# Data-Driven Robust Control for a Closed-Loop Artificial Pancreas

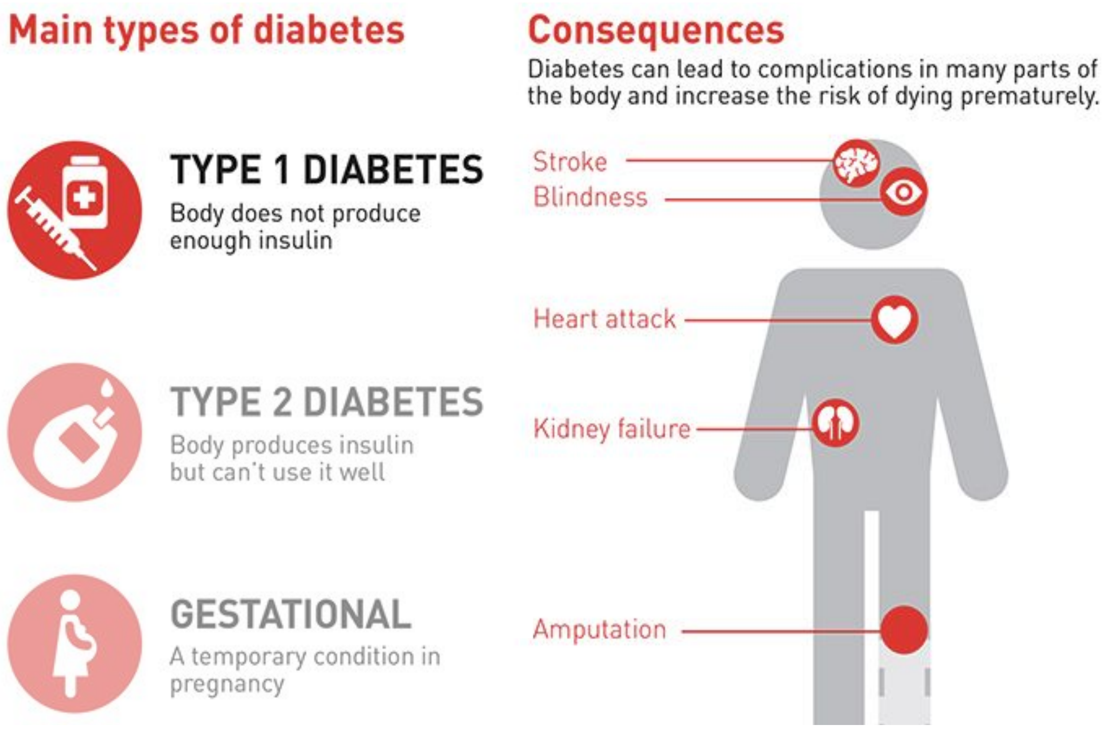
Nicola Paoletti
Department of Computer Science, Stony Brook University, USA

Joint work with: Shan Lin, Scott A Smolka, Kin Sum Liu

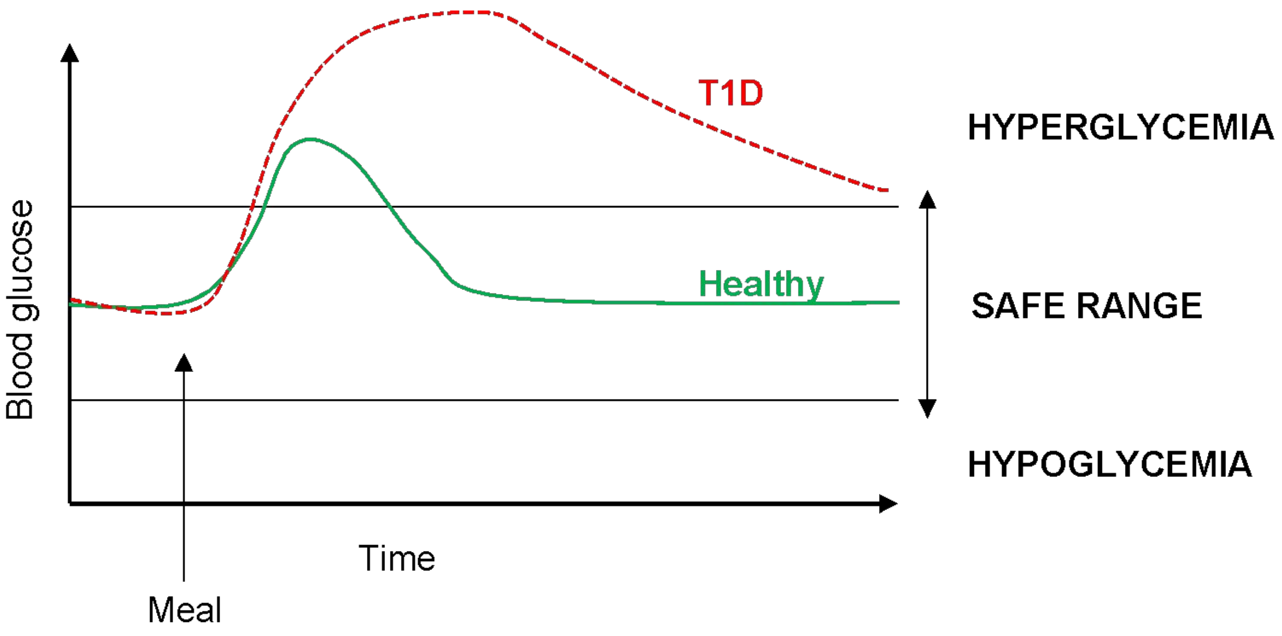
- Supported by NSF CPS Frontier grant *CyberCardia*
- Published in *Computational Methods in Systems Biology 2017* and *IEEE/ACM Transactions on Computational Biology and Bioinformatics (under review)*

Mathworks Research Summit, Newton MA, 4 Jun 2018

# Type 1 diabetes (T1D)




WHO Global report on diabetes, 2016



# T1D therapy

**Glucose monitor (CGM)**

Detects sugars levels under the skin

**Insulin pump**

Delivers bolus insulin (to cover meals) and basal insulin (to cover demand outside meals)

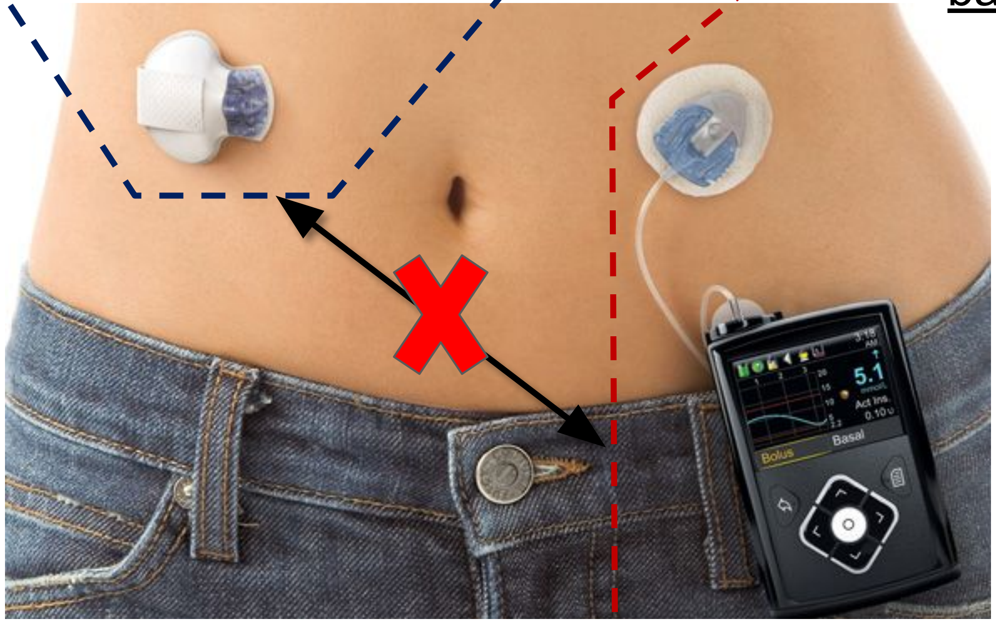
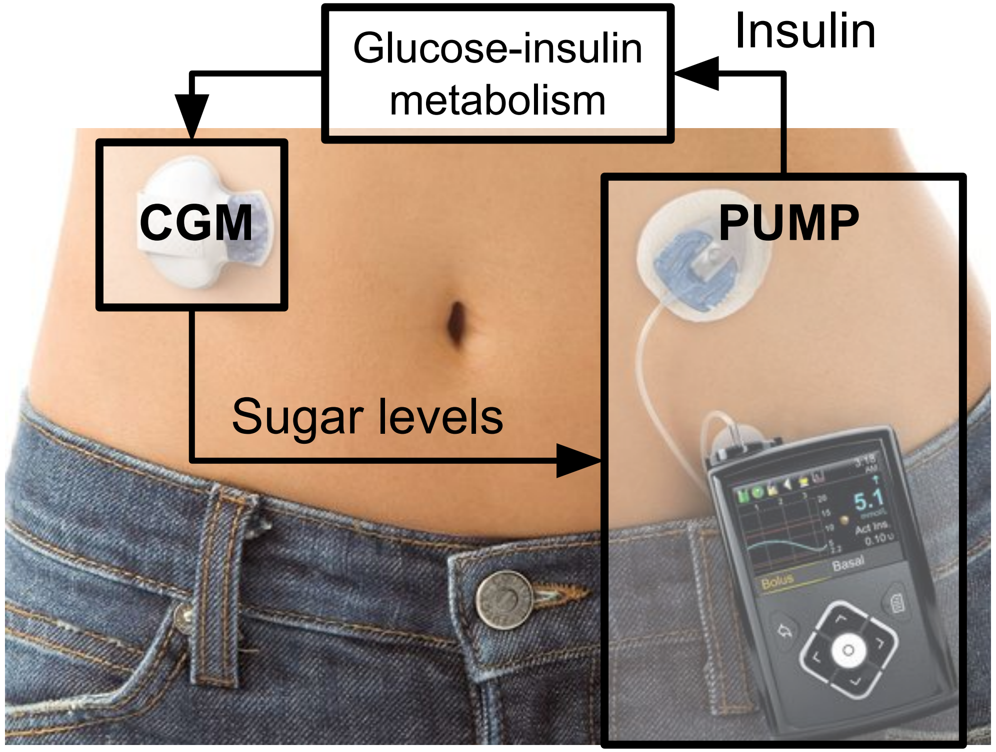



Image from: https://www.medtronic-diabetes.com.au/pump-therapy/what-is-insulin-pump-therapy

## LIMITATIONS

- **Pump and CGM don't communicate with each other**
- Bolus is manually set by the patient with meal announcements → **danger of wrong dosing**

# Closed-loop control, aka Artificial Pancreas (AP)




**<u>Challenges</u>**

→ CGM is a “derived” measure of BG (noisy and delayed)

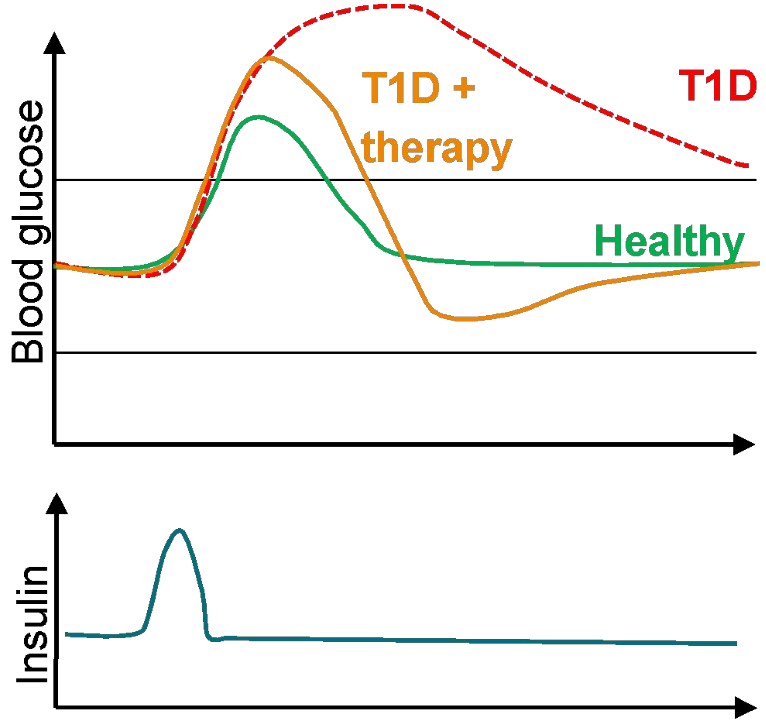
→ **Disturbances** related to patient behavior (<u>Meals and Exercise</u>)

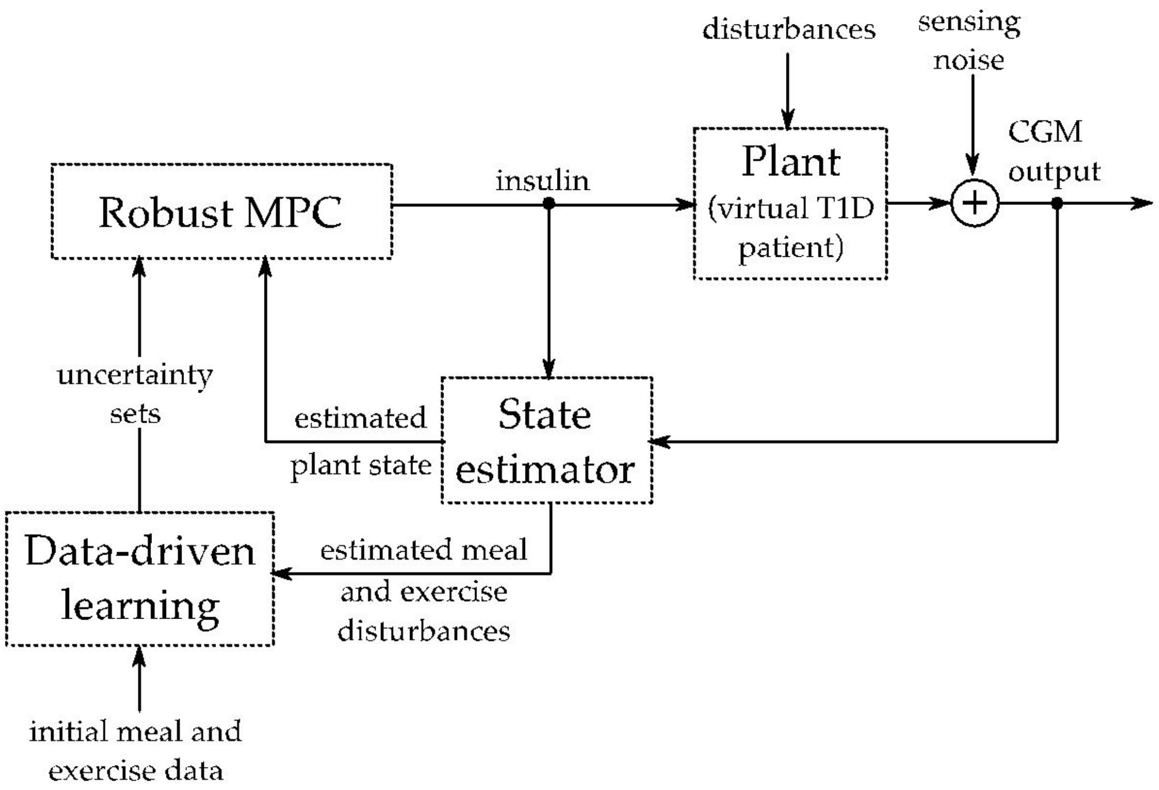
**<u>Not just medical but also a CPS challenge</u>**

# Artificial Pancreas, a control problem

<u>**OUR SOLUTION**</u>: **Data-driven robust model predictive control (MPC)** for the AP:

- Closed-loop control of **both basal and bolus insulin**
- Handles uncertainty by **learning from data**
- Accurate **state estimation from CGM measurements**



# Data-driven uncertainty sets

- Learn from data **uncertainty sets** that **capture realizations of random disturbances** (meal and exercise)

- Method that provides **uncertainty sets with probabilistic guarantees** *[Bertsimas et al., Mathematical Programming 167(2), 235–292, 2018]*:

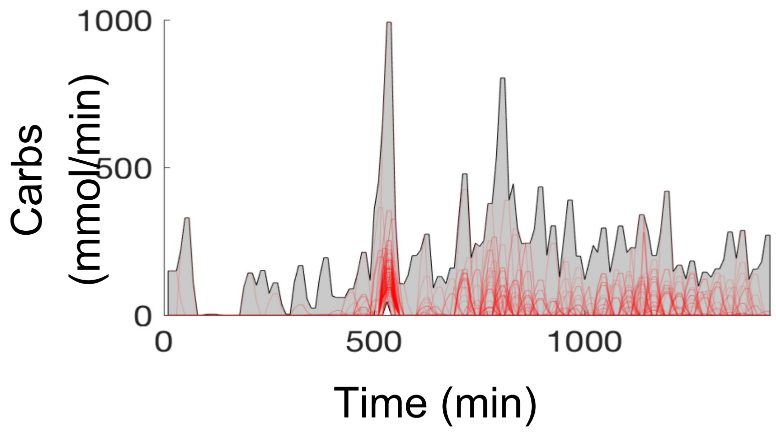
**Meal/exercise data**

(questionnaires, surveys, sensors, …)

nhanes National Health and Nutrition Examination Survey

| | Breakfast | | |
|---|---|---|---|
| **Days** | *Start Time* | *Food1* | *Food2* |
| *1st Day* | 12:49PM | 150g Greek Yogurt | 3 pieces of toast |
| *2nd Day* | 9:00AM | 1 glass whole milk | 150g plain yogurt |
| *3rd Day* | 9:20AM | 1 egg | 3 slices of toast |

**Uncertainty Sets**



# Insulin control and state estimation, formally

**Robust MPC:**

- Find the insulin therapy that minimizes the worst case performance w.r.t. unknown disturbances
- Performance: distance of predicted glucose from target + step-wise discrepancy of control strategy

$$\min_{u^t,\ldots,u^{t+N_c-1}} \max_{\mathbf{d}^t,\ldots,\mathbf{d}^{t+N_p-1}} \sum_{k=1}^{N_p} d(\tilde{\mathbf{x}}(t+k)) + \beta \cdot \sum_{k=0}^{N_c-1} (\Delta u^{t+k})^2$$

**Moving Horizon Estimator (MHE),** “Estimation *a la* MPC”:

- Uses a model to minimize distance between predicted and actual measurements, and between predicted and estimated states over a moving window of length N
- It works also as a **meal estimator:** estimates the most-likely uncertainty parameter values

$$\min_{\substack{\boldsymbol{\chi}(t-N),\ldots\boldsymbol{\chi}(t),\\ \boldsymbol{\delta}^{t-N},\ldots,\boldsymbol{\delta}^{t-1}}} \mu \cdot \|\boldsymbol{\chi}(t-N) - \hat{\mathbf{x}}(t-N)\|^2 + \sum_{k=0}^{N-1} \frac{\|v^{t-k}\|^2}{q^{t-k}}$$

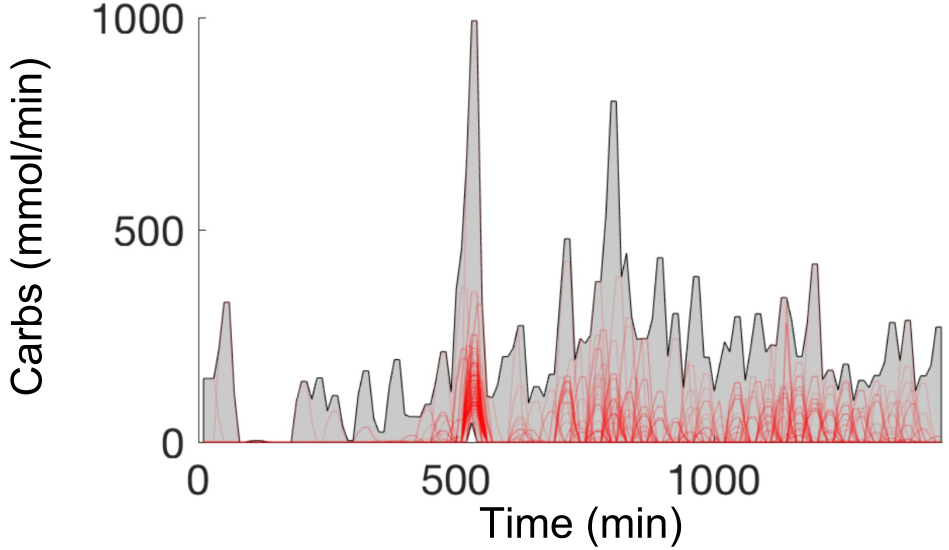
# Virtual patient learnt from NHANES database

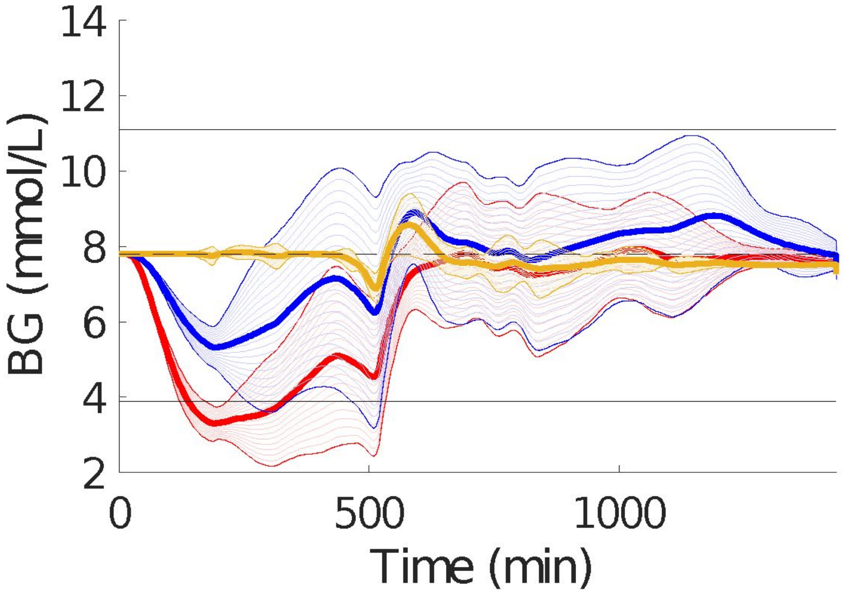
- We learn patient models from CDC's NHANES

National Health and Nutrition Examination Survey

- Meal data from **8,611 participants**
- Data clustered into 10 main groups

GROUP 1: Carbs-rich breakfast




| | T hypo | T in range | T hyper |
|---|---|---|---|
| **Perfect** | 0% | 100% | 0% |
| **Non-robust** | 18.5% | 80.97% | **0.53%** |
| **Robust** | **2.02%** | **93.45%** | 4.52% |

# Summary

- Data-driven robust MPC approach for insulin therapy
- In-silico evaluation on real and synthetic data
- Towards fully closed-loop diabetes therapy

# Ongoing and future work

- Formal synthesis of robust PID controllers [HVC'17] [ICCAD'18, submitted]
- "Human-in-the-loop" control
- Evaluation on real devices and patients