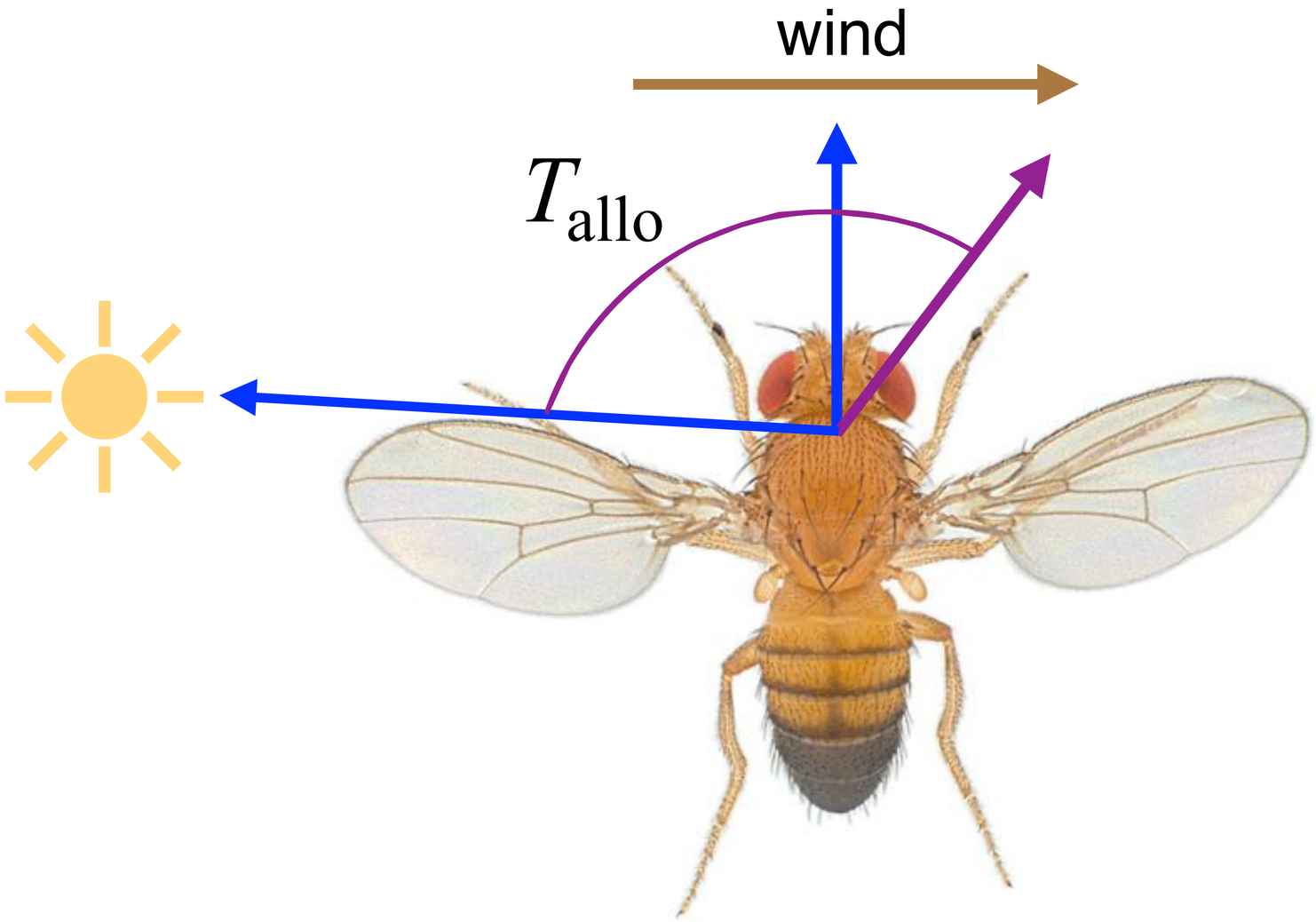
How Do Flies Navigate

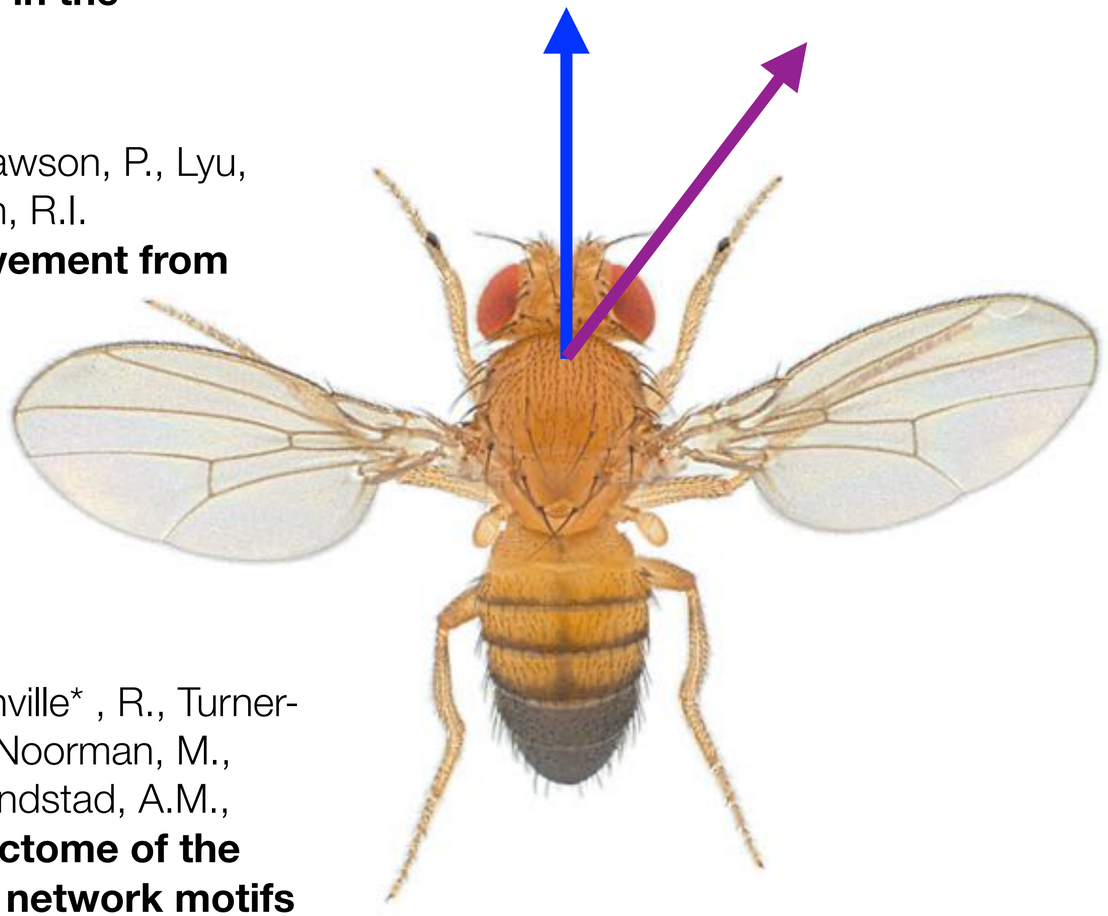
How does a fly know which way it is traveling?



How does a fly know which way it is traveling?

Lyu, C., Abbott, L.F. & Maimon, G. **A neuronal circuit for vector computation builds an allocentric travelling-direction signal in the *Drosophila* fan-shaped body.**

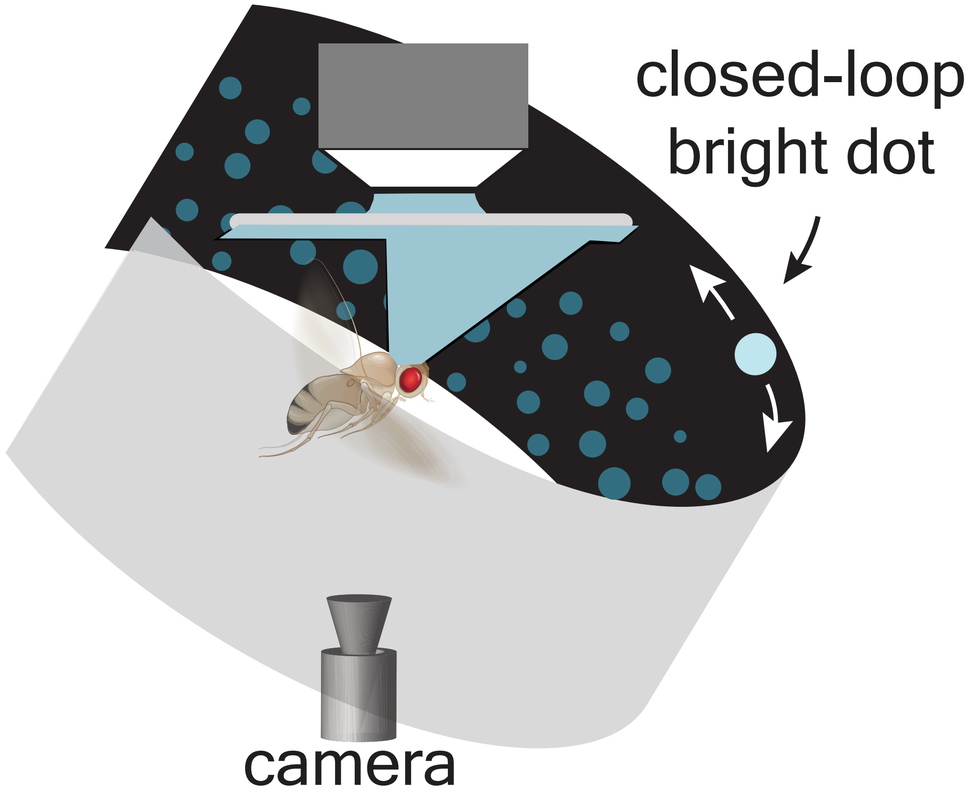
Lu, J., Westeinde* , E., Hamburg*, L., Dawson, P., Lyu, C., Maimon, G., Druckmann, S. & Wilson, R.I. **Transforming representations of movement from body- to world-centric space.**

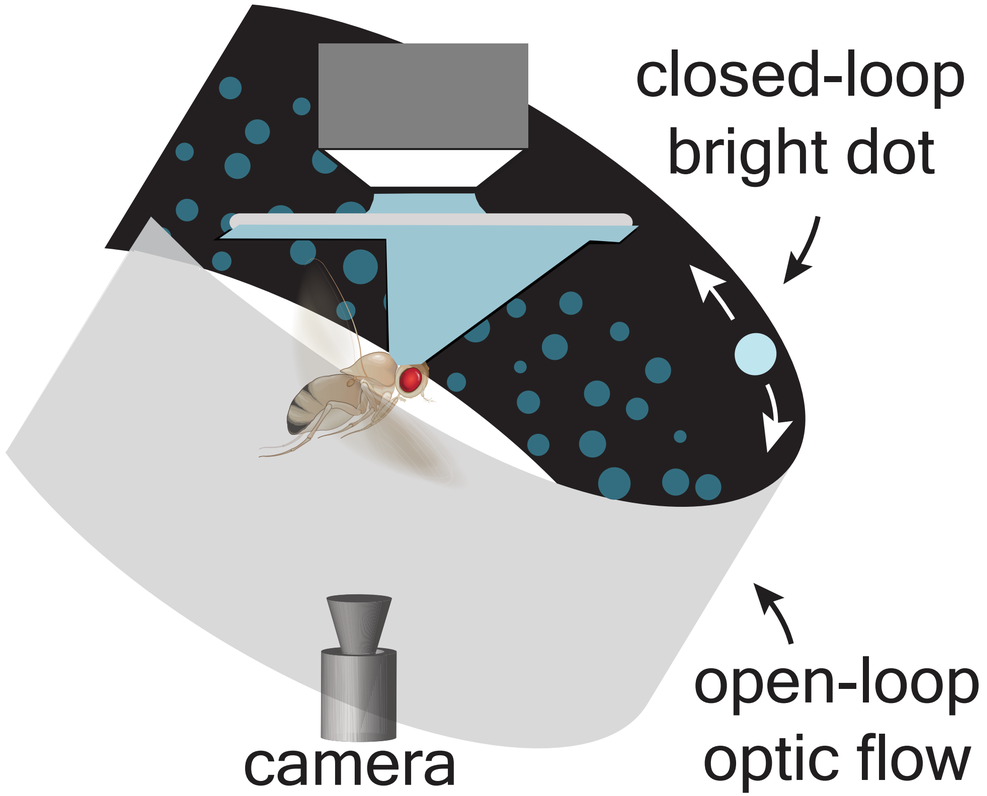


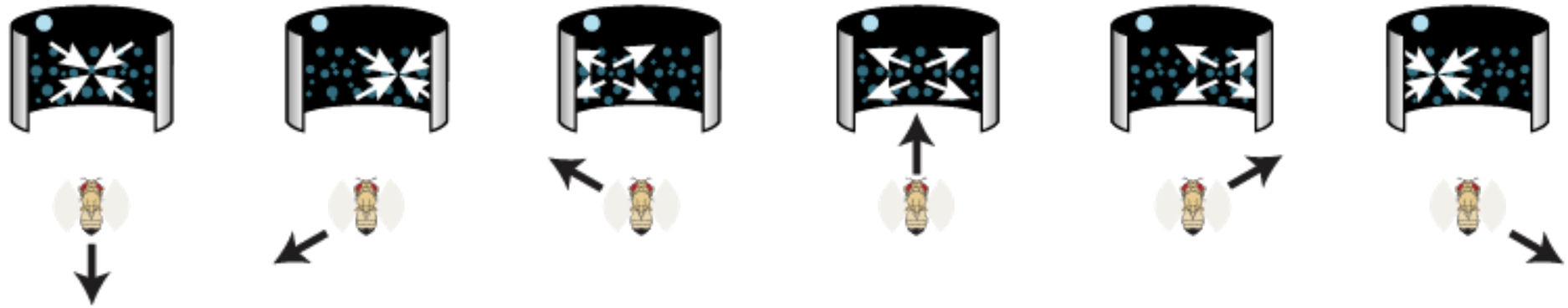
Hulse* , B.K. , Haberkern* , H., Franconville* , R., Turner-Evans* , D.B., Takemura, S., Wolff, T., Noorman, M., Dreher, M., Dan, C., Parekh, R., Hermundstad, A.M., Rubin, G.M. & Jayaraman, V. **A connectome of the *Drosophila* central complex reveals network motifs suitable for flexible navigation and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

Gaby Maimon

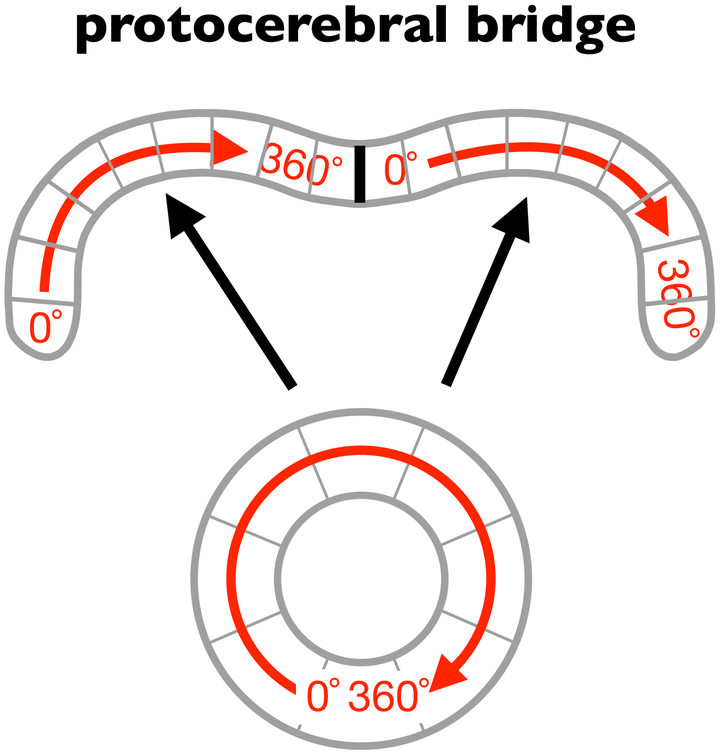
Cheng Lyu


closed-loop
bright dot
camera

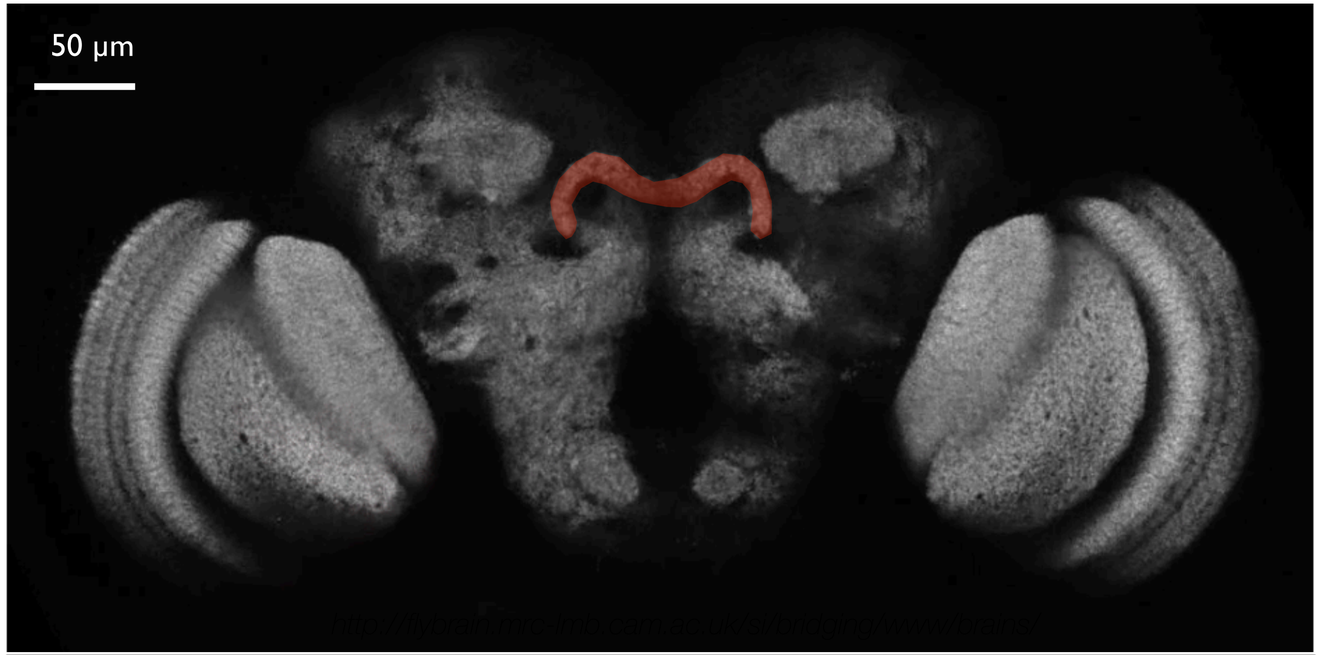

closed-loop
bright dot
open-loop
optic flow
camera



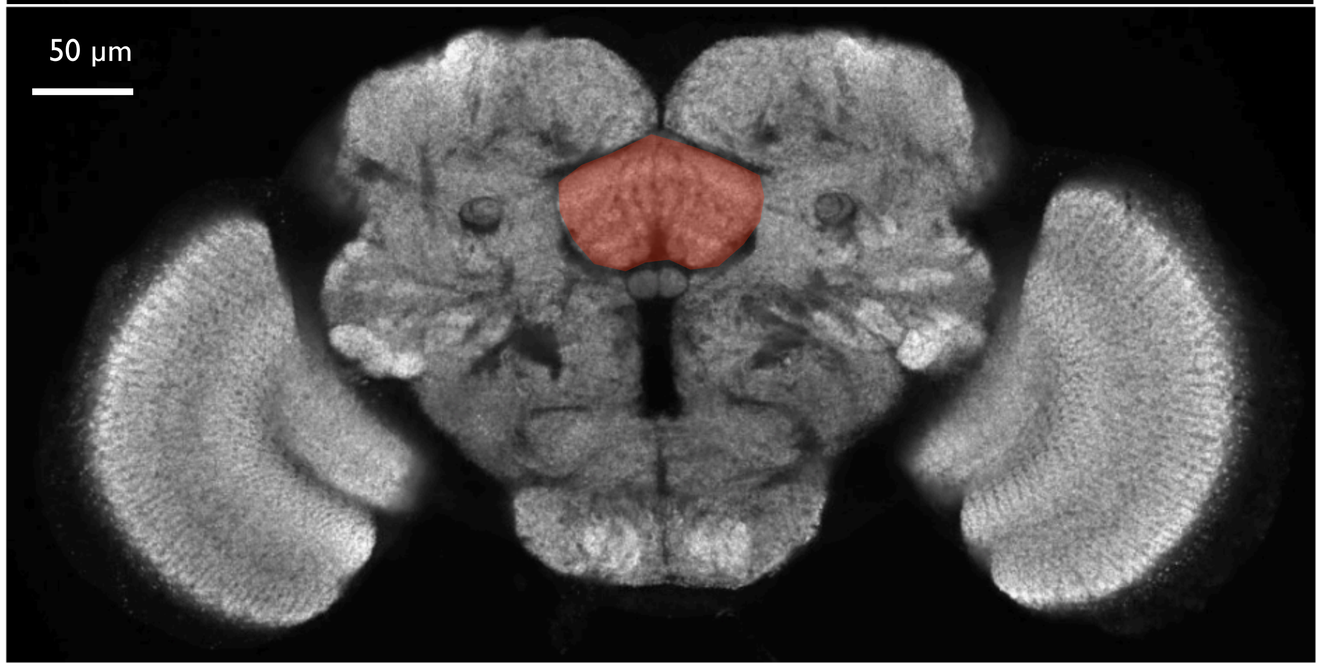
http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/



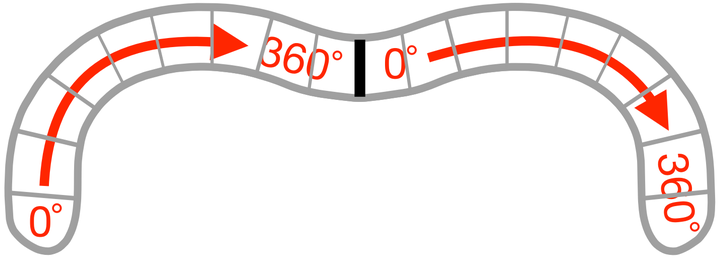
http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/

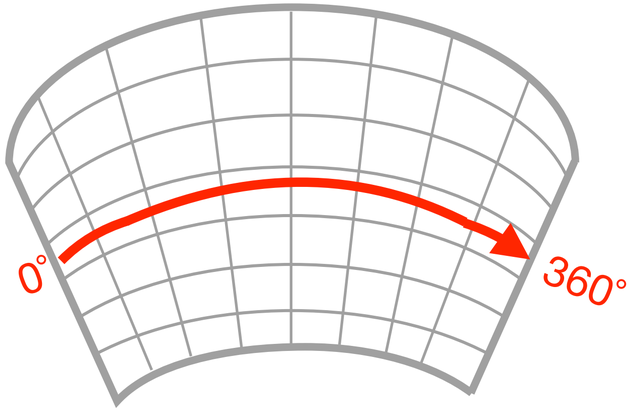


http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/



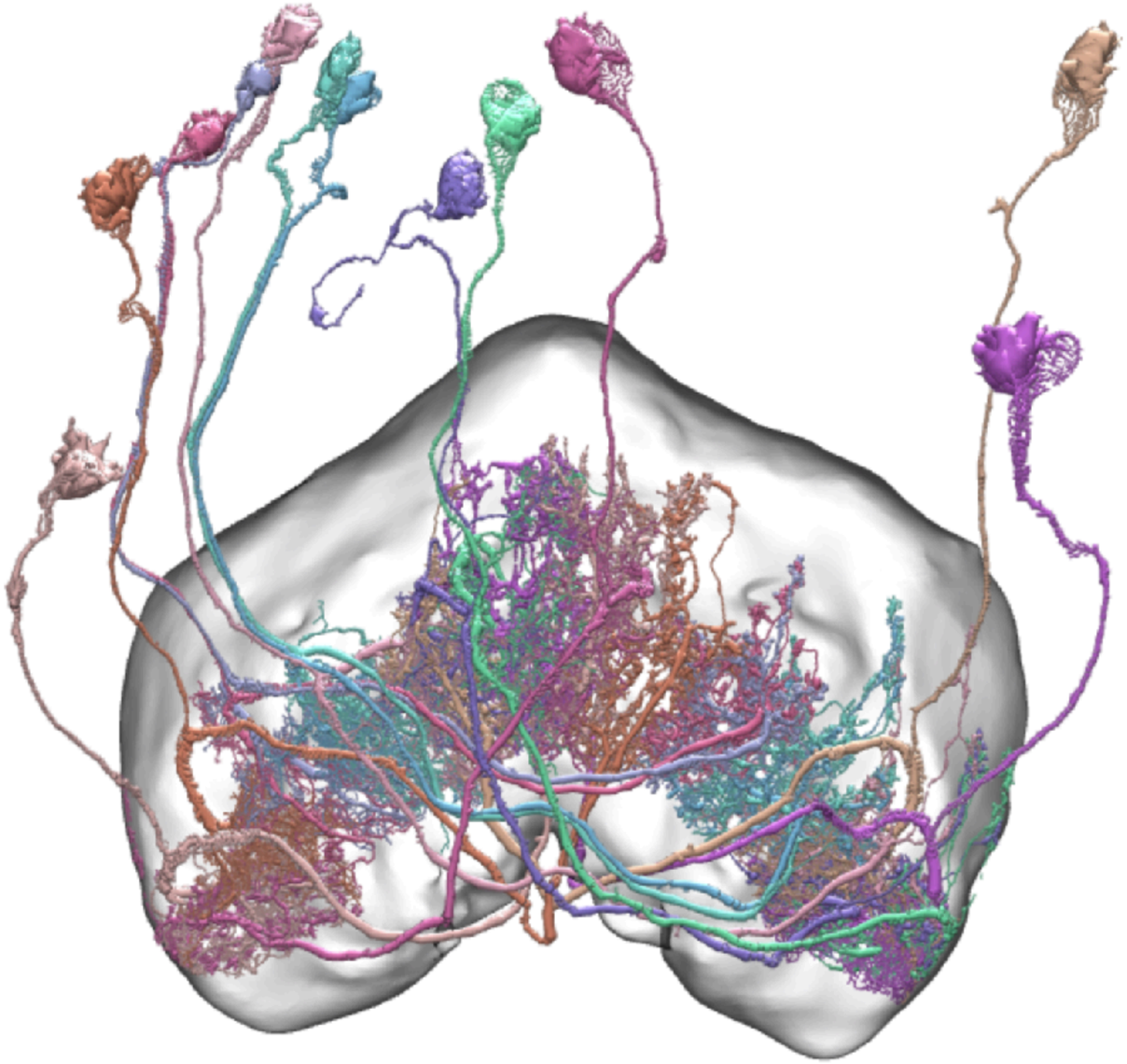
protocerebral bridge

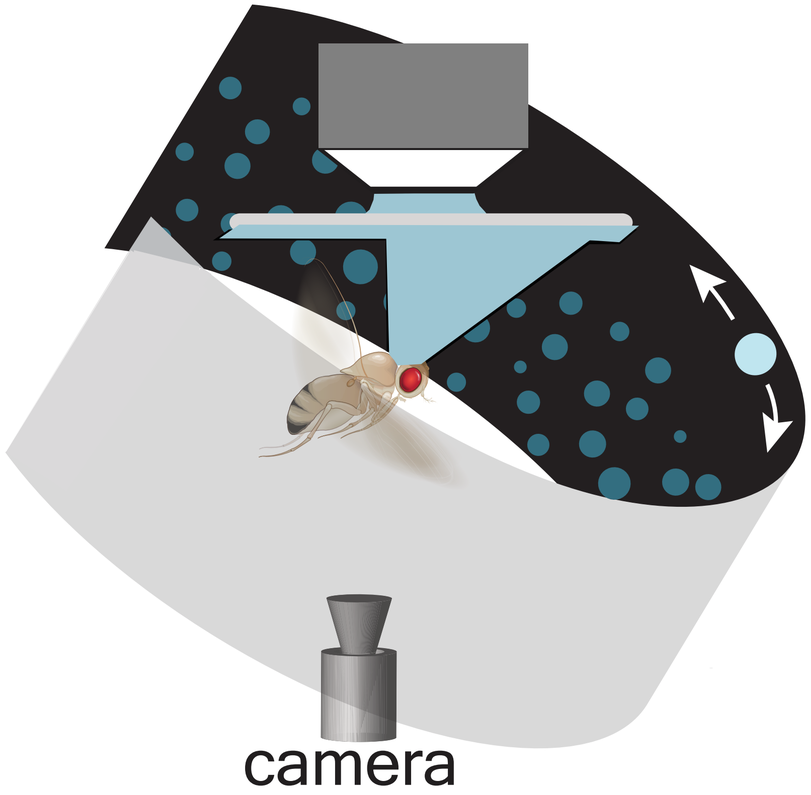




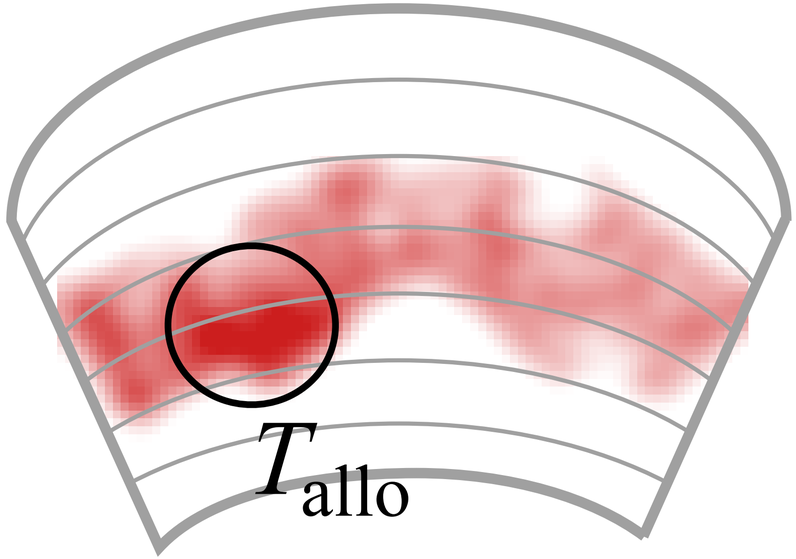
fan-shaped body

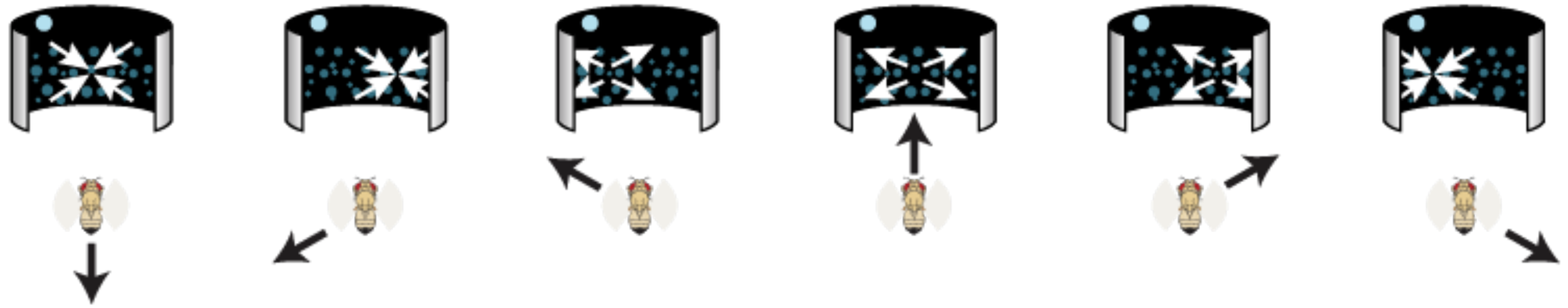
hΔB

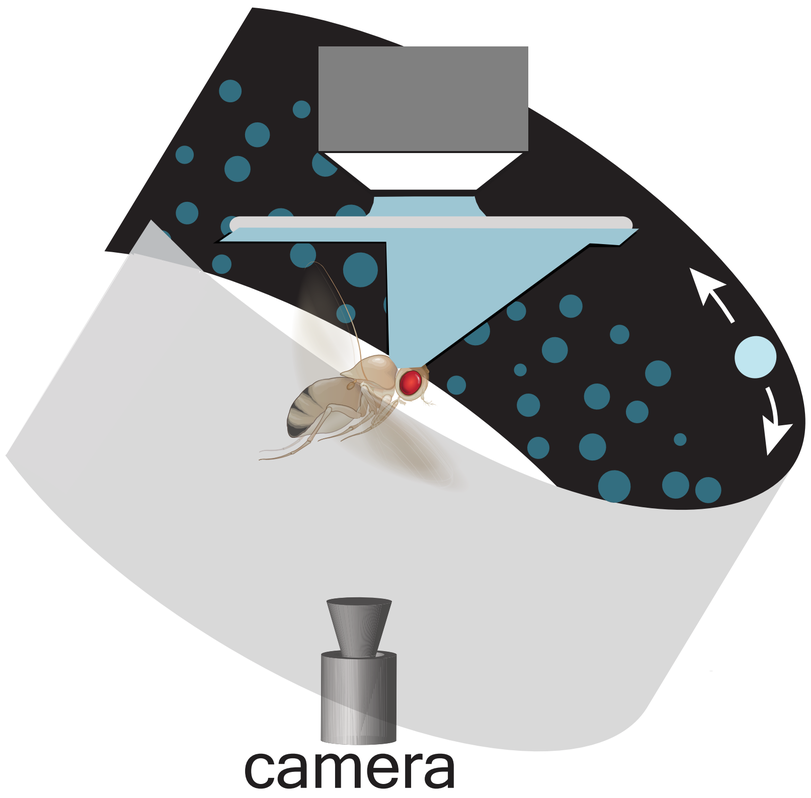


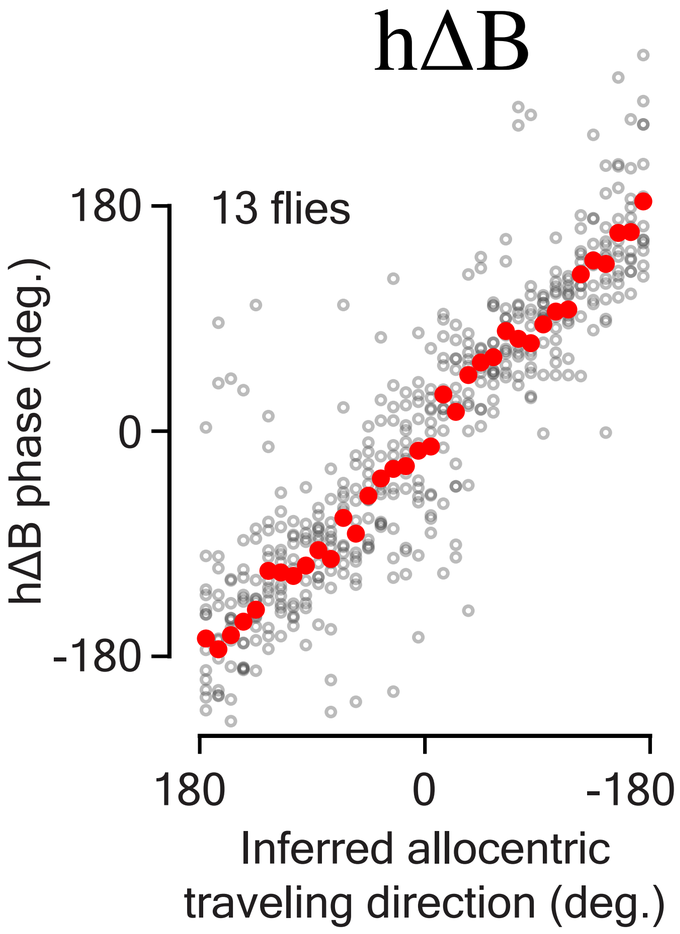


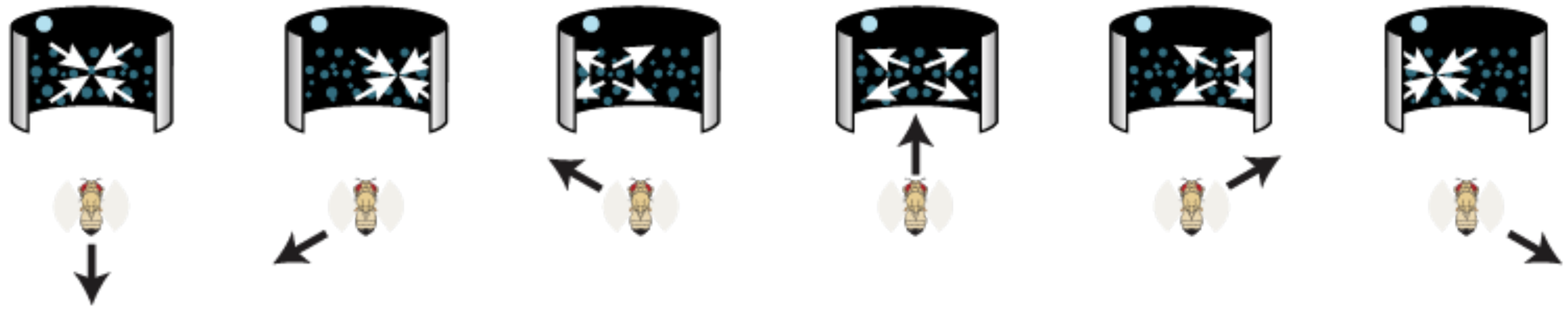
hΔB

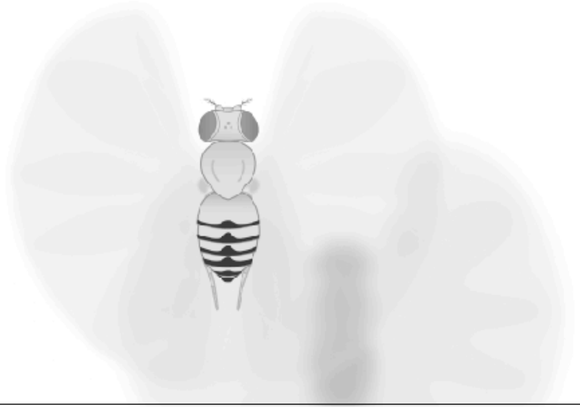


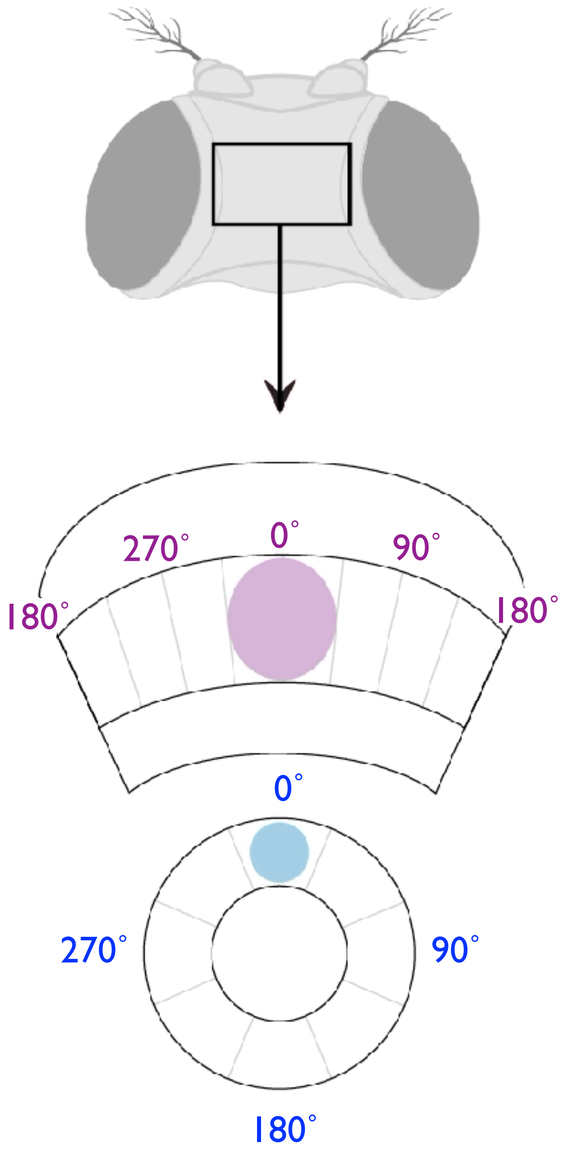



camera


hΔB
13 flies
180
0
-180
hΔB phase (deg.)
180
0
-180
Inferred allocentric
traveling direction (deg.)



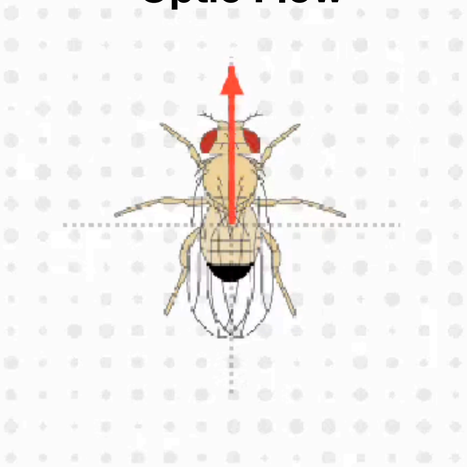




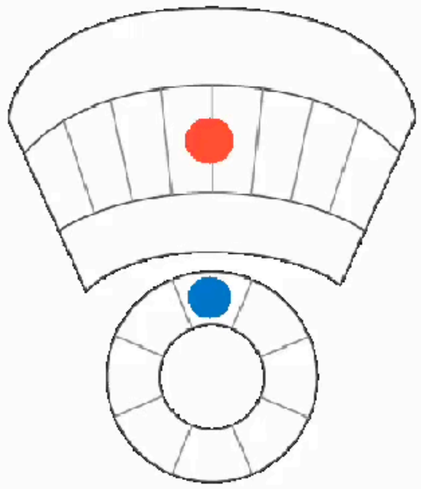
Allocentric traveling direction

Allocentric heading angle

Heading vs Traveling Direction
Optic Flow



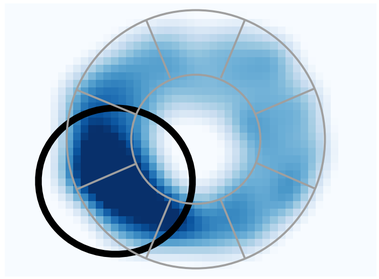
EPG, hDeltaB



How Is It Computed?

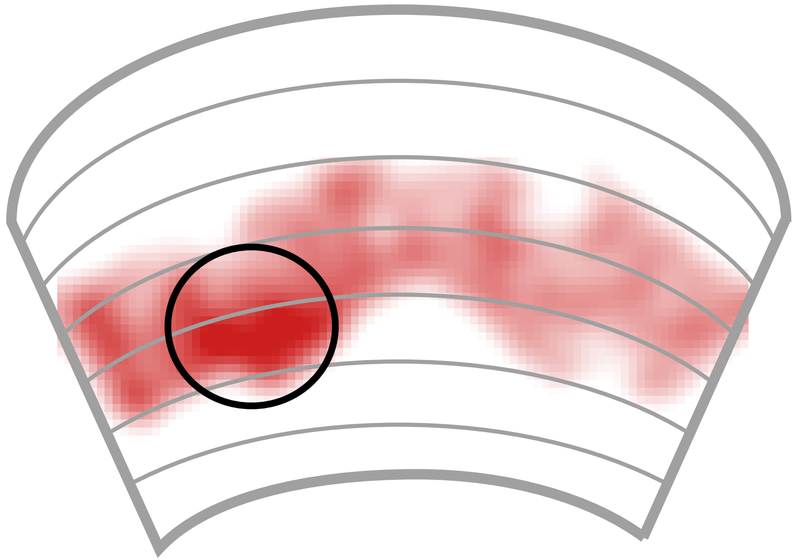
Heading

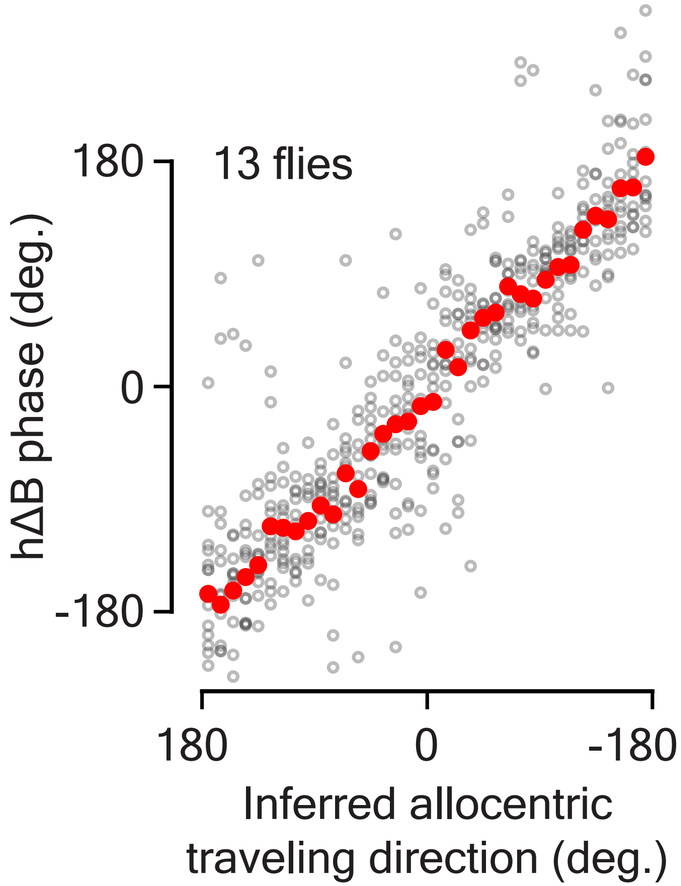
EPG



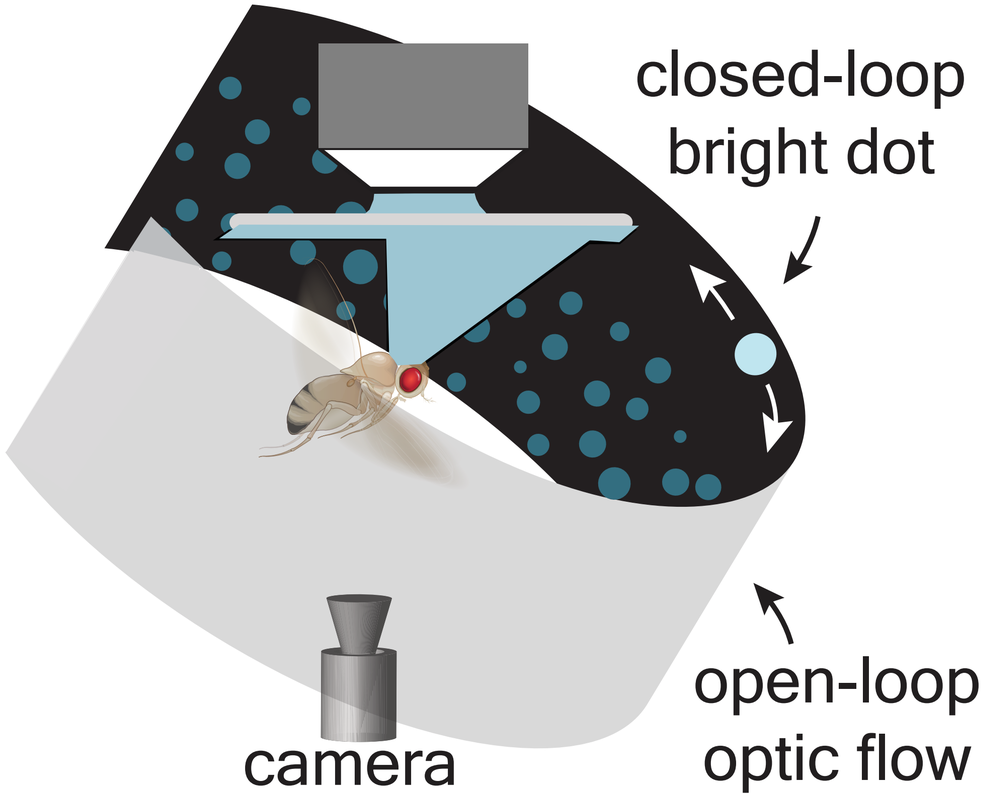
Traveling Direction

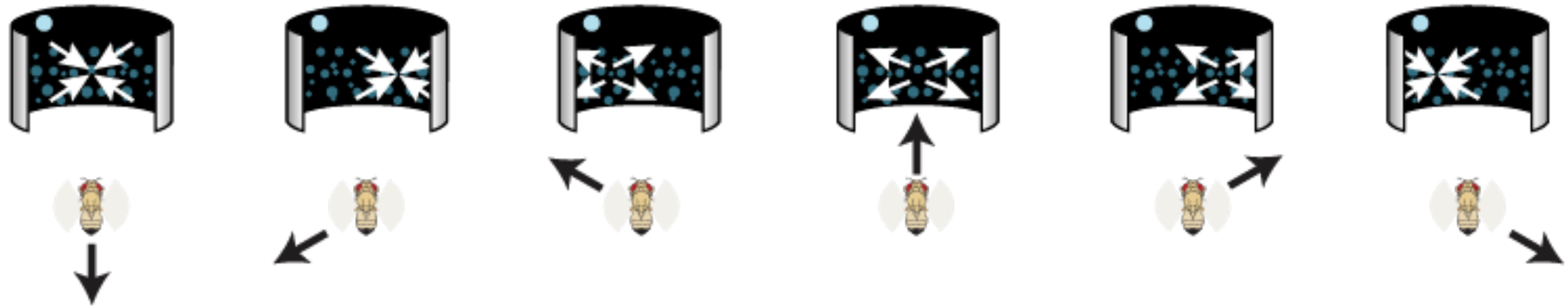
hΔB



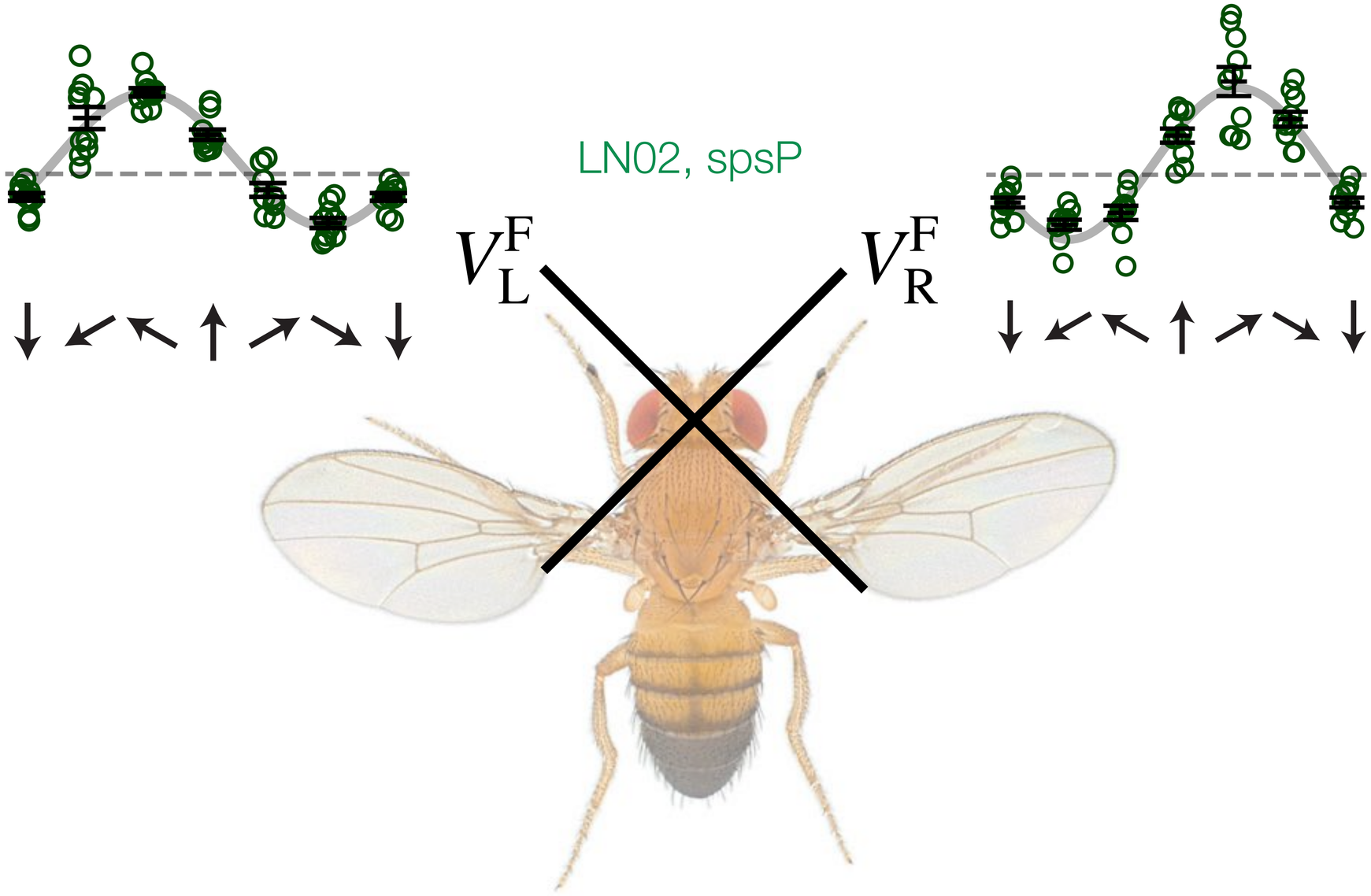


optic flow

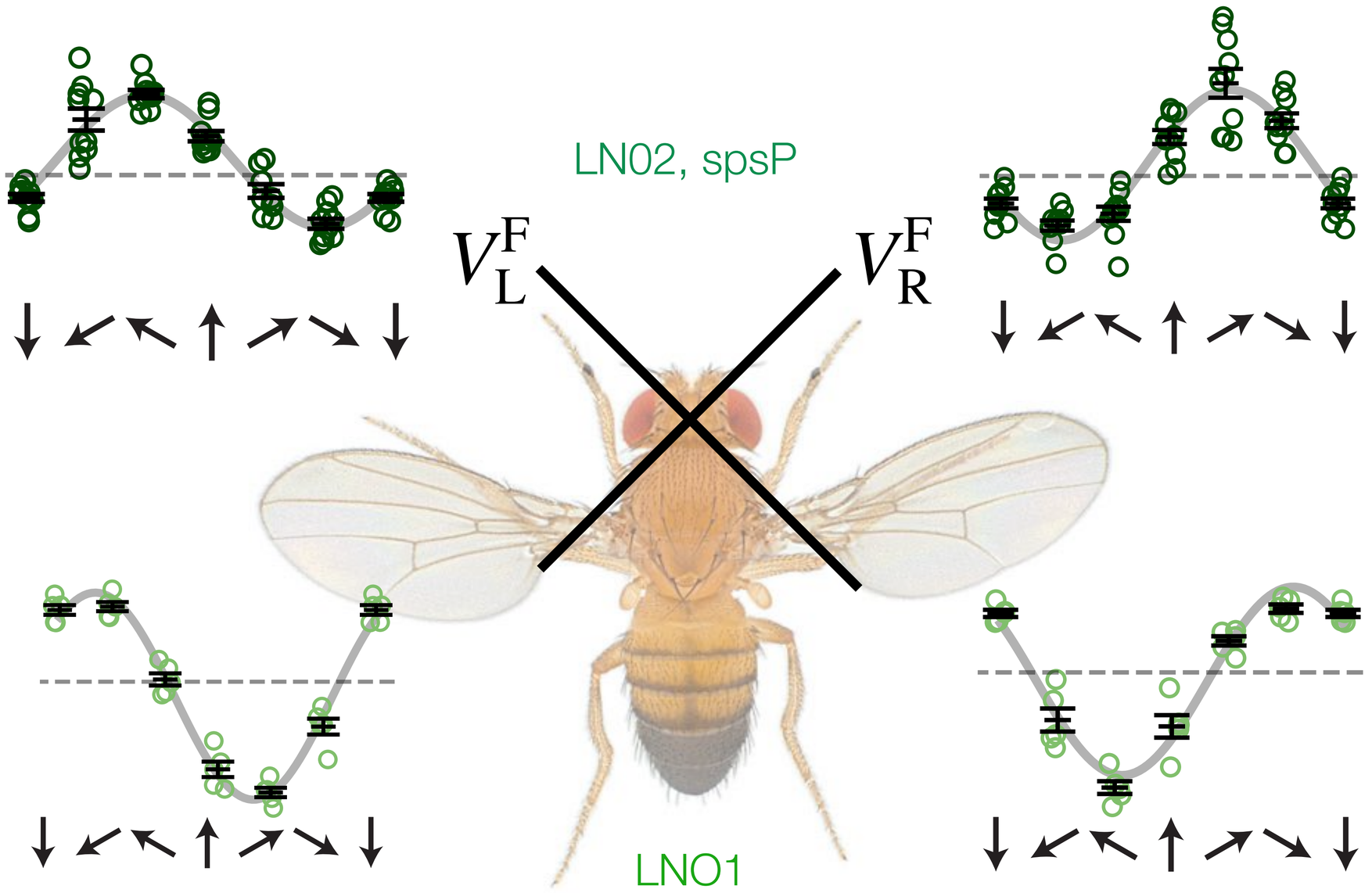

closed-loop
bright dot
open-loop
optic flow
camera



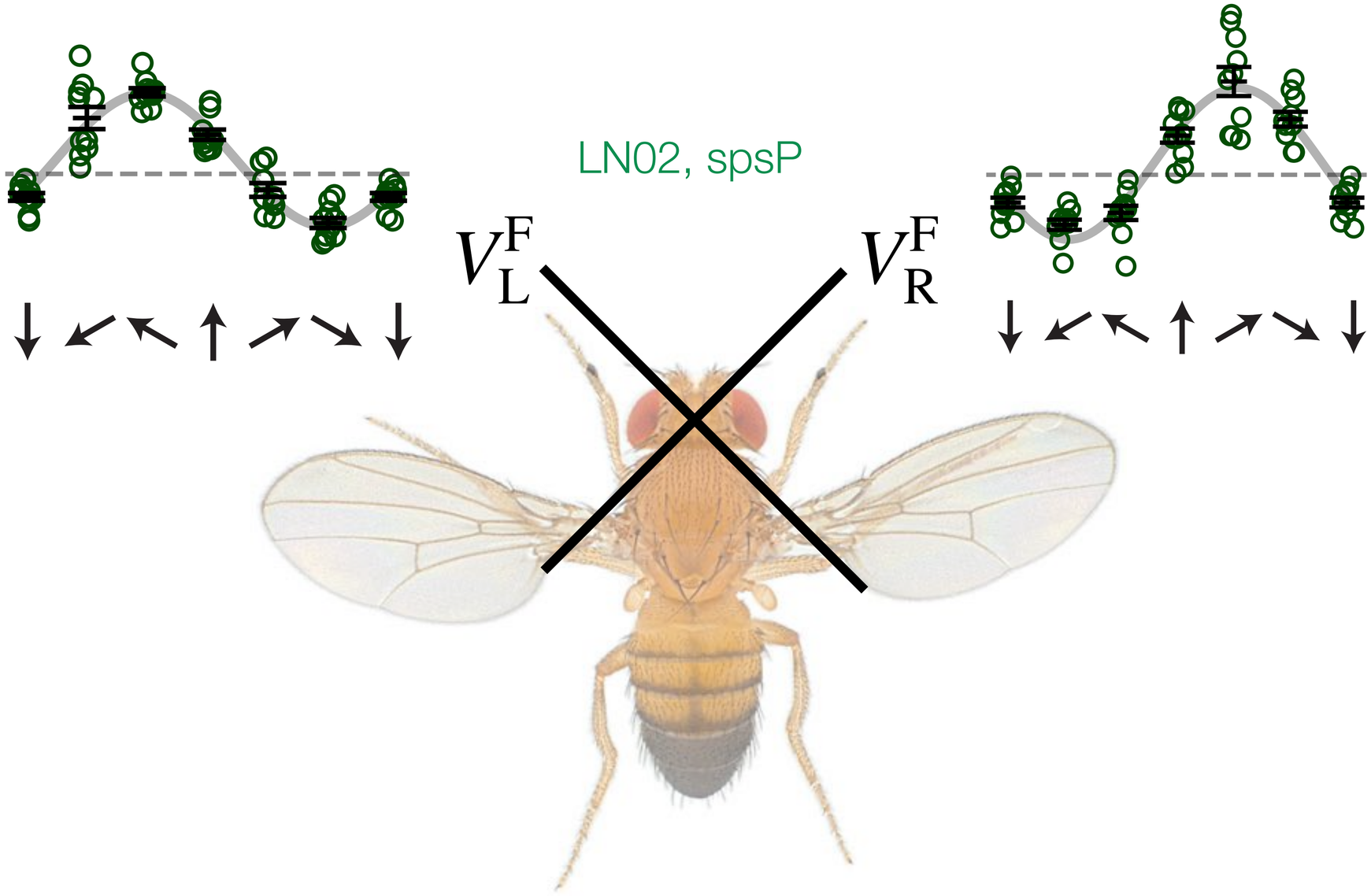
optic flow



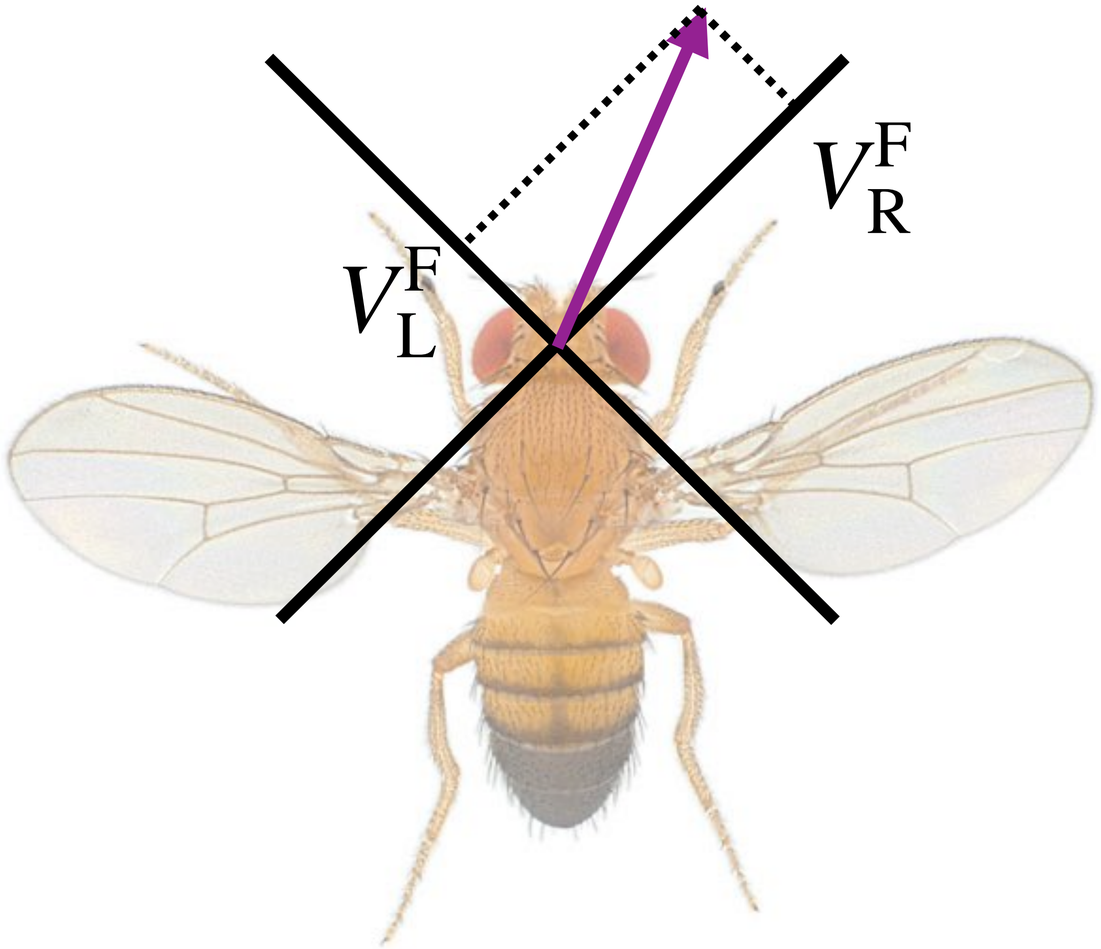
optic flow



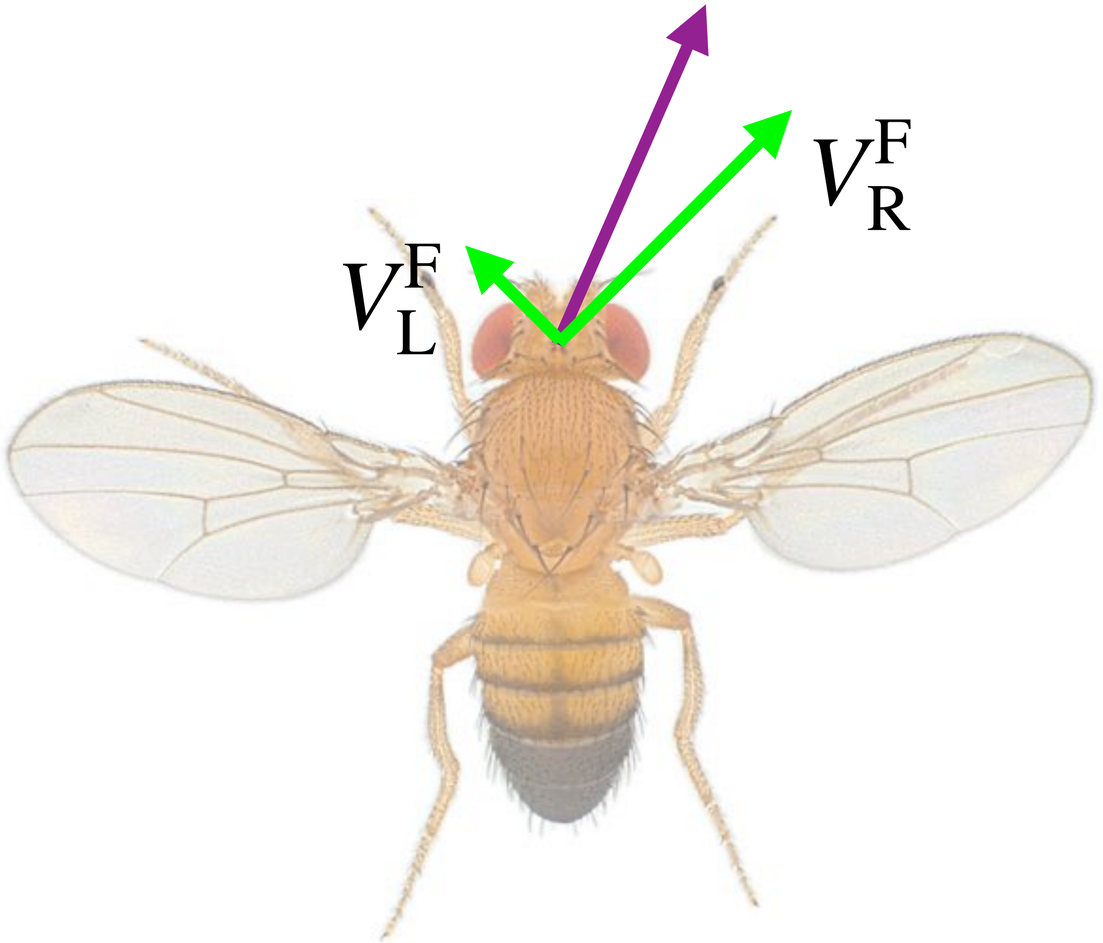
optic flow



optic flow



physics student

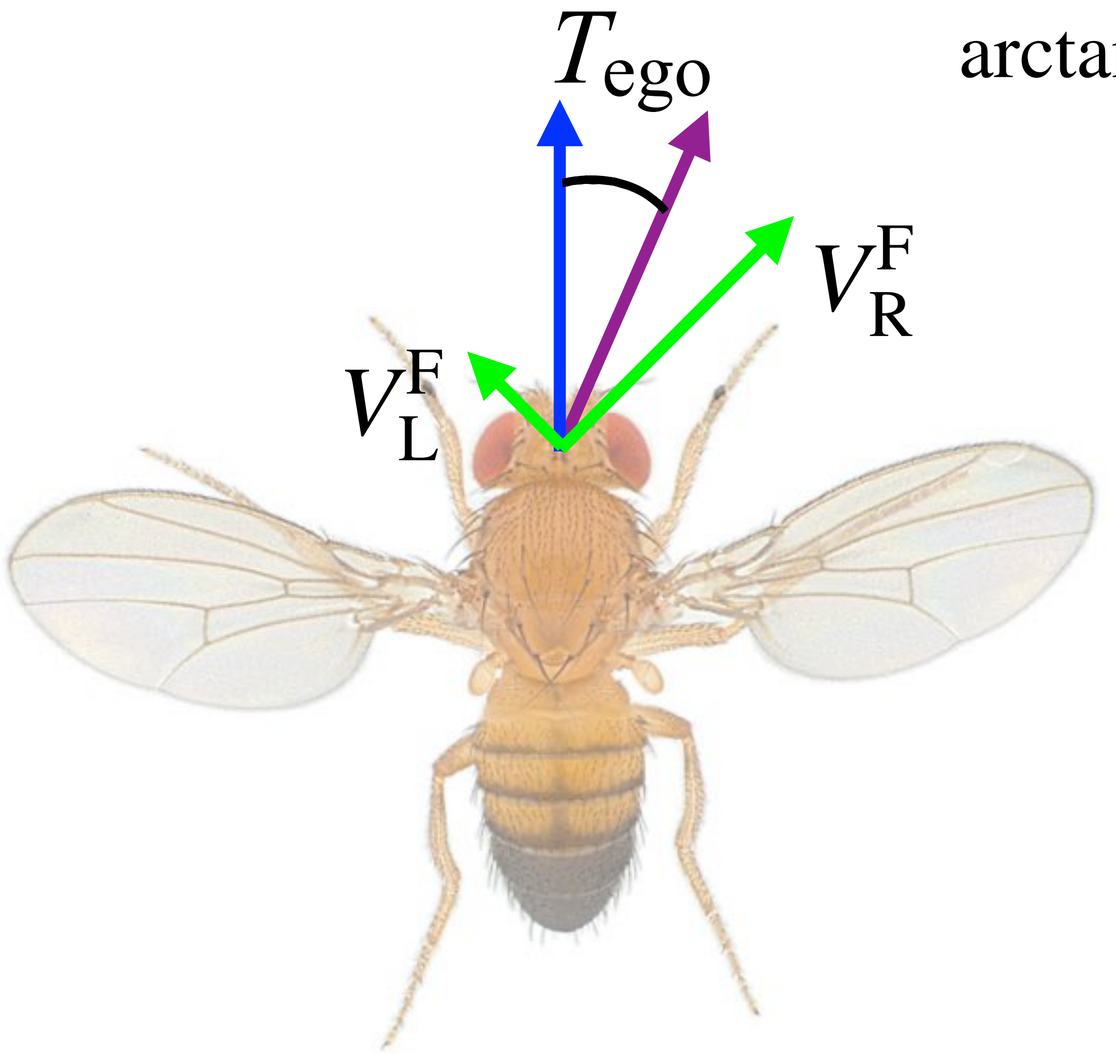


vectors

lengths	angles
$V_{\mathrm{R}}^{\mathrm{F}}$	$+45°$
$V_{\mathrm{L}}^{\mathrm{F}}$	$-45°$

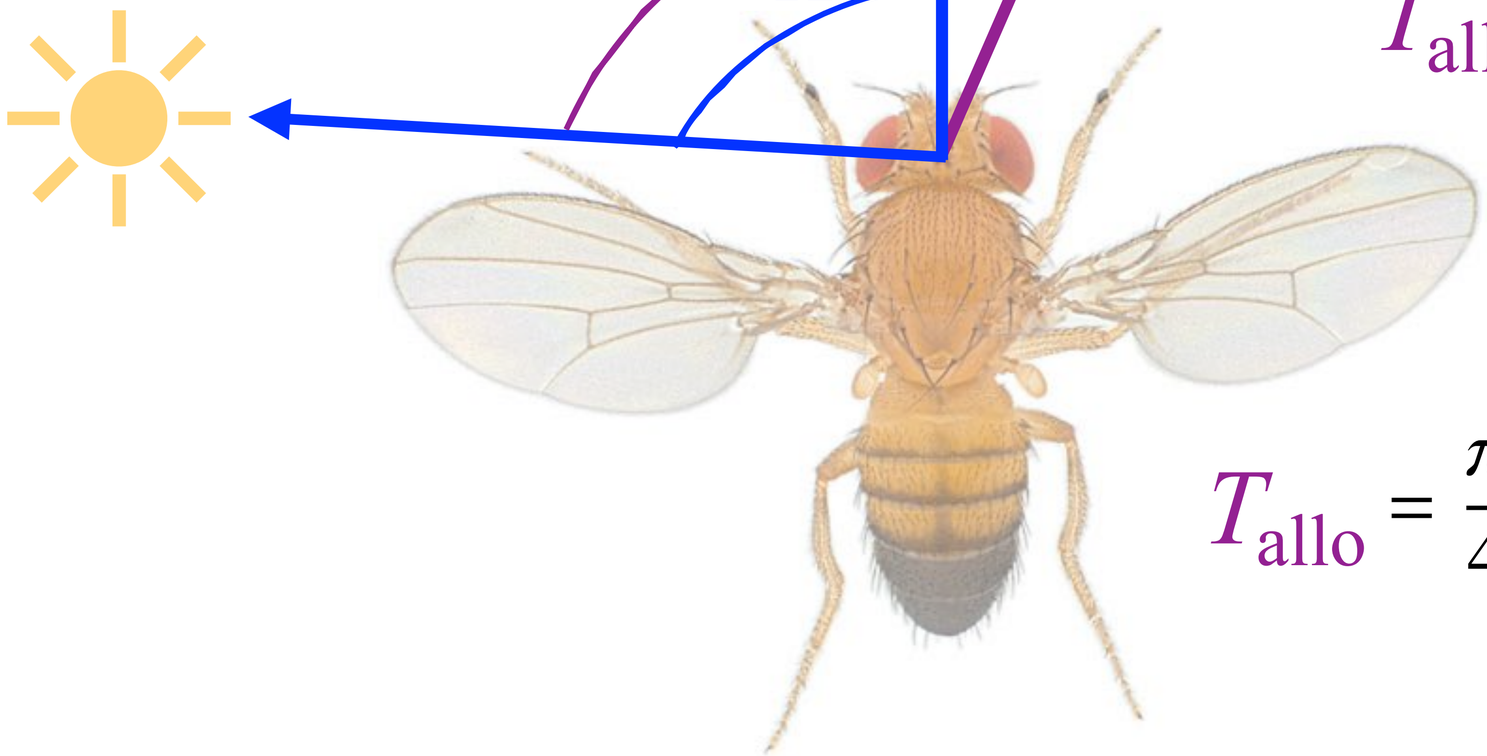
add vectors

physics student



$$\arctan\left(\frac{V_{\text{L}}^{\text{F}}}{V_{\text{R}}^{\text{F}}}\right)$$

physics student

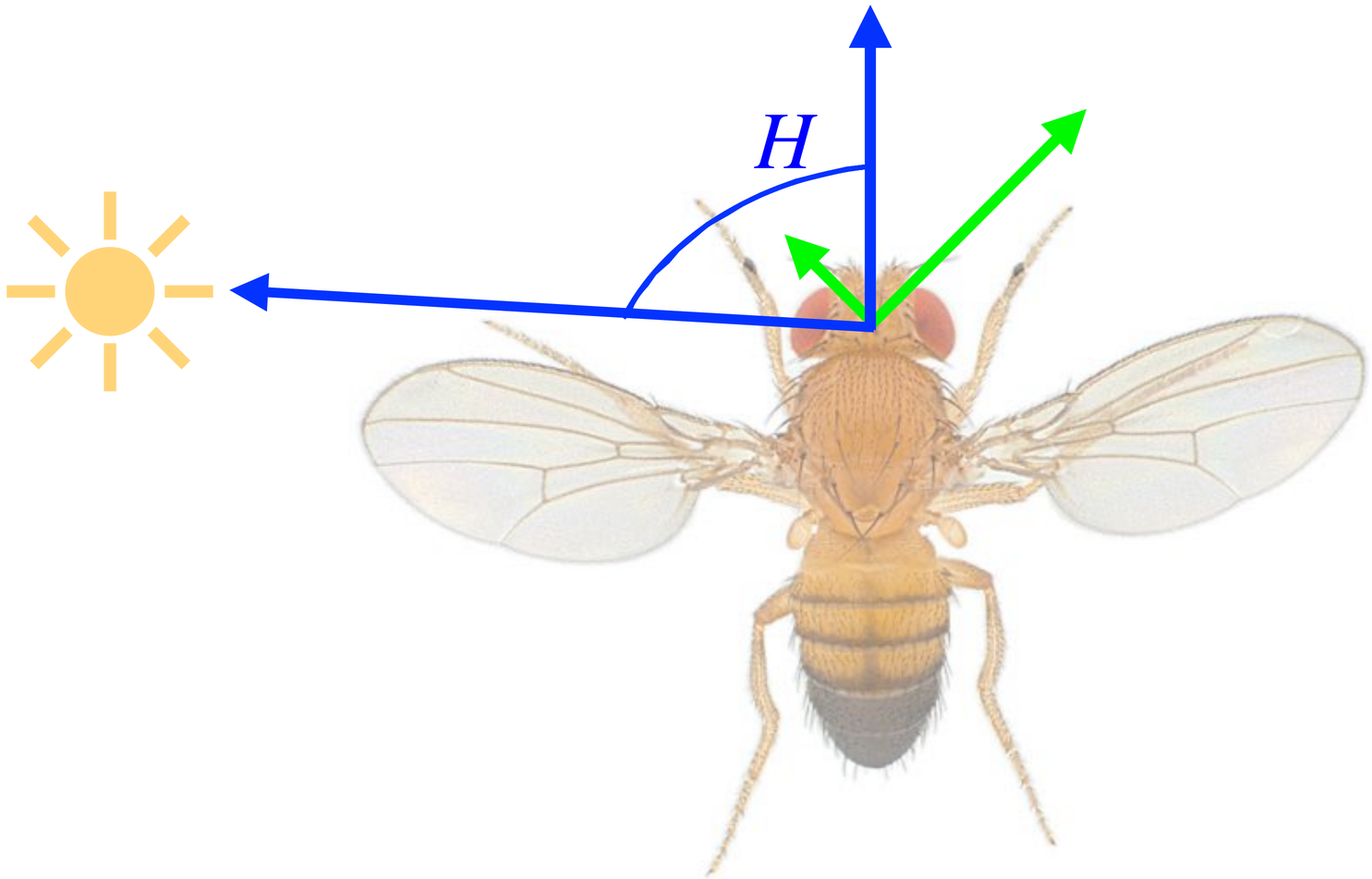


$$T_{\text{ego}} = \frac{\pi}{4} - \arctan\left(\frac{V_{\text{L}}^{\text{F}}}{V_{\text{R}}^{\text{F}}}\right)$$

$$T_{\text{allo}} = T_{\text{ego}} + H$$

$$T_{\text{allo}} = \frac{\pi}{4} - \arctan\left(\frac{V_{\text{L}}^{\text{F}}}{V_{\text{R}}^{\text{F}}}\right) + H$$

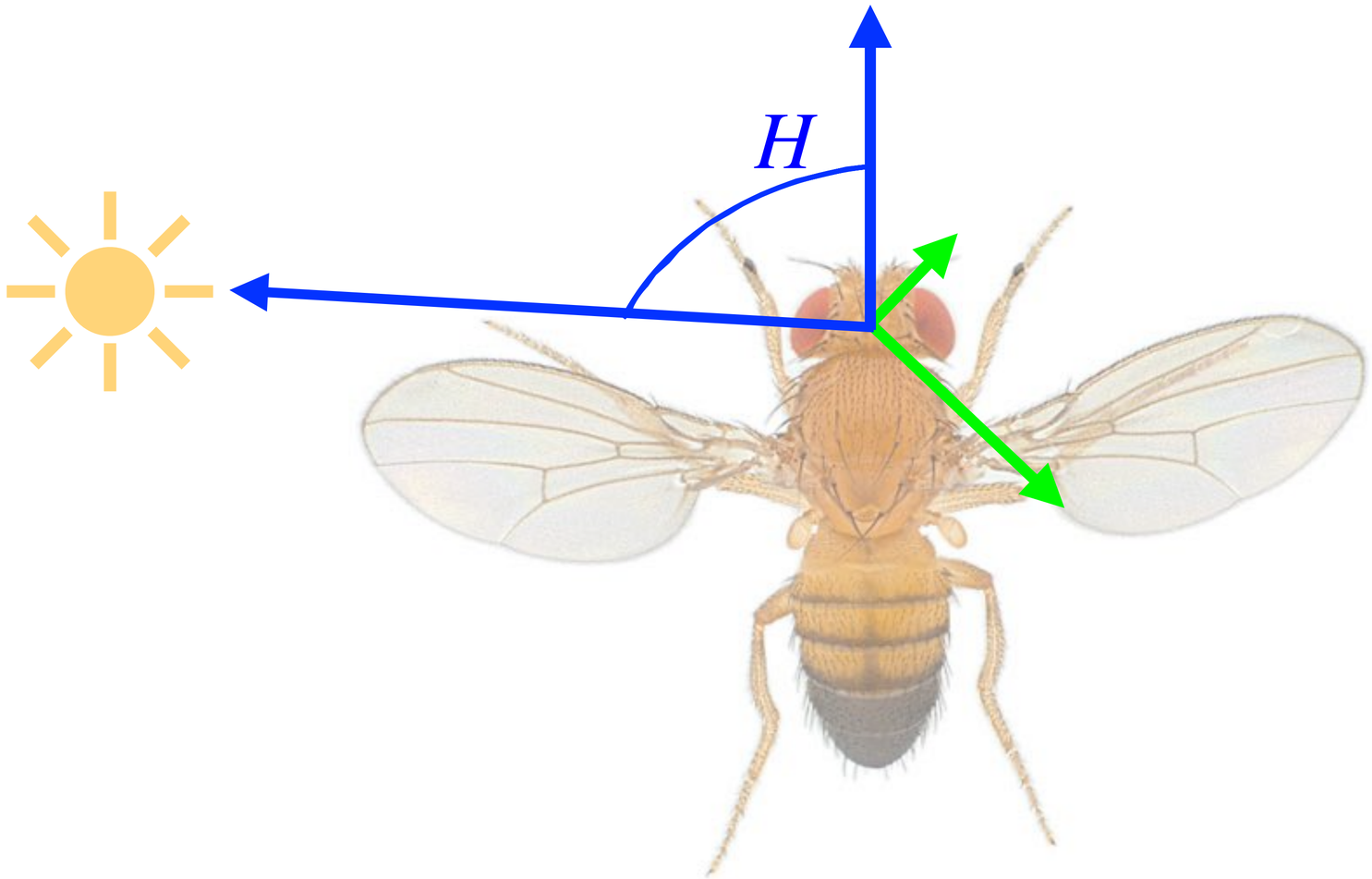
fly



vectors

lengths	angles
$V_{\mathrm{R}}^{\mathrm{F}}$	$+\,45°$
$V_{\mathrm{L}}^{\mathrm{F}}$	$-\,45°$

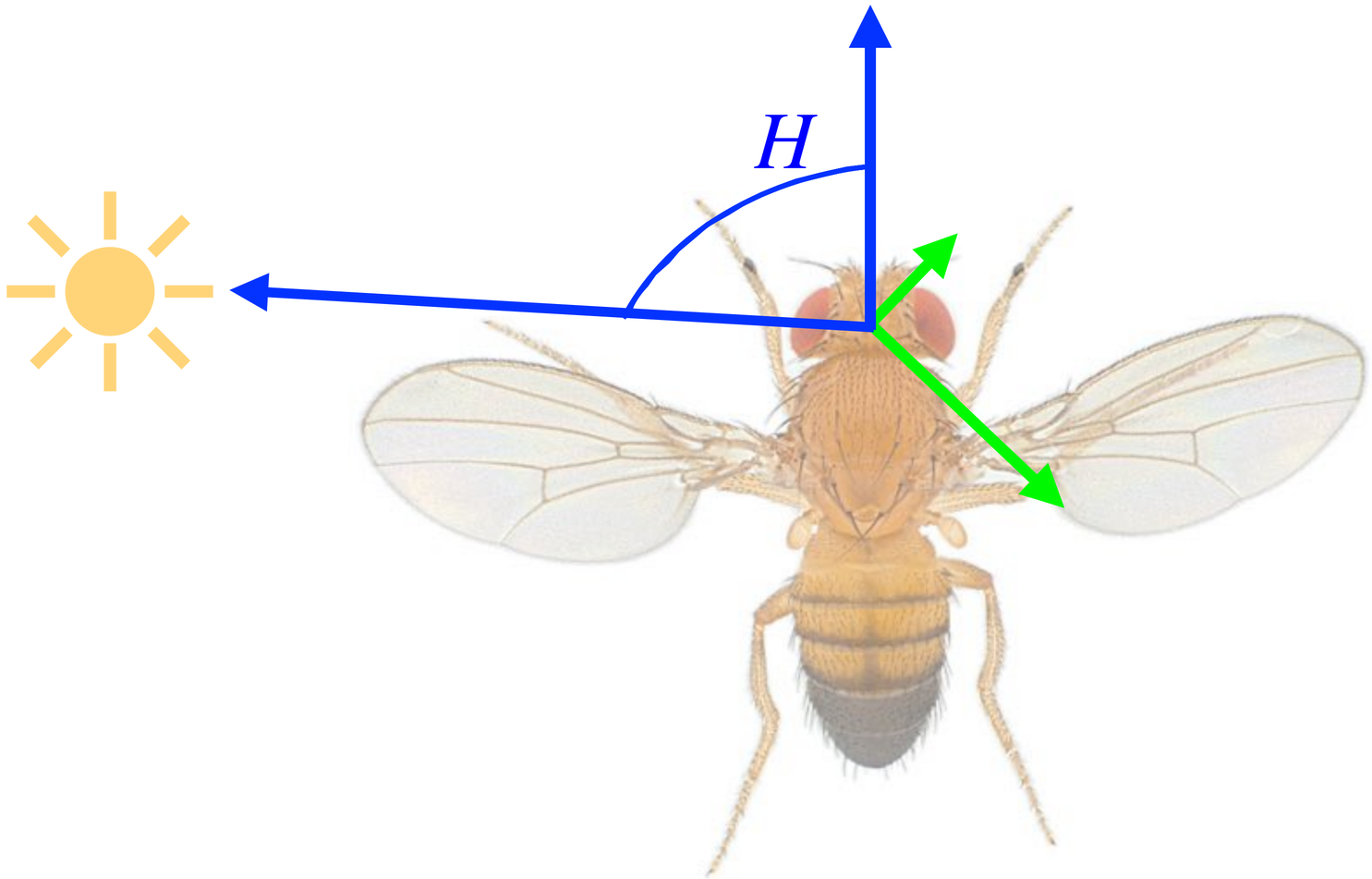
fly



vectors

lengths	angles
$V_{\mathrm{R}}^{\mathrm{F}}$	$+\,45°$
$V_{\mathrm{L}}^{\mathrm{F}}$	$-\,45°$

fly



vectors

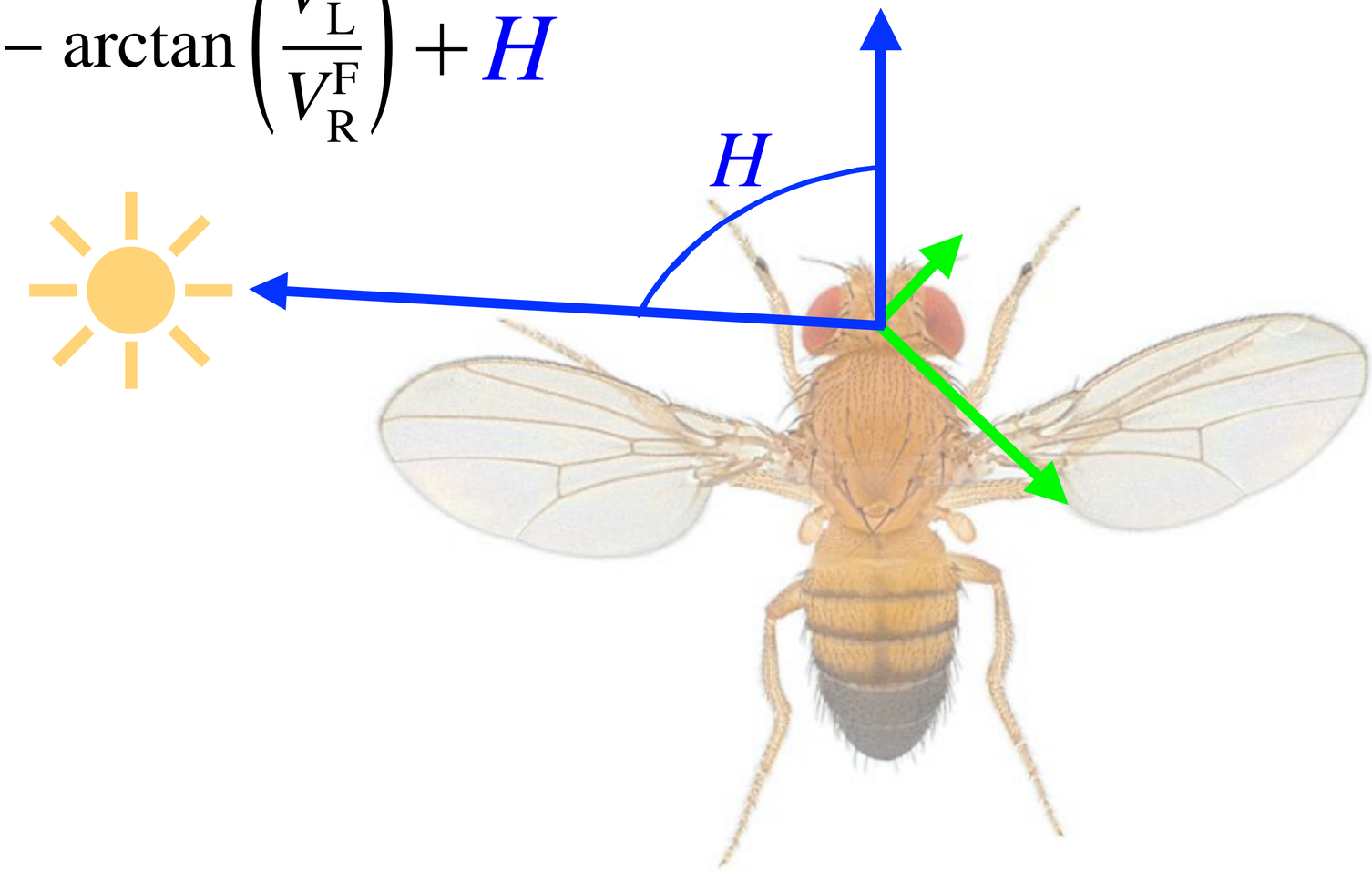
lengths	angles
$V_{\mathrm{R}}^{\mathrm{F}}$	$H + 45°$
$V_{\mathrm{L}}^{\mathrm{F}}$	$H - 45°$

add vectors

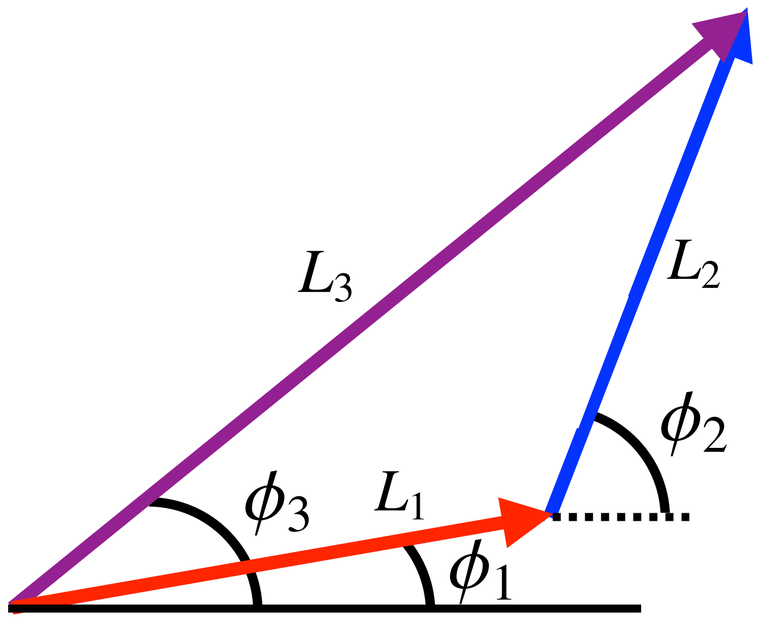
fly

$f(\theta)$

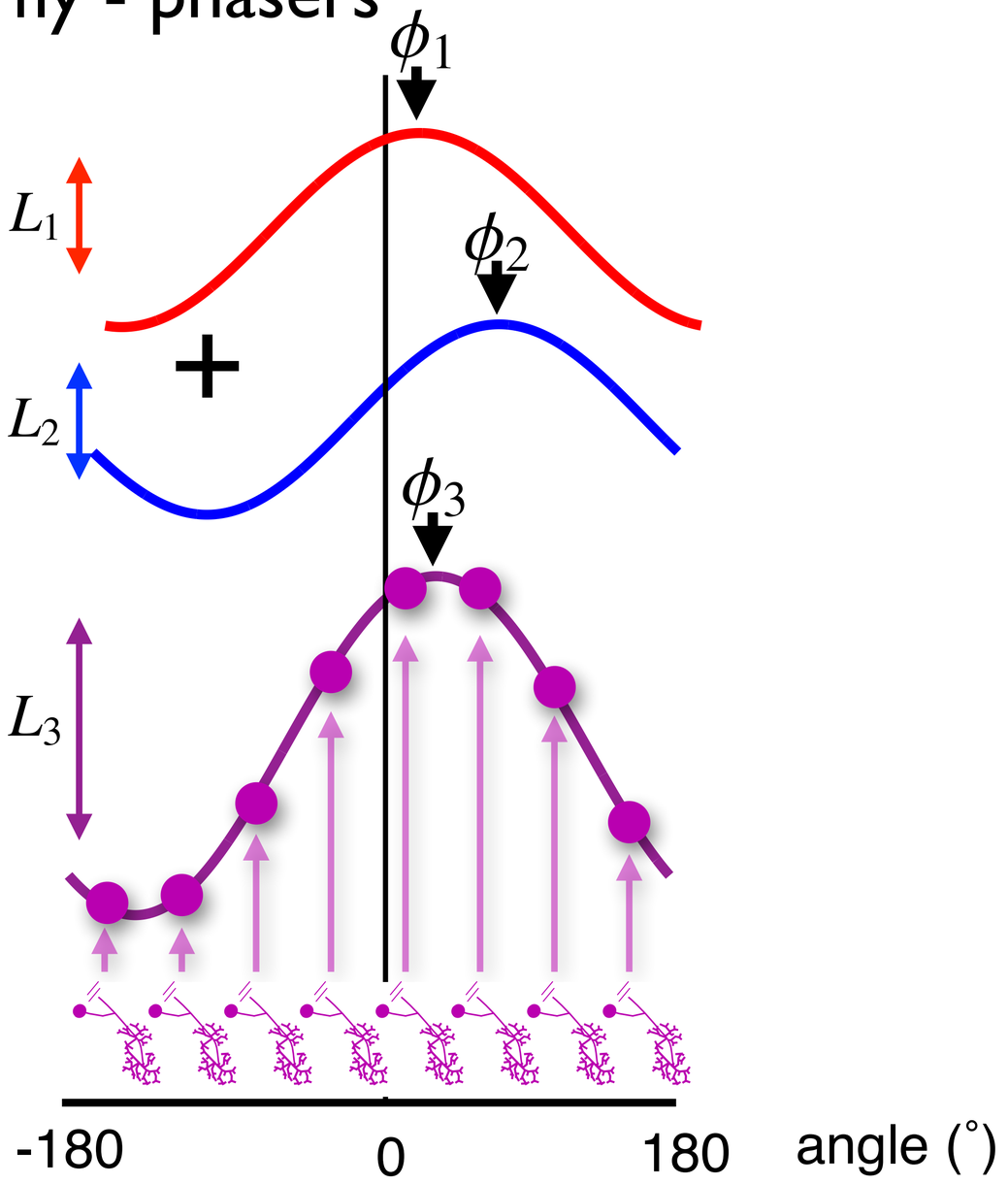
$$T_{\text{allo}} = \theta_{\max} = \frac{\pi}{4} - \arctan\left(\frac{V_{\text{L}}^{\text{F}}}{V_{\text{R}}^{\text{F}}}\right) + H$$



physics student - vectors

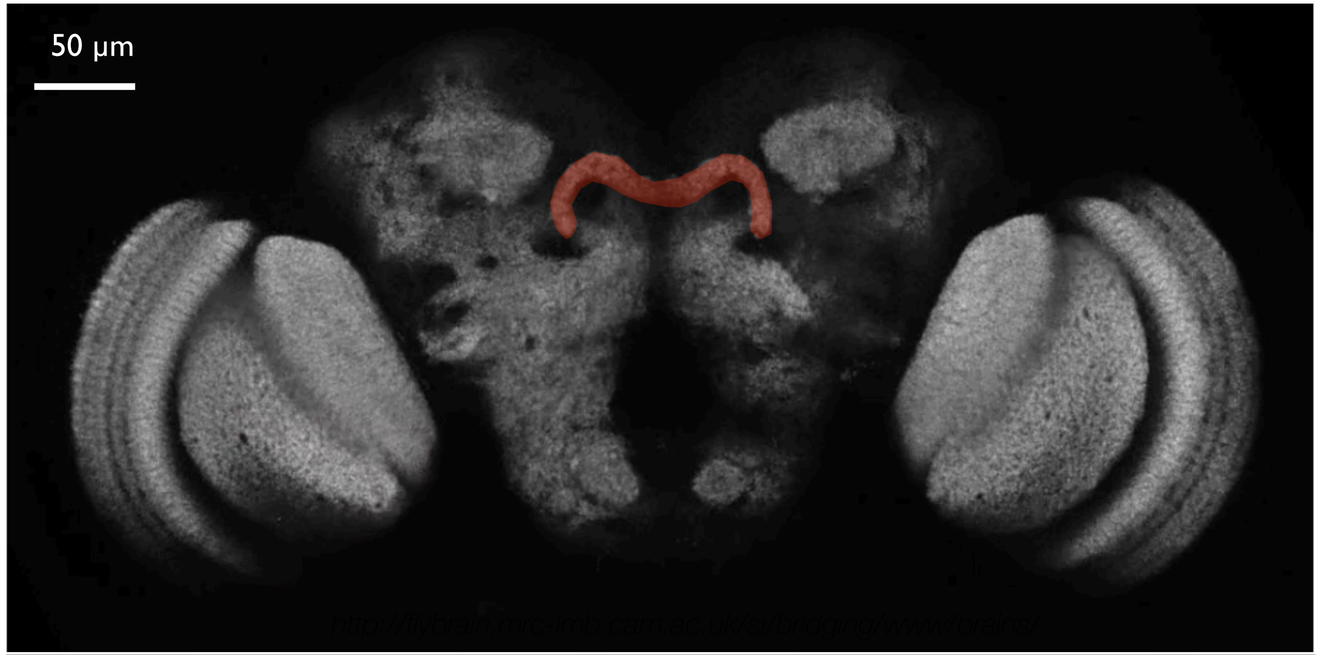


fly - phasers

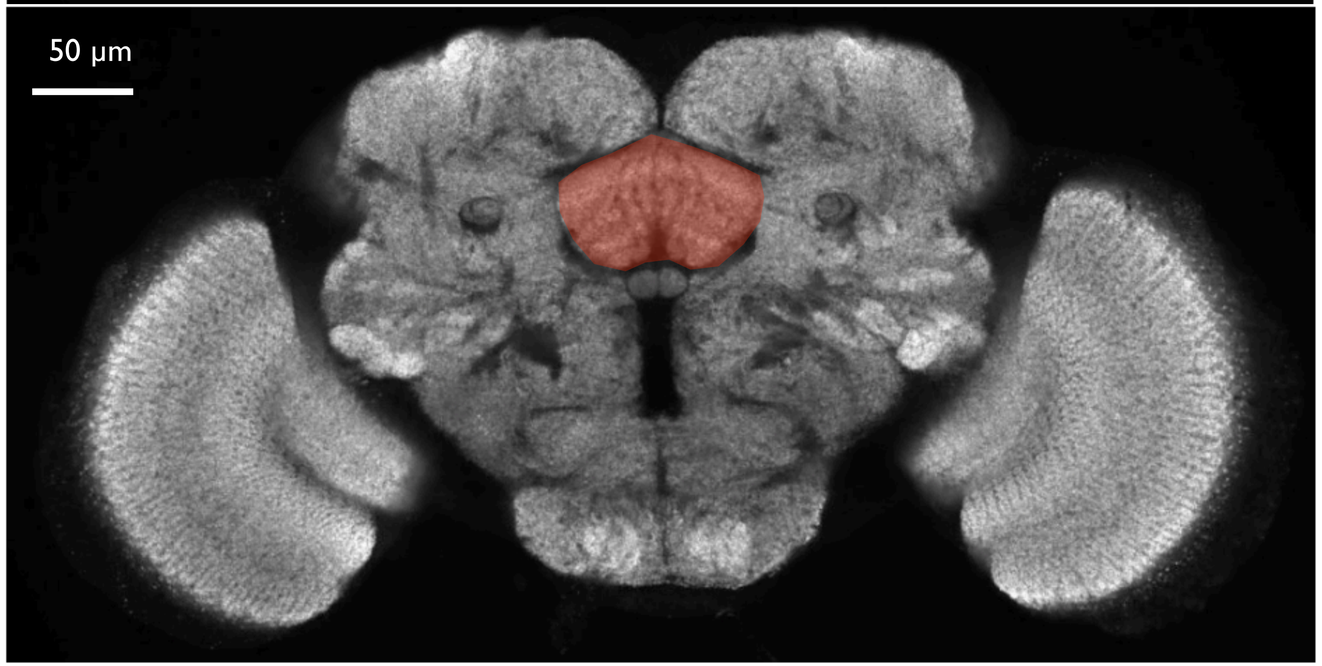


O'Keefe (1991)
Touretzky, Redish & Wan (1993)
Wittmann & Schwegler (1995)
Hartmann & Wehner (1995)
Stone… Webb, Heinze (2017)

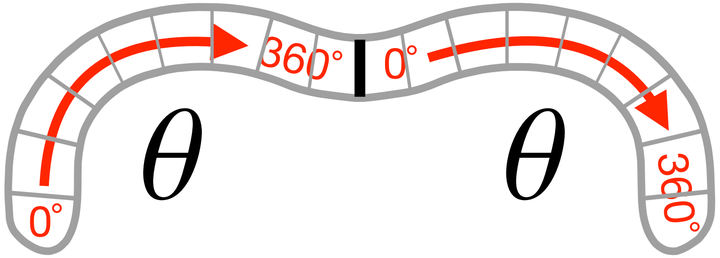
http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/

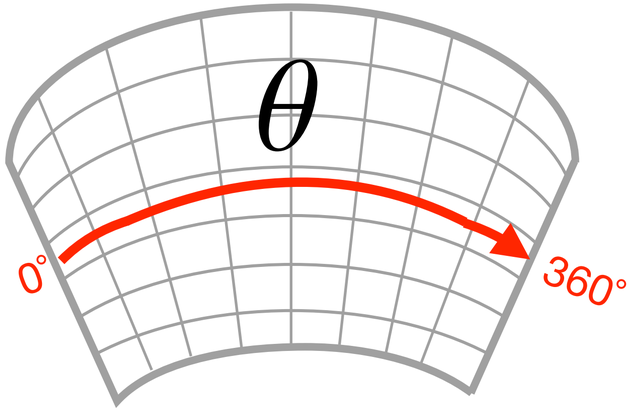


http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/



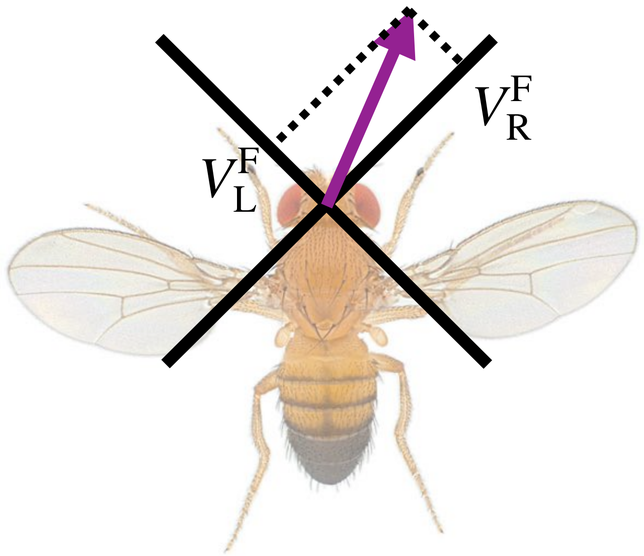
protocerebral bridge





fan-shaped body

✓ 1) optic flow

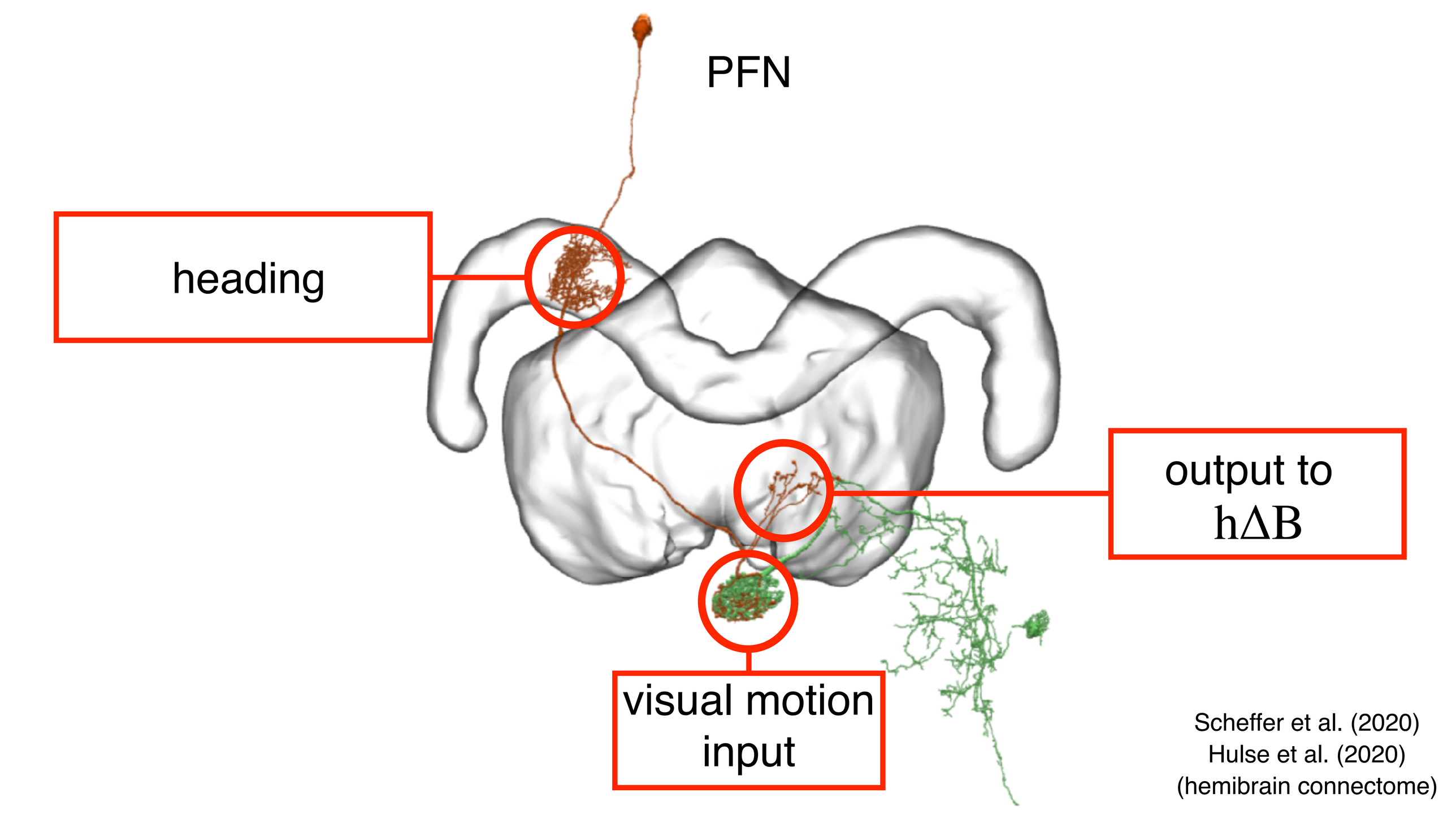


2) $V_R^F \cos\left(\theta - H\right) \quad V_L^F \cos\left(\theta - H\right)$

3) $V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) \quad V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

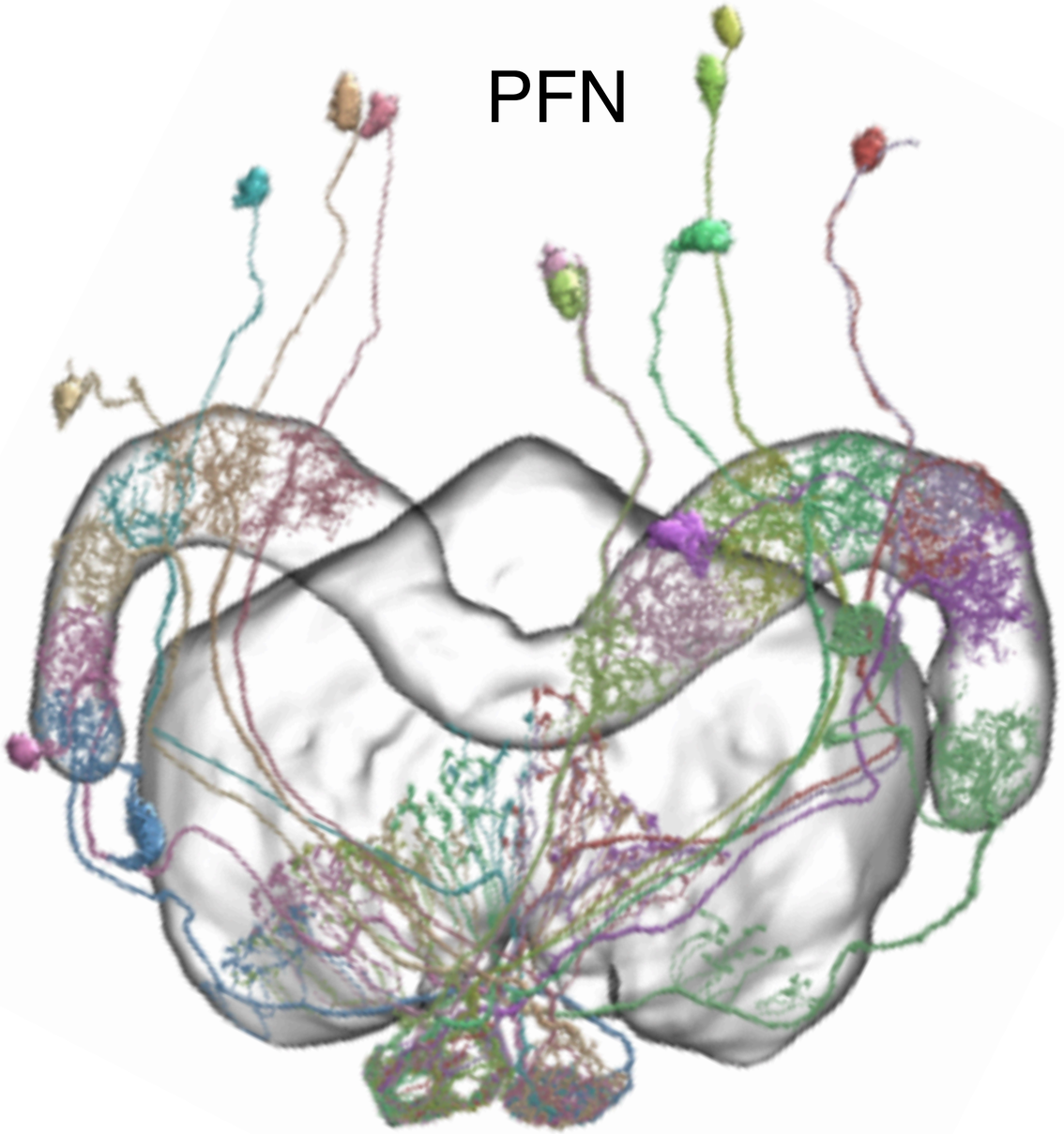
4) $f(\theta) = V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) + V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

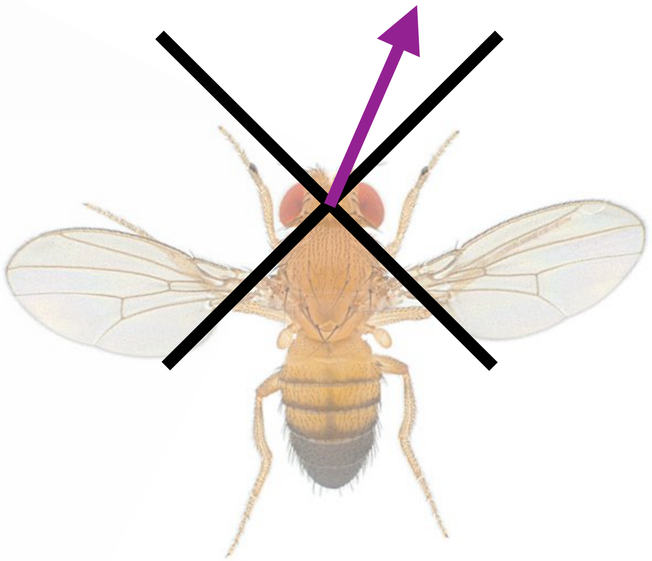
5) Find maximum $h\Delta B$



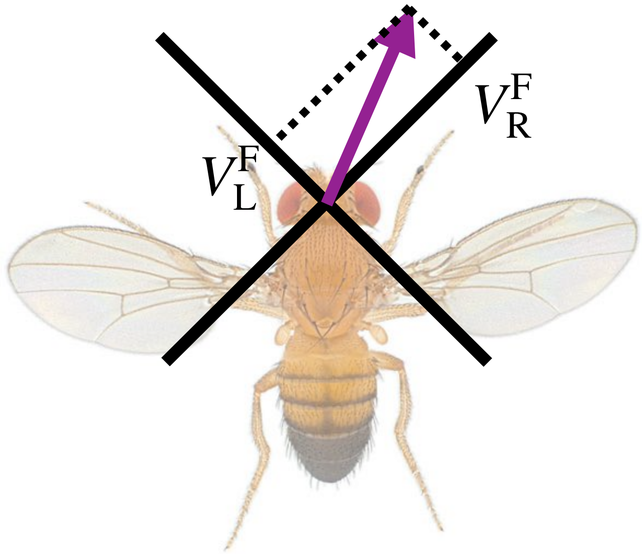
Scheffer et al. (2020)
Hulse et al. (2020)
(hemibrain connectome)

PFN

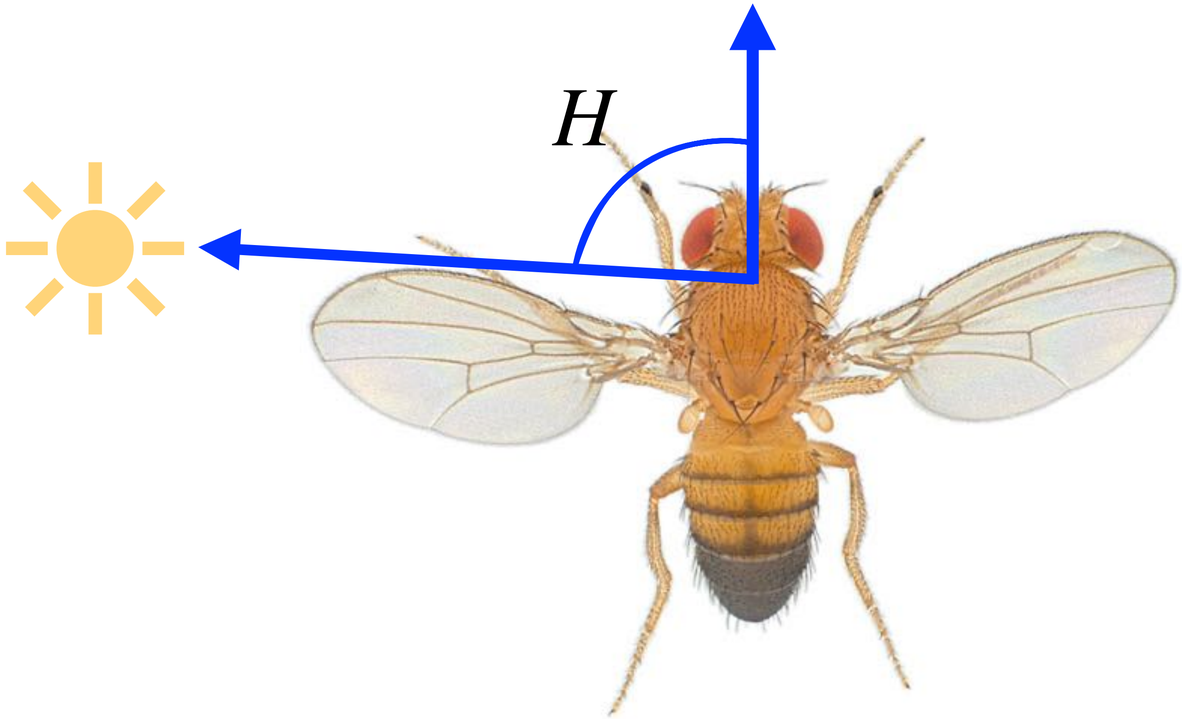




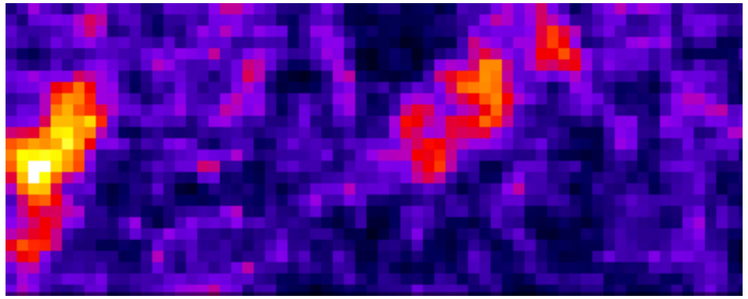
✓ 1) optic flow

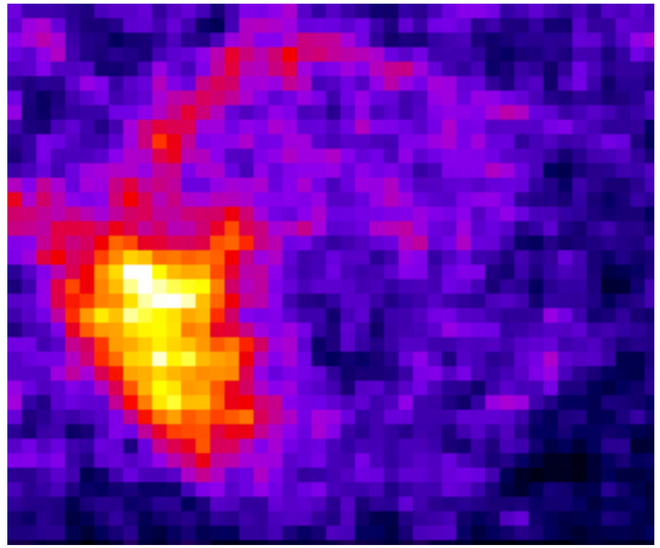


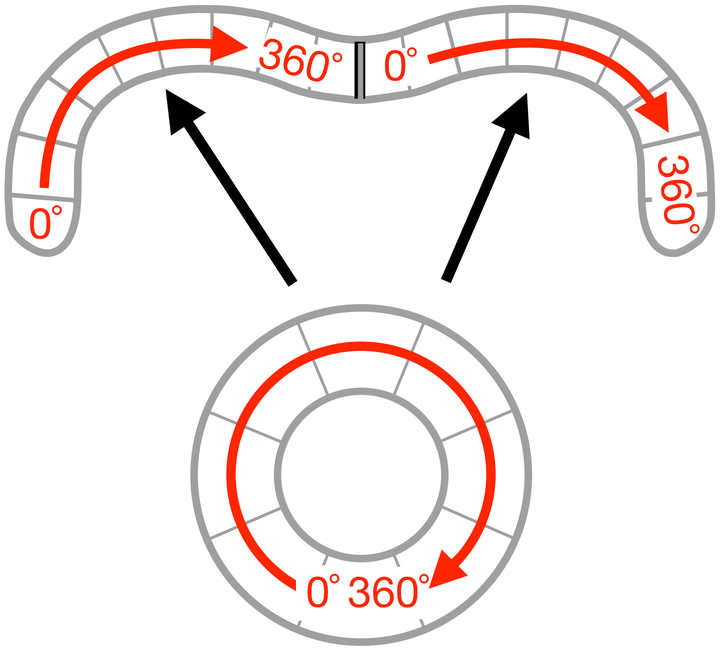
2) $V_R^F \cos\left(\theta - H\right)$ $V_L^F \cos\left(\theta - H\right)$?



EPG



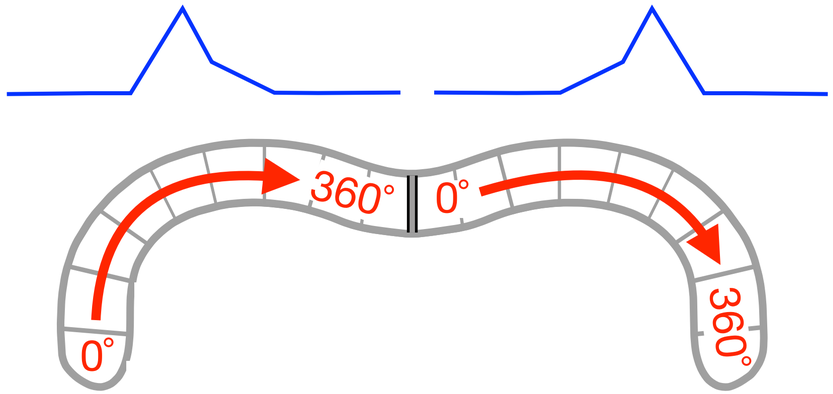




Cheng Lyu

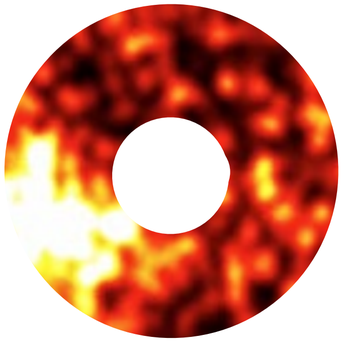
Green, Adachi, Shah, Hirokawa, Magani, Maimon (2017)

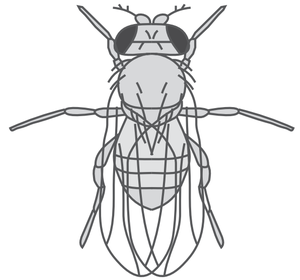
protocerebral bridge



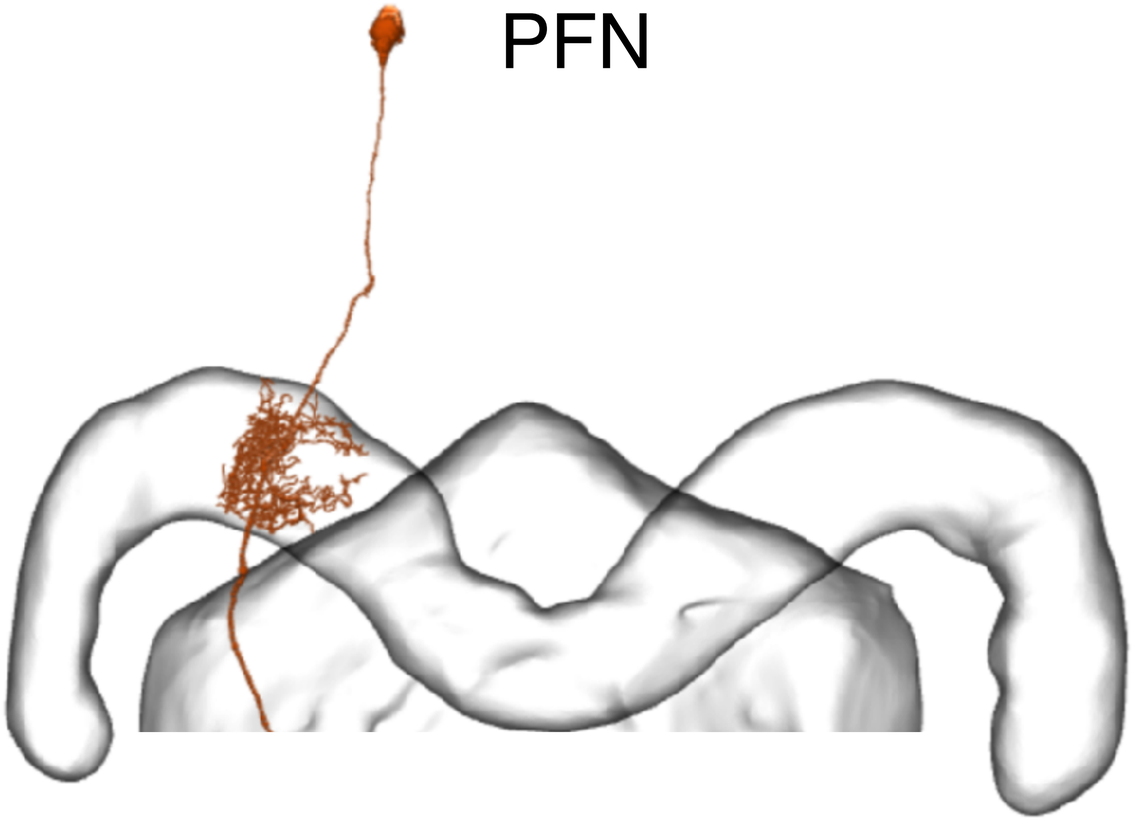
not sinusoidal

ellipsoid body



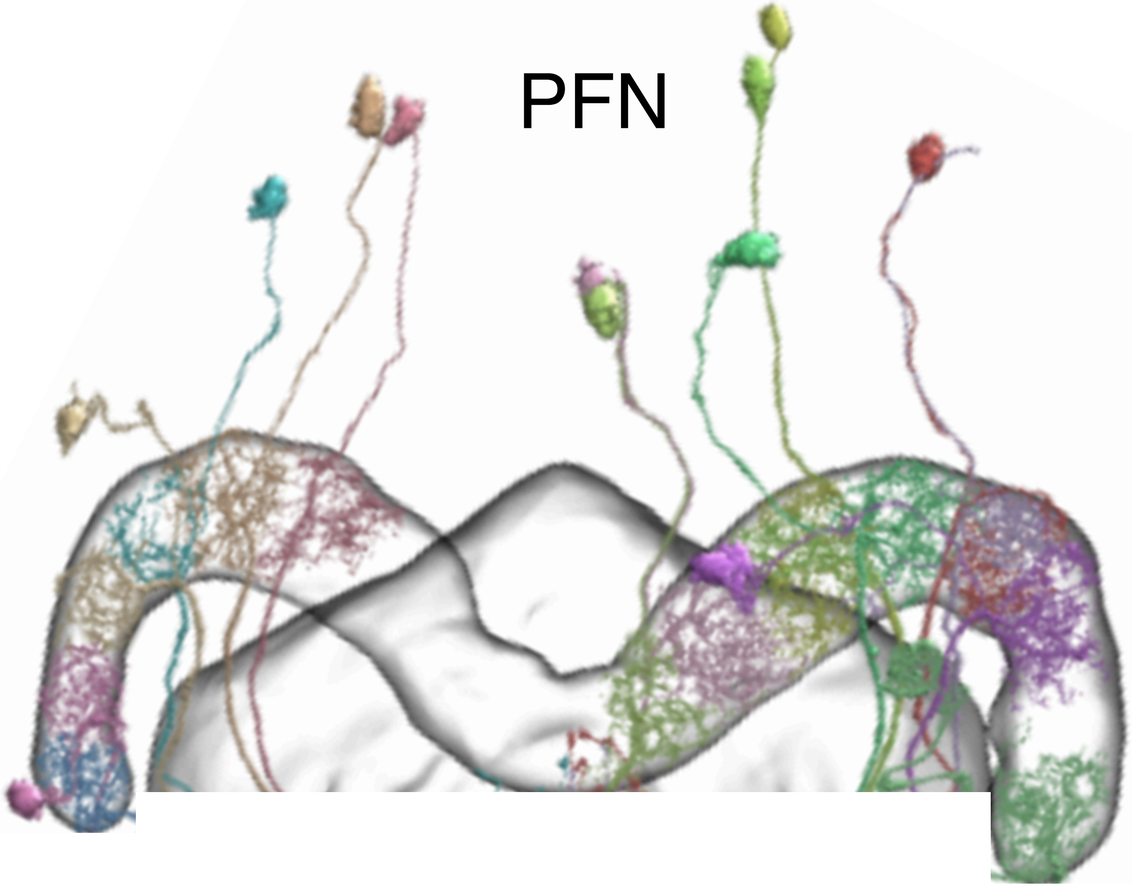


PFN

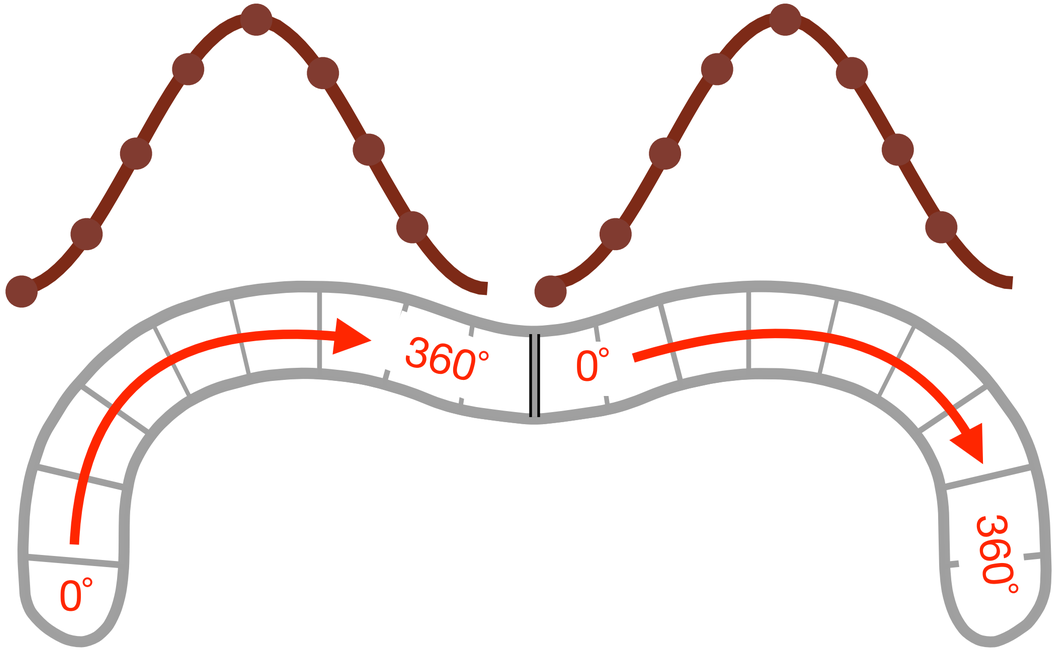


Scheffer et al. (2020)
Hulse et al. (2020)
(hemibrain connectome)

PFN

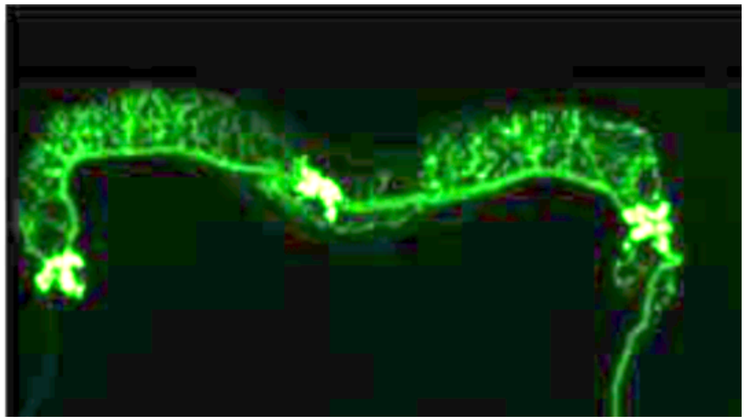


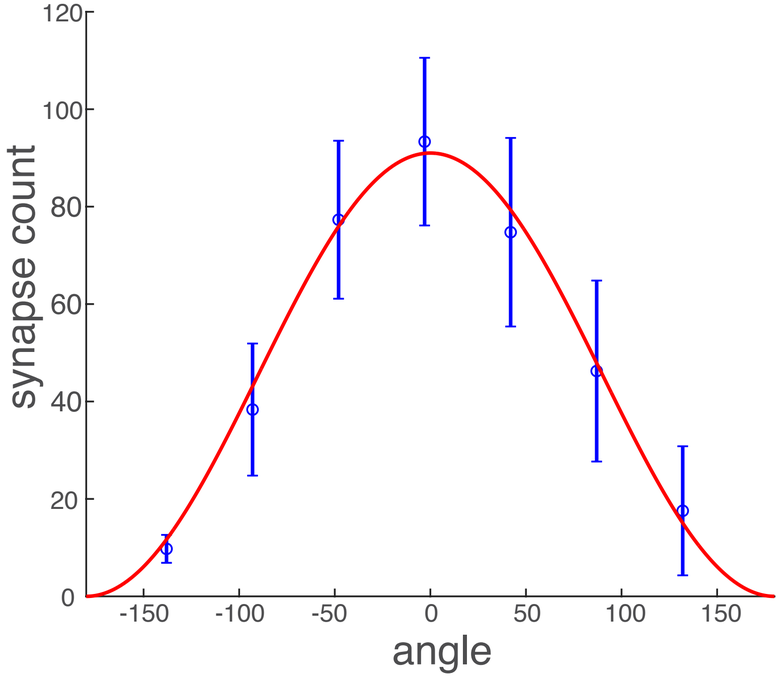
protocerebral bridge

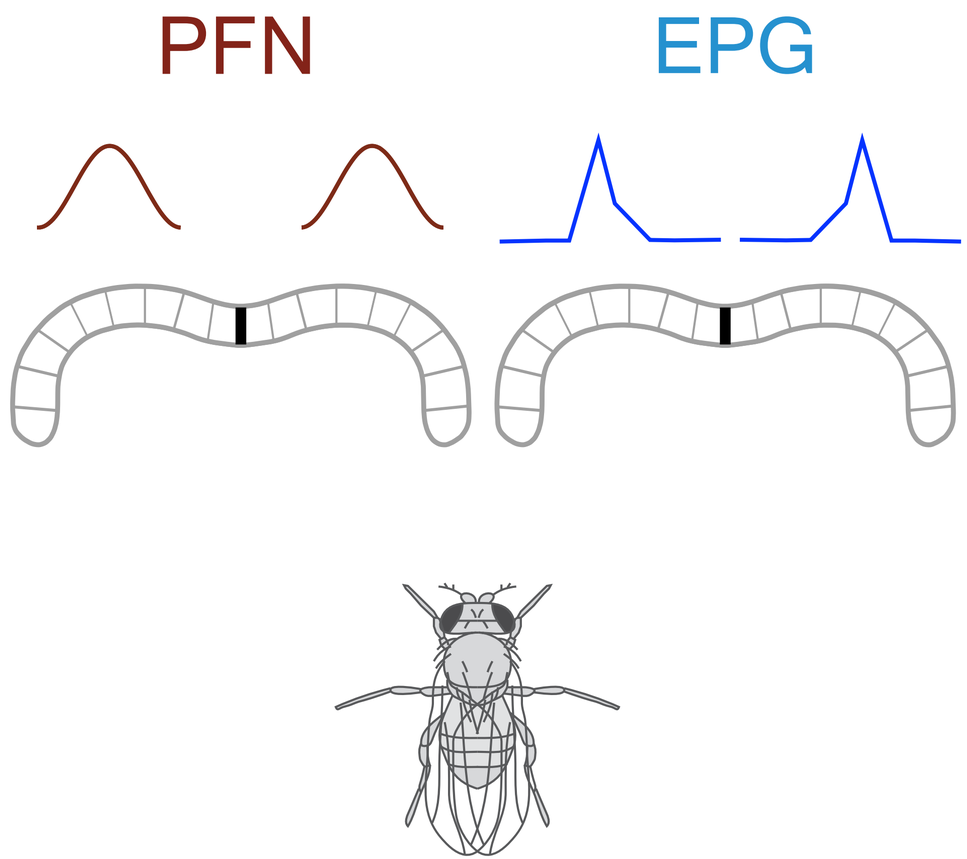


Δ7 cell

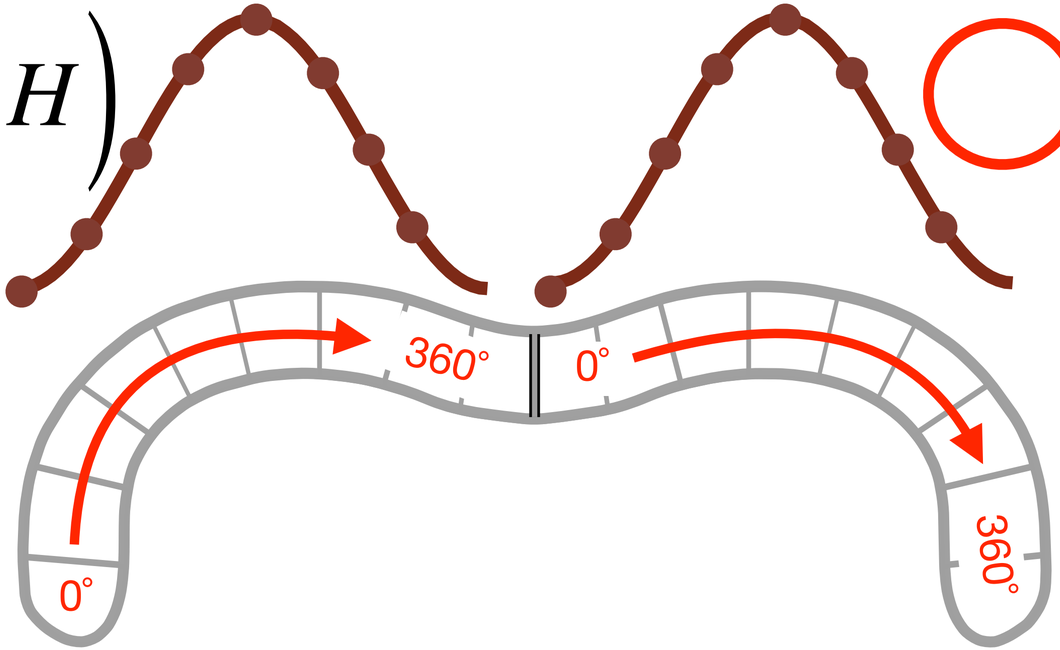
Wolff et al. (2015)





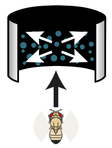

PFN
EPG

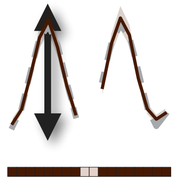
$\cos\left(\theta - H\right)$

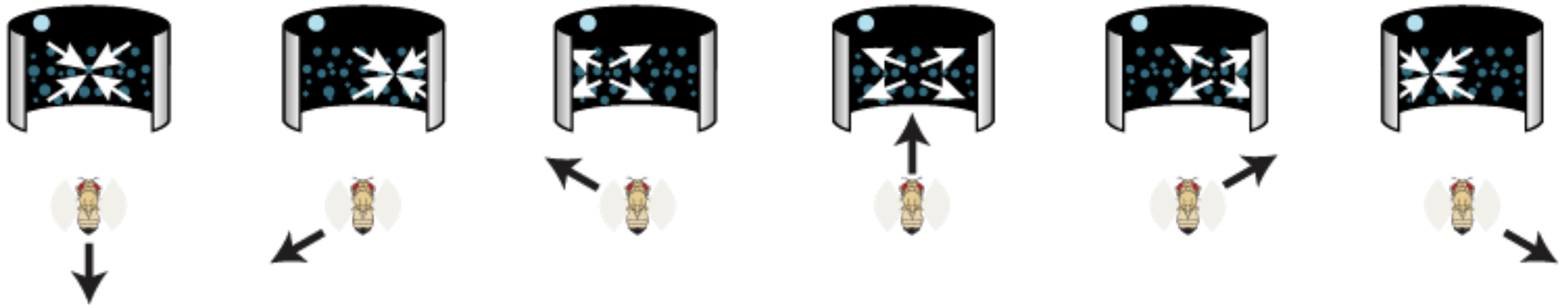


$\cos\left(\theta - H\right)$

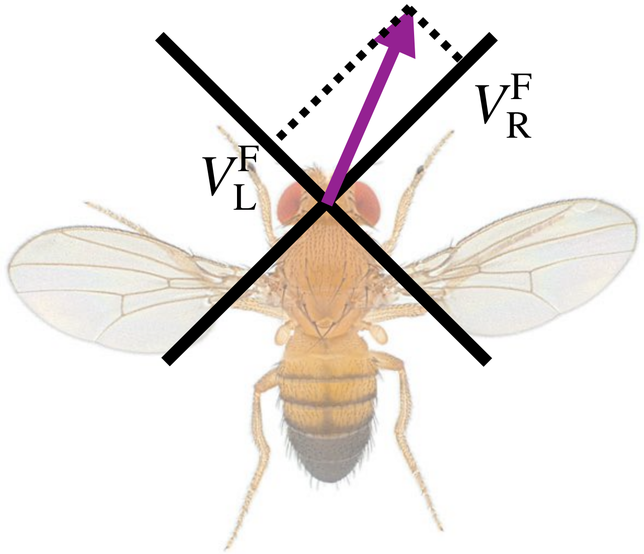
protocerebral bridge







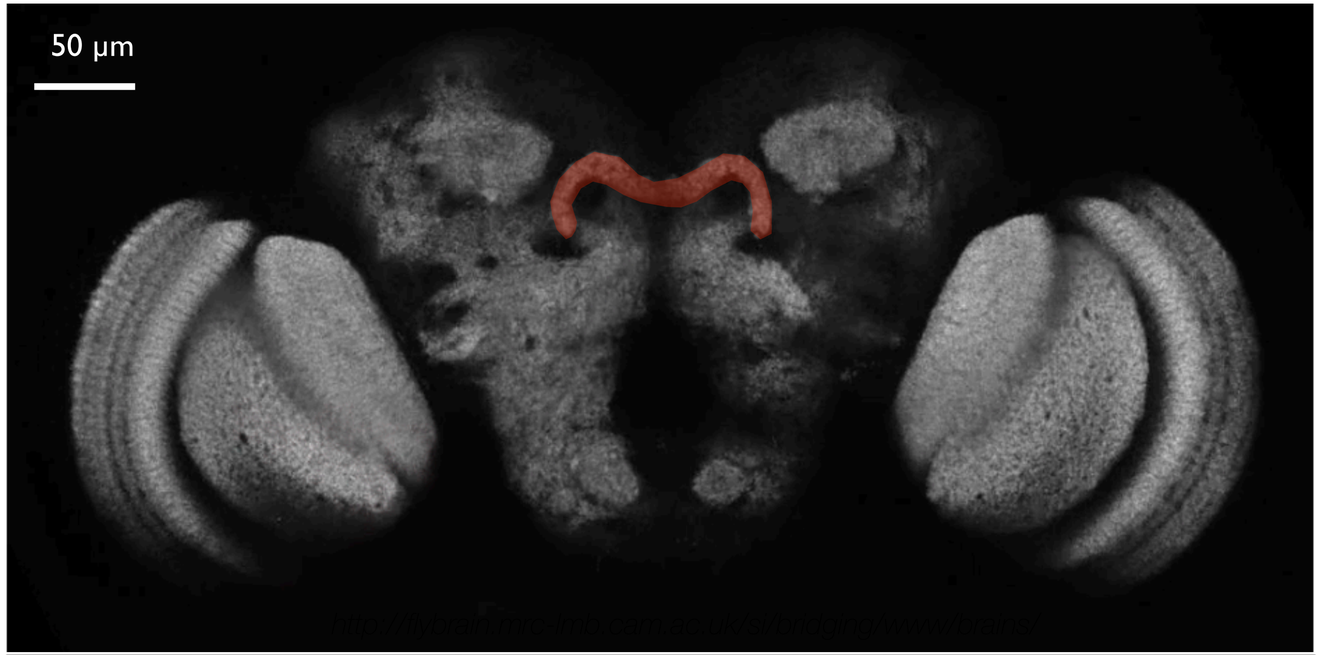
✓ 1) optic flow



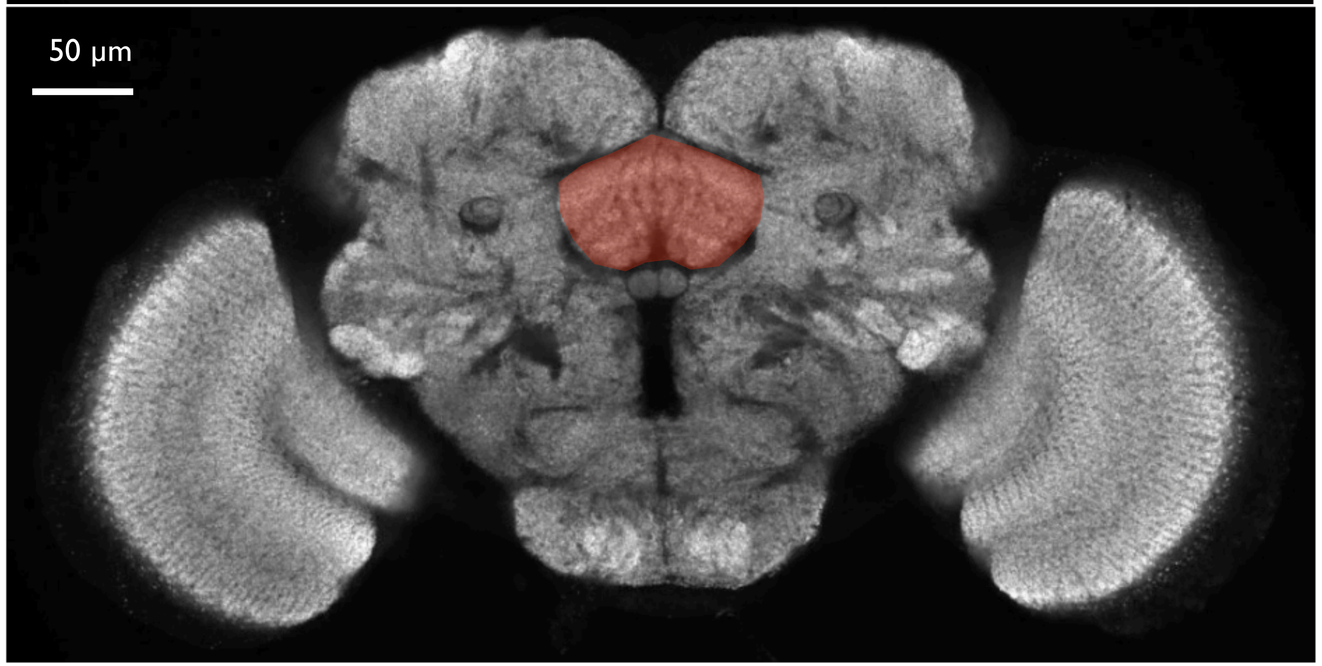
✓ 2) $V_R^F \cos\left(\theta - H\right) \quad V_L^F \cos\left(\theta - H\right)$

3) $V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) \quad V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

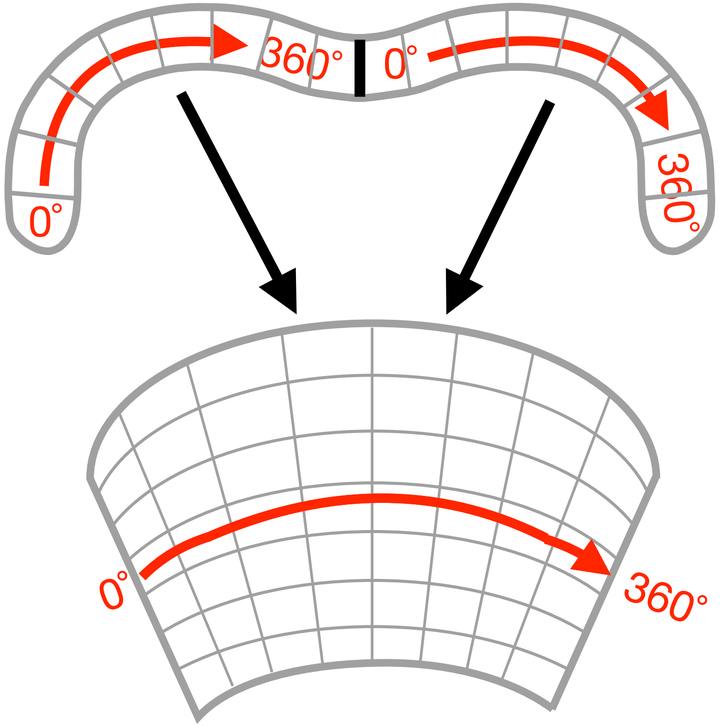
http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/



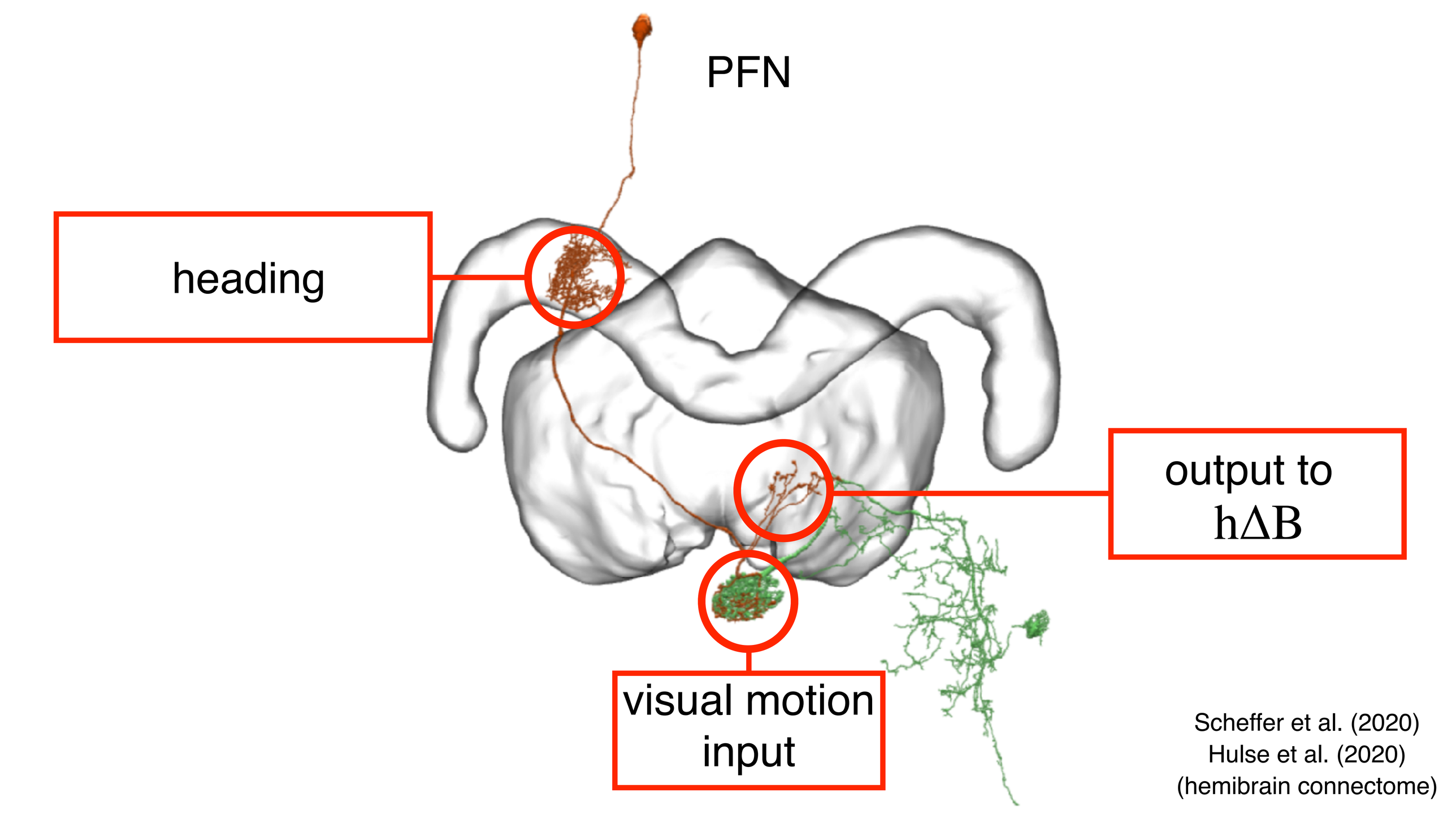
http://flybrain.mrc-lmb.cam.ac.uk/si/bridging/www/brains/



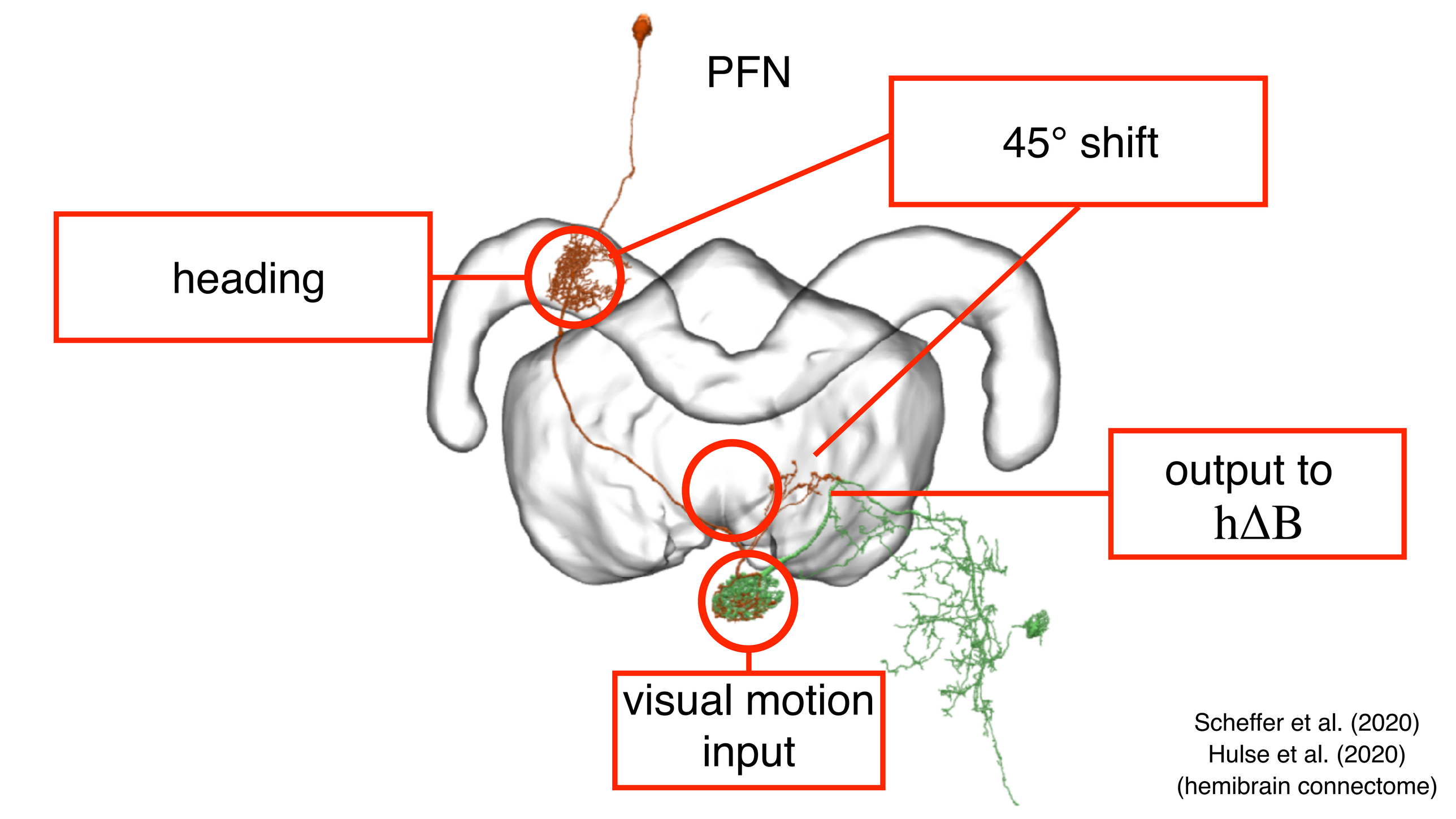
protocerebral bridge



fan-shaped body



Scheffer et al. (2020)
Hulse et al. (2020)
(hemibrain connectome)

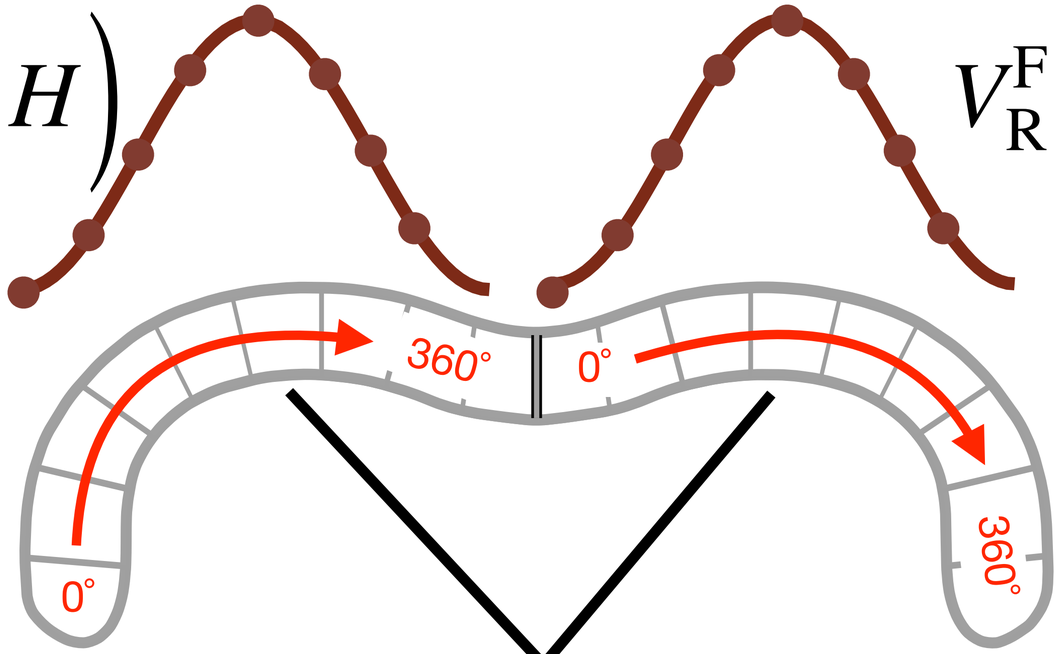


Scheffer et al. (2020)
Hulse et al. (2020)
(hemibrain connectome)

$$V_{\mathrm{L}}^{\mathrm{F}} \cos\left(\theta - H\right)$$

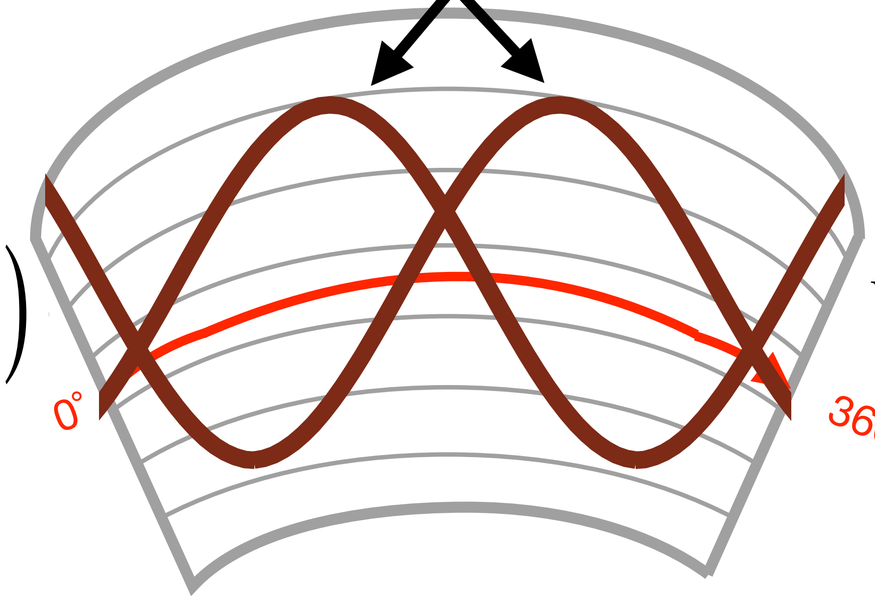
$$V_{\mathrm{R}}^{\mathrm{F}} \cos\left(\theta - H\right)$$

protocerebral bridge



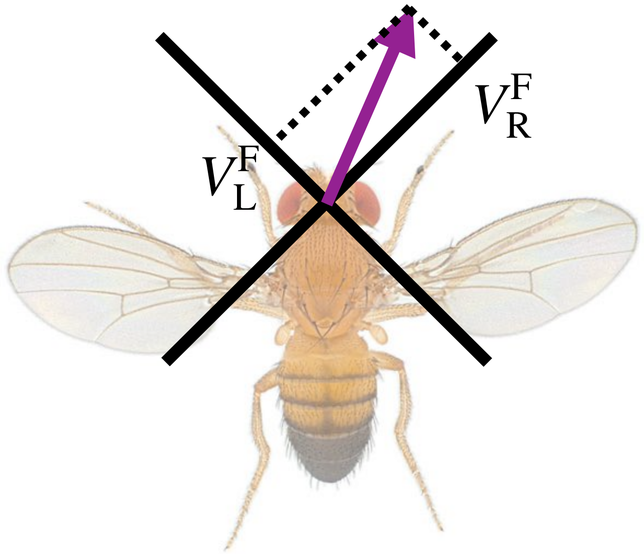
fan-shaped body

$$V_{\mathrm{R}}^{\mathrm{F}} \cos\left(\theta - H - \frac{\pi}{4}\right)$$



$$V_{\mathrm{L}}^{\mathrm{F}} \cos\left(\theta - H + \frac{\pi}{4}\right)$$

✓ 1) optic flow

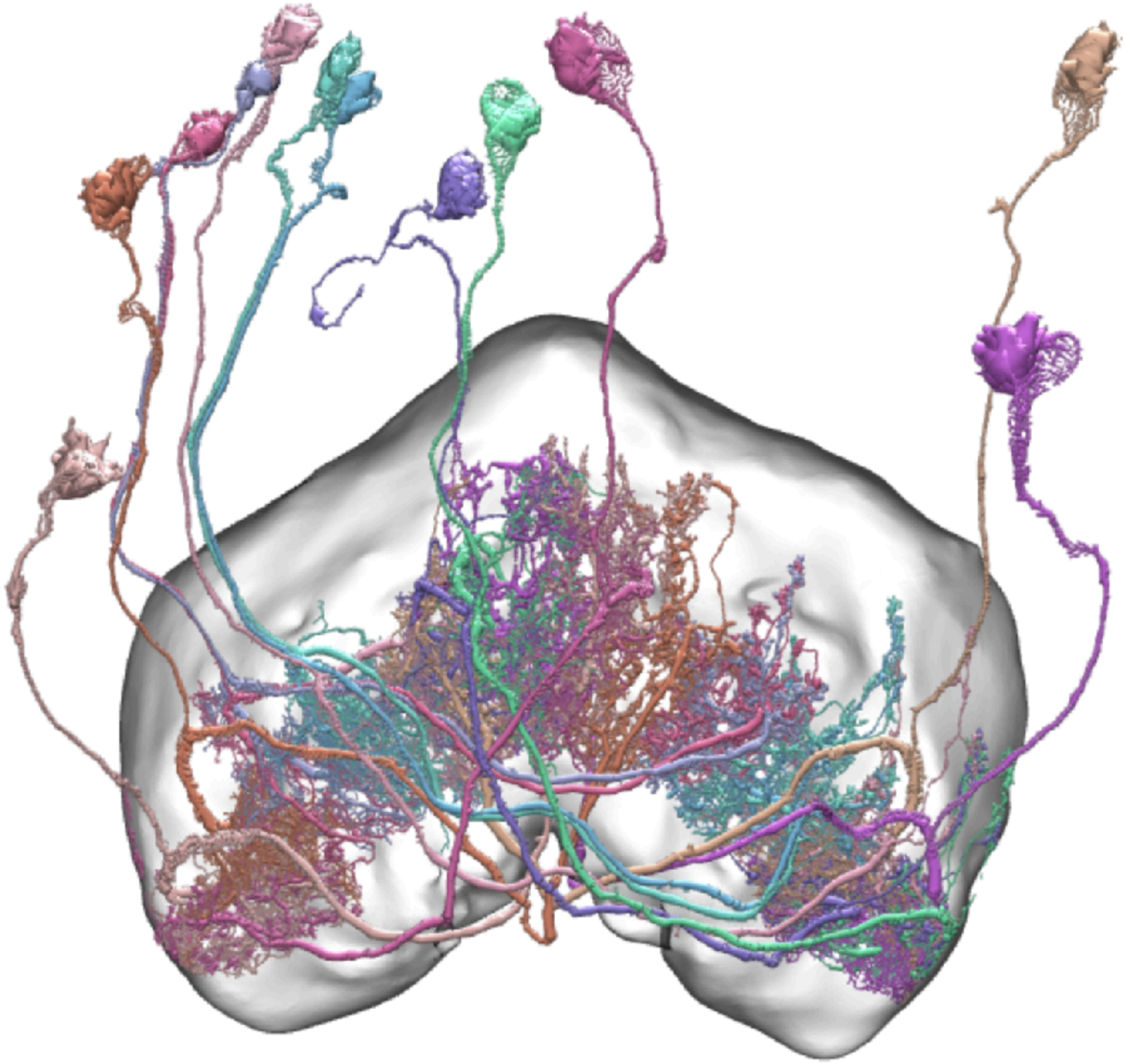


✓ 2) $V_R^F \cos\left(\theta - H\right) \quad V_L^F \cos\left(\theta - H\right)$

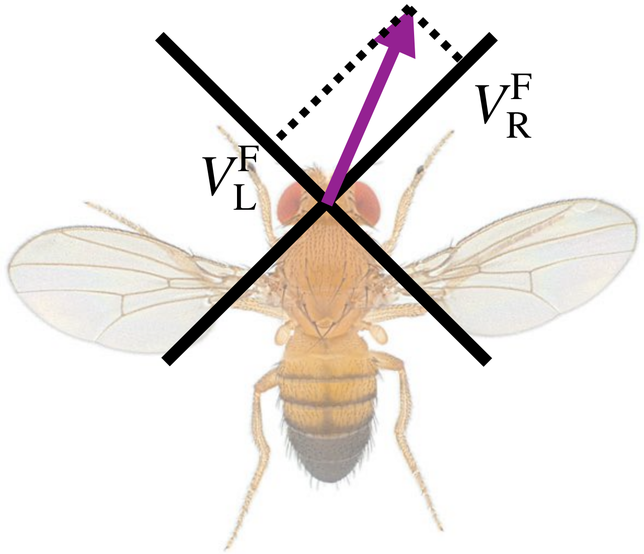
✓ 3) $V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) \quad V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

4) $f(\theta) = V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) + V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

hΔB



✓ 1) optic flow



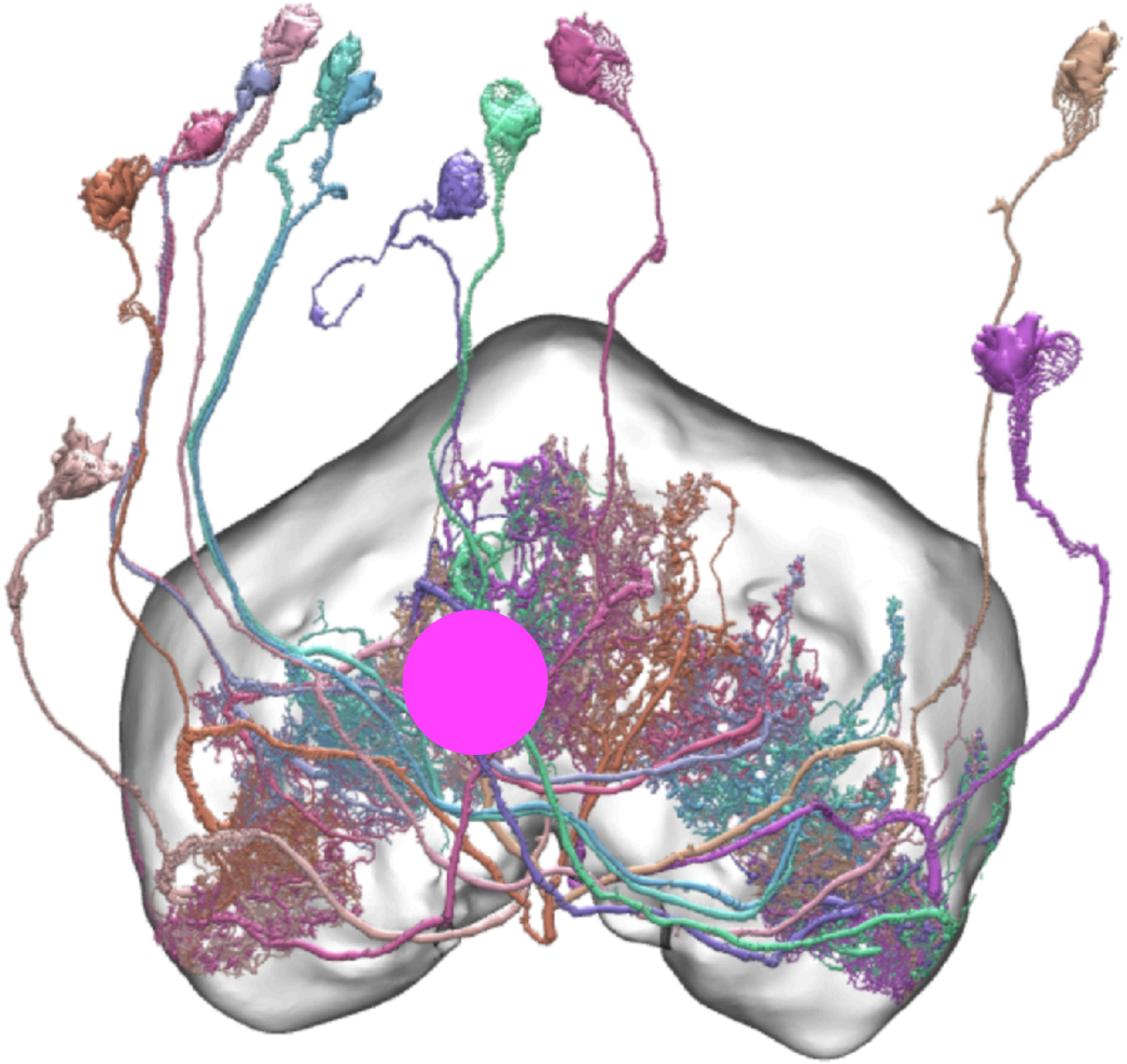
✓ 2) $V_R^F \cos\left(\theta - H\right) \quad V_L^F \cos\left(\theta - H\right)$

✓ 3) $V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) \quad V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

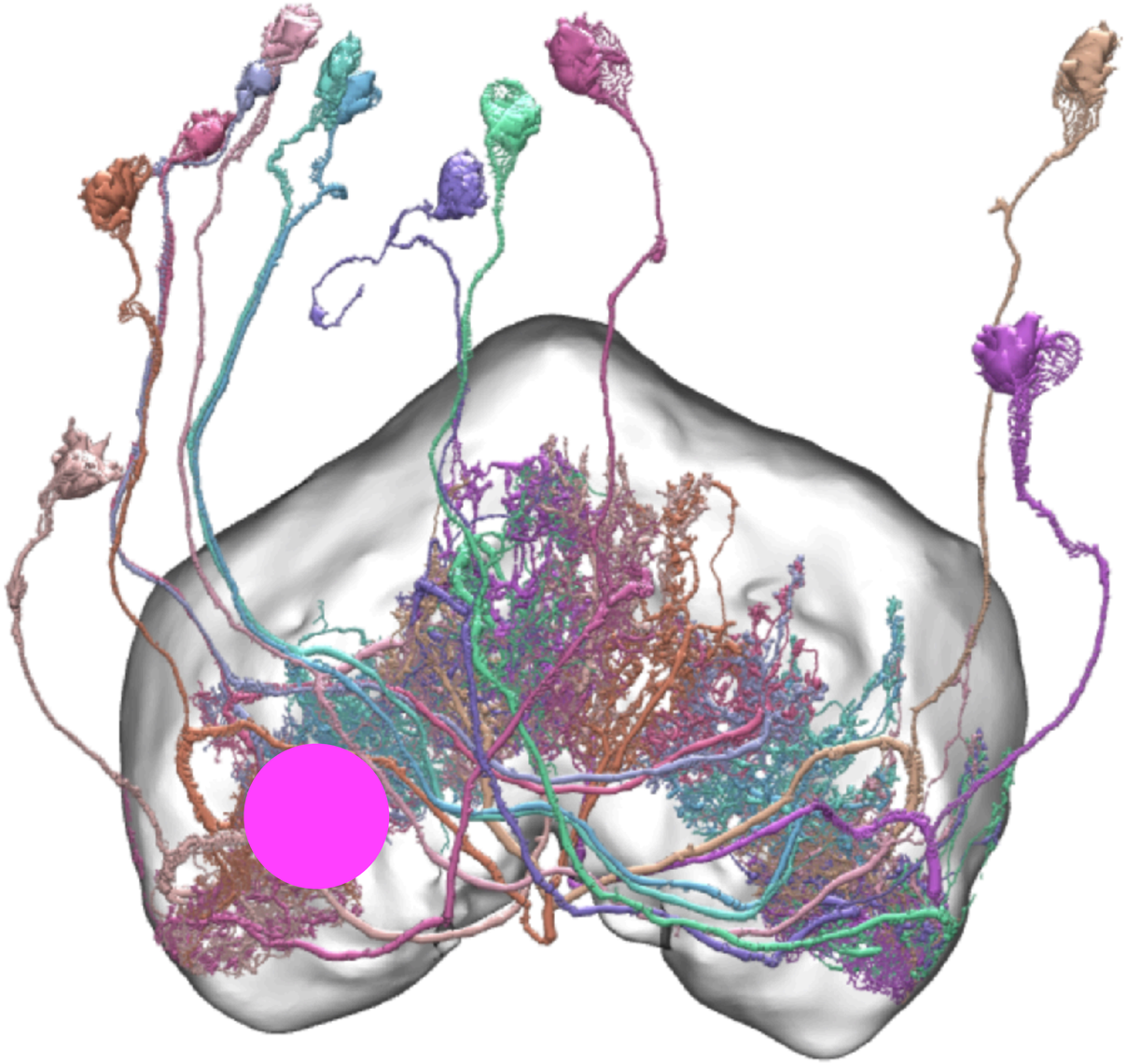
✓ 4) $f(\theta) = V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) + V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

5) Find maximum

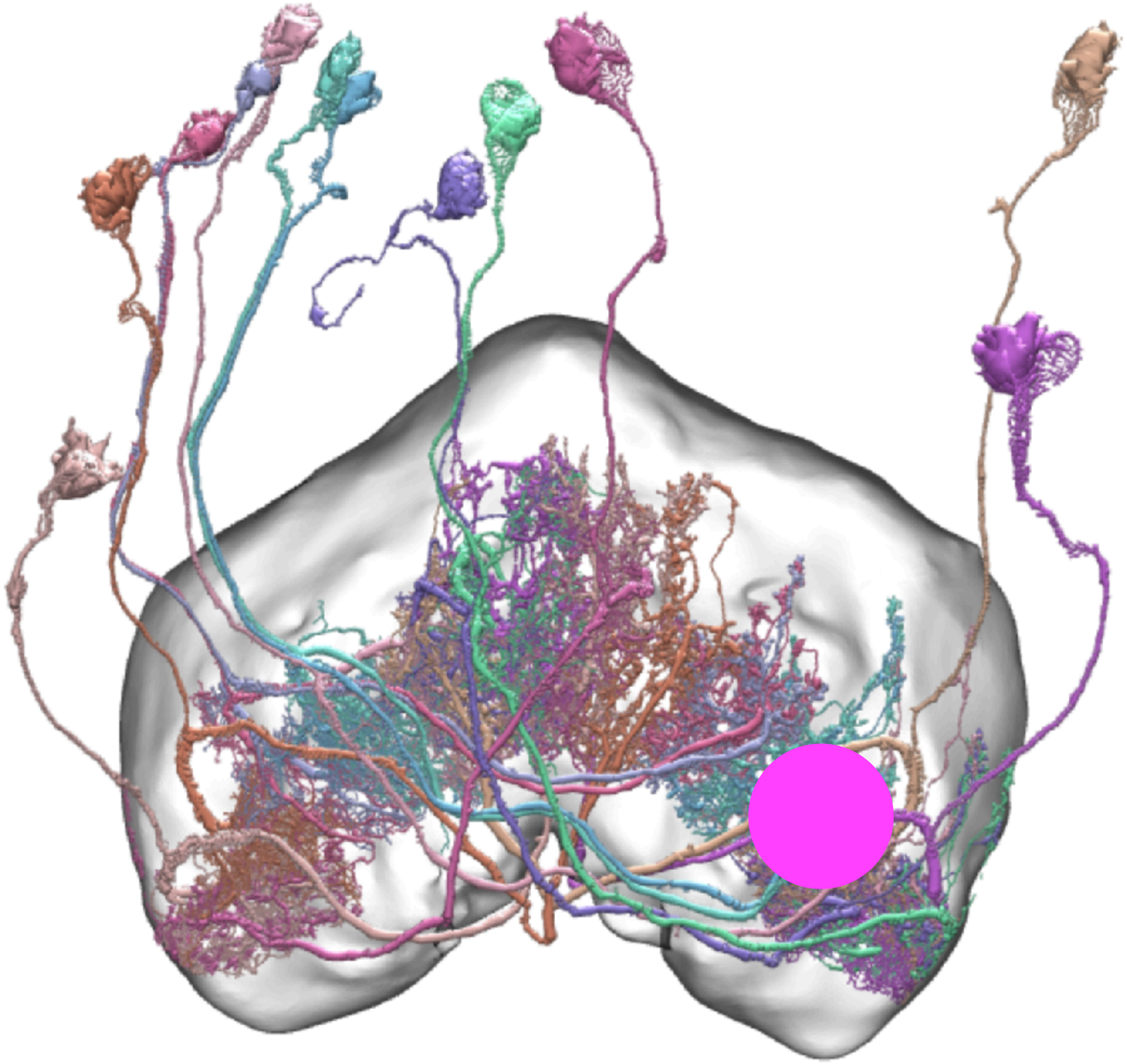
hΔB



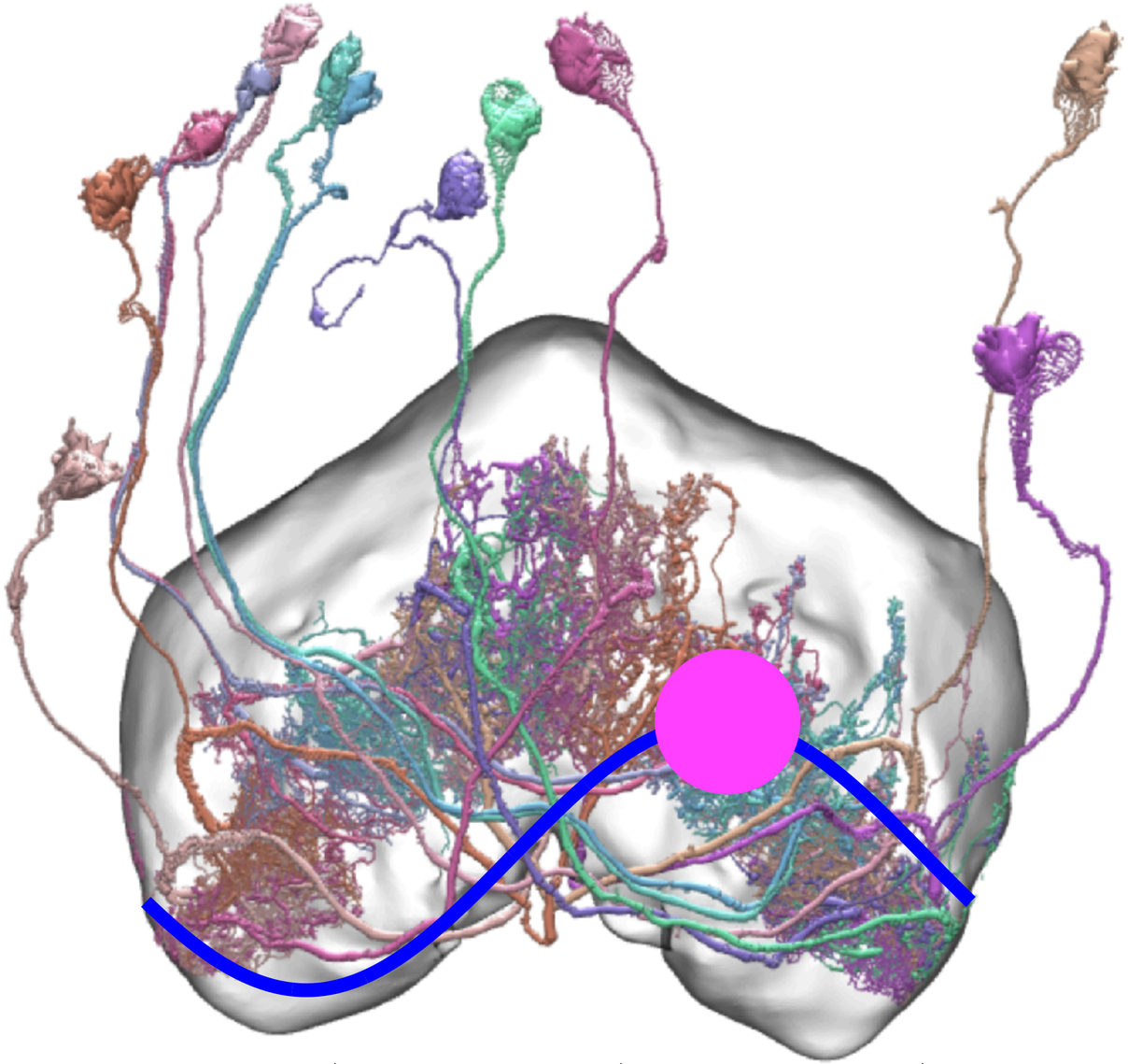
hΔB



hΔB



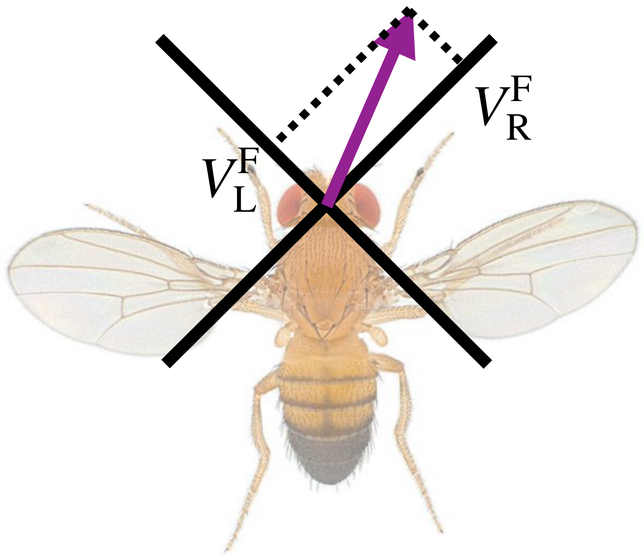
hΔB



$$T_{\mathrm{allo}} = \theta_{\max}$$

$$f(\theta) = V_{\mathrm{R}}^{\mathrm{F}} \cos\left(\theta - H - \frac{\pi}{4}\right) + V_{\mathrm{L}}^{\mathrm{F}} \cos\left(\theta - H + \frac{\pi}{4}\right)$$

✔ 1) optic flow

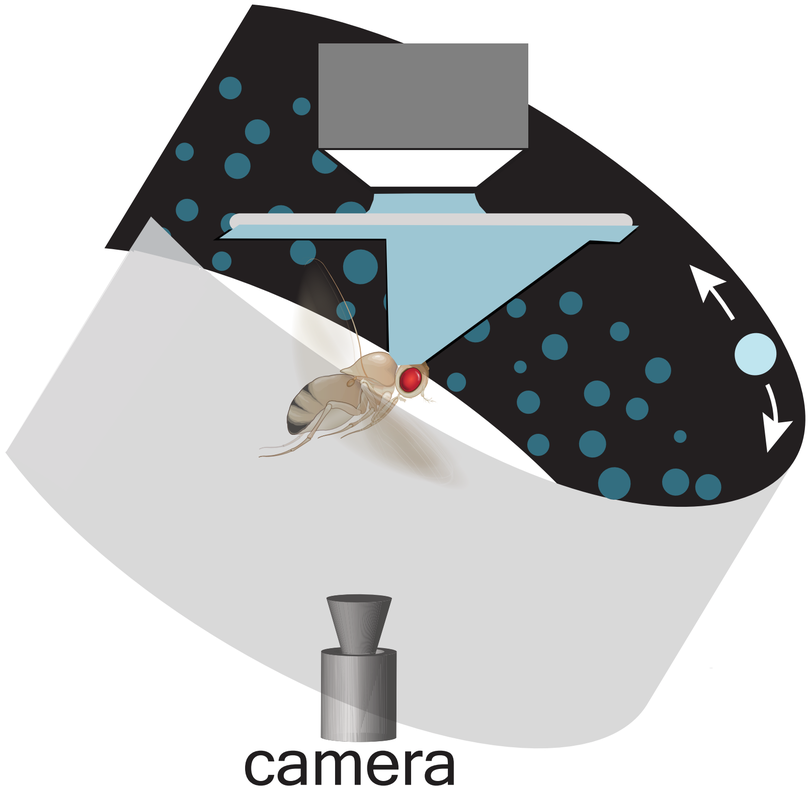


✔ 2) $V_R^F \cos\left(\theta - H\right) \quad V_L^F \cos\left(\theta - H\right)$

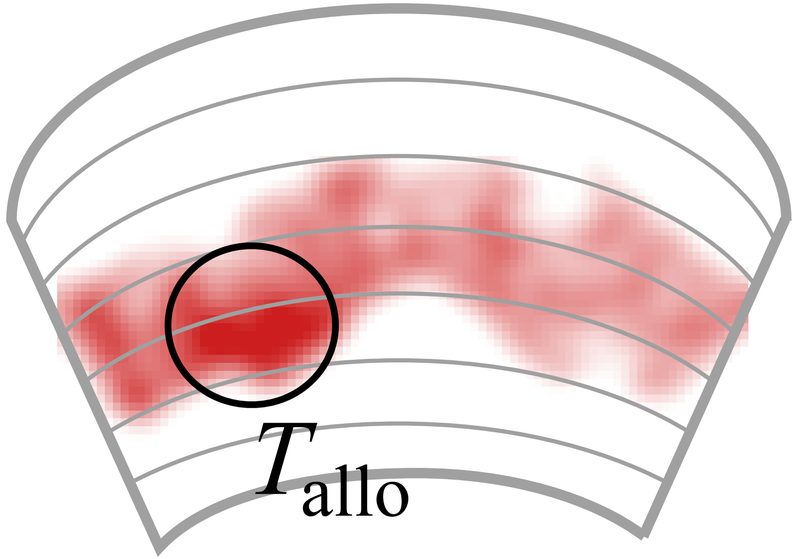
✔ 3) $V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) \quad V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

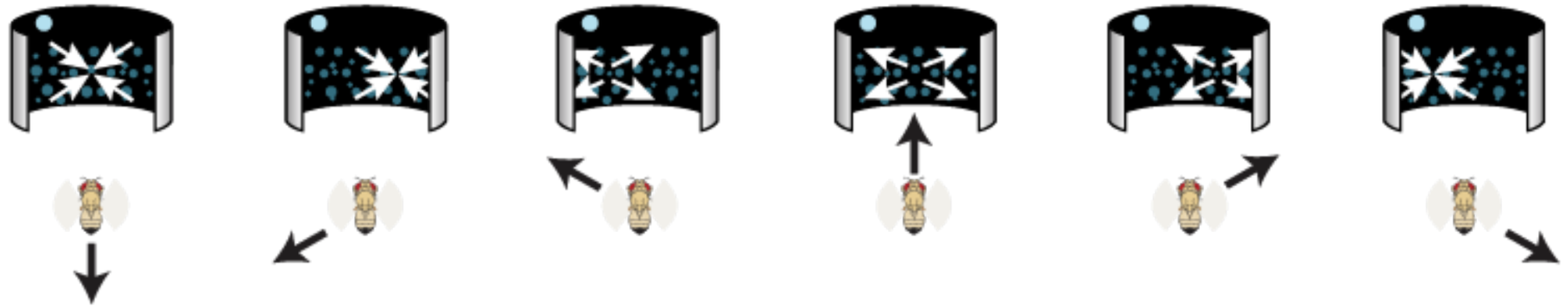
✔ 4) $f(\theta) = V_R^F \cos\left(\theta - H - \frac{\pi}{4}\right) + V_L^F \cos\left(\theta - H + \frac{\pi}{4}\right)$

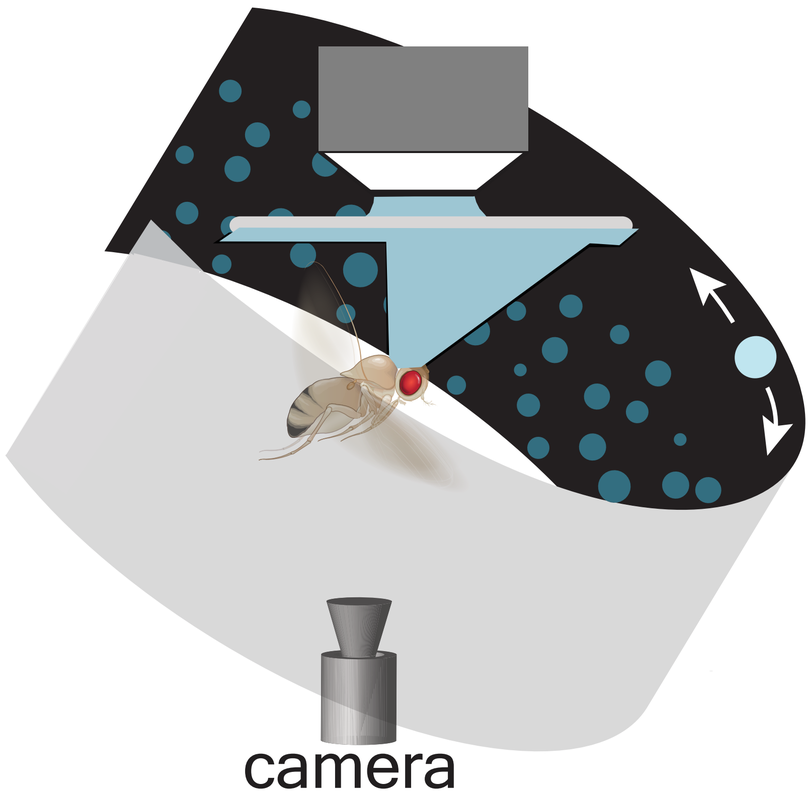
✔ 5) Find maximum

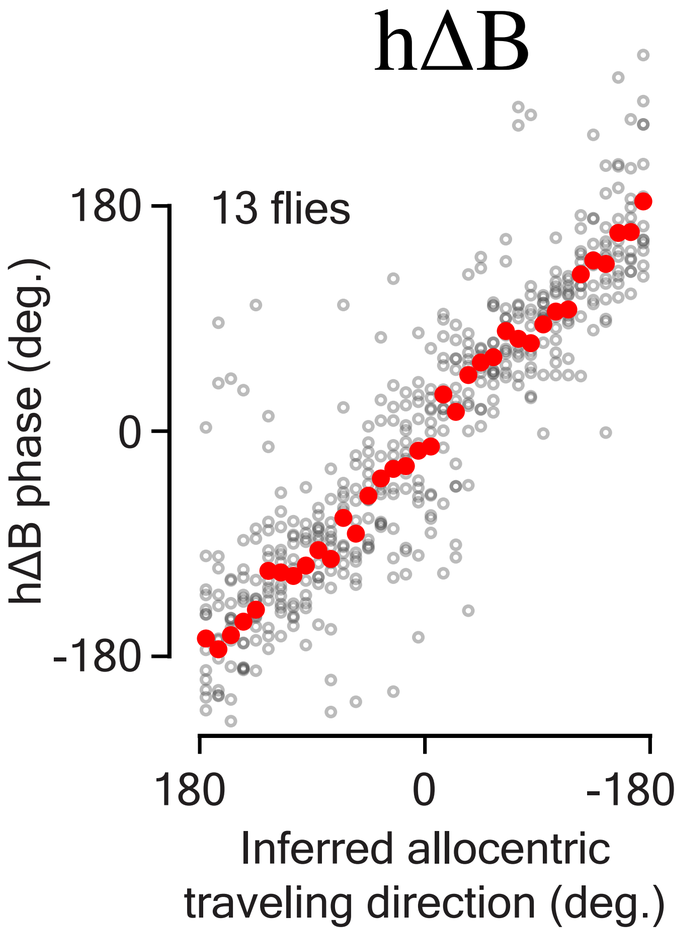


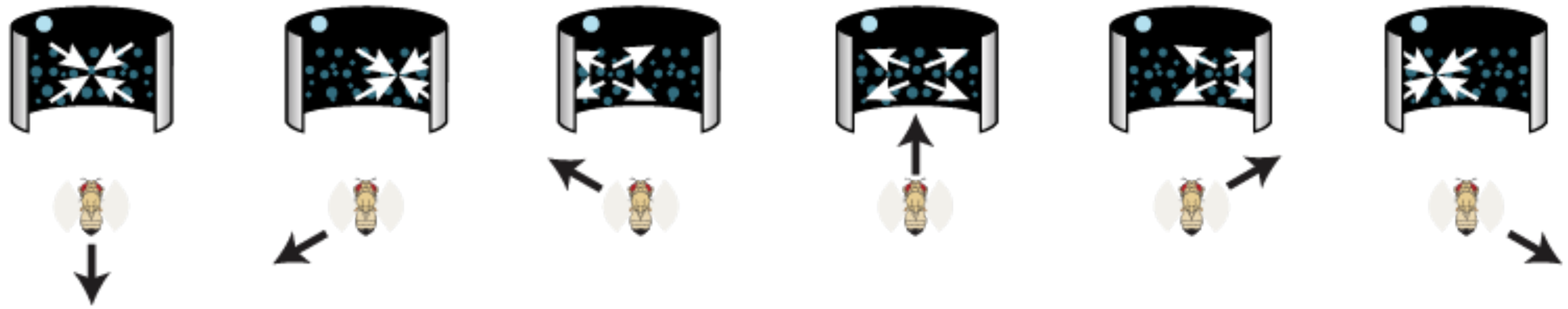
hΔB

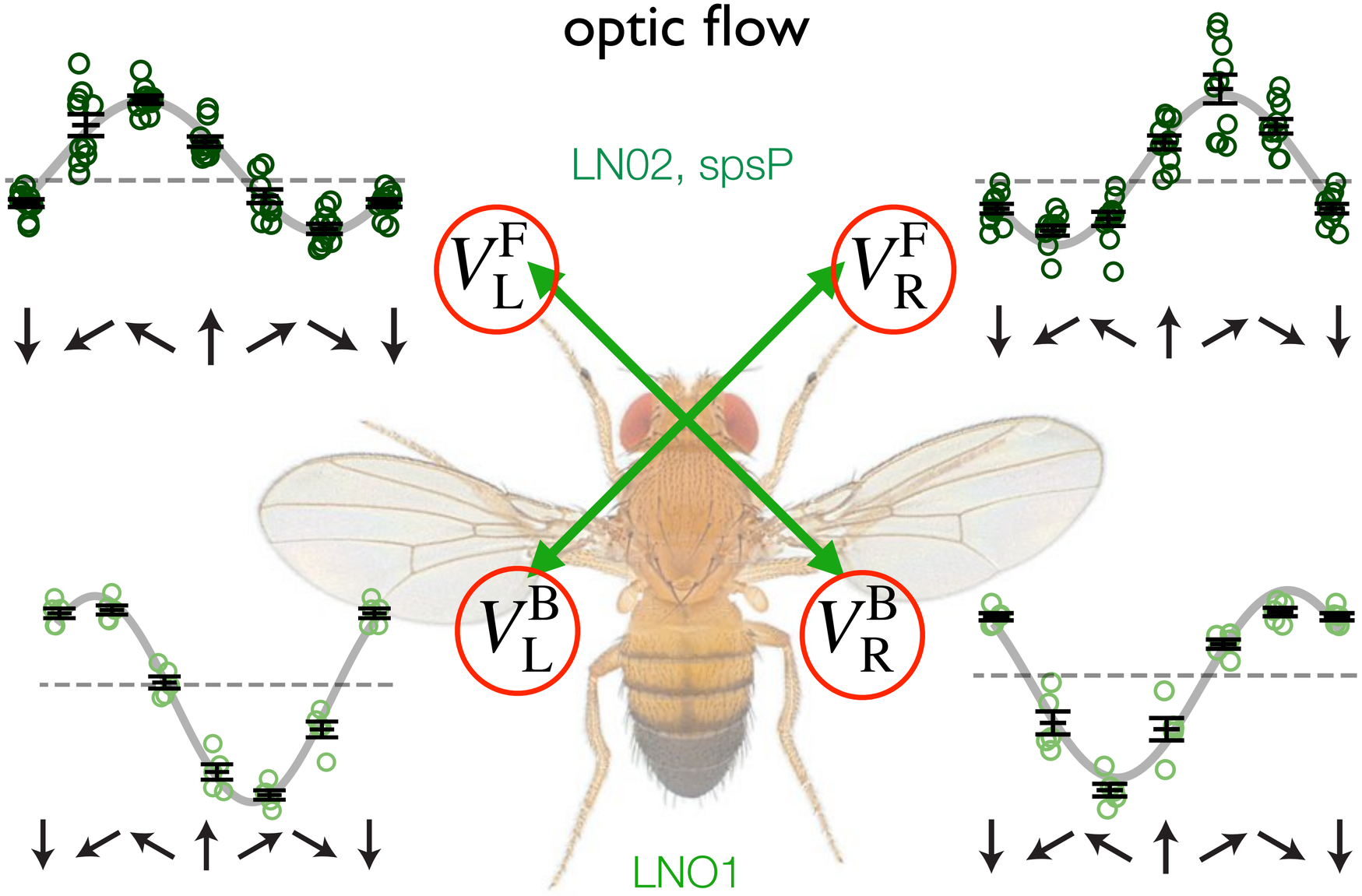


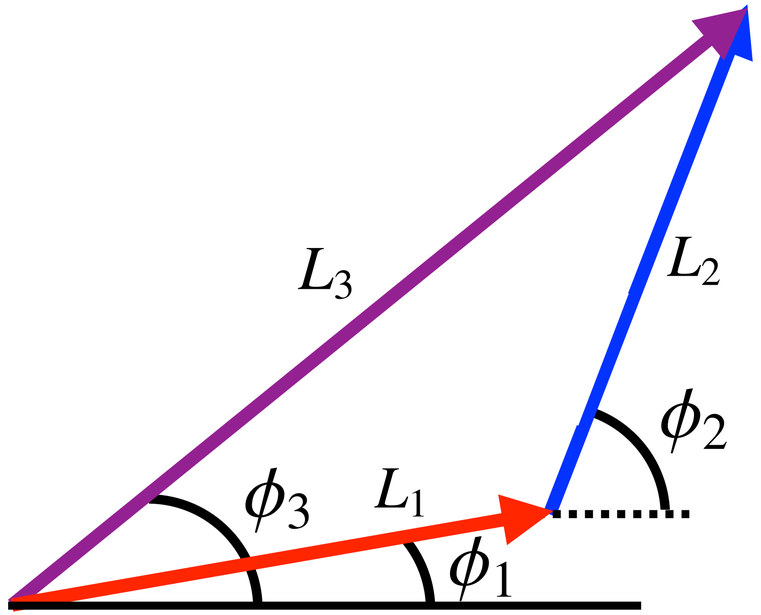


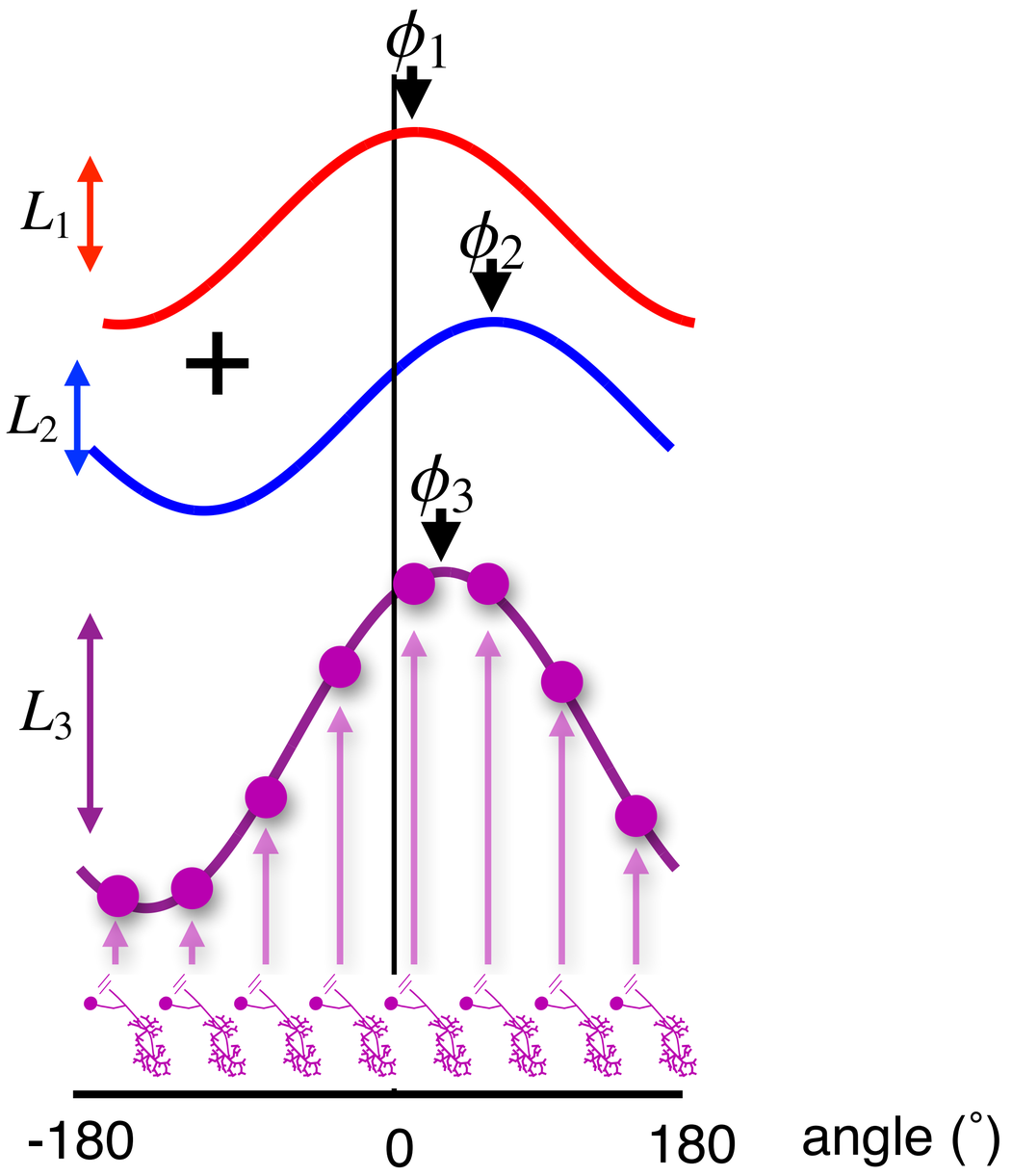

camera

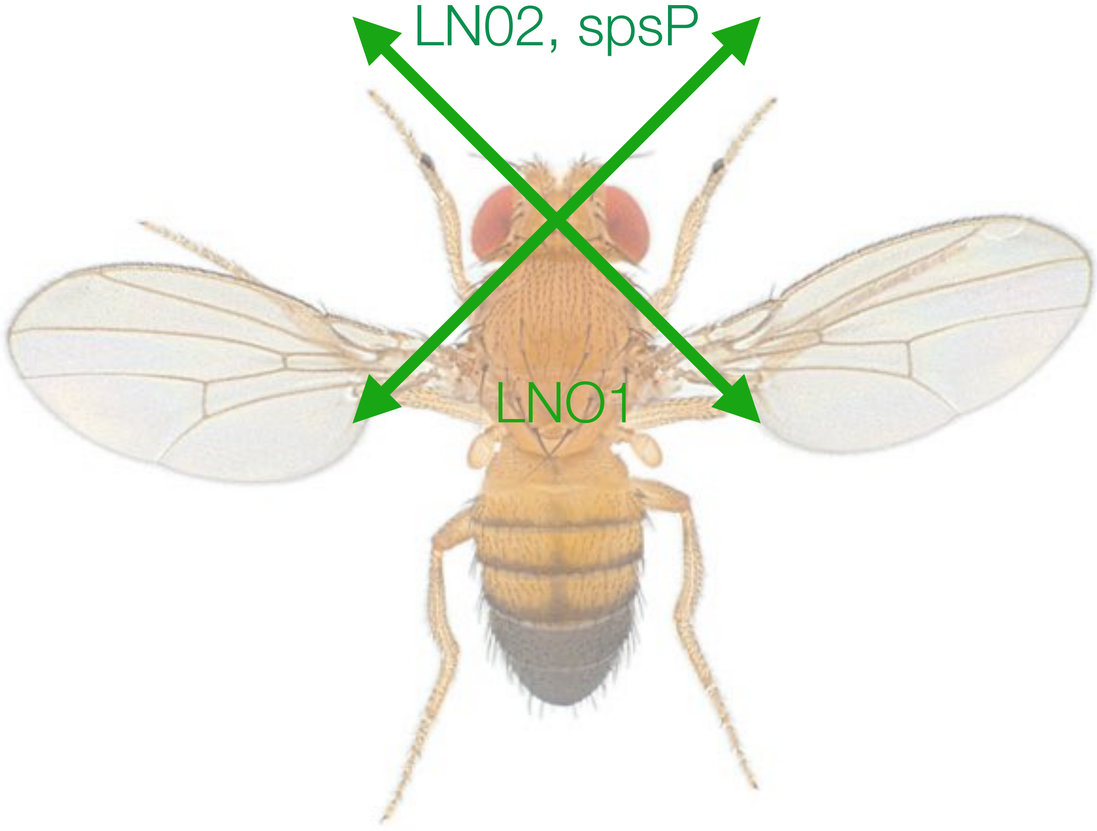

hΔB
13 flies
180
0
-180
hΔB phase (deg.)
180
0
-180
Inferred allocentric
traveling direction (deg.)

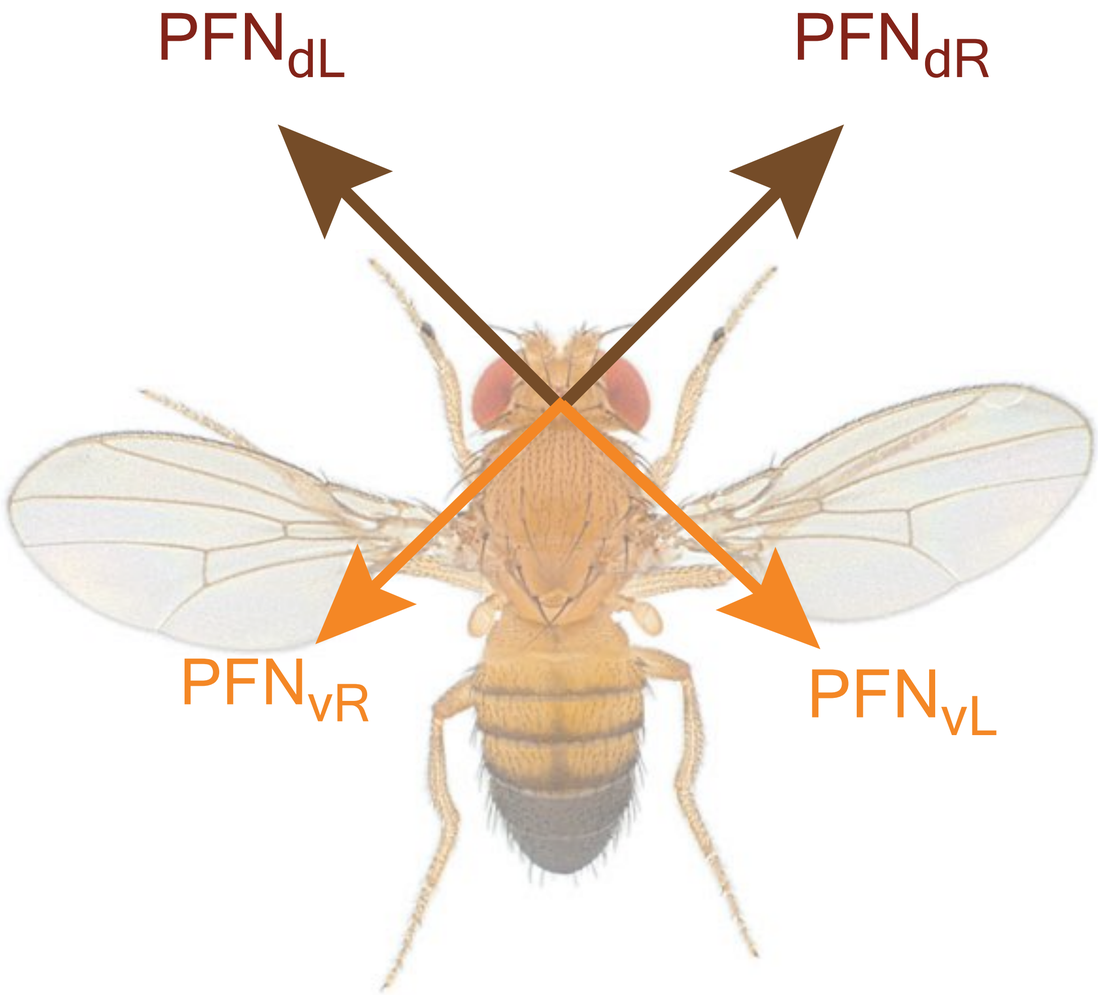



optic flow
LN02, spsP
V_L^F
V_R^F
V_L^B
V_R^B
LNO1


L_3
L_2
ϕ_2
ϕ_3
L_1
ϕ_1

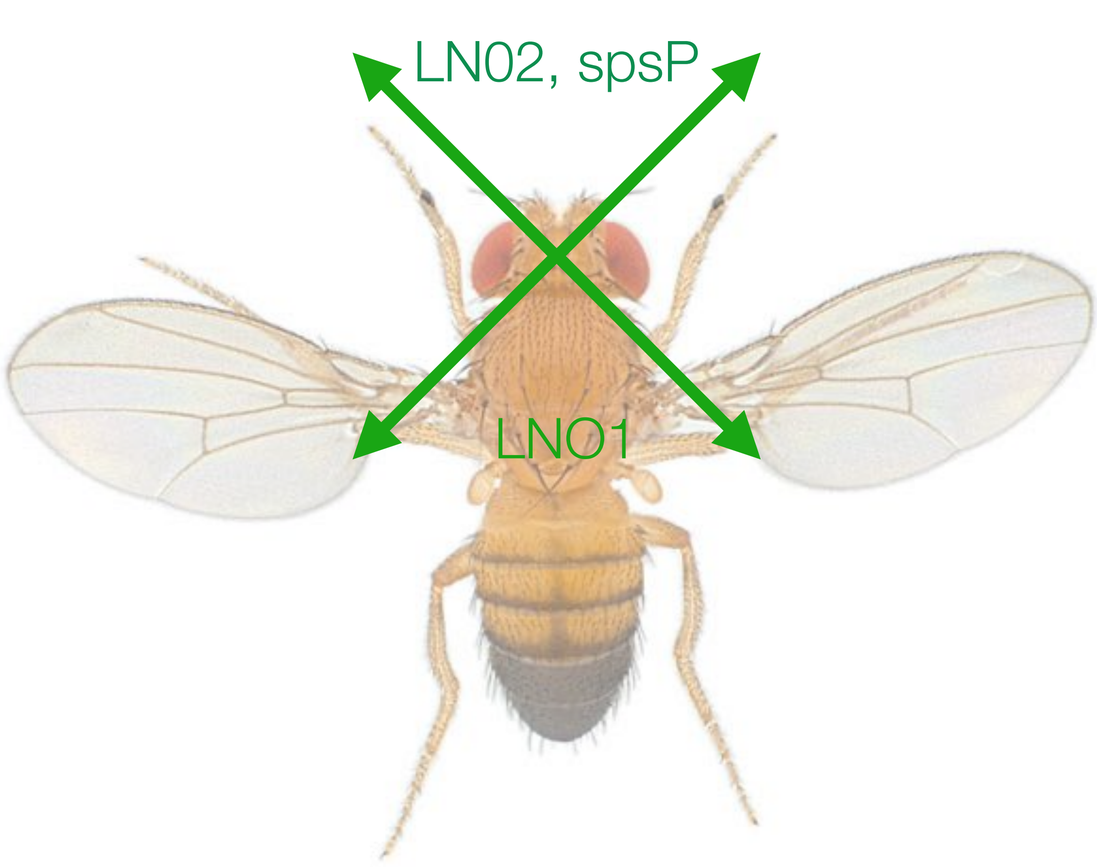

ϕ_1
L_1
ϕ_2
+
L_2
ϕ_3
L_3
-180
0
180
angle (˚)

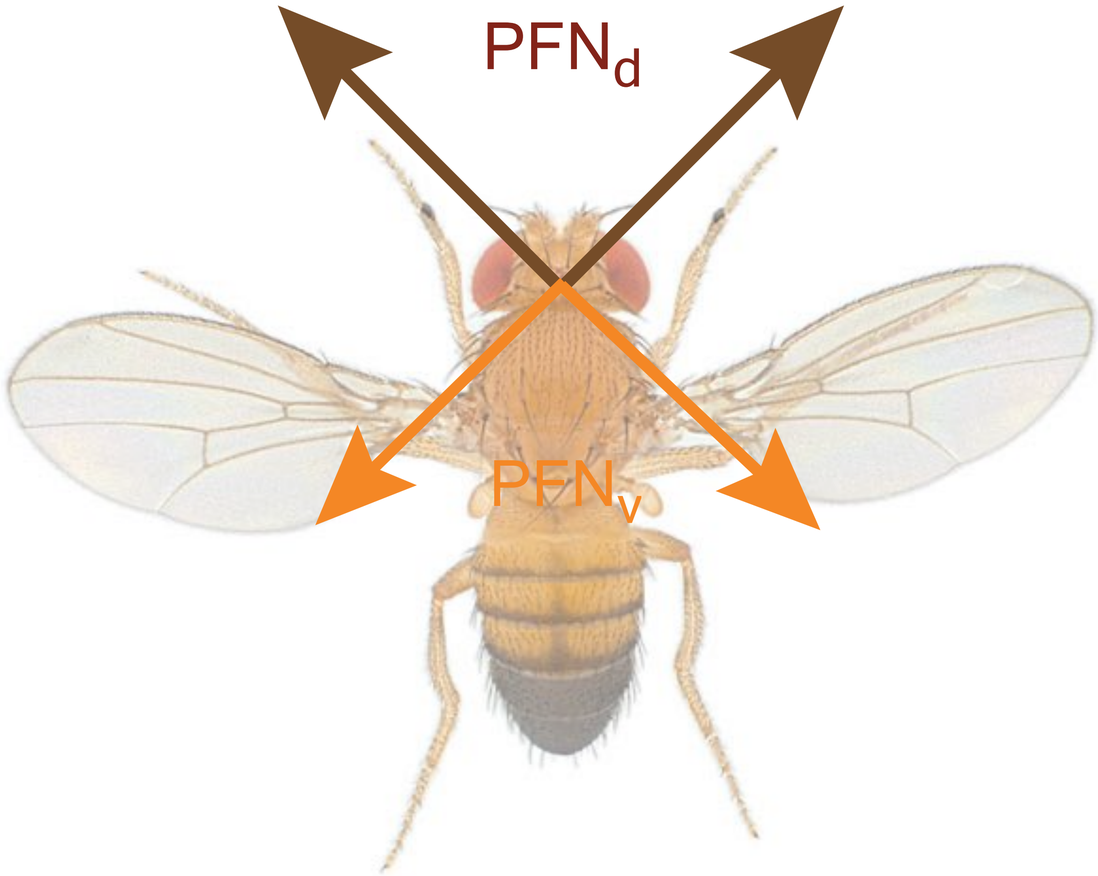

LN02, spsP
LNO1


PFN$_{dL}$
PFN$_{dR}$
PFN$_{vR}$
PFN$_{vL}$

egocentric

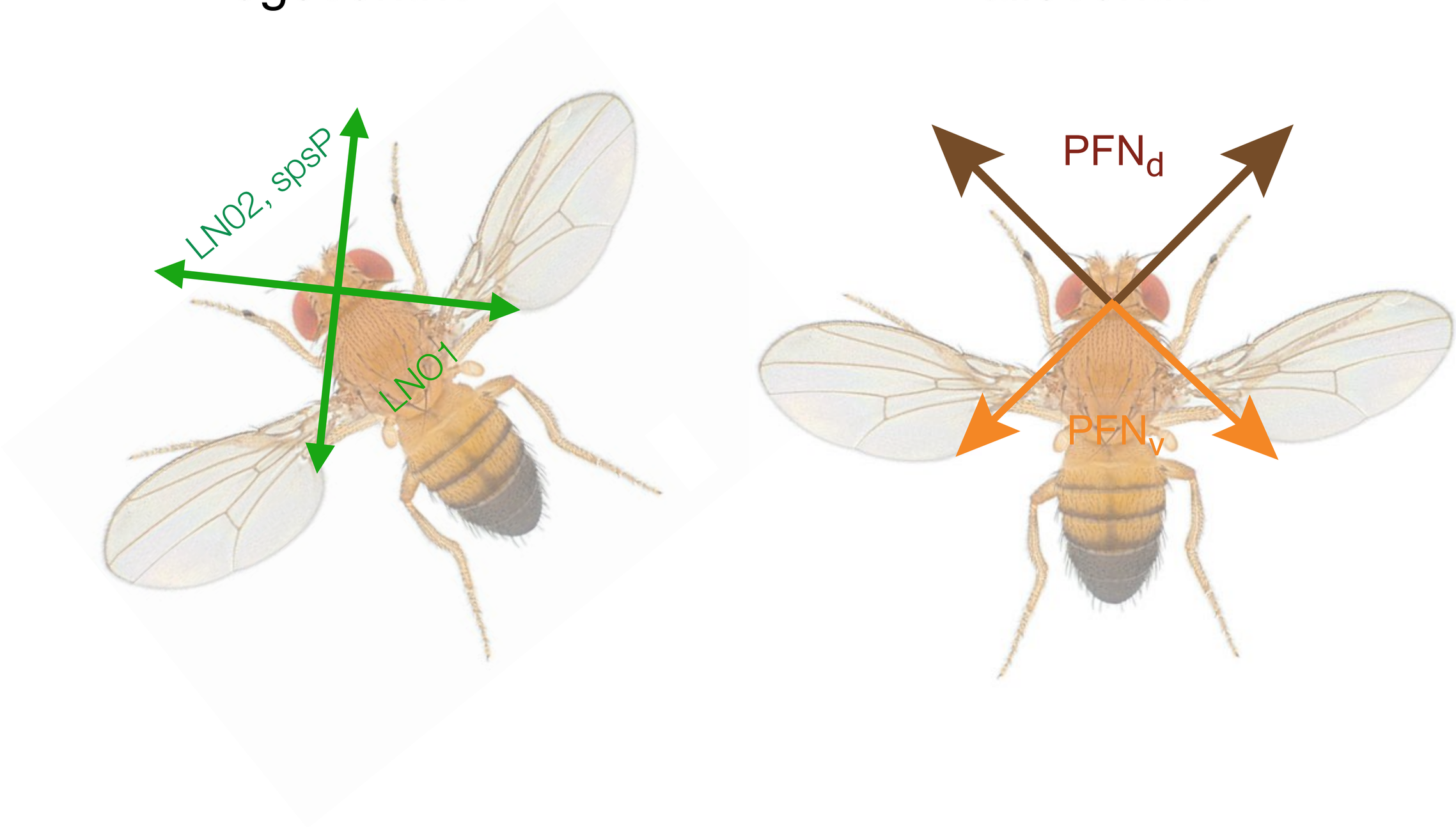
allocentric





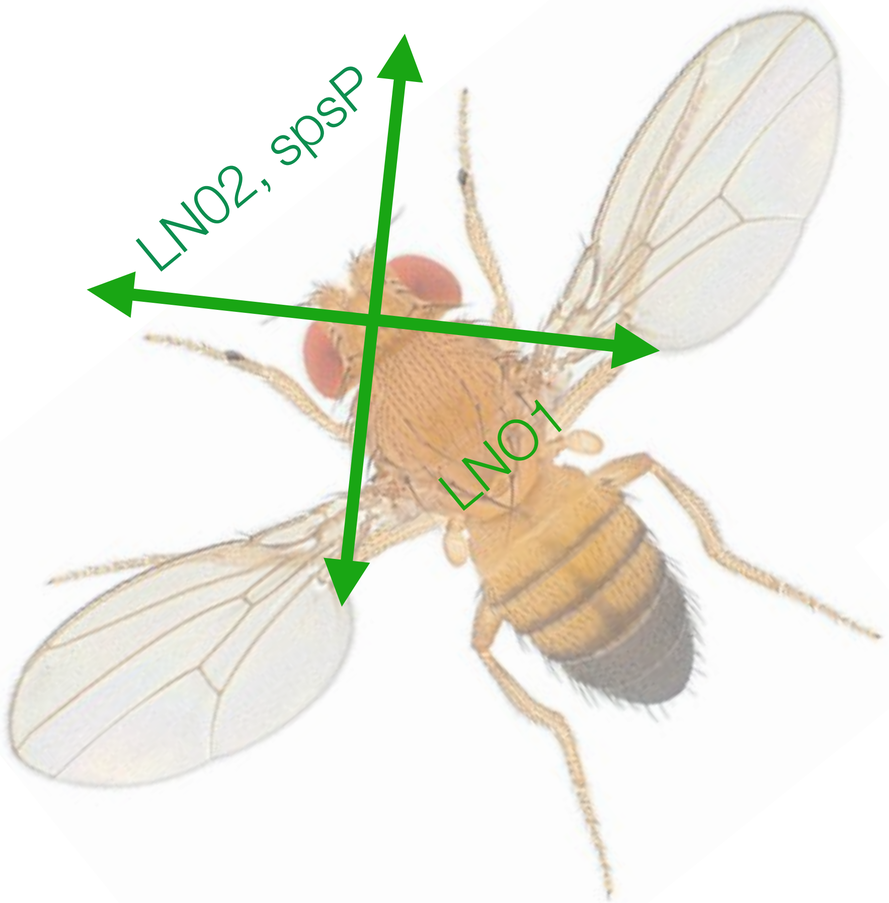
egocentric

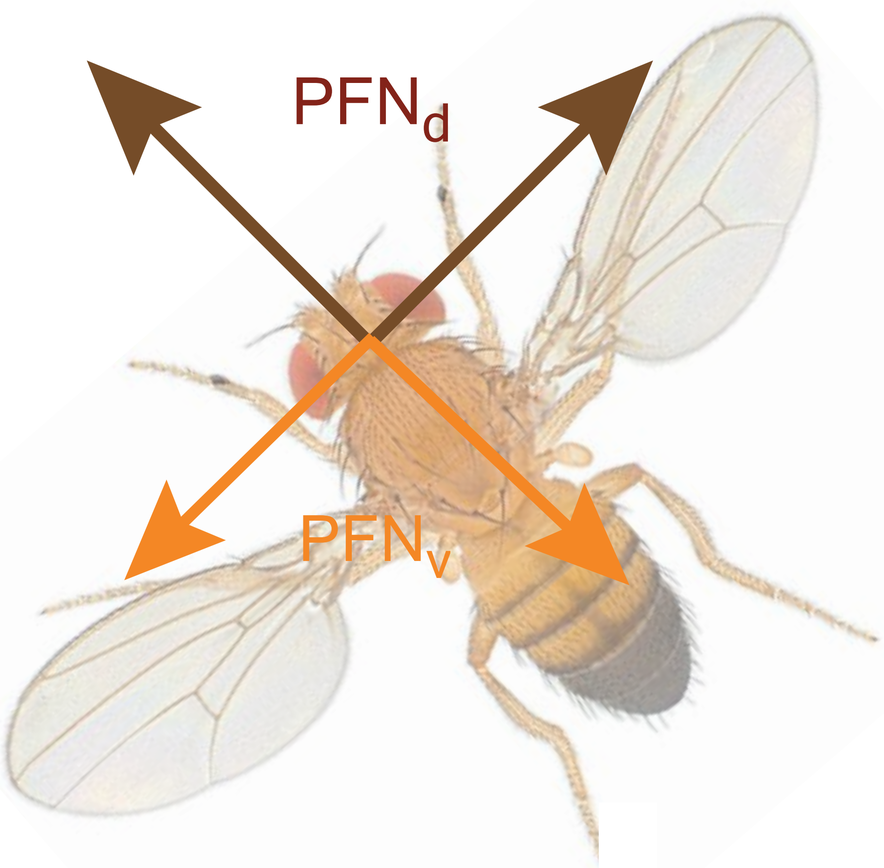
allocentric

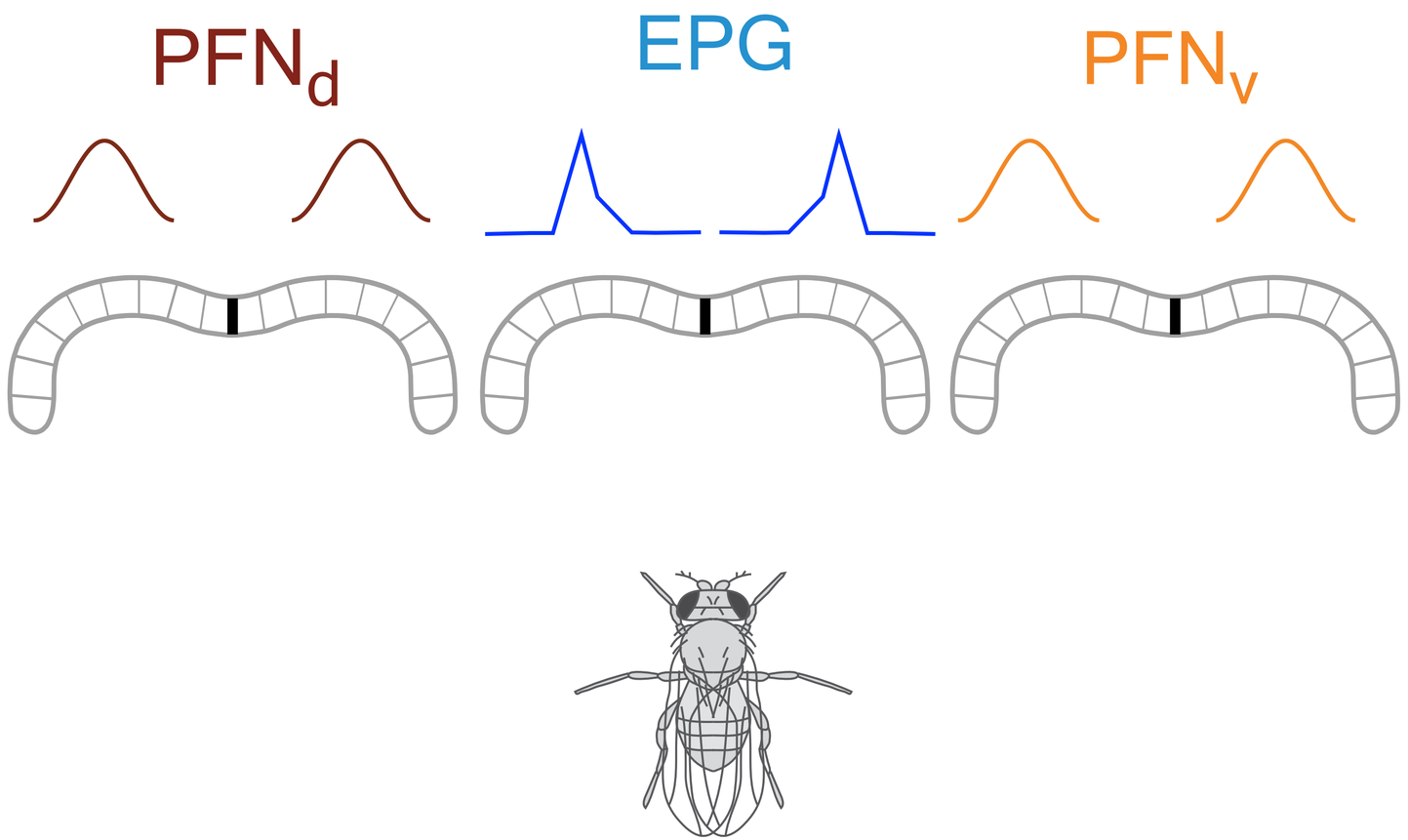


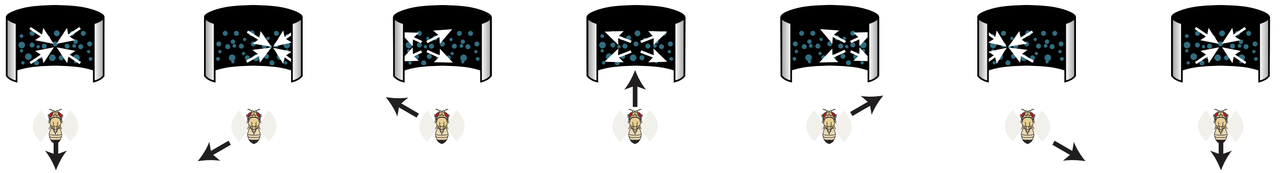
egocentric

allocentric

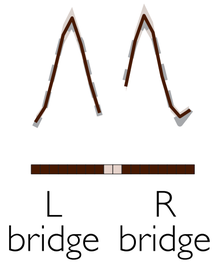




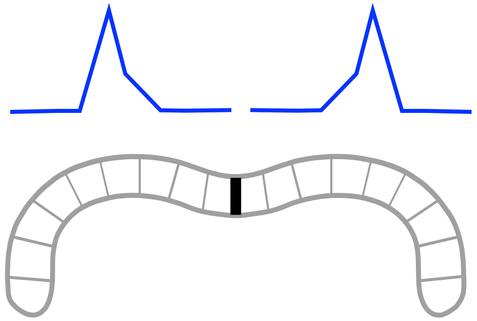

PFN$_d$
EPG
PFN$_v$



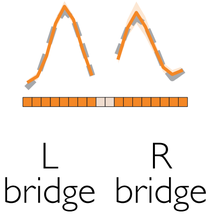
PFN$_d$

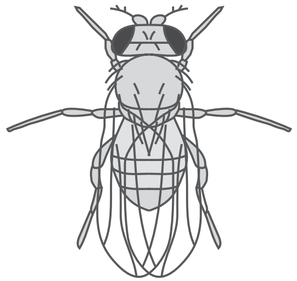


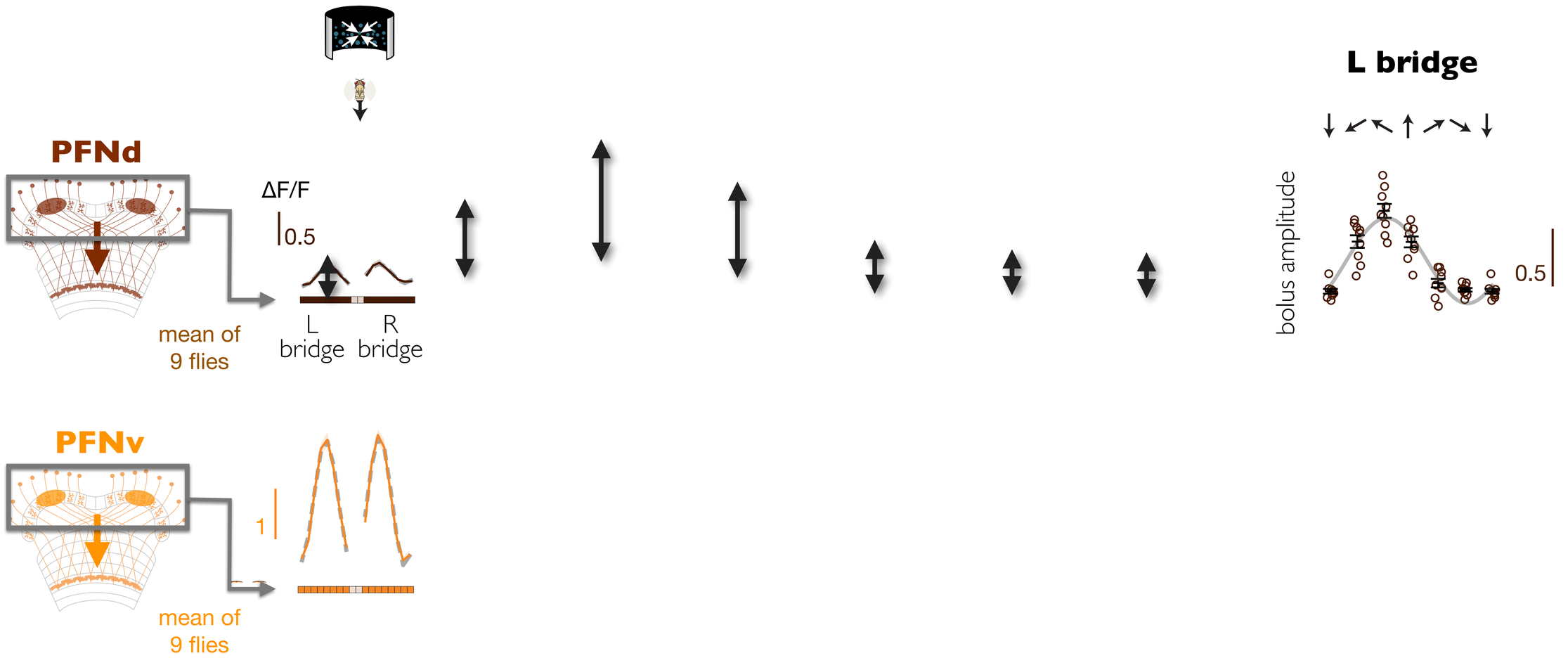
EPG

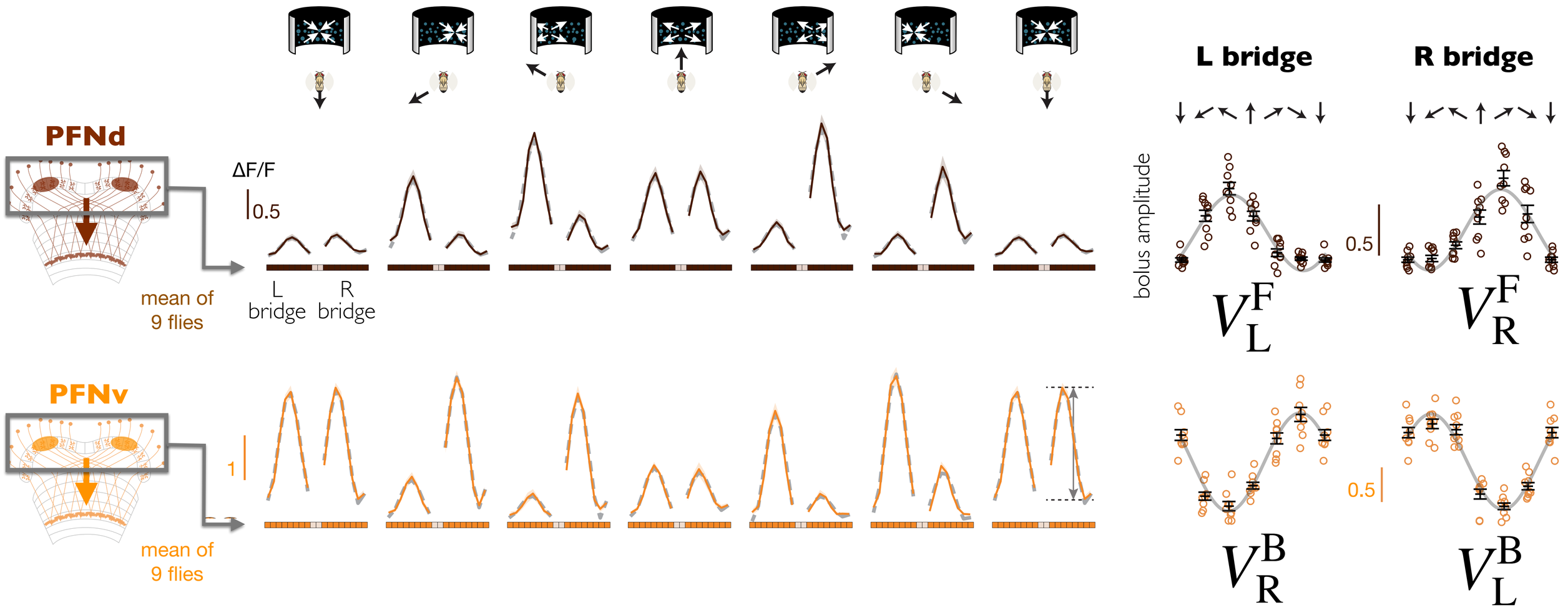


PFN$_v$

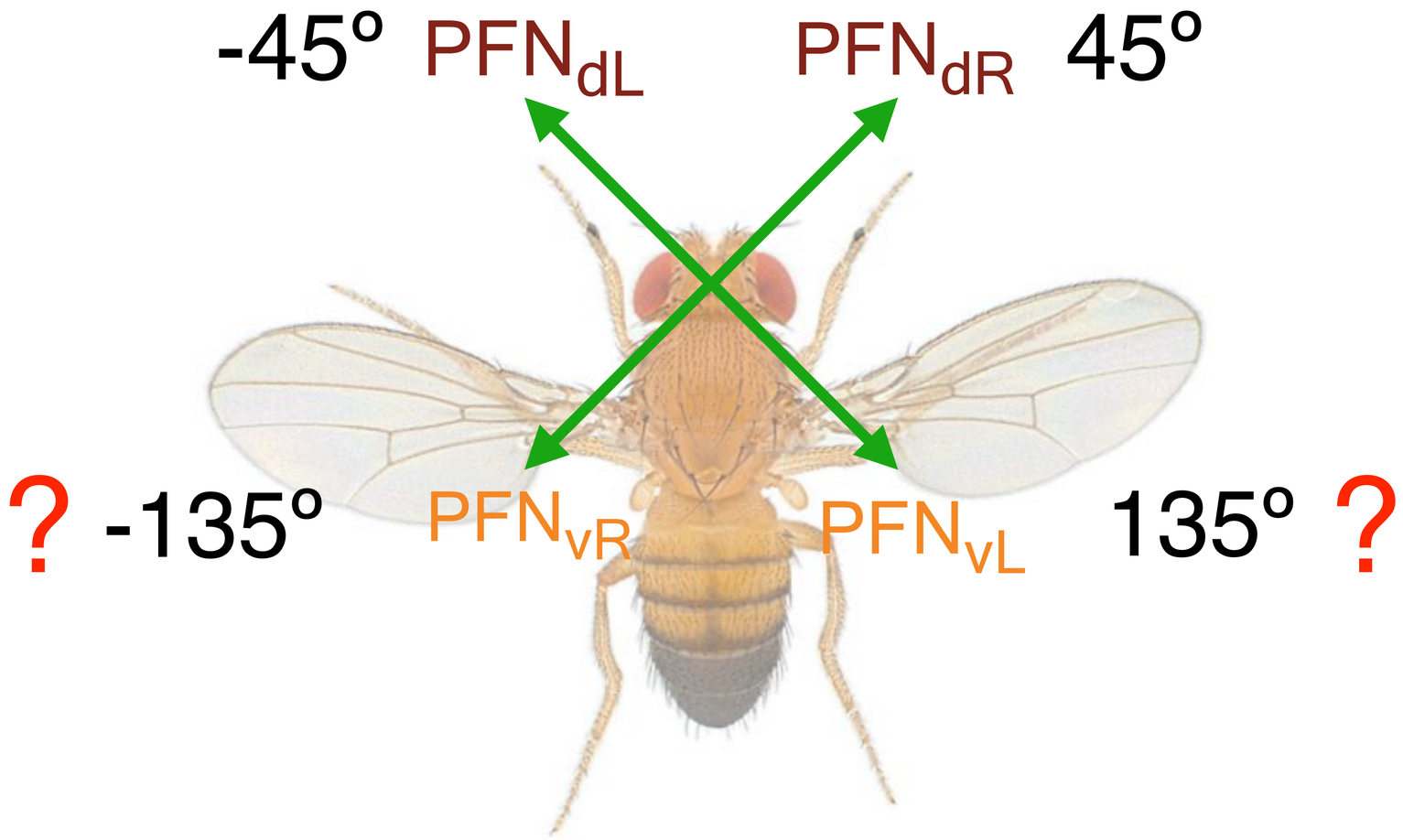





PFNd
ΔF/F
0.5
mean of
9 flies
L
bridge
R
bridge
PFNv
1
mean of
9 flies
L bridge
bolus amplitude
0.5

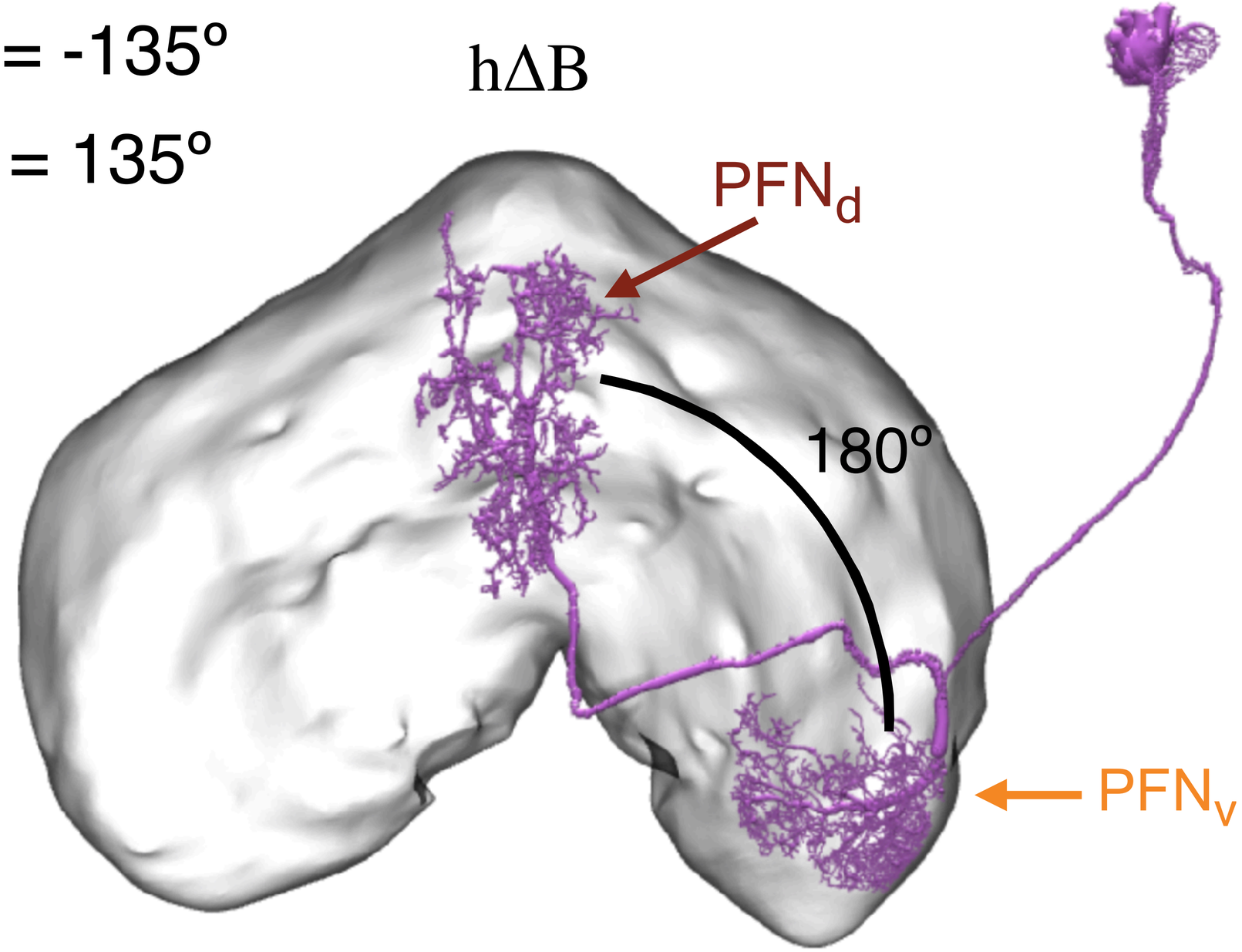

PFNd
ΔF/F
0.5
L bridge
R bridge
mean of 9 flies
PFNv
1
mean of 9 flies
L bridge
R bridge
bolus amplitude
0.5
V_L^F
V_R^F
0.5
V_R^B
V_L^B

sensory projection angle ⟶ anatomical shift



45° - 180° = -135°

-45° + 180° = 135°

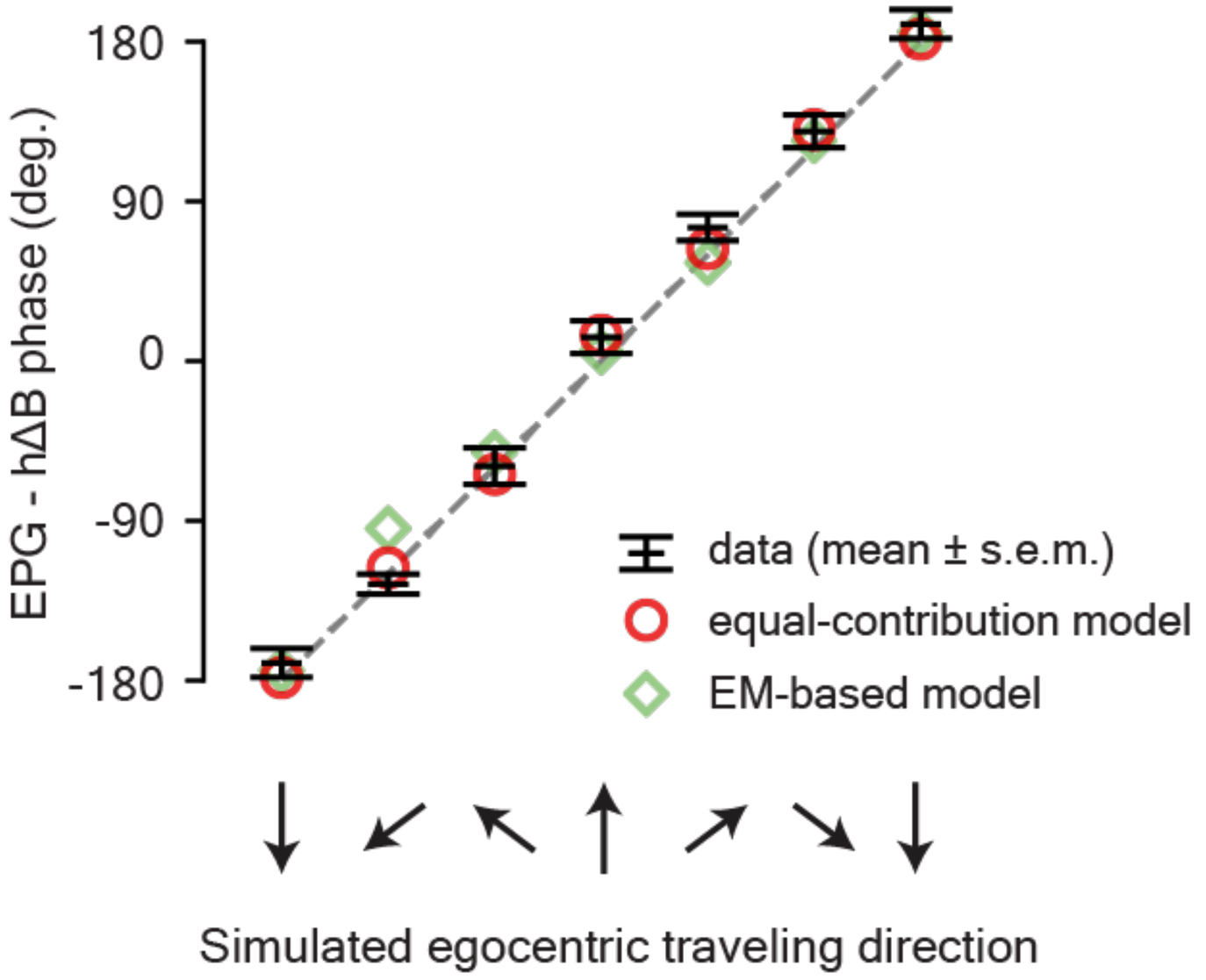


physics student

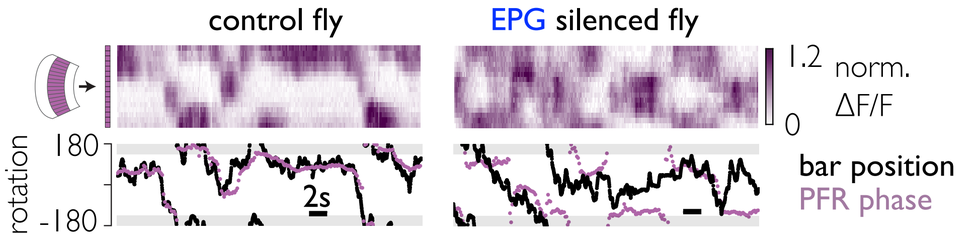
$$
\begin{aligned}
&V_{\mathrm{R}}^{\mathrm{F}}\big(\cos(H+\pi/4),\sin(H+\pi/4)\big)\\
&V_{\mathrm{L}}^{\mathrm{F}}\big(\cos(H-\pi/4),\sin(H-\pi/4)\big)\\
+\;&V_{\mathrm{L}}^{\mathrm{B}}\big(\cos(H-3\pi/4),\sin(H-3\pi/4)\big)\\
&V_{\mathrm{R}}^{\mathrm{B}}\big(\cos(H+3\pi/4),\sin(H+3\pi/4)\big)
\end{aligned}
$$

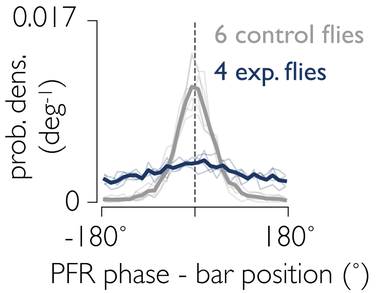
fly

$$
\begin{aligned}
&V_{\mathrm{R}}^{\mathrm{F}}\cos\left(\theta-H-\frac{\pi}{4}\right)\\
&V_{\mathrm{L}}^{\mathrm{F}}\cos\left(\theta-H+\frac{\pi}{4}\right)\\
+\;&V_{\mathrm{L}}^{\mathrm{F}}\cos\left(\theta-H+\frac{3\pi}{4}\right)\\
&V_{\mathrm{L}}^{\mathrm{F}}\cos\left(\theta-H-\frac{3\pi}{4}\right)
\end{aligned}
$$

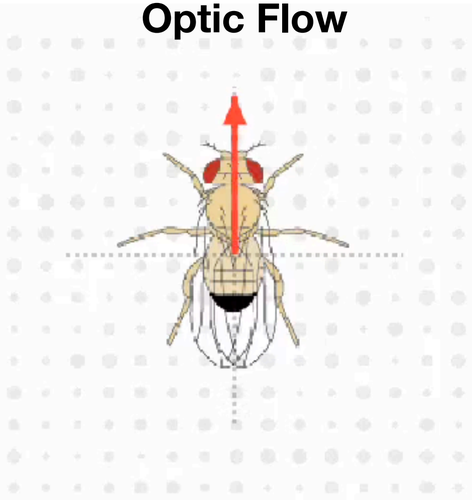

180
90
0
-90
-180
EPG - hΔB phase (deg.)
data (mean ± s.e.m.)
equal-contribution model
EM-based model
Simulated egocentric traveling direction

Inhibit EPGs
by expressing shibire^{TS}

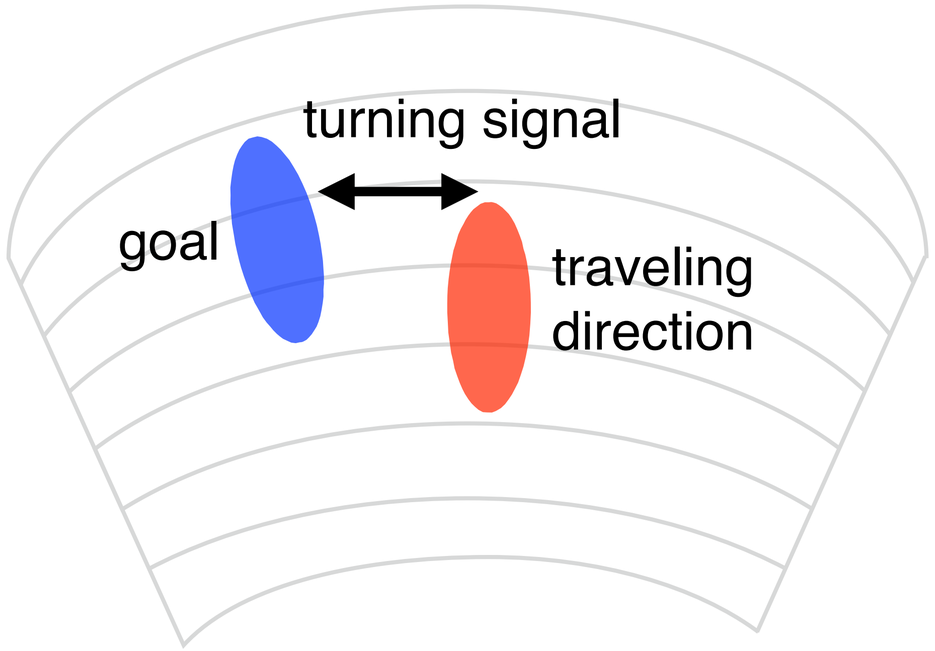




Heading vs Traveling Direction
Optic Flow

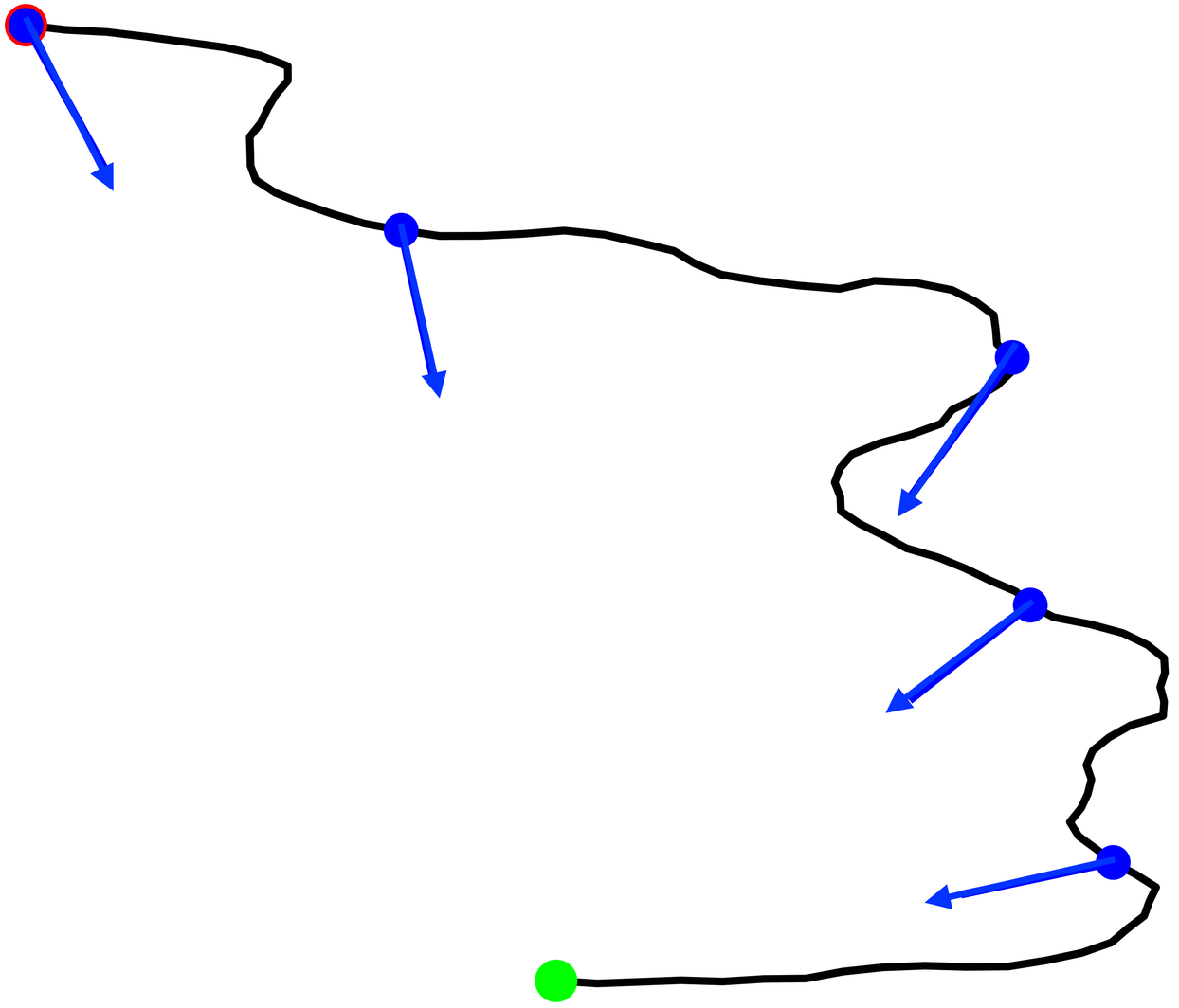


Turning Toward Goal



“Alloception”

Path Integration



Stone, Webb, Adden, Weddig, Honkanen,

Templin, Wcislo, Scimeca, Warrant, Heinze (2017)