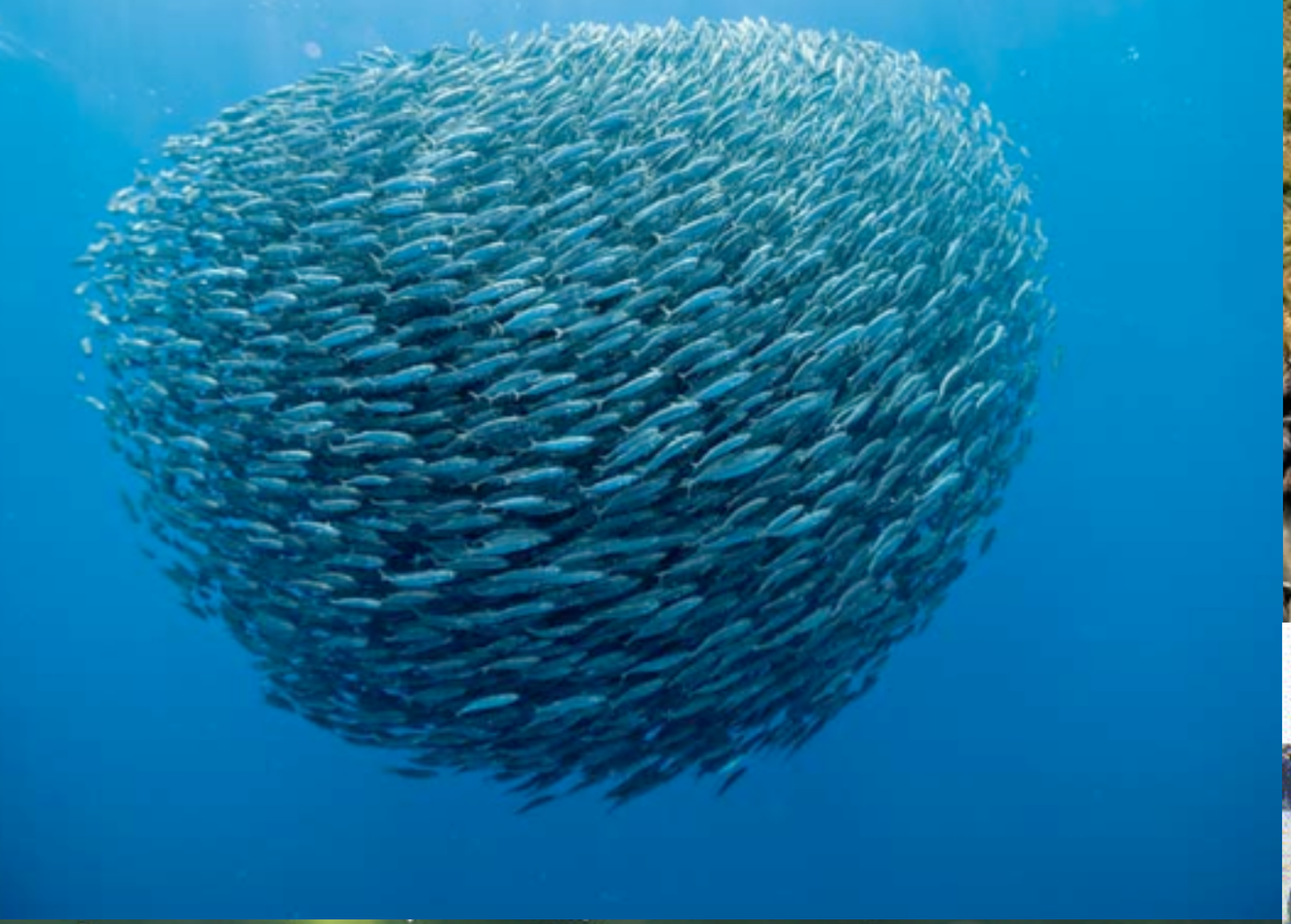
Driving and Response in Insect Swarms

N.T. Ouellette
R. Ni, J.G. Puckett, D.H. Kelley
E.R. Dufresne



Modeling of Aggregations

??

Modeling Ingredients

Empirical Measurements

Individual, isolated behavior

Observe real animals

Interaction range

??

Characterize behavior of individuals and groups

Interaction form

Solve inverse problem to determine rules

Rule variability

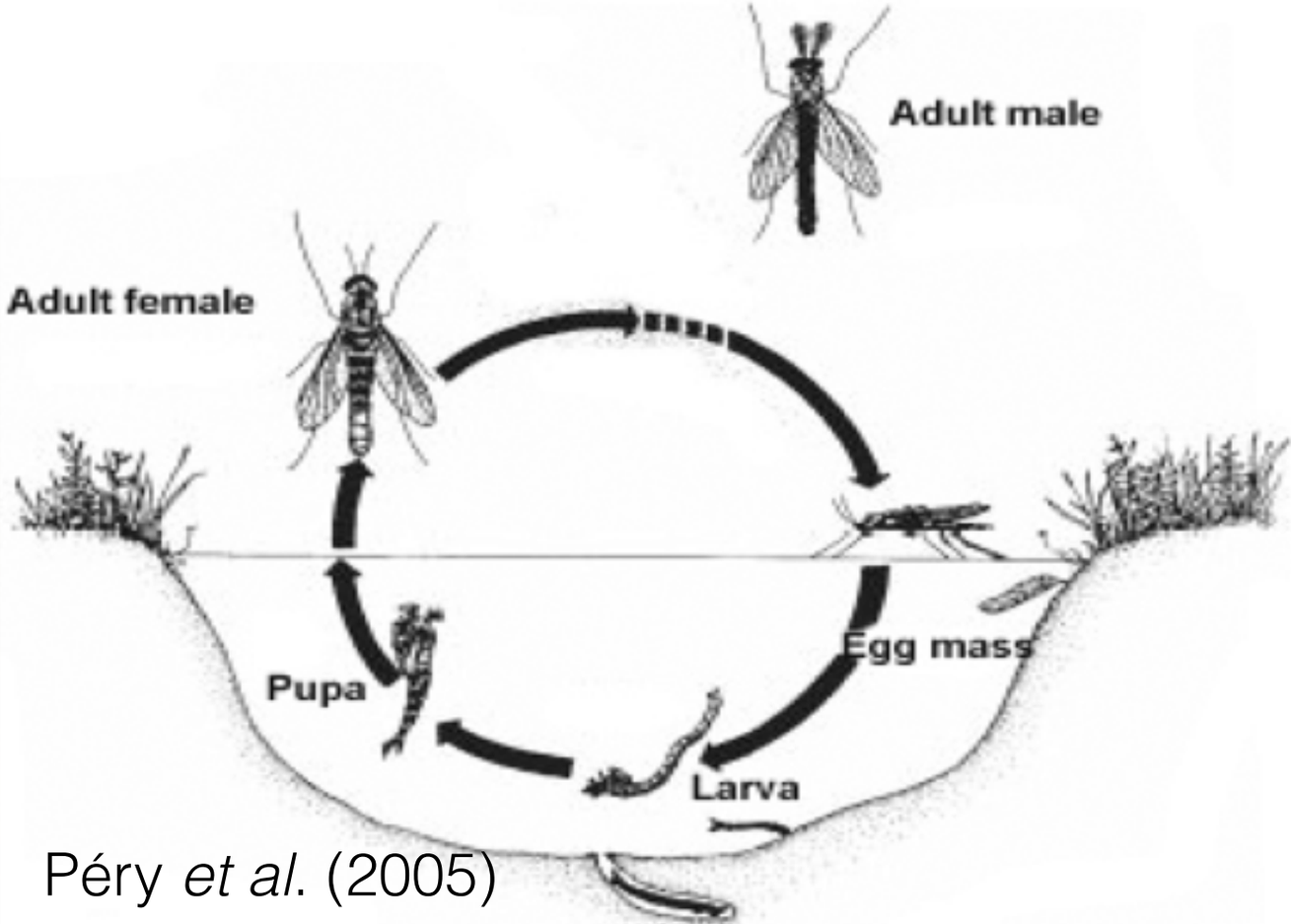
Primarily qualitative information

Laboratory Experiments

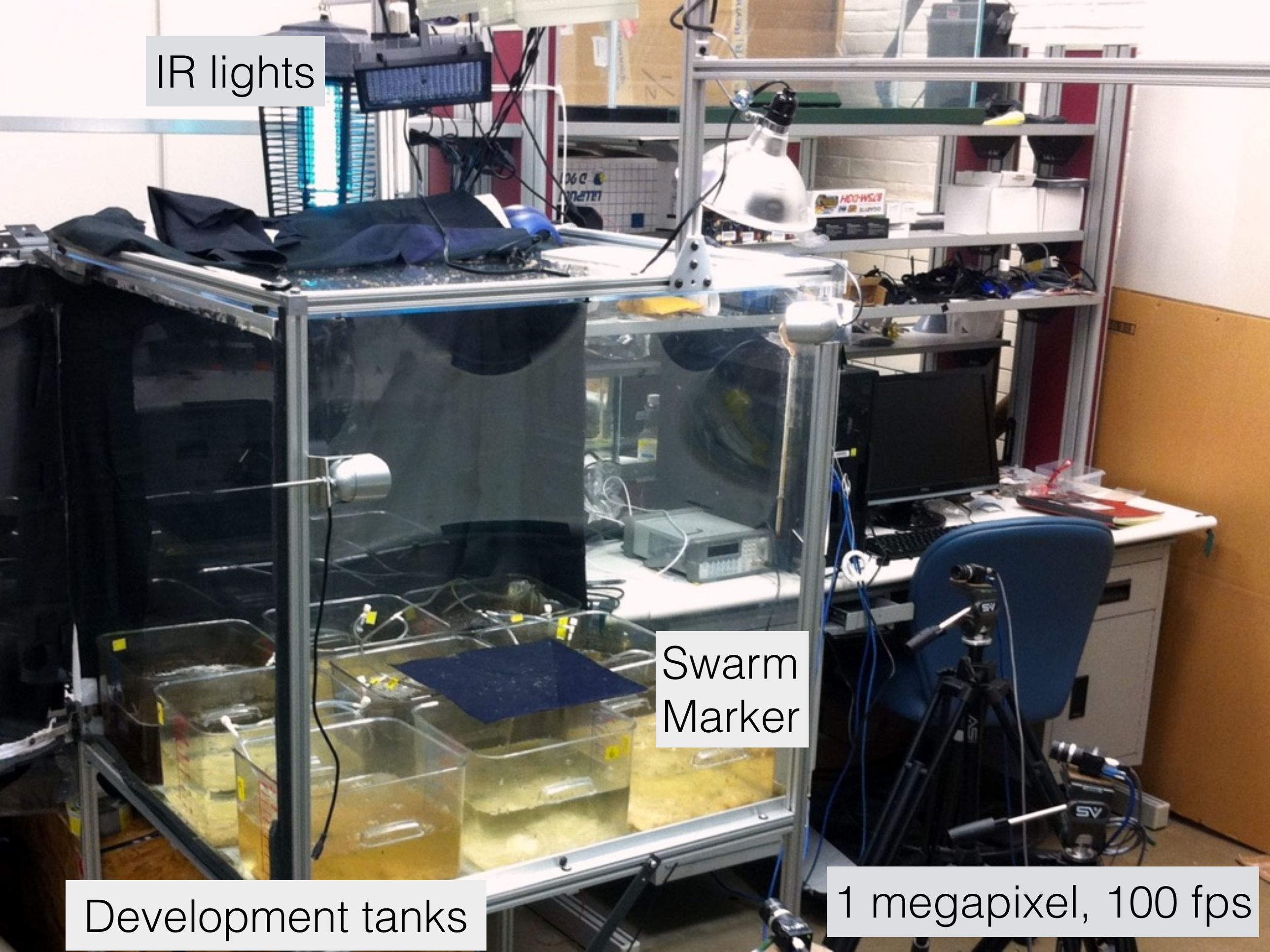
Control of ambient conditions

Repeatable experiments

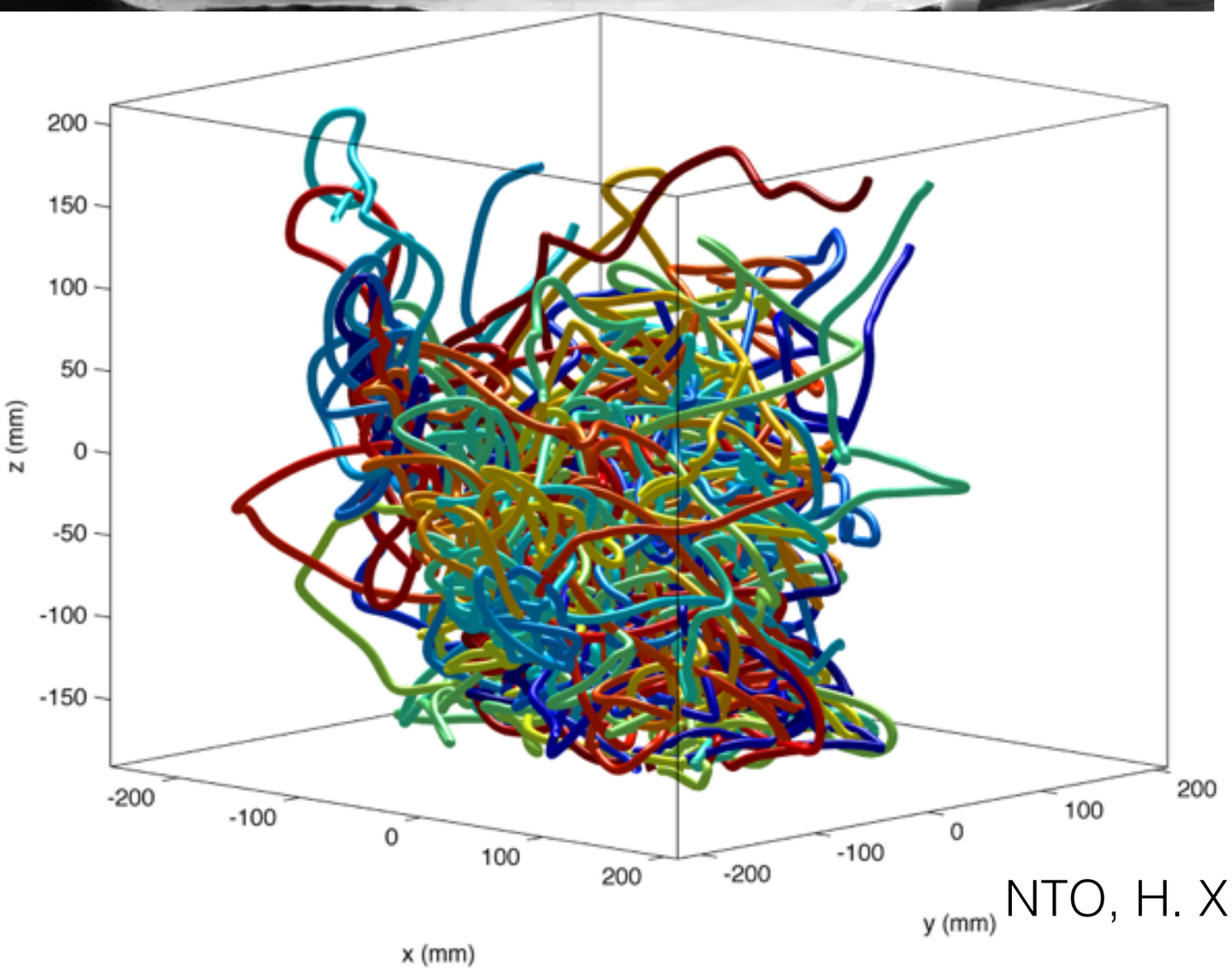
Simple, accurate imaging



Péry *et al*. (2005)


IR lights
Swarm Marker
Development tanks
1 megapixel, 100 fps

Tracking



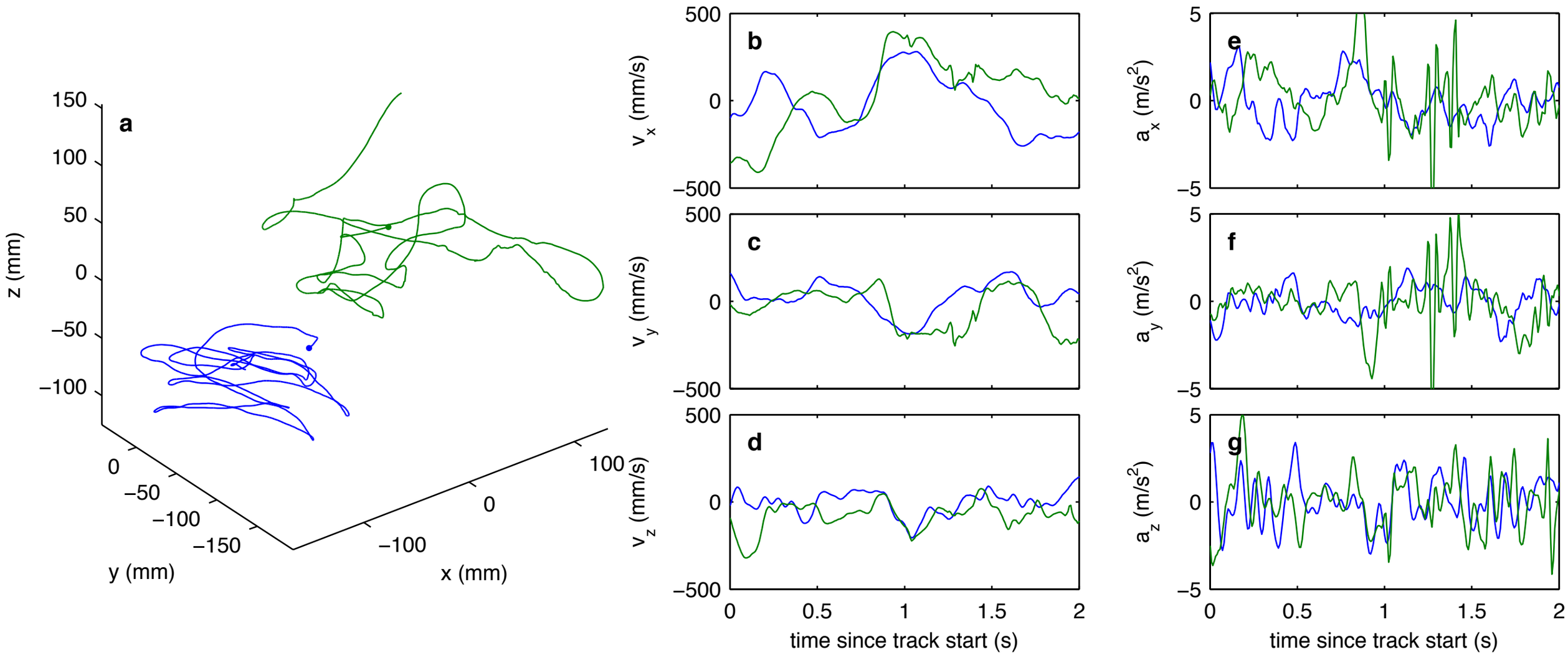
Extract trajectories via 3D particle tracking

Multiframe, predictive algorithm

Measure position, velocity, acceleration, etc.

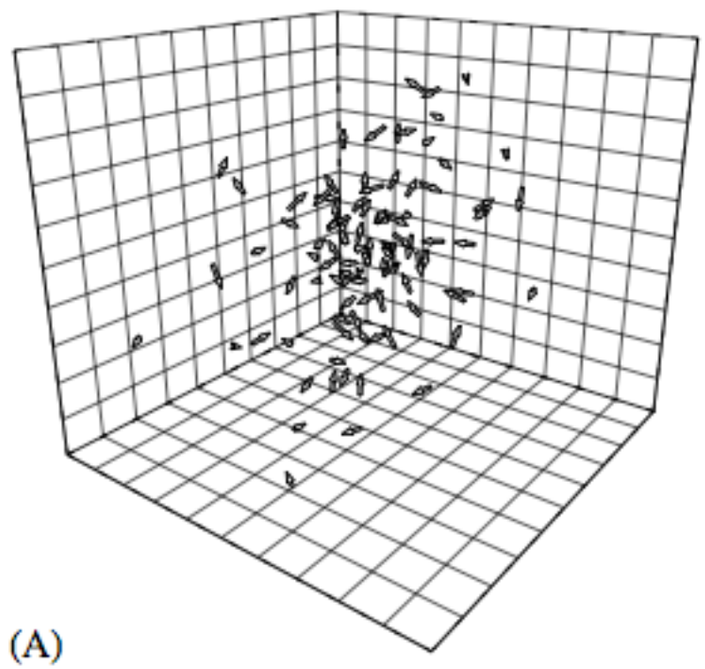
NTO, H. Xu, & E. Bodenschatz, *Exp. Fluids* (2006)
D.H. Kelley & NTO, *Sci. Rep.* (2013)

Kinematics

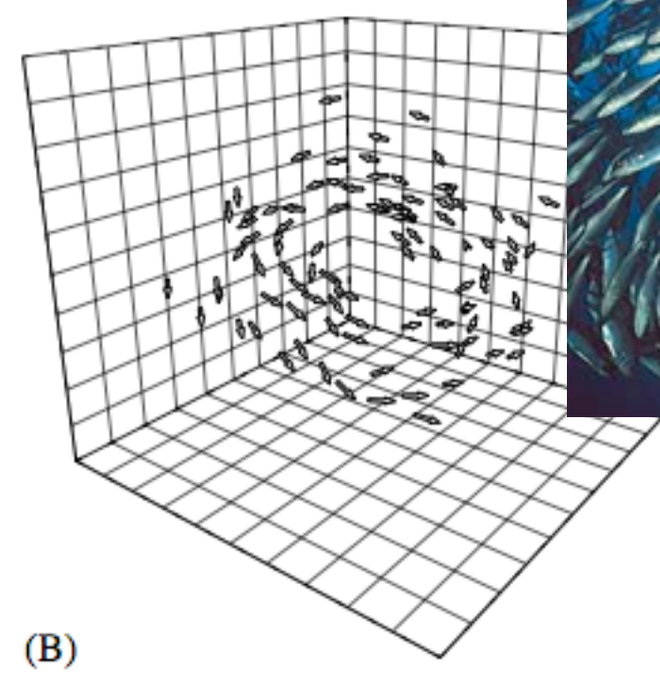


D.H. Kelley & NTO, *Sci. Rep.* (2013)

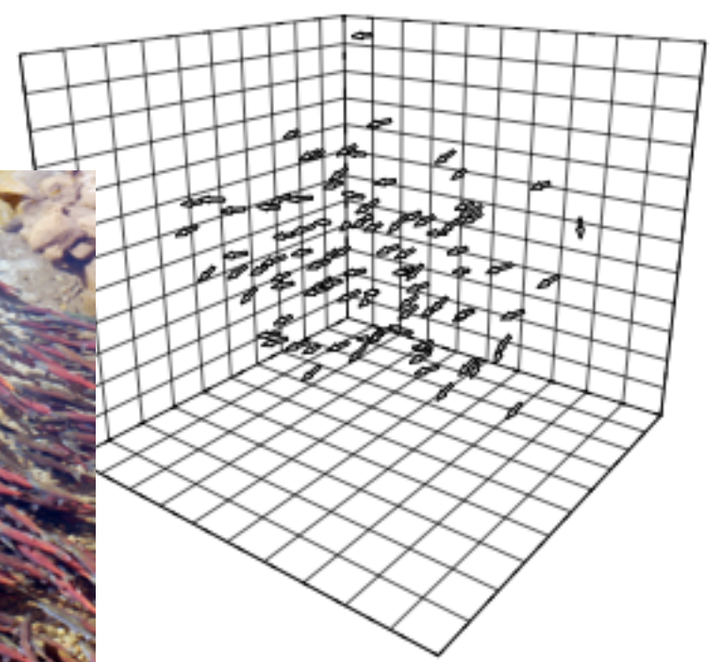
Self-Propelled Particles

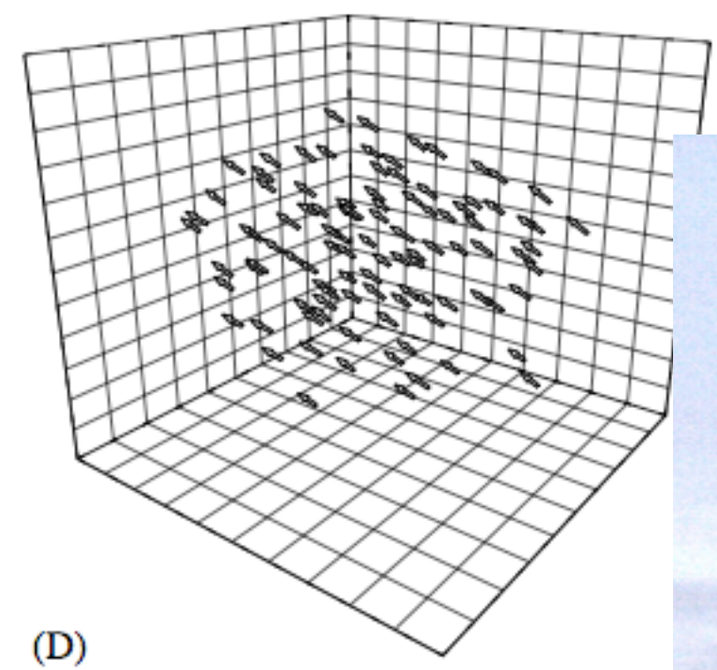


(A)



(B)





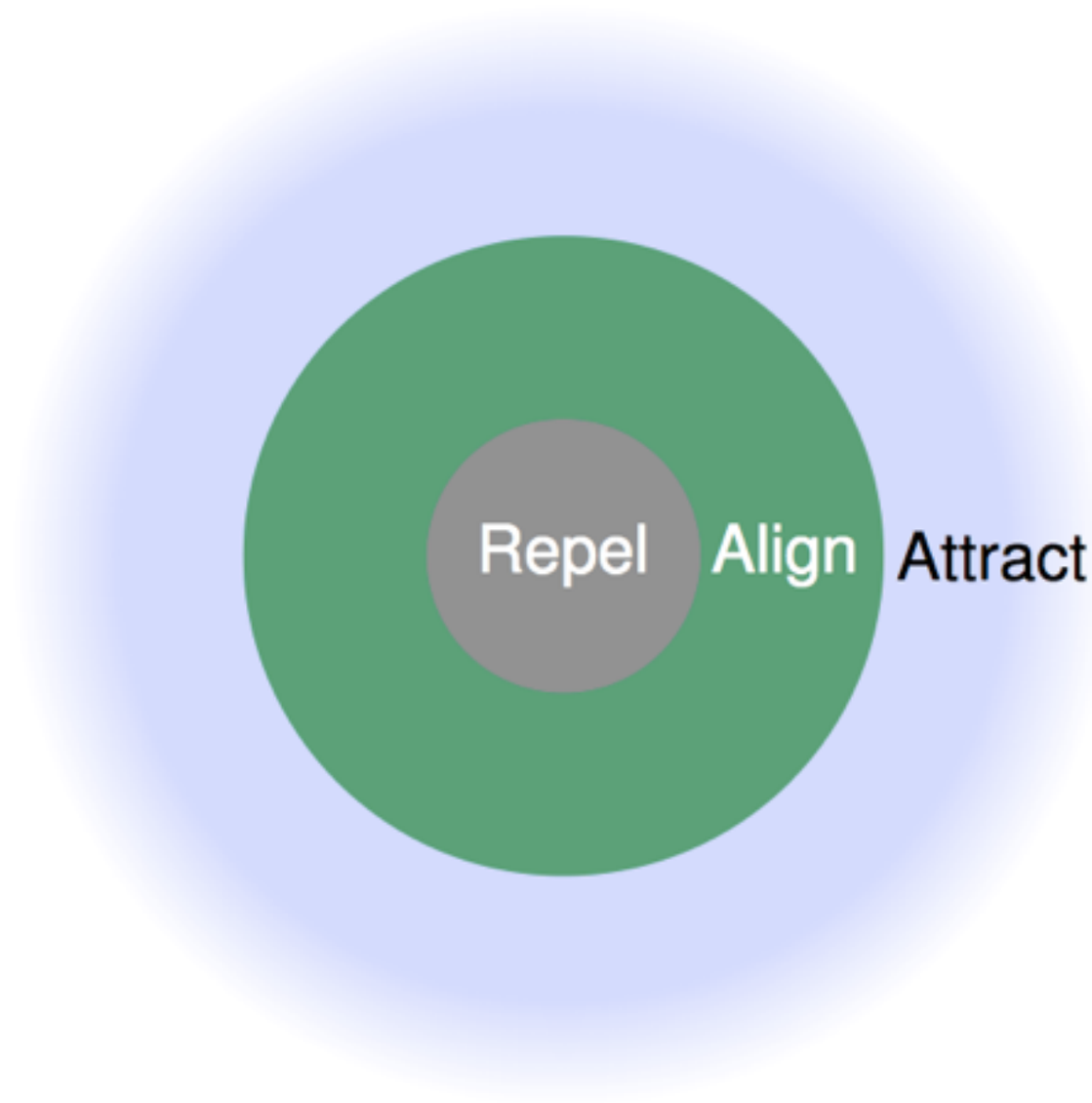
(D)

I.D. Couzin *et al.*, *J. Theor. Biol.* (2002)

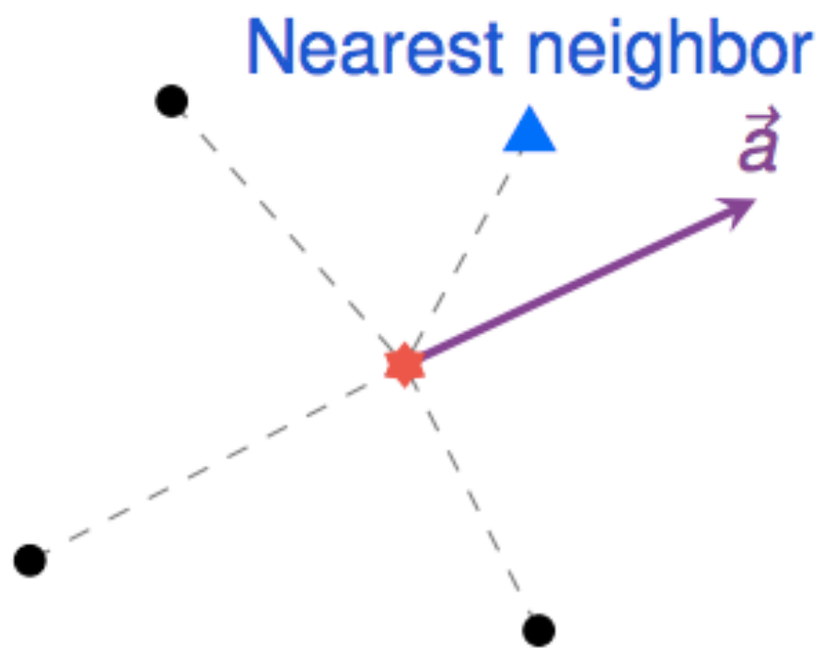
Solving the Inverse Problem?

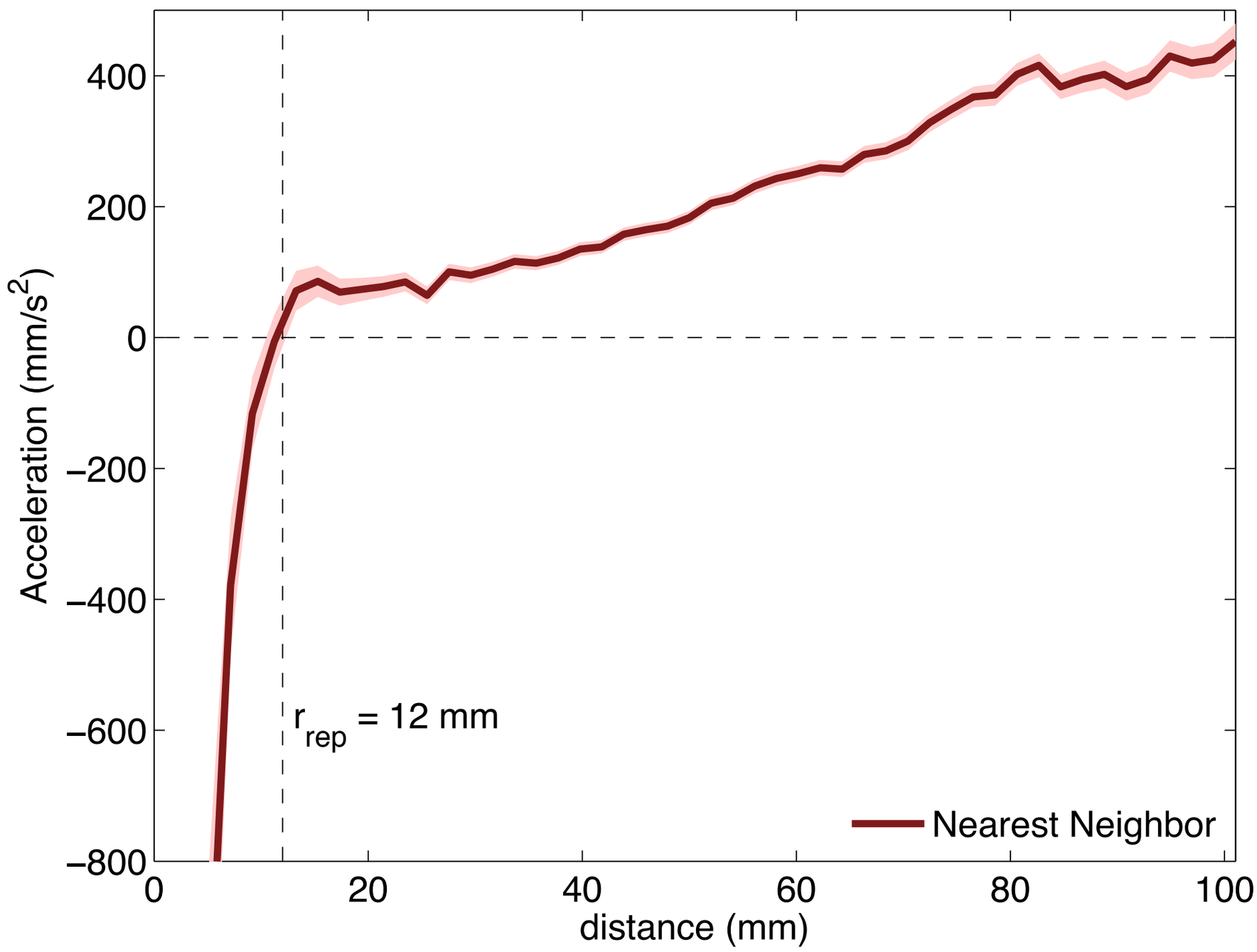
Ingredients:

1. Self-propulsion
2. Short-range repulsion
3. Long-range attraction
4. Intermediate-range alignment



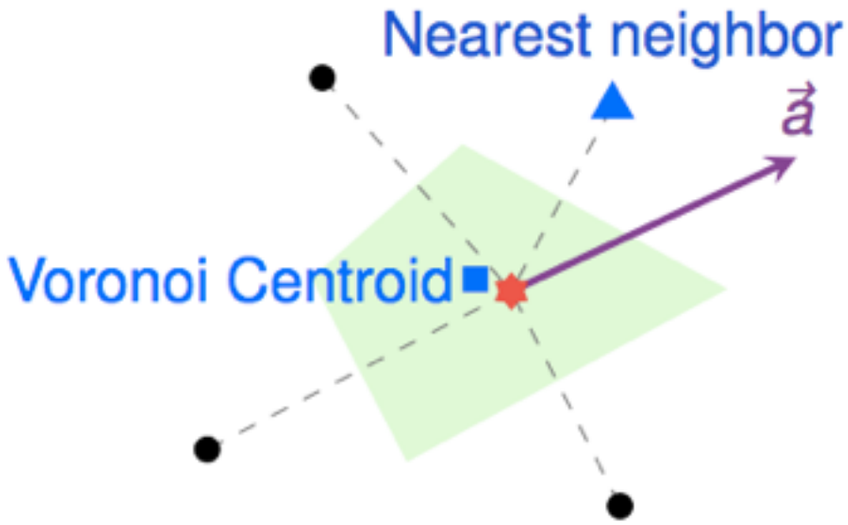
Effective Forces?

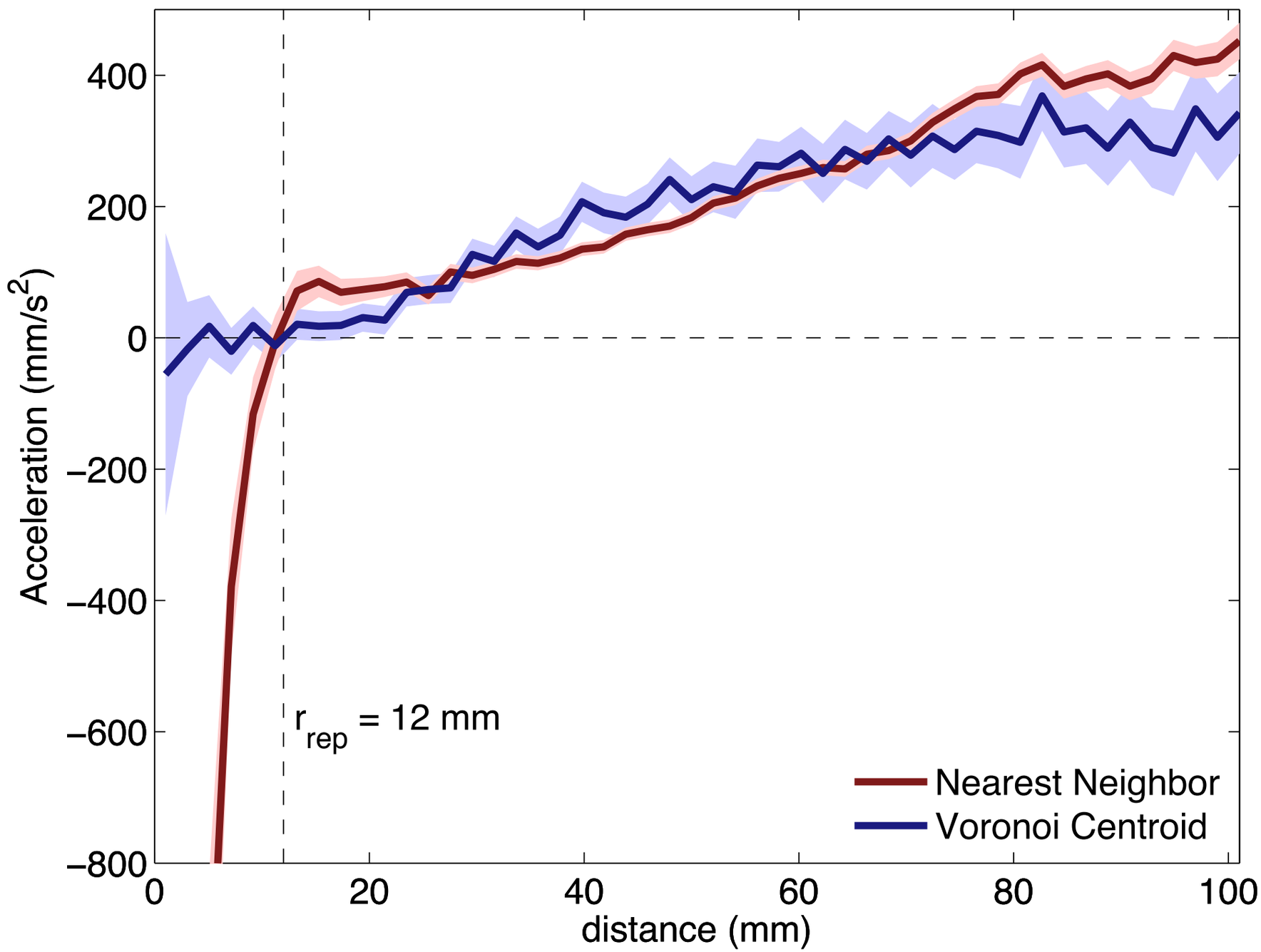




J.G. Puckett, D.H. Kelley, & NTO, *Sci. Rep.* (2014)

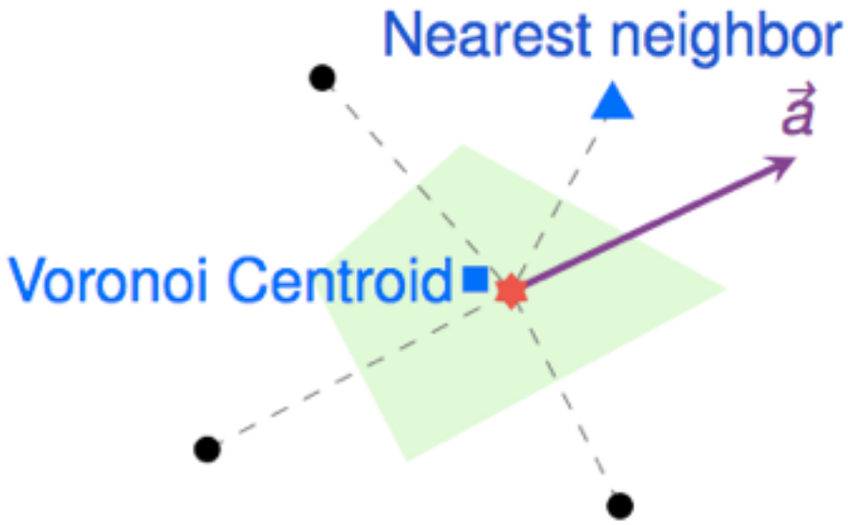
Effective Forces?

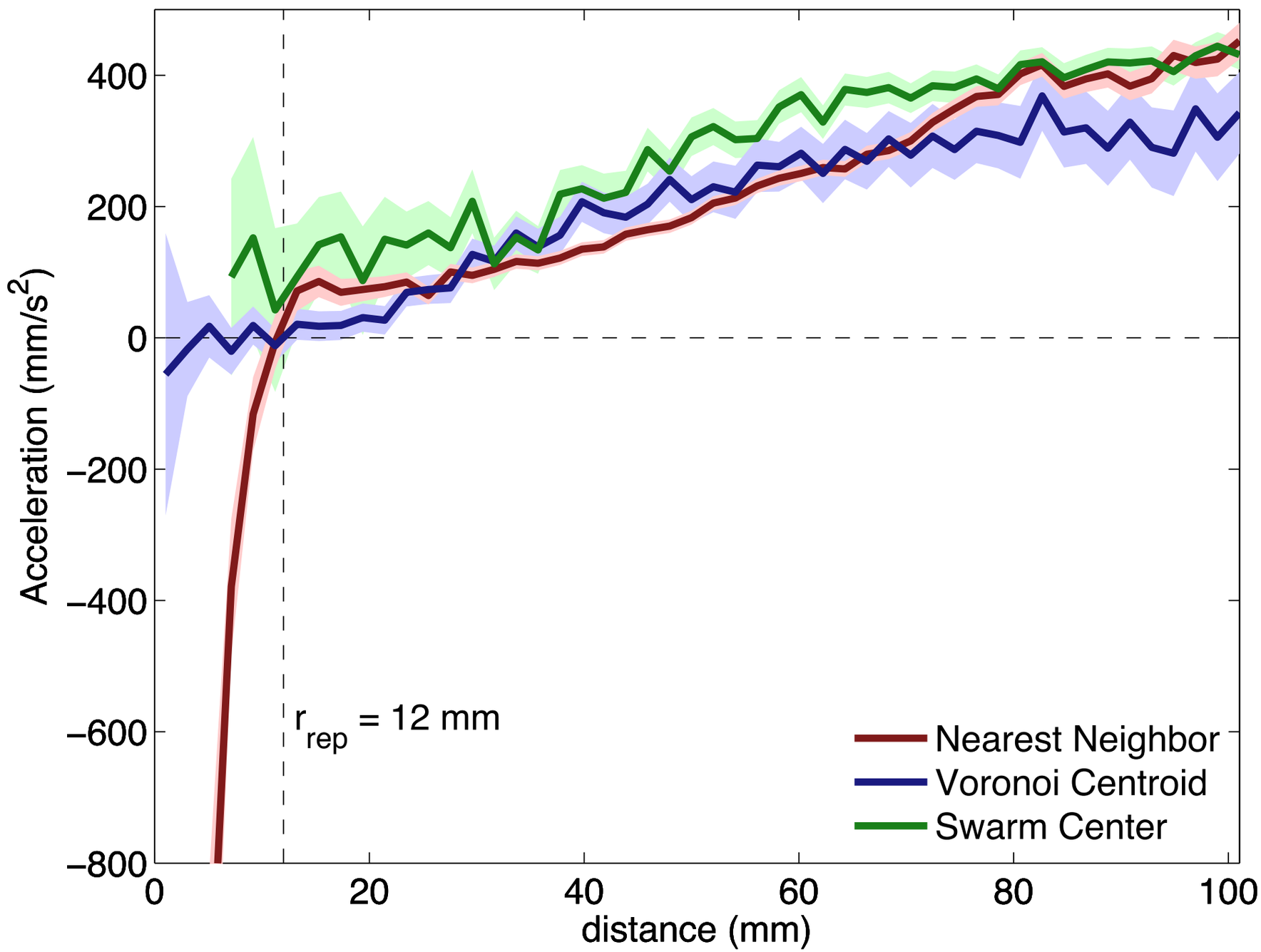




J.G. Puckett, D.H. Kelley, & NTO, *Sci. Rep.* (2014)

Effective Forces?

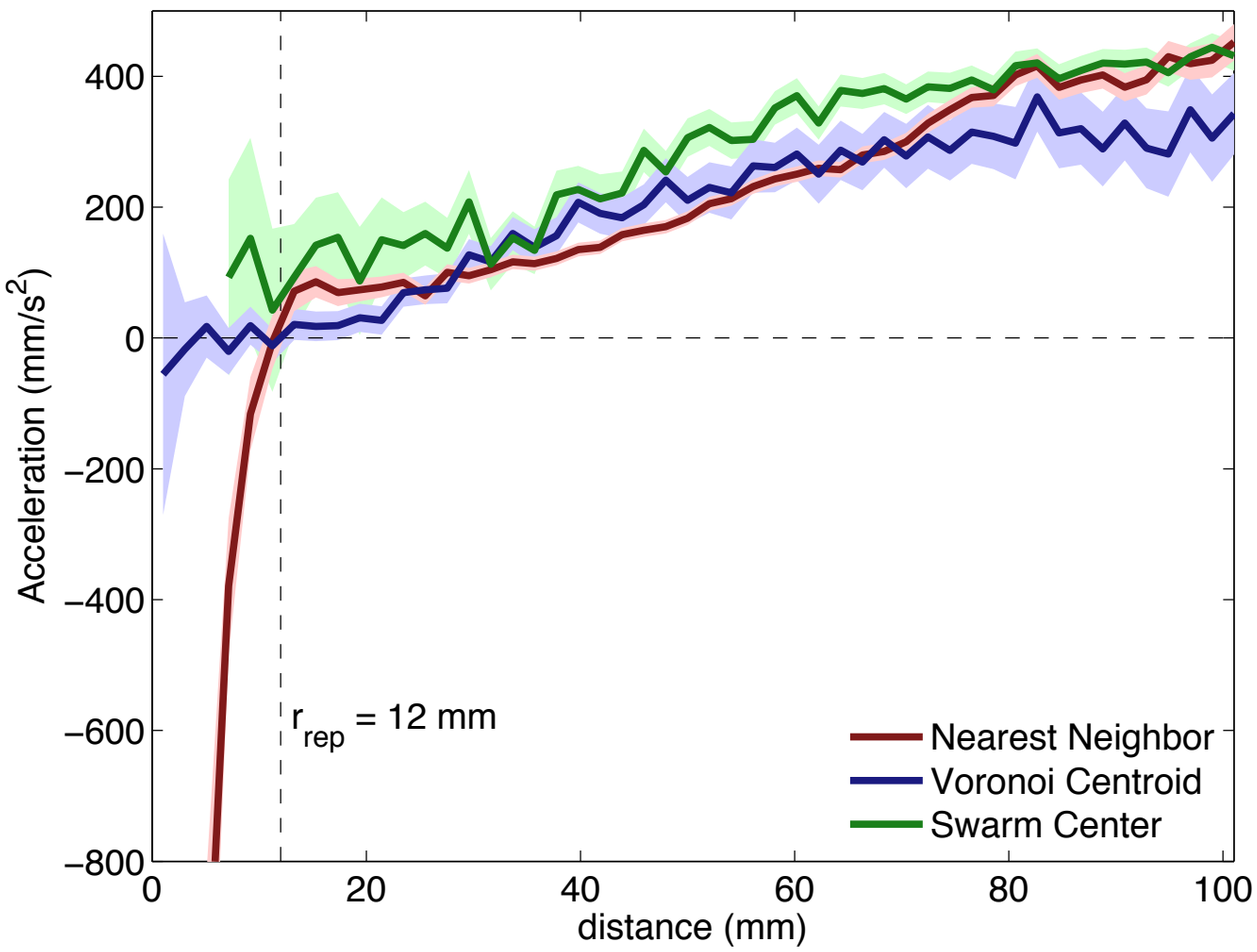




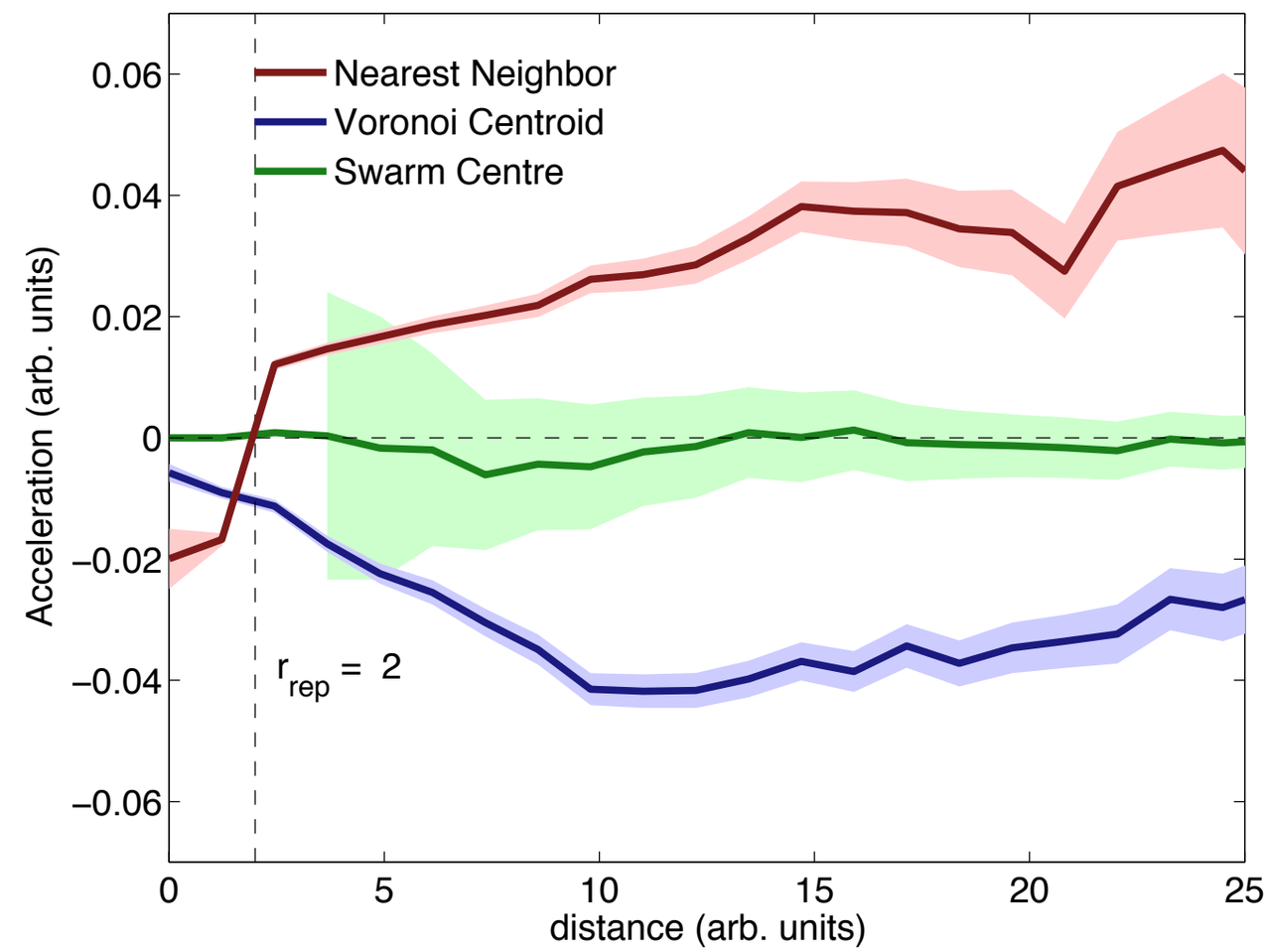
J.G. Puckett, D.H. Kelley, & NTO, *Sci. Rep.* (2014)

Effective Forces?

Experiment



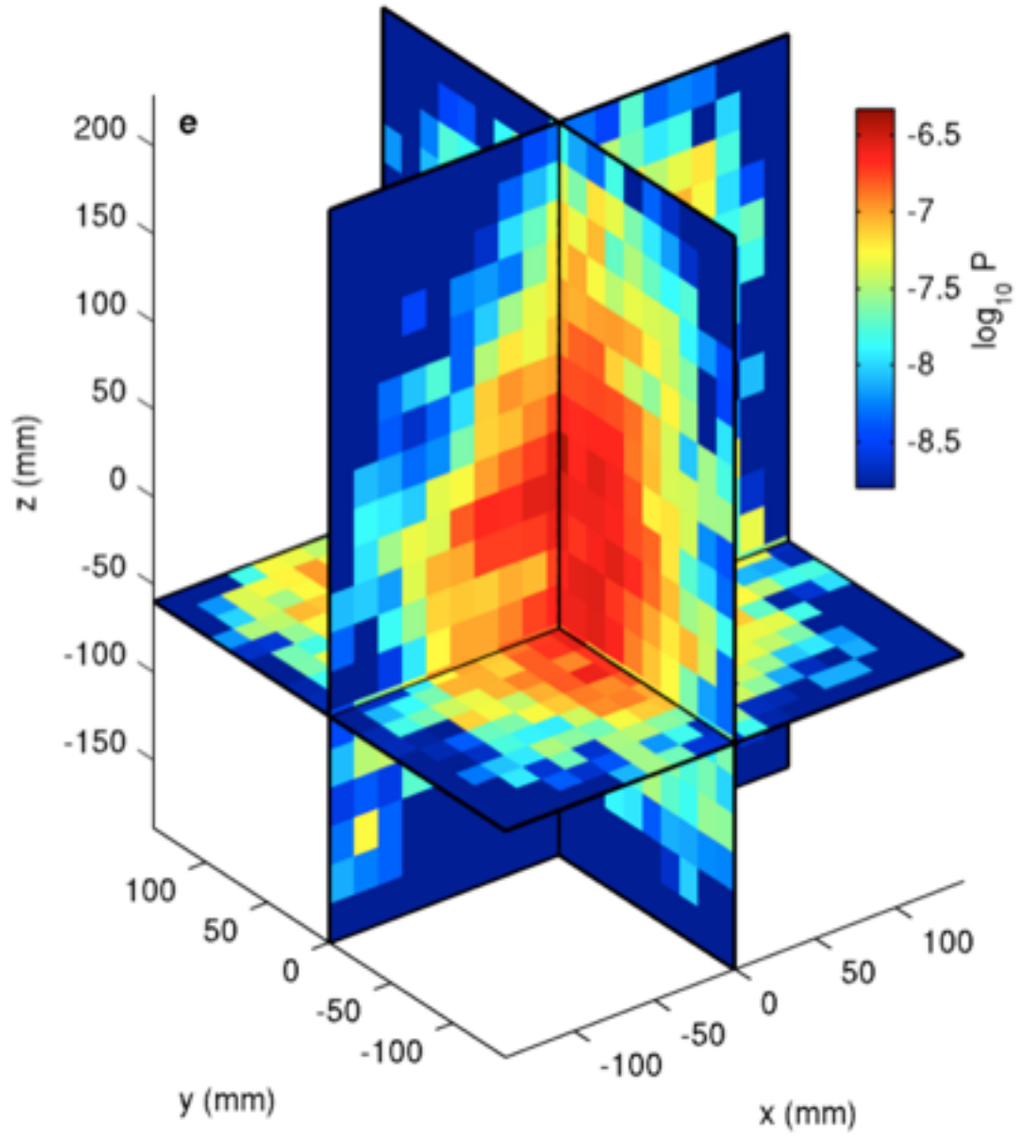
Model

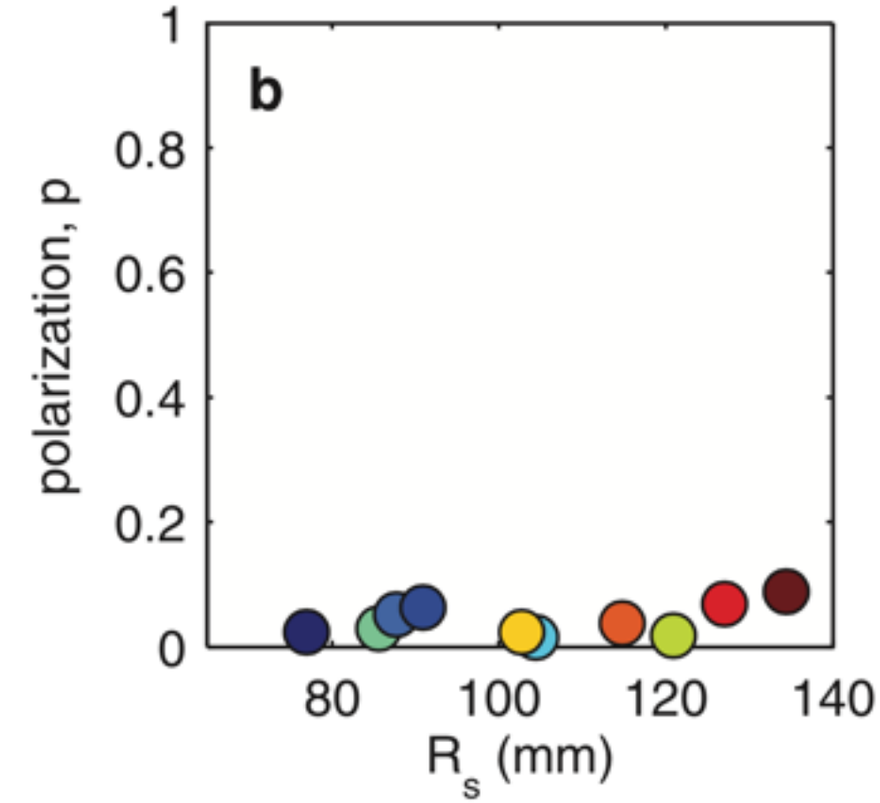


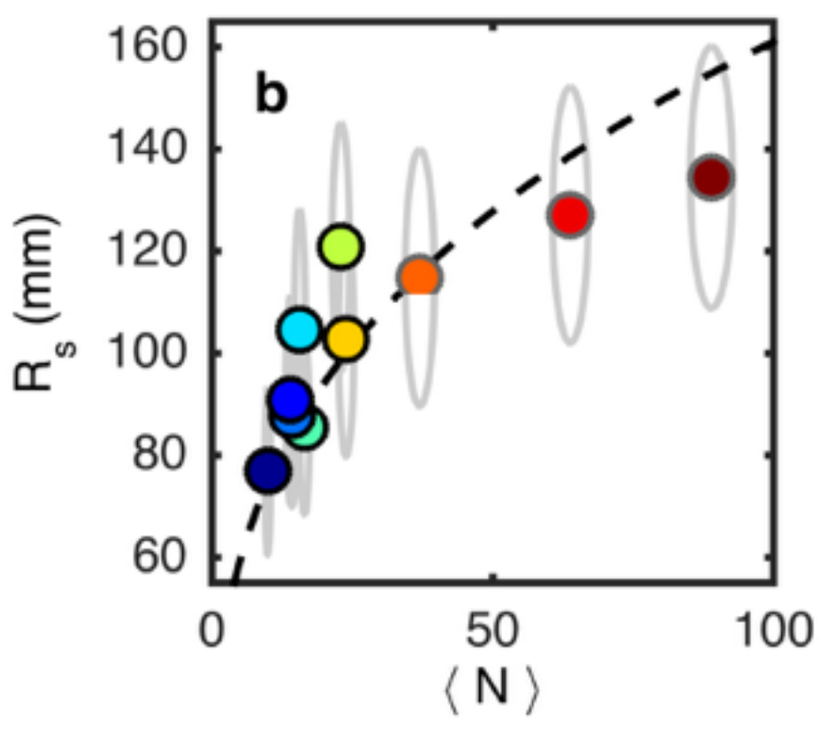
Model reproduces pattern but not statistics:
Overall pattern is not sufficient

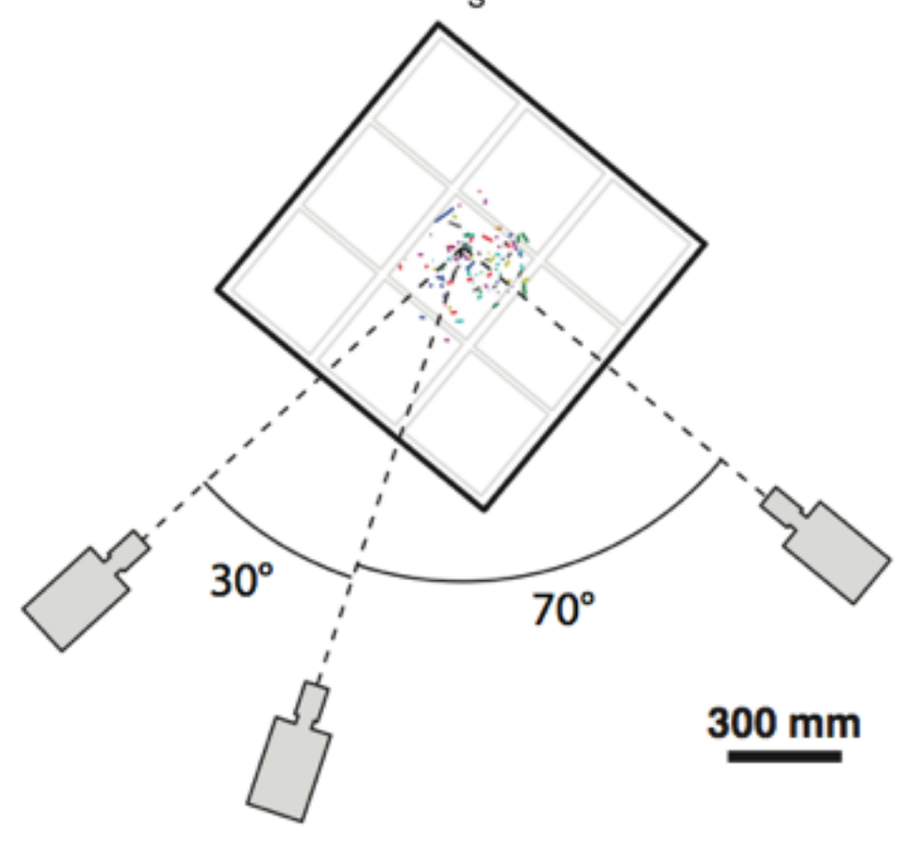
J.G. Puckett, D.H. Kelley, & NTO, *Sci. Rep.* (2014)

Swarm Structure



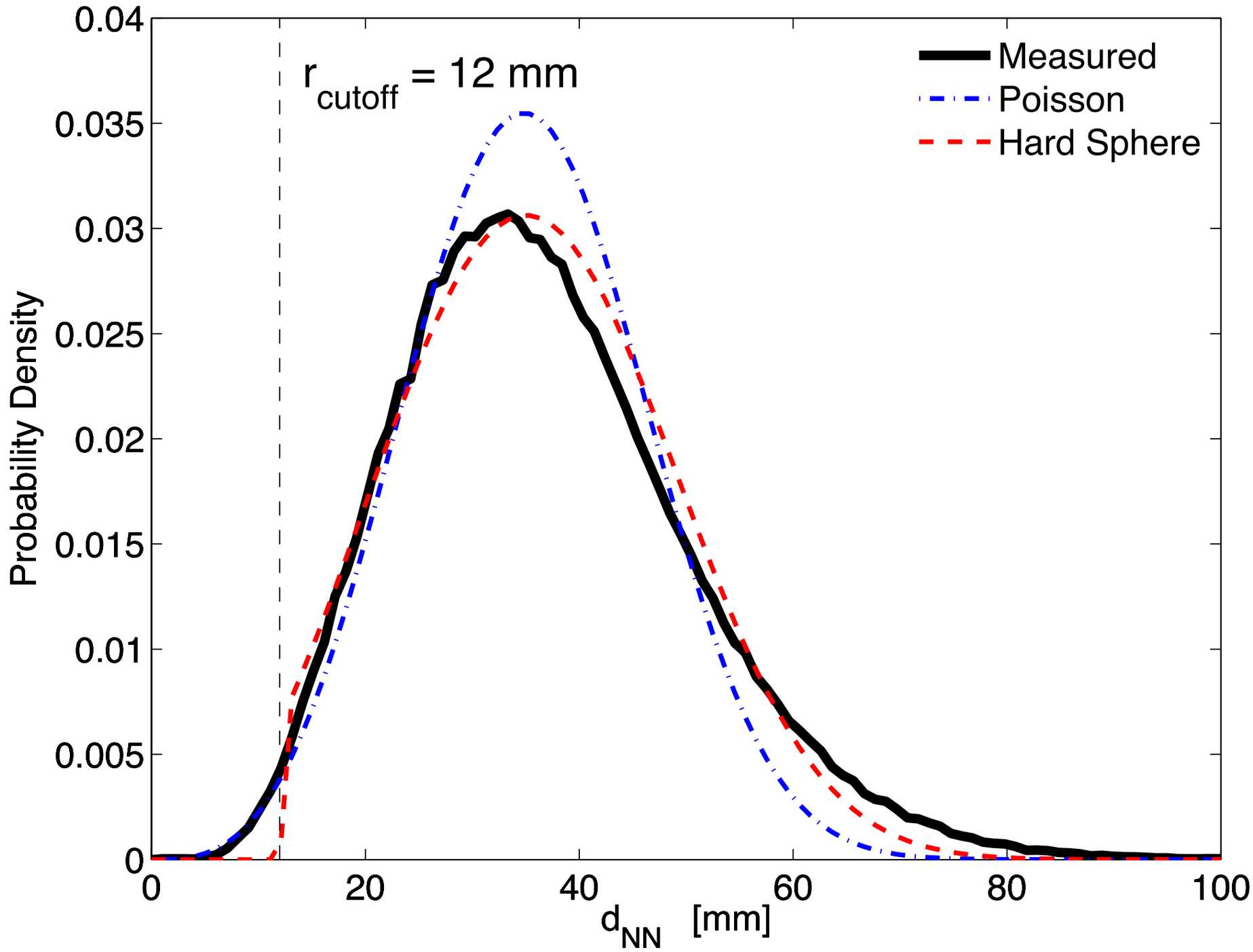






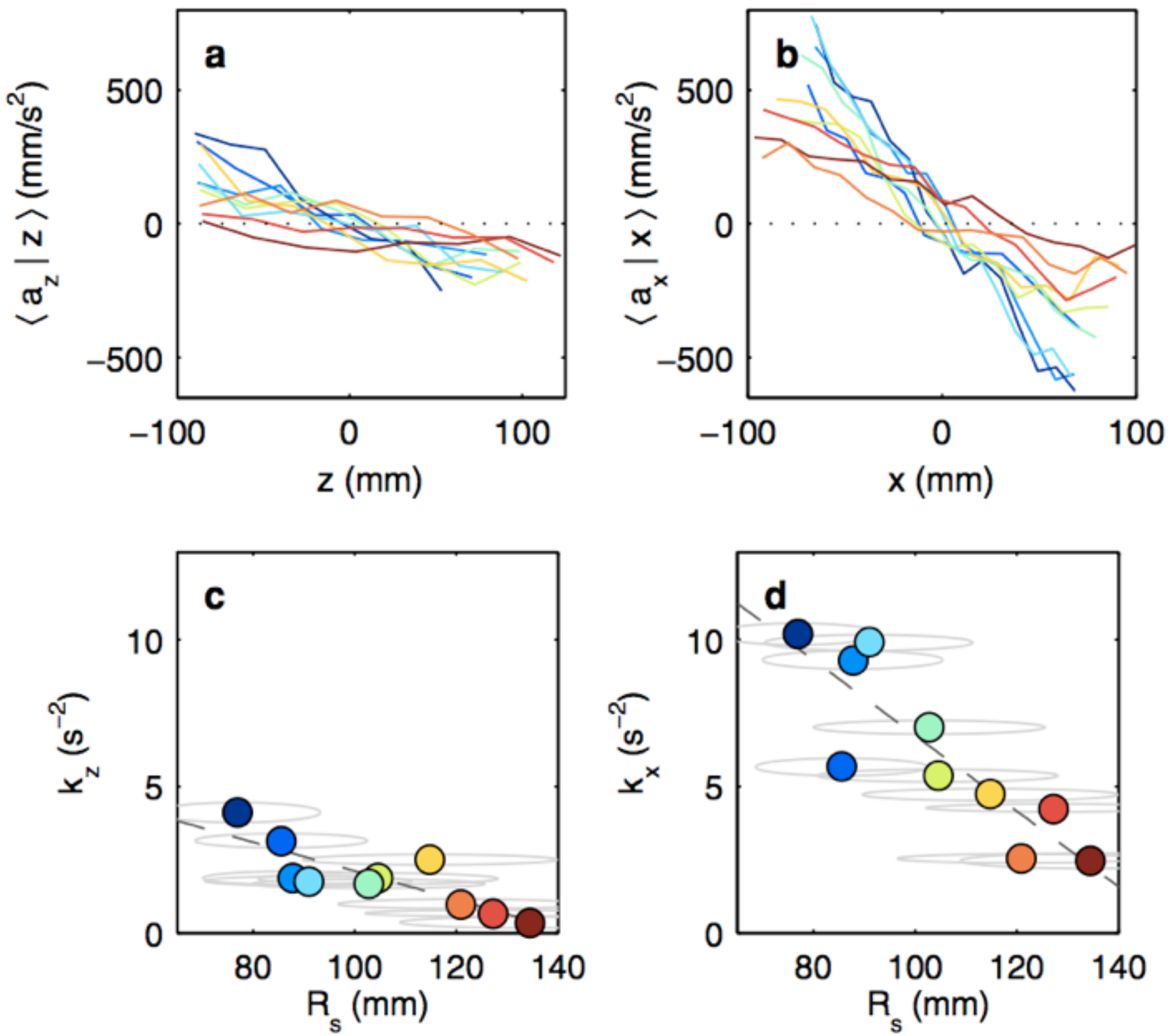
D.H. Kelley & NTO, *Sci. Rep.* (2013)

Relative Positions



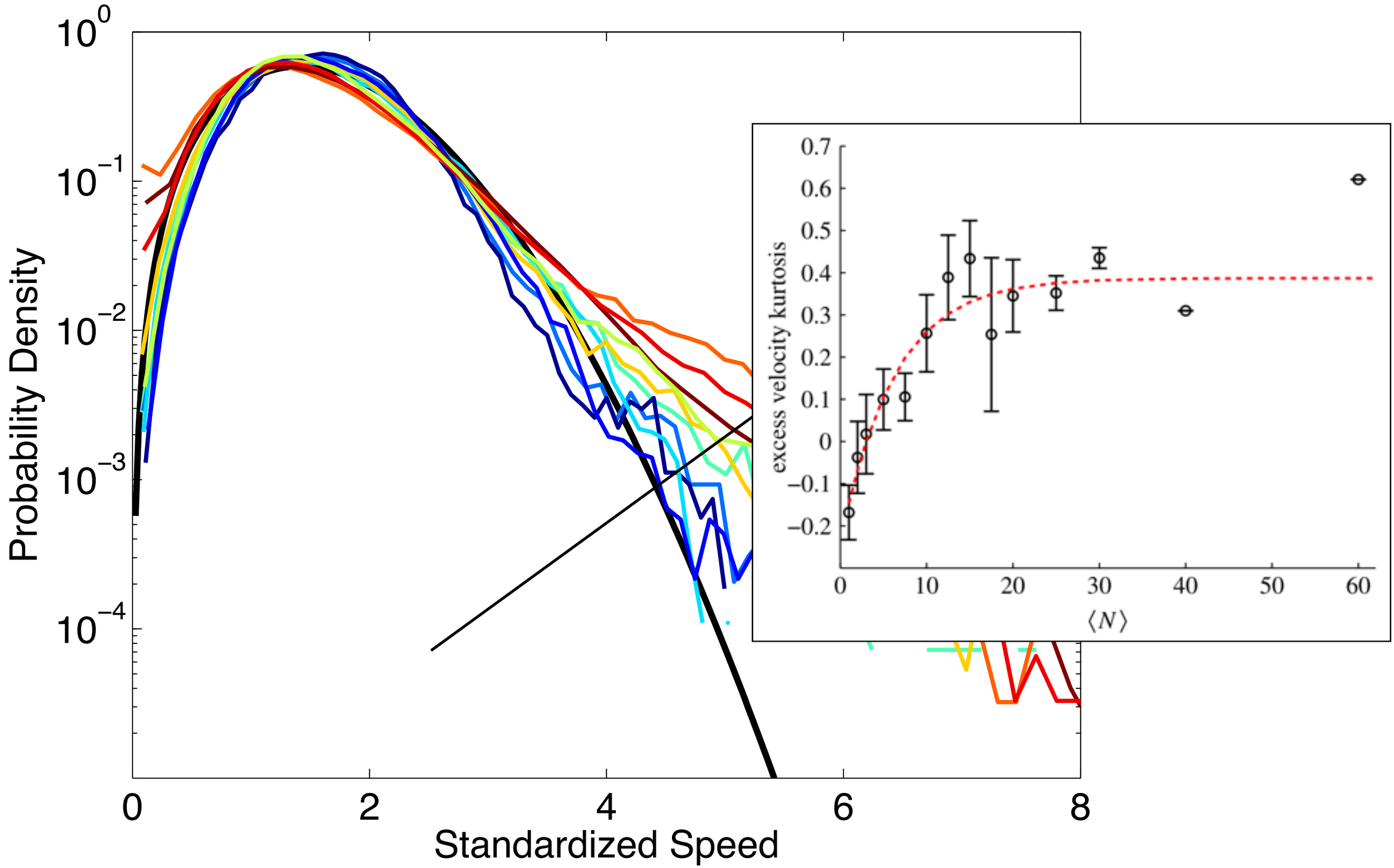
J.G. Puckett, D.H. Kelley, & NTO, *Sci. Rep.* (2014)

Effective Harmonic Trap



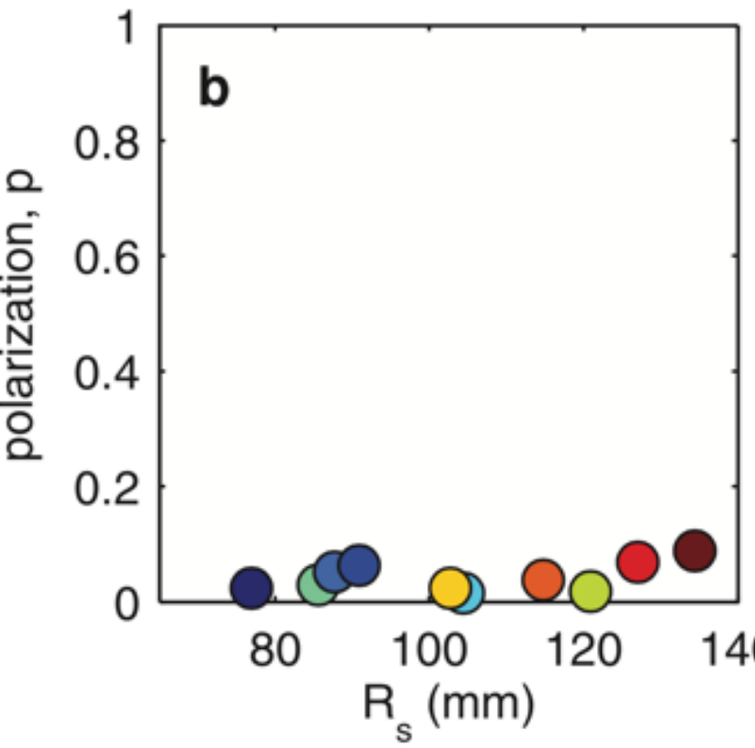
D.H. Kelley & NTO, *Sci. Rep.* (2013)

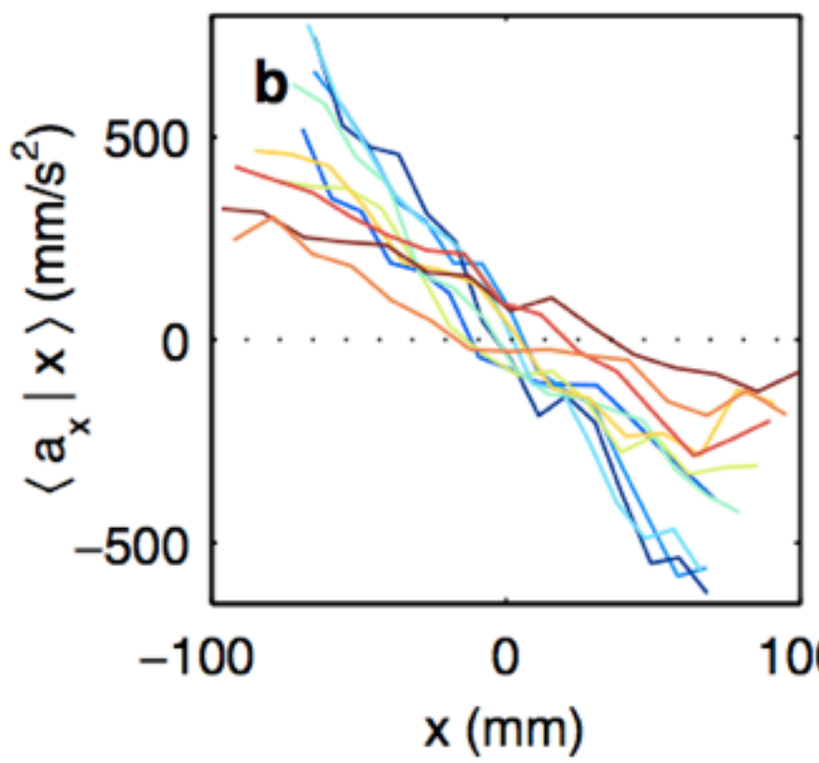
Speed Statistics

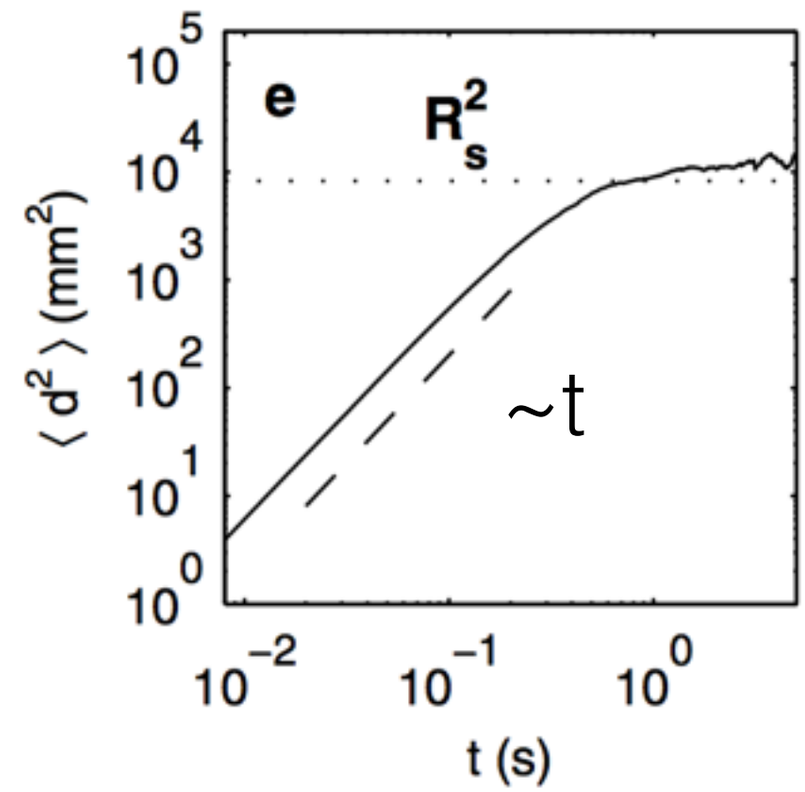


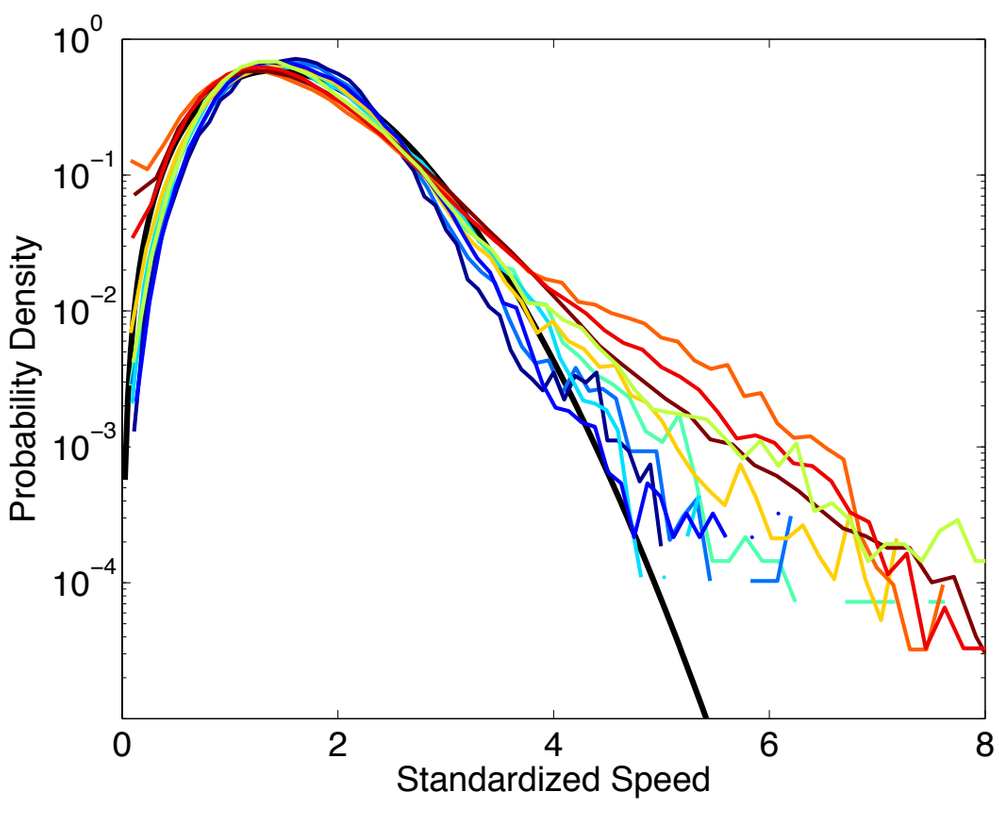
D.H. Kelley & NTO, *Sci. Rep.* (2013)
J.G. Puckett & NTO, *J. R. Soc. Interface* (2014)

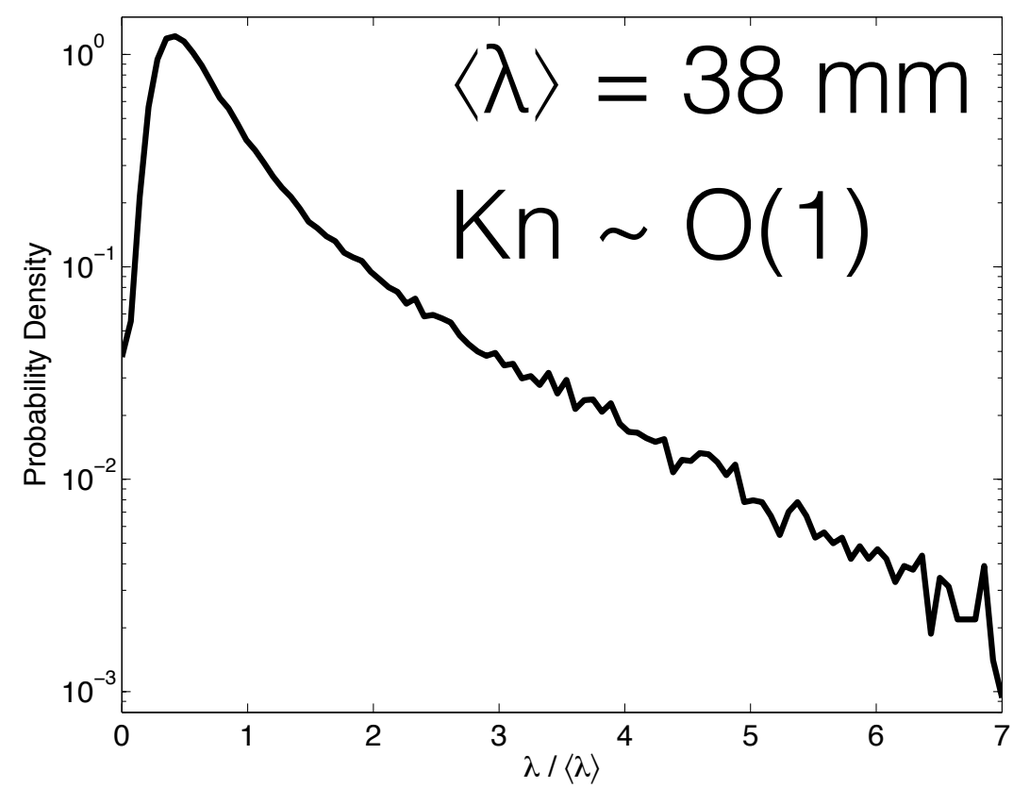
Swarm Properties











Swarm Properties

Swarms are dilute

Swarms are disordered

Interactions are rare

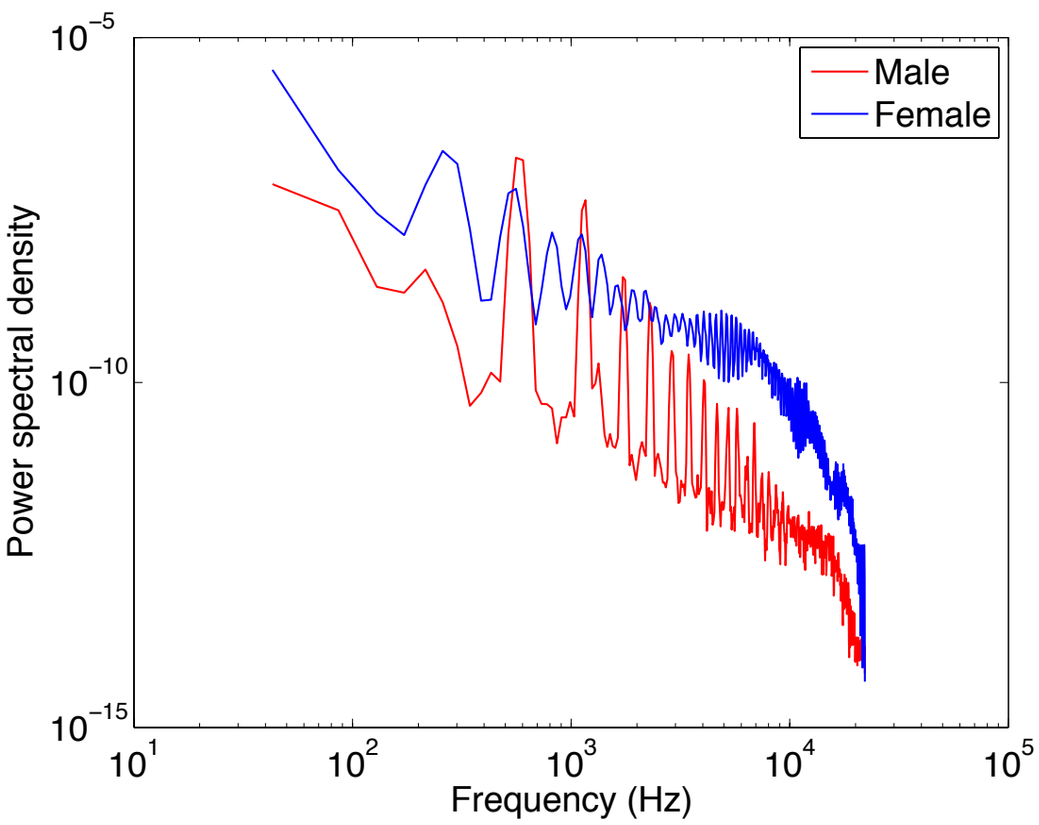
Insects are weakly coupled

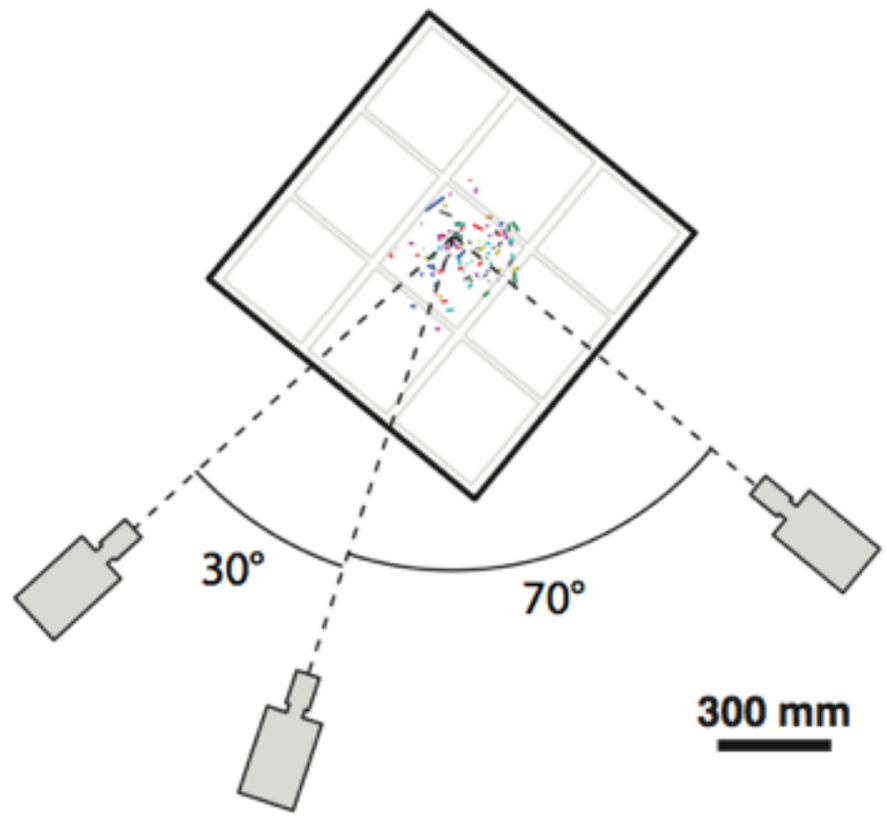
Insects are tightly bound

Swarms are compact

What kind of object is a swarm?

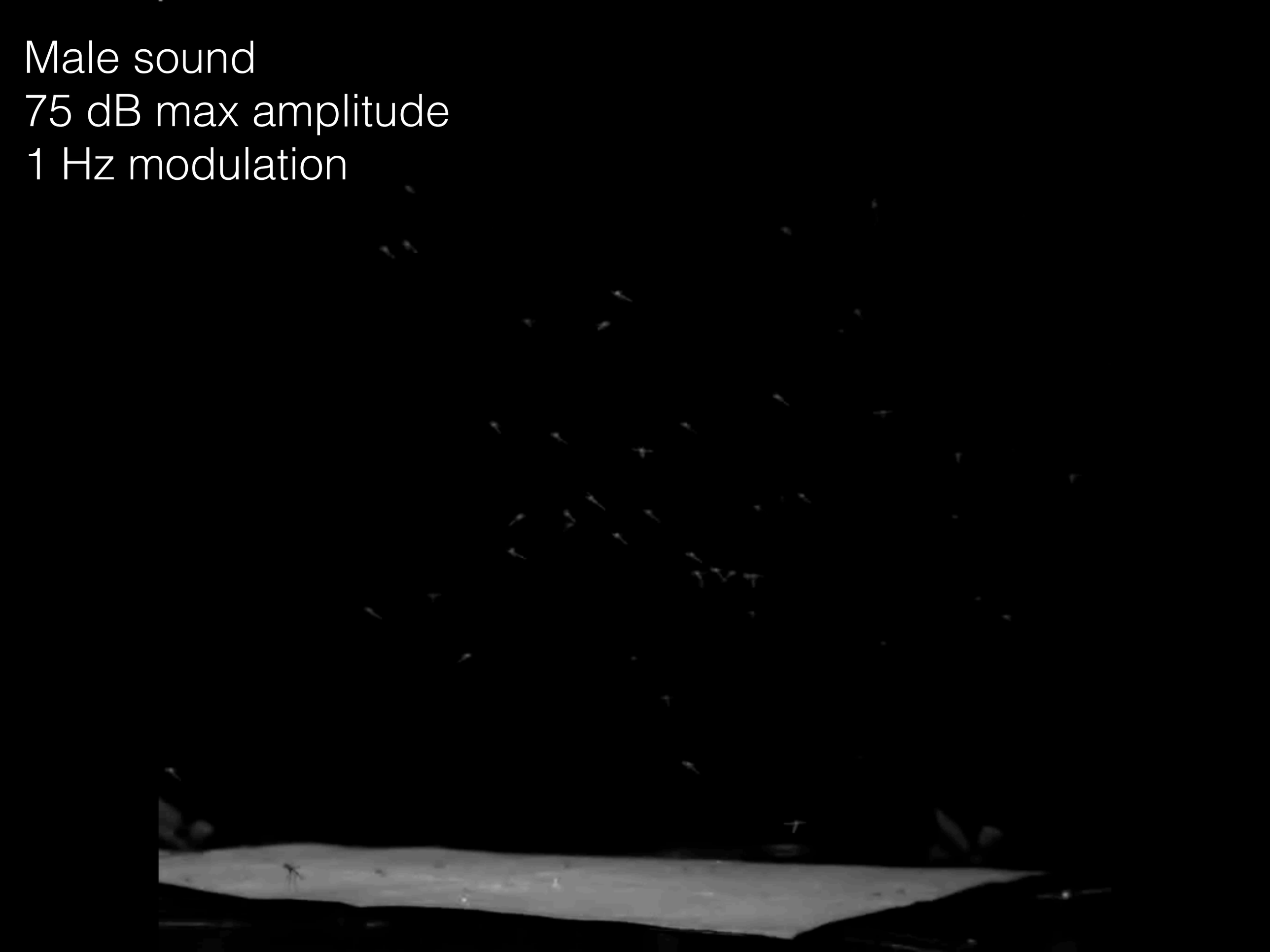
Moving Past Observations…



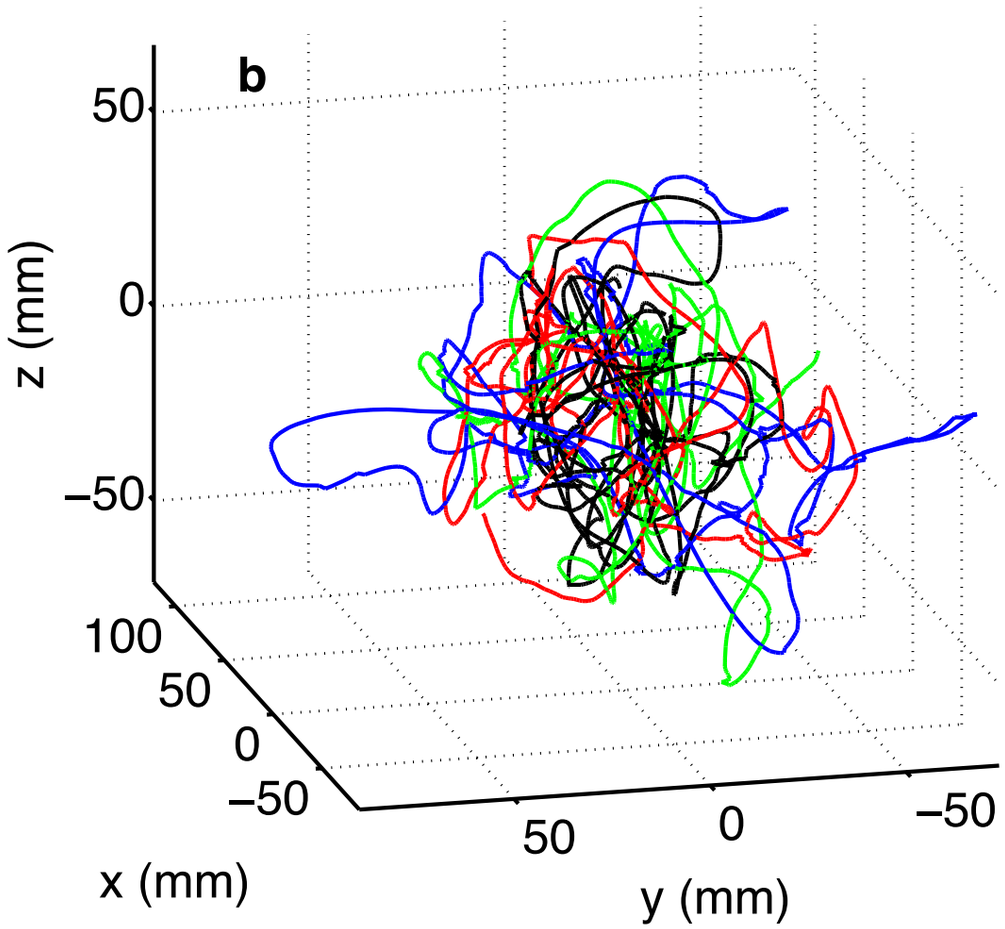


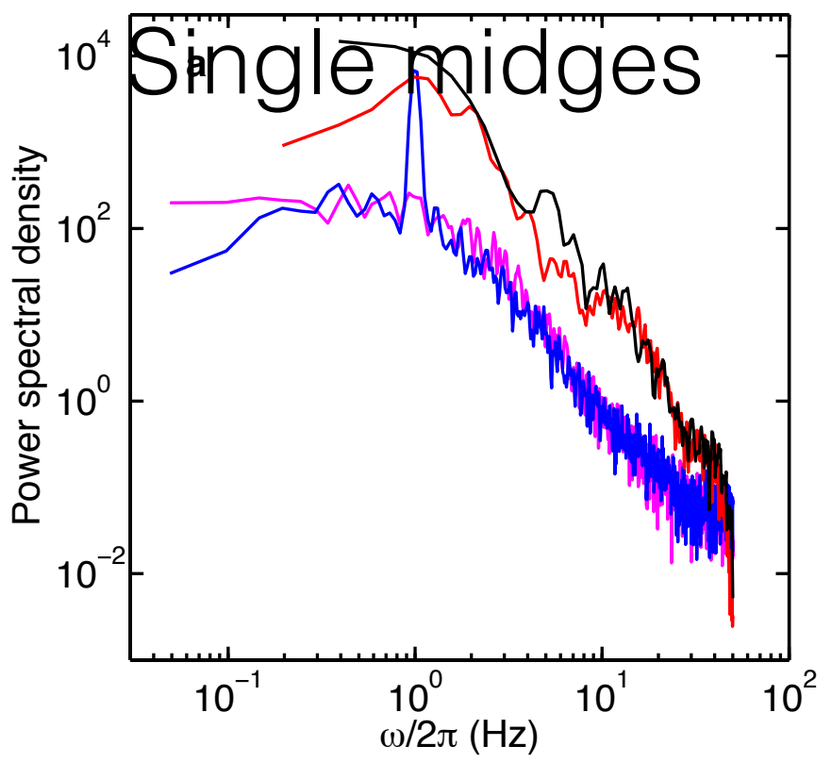
Drive swarms acoustically with amplitude-modulated wingbeat sounds; measure response

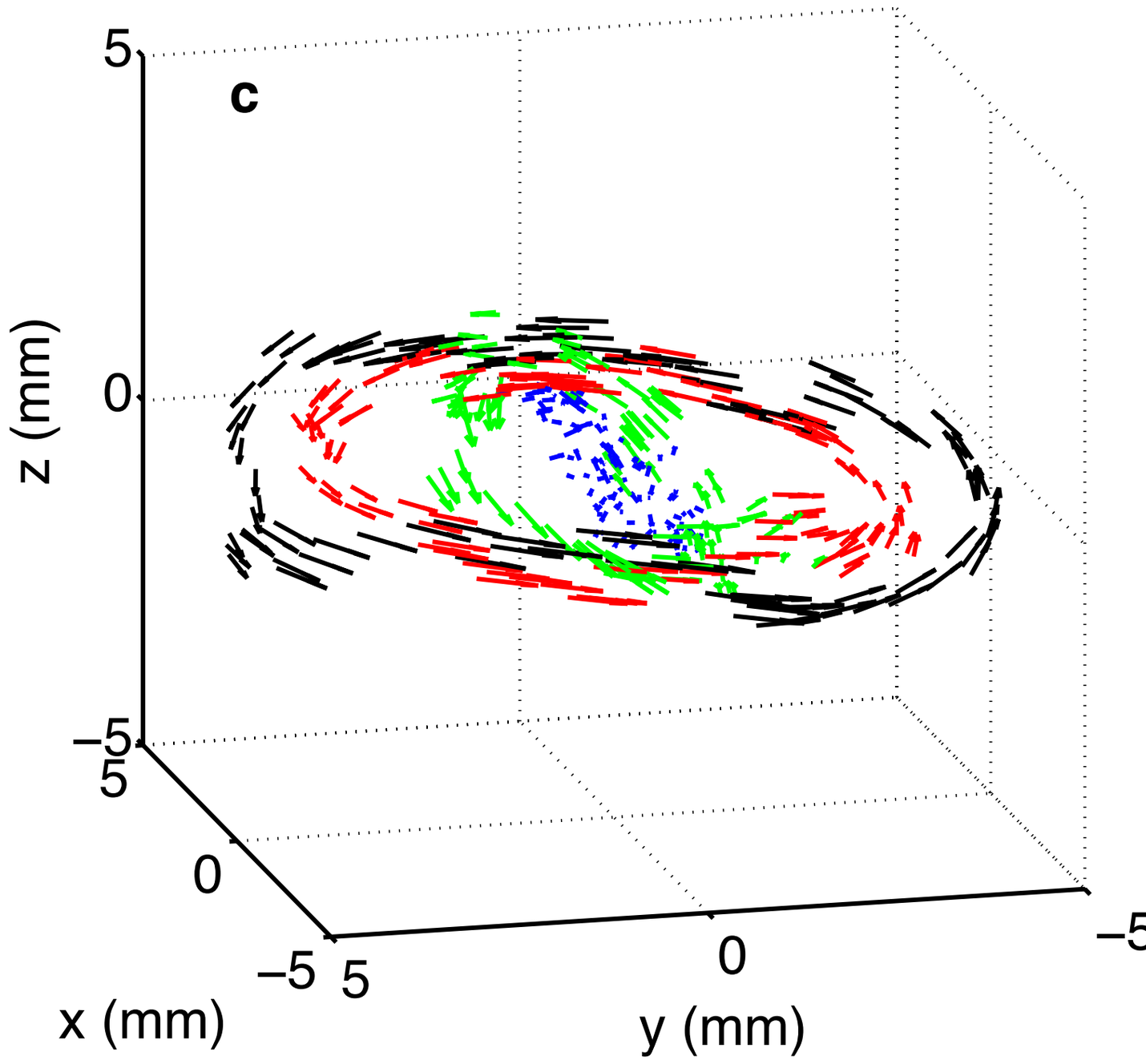
Male sound
75 dB max amplitude
1 Hz modulation



Effect of Driving

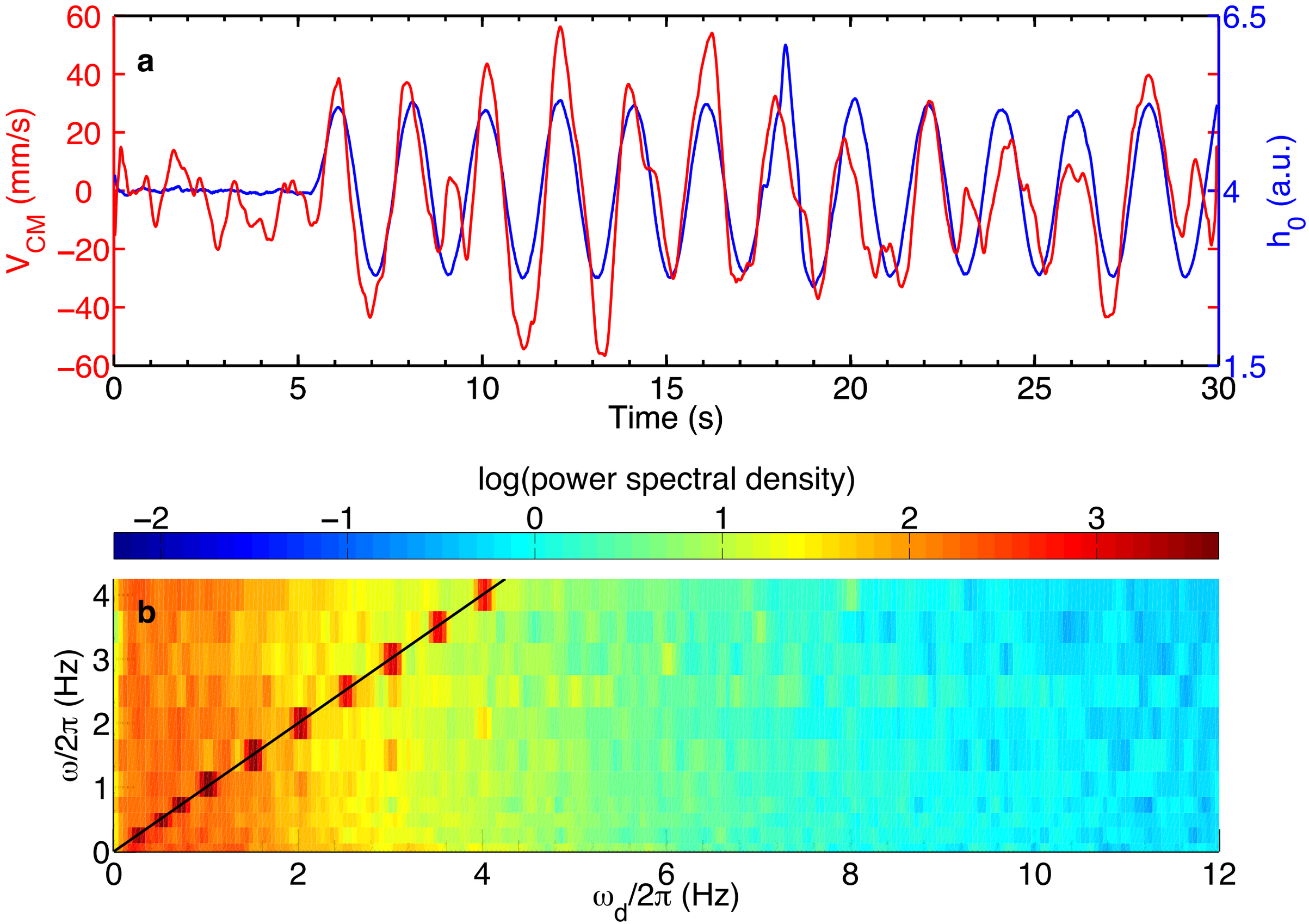






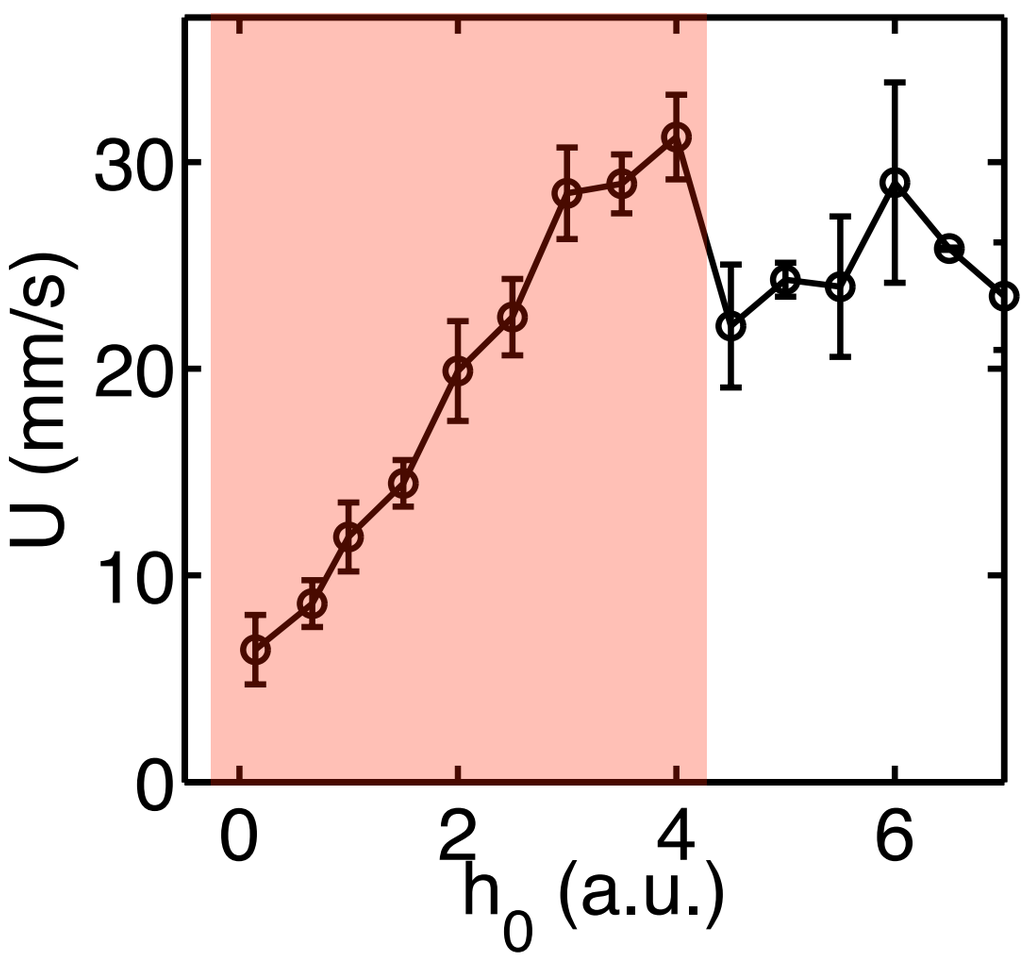
Center of Mass

CM Response

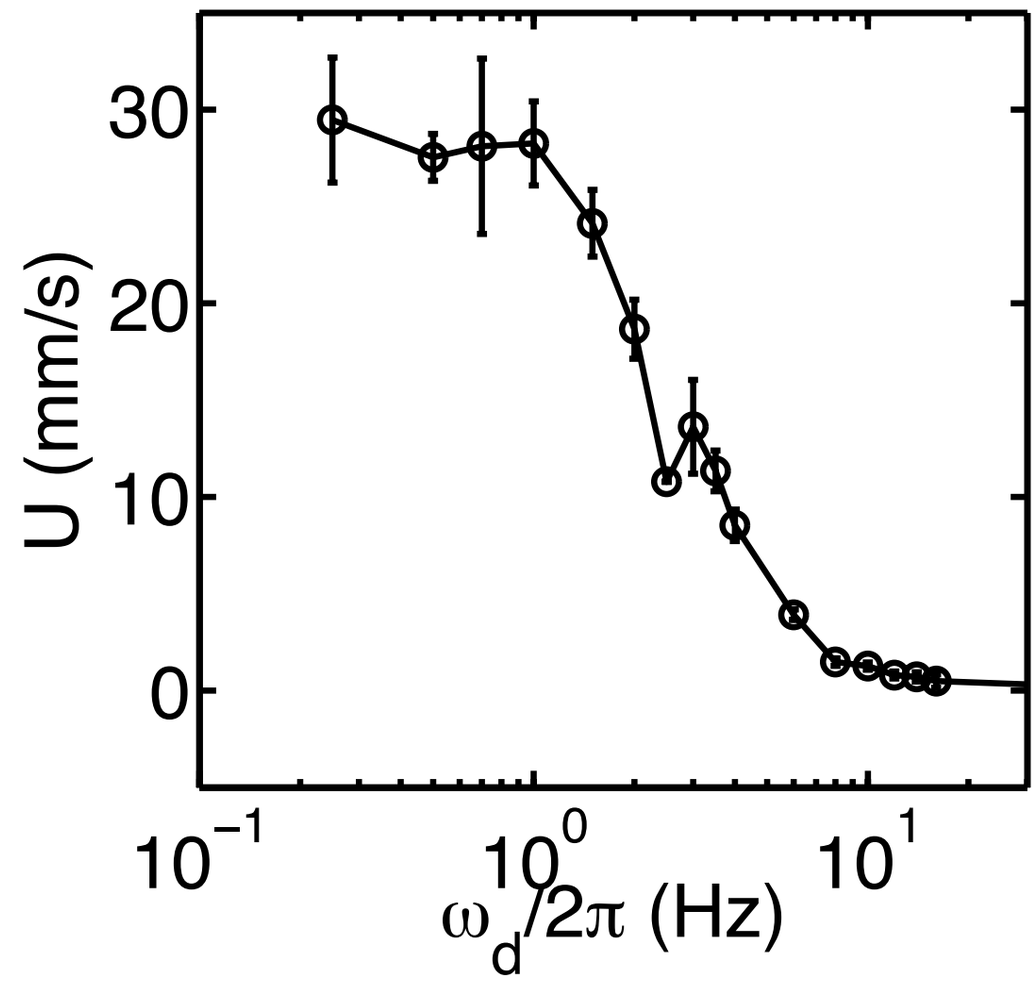

a
V_{CM} (mm/s)
h_0 (a.u.)
Time (s)
60
40
20
0
−20
−40
−60
6.5
4
1.5
0
5
10
15
20
25
30
log(power spectral density)
−2
−1
0
1
2
3
b
$\omega/2\pi$ (Hz)
$\omega_d/2\pi$ (Hz)
0
1
2
3
4
0
2
4
6
8
10
12

Characterizing Response

U: phase-averaged response amplitude



Fixed Frequency

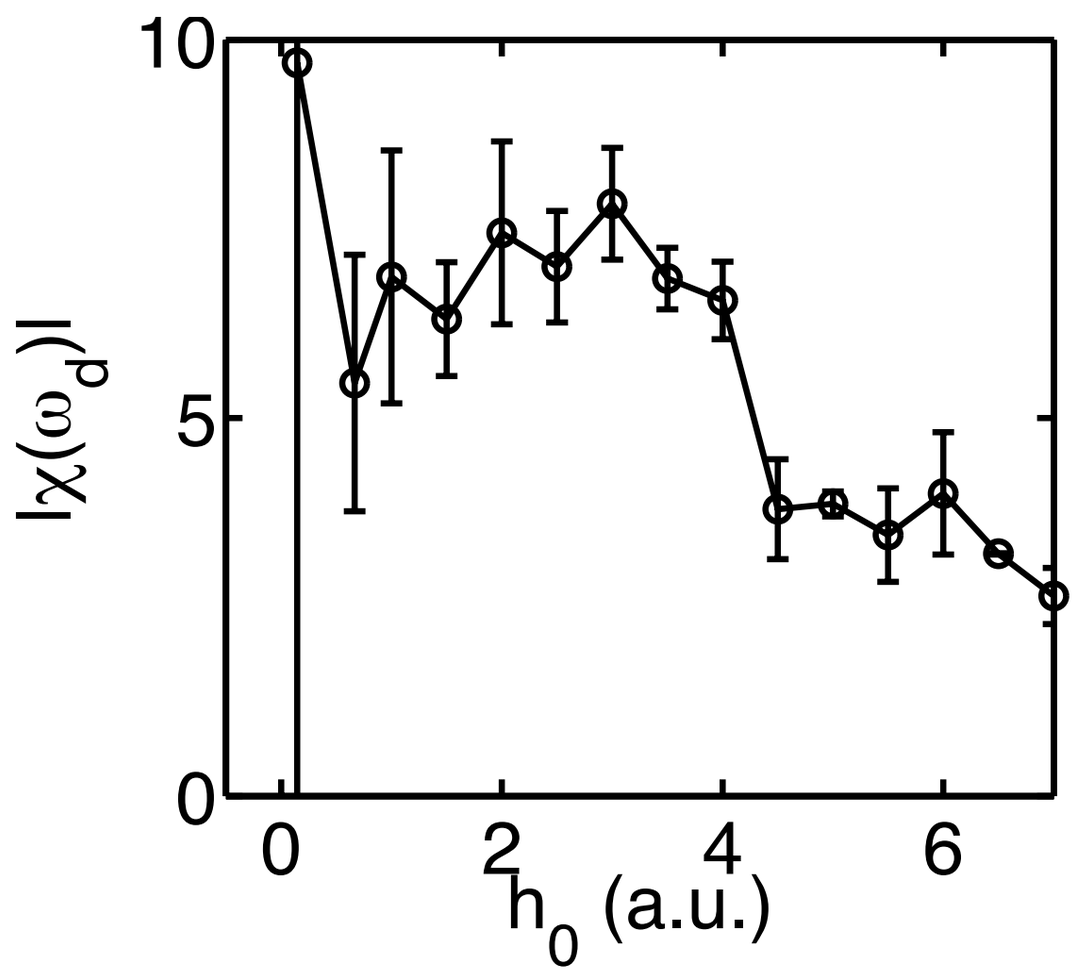


Fixed Amplitude

Linear Response

$$U \sin \omega_d t = |\chi(\omega_d)| h_0 \sin(\omega_d t - \phi)$$

Response Susceptibility Driving



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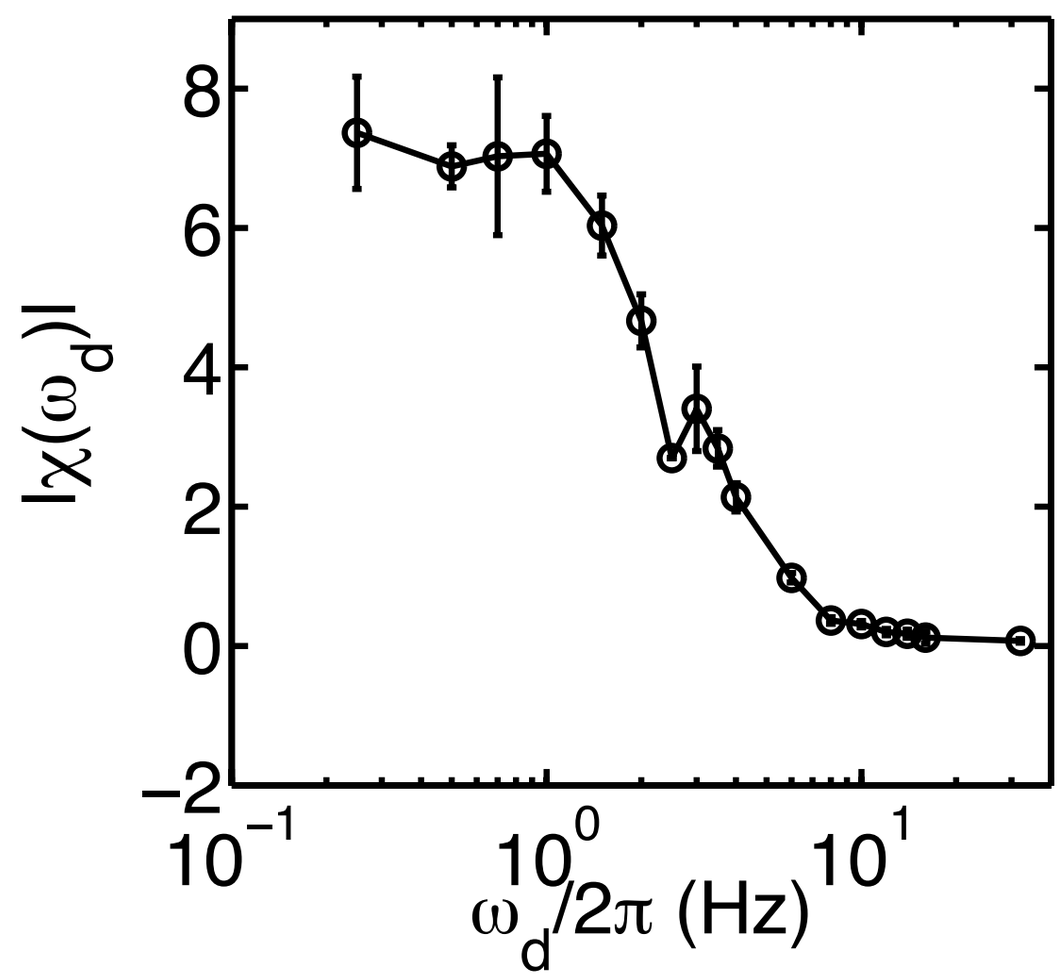
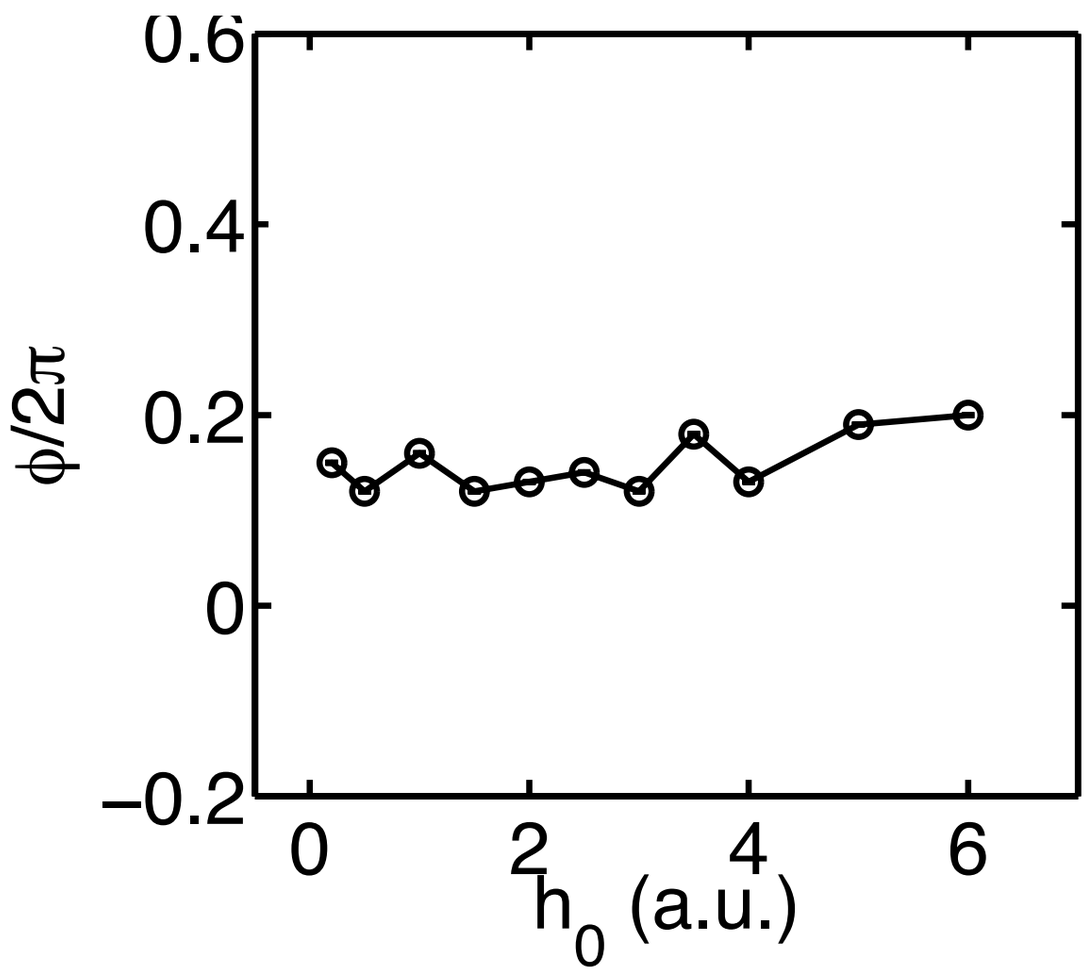


Fixed Amplitude

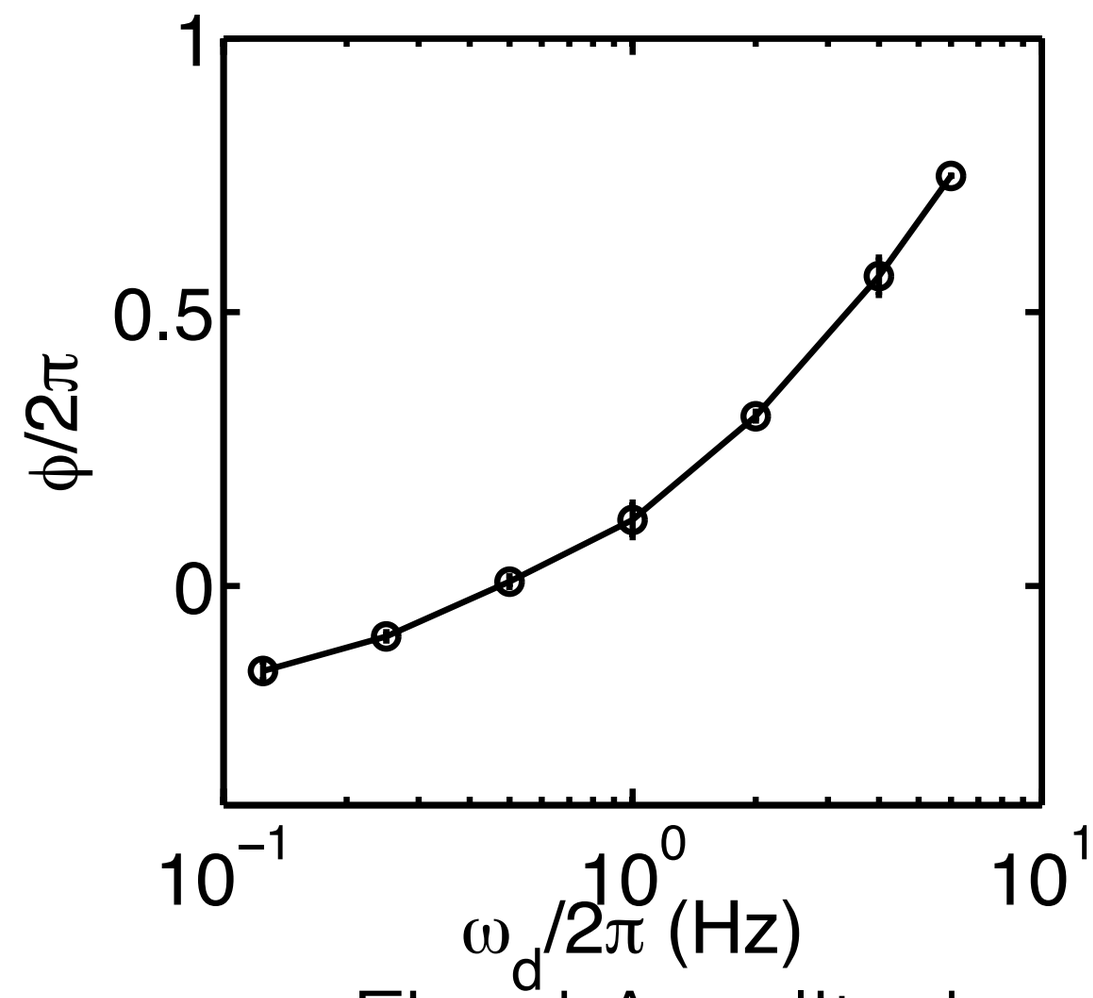
Linear Response

$$U \sin \omega_d t = |\chi(\omega_d)| h_0 \sin(\omega_d t - \phi)$$

Response Susceptibility Driving



Fixed Frequency



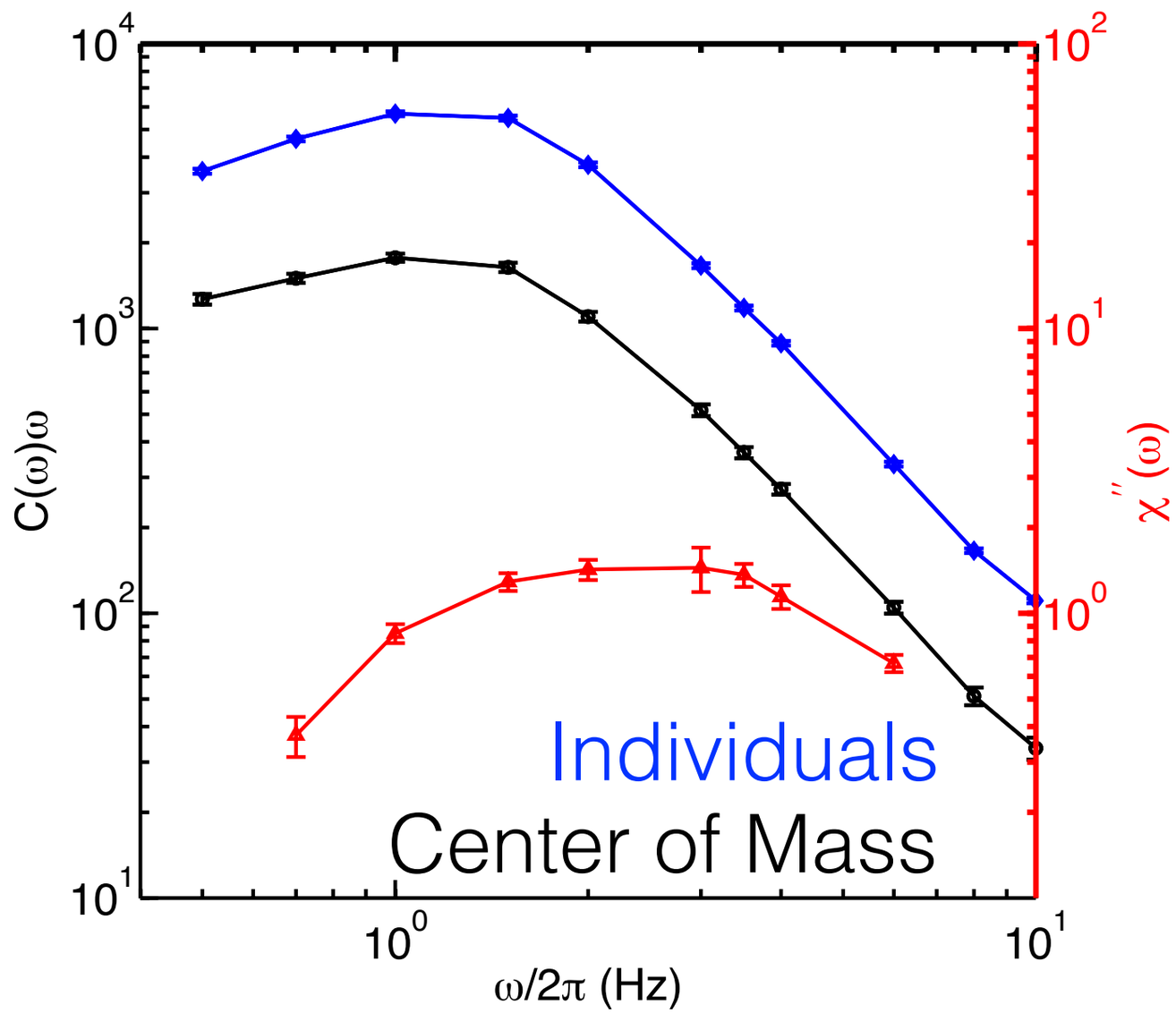
Fixed Amplitude

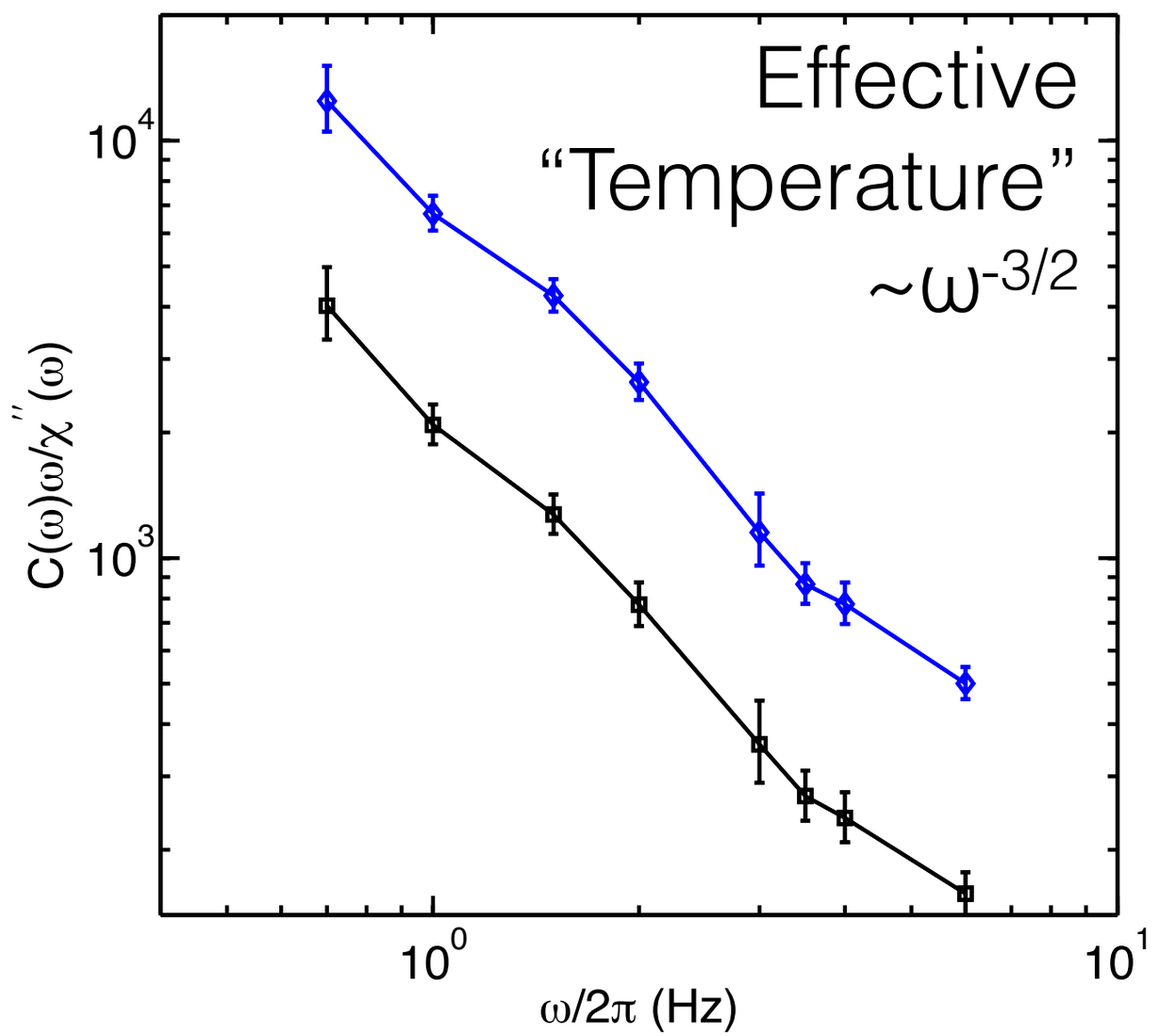
Fluctuation-Response?

In thermal systems, $\chi''(\omega) = \frac{\omega}{2k_B T}\tilde{C}(\omega)$

Response to Driving

Internal Fluctuations





Summary

Empirical measurements of collective behavior allow quantitative model testing

Controlled perturbation/response experiments are key!

Challenge for experiments:
Provide precise, nontrivial results

Challenge for theory:
Explain more than pattern

http://leviathan.eng.yale.edu