Estimating predictive dynamical models of legged locomotion from data



Bora Banjanin
Sam Burden
Talia Moore
Shai Revzen
Robert Full

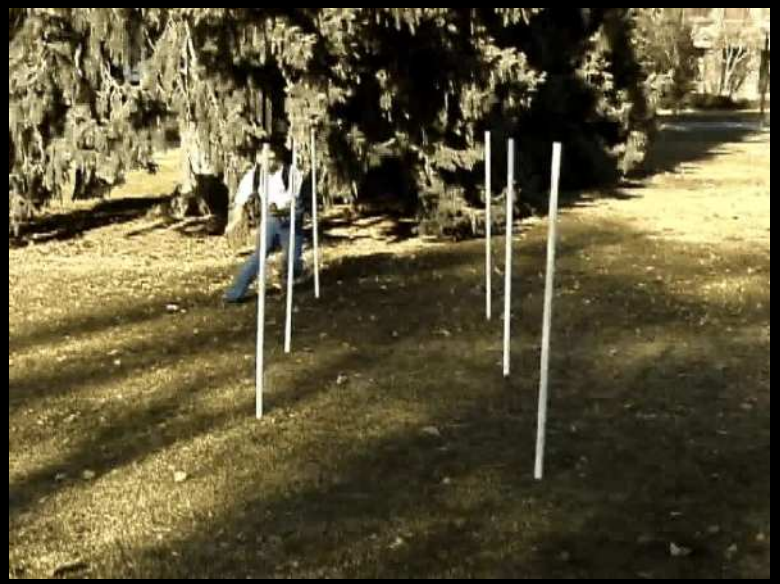
Why predictive dynamical models?

Predictive models generate testable hypotheses:



perturbations

Jindrich, Full *Journal of Experimental Biology* 205(18):2803-2823 2002



treatments

Carrier, Walter, Lee *Journal of Experimental Biology* 204(22):3917-3926 2001

Overview of today's talk

1. Experiments with running cockroaches

2. Experimental results vs existing models

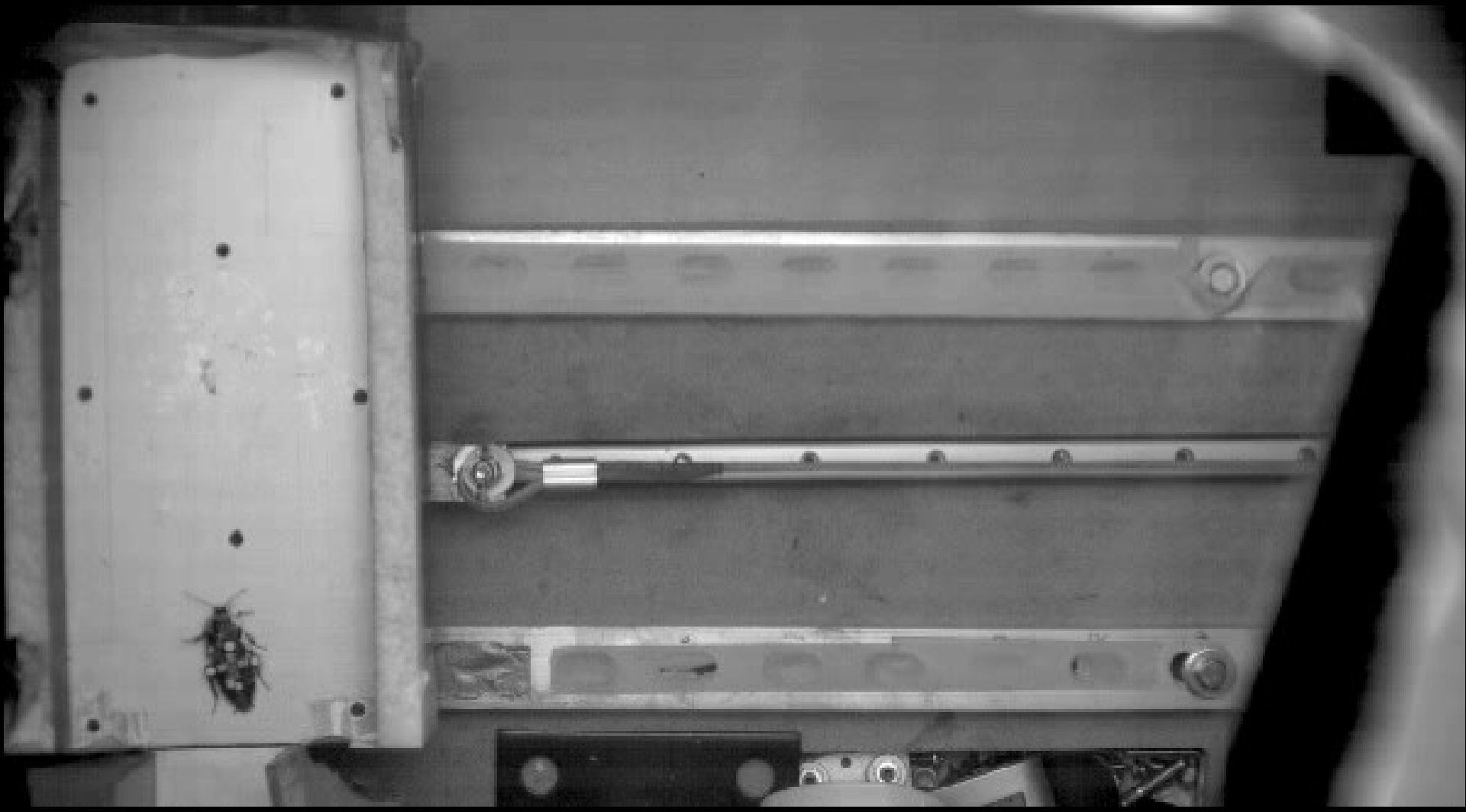
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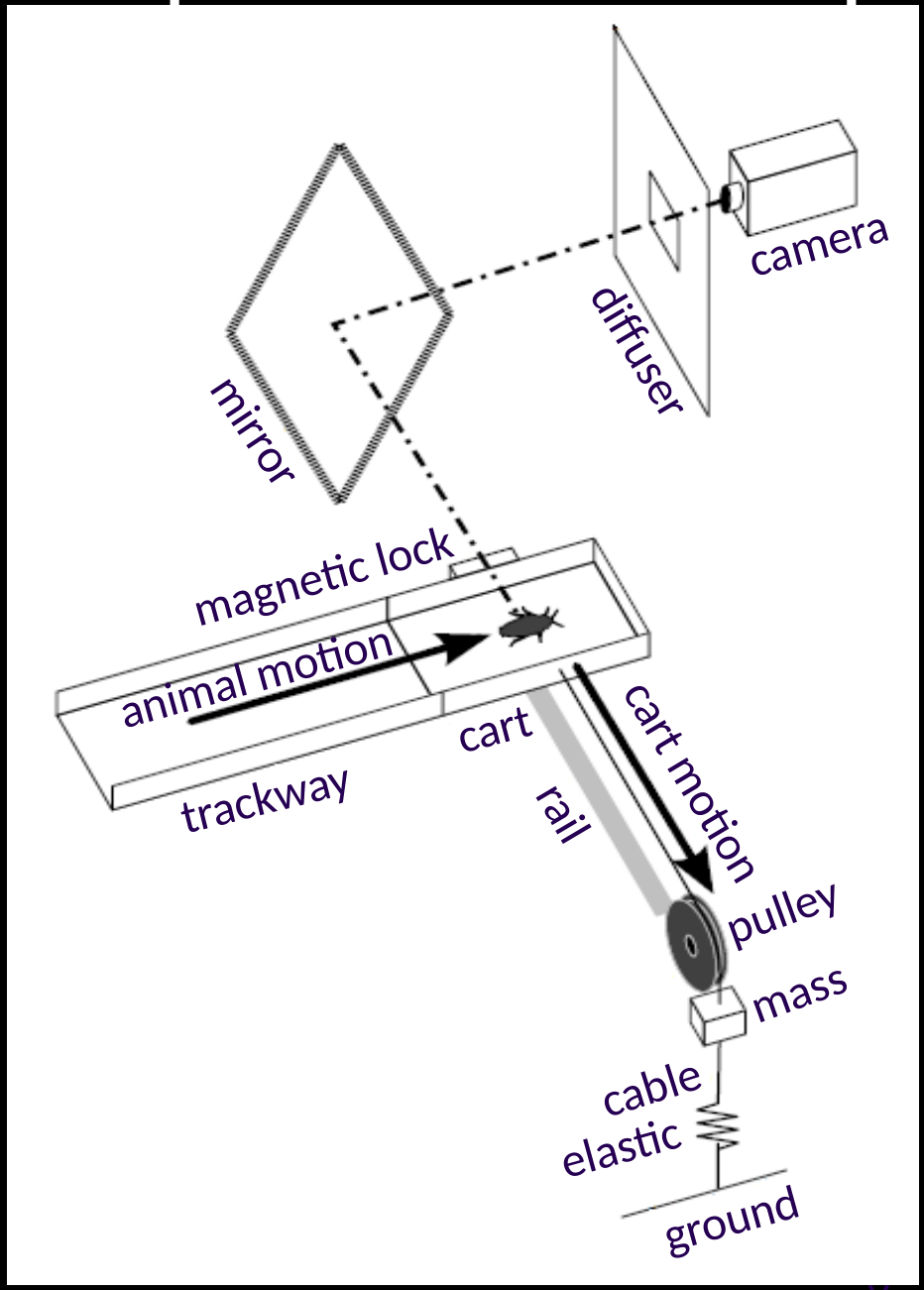

real-time

Lateral perturbation experimental setup

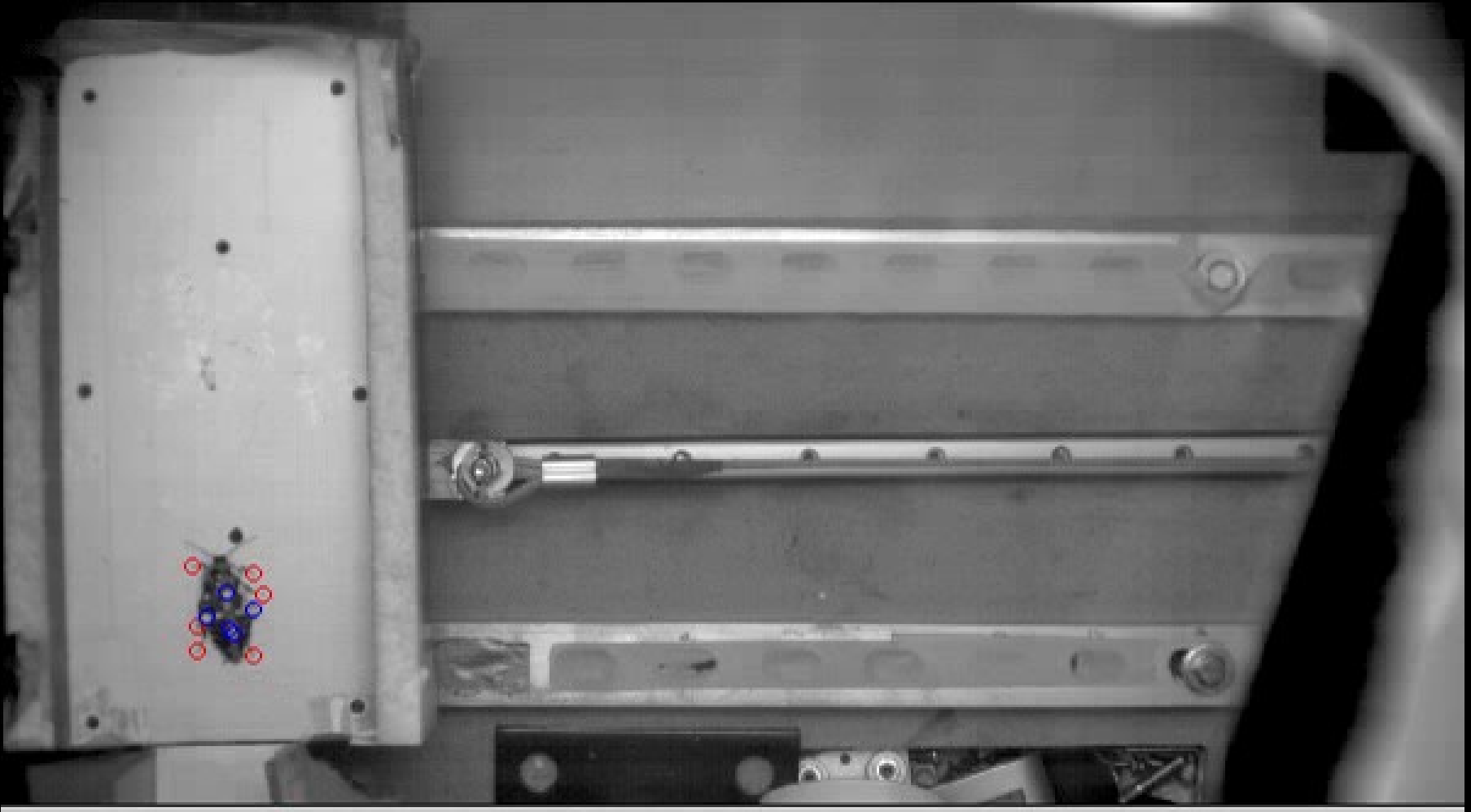
Platform accelerates laterally at 0.6 ± 0.1 g in a 0.1 sec interval providing a 50 ± 3 cm/sec specific impulse, then maintains velocity.

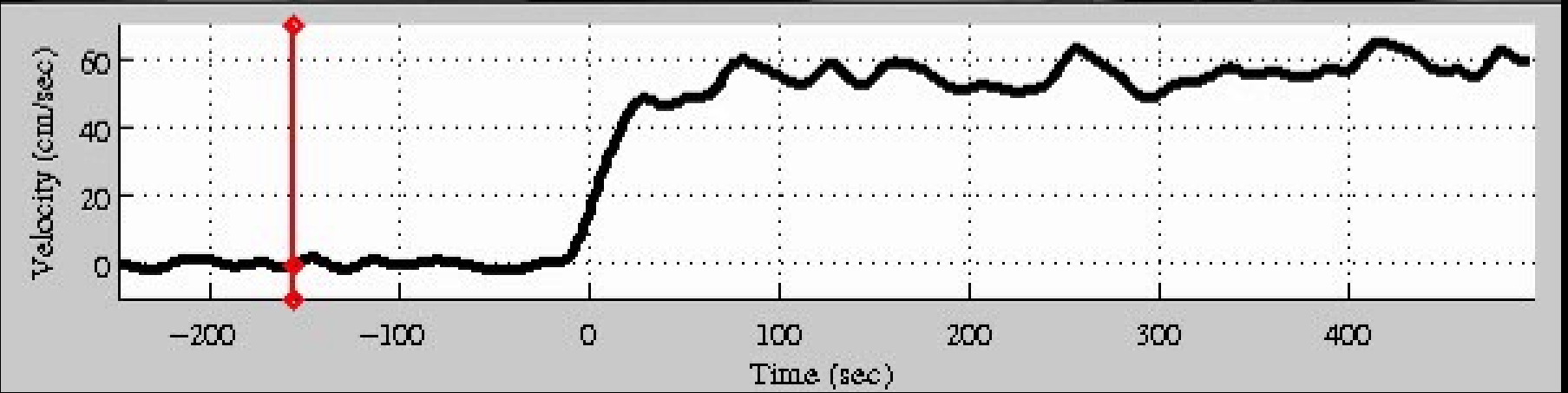
Cockroach running speed:
36 ± 8 cm/sec

Stride frequency:
12.6 ± 2.9 Hz
(~80ms per stride)



Revzen, Burden, Moore, Mongeau, Full
Biological Cybernetics 107(2):179-200 2013





20x

Measured:

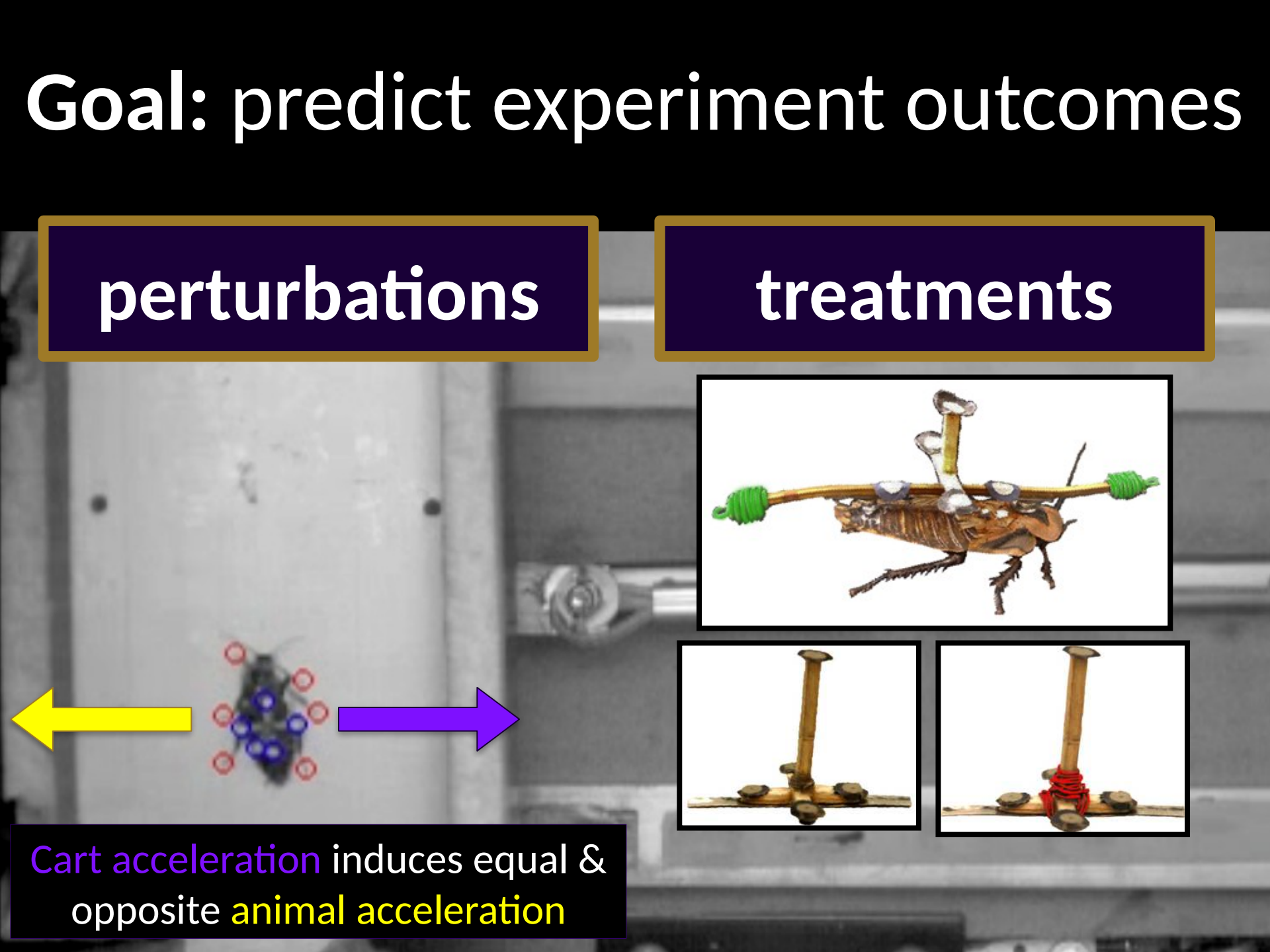
1. position, orientation of body
2. distal position of foot (tarsi)
3. position of cart in lab frame



Goal: predict experiment outcomes

perturbations

treatments



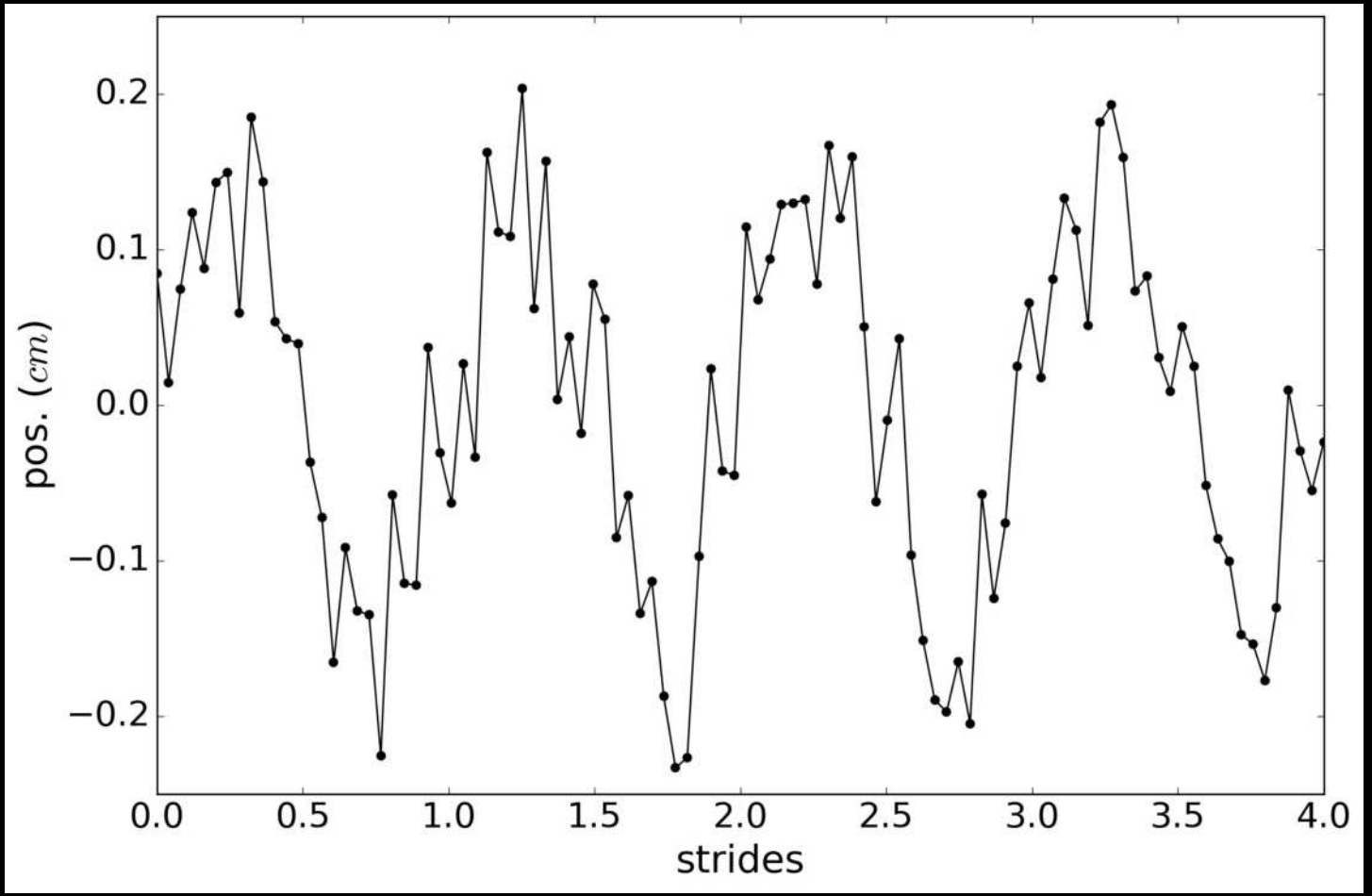
Cart acceleration induces equal & opposite animal acceleration

Steady state empirical distribution

Raw Data:
x y, θ

Kalman Filter

Fourier Fit



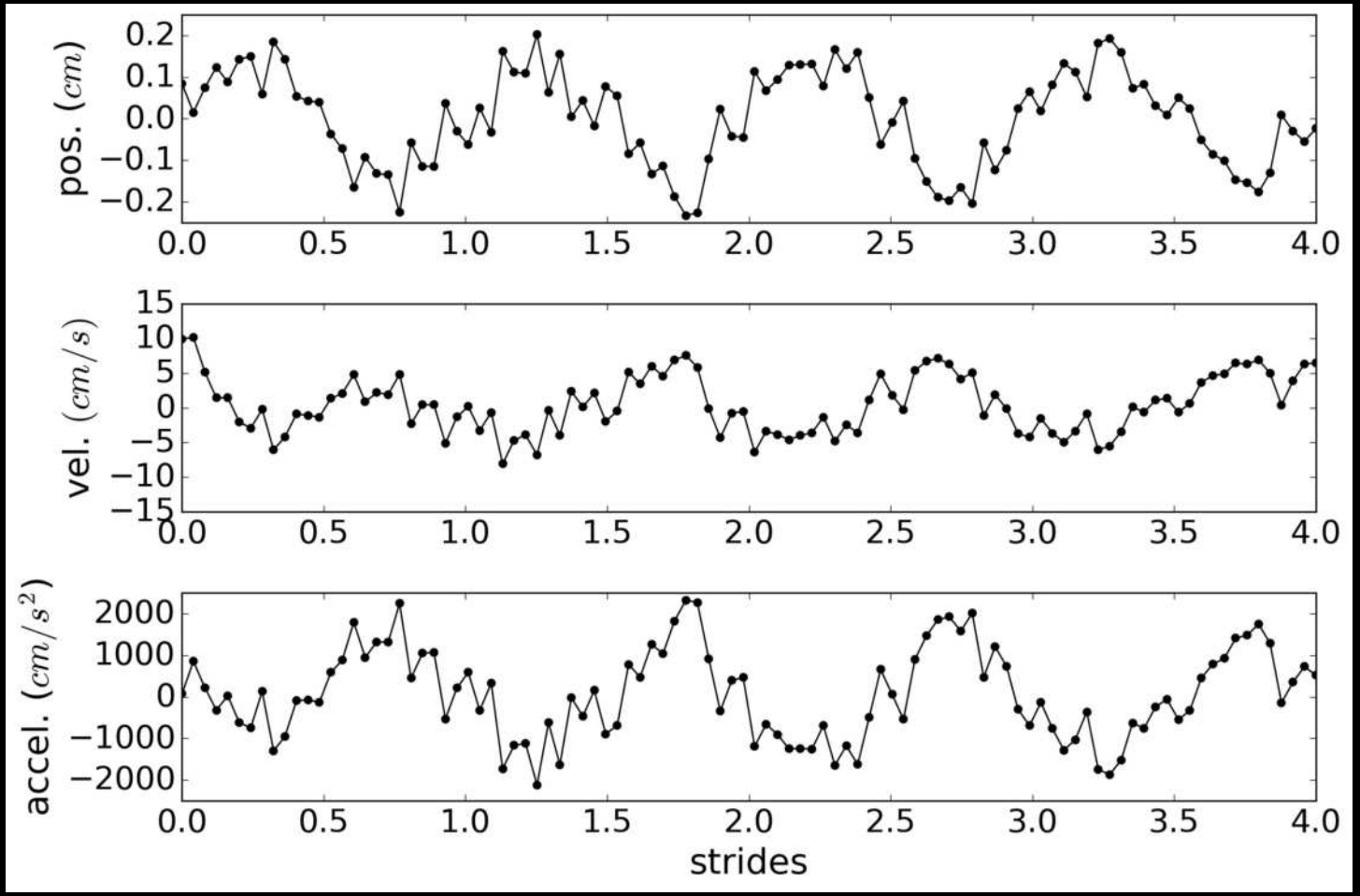
synthethic data – illustrative purposes only

Steady state empirical distribution

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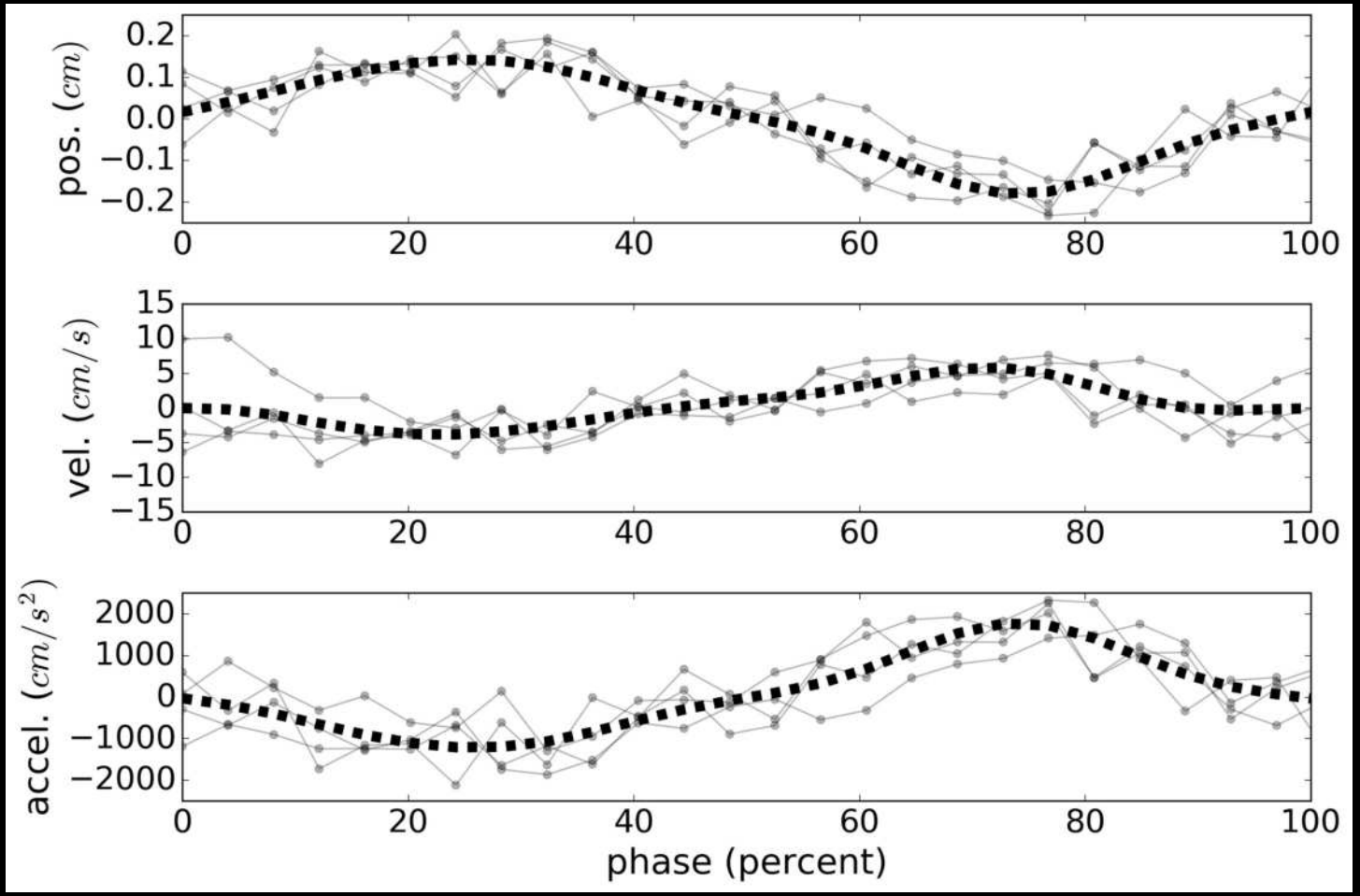
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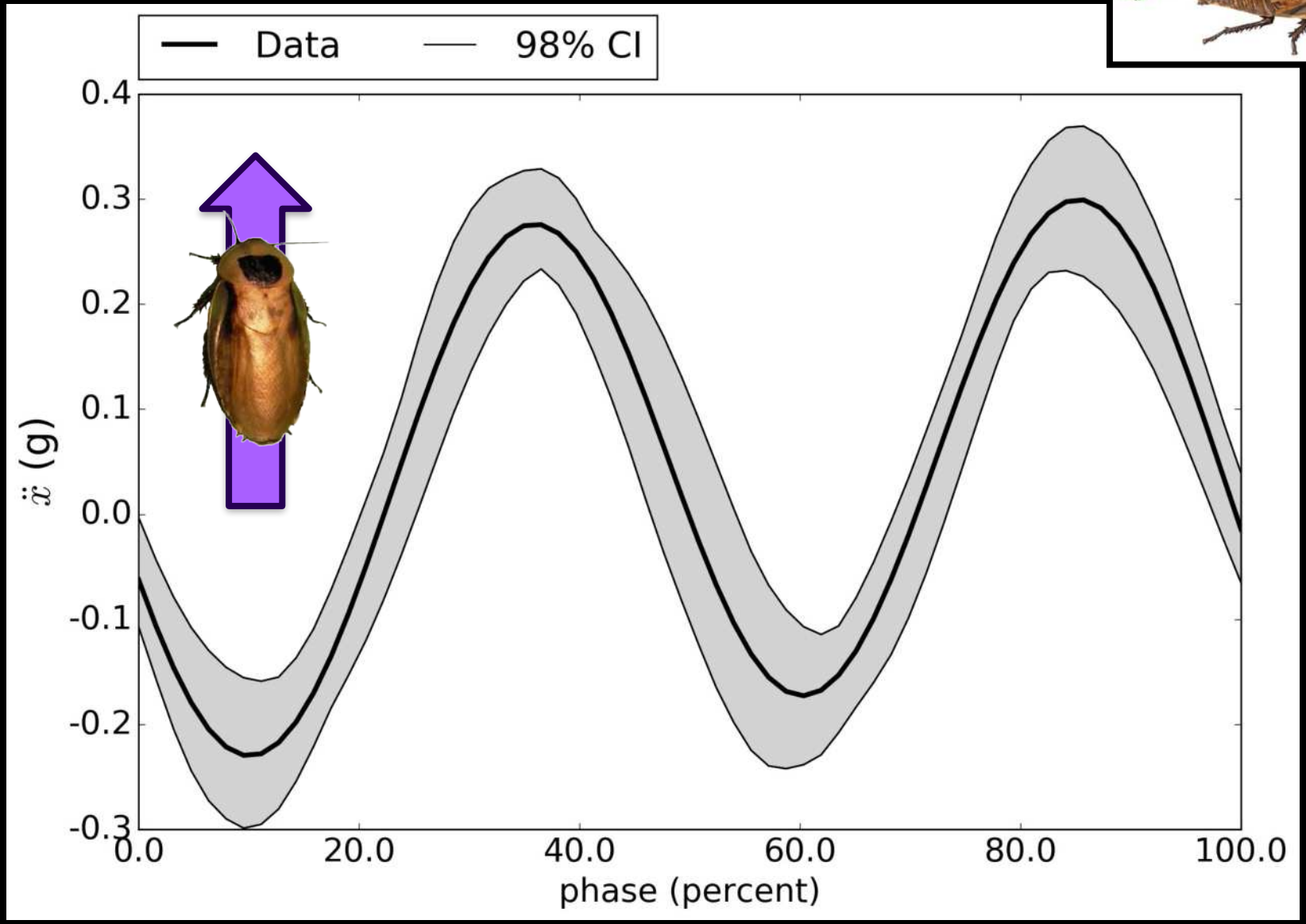
Fourier Fit



synthethic data – illustrative purposes only

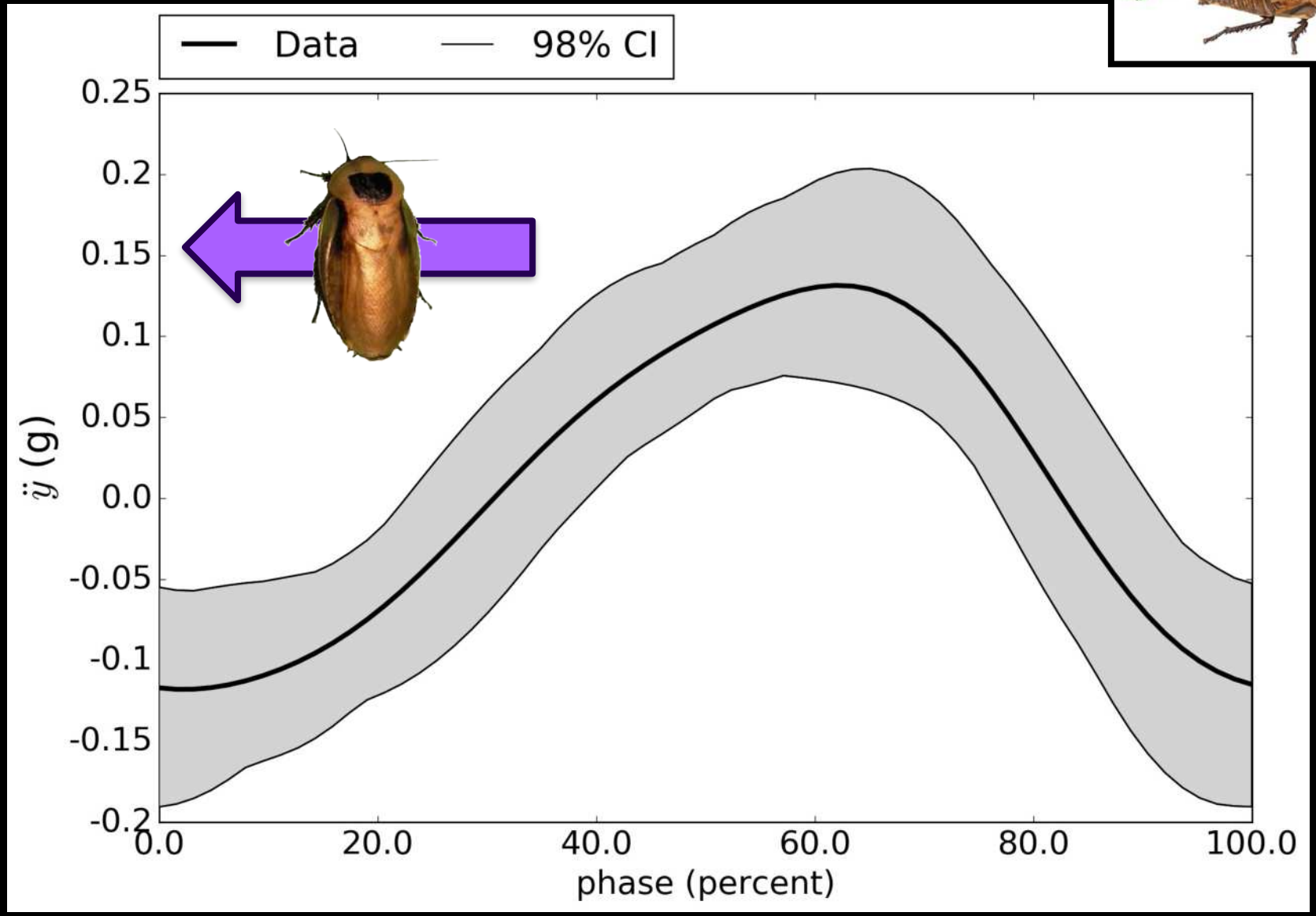
Fore-aft acceleration





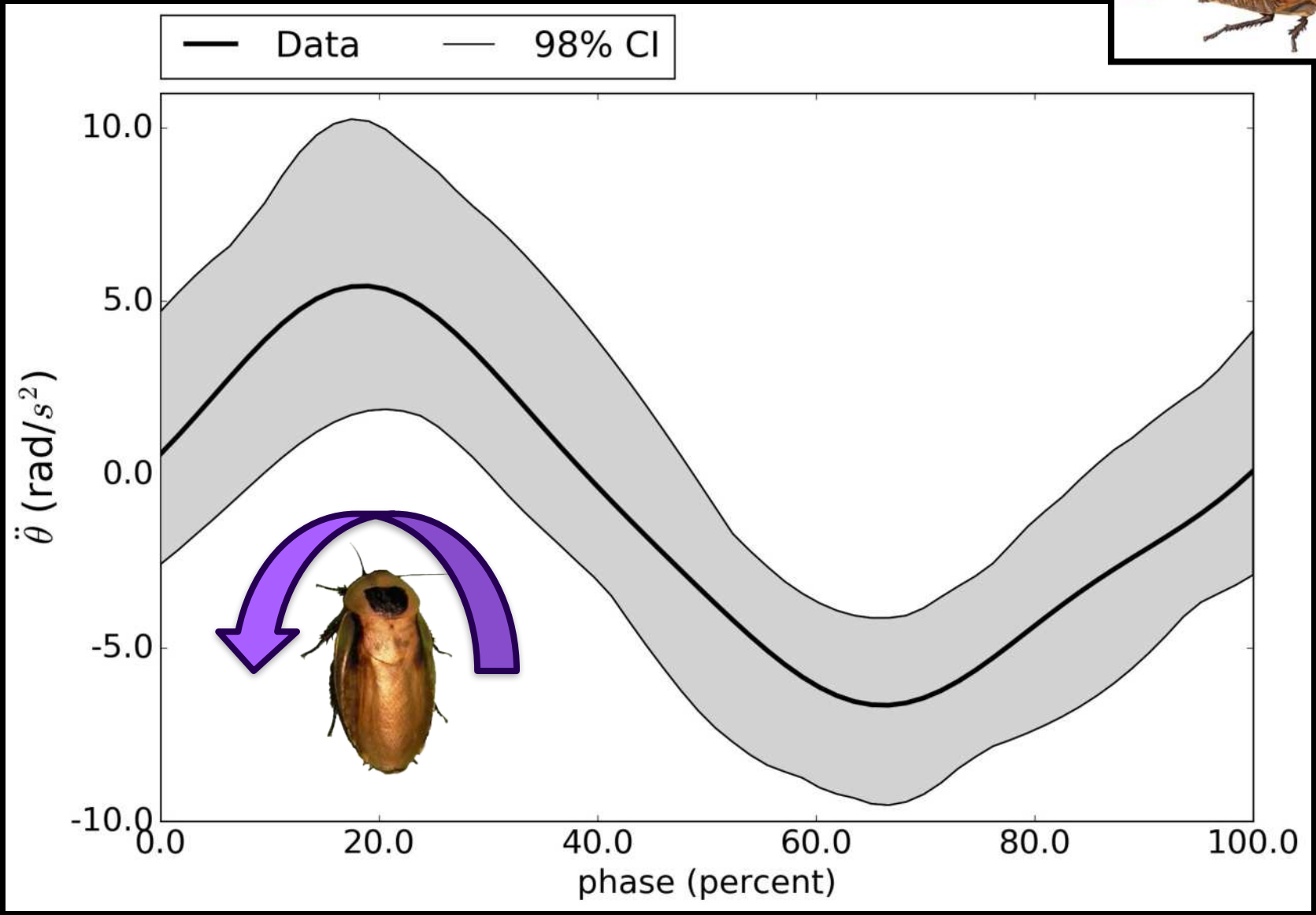
Lateral acceleration





Rotational acceleration





Overview of today's talk

1. Experiments with running cockroaches
   - unperturbed and perturbed
   - with and without mass and inertia treatments

2. Experimental results vs existing models

3. Estimating a predictive dynamical model from data

Overview of today's talk

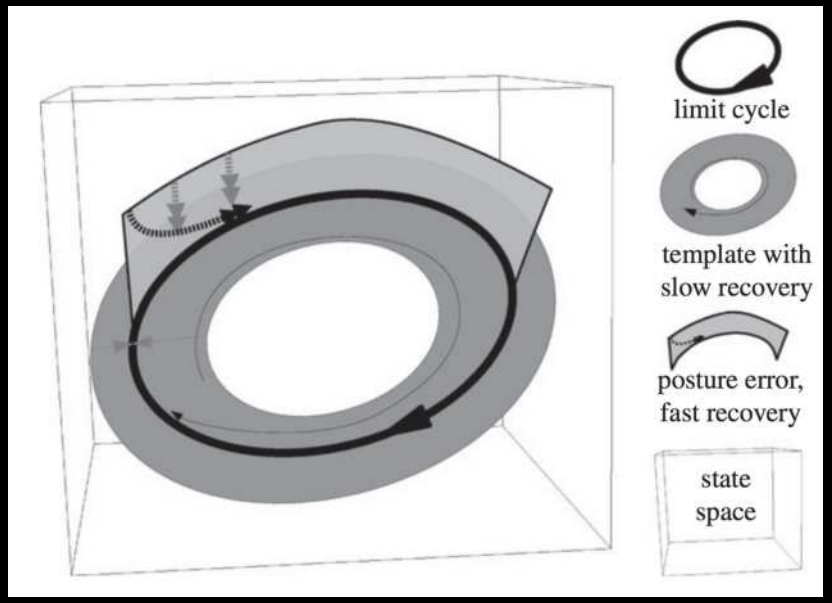
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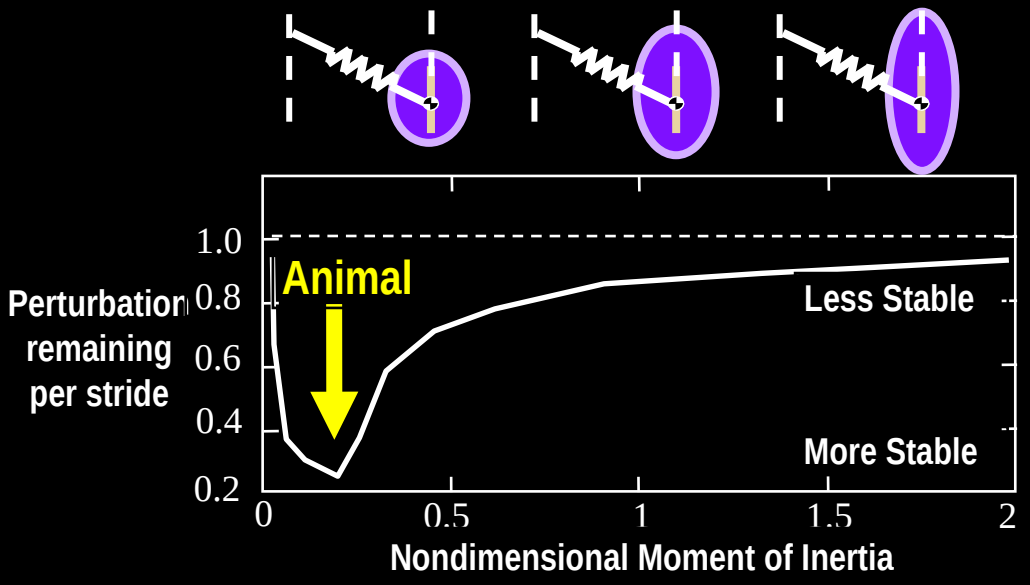
Models of dynamic legged locomotion

data-driven



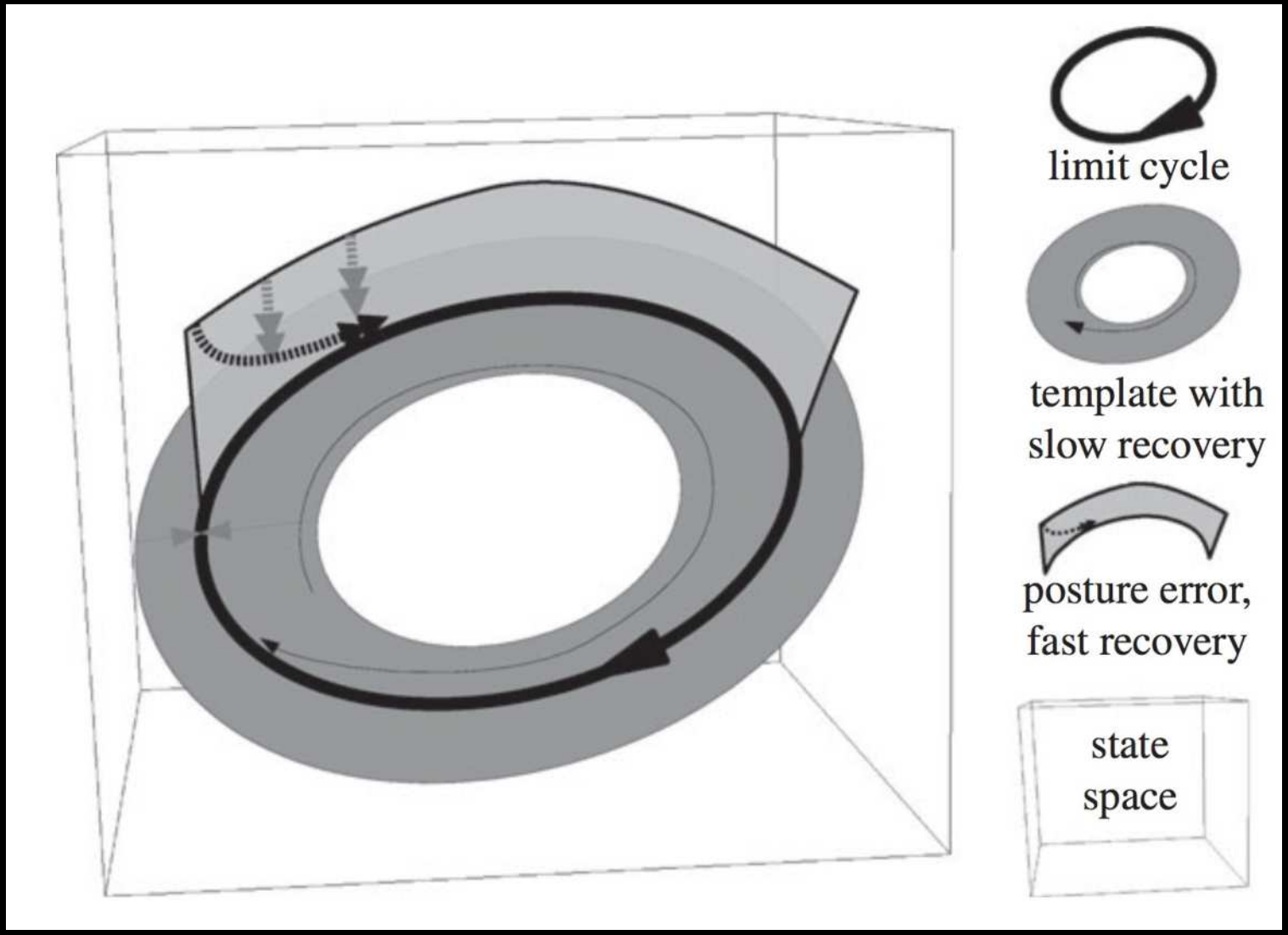
Revzen & Guckenheimer
J. Royal Society Interface 9(70) 2012

analytical



Full, Kubow, Schmitt, Holmes, Koditschek
Integ and Comp Bio 42(1) 2002

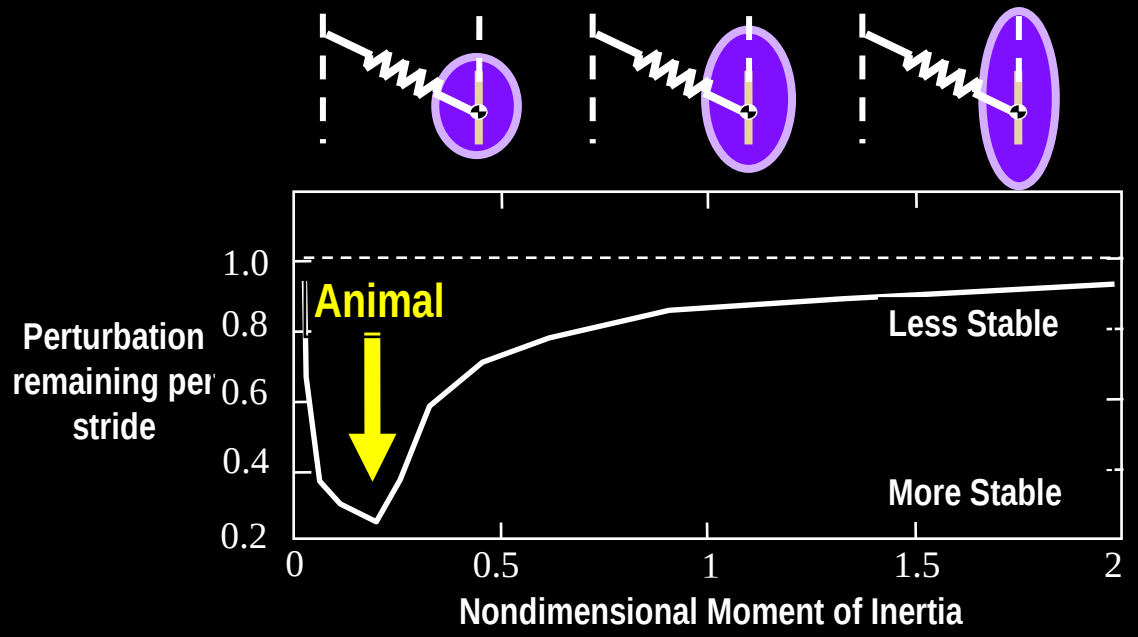
Data-driven models



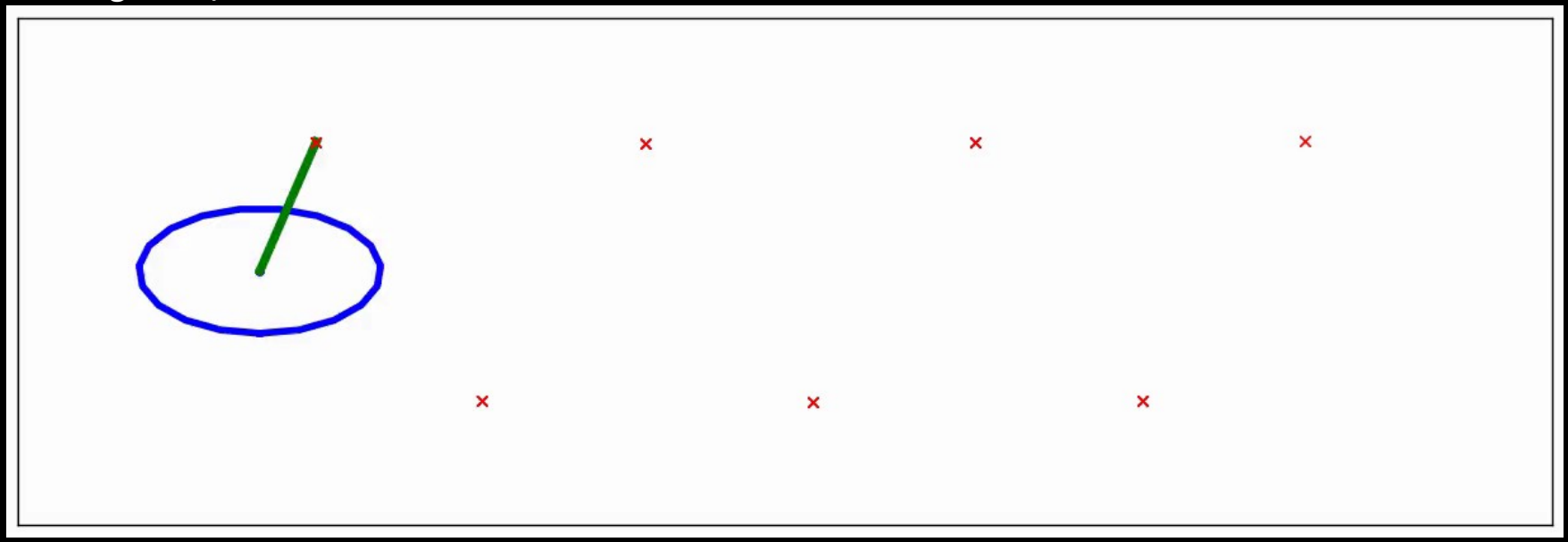
Revzen & Guckenheimer *J. Royal Society Interface* 9(70) 2012; *Phys. Rev. E* 78(5):051907 2008

Lateral Leg Spring (LLS) model

Full, Kubow, Schmitt, Holmes, Koditschek
Integ and Comp Bio 42(1) 2002

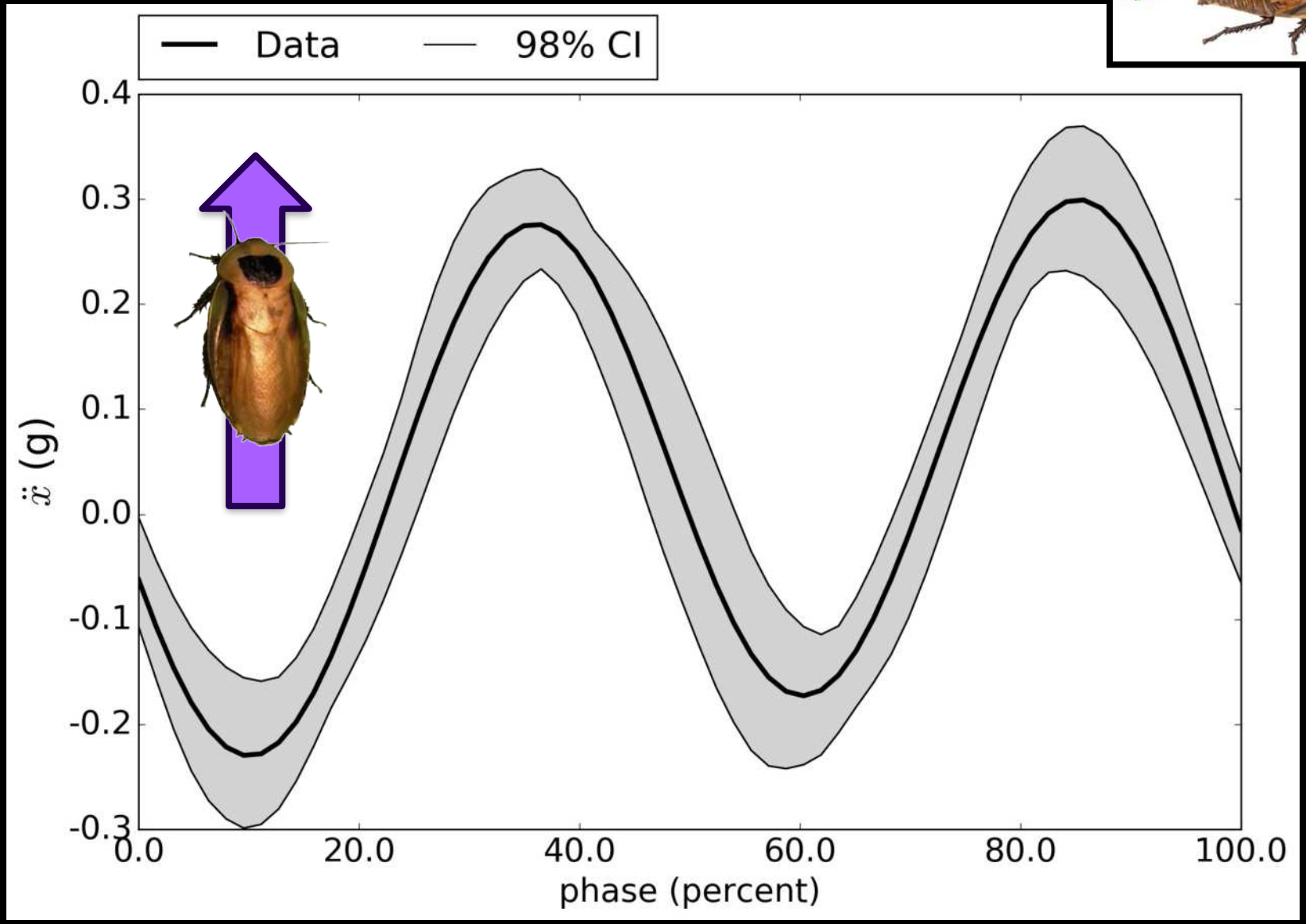


Schmitt & Holmes
Biological Cybernetics 83(505-515) 2000



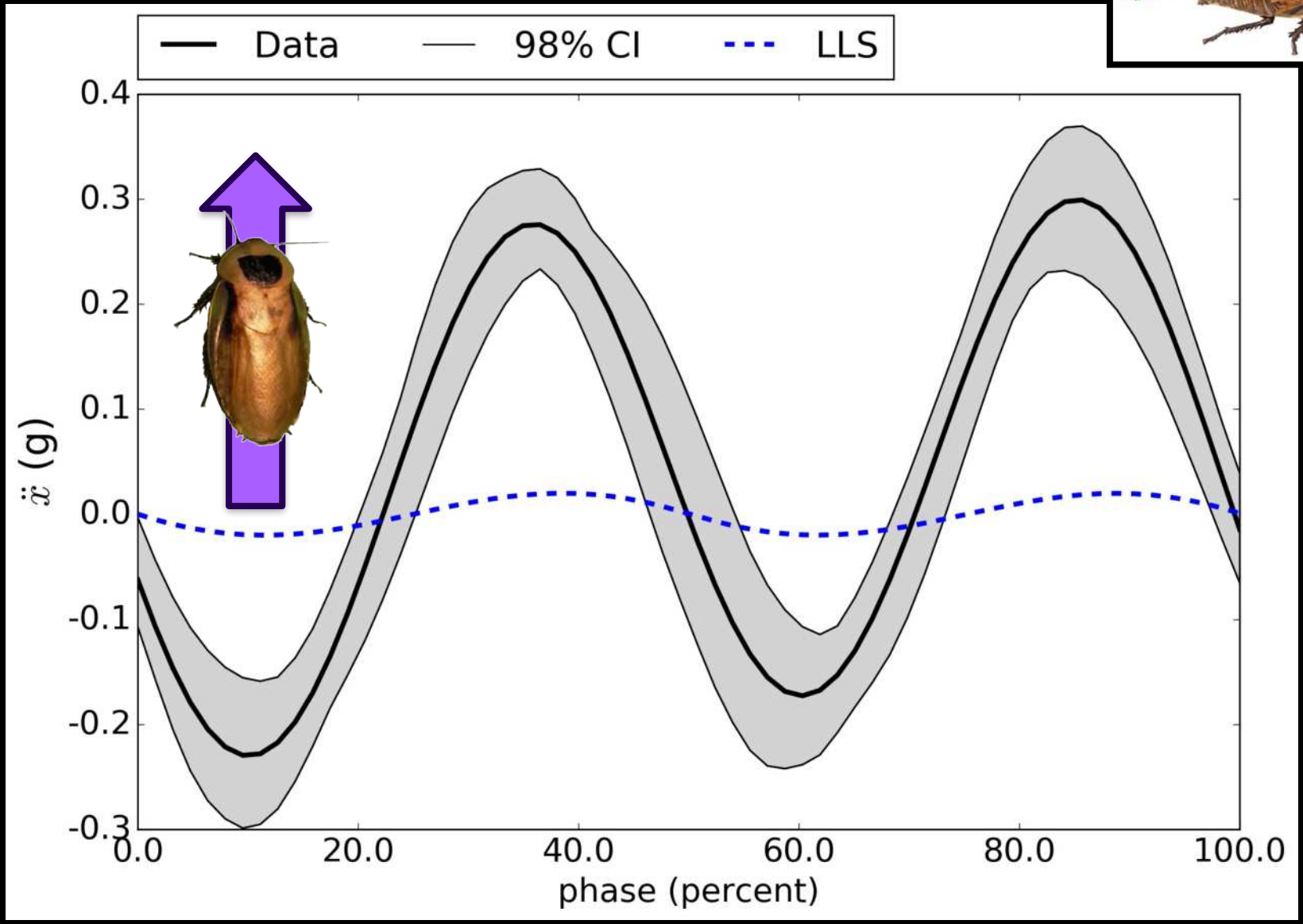
Fore-aft acceleration





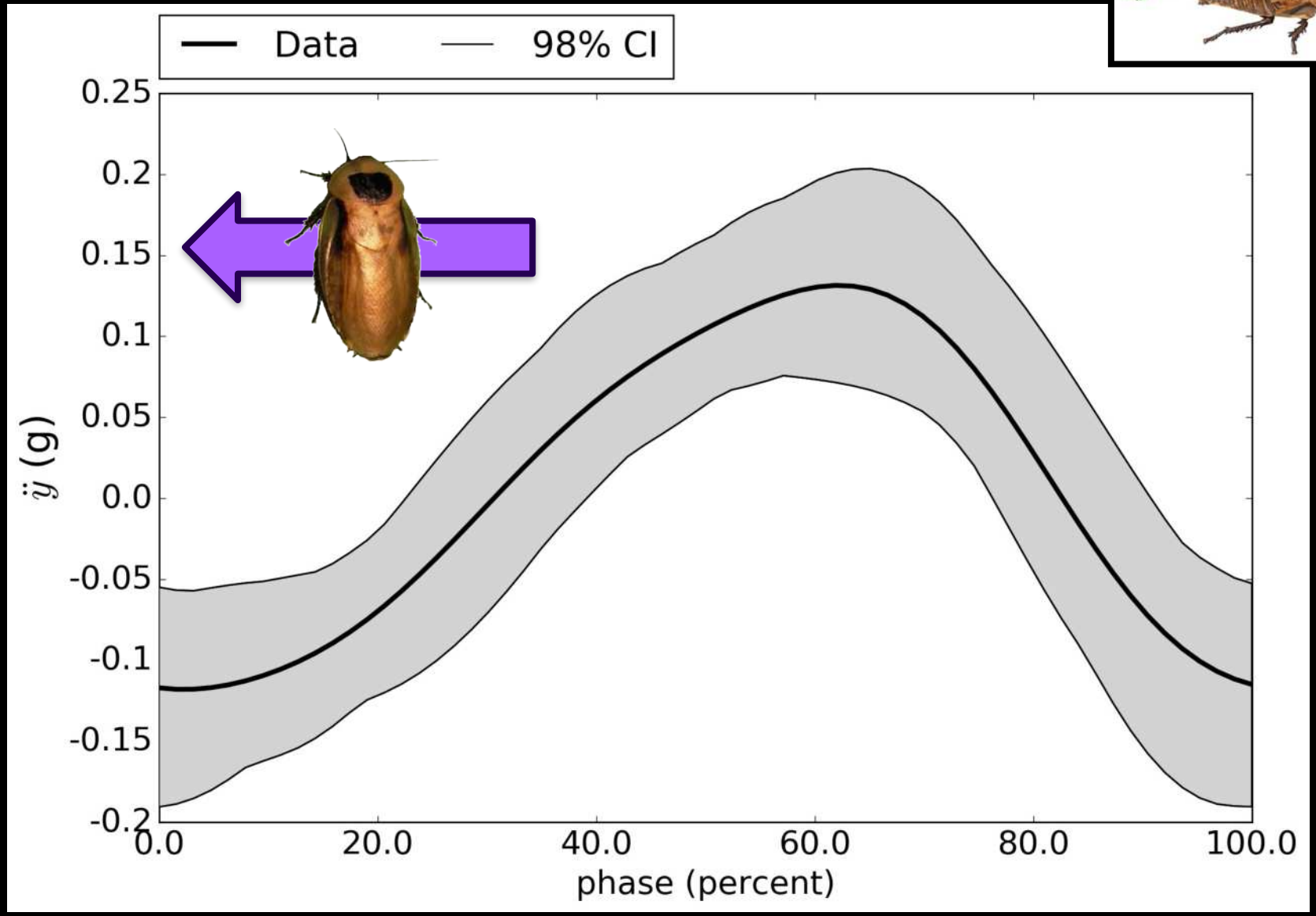
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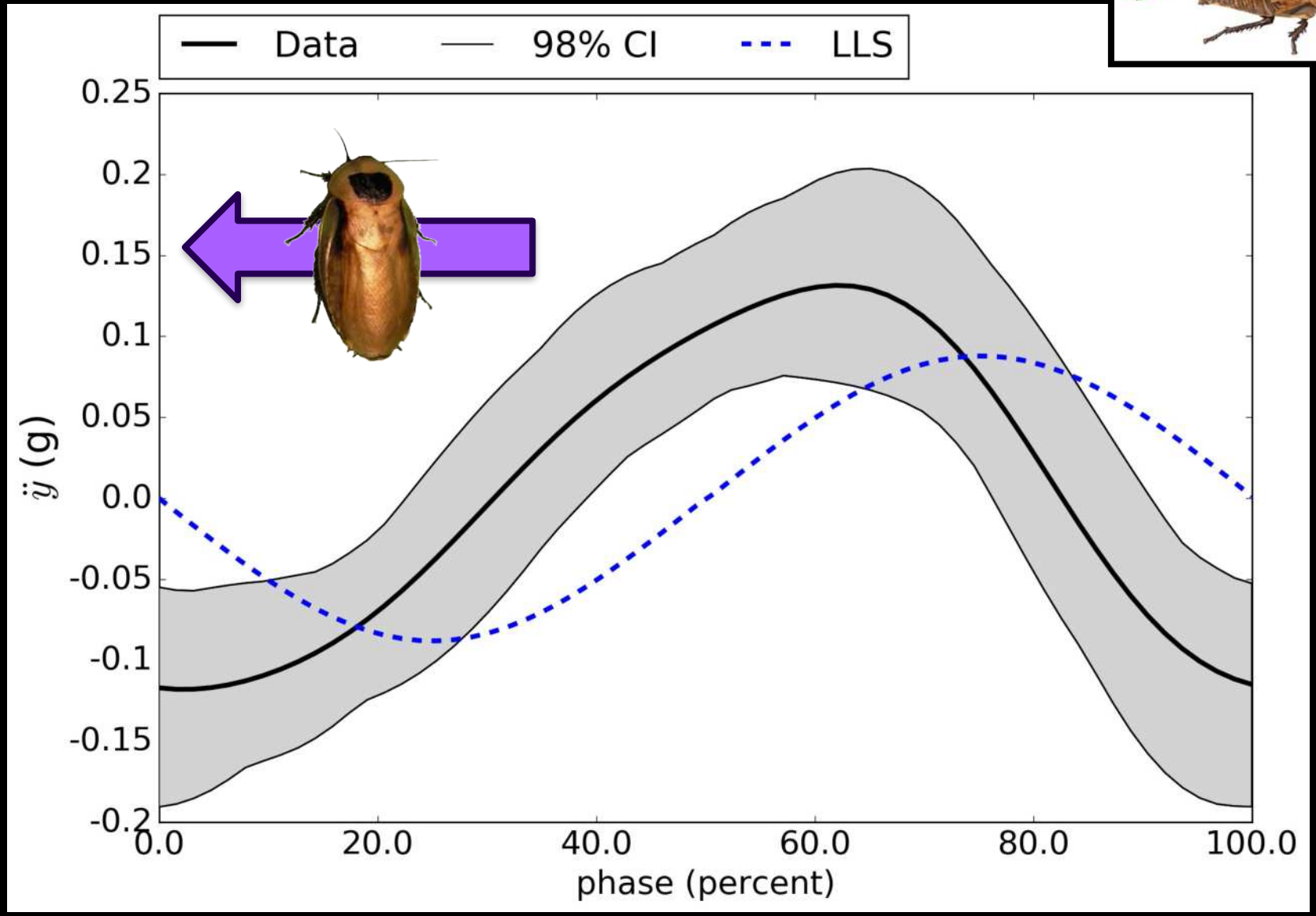
Lateral acceleration





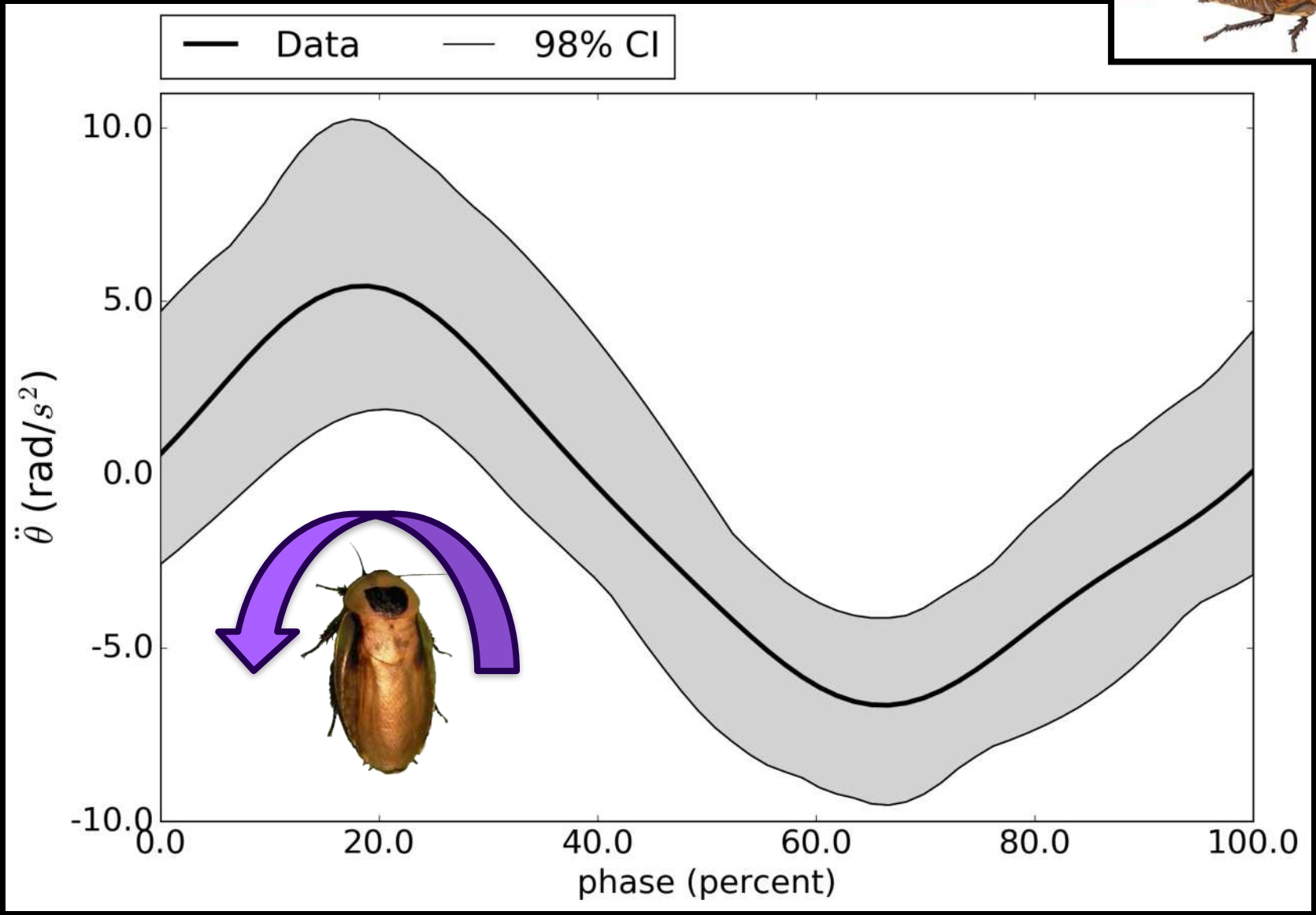
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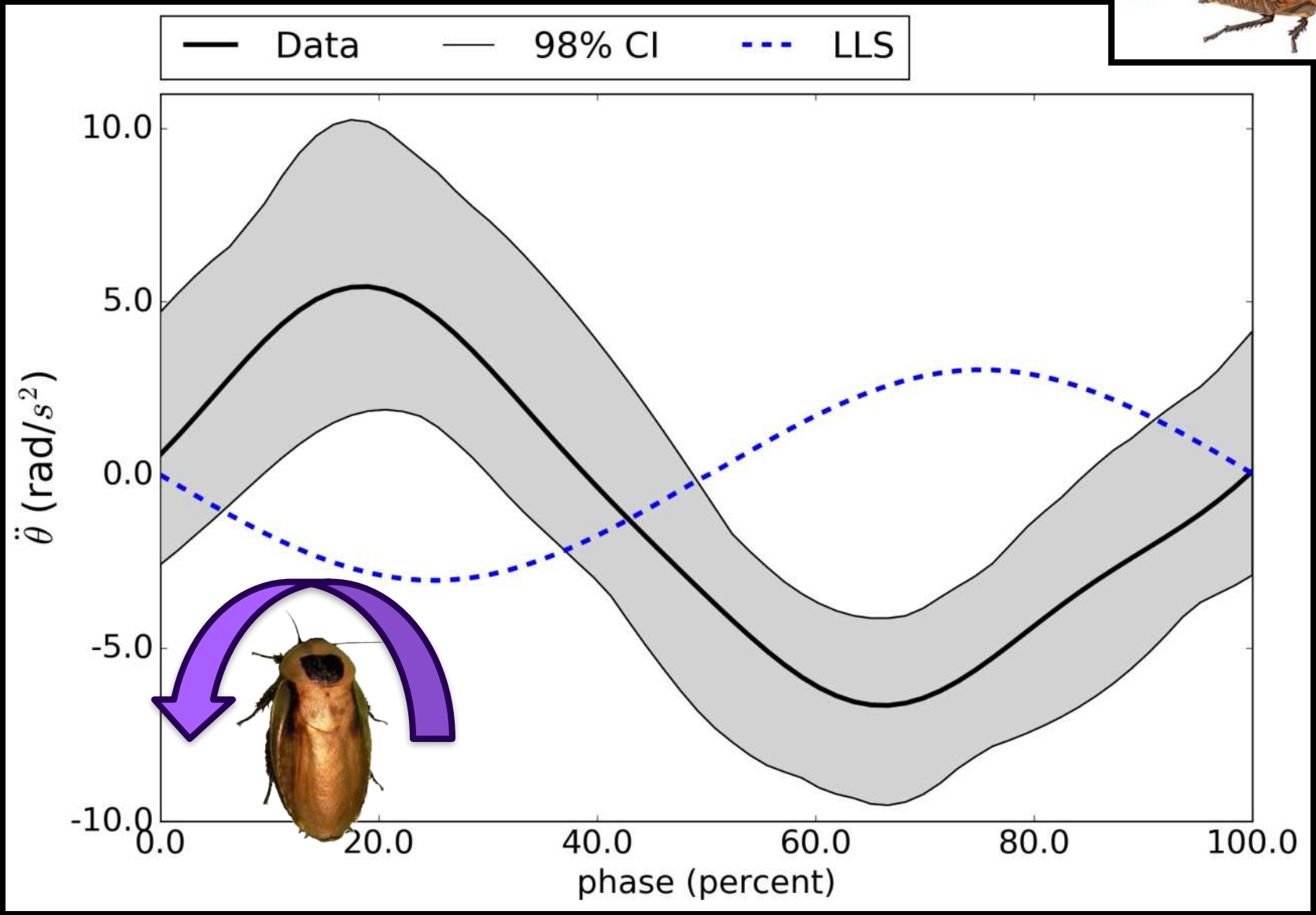
Rotational acceleration



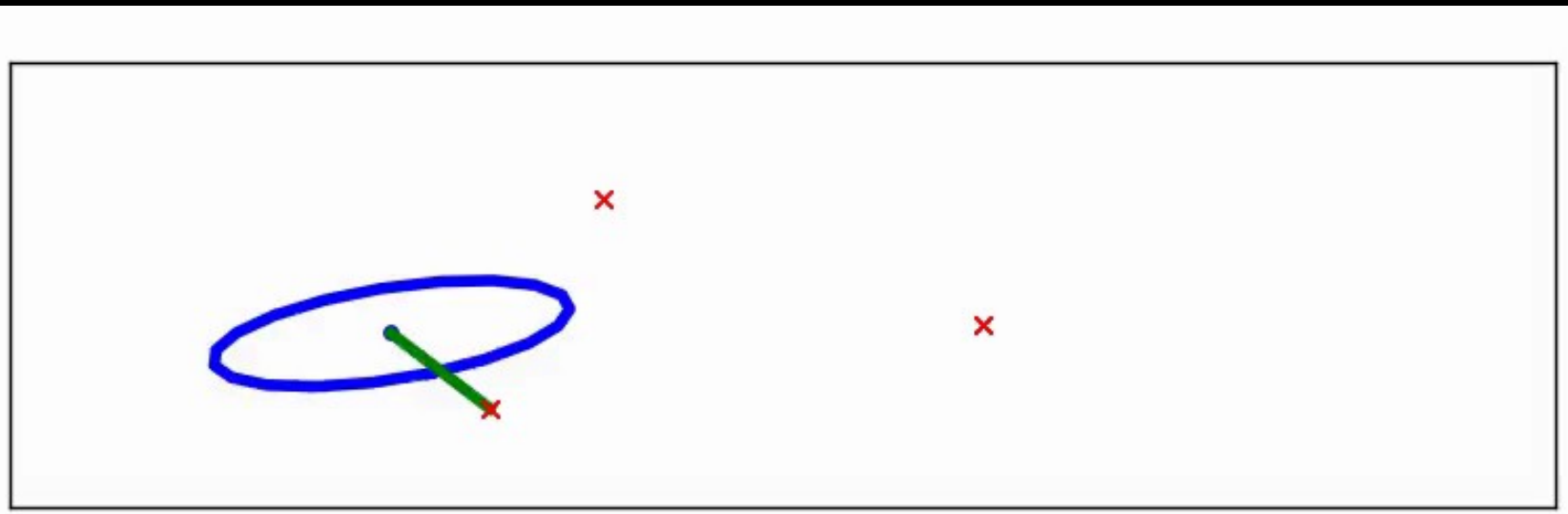


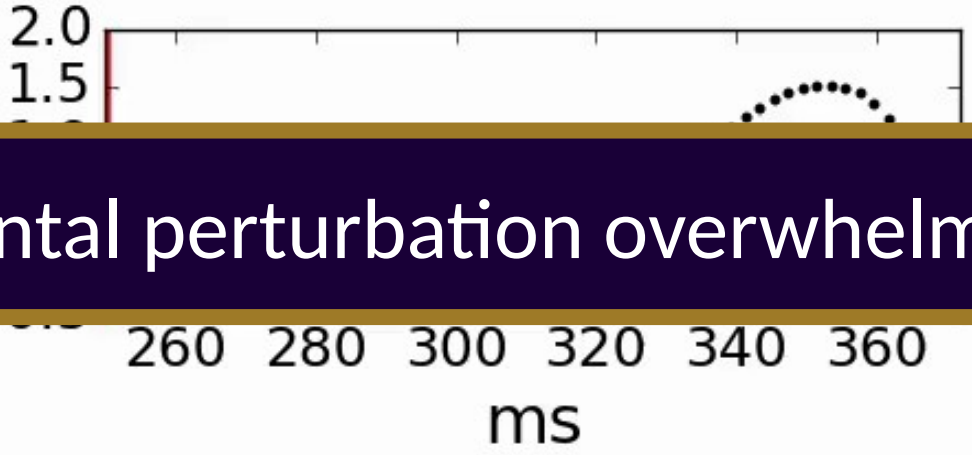
Rotational acceleration





Perturbing analytical models





Experimental perturbation overwhelms the model

Perturbing data-driven models





Can’t apply novel perturbations or treatments

Overview of today's talk

1. Experiment
   - unperturbed and perturbed
   - with and without mass and inertia treatments

2. Experimental results vs existing models
   - cannot apply treatment or perturbation to existing models
   - purely analytical or data-driven models fail to predict outcomes in our experiment

3. Estimating a predictive dynamical model from data

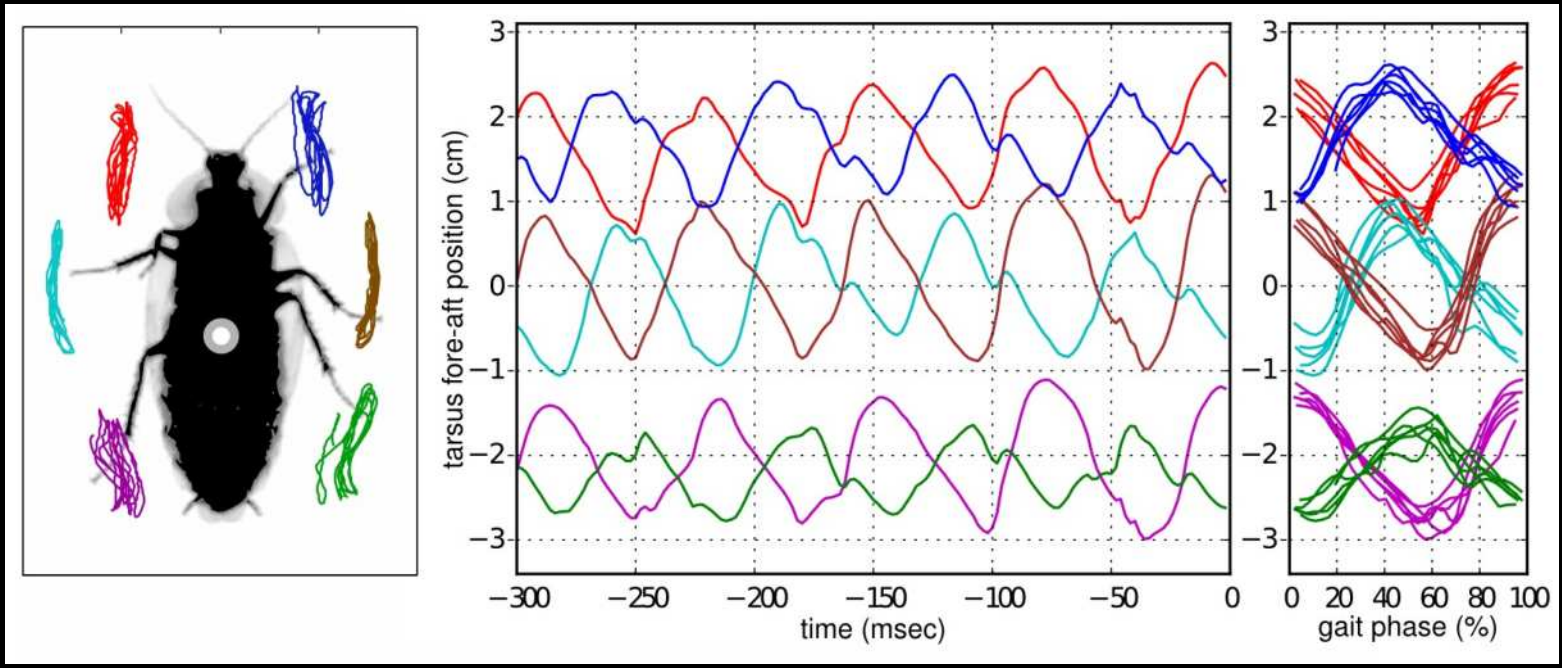
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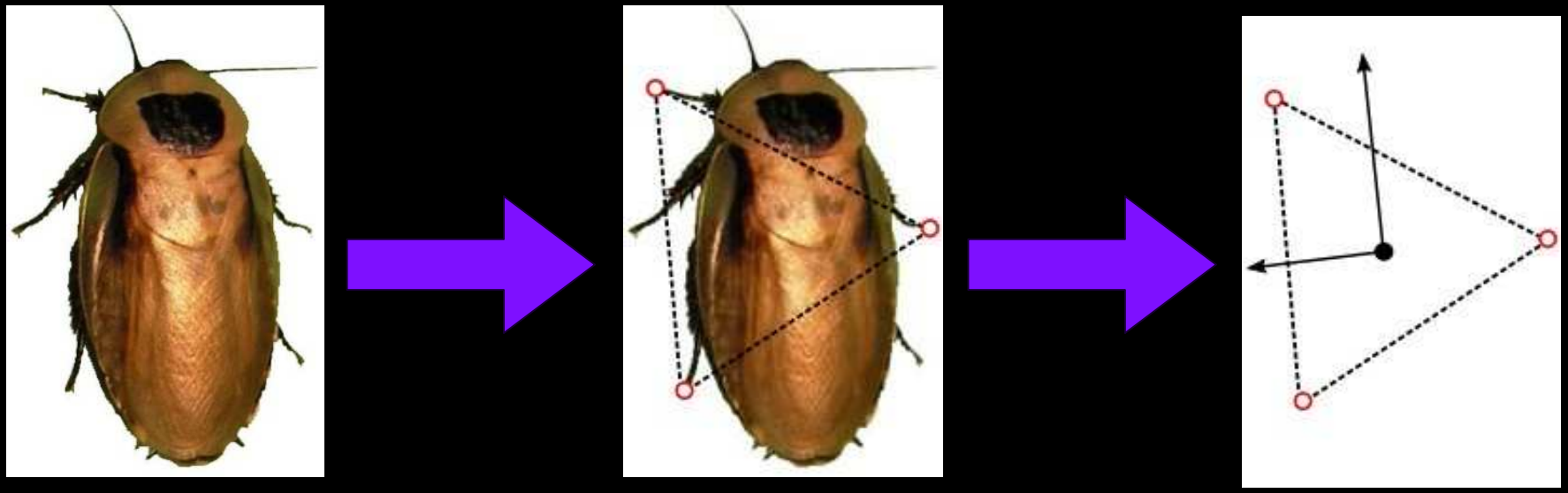
Motivation for proposed model



- Animal executes alternating-tripod gait

Body acceleration determined by pose relative to stance tripod

Step Frame



Determine the stance frame origin and orientation relative to the tripod

Proposed model structure

- body state comprised of:

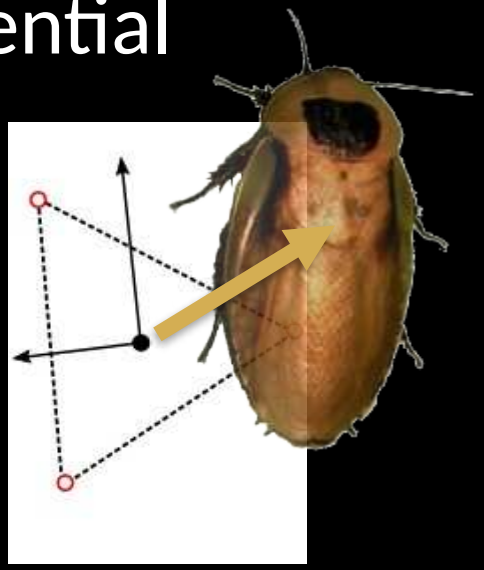
$$q = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$$

– forward position
– lateral position
– body orientation

- body acceleration arises from spring-like potential

$$V = \frac{1}{2}(q - q_0)^T K (q - q_0)$$

$$M\ddot{q} = \frac{d}{dq}V(q) = K(q - q_0)$$



Proposed model enables introduction of novel perturbations and treatments

$$q = \begin{bmatrix} x \\ y \\ \theta \end{bmatrix}$$

– forward position

– lateral position

– body orientation

- body acceleration influenced by
  - – perturbation (e.g. lateral acceleration $a(t)$)
  - – treatment (e.g. inertia distribution M)

$$M\ddot{q} = K(q - q_0) + a(t)$$

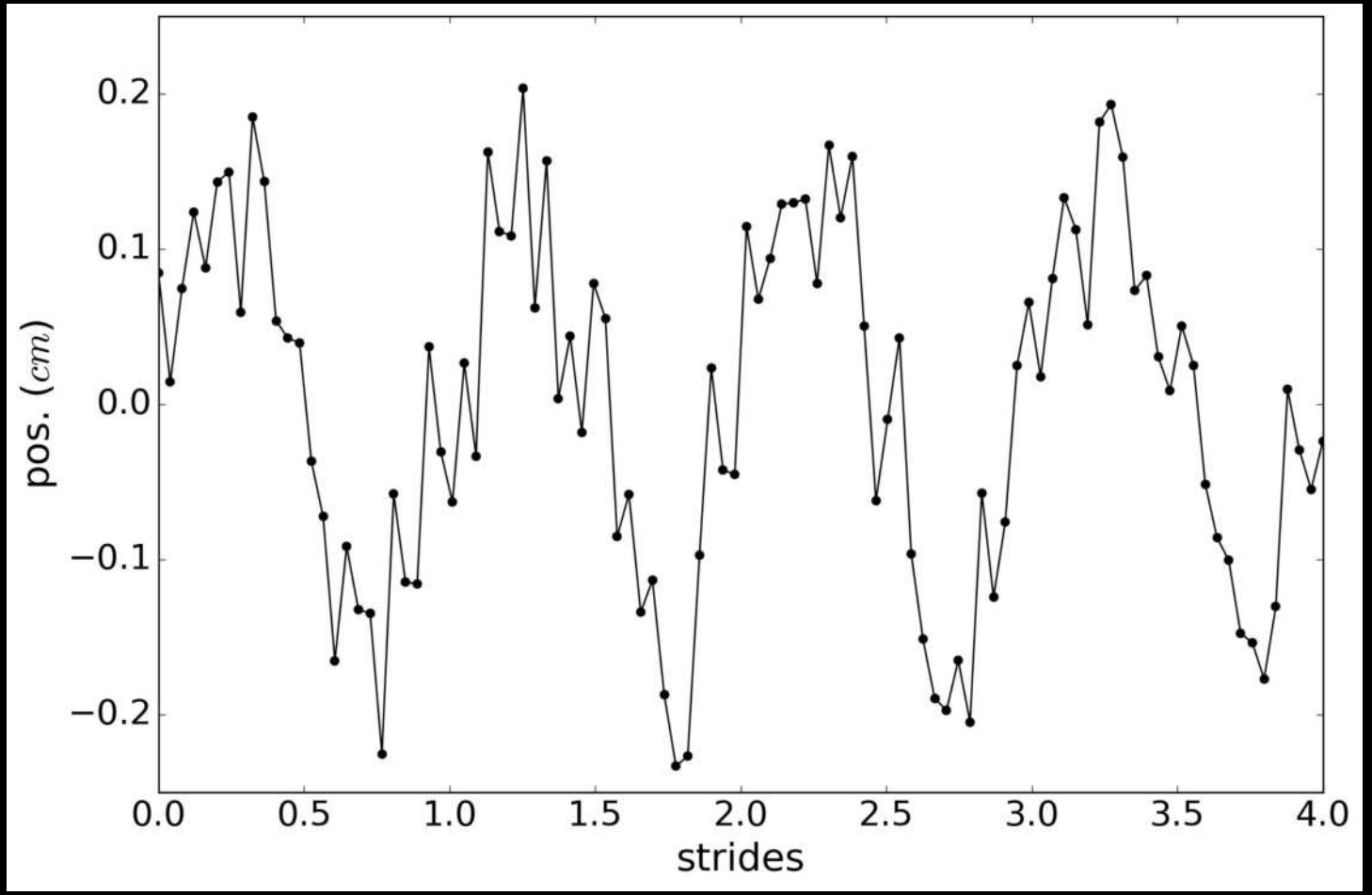
Estimating model parameters from data

Raw Data:
x y, θ

Kalman Filter

Fourier Fit

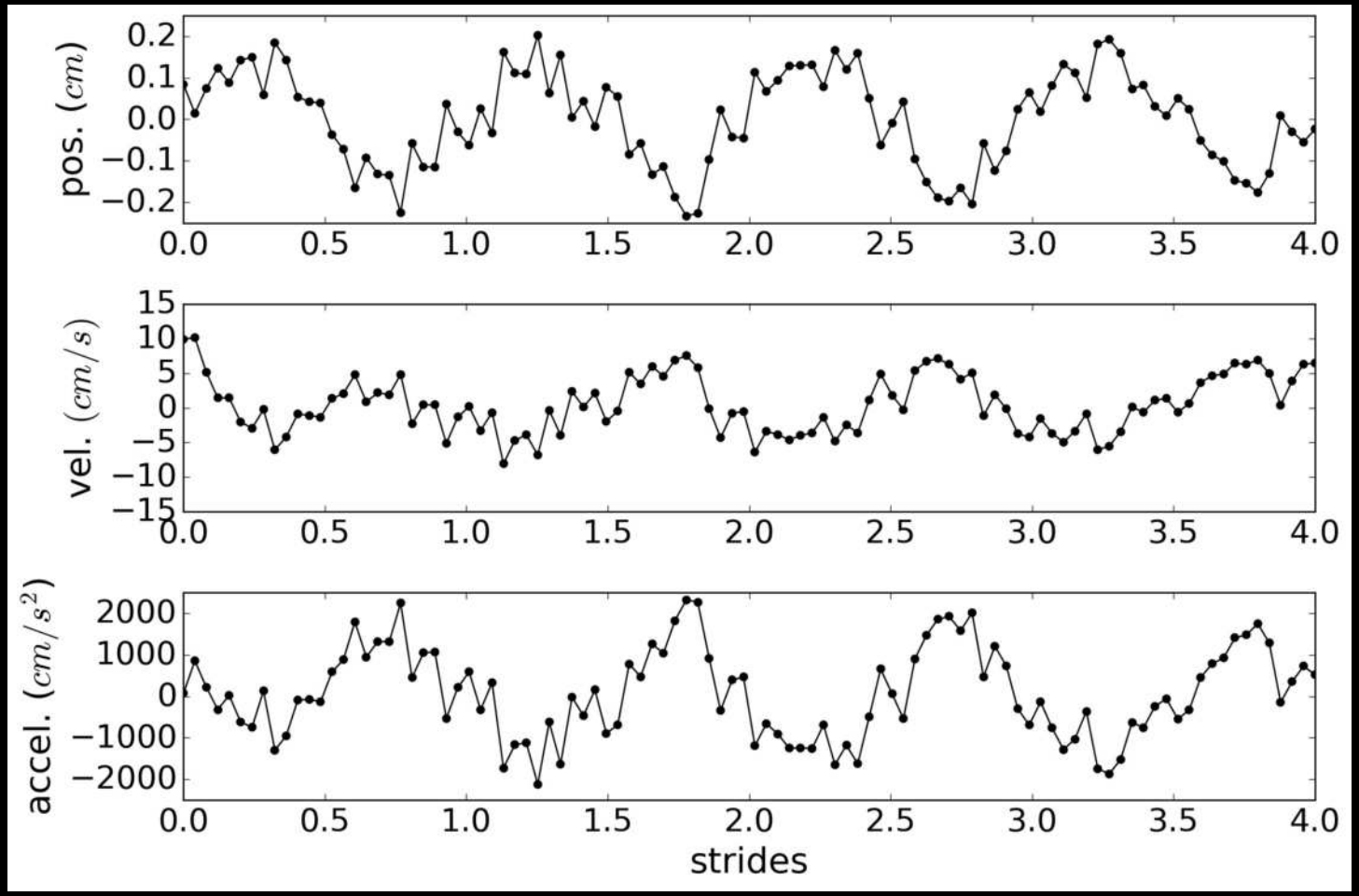
Model Fit:
K, q_o



synthethic data – illustrative purposes only

Estimating model parameters from data

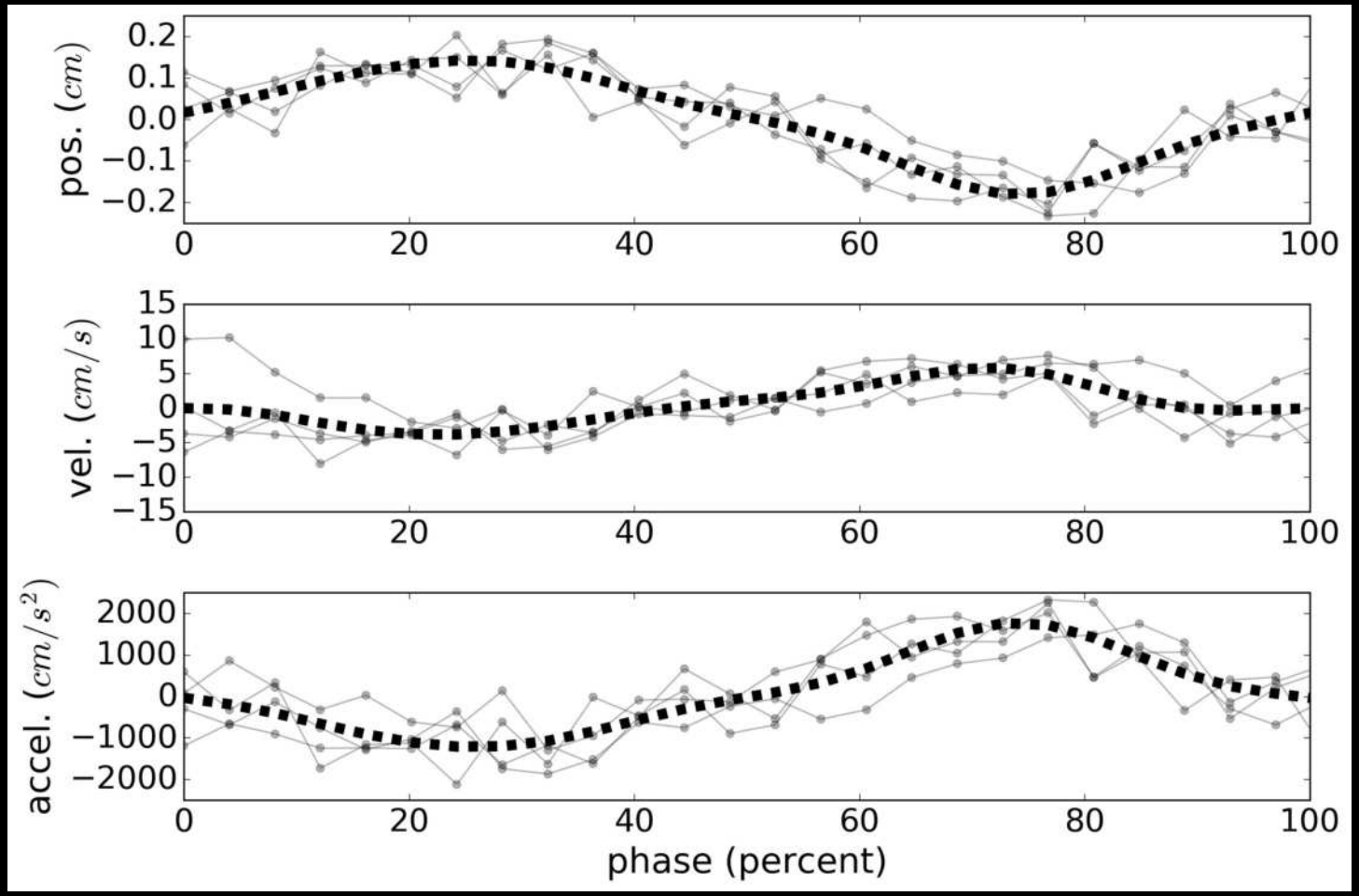
- Raw Data: x y, θ
- Kalman Filter
- Fourier Fit
- Model Fit: K, q_o



synthethic data – illustrative purposes only

Estimating model parameters from data

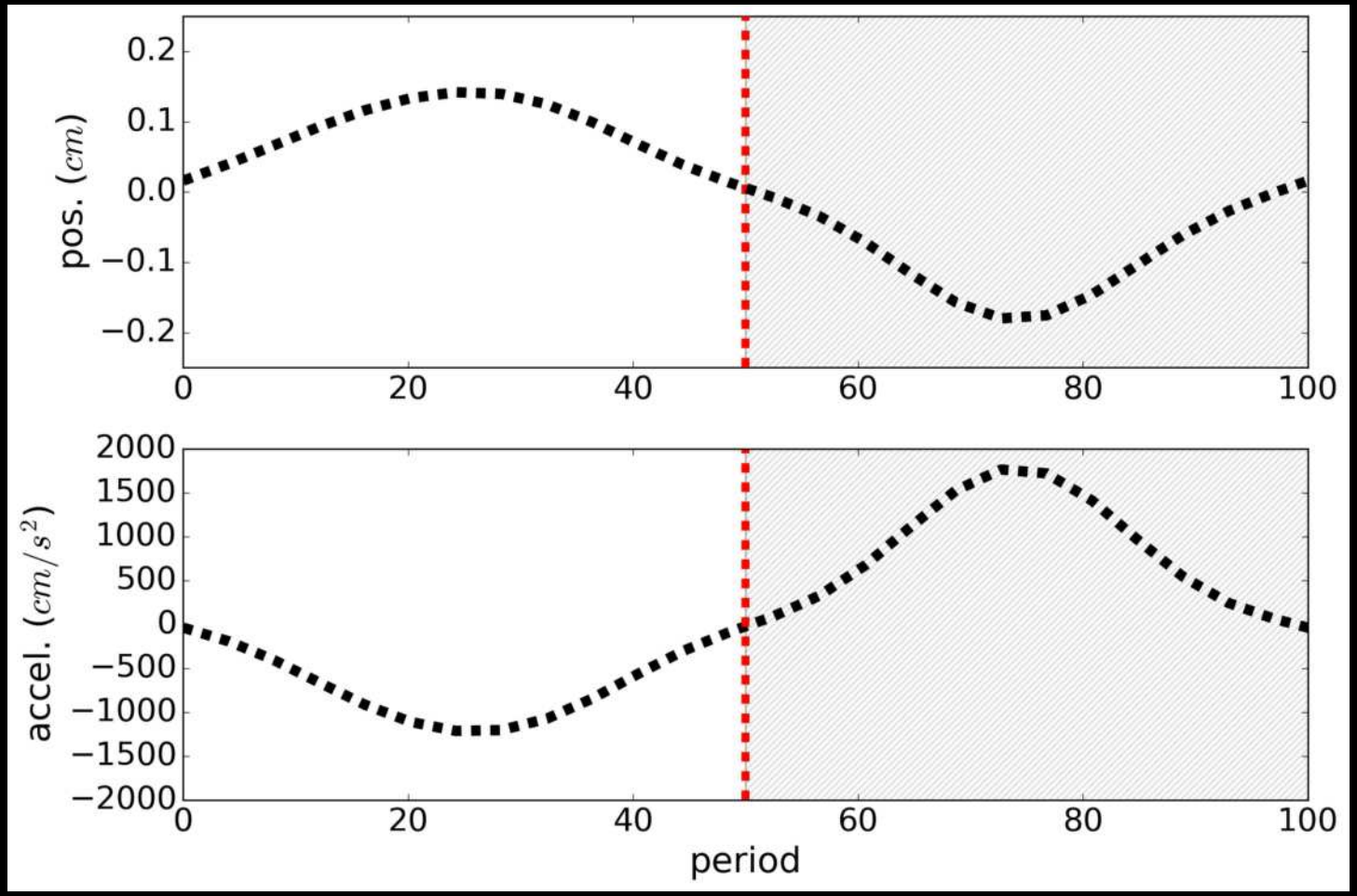
- Raw Data: x y, θ
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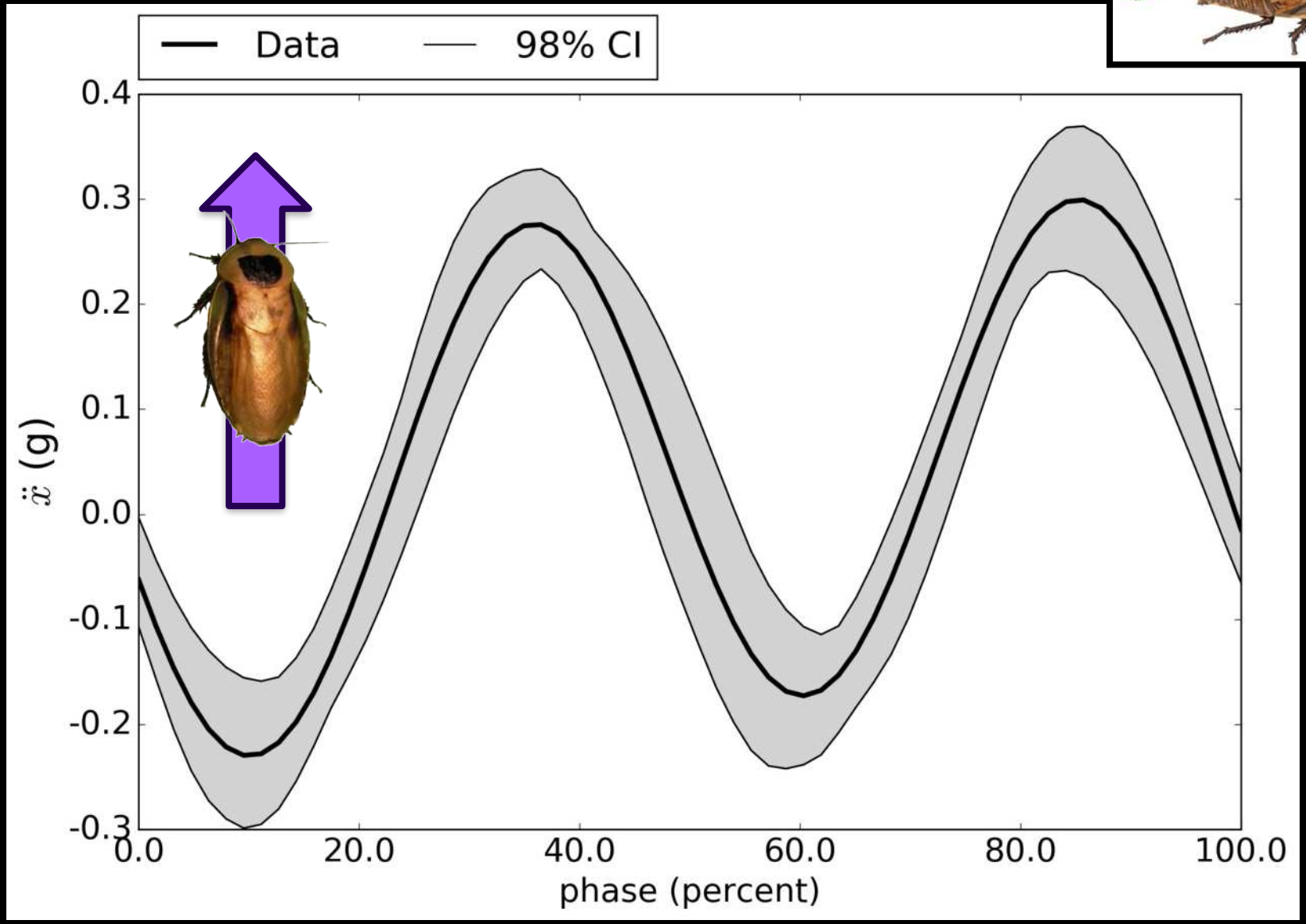
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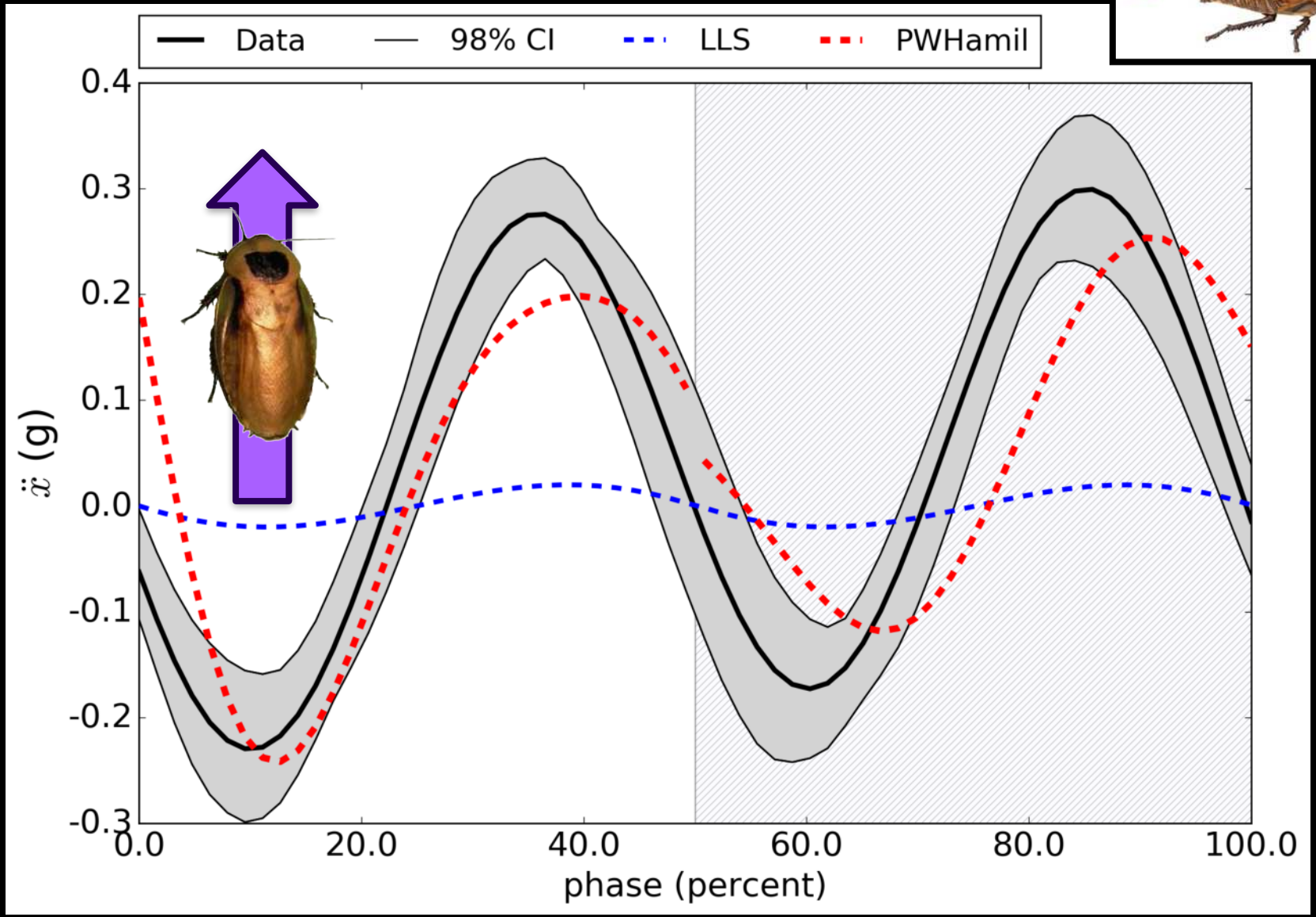
Fore-aft acceleration





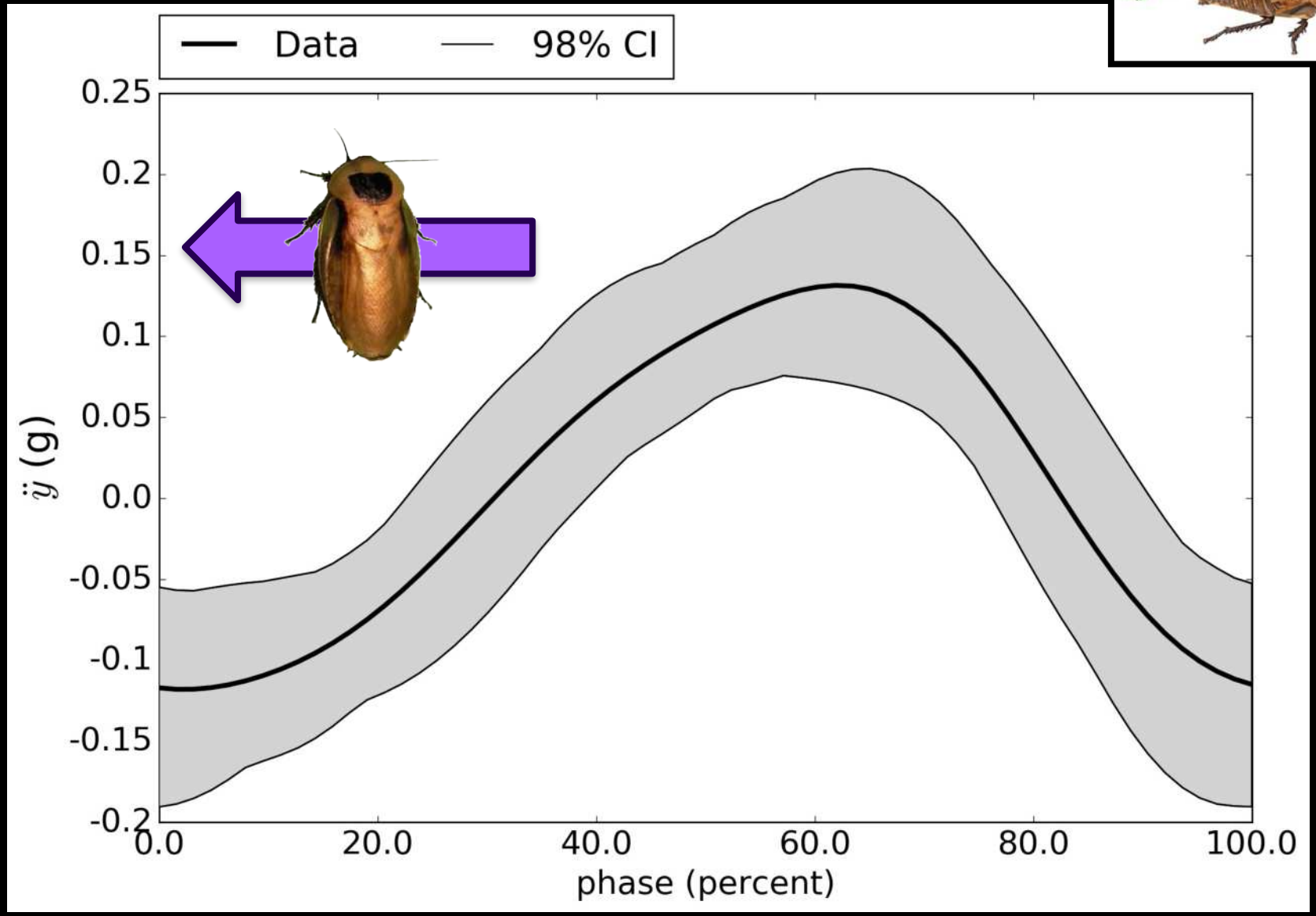
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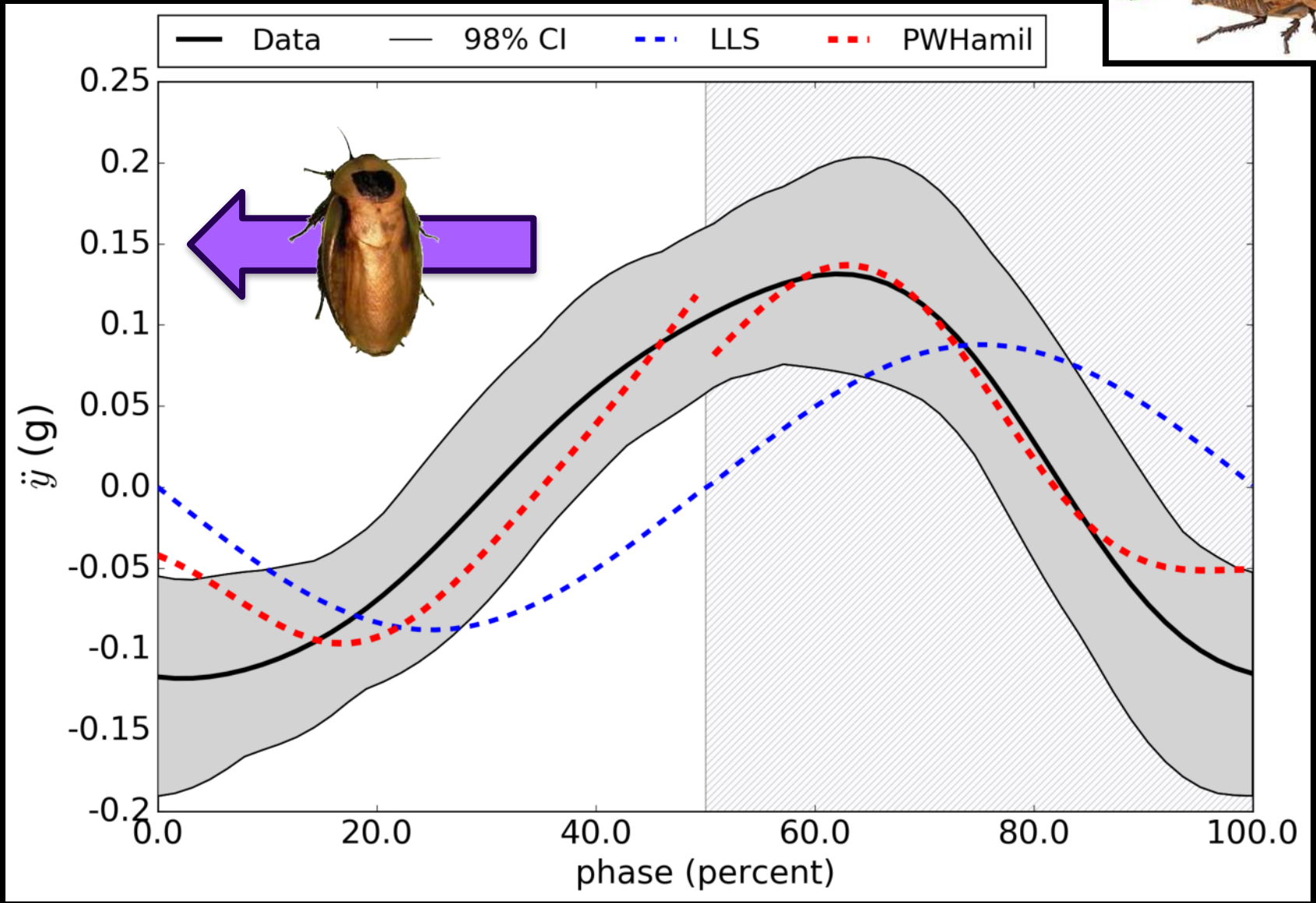
Lateral acceleration





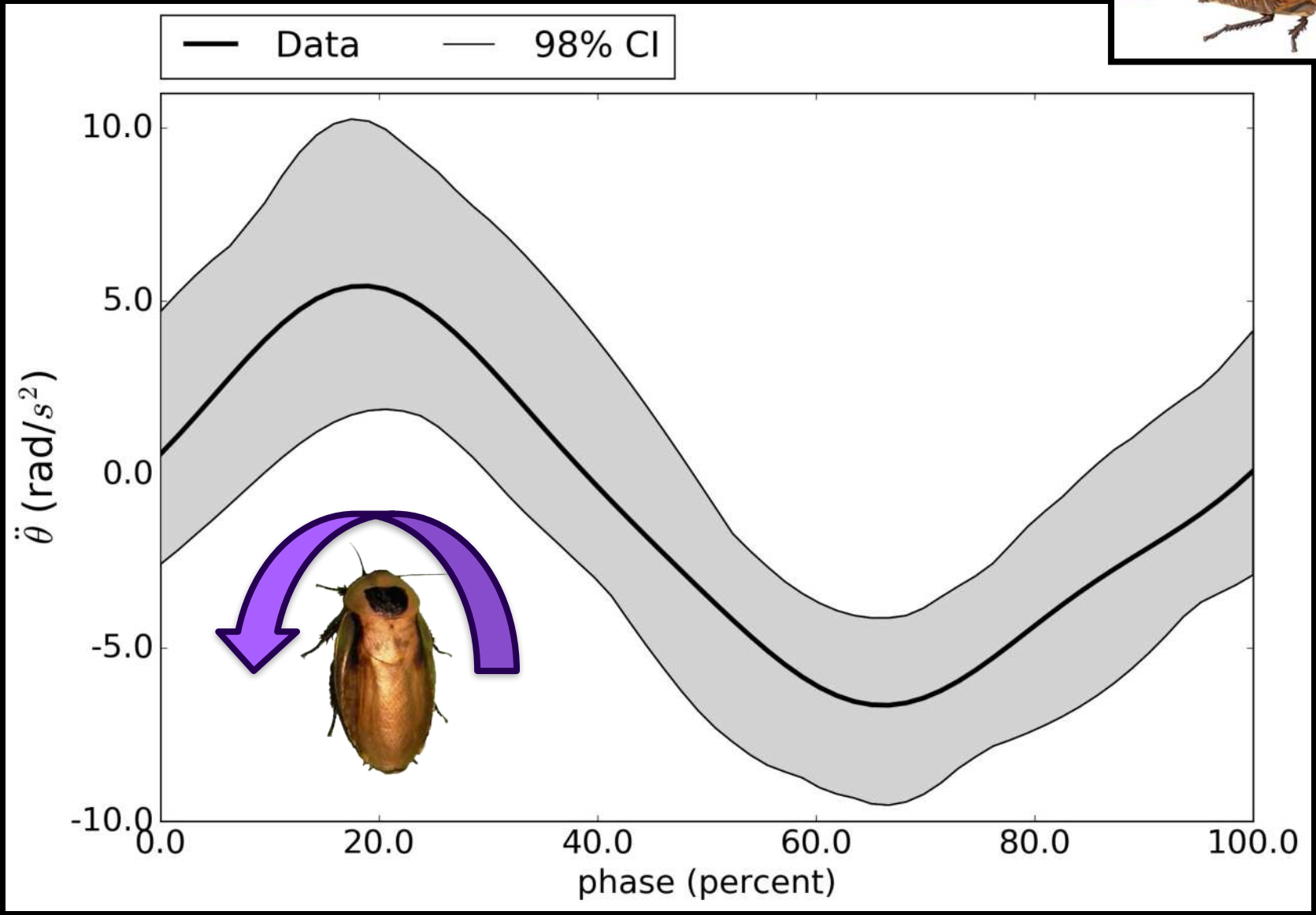
Lateral acceleration





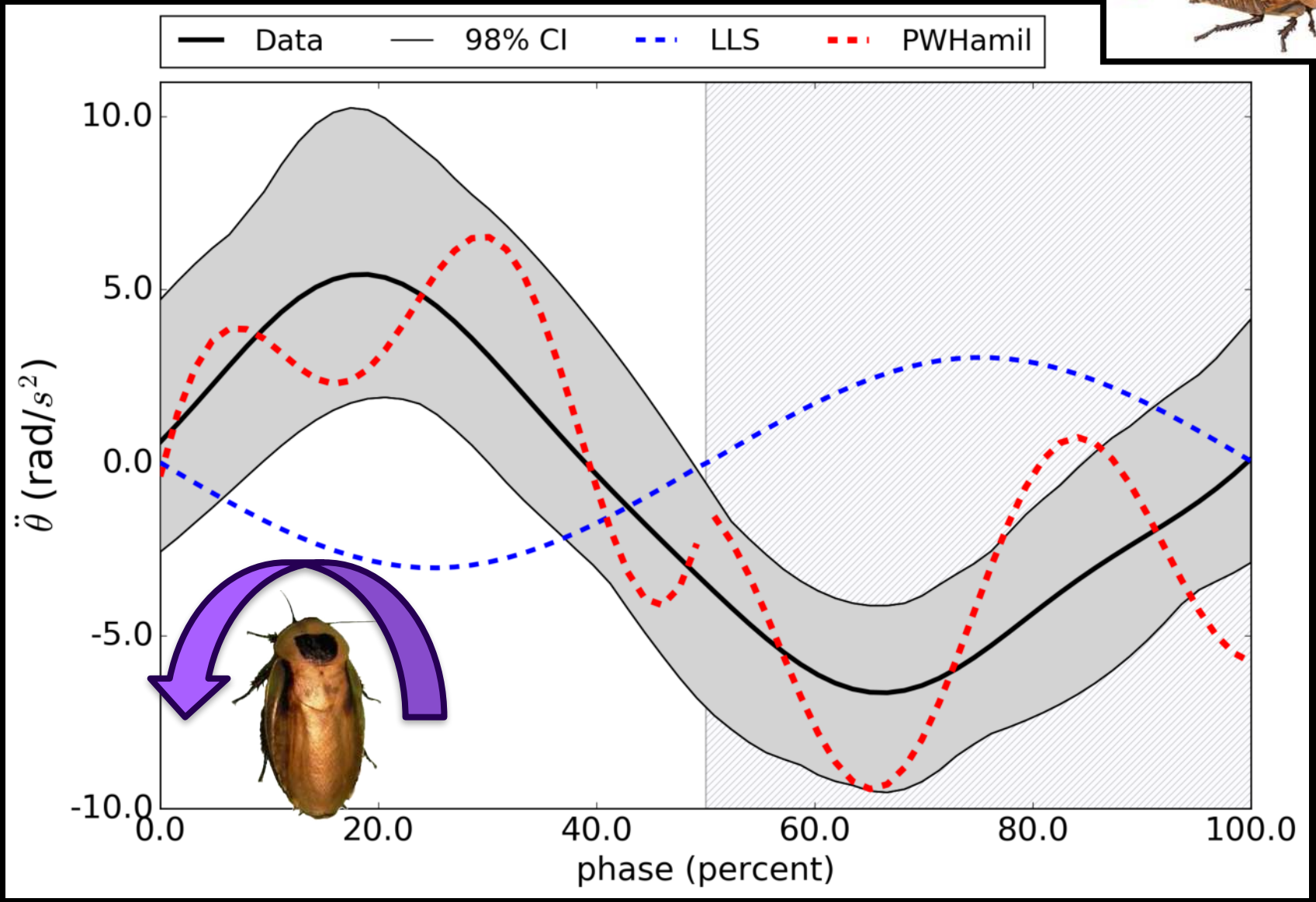
Rotational acceleration





Rotational acceleration





Summary of today's talk

1. Experiment
   - Collected data on cockroach locomotion: steady-state, perturbations, and treatments

2. Experimental results vs existing models
   - purely analytical or data-driven models fail to predict outcomes in our experiment

3. Estimating predictive dynamical model from data
   - proposed a piecewise-defined model structure, estimated parameters from experimental data
   - model yields acceleration predictions that match phasing and magnitude observed in experimental data

Future directions

treatments



robotics

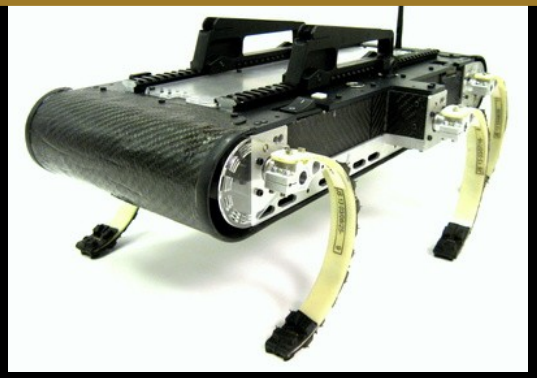


image courtesy of KodLab, UPenn

image courtesy of Steele Lab, UW



perturbations

prosthetics

Collaborators

Sam Burden





Shai Revzen

Talia Moore





Robert Full

Discussion and questions

Thank you for your time!

Animation of data-driven model



