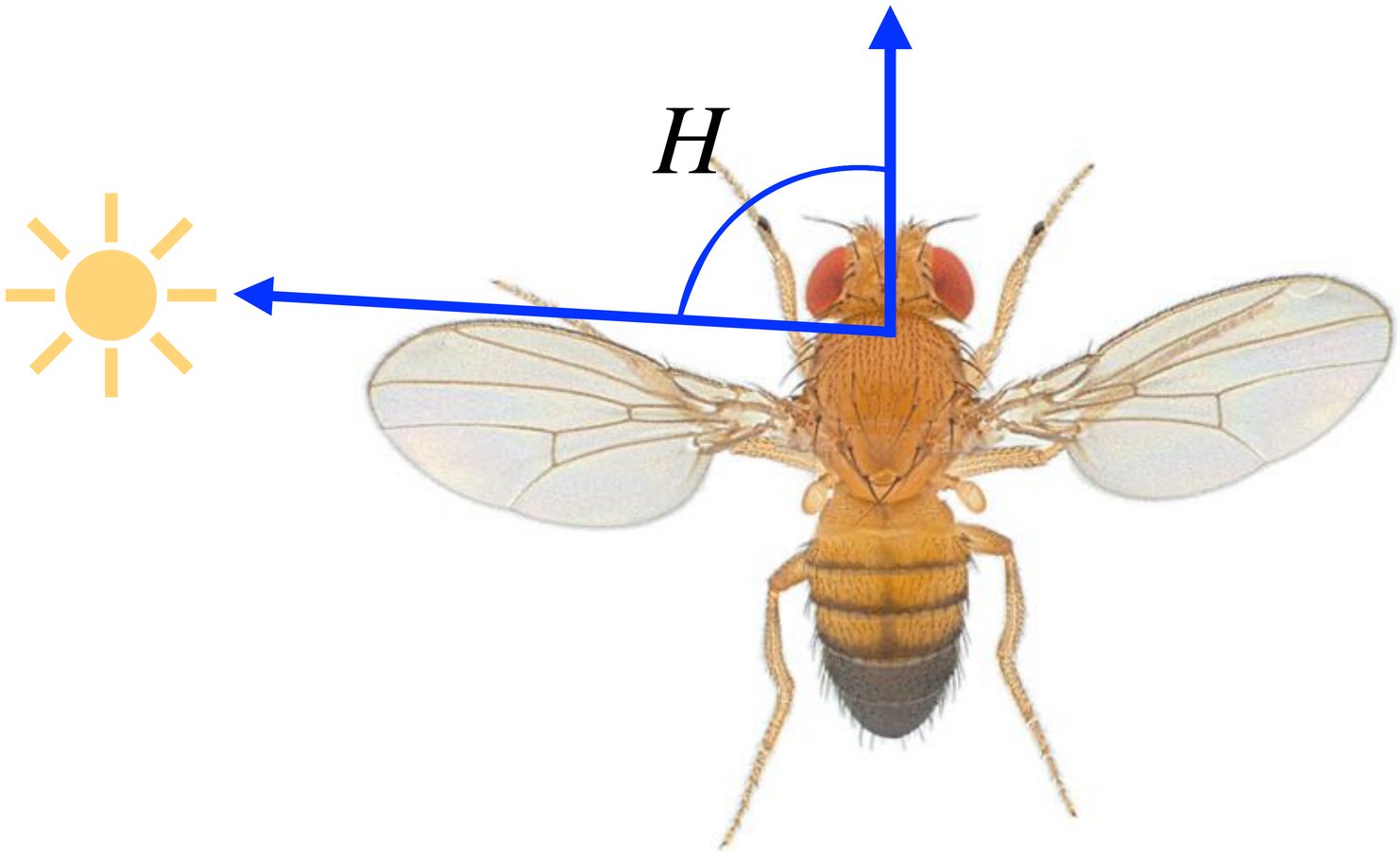
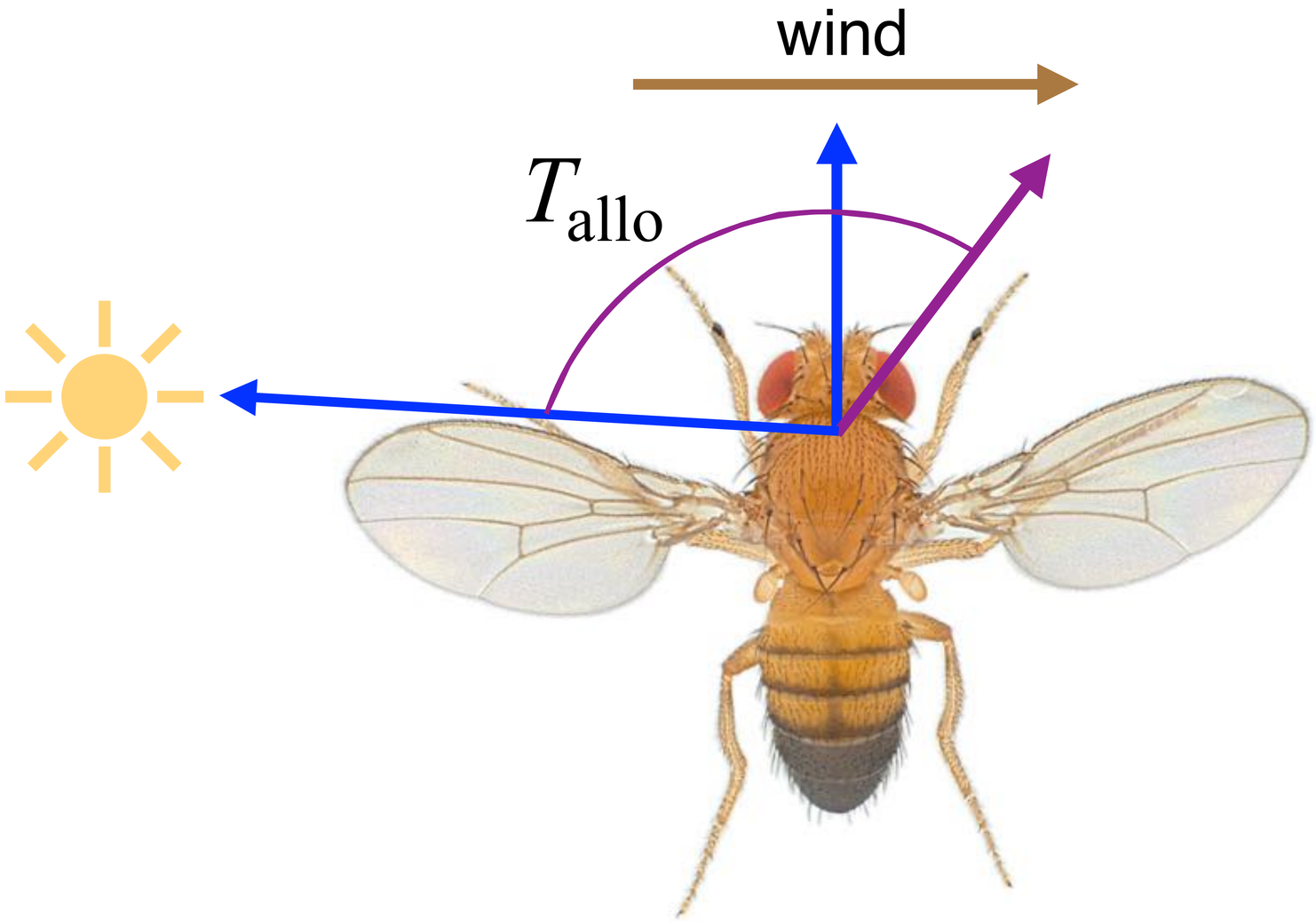
How Do Flies Navigate

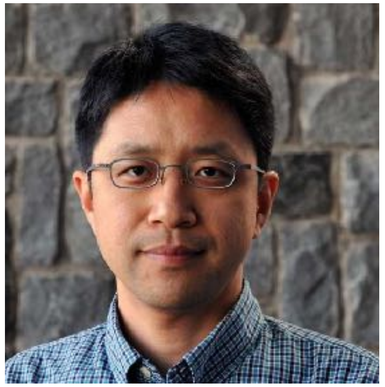
How does a fly know which way it is heading?



How does a fly know which way it is traveling?



Vivek Jayaraman



Sung-Soo Kim

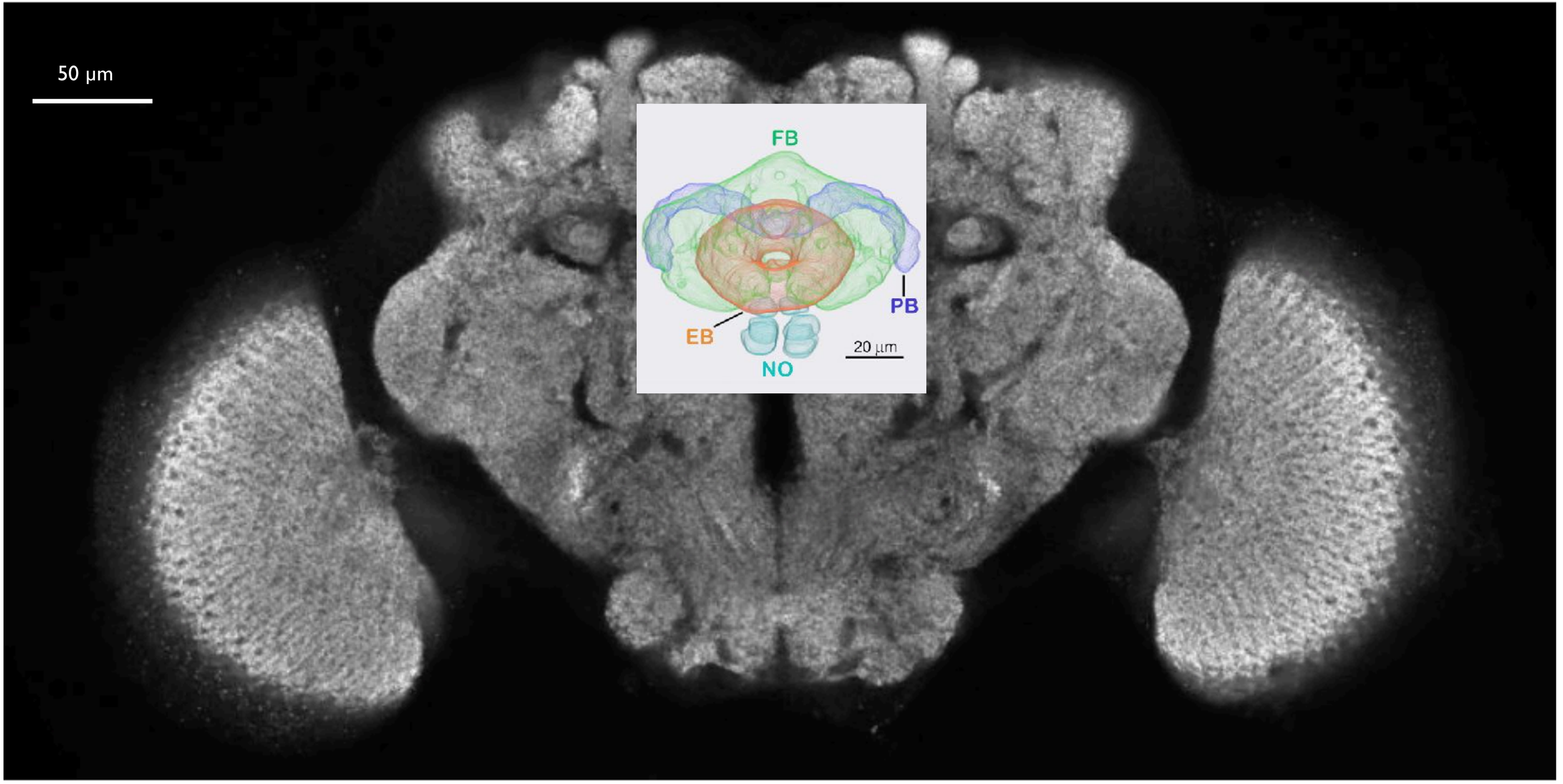
Gaby Maimon

Ann Hermundstad

Sandro Romani

Cheng Lyu

http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/



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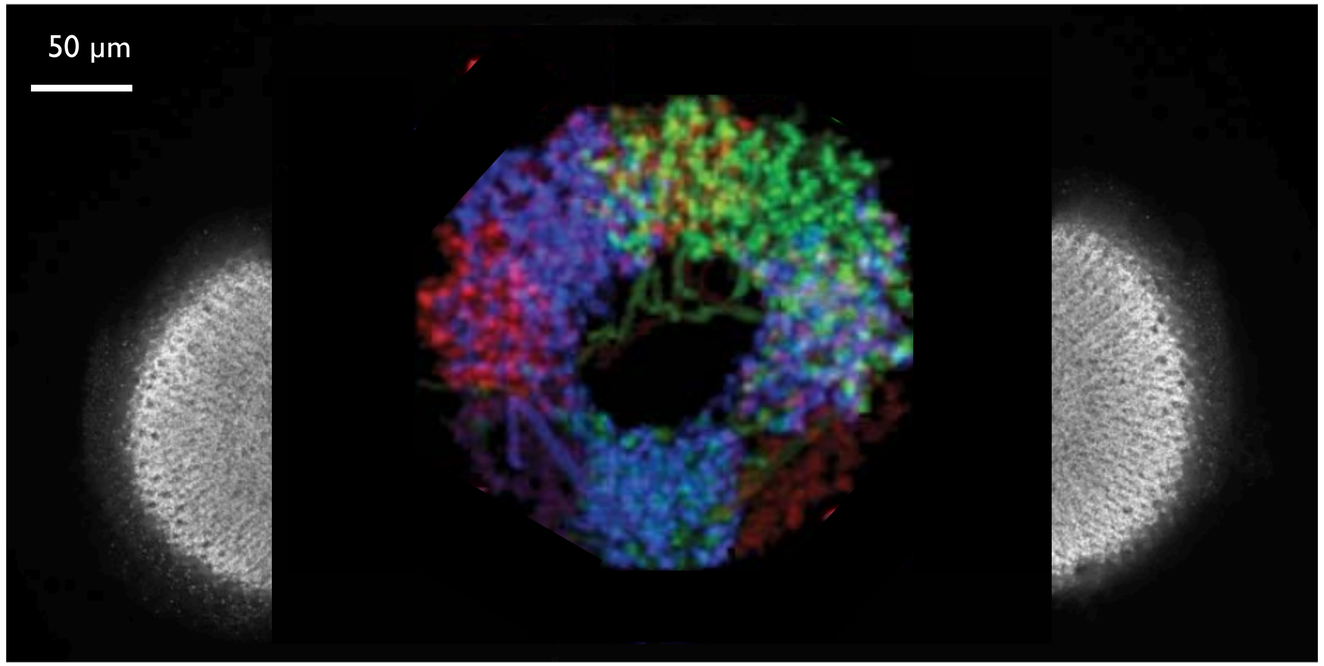

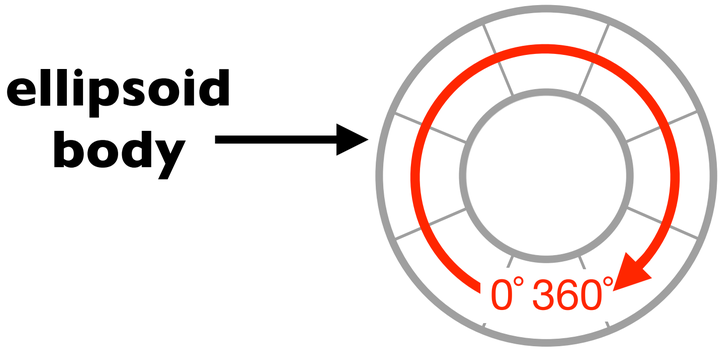

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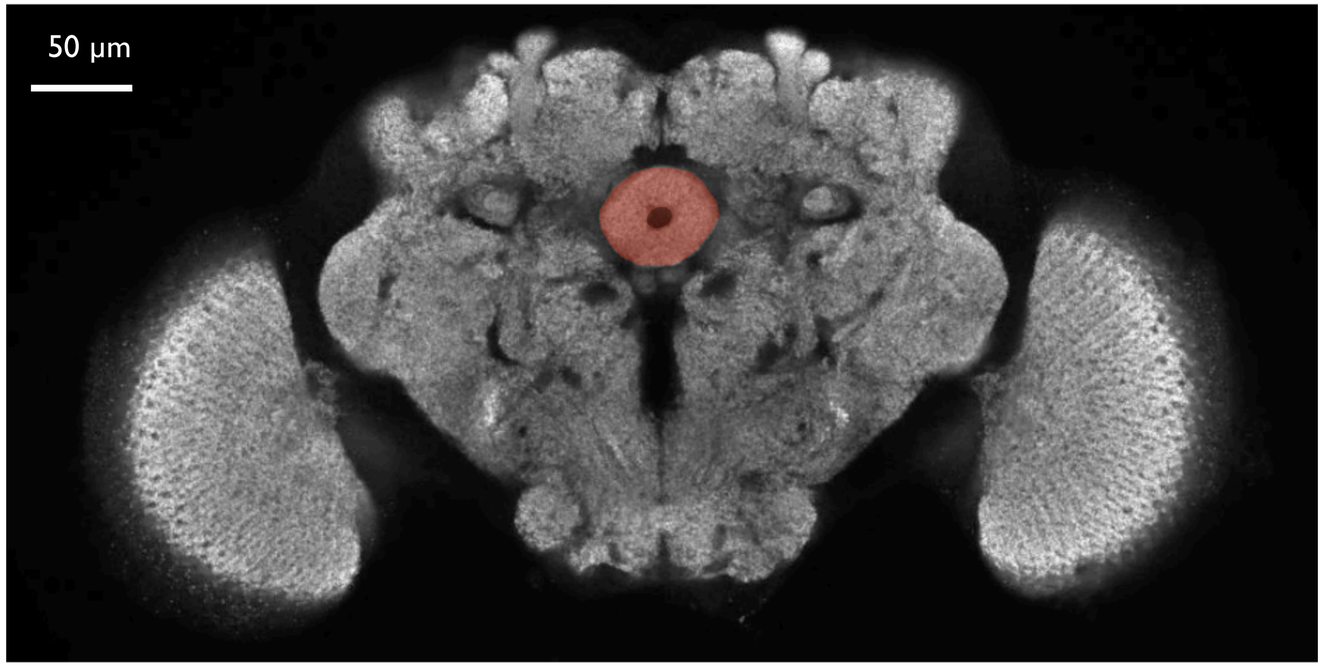
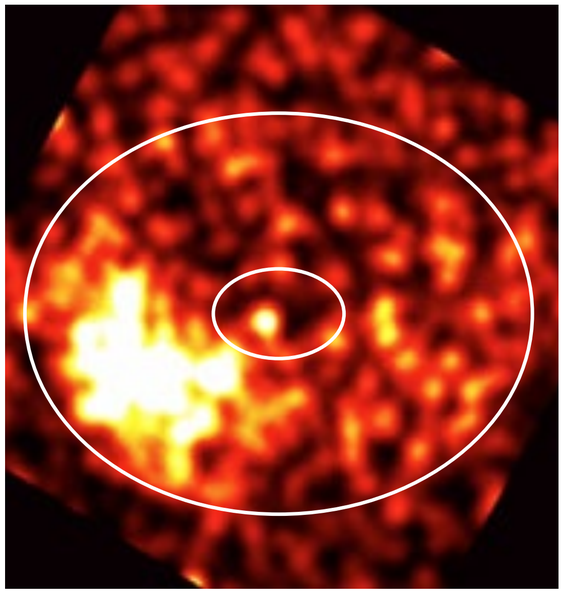
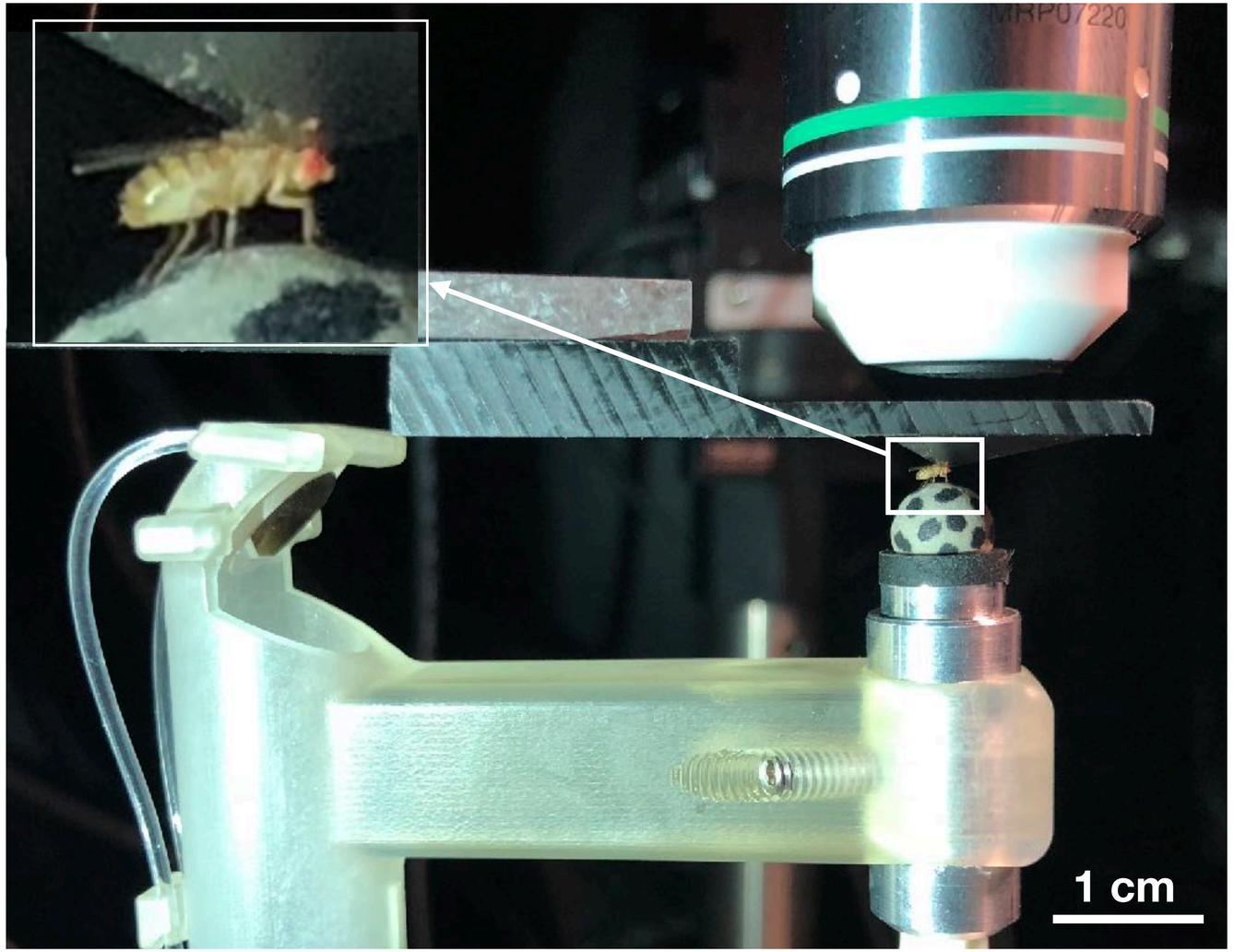


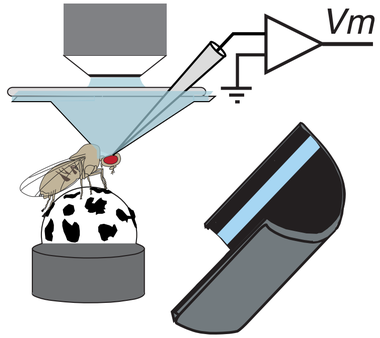
ellipsoid body

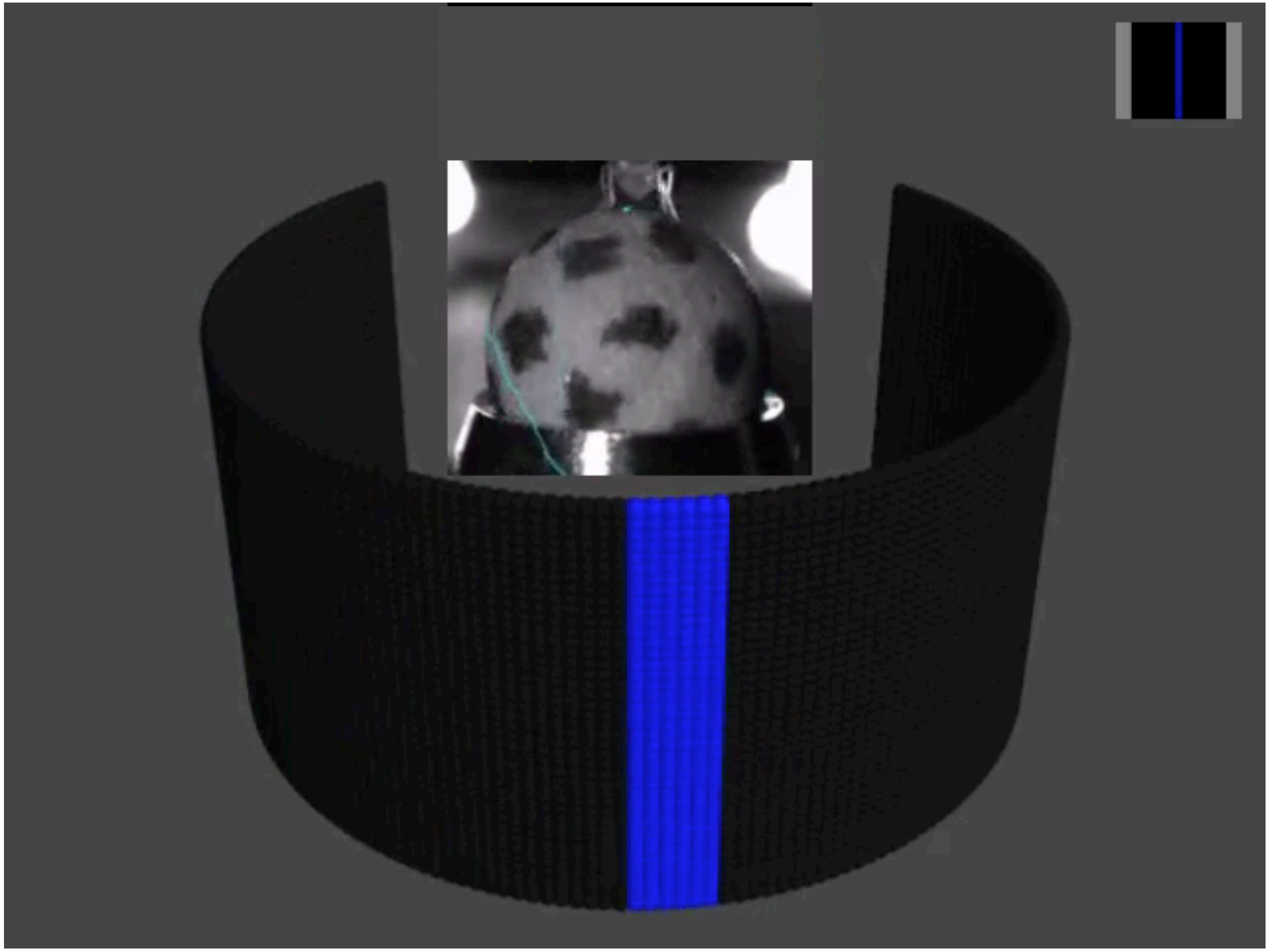
H

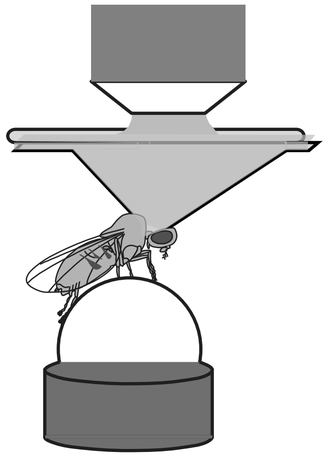


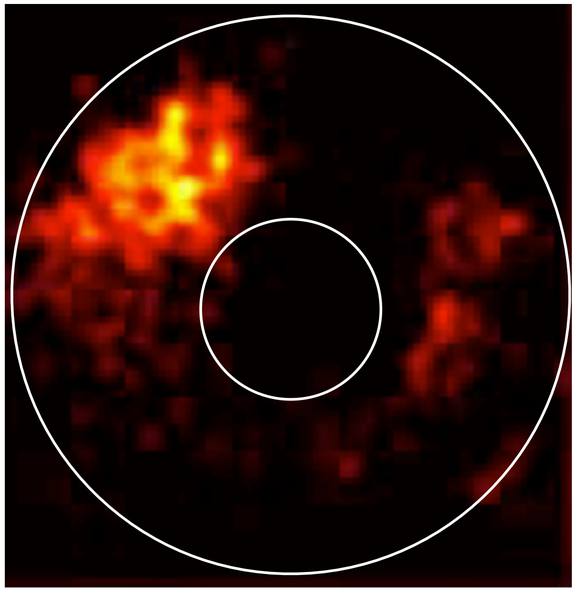
Seelig, Jayaraman (2015)

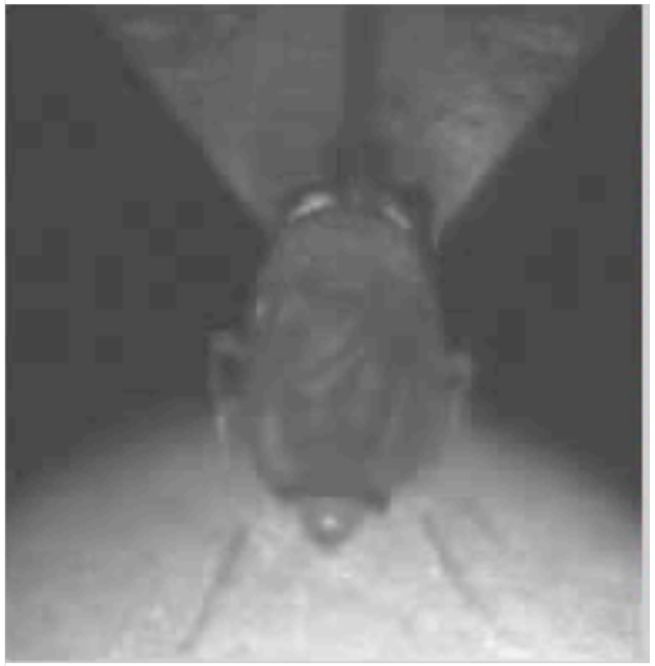

1 cm


Vm

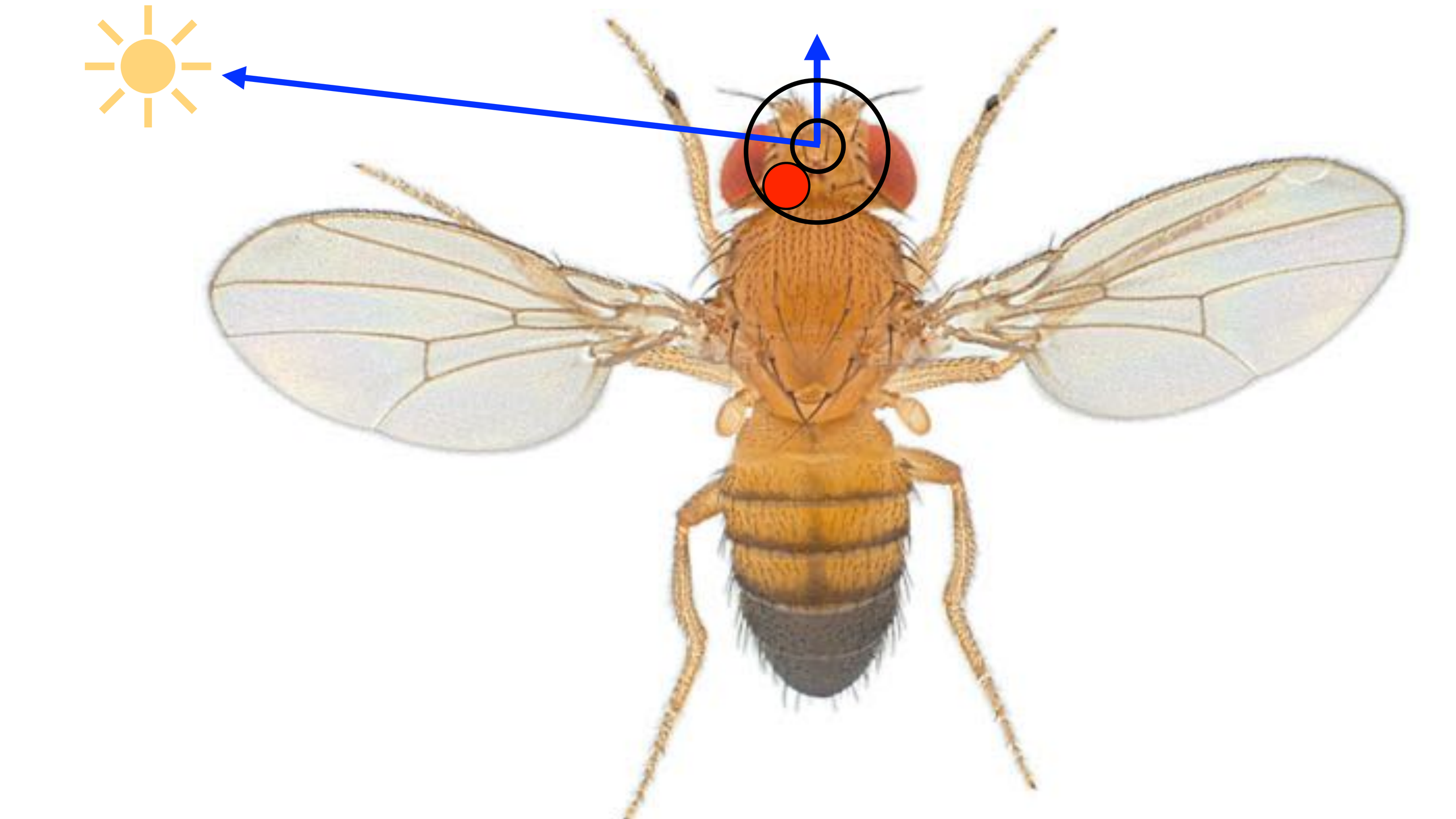


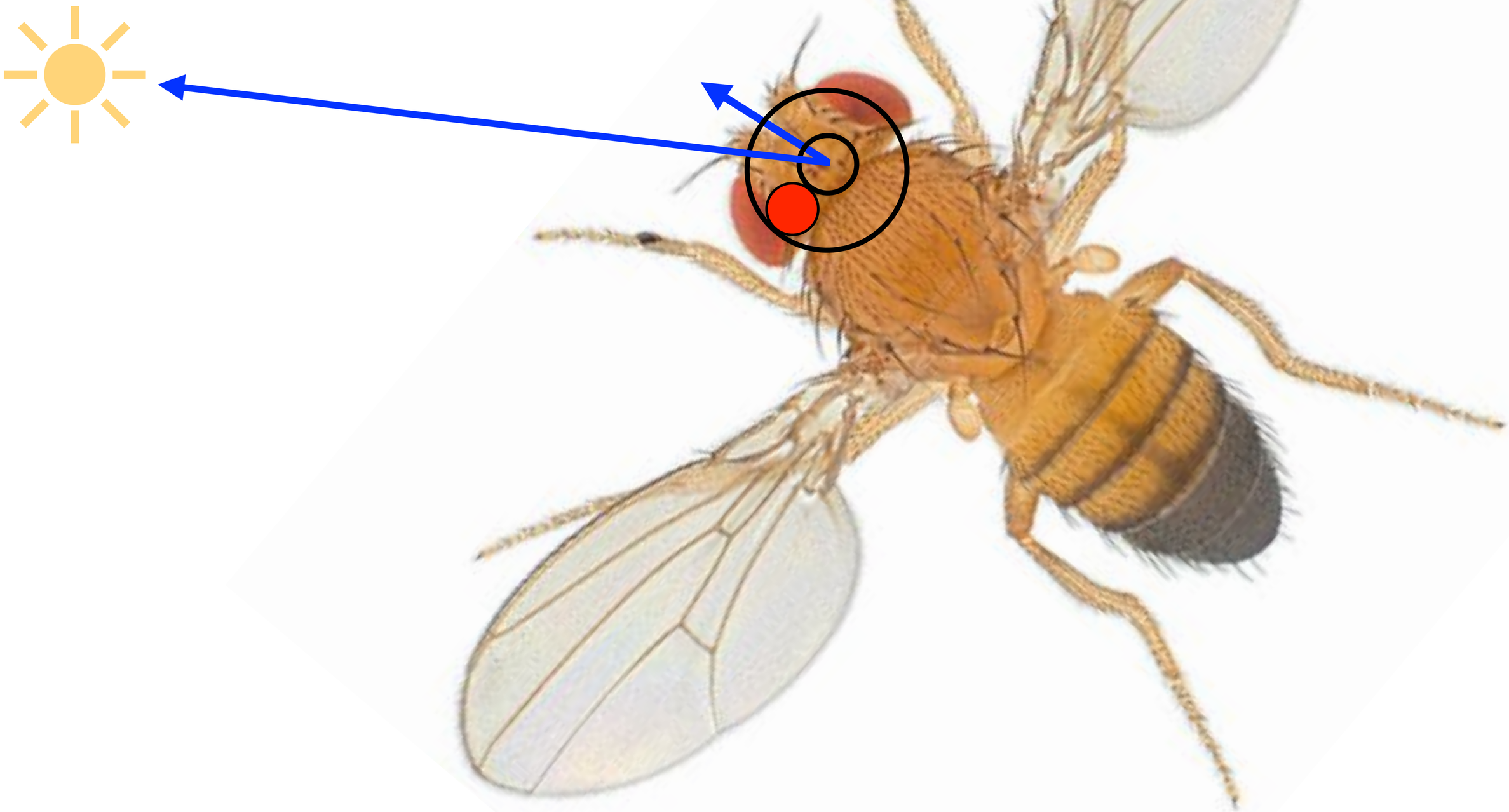


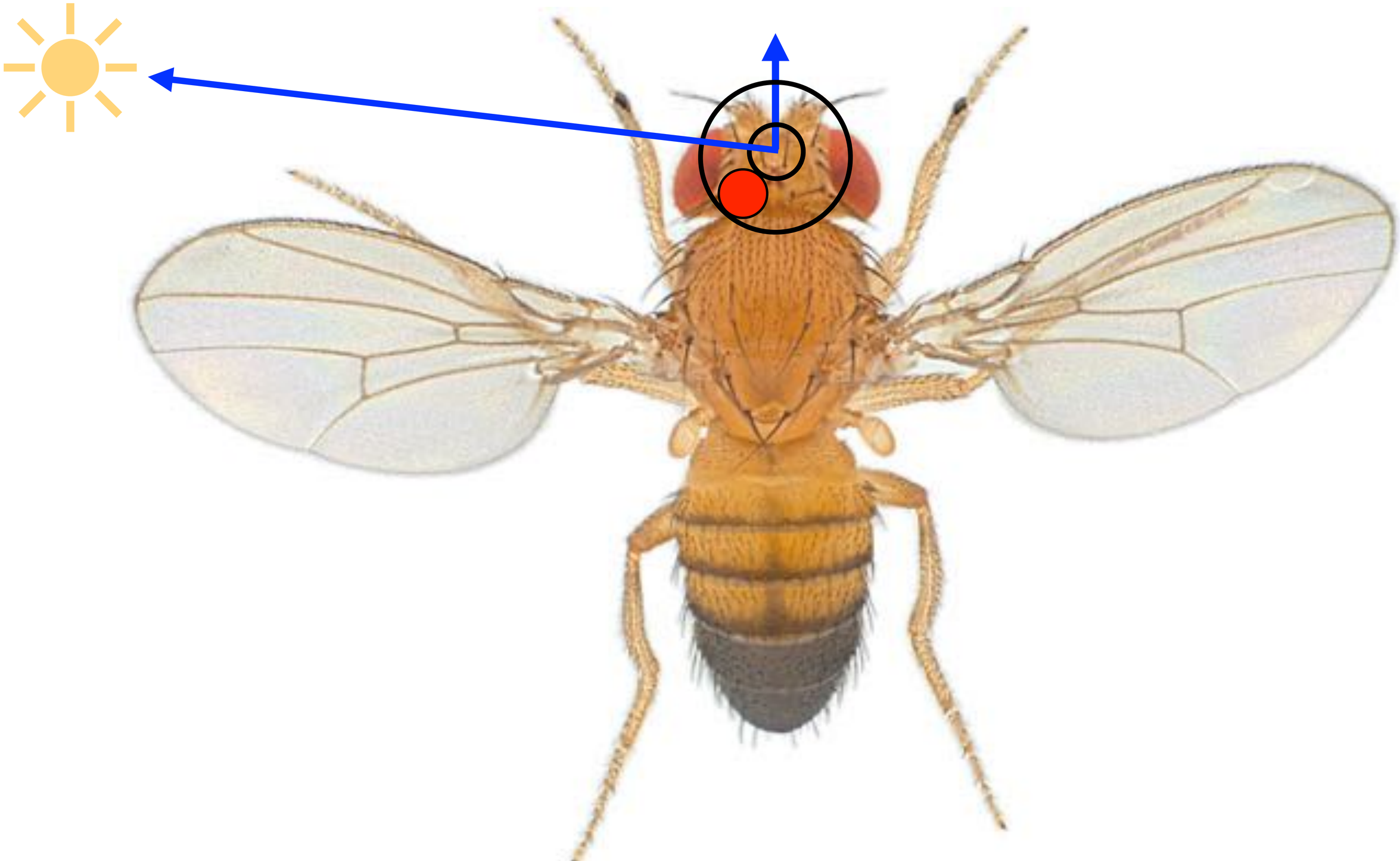




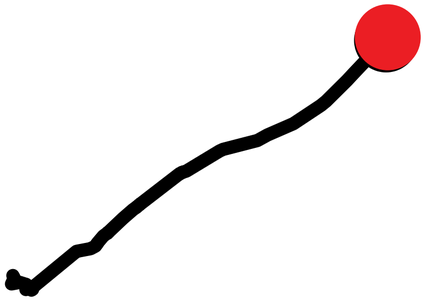
Seelig, Jayaraman (2015)



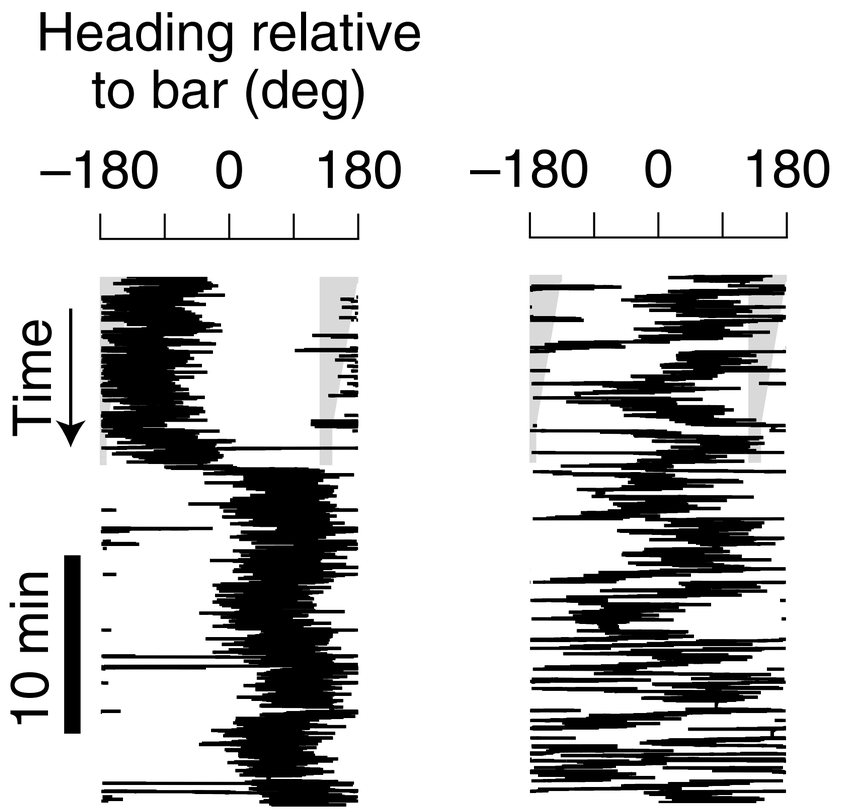


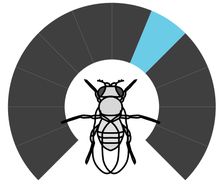


60 minutes



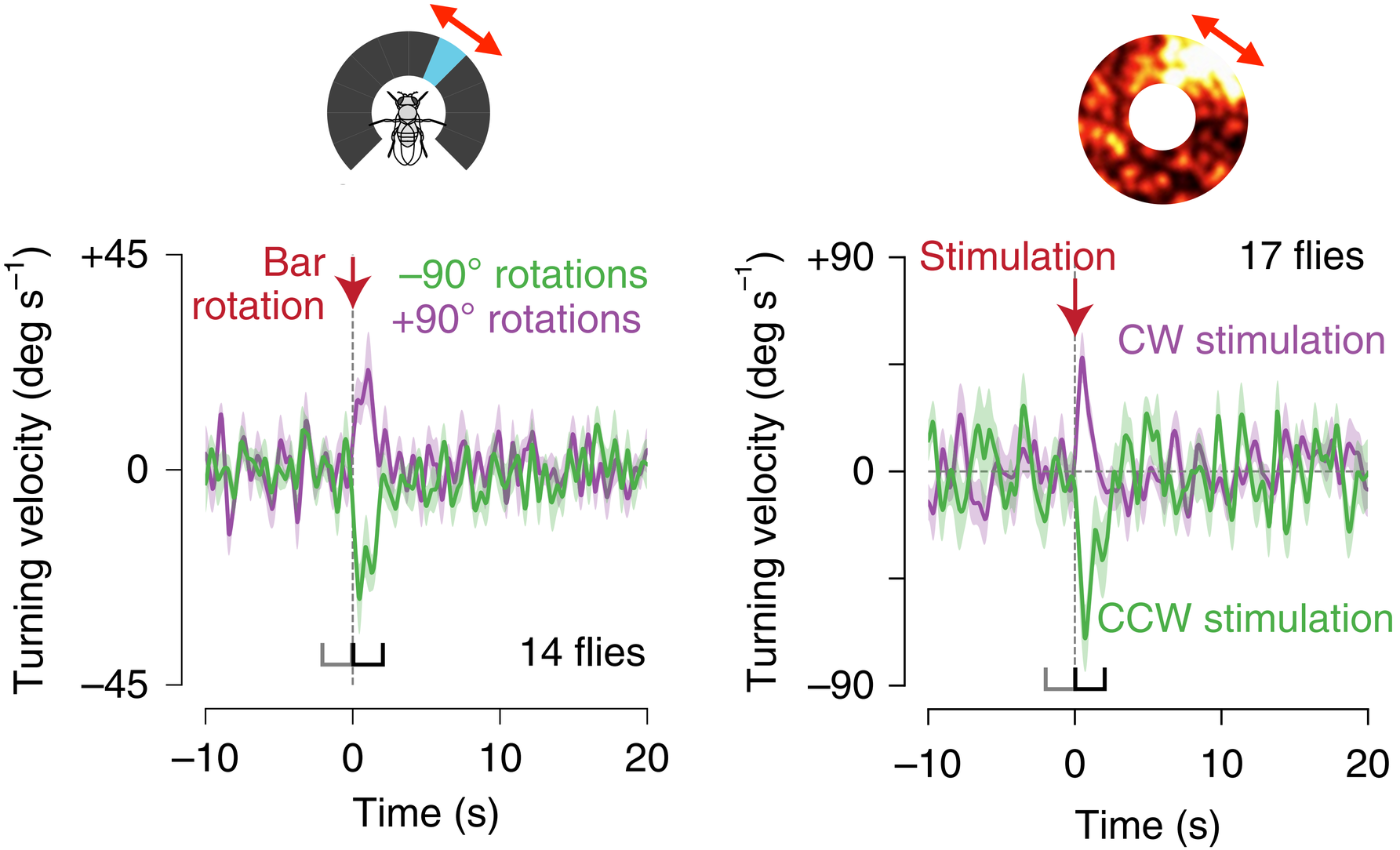
1 m



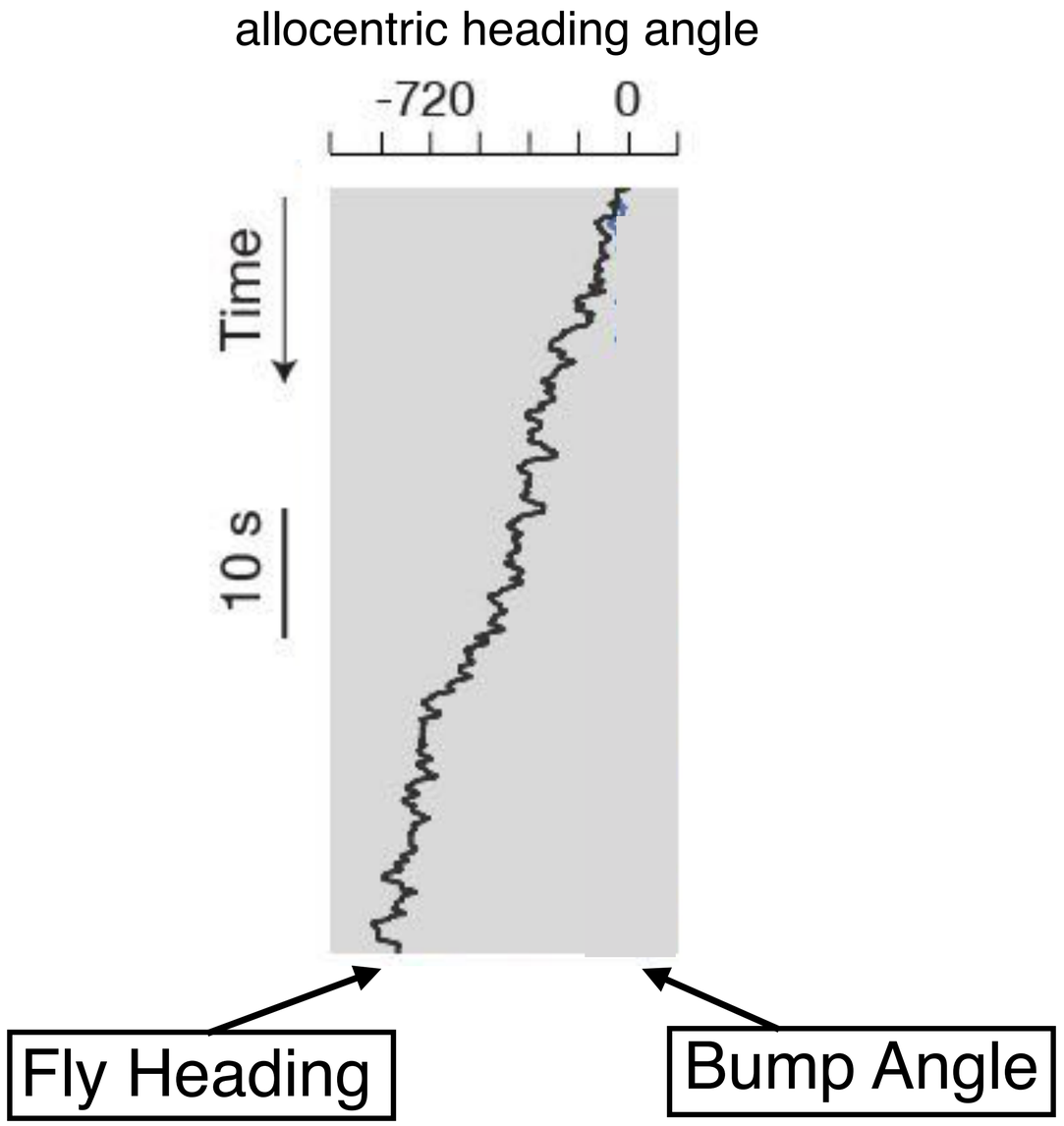


Closed
loop bar

Green, Vijayan, Pires, Adachi, Maimom (2019)

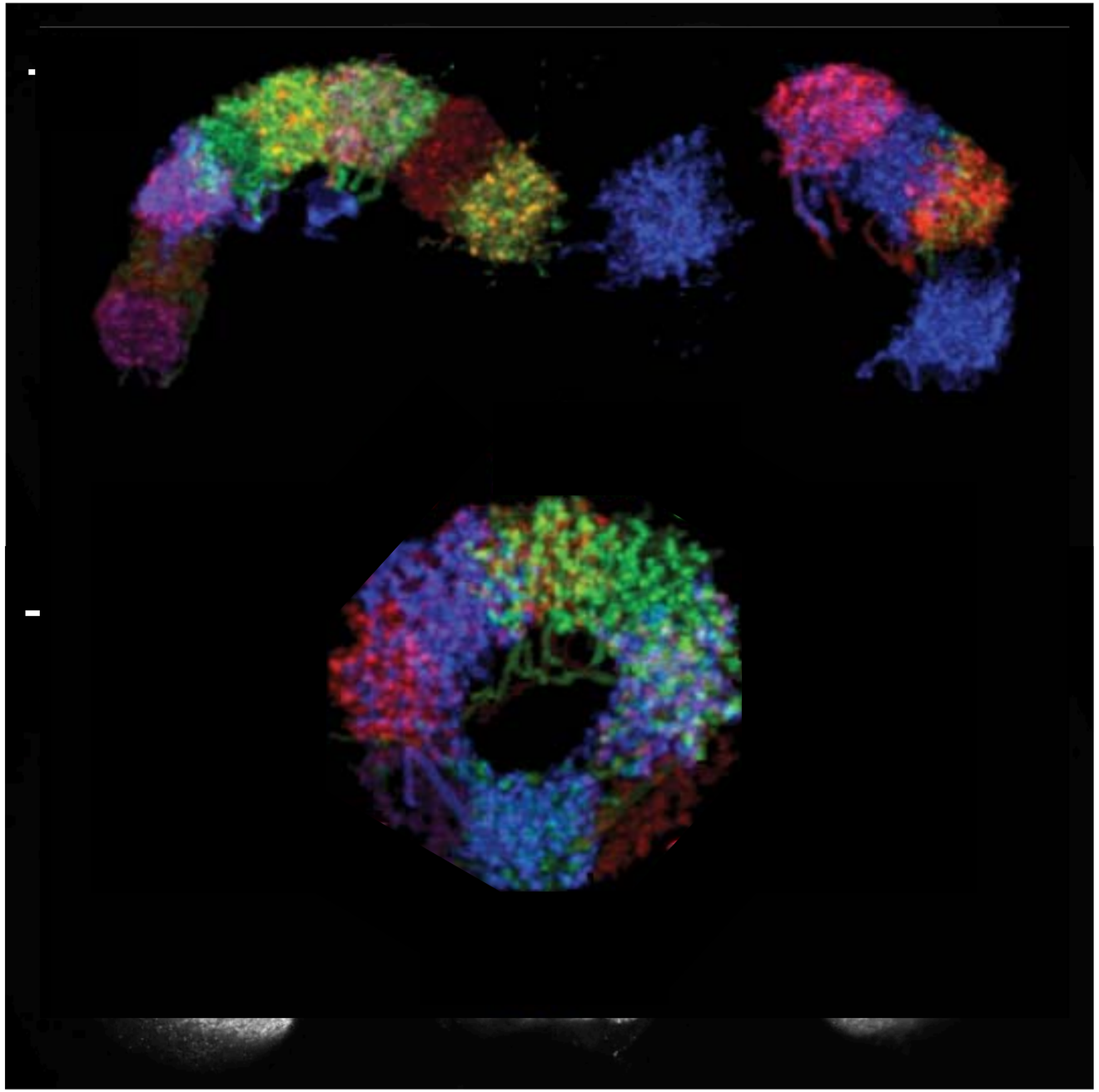


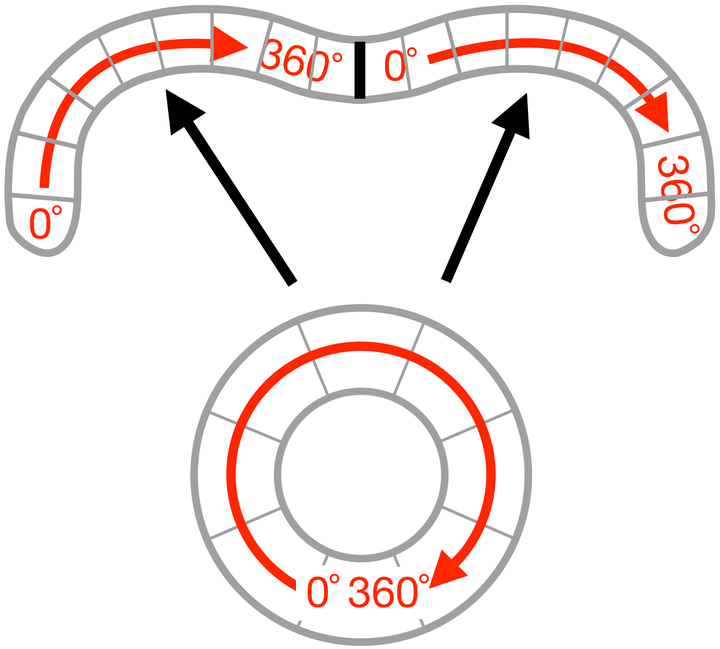
Green, Vijayan, Pires, Adachi, Maimom (2019)

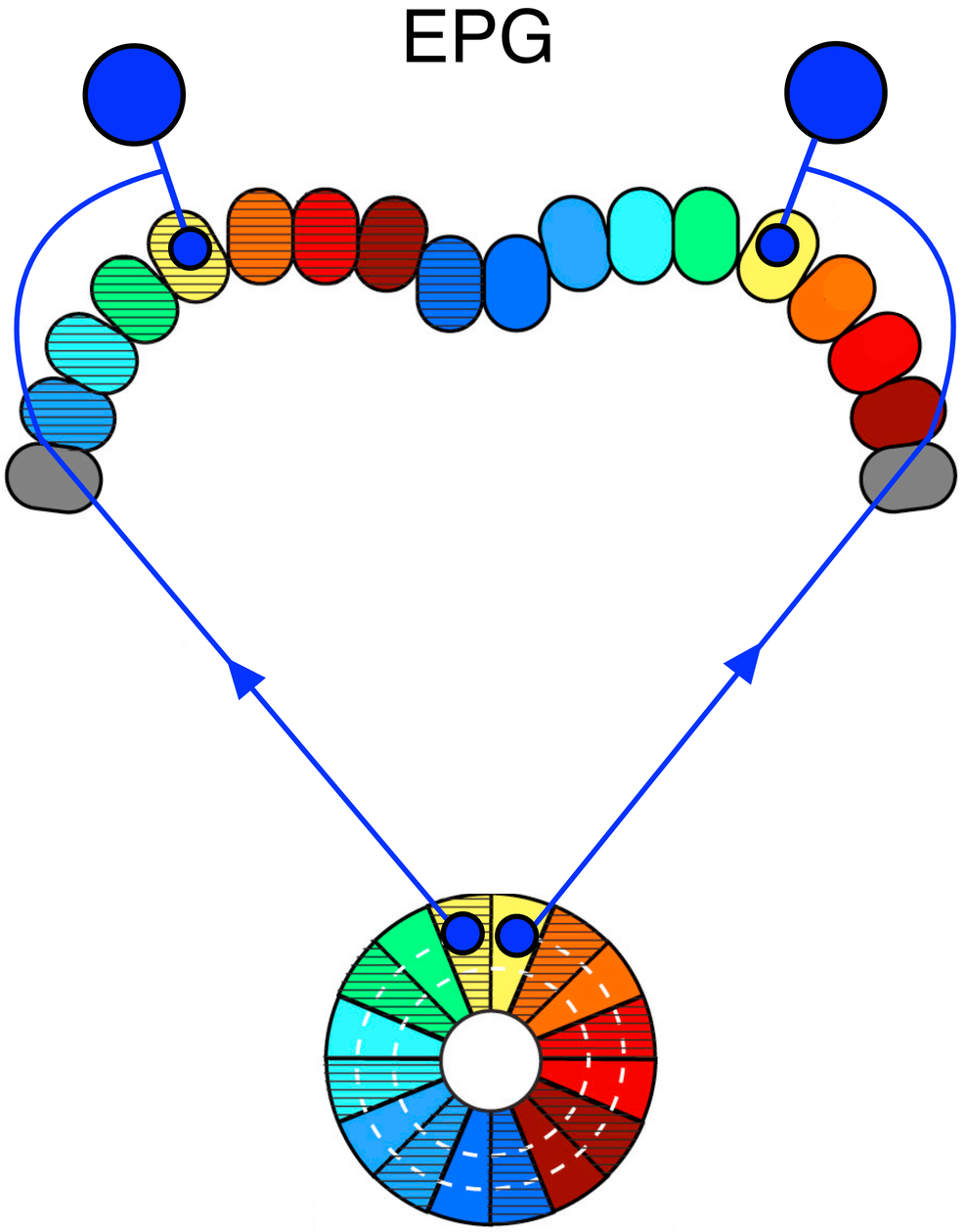


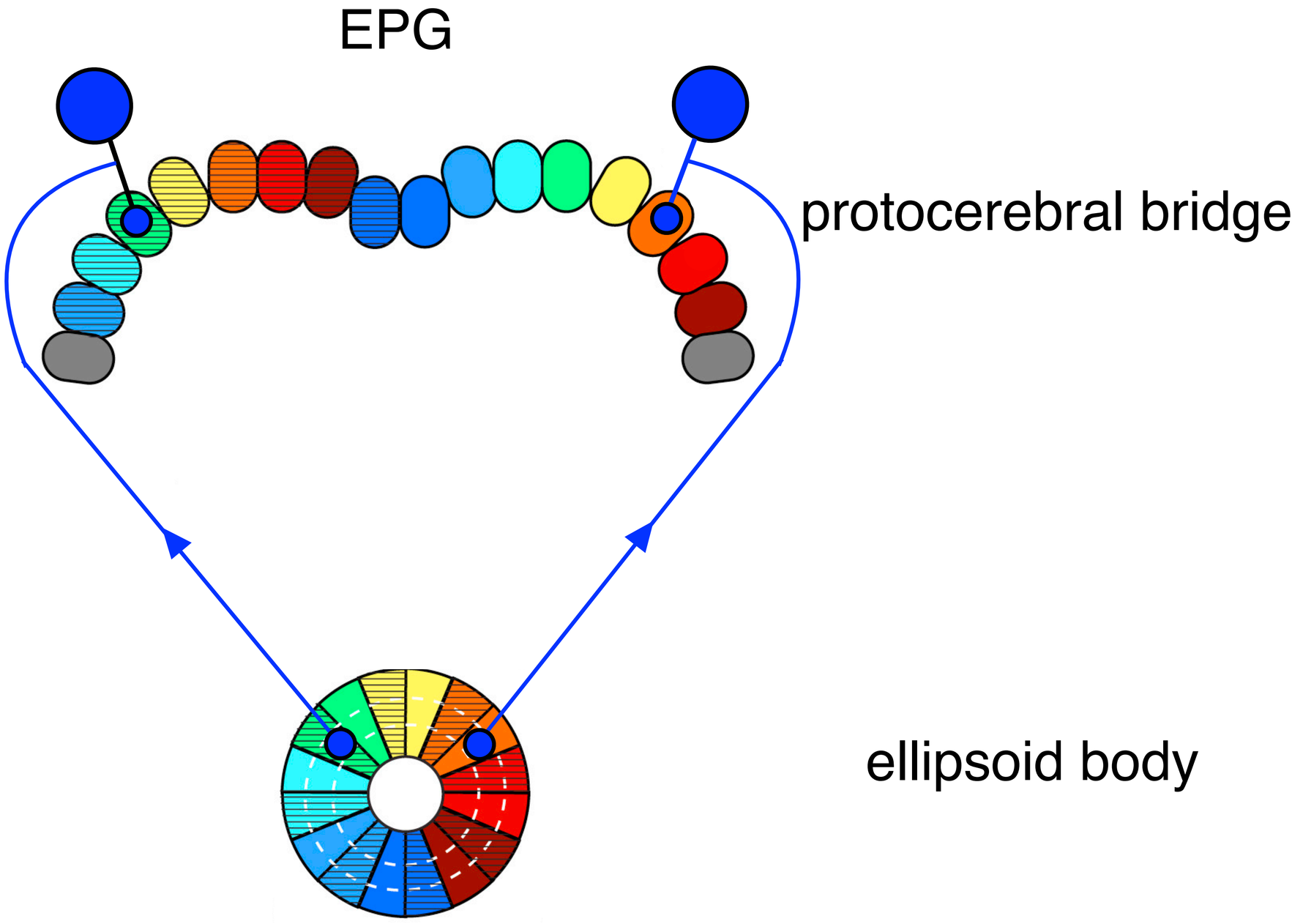
Green, Vijayan, Pires, Adachi, Maimom (2019)

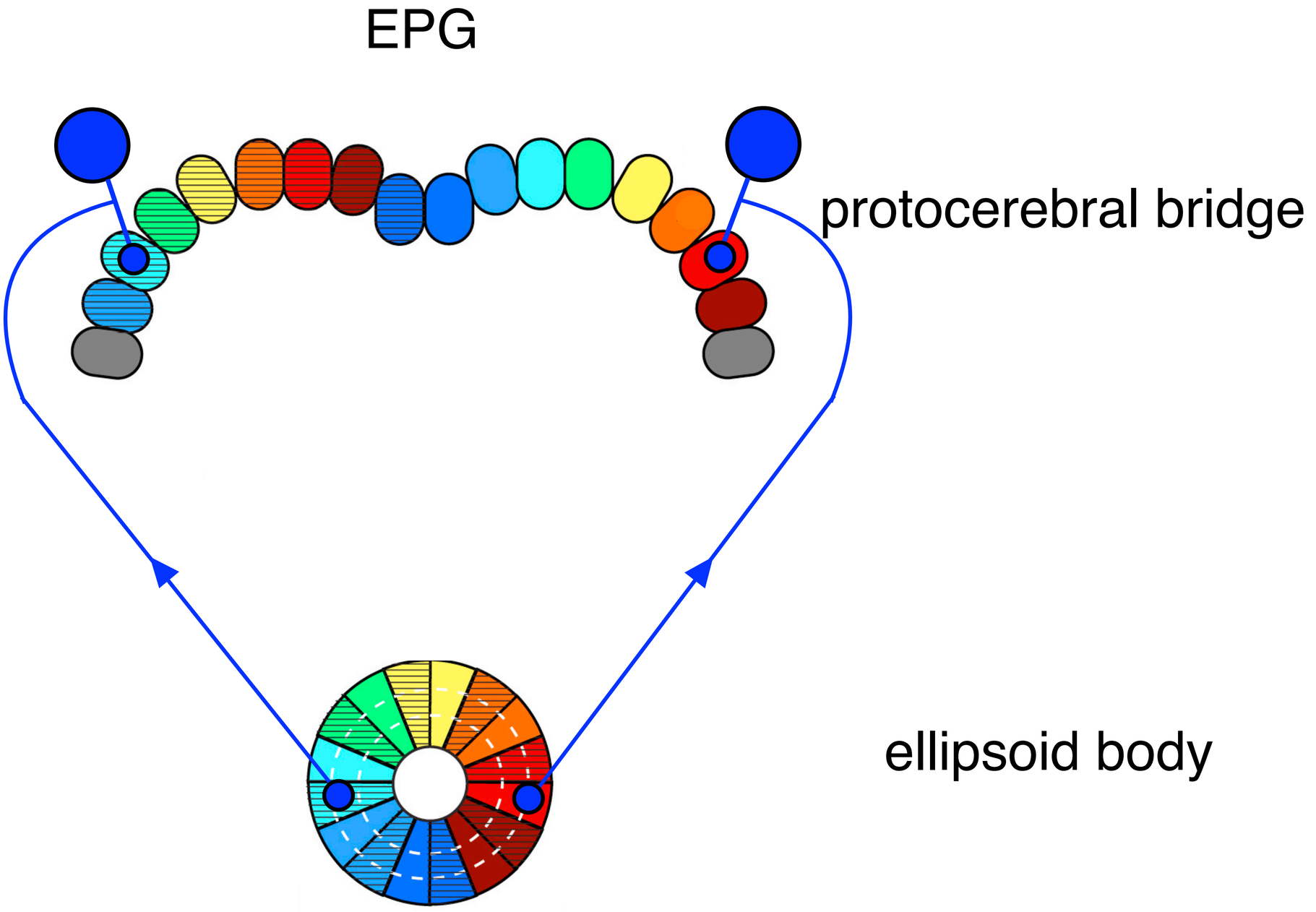
http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/

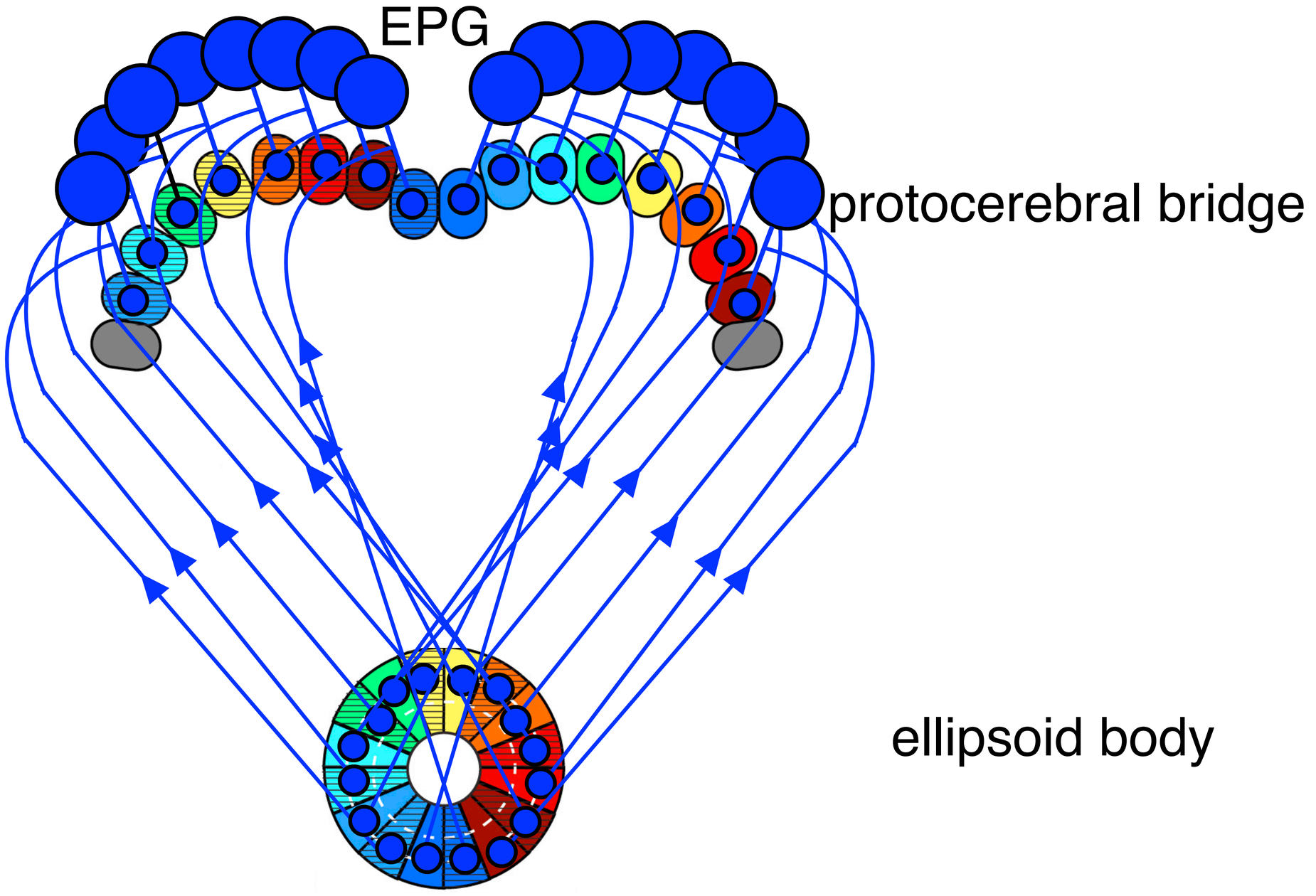




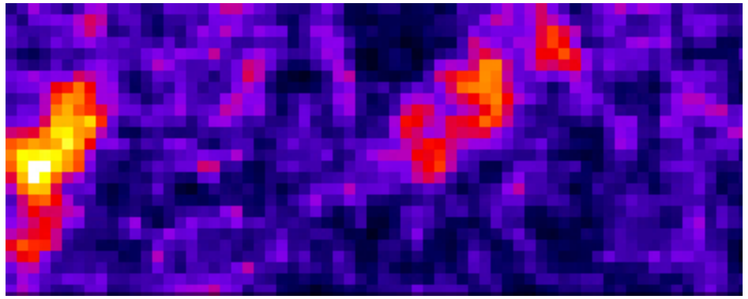

EPG
protocerebral bridge
ellipsoid body

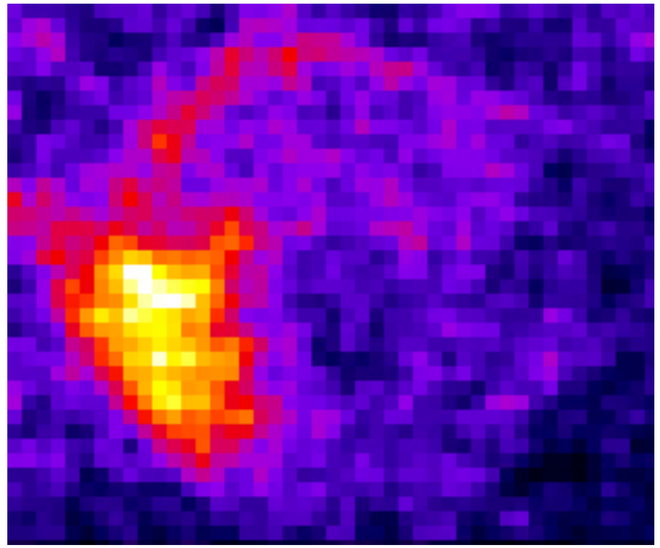

EPG
protocerebral bridge
ellipsoid body

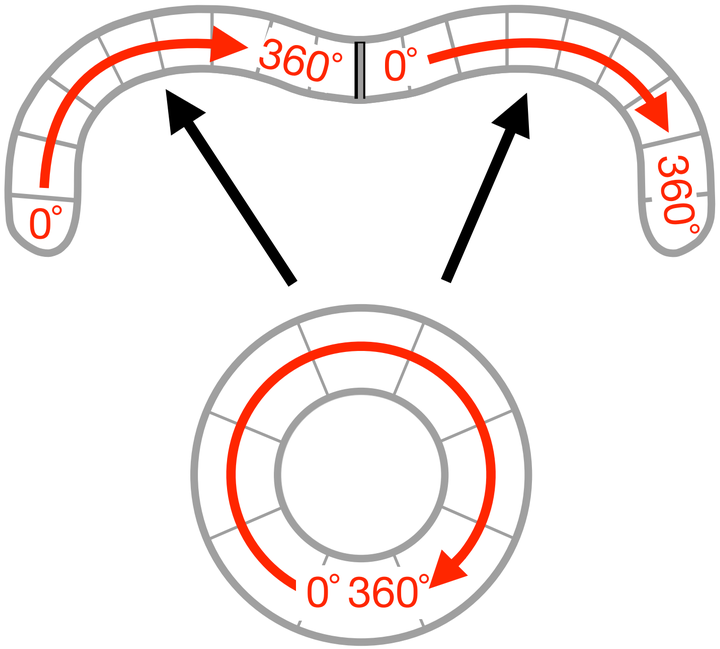

EPG
protocerebral bridge
ellipsoid body


EPG
protocerebral bridge
ellipsoid body

EPG



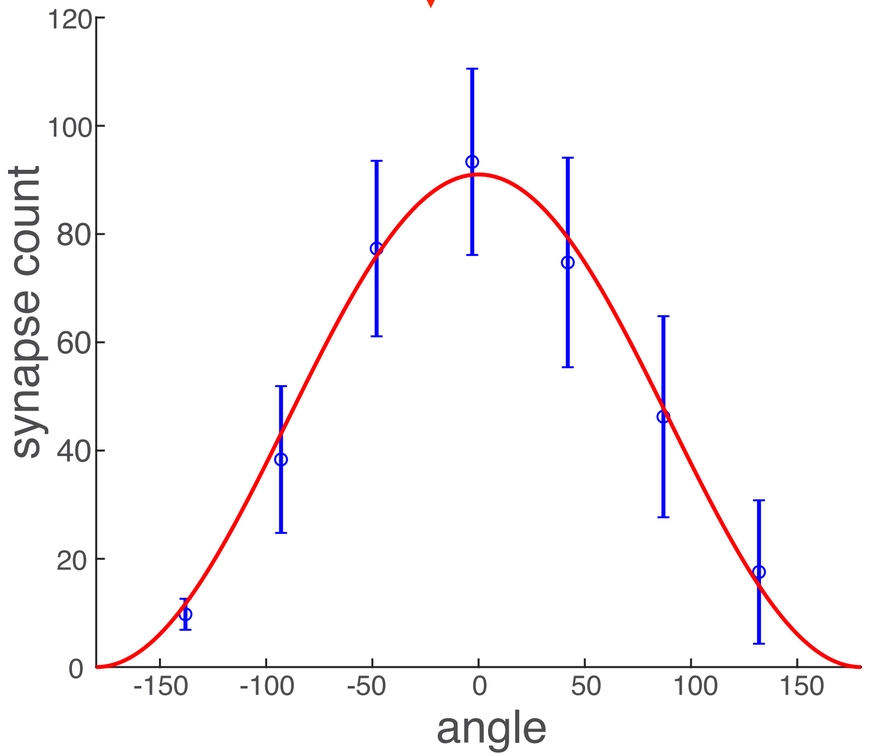


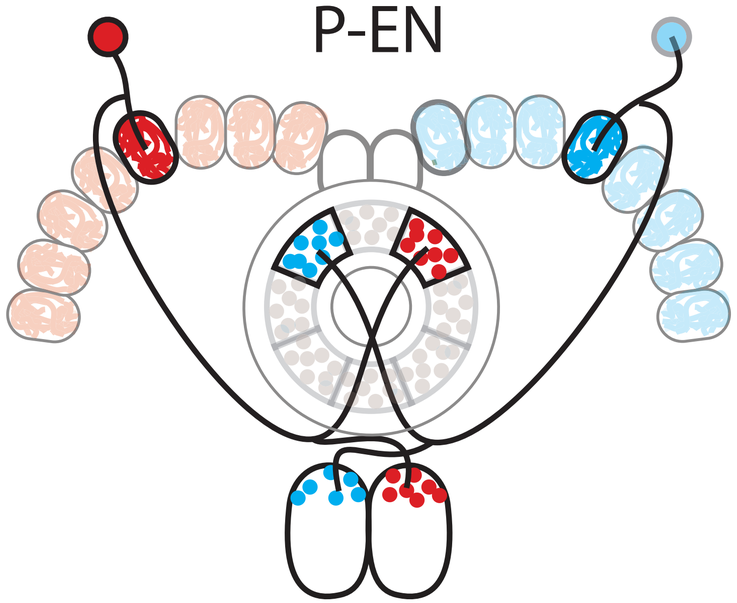


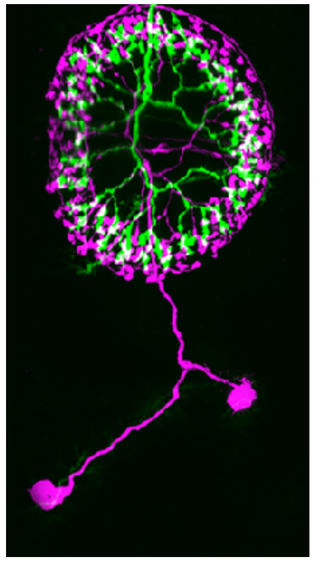
Cheng Lyu

Green, Adachi, Shah, Hirokawa, Magani, Maimon (2017)

$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big[J_0 + J_i \cos(\theta_i - \theta_j) + L\cos(\theta_i - \theta_j + \pi/4) + R\cos(\theta_i - \theta_j - \pi/4) \Big] r_j + \Big[I\cos(V - \theta_i) \Big]$$







Turner-Evans, Wegener, Rouault, Franconville, Wolff, Seelig, Druckmann, Jayaraman (2017)

Green, Adachi, Shah, Hirokawa, Magani, Maimon (2017)

Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)

Ben-Yishai, Bar-Or, Sompolinsky (1995); Skaggs, Knierim, Kudrimoti, McNaughton (1995); Zhang (1996);

Kim, Rouault, Druckmann, Jayaraman (2017); Kakaria, de Bivort (2017); Cope, Sabo, Vasilaki, Barron, Marshall (2017)

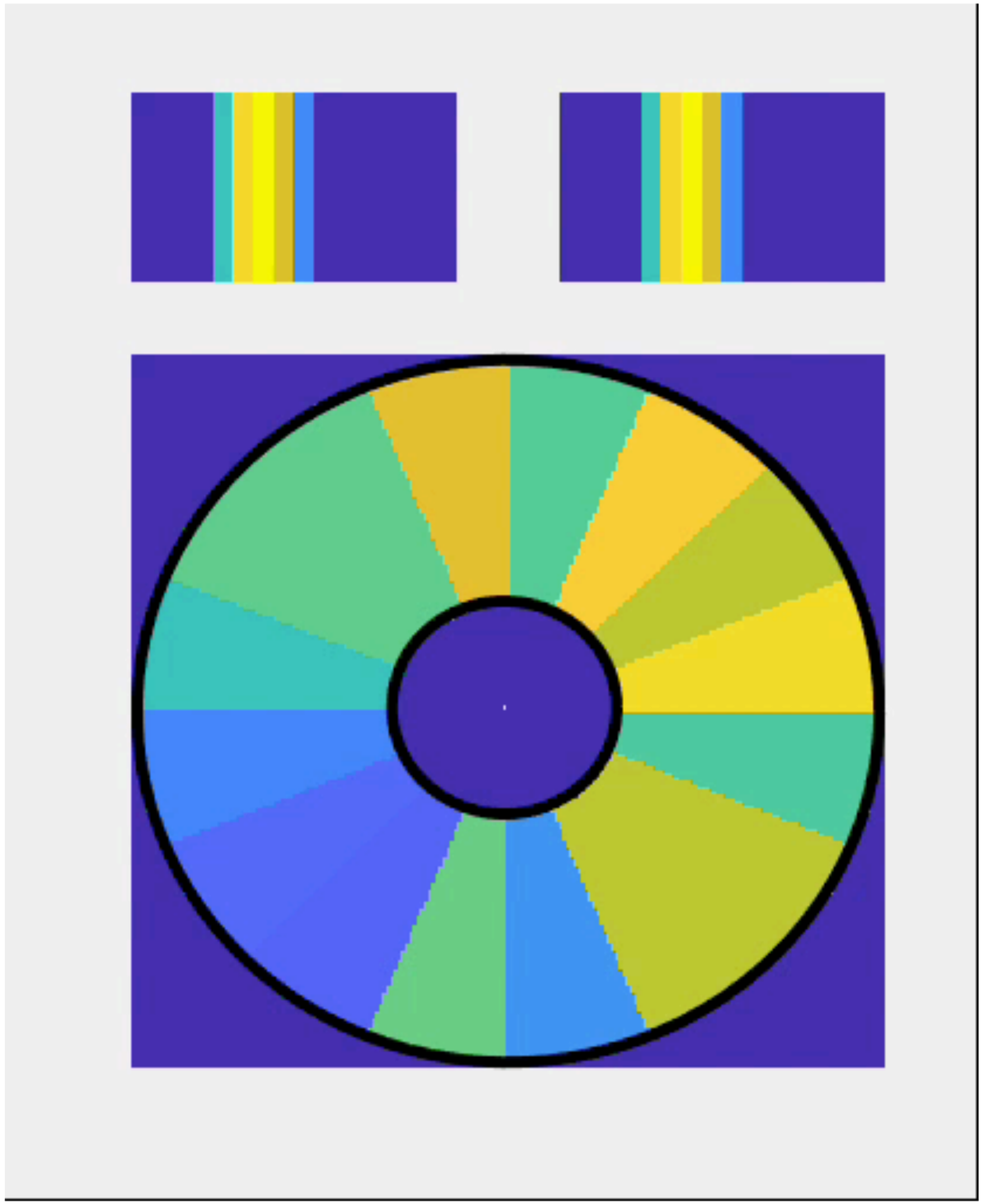
$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) \Big) r_j \Big)$$

$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) + L\cos(\theta_i - \theta_j + \pi/4) + R\cos(\theta_i - \theta_j - \pi/4) \Big) r_j \Big)$$

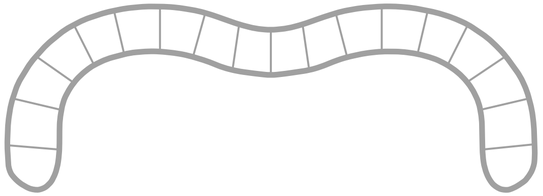
$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) + L\cos(\theta_i - \theta_j + \pi/4) + R\cos(\theta_i - \theta_j - \pi/4) \Big) r_j + I\cos(V - \theta_i) \Big)$$

$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) \Big) r_j + I\cos(V - \theta_i) \Big)$$

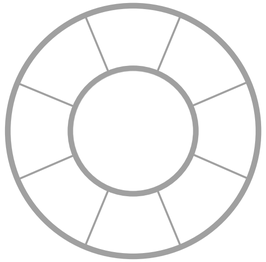
$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) \Big) r_j \Big)$$



protocerebral bridge



ellipsoid body

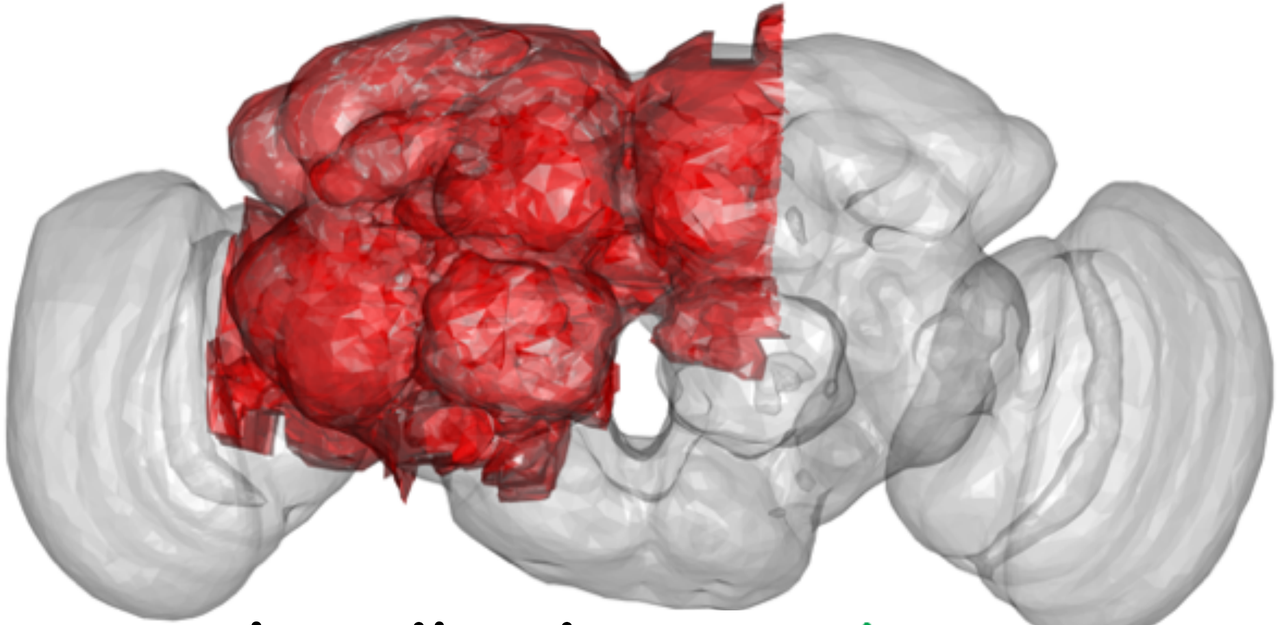


Supporting the Bump

$$J_0 + J_1 \cos(\theta_i - \theta_j)$$

$$\cos(\theta_i - \theta_j) = -\cos(\theta_i - \theta_j - \pi)$$

Complete Fly Brain EM Connectome



hemibrain janelia flyEM Google

https://neuprint.janelia.org/

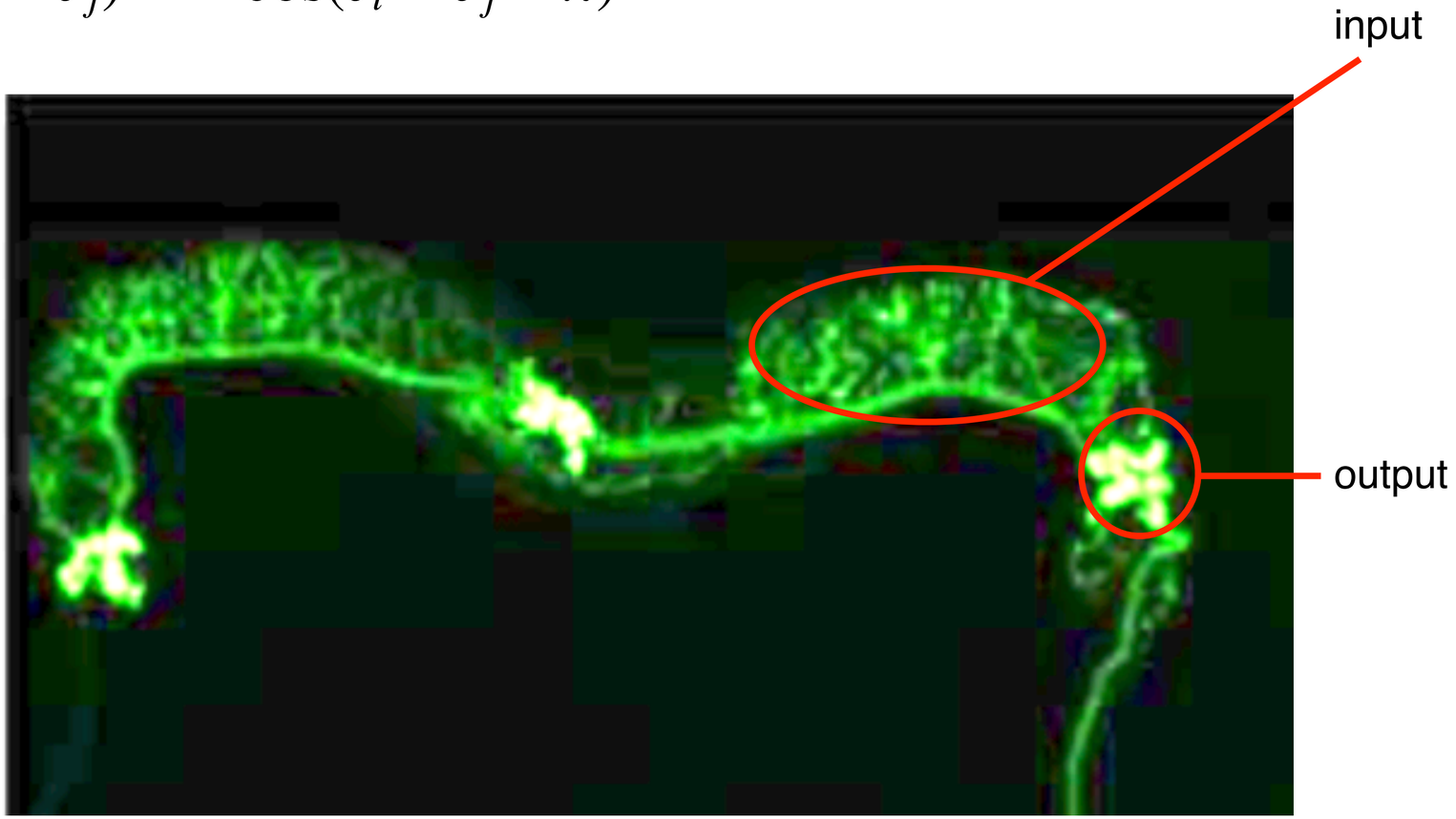
Turner-Evans, Jensen, Ali, Paterson, Sheridan, Ray, Lauritzen, Bock, Jayaraman (2019)

A Connectome of the Adult Drosophila Central Brain

C. Shan Xu, Michal Januszewski, Zhiyuan Lu, Shin-ya Takemura, Kenneth J. Hayworth, Gary Huang, Kazunori Shinomiya, Jeremy Maitin-Shepard, David Ackerman, Stuart Berg, Tim Blakely, John Bogovic, Jody Clements, Tom Dolafi, Philip Hubbard, Dagmar Kainmueller, William Katz, Takashi Kawase, Khaled A. Khairy, Laramie Leavitt, Peter H. Li, Larry Lindsey, Nicole Neubarth, Donald J. Olbris, Hideo Otsuna, Eric T. Troutman, Lowell Umayam, Ting Zhao, Masayoshi Ito, Jens Goldammer, Tanya Wolff, Robert Svirskas, Philipp Schlegel, Erika R. Neace, Christopher J. Knecht Jr., Chelsea X. Alvarado, Dennis A. Bailey, Samantha Ballinger, Jolanta A Borycz, Brandon S. Canino, Natasha Cheatham, Michael Cook, Marisa Dreher, Octave Duclos, Bryon Eubanks, Kelli Fairbanks, Samantha Finley, Nora Forknall, Audrey Francis, Gary Patrick Hopkins, Emily M. Joyce, SungJin Kim, Nicole A. Kirk, Julie Kovalyak, Shirley A. Lauchie, Alanna Lohff, Charli Maldonado, Emily A. Manley, Sari McLin, Caroline Mooney, Miatta Ndama, Omotara Ogundeyi, Nneoma Okeoma, Christopher Ordish, Nicholas Padilla, Christopher Patrick, Tyler Paterson, Elliott E. Phillips, Emily M. Phillips, Neha Rampally, Caitlin Ribeiro, Madelaine K Robertson, Jon Thomson Rymer, Sean M. Ryan, Megan Sammons, Anne K. Scott, Ashley L. Scott, Aya Shinomiya, Claire Smith, Kelsey Smith, Natalie L. Smith, Margaret A. Sobeski, Alia Suleiman, Jackie Swift, Satoko Takemura, Iris Talebi, Dorota Tarnogorska, Emily Tenshaw, Temour Tokhi, John J. Walsh, Tansy Yang, Jane Anne Horne, Feng Li, Ruchi Parekh, Patricia K. Rivlin, Vivek Jayaraman, Kei Ito, Stephan Saalfeld, Reed George, Ian Meinertzhagen, Gerald M. Rubin, Harald F. Hess, Louis K. Scheffer, Viren Jain, Stephen M. Plaza

Hulse* , B.K. , Haberkern* , H., Franconville* , R., Turner-Evans* , D.B., Takemura, S., Wolff, T., Noorman, M., Dreher, M., Dan, C., Parekh, R., Hermundstad, A.M., Rubin, G.M. & Jayaraman, V.
A connectome of the *Drosophila* central complex reveals network motifs suitable for flexible navigation and context-dependent action selection.

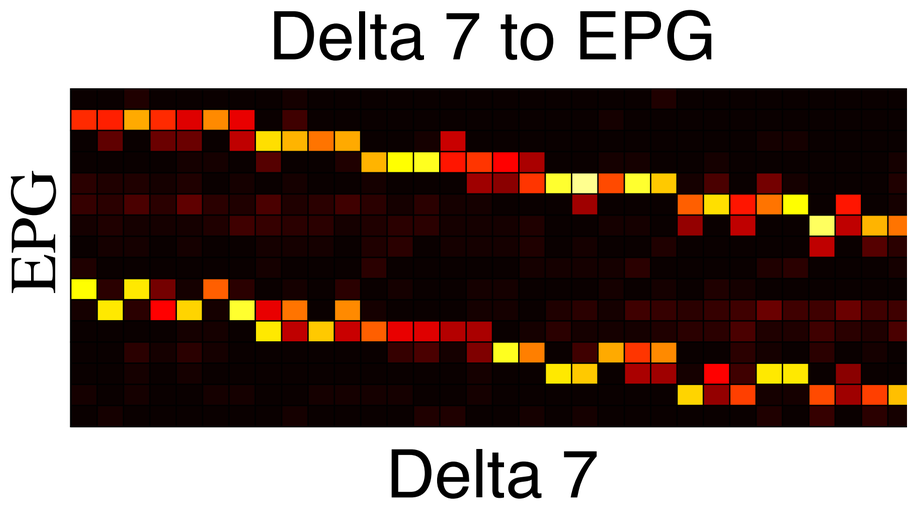
$$\cos(\theta_i - \theta_j) = -\cos(\theta_i - \theta_j - \pi)$$

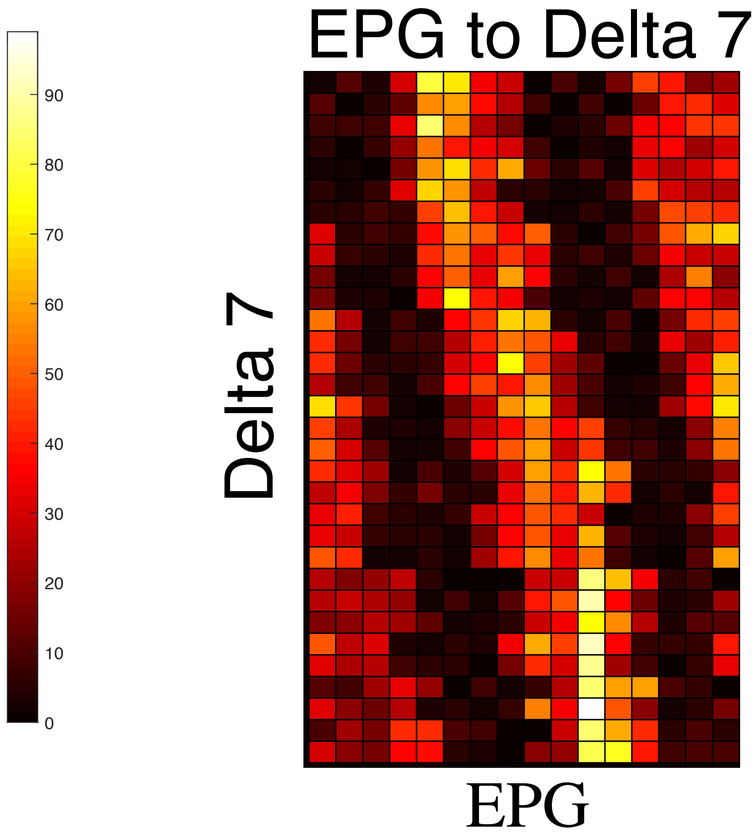


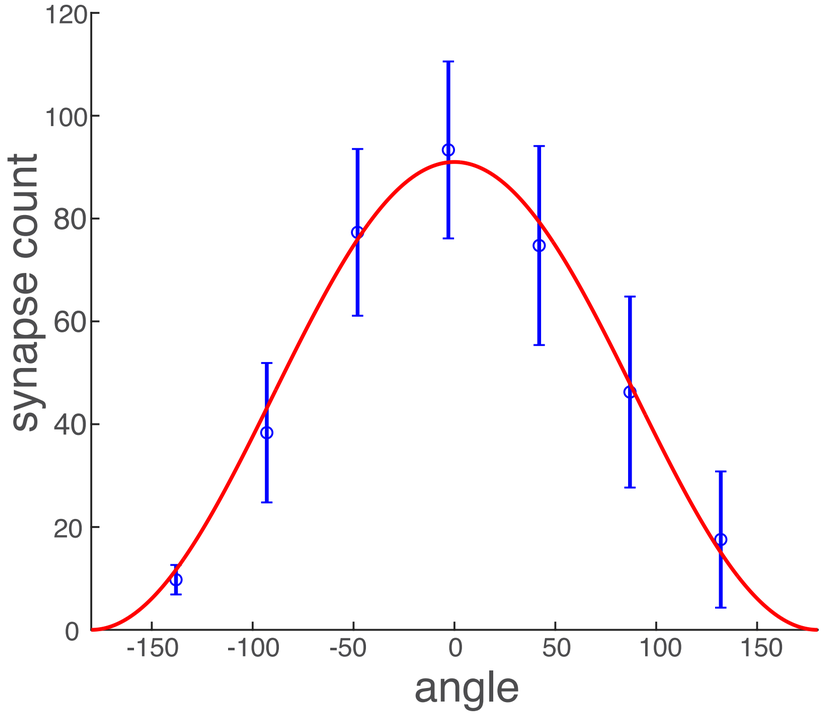
Delta 7

Wolff et al. (2015)

Turner-Evans, Jensen, Ali, Paterson, Sheridan, Ray, Lauritzen, Bock, Jayaraman (2019)


Delta 7 to EPG
EPG
Delta 7


EPG to Delta 7
Delta 7
EPG
90
80
70
60
50
40
30
20
10
0


synapse count
angle
120
100
80
60
40
20
0
-150
-100
-50
0
50
100
150

Supporting the Bump

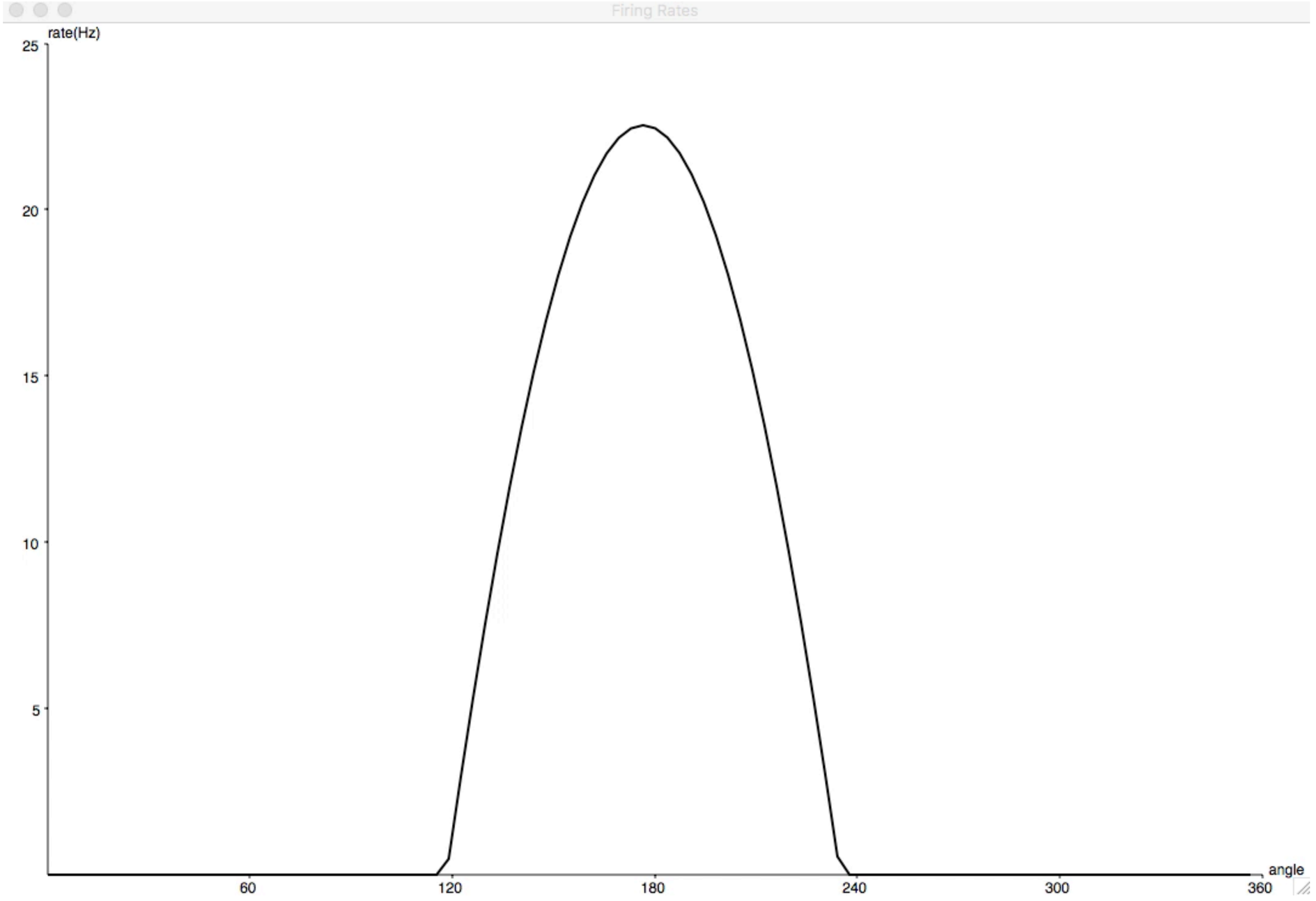
$$J_0 + J_1 \cos(\theta_i - \theta_j)$$

Moving the Bump

$$J_0 + J_1 \cos(\theta_i - \theta_j) + \alpha \sin(\theta_i - \theta_j)$$

Turner-Evans, Wegener, Rouault, Franconville, Wolff, Seelig, Druckmann, Jayaraman (2017)

Green, Adachi, Shah, Hirokawa, Magani, Maimon (2017)


Firing Rates
rate(Hz)
25
20
15
10
5
60
120
180
240
300
360
angle

Supporting the Bump

$$J_0 + J_1 \cos(\theta_i - \theta_j)$$

Moving the Bump

$$J_0 + J_1 \cos(\theta_i - \theta_j) + \alpha \sin(\theta_i - \theta_j)$$

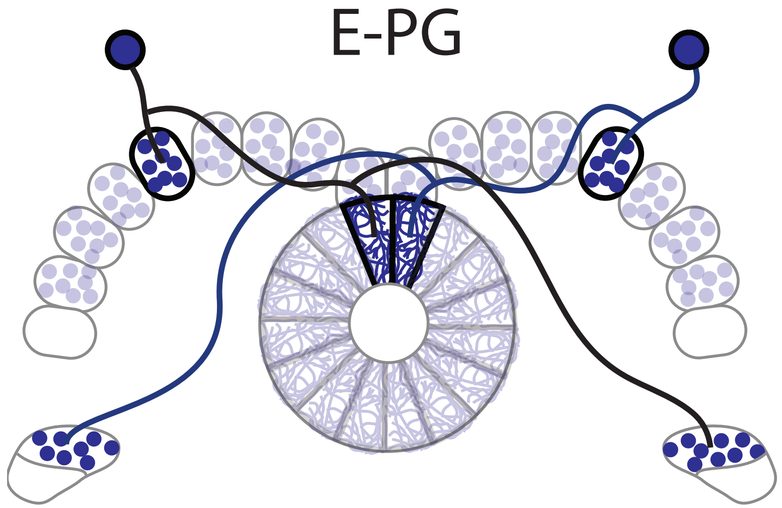
$$J_0 + J_1 \cos(\theta_i - \theta_j) + \alpha' \cos(\theta_i - \theta_j - \Delta)$$

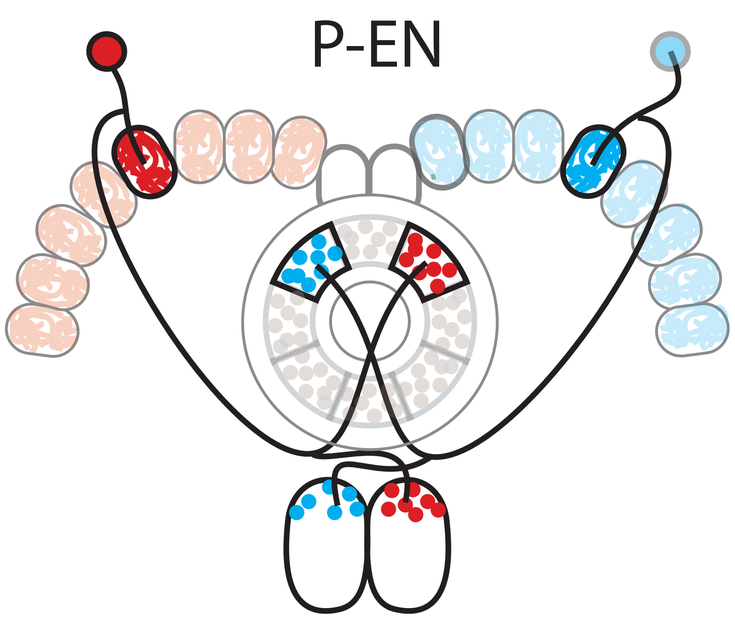
$$= J_0 + J_1(1 + \alpha' \cos(\Delta)) \cos(\theta_i - \theta_j) + \alpha' \sin(\Delta) \sin(\theta_i - \theta_j)$$

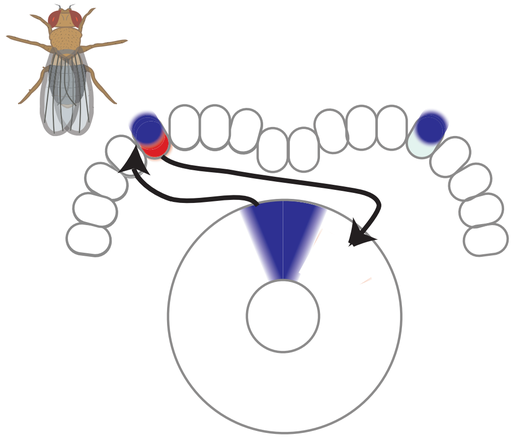
$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) + L\cos(\theta_i - \theta_j + \pi/4) + R\cos(\theta_i - \theta_j - \pi/4) \Big) r_j \Big)$$

$\Delta = 45°$

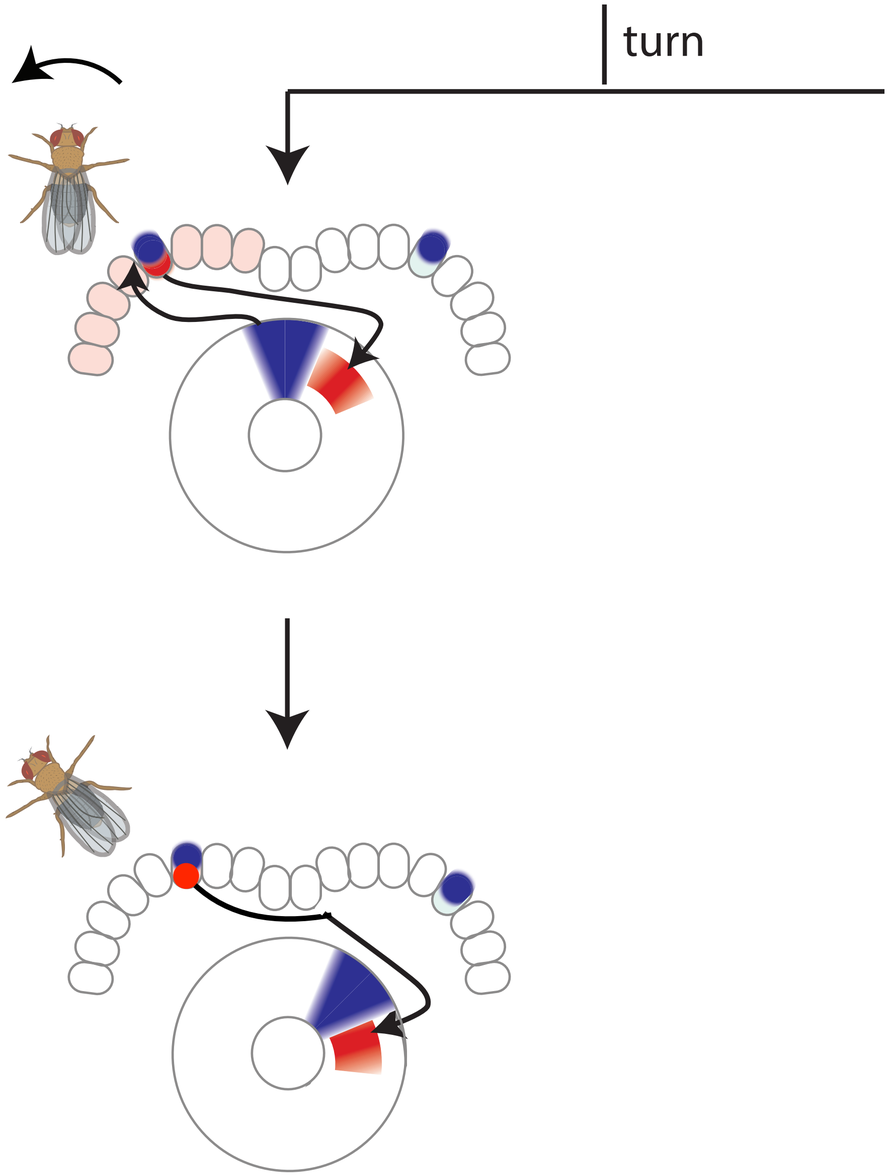
E-PG → P-EN1 → E-PG



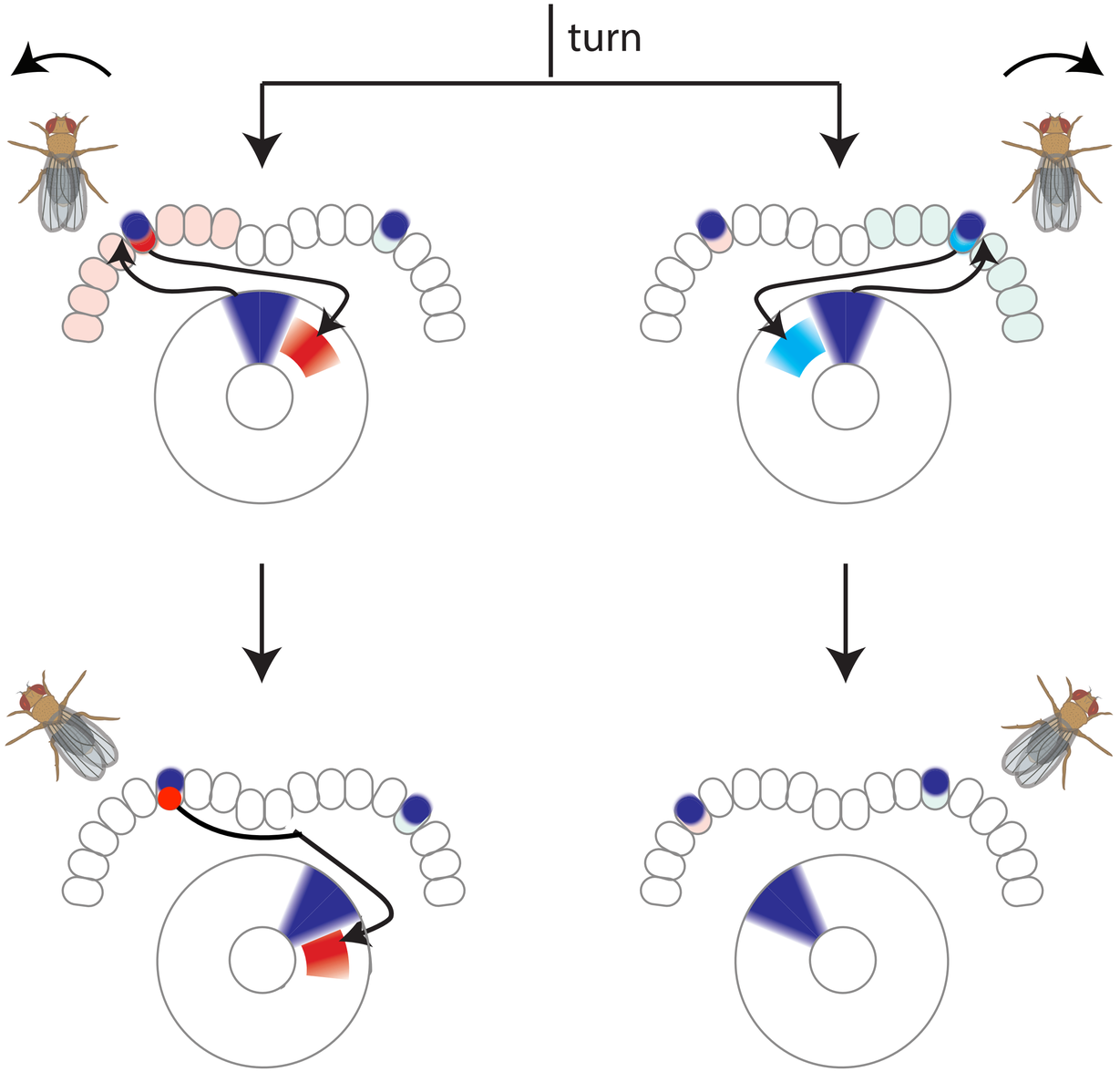




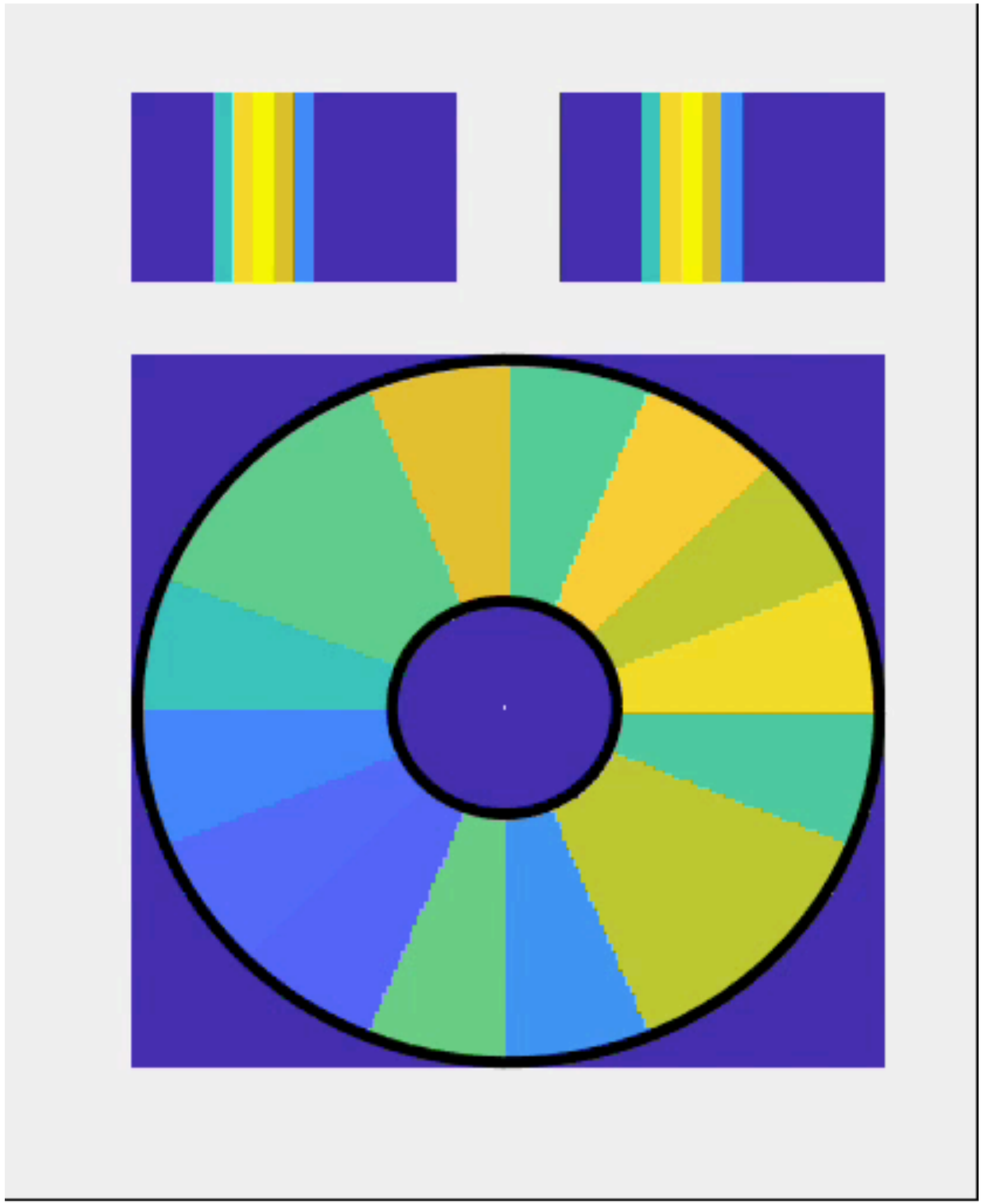
Turner-Evans, Wegener, Rouault, Franconville, Wolff, Seelig, Druckmann, Jayaraman (2017)



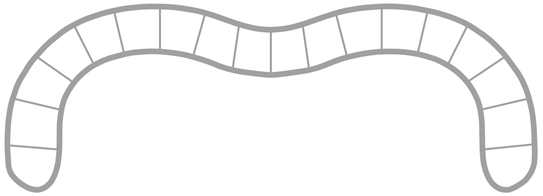
Turner-Evans, Wegener, Rouault, Franconville, Wolff, Seelig, Druckmann, Jayaraman (2017)



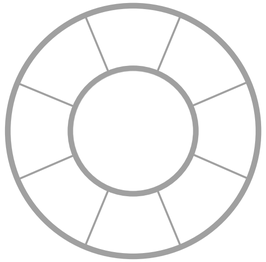
Turner-Evans, Wegener, Rouault, Franconville, Wolff, Seelig, Druckmann, Jayaraman (2017)



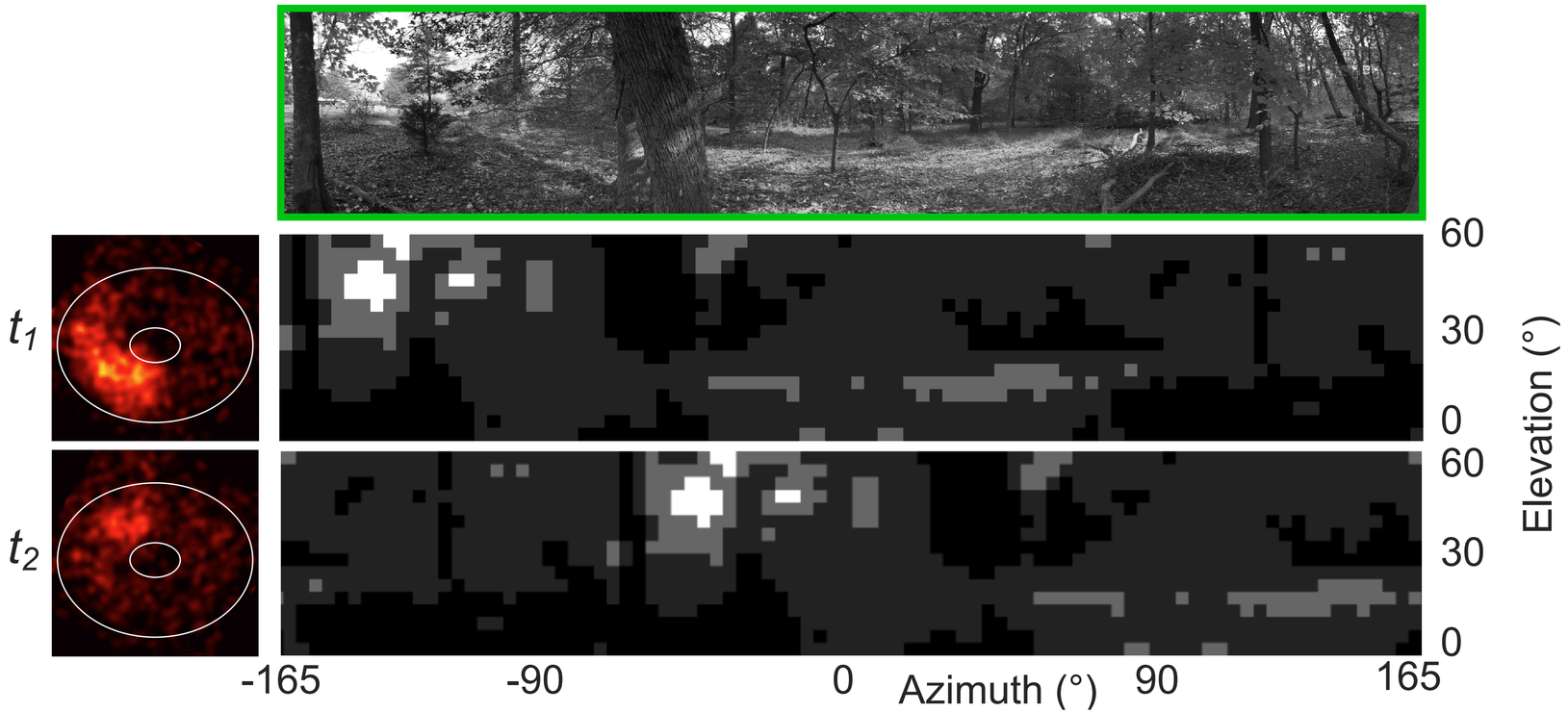
protocerebral bridge



ellipsoid body

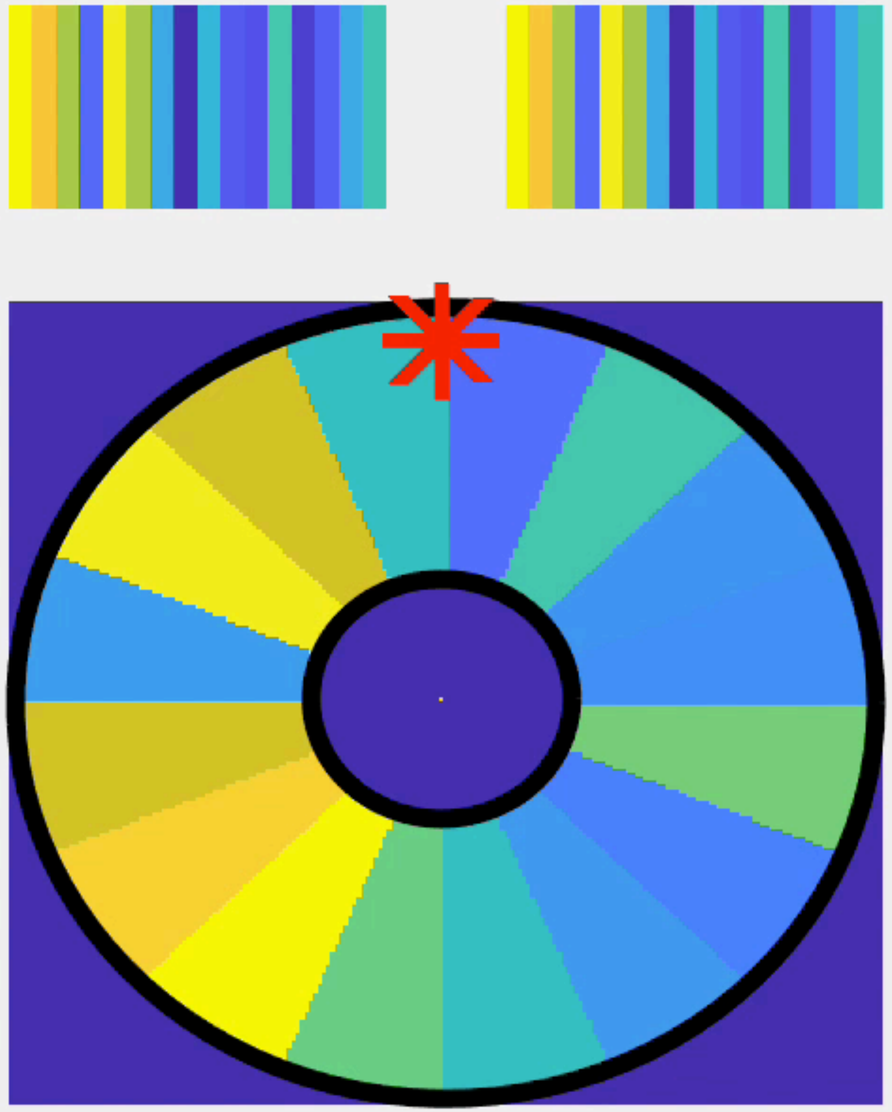


Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)

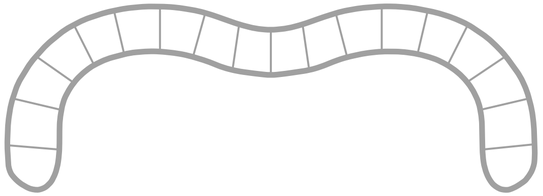


Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)

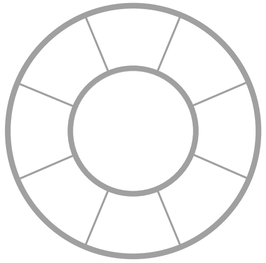
$$\tau \frac{dr_i}{dt} = -r_i + F\Big(\sum_{j=1}^{N} \Big(J_0 + J_1 \cos(\theta_i - \theta_j) \Big) r_j + I \cos(V - \theta_i) \Big)$$



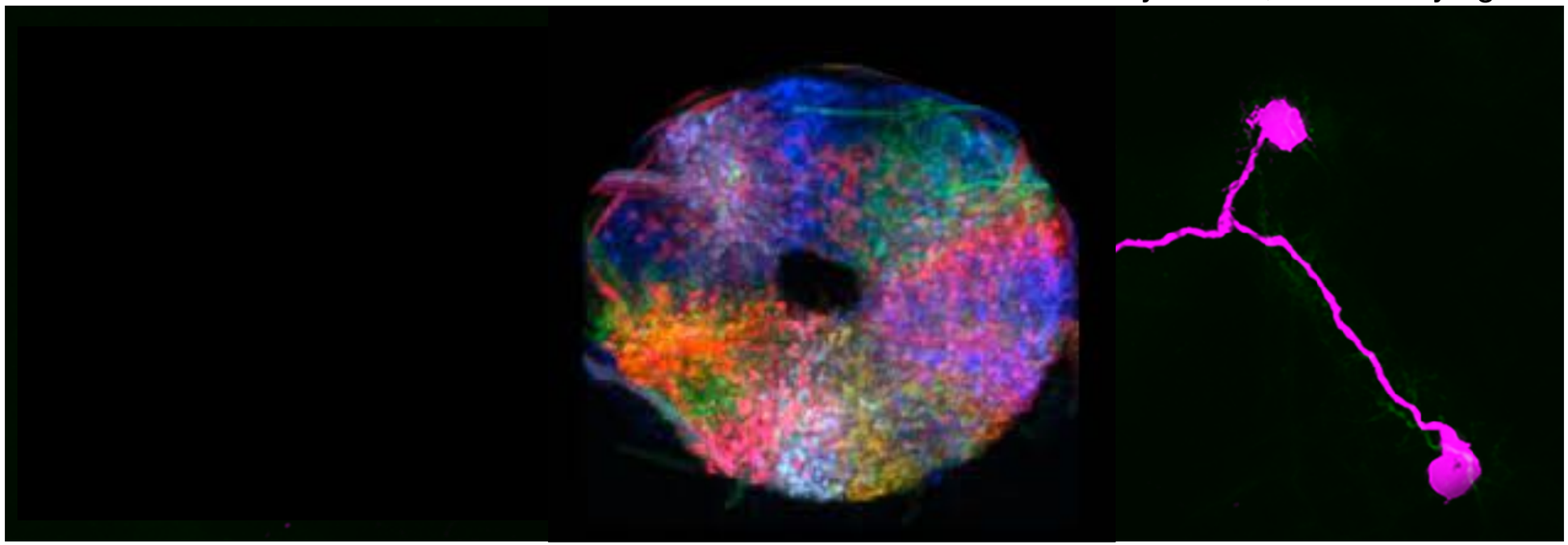
protocerebral bridge

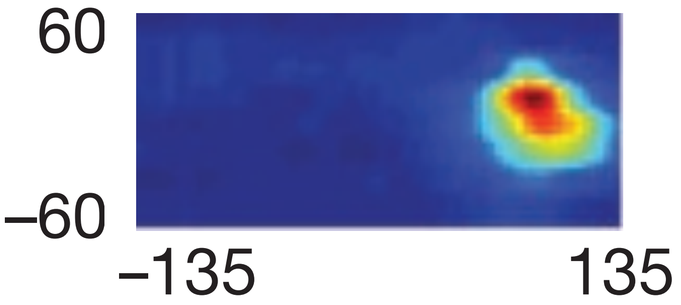


ellipsoid body



Tanya Wolff, Janelia FlyLight

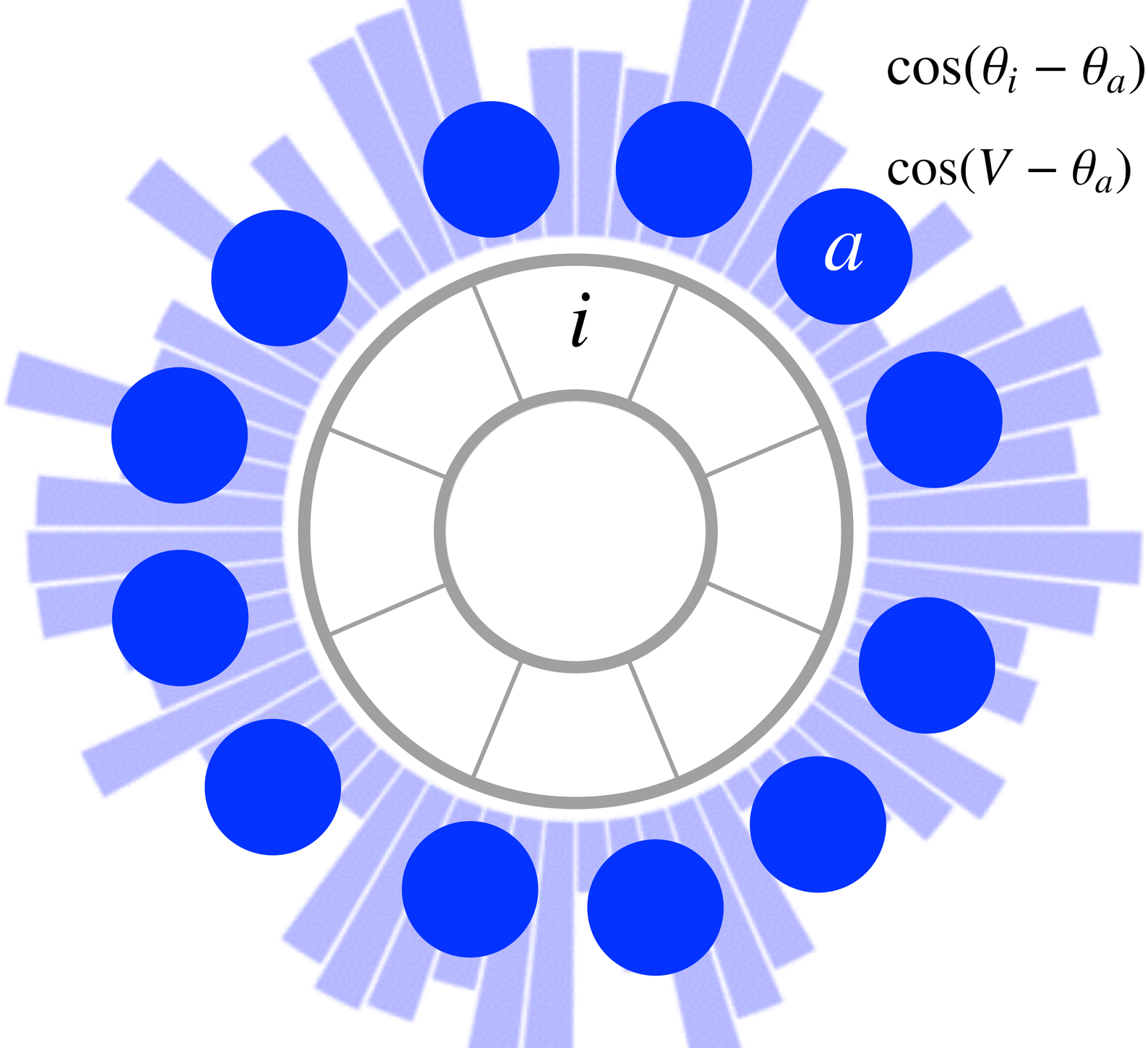




Seelig, Jayaraman (2013)

Fisher, Lu, D’Alessandro, Wilson (2019)

Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)



$\cos(\theta_i - \theta_a)$ ring-to-compass synaptic strength

$\cos(V - \theta_a)$ ring neuron response

$I_i =$

ring-to-compass synaptic strength

$*$

ring neuron response

→ $\cos(V - \theta_i)$

?

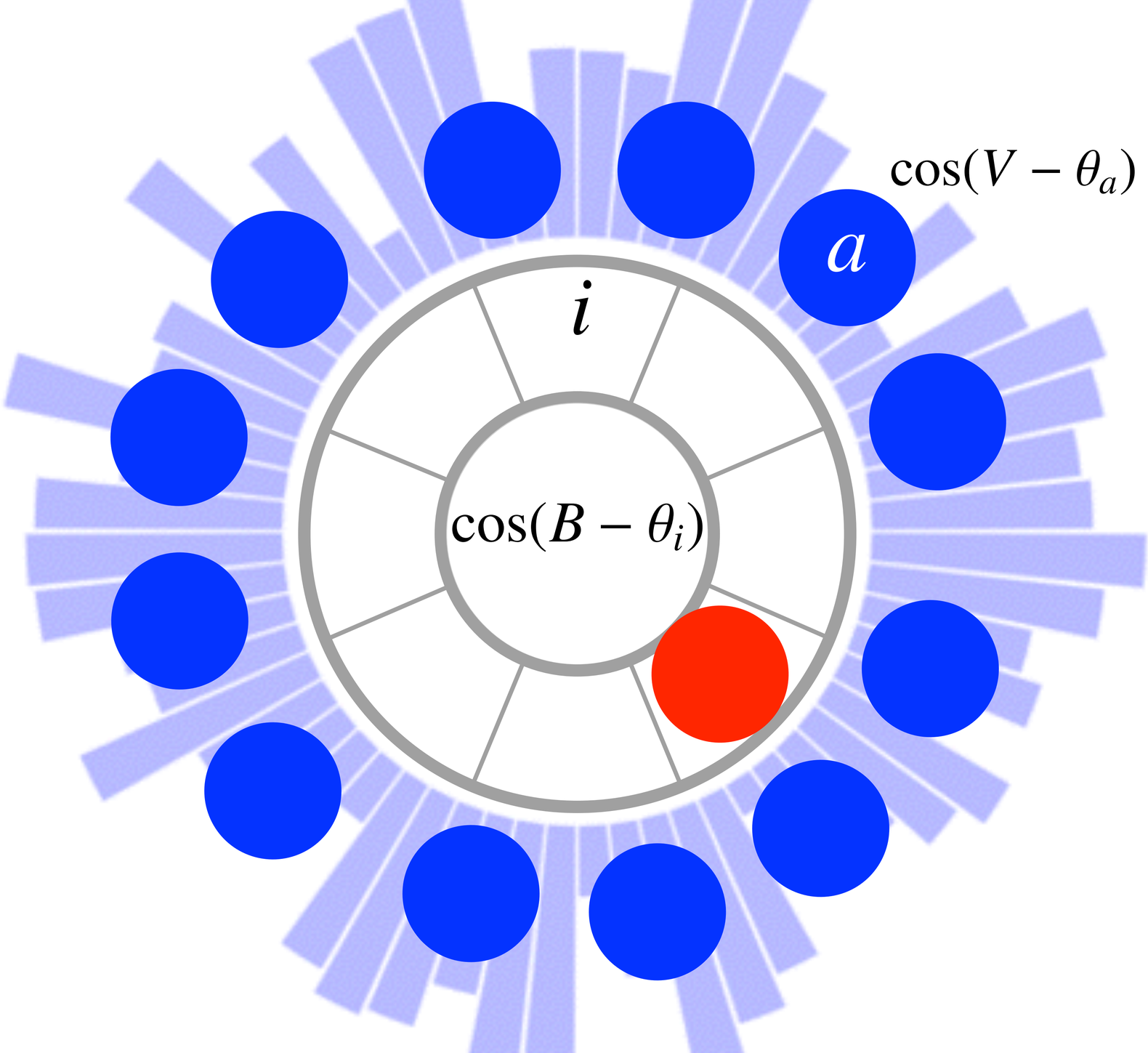
$$I_i = \frac{2}{N}\sum_{a=1}^{N}\cos(\theta_i-\theta_a)\cos(V-\theta_a)$$

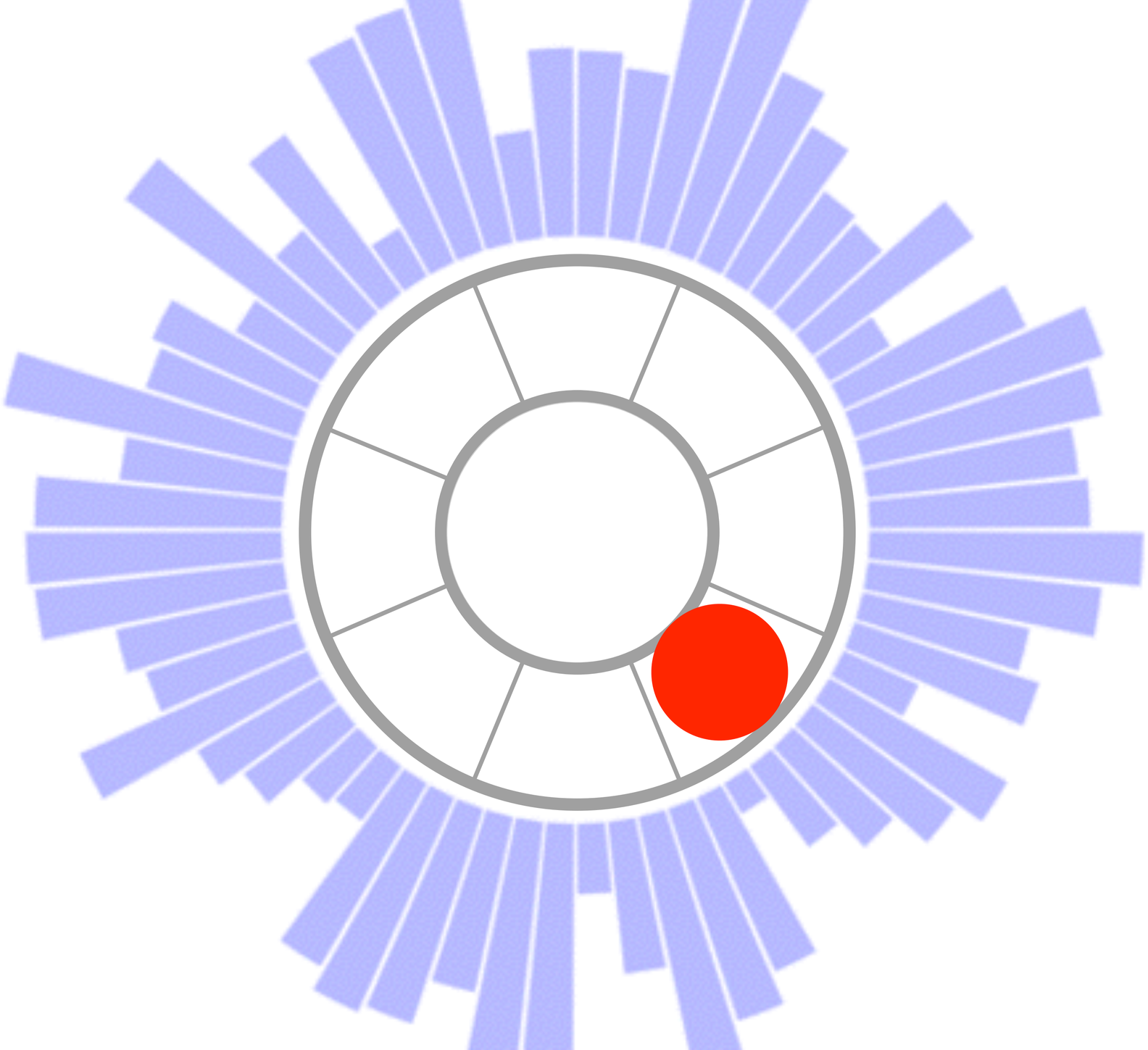
$$= \frac{1}{N}\sum_{a=1}^{N}\Big(\cos(V-\theta_i)+\cos(V+\theta_i-2\theta_a)\Big)$$

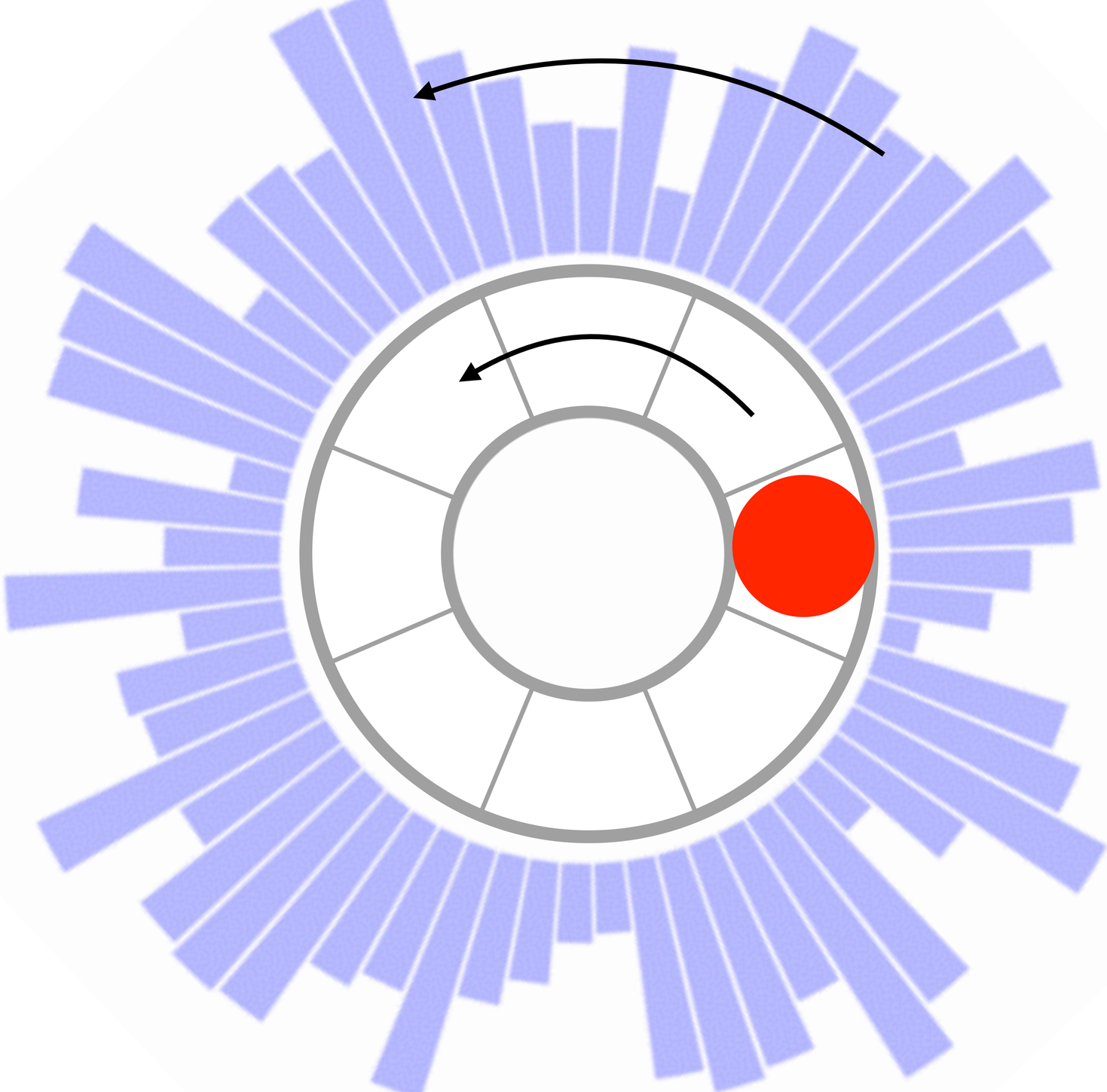
$$= \cos(V-\theta_i)$$

||

0


$\cos(V - \theta_a)$
a
i
$\cos(B - \theta_i)$





bump x ring

change in ring-to-compass synaptic strength

$$\frac{1}{\pi}\cos(B-\theta_i)\cos(V-\theta_a)$$

$$B = V$$

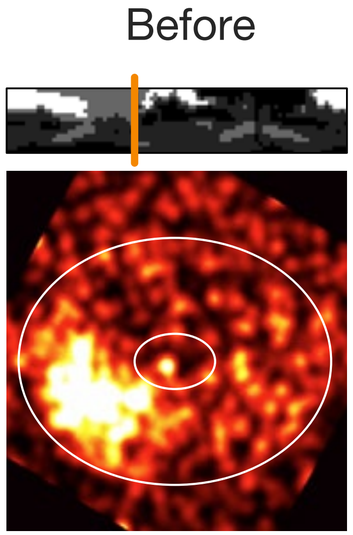
ring-to-compass synaptic strength

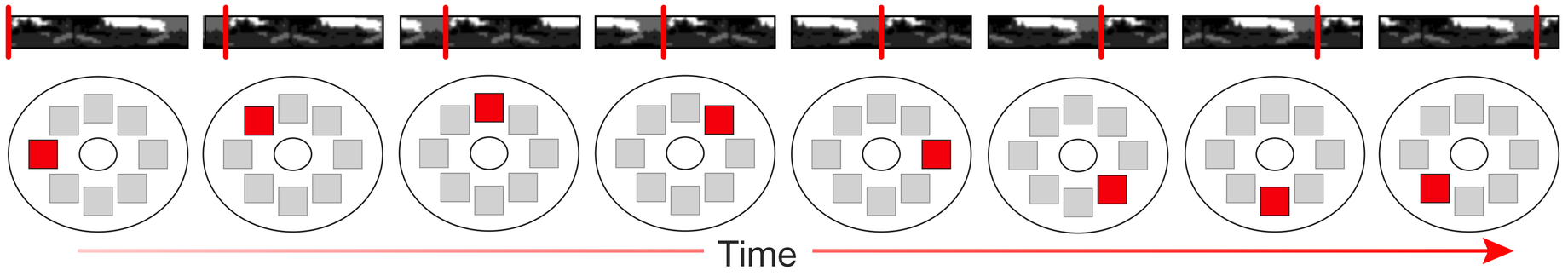
$$\frac{1}{\pi}\int_0^{2\pi} dV\ \cos(V-\theta_i)\cos(V-\theta_a)$$

$$= \frac{1}{2\pi}\int_0^{2\pi} dV \left(\cos(\theta_i-\theta_a) + \cos(2V-\theta_i-\theta_a)\right)$$

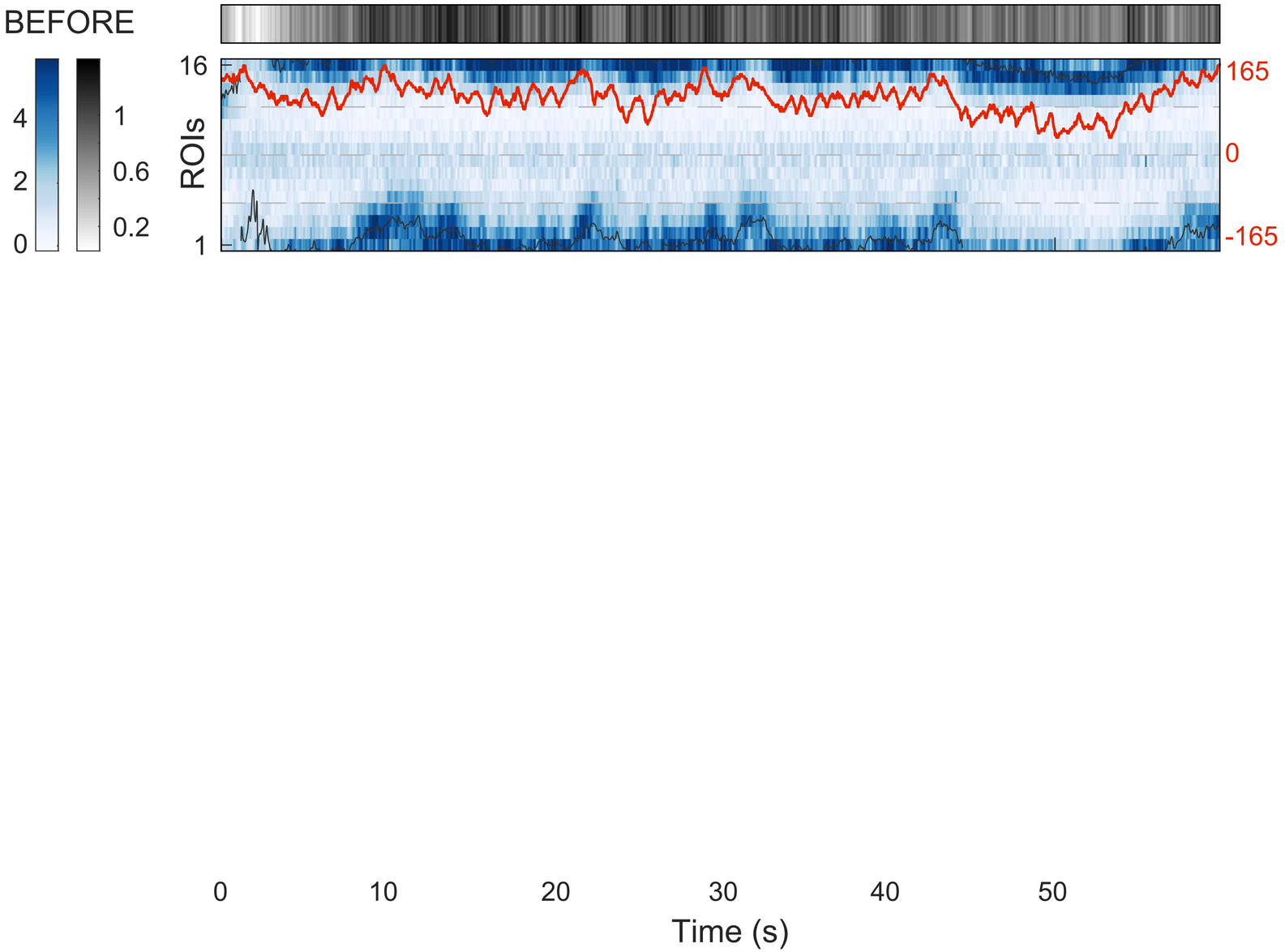
$$= \cos(\theta_i-\theta_a)$$

$$\| \quad 0$$





Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)


BEFORE
4
2
0
1
0.6
0.2
16
ROIs
1
165
0
-165
0
10
20
30
40
50
Time (s)

bump x ring

$$\frac{1}{\pi}\cos(B-\theta_i)\cos(V-\theta_a)$$

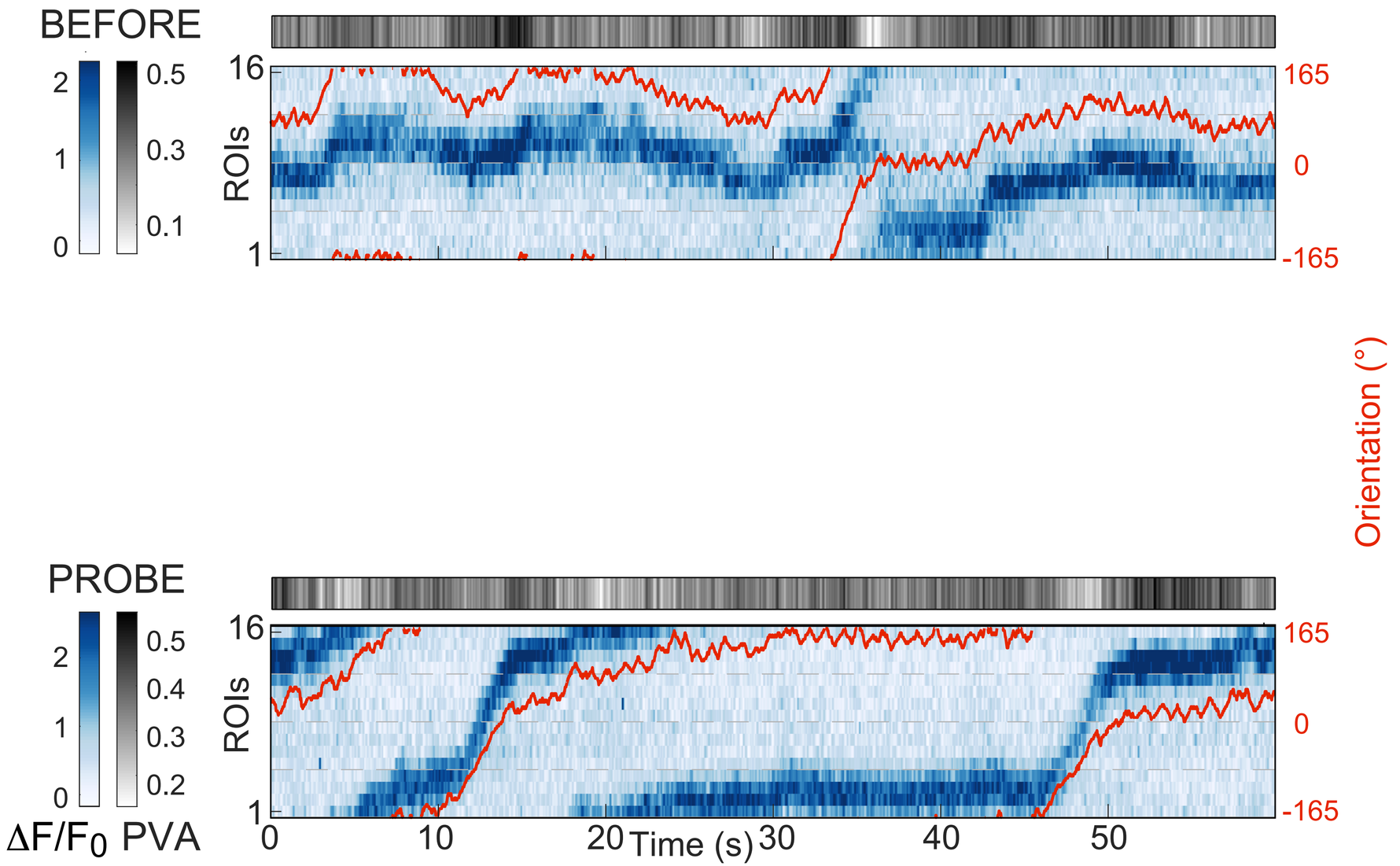
$$B = V$$

$$\frac{1}{\pi}\int_0^{2\pi} dV\ \cos(V-\theta_i)\cos(V-\theta_a)$$

$$= \frac{1}{2\pi}\int_0^{2\pi \to \pi} dV \left(\cos(\theta_i-\theta_a) + \cos(2V-\theta_i-\theta_a)\right)$$

$$\Big\| \quad 0$$

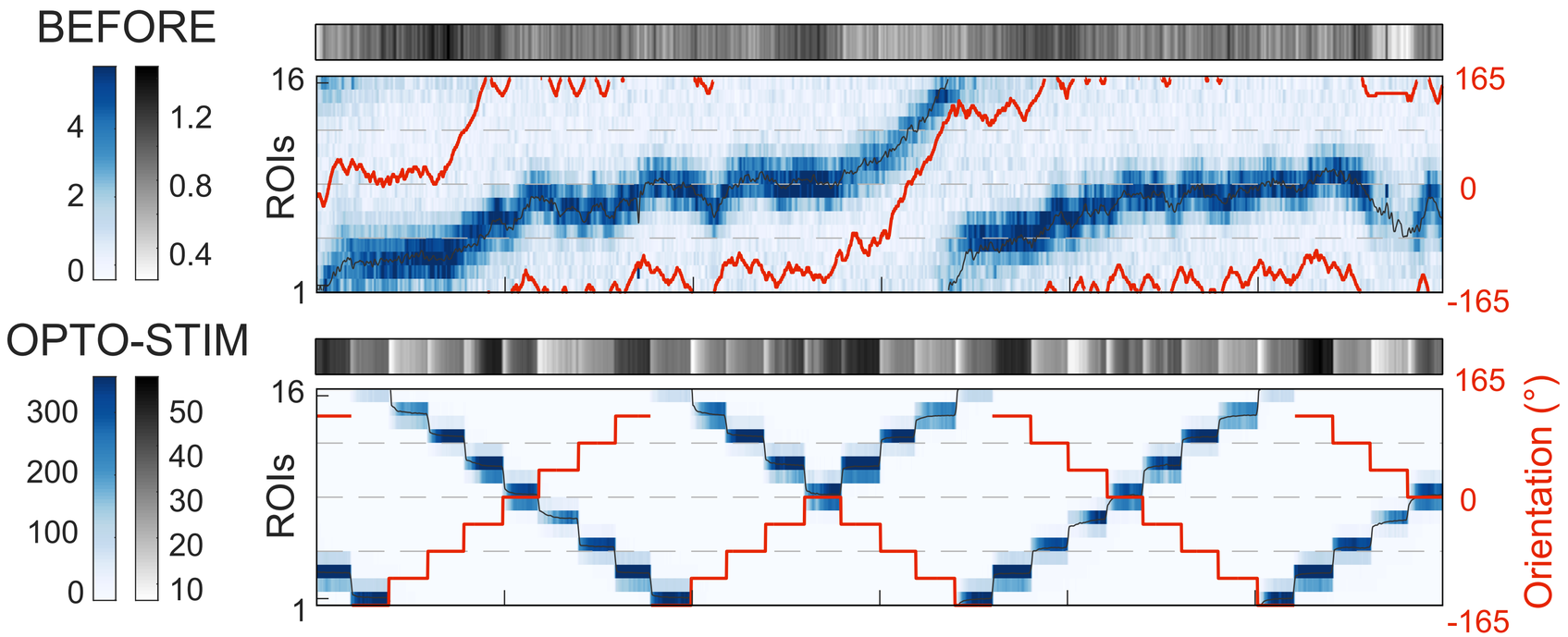
$$= \cos(\theta_i-\theta_a)$$



Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)

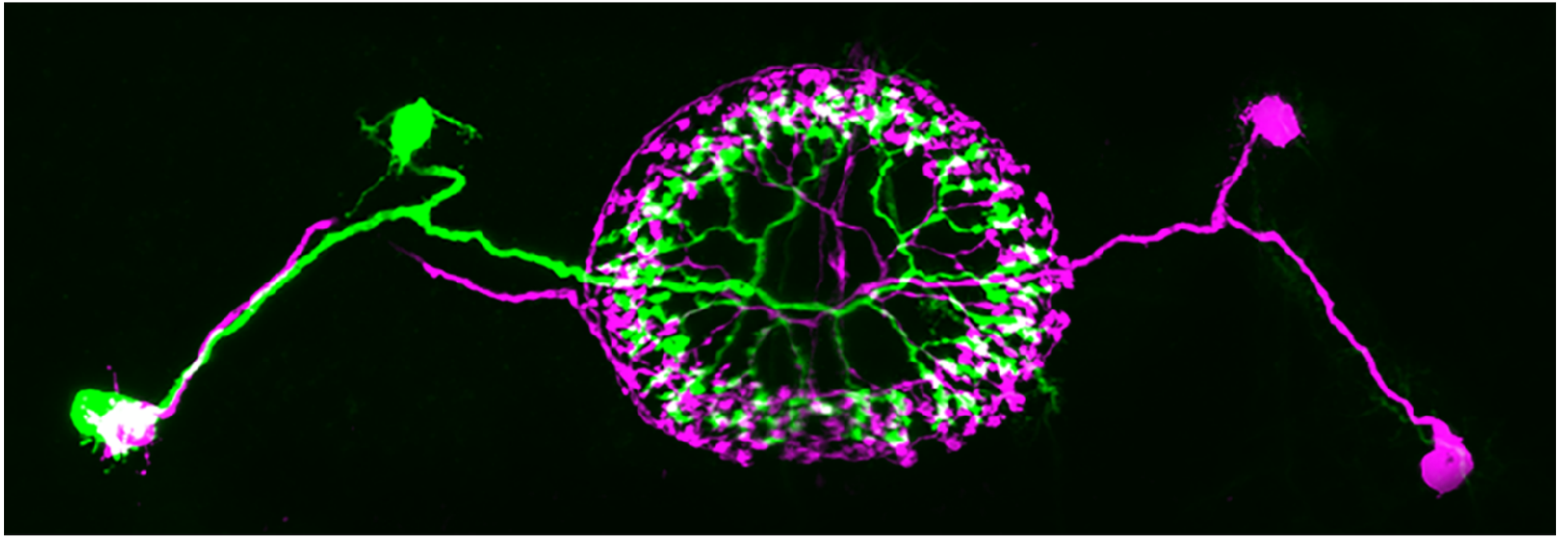
$$B = V \rightarrow \cos(\theta_i - \theta_a) \rightarrow \cos(V - \theta_i)$$

$$B = -V$$

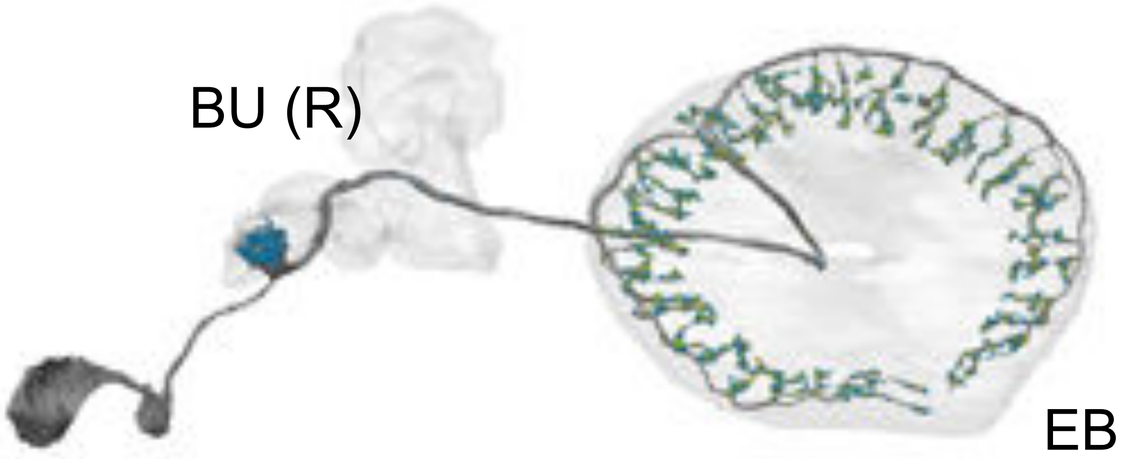


Kim, Hermundstad, Romani, Abbott, Jayaraman (2019)

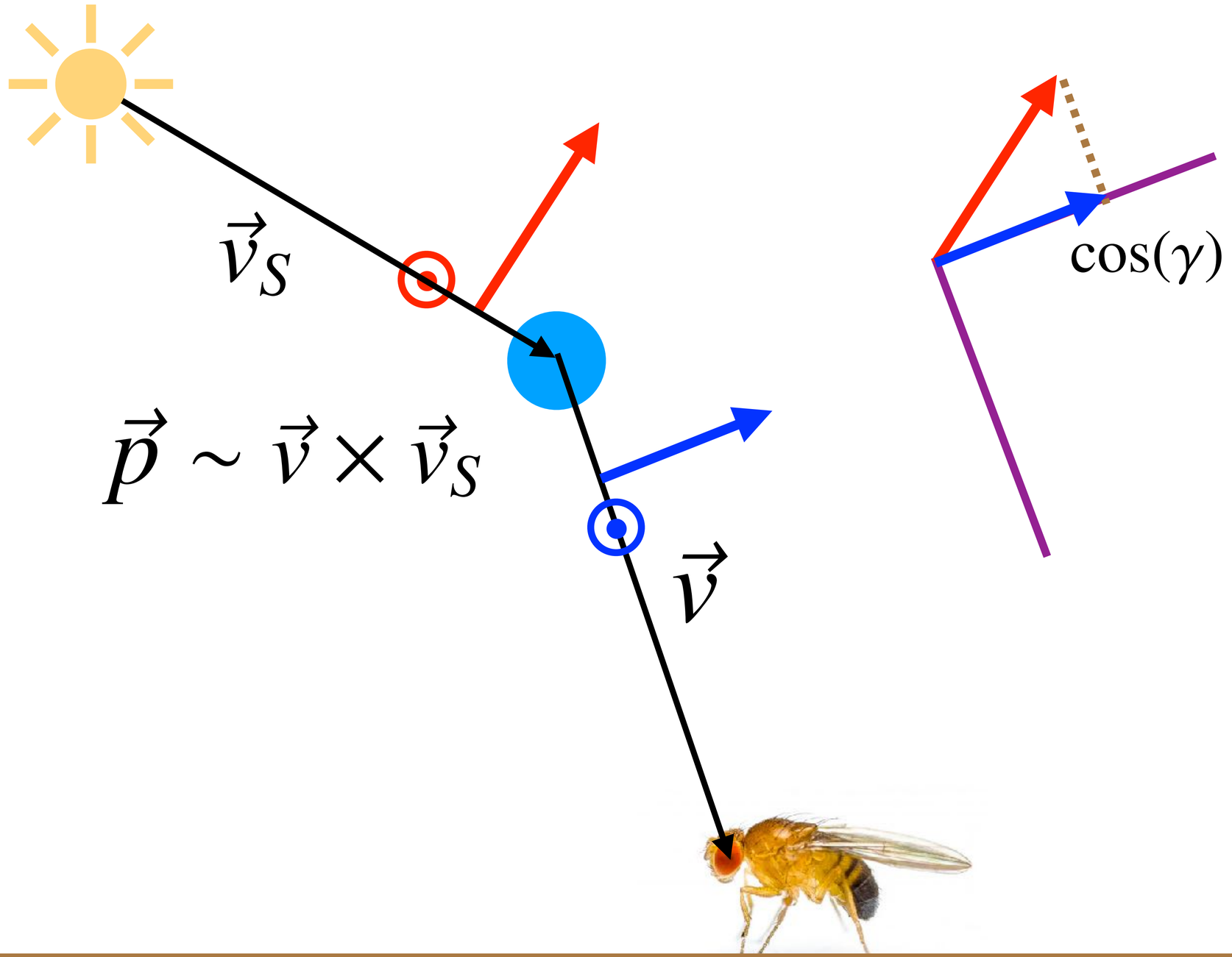
Tanya Wolff, Janelia FlyLight

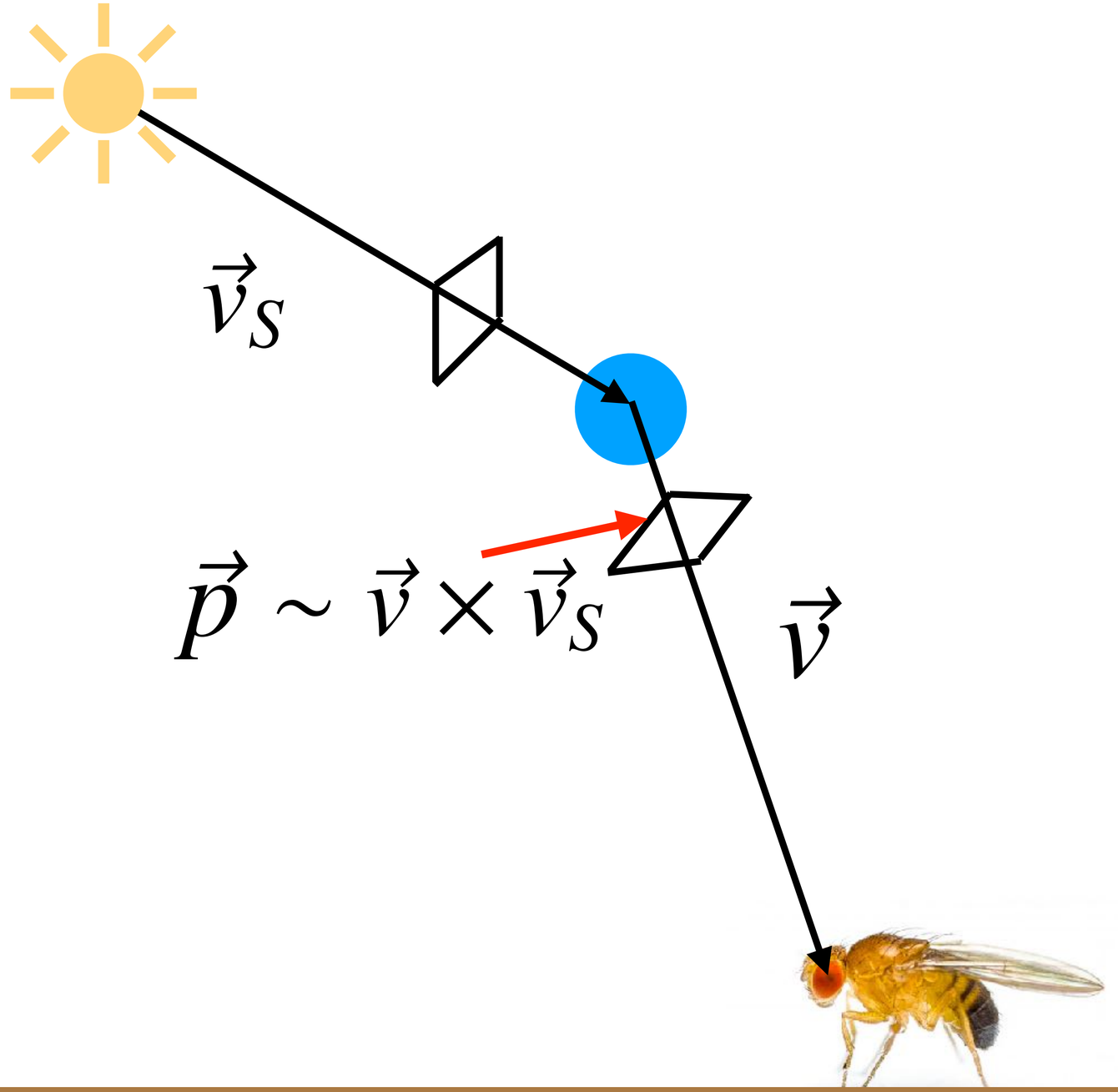


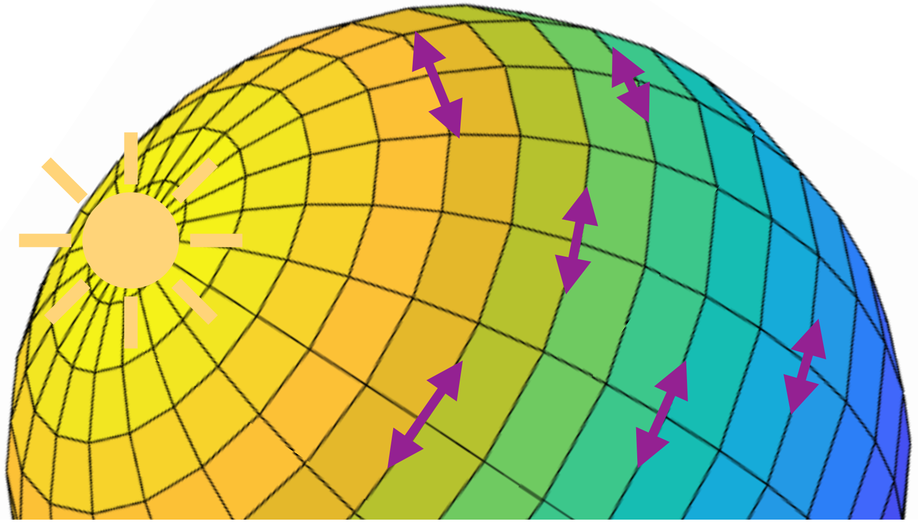
ER4m

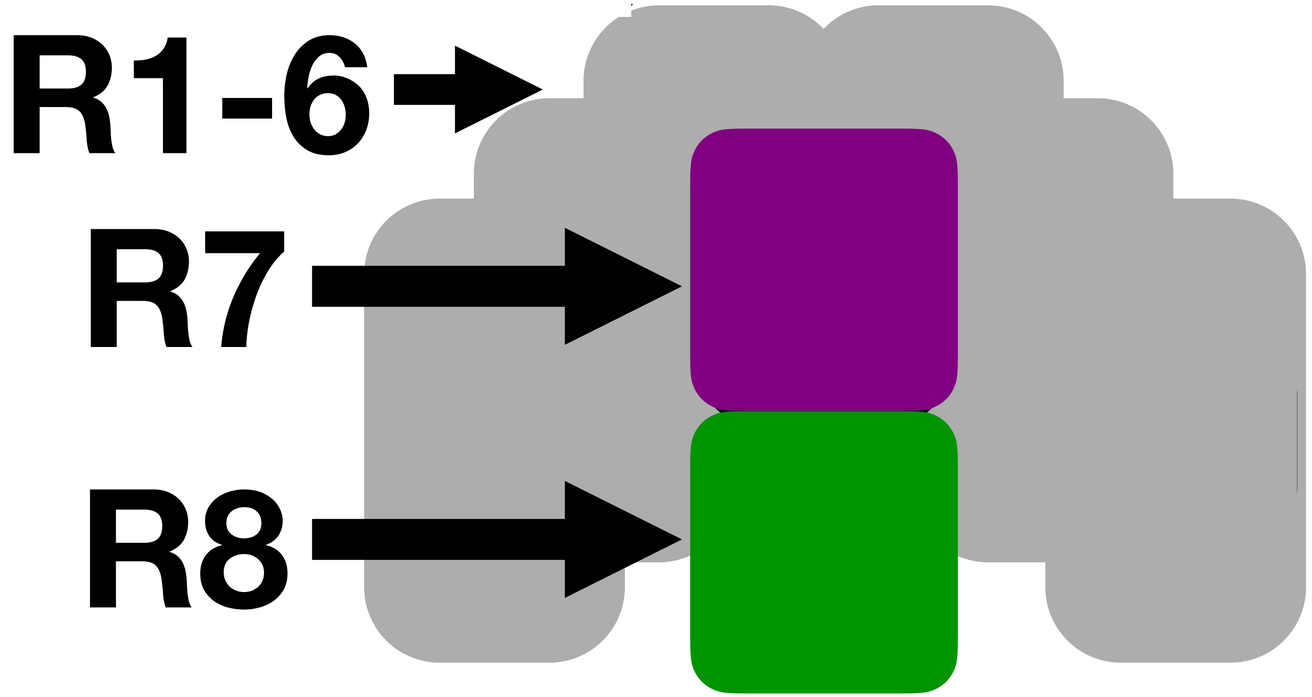


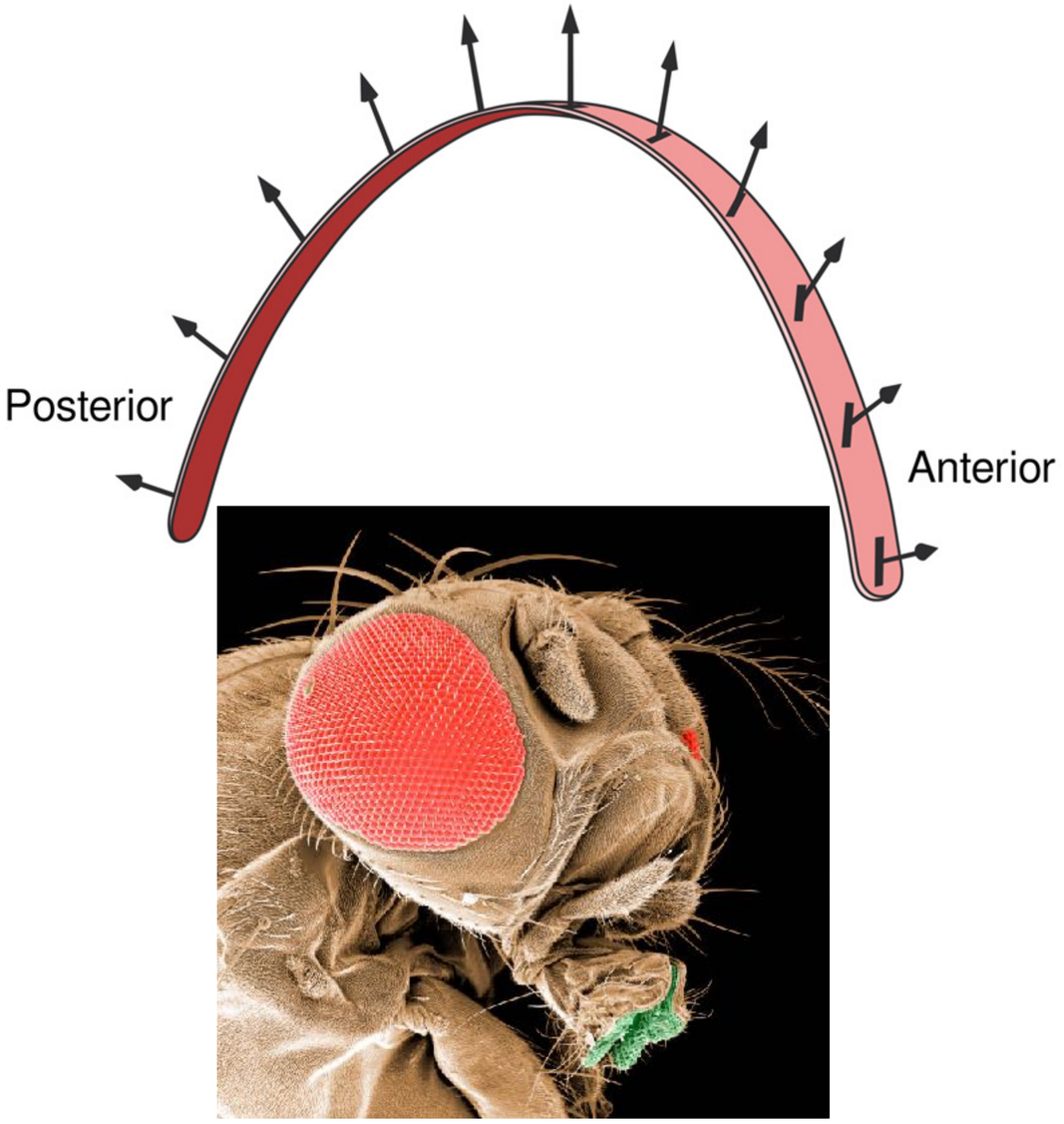
Hulse, Haberkern, Franconville, Turner-Evans, Takemura, Wolff, Noorman, Dreher, Dan, Parekh, Hermundstad, Rubin, Jayaraman (2021)


$\vec{v}_S$
$\vec{p} \sim \vec{v} \times \vec{v}_S$
$\vec{v}$
$\cos(\gamma)$

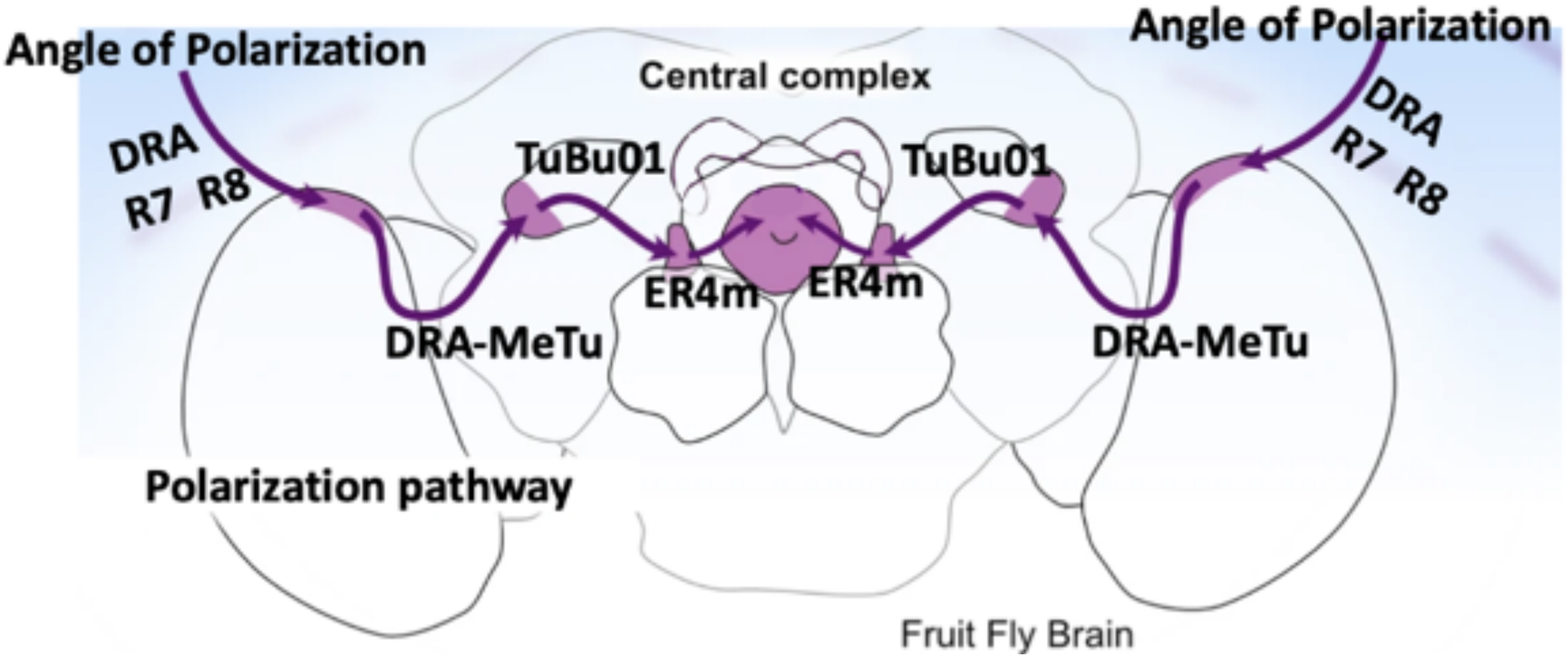

$\vec{v}_S$
$\vec{p} \sim \vec{v} \times \vec{v}_S$
$\vec{v}$




R1-6
R7
R8



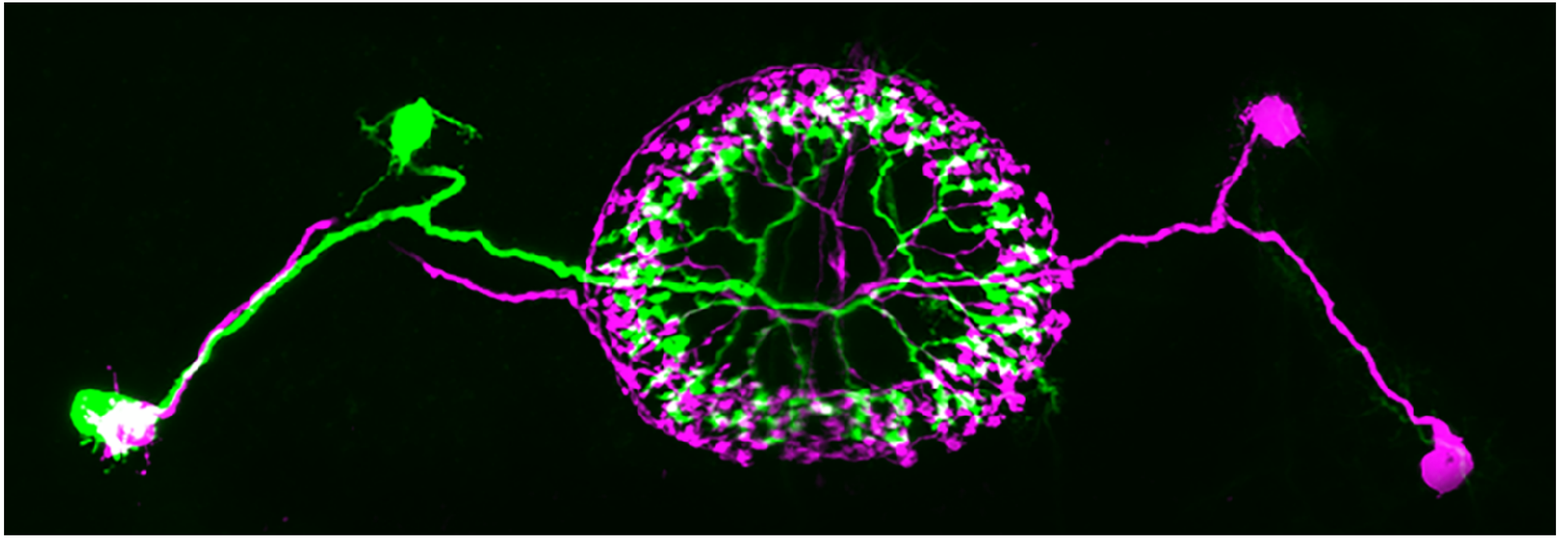
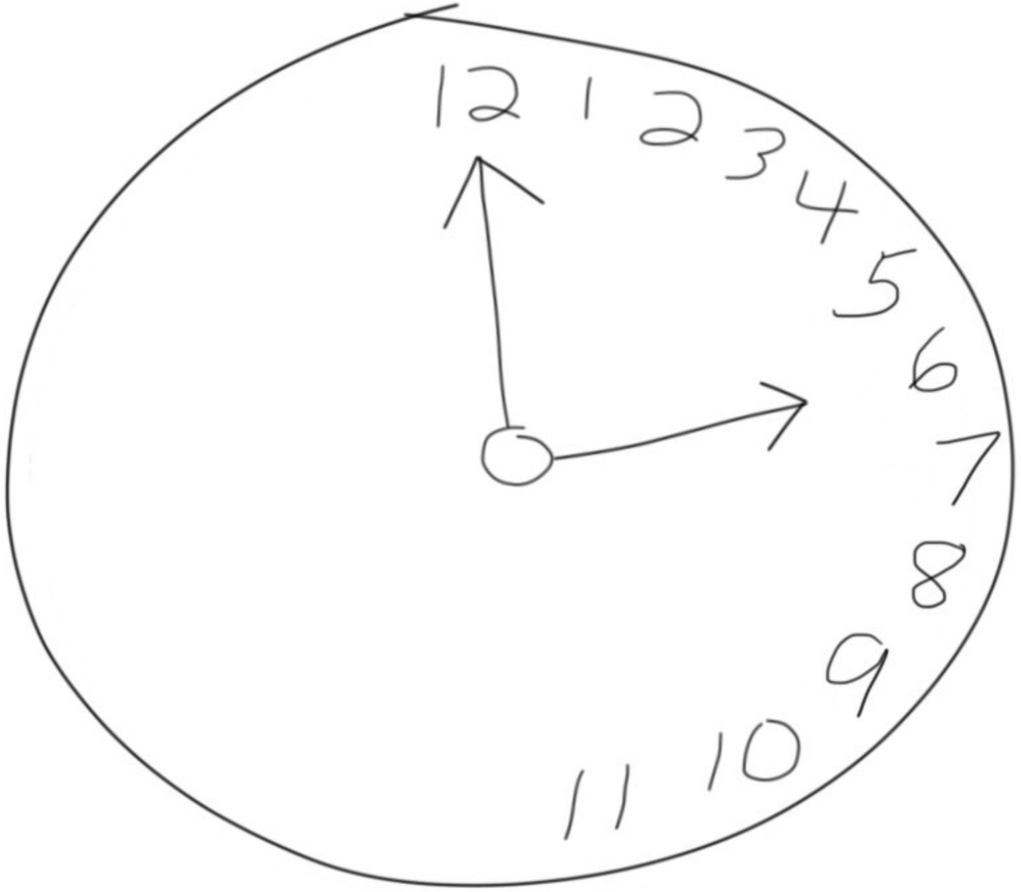
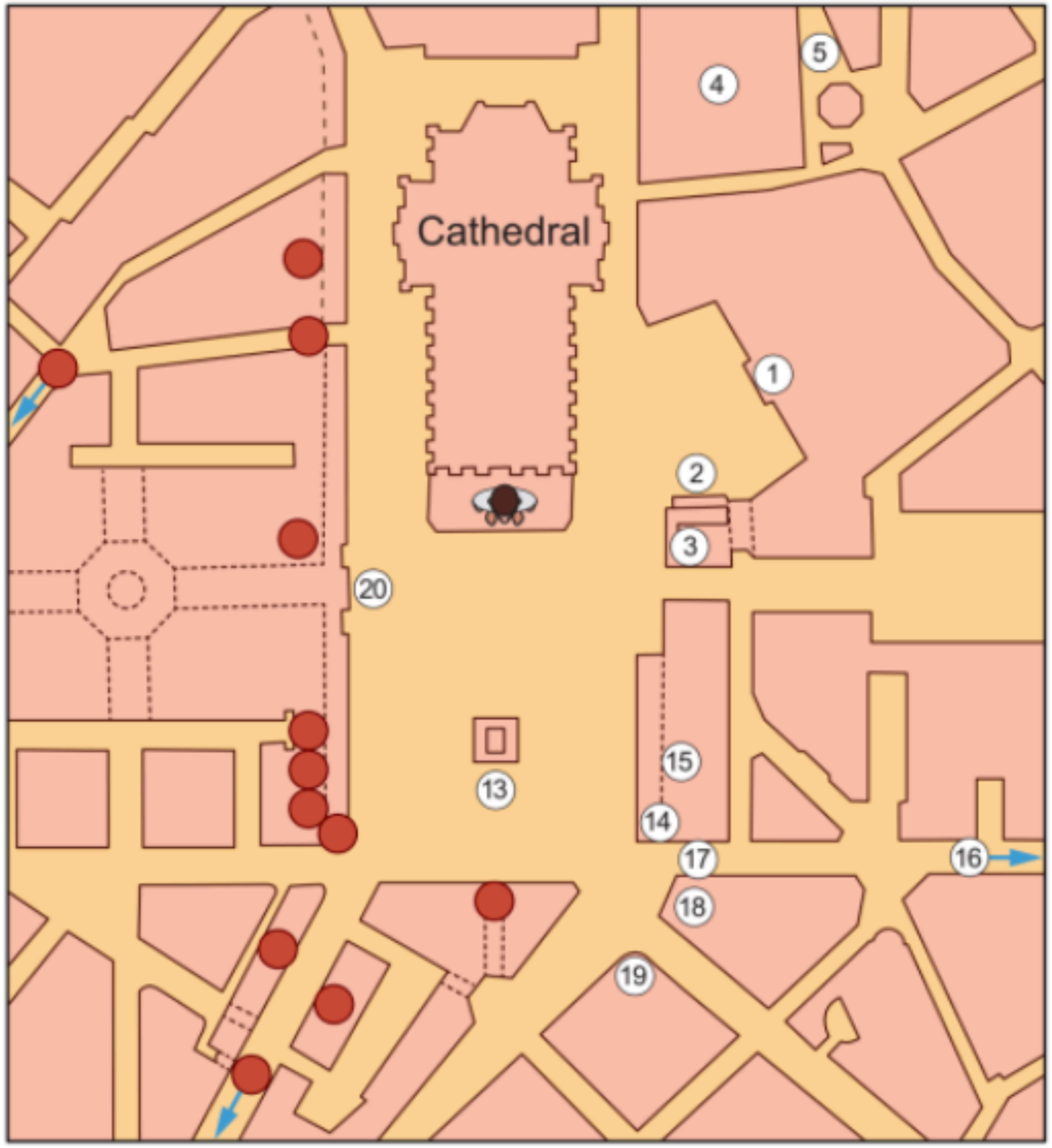
Weir, Henze, Bleul, Baumann-Klausener, Labhart, Dickinson (2016)



Hardcastle, Omoto, Kandimalla, Nguyen, Keles, Boyd, Hartenstein, Frye (2021)

Sharon Su, Rudy Behnia

Tanya Wolff, Janelia FlyLight



Alloception