Model-bounded monitoring of hybrid systems

Masaki Waga[1], Étienne André[2], Ichiro Hasuo[3]

Kyoto University[1], Université de Lorraine[2],
National Institute of Informatics[3]

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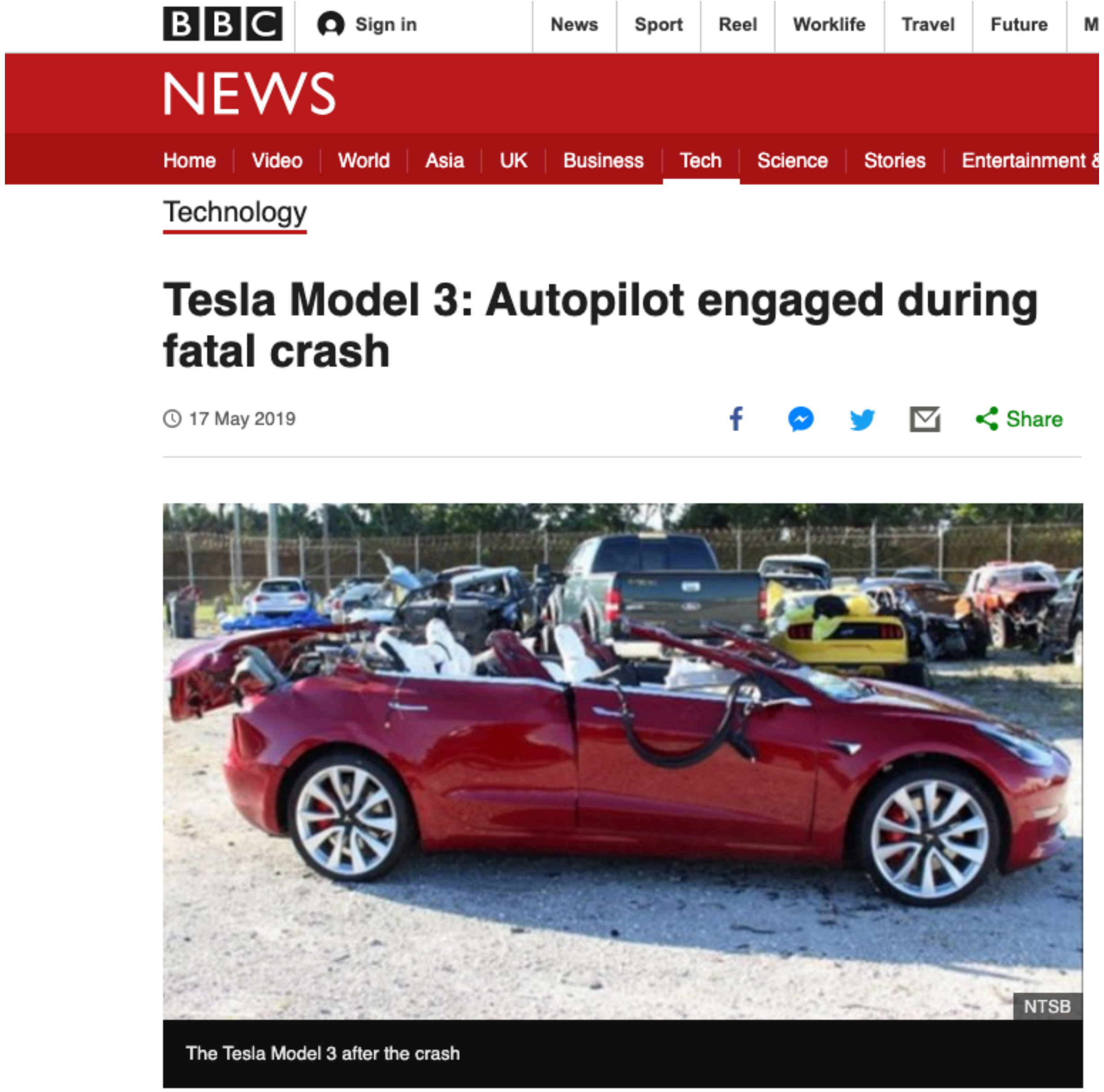
Safety Critical CPSs

Self-driving car crash in Arizona: Red light runner hits Waymo van

Photo by: Air15



Technology

Tesla Model 3: Autopilot engaged during fatal crash

17 May 2019

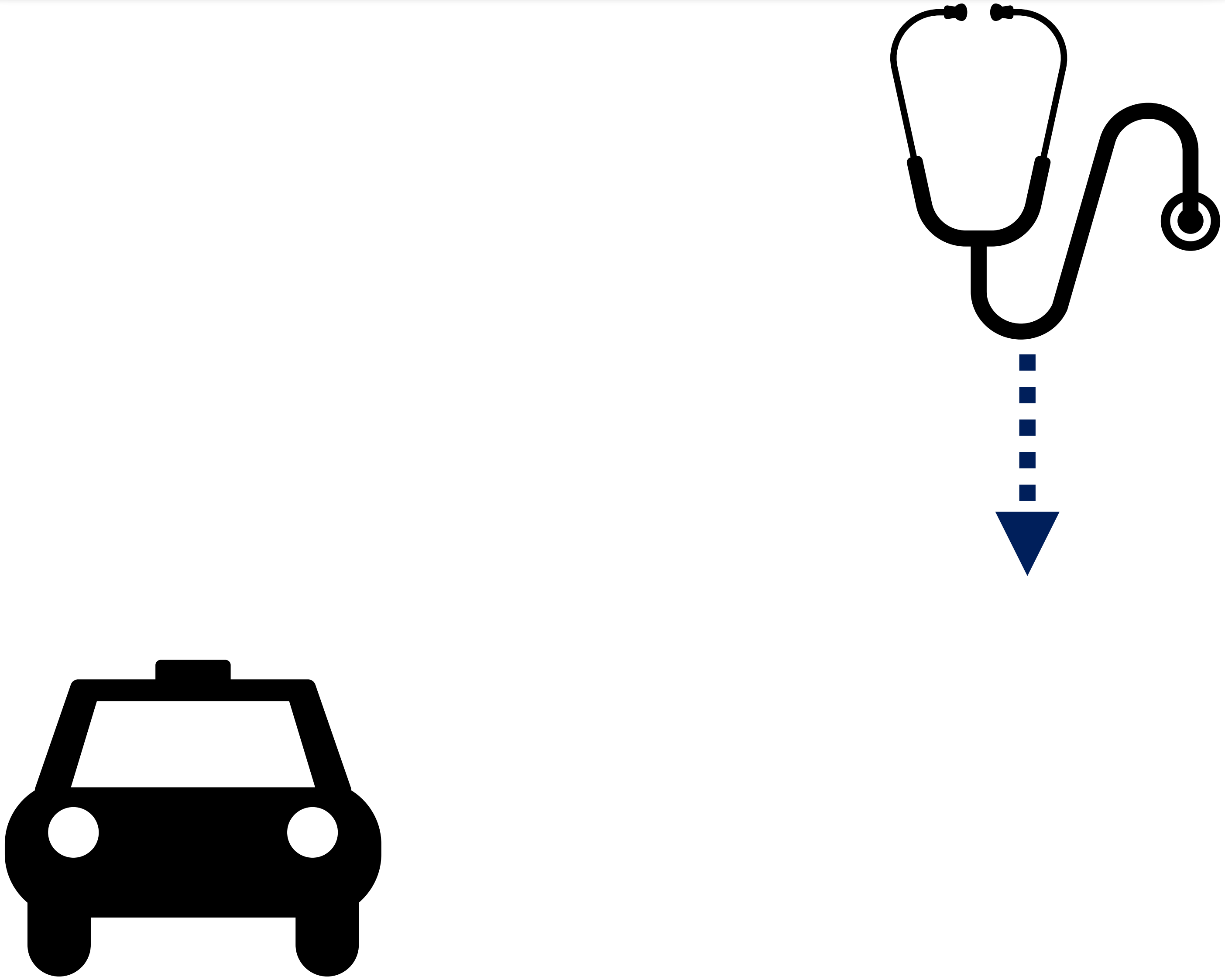
The Tesla Model 3 after the crash

https://www.abc15.com/news/region-southeast-valley/chandler/waymo-car-involved-in-chandler-arizona-crash

https://www.bbc.com/news/technology-48308852

Monitoring

Specification: **No** $(v > 120)$



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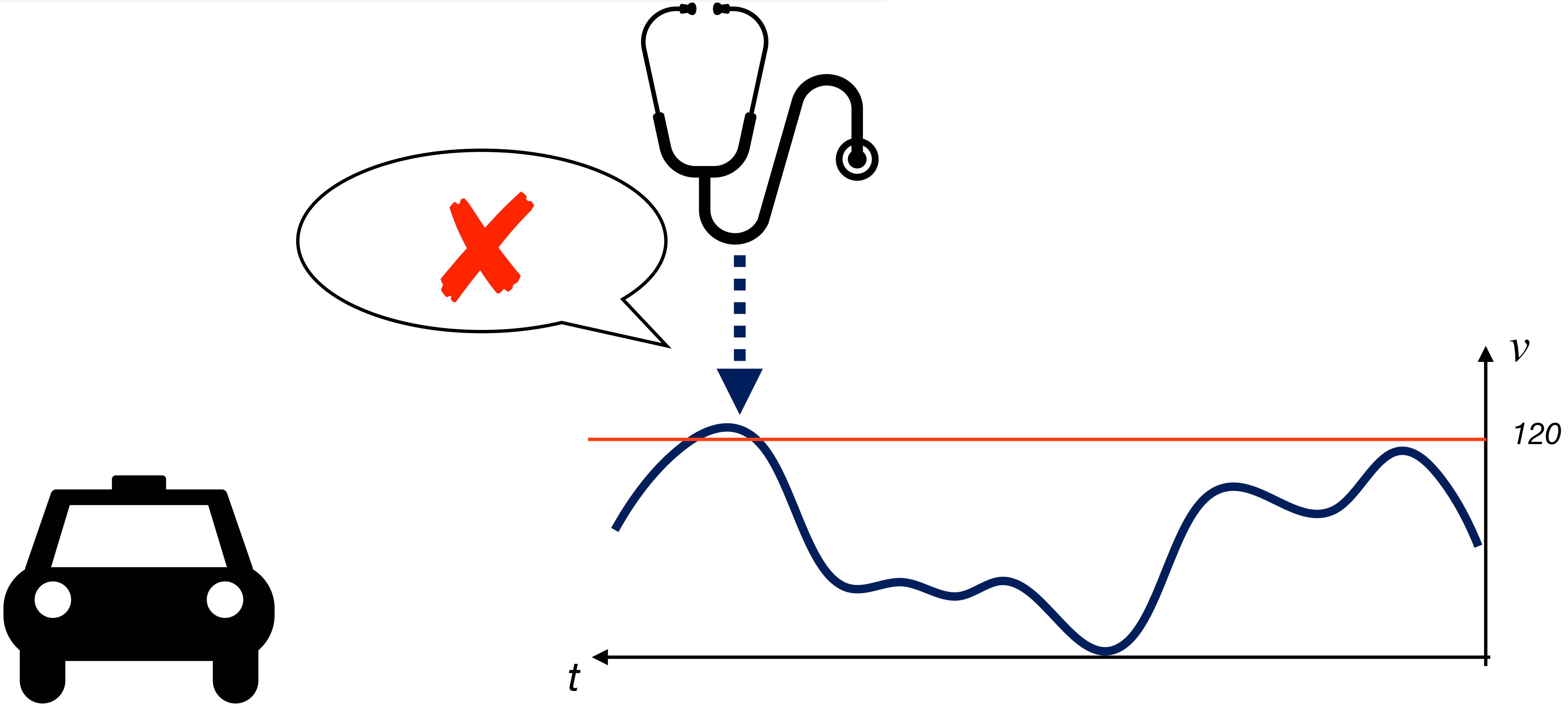

Monitoring with Sampling

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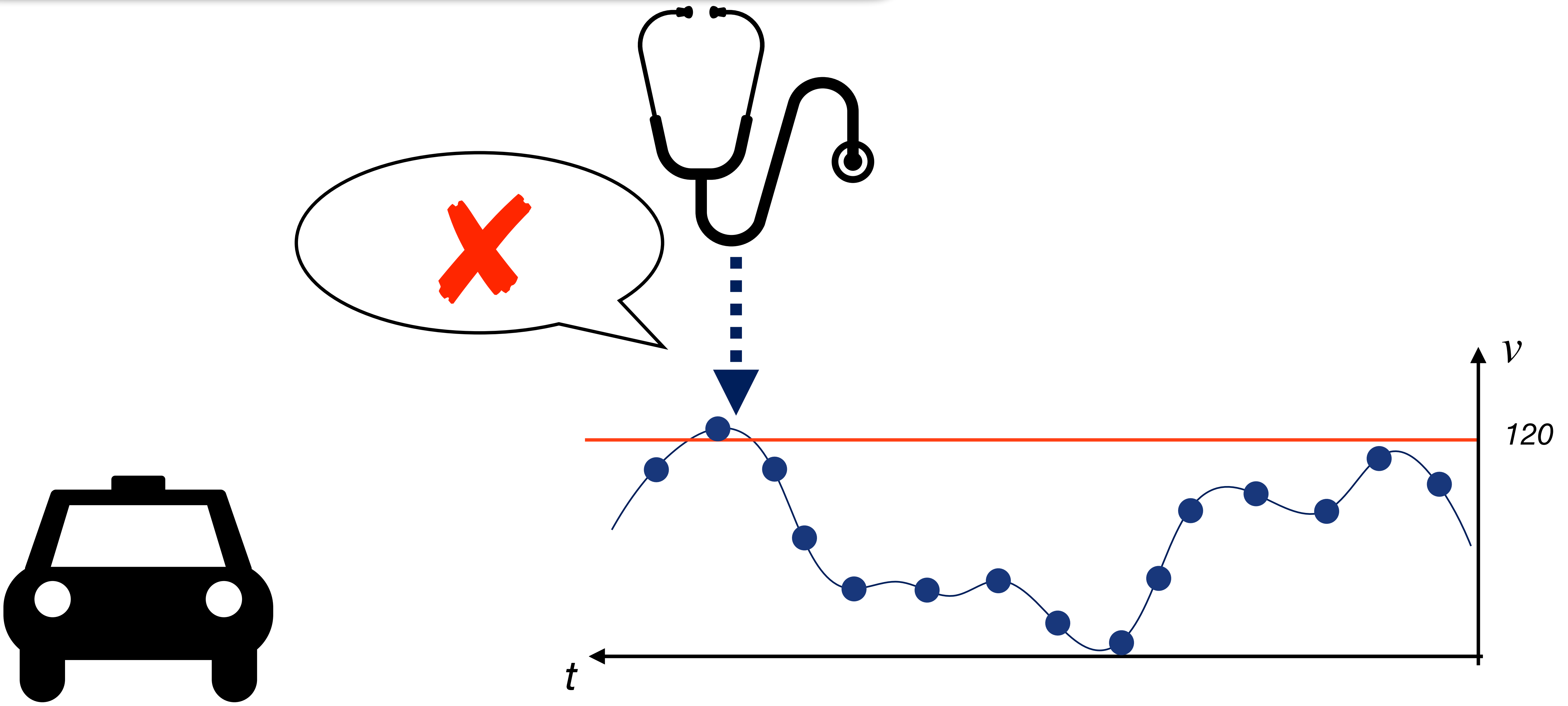

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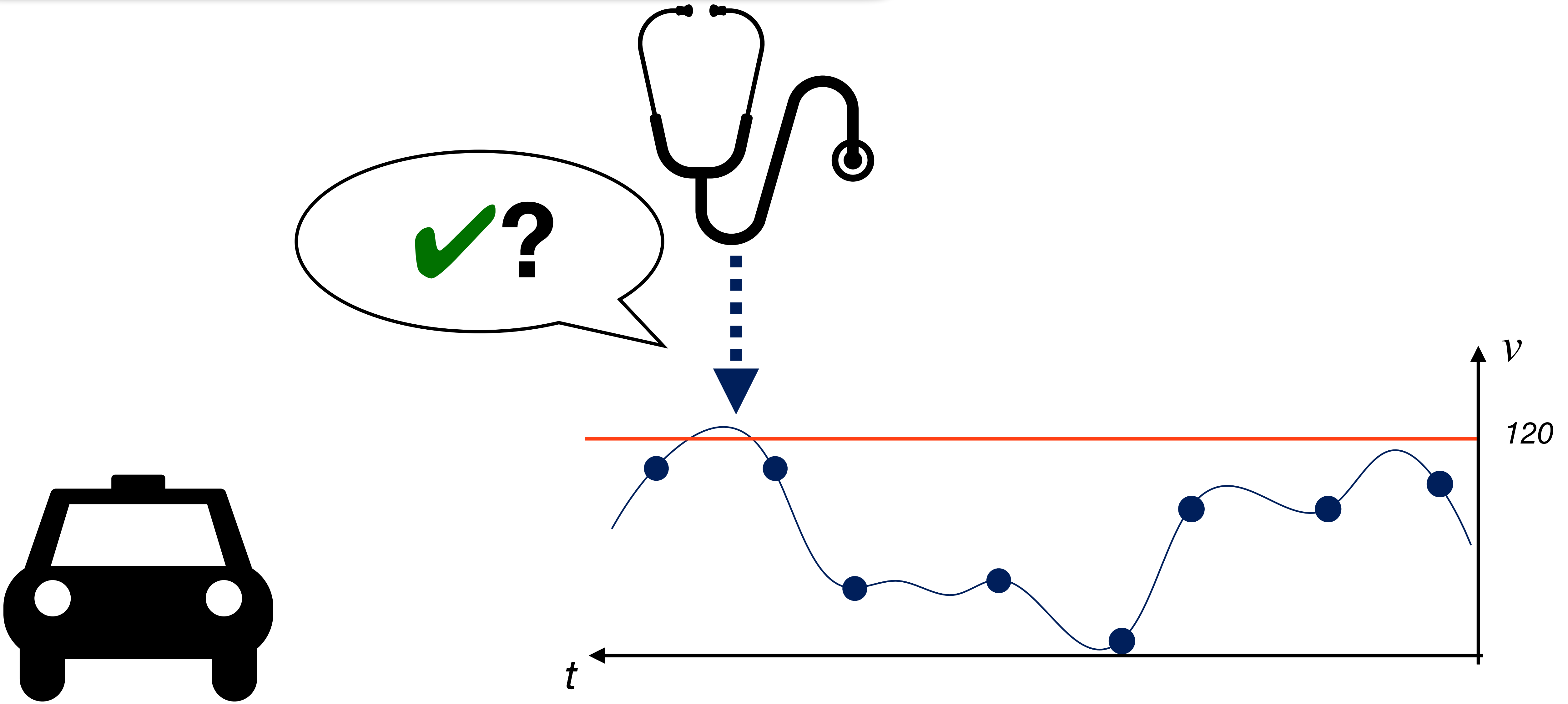

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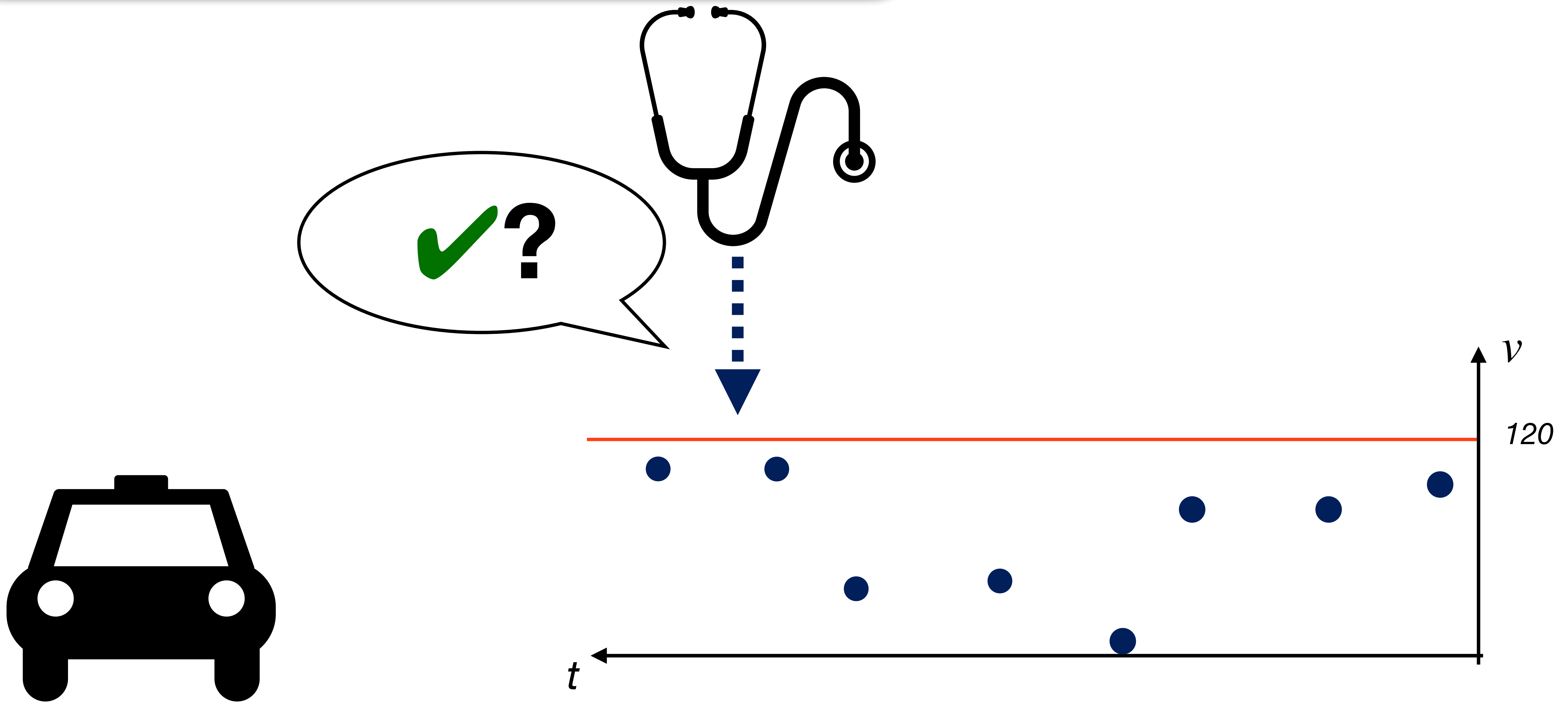

Signal Interpolation

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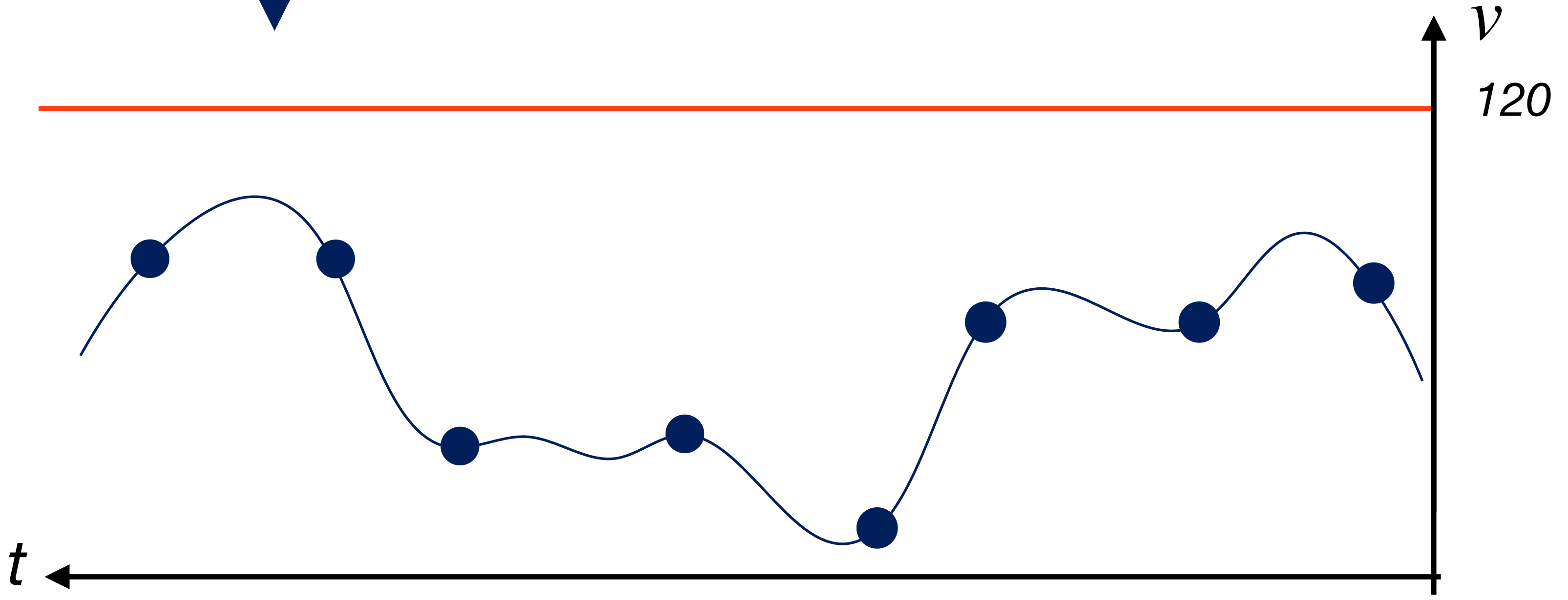

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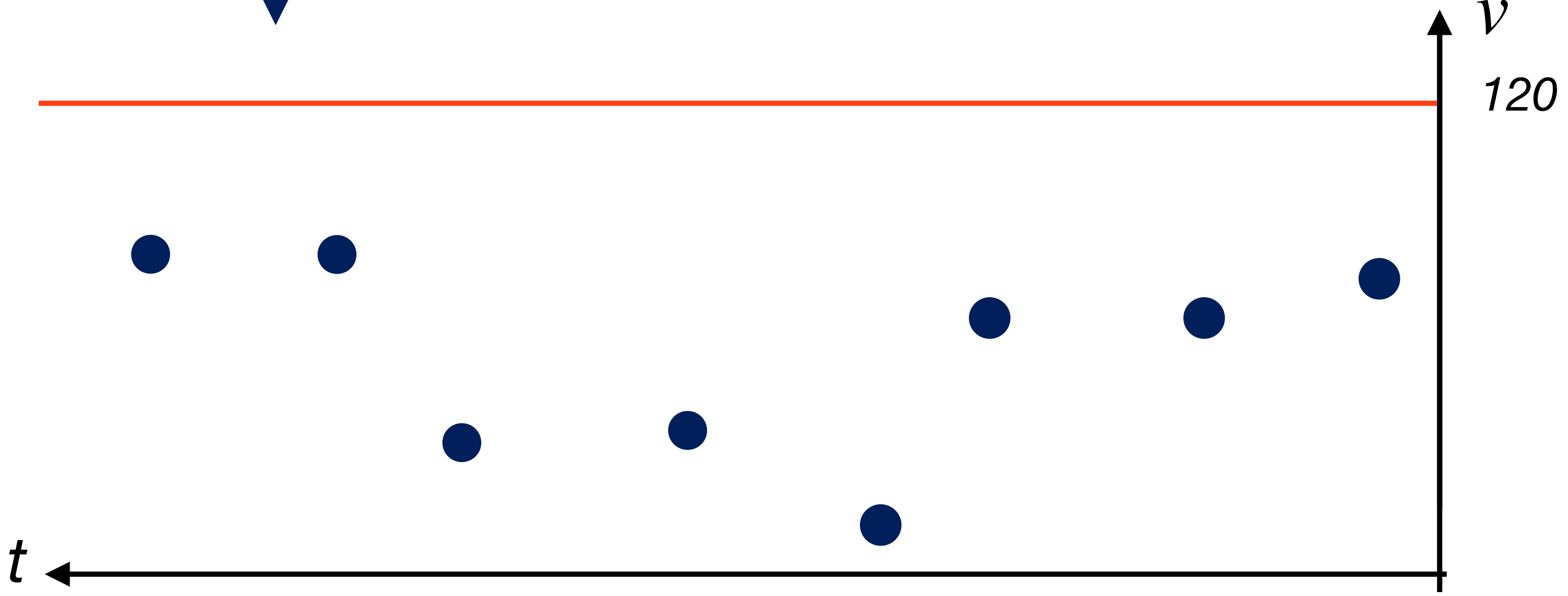

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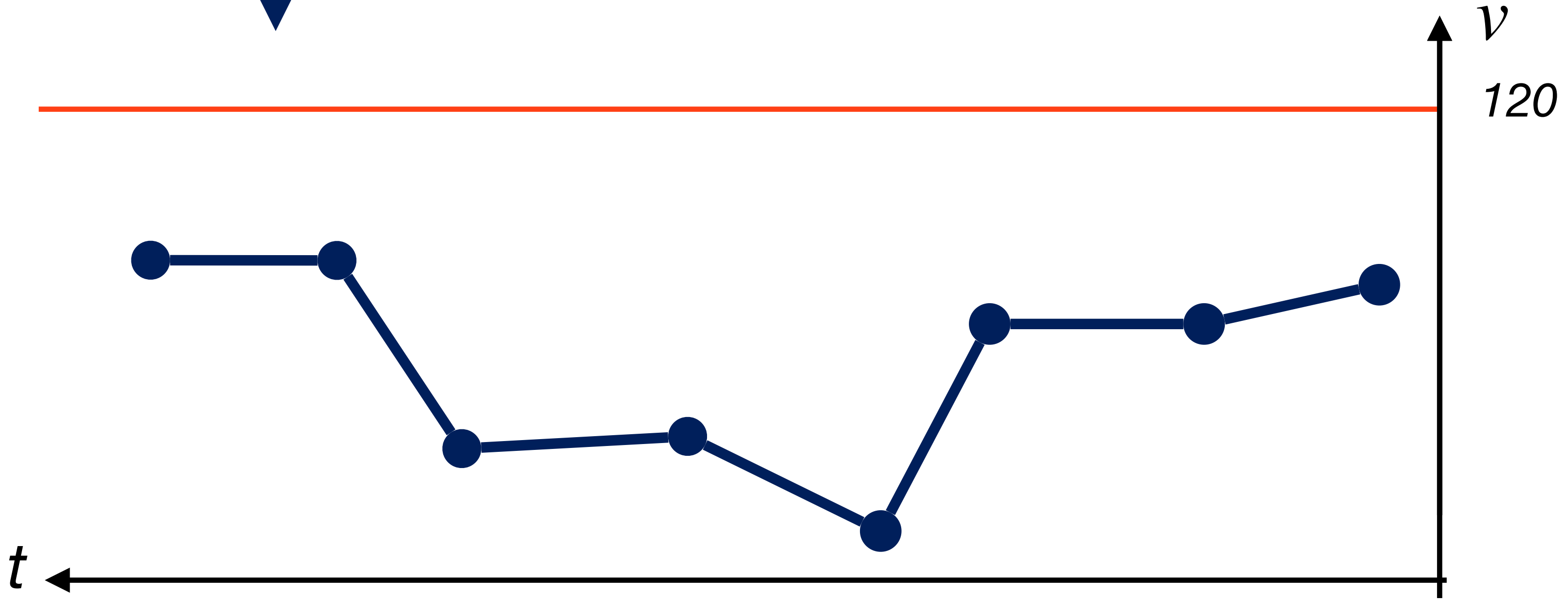

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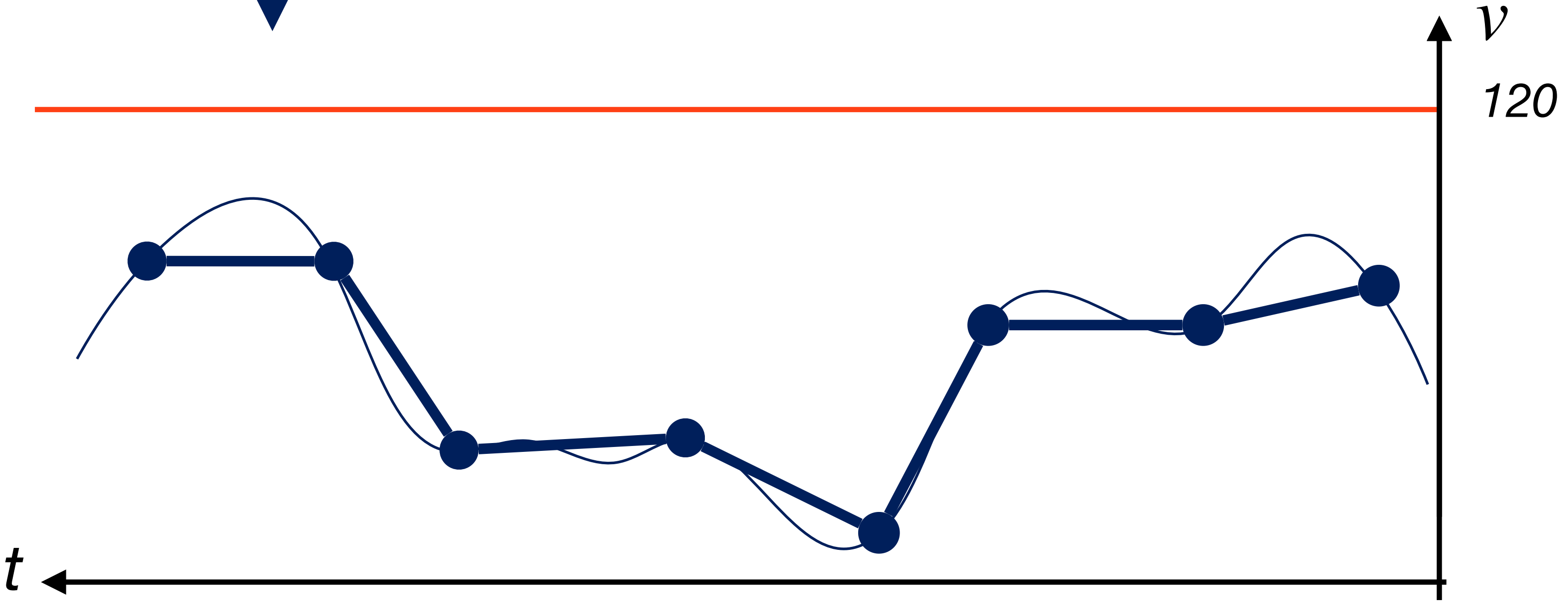

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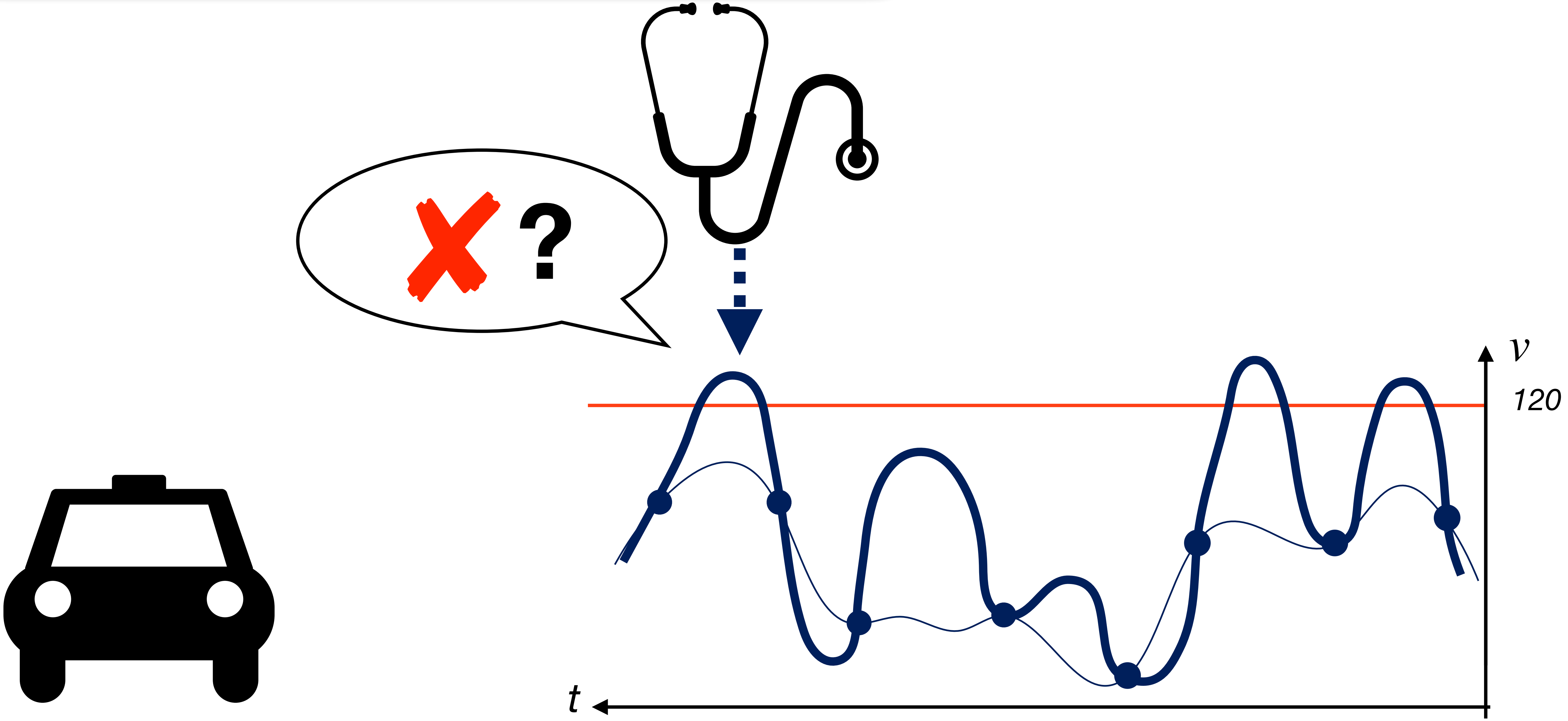
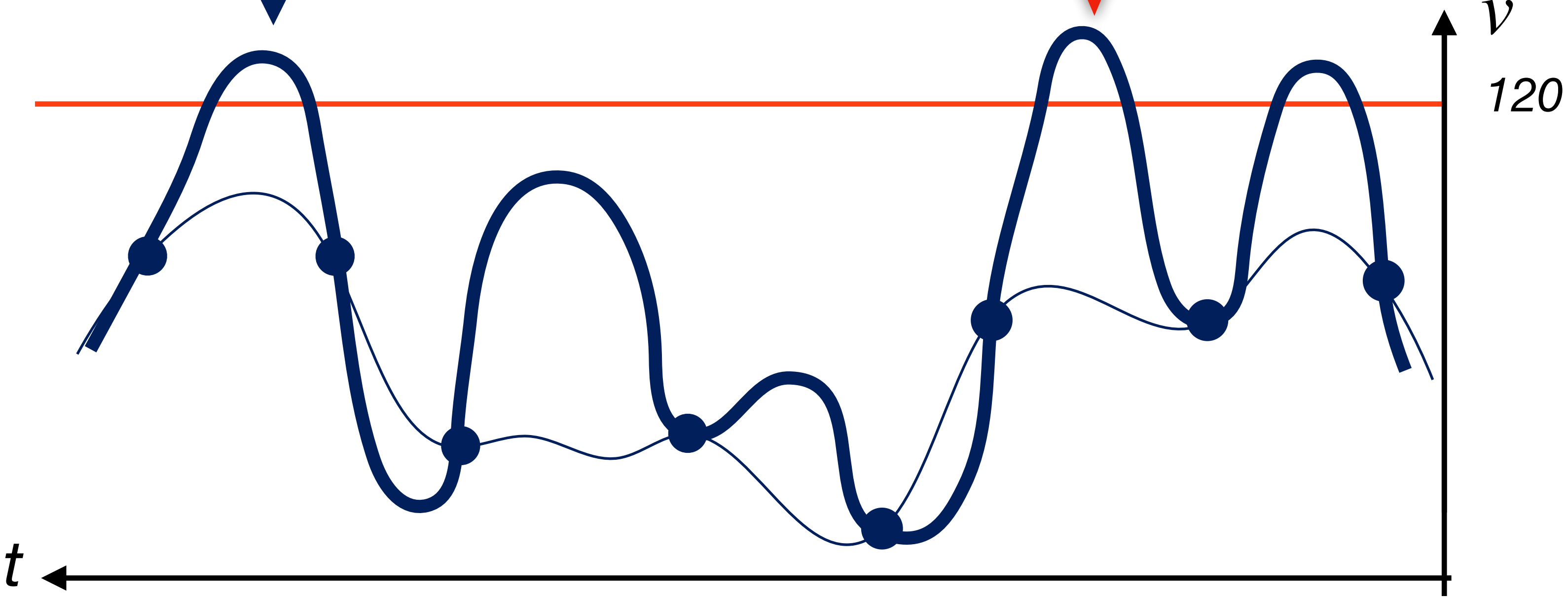


Interpolation with Prior Knowledge

Specification: No $(v > 120)$

Impossible because

$$\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$$



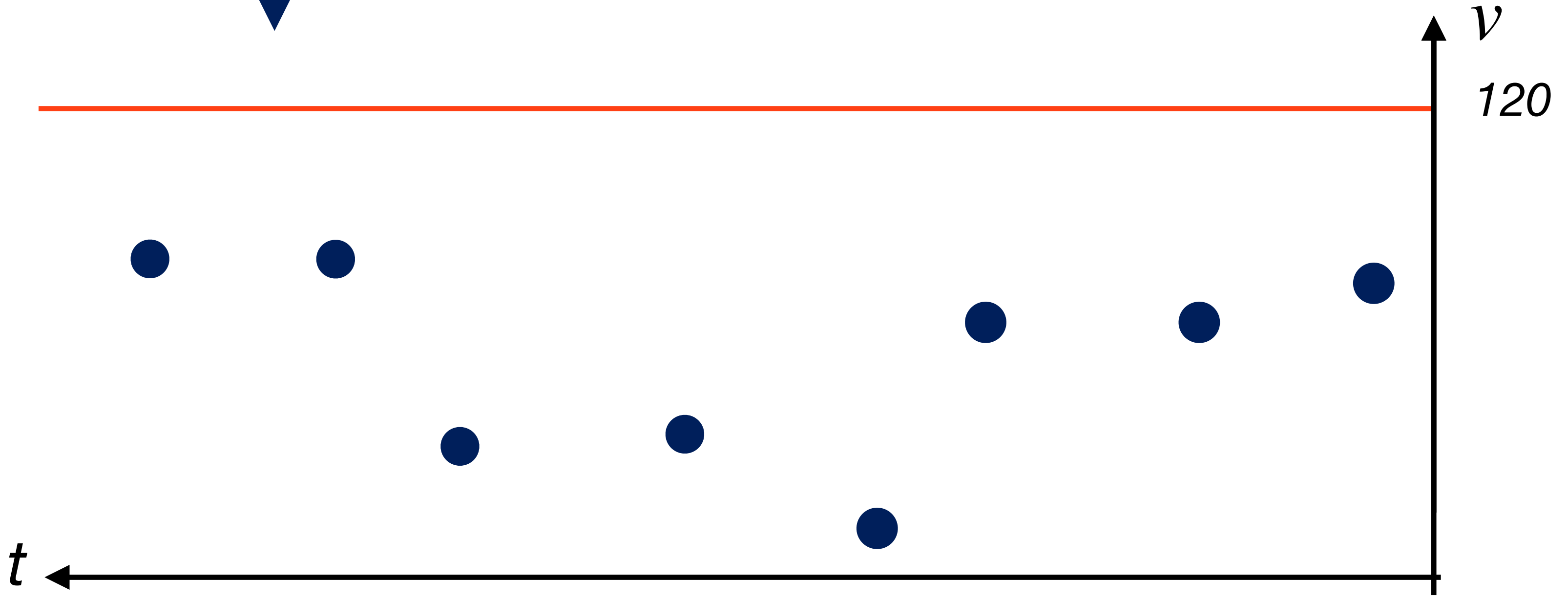
Model-Bounded Monitoring

Our Contribution

Specification: No $(v > 120)$

Knowledge (bounding model)

$$\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$$



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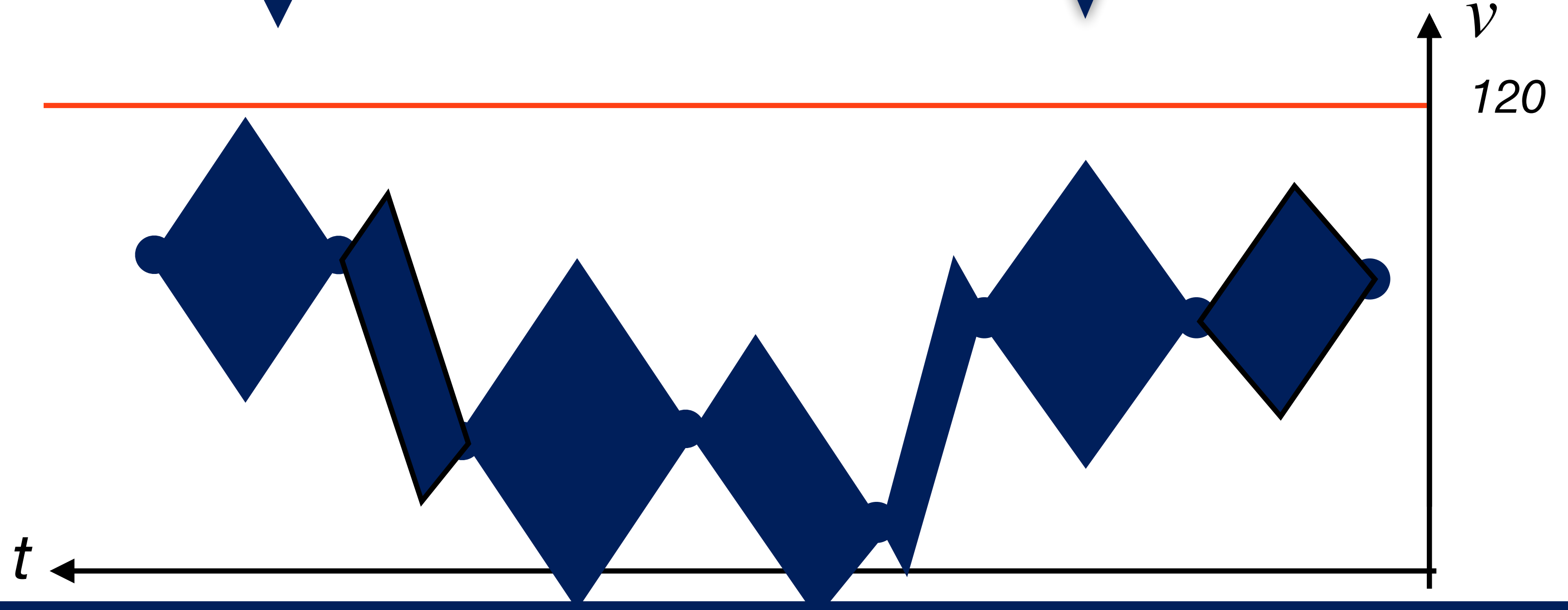
$$\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$$

Feasible execution with $\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$



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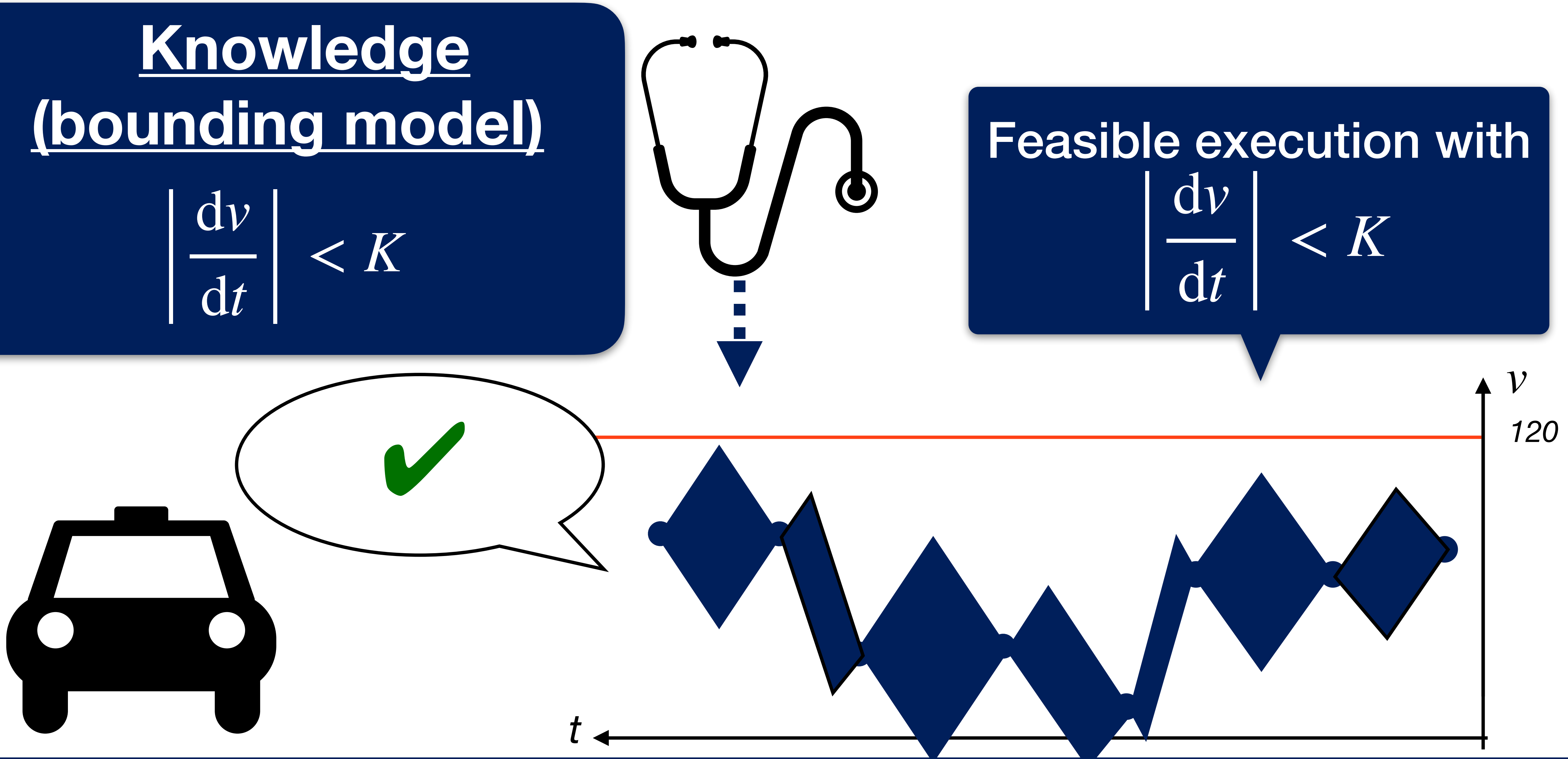


Q. How to Represent Bounding Model?

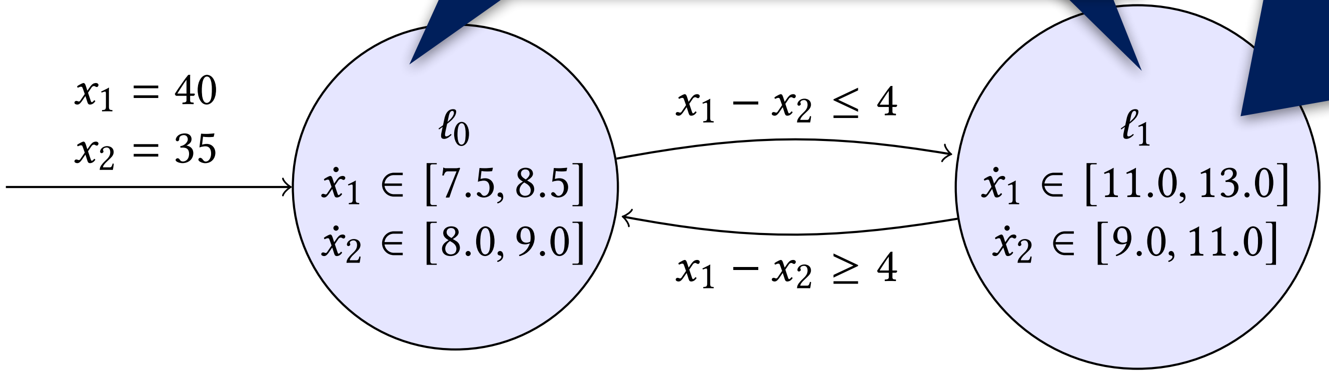
Knowledge (bounding model)

$$\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$$

A. Linear Hybrid Automata

Discrete modes

Derivative by Polyhedron


$x_1 = 40$
$x_2 = 35$
ℓ_0
$\dot{x}_1 \in [7.5, 8.5]$
$\dot{x}_2 \in [8.0, 9.0]$
$x_1 - x_2 \leq 4$
$x_1 - x_2 \geq 4$
ℓ_1
$\dot{x}_1 \in [11.0, 13.0]$
$\dot{x}_2 \in [9.0, 11.0]$

Contributions

- Proposed model-bounded monitoring

  Bounding model (knowledge): linear HAs $\mathscr{M}$

- Formalized with monitored language $L_{\mathrm{mon}}(\mathscr{M})$

  $L_{\mathrm{mon}}(\mathscr{M})$: possible *discrete* observations of $\mathscr{M}$

- Algorithms + implementations

  Idea: bounded-time reachability
  Experiment → effectively monitorable

Model-Bounded Monitoring

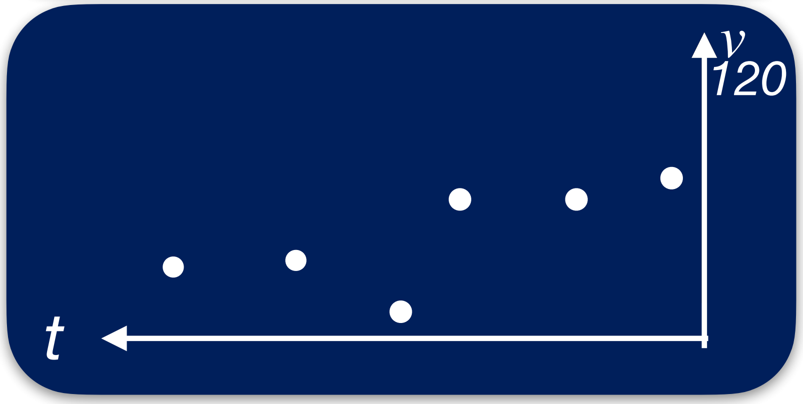
Our Contribution

Given

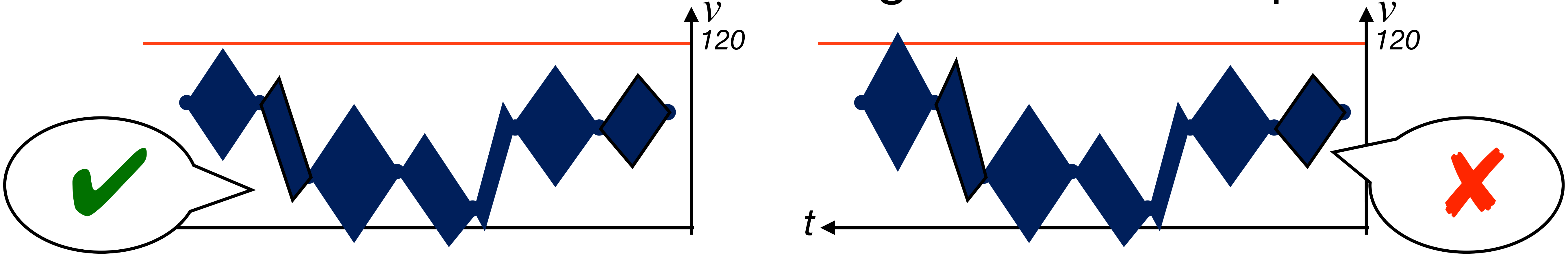
- Bounding model in LHA $\mathscr{M}$
- Safety Specification φ
- Discrete Log w

$$\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$$

No $(v > 120)$



Decide if the actual behavior might violate the spec.



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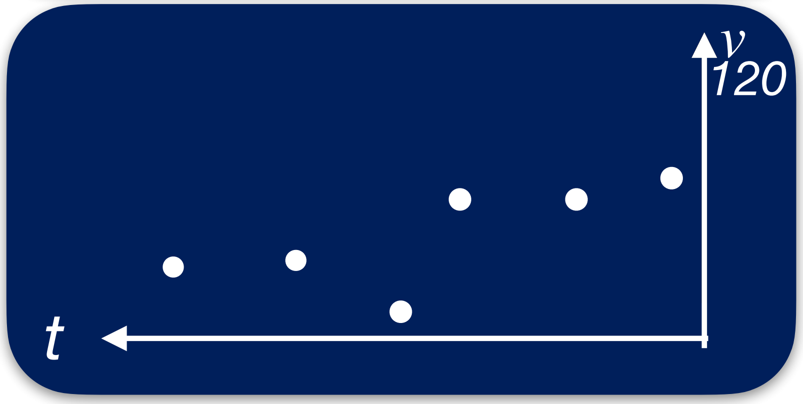

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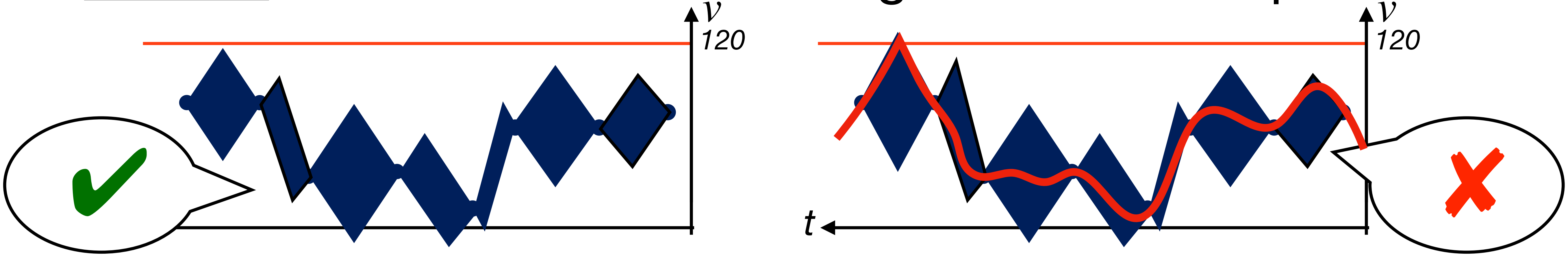

Monitored Language L_{mon}

Our Contribution

Combine cont. exec. of $\mathscr{M}$ and disc. obs. of w

$L_{\mathrm{mon}}(\mathscr{M}) = \{$ Discr. Obs w |

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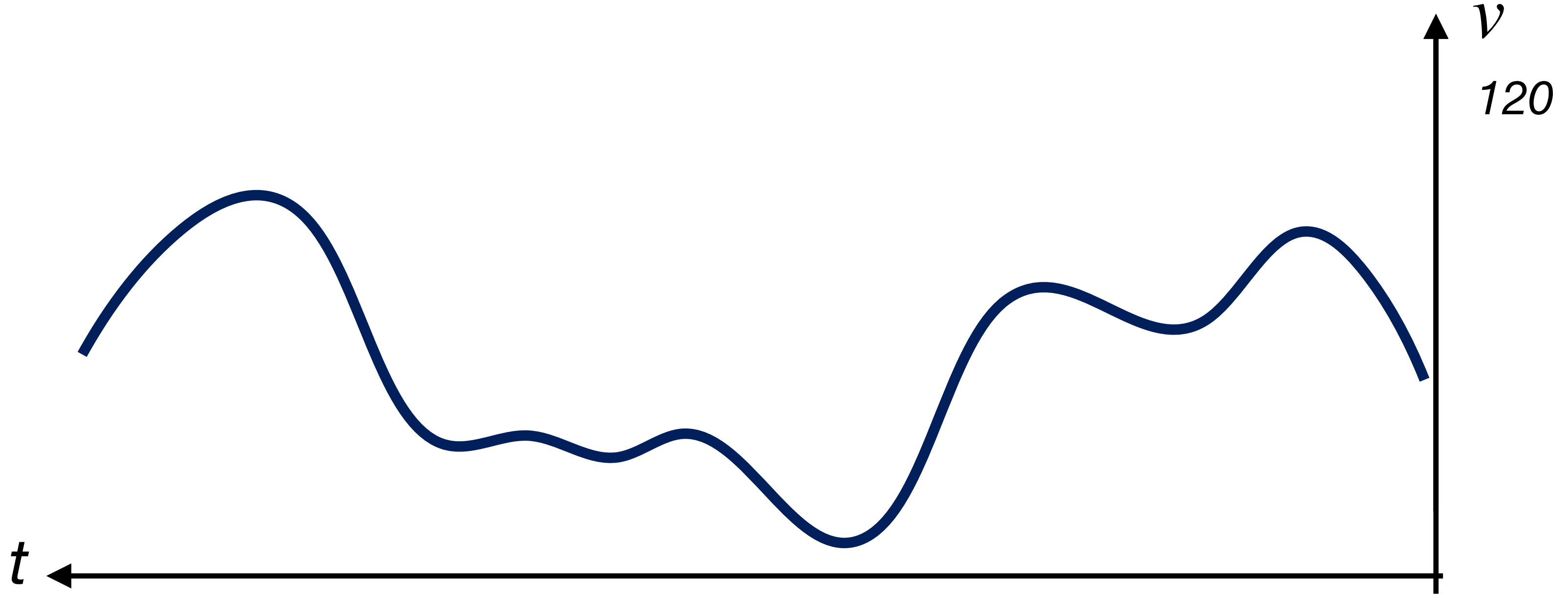
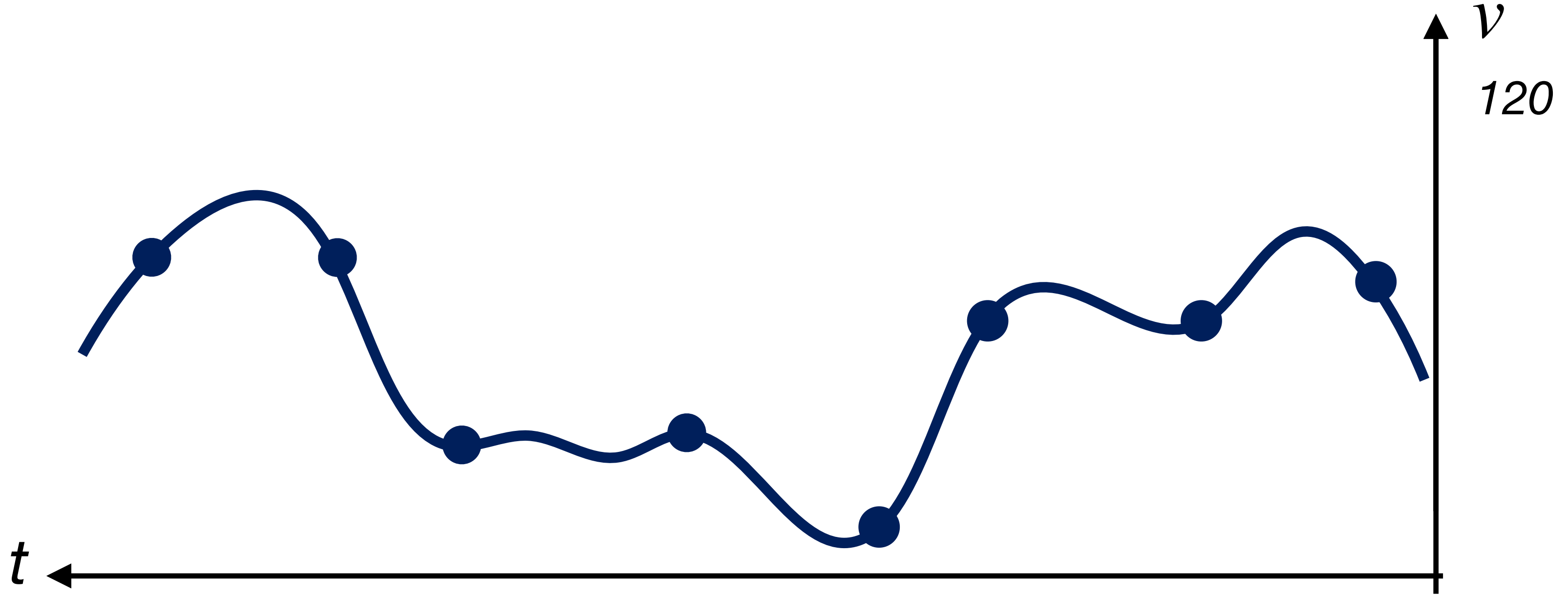


Monitored Language L_{mon}

Our Contribution

Combine cont. exec. of $\mathscr{M}$ and disc. obs. of w

$L_{\mathrm{mon}}(\mathscr{M}) = \{$ Discr. Obs $w \mid \exists$ exec. σ of $\mathscr{M}$ s.t.
w is a sample of $\sigma\ \}$



Workflow of Model-bounded Monitoring

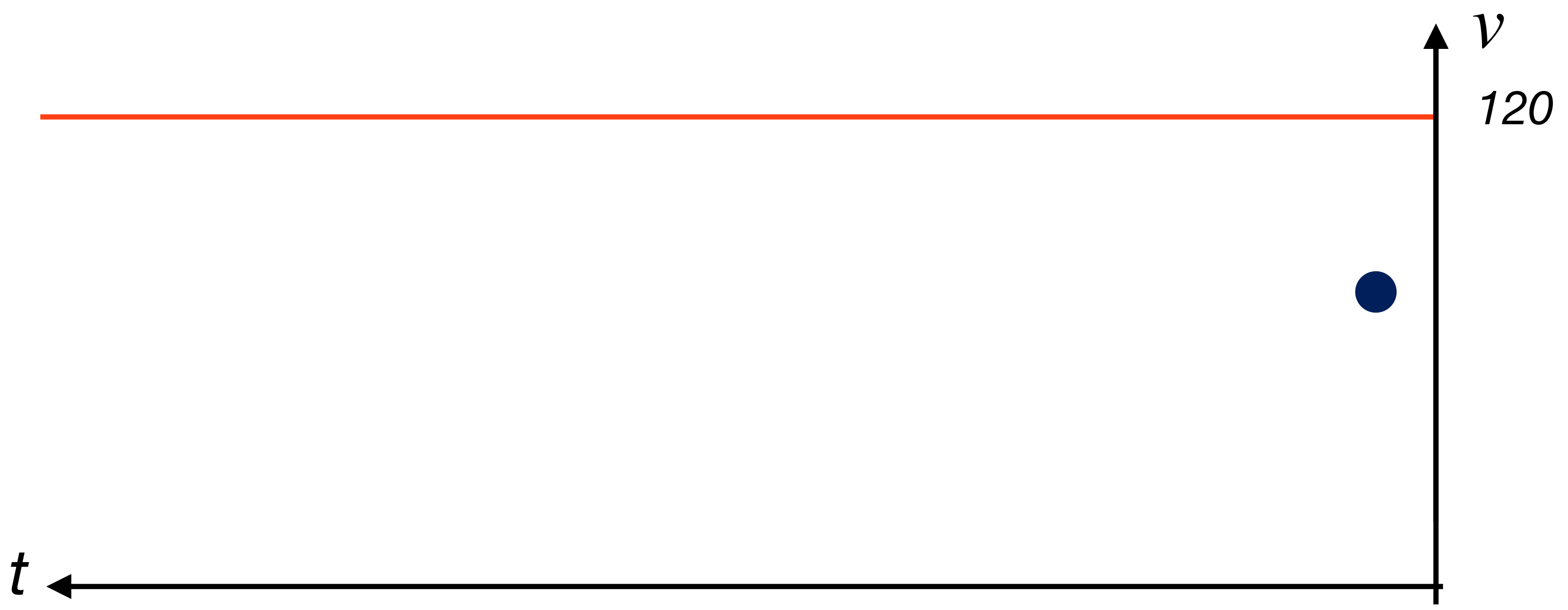
1. Construct an LHA $\mathscr{M}_{\neg\varphi}$ from bounding model $\mathscr{M}$ and spec. φ

   Idea: Product of LHAs

2. Check if $w \in L_{\mathrm{mon}}(\mathscr{M}_{\neg\varphi})$

   Idea: Bounded-time reachability analysis

Algorithm: Bounded-time Reachability



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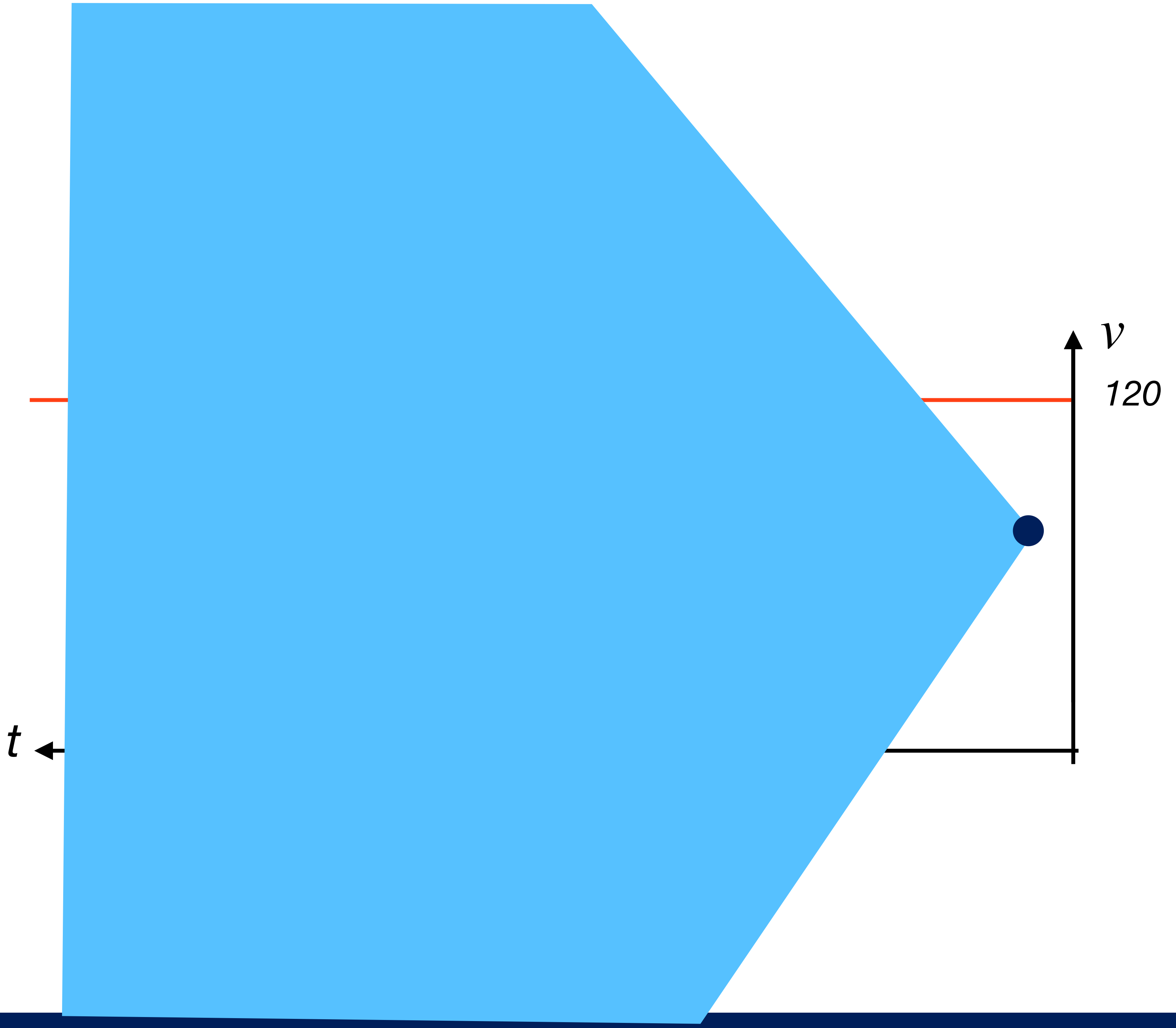

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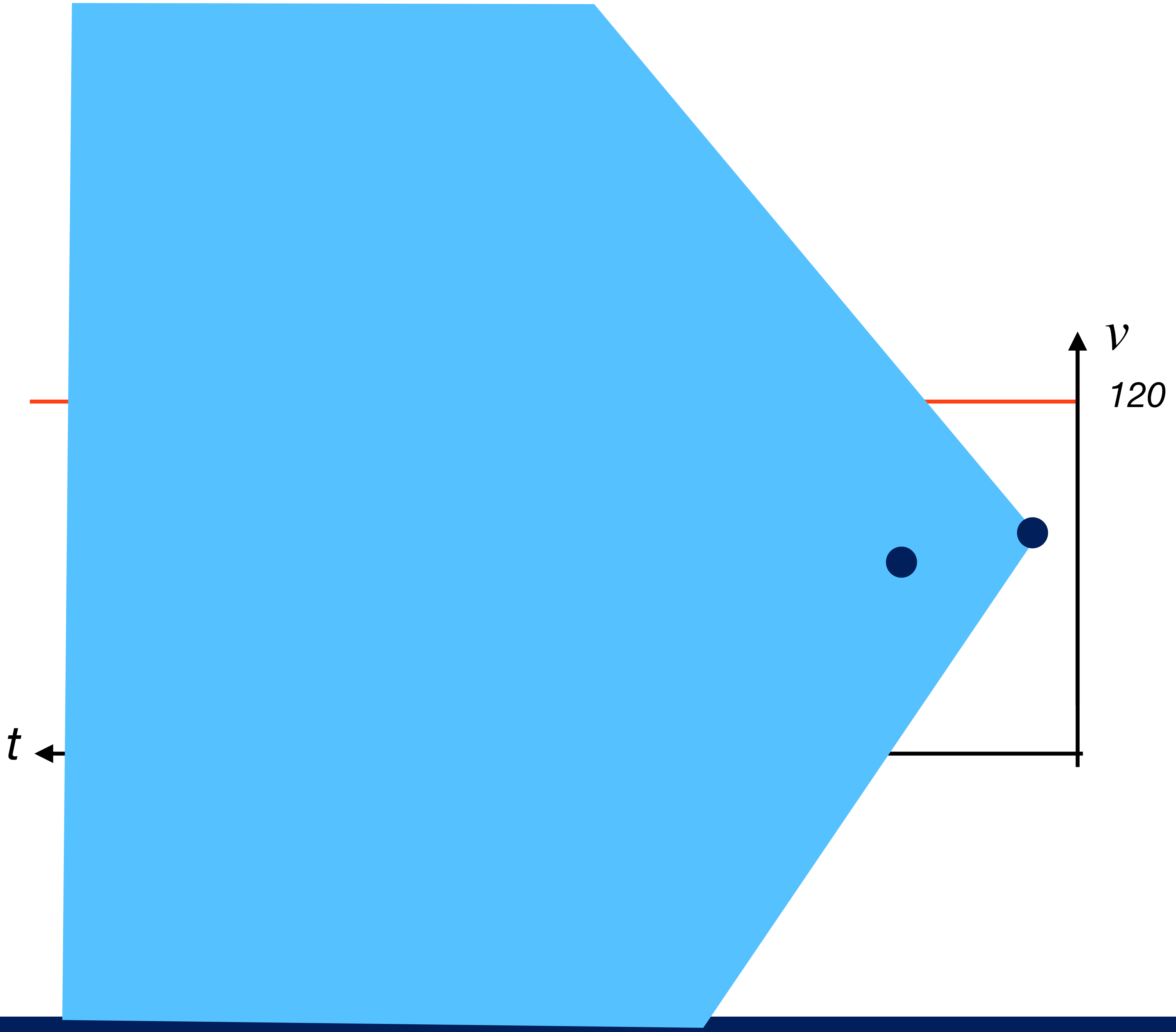

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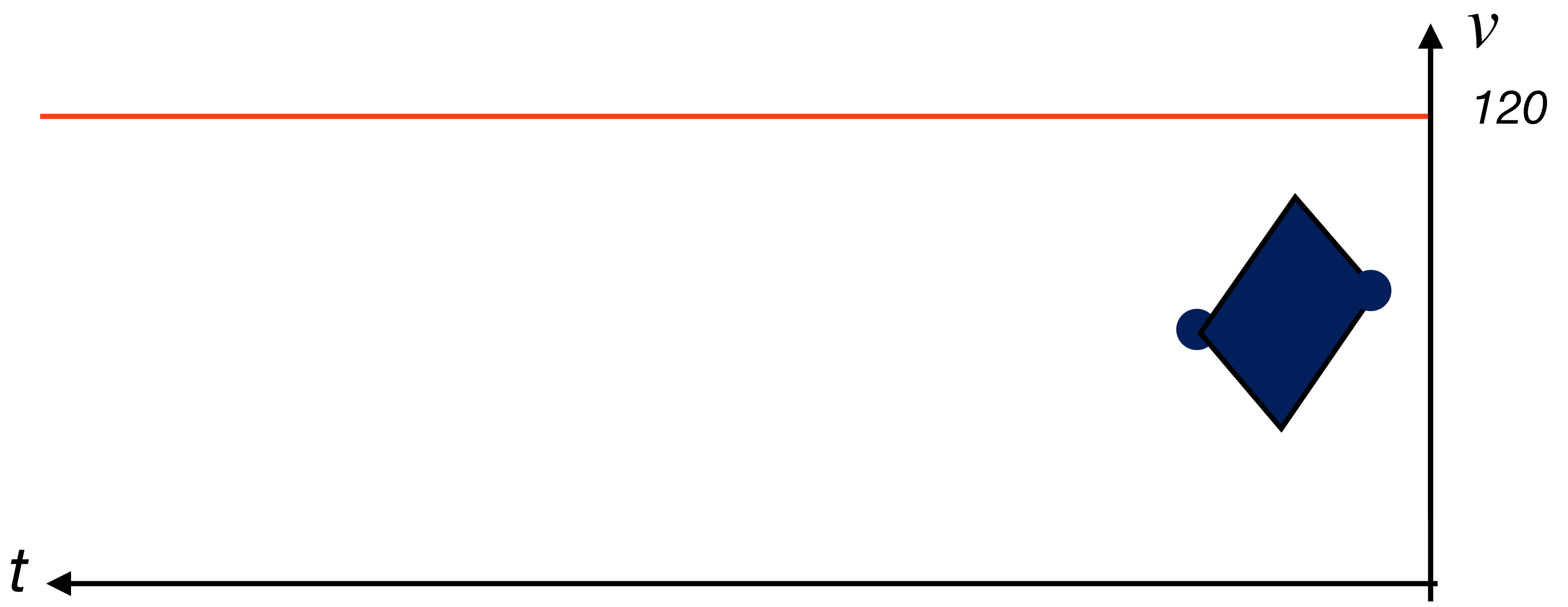

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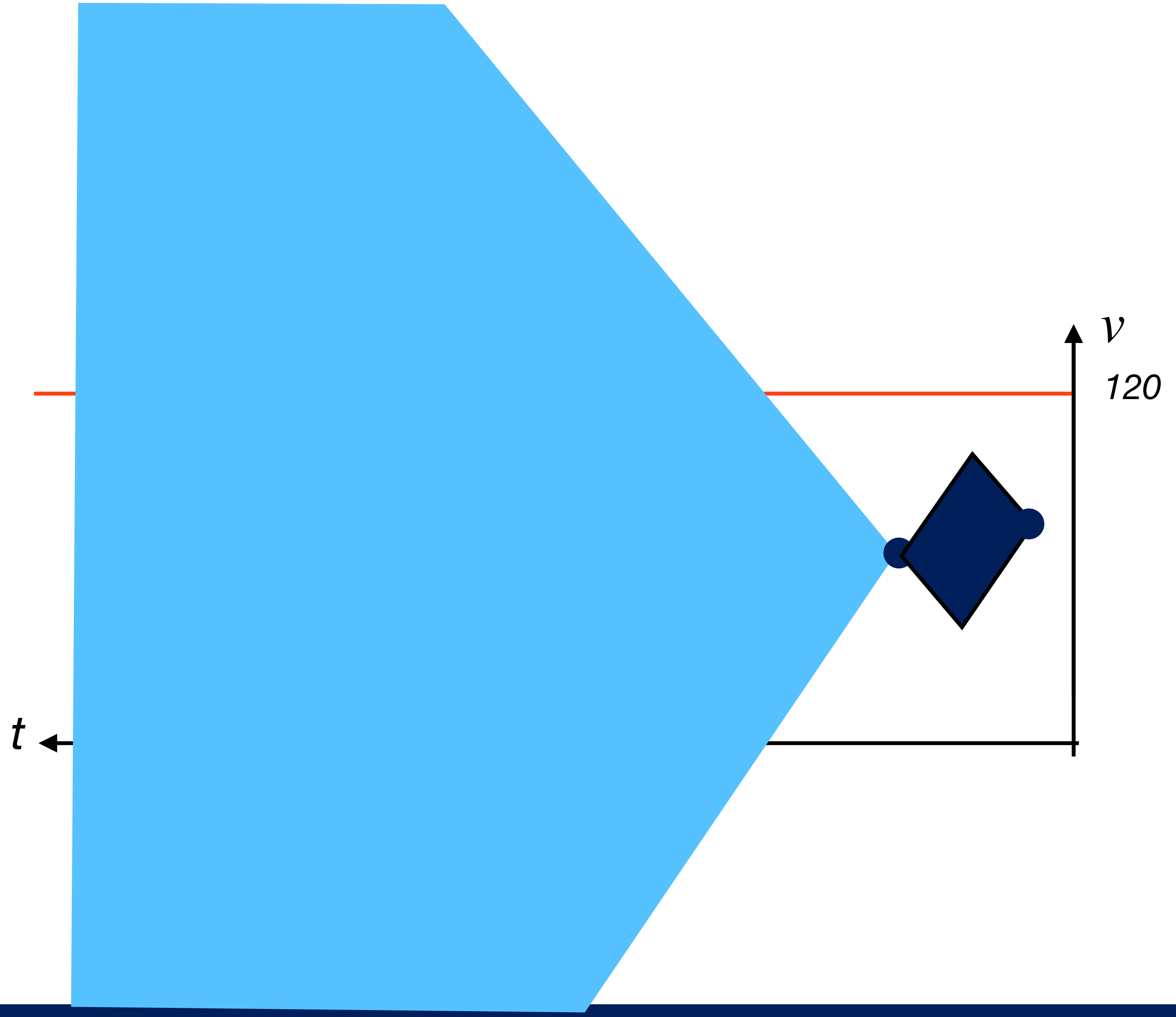

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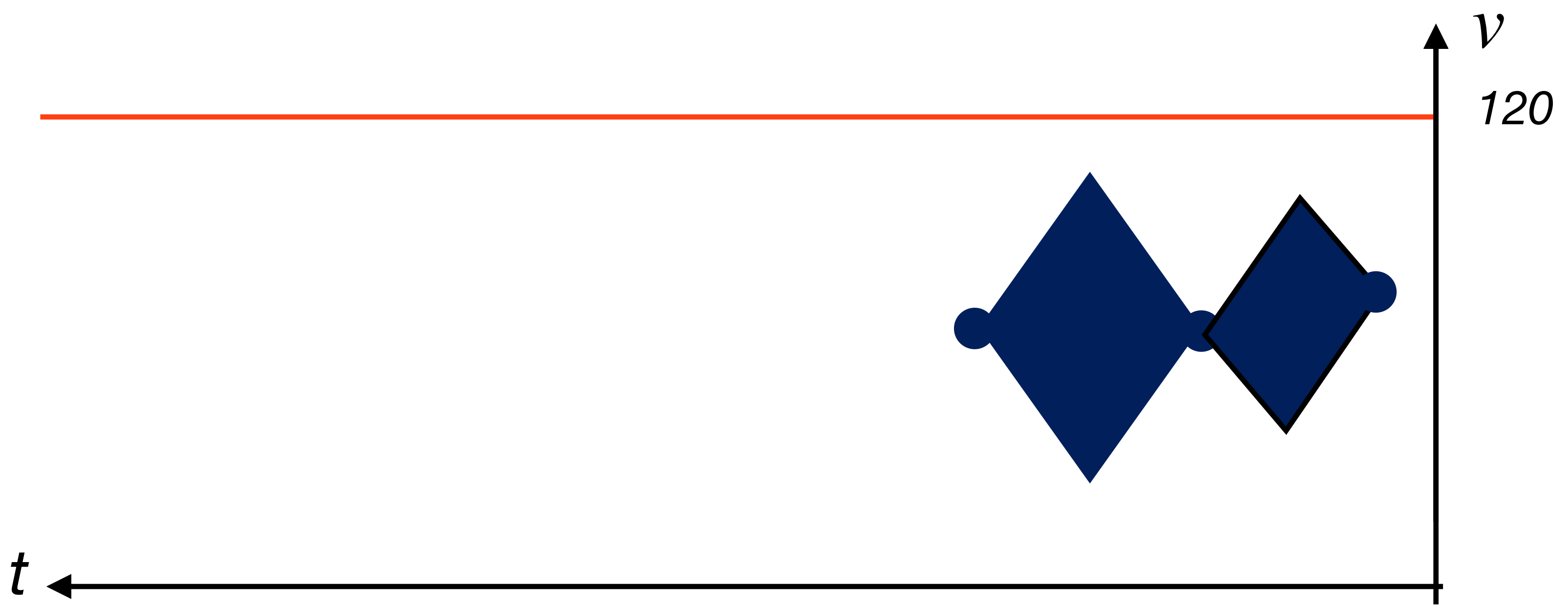

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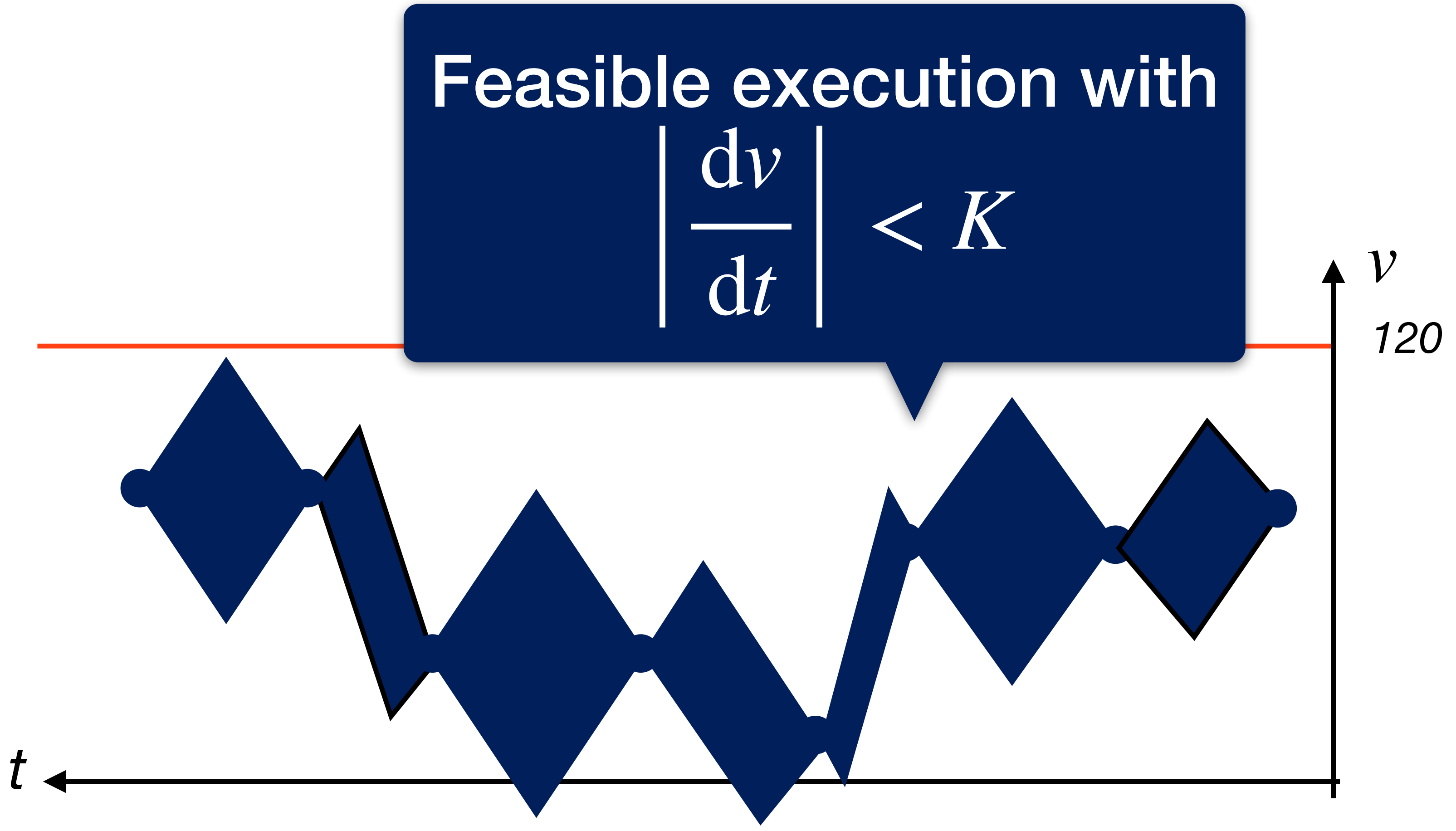

Feasible execution with $\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$

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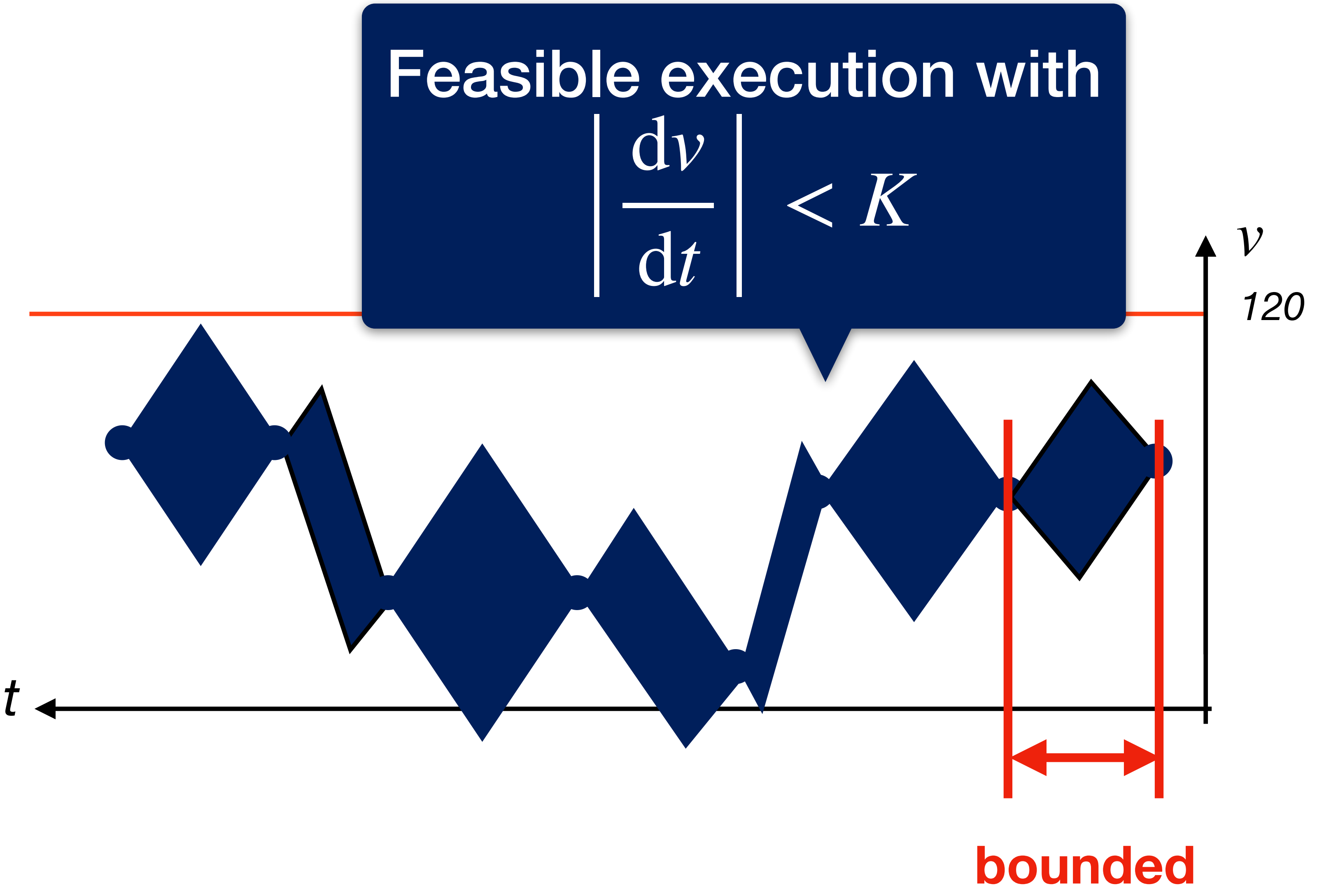


Feasible execution with

$$\left|\frac{\mathrm{d}v}{\mathrm{d}t}\right| < K$$

Implementations

Approach 1: Utilize existing model-checker (PHAVerLite)

Pros: Highly-optimized reachability analysis impl.

Approach 2: Implement dedicated monitor (HAMoni)

Pros: Best performance in theory

Environment of Experiments

- Used 3 benchmarks on adaptive cruise controller (**ACC**) + 1 robot navigation (**NAV**) benchmark
- **ACC**: Cars should not be too close (or no physical contact)

For scalability analysis

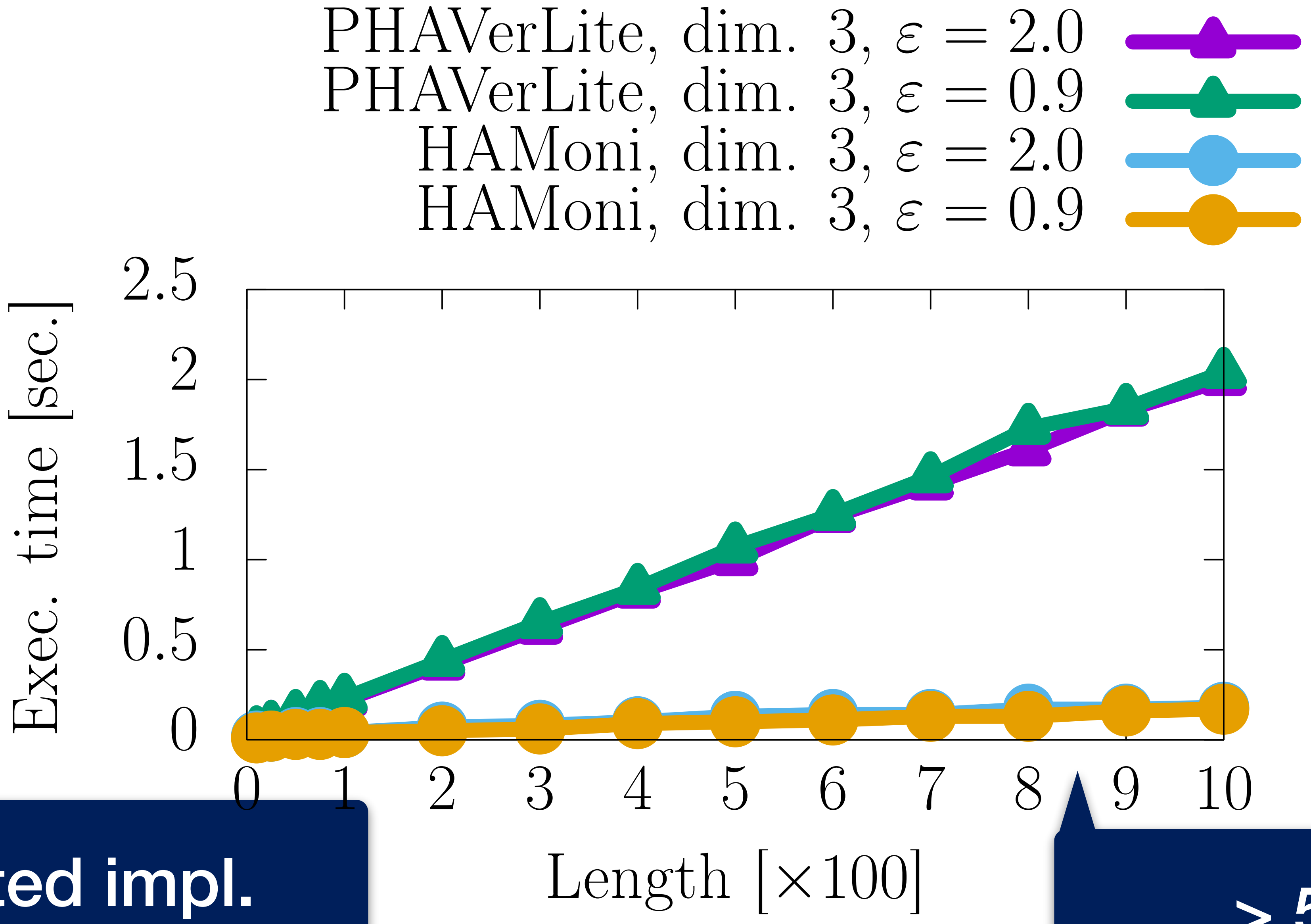
- **NAV**: Do not enter an unsafe region

For false alarms analysis

- Amazon EC2 c4.large instance / Ubuntu 18.04 LTS (64 bit)
  - 2.9 GHz Intel Xeon E5-2666 v3, 2 vCPUs, 3.75 GiB RAM

Experiment Results

Changing Observation Length

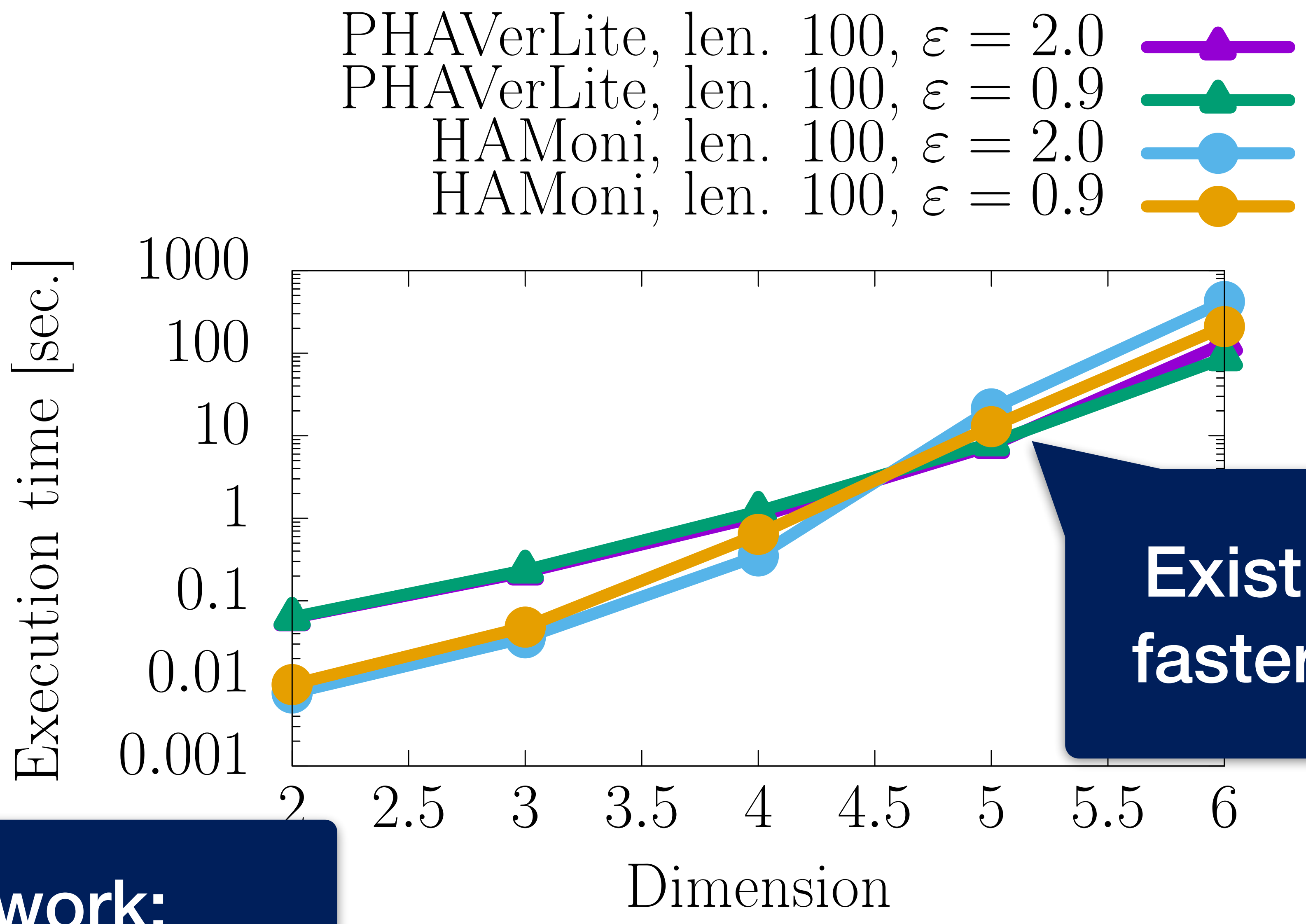


Dedicated impl.
≈ 10x faster

> 5000
samples / sec.

Experiment Results

Changing Model Dimension

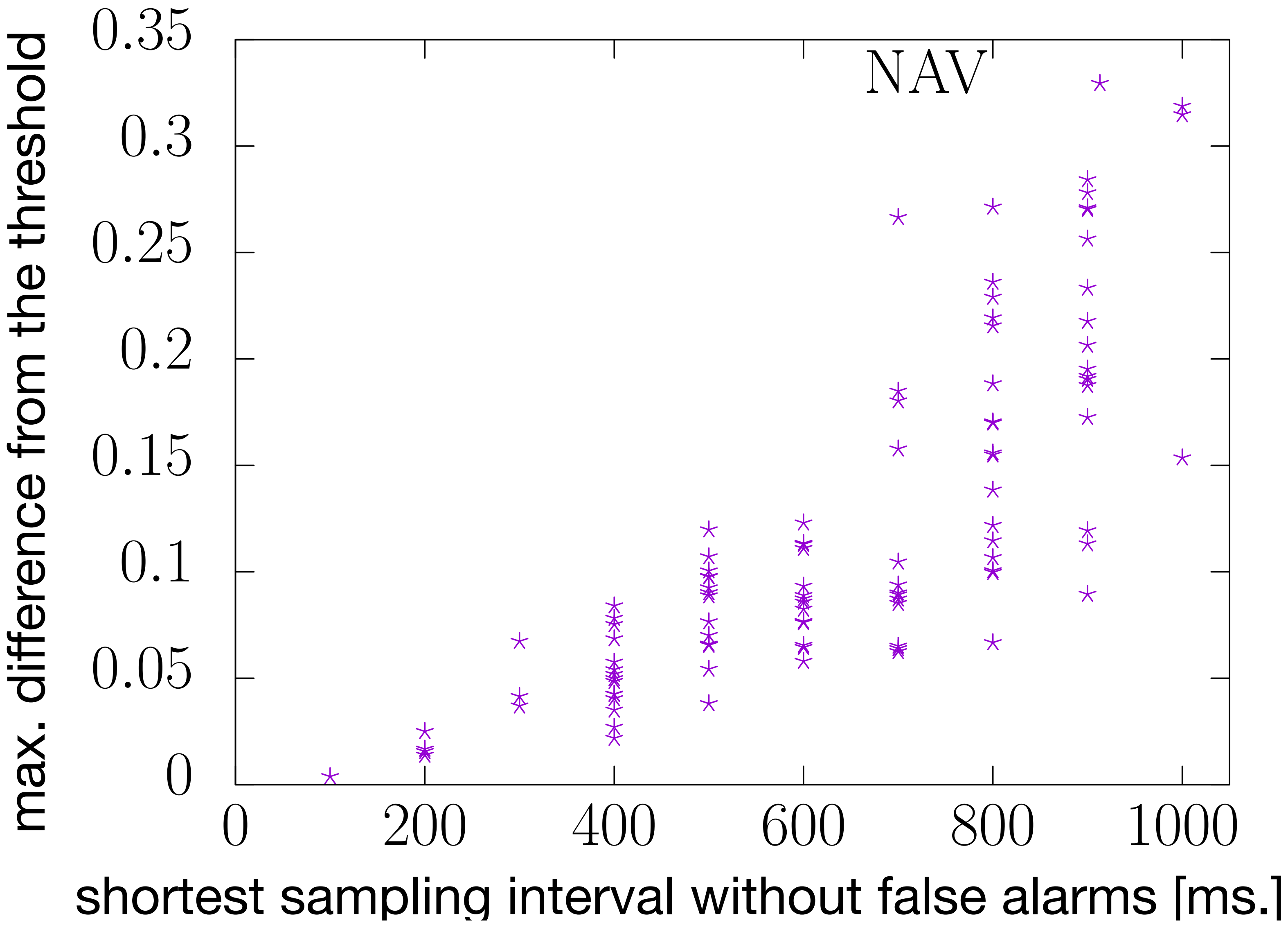


Existing tool was faster for dim. > 6

Future work: further optimization

Experiment Results

False Alarms



False alarm for “very safe” exec.
→ sampling is coarse

Conclusions

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