THE PHYSICS OF THE HEART

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Outline

- A brief review of cardiac physiology
- The classical forward and inverse problems
- The ultimate forward and inverse problems
- Cardiac physics research at Vanderbilt

The cardiac membrane is a planar accelerator that uses gradients of 10^7 volts per meter to accelerate heavy ions to energies of 70 meV.

The Spatial and Temporal Scales of Cardiac Electrodynamics

- Spatial Scale: 10^{24} in volume
  - Ten-centimeter diameter of the entire heart
  - Nanometer pore of gated ion channels
  - Sequence of the proteins that form those channels
- Temporal Scale: 10^{9} in time
  - One-second heart beat
  - Many seconds of a complex arrhythmia
  - Nanosecond conformational changes of protein channels

The Classical Forward and Inverse Problems

- Forward: Given source, find potential/field
  - Predict the ECG or MCG from a description of the cardiac sources.
- Inverse: Given potential/field, find source
  - Determine an effective source for cardiac electrical activity from the ECG or MCG.
  - Estimate the epicardial potentials from the thoracic potential or magnetic field maps.

The **Ultimate** Inverse Problem

From the ECG, identify the behavior of various membrane ion channels to guide pharmacological control of arrhythmias.

The **Ultimate** Forward Problem

- Predict the ECG from knowledge of channel protein structure.
- Predict the global functional consequences of channel-level defects and interventions.

Current Research

- The magnetocardiogram
- The bidomain model
- The magnetic field from cardiac tissue slices
- Cardiac reentry and fibrillation
- The response of cardiac tissue to strong shocks
- The magnetic field from gastrointestinal electrical activity
- The magnetic field from corrosion in aging aircraft
- Non-destructive testing with SQUID magnetometers

Cardiac Reentry

- Self-sustained excitation due to propagating activation wave fronts in the heart that continue to re-excite different regions of tissue rather than terminating after a single excitation
- Anatomical reentry -- activation wave fronts that travel in one direction around an anatomical obstacle
- Functional reentry -- activation circulate around a dynamical phase singularity

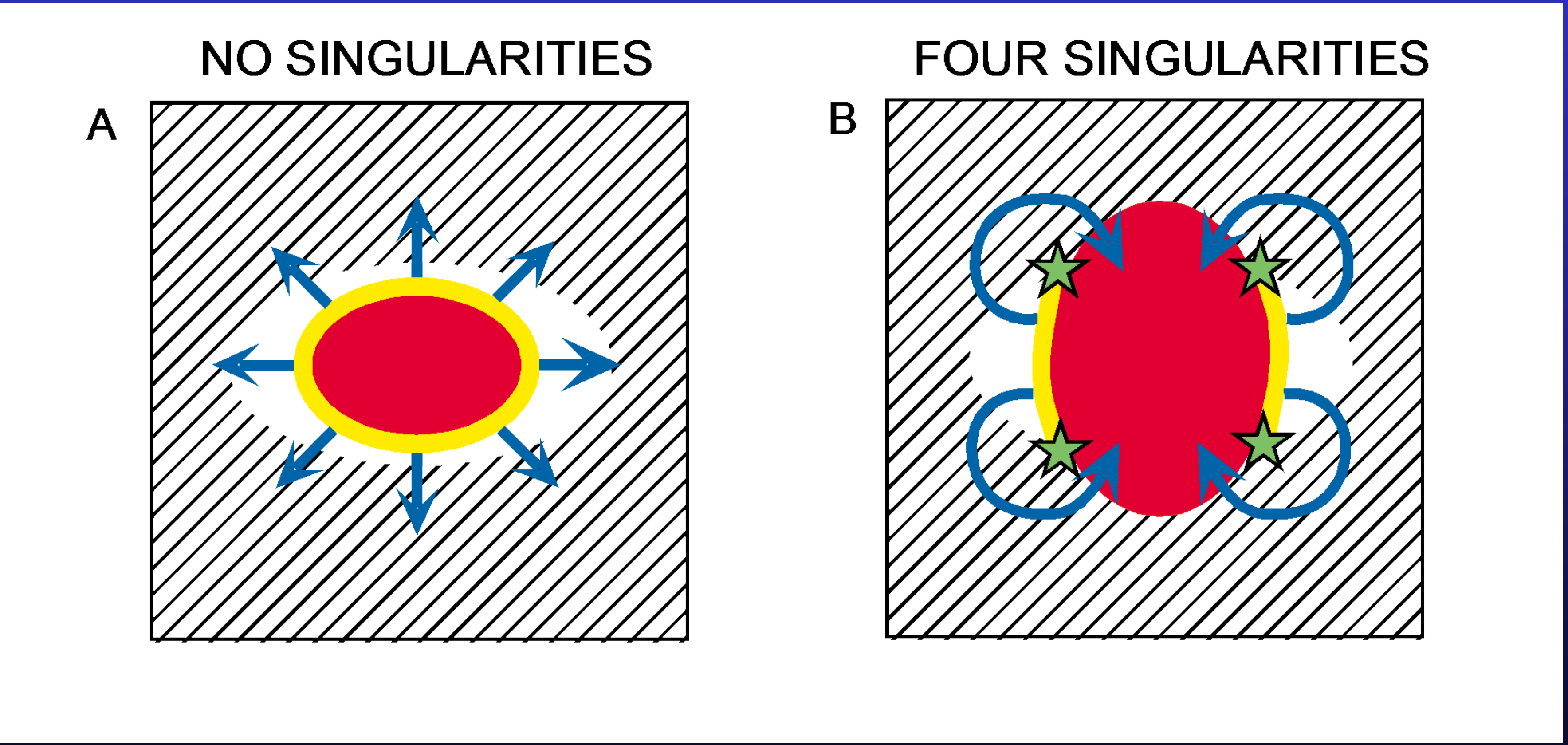
Functional Reentry

- For a normal propagating wave front, the tissue in front of the wave front is resting and excitable, and that behind is depolarized and unexcitable
- Functional reentry occurs when one end of an excitation wave front is a phase singularity -- a region of undetermined phase that is neither resting or depolarized
- The challenge is to create the phase singularity

Winfree's Critical Point Hypothesis

Phase singularities (critical points) are created when the excitability contour T* following the first stimulus (S1) intersects the stimulus threshold contour S* from the second stimulus (S2).

Bidomain Anisotropies and the Critical Point Hypothesis



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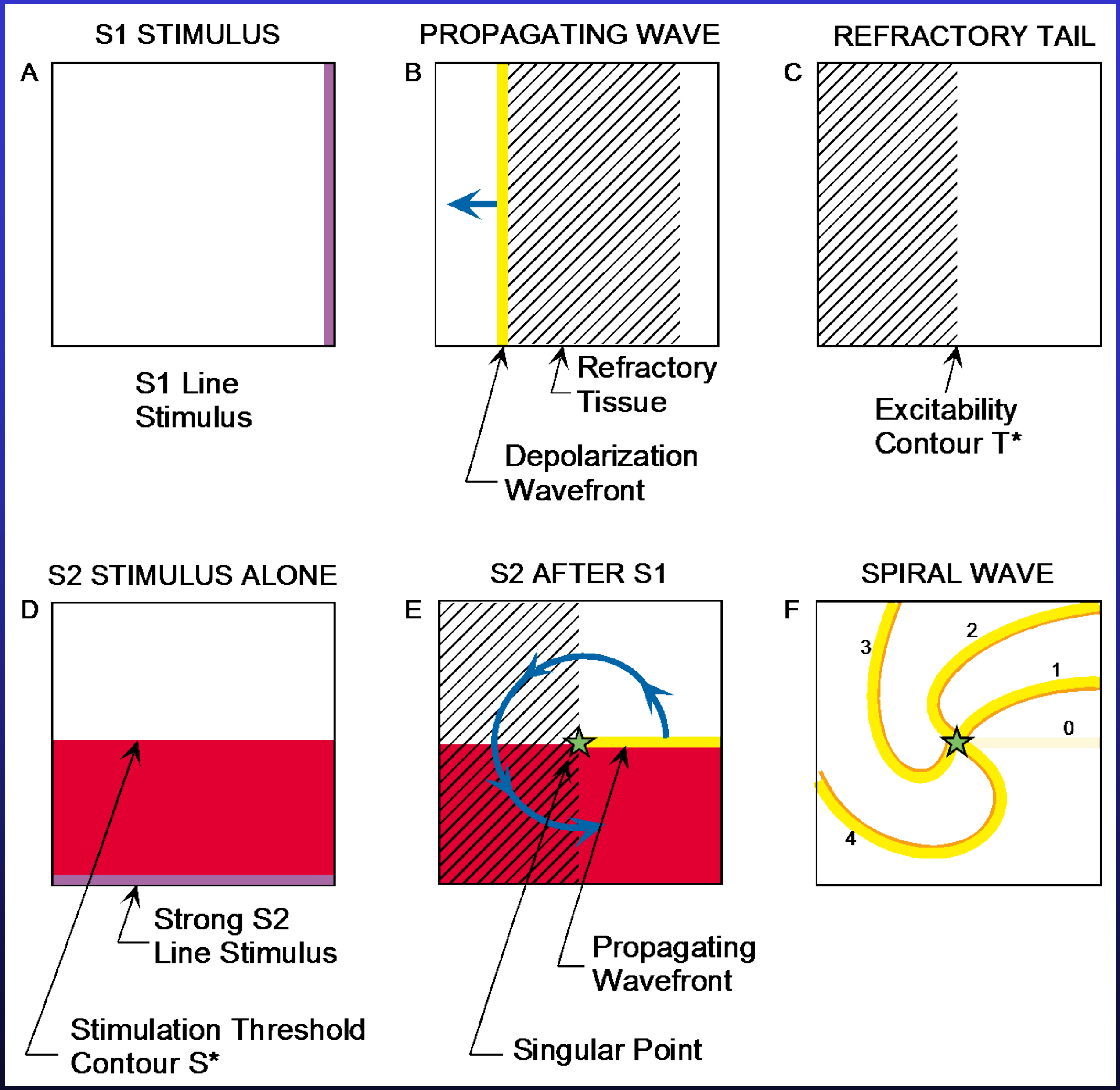
Initiation of Spiral Wave Reentry



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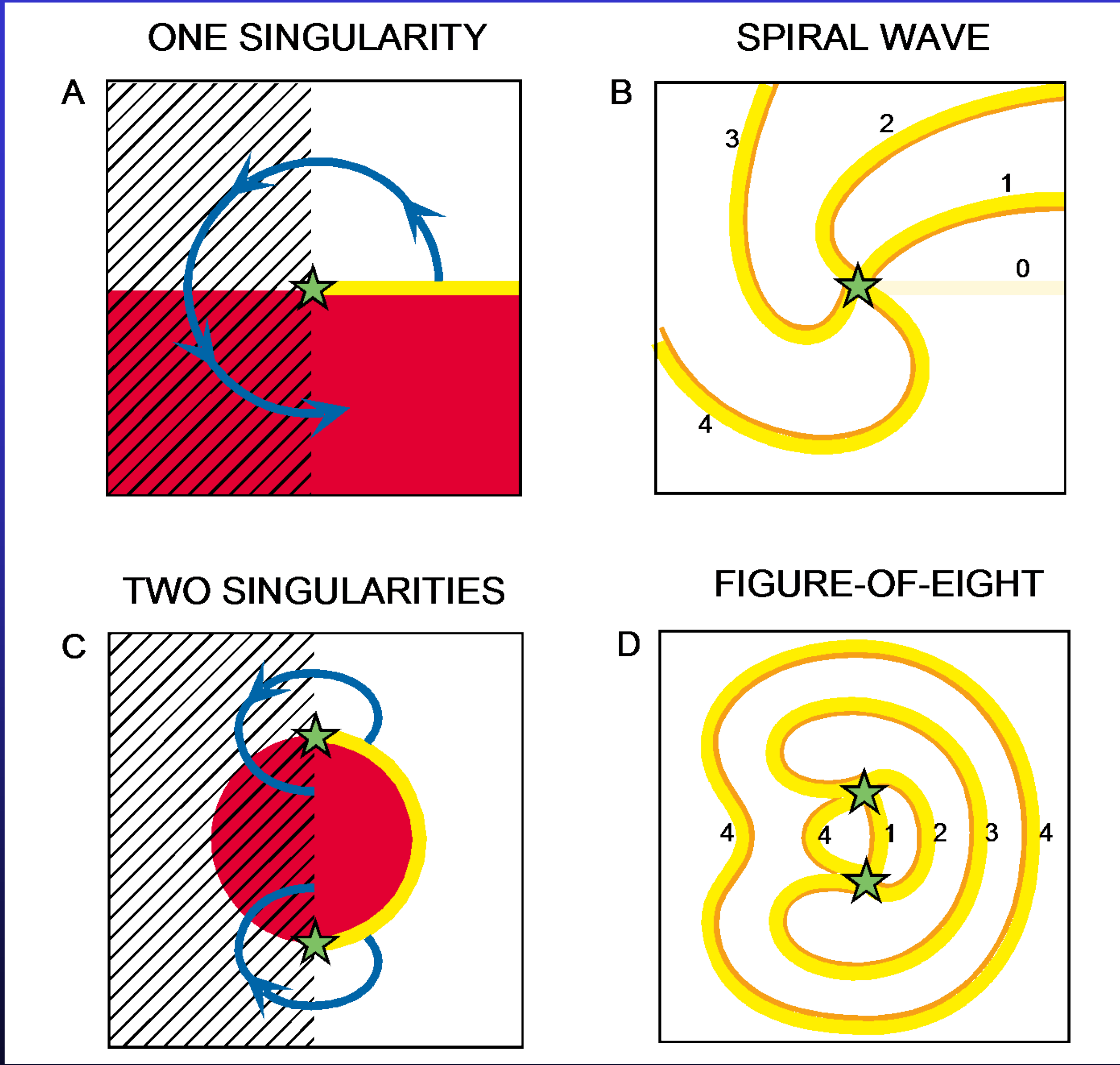
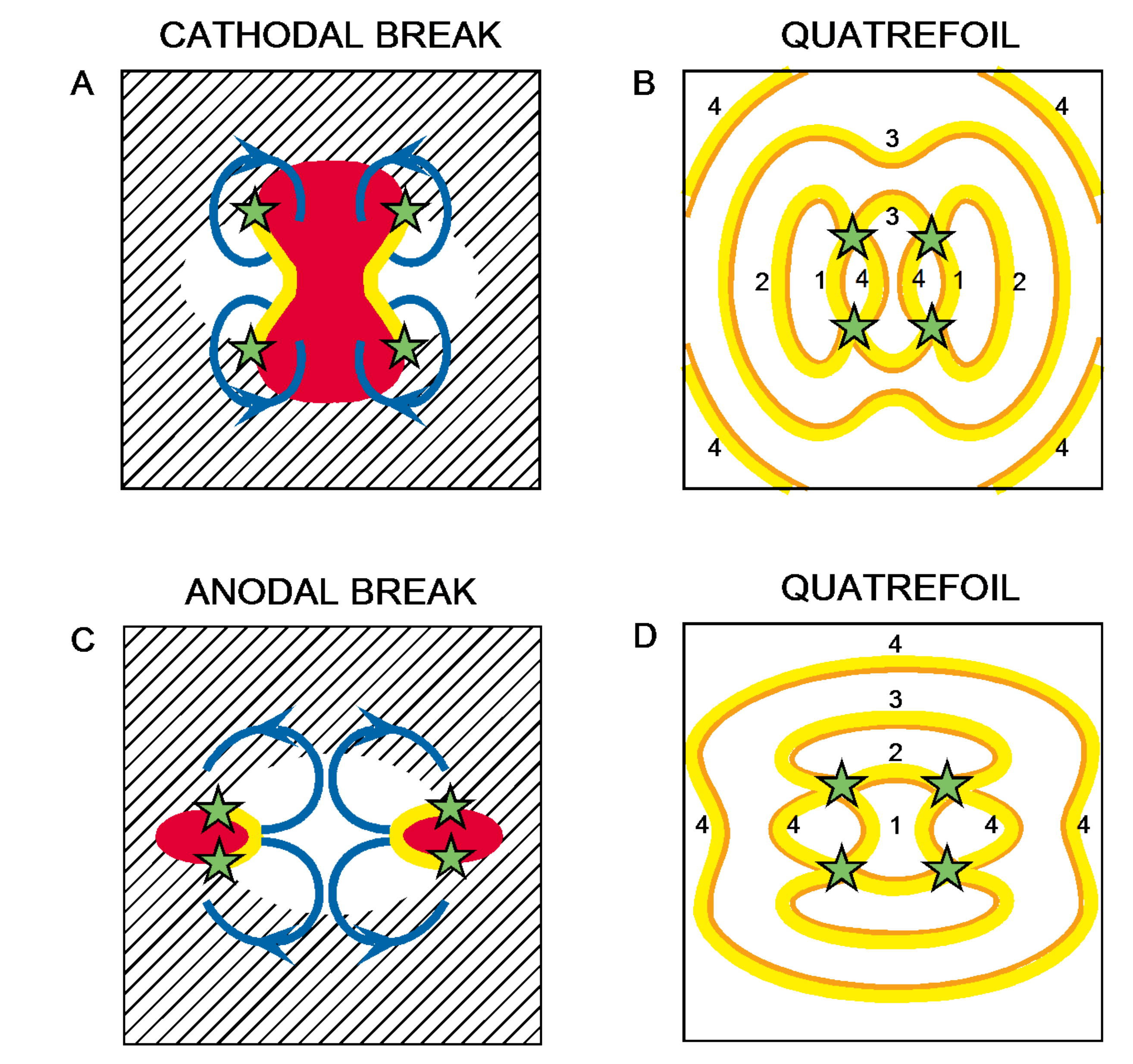
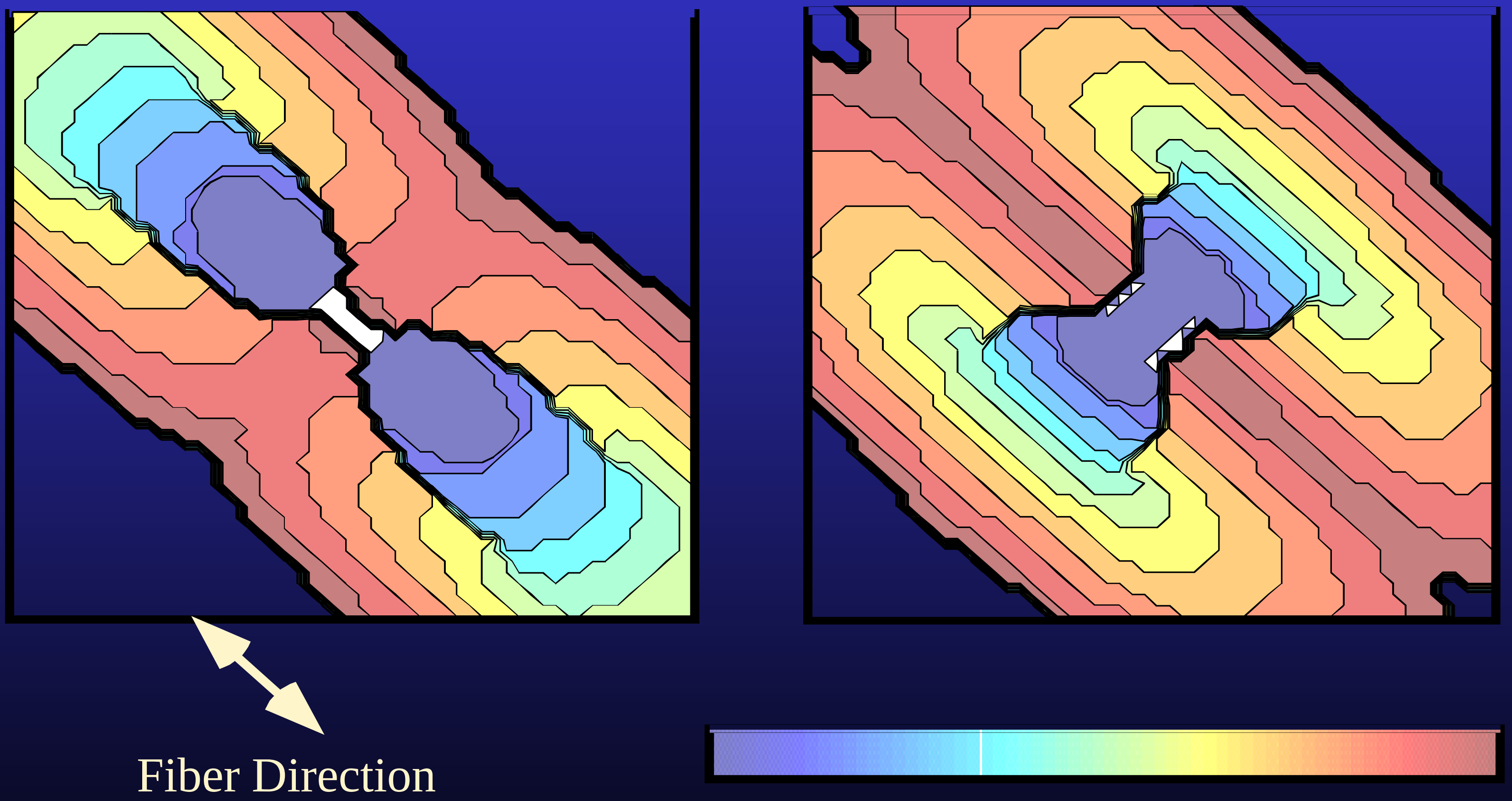
Spiral Wave and Figure-of-Eight Reentry



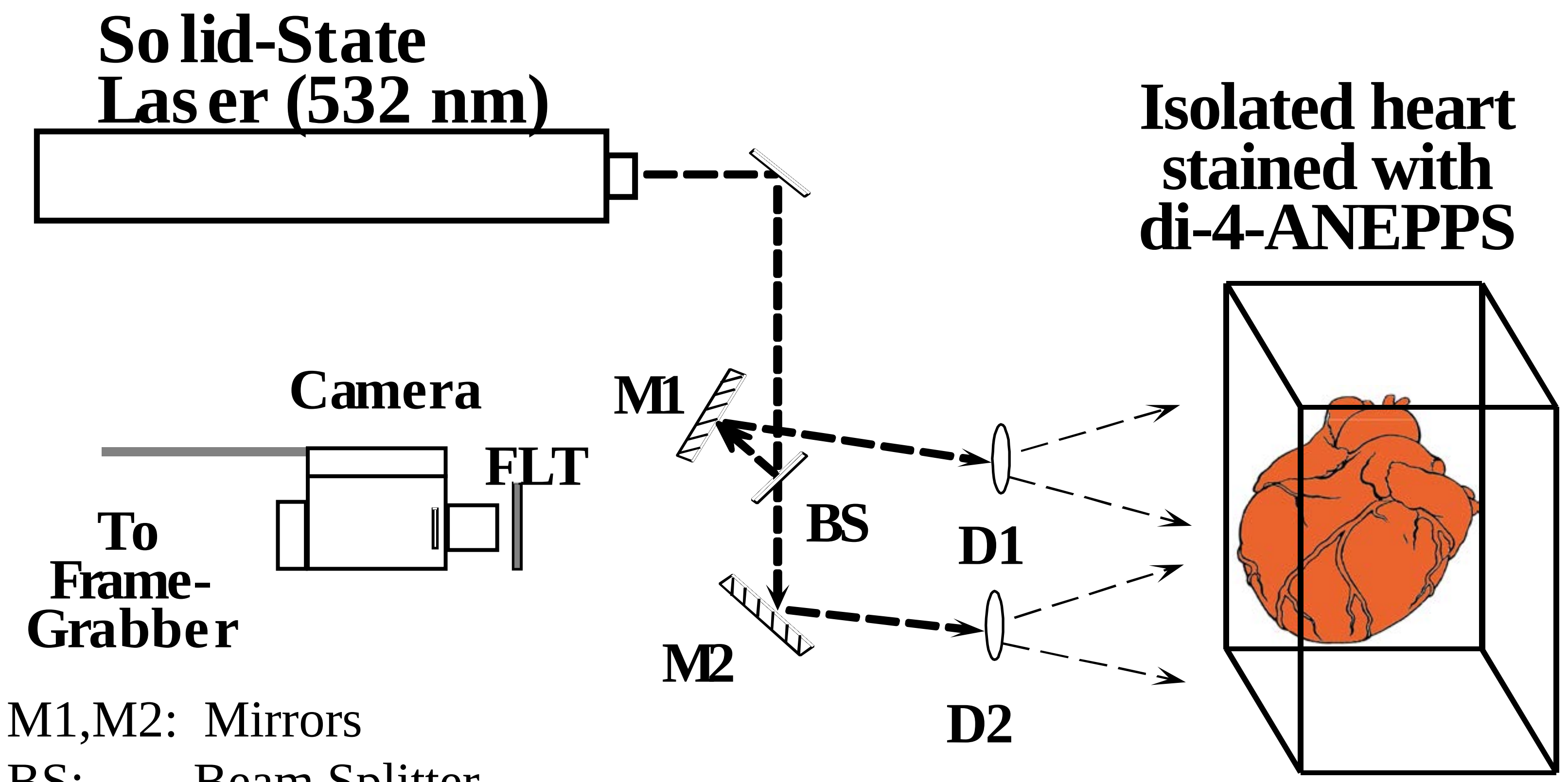
Initiation of Quatrefoil Reentry



Quatrefoil Reentry Predicted by the Bidomain Model



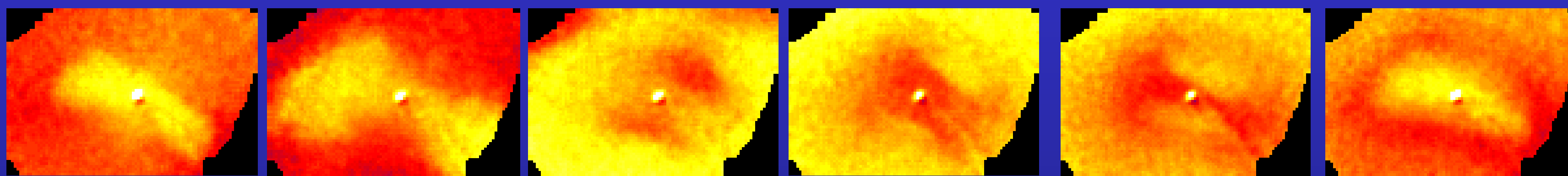
Experimental Setup



M1,M2: Mirrors
BS: Beam Splitter
D1, D2: Diffusers
FLT: Long-Pass Filter (590 nm)

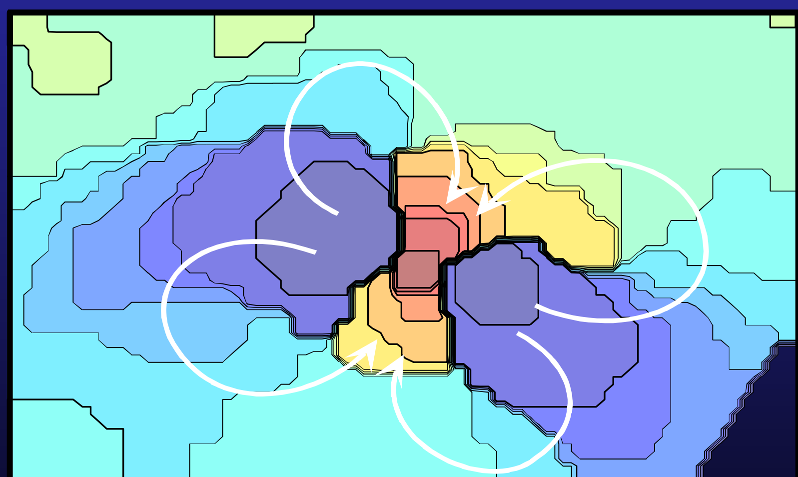
Optical Imaging of Quatrefoil Reentry

Selected frames of cathodal-break movie

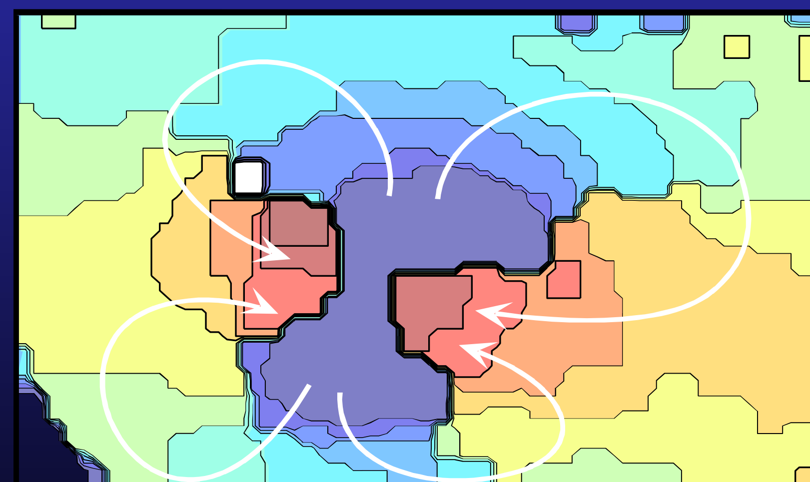


22 45 68 90 113 135

Cathodal-Break Isochrones



Anodal-Break Isochrones



The Challenge

The experimental and theoretical challenge offered by studies of cardiac fibrillation arises from the fact that cardiac electrical activity fully spans both the temporal and spatial scales: a factor of 10^9 in time and 10^{24} in volume.