Enabling Mission Flexibility to Battery Driven Deep Space Endeavors With Generalized Battery-Health-Monitoring Using Physics-Based and Data-Driven Reduced-Order Models

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Outline

I. Introduction

II. Need for physics informed data led reduced-order-model

III. Thermal reduced order model (TROM) for a single cell

IV. Extending TROM to a pack (in-series)

V. Next steps (looking for data to validate models)

Concept: Battery Health Dashboard

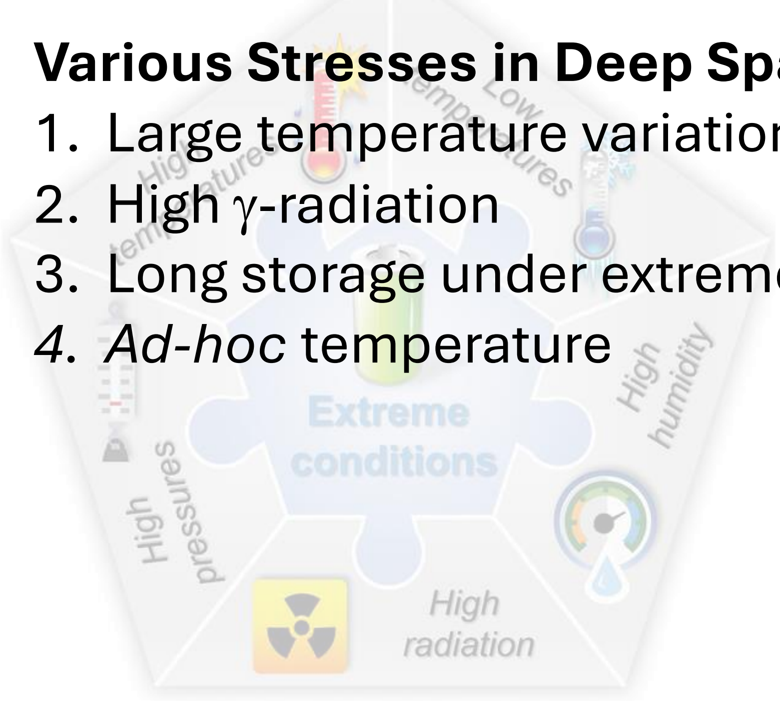
Moving Beyond Conventional "Capacity Driven" Health Monitoring

Proposed Battery State-of-Heath Dashboard

Electrode Health	Electrolyte Health	Thermal Health	Ohmic Health	Electrochemical Interface Health

Various Stresses in Deep Space Missions:

1. Large temperature variations
2. High γ-radiation
3. Long storage under extreme conditions
4. *Ad-hoc* temperature



Commonly monitored signatures:

1. Voltage
2. Time
3. Average current
4. *Ad-hoc* temperature

Challenges:

1. Dependence on data or physics
2. Lack of model adaptability
3. Models lack adaptability based on information content

Simple Lumped Thermal Model

Voltage and temperature contains a lot of information, but can it be extracted?

Chemical decomposition

Electrochemical

$$\frac{\partial T}{\partial t} = \frac{1}{\rho C_p}\left[q_{rev} + q_{irr} + q_{ohm} + q_{chem} - \boxed{q_{conv} - q_{rad} - q_{cond}}\right]$$

Thermodynamic

Ohmic and short-circuit

Heat loss

- Field data lacks information to provide reliable contributions from individual sources
- Difficult to extract cooling and heating terms from a single discharge profile
- Amount of information is dependent on cycling profile and reference performance tests

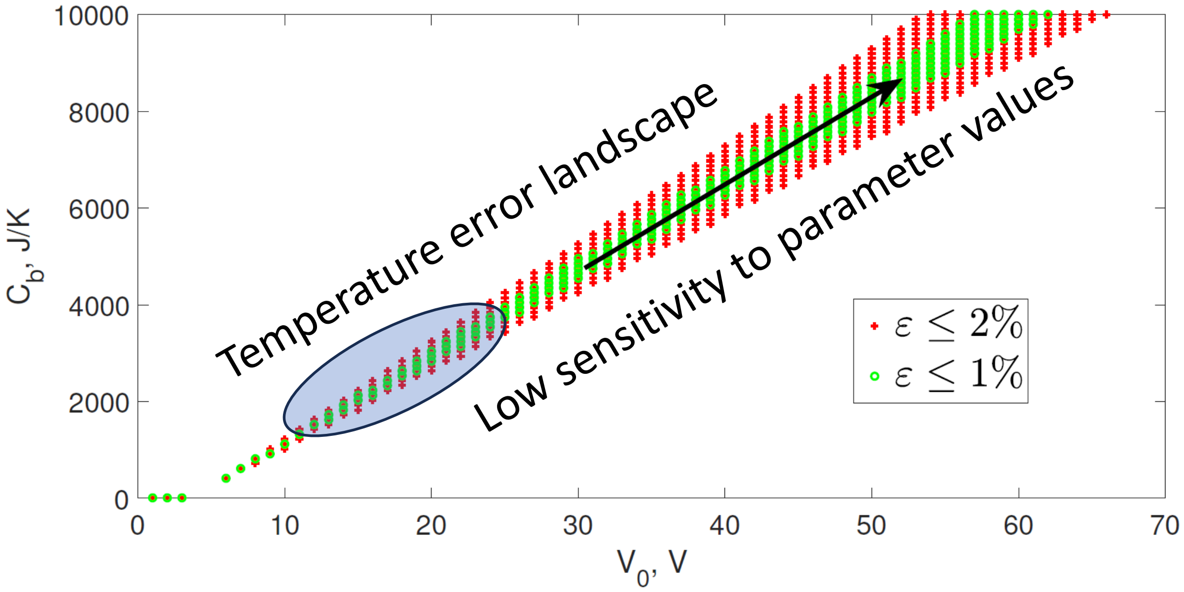
Example for Model Reduction on a Single Cell

1. Field data does not constrain the parameters of the higher fidelity model

2. Consequently, the RMSE landscape is almost degenerate in certain directions in parameter space

3. Moving along the degenerate direction allows to reduce the model with a small penalty in RMSE

4. Adding data will impose additional constraints and partially lift the degeneracy, leading to different reduced-order model (ROM)



Higher fidelity model + Data = ROM

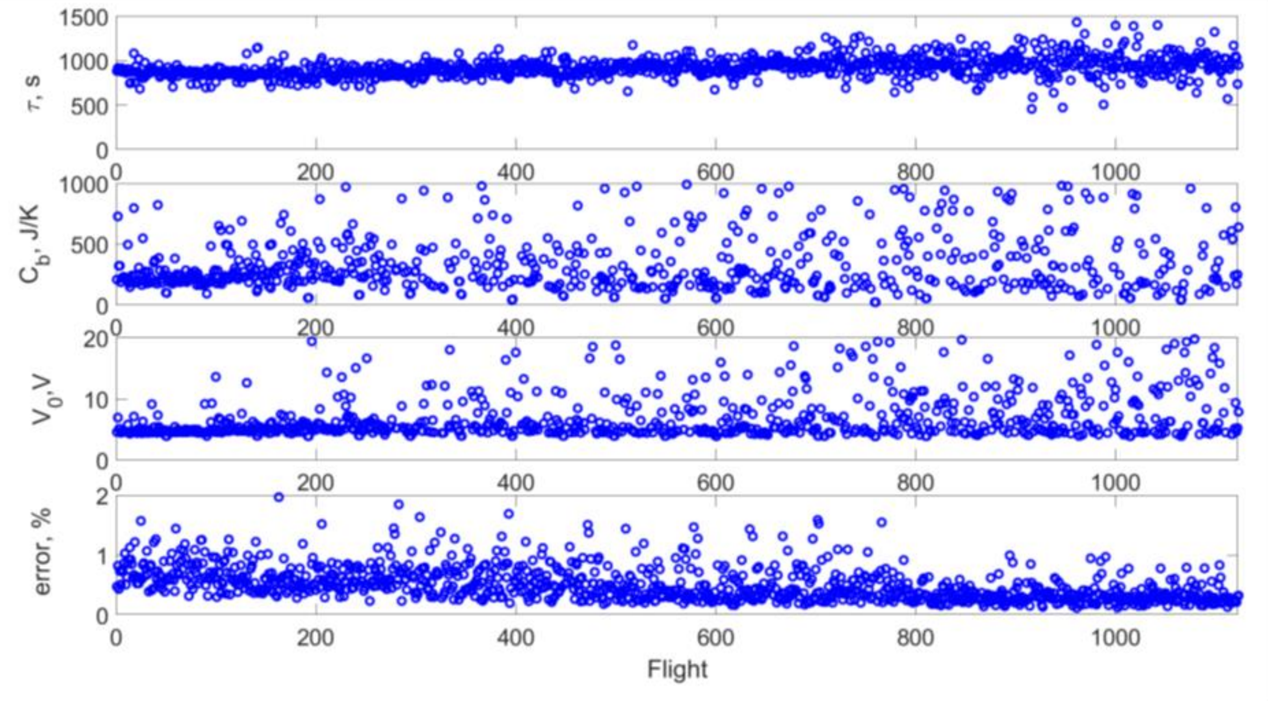
Benefits of ROM: *Identifiability*

3pTROM:

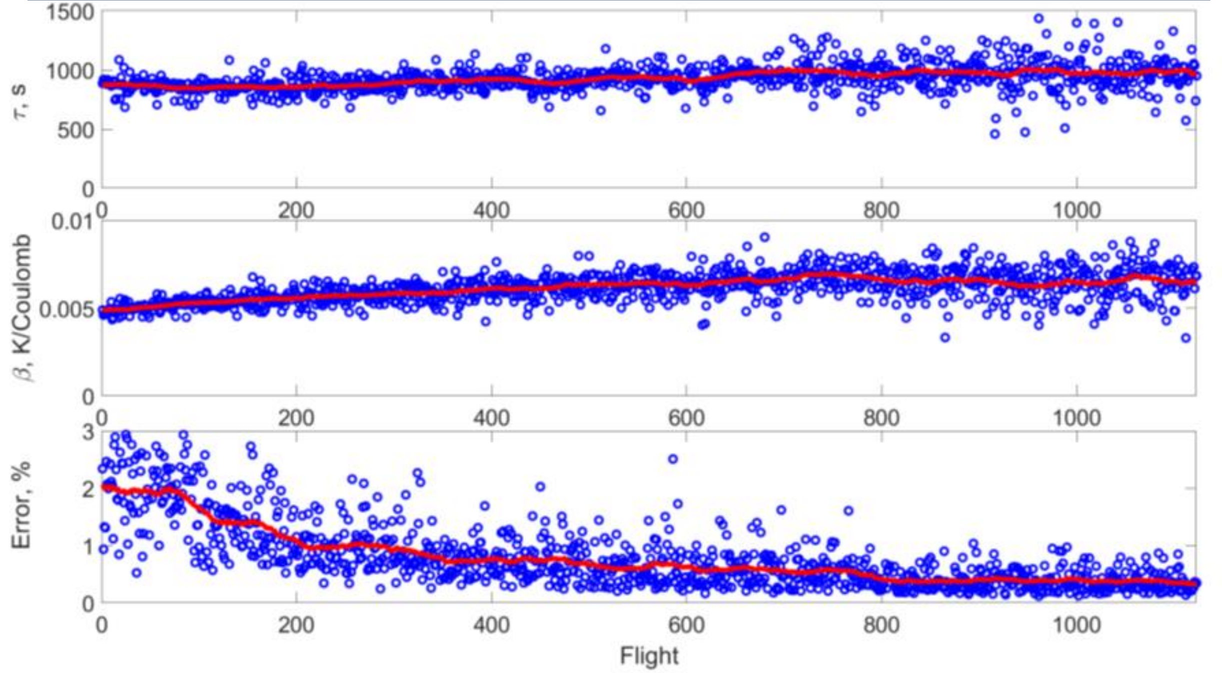
$$T = T_a + [T(0) - T_a]e^{-t/\tau} + C_b^{-1}\int_0^t I(t')[V_0 - V(t')]e^{\frac{t'-t}{\tau}}dt',$$

2pTROM:

$$T = T_a + [T(0) - T_a]e^{-t/\tau} + \beta\int_0^t I(t')e^{\frac{t'-t}{\tau}}dt'$$



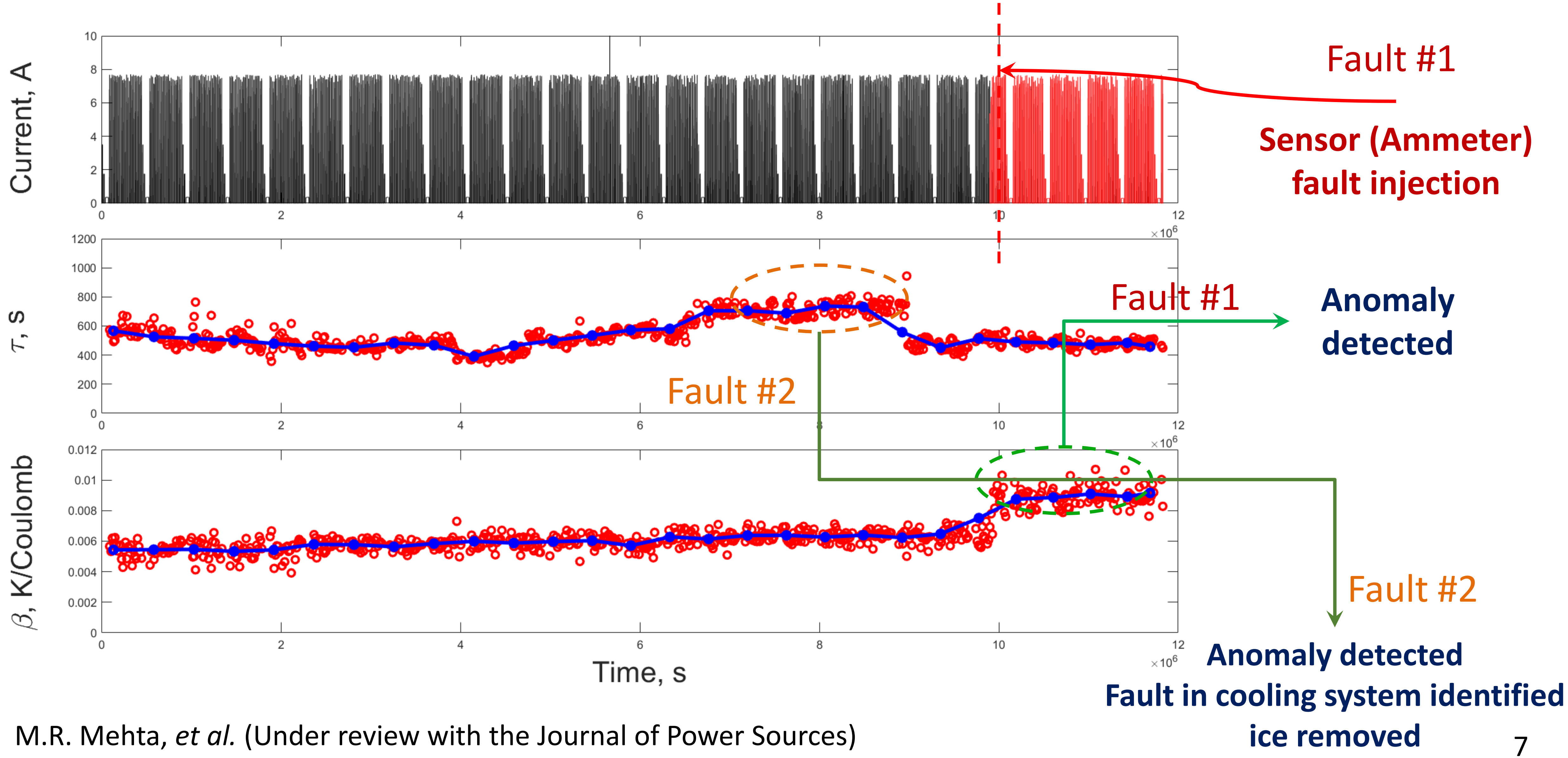
Non-identifiable.



Identifiable

M. Khasin, M.R. Mehta, C. Kulkarni, J.W. Lawson, J. Power Sources 604 (2024) 234442

Benefits of ROM: *Anomaly Detection*



M.R. Mehta, *et al.* (Under review with the Journal of Power Sources)

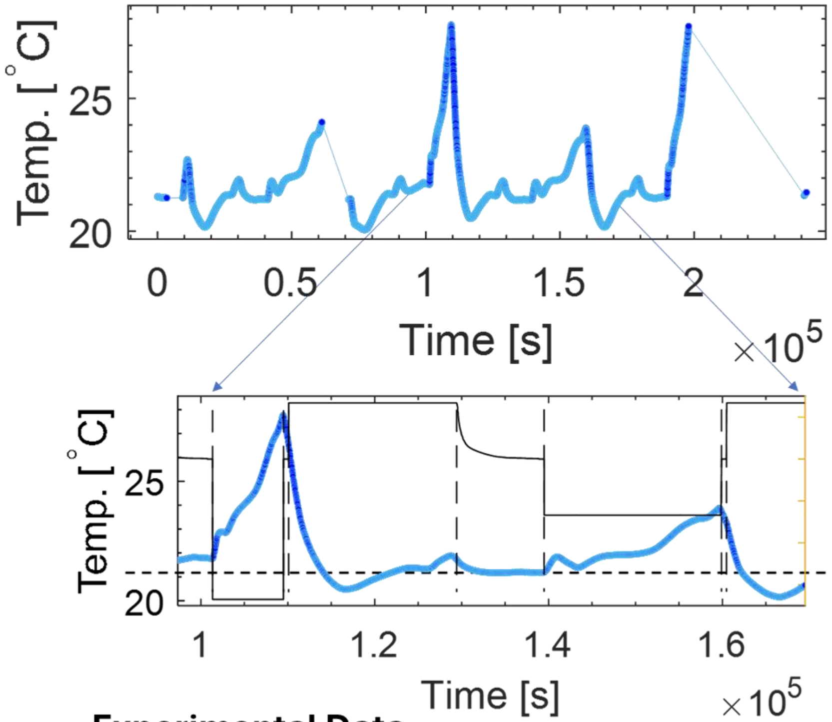
Applying ROM to High Energy Space Cells

Data specifics:

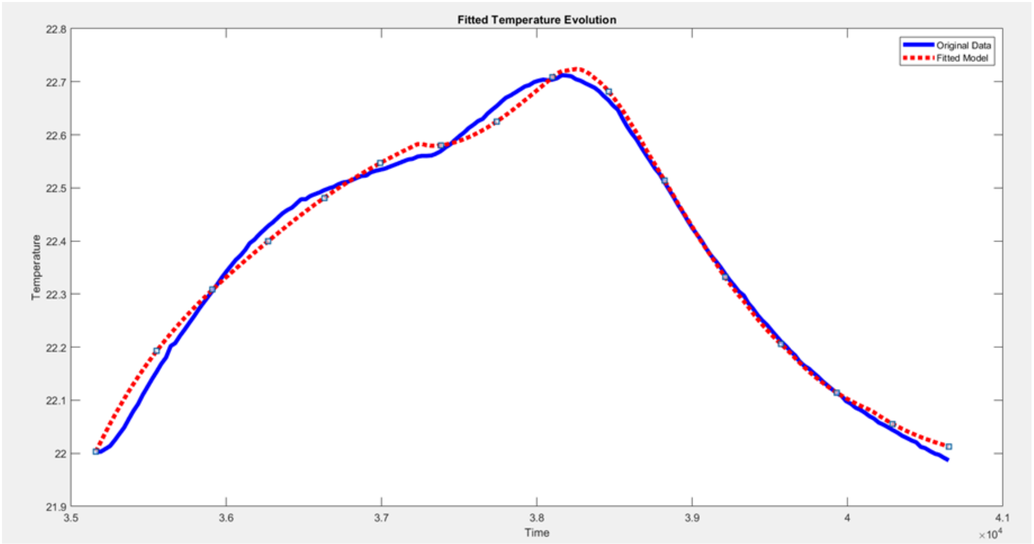
- High-energy space batteries operating at low C-rates (<C/5)
- Data includes partial charge and discharge
- Unfortunately, no battery anomalies were observed

Modeling:

- Modified two-parameter needed to fit both charge and discharge
- Most of the heat contribution comes from thermodynamics



Experimental Data



pseudo3pTROM: 2pTROM with discharge/charge heating term and a single cooling rate

$$T = T_a + [T(0) - T_a]e^{-t/\tau} + \beta_{dis/chg} \int_0^t I(t')e^{\frac{t'-t}{\tau}} dt'$$

Developing a ROM for a Battery pack

N cells connected in series

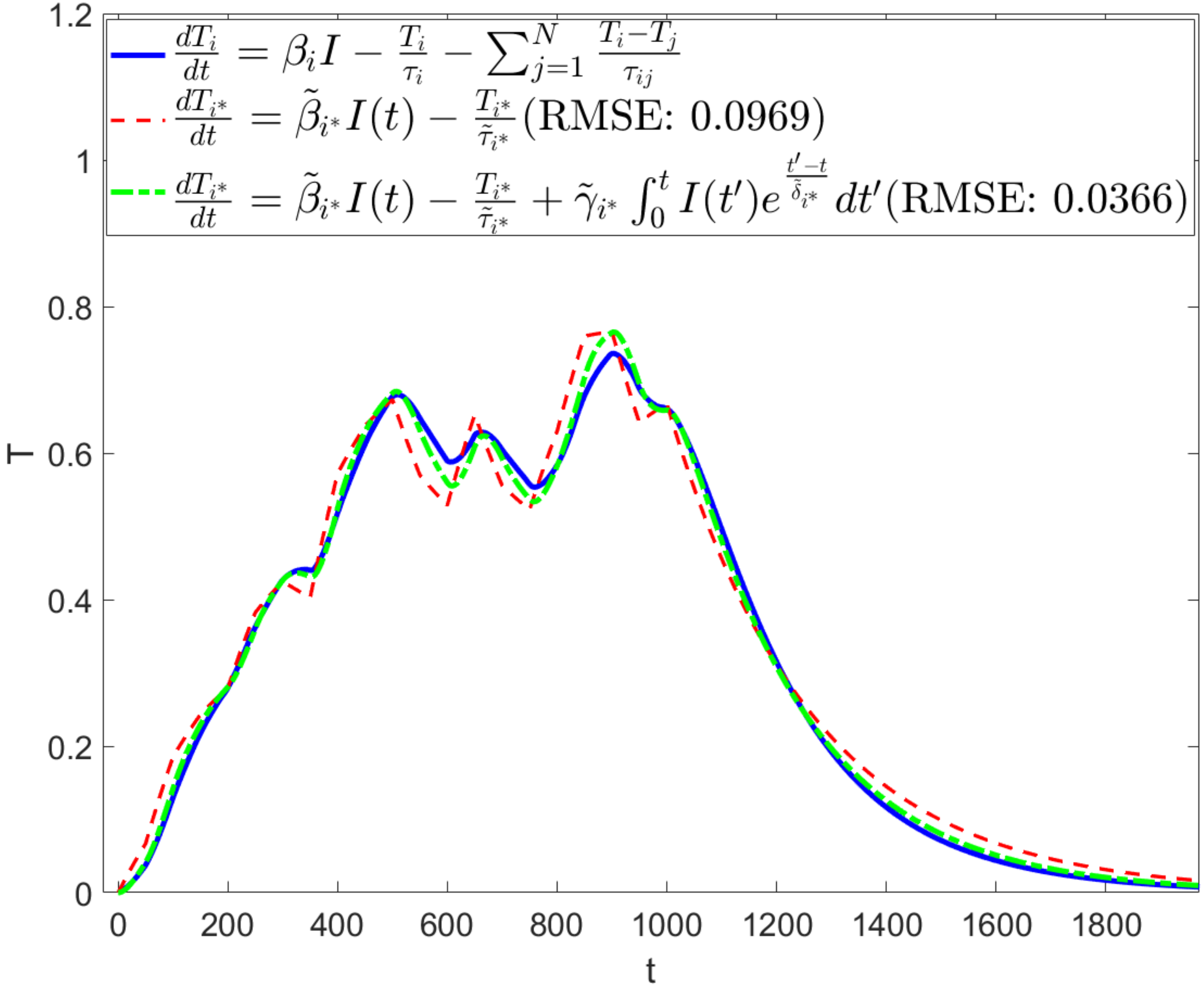
- Full model: $\frac{dT_i}{dt} = \beta_i I - \frac{T_i}{\tau_i} - \sum_{j=1}^{N} \frac{T_i - T_j}{\tau_{ij}}$
- ROM I: $\frac{dT_{i^*}}{dt} = \tilde{\beta}_{i^*} I(t) - \frac{T_{i^*}}{\tilde{\tau}_{i^*}}$
- ROM II: $\frac{dT_{i^*}}{dt} = \tilde{\beta}_{i^*} I(t) - \frac{T_{i^*}}{\tilde{\tau}_{i^*}} + \tilde{\gamma}_{i^*} \int_0^t I(t') e^{\frac{t'-t}{\tilde{\delta}_{i^*}}} dt'$

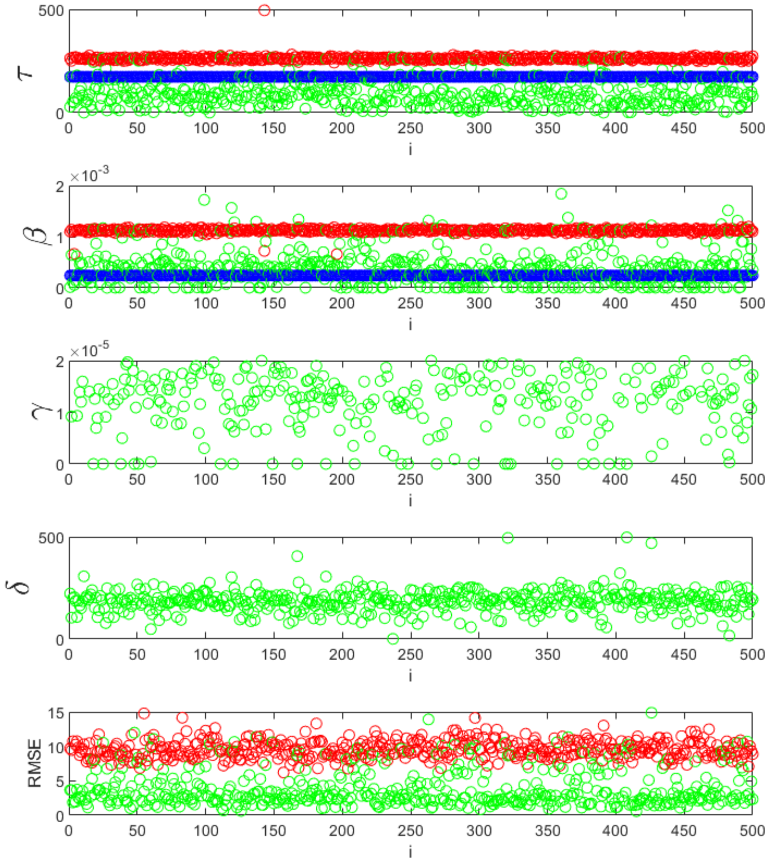
N+1 parameters

2 parameters

4 parameters

Manually Searching Identifiable ROMs

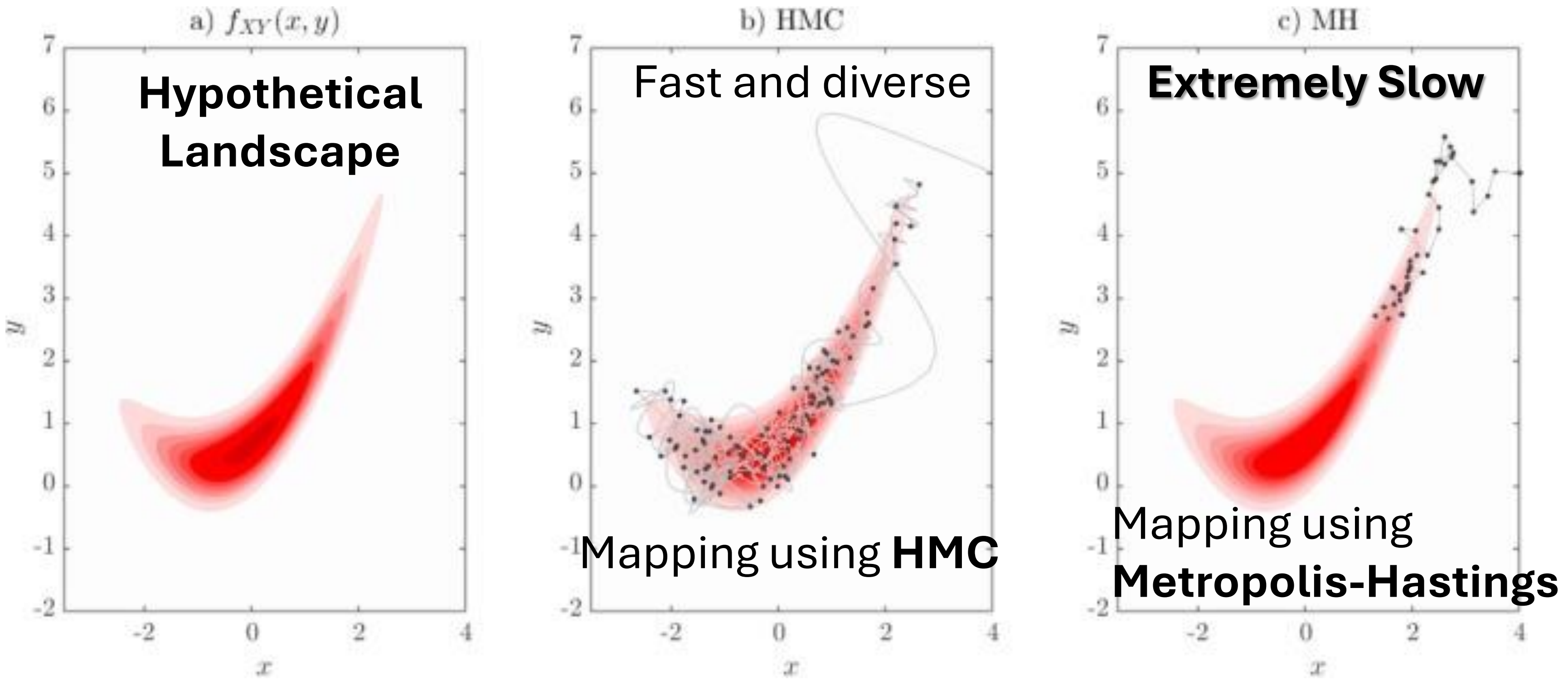




- Full model, local parameters (blue)
- ROM I (red) : identifiable but not accurate
- ROM II (green) accurate but non-identifiable

Automating ROM search with HMC

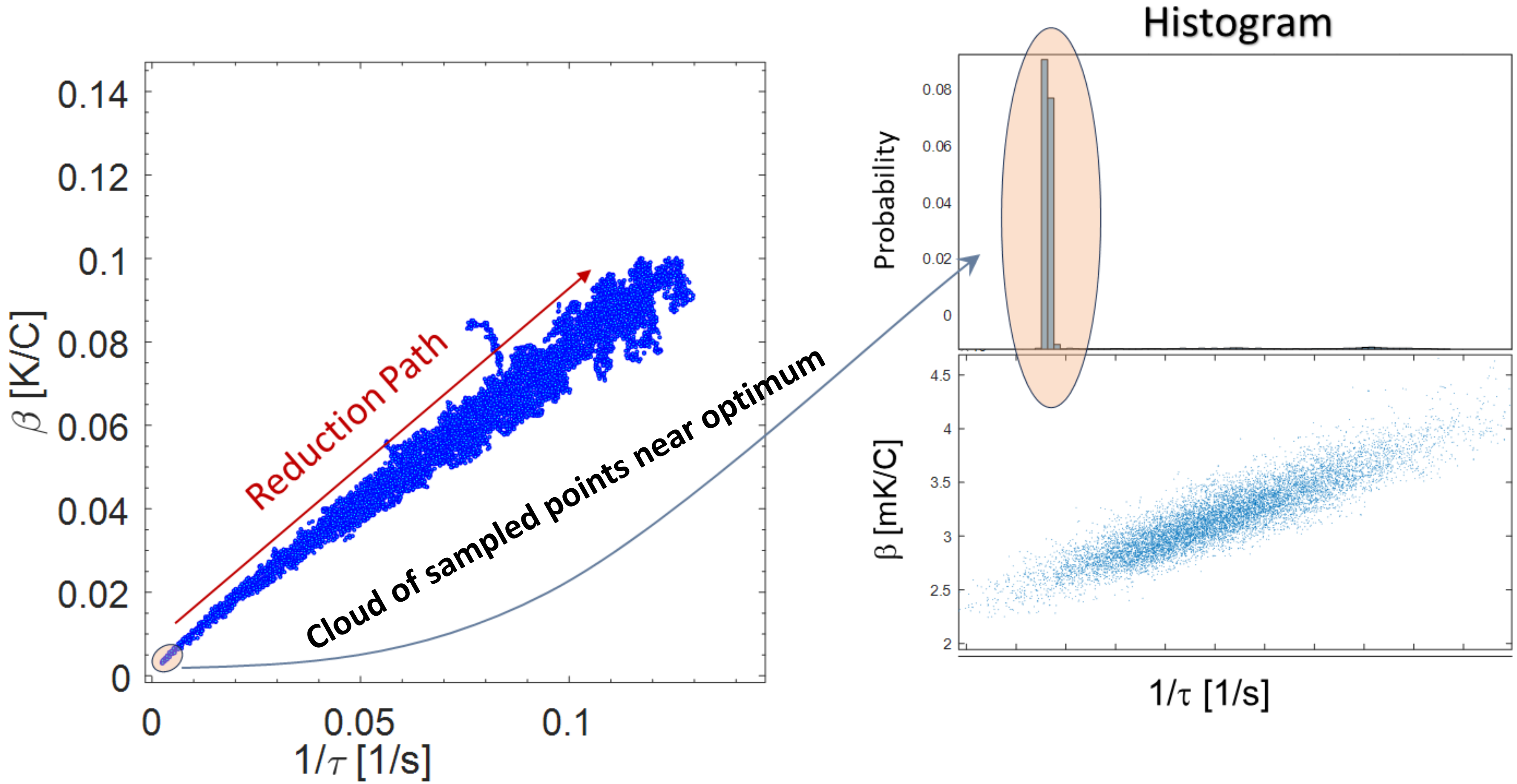
Hamiltonian Monte Carlo



Goal of using HMC: to map out parameter landscape to instruct path for model reduction

Implementation: 1) Matlab using `hmcSampler`, 2) Matlab from scratch, 3) Python using `pymc`

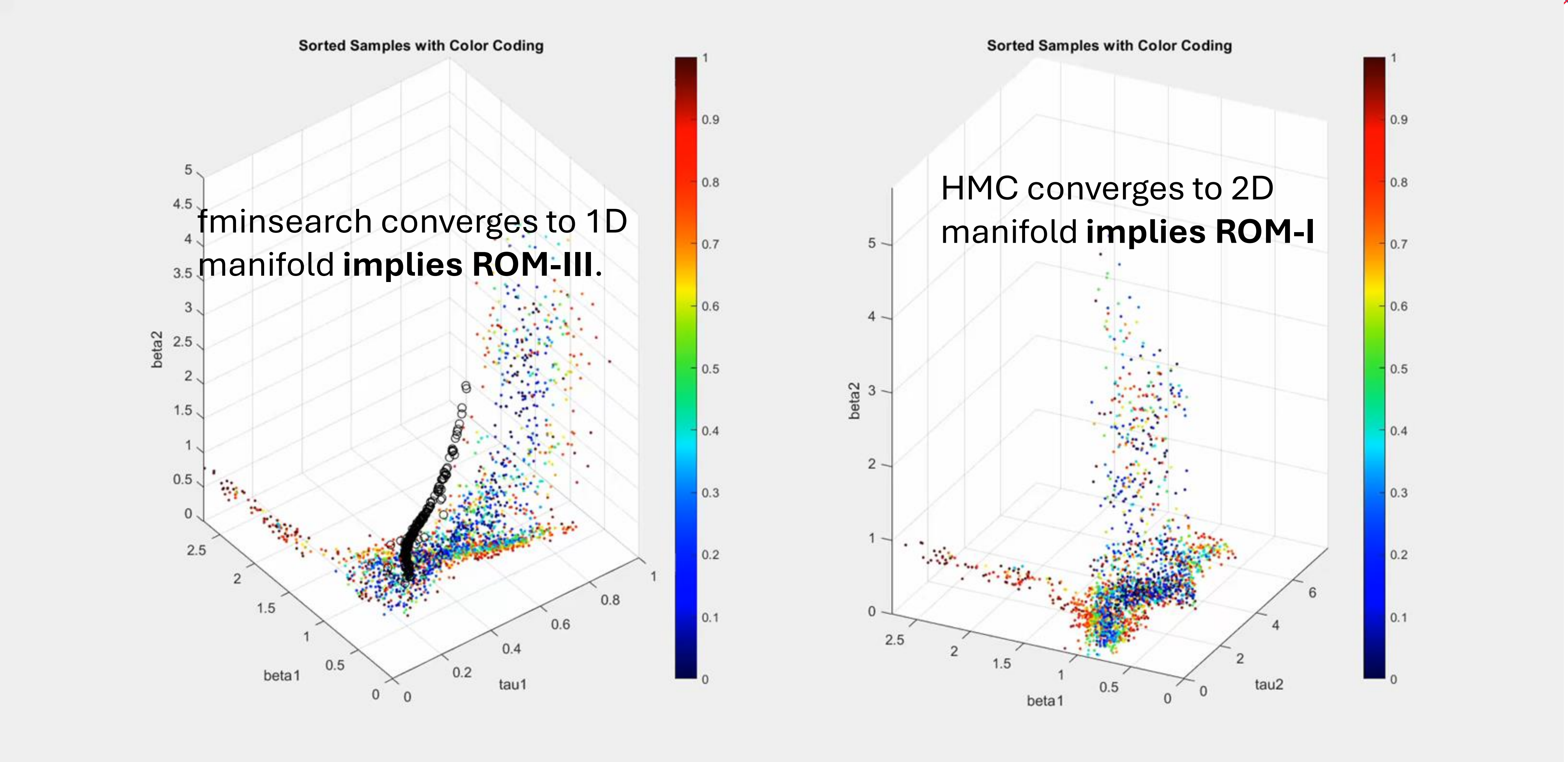
Searching Reduction Path using HMC



Combining all the sampled points
NumSamples: 358,400
Simulation time: Over 4 days

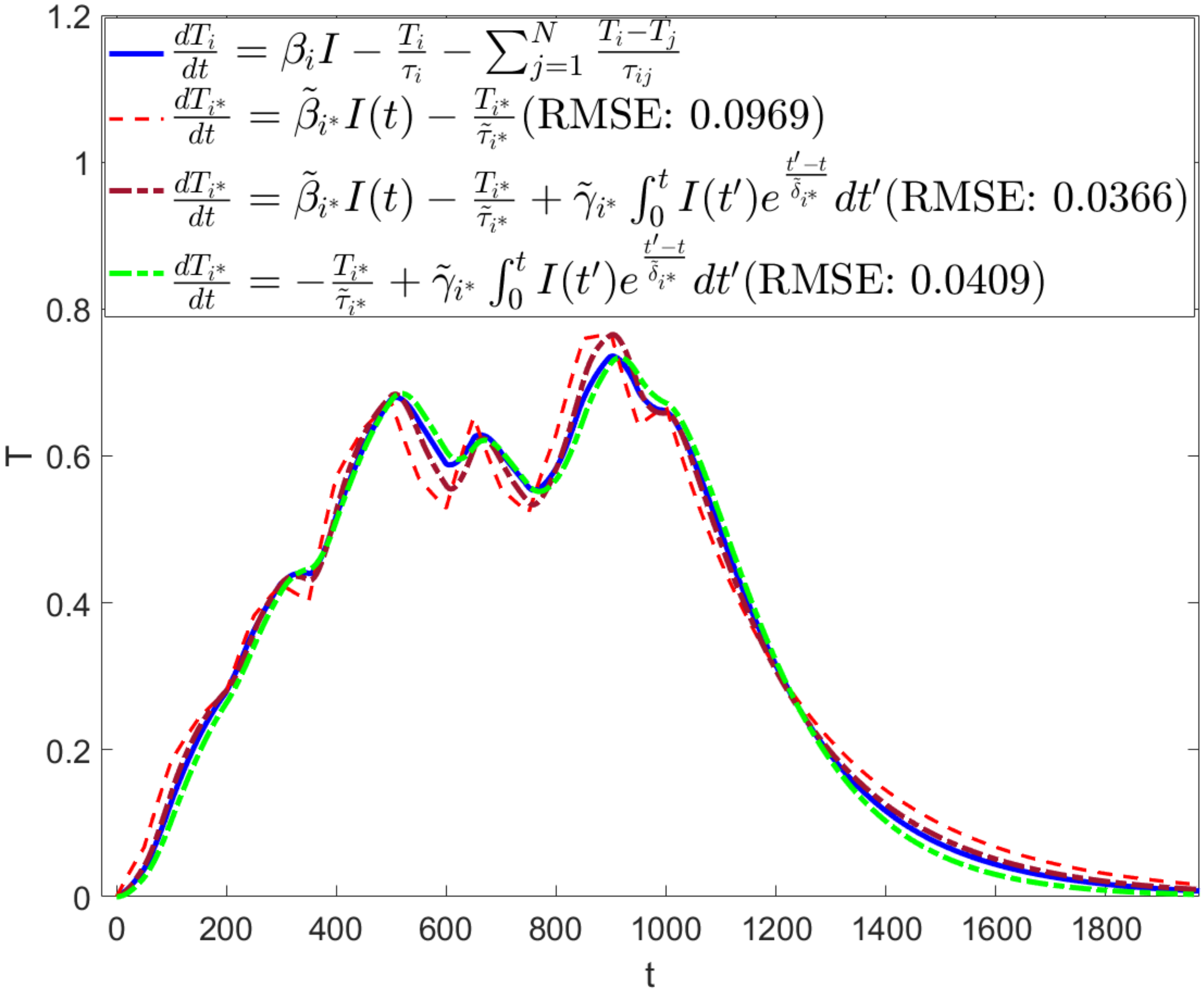
- Custom Objective Function is developed for our integral equation
- Multiple Random Starts using HMC sampler in Matlab
- Large number of samples are needed to identify reduction paths
- Low execution algorithm are needed for automation

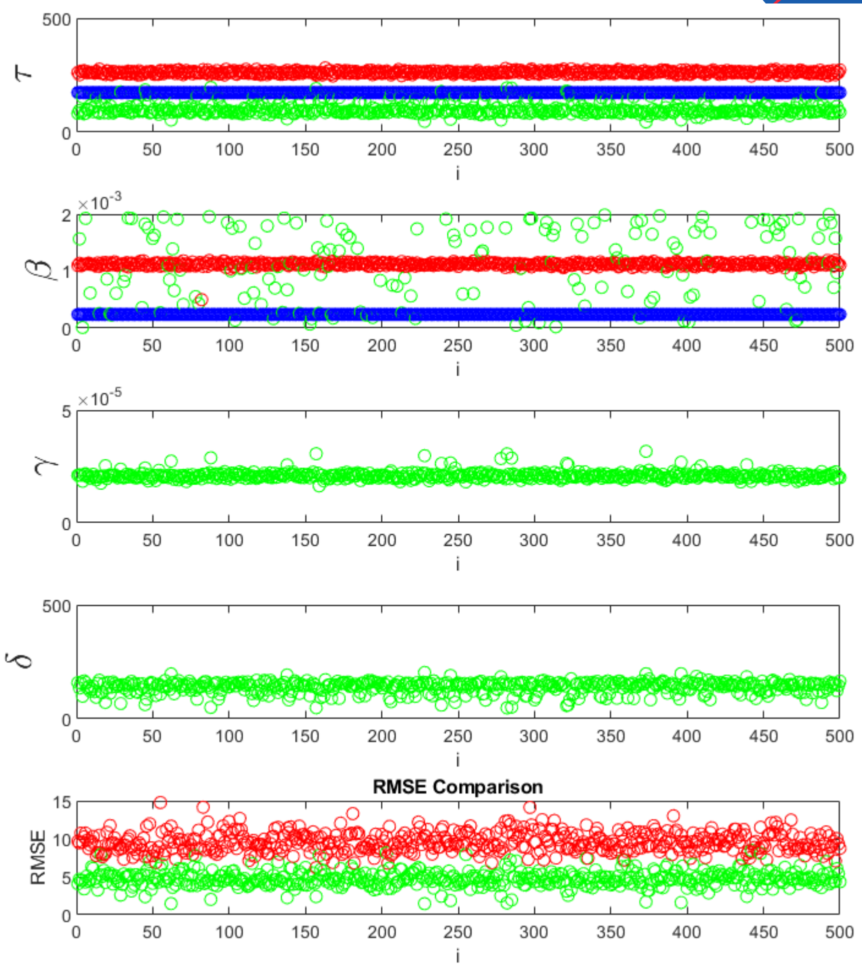
Comparing HMC vs. fminsearch



Inadequate sampling for high dimensional problem can lead to a non-identifiable reduced order model

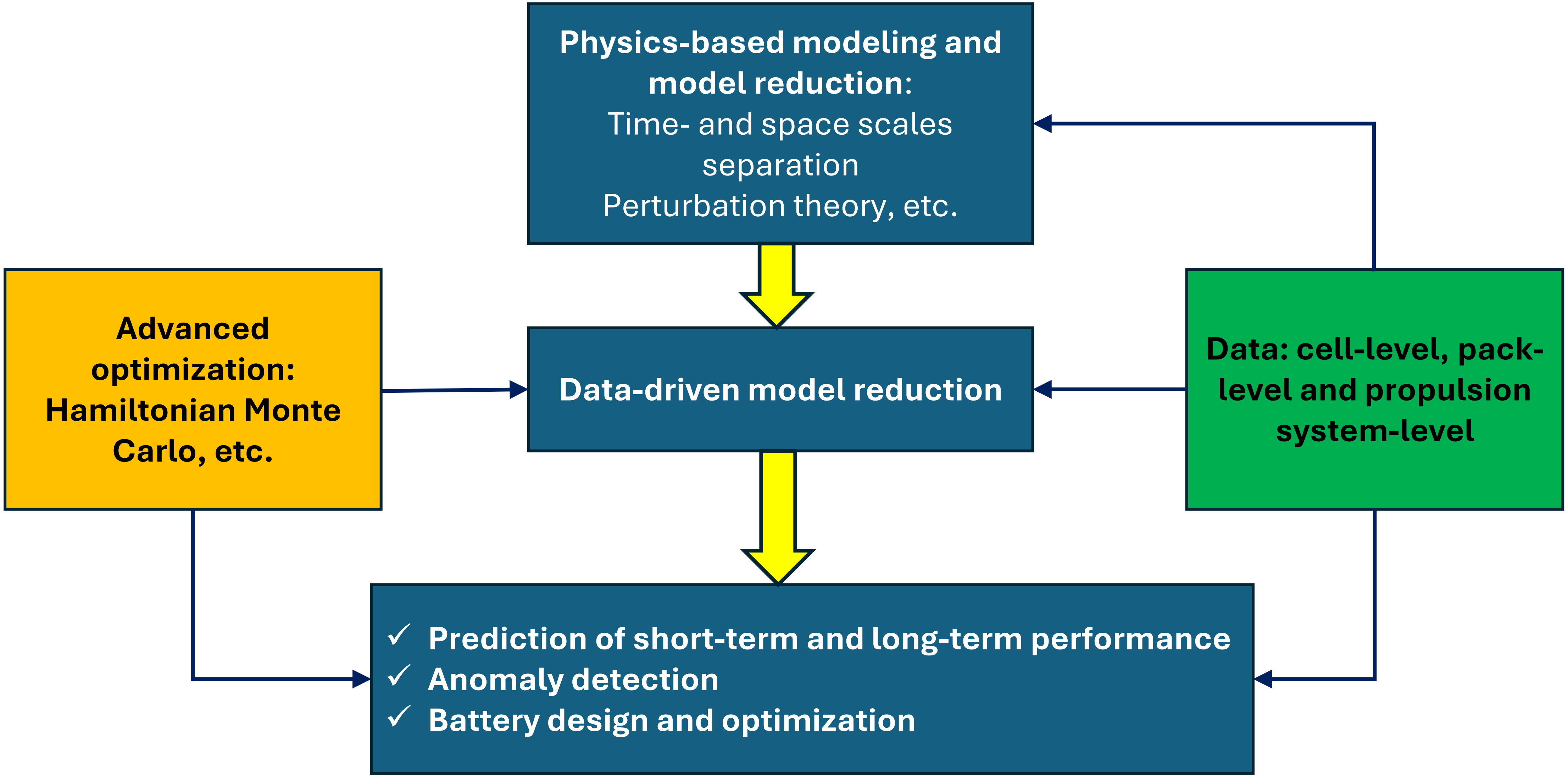
Comparing ROMs (synthetic dataset)





- Full model, local parameters (blue)
- ROM I (red) : identifiable but not accurate
- ROM II (brown) accurate but non-identifiable
- ROM III (green) accurate and identifiable

PIDD Model Reduction Framework



Summary

I. The Battery Dashboard offers insights into various aspects of a battery, enabling better control over discharge time, discharge rate, and storage duration

II. Physics (thermodynamics focused) informed reduced models 3pTROM and 2pTROM are identifiable, thus allowing to monitor internal battery states

III. The 2pTROM model, initially developed for aviation, has been adapted for space batteries to parameterize thermal data related to charging and discharging

IV. Various Reduced Order Models were developed to predict thermal response of a series battery pack

V. Hamiltonian Monte Carlo and Hessian-based automation techniques were developed to efficiently map the parameter landscape and identify paths to model reduction

Backup Slides

Concept: Battery Health Dashboard

Moving Beyond Conventional "Capacity Driven " Health Monitoring

Conventional Battery State-of-Heath

- Loss of cyclable ions
- Change in Cell Resistance

Proposed Battery State-of-Heath Dashboard

- Electrode Health
- Electrolyte Health
- Thermal Health
- Ohmic Health
- Electrochemical Interface Health

Various Stresses in Deep Space Missions:

1. Large temperature variations ()
2. High γ-radiation
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Commonly monitored signatures:

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2. Time
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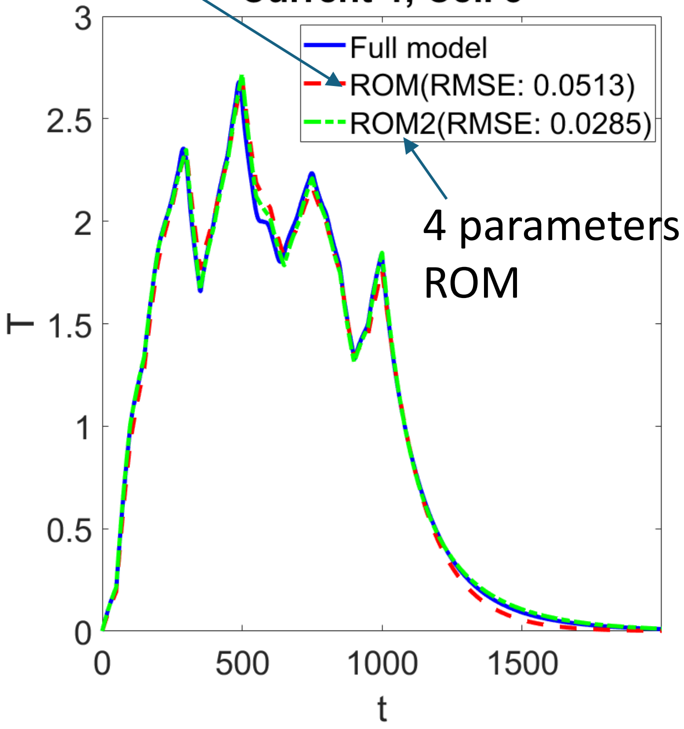
Testing thermal ROM for in-series pack

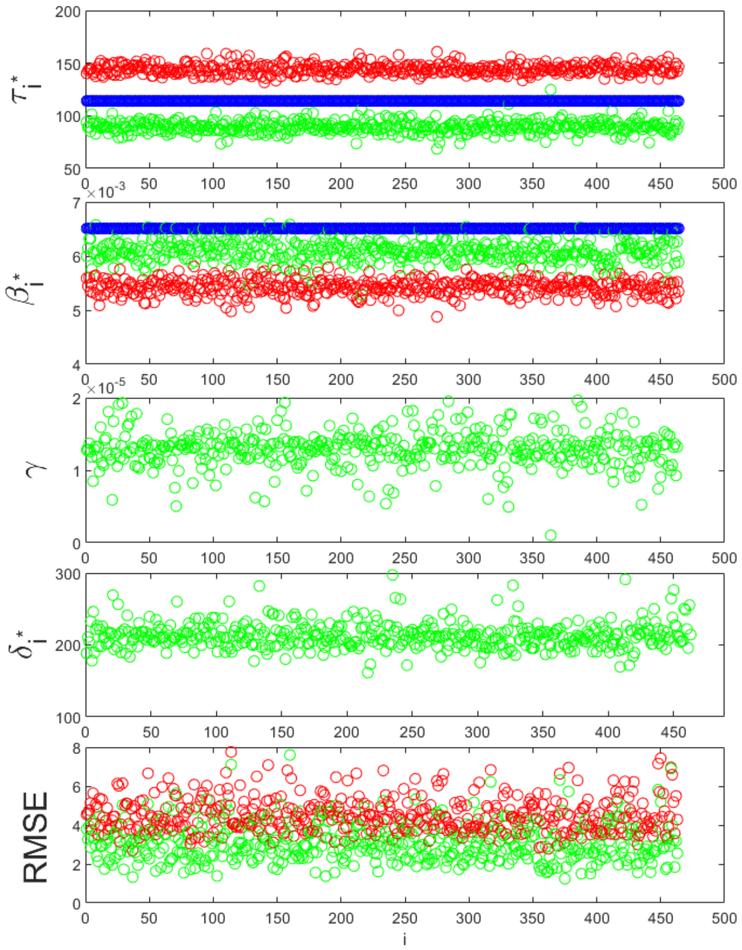
Thermal ROMs vs. synthetic data (full thermal model)

2 parameters ROM



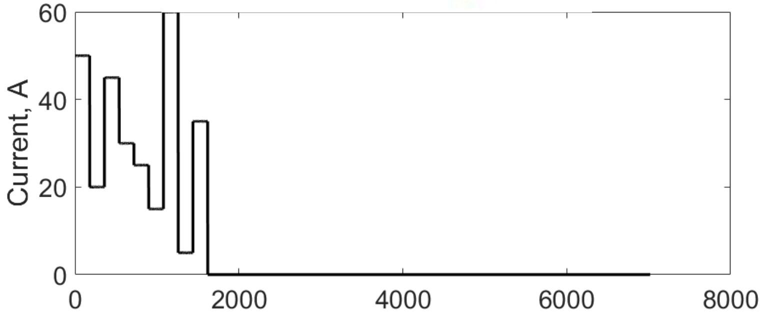
4 parameters ROM

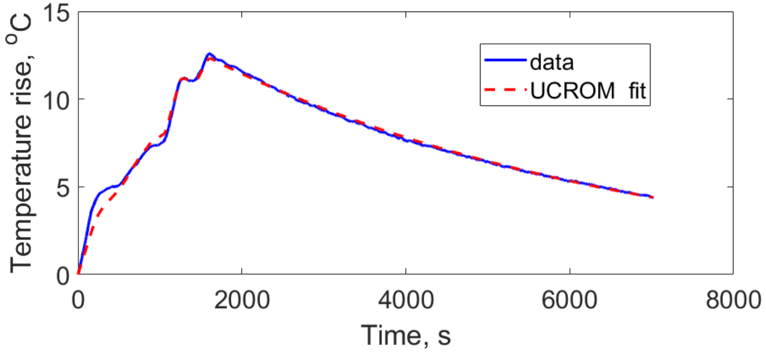
ROMs are accurate



Parameters can be identified

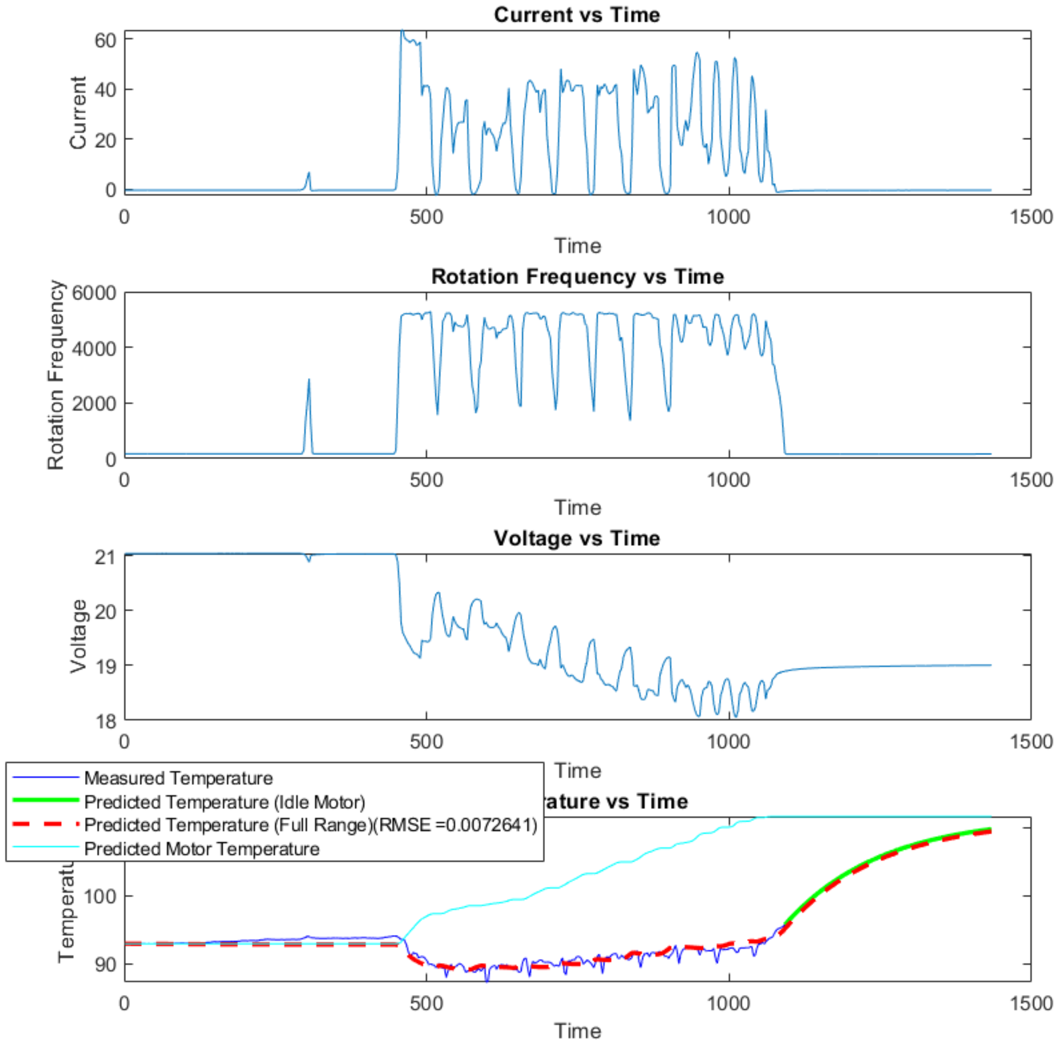
ROM vs lab thermal data





Thermal modeling of in-series packs.

UAV flight test



$$\frac{dT}{dt} = -(T - T_a)a\omega(t)^{\alpha} - \frac{T - T_m(t)}{\tau},$$

$$T_m(t) = T_m(0) + R\int_0^t I(t')^2 dt', \quad T_m(0) = T(0).$$