Nonlinear Dynamics: Theory and Experiment

Principal Investigators

Thomas M. Antonsen, Jr.
(Physics, ECE, IREAP,)

Edward Ott
(ECE, Physics, IREAP)

Wolfgang Losert
(Physics, IPST, IREAP)

Daniel Lathrop
(Physics, IPST, IREAP)

Michelle Girvan
(Physics, IPST, IREAP)

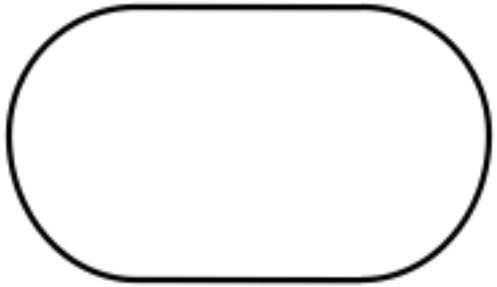
Jim Yorke
(Math, Physics, IPST)

Rajarshi Roy
(Physics, IPST, IREAP)

Wave Chaos

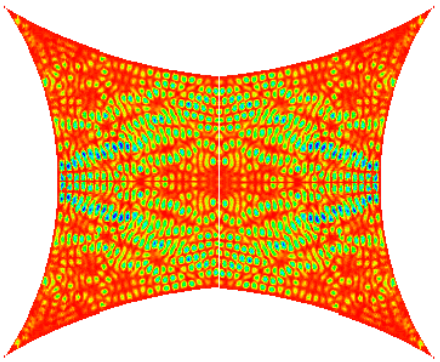
Ed Ott †, Tom Antonsen †, Steve Anlage †, Ming Jer Lee*, Trystan Koch*, Jen Hao Yeh*

- Consider a two-dimensional infinite square-well potential that shows chaos in the classical limit:



- Now solve the electromagnetic wave equation (or Shroedinger equation in the same well)
- Examine solutions in the semi-classical regime: $l << L$

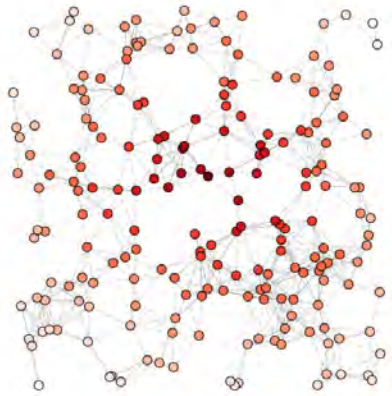
What happens?



† Faculty member
* Graduate student

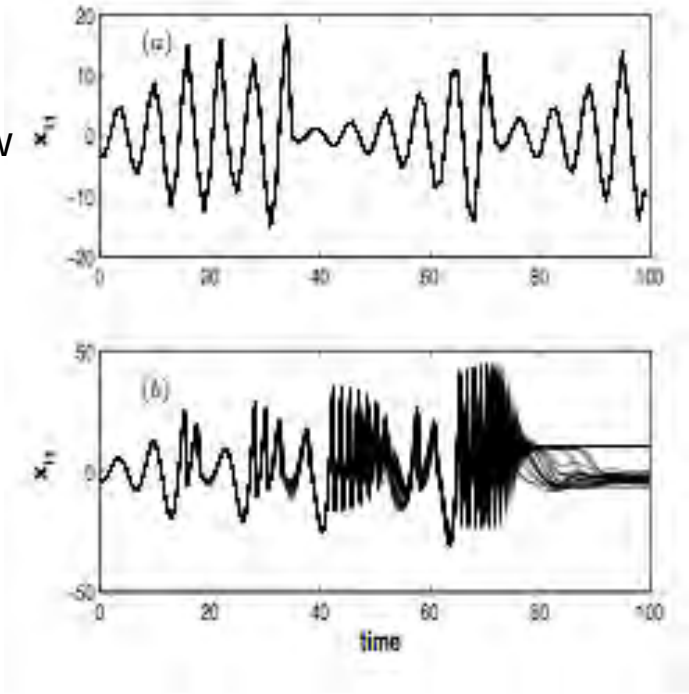
Sample publications:
Phys. Rev. E 86, 046204 (2012)
Phys. Rev. E 85, 015202 (2012)
J. Appl. Phys. 108, 114911 (2010)
Appl. Phys. Lett. 95 , 114103 (2009)

Adaptive synchronization of dynamics on evolving complex networks



Ed Ott †, Raj Roy †, Tom Murphy †, Francesco Sorrentino‡, Bhargava Ravoori*, Adam Cohen*

† Faculty member
‡ Postdoctoral fellow
* Graduate student



- Each node represents a dynamical system capable of exhibiting chaotic dynamics
- Nodes are coupled together in a complex network that evolves slowly with time
- Nodes receive only an aggregate signal from their neighbors
- Nodes adapt in order to maintain synchronization
- Application: sensor networks, communication networks

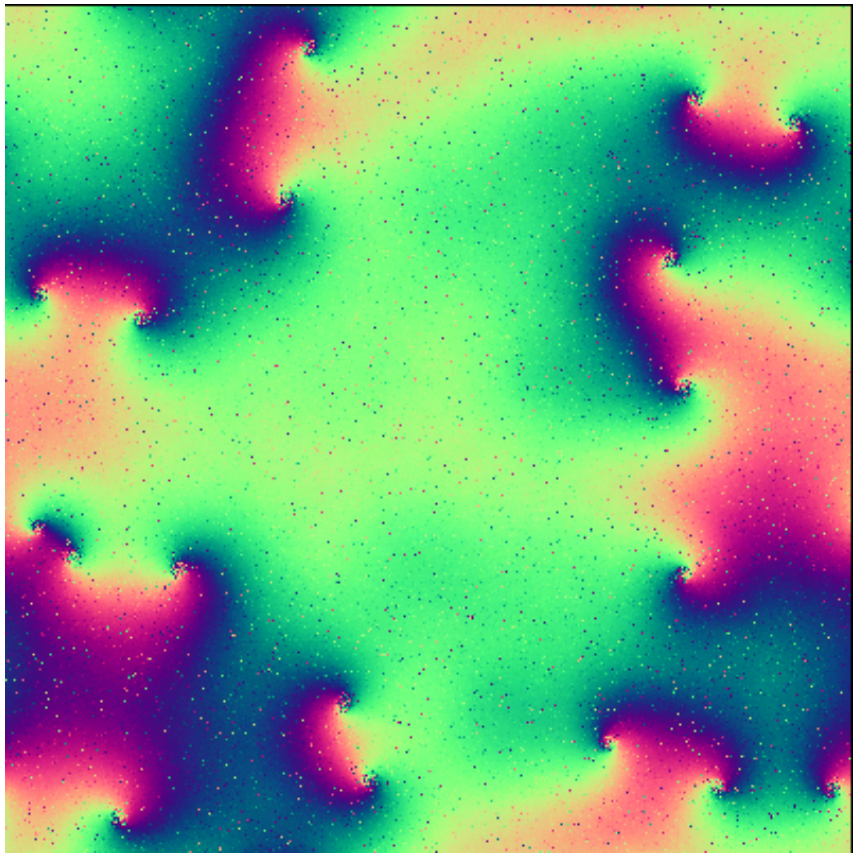
Sample publications:
Phys. Rev. Lett., 110, 064104 (2013)
Chaos 20, 013103 (2010)
Phys. Rev. Lett., 100, 11, 114101, (2008)

What effect does the adaptive strategy have?

- Top: Adaptation implemented
- Bottom: Adaptation not implemented
- Networks start synchronized in both cases

Spatial and Network Coupling of Phase Oscillators

Ed Ott†, Tom Antonsen†, Michelle Girvan†, Wai-Shing Lee*, Gilad Barlev*, John Platig*



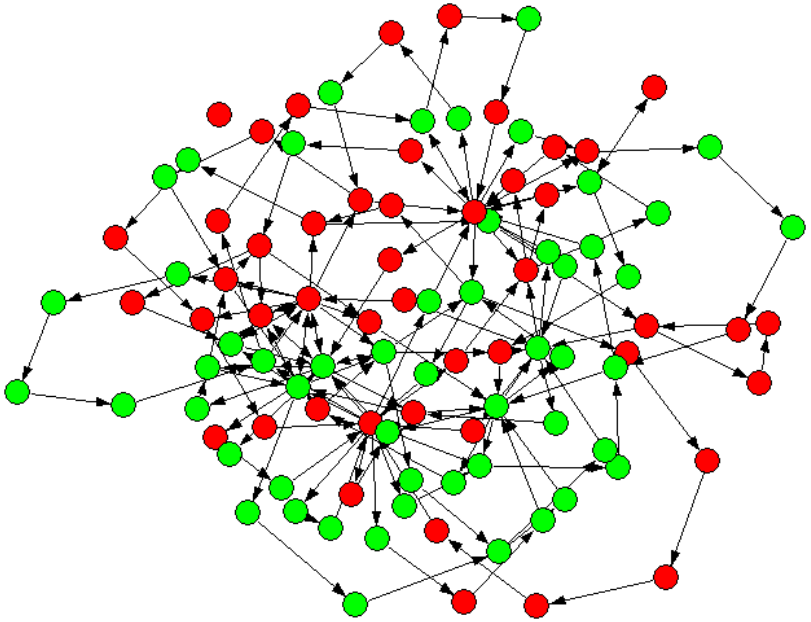
† Faculty member
* Graduate student

- Application: Chemical and biological oscillations
- Time delay equations
- Exhibit rich behavior:
  - Hysteresis
  - Propagating fronts separating coherent and incoherent regions
  - Oscillating spots
  - Spiral waves (with incoherent cores)

Sample publications:
Chaos 22, 013102 (2012)
Chaos 21, 025103 (2011)
Phys. Rev. Lett. 108, 044101 (2009)

Modeling Gene Networks

Michelle Girvan†, Wolfgang Losert†, Ed Ott†, Andrew Pomerance*, Shane Squires*



- Genes on or off
- Discrete updates
- Update function is a random function of neighbor states
- Can predict whether the system's dynamic's will not change significantly under small perturbation (stable) or whether its dynamics are ultimately effected.

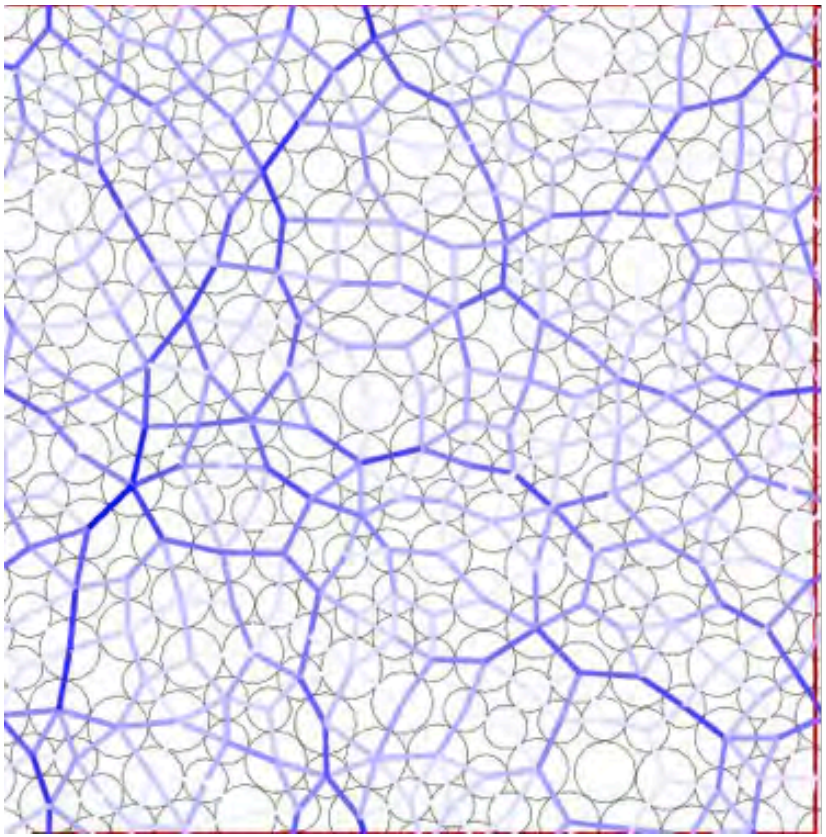
† Faculty member
* Graduate student

Sample publications:
Phys. Rev. Lett. 109, 085701 (2012)
PNAS 106, 8209-8214 (2009)

Granular Networks

Michelle Girvan†, Wolfgang Losert†, Mark Herrera*, Mitch Mailman‡

- Granular materials have been extensively explored at the macroscale (pdes) and at the microscale (particles).
- Networks provide a mesoscale tool with which to investigate granular materials
- We are interested exploring what kinds of insights can be gained by exploring phenomena like jamming, fracture, and reversibility at the network scale



From Corey O'Hern

Sample publications:
Phys. Rev. E 85, 021309 (2012)
Phys. Rev. E 83, 061303 (2011)

† Faculty member
‡ Postdoctoral fellow
* Graduate student

Other theory projects not covered here

- ***Data assimilation for large spatiotemporally chaotic systems, with emphasis on weather forecasting:*** Ed Ott†, Brian Hunt†, Young-Noh Yoon*, Matt Kretchmer*, Dagmar Merkova*
- ***Alternative ways of defining community structure in networks:*** Michelle Girvan†, Ed Ott†, Sanjeev Chauhan*, Geet Duggal*
- ***Gene annotation networks:*** Michelle Girvan†, Wolfgang Losert†, Ed Ott†, Kimbie Glass*
- ***Modeling the dynamics epigenetic patterns:*** Ed Ott†, Michelle Girvan†, Wai Lim Ku*
- ***Methods for genome assembly:*** Jim Yorke†, Michelle Girvan†, Aleksey Zimin‡, Karl Schmitt*
- ***Nonlinear dynamics of cold trapped atoms:*** Tom Antonsen†, Ed Ott†, Mark Herrera*
- ***Flocking dynamics:*** Ed Ott†, Tom Antonsen†, Nick Mecholsky*
- And more…

† Faculty member
‡ Research scientist
* Graduate student

Sponsors:

SCIENCE TO SHAPE THE FUTURE OF THE ARMY
ARMY RESEARCH OFFICE
1951
DEPARTMENT OF THE NAVY
USN
ONR
Science & Technology
NSF
AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
UNITED STATES AIR FORCE
NATIONAL CANCER INSTITUTE
Microsoft

Nonlinear Dynamics in Optical Systems

Physics Department External Review
Overview of Research

Roy-Murphy Lab

L to R (in IREAP lab)

Stephanie Miller
Biophysics PhD program

Aaron Hagerstrom
Physics PhD program

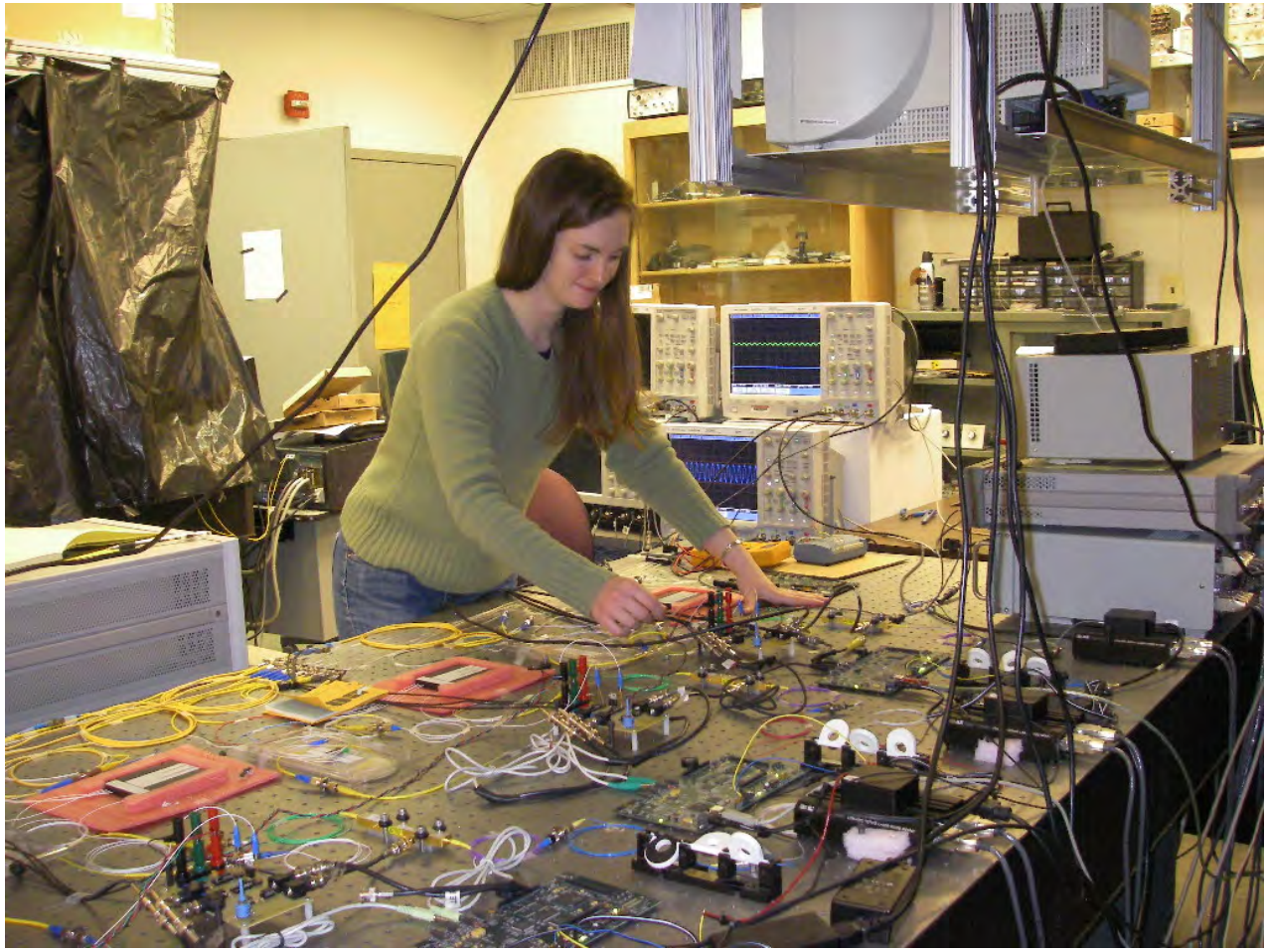
Caitlin Williams
Physics PhD program

Hien Dao
Chemical Physics PhD program

Tom Murphy
ECE Professor, Director of IREAP

Other collaborators, 2013
John Rodgers, IREAP
Francesco Sorrentino ,U New Mexico Mech Engg
Louis Pecora, Naval Research Lab
Visiting Professor Ulrike Feudel (April – Oct 2013)
Rafael Setra (REU student Summer 2013)
Photograph by Rajarshi Roy

Optoelectronic Network Synchrony
Predictive Sync, Adaptive Sync, Optimal Sync, Group Sync,



Caitlin Williams in Optics Lab

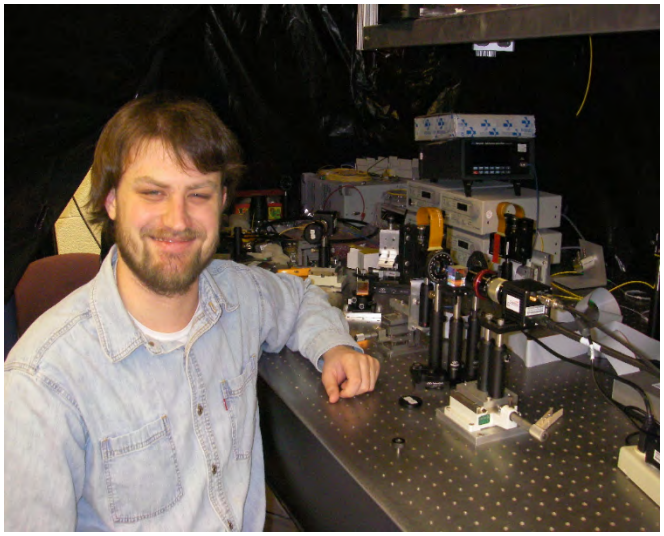
Sample Publications

1. PRL**101**, 154102 (2008).
2. Phil. Trans. Royal Soc. A **368**, 343-366, (2010)
3. Chaos **20**, 043142 (2010)
4. PRL **107**, 034102 (2011)
5. PRL **110**, 064104 (2013)

Chimera States in Light

Hagerstrom et al., Nature Physics **8**, 658-661 (2012)

Coupled-Map Lattices in the Lab



Aaron Hagerstrom with Liquid Crystal Spatial Light Modulator apparatus

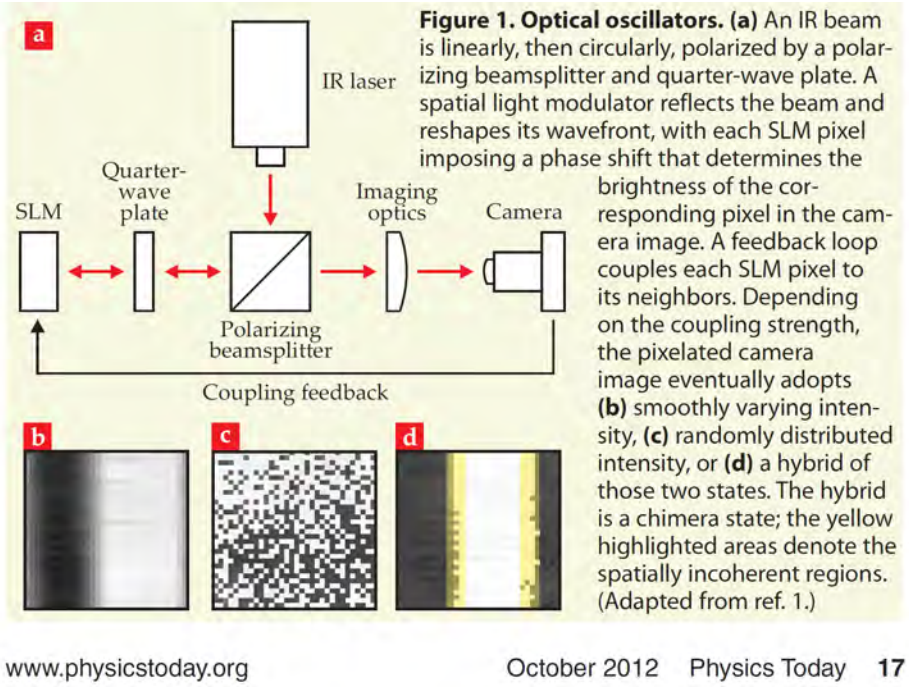


Figure 1. Optical oscillators. (a) An IR beam is linearly, then circularly, polarized by a polarizing beamsplitter and quarter-wave plate. A spatial light modulator reflects the beam and reshapes its wavefront, with each SLM pixel imposing a phase shift that determines the brightness of the corresponding pixel in the camera image. A feedback loop couples each SLM pixel to its neighbors. Depending on the coupling strength, the pixelated camera image eventually adopts **(b)** smoothly varying intensity, **(c)** randomly distributed intensity, or **(d)** a hybrid of those two states. The hybrid is a chimera state; the yellow highlighted areas denote the spatially incoherent regions. (Adapted from ref. 1.)

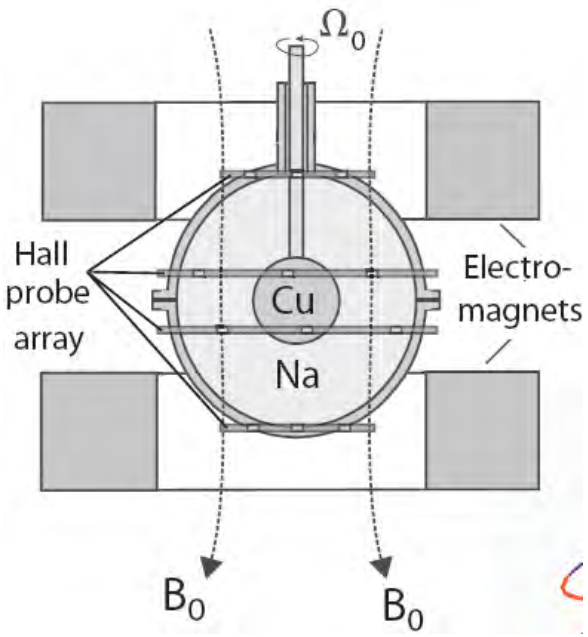
Sync and desync oscillators coexist in large ensembles
of non-locally coupled, identical nonlinear dynamical phase oscillators
Can they be observed in real experimental systems?
Theory and predictions since 2002
by Y. Kuramoto, S. Strogatz, Carlo Laing, Danny Abrams……

Rapidly Rotating Experiments

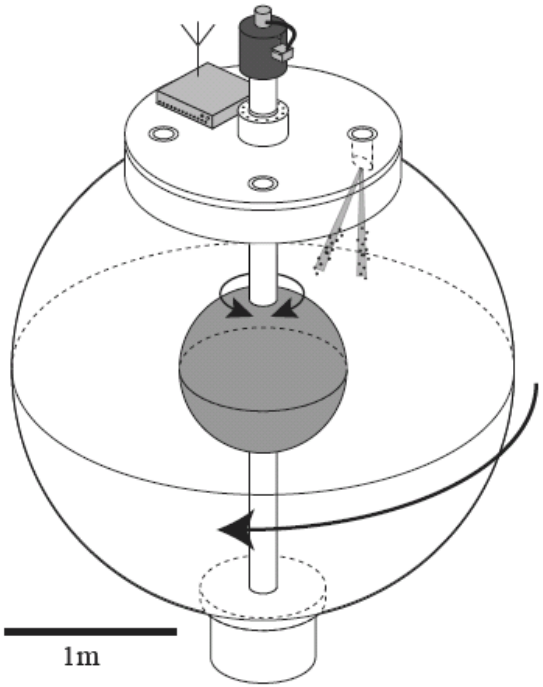
as laboratory models of planetary cores

(Lathrop)

30 cm diameter
Sodium Experiment



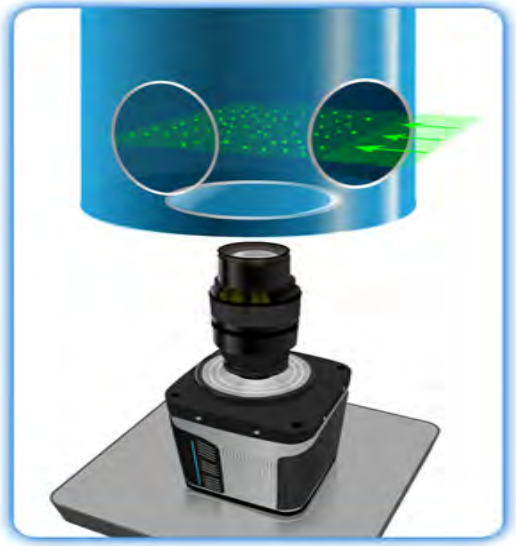
3 m diameter
Sodium Experiment



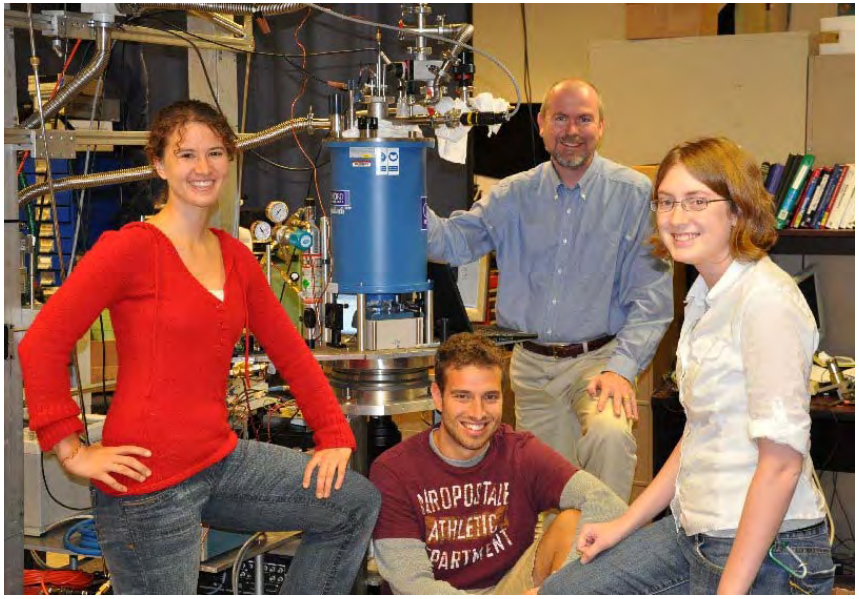
Research Goals:

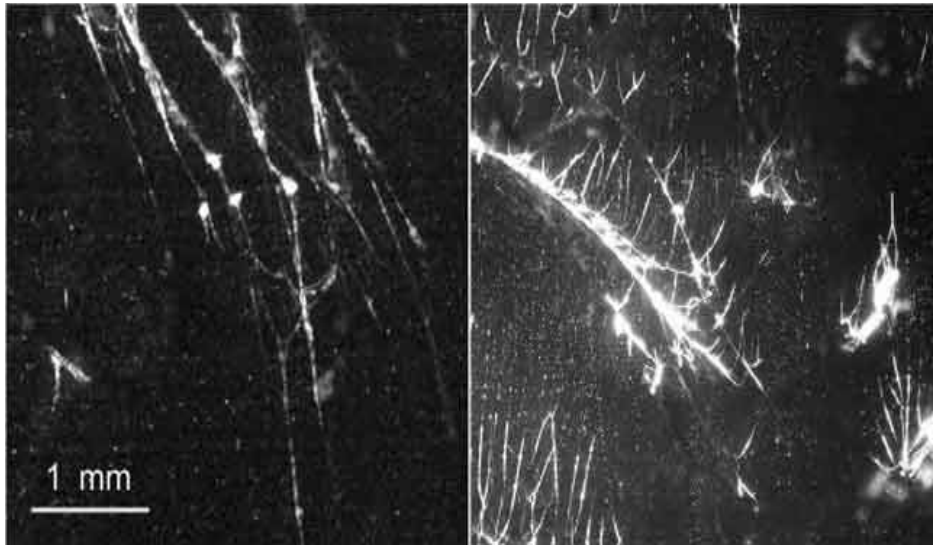
- **Create a homogeneous, Earth-like dynamo in the lab**
- **Demonstrate a self-generating magnetic field in an unconstrained flow**
- **Characterize the nature of the transition to dynamo action**
- **Explore the mechanism which causes Earth's magnetic field to saturate**
- **Understand the dynamics of the saturated field, with particular interest in pole reversals**

Quantum Turbulence *(Lathrop)*



Visualizing Flows in Superfluid Helium

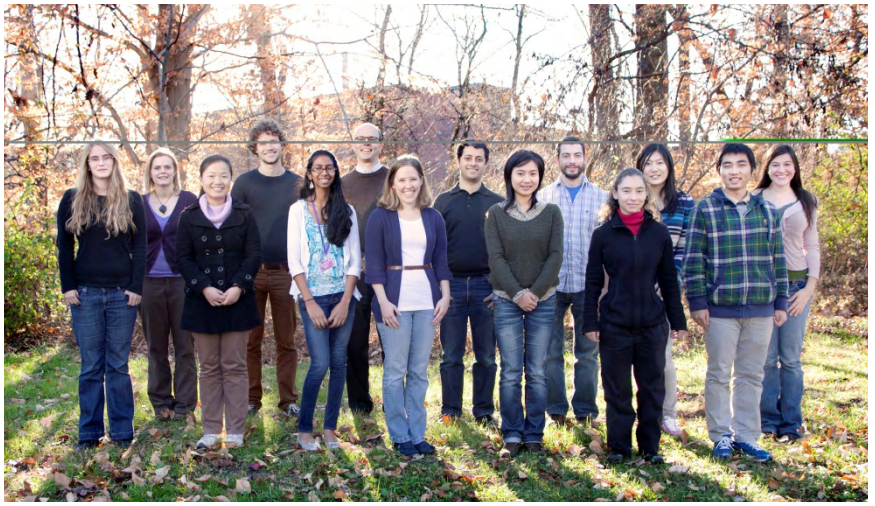




Research Goal:
Understand the dynamics of vortex defects and their impact on phase transitions

Awards:
Andreas Acrivos Dissertation Award (Matthew Paoletti, 2010)
Stanley Corrsin Award (Daniel P. Lathrop, 2012)

Cell Dynamics (Losert)



<u>Students</u>
Desu Chen
Can Guven
Deborah Hemingway
Mark Herrera
Rachel Lee
Eleanor Ory
(w/ Upahyaya)

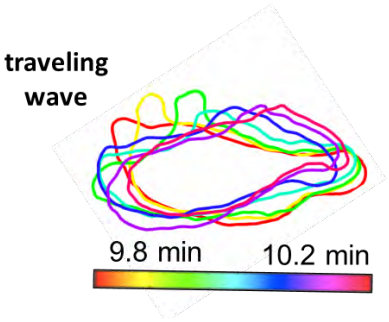
Joshua Parker
Yang Shen
Xiaoyu Sun
Chenlu Wang

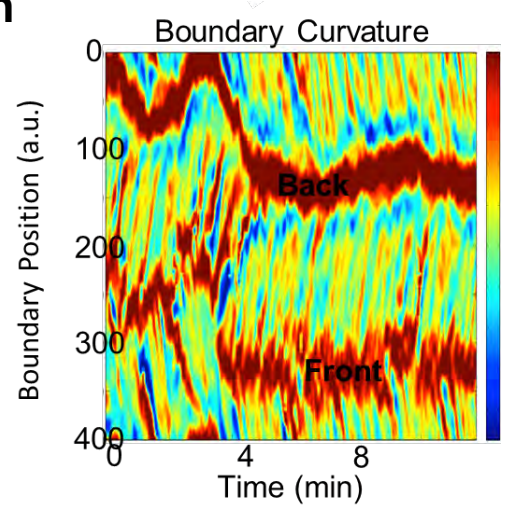
<u>Postdoc</u>
Julian Candia

: Experiment

of migrating cells.

These waves facilitate **contact guidance and synchronization**

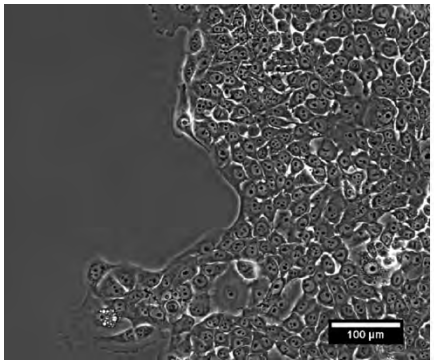


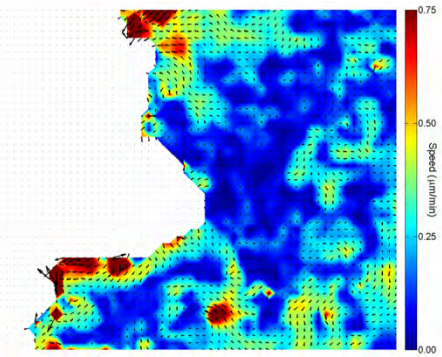


Driscoll et al, Physical Biology (2011), PLOS Comp. Biol.(2012)

Applied tools from fluid and sand flows to **quantify collective cell migration.**

Connecting collective motion and "metastatic potential"

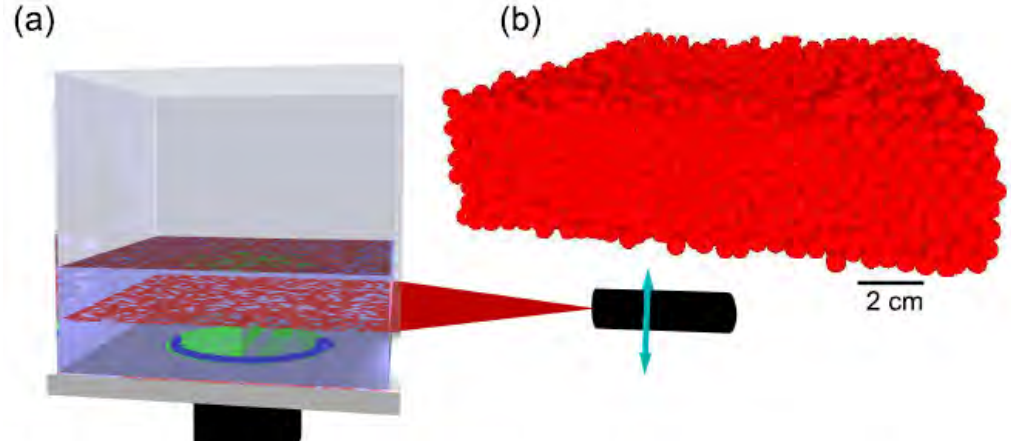




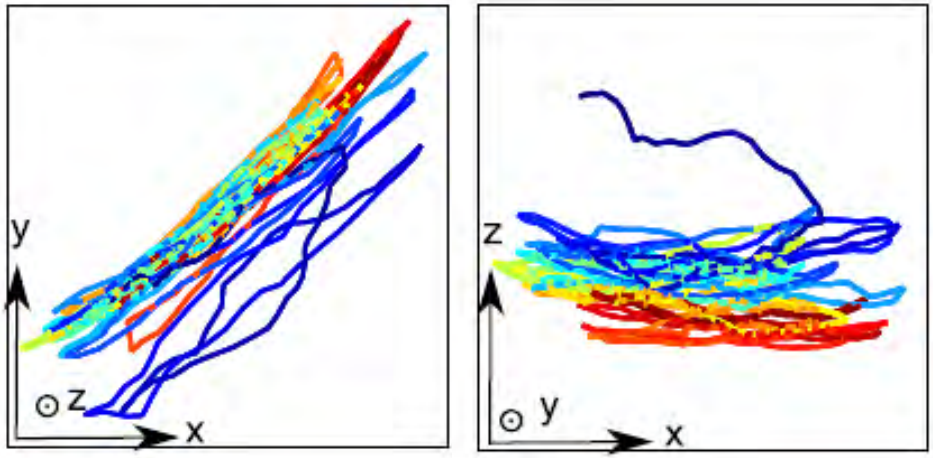
Weiger et al, PLOS One (2012)
Lee et al, New Journal of Physics (2013)

Granular Dynamics *(Losert)*

Developed 3D imaging of particle motion and rotation inside granular matter



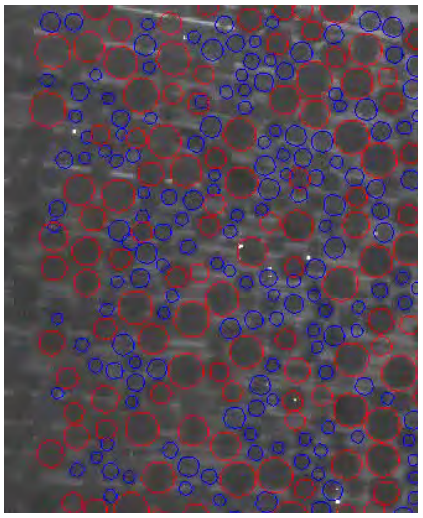
How reversible are particle trajectories?

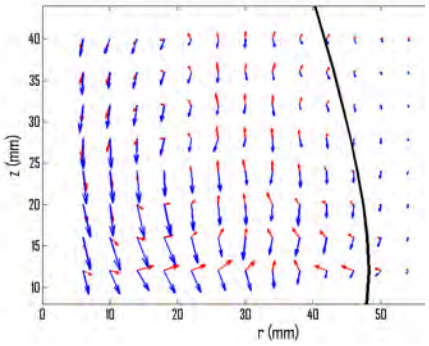


Slotterback et al PRL (2008), PRE (2012)

Dijksman et al PRE (2010), J. Sci Instruments (2011)

How do mixtures segregate at the particle scale?





Harrington et al

Biological Physics

Jayanth Banavar

Michelle Girvan

Arthur La Porta

Wolfgang Losert

Rajarshi Roy

Arpita Upadhyaya

- Theory: Dynamics of Living Systems – emergent properties

  Raj Roy, Michelle Girvan, Jayanth Banavar

- Experiment: Cell Mechanics and Dynamics

  Arpita Upadhyaya, Wolfgang Losert, Arthur La Porta

Biophysics Group Activity 1:
New Biophysics Graduate Program

The Program, started in 2009 brings together faculty from biology, chemistry, biochemistry, engineering, applied math, and physics

The curriculum is tailored to each student's background and research interests by a committee of three faculty members.

19 Graduate students
6 mentored by Physics faculty

Strong Connections to National Labs:
3 students NIST co-advised
2 students NIH co-advised

Biophysics Group Activity 2: Partnership with the NIH

Official Partnership between the University of Maryland and the National Institutes of Health (with the National Cancer Institute as lead), initiated by the Physics Department, started in 2010

Goal: Apply Nonlinear Dynamics, Biophysics, Bioengineering, and Bioinformatics expertise to problems in Cancer Research

Physics Participants: Banavar, Girvan, Losert (Partnership Director), Upadhyaya

Seed Support (from NCI-CCR director)

-4 new seed projects every year

-3 physics students since 2010

Outcomes:

-Publications by joint students

-NIH funding

Emergent Properties of living Systems – PI: Jayanth Banavar

From cellular characteristics to disease diagnosis

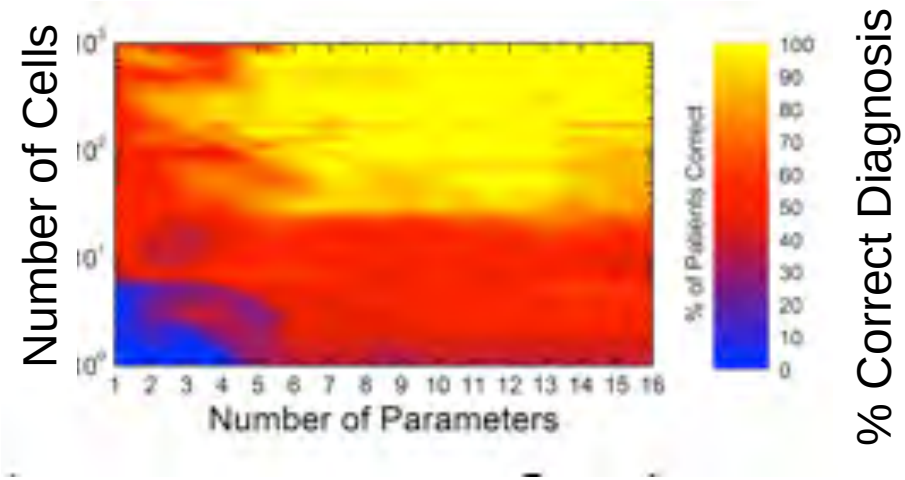
Julian Candia, Yang Shen, Wolfgang Losert, Jayanth Banavar
Robert Nussenblatt (NEI,NIH), Curt Civin (UM Medical School)

Novel Data: Multiparameter single cell measurements

High throughput microscopy

Single cell genomics

Questions: Are disease characteristics inherent to each cell or an emergent property of multiple cells / markers?



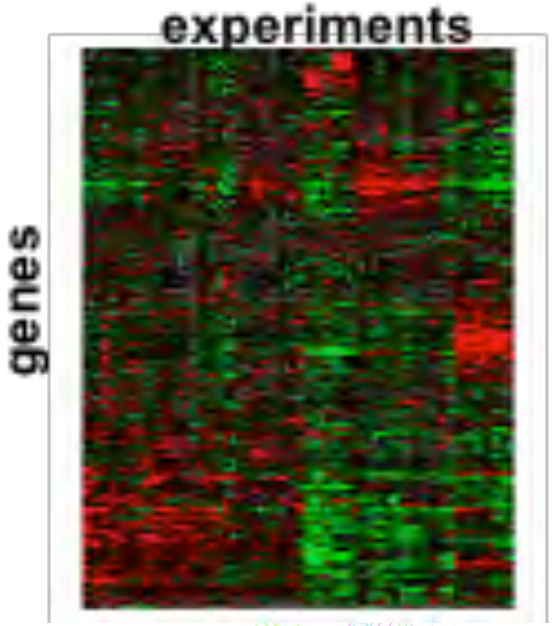
Gene Networks and Dynamics: PI Michelle Girvan

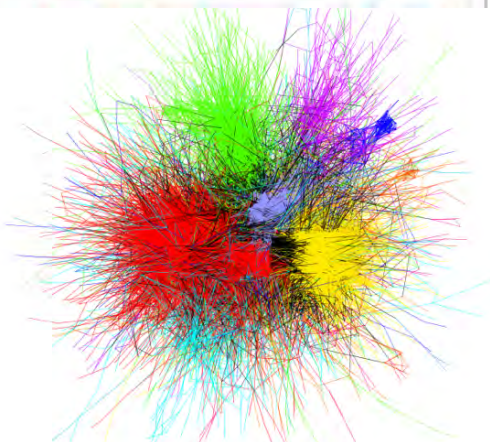
Gene Expression in Cancer

John Platig, Michelle Girvan, Ed Ott, Wolfgang Losert, Lou Staudt (NIH)

Tasks:

- Infer a gene network from expression data across experiments
- By analyzing the network structure, identify the transcription factors that play key regulatory roles in cancerous cells





Neuroscience: Dynamics, Information, Synchronization: PI Raj Roy

Collaboration with D. Plenz, NIH

Hongdian Yang, Dietmar Plenz and Woodrow Shew

Hongdian Yang (First Ph.D of the Biophysics Graduate Program at UMD, 2011)
Is a postdoc in Neuroscience at Johns Hopkins since June 2012.

Woody Shew is now Assistant Professor of Physics at the U of Arkansas in Fayetteville since Jan 2012

Neuroscience: Dynamics, Information, Synchronization: PI Raj Roy

Neuronal Avalanches and Criticality
Balance between excitation and inhibition

Neuronal Avalanches Imply Maximum Dynamic Range in Cortical Networks at Criticality

Woodrow L. Shew,[1] Hongdian Yang (杨黉典),[1,2] Thomas Petermann,[1] Rajarshi Roy,[2] and Dietmar Plenz[1]
[1]Section on Critical Brain Dynamics, Laboratory of Systems Neuroscience, National Institute of Mental Health, Bethesda, Maryland 20892, and [2]Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742

J. Neuroscience **29** (49):15595–15600 (2009).
72 citations

Information Capacity and Transmission Are Maximized in Balanced Cortical Networks with Neuronal Avalanches

Woodrow L. Shew,[1*] Hongdian Yang 杨黉典,[1,2*] Shan Yu 余山,[1] Rajarshi Roy,[2] and Dietmar Plenz[1]
[1]Section on Critical Brain Dynamics, Laboratory of Systems Neuroscience, National Institutes of Mental Health, Bethesda, Maryland 20892, and [2]Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742

J. Neuroscience **31**, 55-63 (2011).

Maximal Variability of Phase Synchrony in Cortical Networks with Neuronal Avalanches

Hongdian Yang (杨黉典),[1,2] Woodrow L. Shew,[1] Rajarshi Roy,[3] and Dietmar Plenz[1]

J. Neuroscience **32**, 1061-1072 (2012)

"Peak Variability and Optimal Performance in Cortical Networks at Criticality," Hongdian Yang, W. L. Shew, Rajarshi Roy and D. Plenz, Chapter to appear in *Criticality in Neural Systems* (2013), edited by D. Plenz, E. Niebur and H. G. Schuster.

Cell and Cytoskeletal Mechanics – PI: Arpita Upadhyaya

Research focused on understand various aspects of biological motion – in particular its physical basis and its biochemical control.

<u>Funding:</u> Sloan Foundation
NSF (Physics of Living Systems)
NSF (Cellular Systems Cluster)
UMD/NCI Cancer Technology

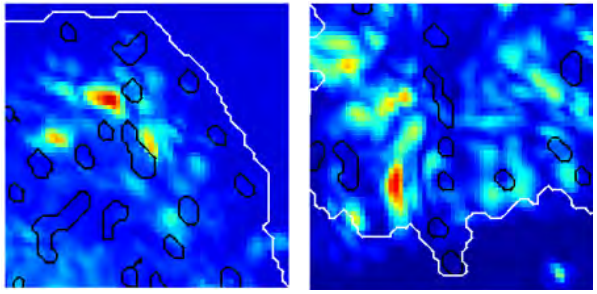
<u>Recent Honors for Students:</u>
Christy Ketchum (ARCS Fellowship)

<u>Collaborators:</u>
Dr. Larry Samelson (NIH)
Dr. Wenxia Song (UMD)

Students
King Lam Hui (Grad)
Echo Ory (Grad) (w/ Losert)
Christy Ketchum(Grad)
Ming Zhang (UG)
Sae In Kwak (UG)
Brian Grooman (Grad)
Jessica Wayt (UG)
Mike Azatov (Grad)
Shirong Zhang (UG)

Cell and Cytoskeletal Mechanics – PI: Arpita Upadhyaya

Membrane topography and fluctuations correlate with signaling assemblies

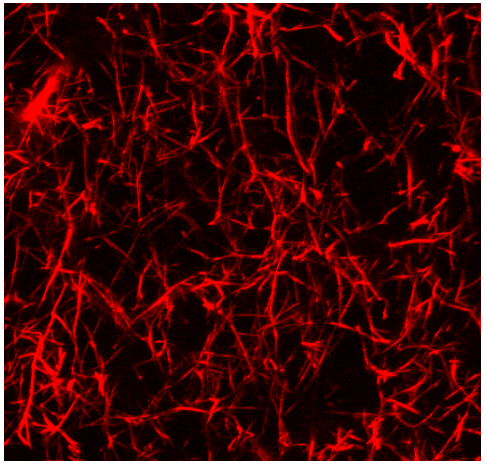


Hui et al, Biophys. J., 2012

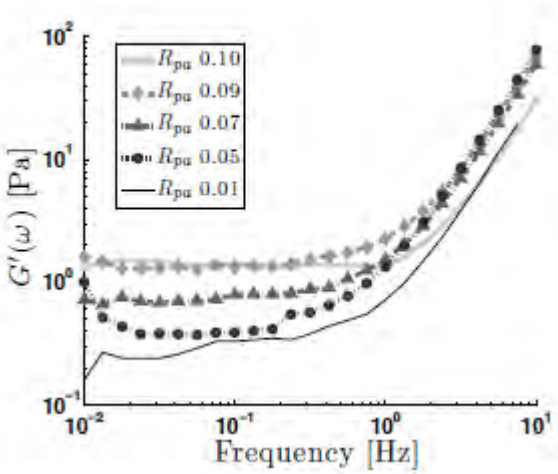
Microstructure of crosslinked actin networks determines their mechanical properties

Grooman et al., PLoS One, 2012

Brian Grooman



Confocal image of a crosslinked actin network



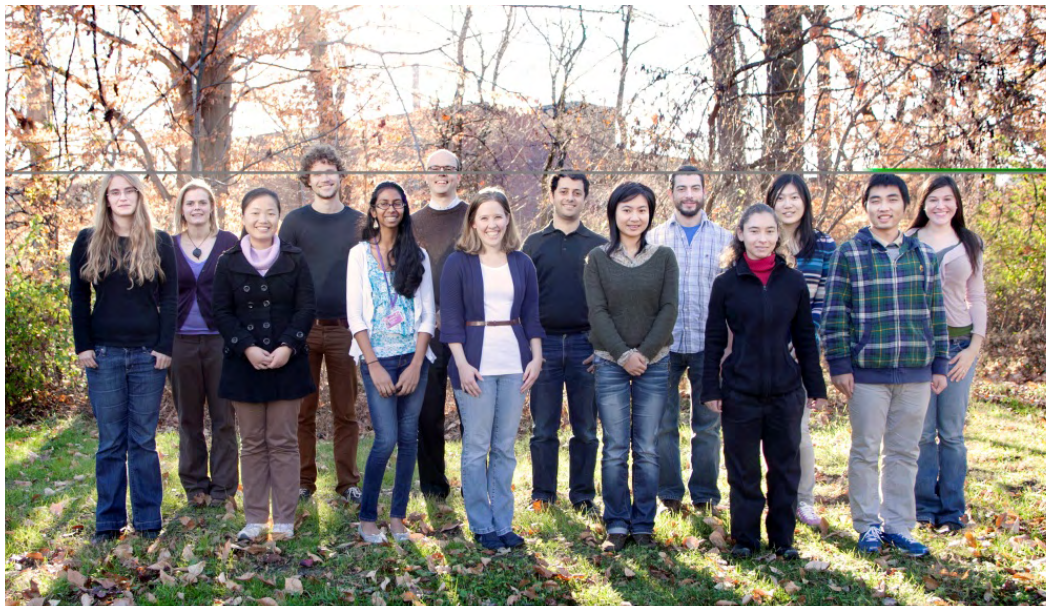
Rheometry measurement of network viscoelasticity

Cell Statistics and Dynamics – PI: Wolfgang Losert

Experiment and modeling of emergent dynamical properties of migrating Cells and Tissues.

A special focus is on applications to cancer research.

NIH-R01
NSF-Physics of Living System
DOD-Era of Hope Award (PI Stuart Martin, UM Medical School)



<u>Honors /Fellowships for Students/Postdocs:</u>
Erin Rericha (Burroughs Wellcome Award)
Mark Herrera (DOD Fellowship)
Joshua Parker (DOD Fellowship)
Rachel Lee (ARCS Fellowship)

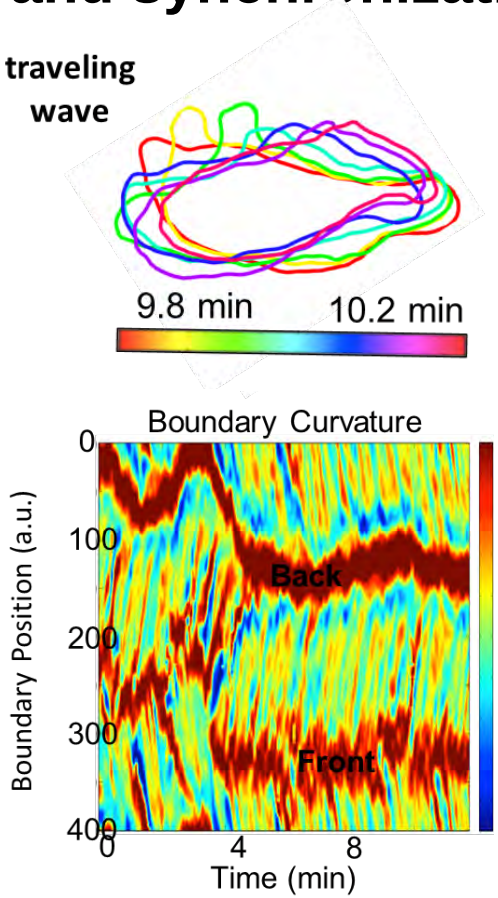
<u>Students</u>
Desu Chen
Can Guven
Deborah Hemingway
Mark Herrera
Rachel Lee
Eleanor Ory
(w/ Upahyaya)
Joshua Parker
Yang Shen
Xiaoyu Sun
Chenlu Wang

<u>Postdoc</u>
Julian Candia

Cell Statistics and Dynamics – PI: Wolfgang Losert

Discovered **wave-like character of migrating cells.**

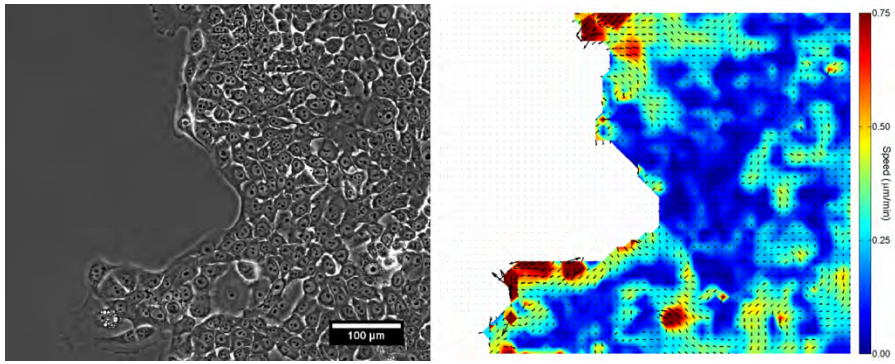
These waves facilitate **contact guidance and synchronization**



Driscoll et al, Physical Biology (2011), PLOS Comp. Biol.(2012)

Applied tools from fluid and sand flows to **quantify collective cell migration.**

Connecting collective motion and "metastatic potential"



Weiger et al, PLOS One (2012)
Lee et al, New Journal of Physics (2013)

Phenotyping the Dynamics of Development (With Janelia Farms)