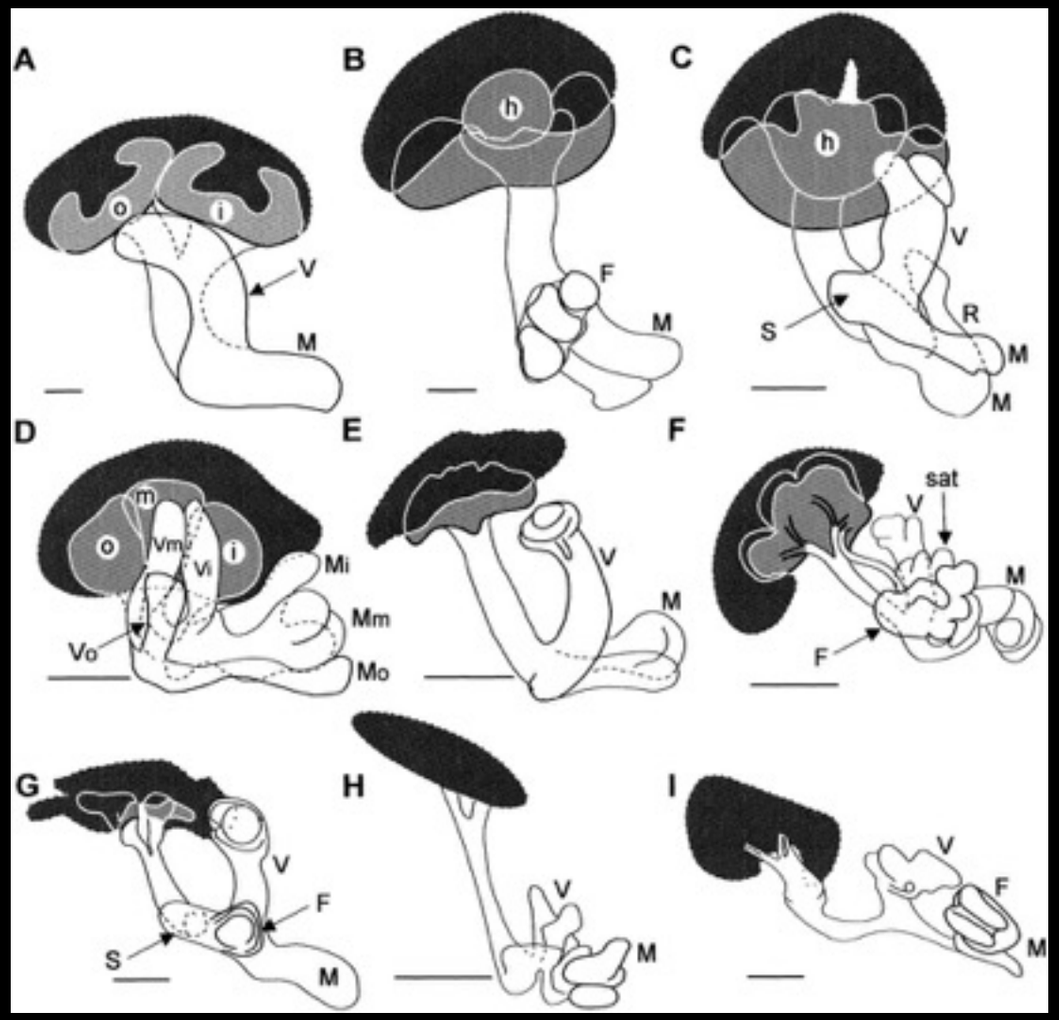
Courtesy of Jurgen Berger. Used with permission.

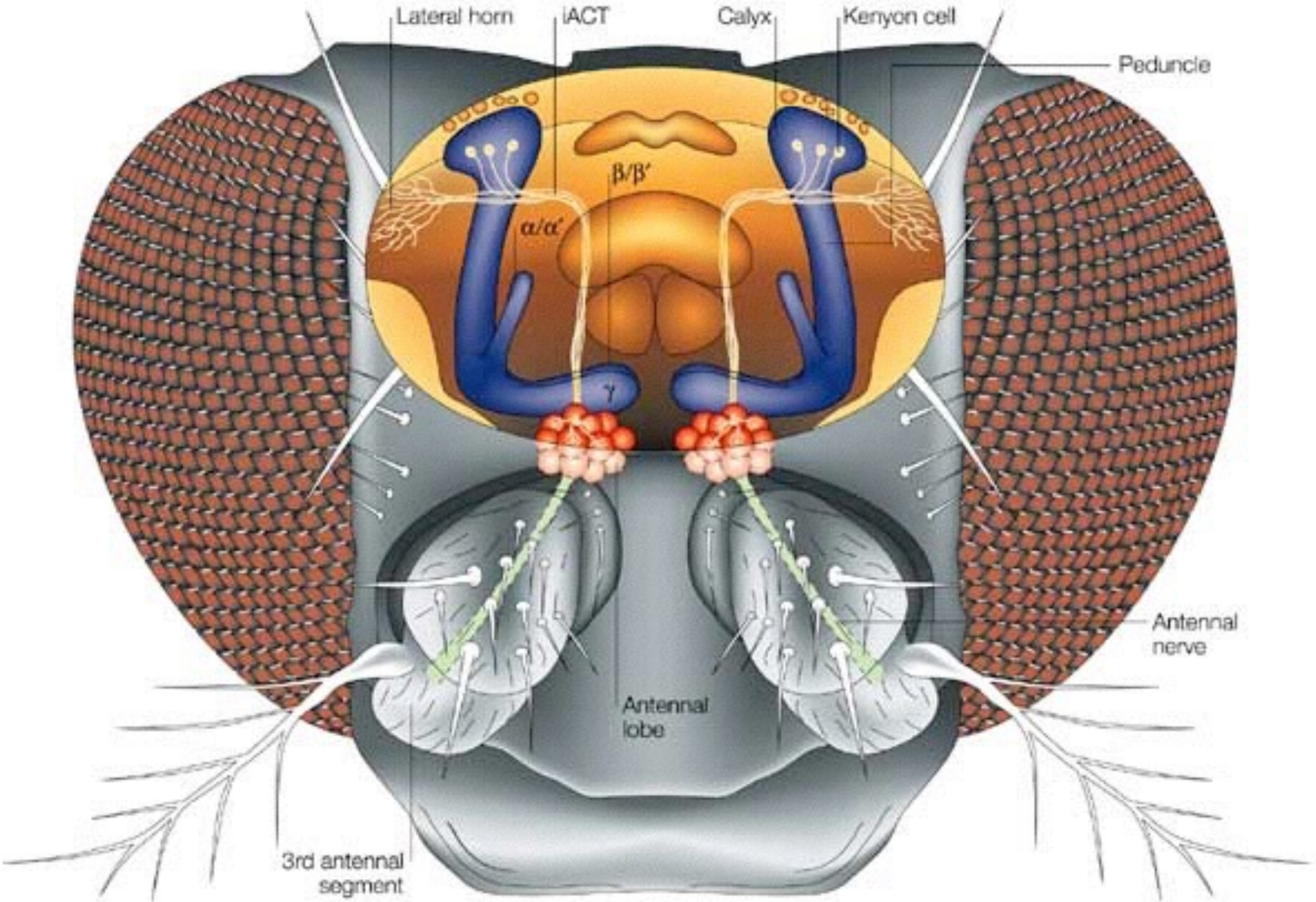
Mushroom body endows organisms with a degree of free will or intelligent control over instinctive actions - Dujardin, 1850



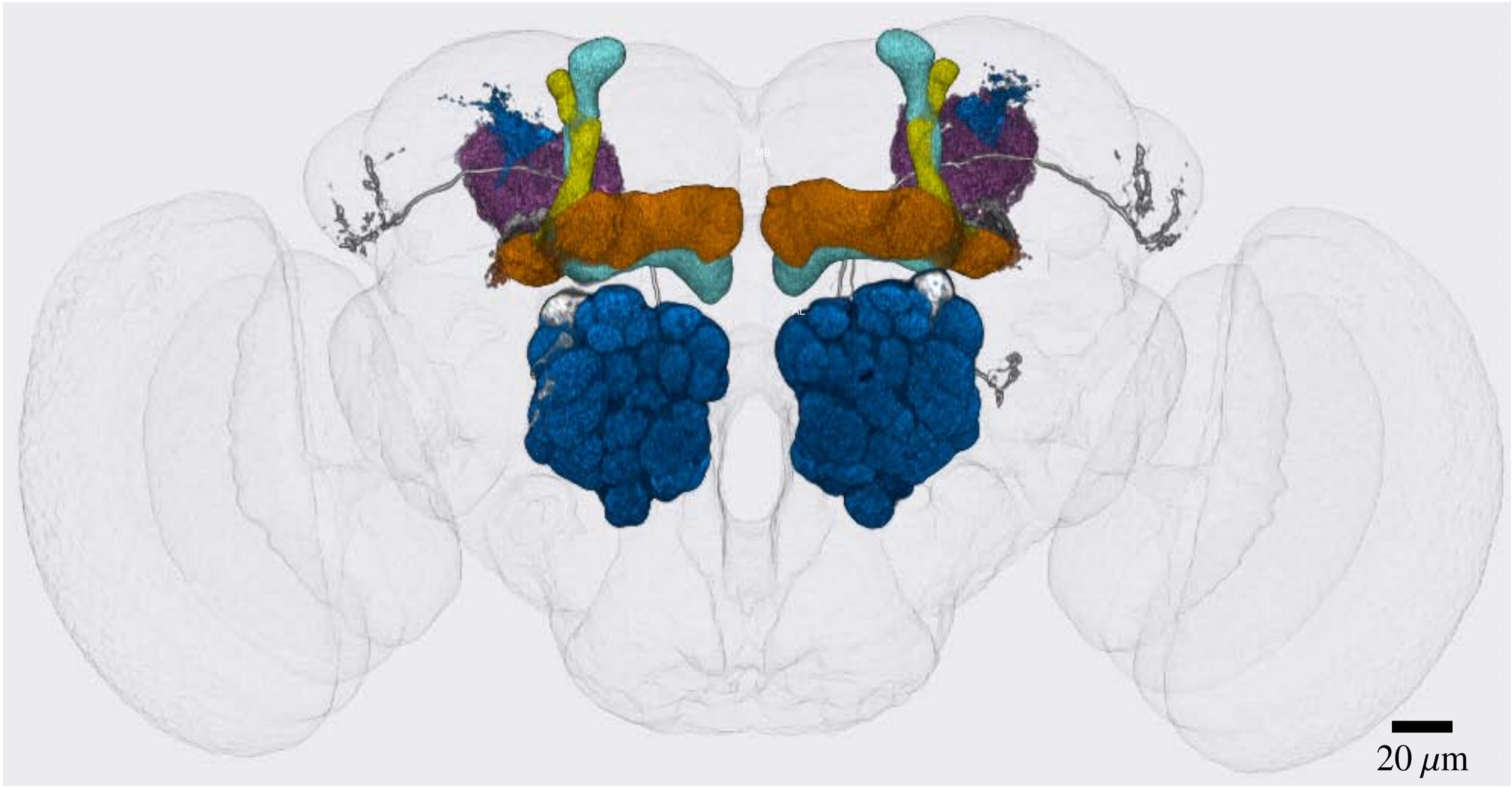
(Strausfeld et al., 1998)

Courtesy of Cold Spring Harbor Laboratory Press. Used with permission.

Photos removed due to copyright restrictions. Please see the video.



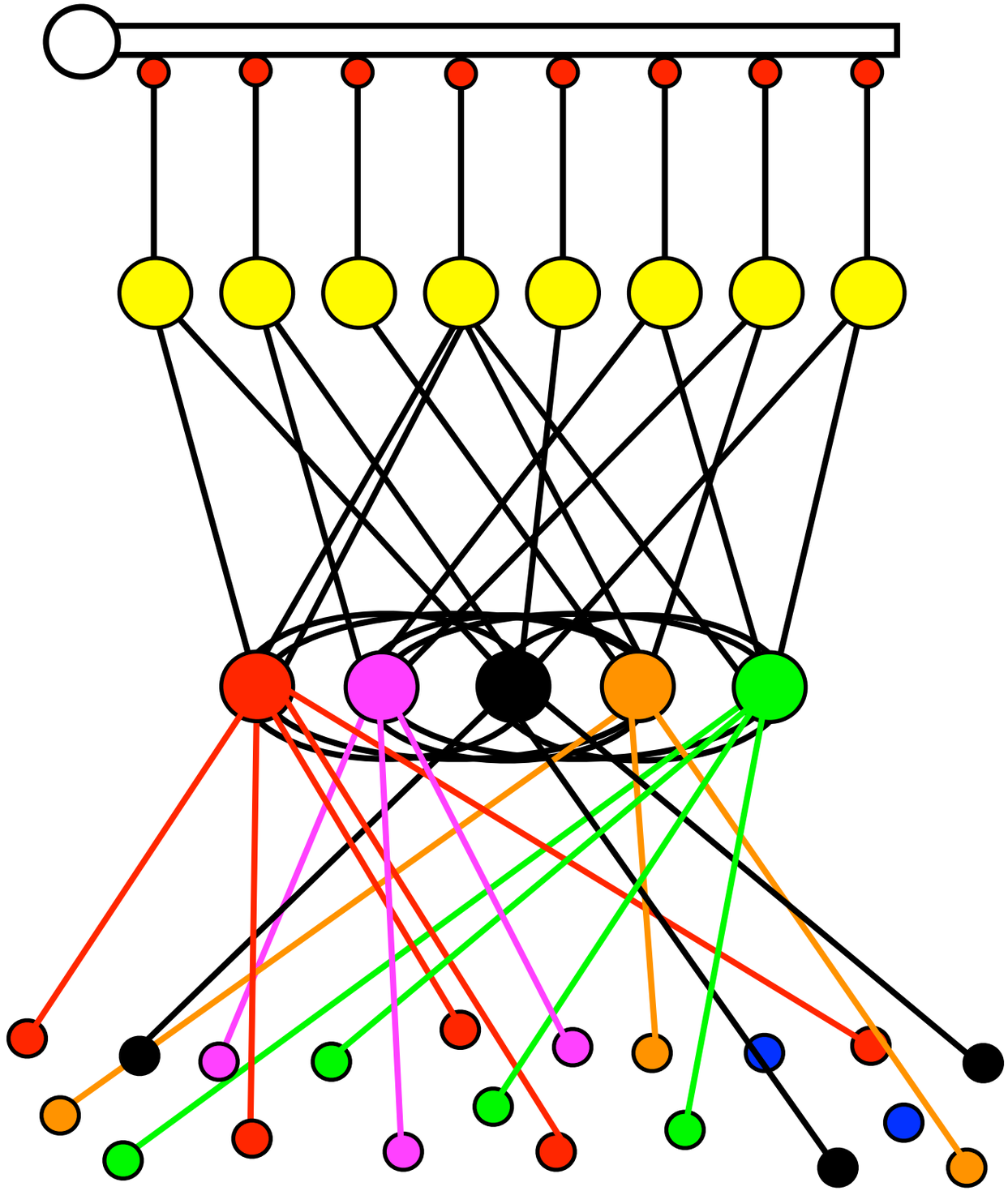
Reprinted by permission from Macmillan Publishers Ltd: Nature.
Source: Heisenberg, Martin. "Mushroom body memoir: From maps to models." Nature Reviews Neuroscience 4, no. 4 (2003): 266-275. ©2003.



Courtesy of eLife. Used with permission.

PN
N~200/50
D ~ 35

ORN
N ~ 1000/50
D ~ 30

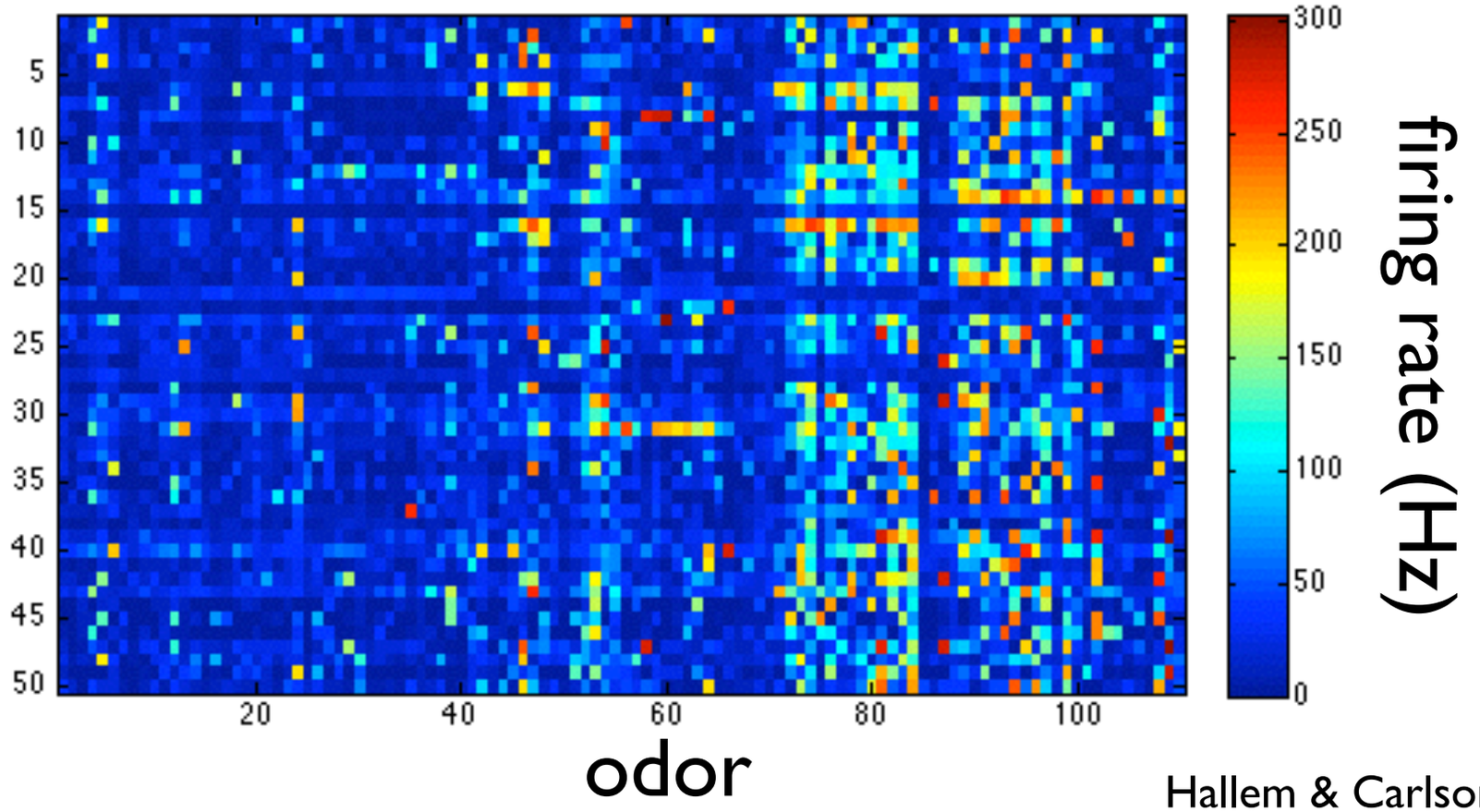


pooling
noise
reduction
normalization

input

D = 30

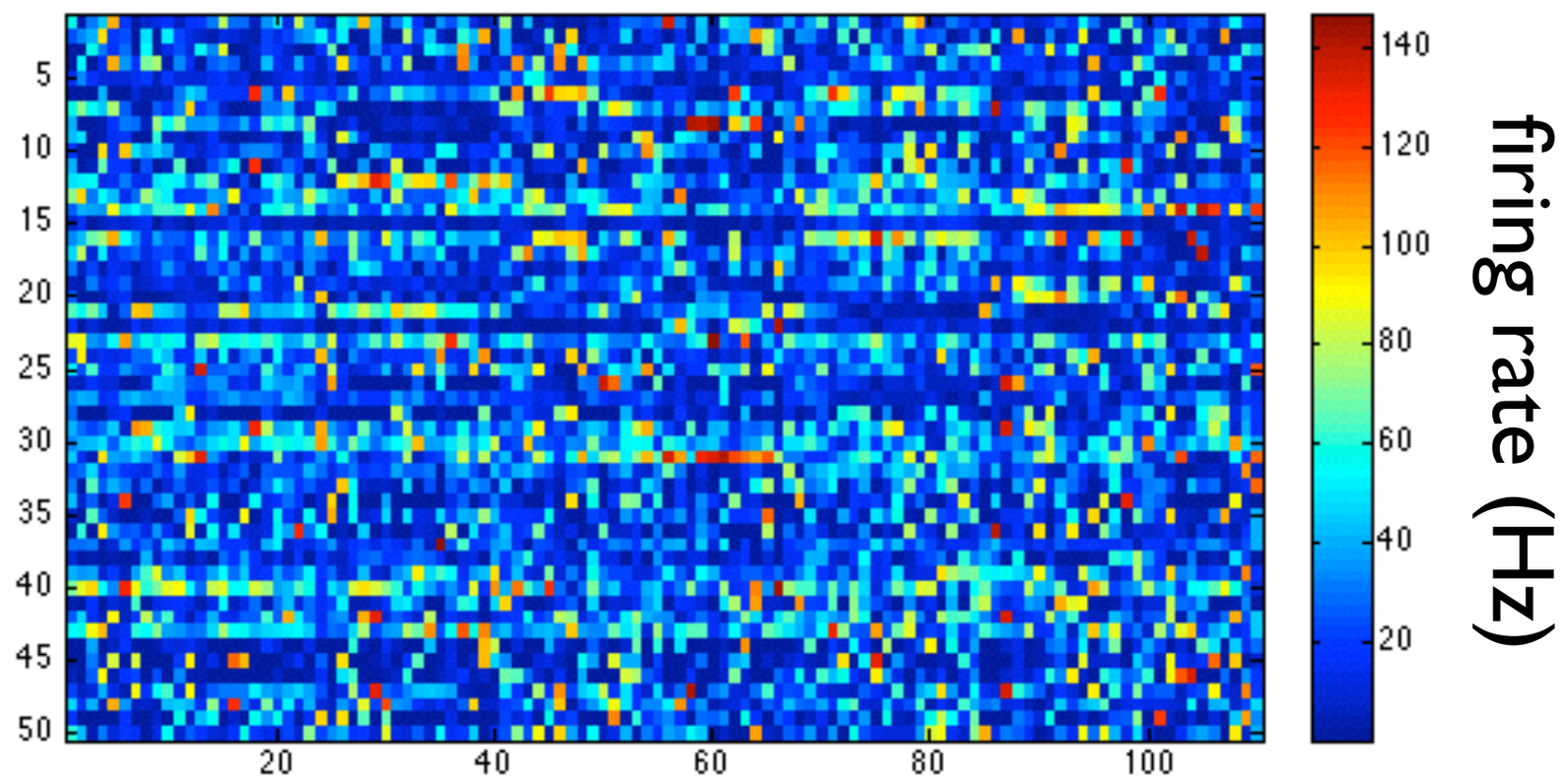
ORN



Hallem & Carlson 2006

D = 35

PN



Courtesy of PNAS. Used with permission.

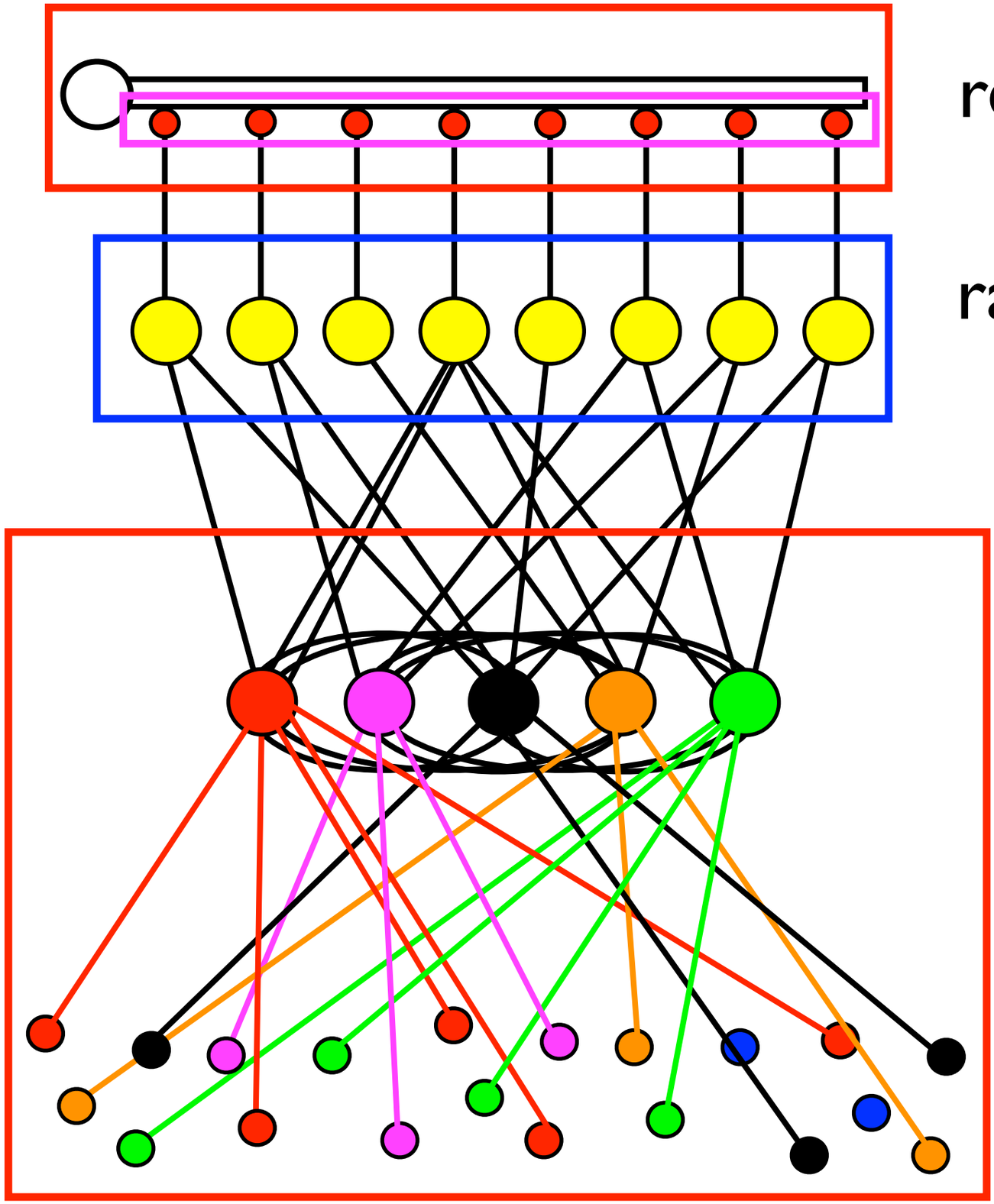
Olsen, Bhandawat, Wilson 2010
with Sean Luo, Richard Axel

MBON
N ~ 34/21
D ~ 20

KC
N ~ 2000/7
D ~ 1000

PN
N~200/50
D ~ 35

ORN
N ~ 1000/50
D ~ 30

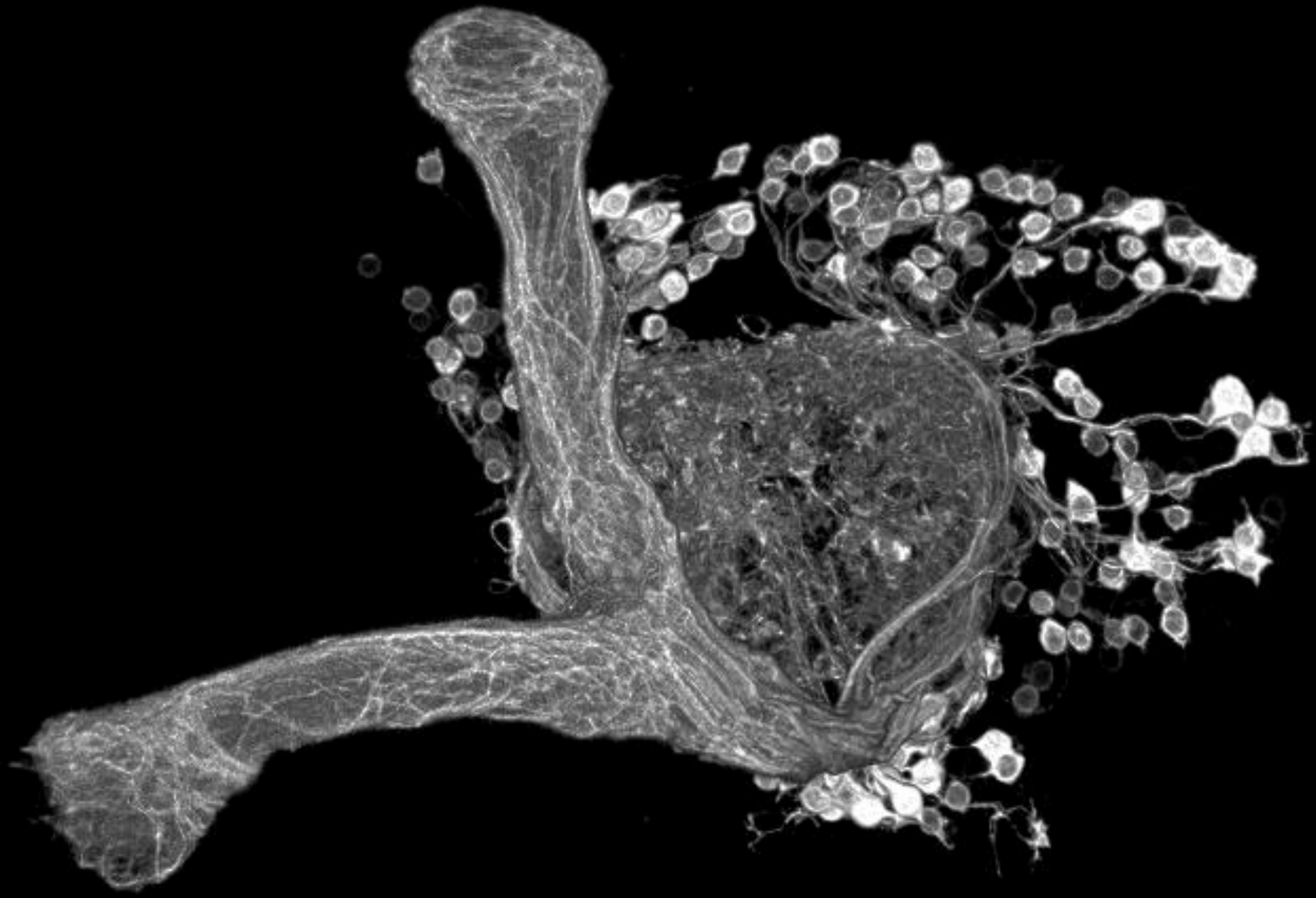


readout layer(s)

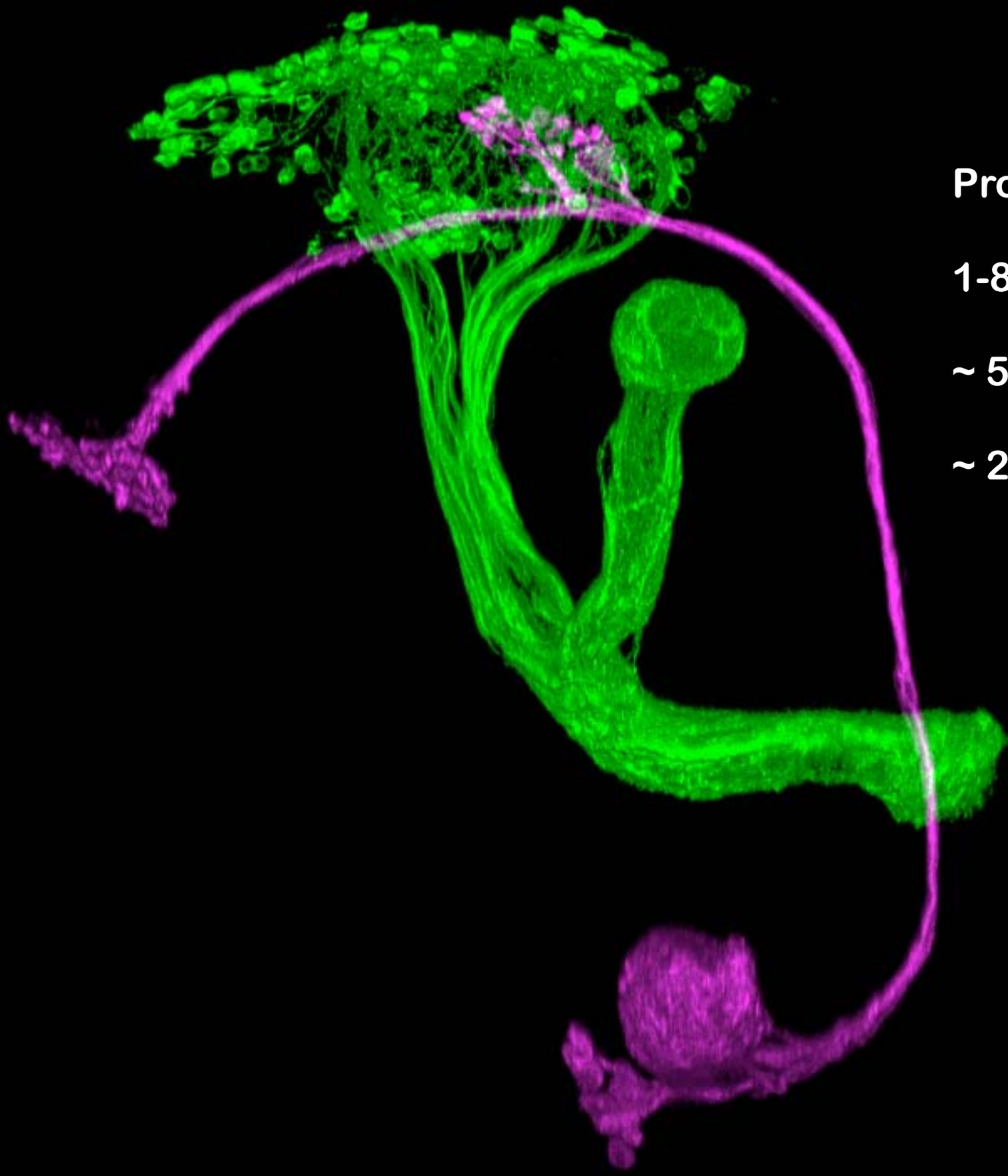
random, high-D
hidden layer

pooling
noise
reduction
normalization

input



Courtesy of Yoshi Aso. Used with permission.



Projection neurons

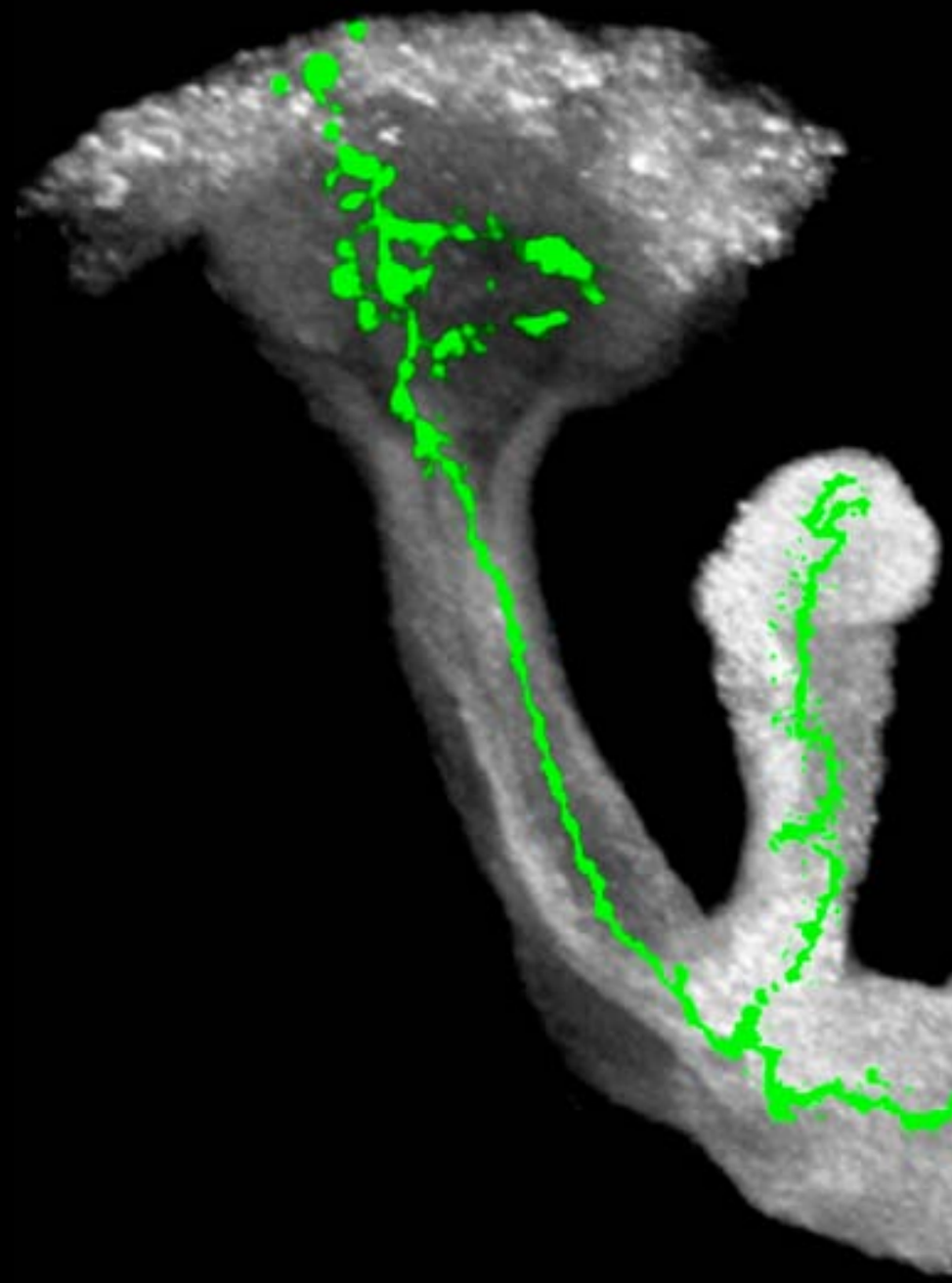
1-8 cells/type

~ 50 types

~ 200 cells

Yoshi Aso, Daisuke Hattori

Courtesy of Yoshi Aso. Used with permission.



Kenyon cells

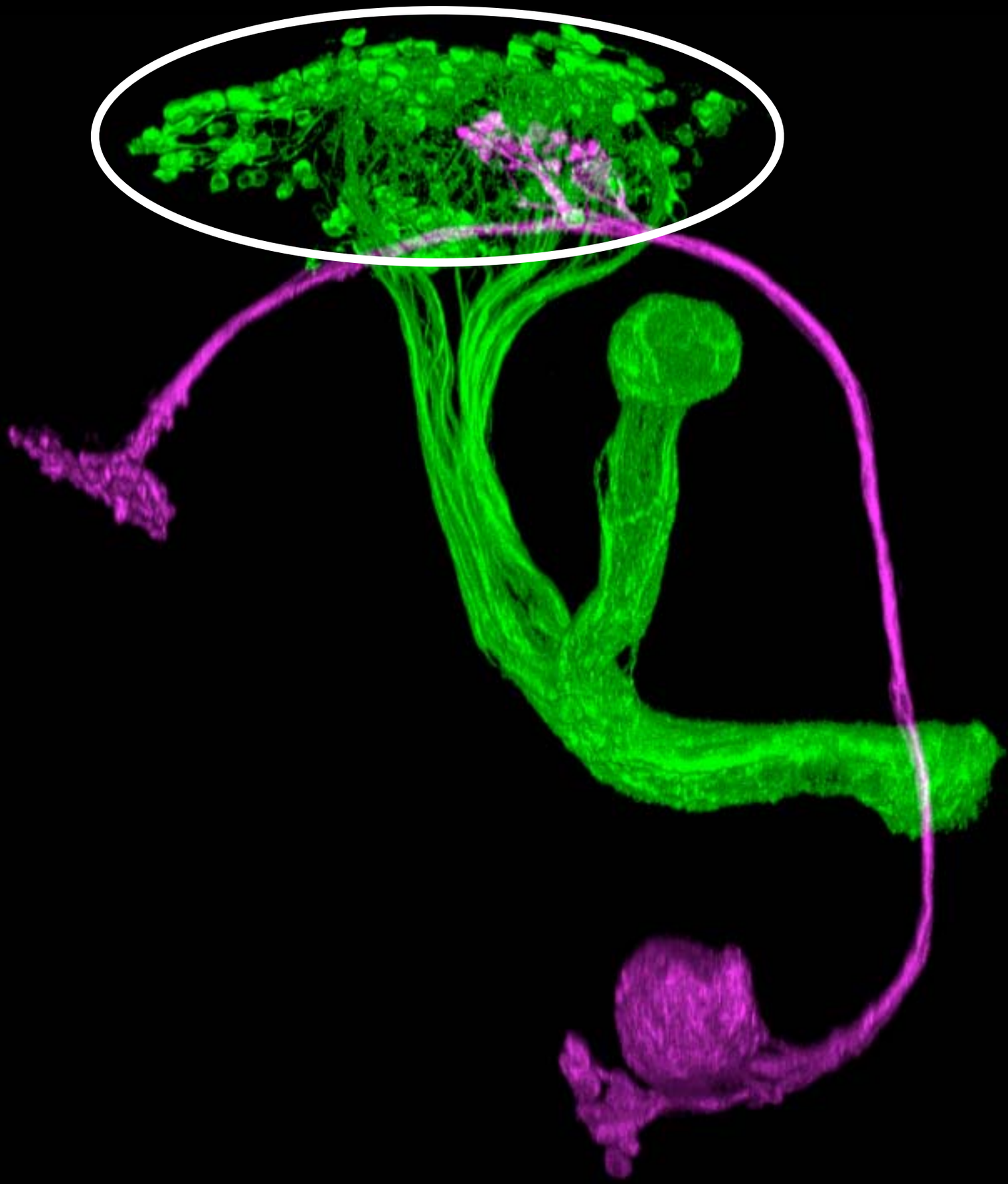
70-600 cells/type

~ 7 types

~ 2000 cells

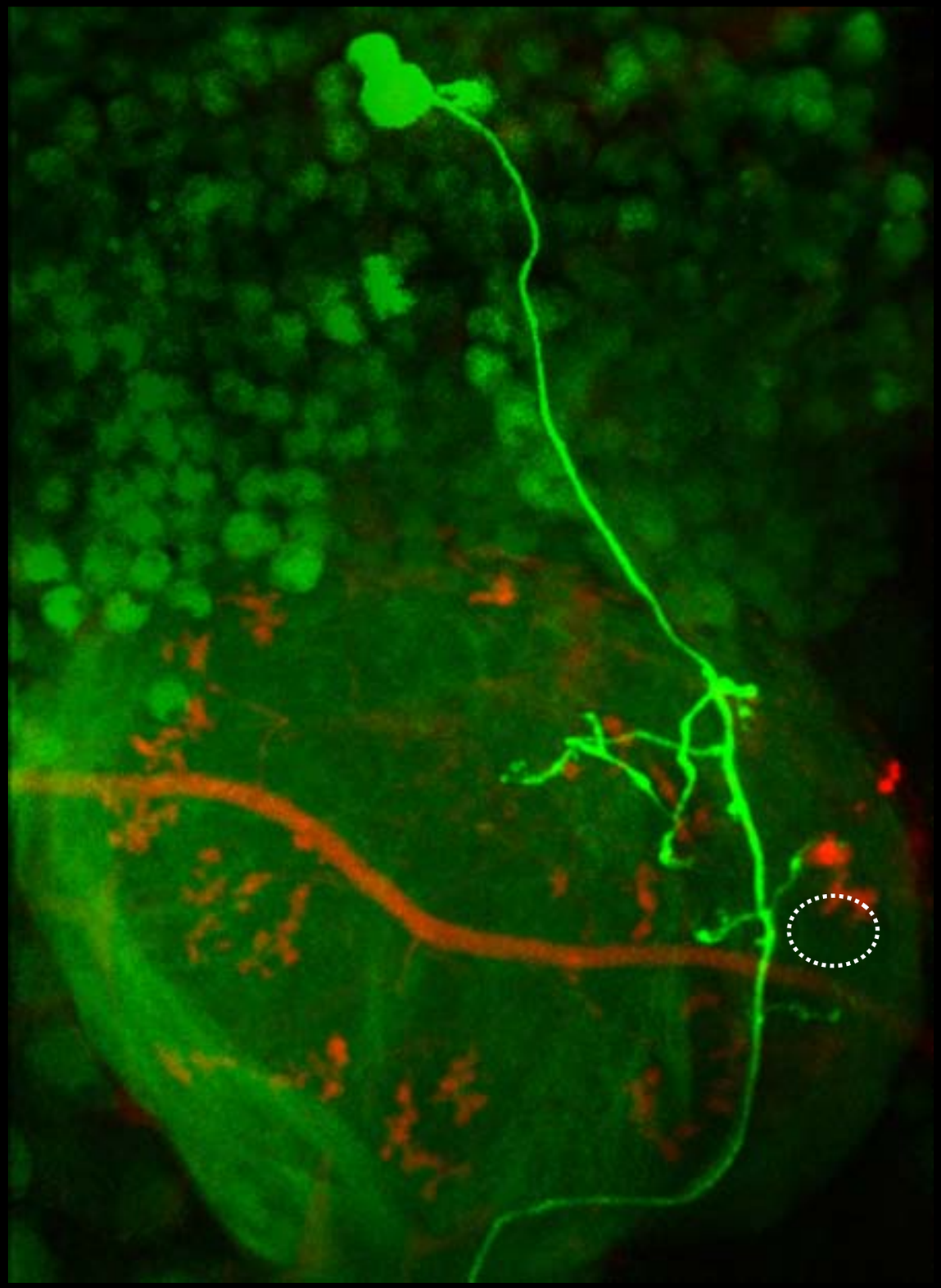
Courtesy of Yoshi Aso. Used with permission.

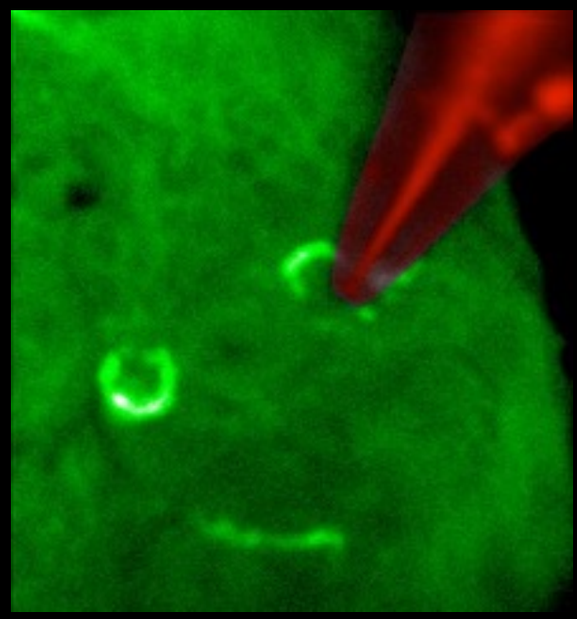
Yoshi Aso, Daisuke Hattori

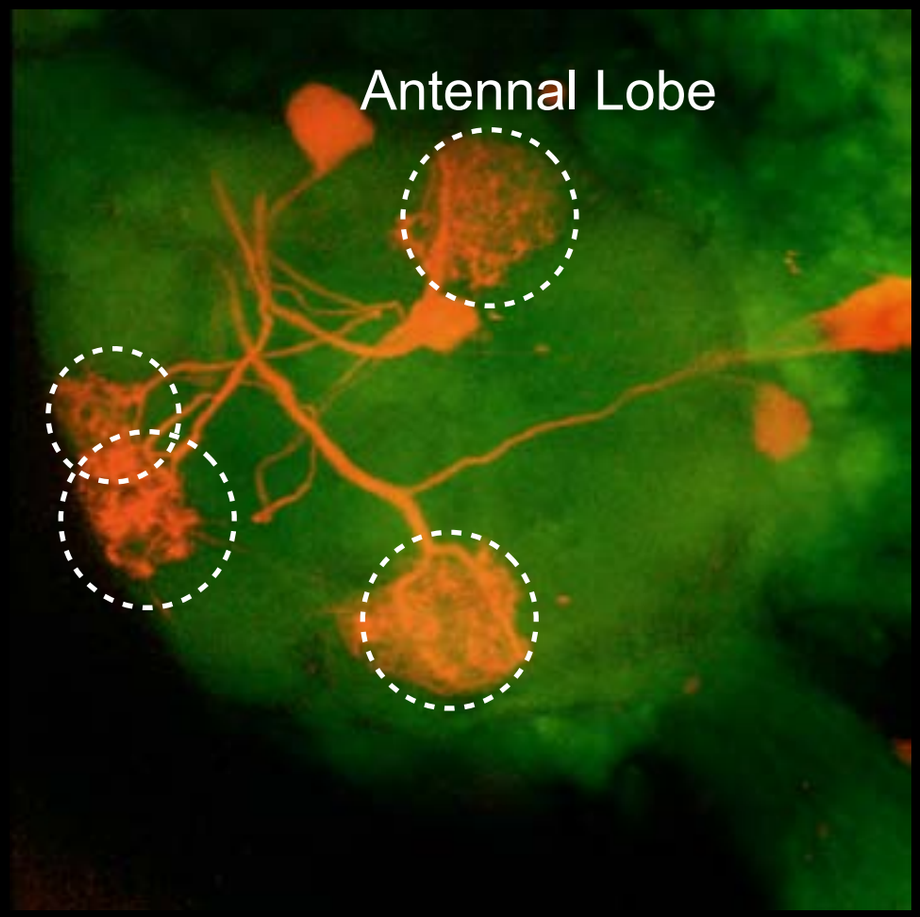


Yoshi Aso, Daisuke Hattori

Courtesy of Yoshi Aso. Used with permission.

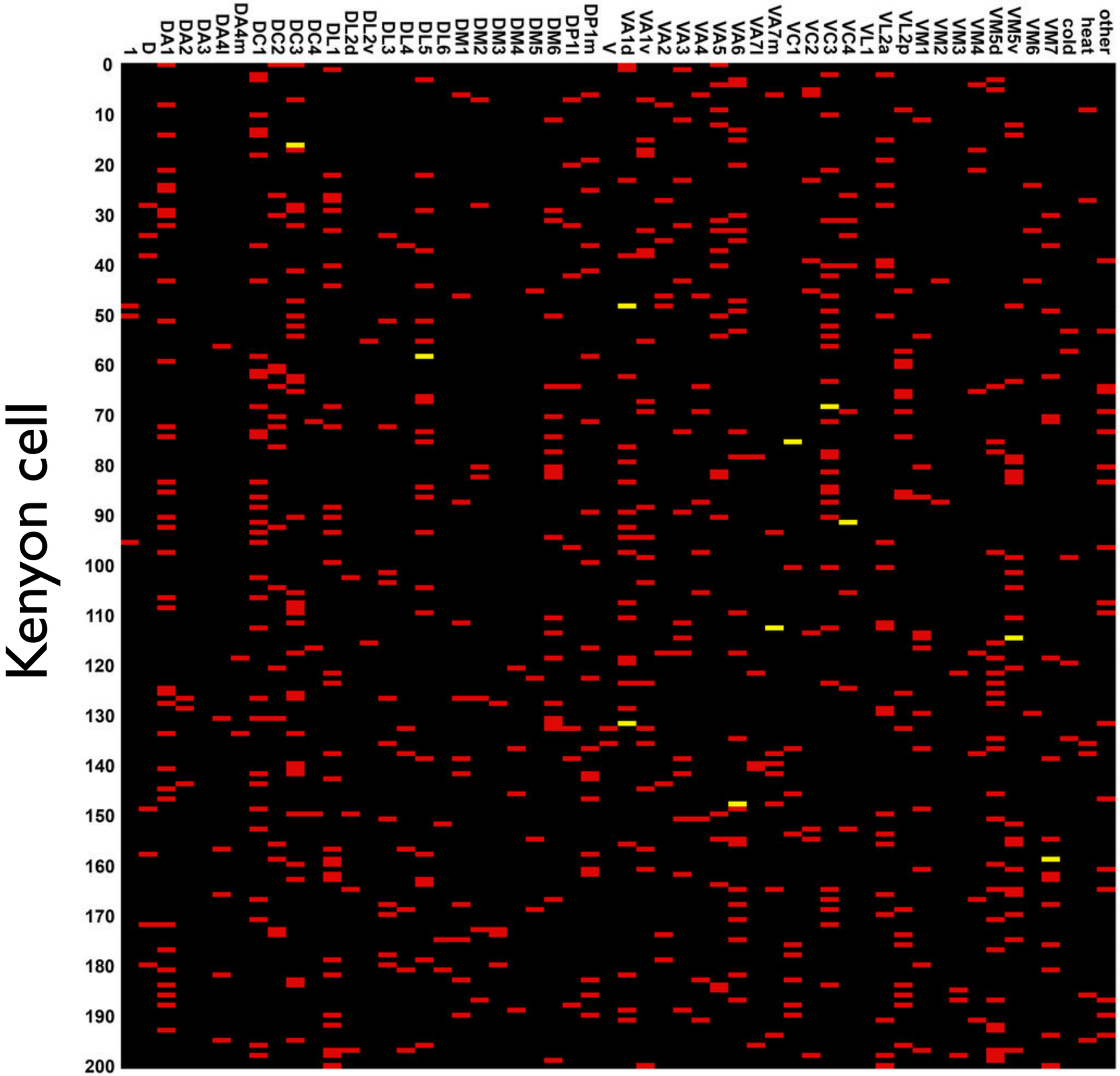


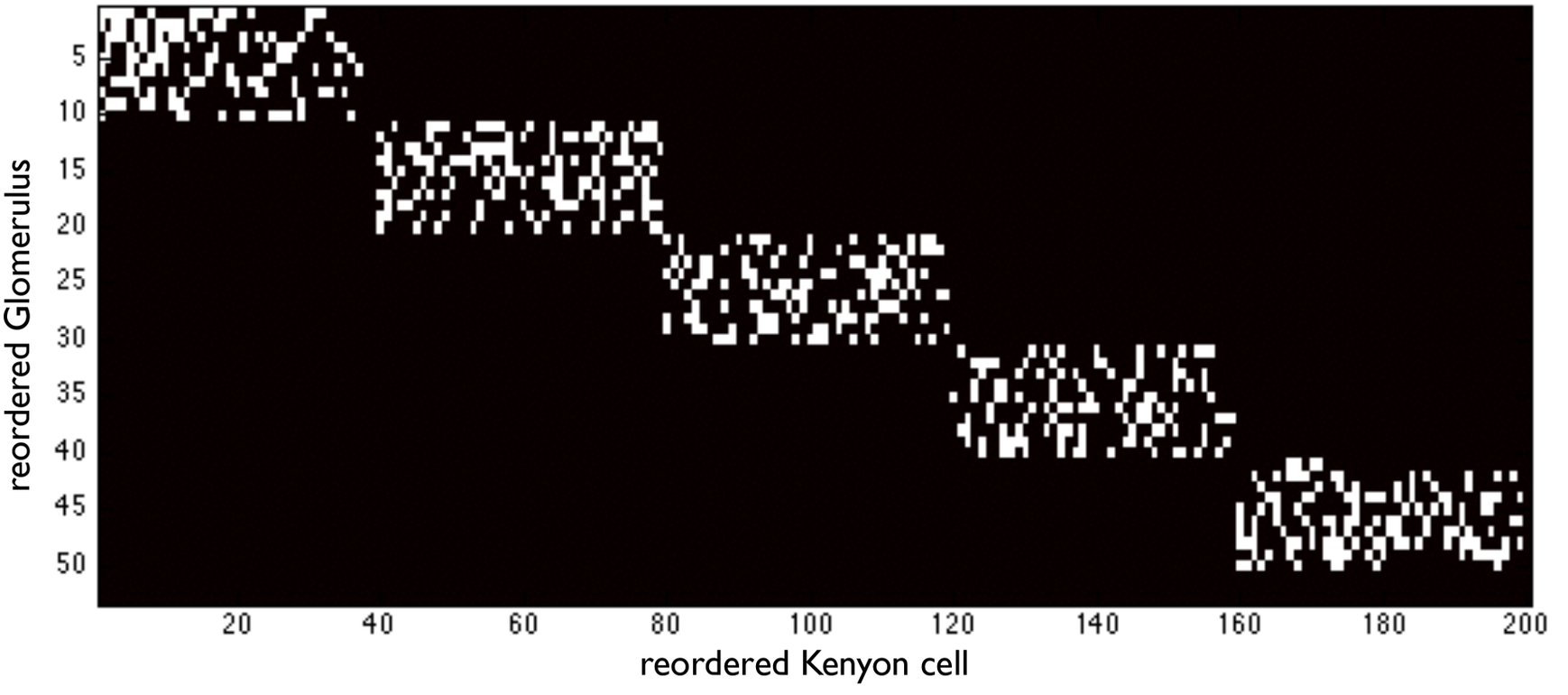


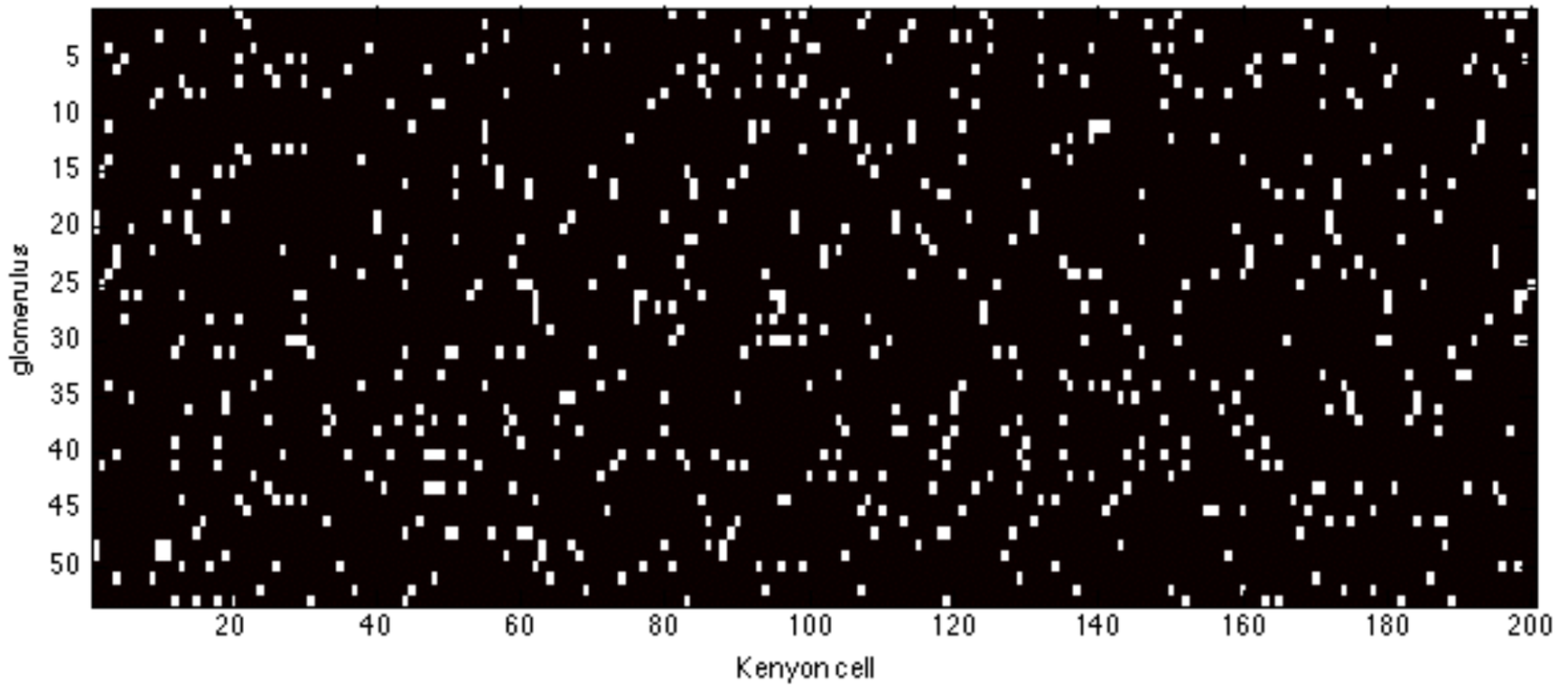


Caron, Ruta, Abbott, Richard Axel, 2013

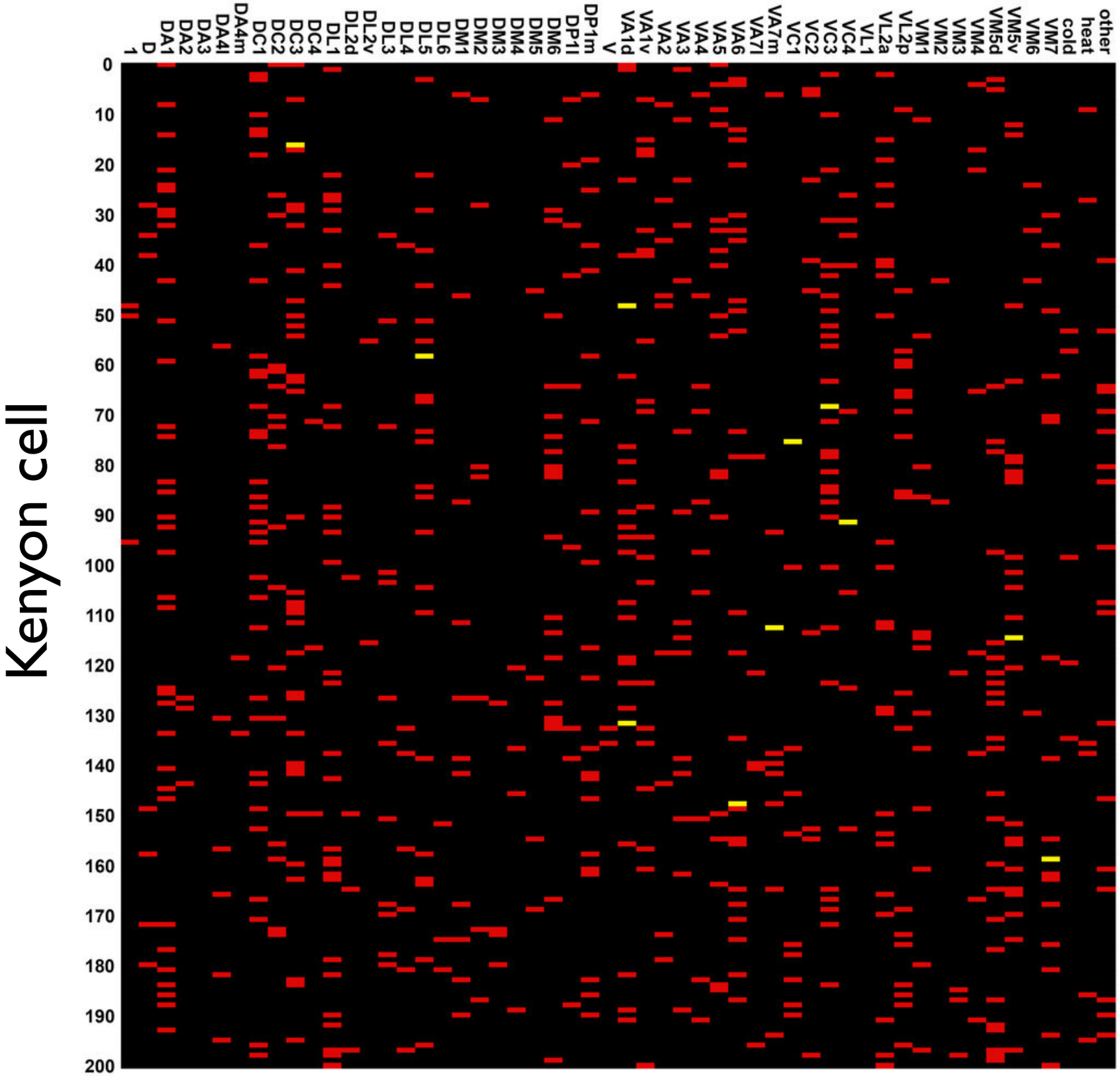
glomerulus



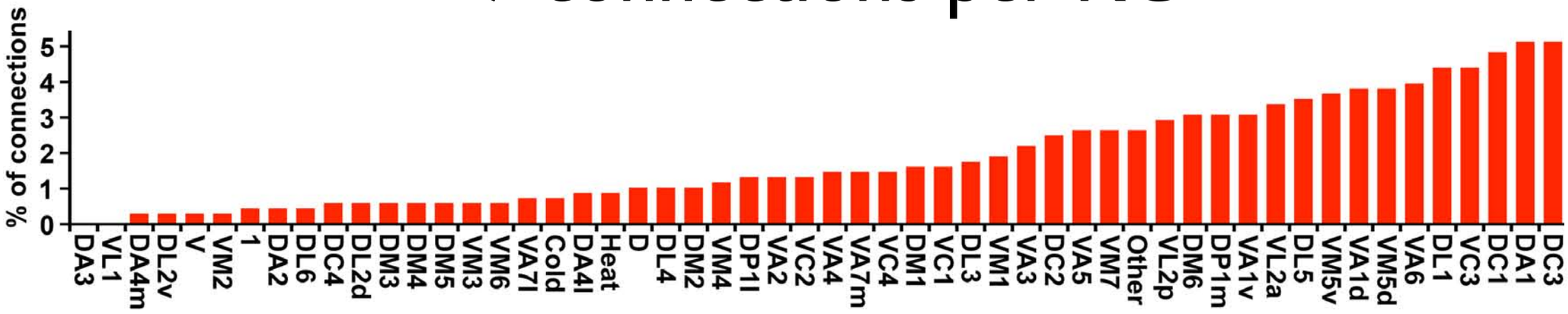

reordered Glomerulus
5
10
15
20
25
30
35
40
45
50
20
40
60
80
100
120
140
160
180
200
reordered Kenyon cell


glomerulus
5
10
15
20
25
30
35
40
45
50
20
40
60
80
100
120
140
160
180
200
Kenyon cell

glomerulus



~7 connections per KC



Further structure?

No

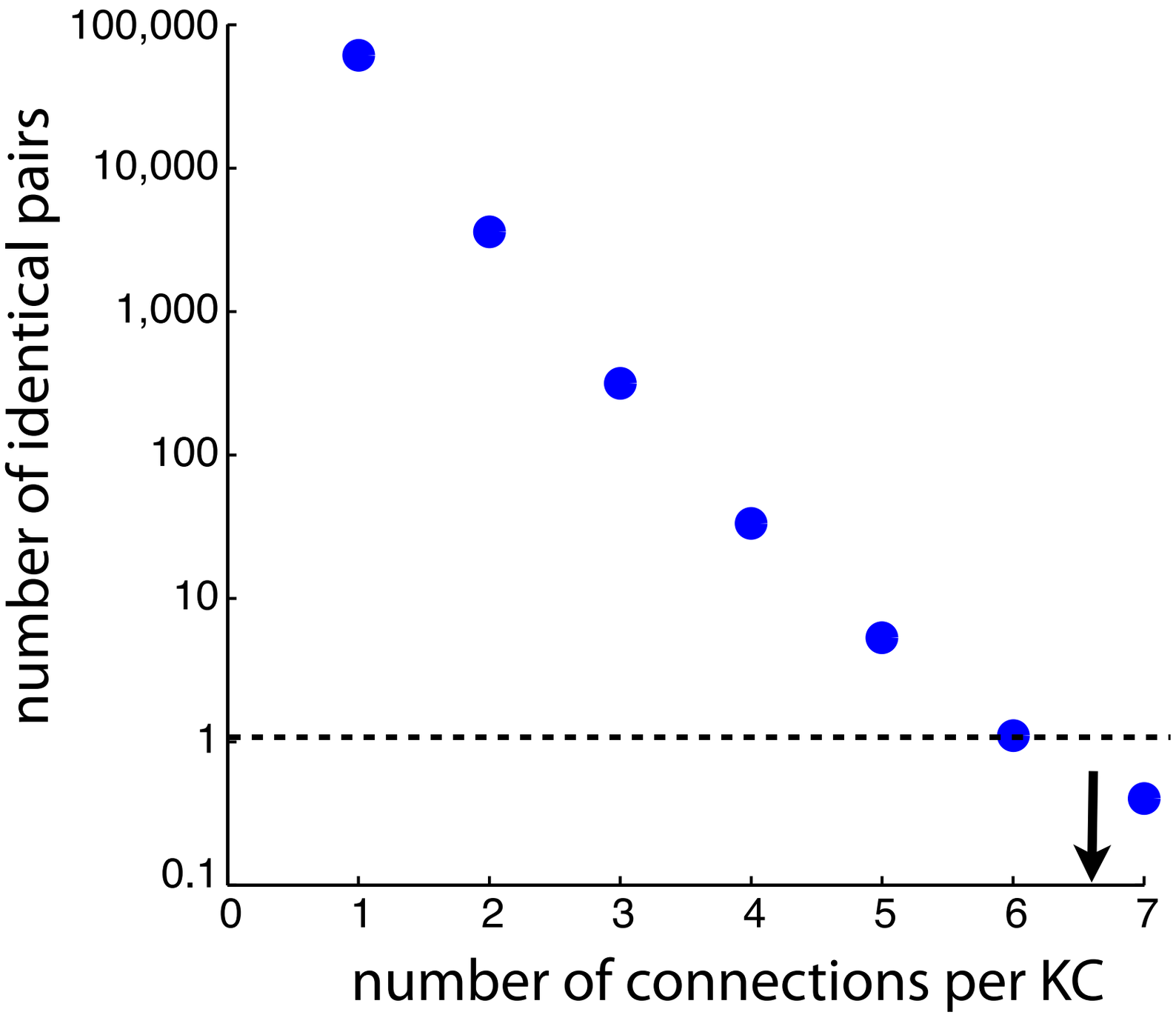
all tests consistent with random draws
from this glomerular distribution

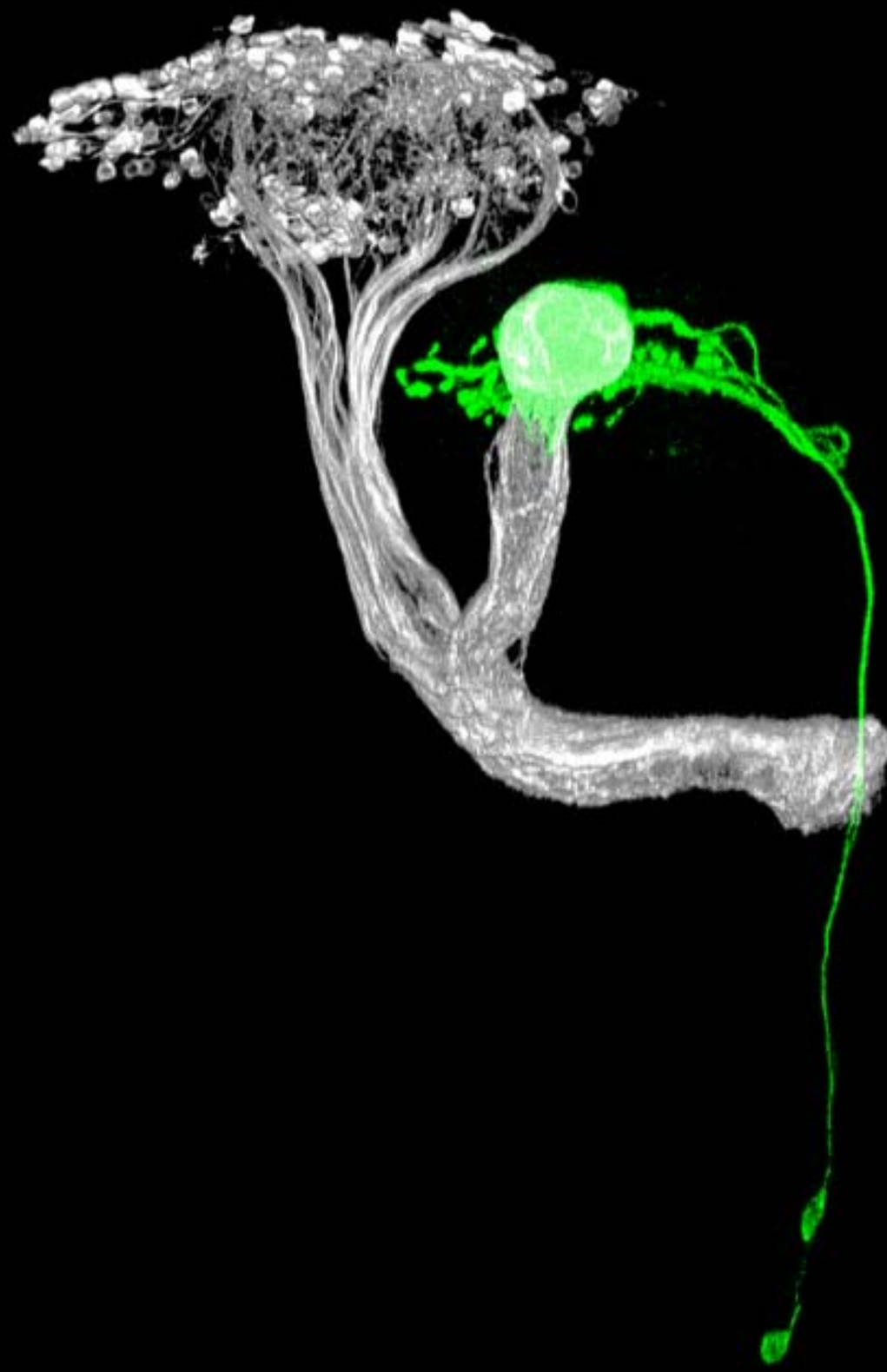
Murthy, Fiete, Laurent 2008

Caron, Ruta, Abbott, Richard Axel 2013

Gruntman, Turner 2013

Why 7 connections?





MB-Output neurons

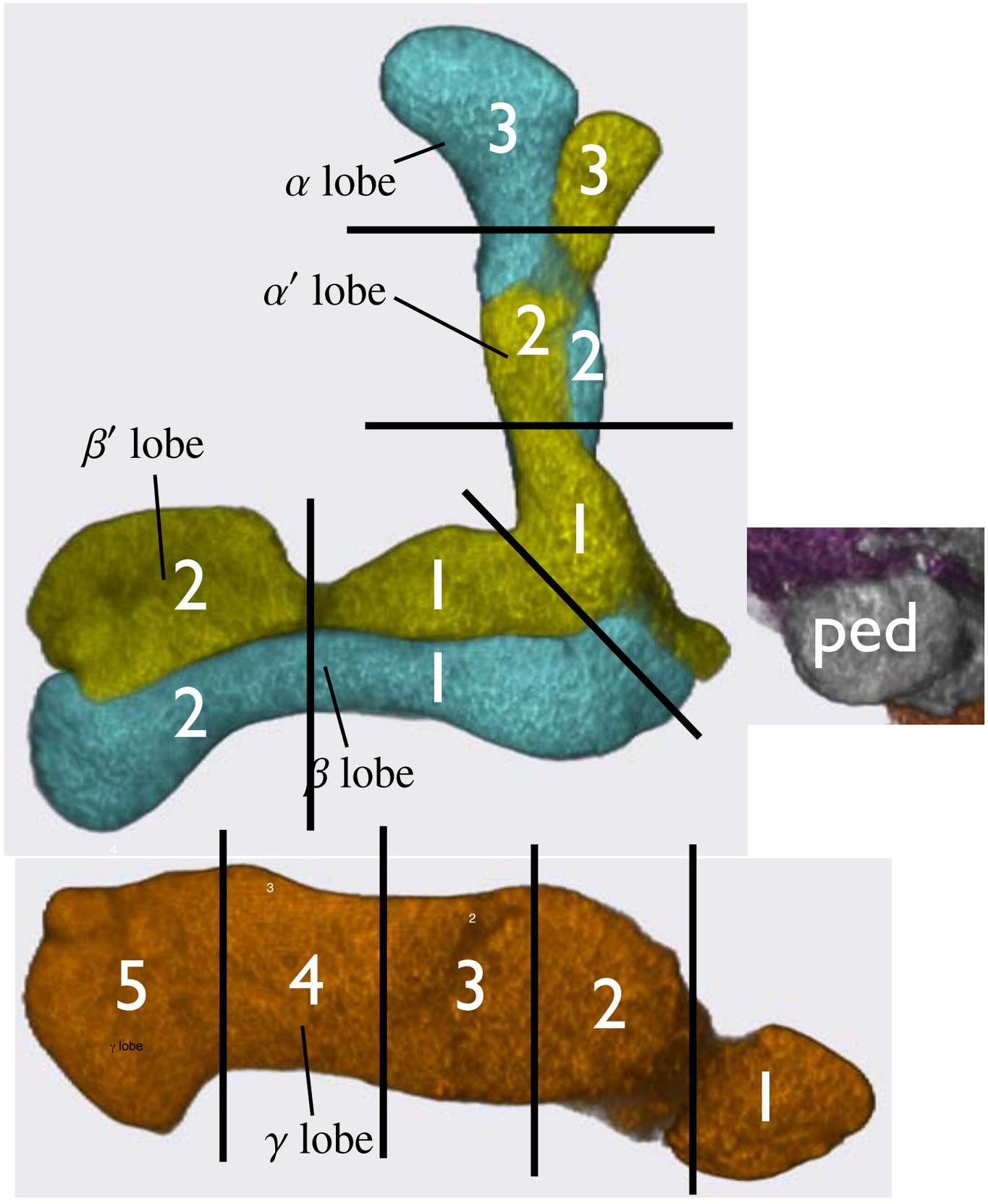
1-7 cells/type

21 types

34 cells

Courtesy of Yoshi Aso. Used with permission.

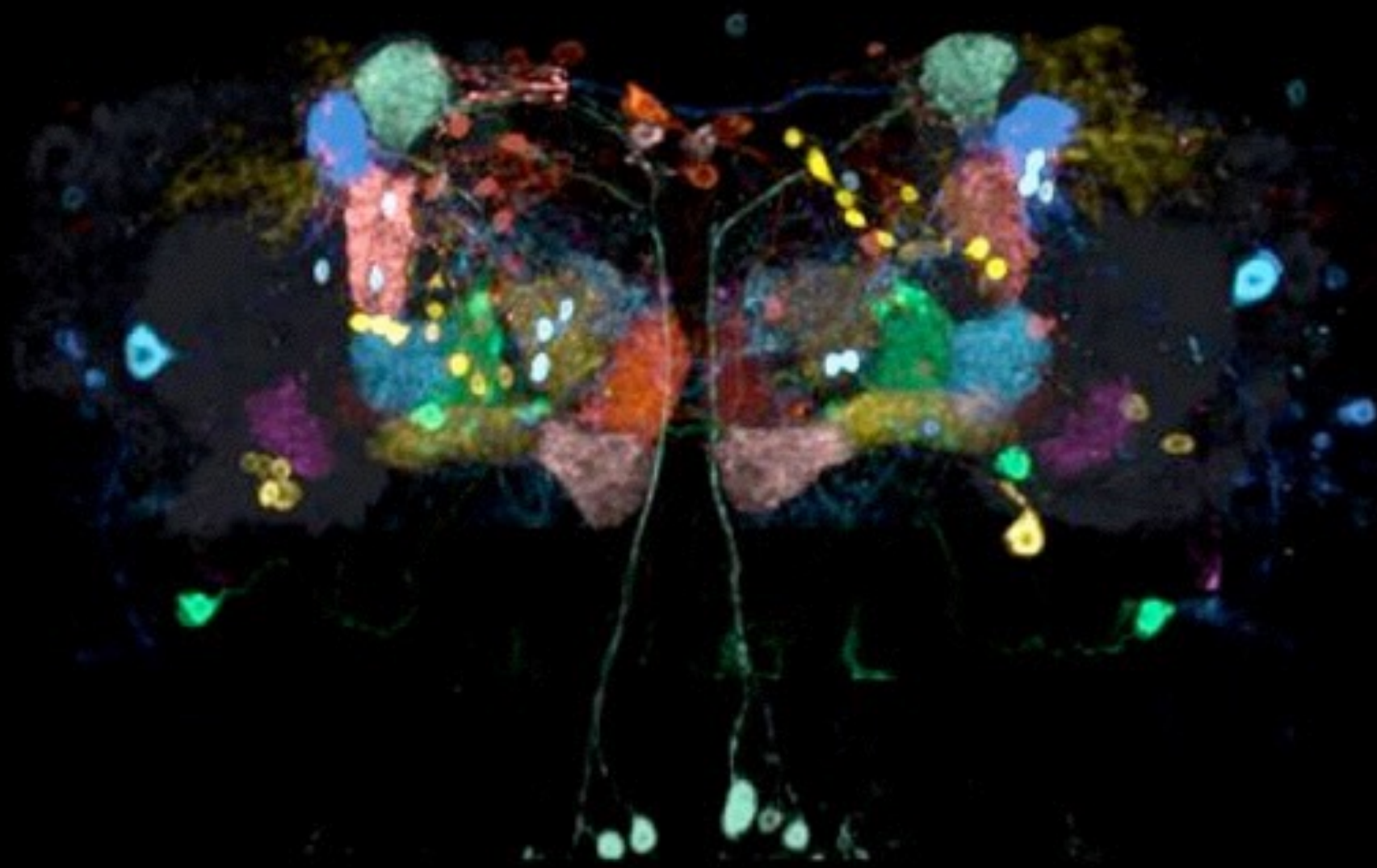
Yoshi Aso, Daisuke Hattori



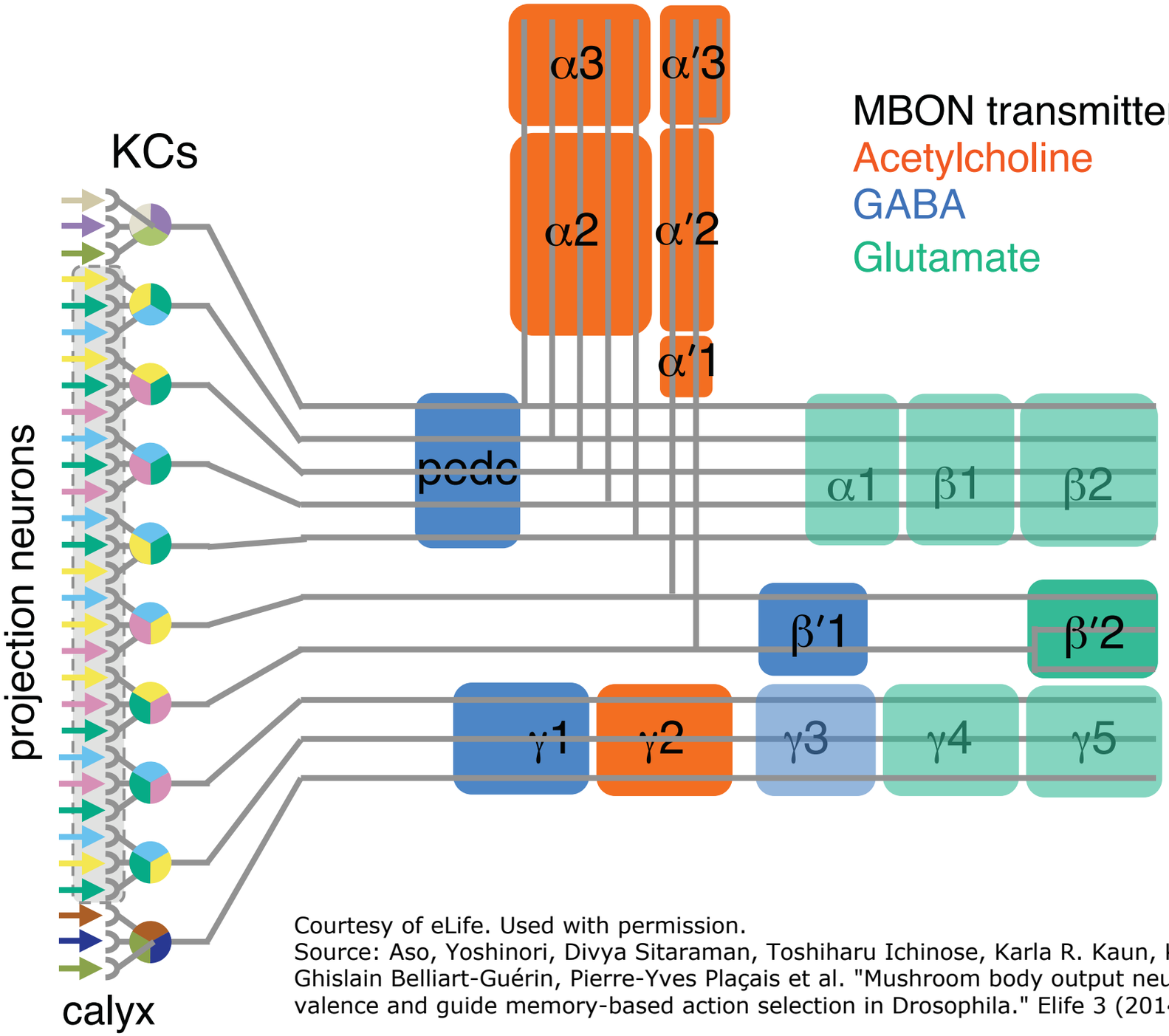
Tanaka, Tanimoto, Ito 2008

Mushroom Body Extrinsic Neurons

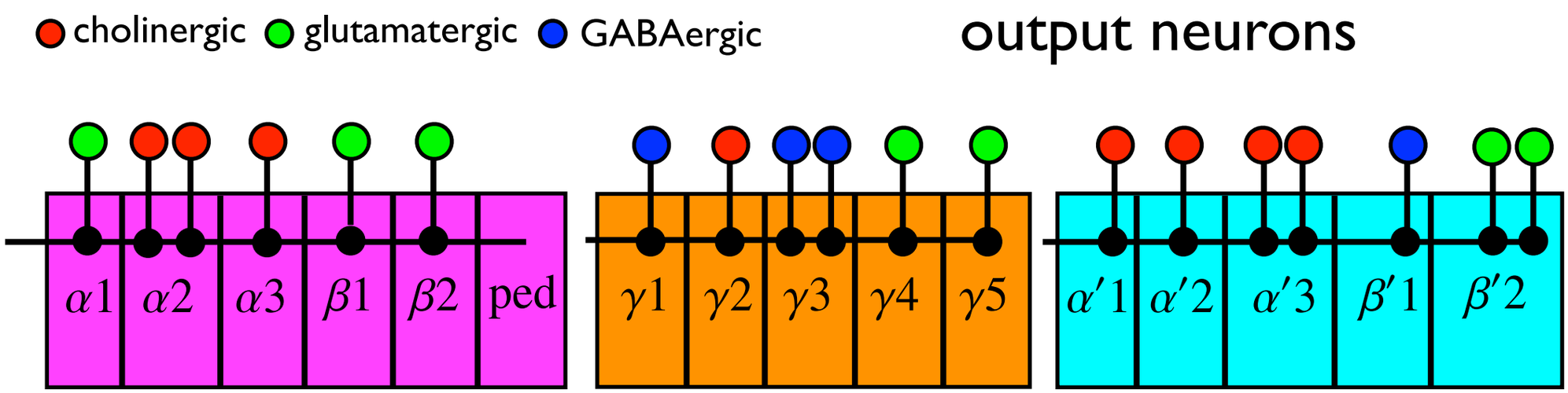
Registration of 13 Gal4 lines



Yoshinori Aso, Daisuke Hattori, Yang Yu, Rebecca M Johnston, Nirmala A Iyer, Teri-TB Ngo, Heather Dionne, LF Abbott, Richard Axel, Hiromu Tanimoto, Gerald M Rubin, 2014



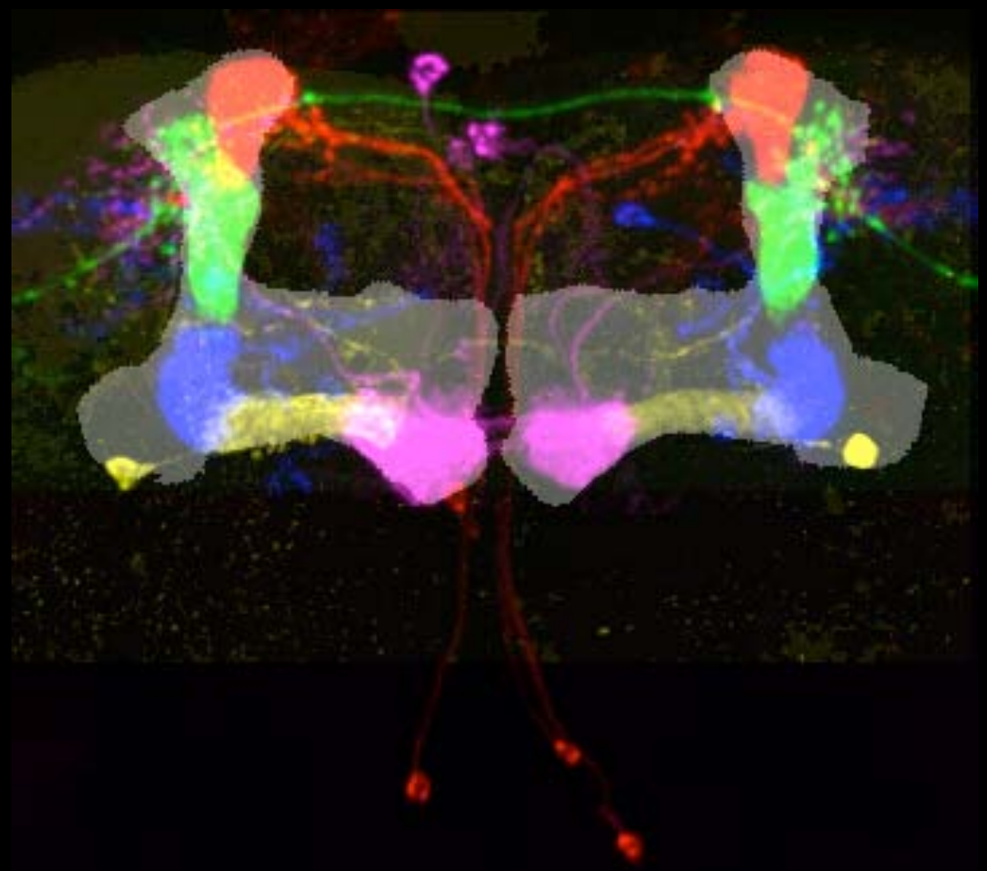
Courtesy of eLife. Used with permission.
Source: Aso, Yoshinori, Divya Sitaraman, Toshiharu Ichinose, Karla R. Kaun, Katrin Vogt, Ghislain Belliart-Guérin, Pierre-Yves Plaçais et al. "Mushroom body output neurons encode valence and guide memory-based action selection in Drosophila." Elife 3 (2014): e04580.


cholinergic
glutamatergic
GABAergic
output neurons
α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2

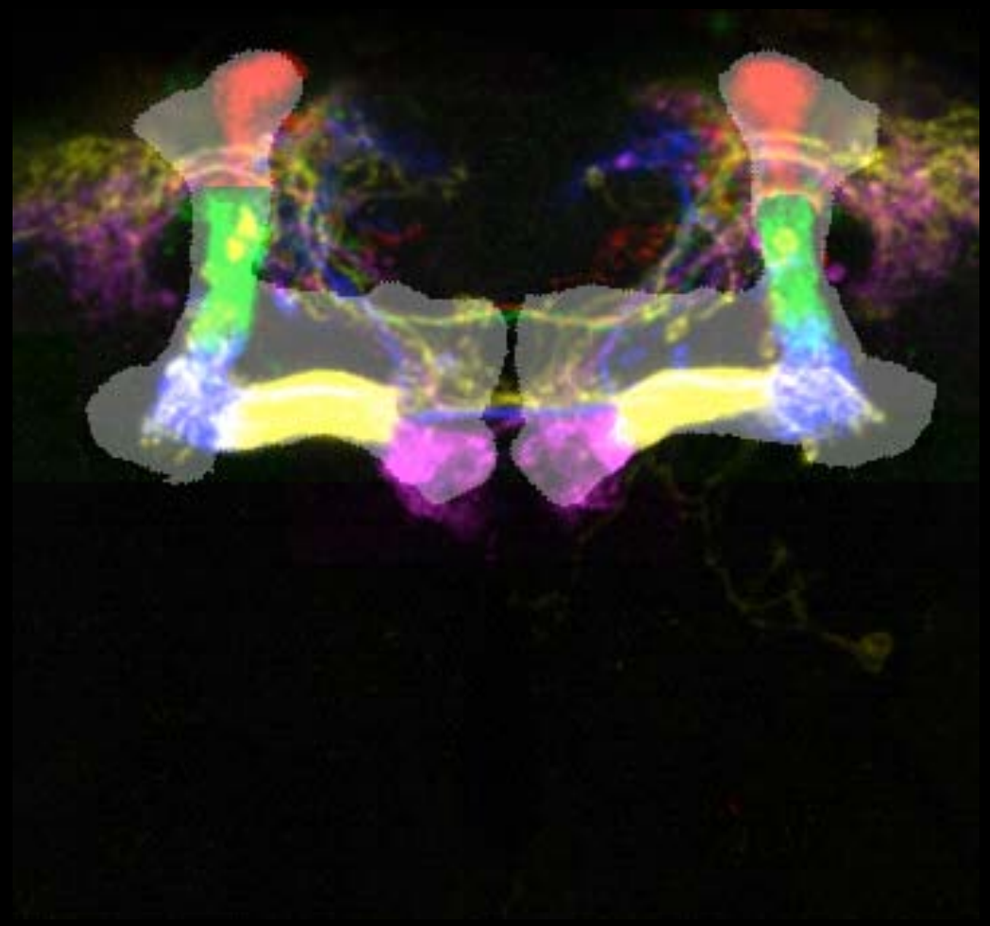
Mushroom body lobe synaptic units

Neurons innervating α/β lobes

Output neurons

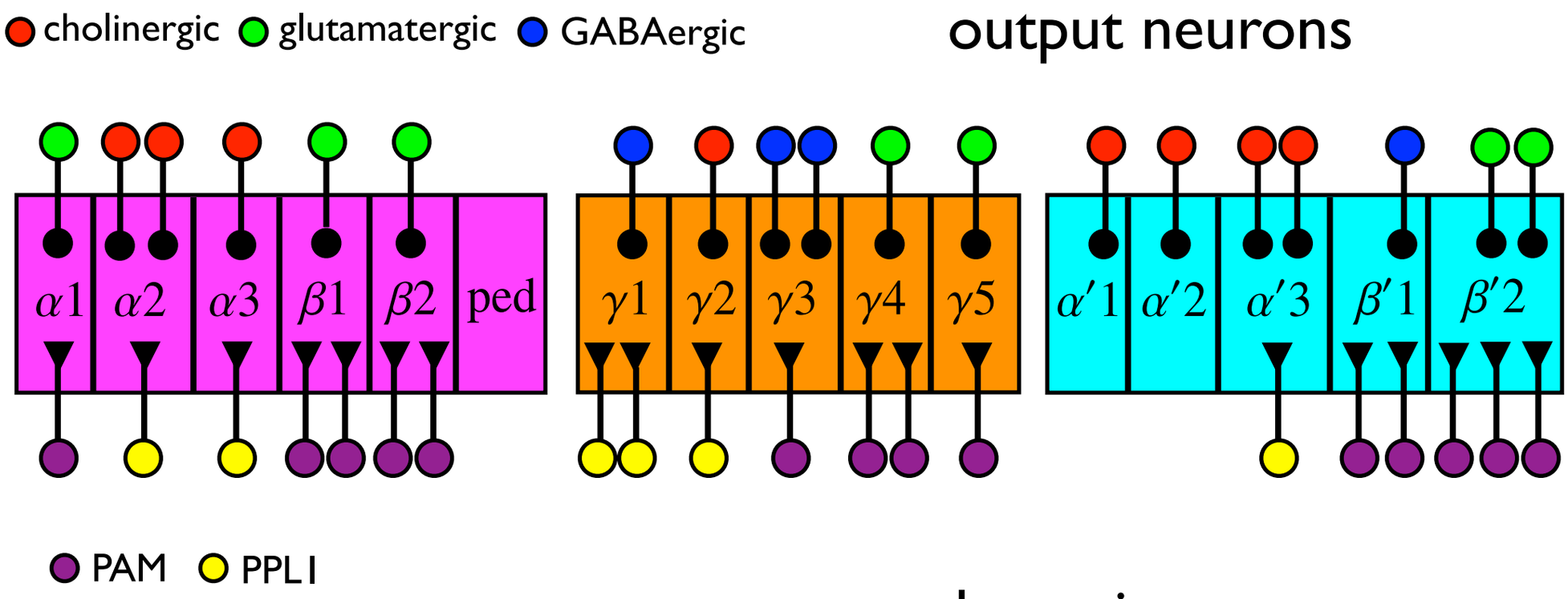


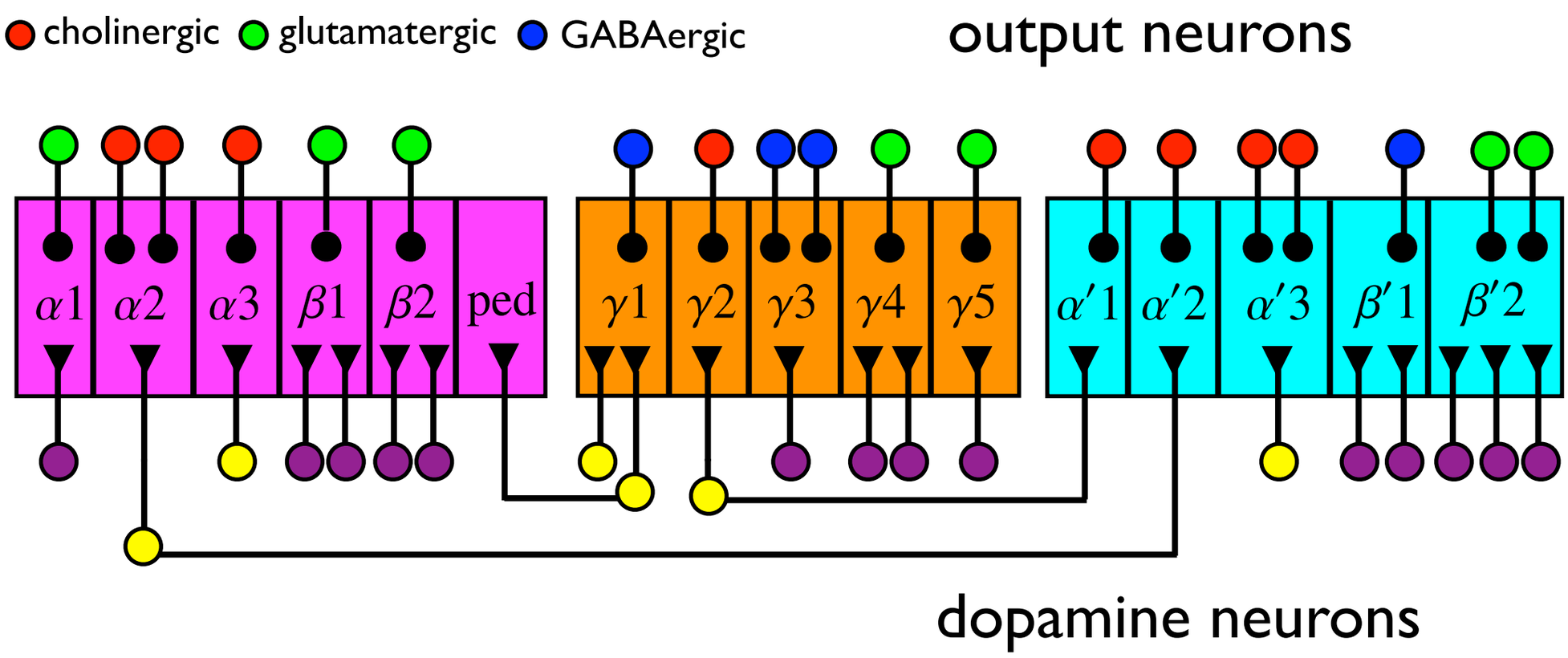
Dopaminergic neurons

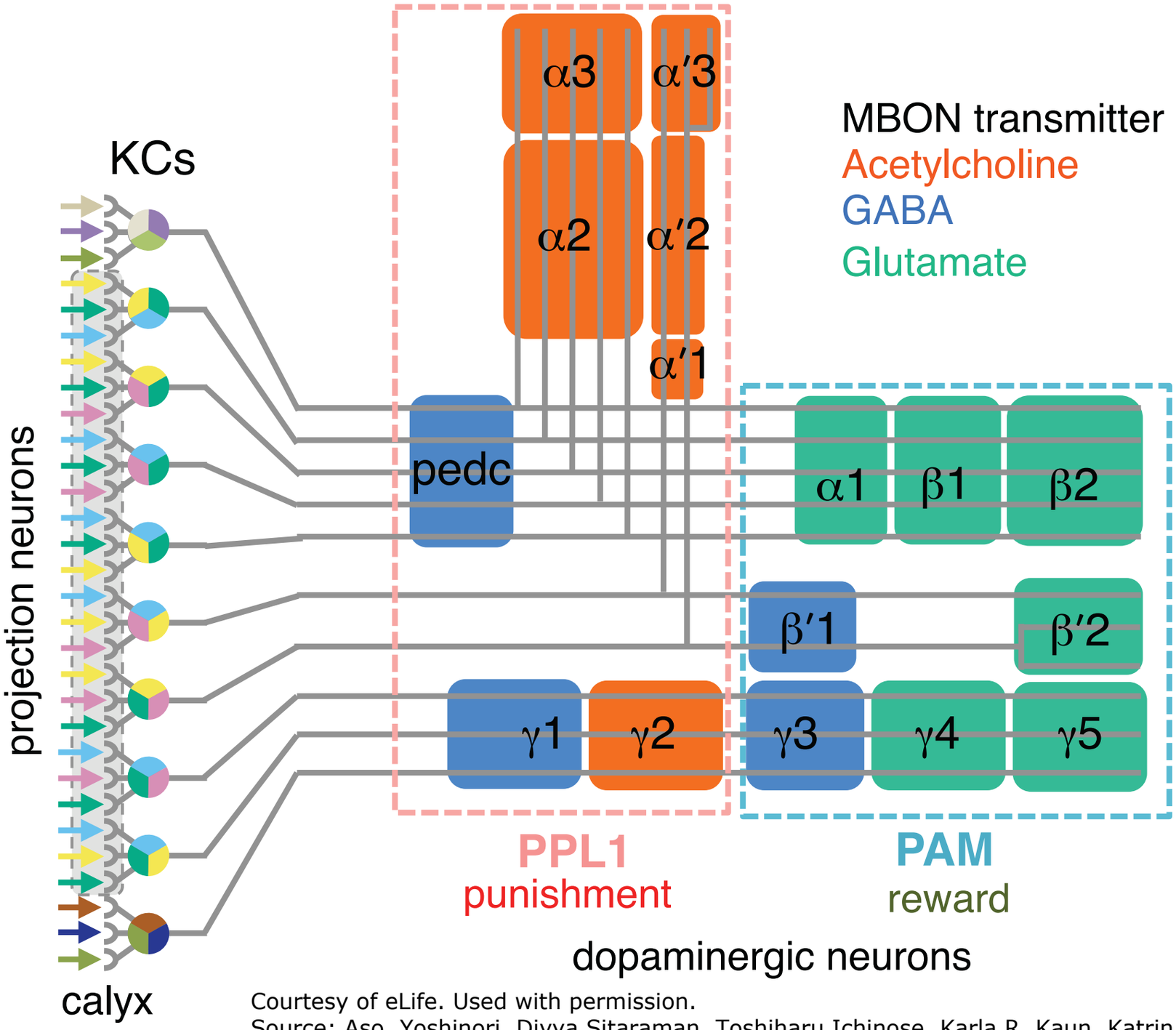


Courtesy of eLife. Used with permission.
Source: Aso, Yoshinori, Divya Sitaraman, Toshiharu Ichinose, Karla R. Kaun, Katrin Vogt, Ghislain Belliart-Guérin, Pierre-Yves Plaçais et al. "Mushroom body output neurons encode valence and guide memory-based action selection in Drosophila." Elife 3 (2014): e04580.

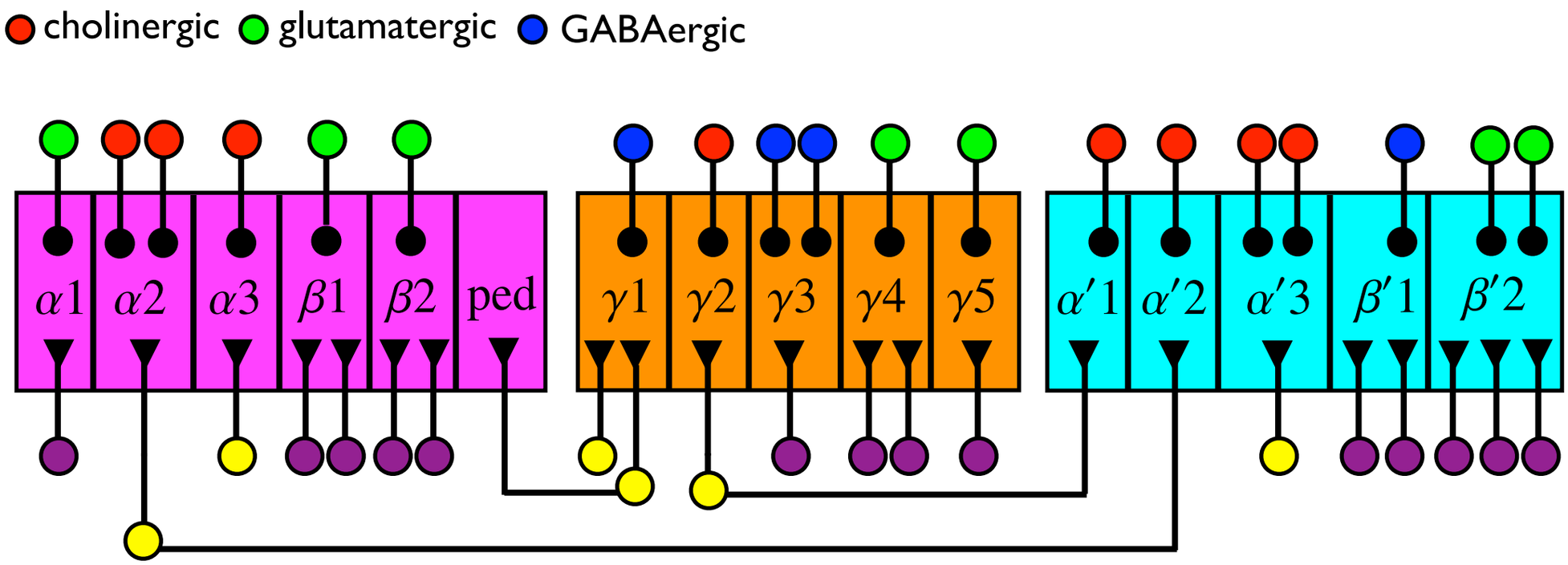
Yoshinori Aso, Daisuke Hattori, Yang Yu, Rebecca M Johnston, Nirmala A Iyer, Teri-TB Ngo, Heather Dionne, LF Abbott, Richard Axel, Hiromu Tanimoto, Gerald M Rubin, 2014

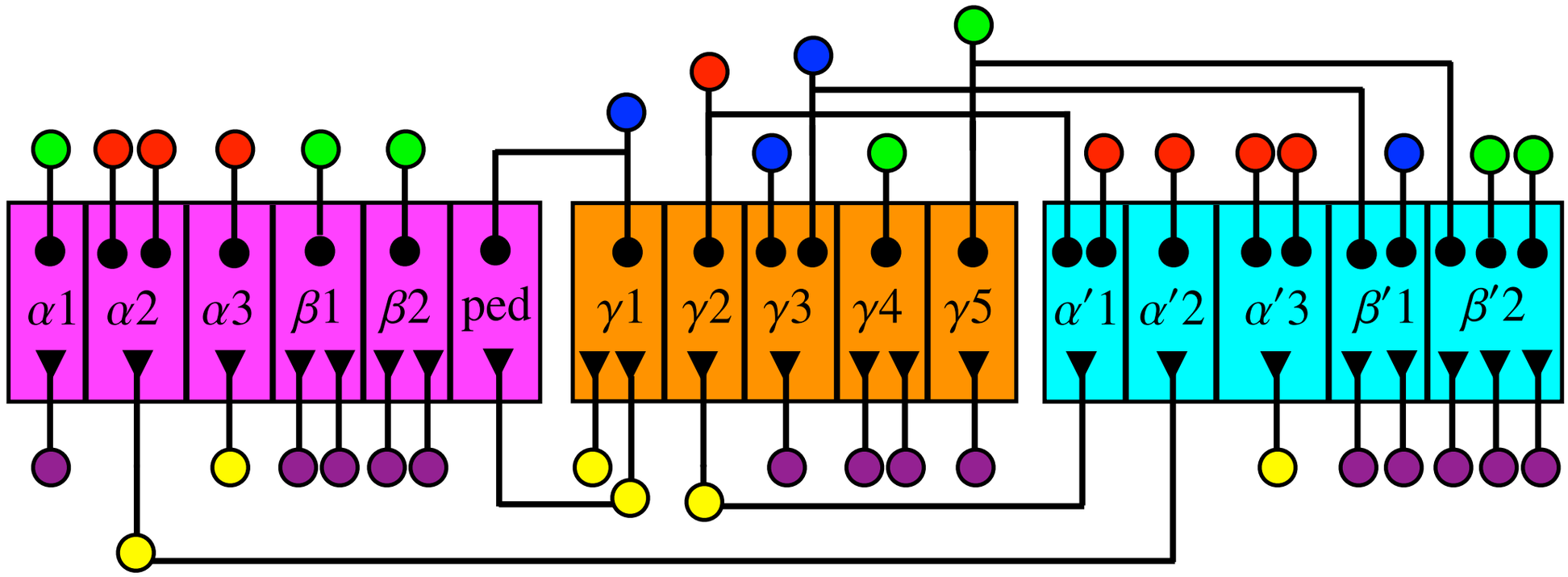

cholinergic
glutamatergic
GABAergic
output neurons
α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2
PAM
PPL1
dopamine neurons

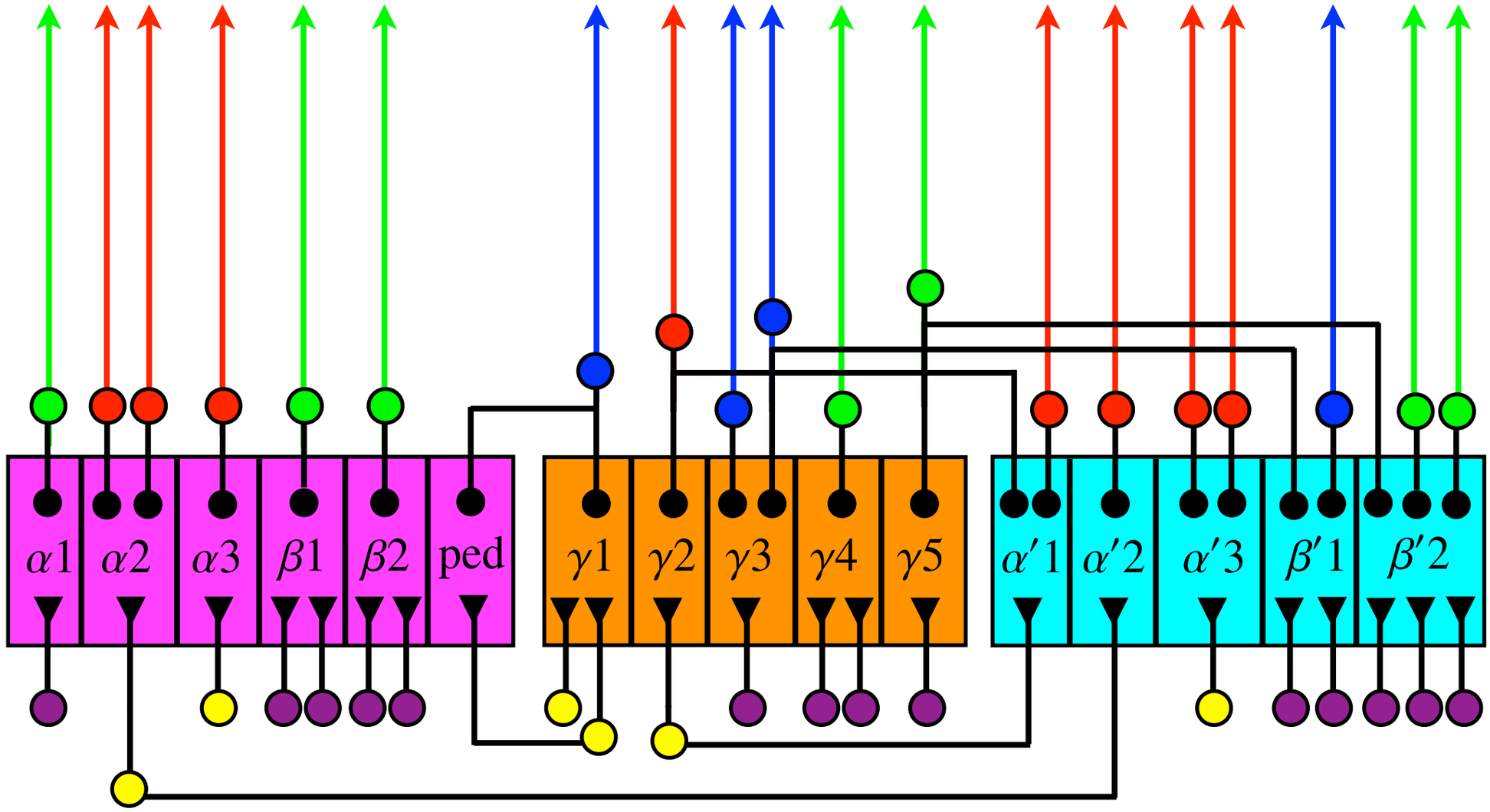

cholinergic
glutamatergic
GABAergic
output neurons
α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2
dopamine neurons

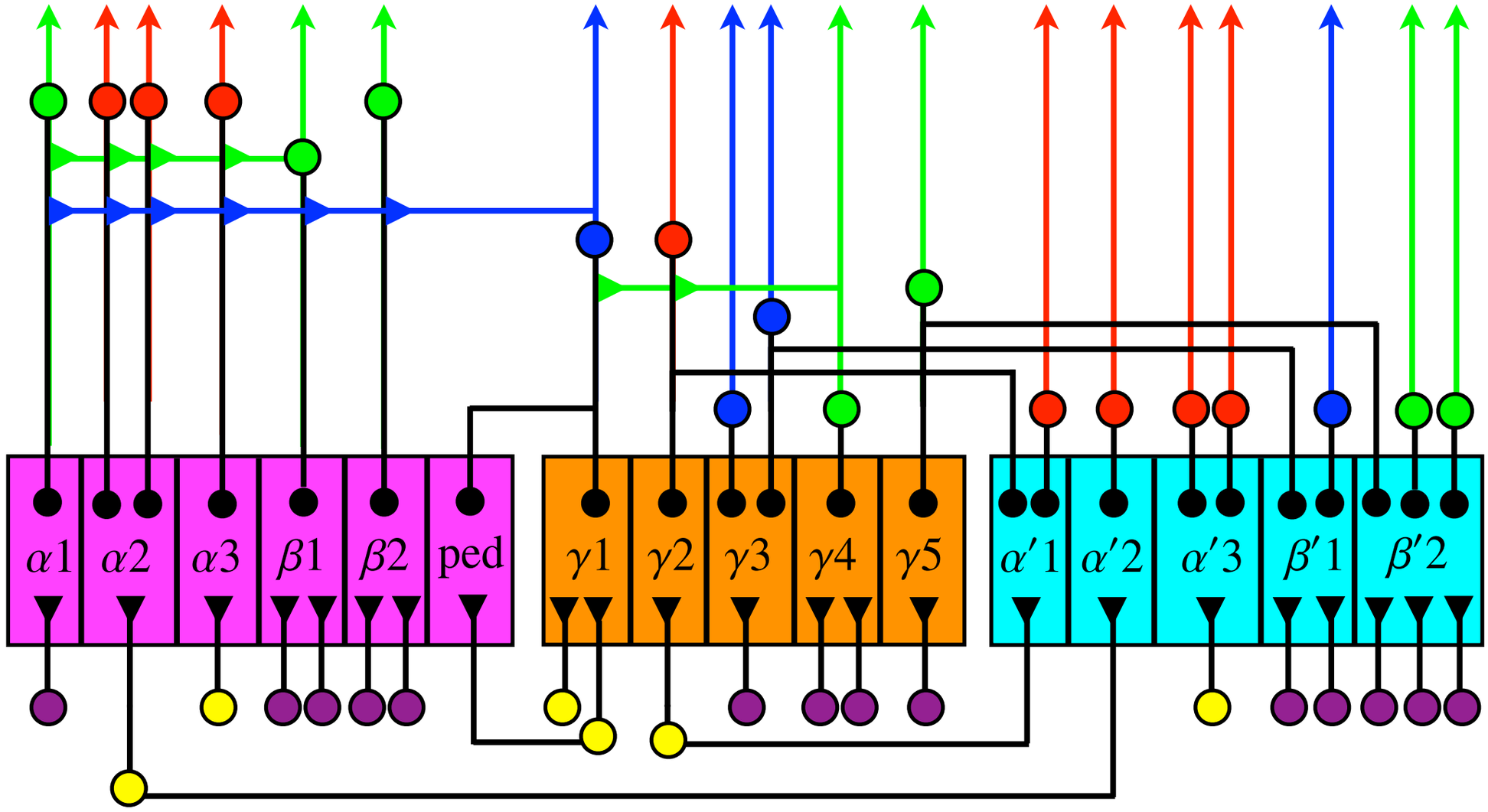


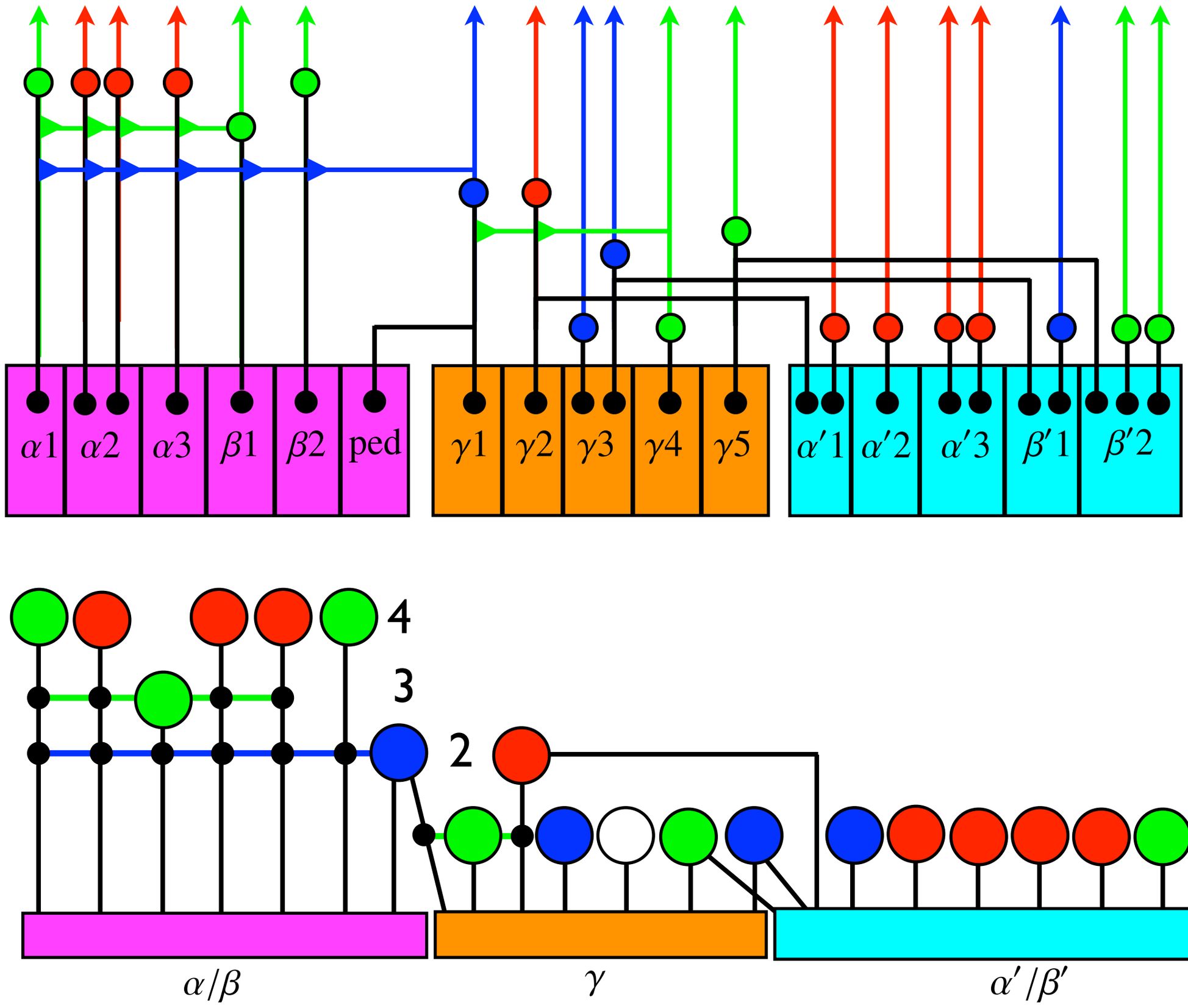
Courtesy of eLife. Used with permission.
Source: Aso, Yoshinori, Divya Sitaraman, Toshiharu Ichinose, Karla R. Kaun, Katrin Vogt, Ghislain Belliart-Guérin, Pierre-Yves Plaçais et al. "Mushroom body output neurons encode valence and guide memory-based action selection in Drosophila." Elife 3 (2014): e04580.


cholinergic
glutamatergic
GABAergic
α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2

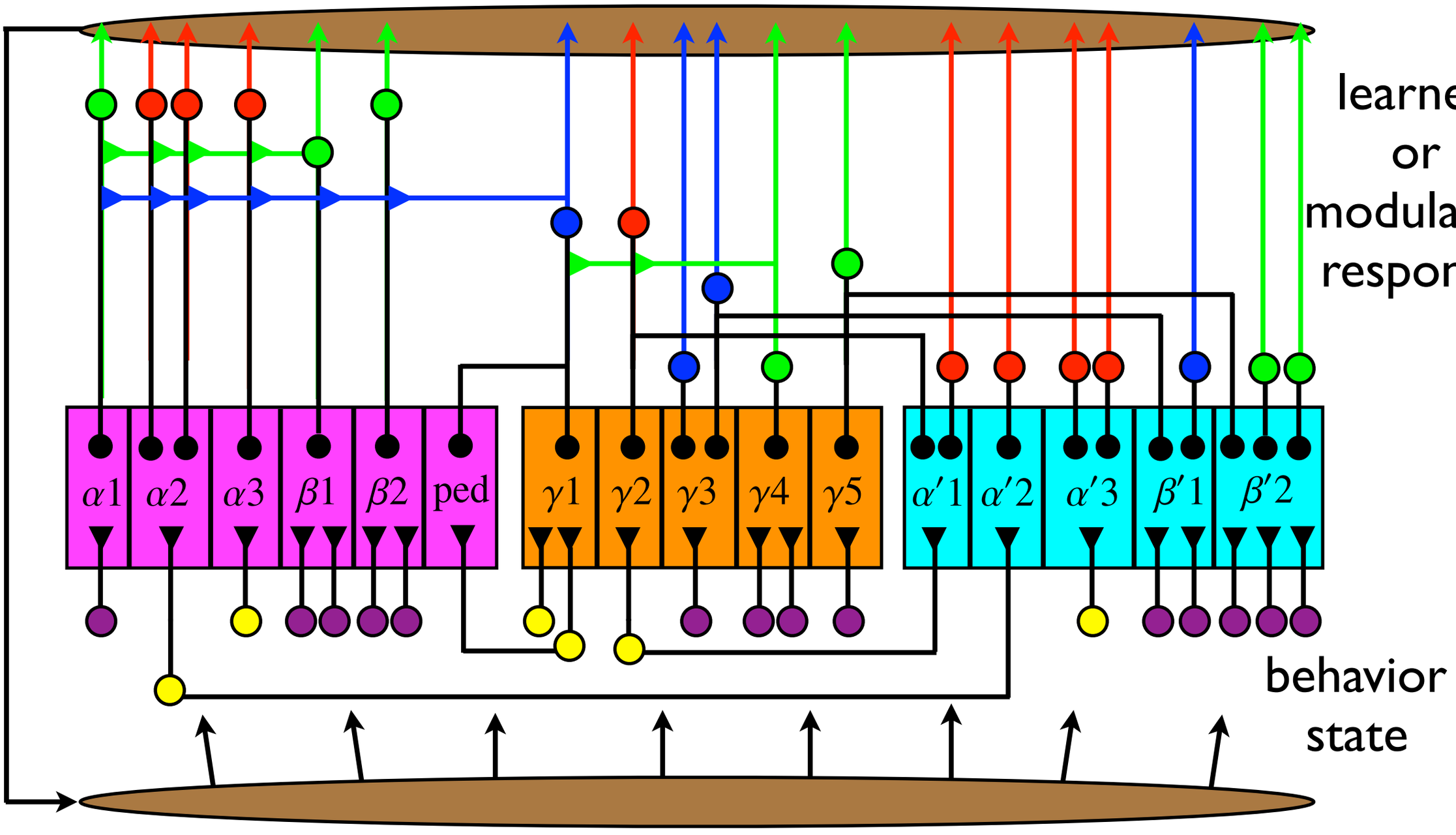

α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2


α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2

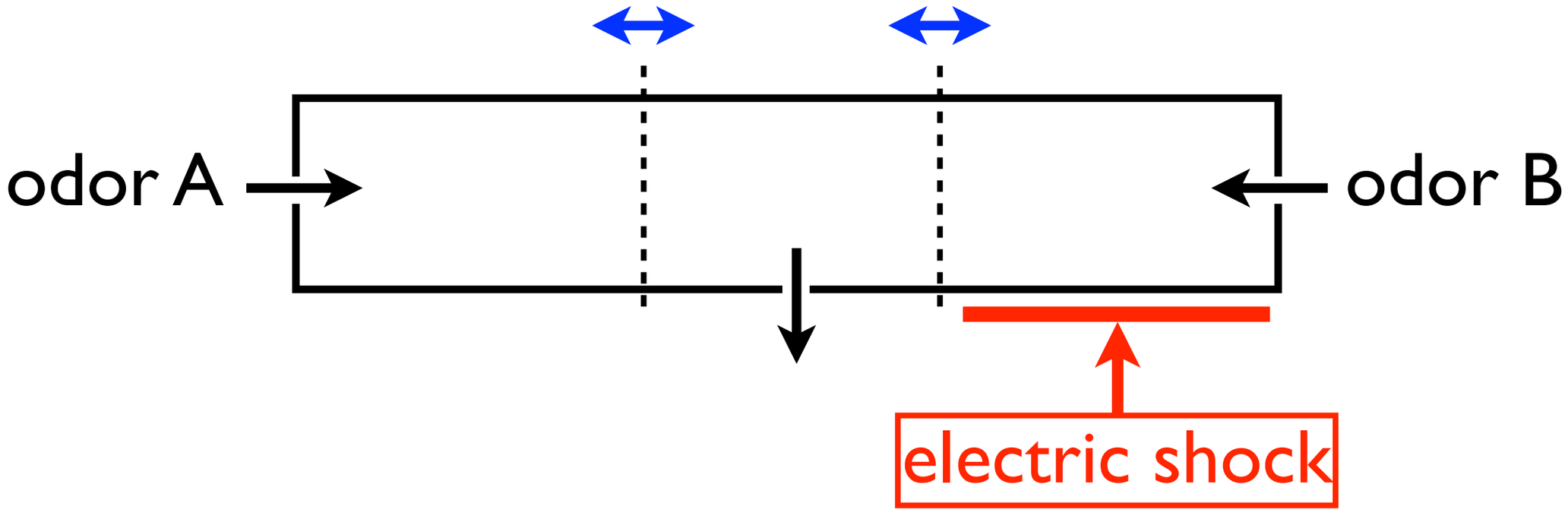

α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2


α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2
4
3
2
1
α/β
γ
α′/β′

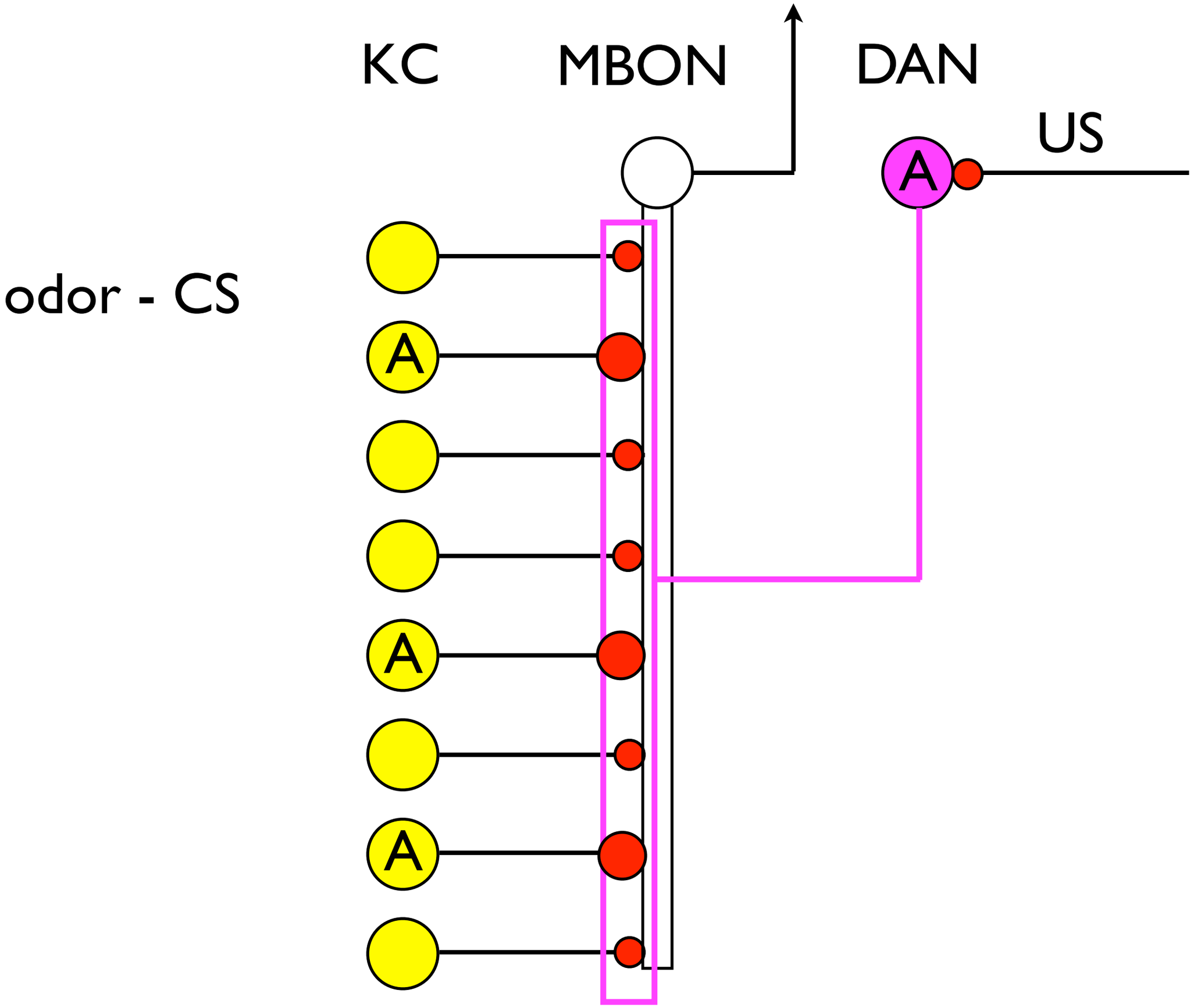
crepine, superior medial, intermediate and lateral protocerebrum, lateral horn

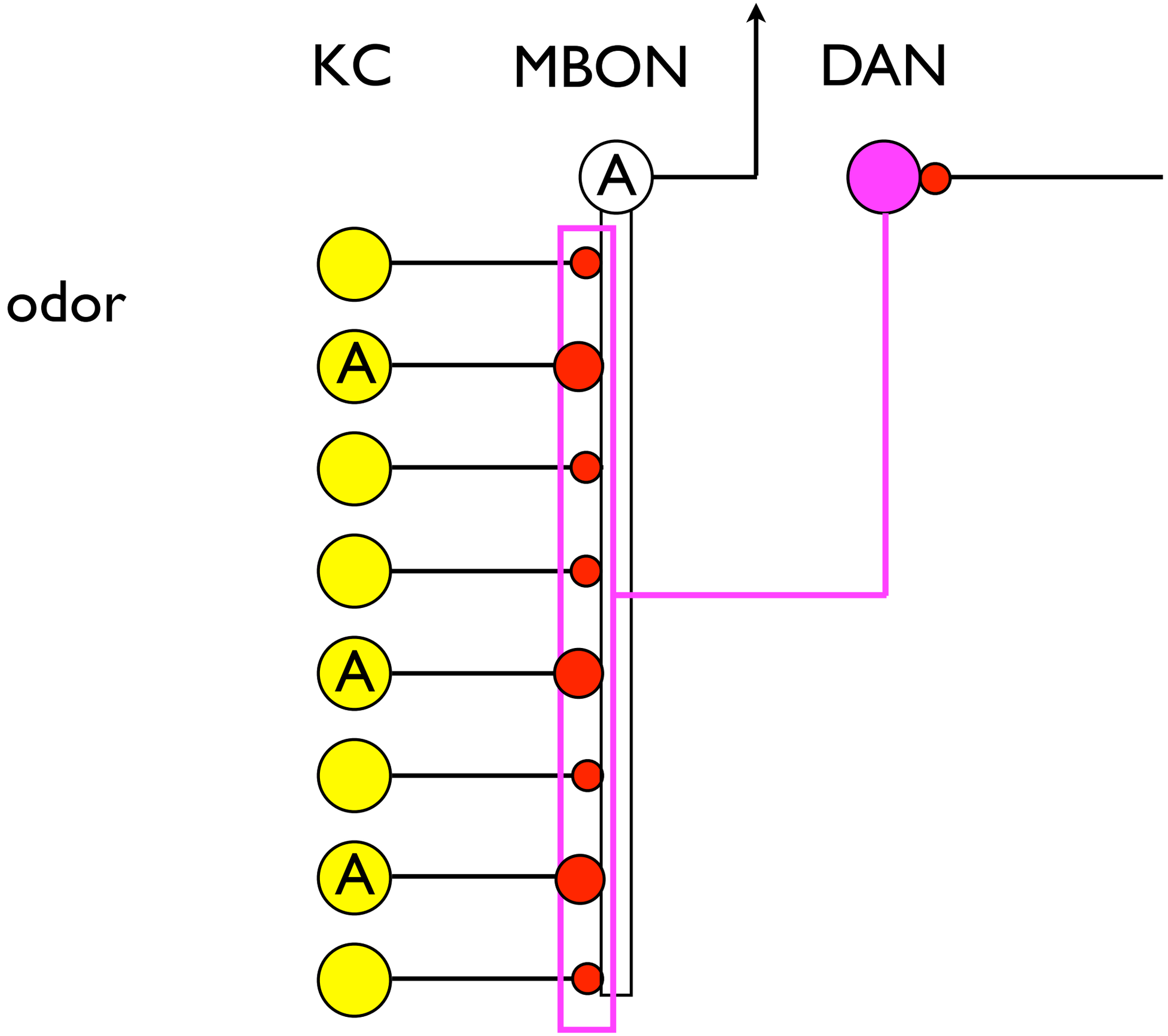


classical conditioning

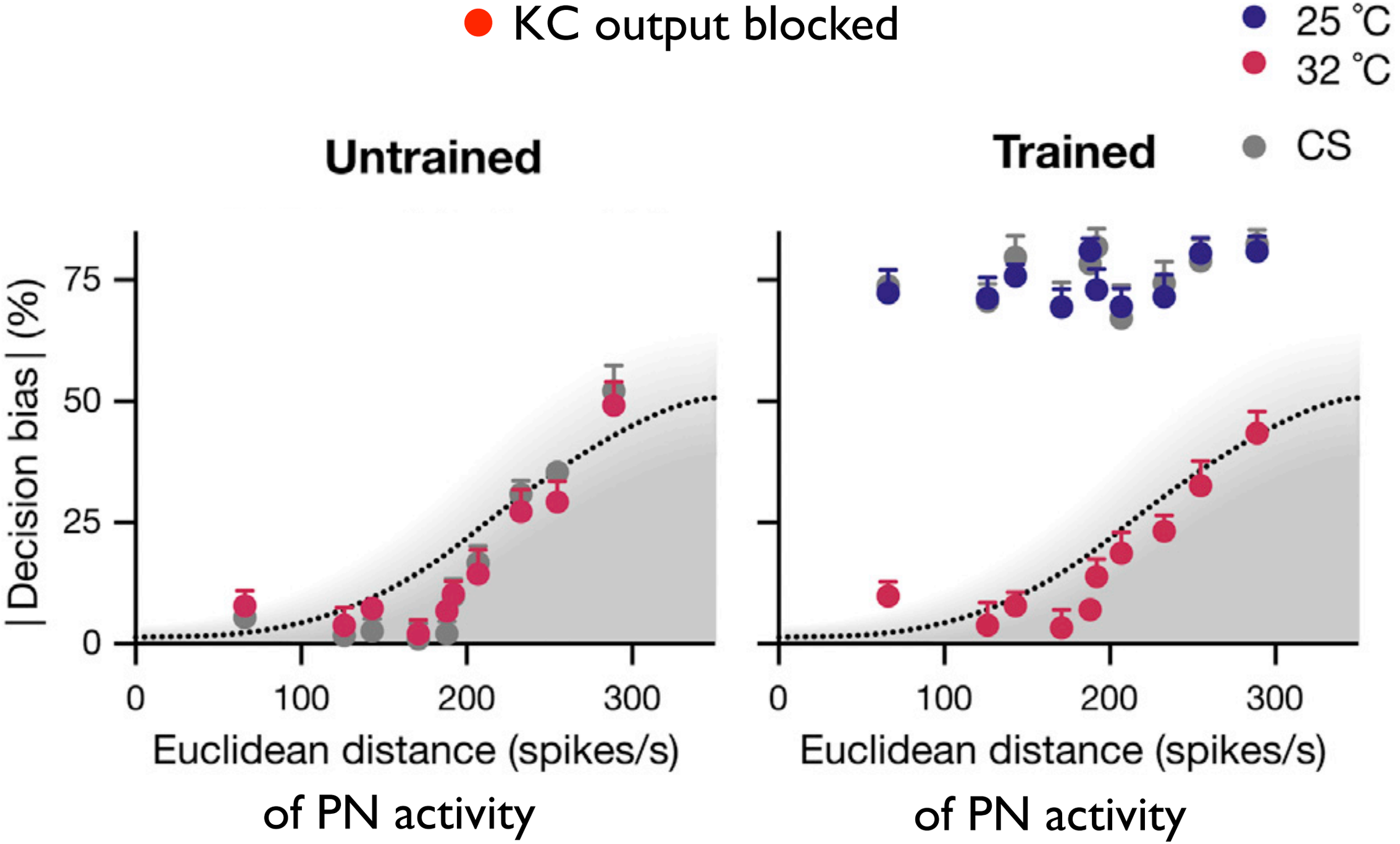


Moshe Parnas, Andrew C. Lin, Wolf Huetteroth, Gero Miesenbock 2013


KC
MBON
DAN
US
odor - CS
A
A
A


KC
MBON
DAN
odor
A
A
A
A

● KC output blocked



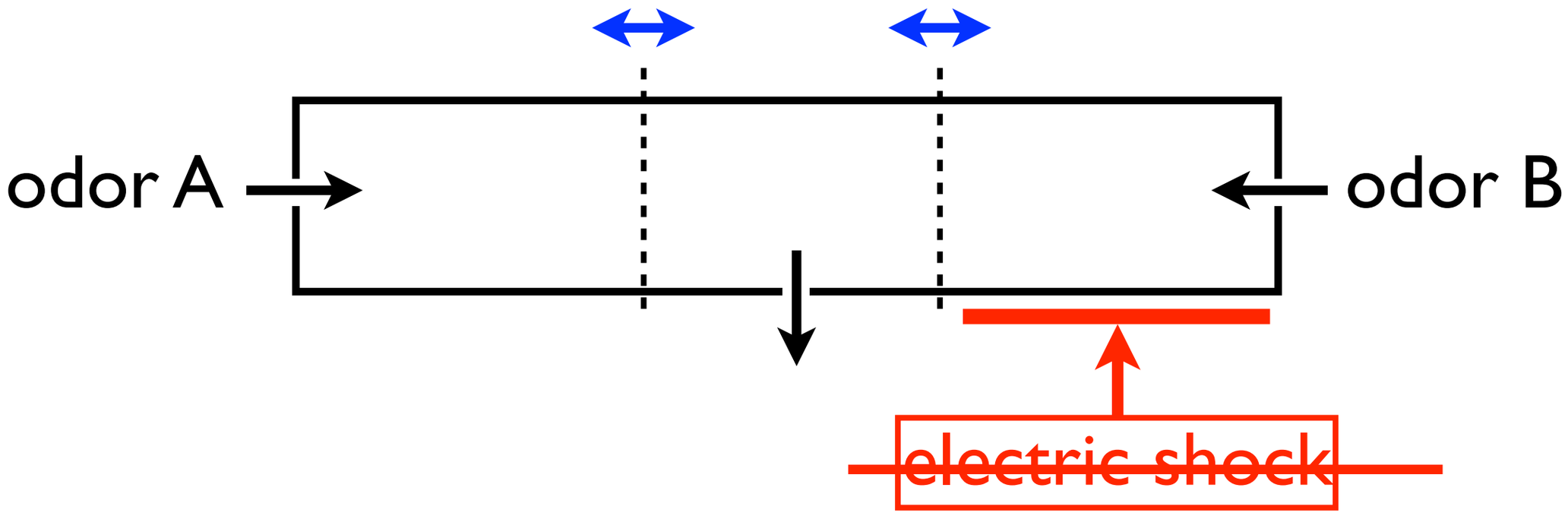
of PN activity

of PN activity

Source: Parnas, Moshe, Andrew C. Lin, Wolf Huetteroth, and Gero Miesenböck. "Odor discrimination in Drosophila: From neural population codes to behavior." Neuron 79, no. 5 (2013): 932-944.

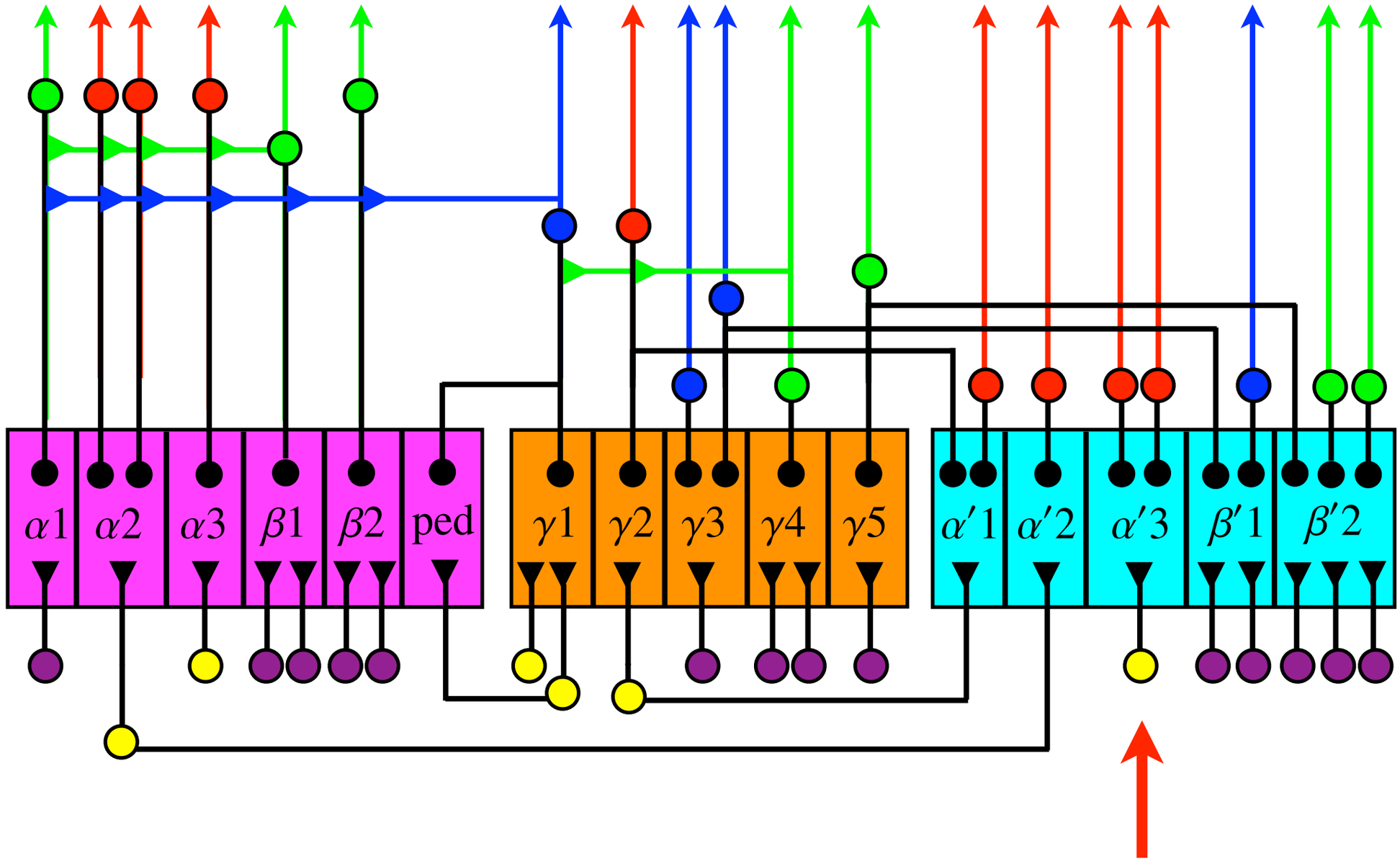
Moshe Parnas, Andrew C. Lin, Wolf Huetteroth, Gero Miesenbock, 2013

classical conditioning



dopamine neuron activation

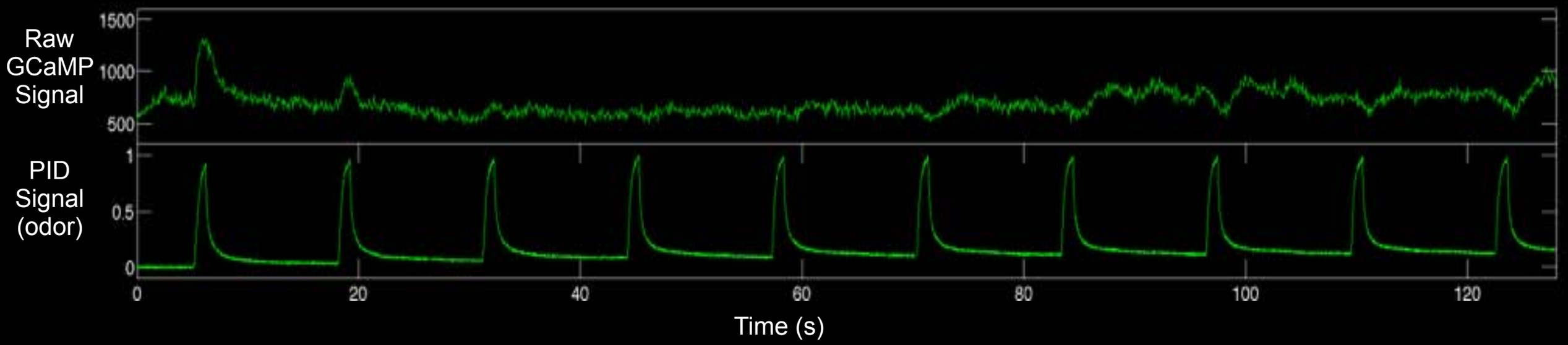
recognition memory



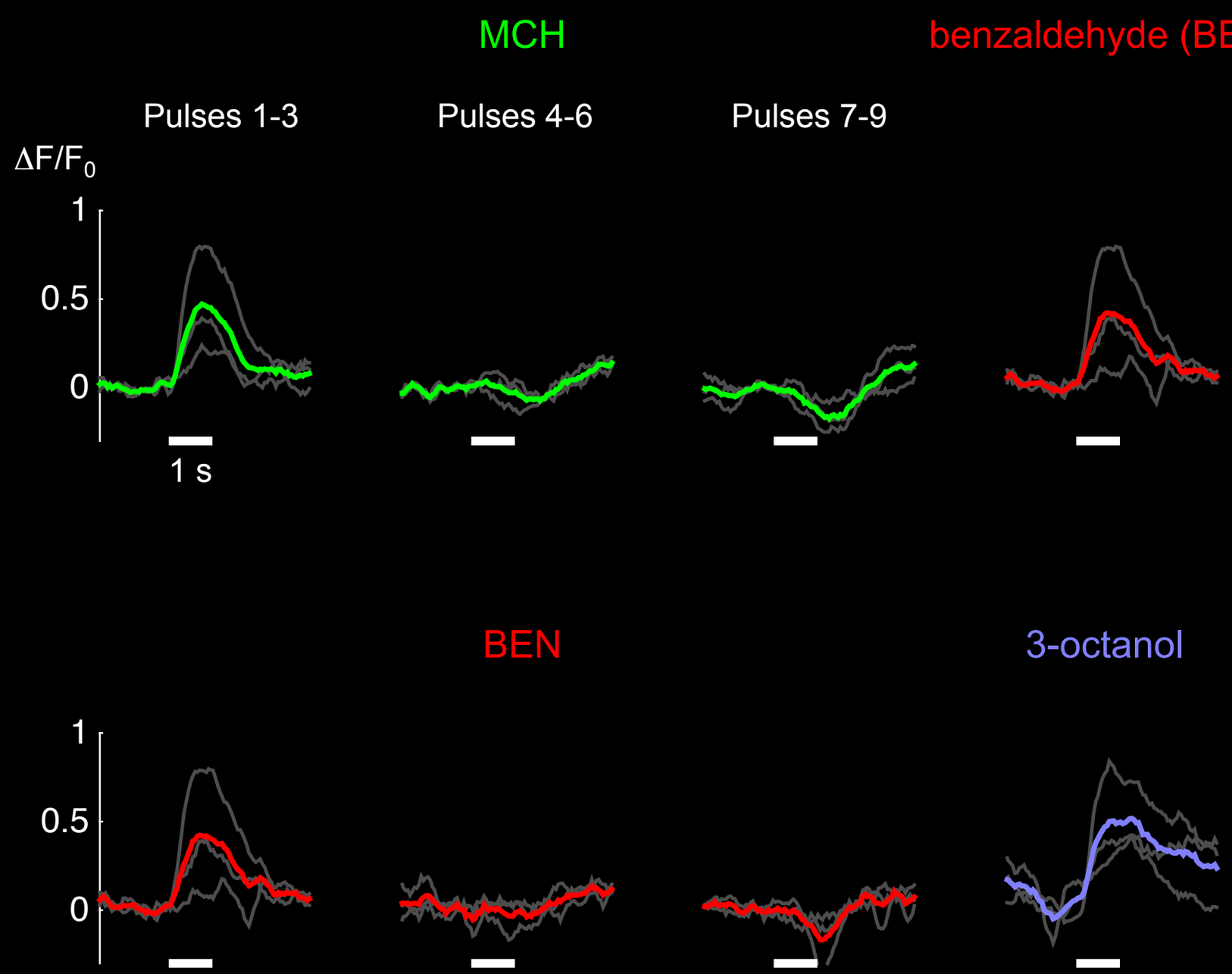
Daisuke Hattori, Richard Axel

MBON-α'3 activity depresses upon repetitive odor stimulation

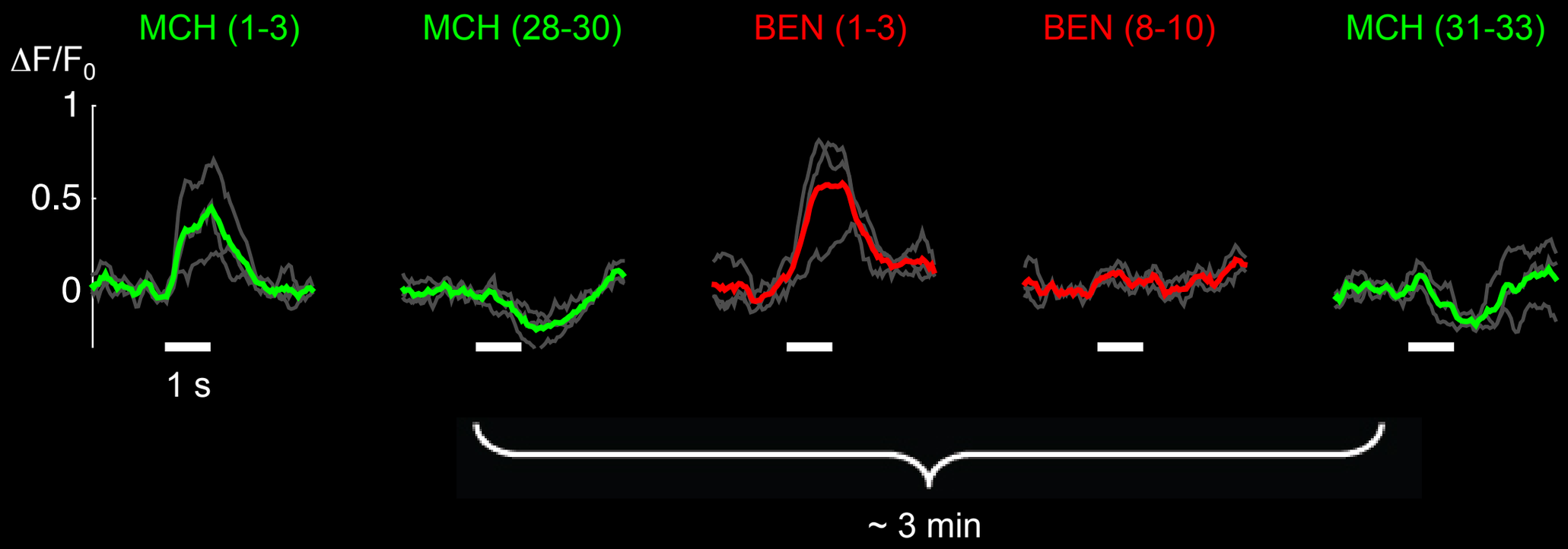
4-methylcyclohexanol (MCH)



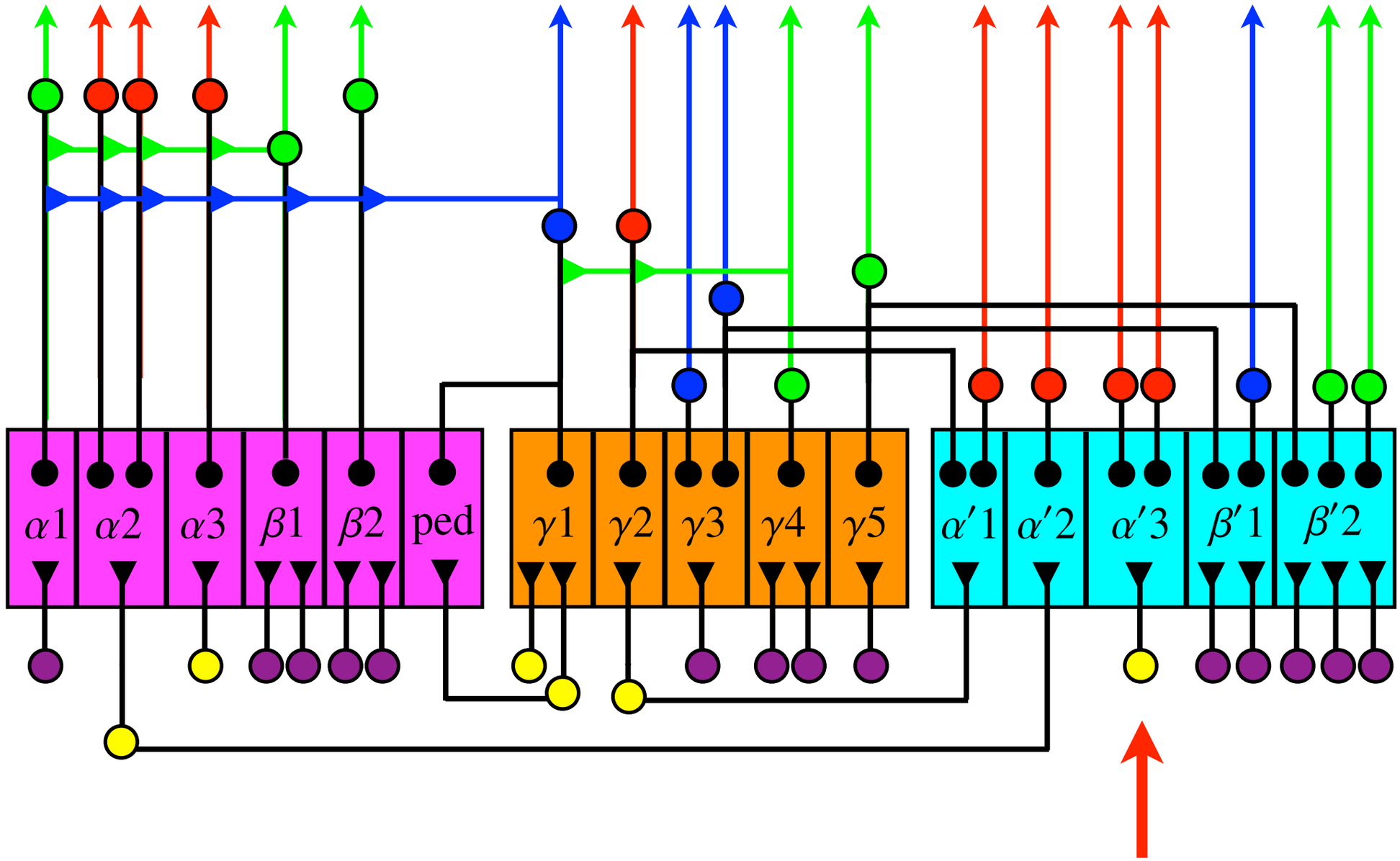
MBON-α'3 depression is specific to repeated odor



MBON-α'3 depression is persistent

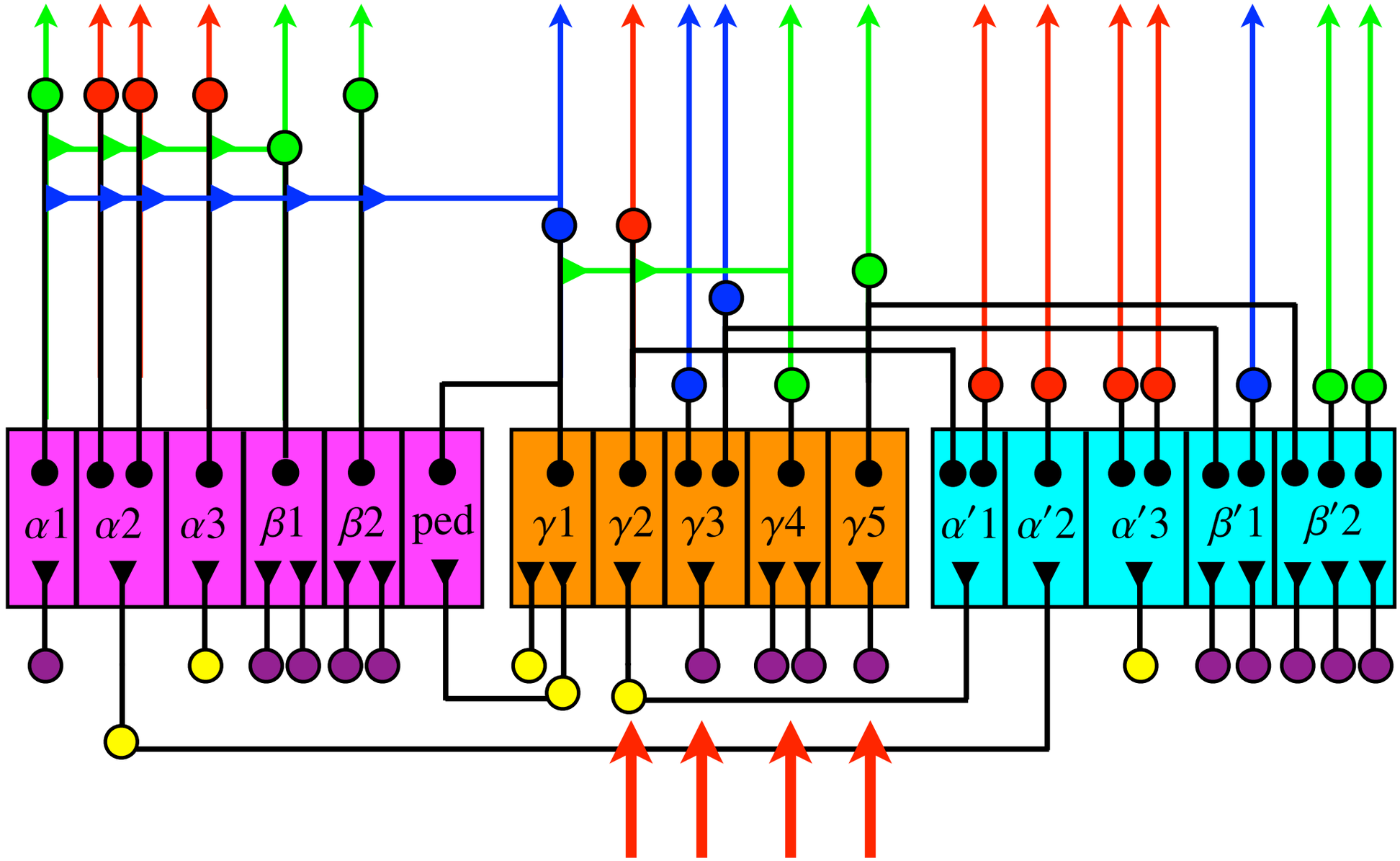


recognition memory

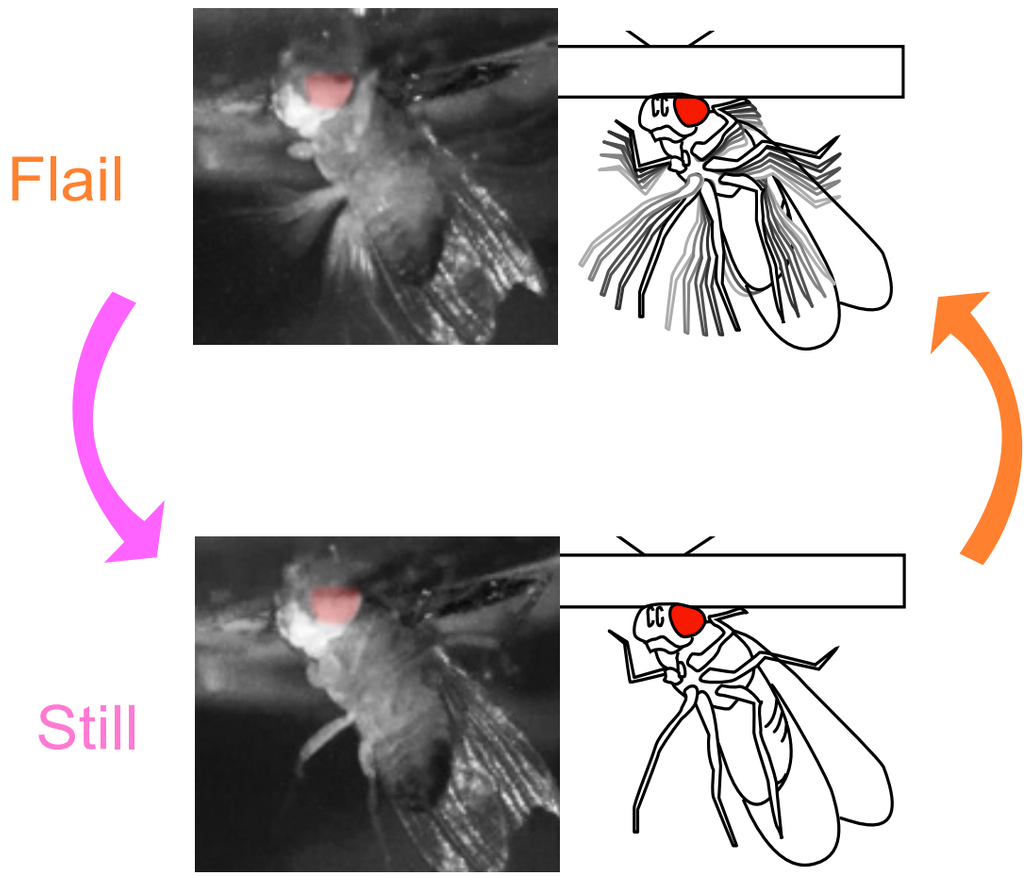


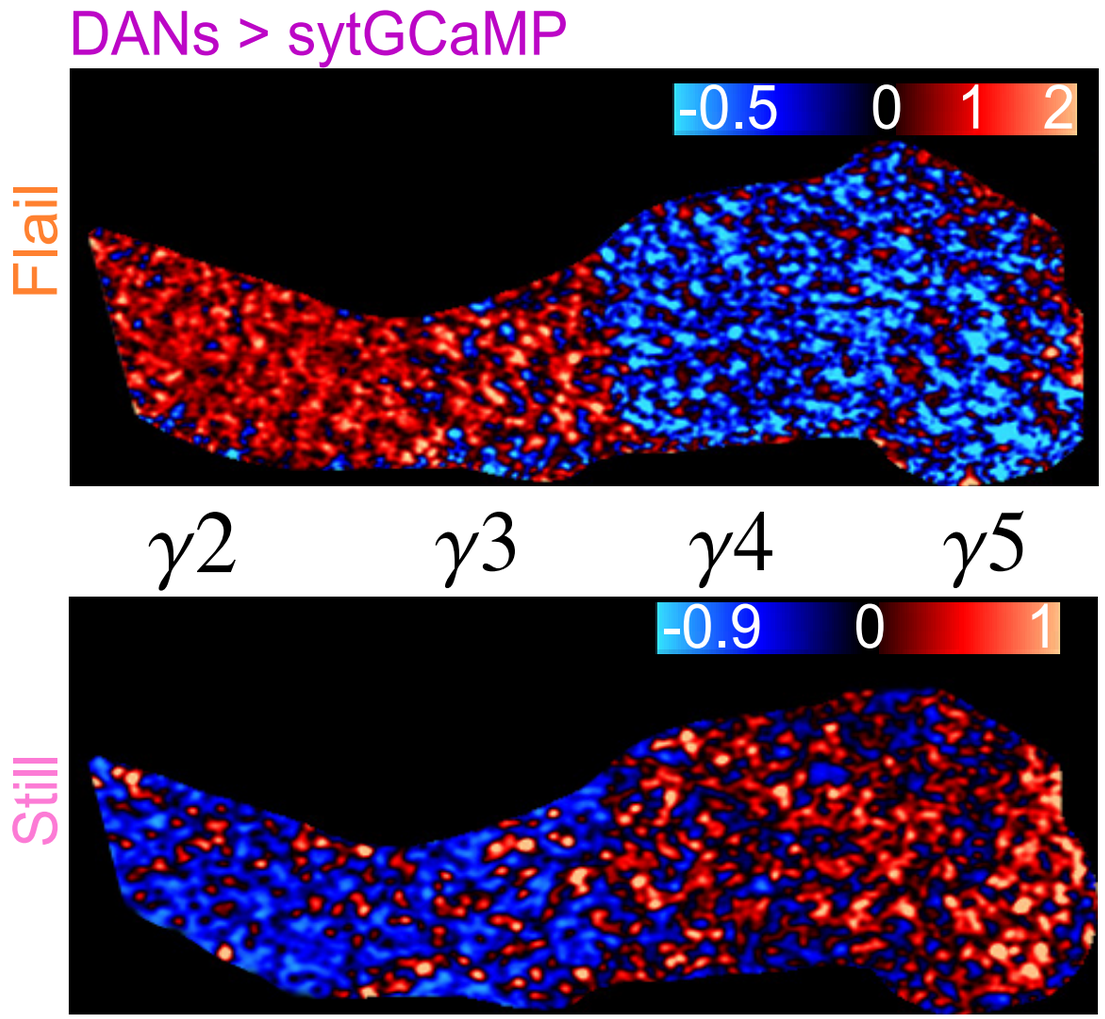
Daisuke Hattori, Richard Axel

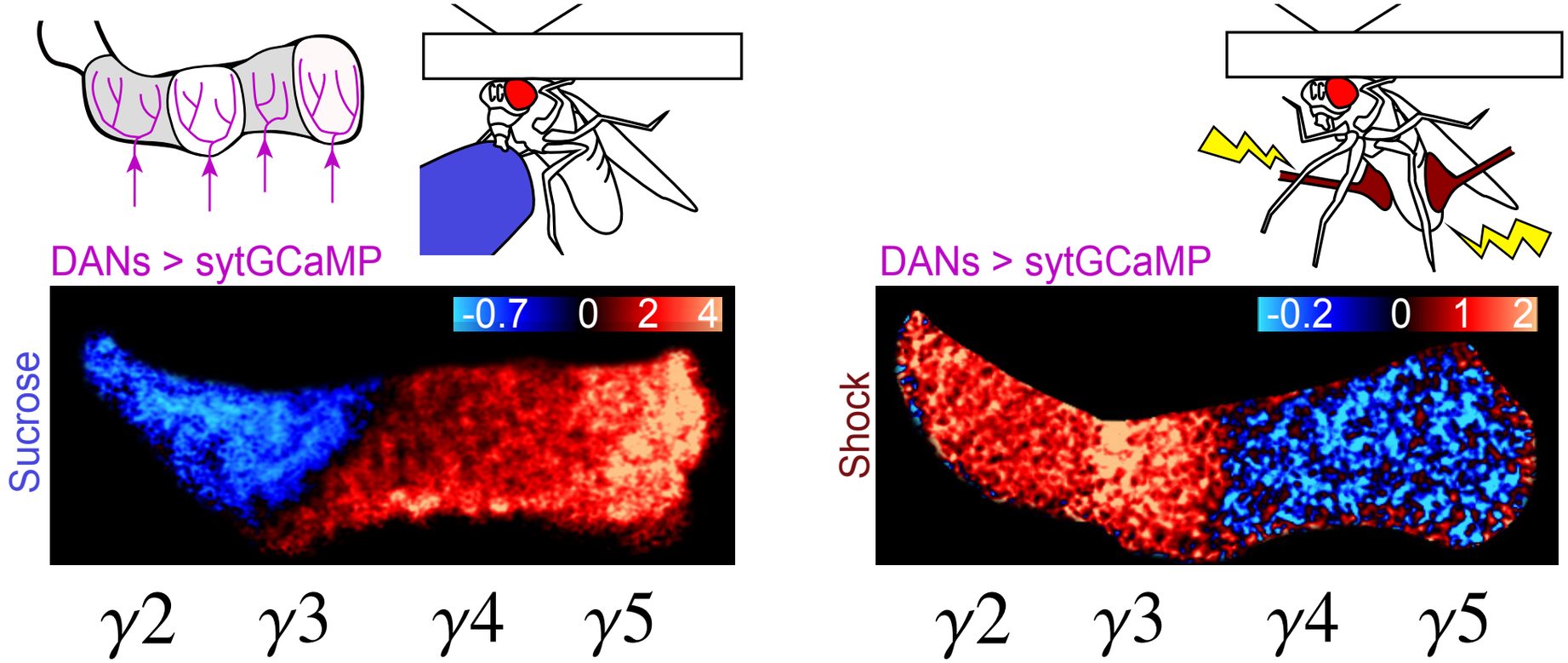
internal state



Raphael Cohn, Vanessa Ruta, 2015

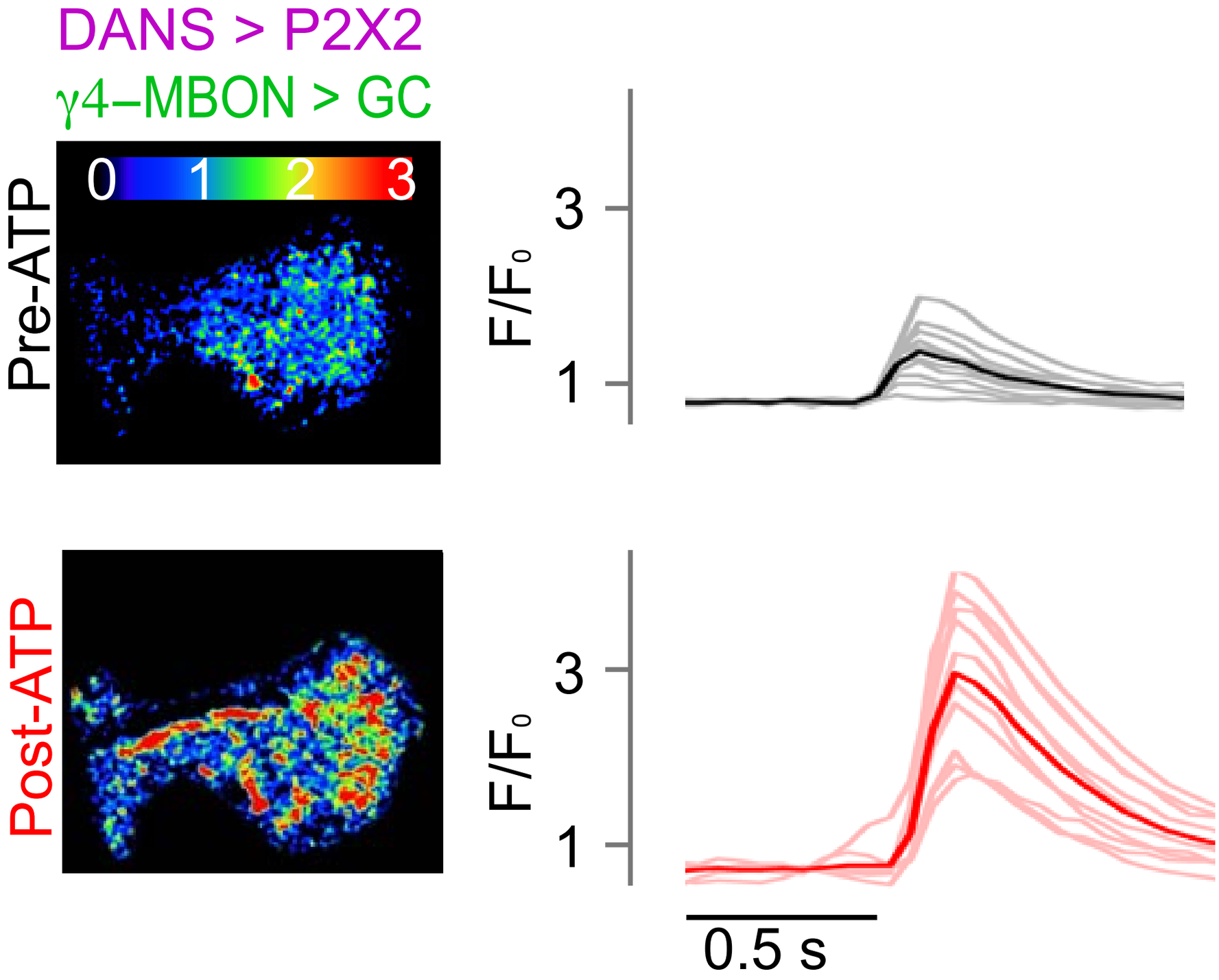






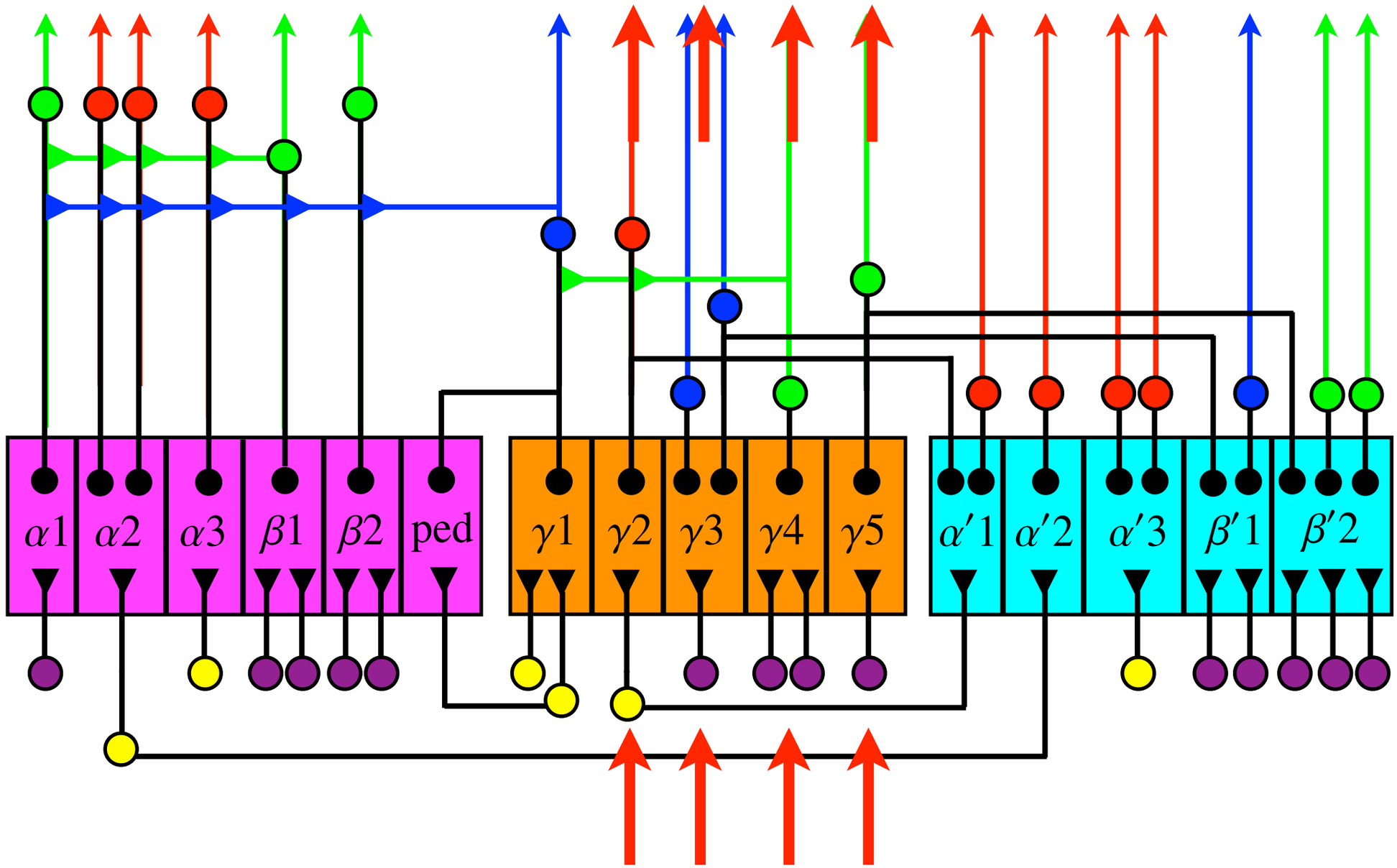
Source: Cohn, Raphael, Ianessa Morantte, and Vanessa Ruta. "Coordinated and compartmentalized neuromodulation shapes sensory processing in Drosophila." Cell 163, no. 7 (2015): 1742-1755.

Raphael Cohn, Vanessa Ruta, 2015

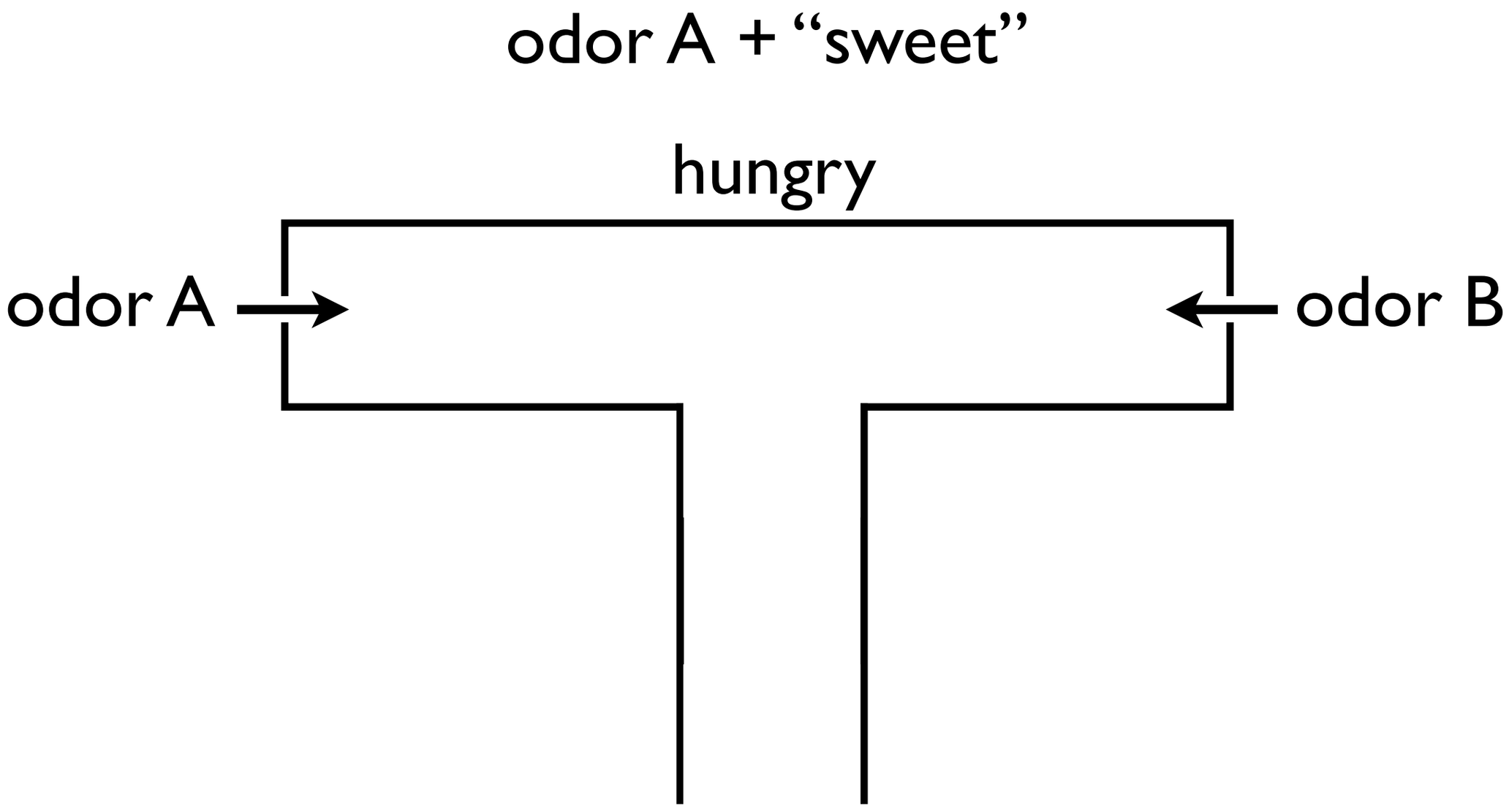


Source: Cohn, Raphael, Ianessa Morantte, and Vanessa Ruta. "Coordinated and compartmentalized neuromodulation shapes sensory processing in Drosophila." Cell 163, no. 7 (2015): 1742-1755.

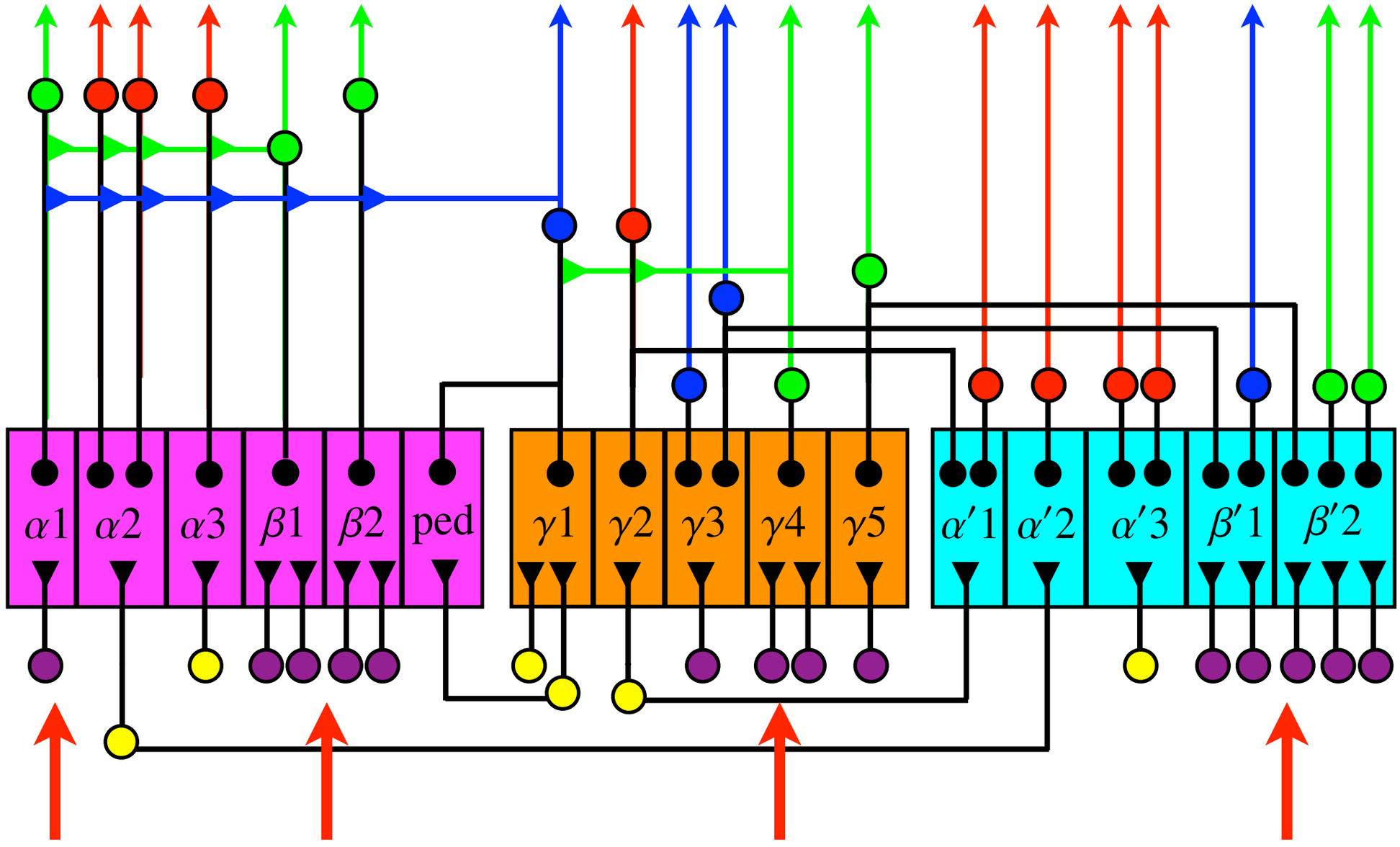
internal state affects routing

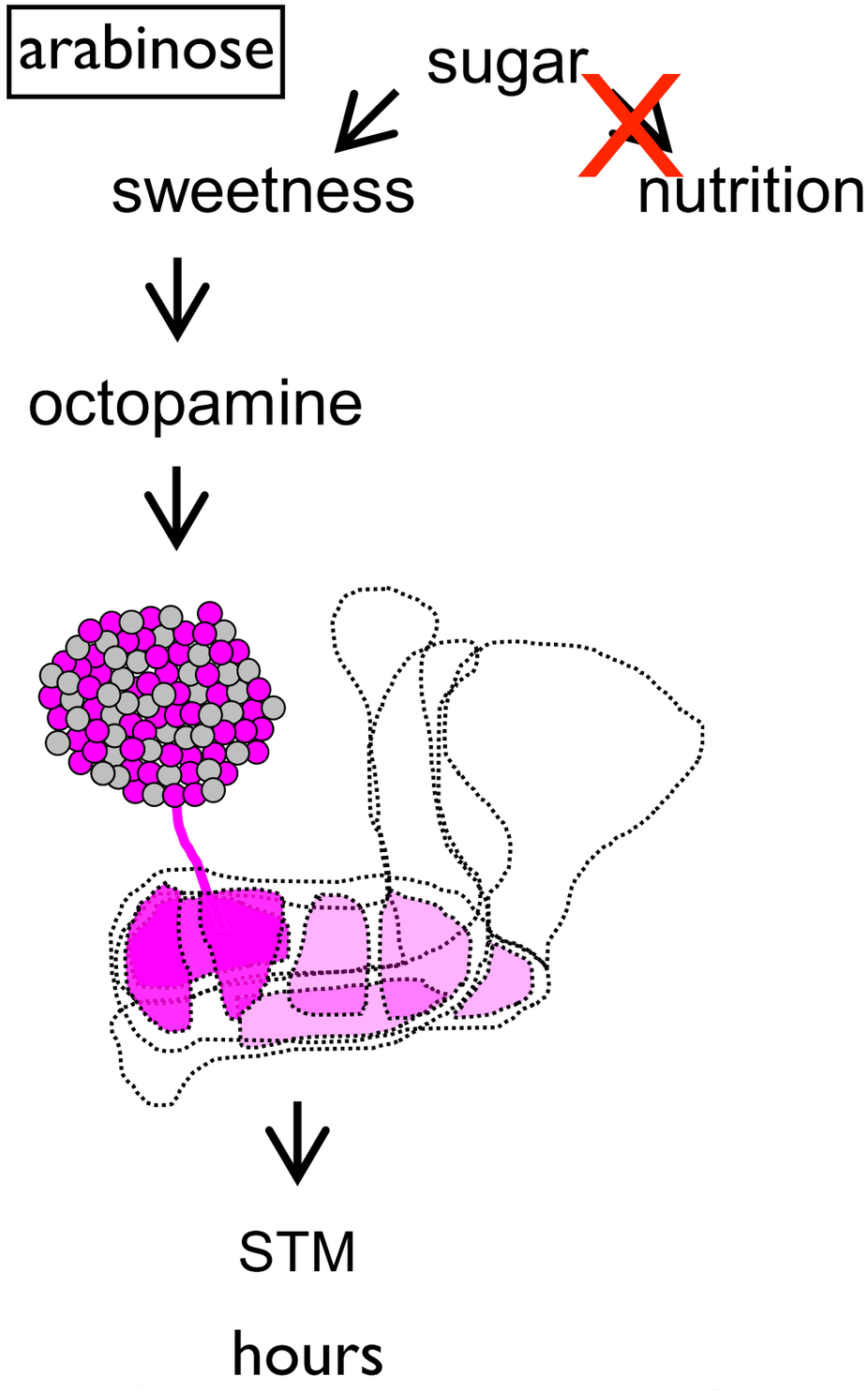


internal state affects memory

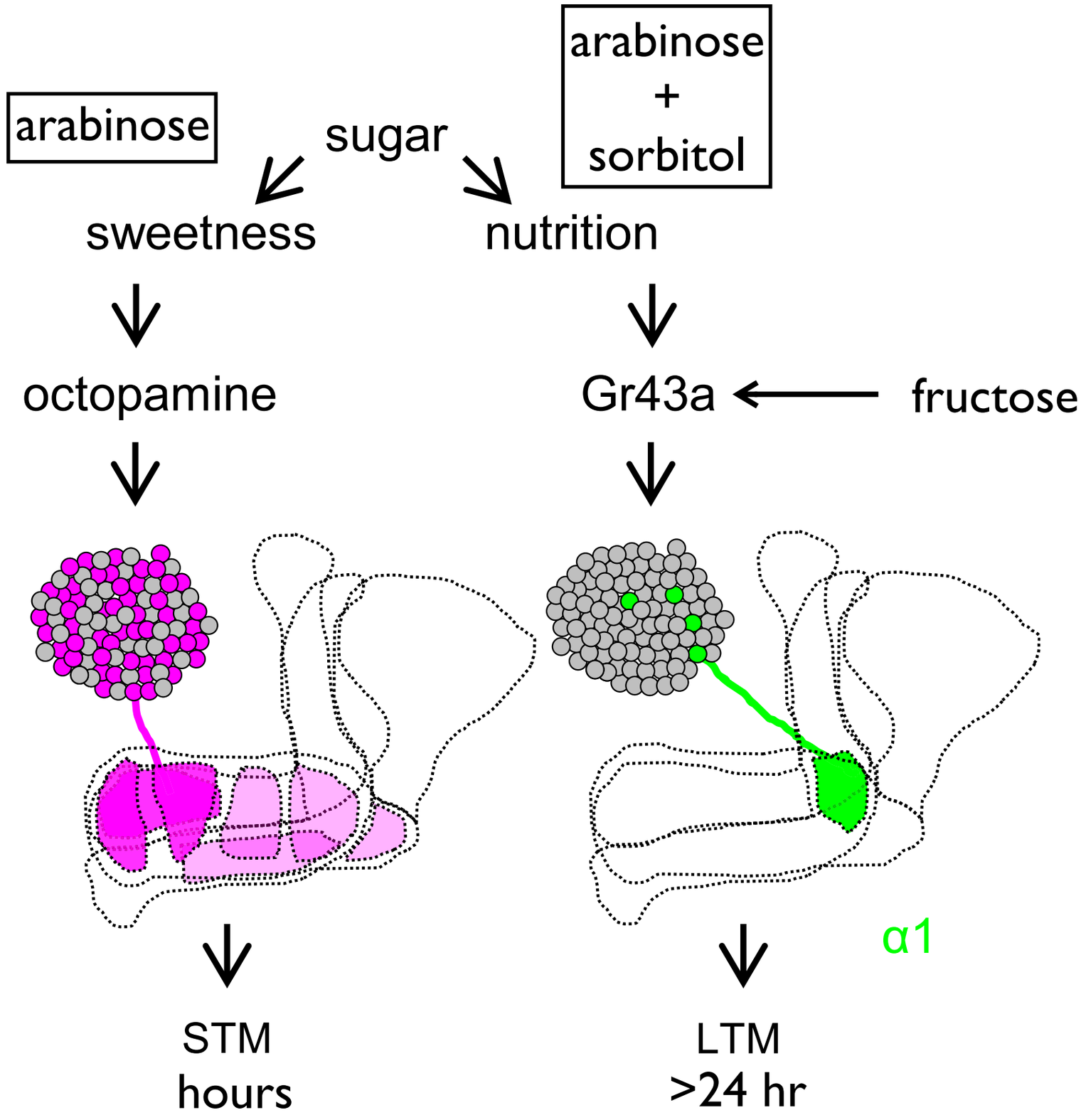


Nobuhiro Yamagata, Toshiharu Ichinose, Yoshinori Aso, Pierre-Yves Plaçais, Anja B. Friedrich, Richard J. Sima, Thomas Preat, Gerald M. Rubin, Hiromu Tanimoto, 2014


α1
α2
α3
β1
β2
ped
γ1
γ2
γ3
γ4
γ5
α′1
α′2
α′3
β′1
β′2



Nobuhiro Yamagata, Toshiharu Ichinose, Yoshinori Aso, Pierre-Yves Plaçais, Anja B. Friedrich, Richard J. Sima, Thomas Preat, Gerald M. Rubin, Hiromu Tanimoto, 2014



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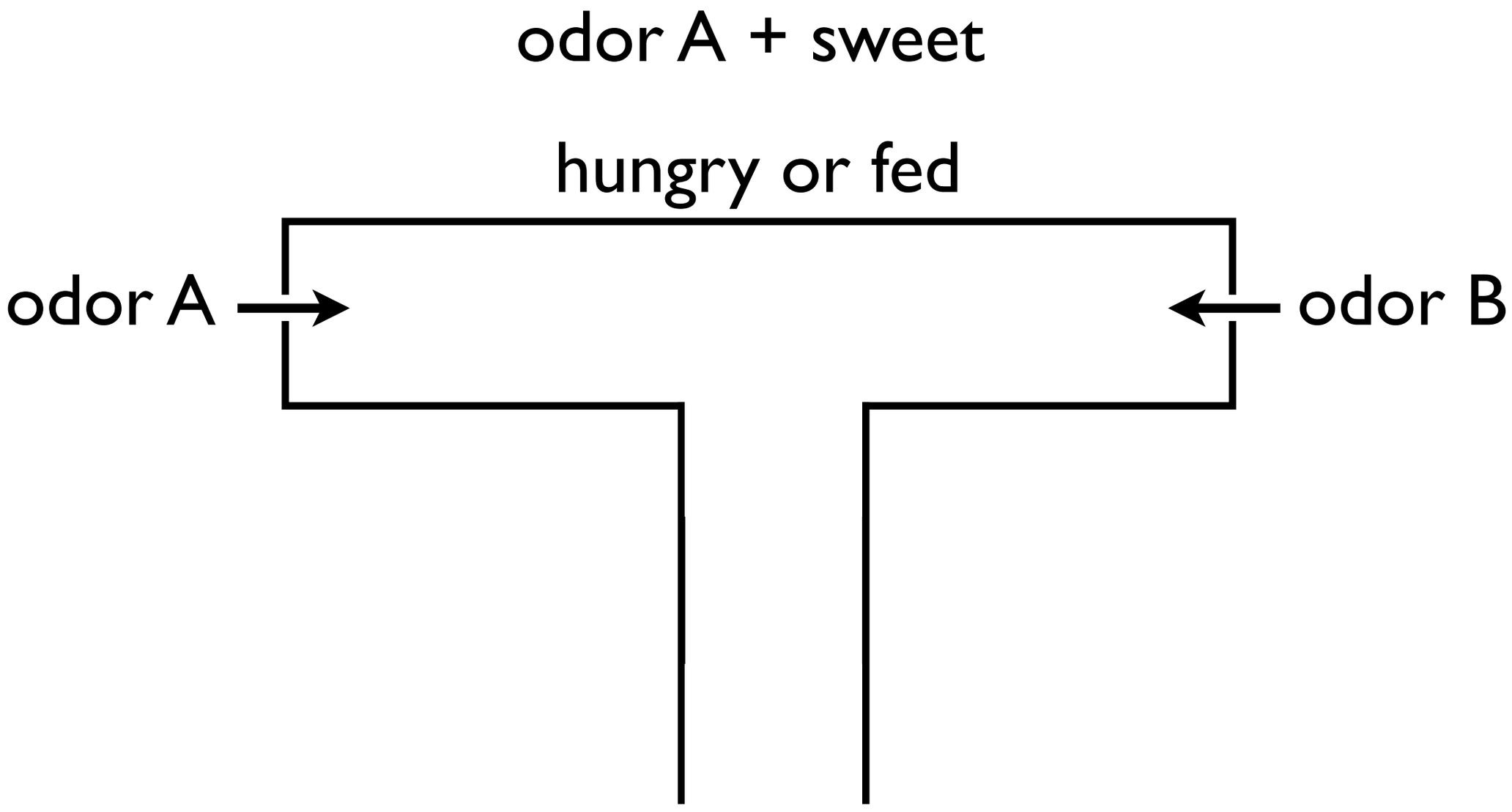
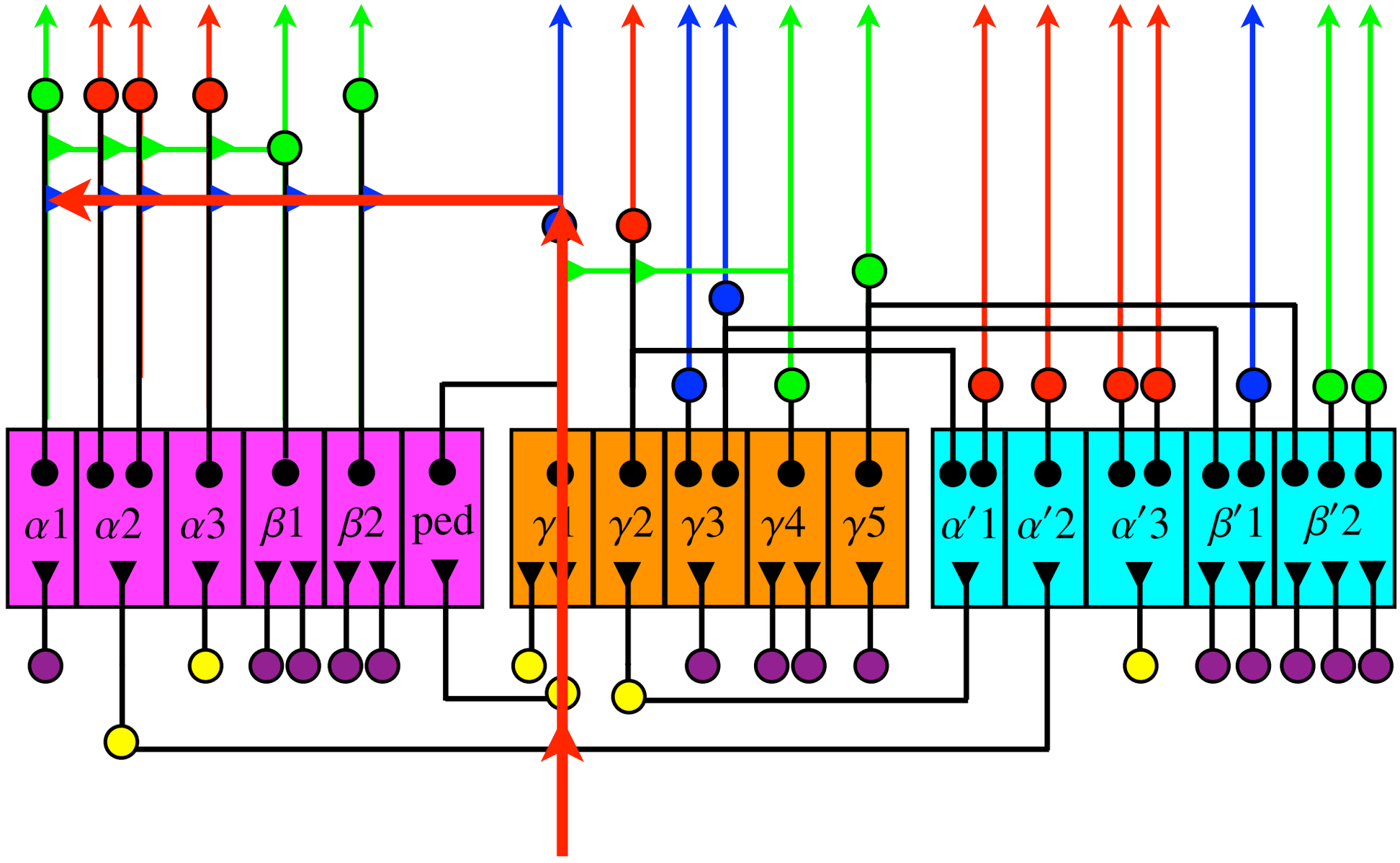
Source: Yamagata, Nobuhiro, Toshiharu Ichinose, Yoshinori Aso, Pierre-Yves Plaçais, Anja B. Friedrich, Richard J. Sima, Thomas Preat, Gerald M. Rubin, and Hiromu Tanimoto. "Distinct dopamine neurons mediate reward signals for short-and long-term memories." Proceedings of the National Academy of Sciences 112, no. 2 (2015): 578-583.

Nobuhiro Yamagata, Toshiharu Ichinose, Yoshinori Aso, Pierre-Yves Plaçais, Anja B. Friedrich, Richard J. Sima, Thomas Preat, Gerald M. Rubin, Hiromu Tanimoto, 2014

internal state and gating



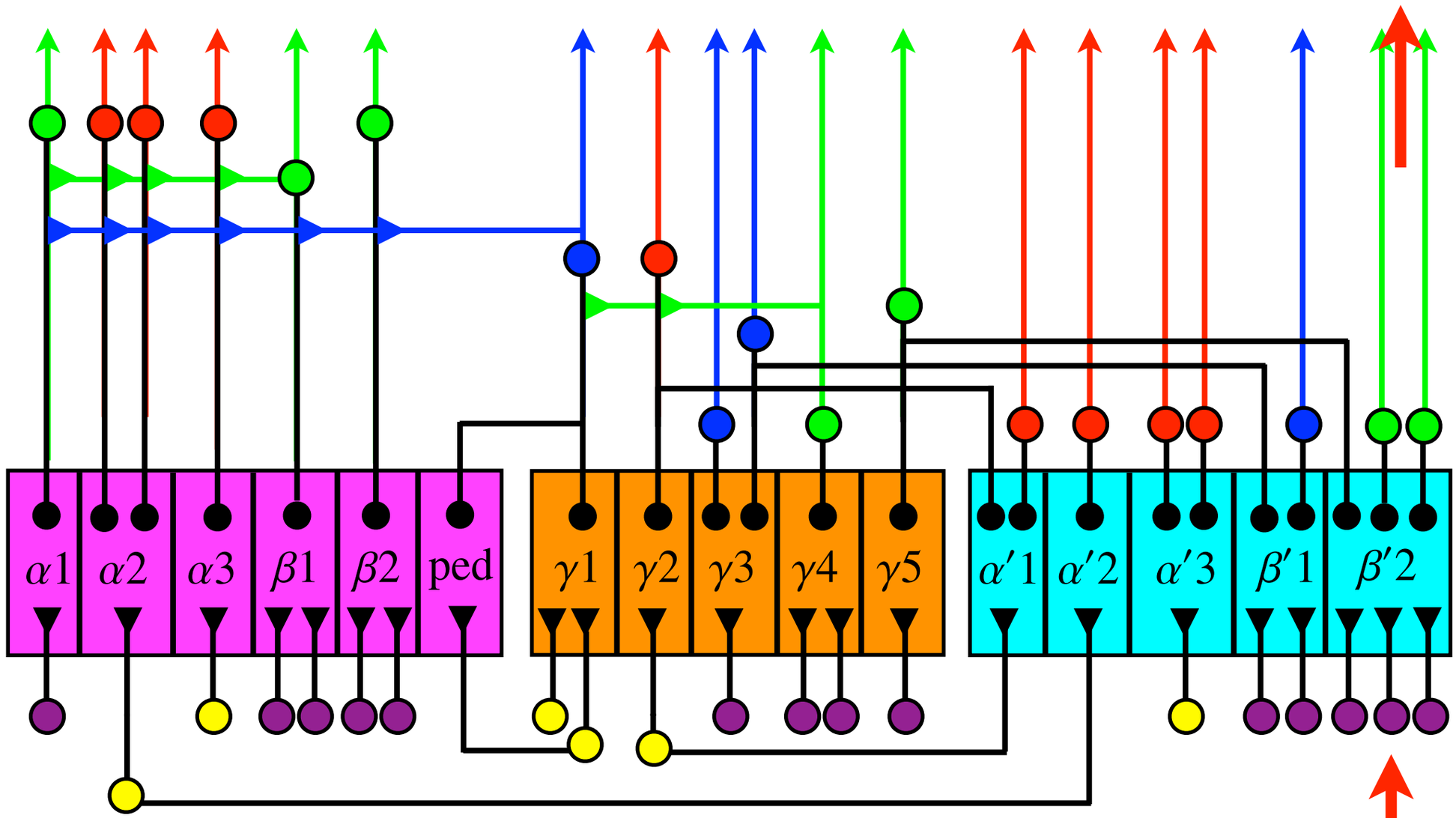
Michael J. Krashes, Shamik DasGupta, Andrew Vreede,
Benjamin White, J. Douglas Armstrong, Scott Waddell, 2009



activated in fed state
silenced in hungry state

Michael J. Krashes, Shamik DasGupta, Andrew Vreede,
Benjamin White, J. Douglas Armstrong, Scott Waddell, 2009

CO2 avoidance



modulation
by food & hunger

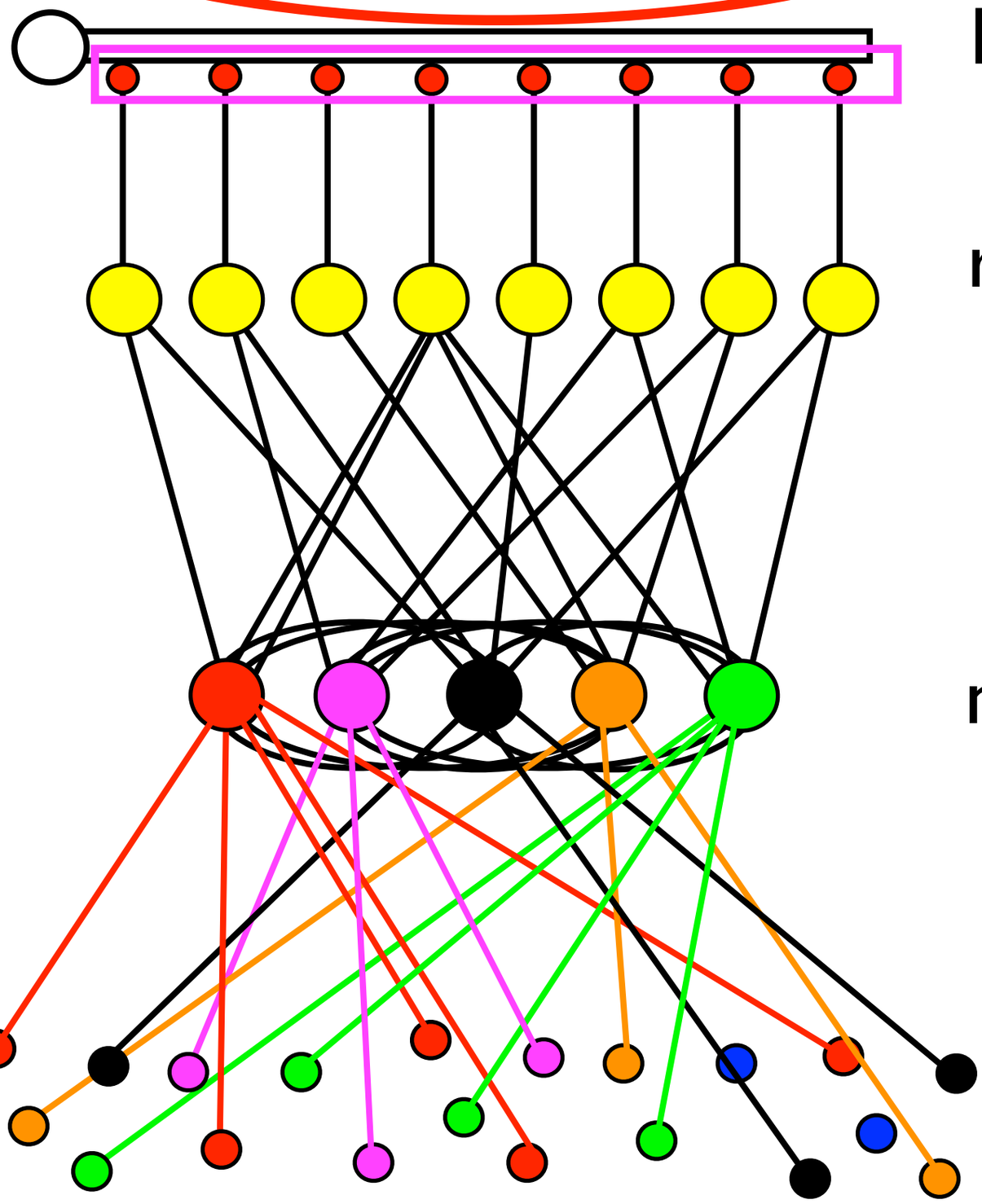
Laurence Lewis, K.P. Siju, Yoshinori Aso, Anja B. Friedrich, Alexander J.B. Bulteel, Gerald M. Rubin, and Ilona C. Grunwald Kadow, 2015

multiple forms of
modulation and plasticity

highly
structured

random

highly
stereotyped



perceptron-like
readout

random, high-D
representation

pooling
noise reduction
normalization

input

Resource: Brains, Minds and Machines Summer Course
Tomaso Poggio and Gabriel Kreiman