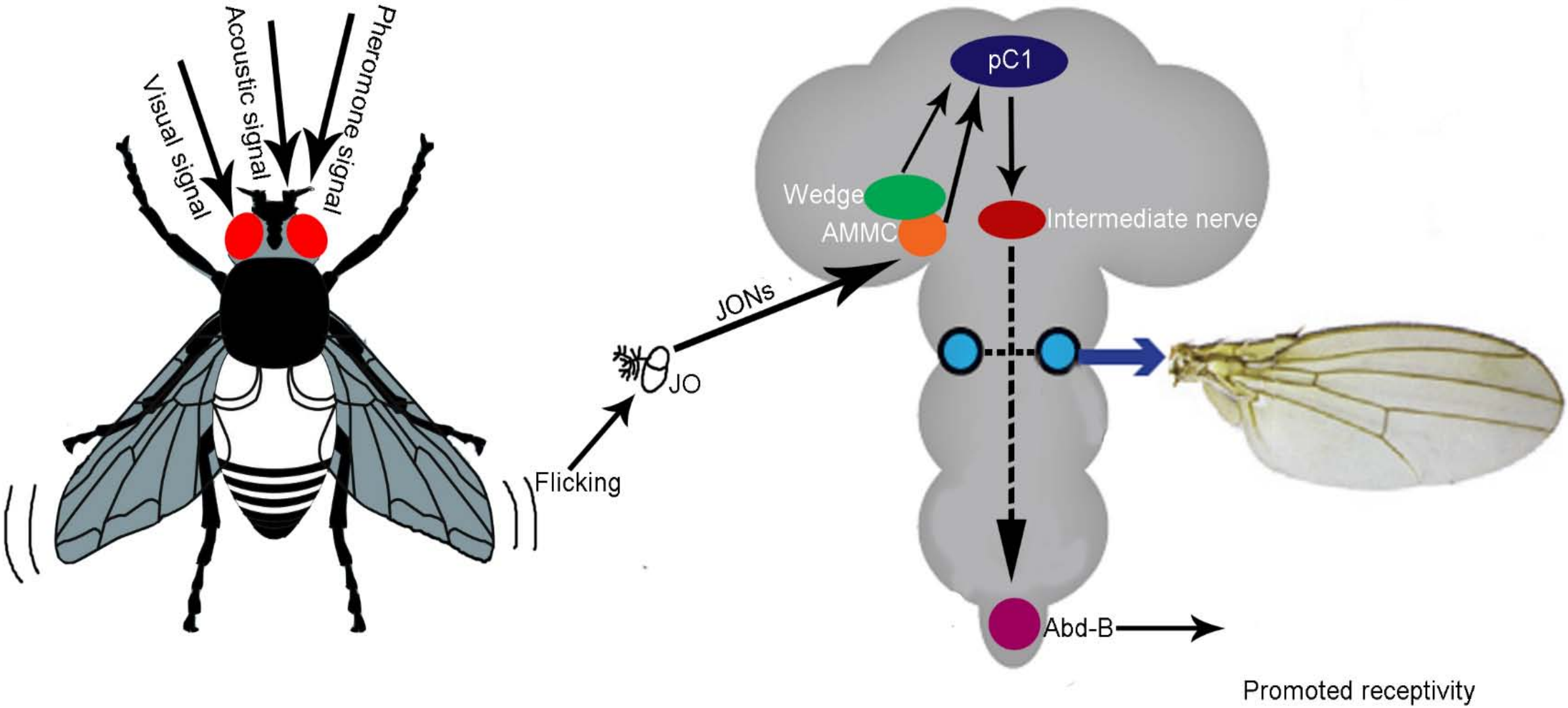
Johnston’s organ neurons modulates aggression



RNAi-mediated knockdown in the hearing genes modulate aggression



Conclusion


Visual signal
Acoustic signal
Pheromone signal
Flicking
JO
JONs
pC1
Wedge
AMMC
Intermediate nerve
Abd-B
Promoted receptivity

Thank you