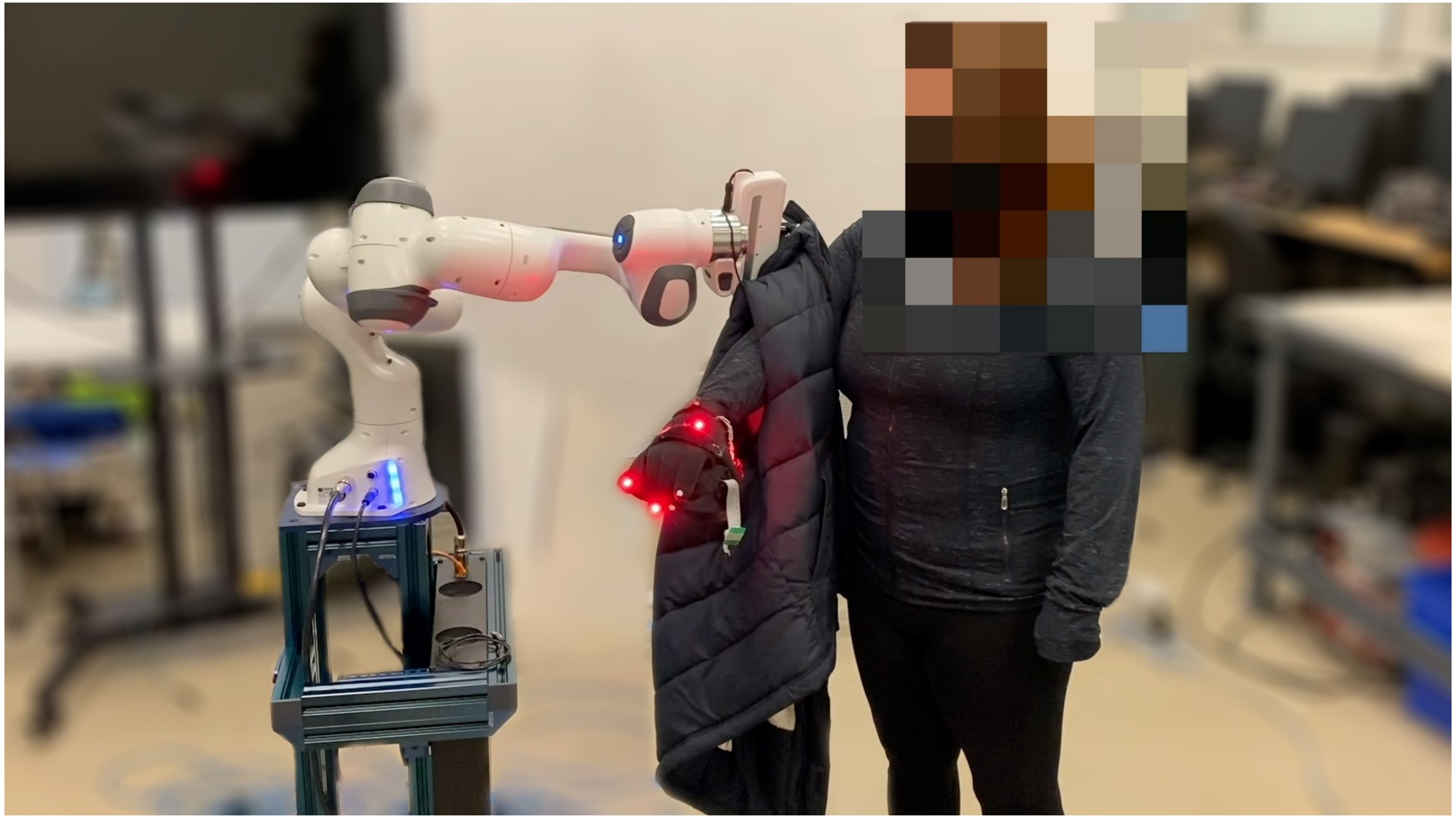
Provably Safe and Efficient Motion Planning with Uncertain Human Dynamics

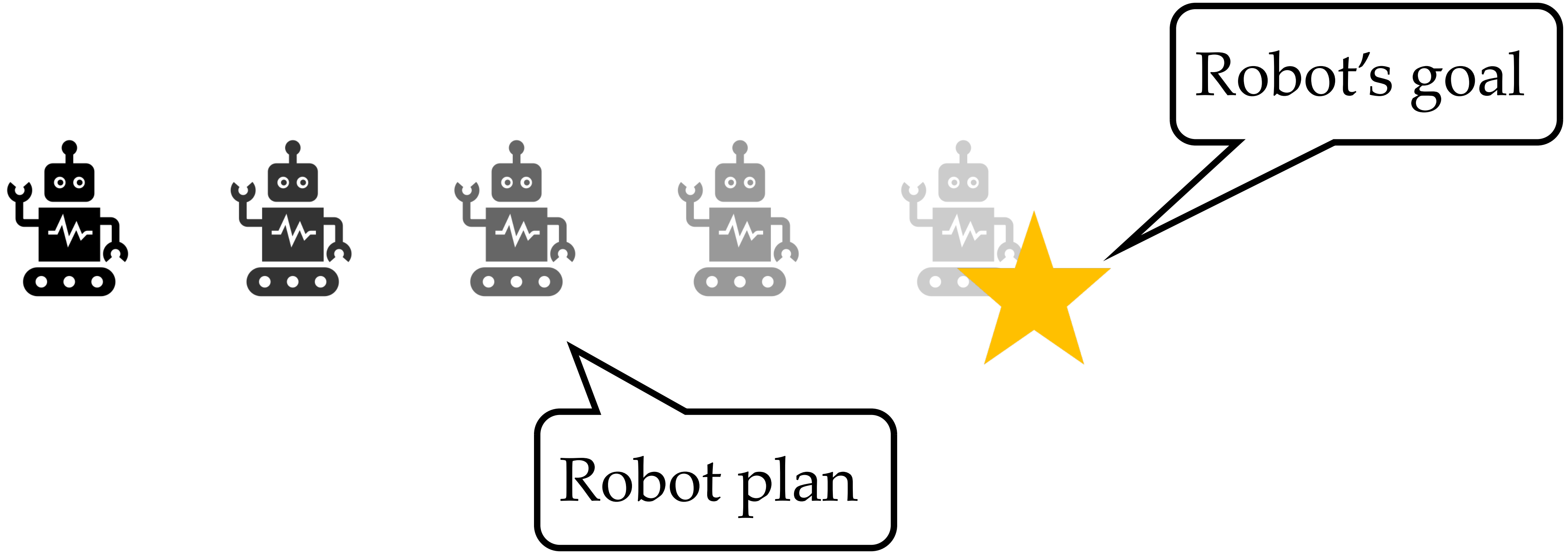
Shen Li, Nadia Figueroa, Ankit Shah, Julie A. Shah

https://safe-dressing.github.io/

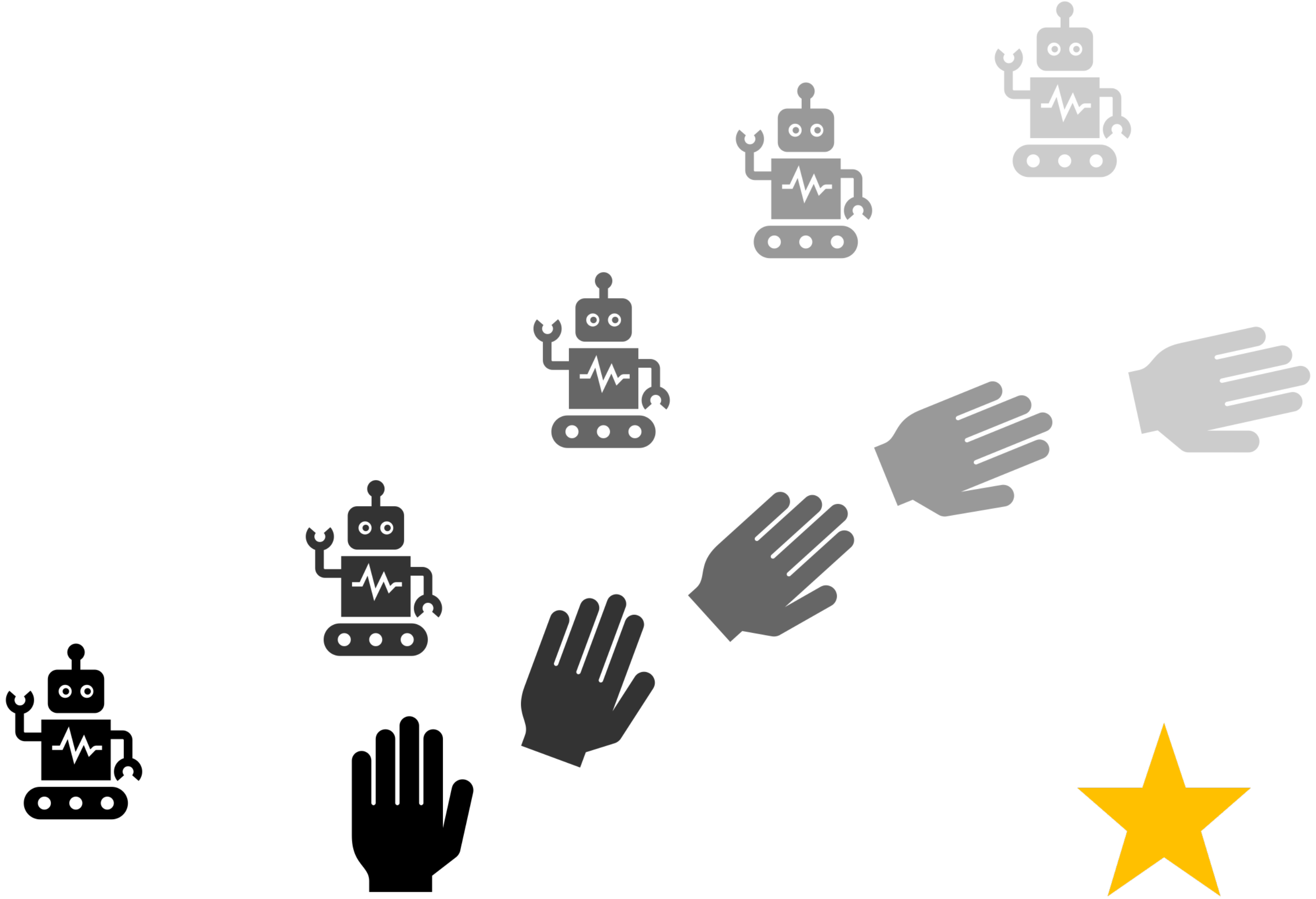
Robot-assisted Dressing

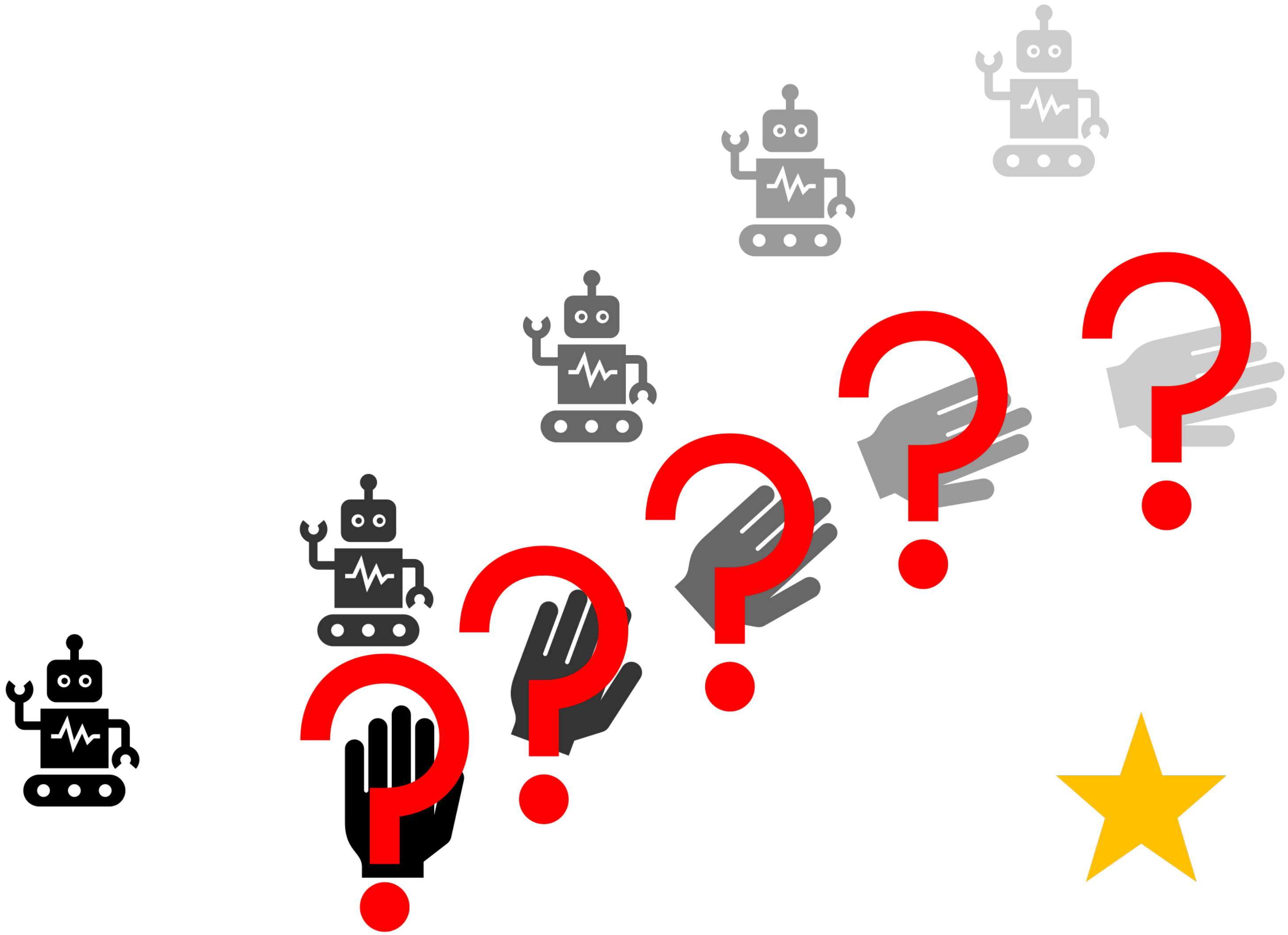


Human Physical Safety

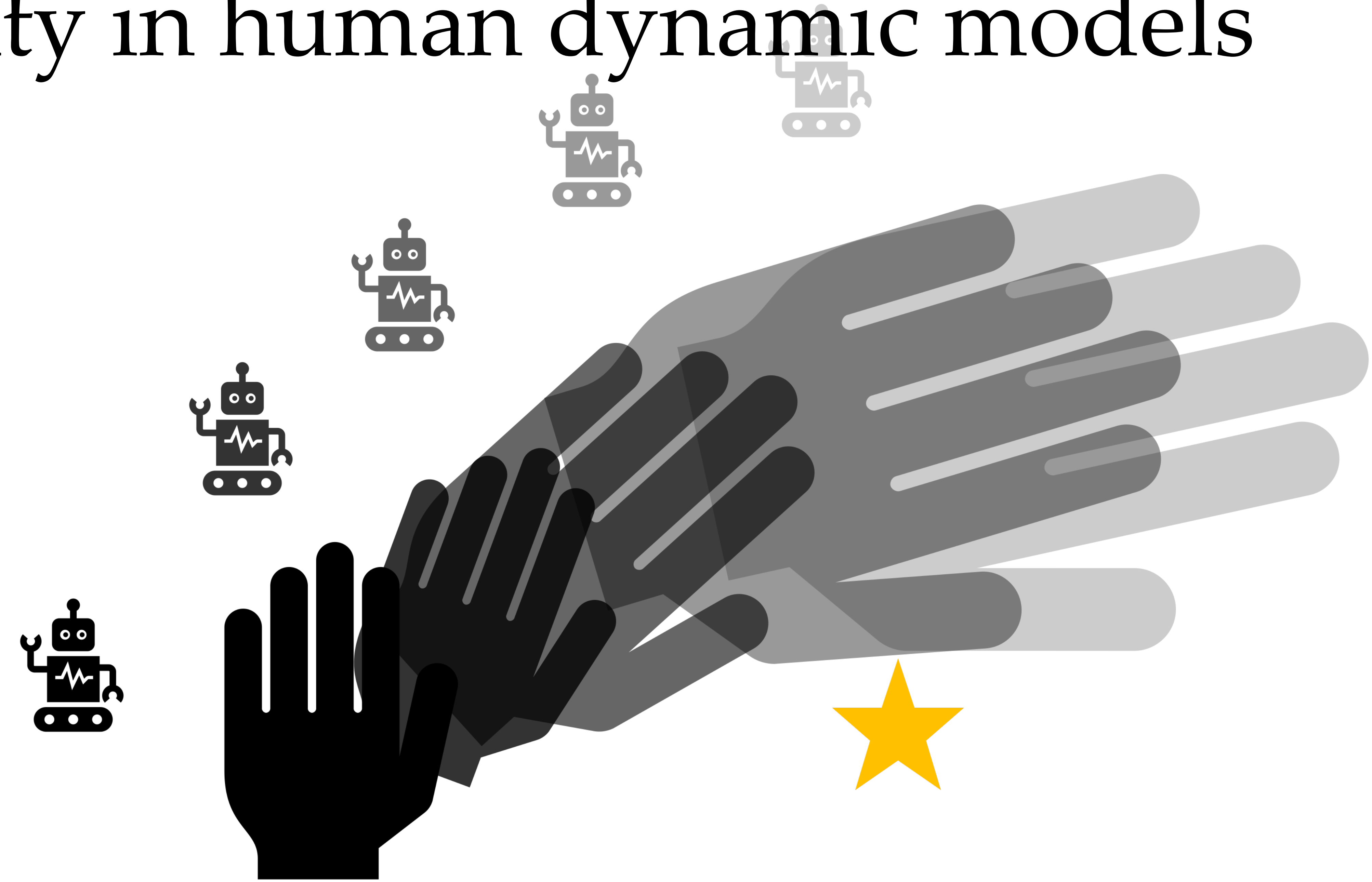

Robot's goal
Robot plan

Human-aware motion planners
Safety = collision avoidance



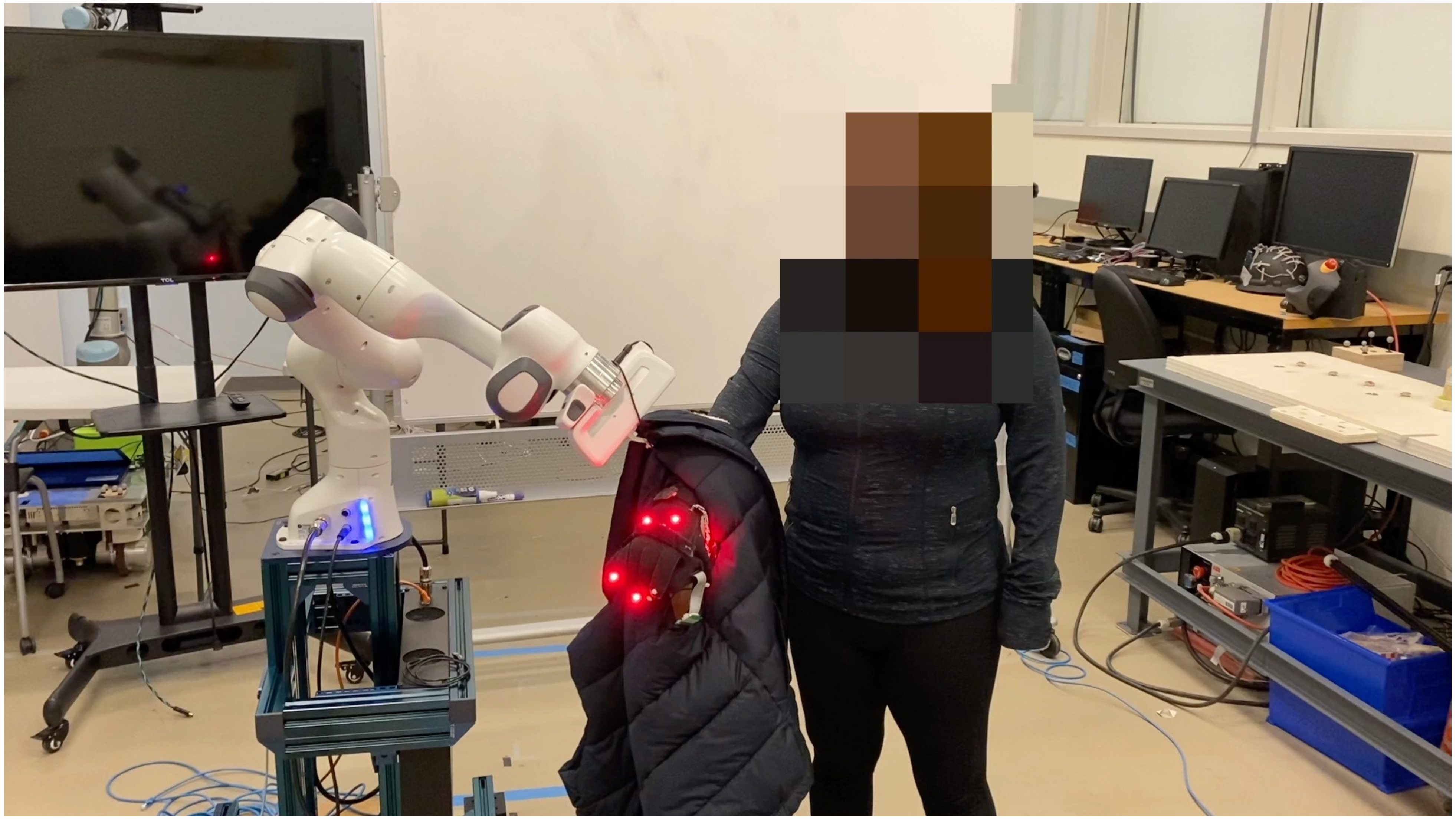


Uncertainty in human dynamic models

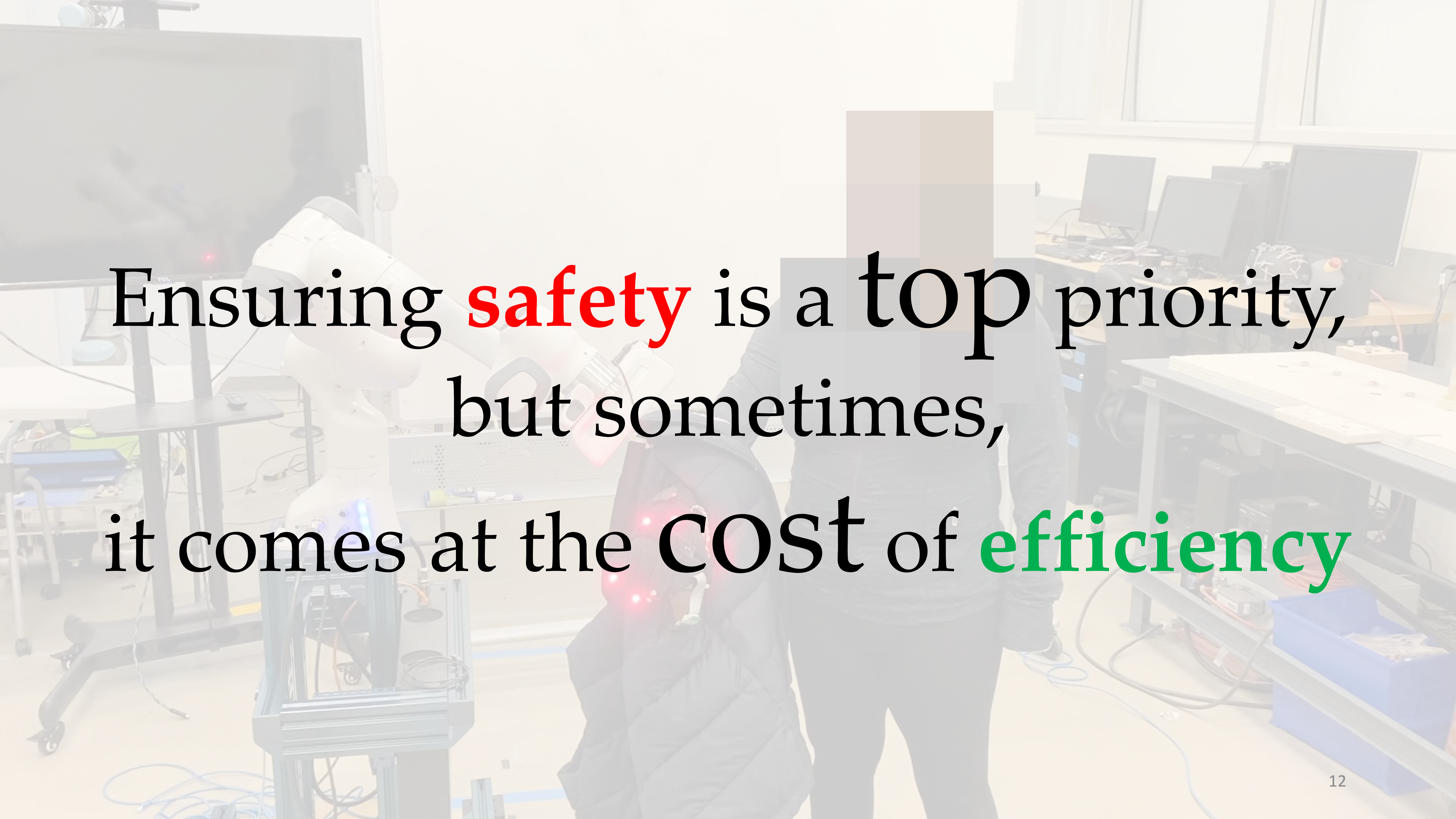


Overly conservative
=> Inefficient

“Freezing robot problem” under uncertainty



Trautman and Krause. IROS, 2010


Ensuring safety is a top priority,
but sometimes,
it comes at the cost of efficiency

Ensure human safety
&& Improve task efficiency

Ensure human safety

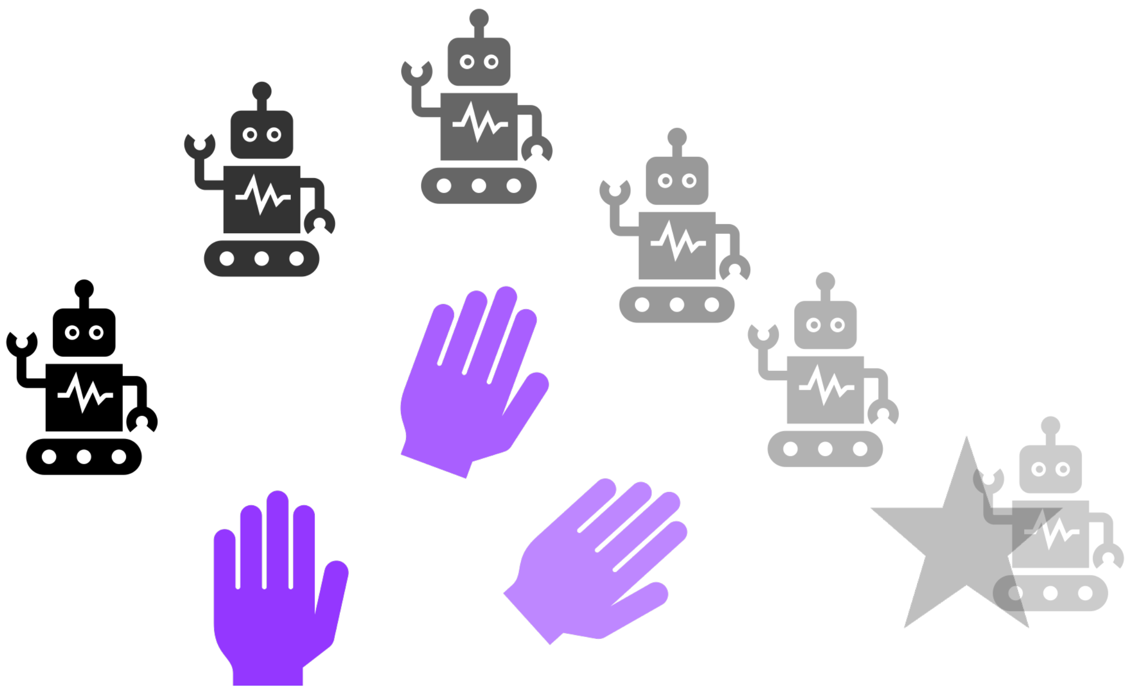
&& Improve task efficiency

Collision avoidance

OR safe impact

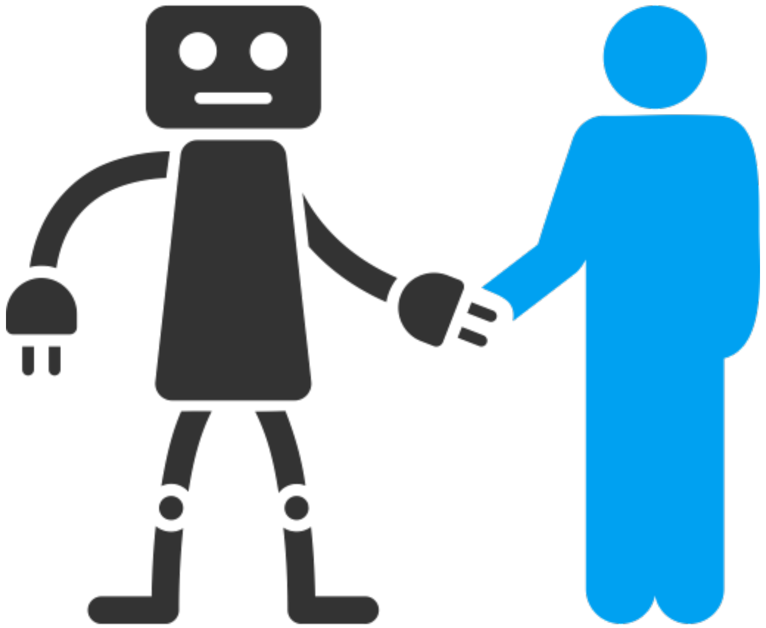
Human-aware motion planners

Collision avoidance



Compliant controllers

Reduce contact force



Lasota et al. Foundations and Trends in Robotics, 2017

Human-aware motion planners

Collision avoidance

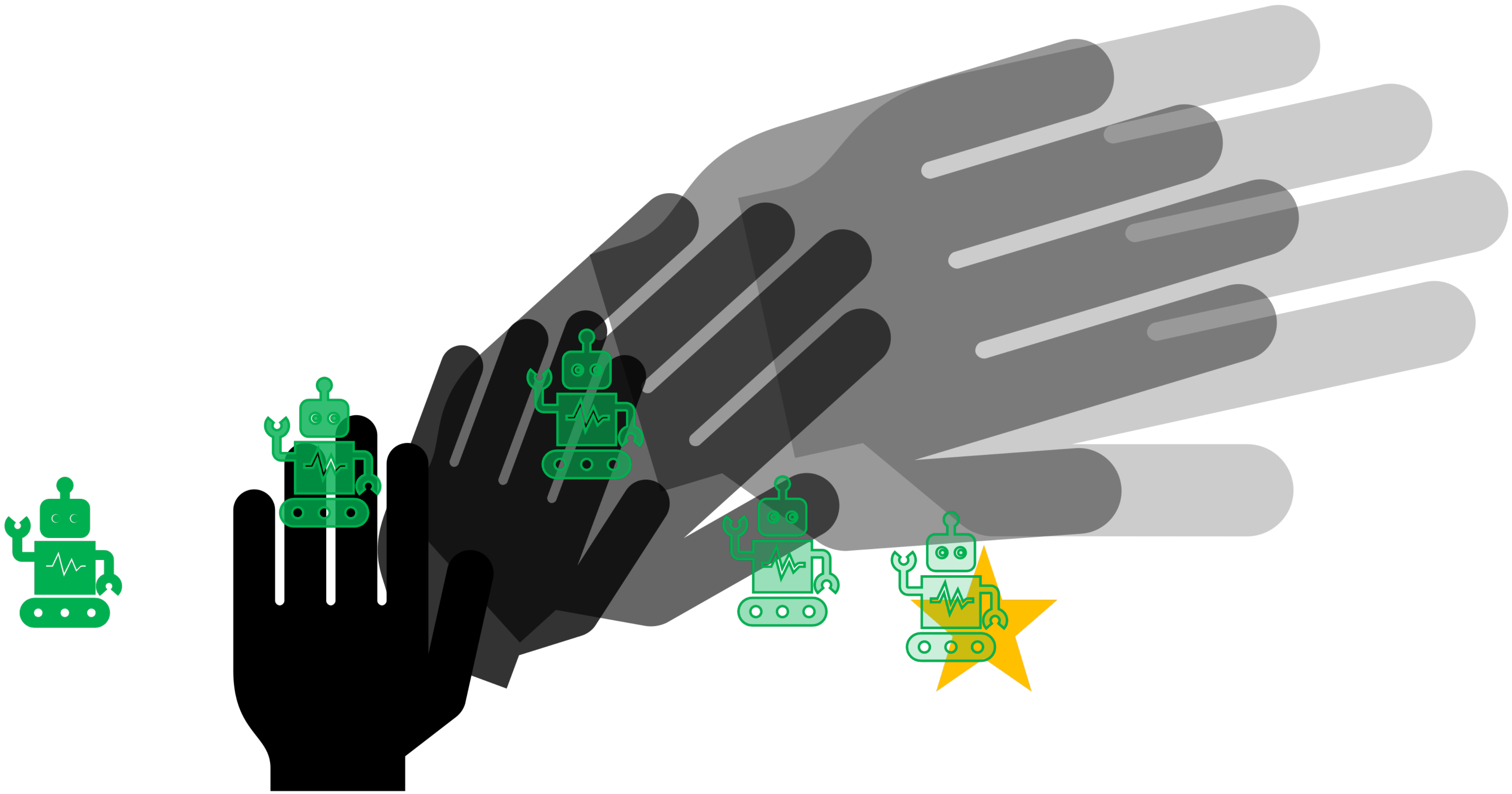
Compliant controllers

Reduce contact force

$$\underbrace{\hspace{10em}}$$

Collision avoidance OR safe impact

Lasota et al. Foundations and Trends in Robotics, 2017



Ensure human safety

&& Improve task efficiency

Collision avoidance

OR safe impact

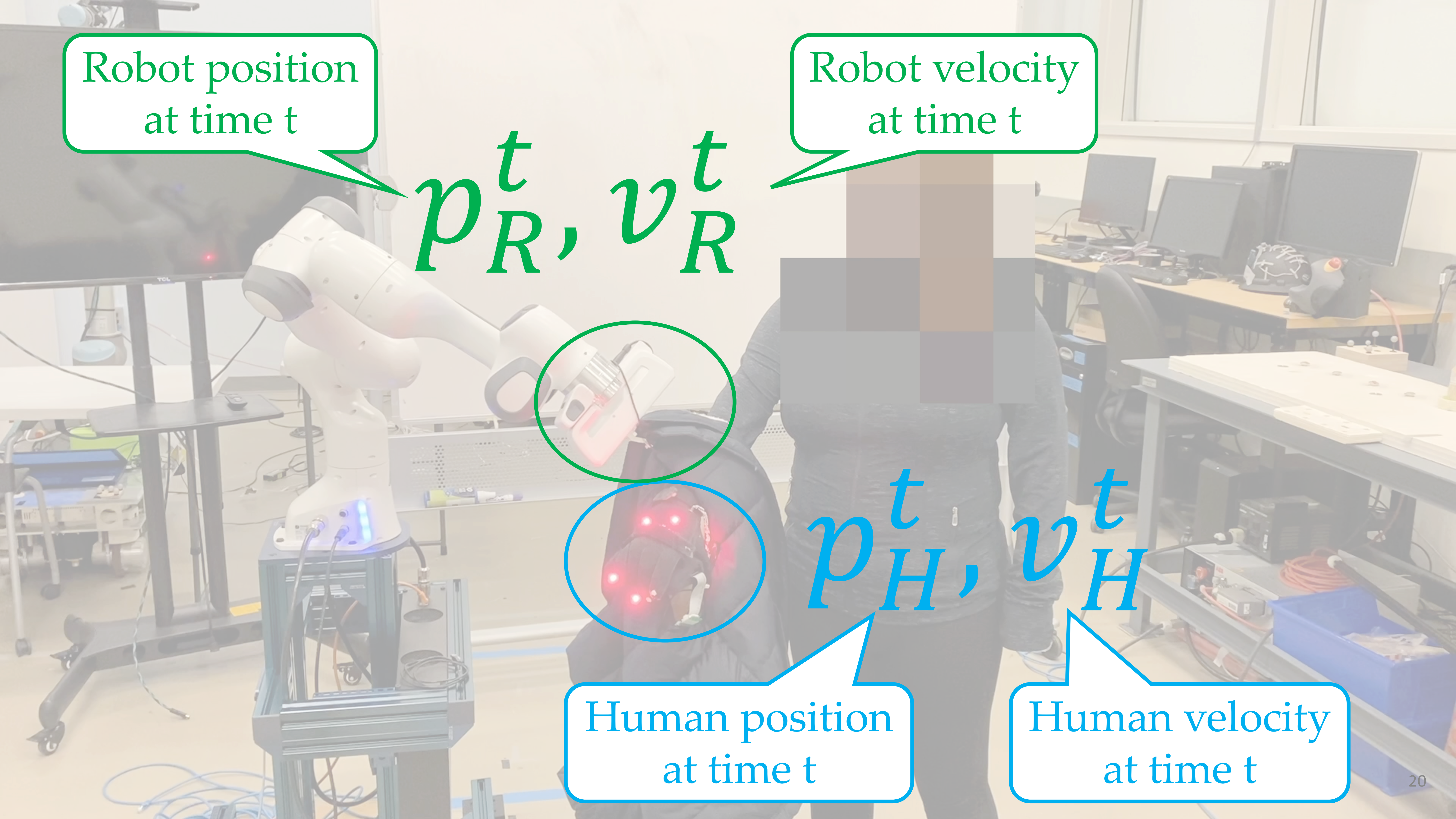
MPC + high probability **safety** guarantee

Ensure human safety

&& Improve task efficiency

Collision avoidance

OR safe impact


Robot position at time t
Robot velocity at time t
p_R^t, v_R^t
p_H^t, v_H^t
Human position at time t
Human velocity at time t

Assumption: deterministic && “smooth”

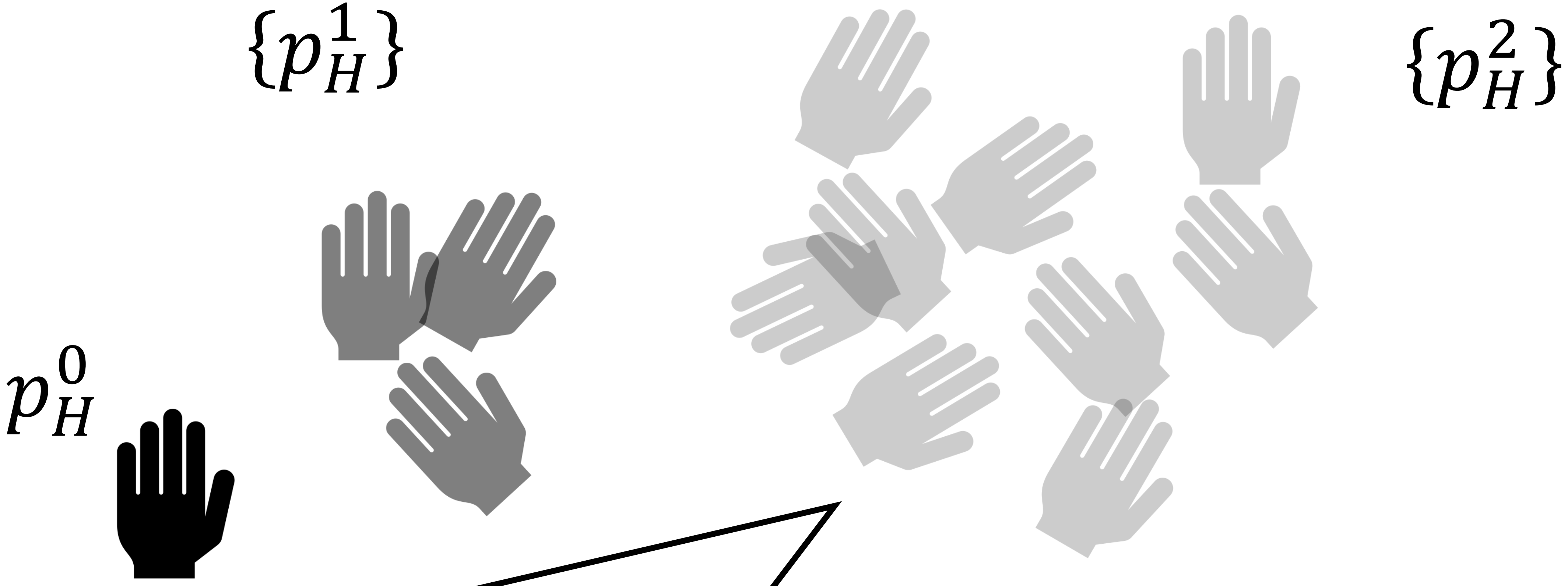
Gaussian Process

$$p_H^{t+1} = p_H^t + g(p_H^t, p_R^t)$$

$$v_H^{t+1} = \frac{1}{h}(p_H^{t+1} - p_H^t)$$

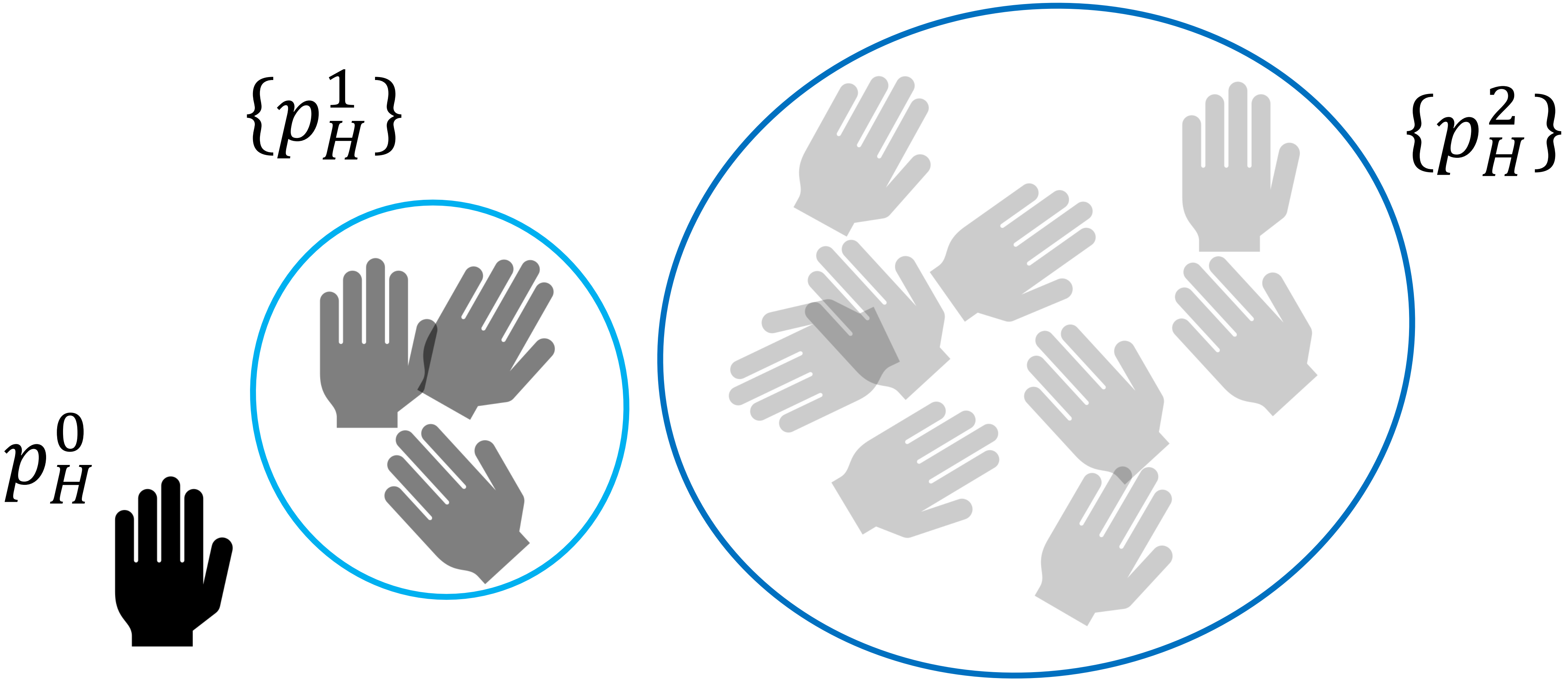
The length of time-steps

Human motion prediction

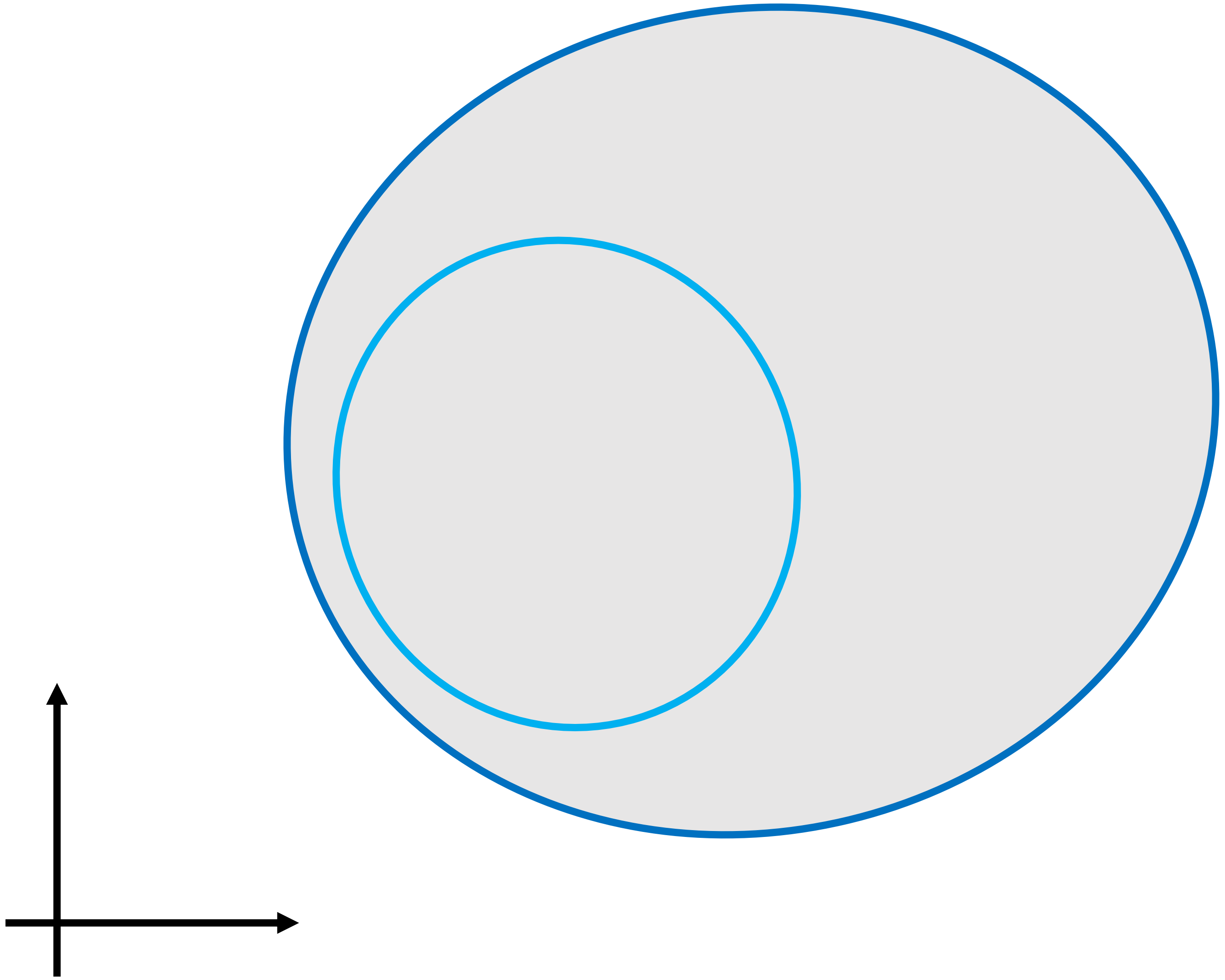


Uncertainty in the human dynamic model:

$$p_H^{t+1} = p_H^t + g(p_H^t, p_R^t)$$



Koller, Berkenkamp, Turchetta, Boedecker, and Krause. Learning-based model predictive control for safe exploration and reinforcement learning. 2019.



Velocity space

Koller, Berkenkamp, Turchetta, Boedecker, and Krause. Learning-based model predictive control for safe exploration and reinforcement learning. 2019.

Corollary 1:

……

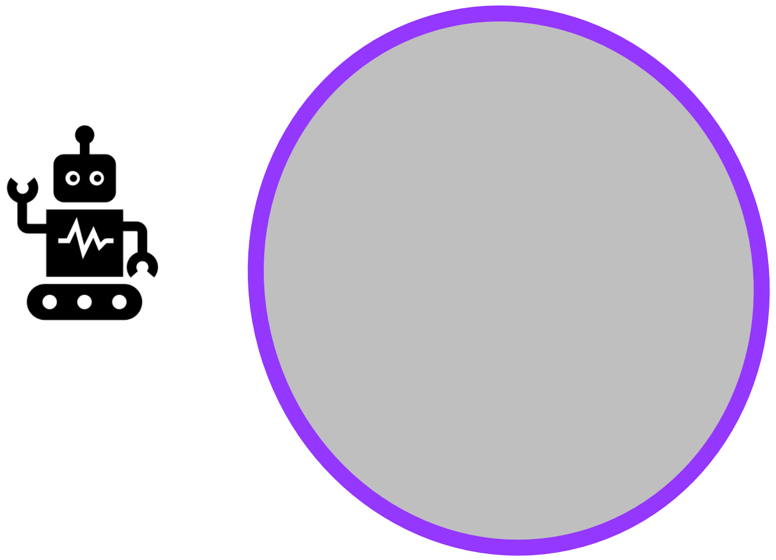
With a high probability:

$\forall t \in [1 \ldots T]$, human pos, vel $\in$ ellipsoids

Collision avoidance

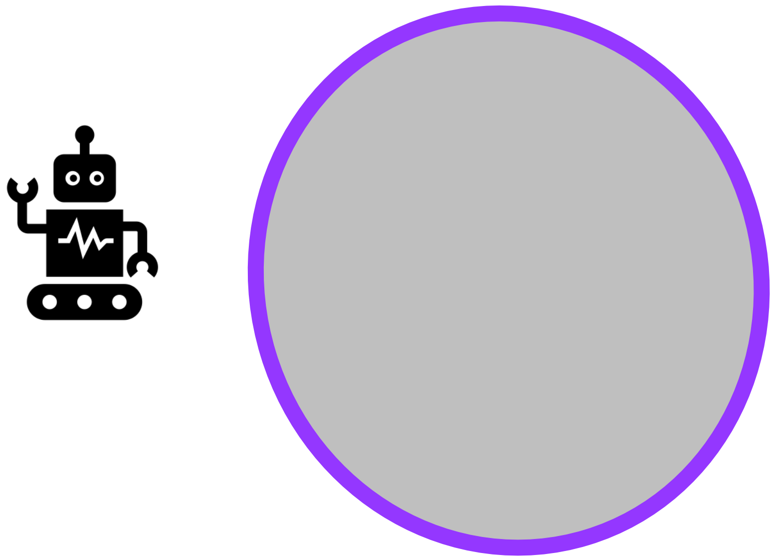
A constraint over

- Robot pos
- Human pos ellipsoid



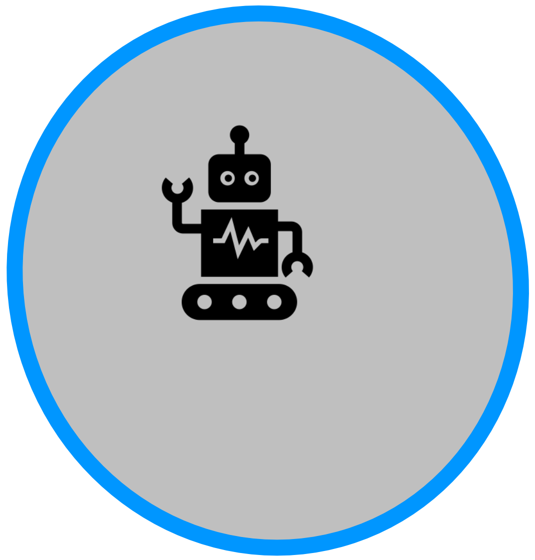
Collision avoidance

A constraint over
- Robot pos
- Human pos ellipsoid



Safe impact

Constraints over
- Robot vel
- Human vel ellipsoid



Collision avoidance

OR

Safe impact

A constraint over
- Robot pos
- Human pos ellipsoid

Constraints over
- Robot vel
- Human vel ellipsoid

Surrogate constraints

Human model

Gaussian Process

Ellipsoidal prediction

Collision avoidance
OR safe impact

Surrogate constraint

MPC

High probability safety guarantee

$$\Pr[\forall t \in \mathbb{N}, \text{safe}] > 1 - \delta$$

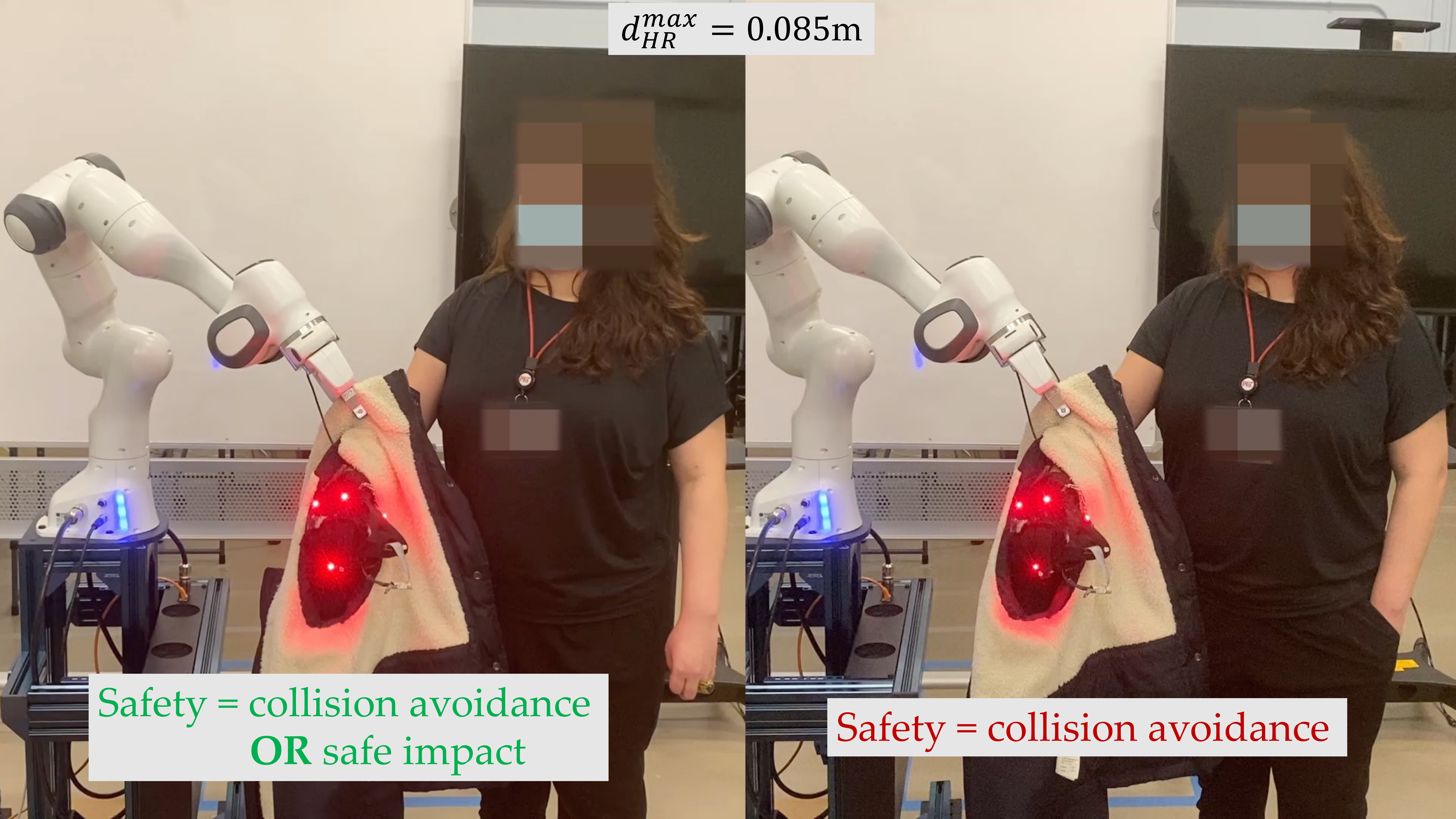
MPC + high probability **safety** guarantee

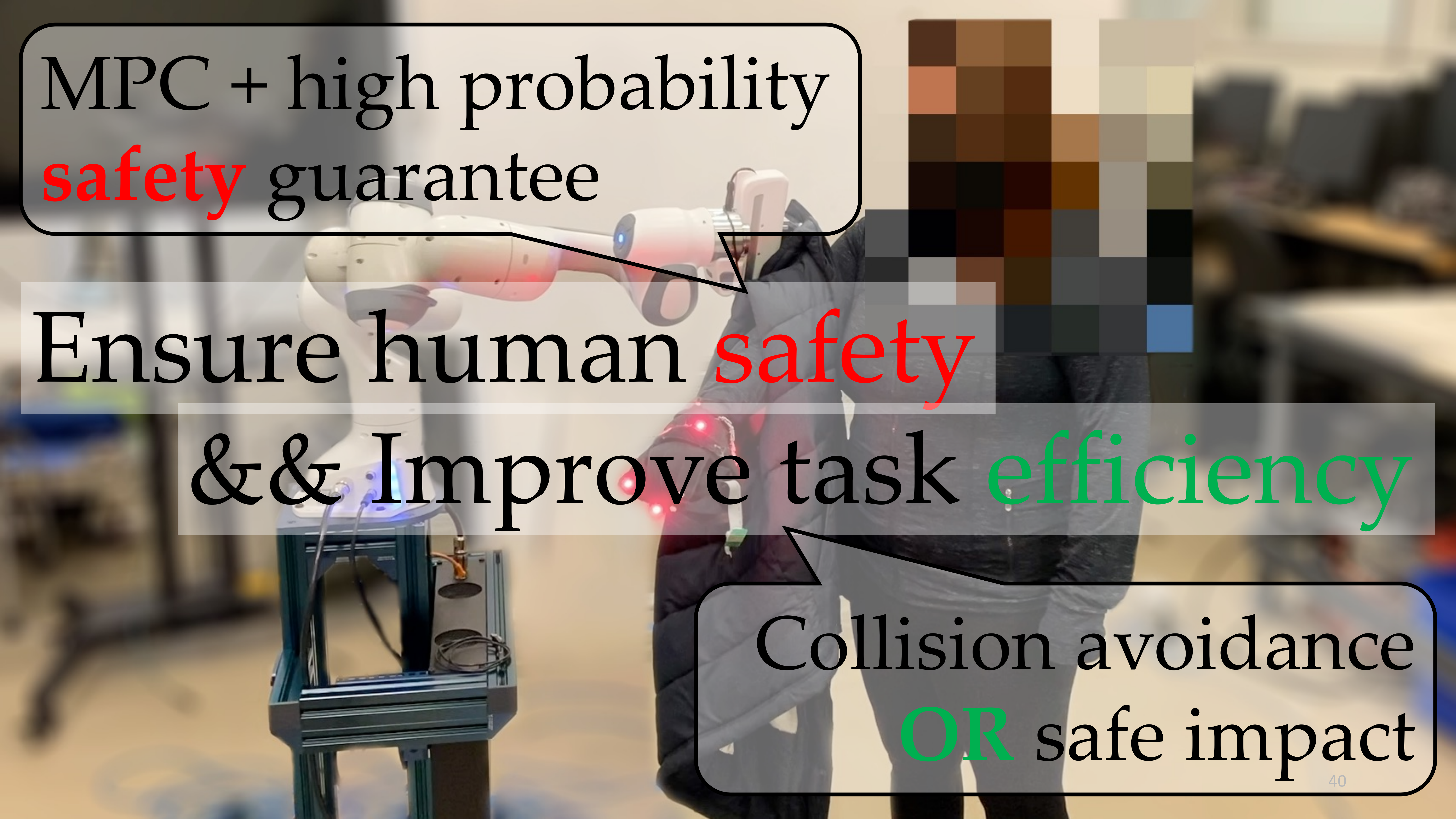
Ensure human safety

&& Improve task efficiency

Collision avoidance

OR safe impact


$d_{HR}^{max} = 0.085$m
Safety = collision avoidance
OR safe impact
Safety = collision avoidance


MPC + high probability safety guarantee
Ensure human safety
&& Improve task efficiency
Collision avoidance OR safe impact