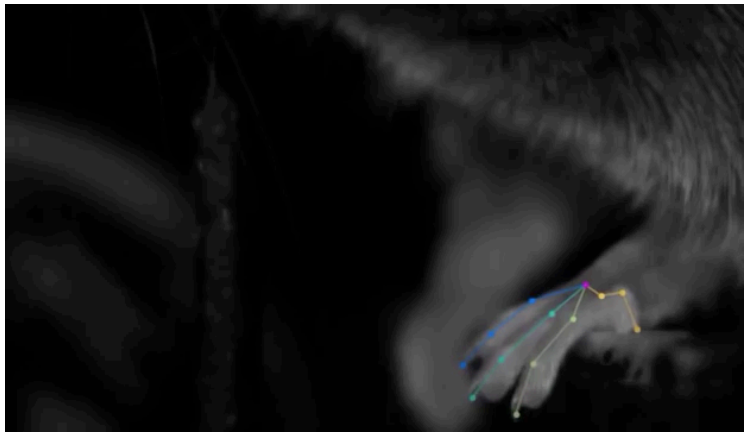
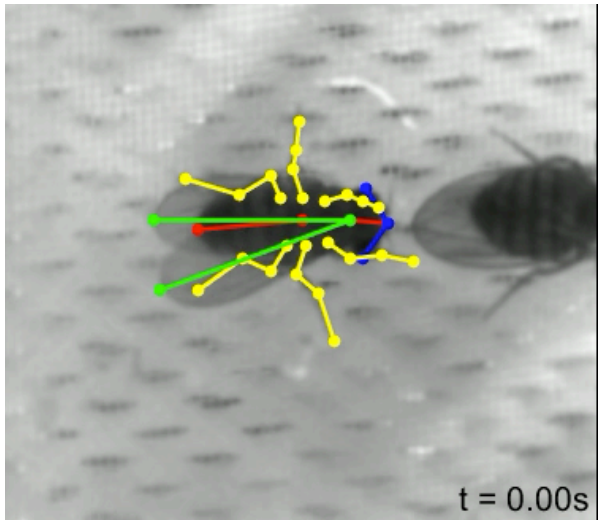


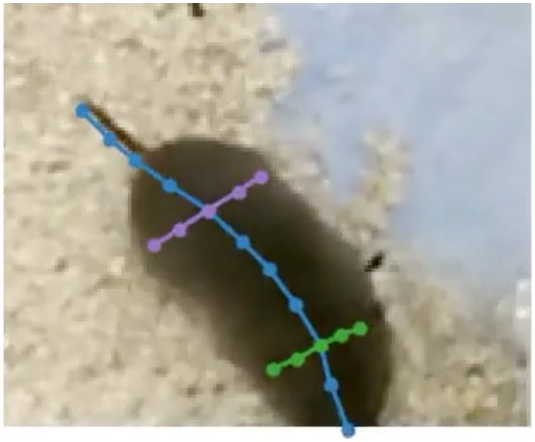
*Mathis et al (2018)*

*Machado et al, 2015*

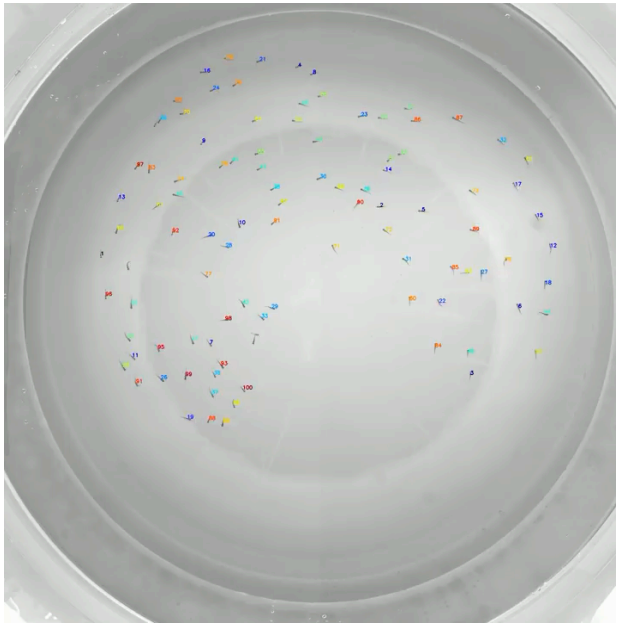


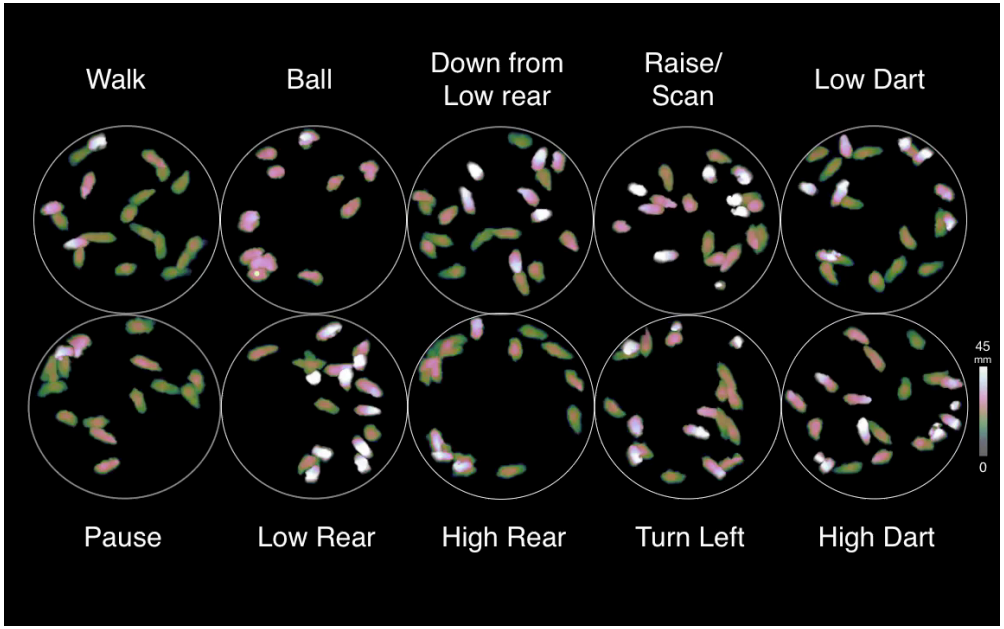

*Pereira et al (2018)*

*Kanishk Jain*

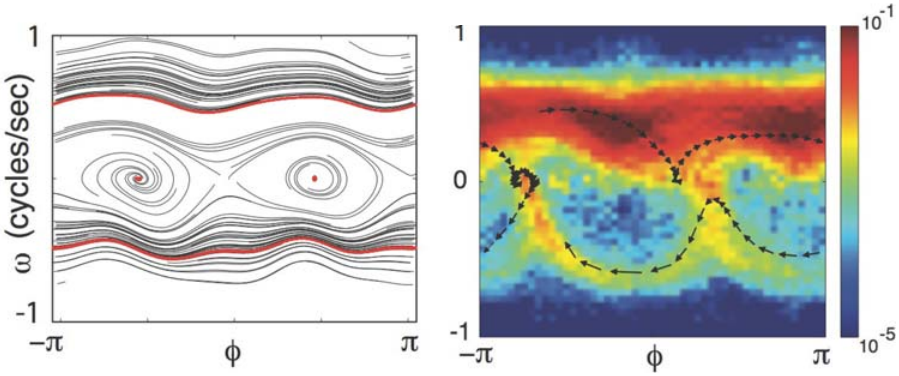


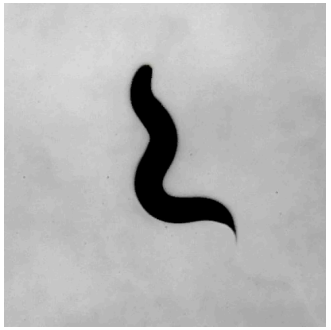
*Romero-Ferrero et al, 2019*



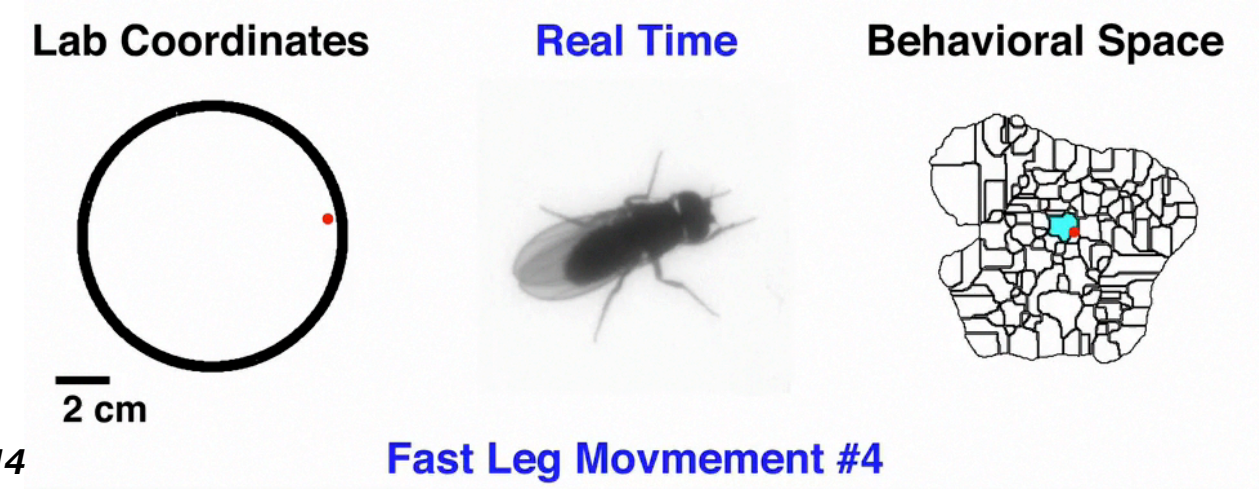



*Wiltschko et al, 2015*



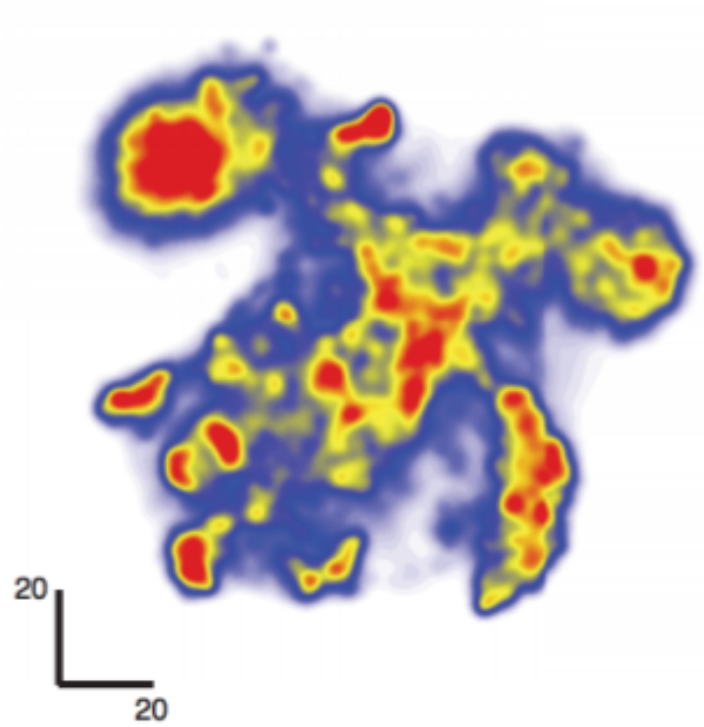



*Stephens et al, 2008*




*GJB et al, 2014*

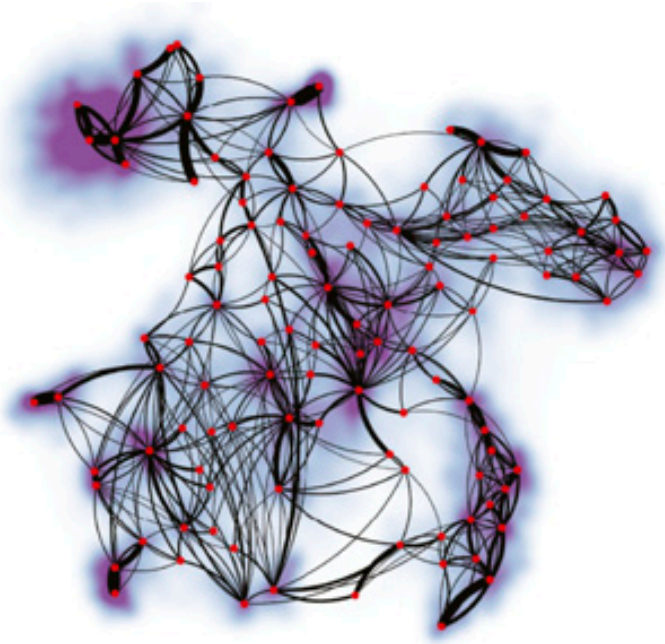
**Individual Flies:**





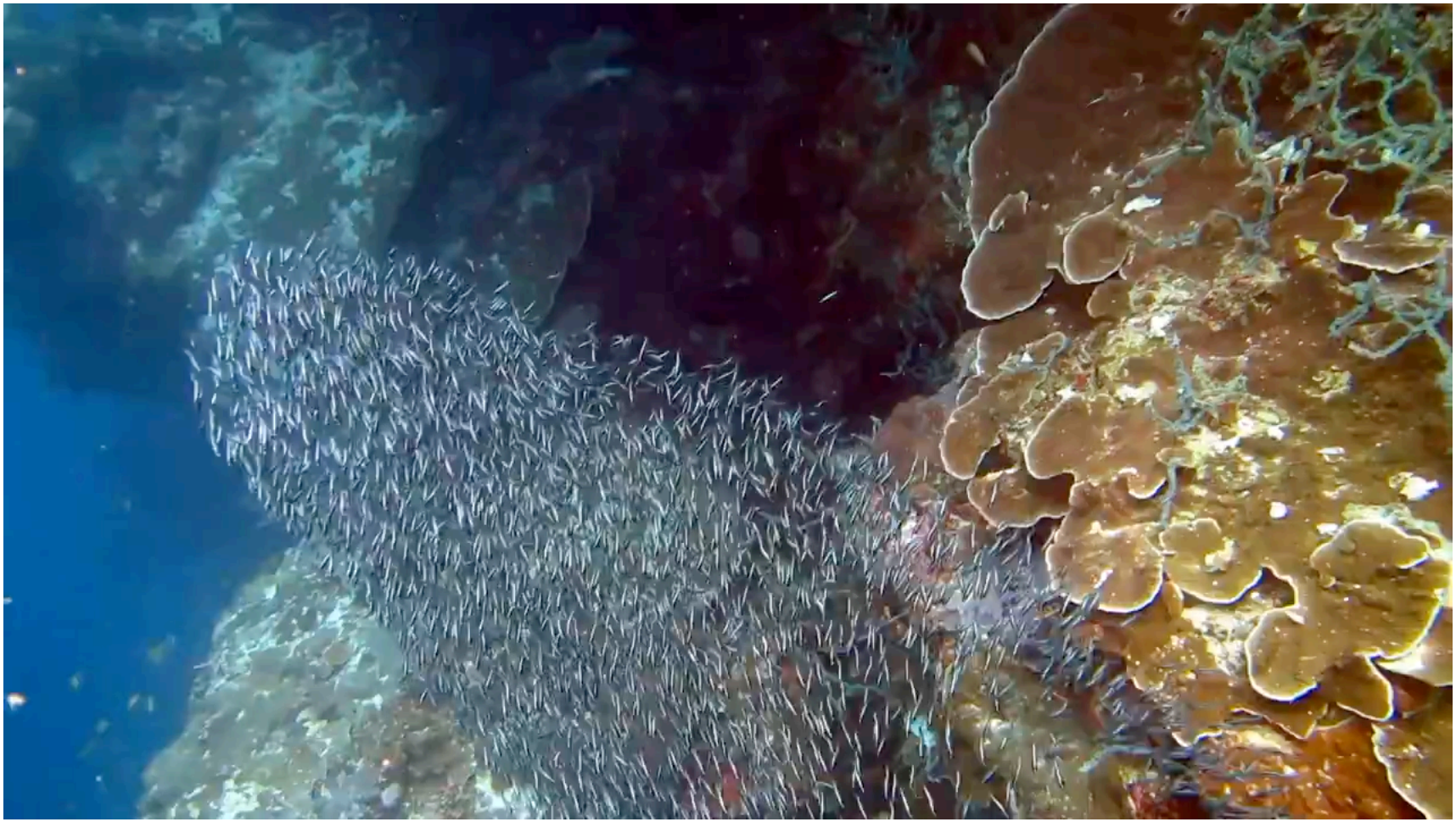
*GJB et al, 2016*

**Individual Flies:**

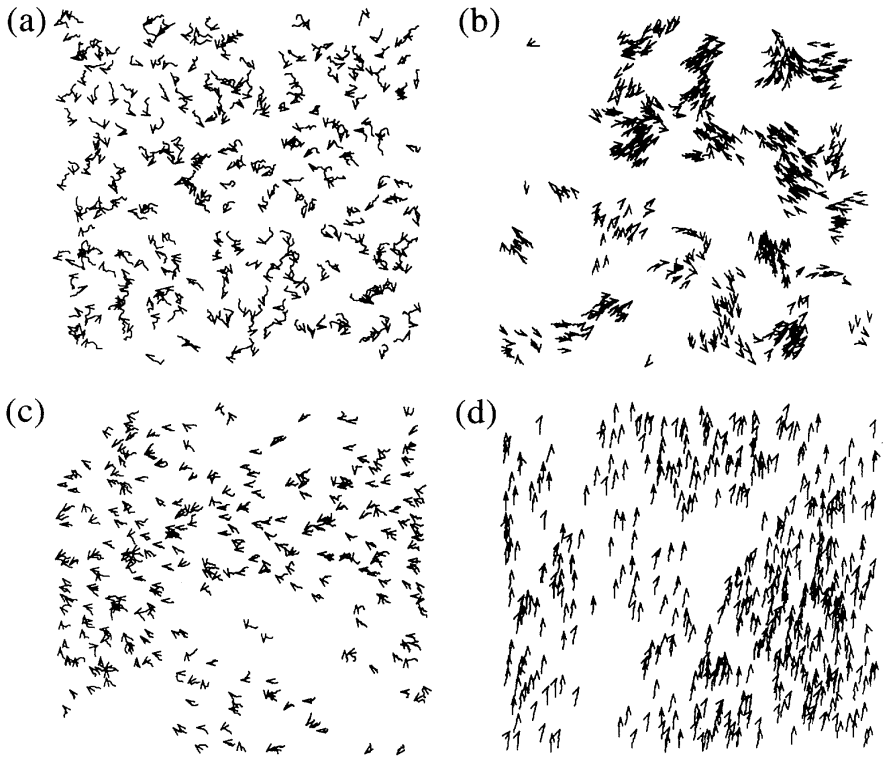


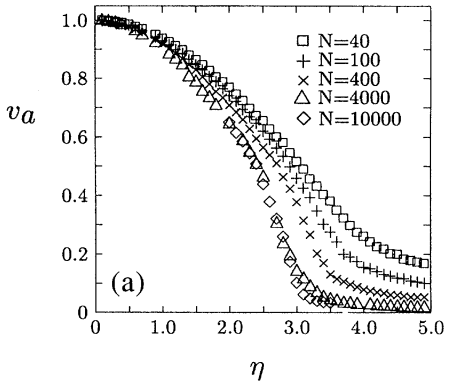

= .5

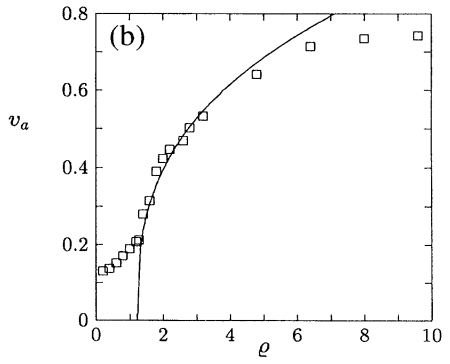
# A prelude



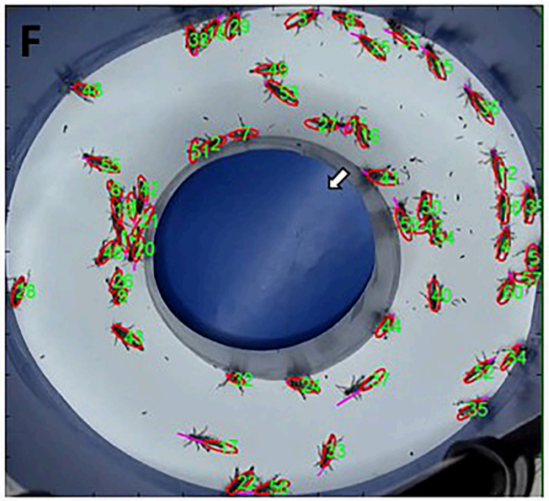
$$\mathbf{x}_i(t+1) = \mathbf{x}_i(t) + \mathbf{v}_i(t)\Delta t$$
$$\theta(t+1) = \langle\theta(t)\rangle_r + \Delta\theta$$



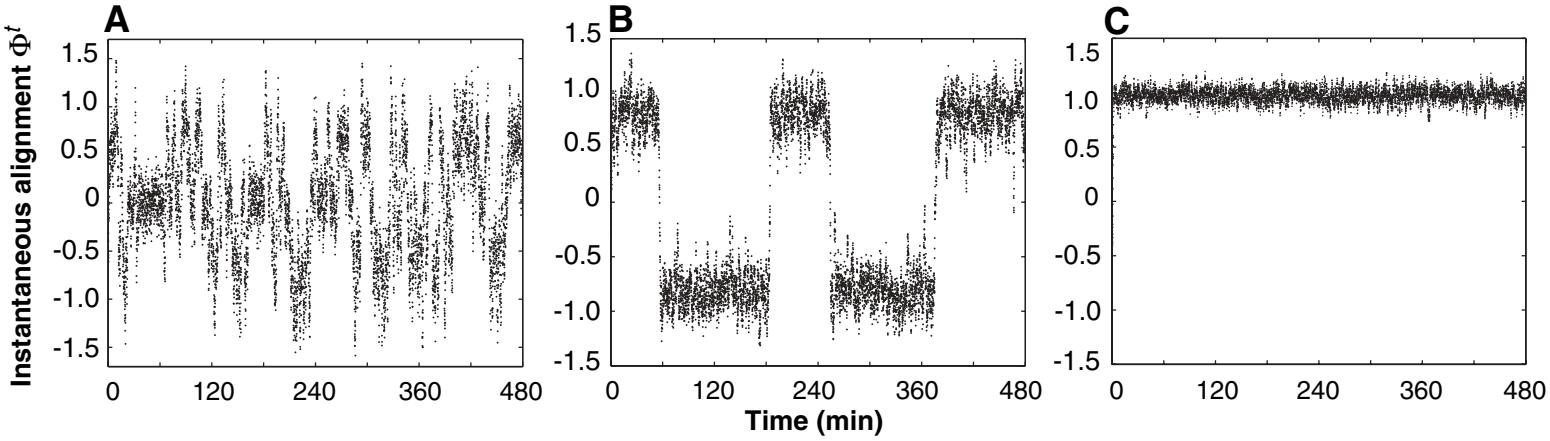




***Vicsek et al, 1995***

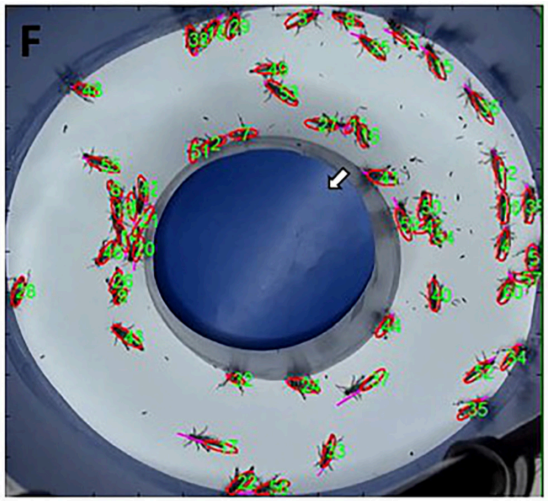


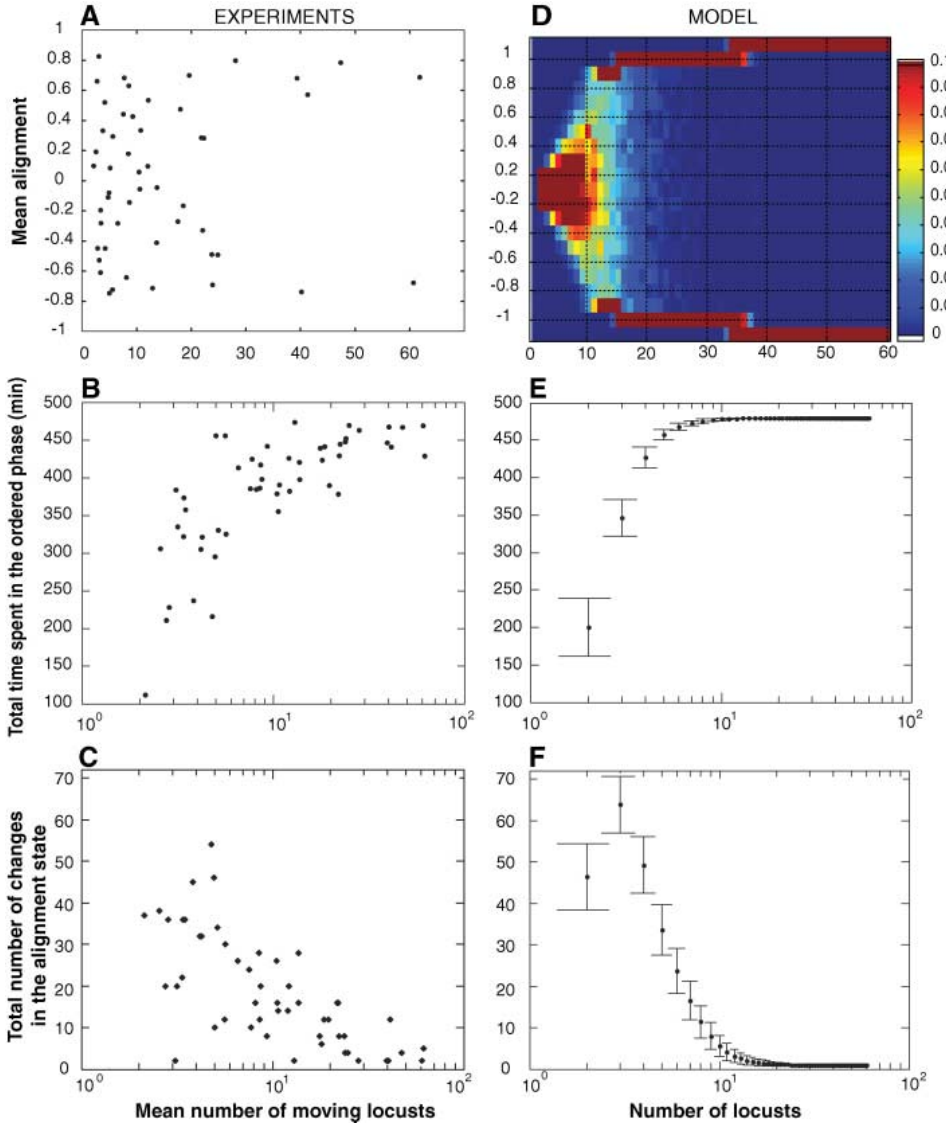

$$\chi = \arcsin[\sin(\theta - \alpha)]$$

$$\Phi^t = \frac{2}{m\pi}\sum_{i=1}^{m}\chi_i^t$$



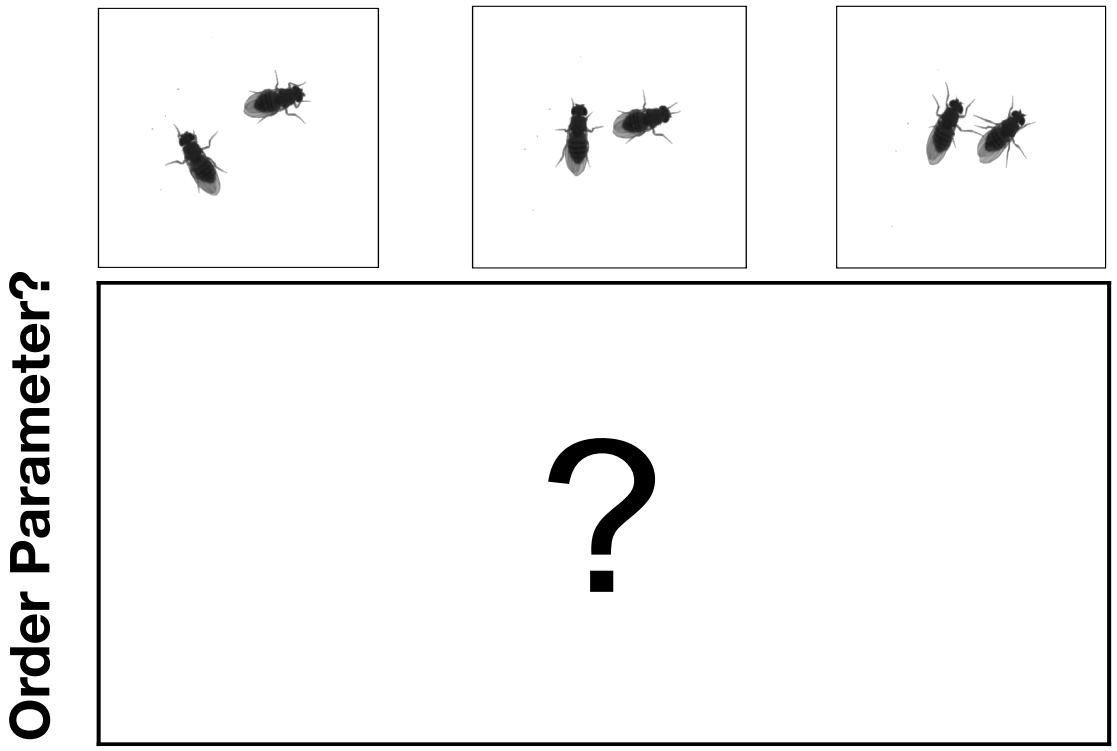

***Buhl et al, 2006***



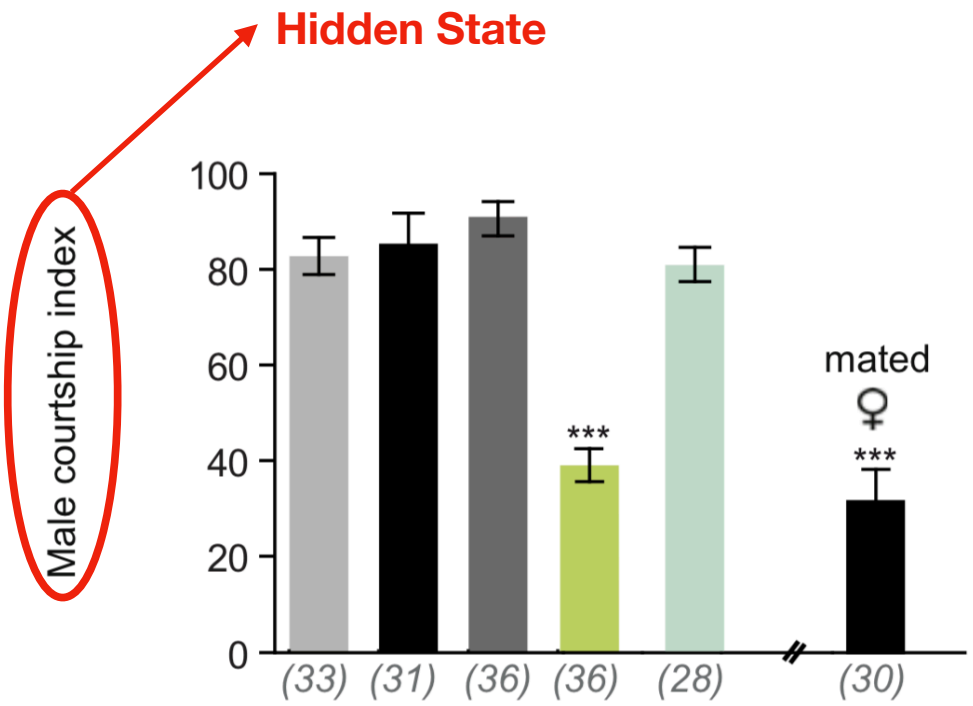

***Buhl et al, 2006***

***Iain Couzin***


Order Parameter?
?
Control Parameter?

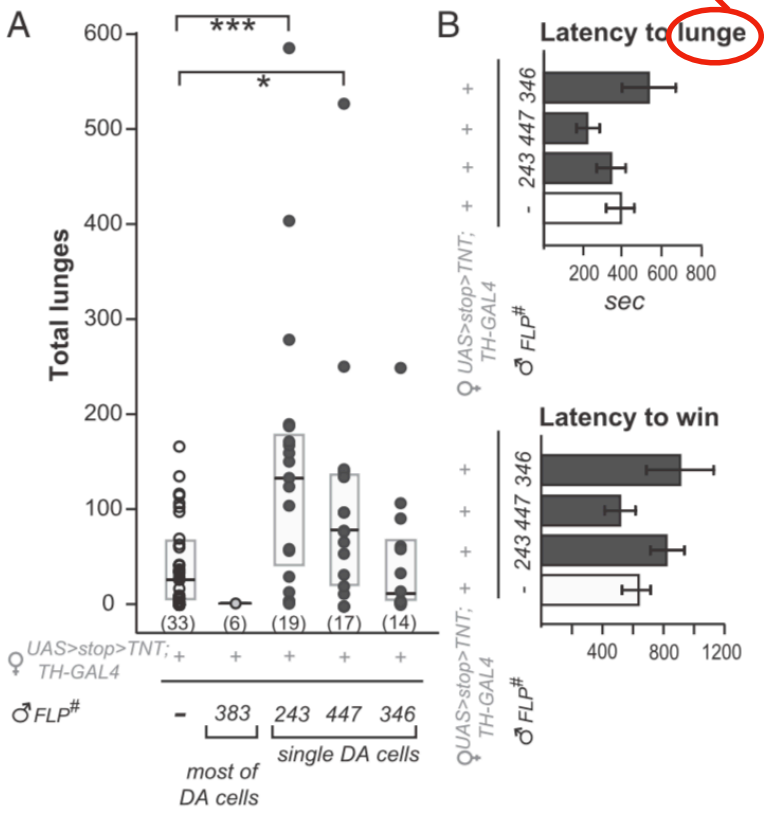
# Classical Method: Indices or Representative Behaviors

Hidden State

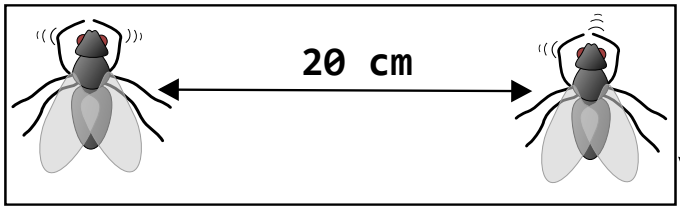


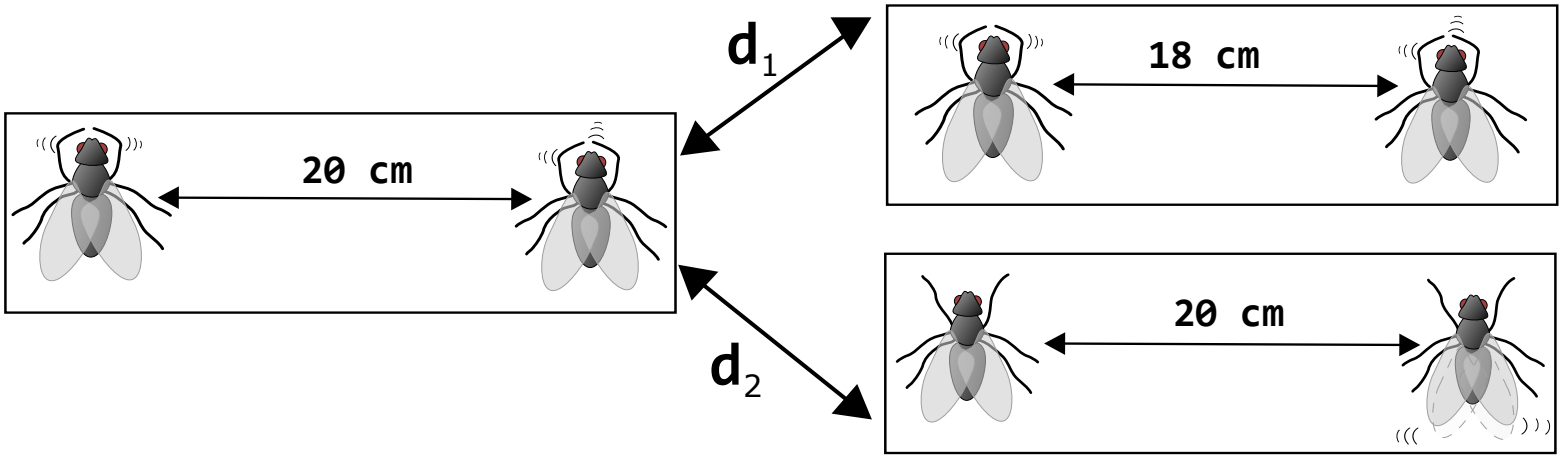

Rezável et al, 2012

Focal Behavior

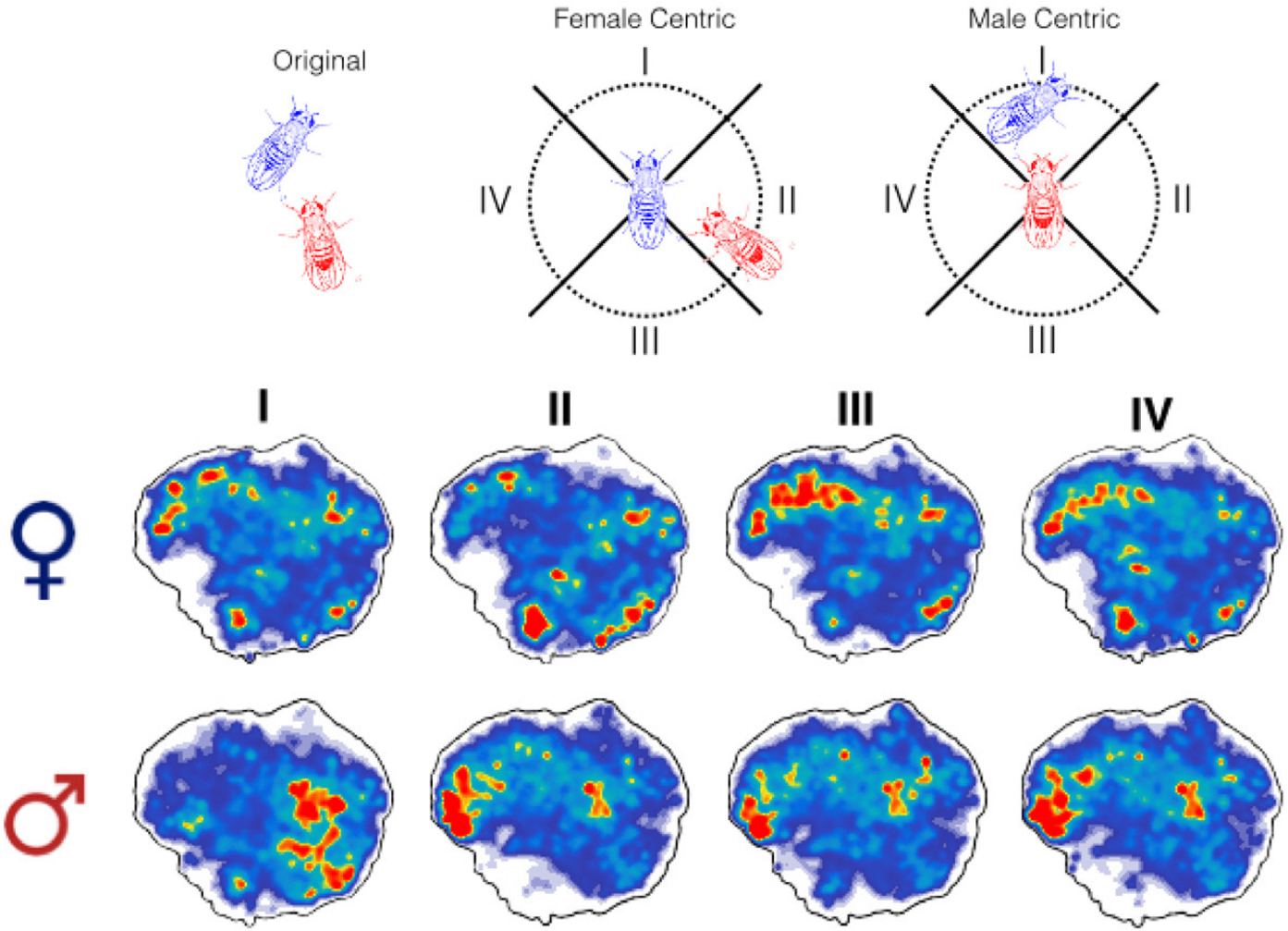


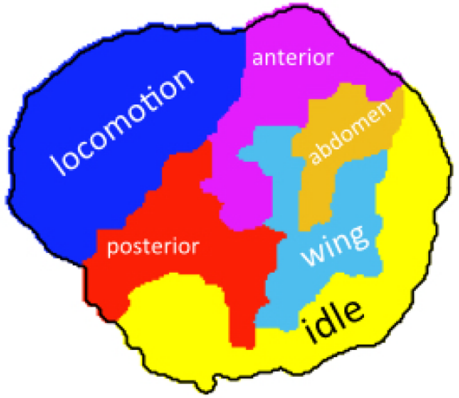

Alekseyenko et al, 2013


20 cm


20 cm
d1
18 cm
d2
20 cm

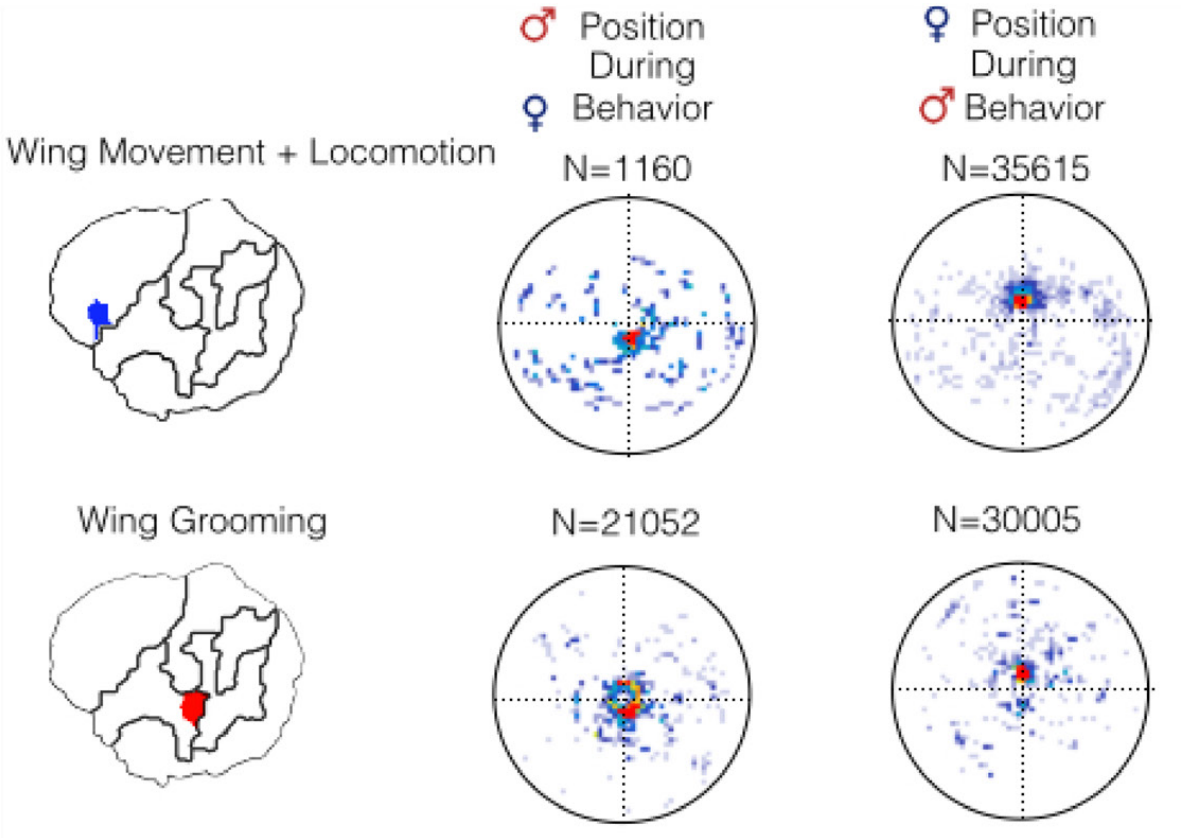
$p(\text{Behavior}|\vec{x}_1, \vec{x}_2)$

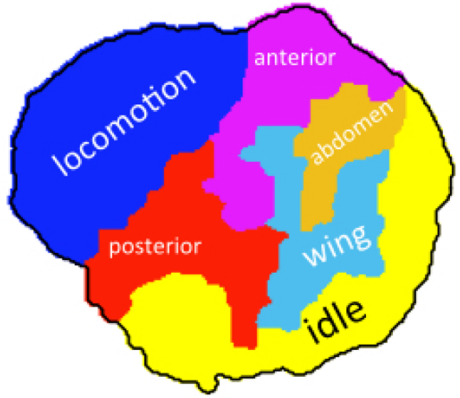



*Klibaite et al, Physical Biology (2017)*

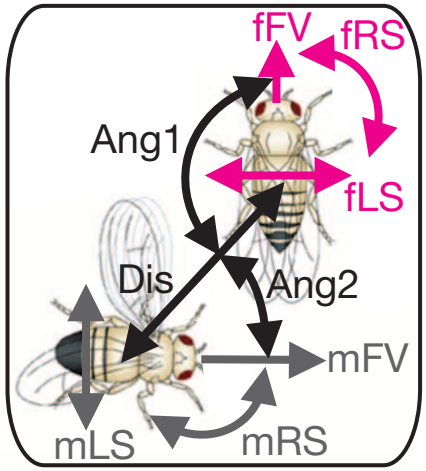
$p(\vec{x}_1, \vec{x}_2|\text{Behavior})$

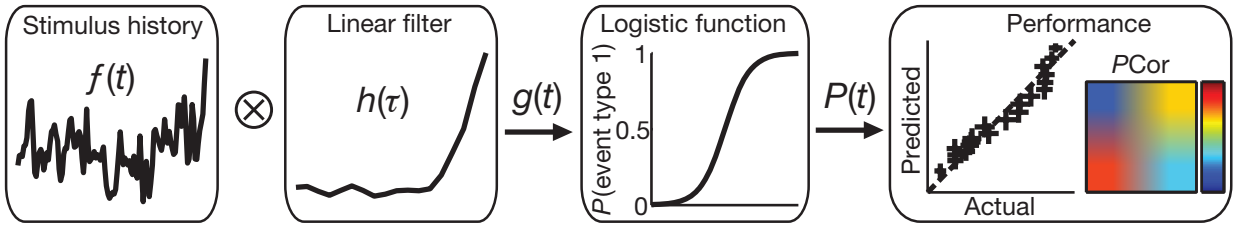


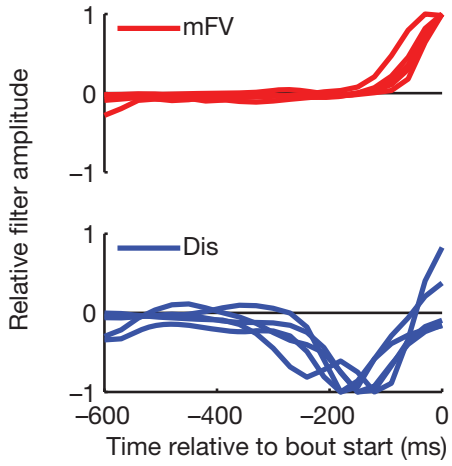

*Klibaite et al, Physical Biology (2017)*

## Linking individuals through regression:

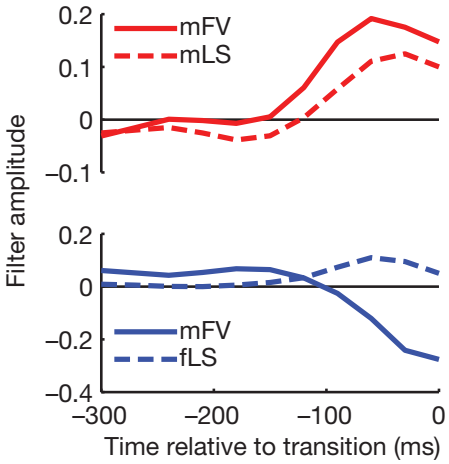


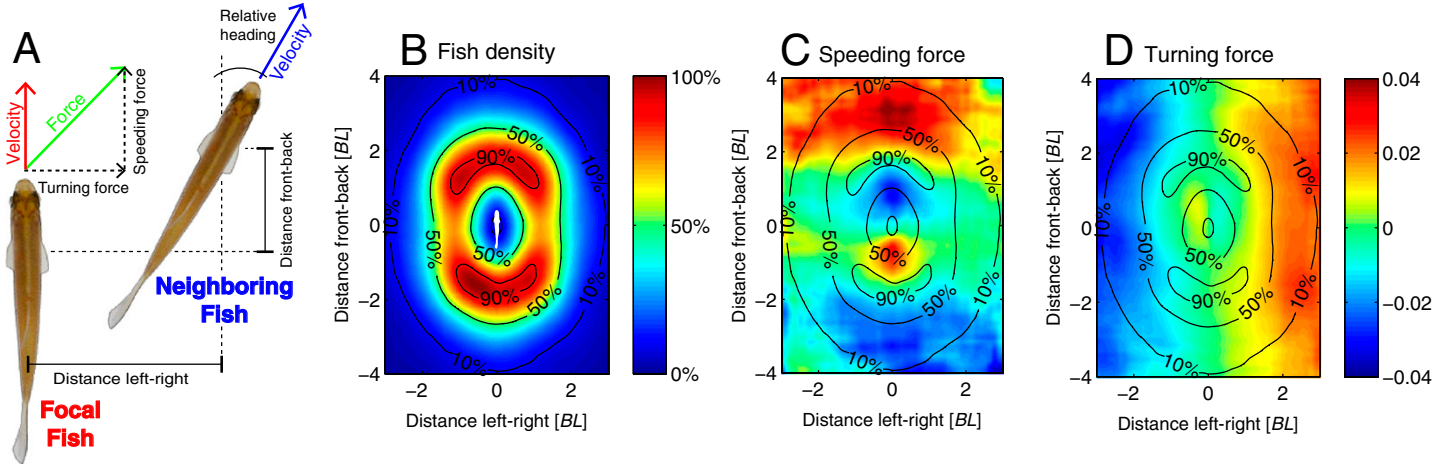

### Before start of sine song:




### Before sine to pulse song transitions:



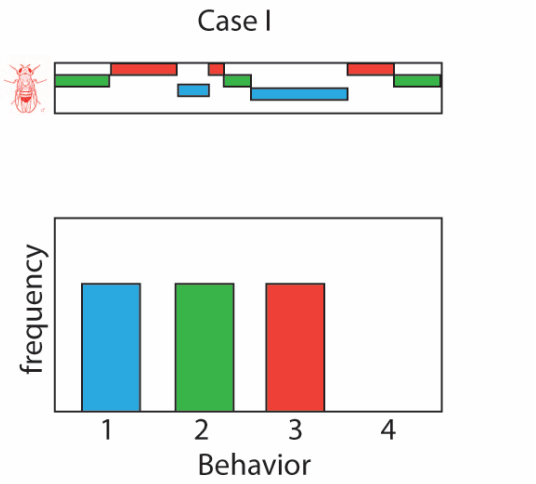

Coen et al, 2014




# Inferring the structure and dynamics of interactions in schooling fish

Yael Katz[a], Kolbjørn Tunstrøm[a], Christos C. Ioannou[a], Cristián Huepe[b], and Iain D. Couzin[a,1]

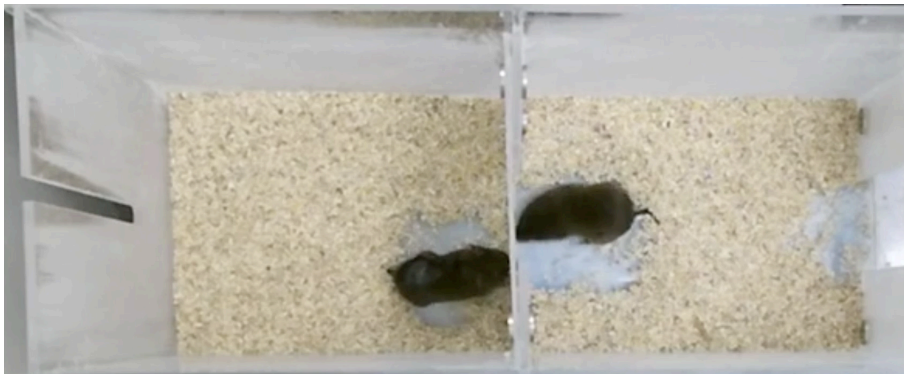
## What is an interaction?

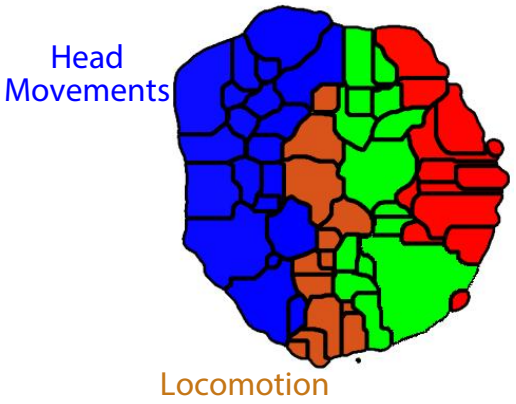



***Synchronization*** ***Similar Repertoires*** ***Emerging Behaviors***

***Or Maybe Predictability?***

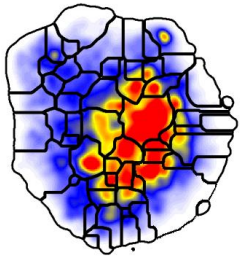
*Klibaite & Shaevitz, bioRxiv (2019)*



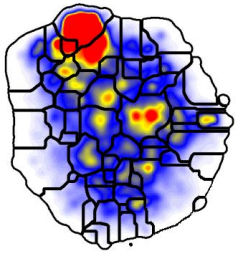



FIRST TRIAD

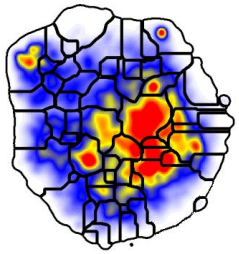
Map of Partner, with Subject



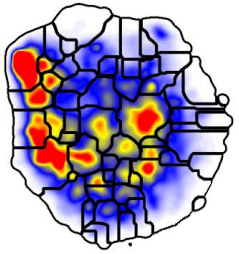
Map of Stranger, with Subject



Map of Subject, with Partner

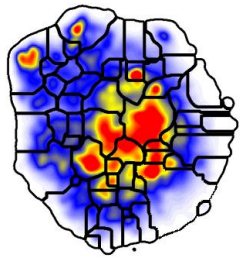


Map of Subject, with Stranger

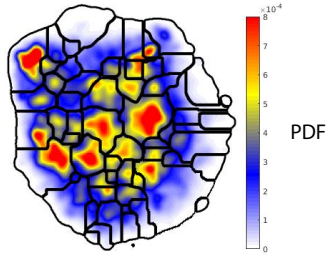


SECOND TRIAD

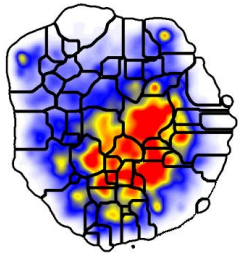
Map of Partner, with Subject



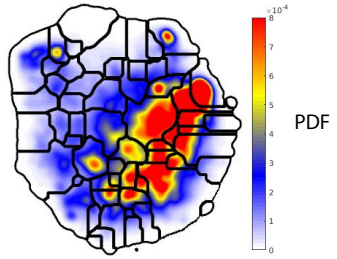
Map of Stranger, with Subject



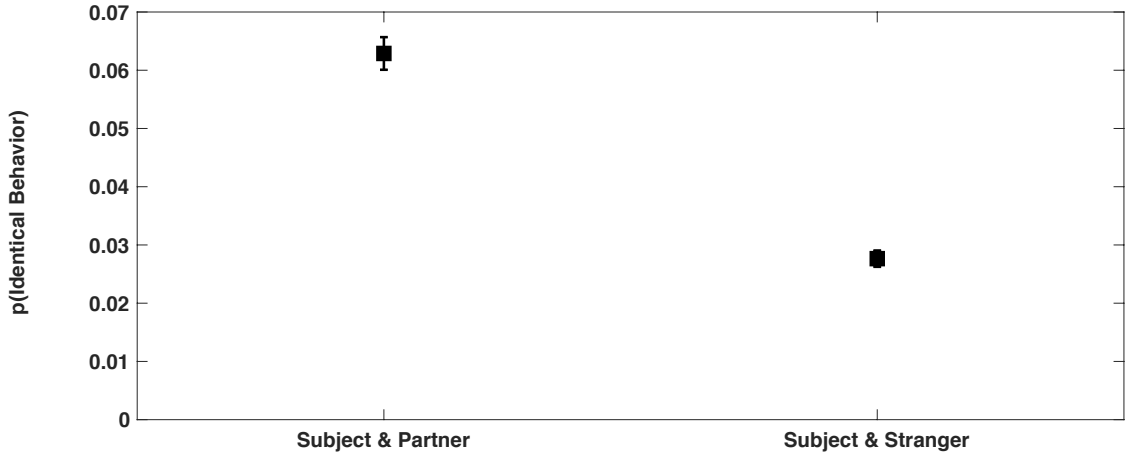

Map of Subject, with Partner



Map of Subject, with Stranger




**Sena Agezo**
**Robert Liu**




FIRST TRIAD

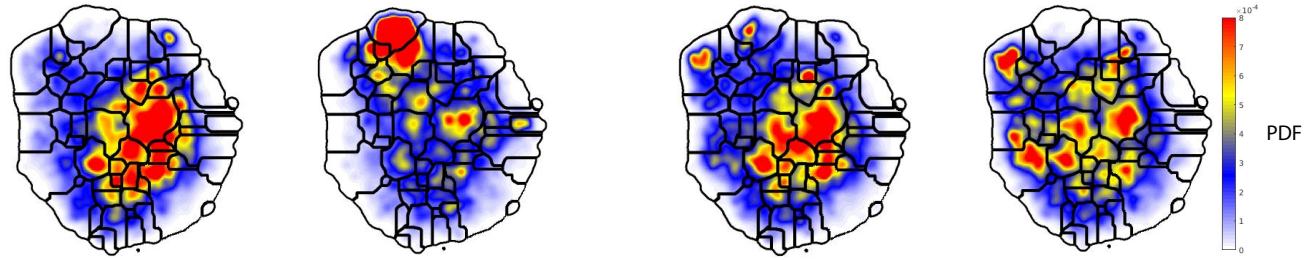
SECOND TRIAD

Map of Partner, with Subject

Map of Stranger, with Subject

Map of Partner, with Subject

Map of Stranger, with Subject

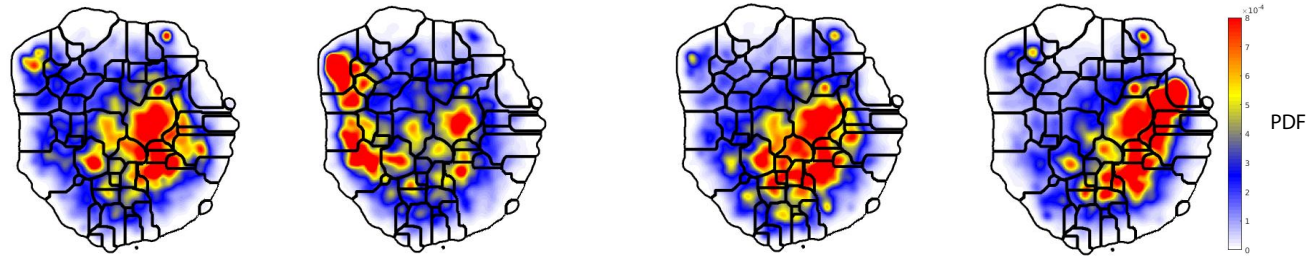



Map of Subject, with Partner

Map of Subject, with Stranger

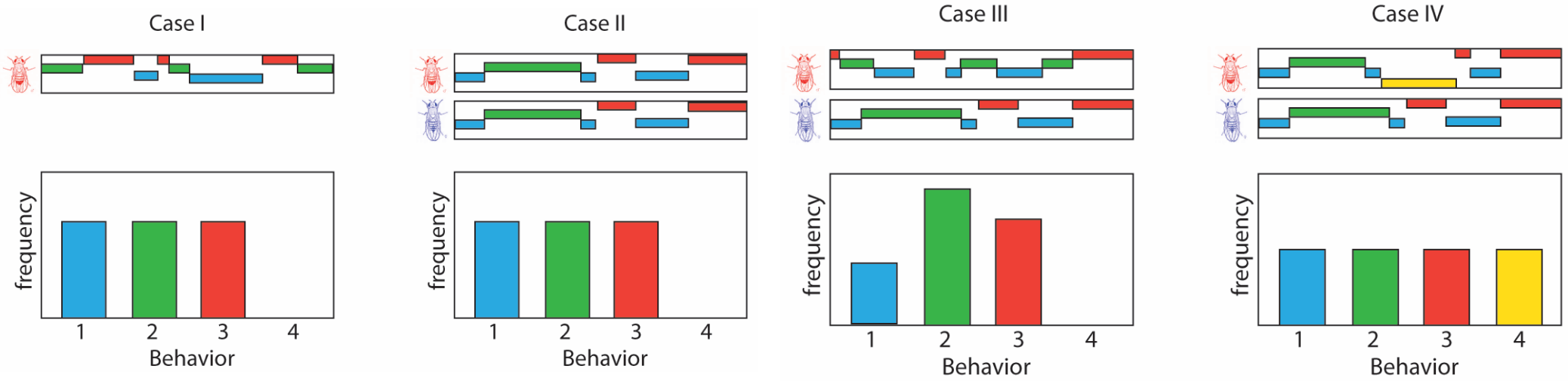
Map of Subject, with Partner

Map of Subject, with Stranger




**Sena Agezo**
**Robert Liu**

## What is an interaction?

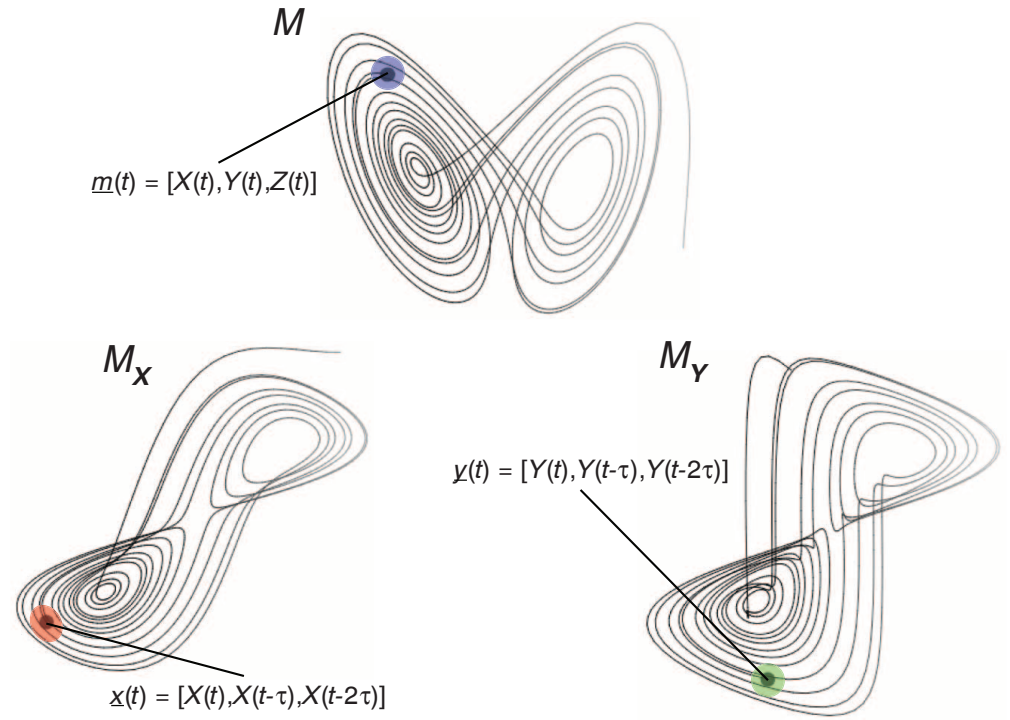



***Synchronization*** ***Similar Repertoires*** ***Emerging Behaviors***

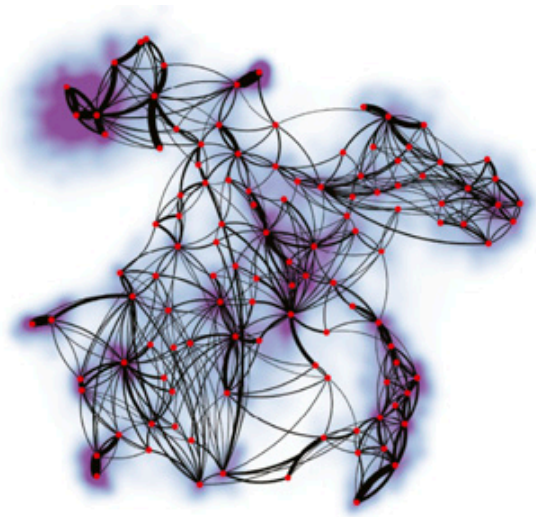
***Or Maybe Predictability?***

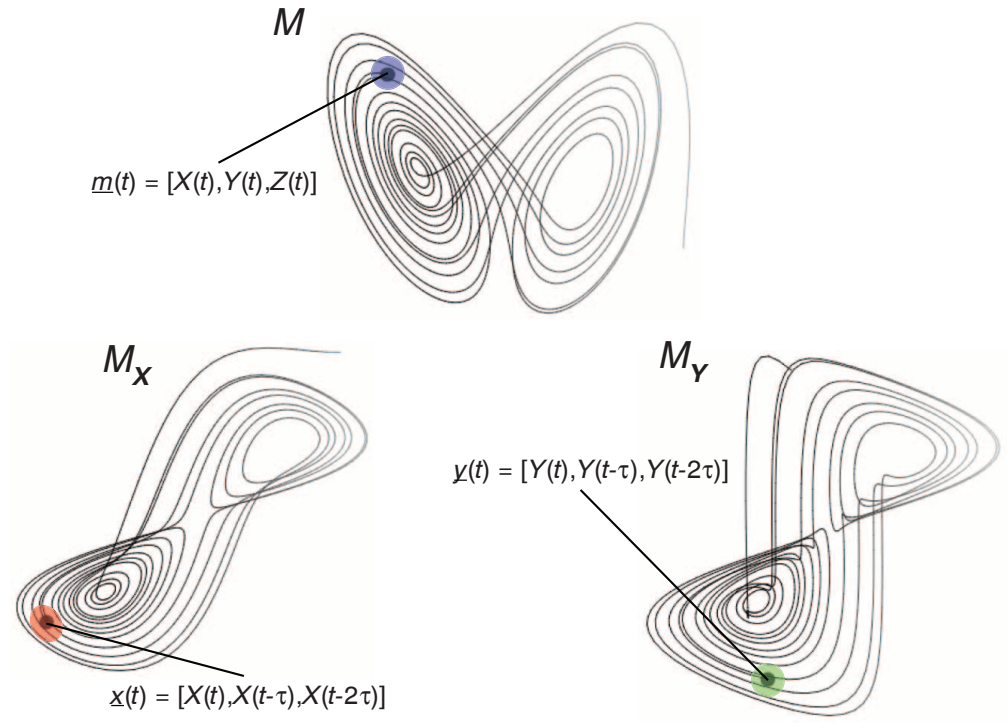
*Klibaite & Shaevitz, bioRxiv (2019)*

## How can we think about predictability as a <u>dynamical</u> property?

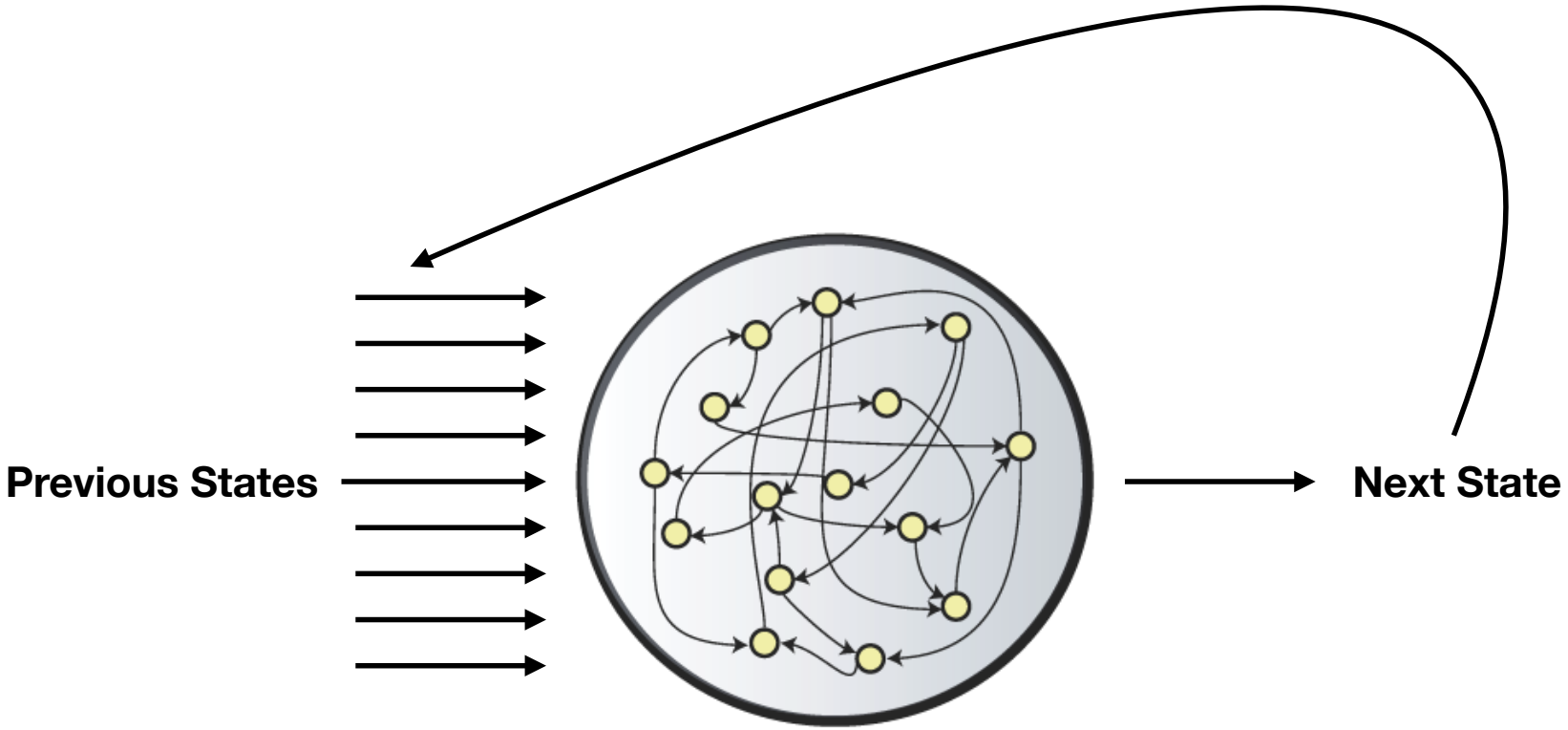


## How can we think about predictability as a <u>dynamical</u> property?

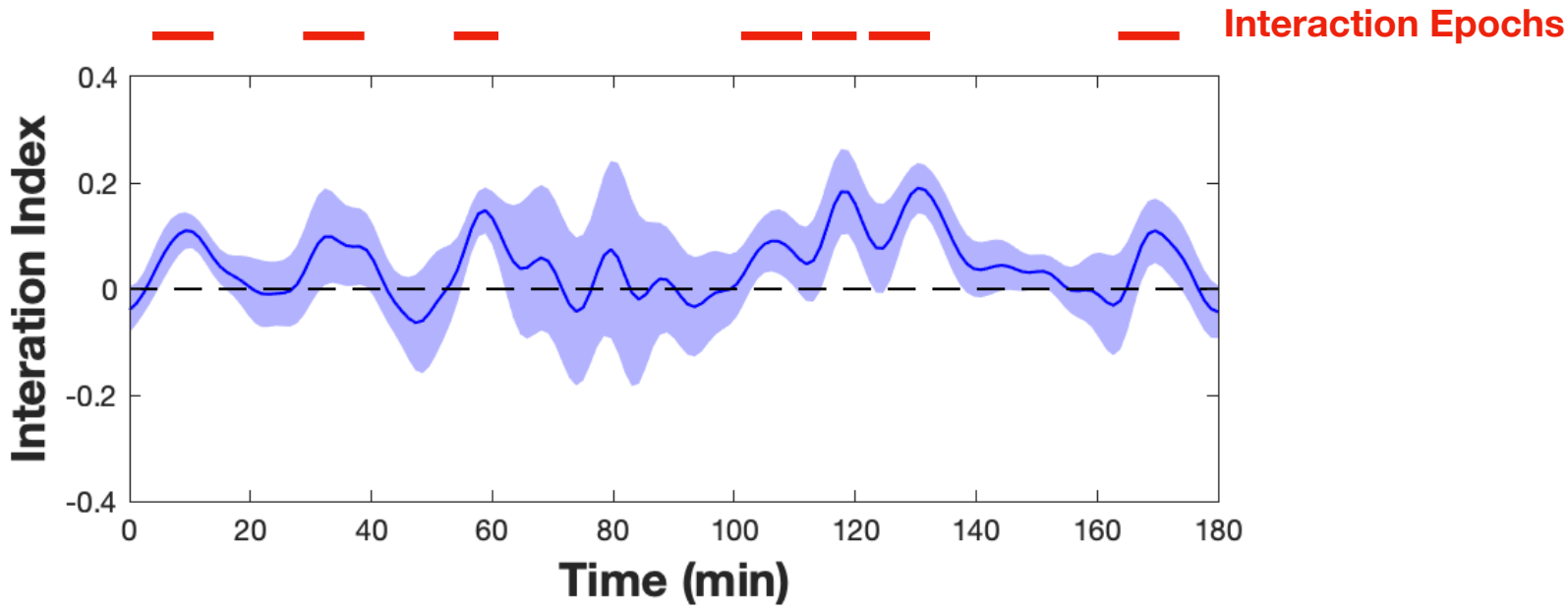




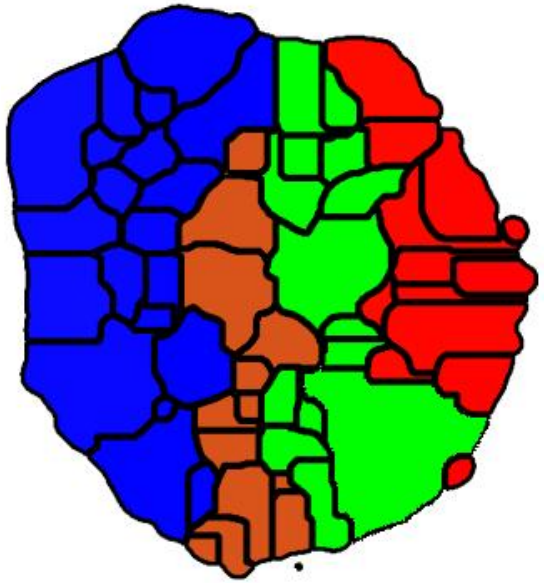

**Problem: We don't have a continuous dynamical system…**




*Long Short Term Memory (LSTM)*


Interaction Epochs
Interation Index
0.4
0.2
0
-0.2
-0.4
0
20
40
60
80
100
120
140
160
180
Time (min)

Head Movements

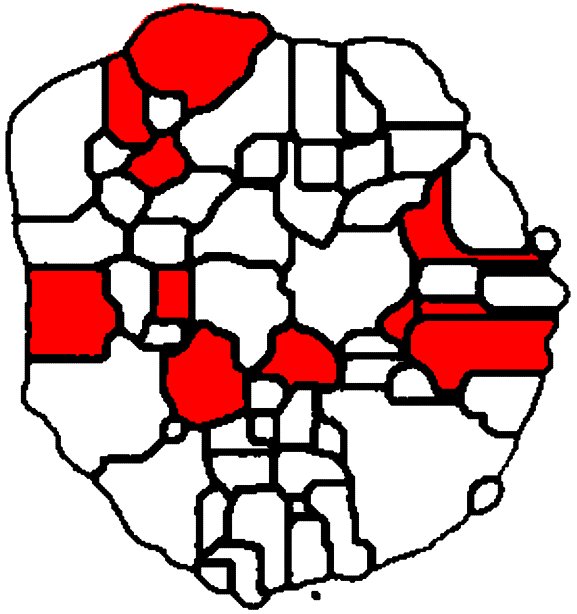


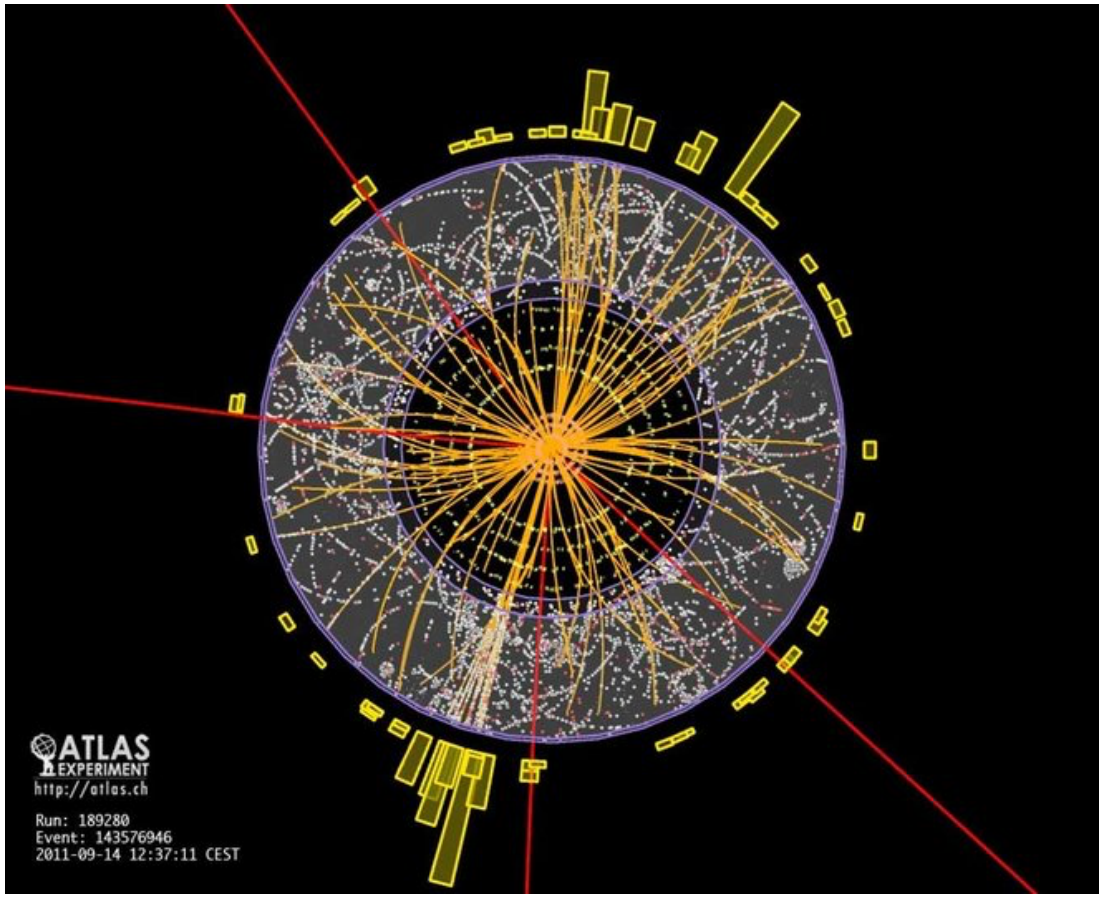
Posterior Body Movements

Locomotion

Inactive/ resting-like Behavior

**Regions with Statistically-Significant Enrichment in Interacting Epochs**

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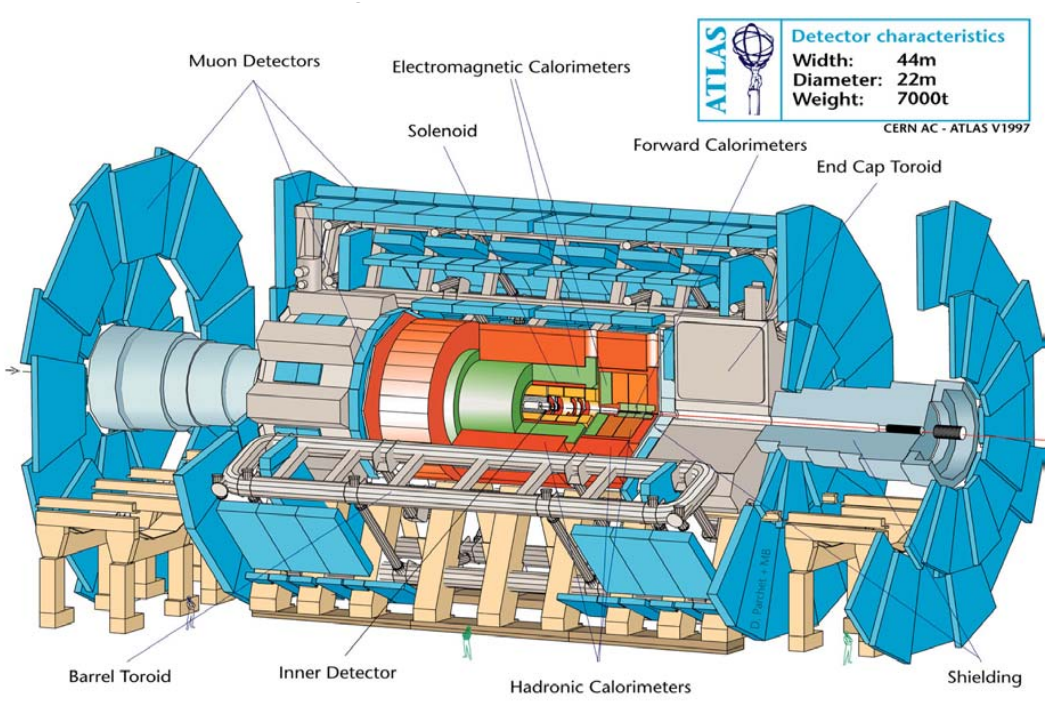
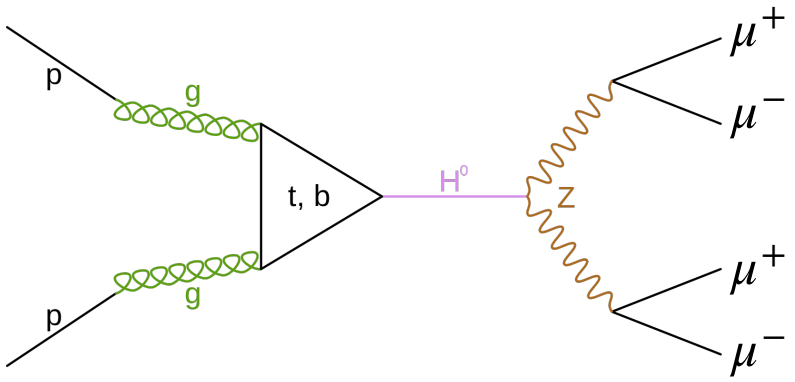
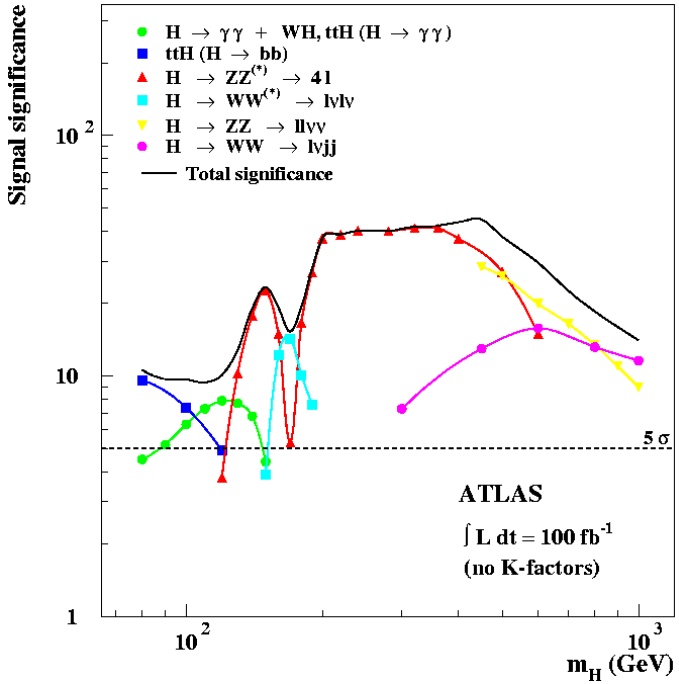
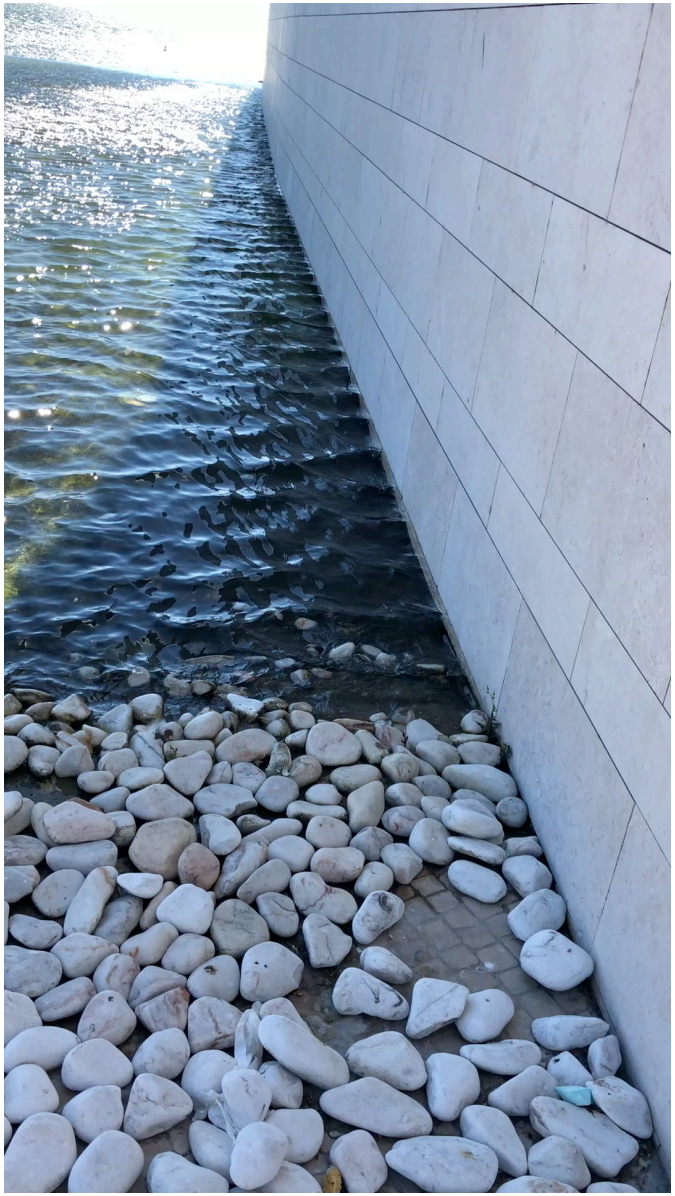
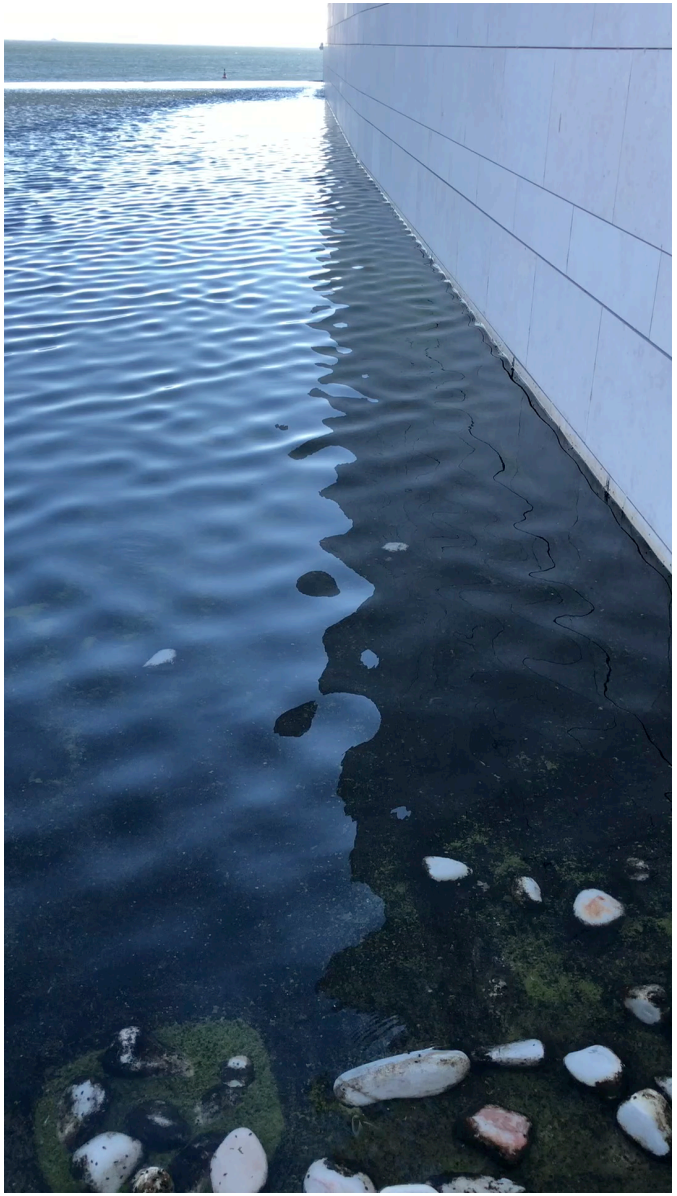
Event: 143576946
2011-09-14 12:37:11 CEST


ATLAS
Detector characteristics
Width: 44m
Diameter: 22m
Weight: 7000t
CERN AC - ATLAS V1997
Muon Detectors
Electromagnetic Calorimeters
Solenoid
Forward Calorimeters
End Cap Toroid
Barrel Toroid
Inner Detector
Hadronic Calorimeters
Shielding


p
g
t, b
H⁰
Z
μ⁺
μ⁻
p
g
μ⁺
μ⁻


Signal significance
H → γγ + WH, ttH (H → γγ)
ttH (H → bb)
H → ZZ(*) → 4l
H → WW(*) → lνlν
H → ZZ → llνν
H → WW → lνjj
Total significance
10²
10
1
5σ
ATLAS
∫ L dt = 100 fb⁻¹
(no K-factors)
10²
10³
m_H (GeV)





$h(x,t)$ ⟶

⟶ Measure $h(x,t)$ and $E$

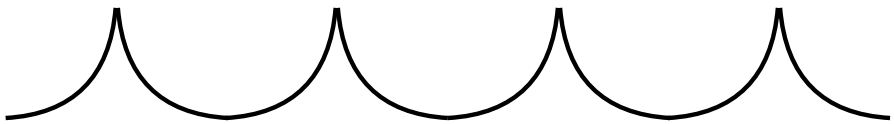
↓

Train Model to Accurately
Predict $h(x,t\,|\,E)$

↓

Correctly Output
Future Untrained $h(x,t\,|\,E)$

$h(x,t)$ →



→ Navier-Stokes Equations

*(conservation of mass & momentum)*

$$\rho\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u} = -\nabla p + \nu\nabla^2\mathbf{u} + \mathbf{f}$$

$$\nabla^2 p = 0$$

↓

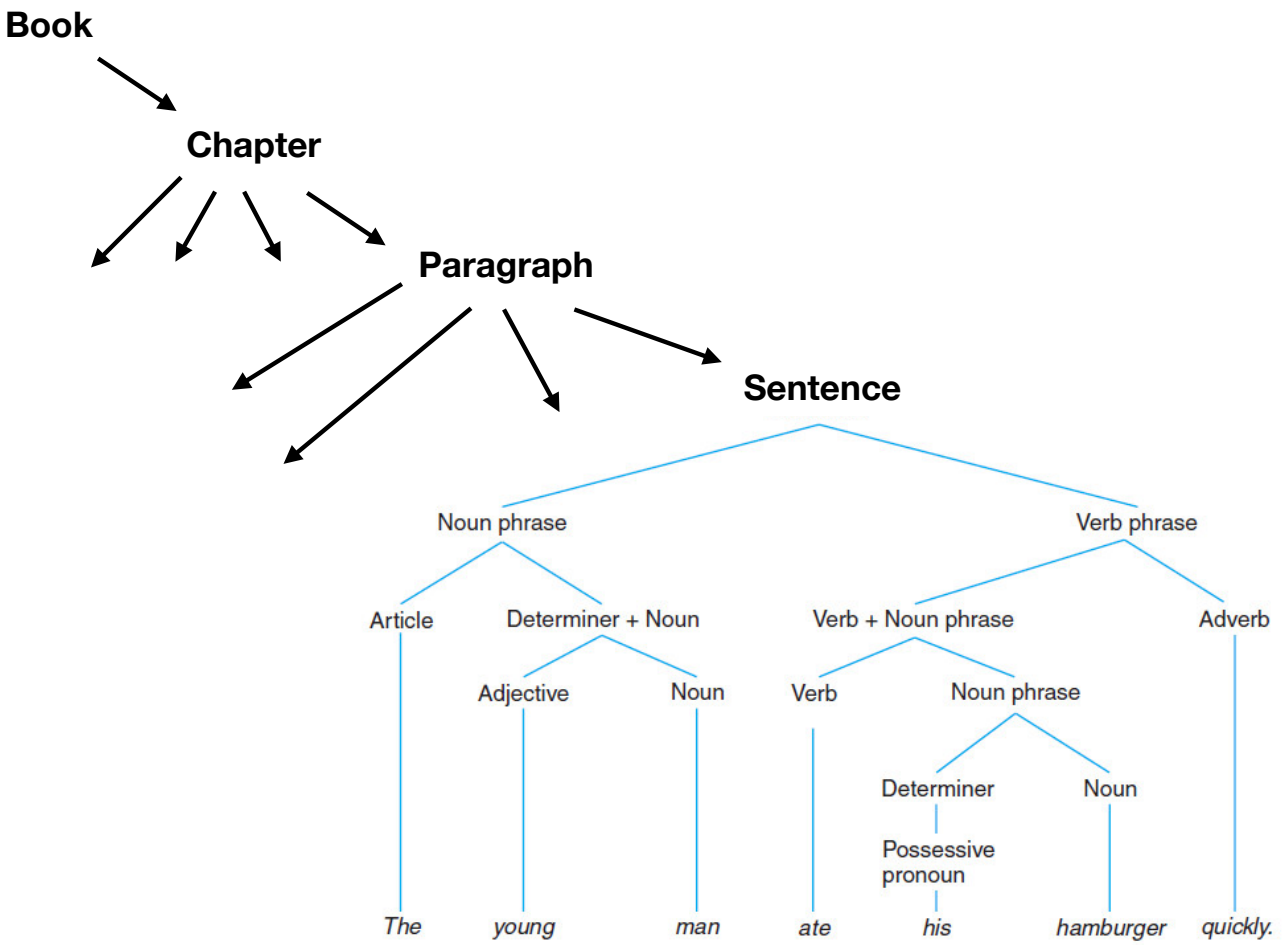
1-D Shallow Water Approximation

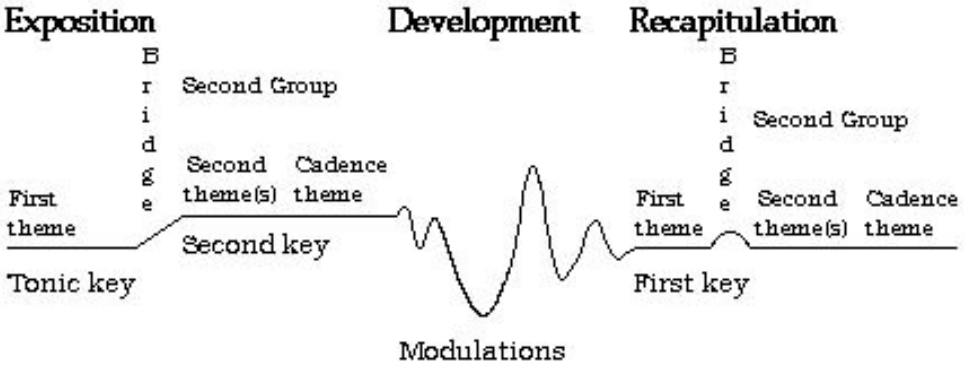
$$\frac{\partial h(x,t)}{\partial t} + \frac{\partial [h(x,t)u]}{\partial x} = 0$$

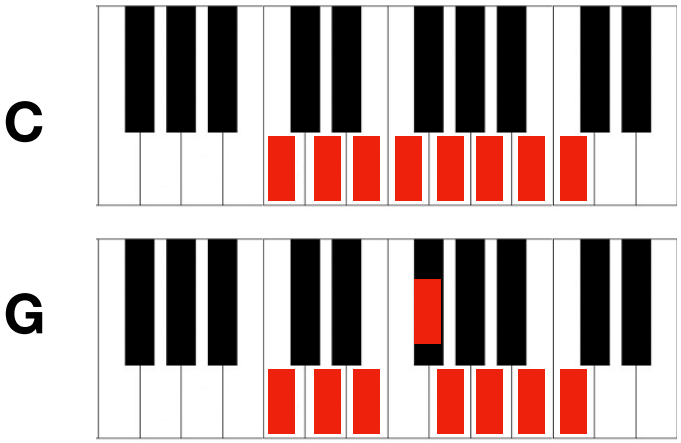
↓

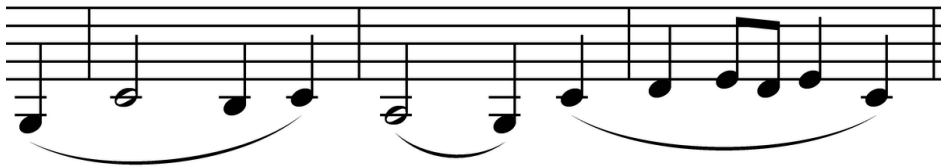
Linearization

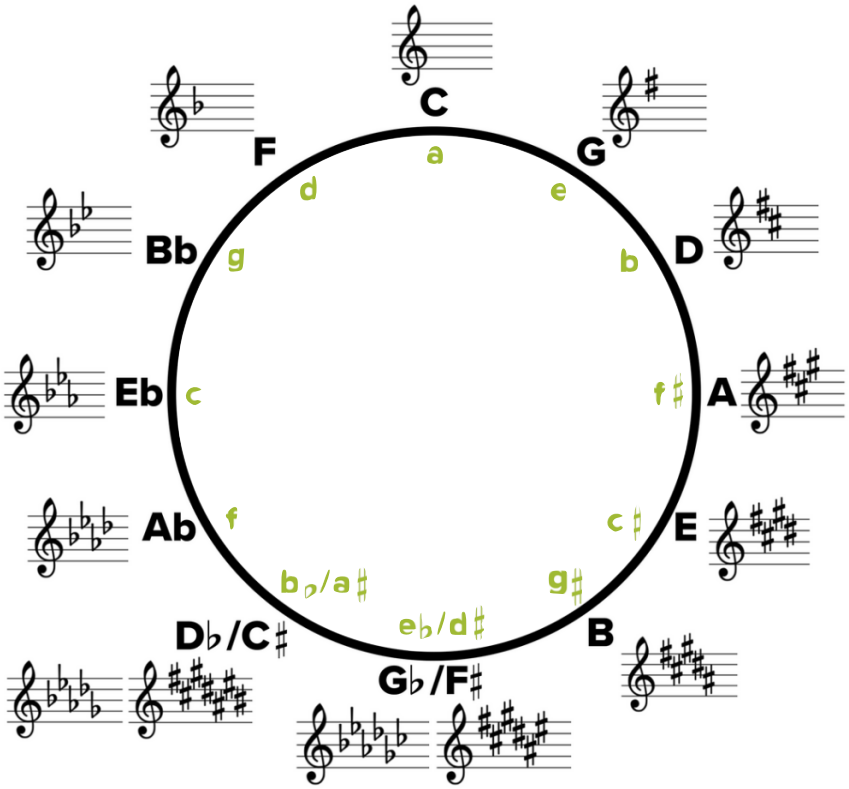
$$\lambda = \sqrt{\frac{U^2}{Hg}} \qquad A = \frac{U^2 W}{g}$$


Book
Chapter
Paragraph
Sentence
Noun phrase
Verb phrase
Article
Determiner + Noun
Verb + Noun phrase
Adverb
Adjective
Noun
Verb
Noun phrase
Determiner
Noun
Possessive pronoun
The
young
man
ate
his
hamburger
quickly.


Exposition
Development
Recapitulation
Bridge
Second Group
First theme
Second theme(s)
Cadence theme
Second key
Tonic key
First key
Modulations


C
G




C
a
G
e
D
b
A
f♯
E
c♯
B
g♯
G♭/F♯
e♭/d♯
D♭/C♯
b♭/a♯
Ab
f
Eb
c
Bb
g
F
d