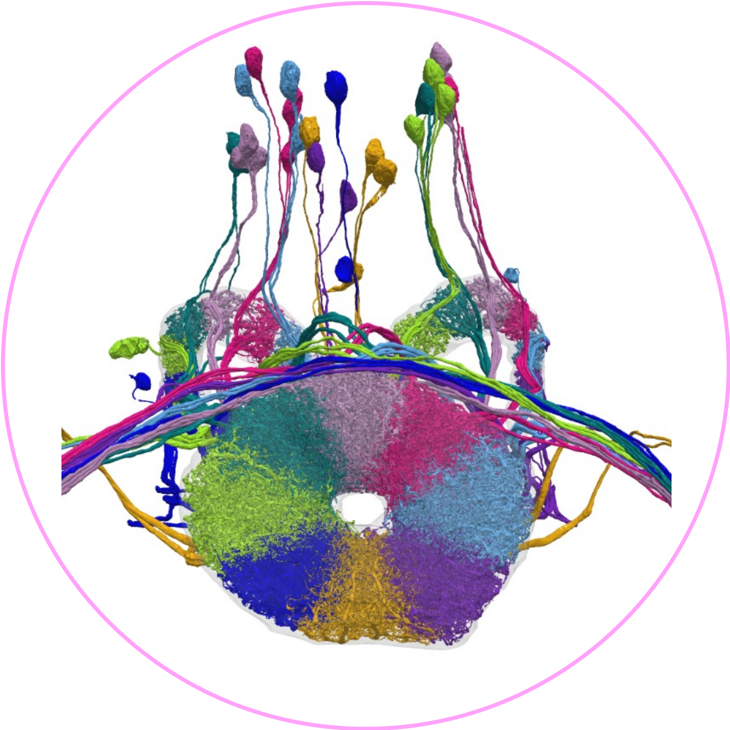
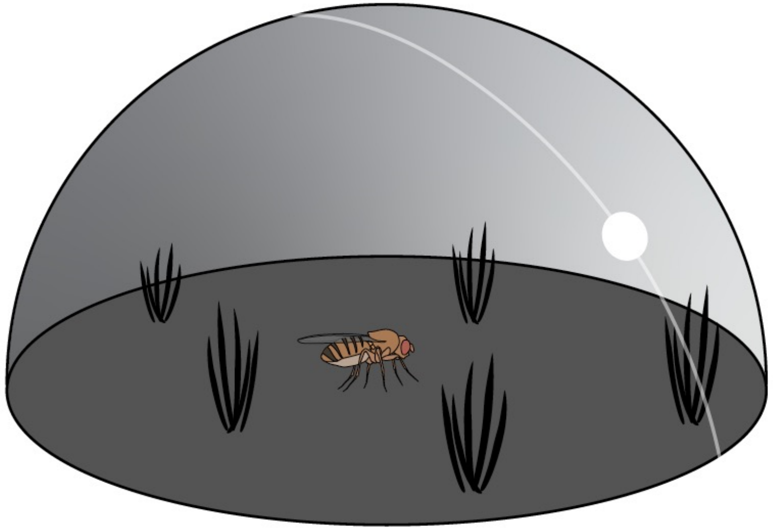
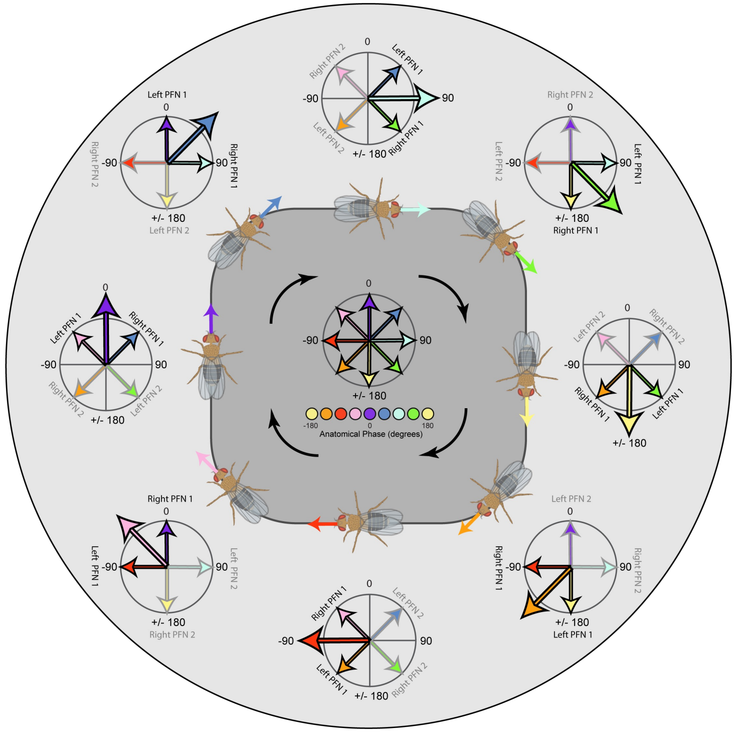
How connectomes can help us understand navigational attractor dynamics





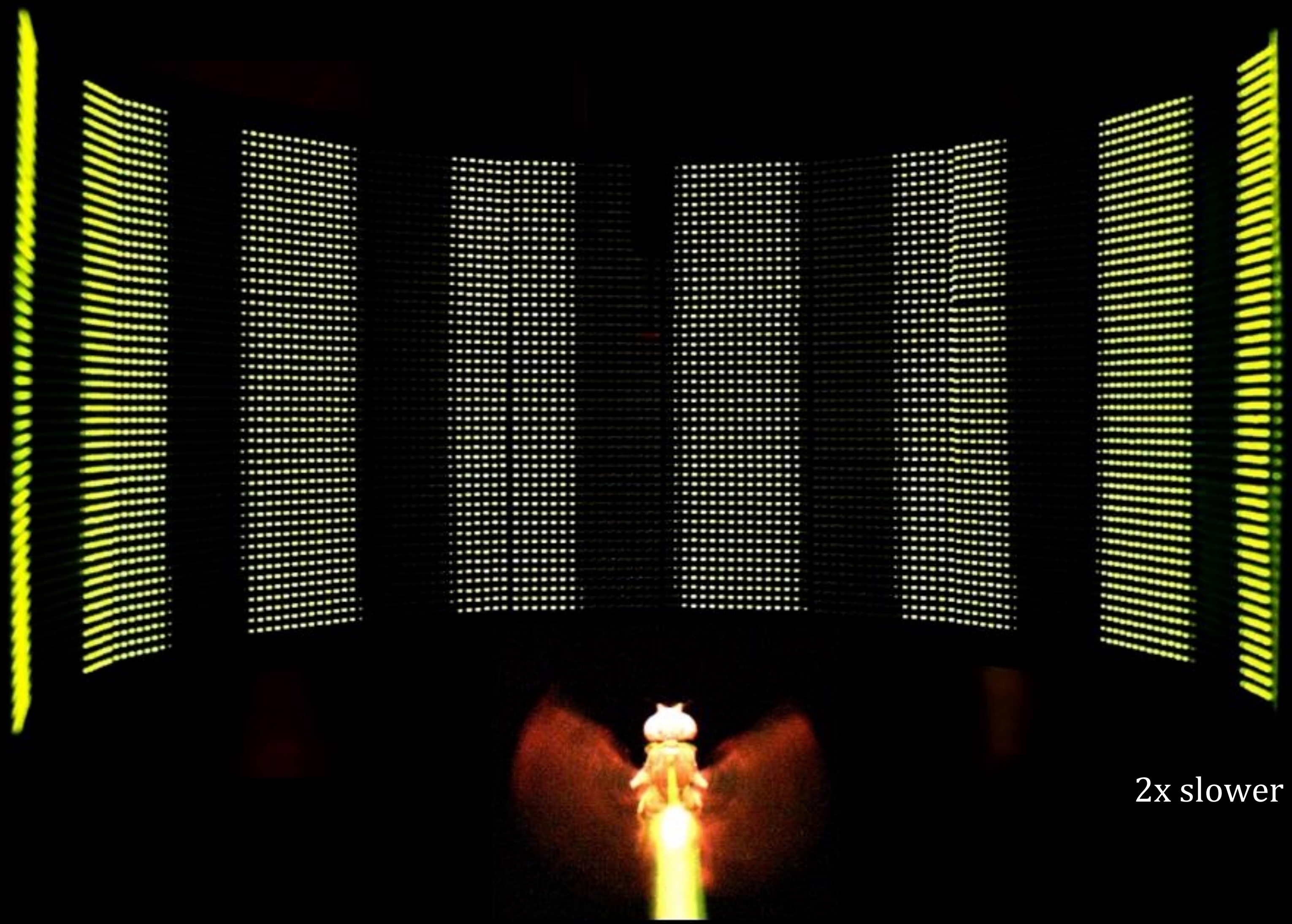


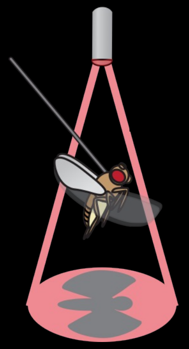
Vivek Jayaraman

hhmi | janelia Research Campus

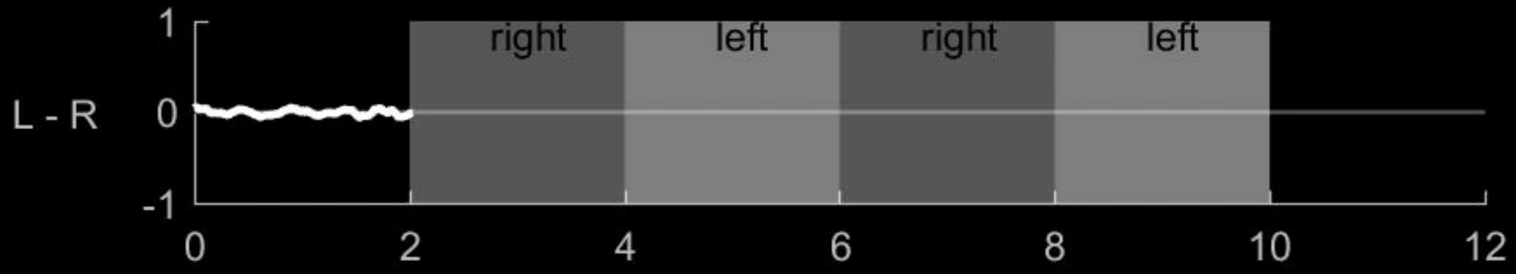
IPAM, UCLA Workshop: Mathematical Approaches for Connectome Analysis

February 12th, 2024





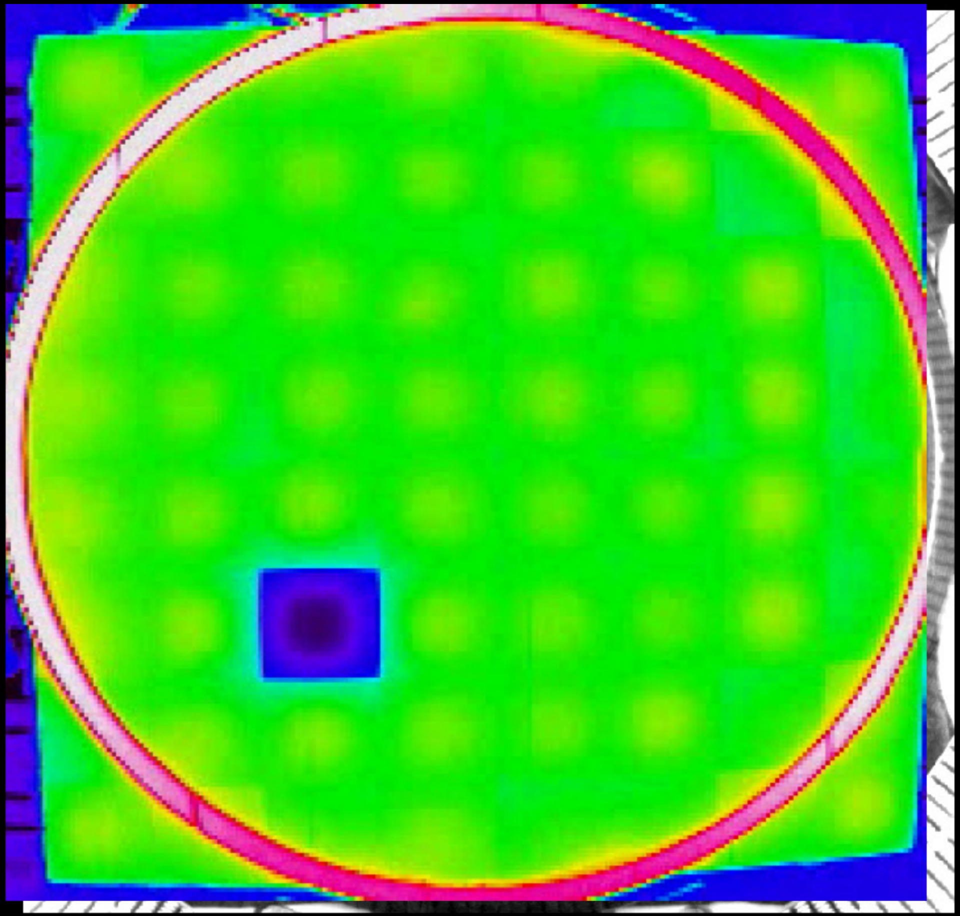
measuring
wing-beat
shadow



2x slower

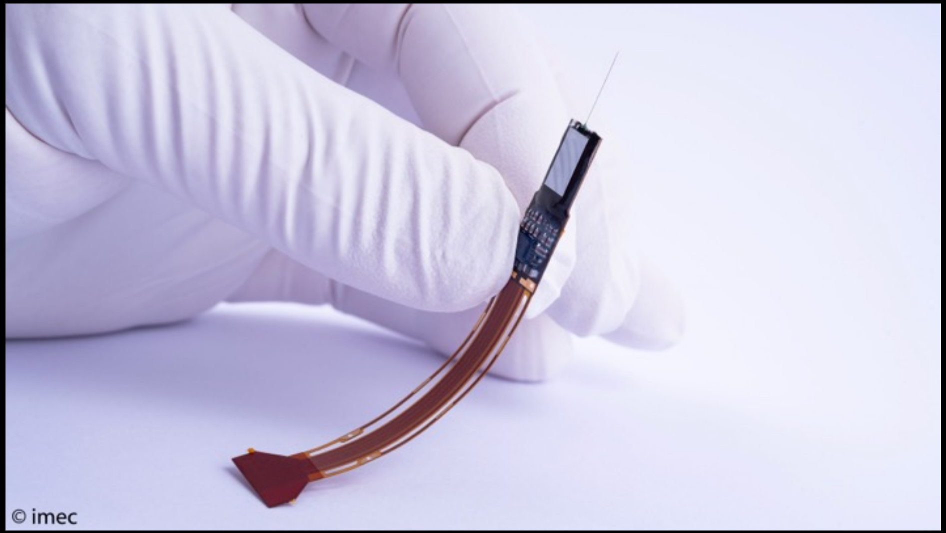
Isaacson et al. (2022)

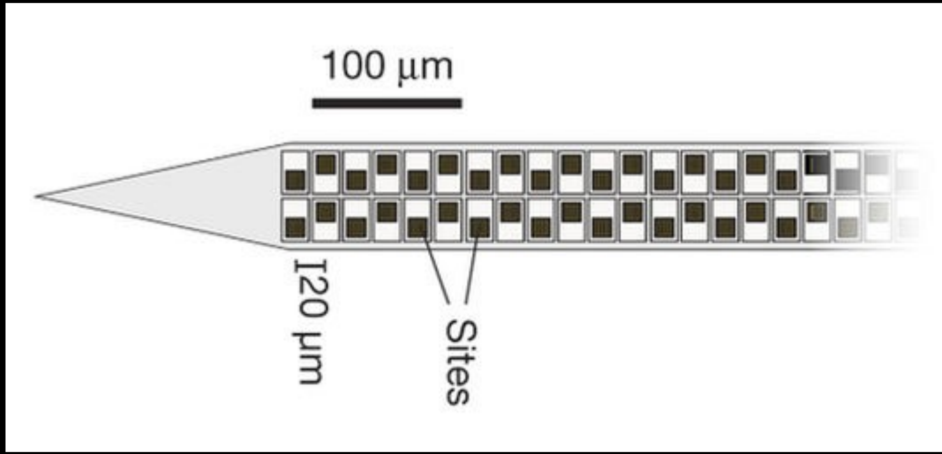
Thermal place learning



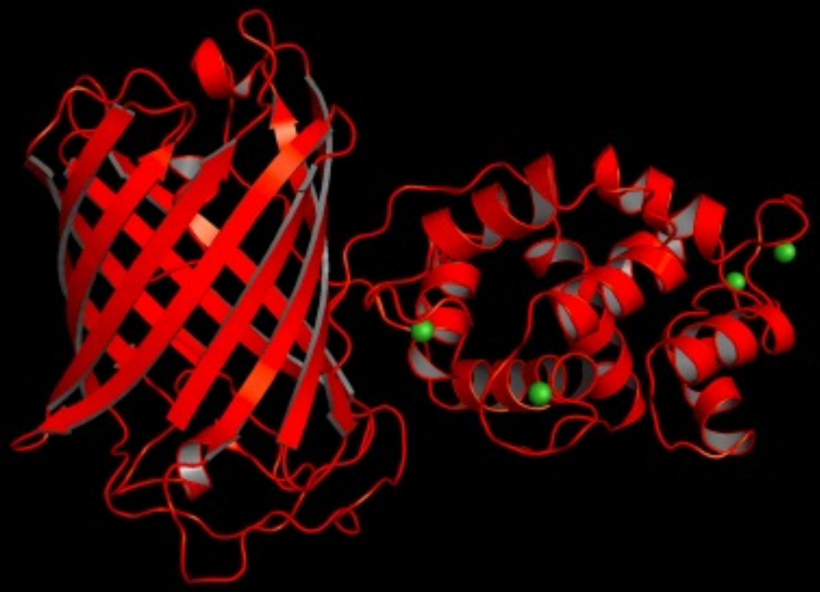
* tracking by Ctrax (Branson et al. 2009)

Ofstad, Zuker & Reiser, (2011)



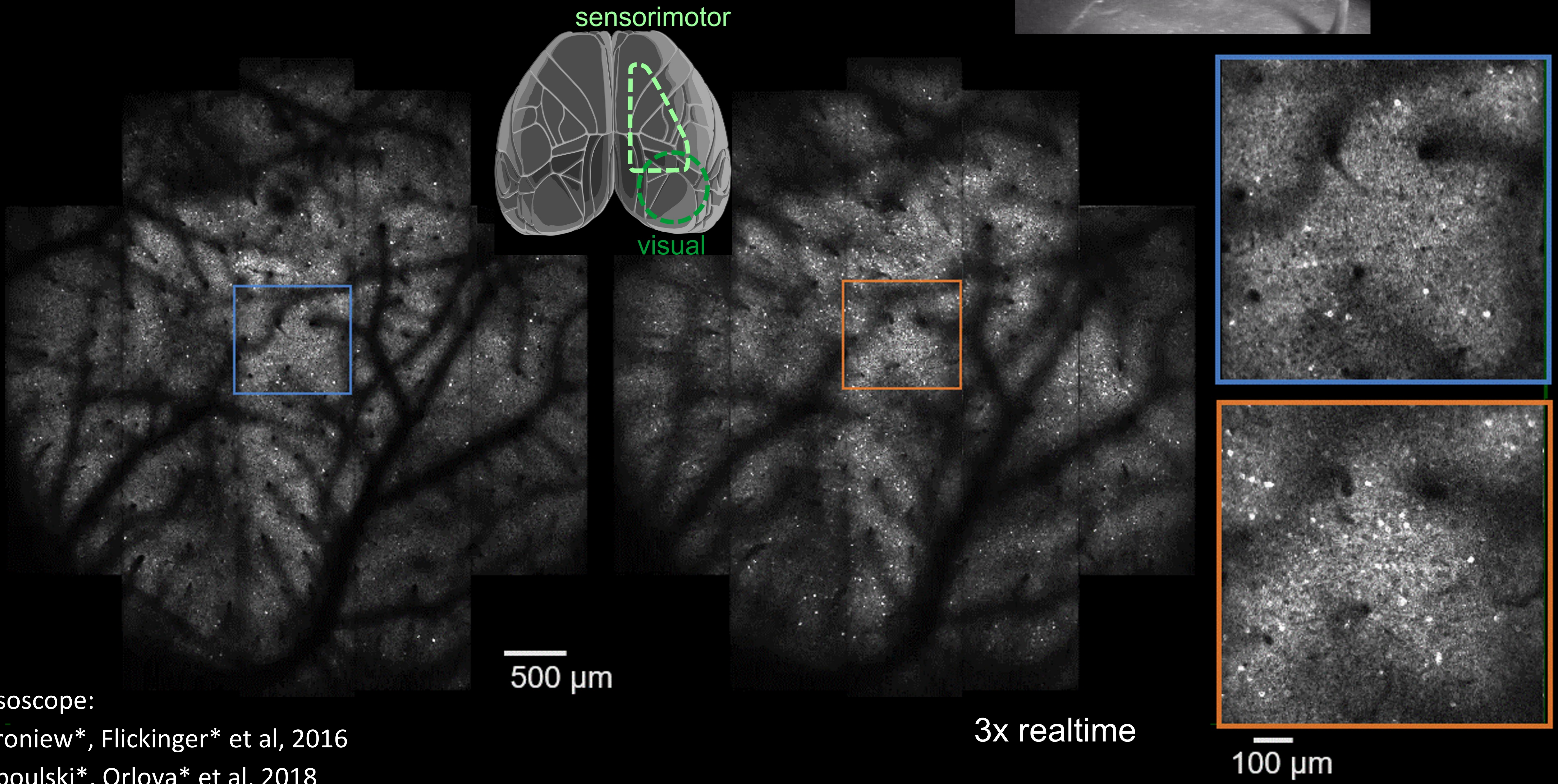


NeuroPixels project
(Janelia, imec, Allen Institute, UCL)



Janelia GENIE team

50,000 simultaneously-recorded neurons

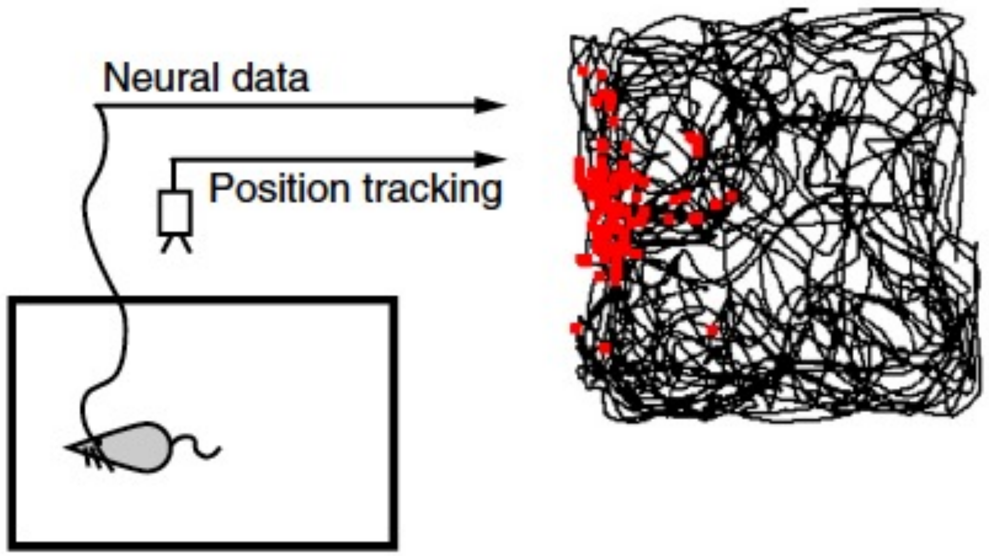


Mesoscope:

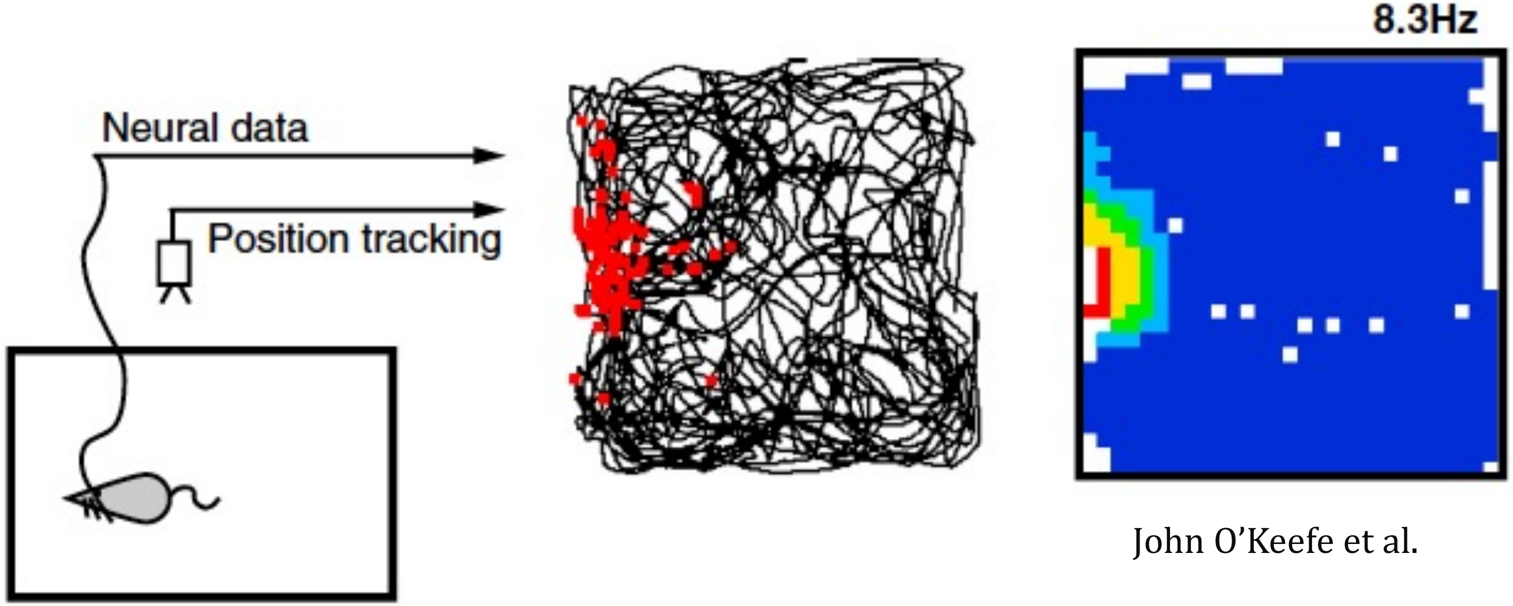
Sofroniew*, Flickinger* et al, 2016

Tsyboulski*, Orlova* et al, 2018

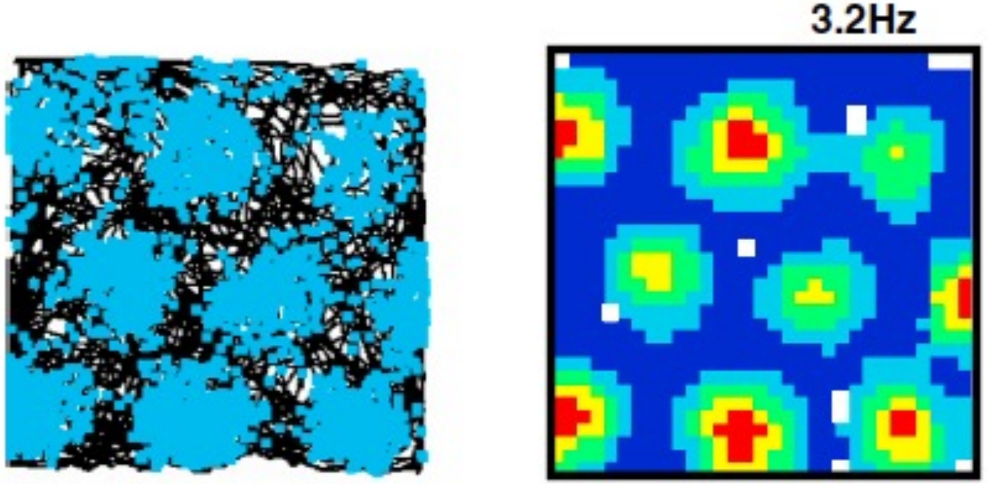
Internal representations for flexible navigation



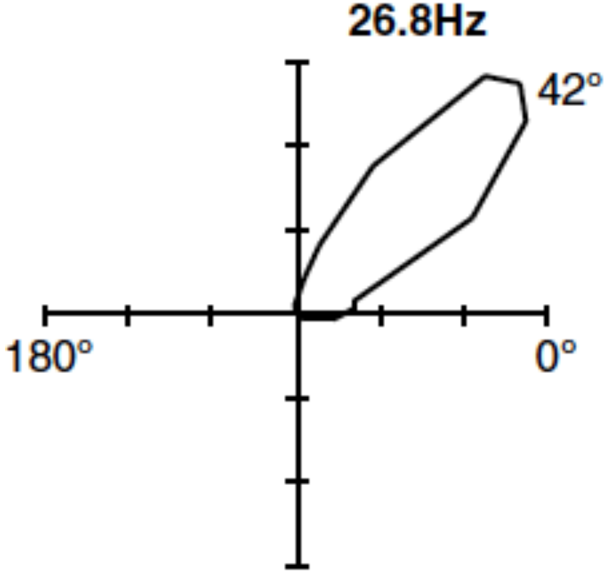
Internal representations for flexible navigation



John O'Keefe et al.



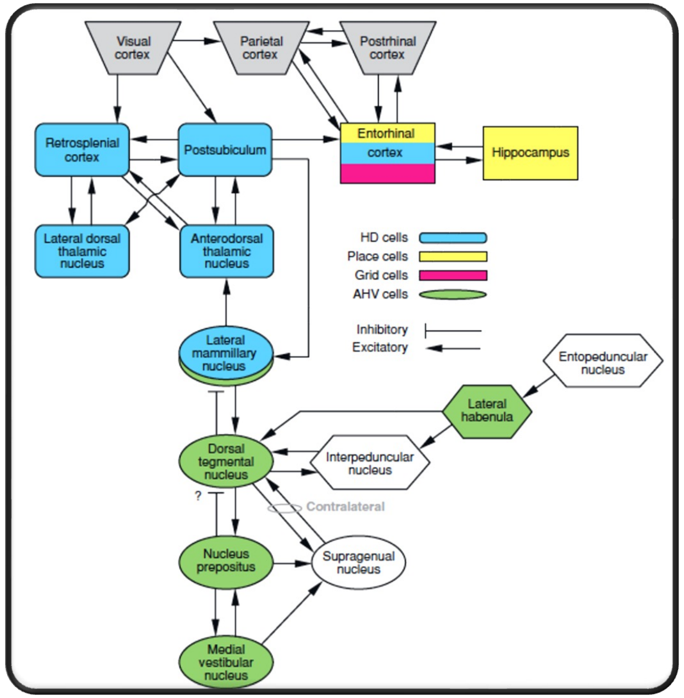
Edvard & May-Britt Moser et al.



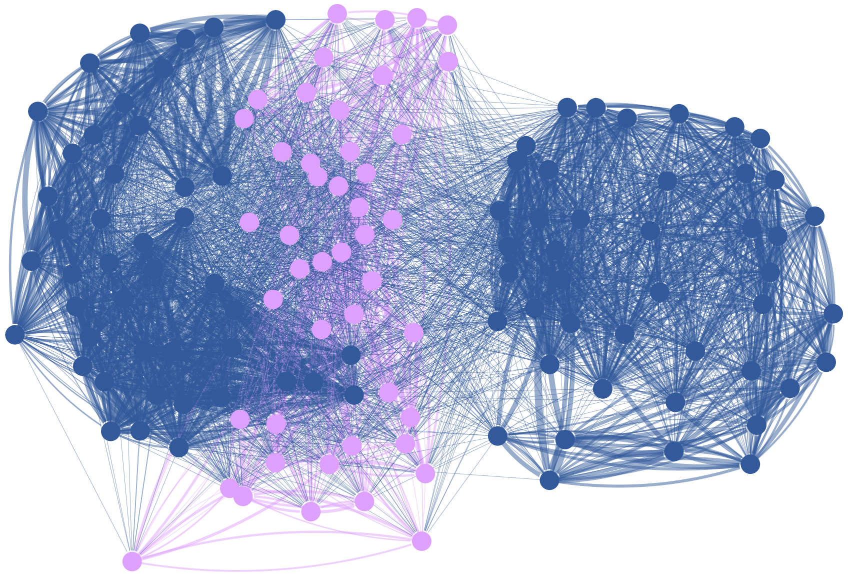
Jeff Taube & James Ranck et al.

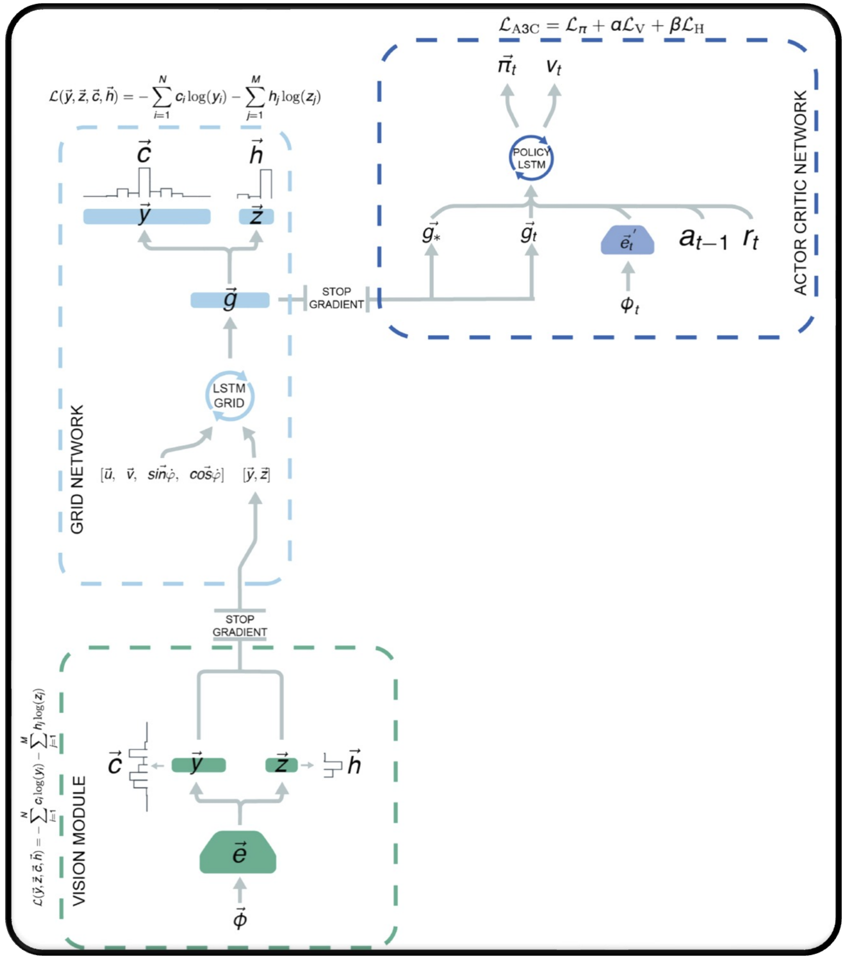
Barry & Burgess, Curr. Biol. (2014)

These representations are generated within densely recurrent brain networks



Taube (2007)

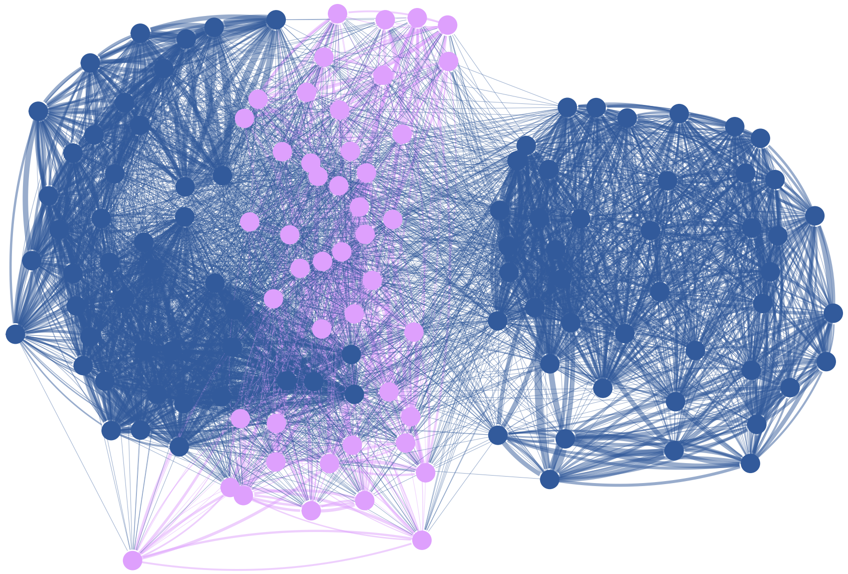




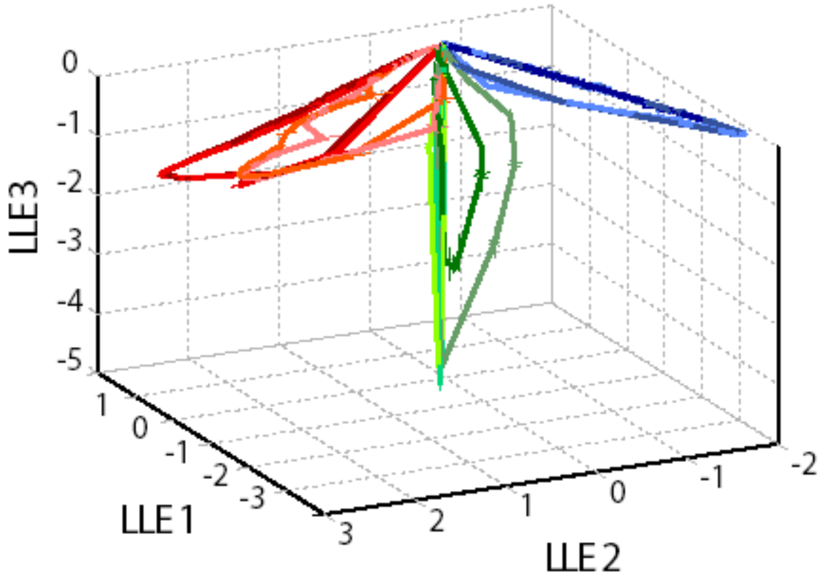
Banino et al. (2018); Cueva & Wei (2018)
see also: Uria et al. (2020); Cueva & Wei (2020)

conjunctive coding

mixed selectivity



manifolds

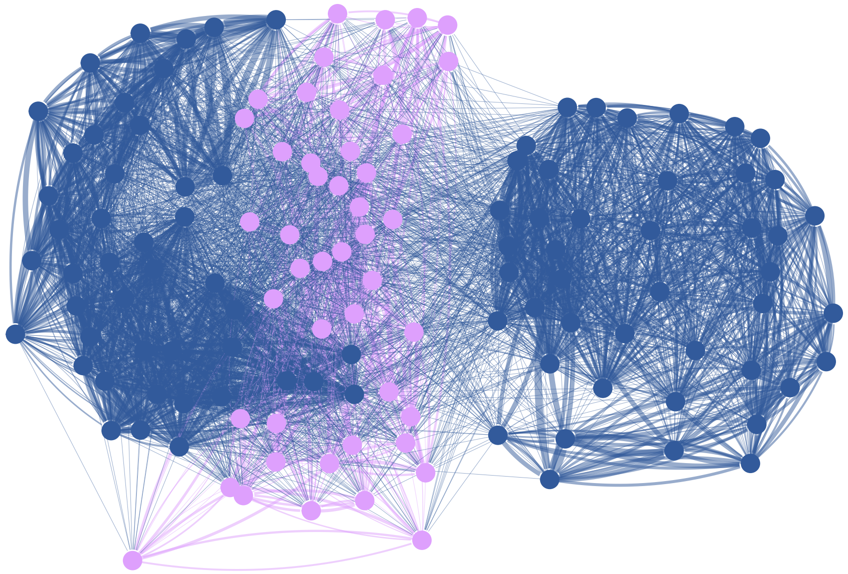


Stopfer*, Jayaraman* & Laurent (2003)

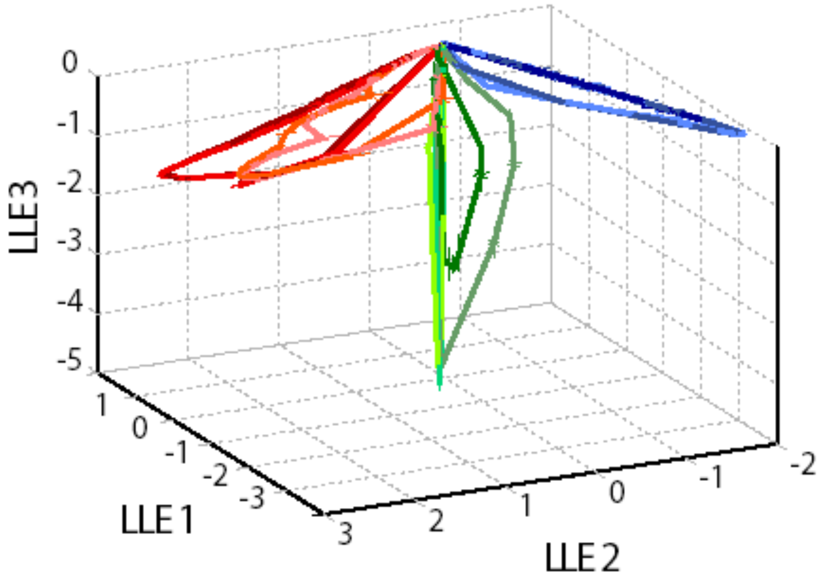
How do these representations arise?

conjunctive coding

mixed selectivity



manifolds

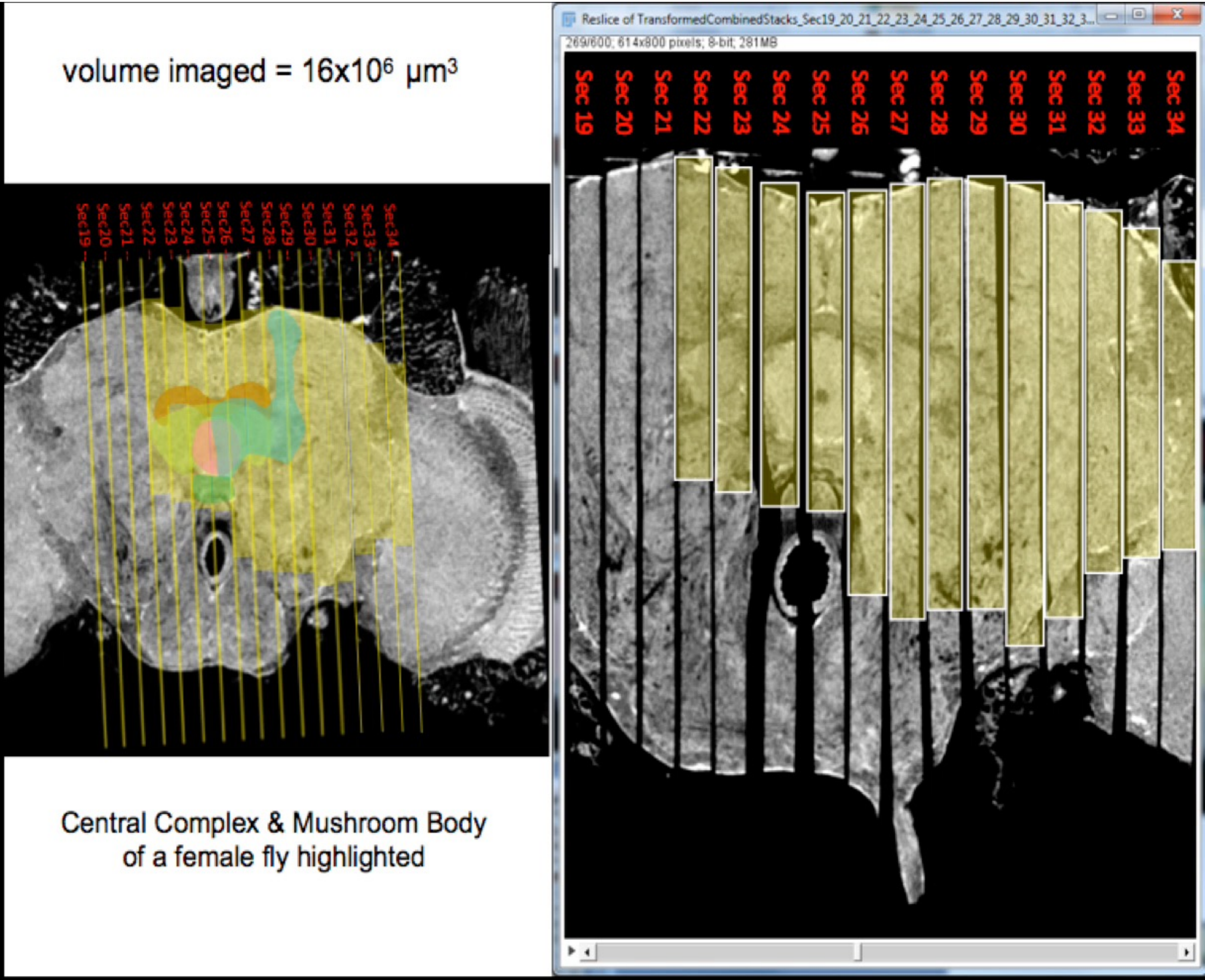


Stopfer*, Jayaraman* & Laurent (2003)

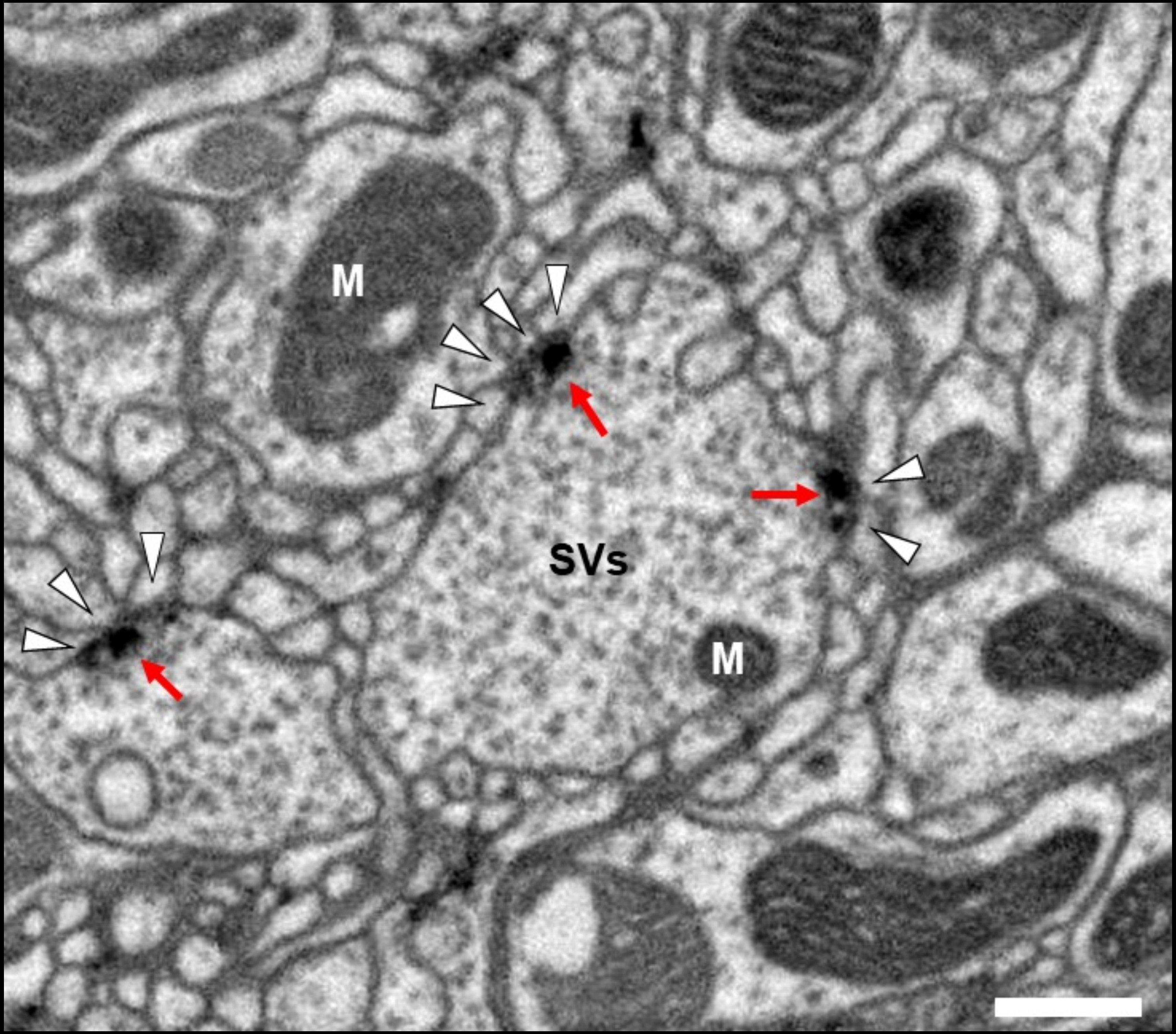
Fly "Hemi-Brain" Connectome Project

janelia flyEM

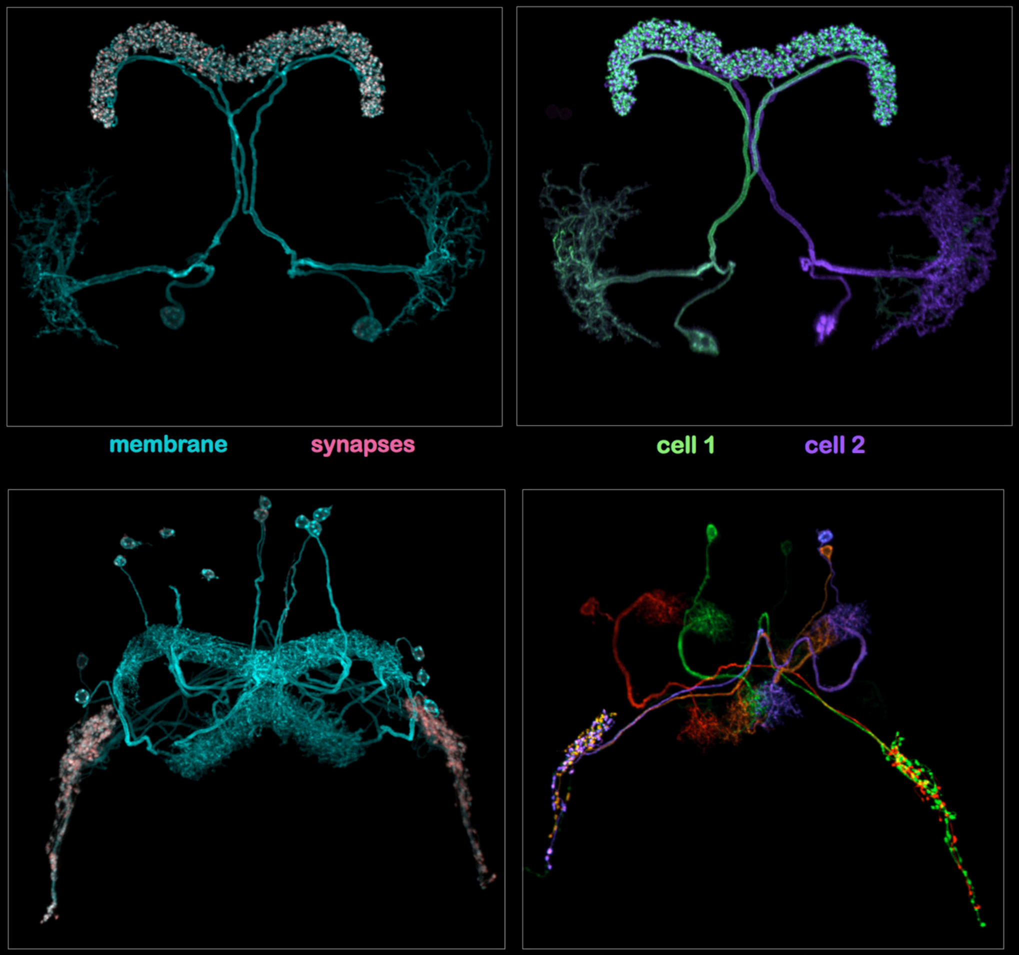
Google

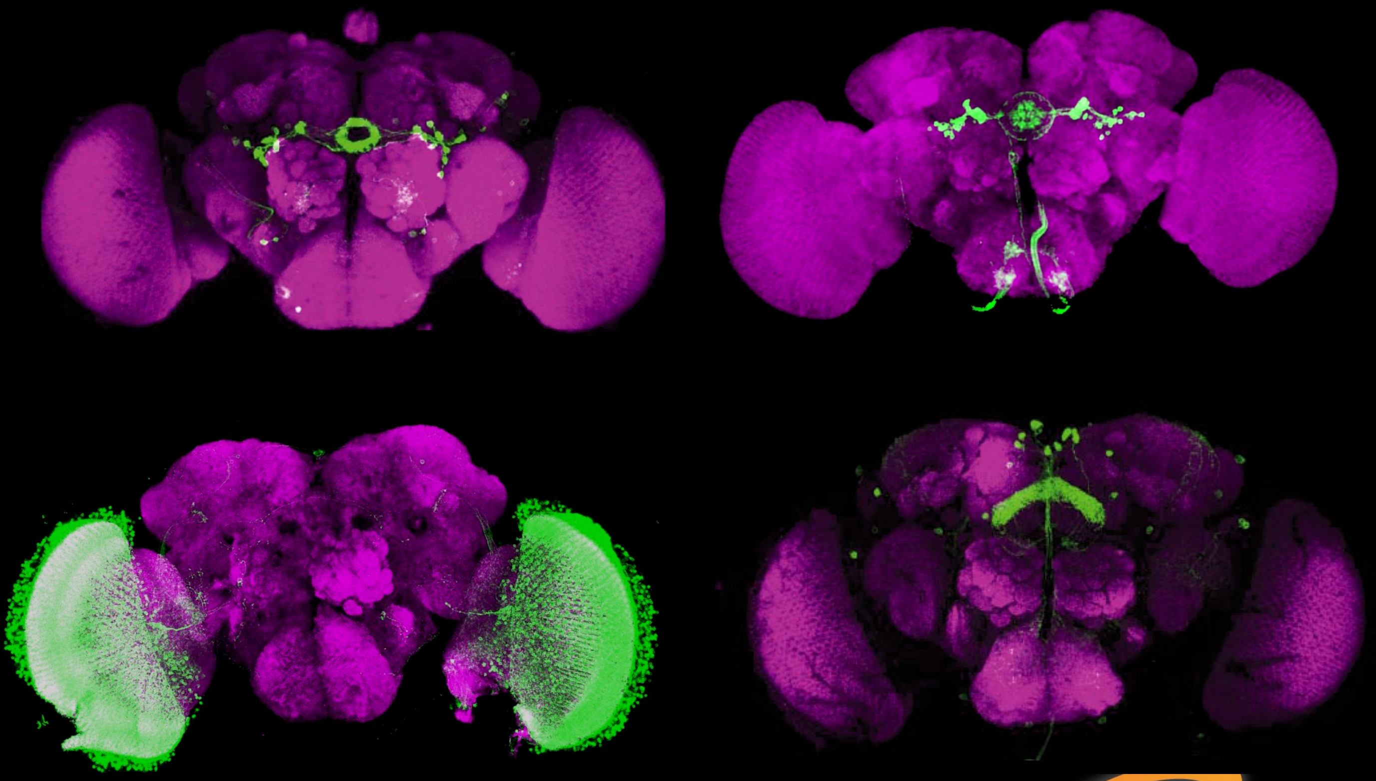


Xu et al. (2017); Scheffer et al. (2020)


M
SVs
M

Neurons come in different types

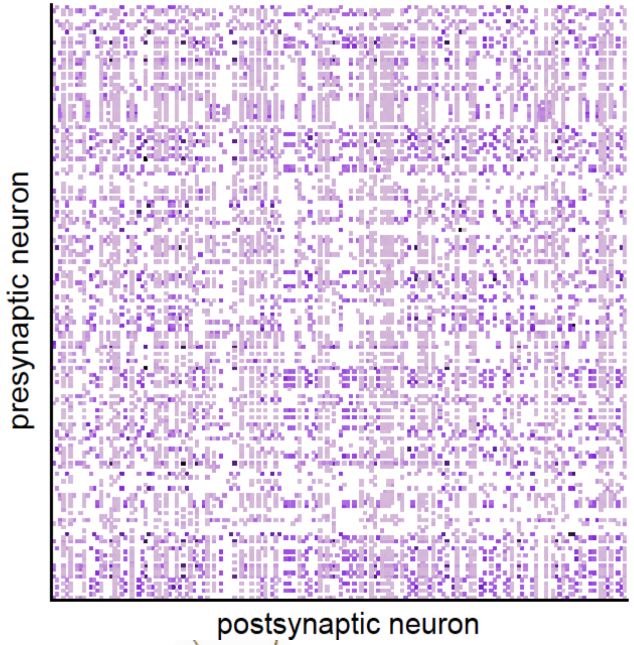


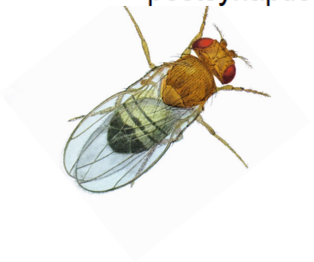


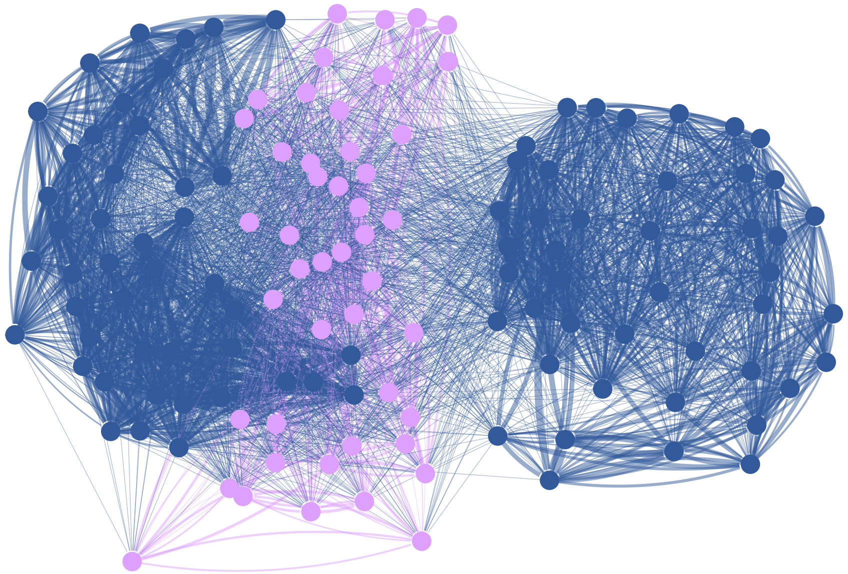
FlyLight

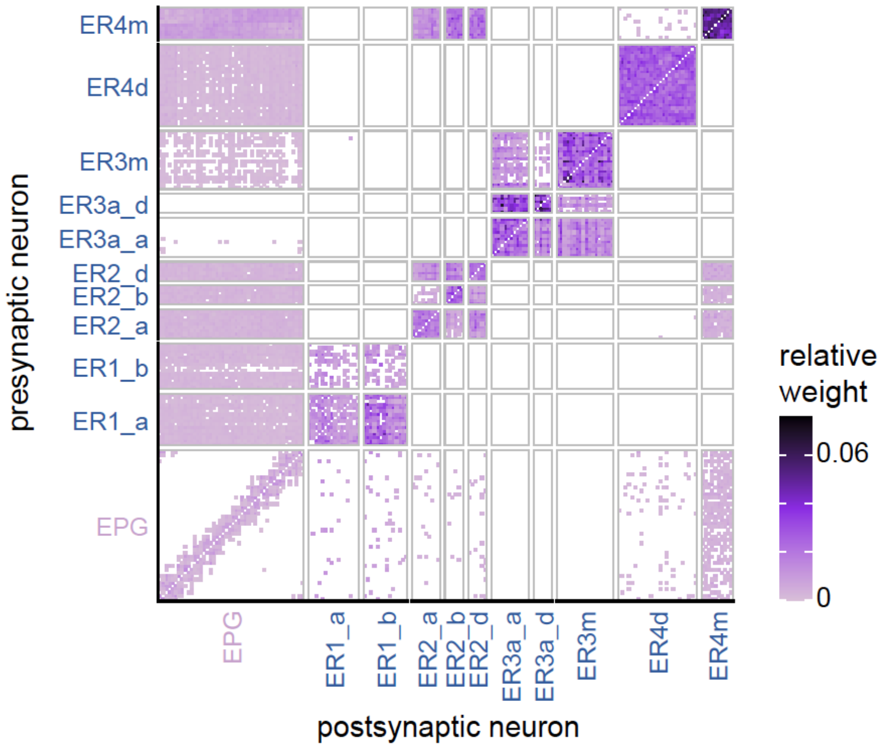
Rubin lab
Dickson lab

Cell types matter



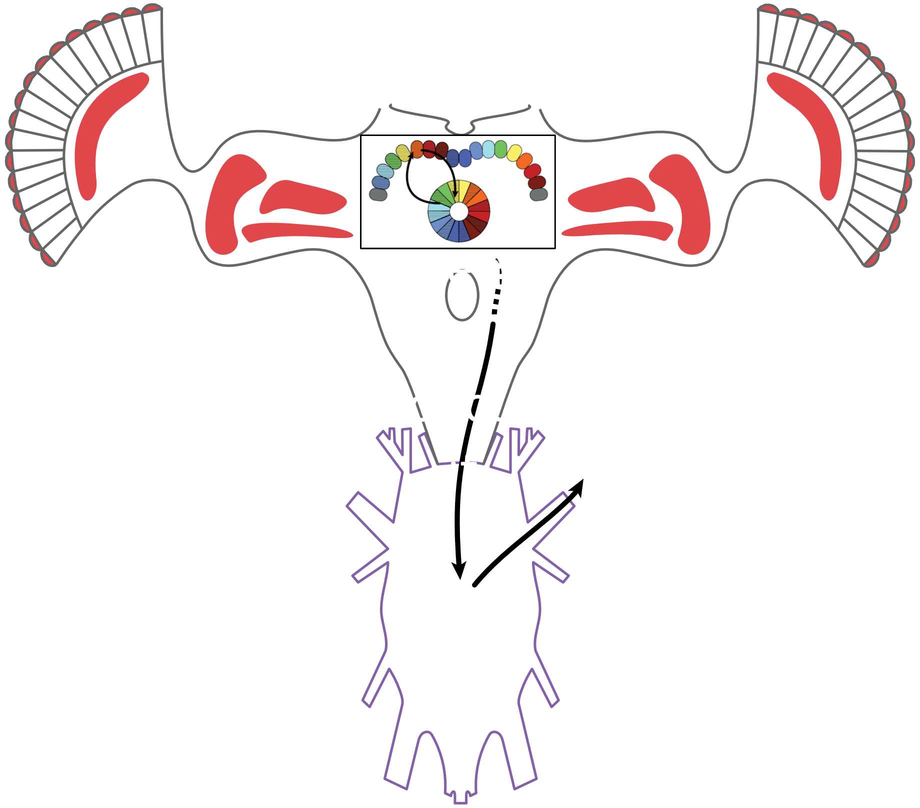




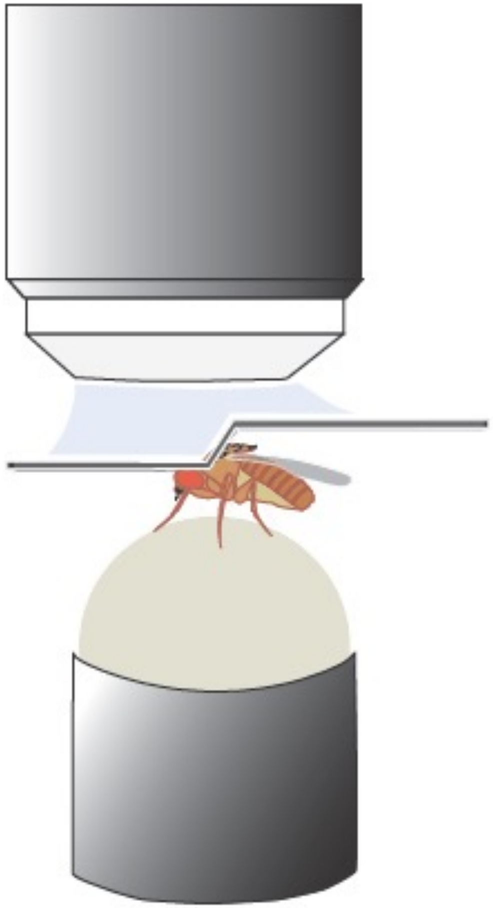


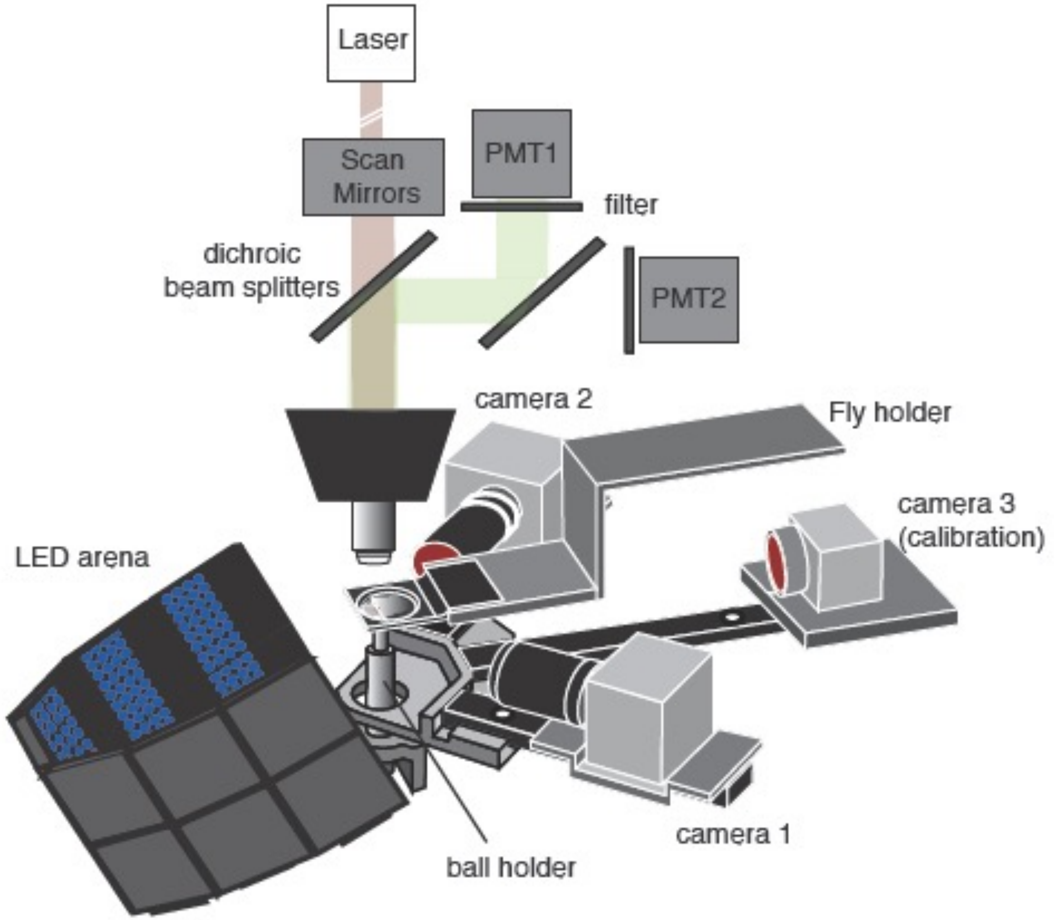
Knowledge of cell type

The central complex: internal-representation-driven flexibility



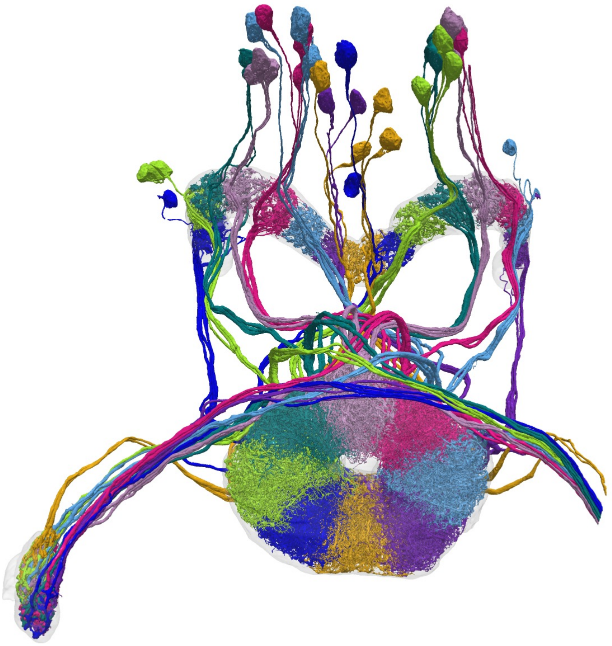
Adapted from M.A. Frye & M.H. Dickinson (2003)

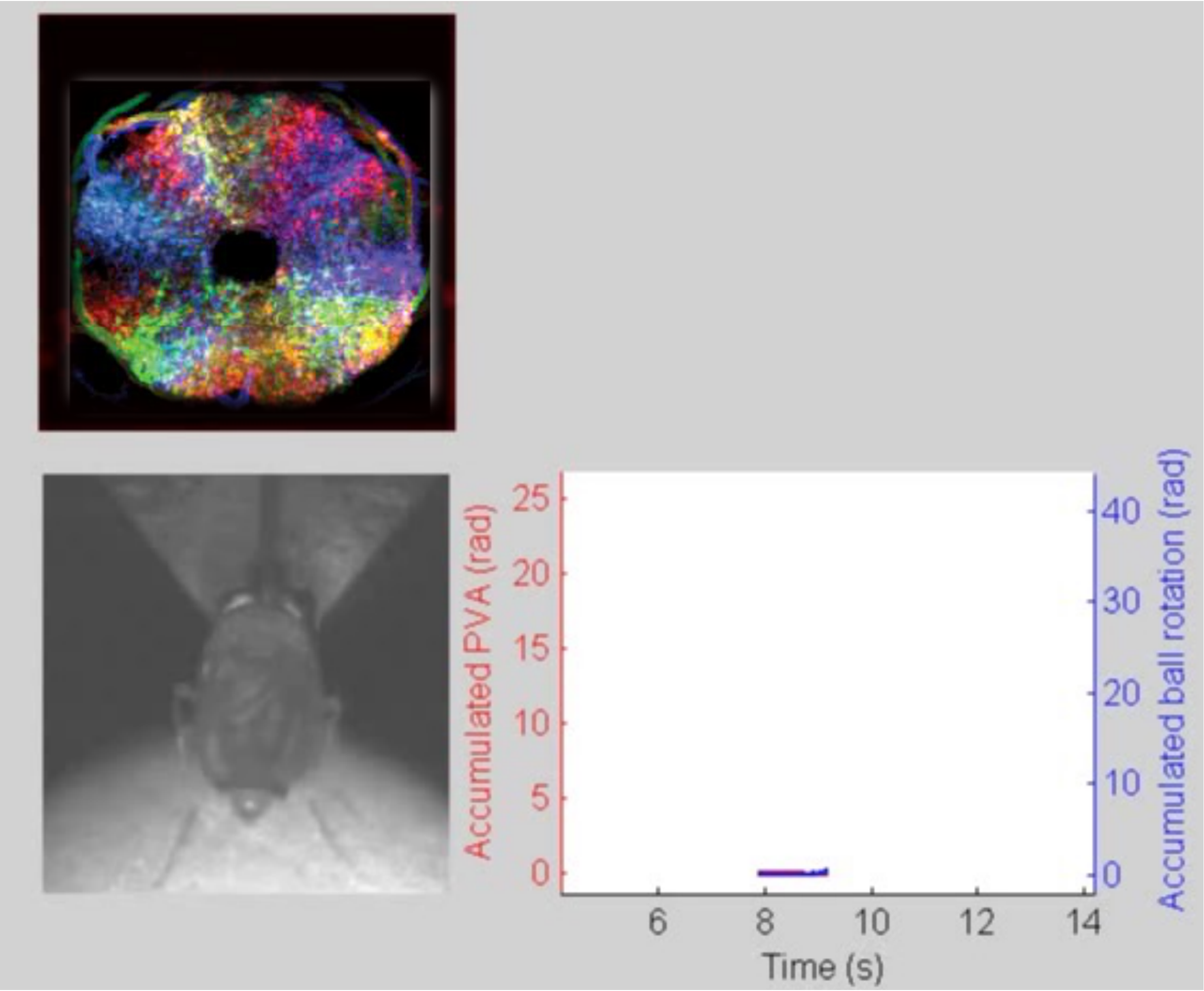




Seelig*, Chiappe*, Lott* et al. (2010)

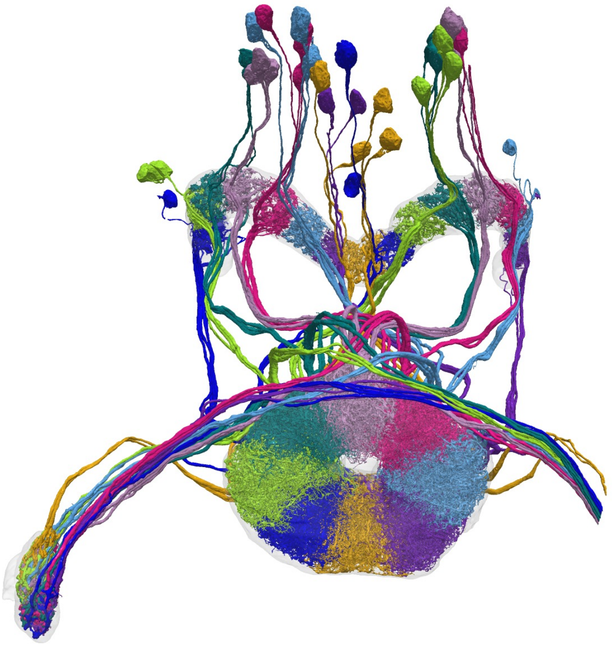
A compass that updates with self-motion

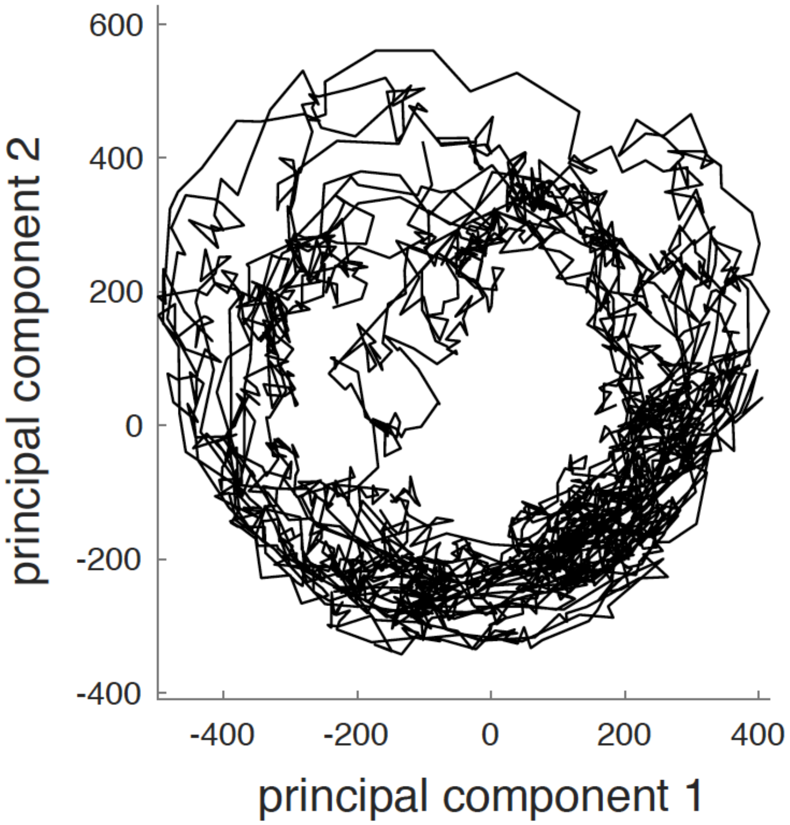




J.D. Seelig & V. Jayaraman (2015)

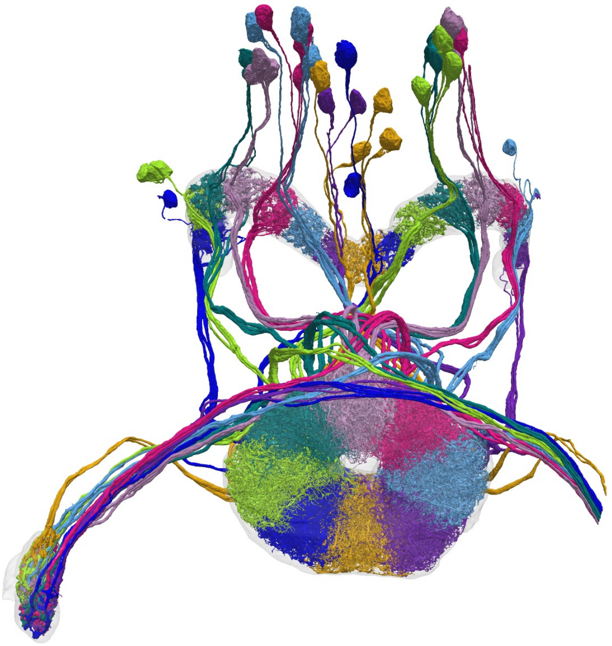
Population activity dynamics lie on a ring

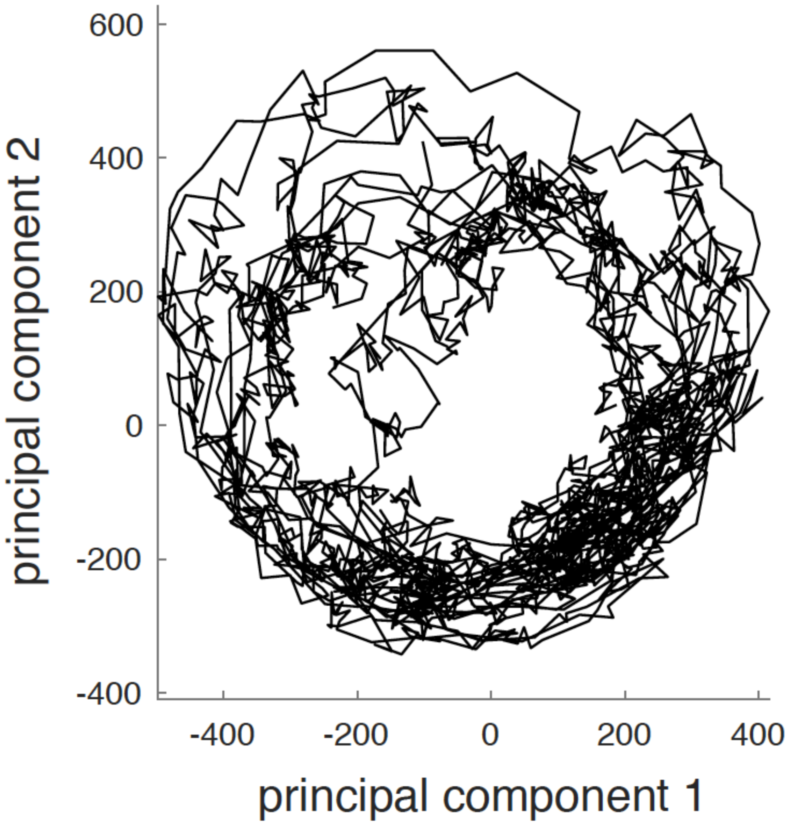




Brad Hulse

Ring attractor networks: theory-rich area





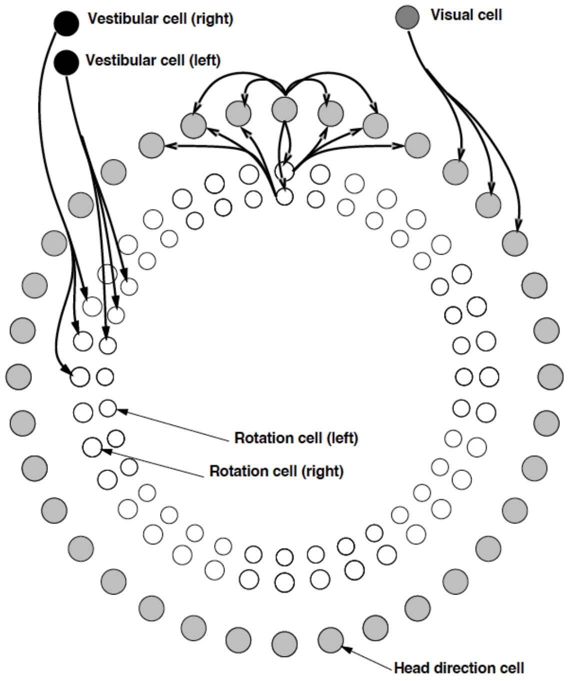
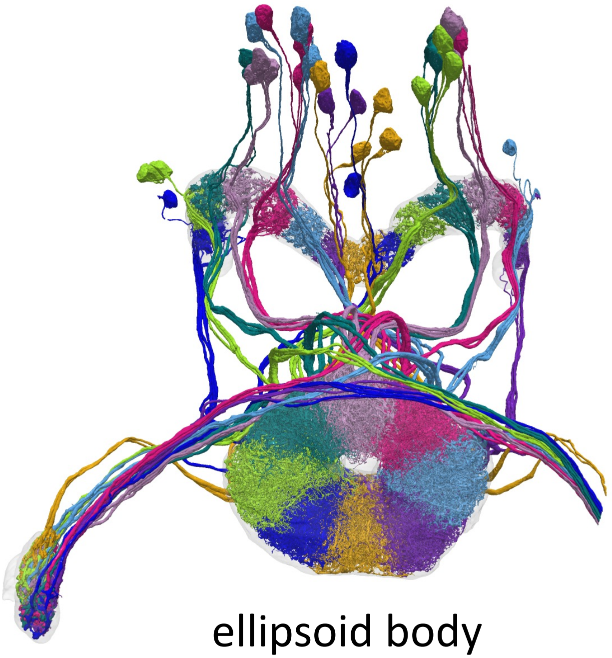


Figure 3: Architecture of the head direction cell model.

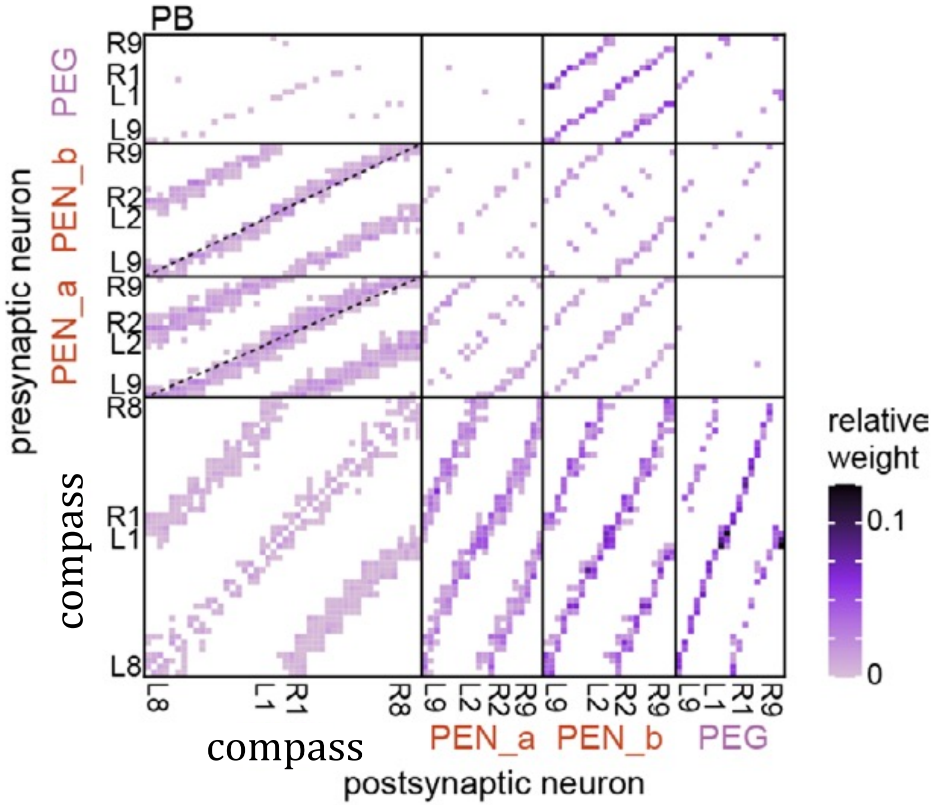
*Ben-Yishai et al. (1995); Skaggs, McNaughton et al. (1995); Zhang (1996); Hansel and Sompolinsky (1998); Xie, Hahnloser & Seung (2002); Wu and Amari (2005) ; Wimmer, Compte et al. (2014); **Noorman et al. (2022)**; …*

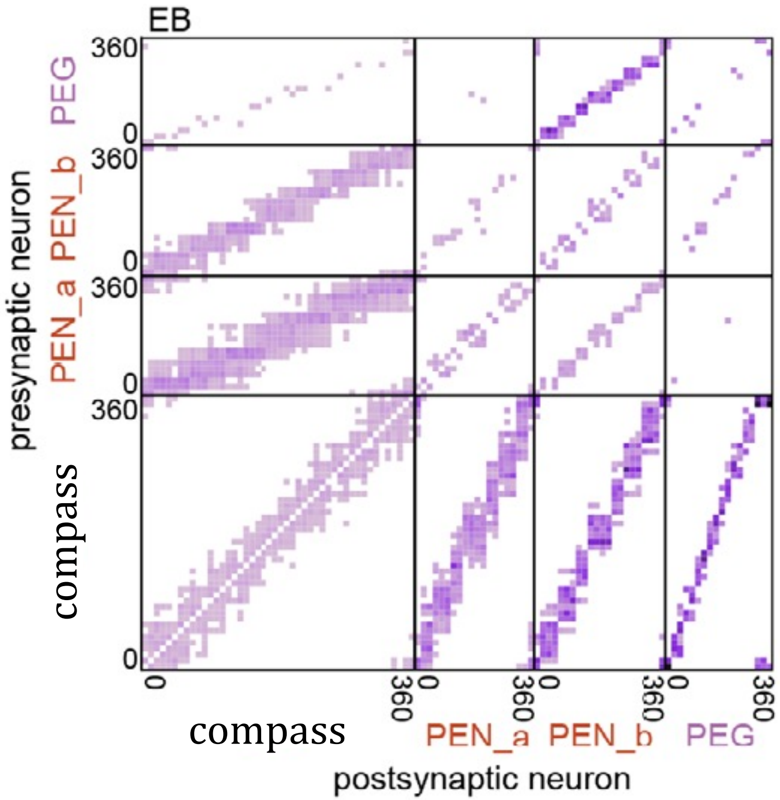
Looking at the connectome with a theory-inspired lens

protocerebral bridge
(PB)



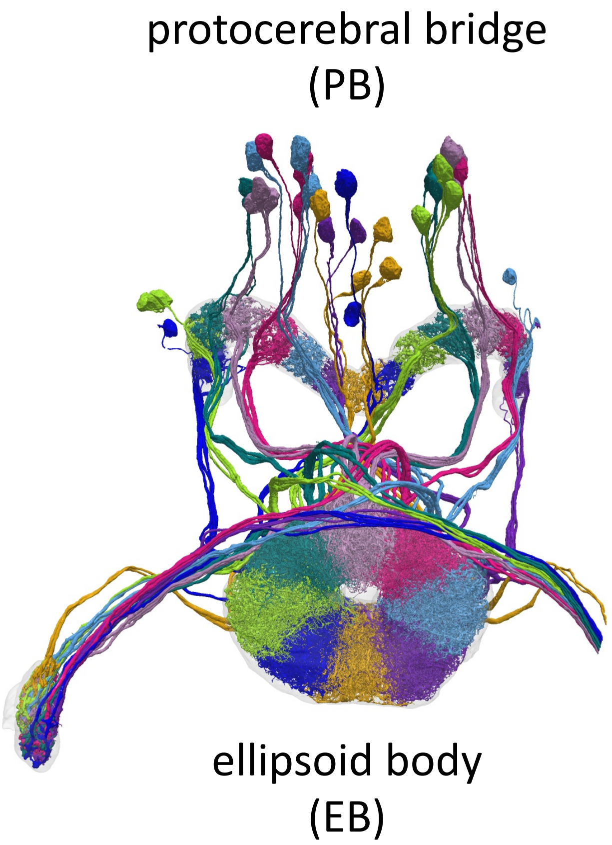
ellipsoid body
(EB)

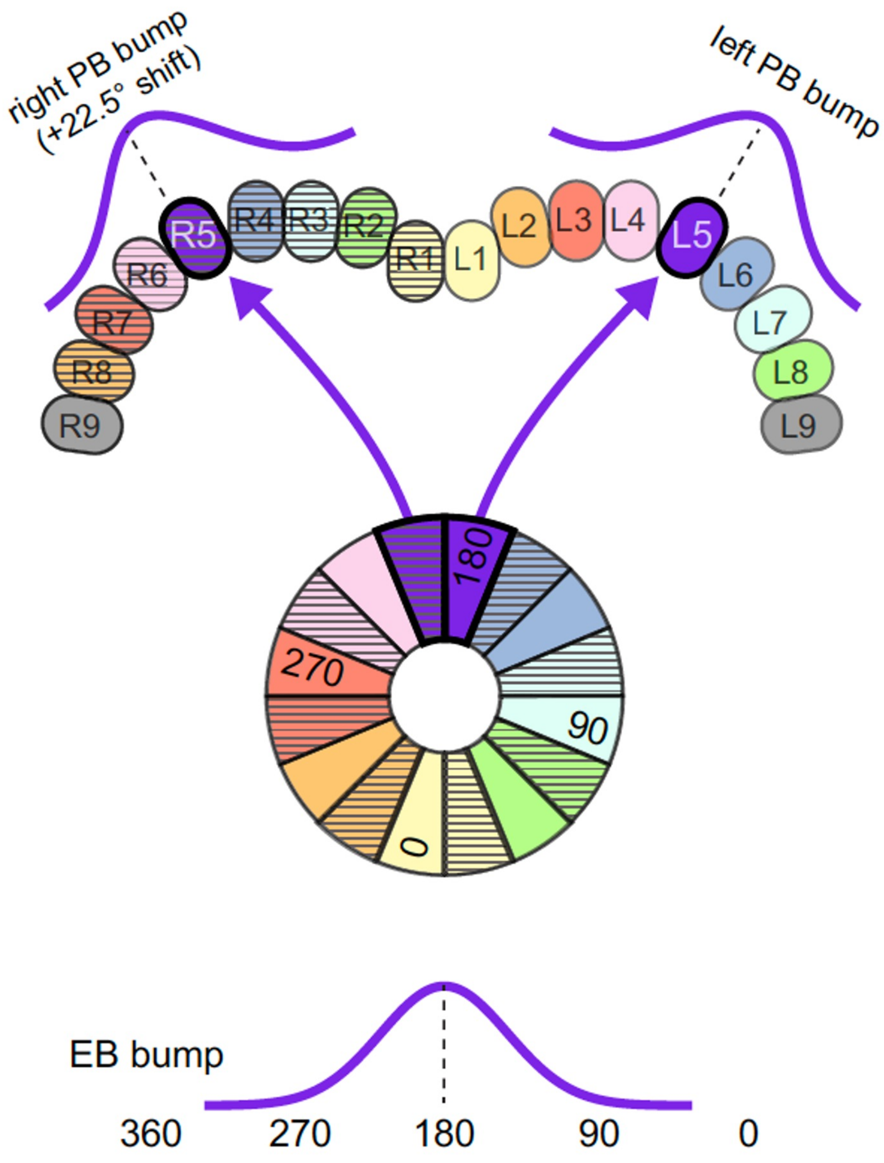


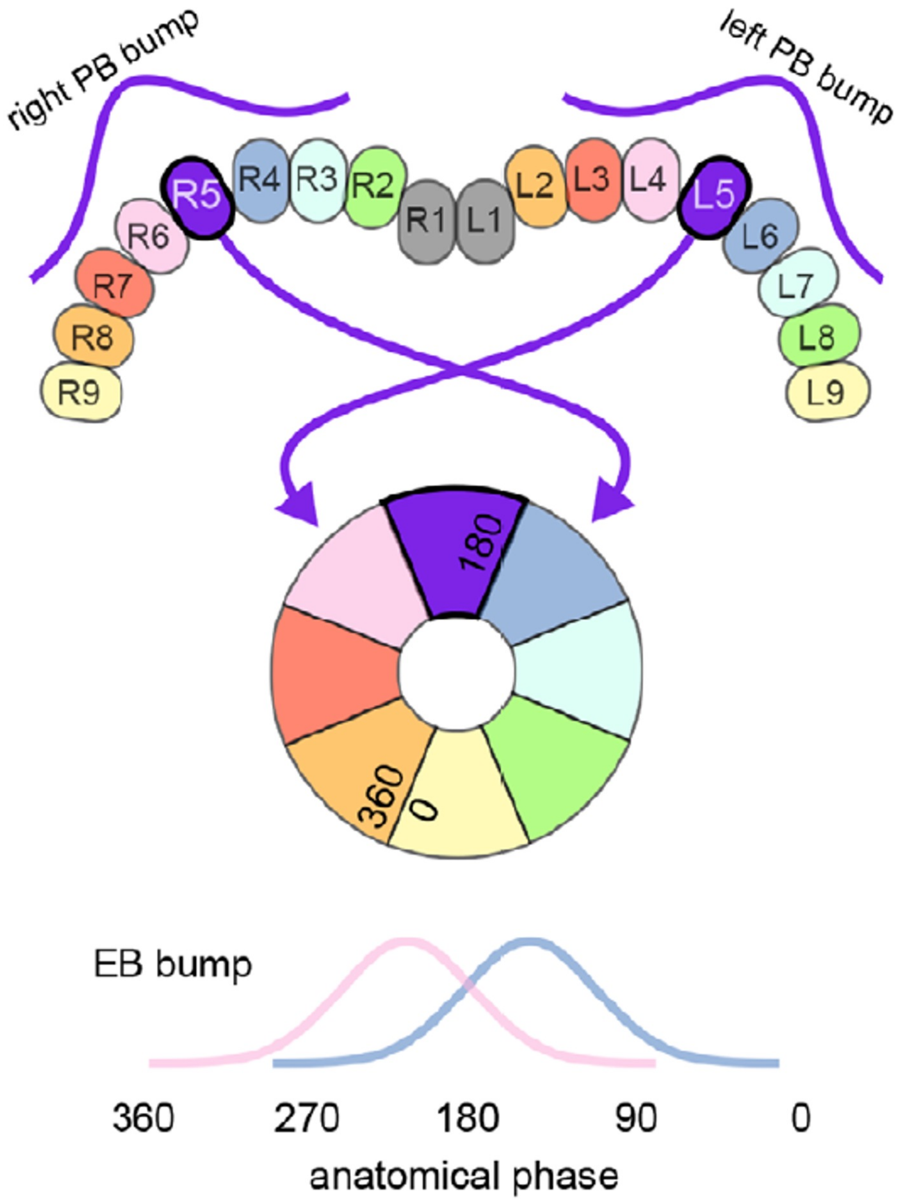


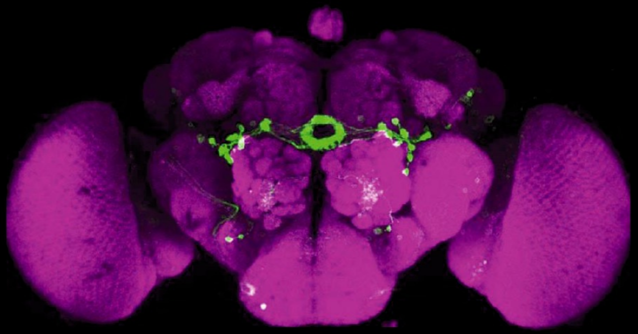
D.B. Turner-Evans*, S. Wegener* et al. (2017), J. Green et al. (Maimon lab) (2017), D.B. Turner-Evans et al. (2020)

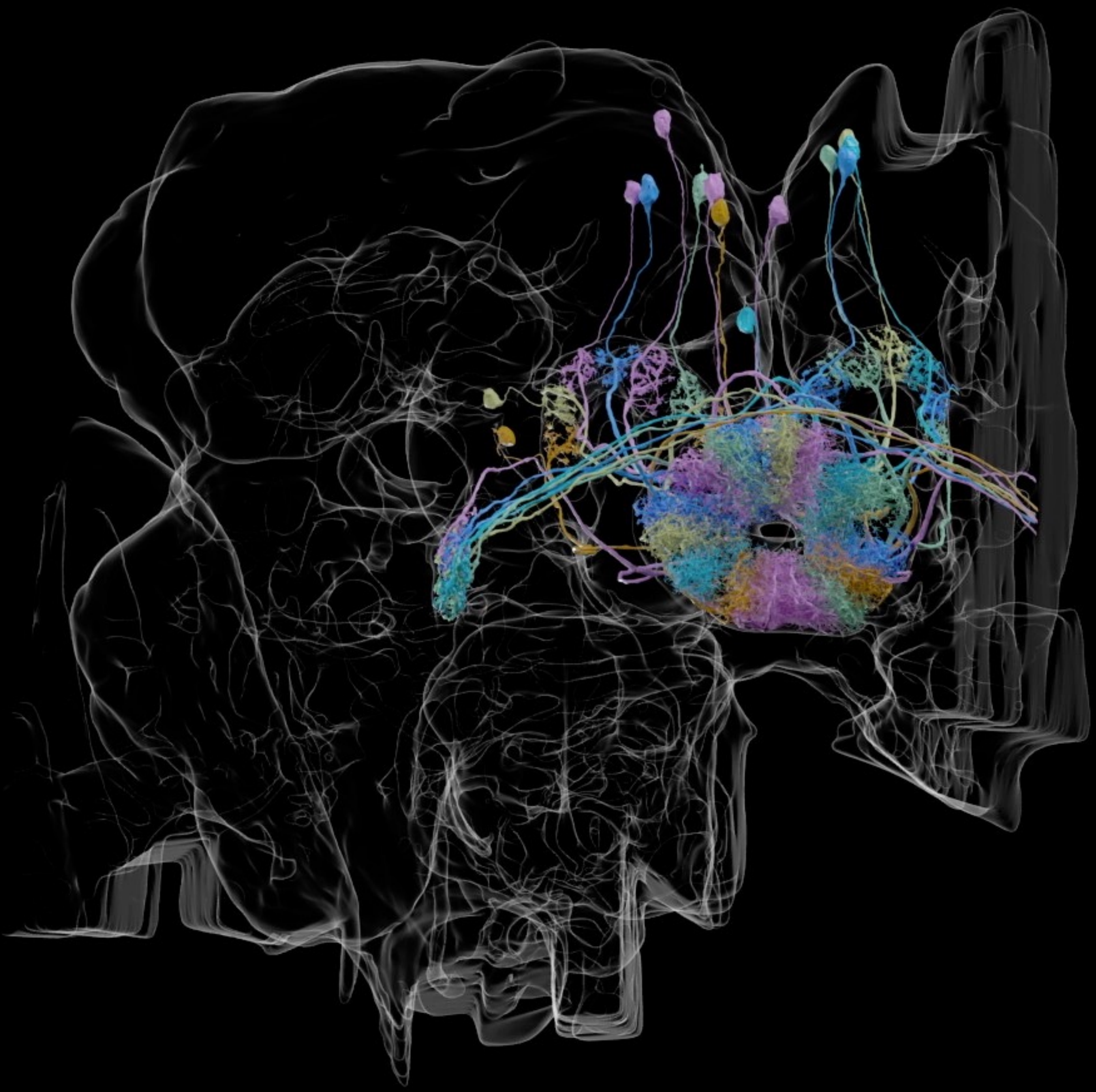
Phase-shifted population updates the compass







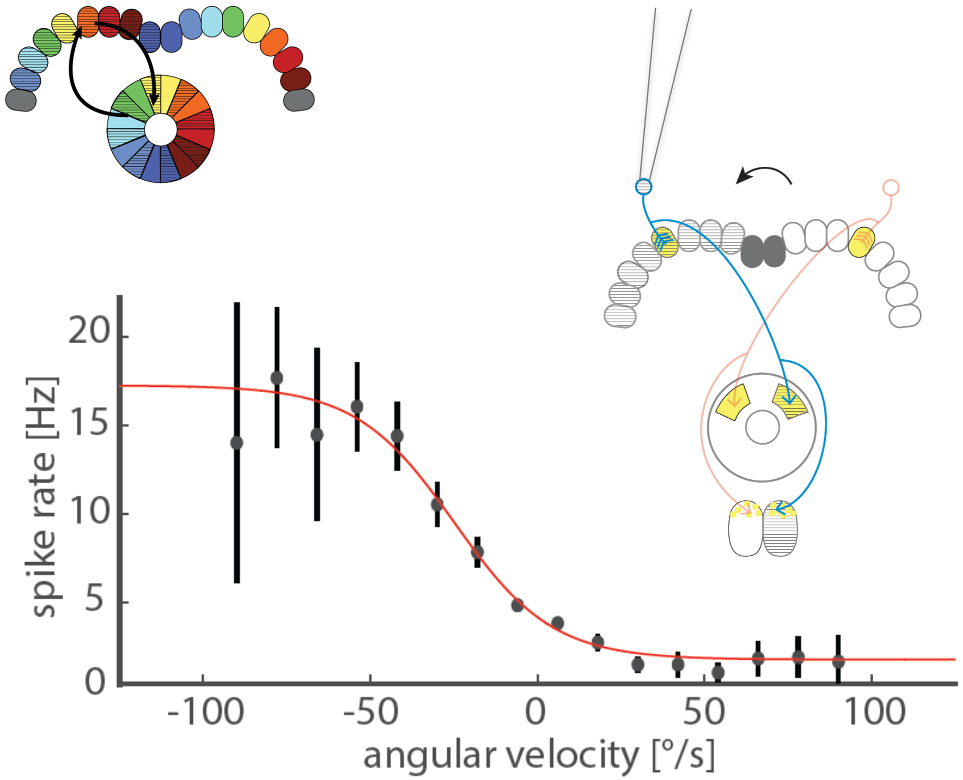


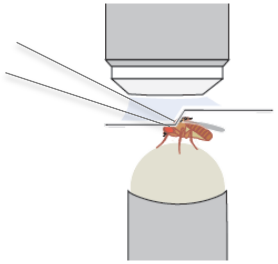


Video credits:
Philip Hubbard &
Shin-ya Takemura

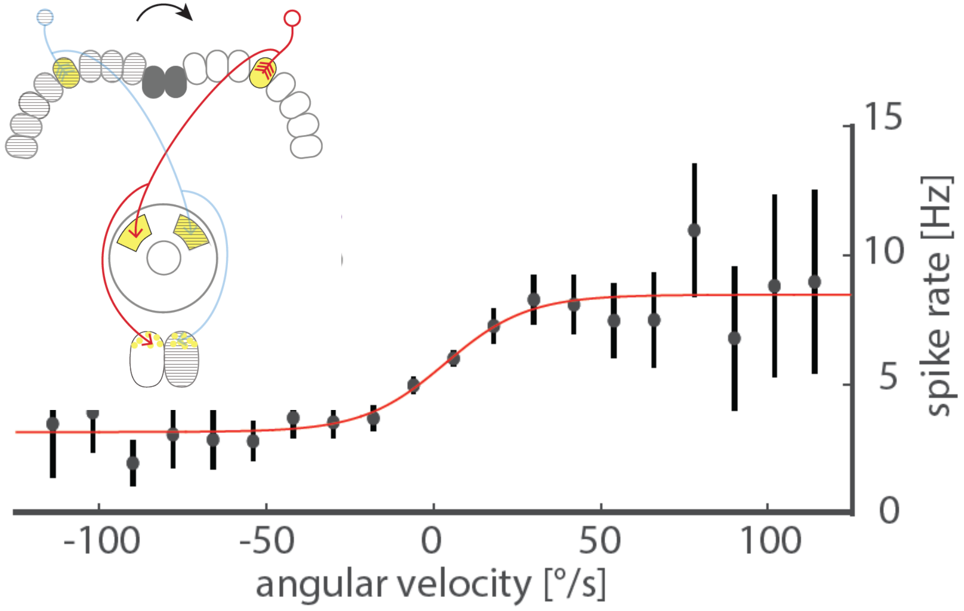
janelia flyEM

Scheffer et al. (2020); Hulse et al. (2021)



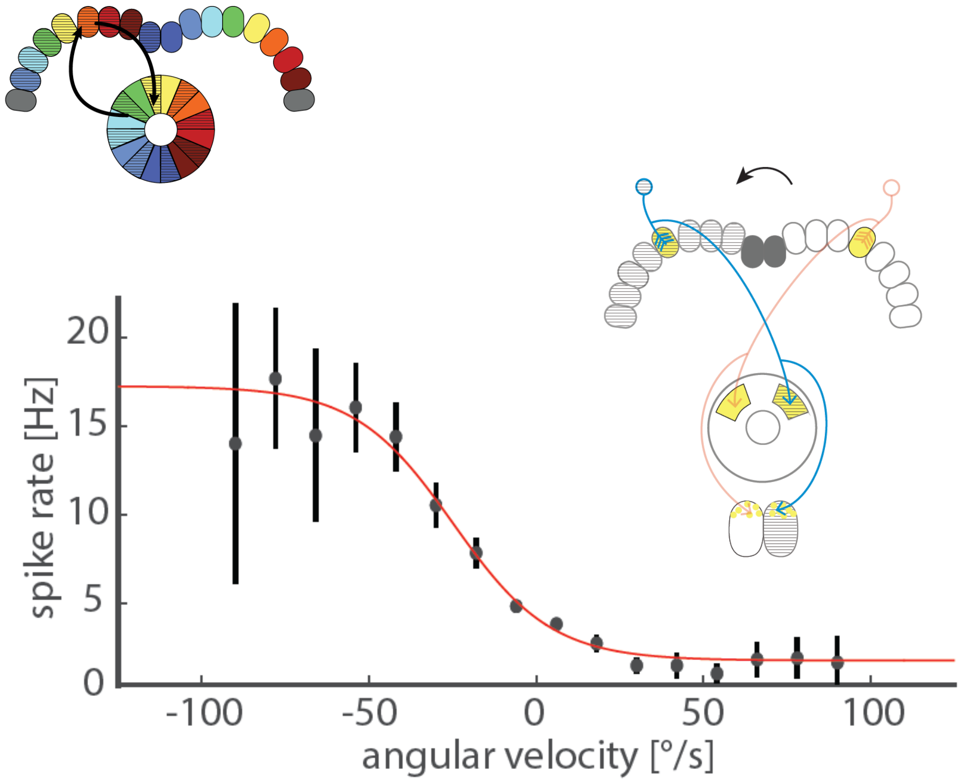


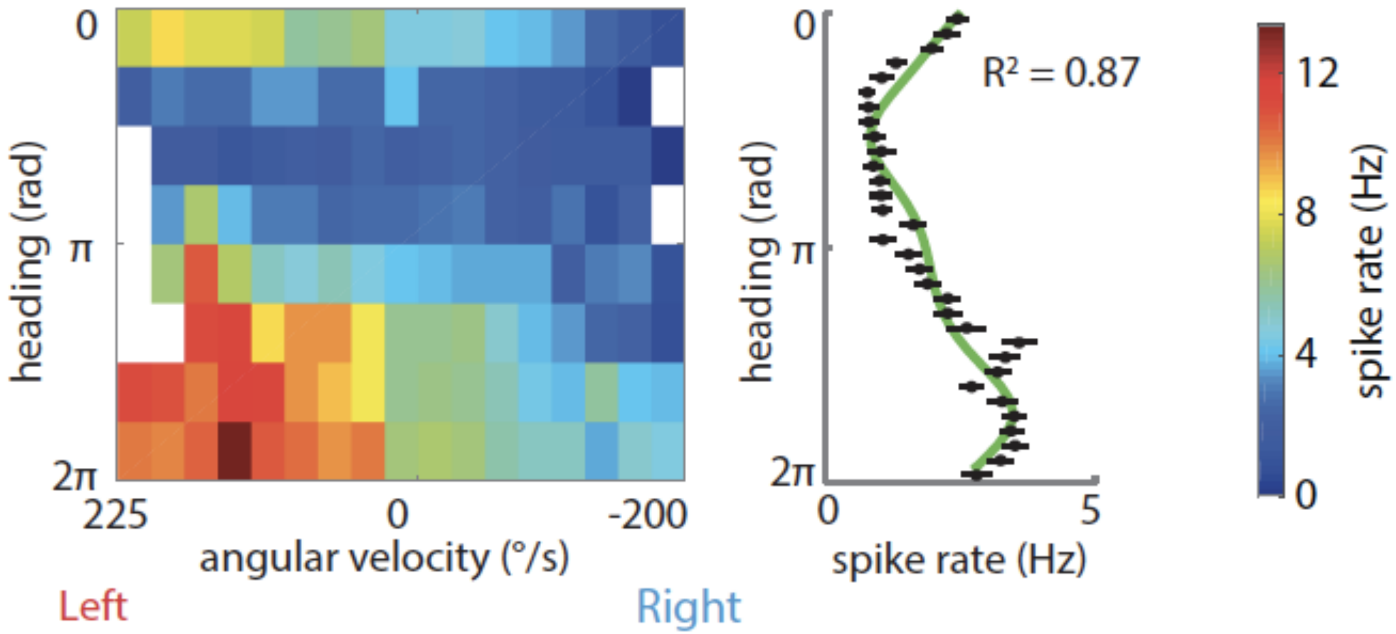
PEN neurons



D.B. Turner-Evans*, **S. Wegener*** et al. (2017)

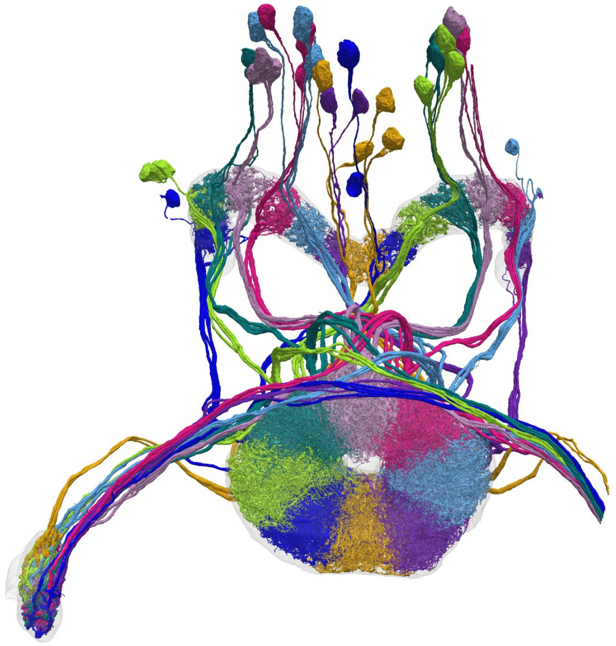
A conjunctive encoding of heading & velocity

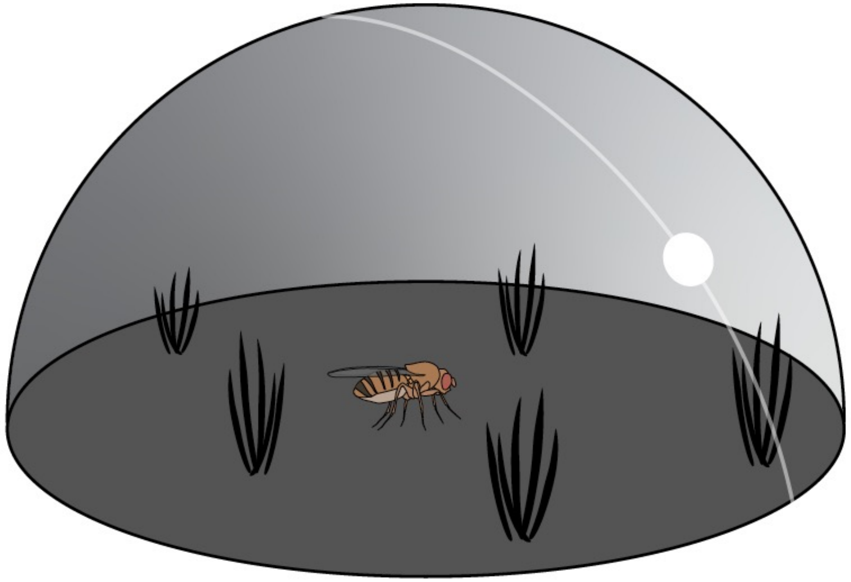




D.B. Turner-Evans*, **S. Wegener*** et al. (2017)

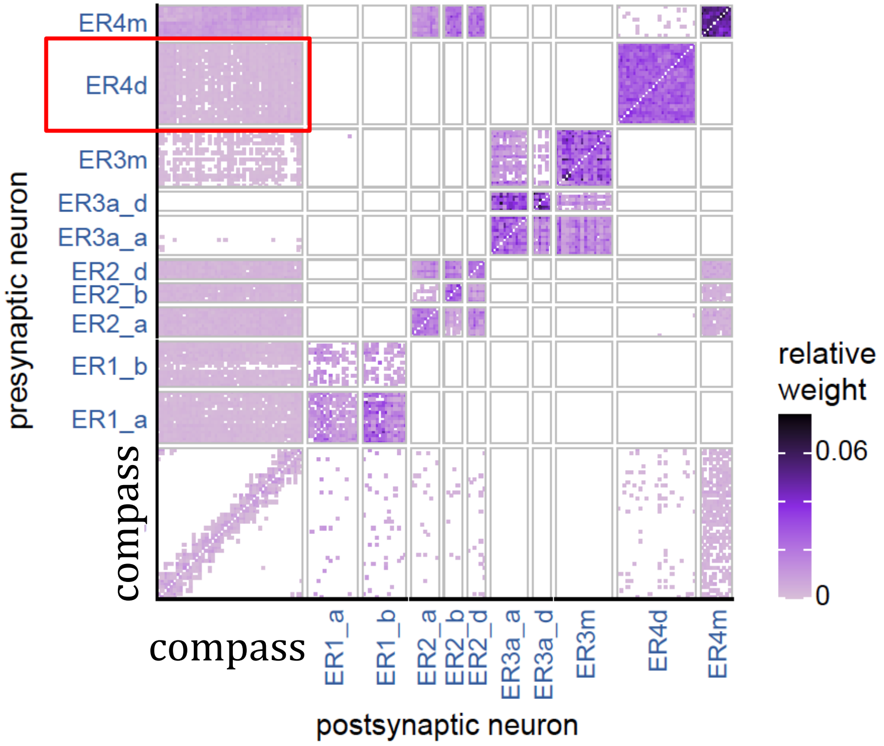
Self-motion input must be combined with localizing sensory input

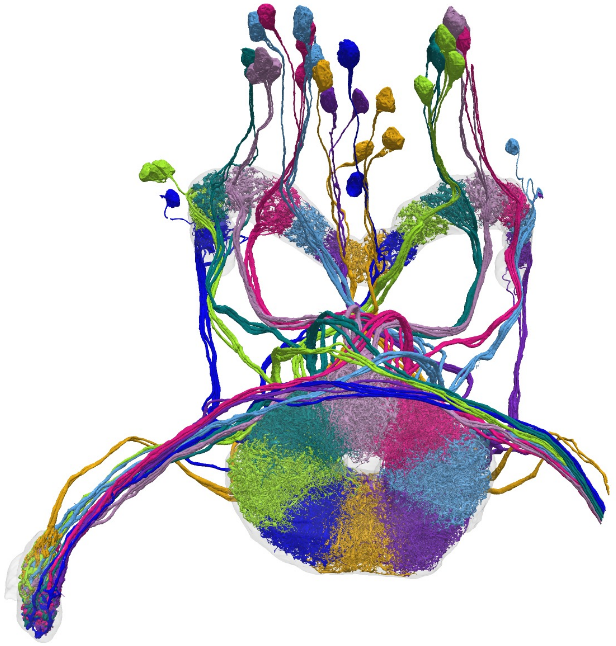




B.K. Hulse*, **H. Haberkern***, R. Franconville*, D.B. Turner-Evans* et al. (2021)

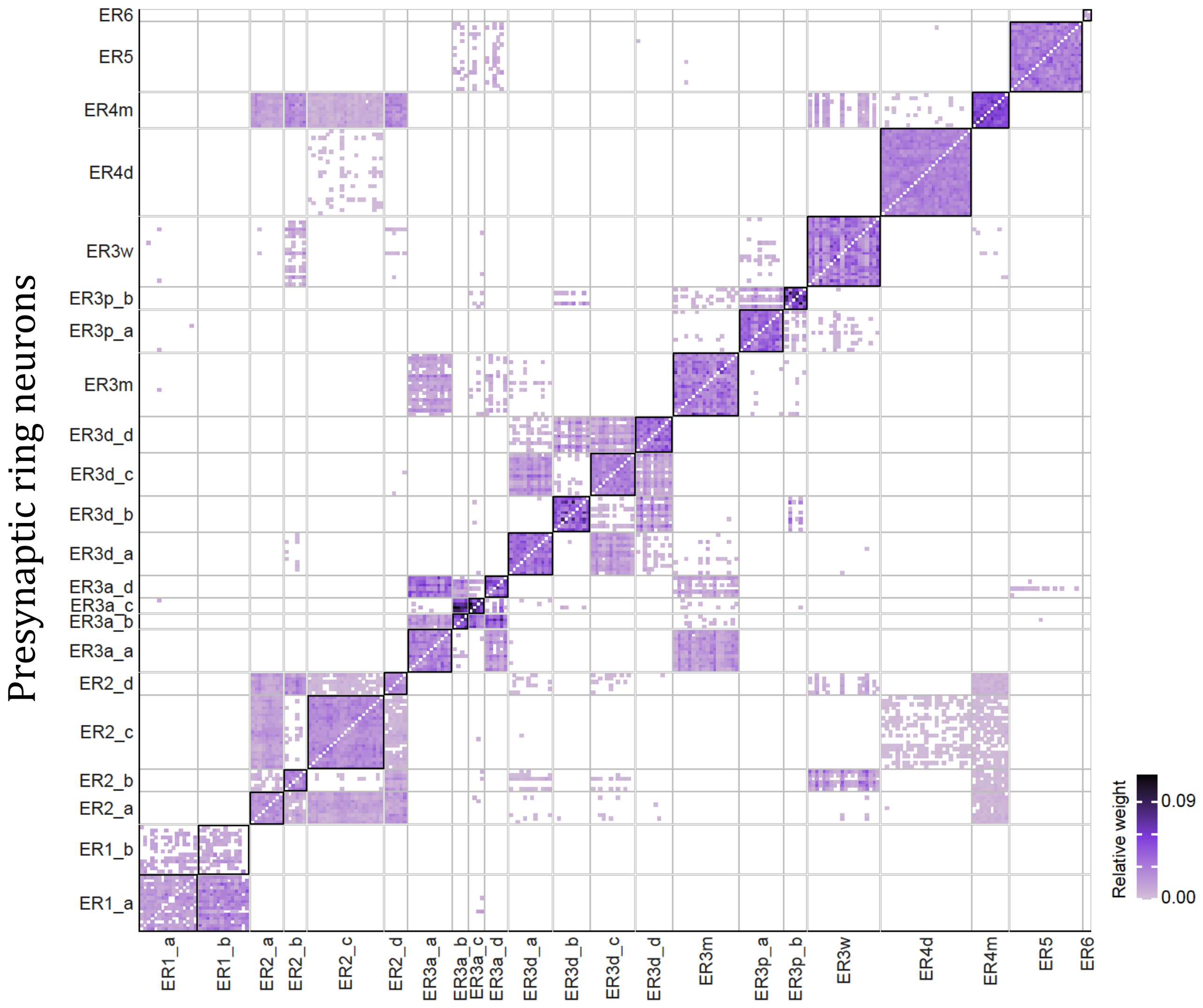
Most "sensory" neurons individually synapse onto all compass neurons



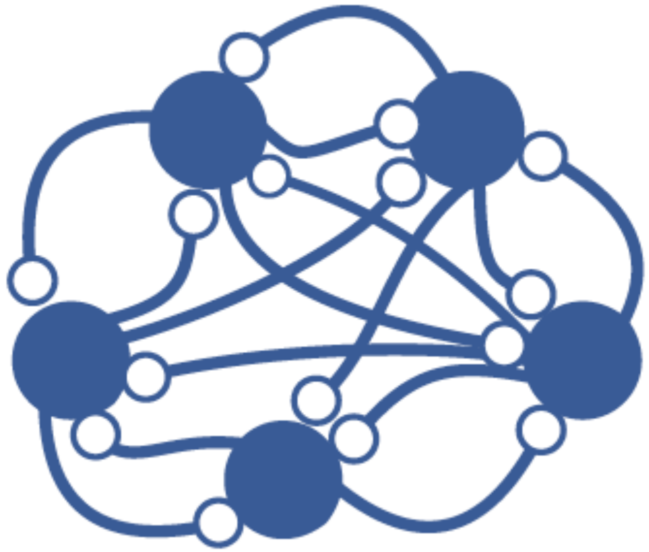


B.K. Hulse*, **H. Haberkern***, R. Franconville*, D.B. Turner-Evans* et al. (2021)

Input neurons synapse onto each other



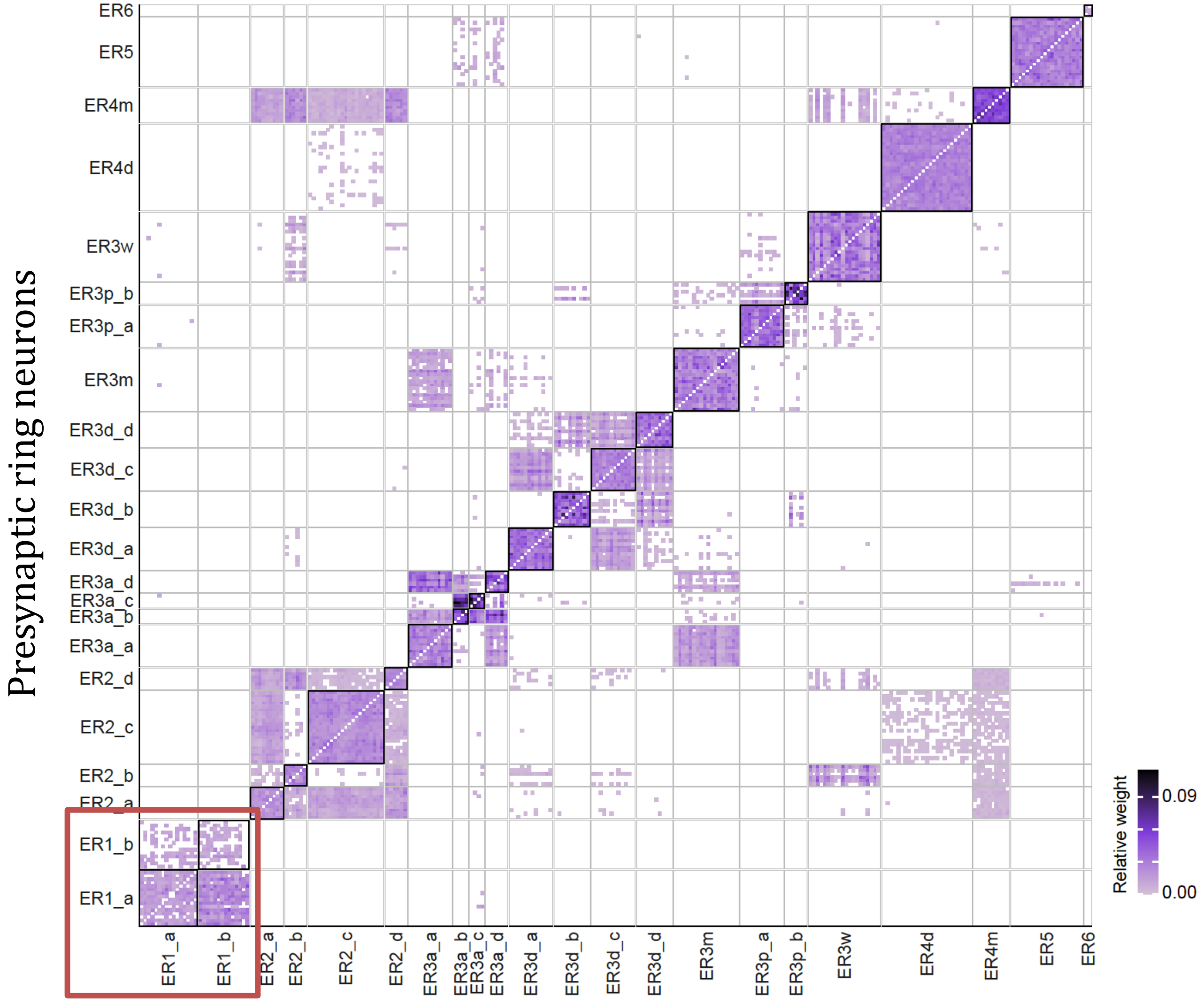
~All-to-all inhibition within type

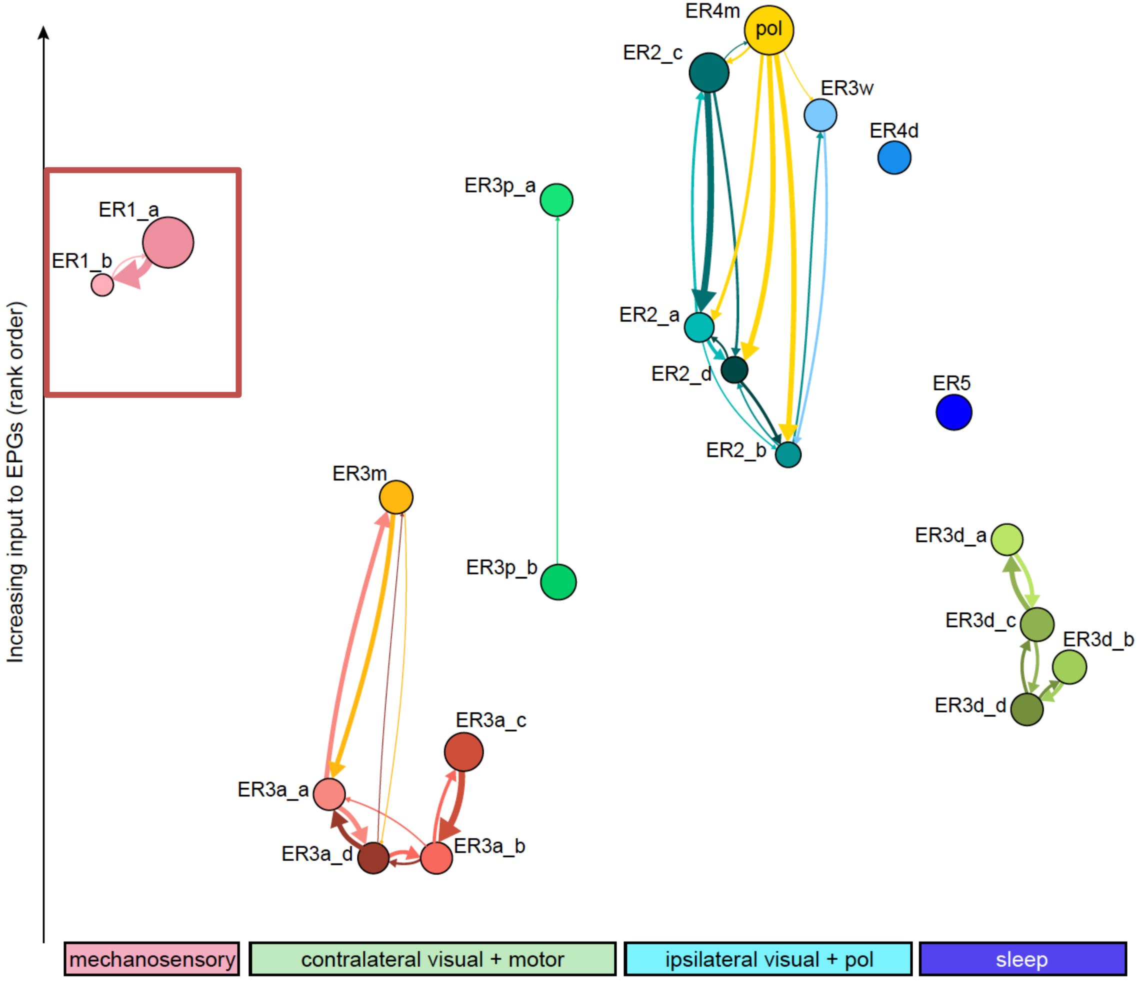


Stimulus selection/ noise suppression

B.K. Hulse*, **H. Haberkern***, R. Franconville*, D.B. Turner-Evans* et al. (2021)

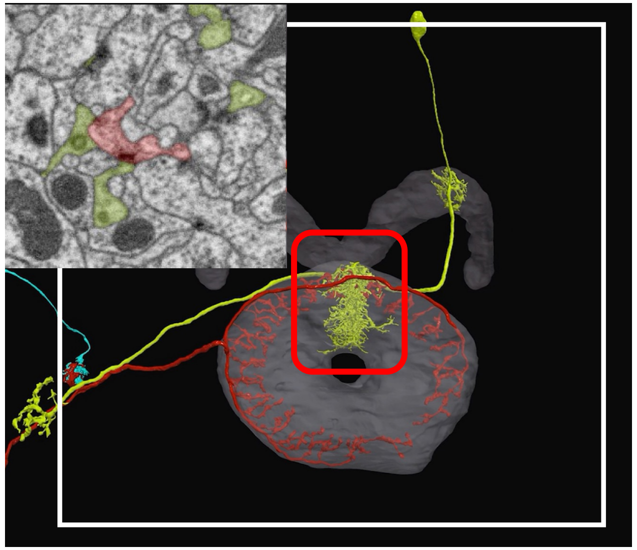
A hierarchy of sensory inputs to the compass





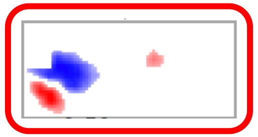
B.K. Hulse*, **H. Haberkern***, R. Franconville*, D.B. Turner-Evans* et al. (2021)

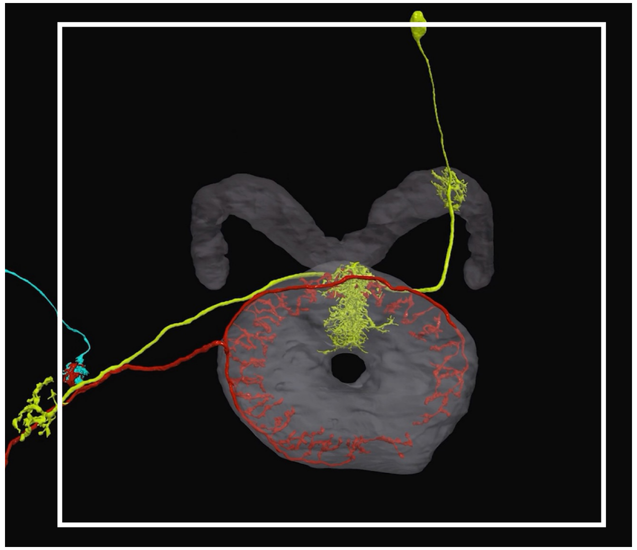
Each input “ring” neuron connects to all compass neurons



B.K. Hulse*, **H. Haberkern***, R. Franconville*, D.B. Turner-Evans* et al. (2021)

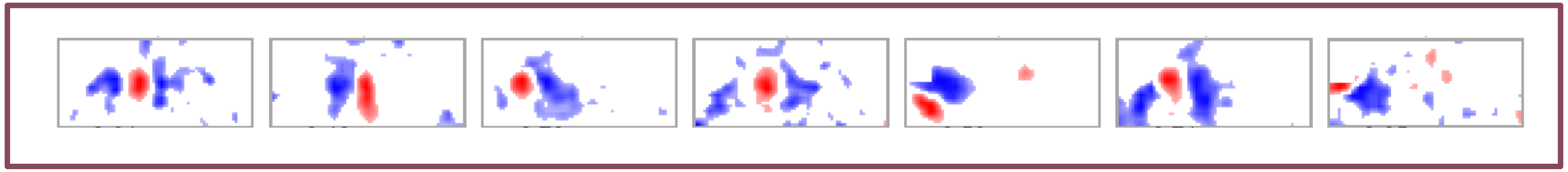
Visual feature input to the compass

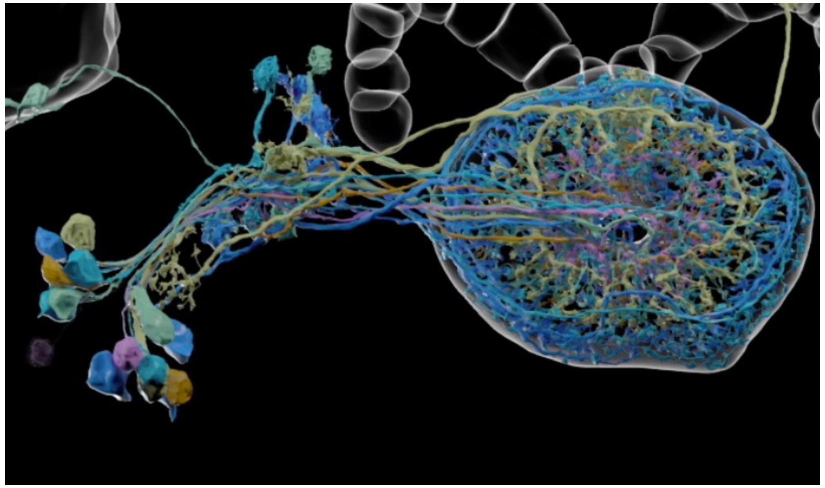




J.D. Seelig & V. Jayaraman (2013), Y. Sun et al. (2017), H.M. Shiozaki & H. Kazama (2017), J.J. Omoto et al. (2017), B.J. Hardcastle et al. (2021)

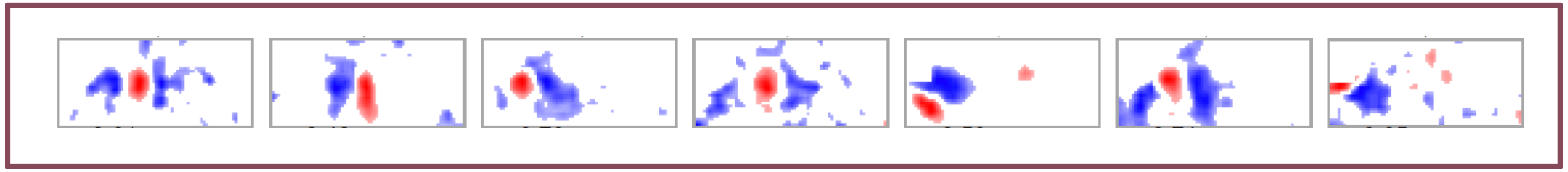
Sample visual receptive fields

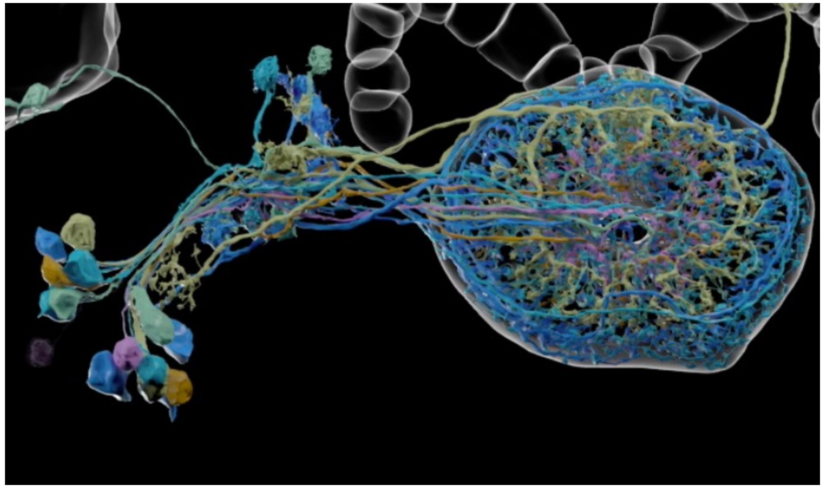




J.D. Seelig & V. Jayaraman (2013), Y. Sun et al. (2017), H.M. Shiozaki & H. Kazama (2017), J.J. Omoto et al. (2017), B.J. Hardcastle et al. (2021)

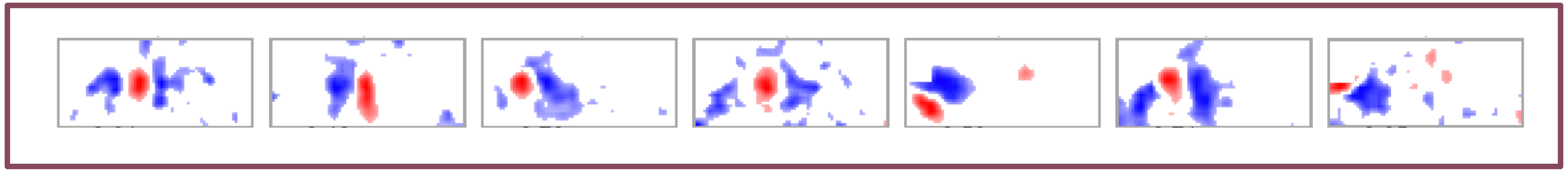
But these synapses are plastic

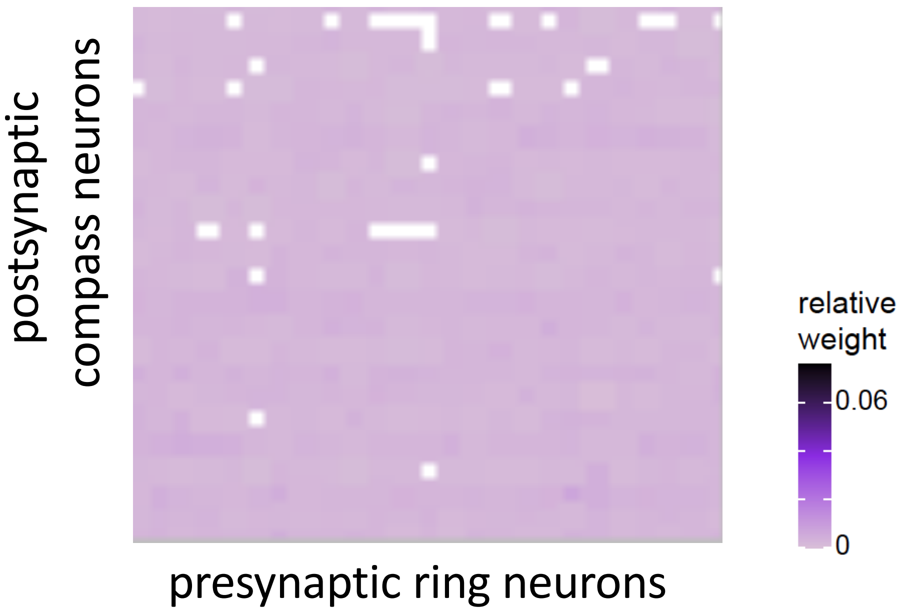




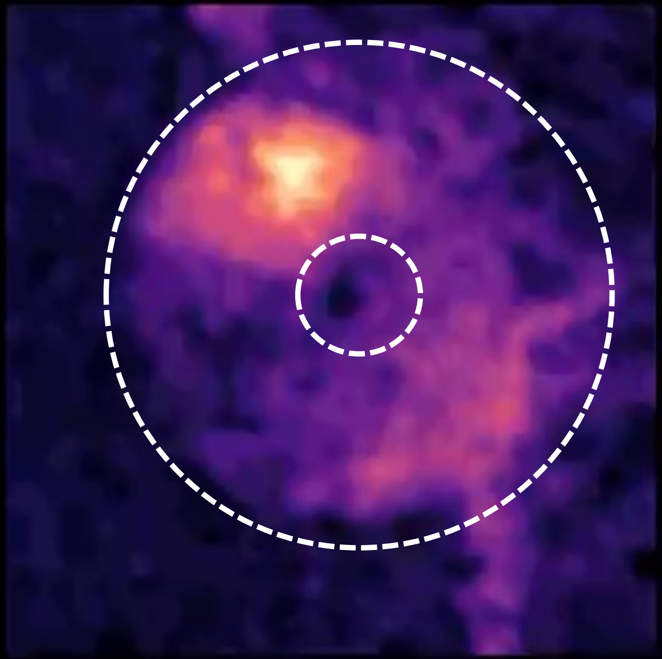
S.S. Kim et al. (2019), Y. Fisher et al. (2019,2022), C. Dan et al. (2021,2022); See also: A. Cope et al. (2017), J. Green & G. Maimon (2018)

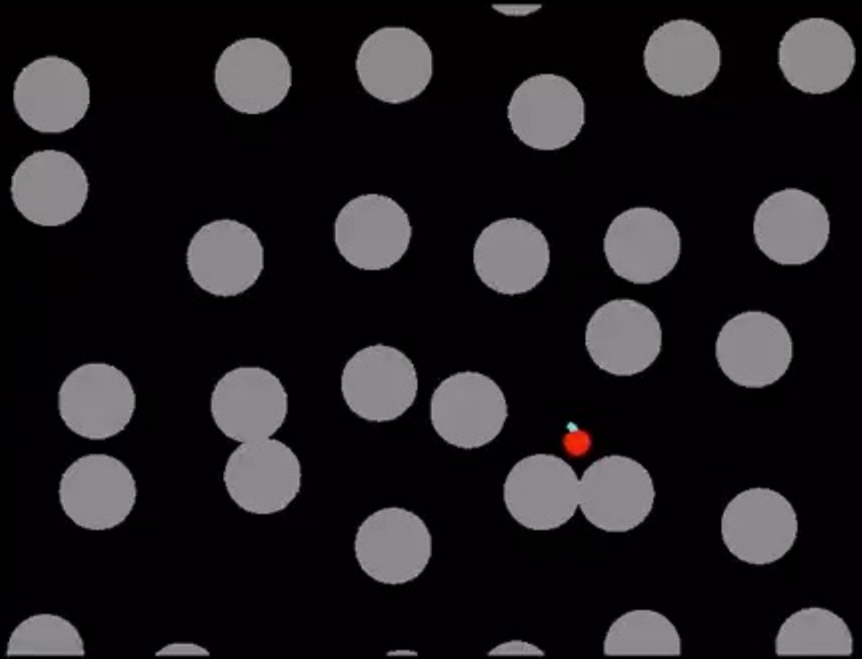
Mapping visual scenes onto the compass





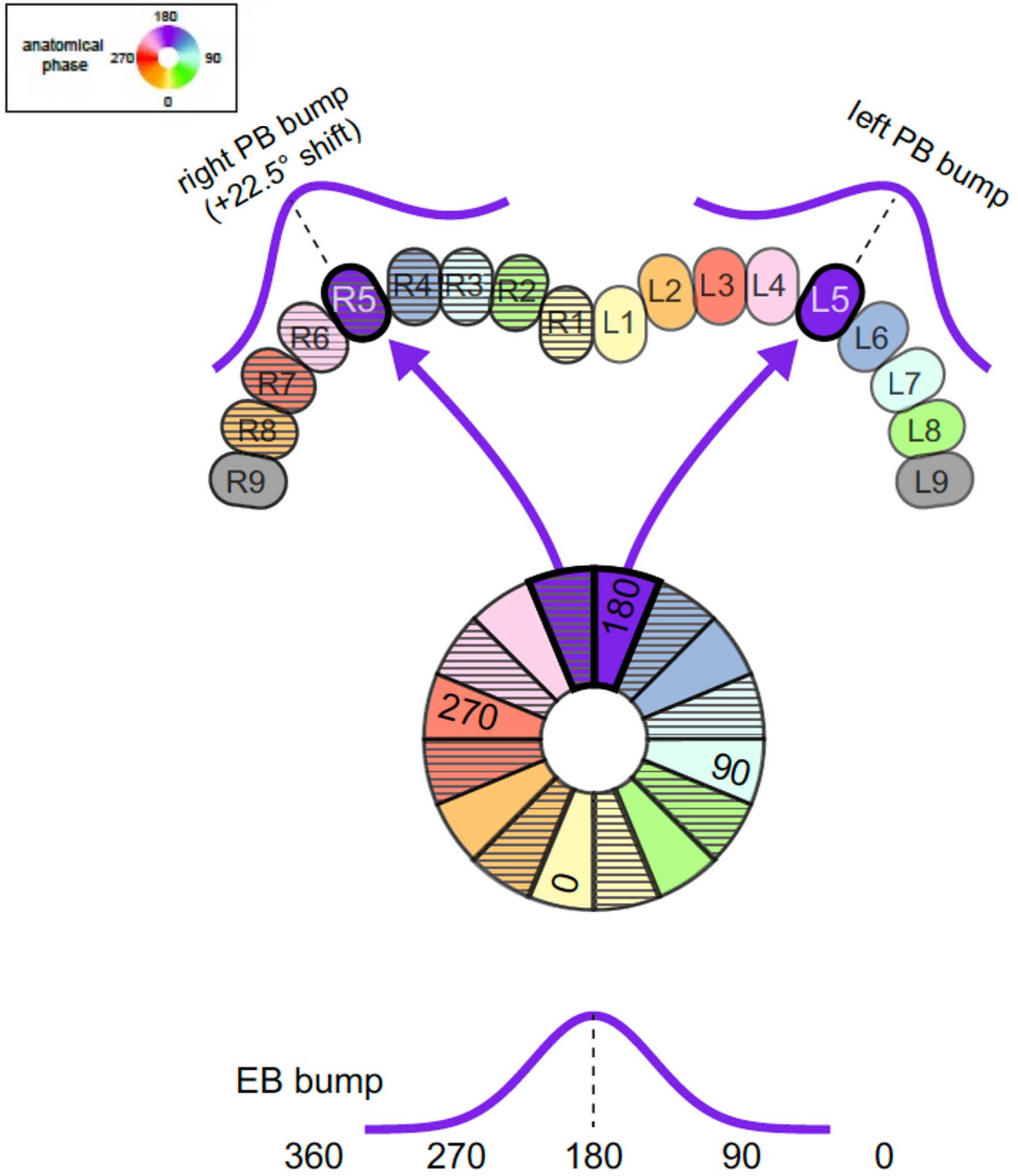
S.S. Kim et al. (2019), Y. Fisher et al. (2019,2022), C. Dan et al. (2021,2022); See also: A. Cope et al. (2017), J. Green & G. Maimon (2018)

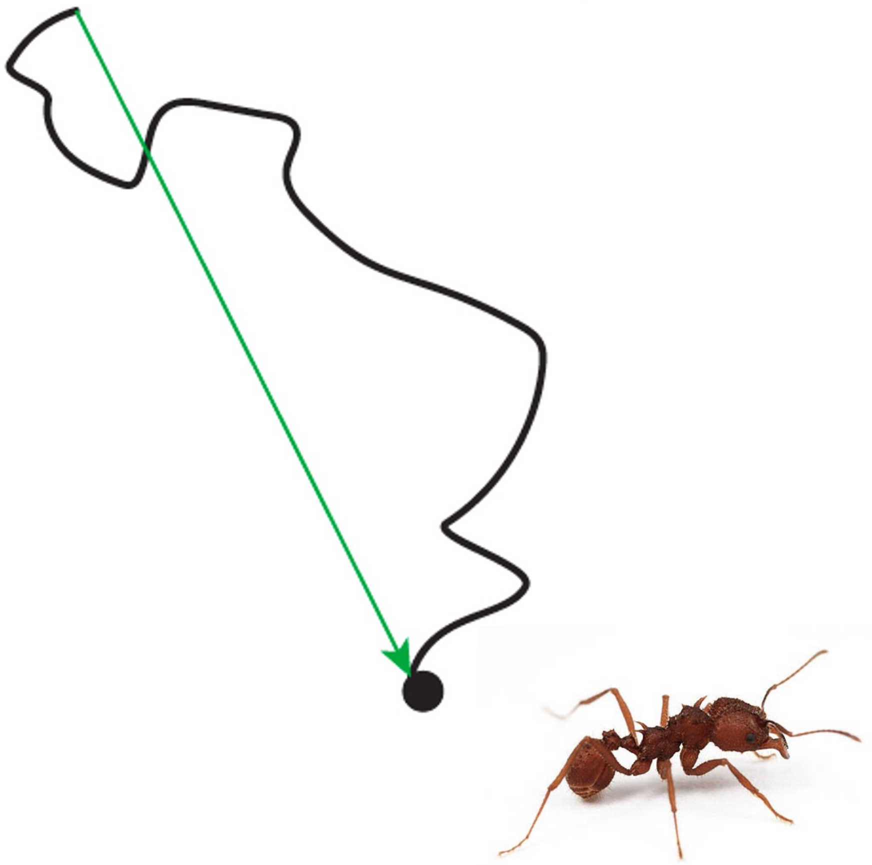




Hannah Haberkern

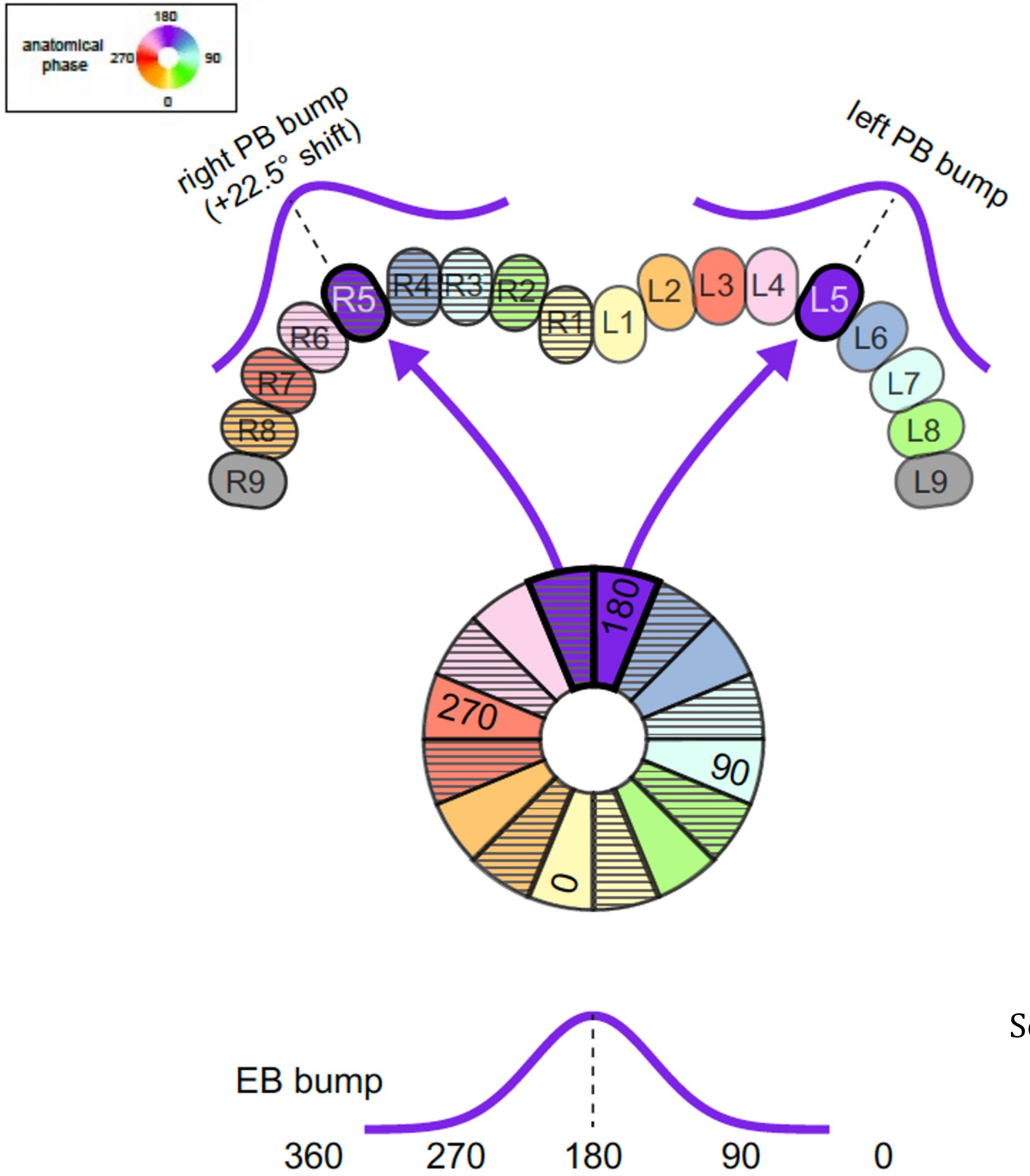
A heading **vector** for goal-driven navigation





Wehner et al.

A heading **vector** for goal-driven navigation



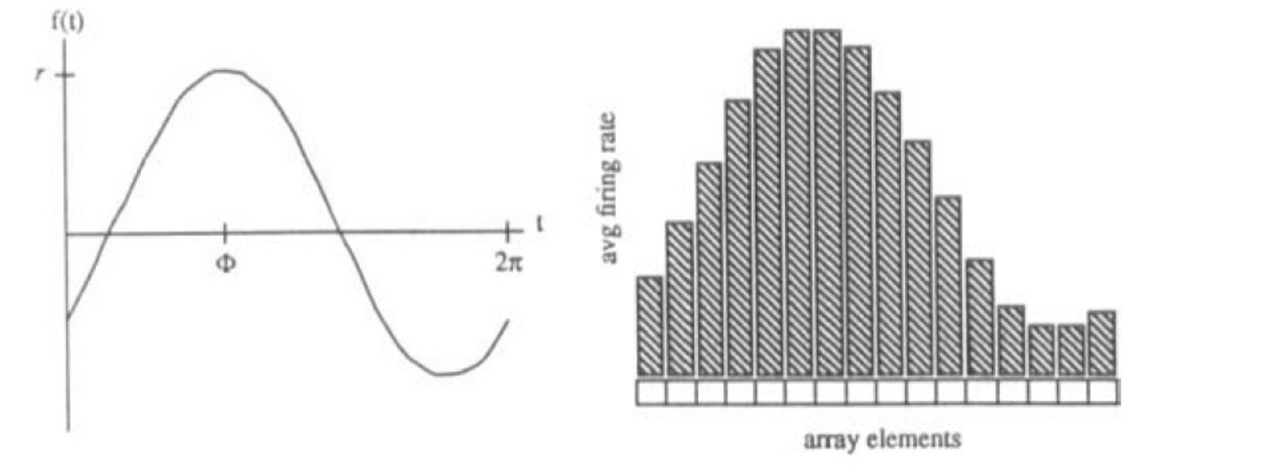
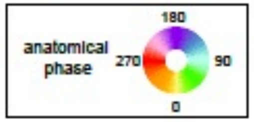


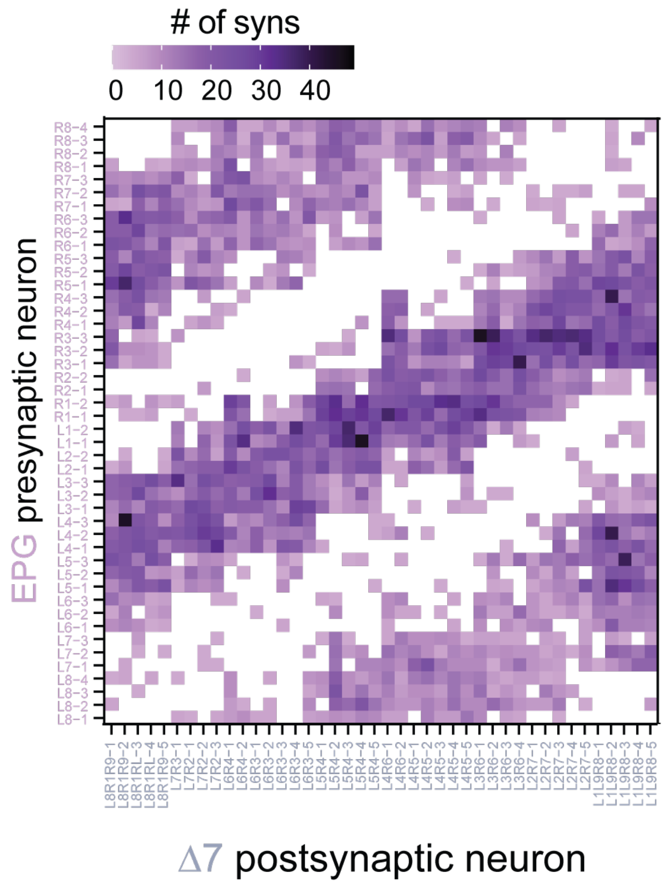
Figure 1: The phasor (r, ϕ) and its sinusoidal array representation.

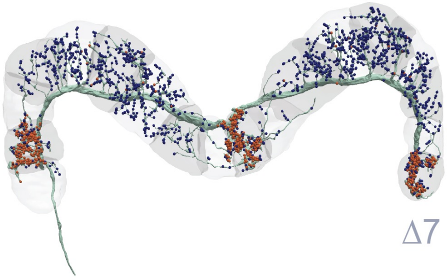
Touretzky et al., Neural Computation (1993)

See also: Zipser and Andersen, 1988; Andersen et al., (1993); Salinas and Abbott, (1995); Pouget and Sejnowski, (1997); Pouget and Snyder, (2000); Todorov 2002

Heading activity bump is formatted as a cosine



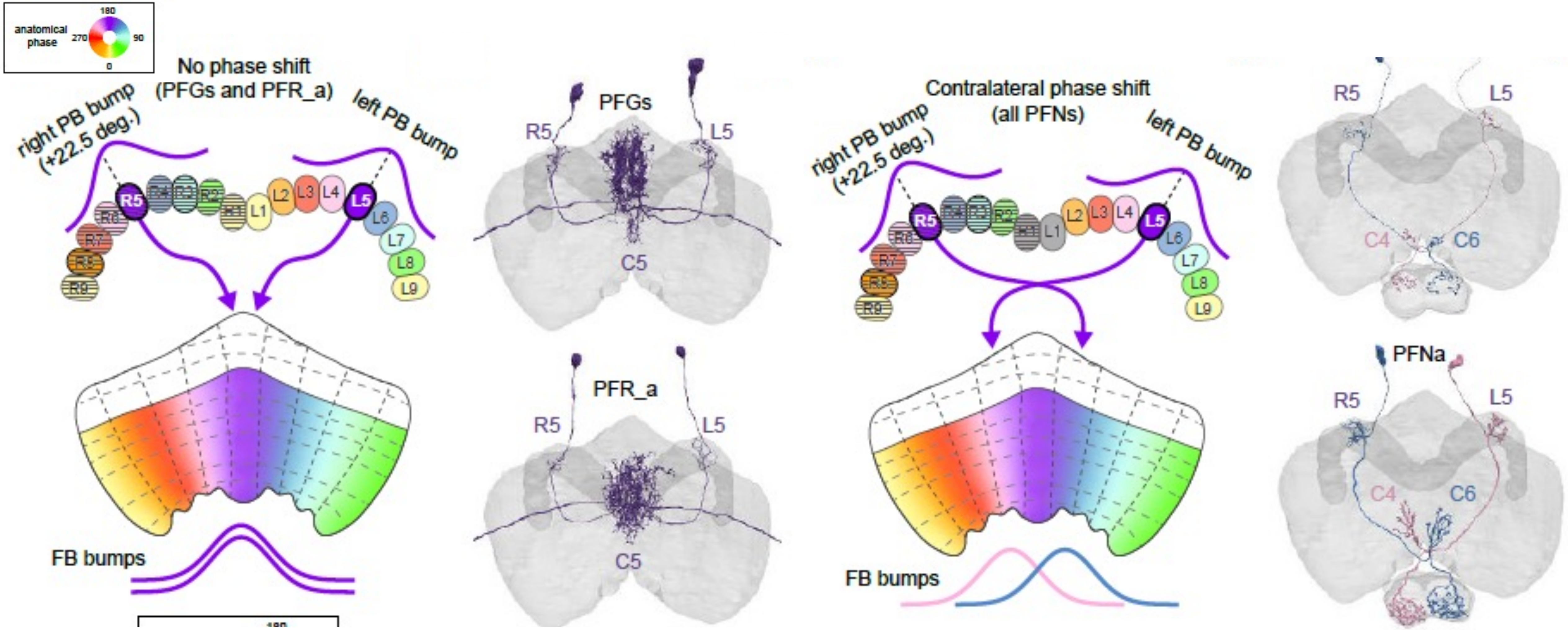




See also: Lyu et al. (2022)

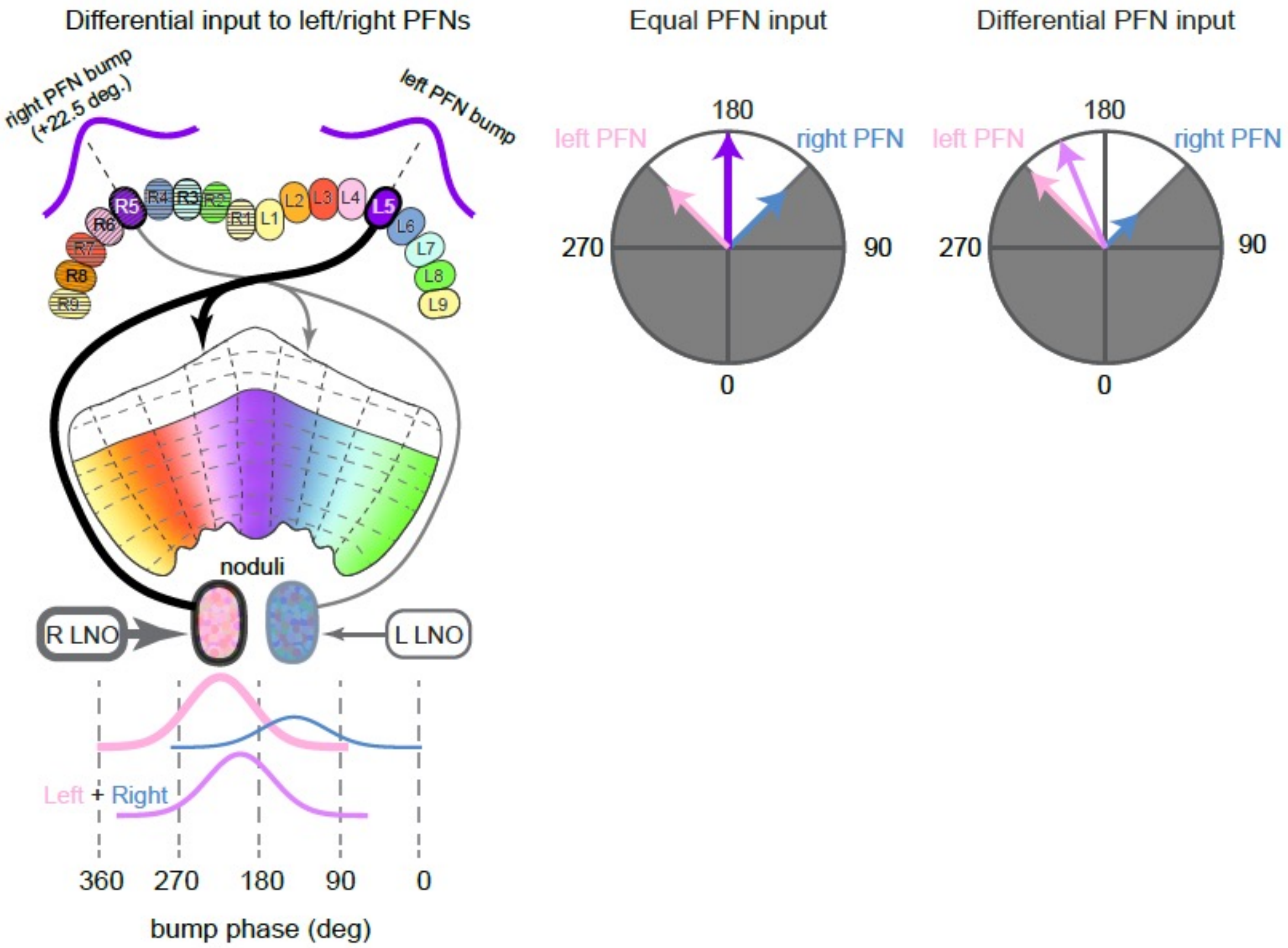
B.K. Hulse*, H. Haberkern*, R. Franconville*, **D.B. Turner-Evans*** et al. (2021)

Anatomical phase shifts in the fan-shaped body (FB)



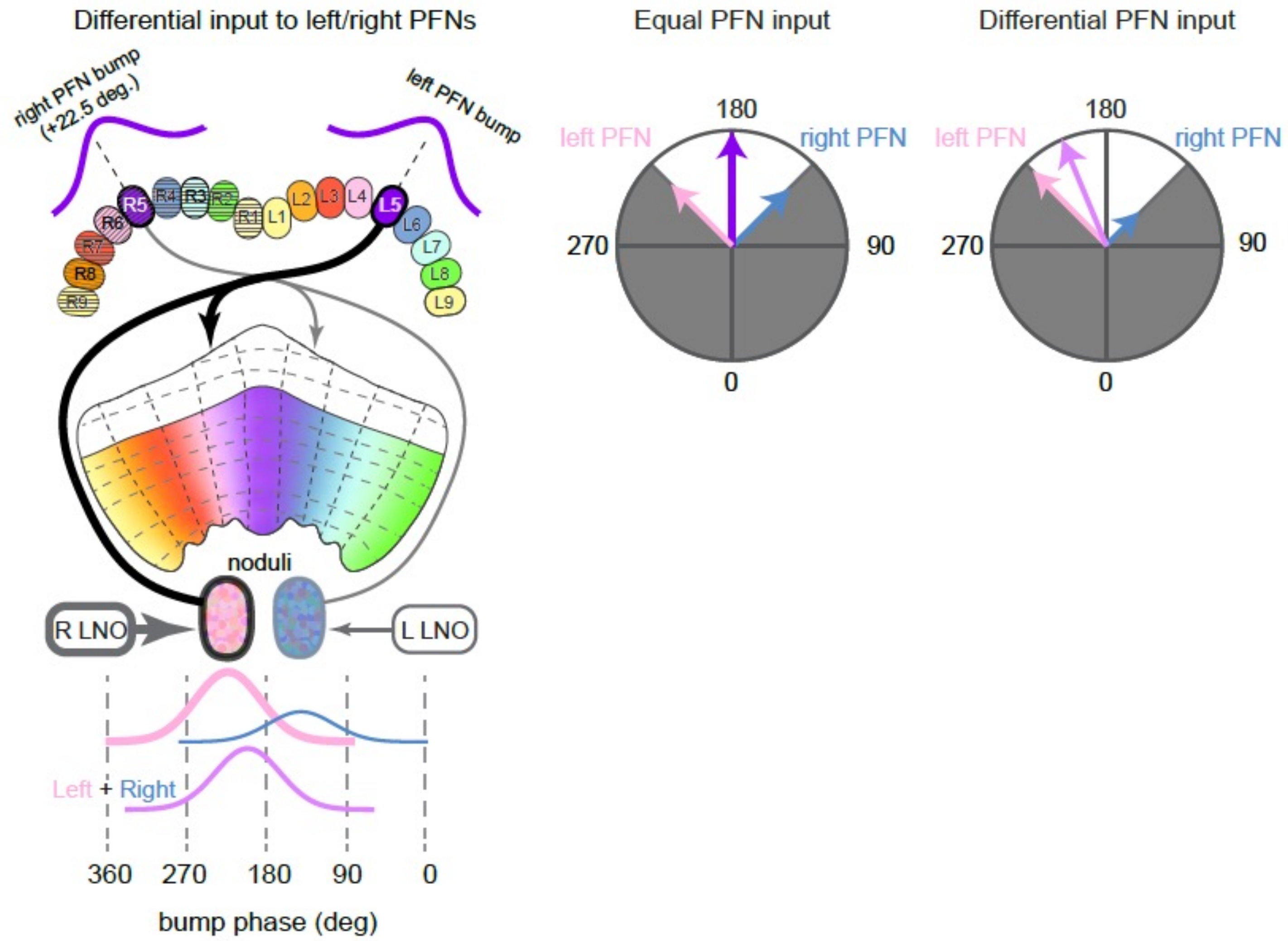
See also: Stone et al. (2017) (Heinze & Webb labs) **B.K. Hulse***, H. Haberkern*, R. Franconville*, D.B. Turner-Evans* et al. (2021)

A circuit motif for coordinate transformations



B.K. Hulse*, H. Haberkern*, R. Franconville*, D.B. Turner-Evans* et al. (2021)

A circuit motif for coordinate transformations

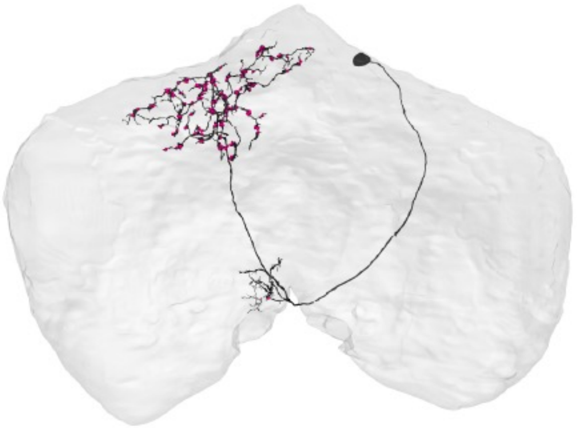


Stone et al., Current Bio. (2017)
Shiozaki, et al., Neuron (2020)
Currier et al., eLife (2020)

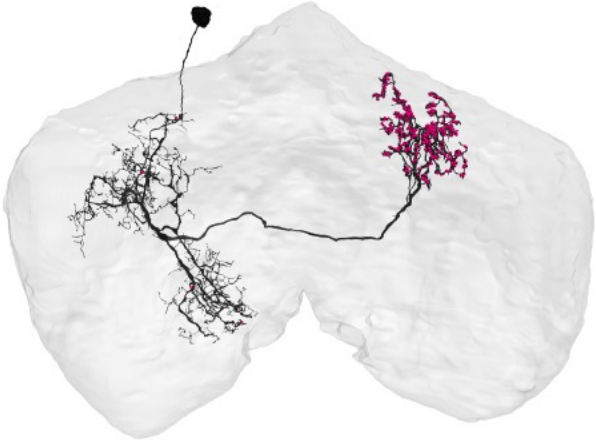
Self-motion input

See also: C. Lyu et al. (2022); J. Lu et al. (2022)

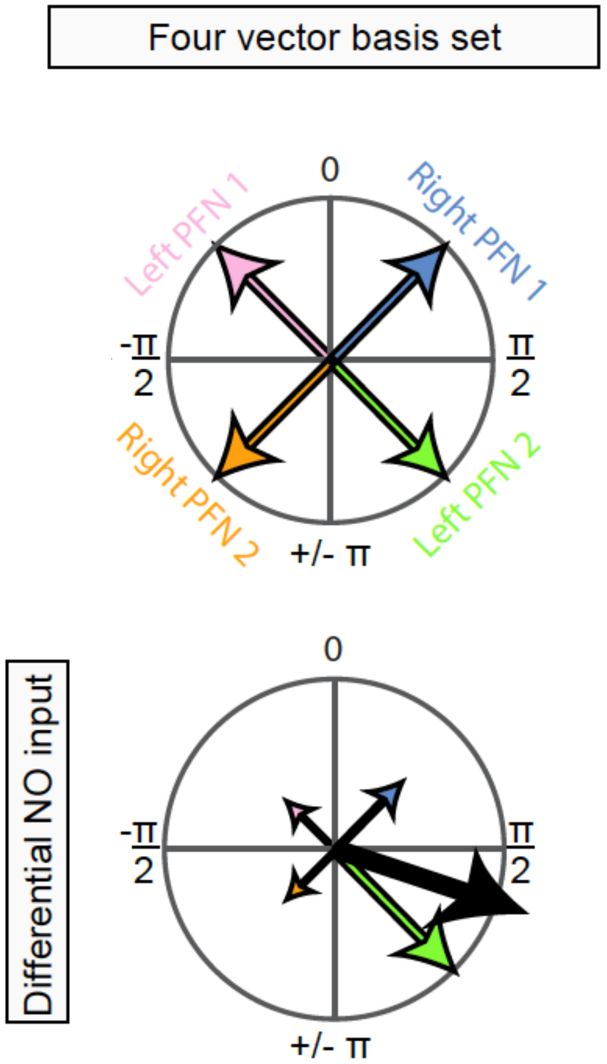
B.K. Hulse*, H. Haberkern*, R. Franconville*, D.B. Turner-Evans* et al. (2021)



vΔ (vΔD)



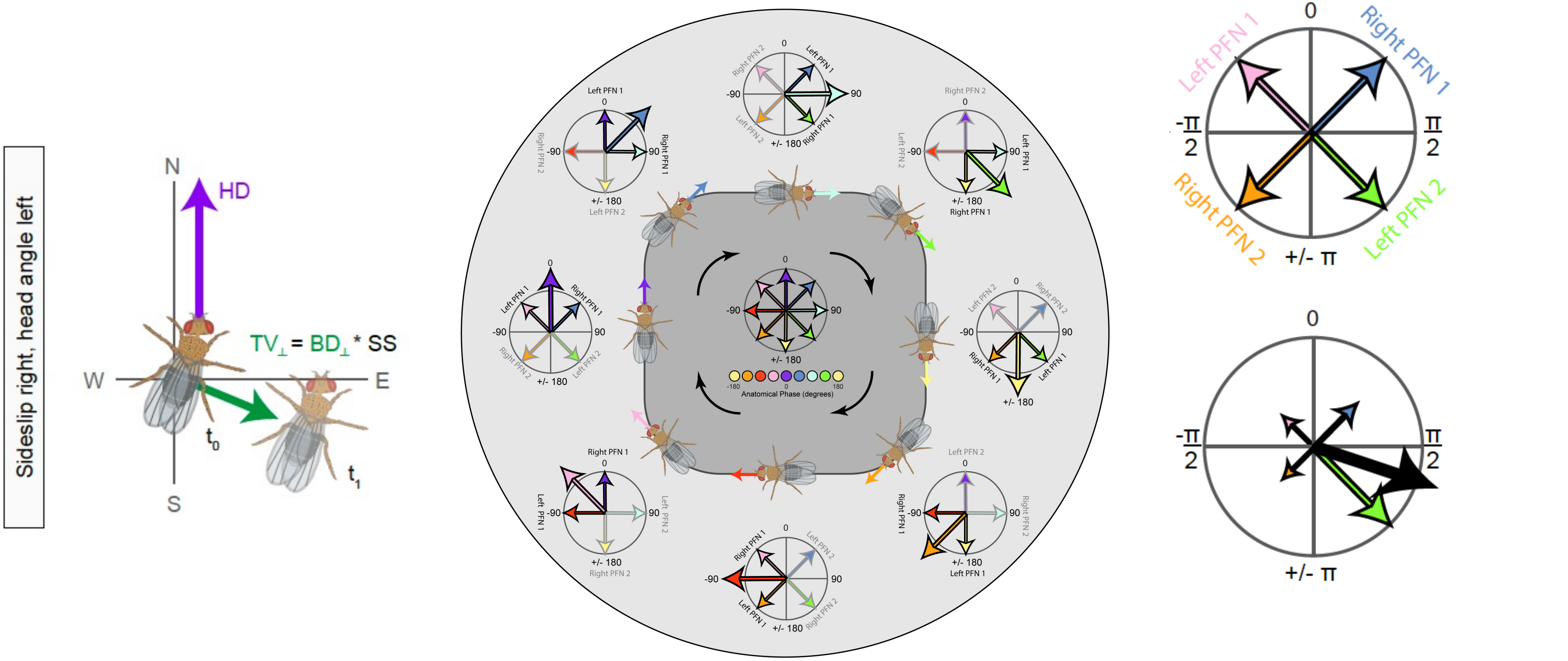
hΔ (hΔC)



= 180° phase shift!

B.K. Hulse*, H. Haberkern*, R. Franconville*, D.B. Turner-Evans* et al. (2021)

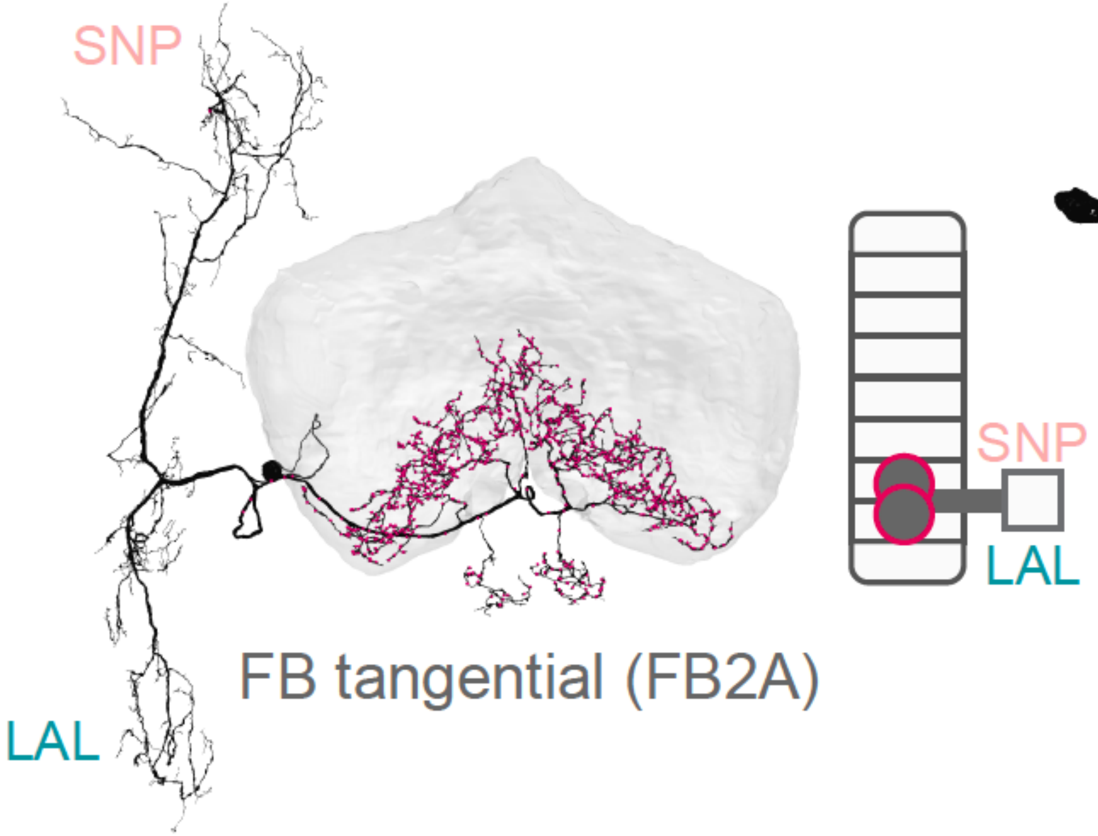
A 4-vector basis set for arbitrary vector computation

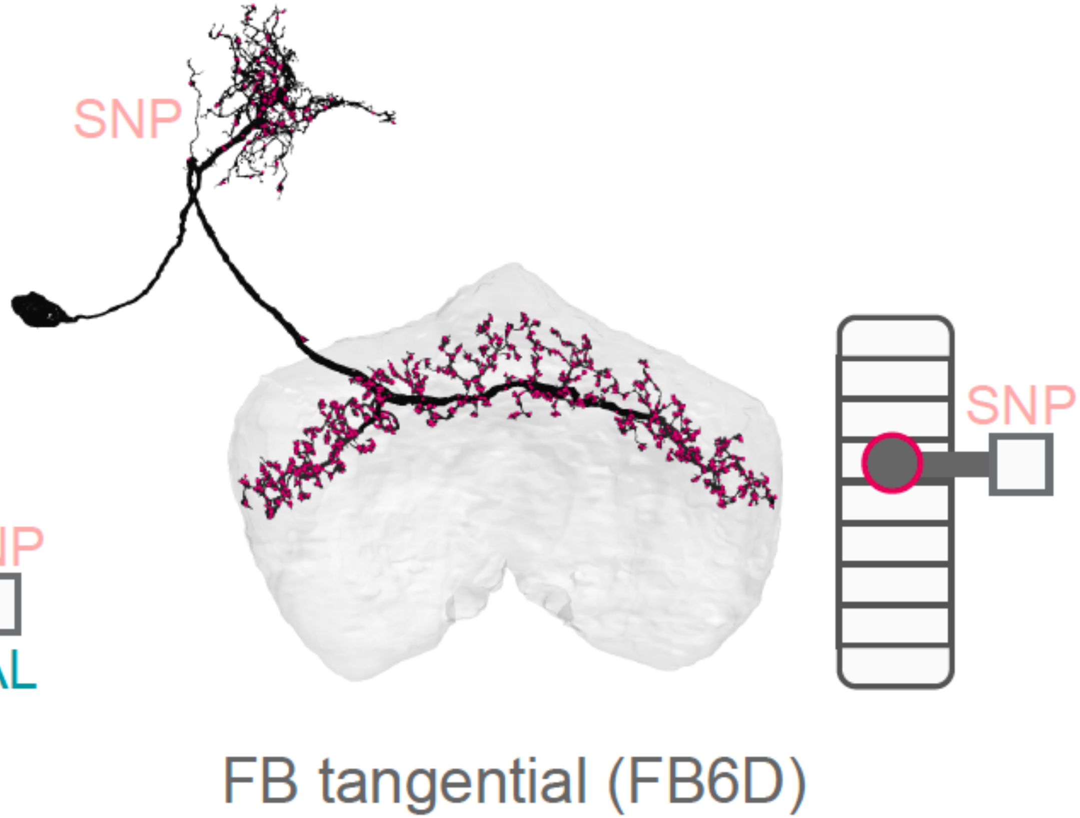


See also: Lyu et al. (2022); Lu et al. (2022)

B.K. Hulse*, H. Haberkern*, R. Franconville*, D.B. Turner-Evans* et al. (2021)

Setting context for goal-driven behavior with a variety of "tangential" neurons



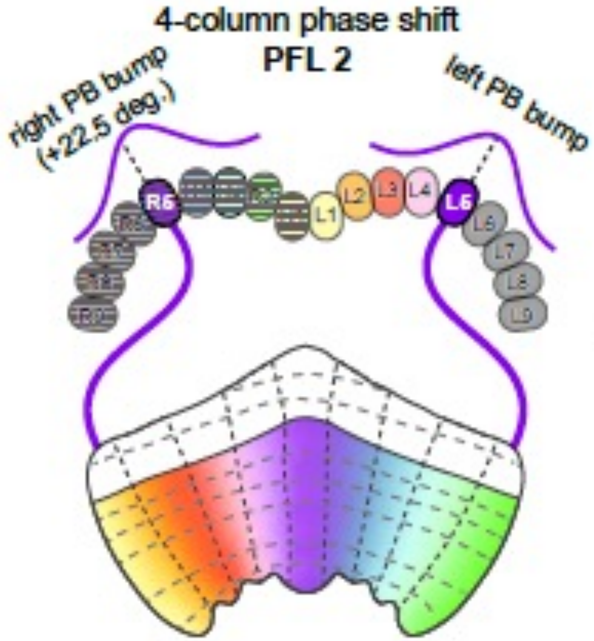


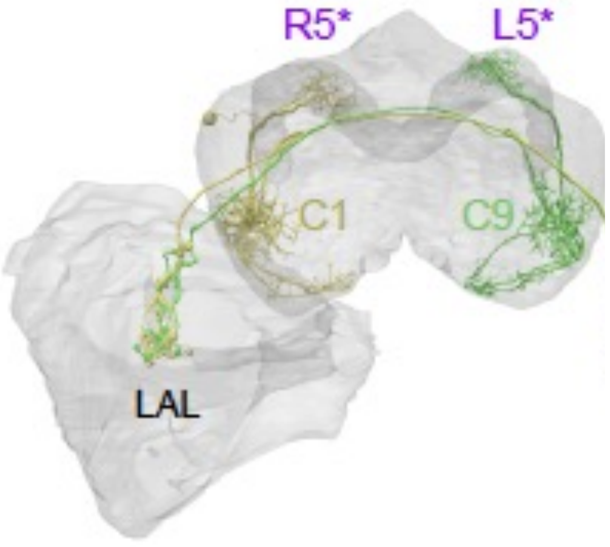
See also: Stone et al. (2017); Sun et al. (2020); Goulard et al. (2021); Pires et al. (2024); Matheson et al. (2021)

Dan, Hulse, Kappagantula, Jayaraman & Hermundstad, (2021, 2022)

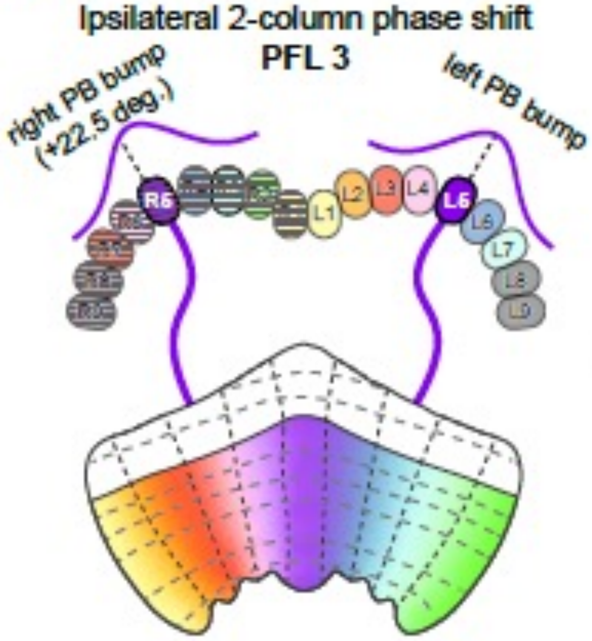
Phase shifts enable rapid learning of goal-heading-driven behavior

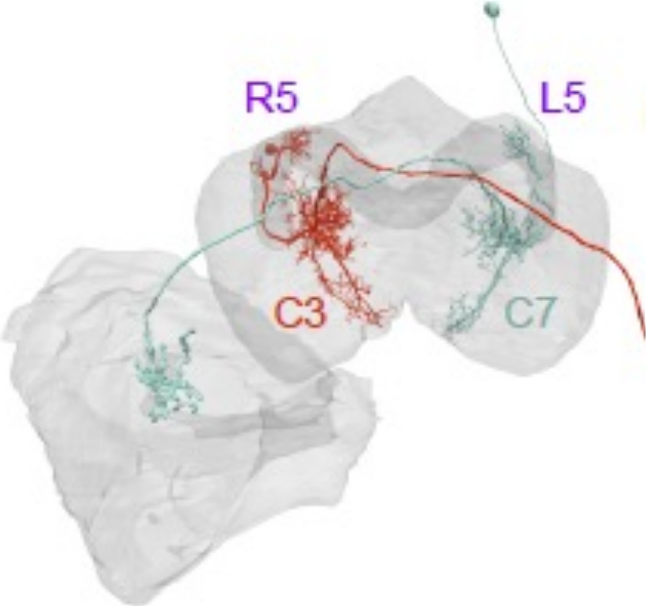
180° phase shift (forward movement)





90° phase shift (turn distribution)

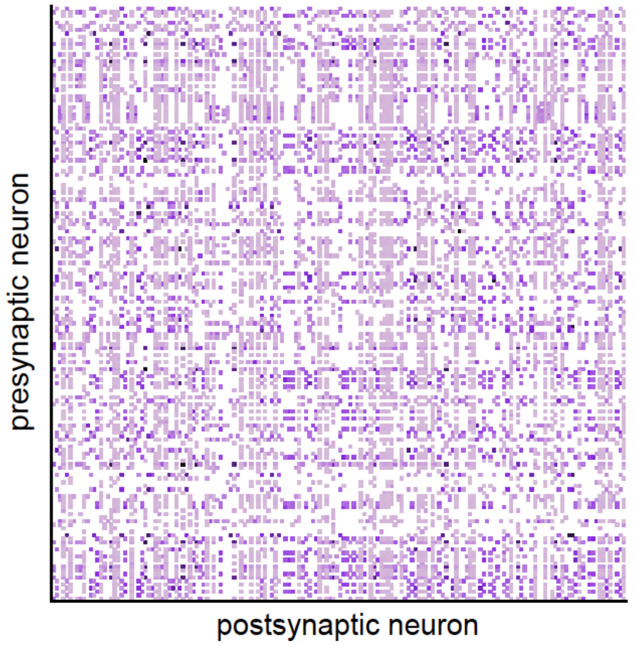


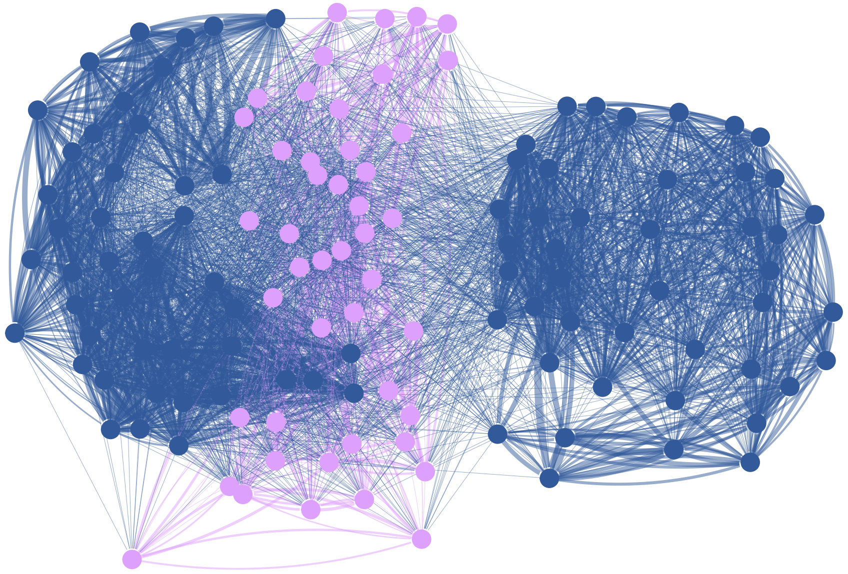


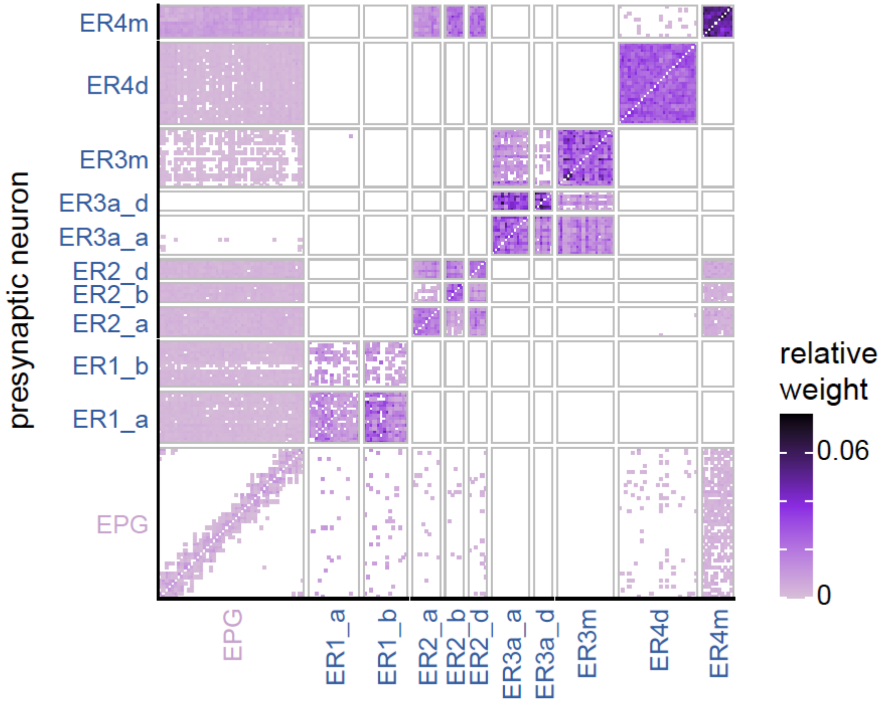
See also: Stone et al. (2017);
Sun et al. (2020); Goulard et al. (2021);
Pires et al. (2024); Westeinde et al. (2024)

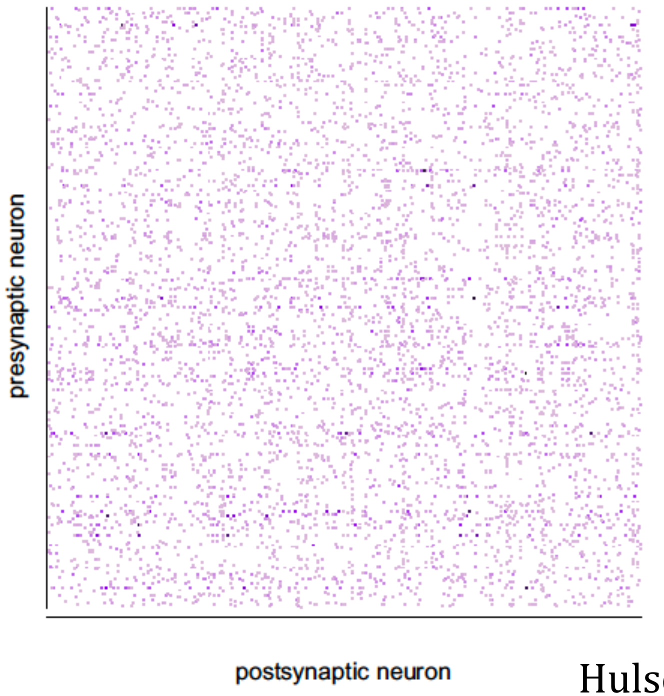
Dan, Hulse, Kappagantula, Jayaraman & Hermundstad, (2021, 2022)

B.K. Hulse*, H. Haberkern*, R. Franconville*, D.B. Turner-Evans* et al. (2021)



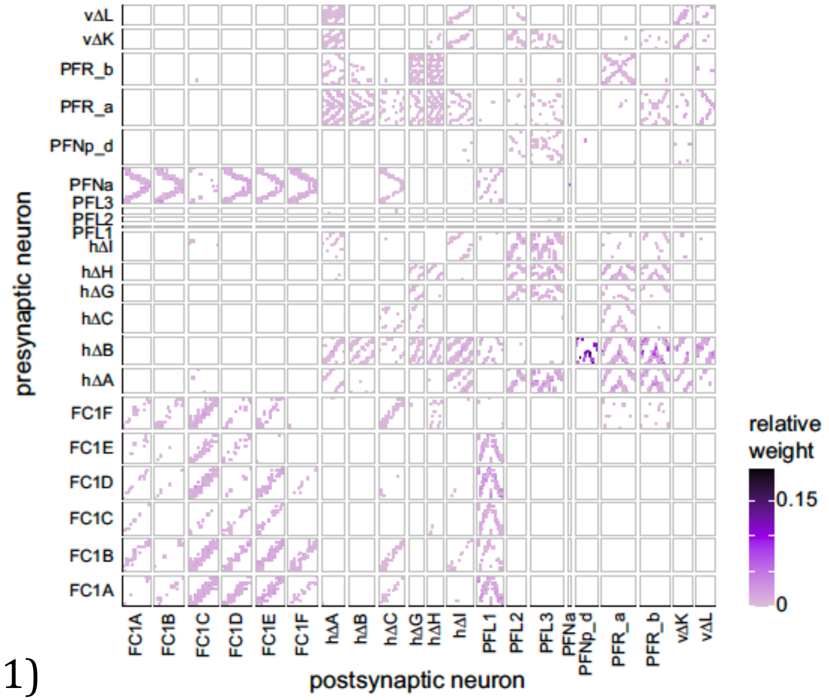






Knowledge of cell type /connectivity

"mixed selectivity"
"conjunctive coding" ?



Hulse*, Haberkern*, Franconville*, **Turner-Evans*** et al. (2021)

The lab

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(½ Hermundstad lab)

Chad Sauvola

Shivam Chitnis

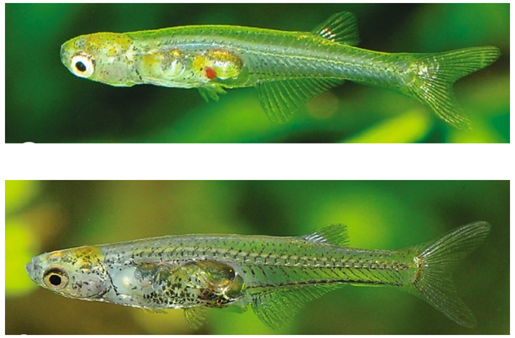
Angel Stanoev
(½ Romani lab)

Pavithraa Seenivasan
(½ Reiser lab)

Chuntao Dan

Kristin Henderson

Deepika Gupta
(½ Shroff lab)



Britz et al. (2021)

Lab coordinator
Dianne Pereira

Past members & collaborators

at this workshop

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(MPI GL, CAESAR)

Eugenia Chiappe
(Grp Ldr, Champalimaud)

Stephanie Wegener
(DFG, Germany)

Sung Soo Kim*
(Asst. Prof., UCSB)

Dan Turner-Evans
(Asst. Prof., UCSC)

Romain Franconville

Hannah Haberkern
(Group Leader, U. Würzburg)

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Marcella Noorman*
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Sandro Romani*
Larry Abbott*

Gerry Rubin
+
Tanya Wolff
Aljoscha Nern

Michael Reiser
+
lab

Yoshi Aso
+
lab

Janelia Experimental Technology

Scientific Computing

Quantitative Genomics

Visiting scientists
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Carlos Ribeiro

Aisha Hamid
Syed Mubarak

FlyEM

FlyCore

FlyLight

GENIE

Project Pipeline Support

Project Technical Resources

Dreher Design Studio

Josh Dudman
Luke Coddington

Chie Satou
Misha Ahrens
Hari Shroff
Kristin Branson
+
lab

Aquatics

MCN-NET
(Carmen Morrow)

+
Many, many more!