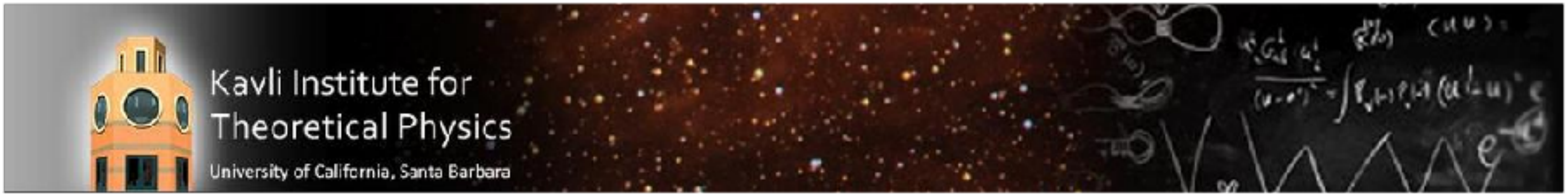
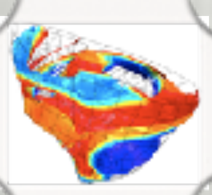


CARDIAC ELECTRO-MECHANICS & MEF:
THE STRESS-ASSISTED DIFFUSION 'SAD' APPROACH

ALESSIO GIZZI
UNIVERSITY CAMPUS BIO-MEDICO OF ROME



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ACKNOWLEDGMENTS

ALESSANDRO LOPPINI
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RICARDO RUIZ-BAIER
UNIVERSITY OF OXFORD

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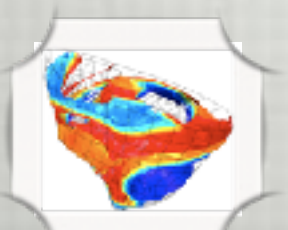
EMILIA ENTCHEVA

FLAVIO H. FENTON

DAISUKE SATO

YOHANNES SHIFERAW



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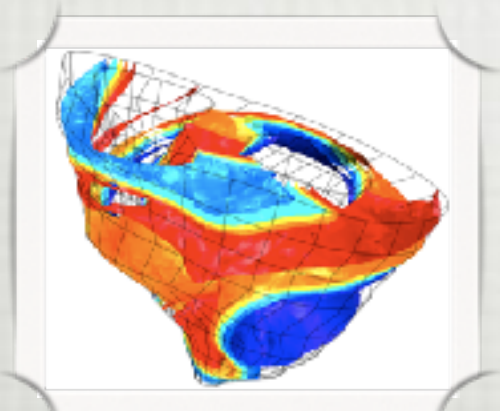

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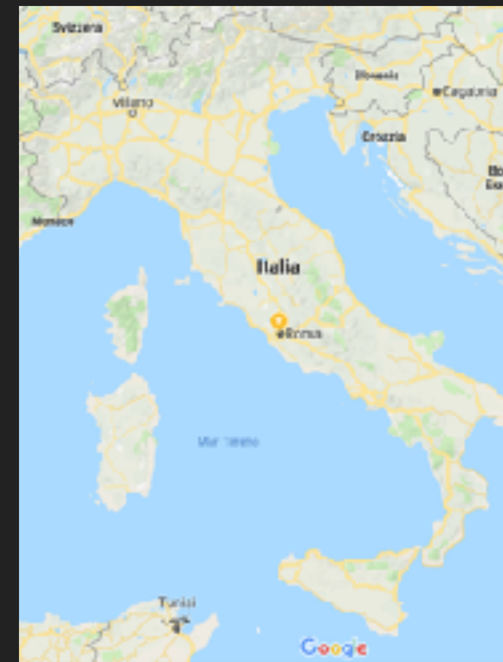

SIMONETTA FILIPPI (HEAD)
CHRISTIAN CHERUBINI (ASSOCIATE PROF.)
LETIZIA CHIODO (ASSISTANT PROF.)
ALESSIO GIZZI (ASSISTANT PROF.)
ALESSANDRO LOPPINI (ASSISTANT PROF.)
MARTINA NICOLETTI (PHD)

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NONLINEAR PHYSICS & MATHEMATICAL MODELING LAB

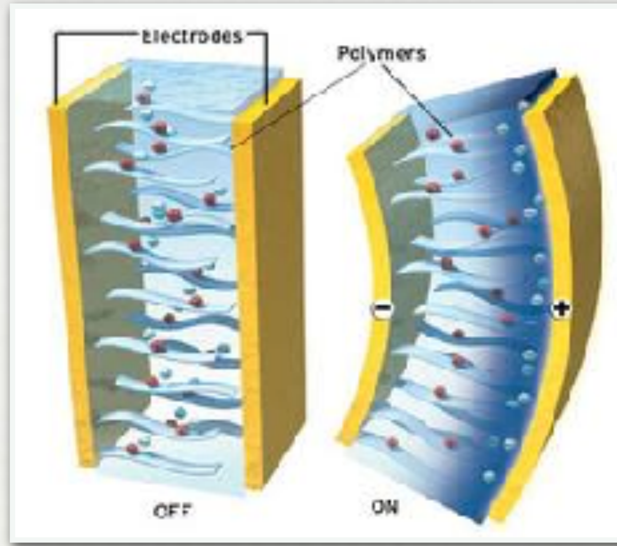
CAMPUS BIO-MEDICO UNIVERSITY OF ROME

INTERNATIONAL CENTER FOR RELATIVISTIC ASTROPHYSICS NETWORK

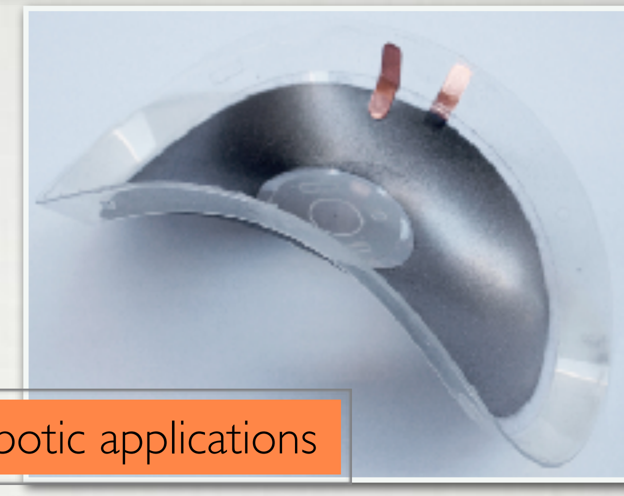
ACTIVE DEFORMABLE MEDIA

- ELECTRO-ACTIVE POLIMERS (EAP)

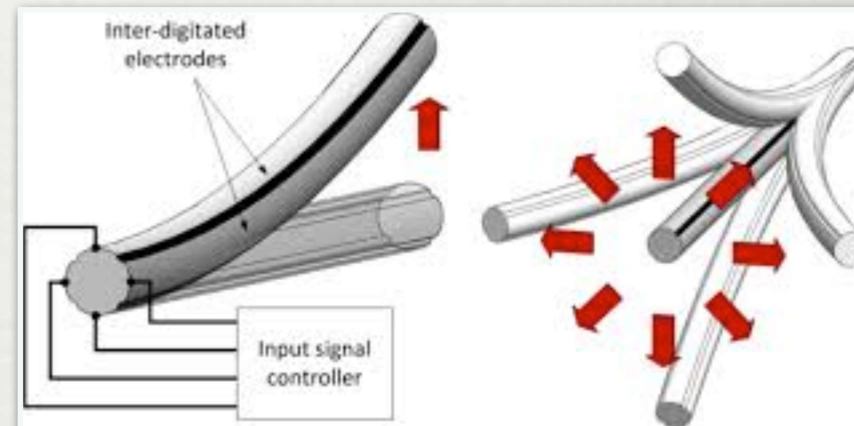
Ion exchange resins



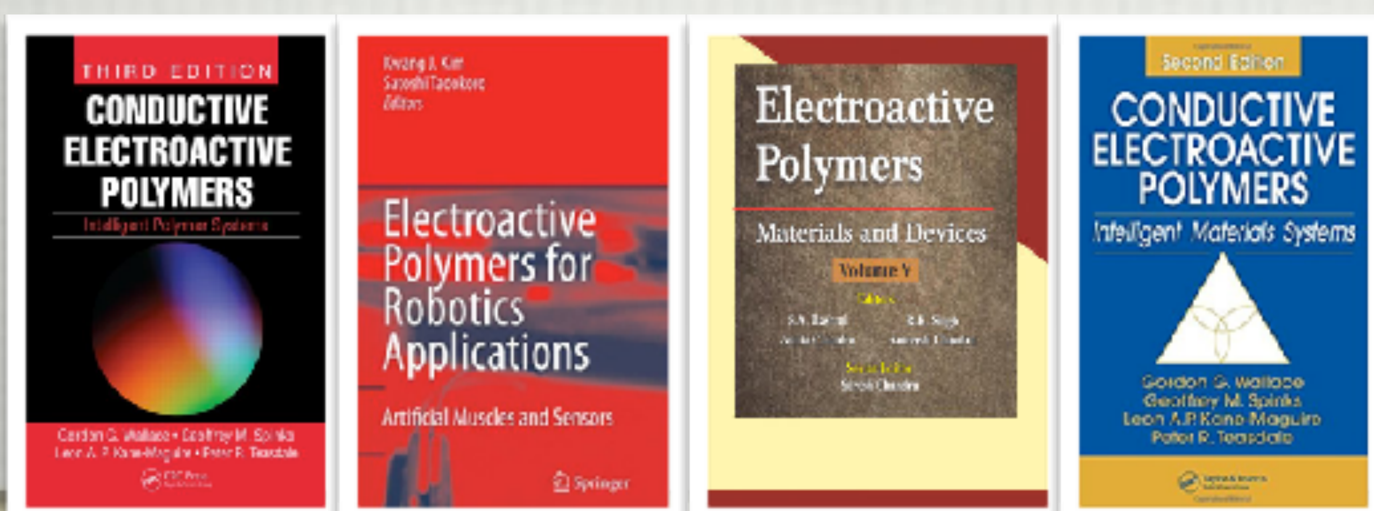
Multiple materials

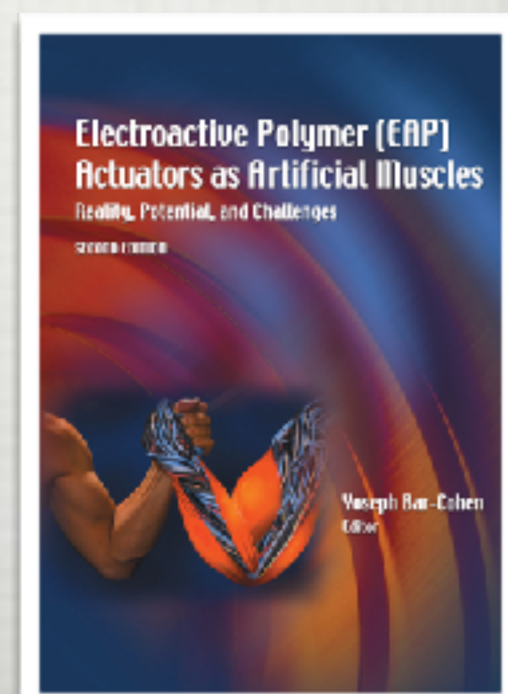


Robotic applications



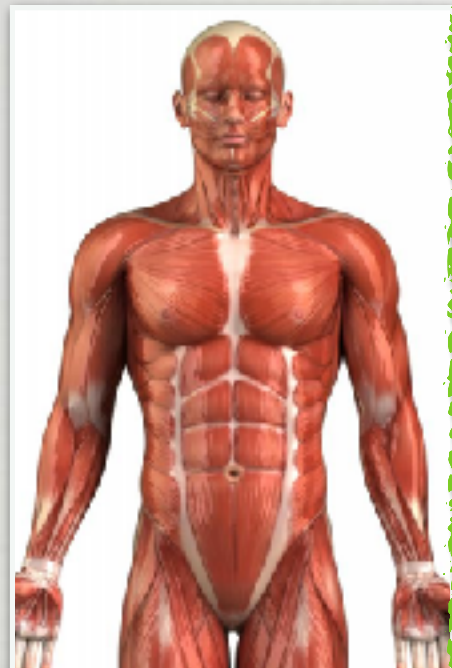
- ELECTRO-ACTIVE POLYMER (EAP) ARE BASED ON **ION-EXCHANGE PROPERTIES** OF RESINS
- EAP ARE USED IN SEVERAL **CHEMICAL & ROBOTIC APPLICATIONS - ARTIFICIAL MUSCLES**



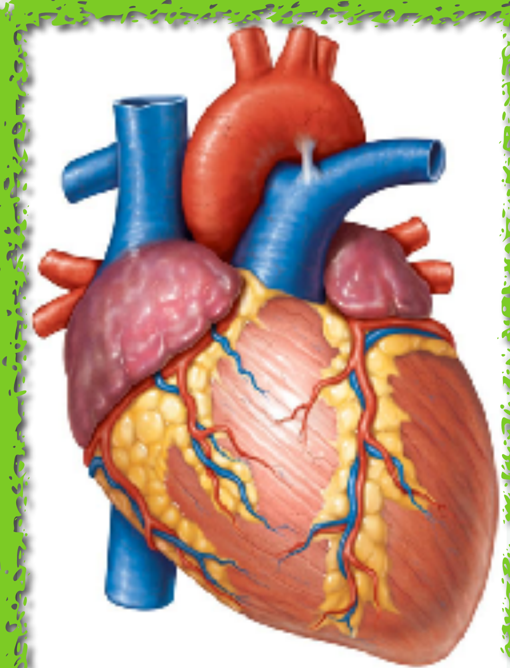


ACTIVE DEFORMABLE MEDIA

- **BIOLOGICAL TISSUES**



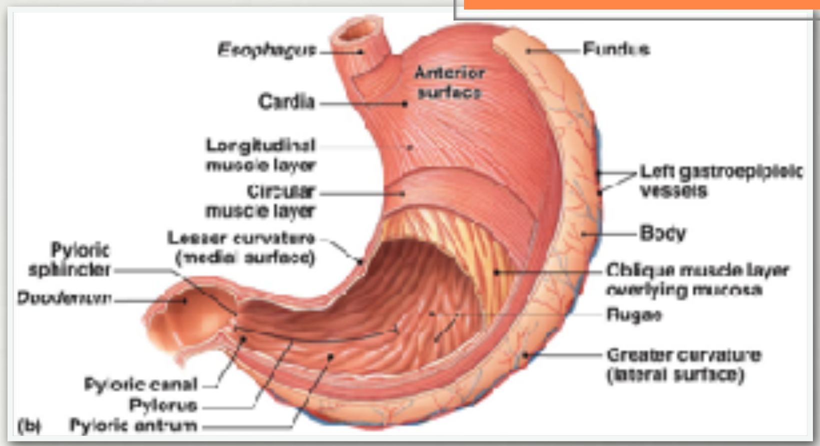
Skeletal Muscles



Heart

Intestines

Stomach



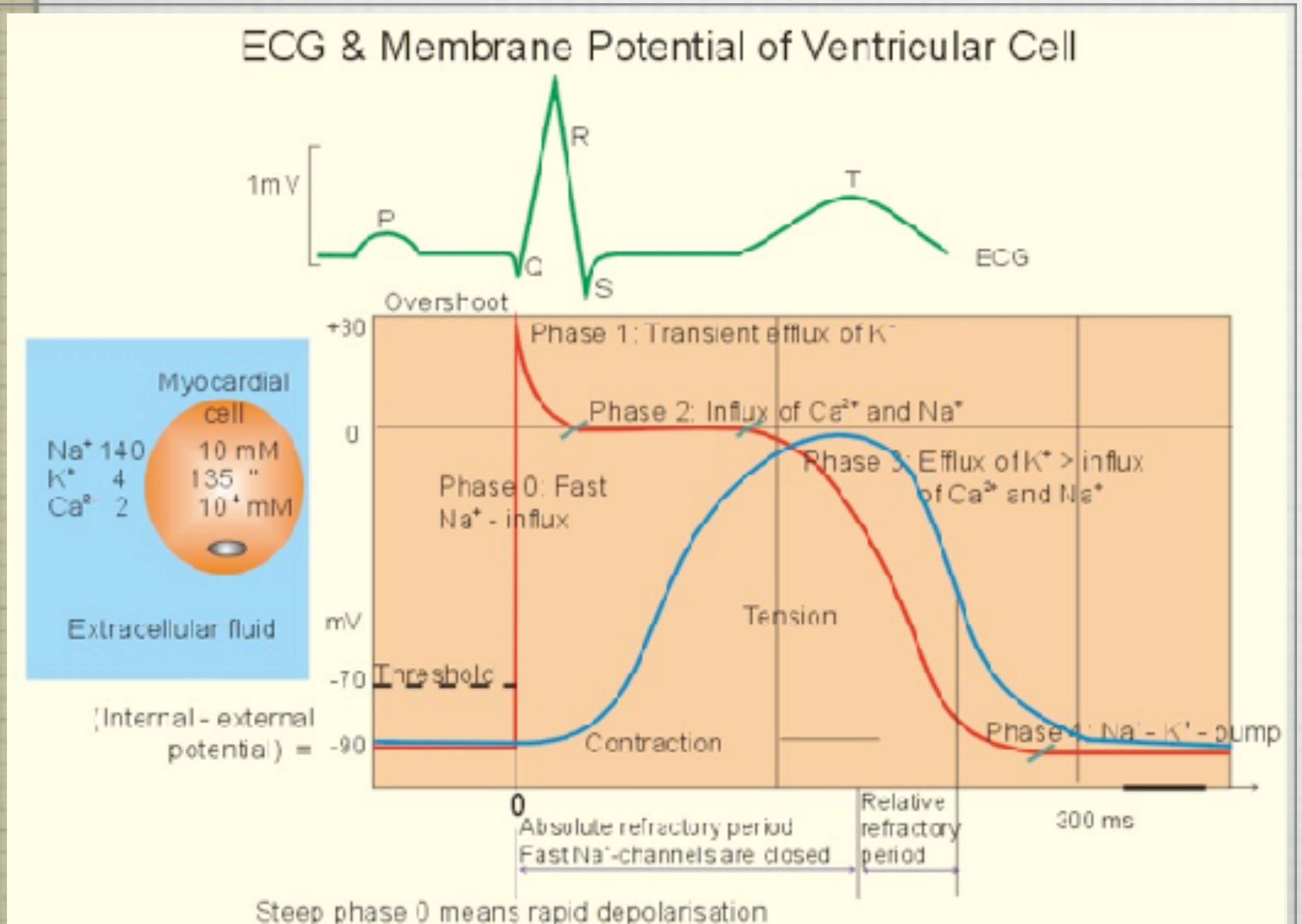
Eye's Iris

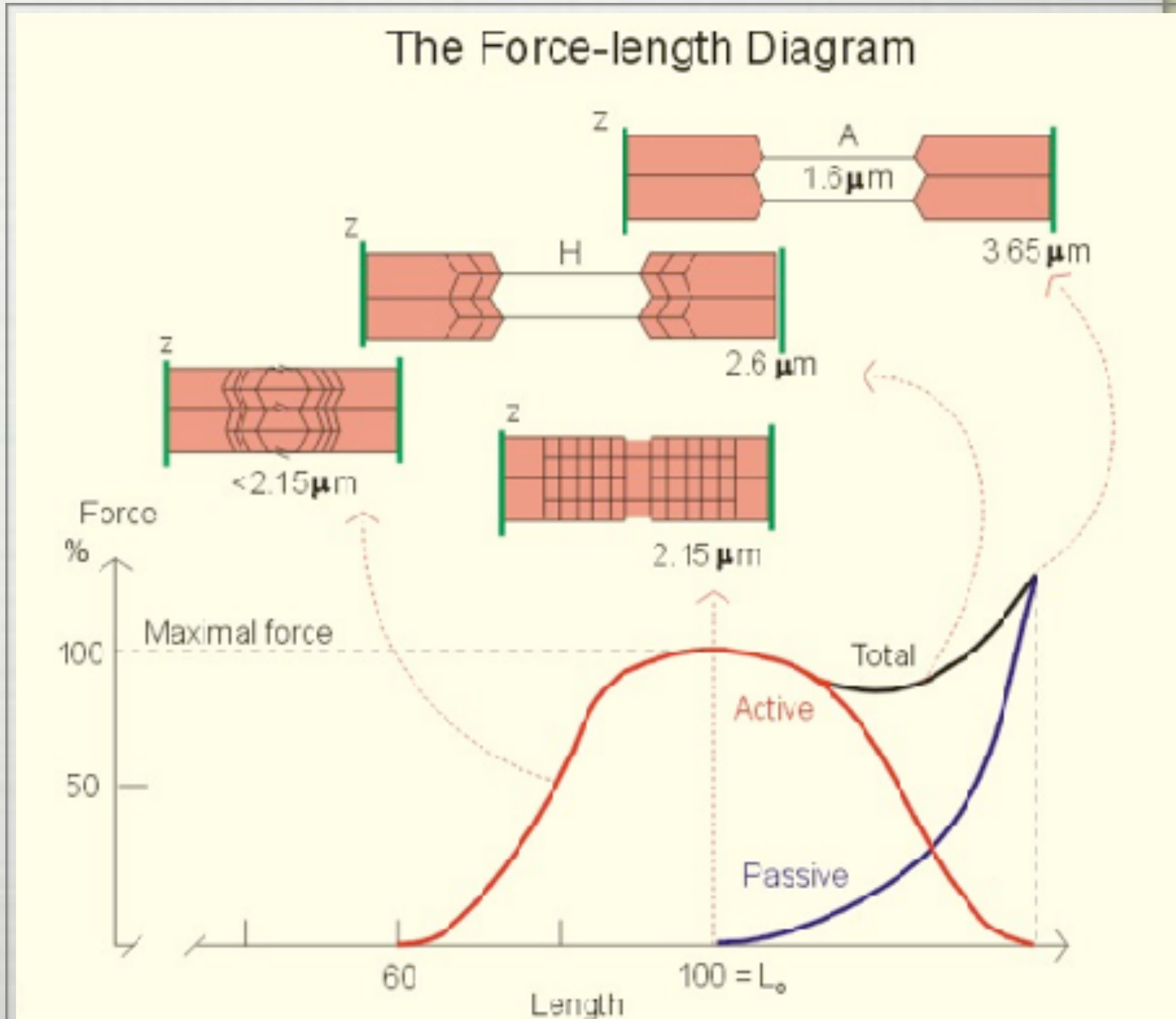
- BIOLOGICAL ACTIVE TISSUES: HEART, SKELETAL MUSCLE, GASTRO-INTESTINE, EYE'S IRIS…
- SHOW THE ABILITY TO DEVELOP **CONTRACTIONS**, PRODUCING THE MECHANICAL FORCES NECESSARY TO THE ORGAN'S FUNCTION.
- CONTRACTIONS ORIGINATED BY AN **ELECTRIC POTENTIAL** DUE TO TRANSMEMBRANE (K^-, NA^-) AND INTRACELLULAR **IONS** (CA^{++})

EXCITATION-CONTRACTION

Biophysical Motivation

- **MACROSCOPIC** CORRELATION BETWEEN:
  - THE 5 ECG PHASES
  - THE TRANSMEMBRANE POTENTIAL
  - THE CONTRACTION WAVE FOR A MUSCULAR FIBER (CALCIUM)
- **MICROSCOPIC** RELATION BETWEEN: **ACTIVE - PASSIVE CONTRIBUTIONS**

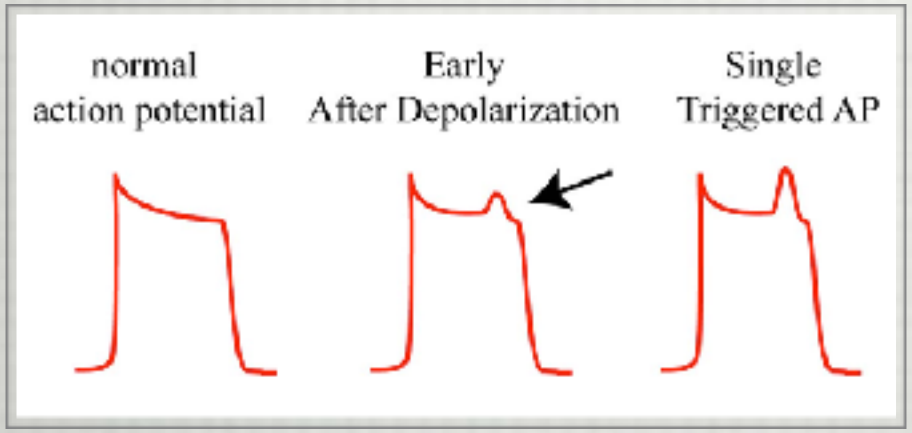


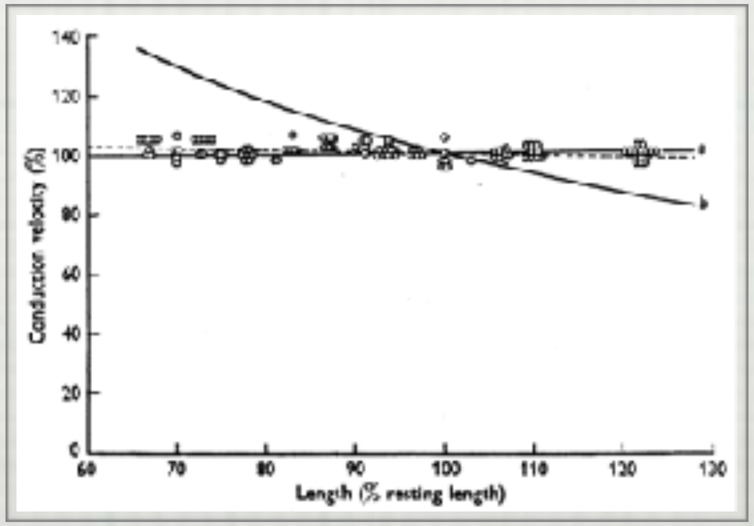


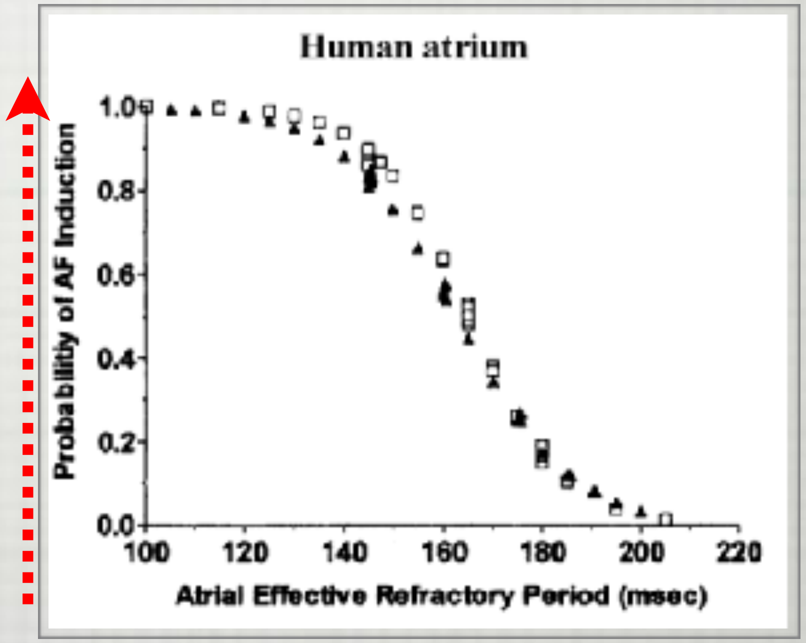
ATRIAL MEF

Biophysical Motivation

- ROLE OF **MECHANO-ELECTRIC FEEDBACK (MEF)** IN **ARRHYTHMOGENESIS**
- **STRETCH** CONTRIBUTES TO:
  - 1) FOCAL ARRHYTHMIAS BY INDUCING **EARLY AFTER-DEPOLARIZATIONS**
  - 2) REENTRANT ARRHYTHMIAS BY
    - SHORTENING THE **CONDUCTION VELOCITY**
    - SHORTENING **REFRACTORY PERIOD** INCREASING **SPATIAL DISPERSION**



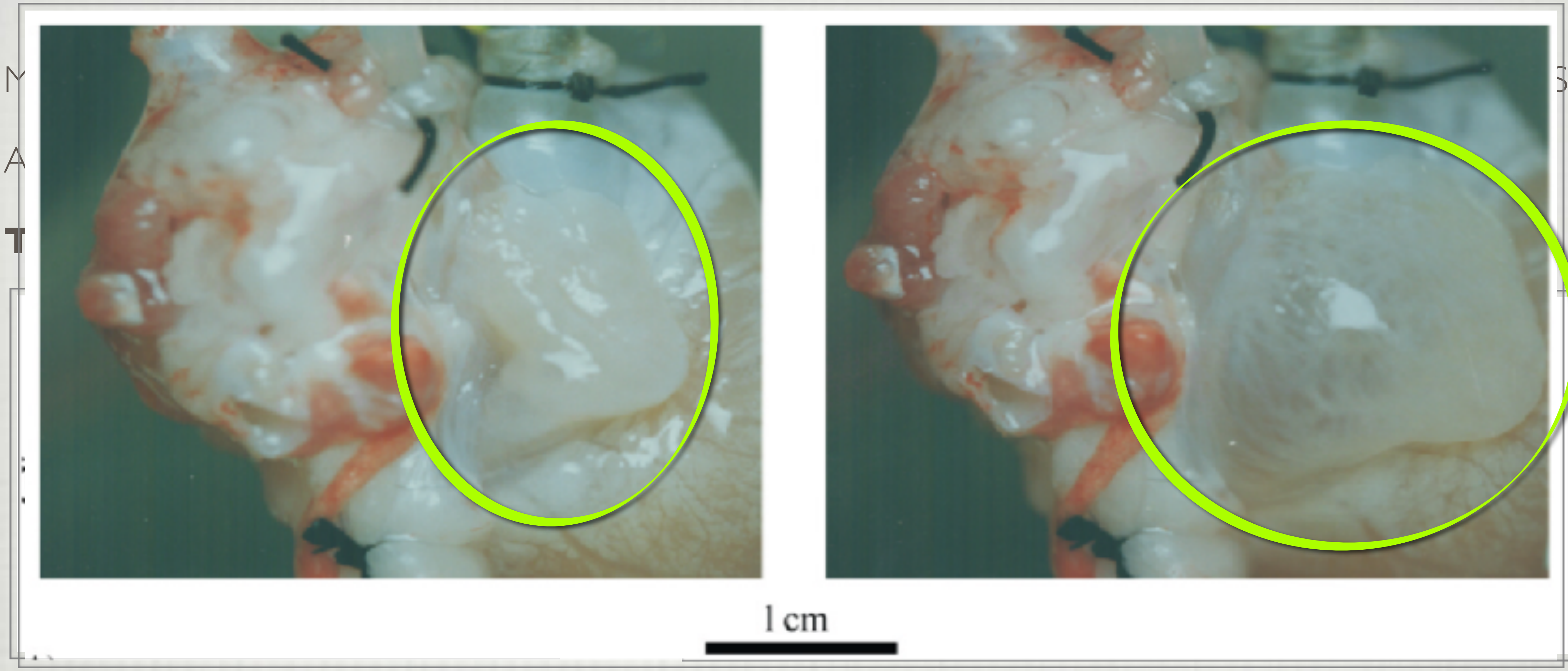


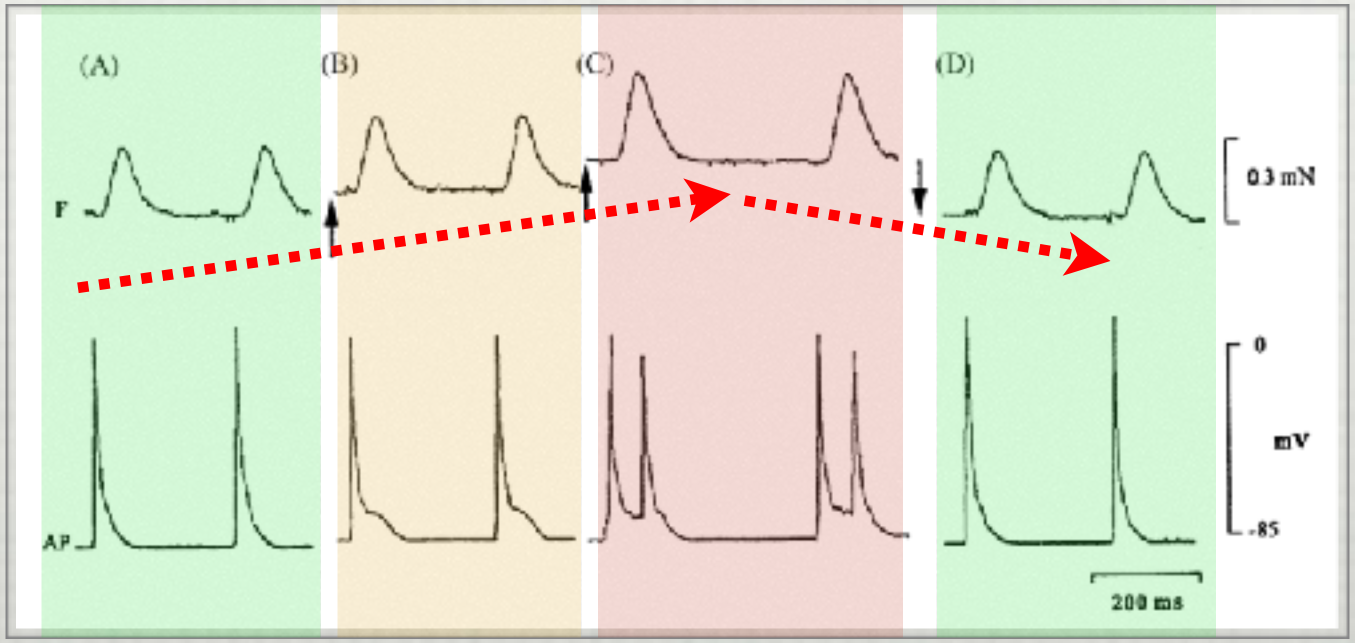


RAVELLI 2003

ATRIAL MEF

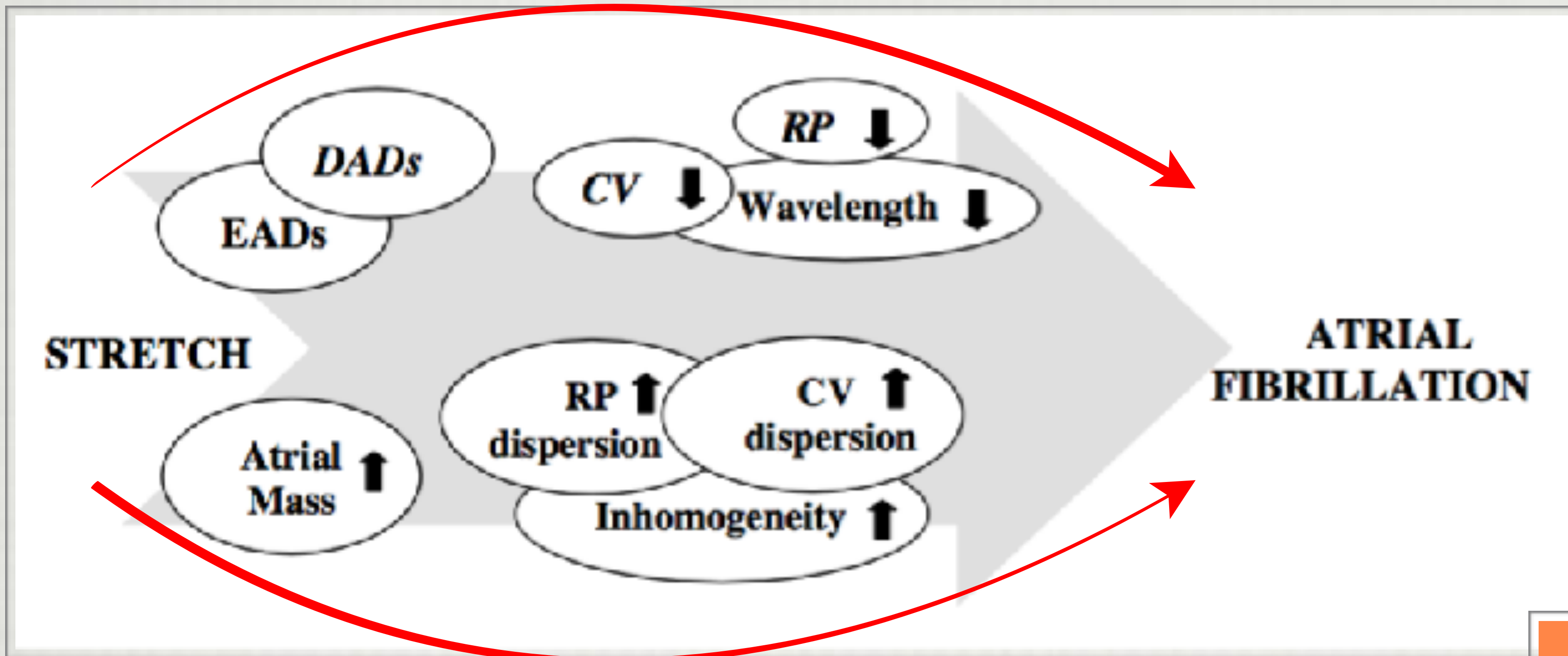
Biophysical Motivation





RAVELLI 2003

ATRIAL MEF



Complex Problem

Summary of the effects of acute stretch on atrial refractoriness in in vivo studies

Dilatation models	Species	ΔP (mmHg)	Atrial RP	Atrial RP dispersion	References
Simultaneous AV pacing	Dog	5	↑	—	Kaseda and Zipes (1988)
	Human	3.5	↑	—	Klein et al. (1990)
	Human	4	↑	↑	Chen et al. (1999)
	Human	4	↔	—	Calkins et al. (1992b)
	Human	8(peak)	↓	—	Calkins et al. (1992a)
	Human	7.4	↓	↑	Tse et al. (2001)
SVT	Human	2.7	↑	—	Klein et al. (1990)
	Human	4.5	↑	↑	Chen et al. (1998)
Volume overload	Dog	⩾4	↑	—	Sideris et al. (1994)
	Dog	1.2	↑	↑	Satoh and Zipes (1996)
	Goat	4.5	↔	—	Wijffels et al. (1997)
Balloon inflation	Dog	8	↓	—	Solti et al. (1989)

SVT is supraventricular tachycardia, ΔP the average change in mean atrial pressure, RP refractory period. The parameter measured increased (↑), decreased (↓), or did not change (↔).

RAVELLI 2003

ACTIVE ELECTRO-MECHANICS (EM)

- **ELECTRO-ACTIVE SYSTEMS'** CHARACTERS:
  - DEFORMATIONS MAY INDUCE A **CHANGE** OF THE EVENTUAL **INITIAL ISOTROPY** OF A BODY
  - AN **INTERMEDIATE NON COMPATIBLE CONFIGURATION** IS USUALLY ACCOUNTED FOR (MULTIPLICATIVE DECOMPOSITION)
  - GENERALIZED CONSTITUTIVE EQUATIONS USUALLY IMPLY MULTIPLE PHYSICAL COUPLINGS (VISCOSITY, DAMAGE, GROWTH, TEMPERATURE)

- **ELECTRO-ACTIVE BIOLOGICAL SYSTEMS'** CHARACTERS:
  - THE **INTERNAL ACTIN-MYOSIN BINDING** (EXCITATION-CONTRACTION - MEF) CAN BE CONSIDERED AS A **MICRO-STRUCTURAL ALTERATION OF THE INTERNAL KINEMATIC STATE** OF THE MUSCLE FIBRE, WHICH LEADS TO CHANGES IN THE MACROSCOPIC BEHAVIOR

GIZZI ET AL. 2015
YANG ET AL. 2006

ACTIVE ELECTRO-MECHANICS (EM)

- **ACTIVE STRESS** *(NASH & PANFILOV 2004)*
  - MOST USED APPROACH IN CARDIAC ELECTRO-MECHANICS

Proof of Concept

- **ACTIVE STRAIN** *(CHERUBINI ET AL. 2008, AMBROSI ET AL. 2011, RUIZ-BAIER ET AL. 2012)*
  - REPRESENTS AN EIGENDEFORMATION APPROACH WELL ESTABLISHED FOR REALISTIC CARDIAC ELECTRO-MECHANICAL APPLICATIONS
  - **MULTIPLICATIVE DECOMPOSITION** OF THE DEFORMATION GRADIENT TENSOR
- **THERMODYNAMIC APPROACH** *(GIZZI ET AL. 2015)*
  - **RELATES** THE CONCEPTS OF **ACTIVE DEFORMATION** & **ACTIVE STRESS** THROUGH THERMODYNAMICAL ARGUMENTS
  - **ADDITIVE DECOMPOSITION OF THE STRAIN ENERGY**
  - **MAXWELL ELECTRO-STATICS**

LIMITATION

The active stress model does not derive from thermodynamical arguments

Active Stress Approach

$$\mathbf{P} = \mathbf{P}^p + \mathbf{P}^a$$

Passive Stress | Active Stress

ADVANTAGES

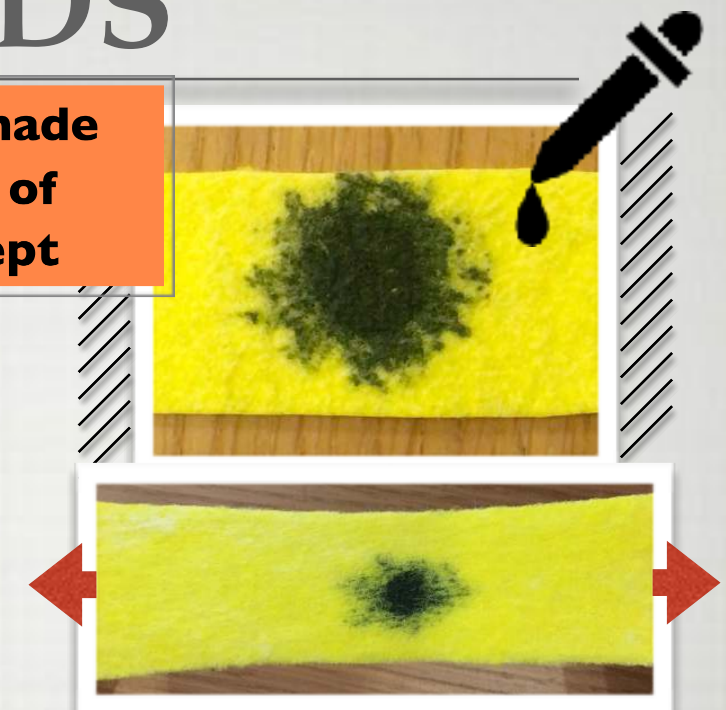
Easy to implement in numerical codes for a proof of concept theoretical study

DIFFUSION IN SOLIDS

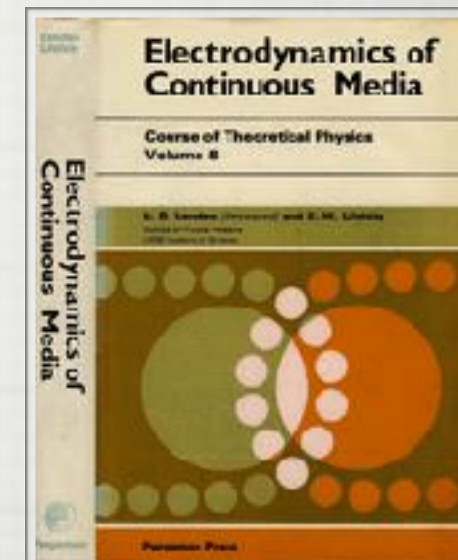
- **INFINITESIMAL ELECTRO-DYNAMICS**
- RATIONALIZE **DIFFUSION IN SOLIDS** BASED ON <u>CONSERVATION OF MOMENTUM</u> FOR THE DIFFUSING SPECIES
- THE BALANCE EQUATION CONTAINS:
  - **STRESS SUPPORTED BY THE DIFFUSING SPECIES**
  - **DIFFUSIVE FORCE** VECTOR FOR THE EXCHANGE OF MOMENTUM BETWEEN THE DIFFUSING SPECIES AND THE SOLID MATRIX
- **INTERDIFFUSING MATERIALS** ARE ACCOUNTED FOR BY THE CONSTITUTIVE PRESCRIPTIONS (APPLIED TO <u>METALLURGY</u>, <u>POLYMER PHYSICS</u>, <u>GEOPHYSICS</u>)

☆ THESE TWO QUANTITIES ARE **NOT** IDENTIFIED IN THE **CLASSICAL DIFFUSION** INTERPRETATION

Homemade Proof of Concept



LANDAU, LIFSHITZ



COTTRELL, FLYNN

JOURNAL OF POLYMER SCIENCE: Polymer Physics Edition VOL. 11 (1973)

On the Stress-Dependent Diffusion Equation

Acta Mechanica 37, 265—290 (1980) ACTA MECHANICA © by Springer-Verlag 1980

On the Problem of Diffusion in Solids

By

E. C. Aifantis, Urbana, Illinois

Acta Mechanica 45, 273—296 (1982) ACTA MECHANICA © by Springer-Verlag 1982

On the Theory of Stress-Assisted Diffusion, I

By

R. K. Wilson and E. C. Aifantis, Urbana, Illinois

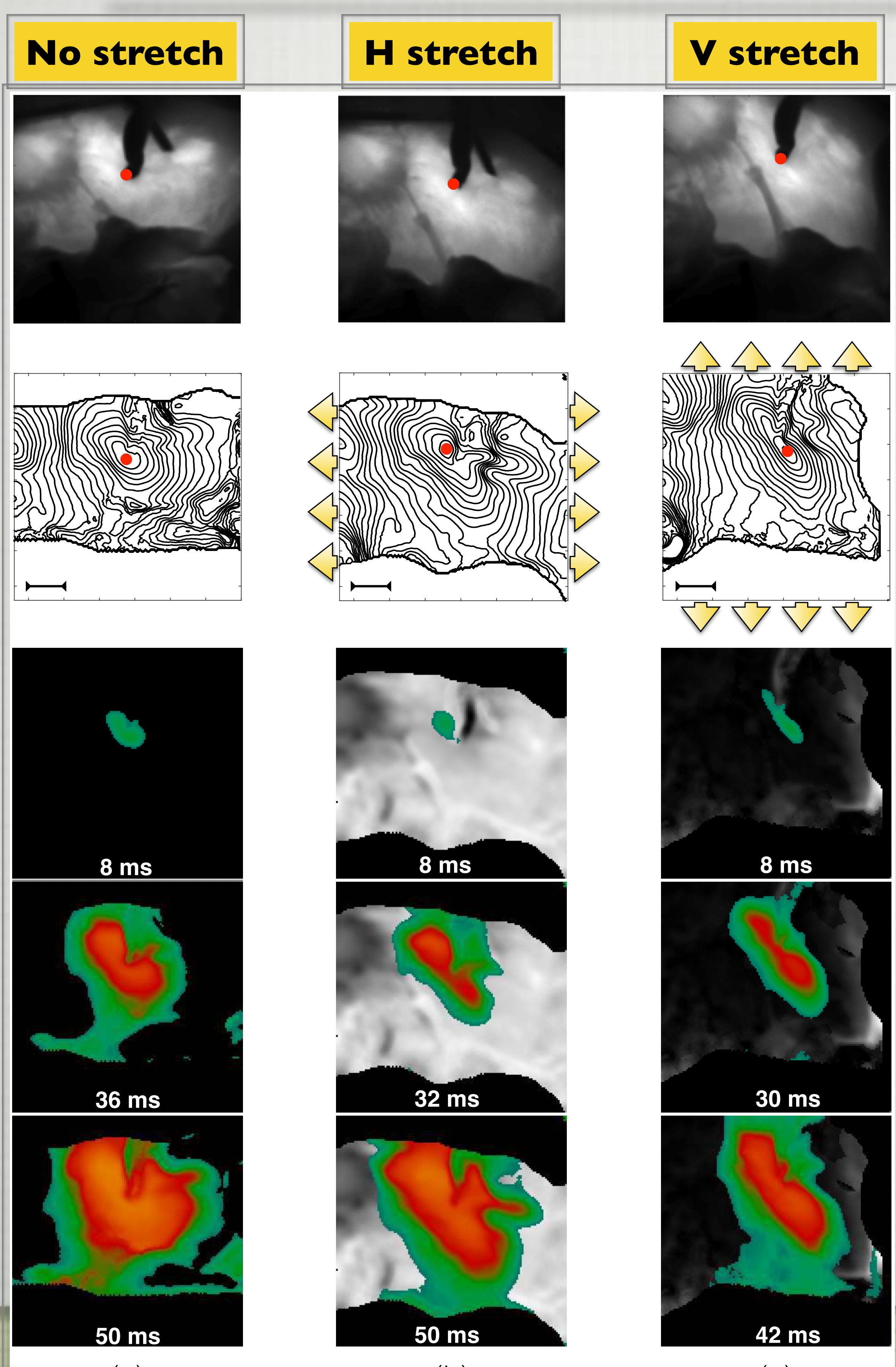
Acta Mechanica 47, 117—151 (1983) ACTA MECHANICA © by Springer-Verlag 1983

On the Theory of Stress-Assisted Diffusion, II

By

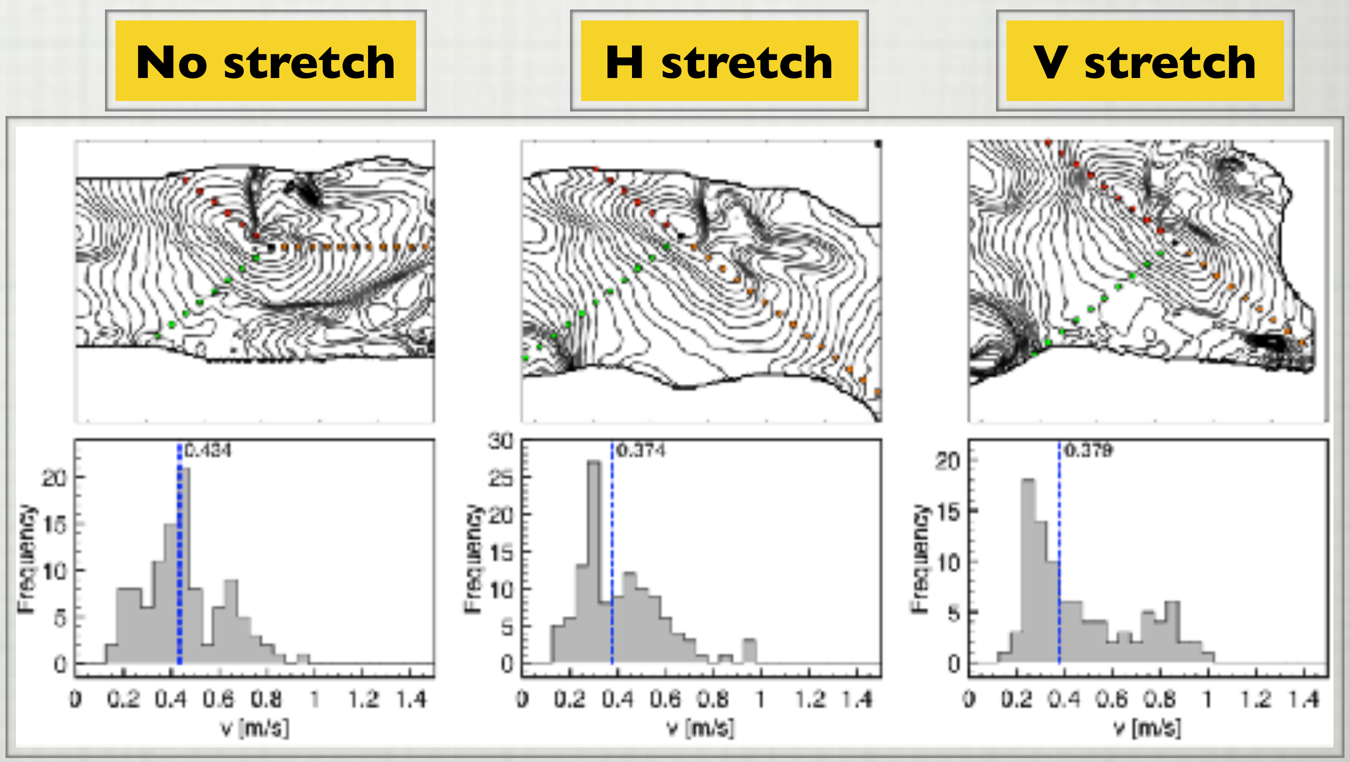
D. J. Unger and E. C. Aifantis, Minneapolis, Minnesota

STRETCHED VENTRICLES



Pig Right Ventricle Proof of Concept

Enhanced Anisotropy



Reduced CV

STRESS-ASSISTED DIFFUSION ‘SAD’

- THE **BASIC PHENOMENOLOGY** IS THE SAME EITHER IF “MICROPOROSITY” OR “MACROPOROSITY” IS INVOLVED.
- DIFFUSION OF A **DILUTE SOLUTE IN A SOLID MATRIX**.
- GENERALIZE THE THEORETICAL WORK OF **FICK** (*A PHENOMENOLOGICAL DESCRIPTION OF DIFFUSION THAT PRECEDES ANY EXPERIMENTAL WORK*) WHICH IS **CURRENTLY APPLIED** IN ANY ELECTROPHYSIOLOGICAL MODELING (CABLE EQUATION).
- THE THEORY OF **CONTINUOUSLY DISTRIBUTED MATTER** (*EULER’S AXIOMS*) LEADS TO THE **BALANCE OF MOMENTUM**.
- **CONSTITUTIVE EQUATIONS** WILL DIFFERENTIATE BETWEEN:
  - **DIFFUSION IN STRESSED SOLIDS**
  - **DIFFUSION OF VISCOUS SOLUTE**
  - **DIFFUSION IN ELASTIC & INELASTIC MATERIALS**
- FRAMED WITHIN THE **THEORY OF MIXTURES**: *ATKIN & CRAINE, BOWEN, TRUSDELL, MAXWELL’S GASES THEORY*

Voltage Membrane as “continuum”

Slow diffusion

Matrix macroscopically rigid

Macroscopic response independent on the diffusion process

Diffusion process strongly dependent on the mechanical state

‘SAD’ THEORETICAL DERIVATION

Local form of Mass and Momentum balances

Universal restrictions to ALL diffusion processes

Density (mass of diffusing substance)

Velocity (average mobility)

Mass supply (rate of mass creation)

$$\rho_t + \mathrm{div}(\rho \mathbf{v}) = q$$

$$\mathrm{div}\,\mathbf{T} + \mathbf{b} + \mathbf{p} = \rho[\mathbf{v}_t + (\mathrm{grad}\mathbf{v})\mathbf{v}]$$

Stress of the diffusing substance on itself (Symmetric - no body couples)

External body forces (gravity)

Diffusive forse (volume-distributed force exerted by the solid on the diffusing species)

Acceleration (material time derivative of the velocity)

‘SAD’ THEORETICAL DERIVATION

Hp.1 Diffusive species do not support shear stress

Hp.2 Only the hydrostatic component of the stress affects the stress of the diffusing species

$$\rho_t + \mathrm{div}(\rho \mathbf{v}) = r$$

$$\mathrm{div}\,\mathbf{T} + \mathbf{b} + \mathbf{p} = \rho[\mathbf{v}_t + (\mathrm{grad}\mathbf{v})\mathbf{v}]$$

$$\rho_t + \mathrm{div}(\mathbf{j}) = 0$$

$$\mathrm{div}\,\mathbf{T} + \mathbf{p} = 0$$

Representation theorems for non-linear isotropic or anisotropic vector and tensor functions (Spencer)

Nonlinear Stress (S) in the solid

$$\mathbf{\Gamma}_i = \gamma_{i1}(\rho, J_1, J_2, J_3)\mathbf{I} + \gamma_{i2}(\rho, J_1, J_2, J_3)\mathbf{S} + \gamma_{i3}(\rho, J_1, J_2, J_3)\mathbf{S}^2$$

J_1, J_2, J_3 The principal invariants of the stress tensor S in the solid (frame indifferent)

$$\mathbf{j} = -(\alpha_0\mathbf{I} + \alpha_1\mathbf{S} + \alpha_2\mathbf{S}^2)\mathrm{grad}\rho + (\alpha_0^*\mathbf{I} + \alpha_1^*\mathbf{S} + \alpha_2^*\mathbf{S}^2)\mathrm{grad}(\mathrm{tr}\,\mathbf{S})$$

Hp.3 Incompressibility

$$\mathbf{B} = \mathbf{F}\mathbf{F}^T$$ Strain measure

$$\mathbf{j} = -(\alpha_0\mathbf{I} + \alpha_1\mathbf{S} + \alpha_2\mathbf{S}^2)\mathrm{grad}\rho \iff \mathbf{j} = -(\beta_0\mathbf{I} + \beta_1\mathbf{B} + \beta_{-1}\mathbf{B}^{-1})\mathrm{grad}\rho$$

Named in the Literature: “Stress-Assisted Diffusion Equation”

EM-SAD: A MINIMAL MODEL

Classical cubic "Bistable" function

2v Reaction-Diffusion (RD) Model *(Nash & Panfilov 2004)*

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial x_i} d_{ij}(\sigma_{ij}) \frac{\partial V}{\partial x_j} + I_{\text{ion}}(V, r)$$

$$\frac{dr}{dt} = f(V, r)$$

NO SAC

RD Constitutive Equations

$$I_{\text{ion}} = -kV(V-a)(V-1) - rV$$

$$f(V, r) = \left(\varepsilon + \frac{\mu_1 r}{\mu_2 + V} \right) (-r - kV(V - b - 1))$$

Nonlinear "Recovery" dynamics

Active Stress Formulation *(Nash & Panfilov 2004)*

$$\frac{\partial T_a}{\partial t} = \epsilon(V)(k_{T_a} V - T_a)$$

Equilibrium

$$\frac{\partial \sigma_{ij}}{\partial x_i} = 0 \qquad J = 1$$

$$\sigma_{ij} = \sigma_{ij}^{\text{passive}} + \sigma_{ij}^{\text{active}}$$

Representation Formula for 2nd Order Isotropic Tensors

Two additional Material Parameters

$$d_{ij}(\sigma_{ij}) = D_0 \left(\delta_{ij} + D_1 \sigma_{ij} + D_2 \sigma_{ik} \sigma_{kj} \right)$$

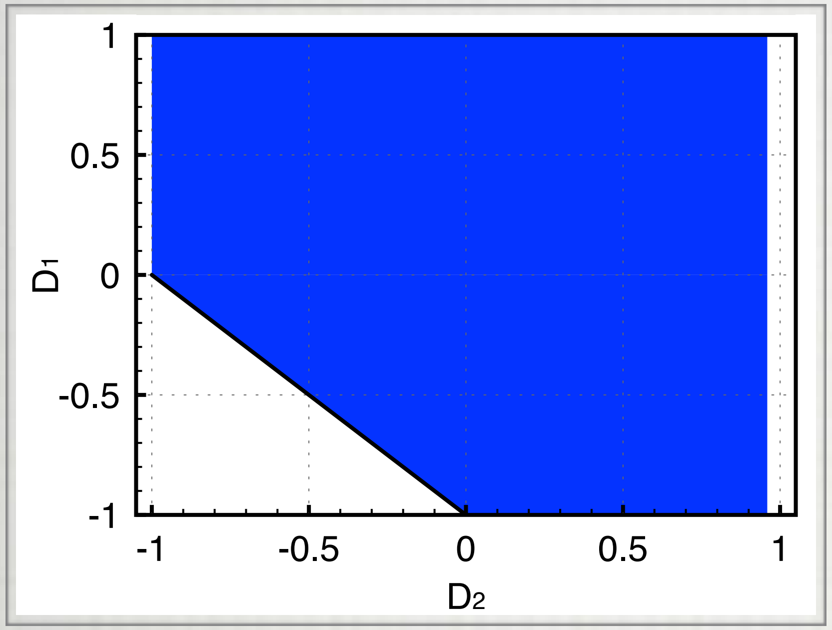
***Isotropic* Stress-Assisted Diffusion Model**

$$\sigma_{ij} = 2c_1 b_{ij} - 2c_2 b_{ij}^{-1} - p\delta_{ij} + T_a \delta_{ij}$$

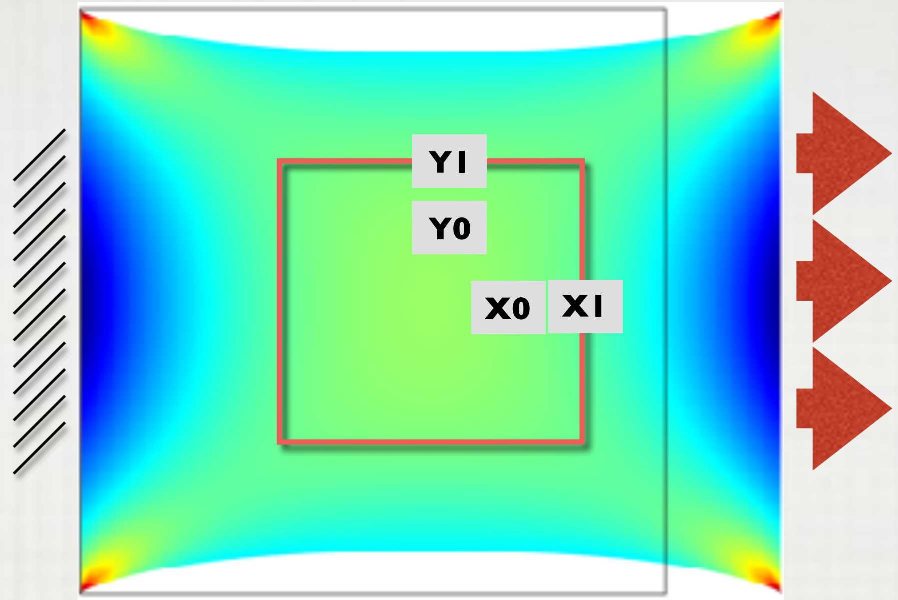
Passive Neo-Hookean material with ISOTROPIC diffusion & ACTIVE stress

EM-SAD: PARAMETER SPACE

Theoretical Normalized Case



$$\sigma_1 = 1 \;\; \text{or} \;\; \sigma_2 = 1$$



2D Static Uniaxial Tensile State

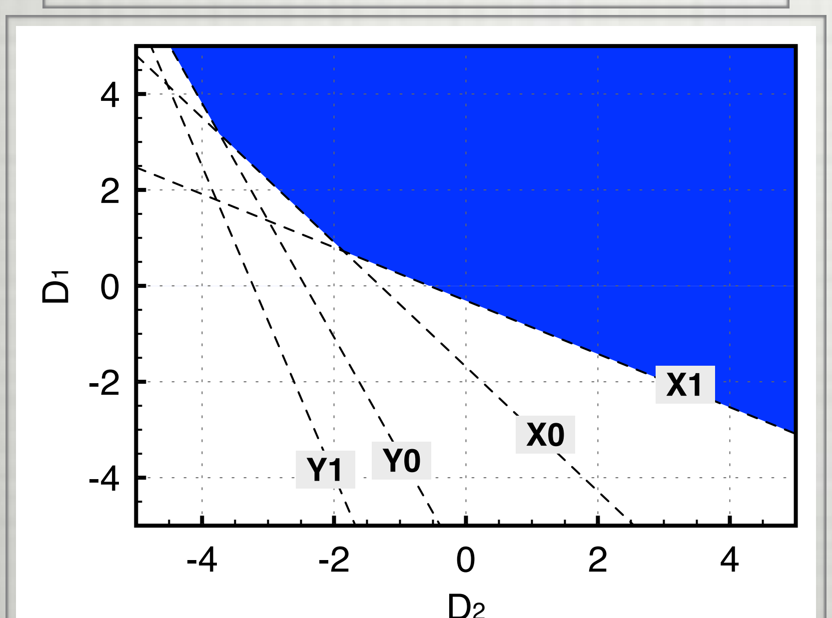
Log von Mises stress

$$[\sigma_{ij}] = \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix}$$

$$[\sigma_{ik}\sigma_{kj}] = \begin{bmatrix} \sigma_1^2 & 0 \\ 0 & \sigma_2^2 \end{bmatrix}$$

$$d_{ij}(\sigma_{ij}) = D_0 \left(\delta_{ij} + D_1 \sigma_{ij} + D_2 \sigma_{ik} \sigma_{kj} \right)$$

Computed Stress



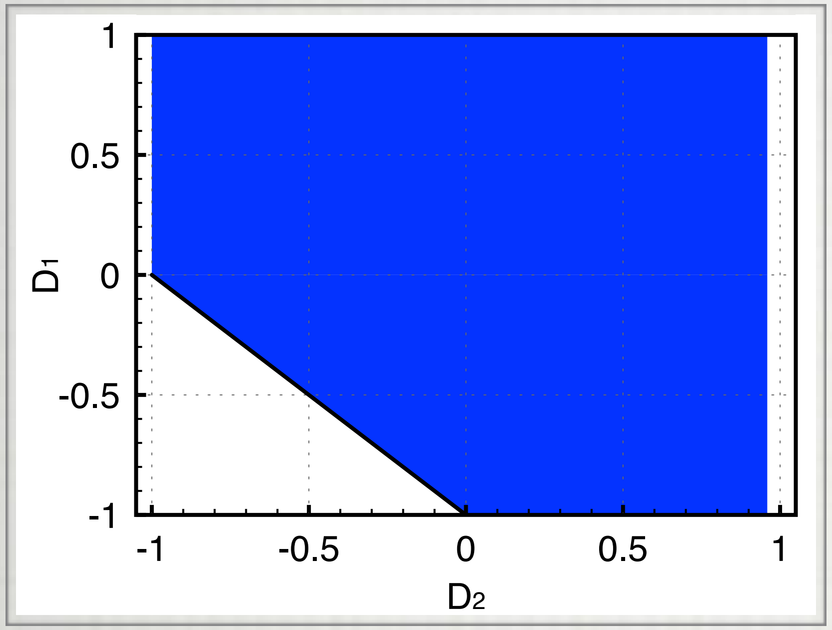
$$[d_{ij}] = \begin{bmatrix} 1 + D_1\sigma_1 + D_2\sigma_1^2 & 0 \\ 0 & 1 + D_1\sigma_2 + D_2\sigma_2^2 \end{bmatrix}$$

Ellipticity regime
(Non-negative diffusion)

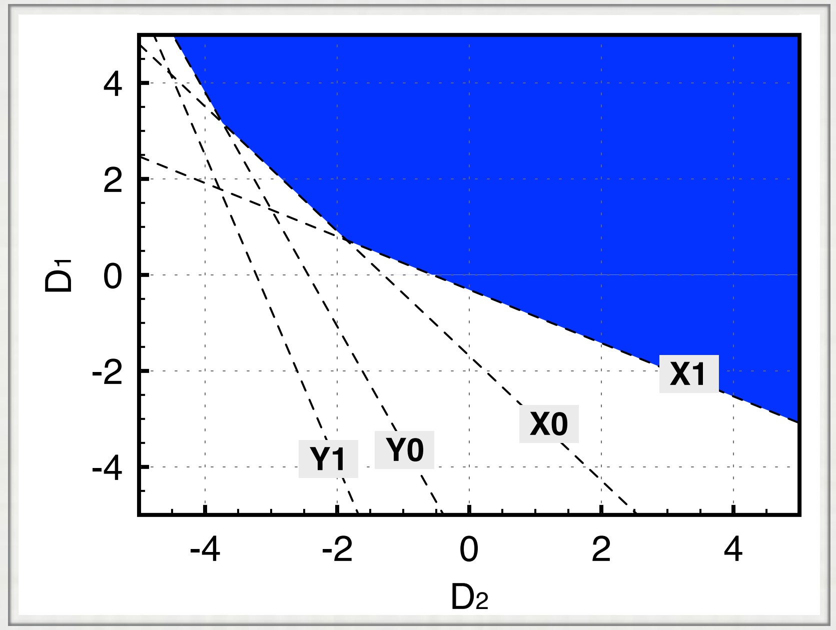
$$1 + D_1\sigma_1 + D_2\sigma_1^2 > 0\,, \quad \rightarrow \quad 4D_2 > D_1^2$$

EM-SAD: PARAMETER SPACE

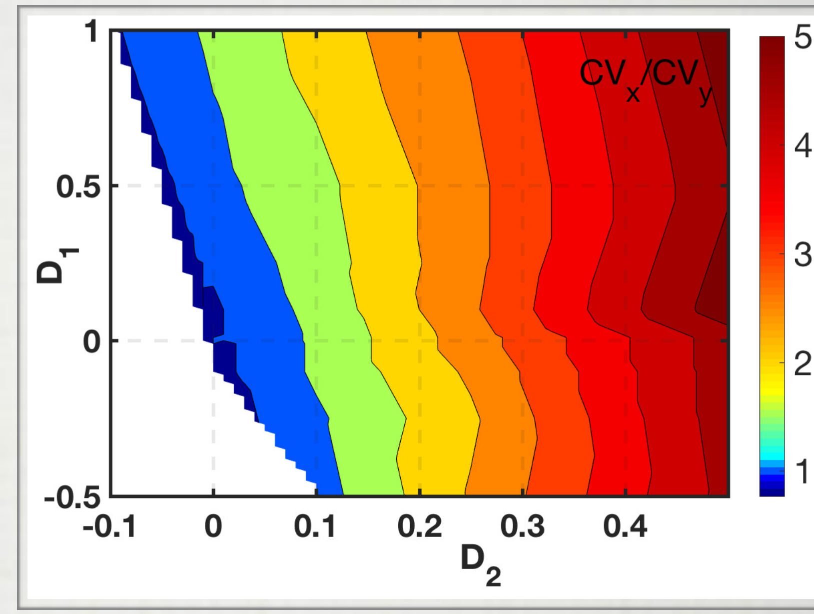
Theoretical Normalized Case



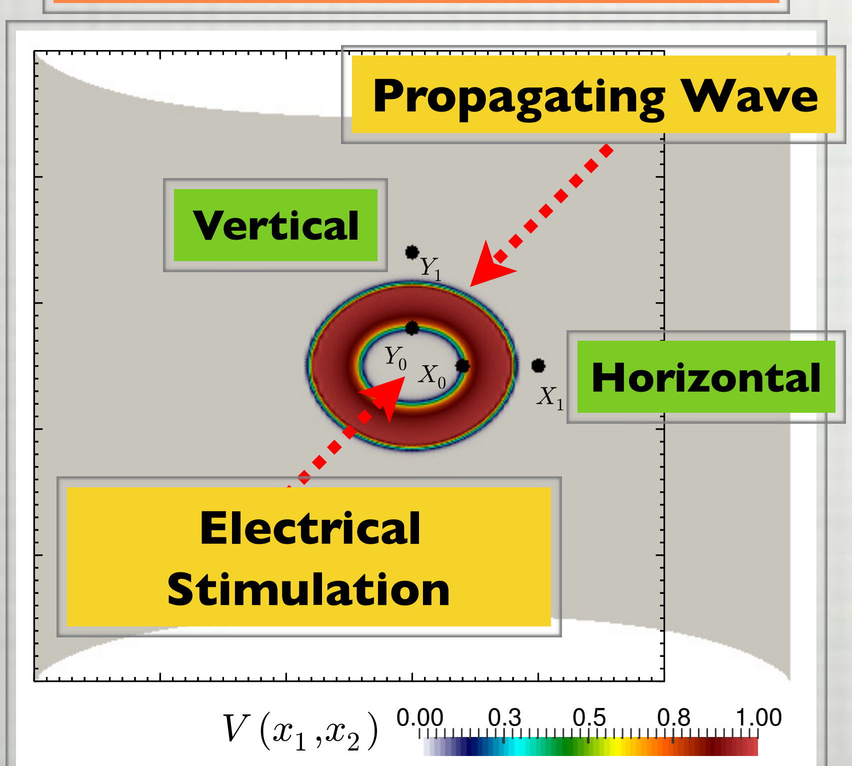
Computed Stress



Numerical-Physical CV



Conduction Velocity

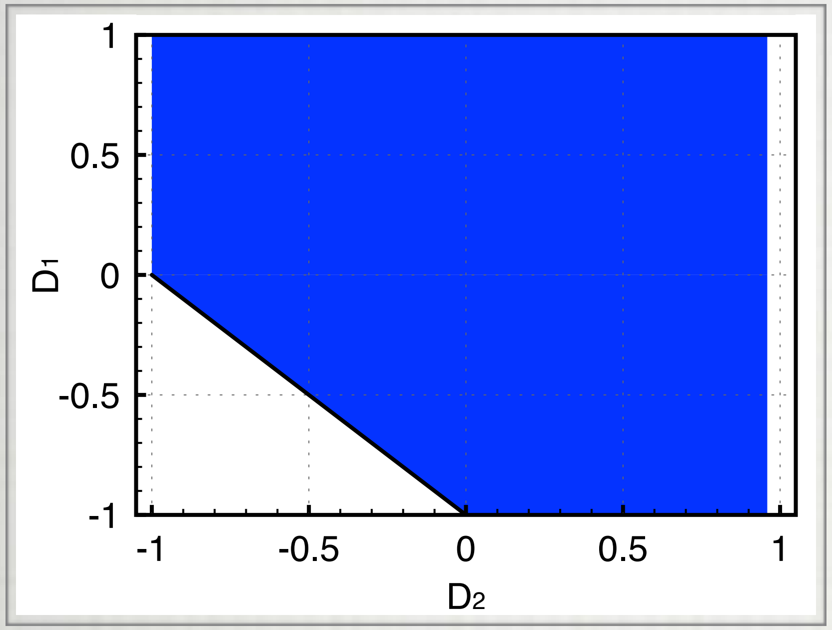


$$d_{ij}(\sigma_{ij}) = D_0\left(\delta_{ij} + D_1\sigma_{ij} + D_2\sigma_{ik}\sigma_{kj}\right)$$

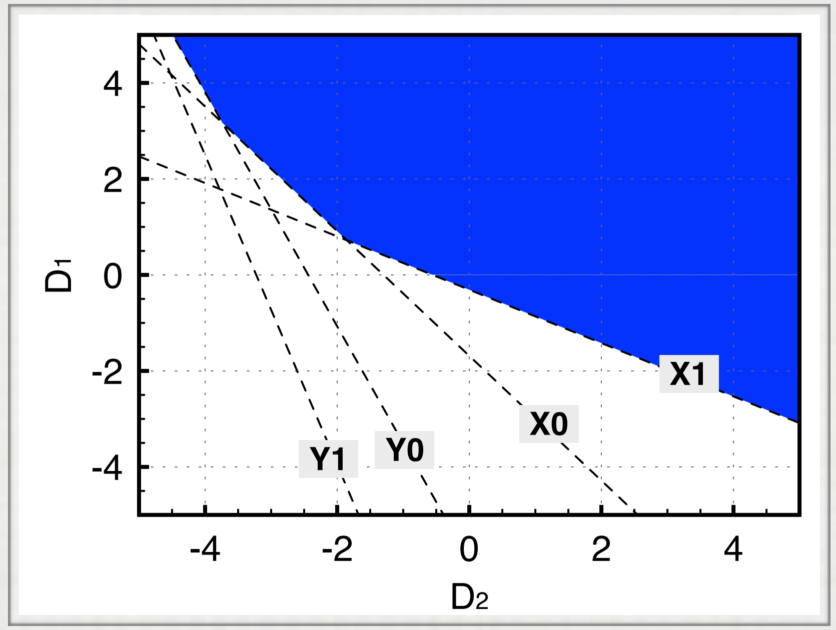
1. **Calculate the <u>Conduction Velocity</u> of the <u>Excitation Wave</u> (Voltage) for different combinations of the Material Parameters**
2. **Compute the ratio CVx/CVy**

EM-SAD: PARAMETER SPACE

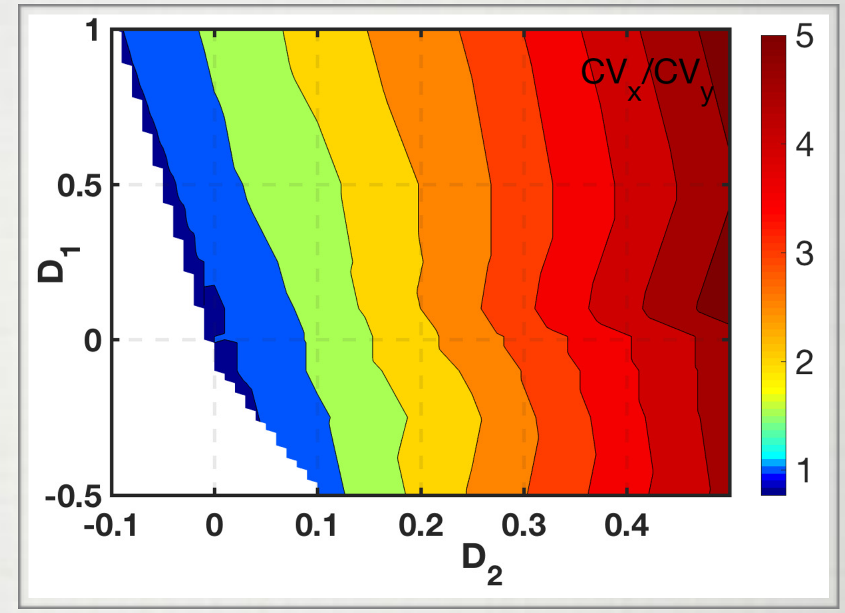
Theoretical Normalized Case



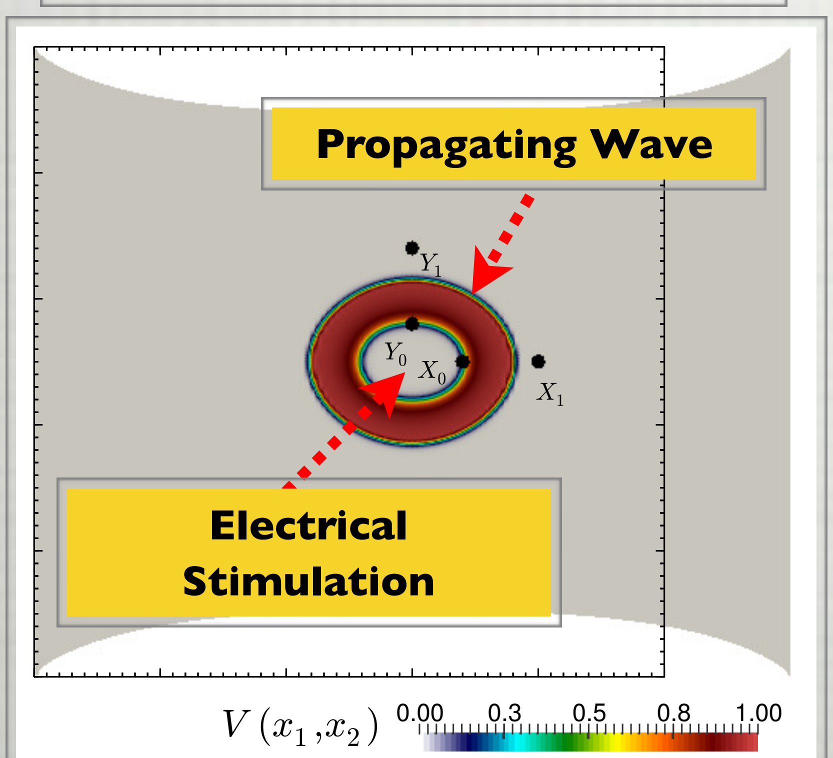
Computed Stress



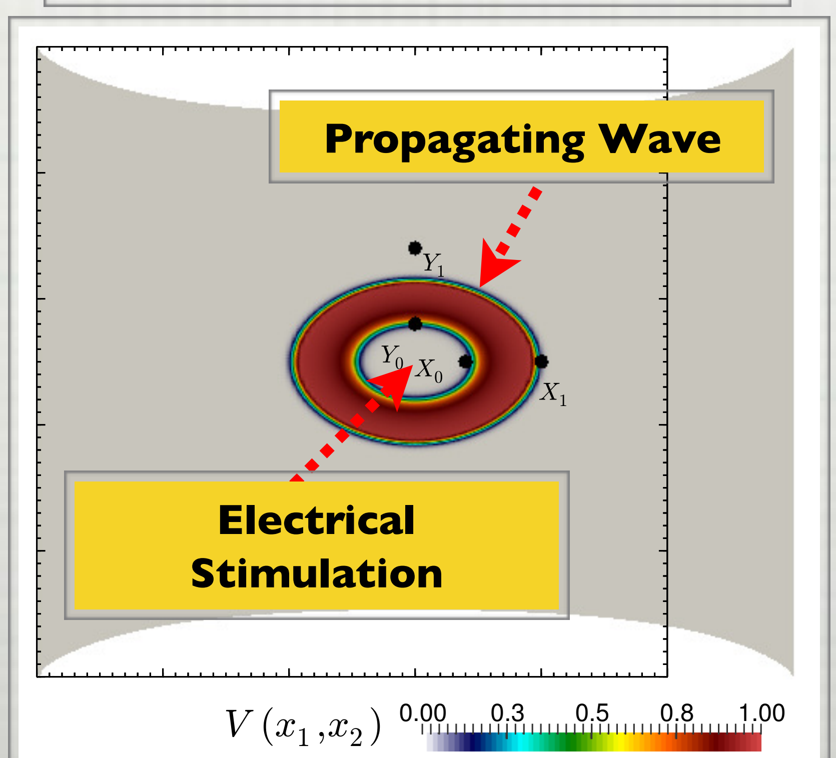
Numerical-Physical CV



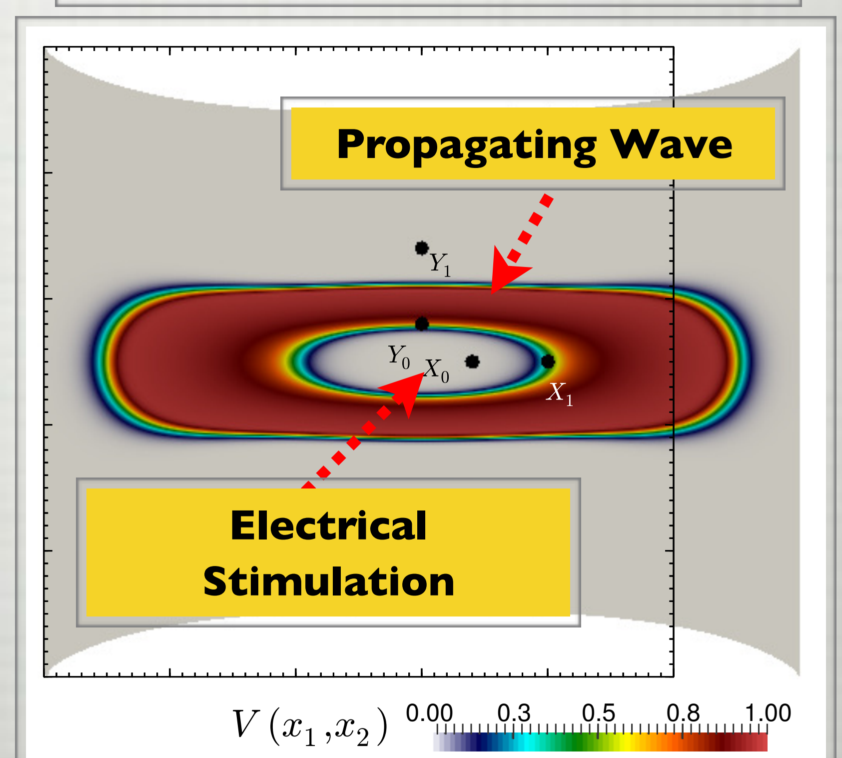
$D_1 = 0, D_2 = 0$



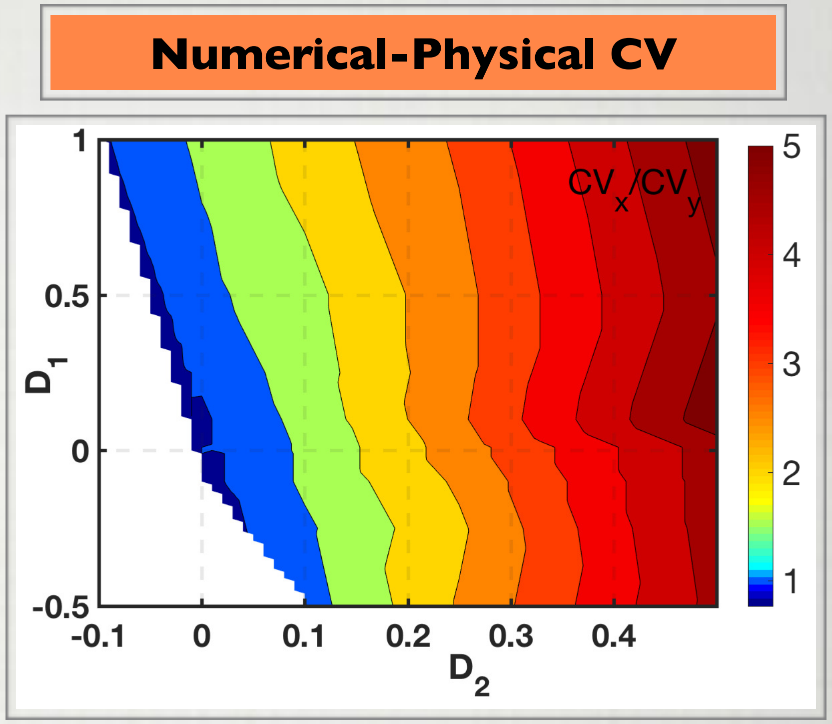
$D_1 = -0.01, D_2 = 0.01$

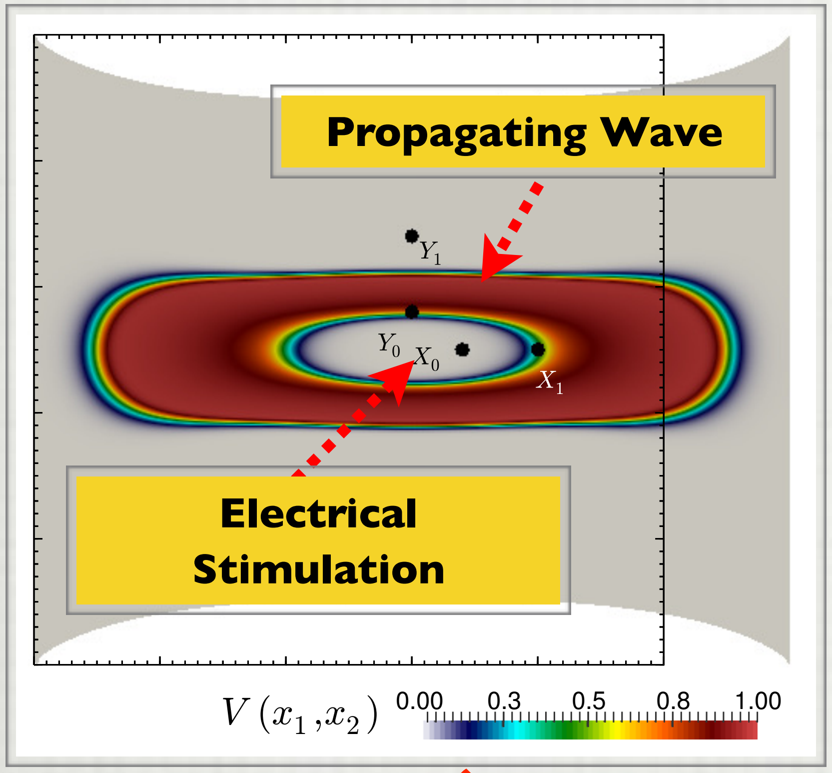


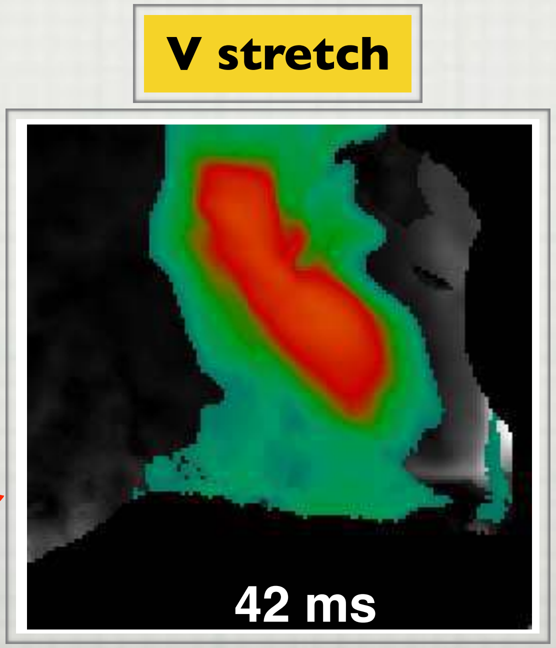
$D_1 = -0.25, D_2 = 0.25$



EM-SAD: PARAMETER SPACE

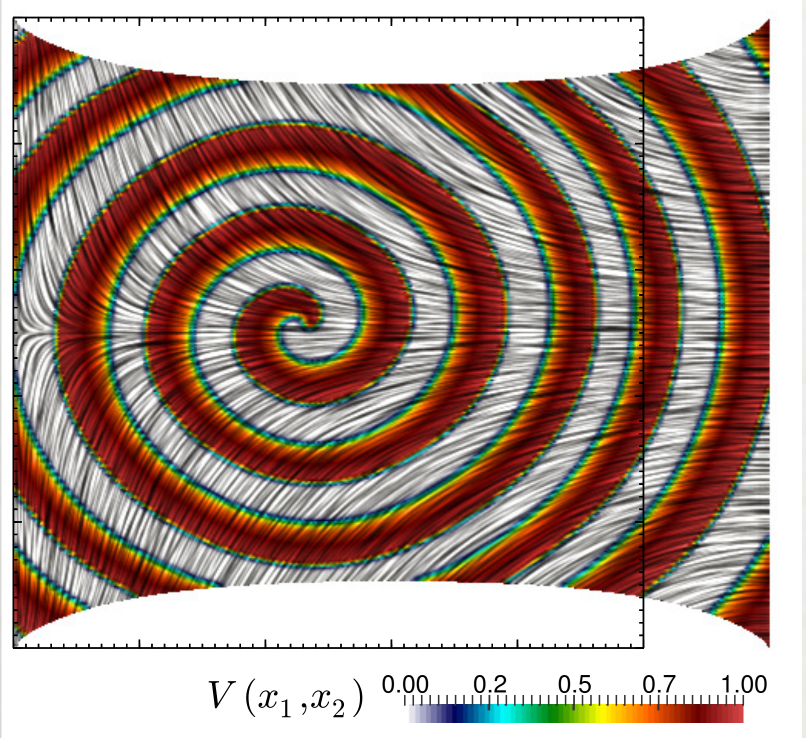






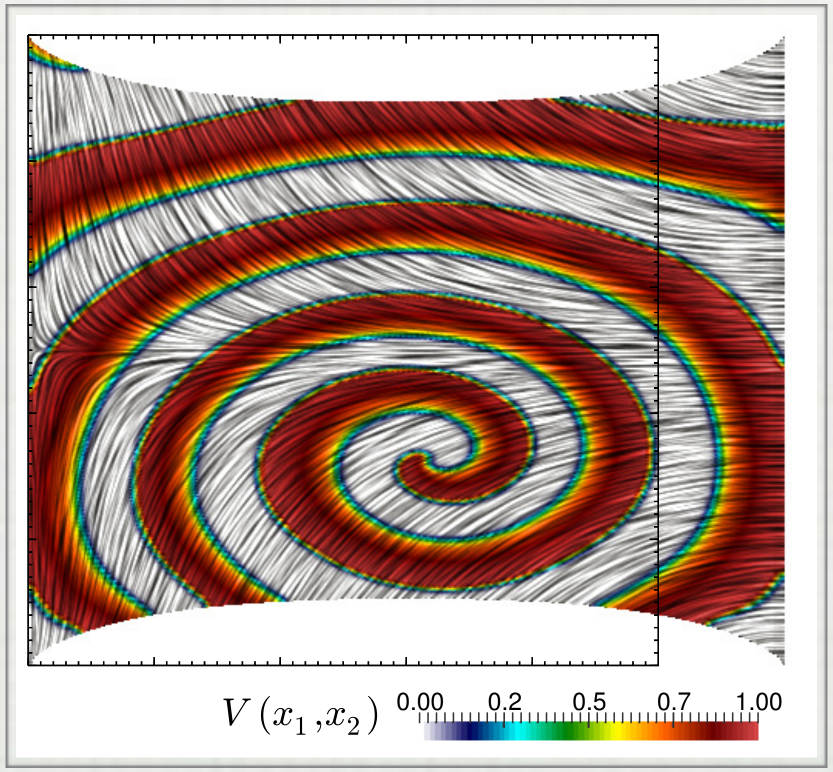
EM-SAD: INDUCED SPIRAL DRIFT

Nash & Panfilov 2004
Active Stress Model
NO DRIFT



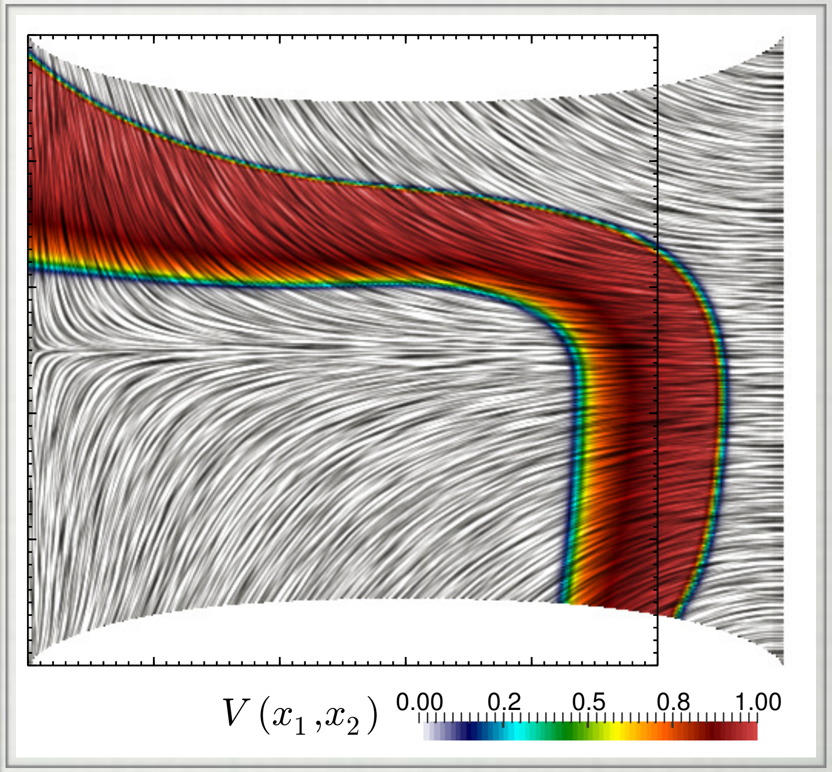
$D_1 = 0, D_2 = 0$

Novel
Stress-Assisted Diffusion
DIRECTIONAL SPIRAL DRIFT

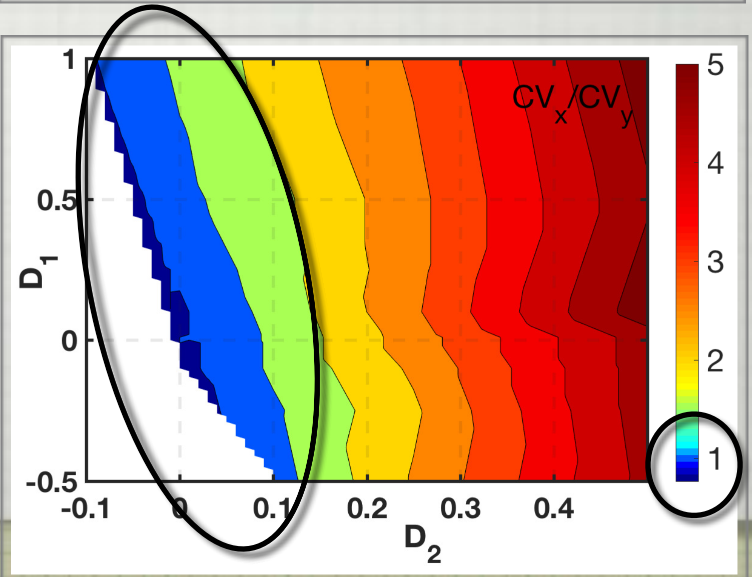


$D_1 = -0.015, D_2 = 0.015$

Novel
Stress-Assisted Diffusion
UNEXPECTED
DISTORTED EXCITATION

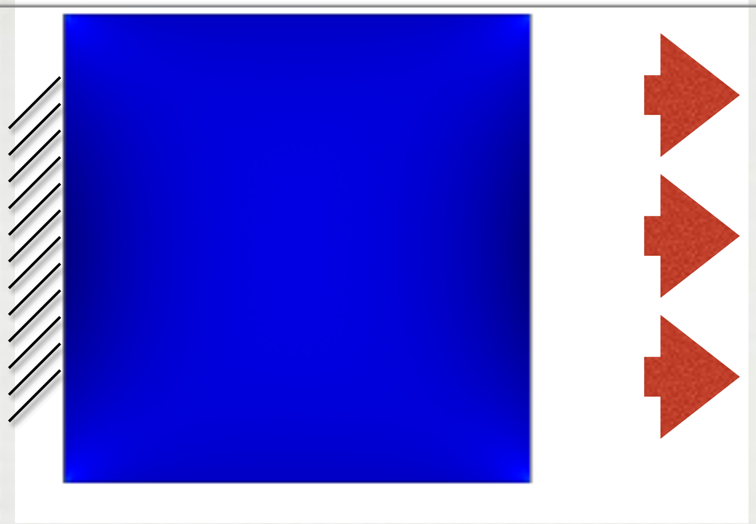


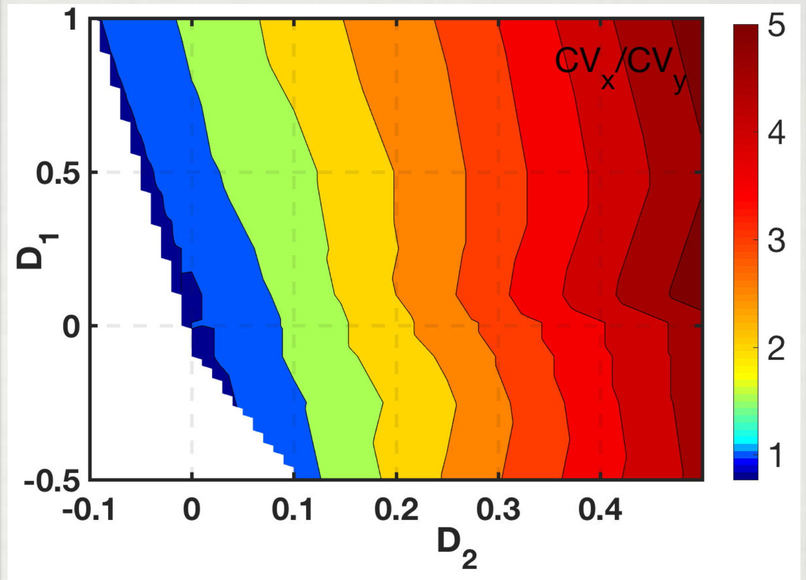
$D_1 = 0.15, D_2 = 0.015$



EM-SAD: ENHANCED MEANDERING

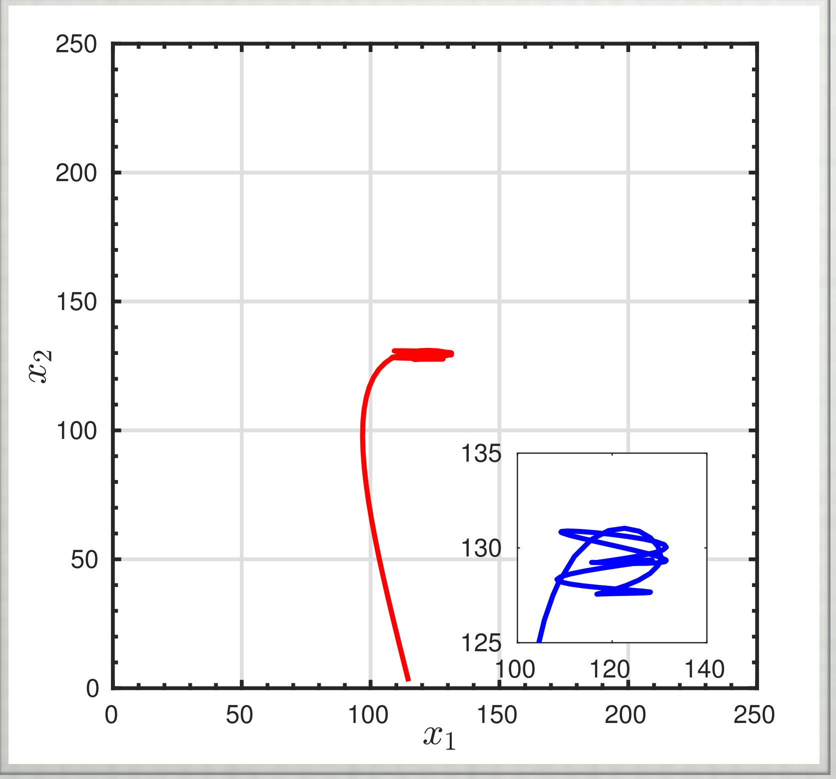
Uniaxial Sinusoidal Mechanical Loading



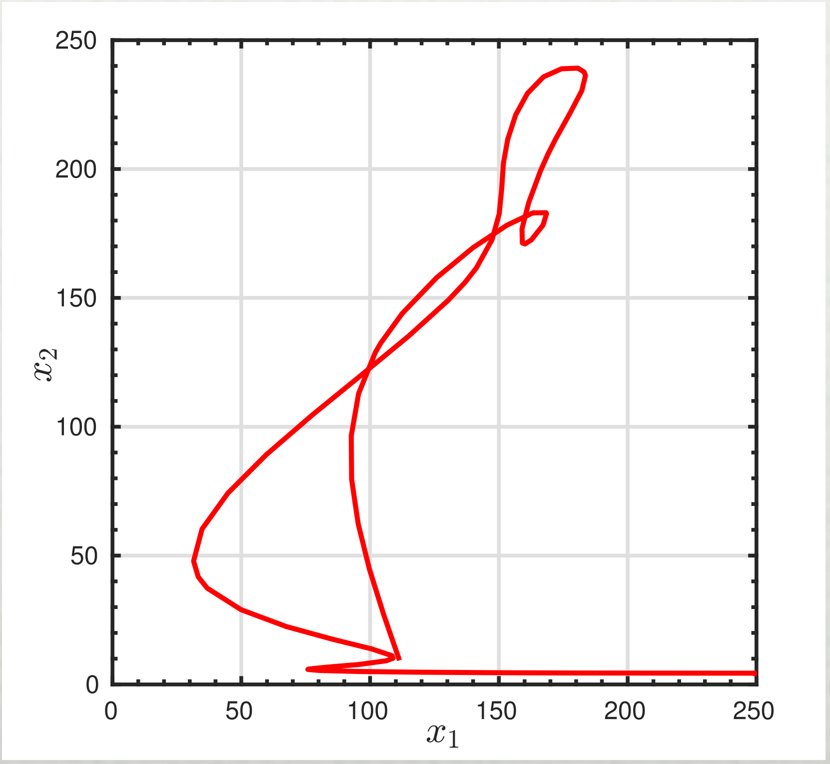


$$\mathbf{u} = \left[50\sin^2\left(\frac{\pi}{50}[t-t^*]\right), 0\right]^T$$

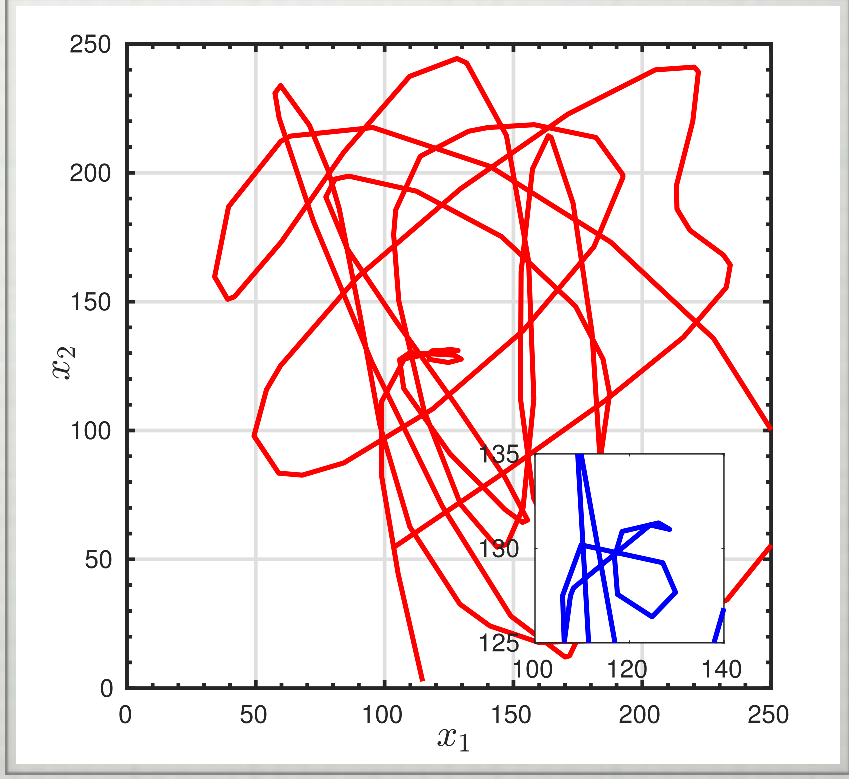
$D_1 = -0.015, D_2 = 0.015$



$D_1 = 0.275, D_2 = -0.275$



$D_1 = -0.5, D_2 = 0.5$



EM - SAD & SAC (MINIMAL)

2v Reaction-Diffusion (RD) Model

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial x_i} d_{ij}(\sigma_{ij}) \frac{\partial V}{\partial x_j} + I_{\text{ion}}(V, r) + I_{\text{sac}}(\lambda, V)$$

$$\frac{dr}{dt} = f(V, r)$$

Active Stress Formulation

$$\frac{\partial T_a}{\partial t} = \epsilon(V)(k_{T_a} V - T_a)$$

RD Constitutive Equations

$$I_{\text{ion}} = -kV(V-a)(V-1) - rV$$

$$f(V, r) = \left(\varepsilon + \frac{\mu_1 r}{\mu_2 + V}\right)(-r - kV(V - b - 1))$$

Isotropic Stress-Assisted Diffusion Model

$$d_{ij}(\sigma_{ij}) = D_0\left(\delta_{ij} + D_1 \sigma_{ij} + D_2 \sigma_{ik} \sigma_{kj}\right)$$

$$I_{\text{sac}}(\lambda, V) = G_s H_{\text{sac}}(\lambda - 1)(V_{\text{sac}} - V)$$

YES SAC

Equilibrium

$$\frac{\partial \sigma_{ij}}{\partial x_i} = 0 \qquad J = 1$$

$$\sigma_{ij} = 2c_1 b_{ij} - 2c_2 b_{ij}^{-1} - p\delta_{ij} + T_a \delta_{ij}$$

Minimal model of Stretch-Activated Currents

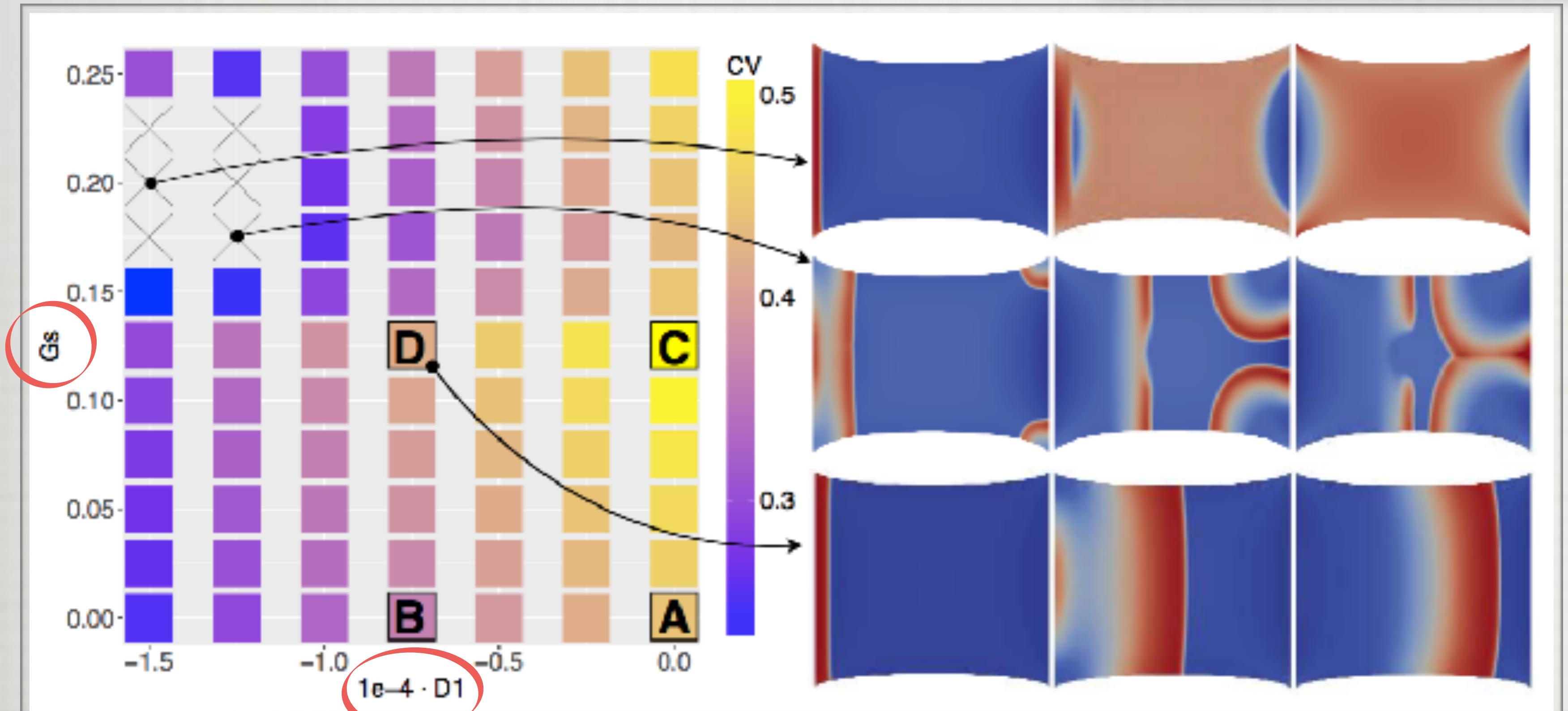
EM - SAD & SAC

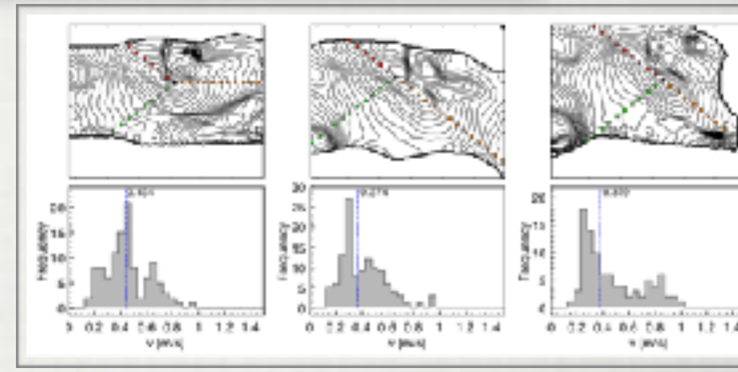
fixed

$$d_{ij}(\sigma_{ij}) = D_0 \left(\delta_{ij} + D_1 \sigma_{ij} + D_2 \sigma_{ik}\sigma_{kj}\right)$$

$$I_{\text{sac}}(\lambda, V) = G_s H_{\text{sac}}(\lambda - 1)(V_{\text{sac}} - V)$$

Conduction Velocity Analysis (planar wave)

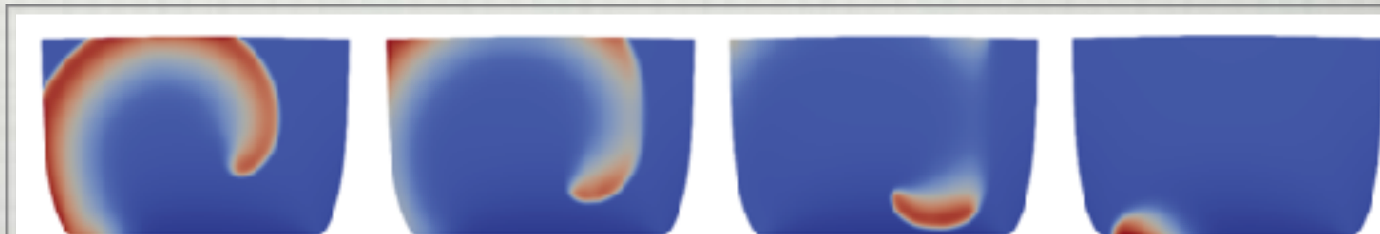




Two Competing Effects

Importance of "Mechanical" Boundary Conditions

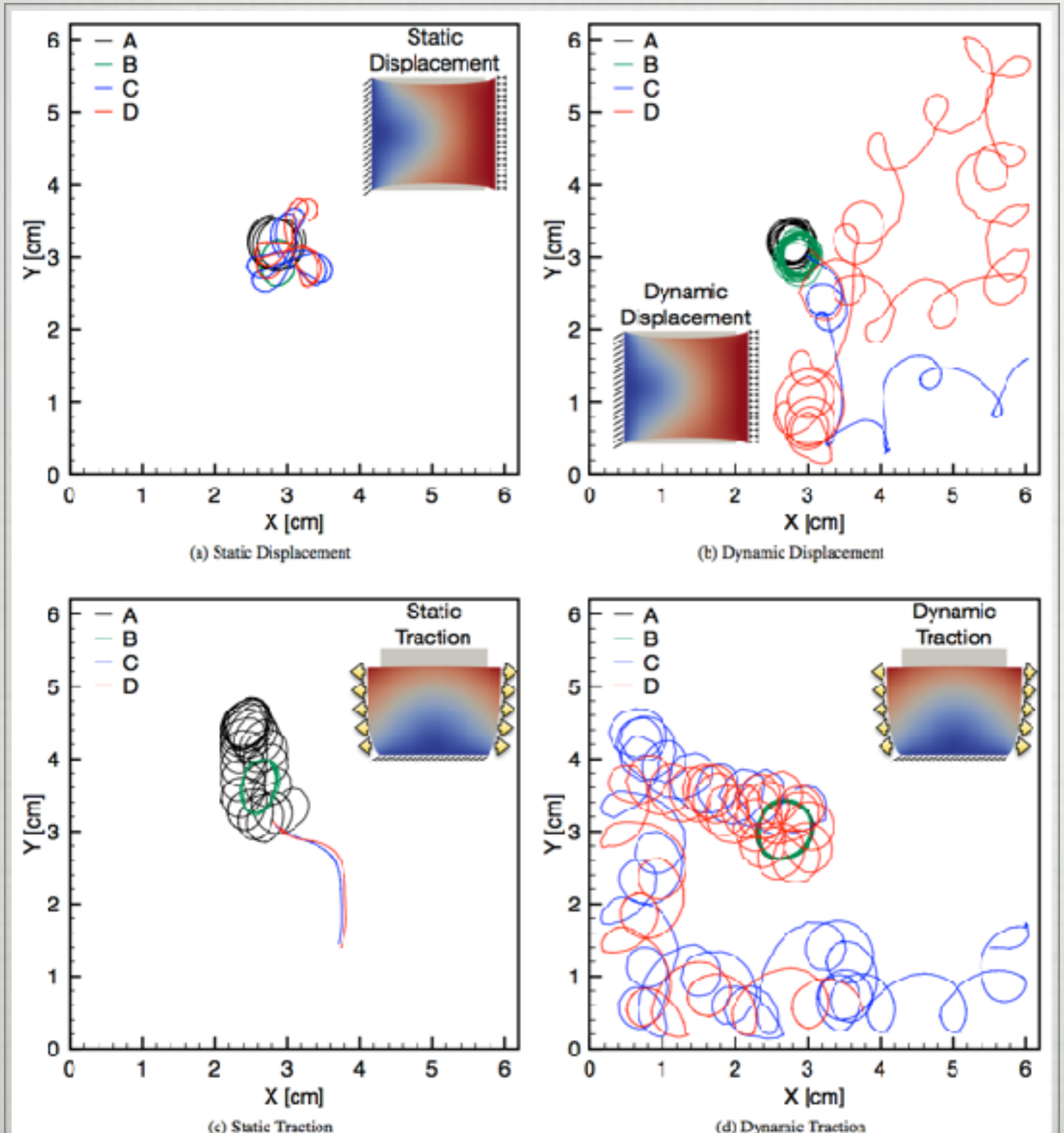
Static/Dynamic & Displacement/ Traction Boundary Conditions greatly affects the emerging dynamics



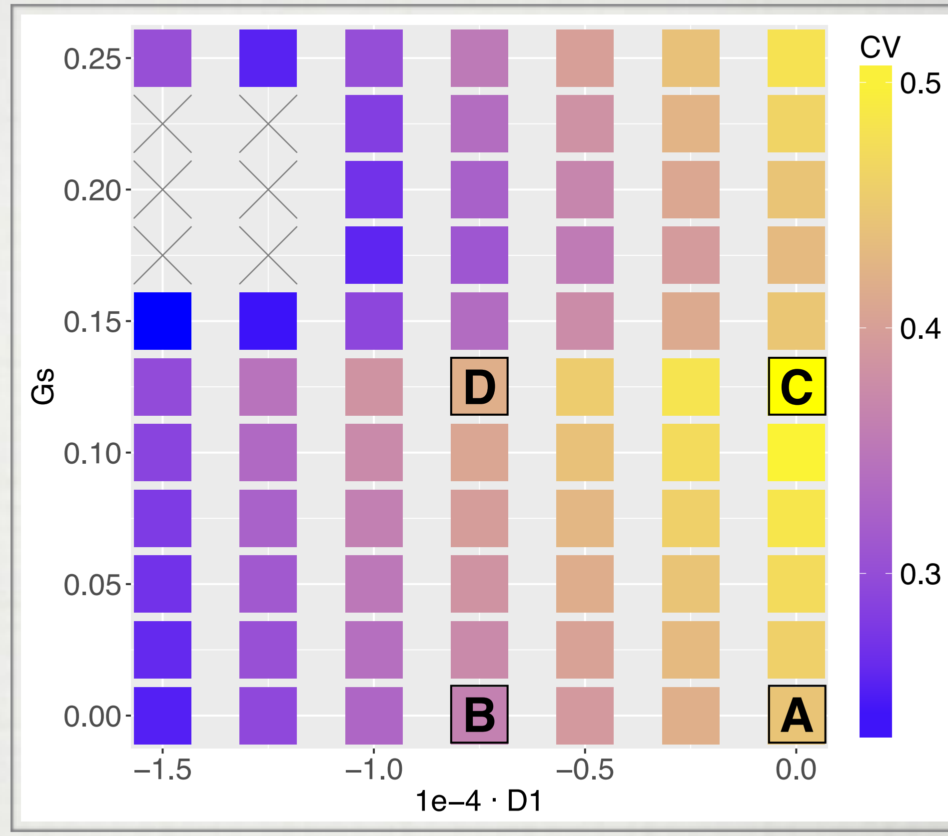
Dynamic Traction: $(D_1, G_s) = (-0.75 \cdot 10^{-4}, 0.125)$

EM - SAD & SAC

Spiral Tip Meandering



(a) Static Displacement (b) Dynamic Displacement (c) Static Traction (d) Dynamic Traction



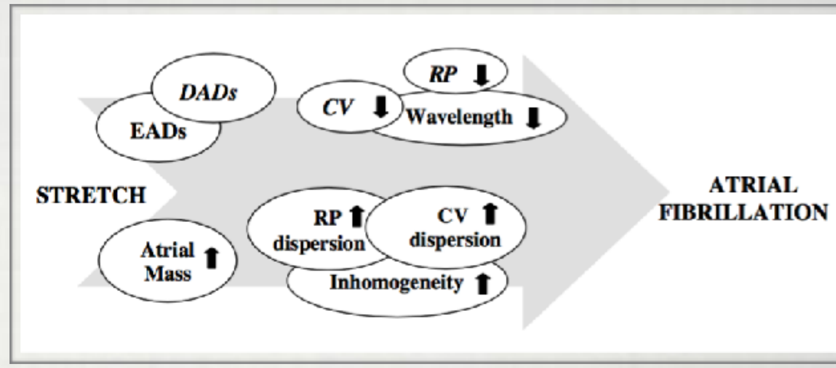
SAD stabilizes meandering

SAC generates irregular behavior

Static/Dynamic & Displacement/Traction BCs conduct to different scenarios

EM - SAD & SAC ... ?

Complex Problem



- ☑ **GENERALIZED ELECTRO-MECHANICAL FRAMEWORK WITH MULTIPLE MEF EFFECTS**

SAD → $d_{ij}(\sigma_{ij})$ **SAC** → $I_{SAC}(\lambda)$

$$\frac{\partial V}{\partial t} = \frac{\partial}{\partial x_i} d_{ij}(\sigma_{ij}) \frac{\partial V}{\partial x_j} + I_{\text{ion}}(V, r) + I_{SAC}(\lambda)$$

Homogenized → **Modify the "Diffusion"** → **Anisotropy & Conduction Block** → **Wave break & Arrhythmias Onset**

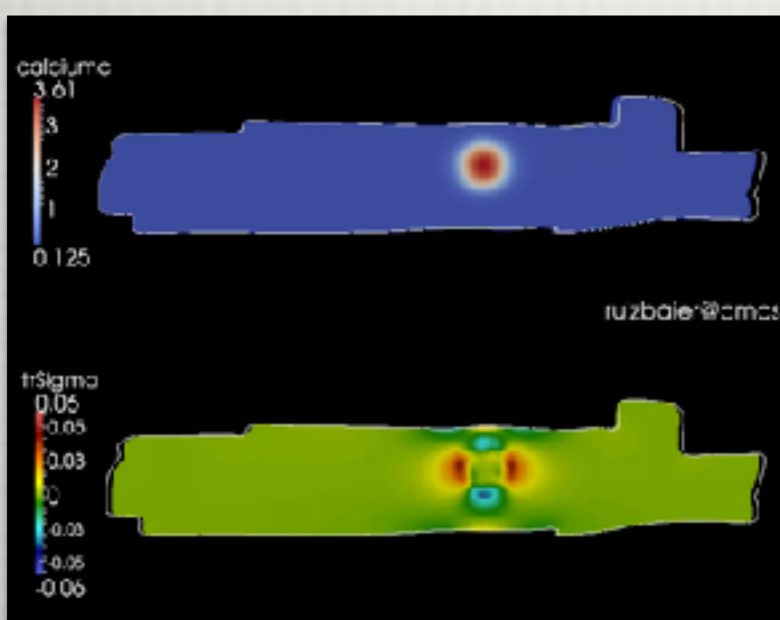
Local → **Modify the "Reaction"** → **Extra Activations & Hyperpolarization** → **Ectopic beats & Arrhythmias Onset**

LIMITATIONS…

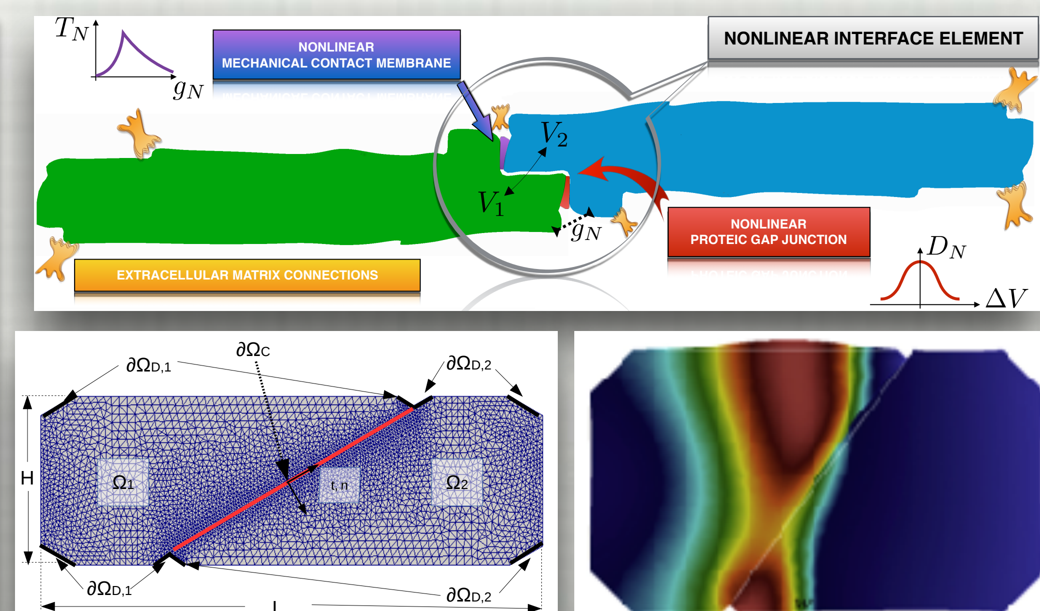
- ☑ GENERALIZED ELECTRO-MECHANICAL FRAMEWORK
- ☑ STRESS-ASSISTED DIFFUSION
- ☑ SAC VS. SAD
- ☑ ISOTROPIC HYPERELASTIC MATERIALS CAN UNDERGO ANISOTROPIC REACTION-DIFFUSION DYNAMICS
- ☑ MINIMAL PROOF OF CONCEPT

OPEN QUESTIONS...

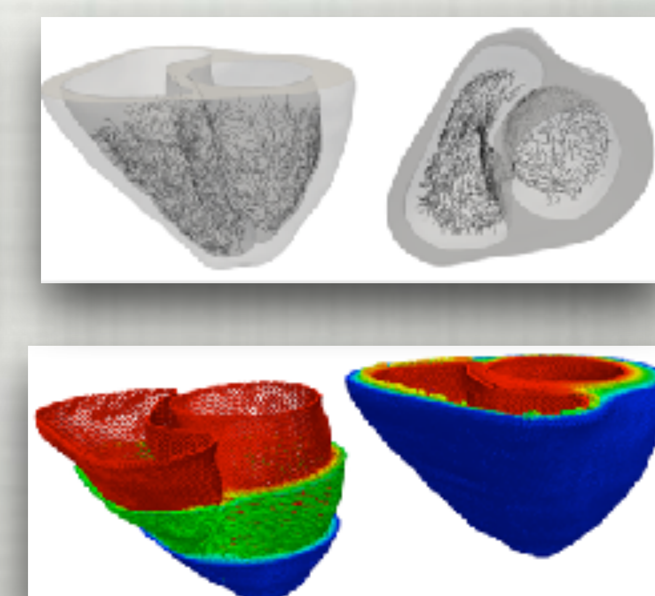
- MULTISCALE MODELING
  - FROM CELL-CELL COUPLING TO TISSUE SCALE (EMERGENT PHENOMENA)
  - PHYSIOLOGICAL MODELING (ROLE OF CALCIUM)
- MODEL VALIDATION: SAC & SAD LIMITS
- ...



RUIZ-BAIER, AG ET AL. 2014



LENARDA, AG, PAGGI 2018



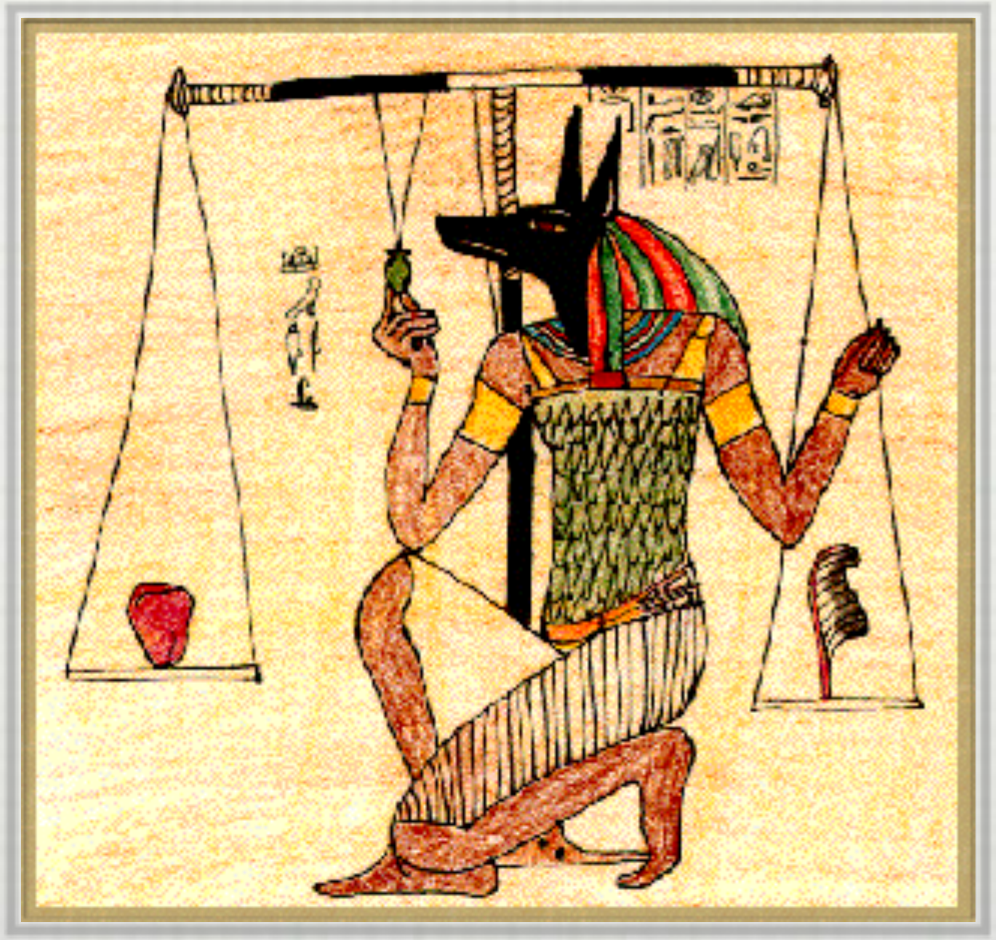
HURTADO, CASTRO, AG 2016

A. T. WINFREE, 2000

PRINCETON GRADUATE SCHOOL CENTENNIAL

ANUBIS IN THE DESERT EST OF EGYPT - 3RD MILLENNIUM BCE

"Weighing the heart against the feather of Truth"



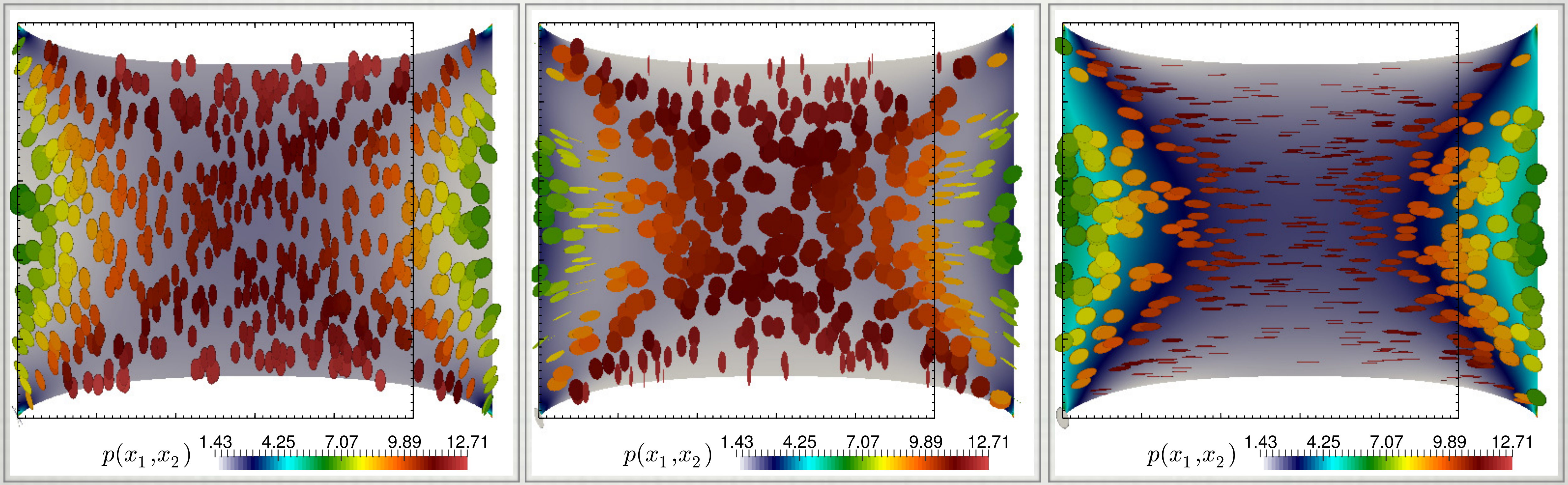
we are still trying...

EM-SAD: INDUCED ANISOTROPY

Tensorial Glyph representation with Pressure levels

$D_0 C_{IJ}^{-1}$ → D_{IJ} ← S_{IJ}

Isotropic Diffusion | **Stress-Assisted Diffusion** | **Stress tensor**



Eigenvalue/Eigenvector rendering of the a Second Order Tensor in a two-dimensional view

$$\sigma_{ij} = 2c_1 b_{ij} - 2c_2 b_{ij}^{-1} - p\delta_{ij} + T_a \delta_{ij}$$

Solve local eigenvalue problems using the tensor at hand and display an ellipsoid whose shape and size depend on the local eigendirection

$$d_{ij}(\sigma_{ij}) = D_0 \left(\delta_{ij} + D_1 \sigma_{ij} + D_2 \sigma_{ik}\sigma_{kj}\right)$$