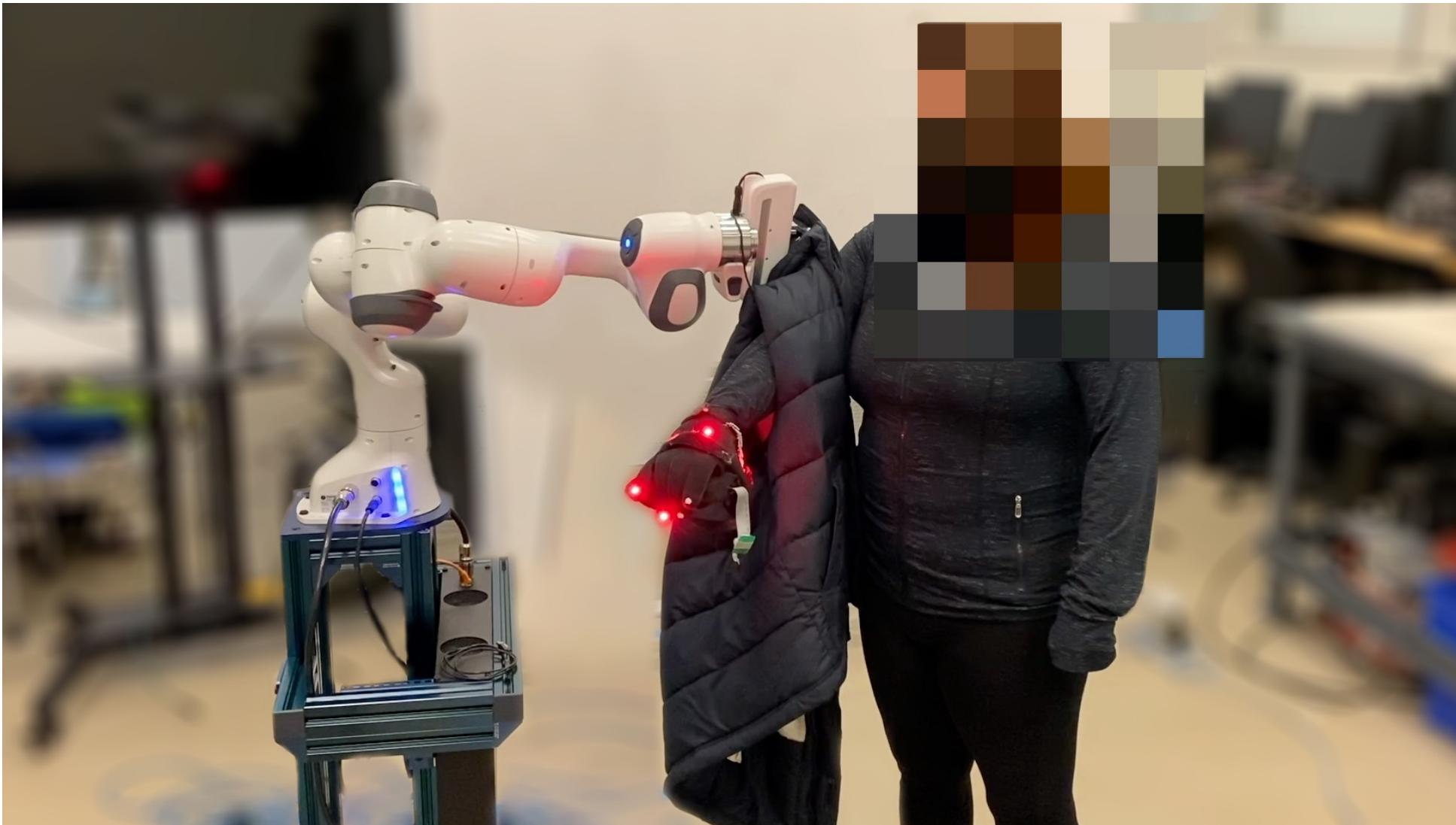


Provably Safe and Efficient Motion Planning with Uncertain Human Dynamics

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



Robot-assisted Dressing



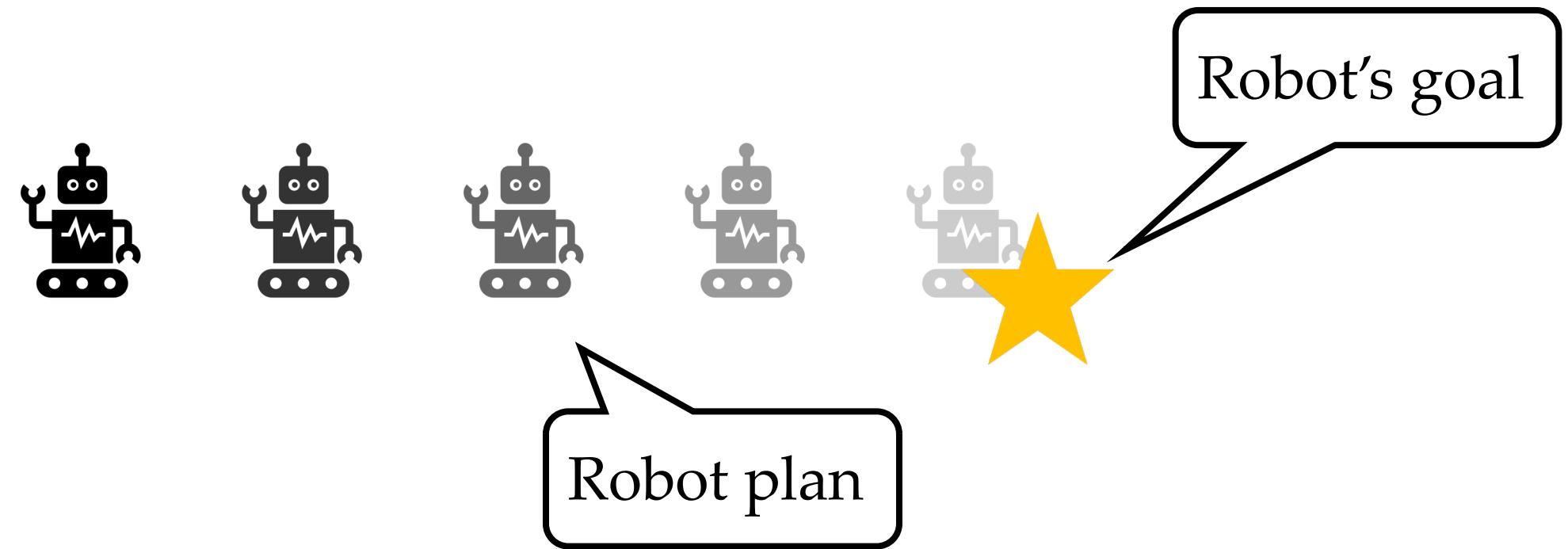
Human Physical Safety



Human Physical Safety

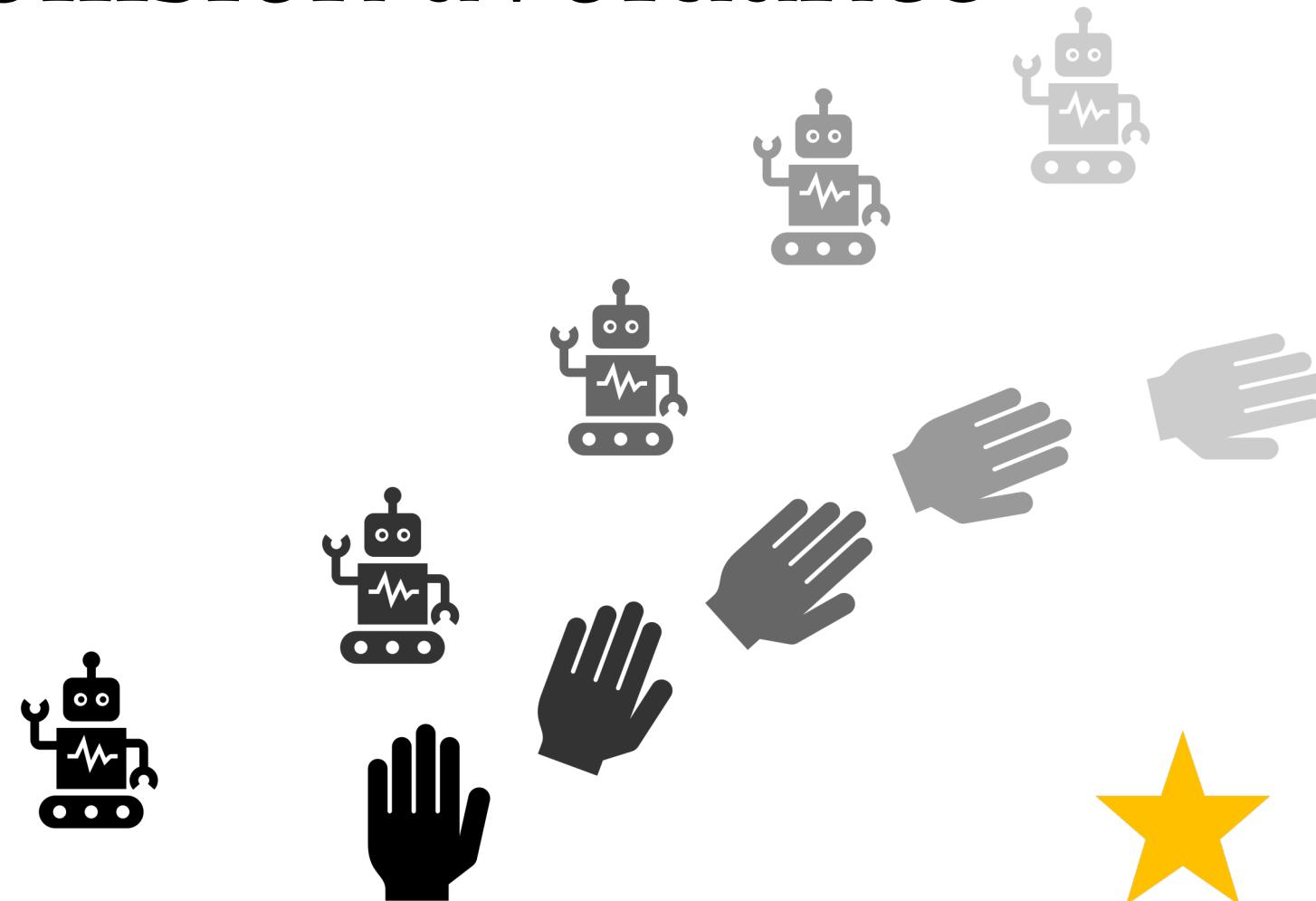


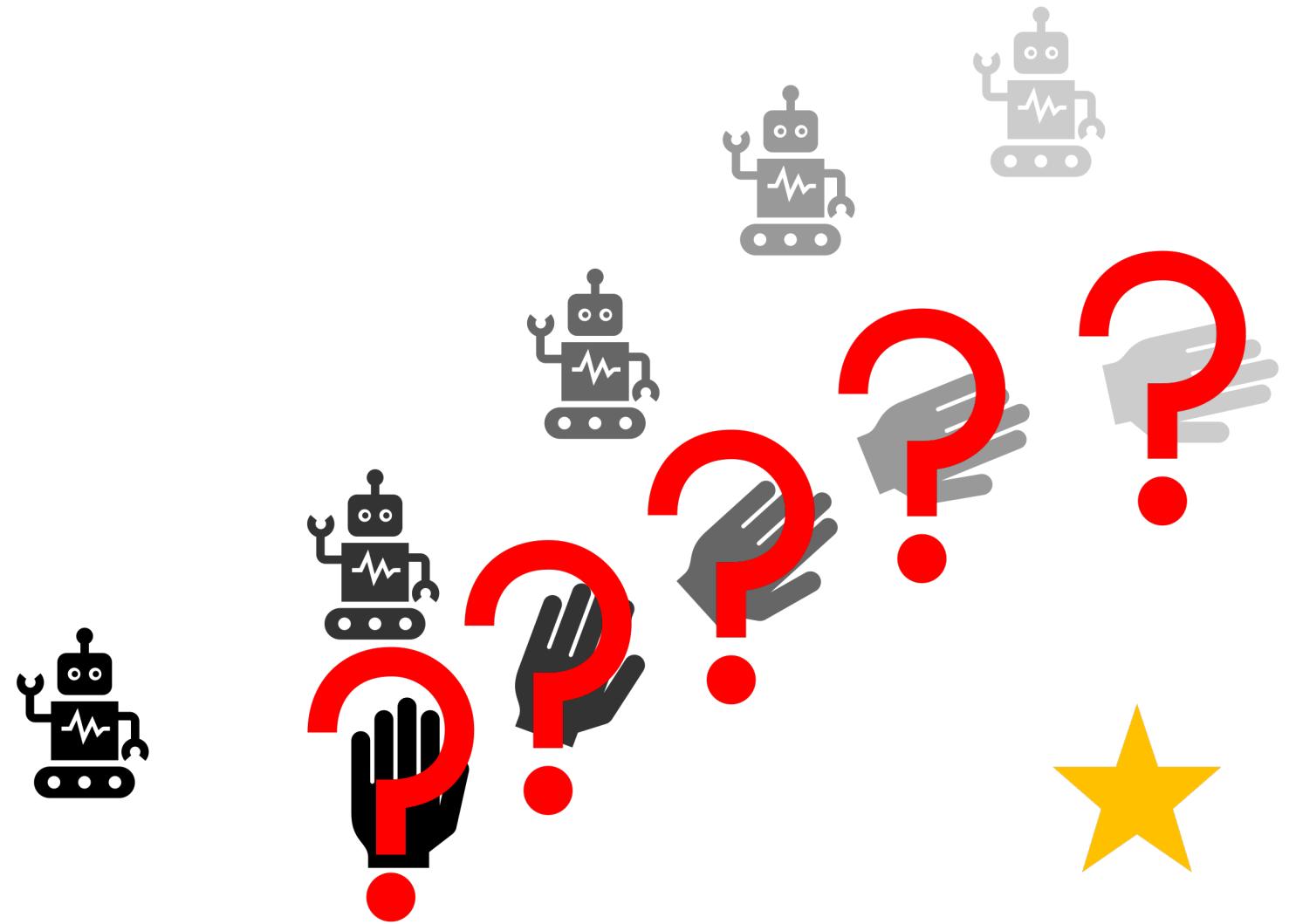
Uncertainty
in human dynamic model



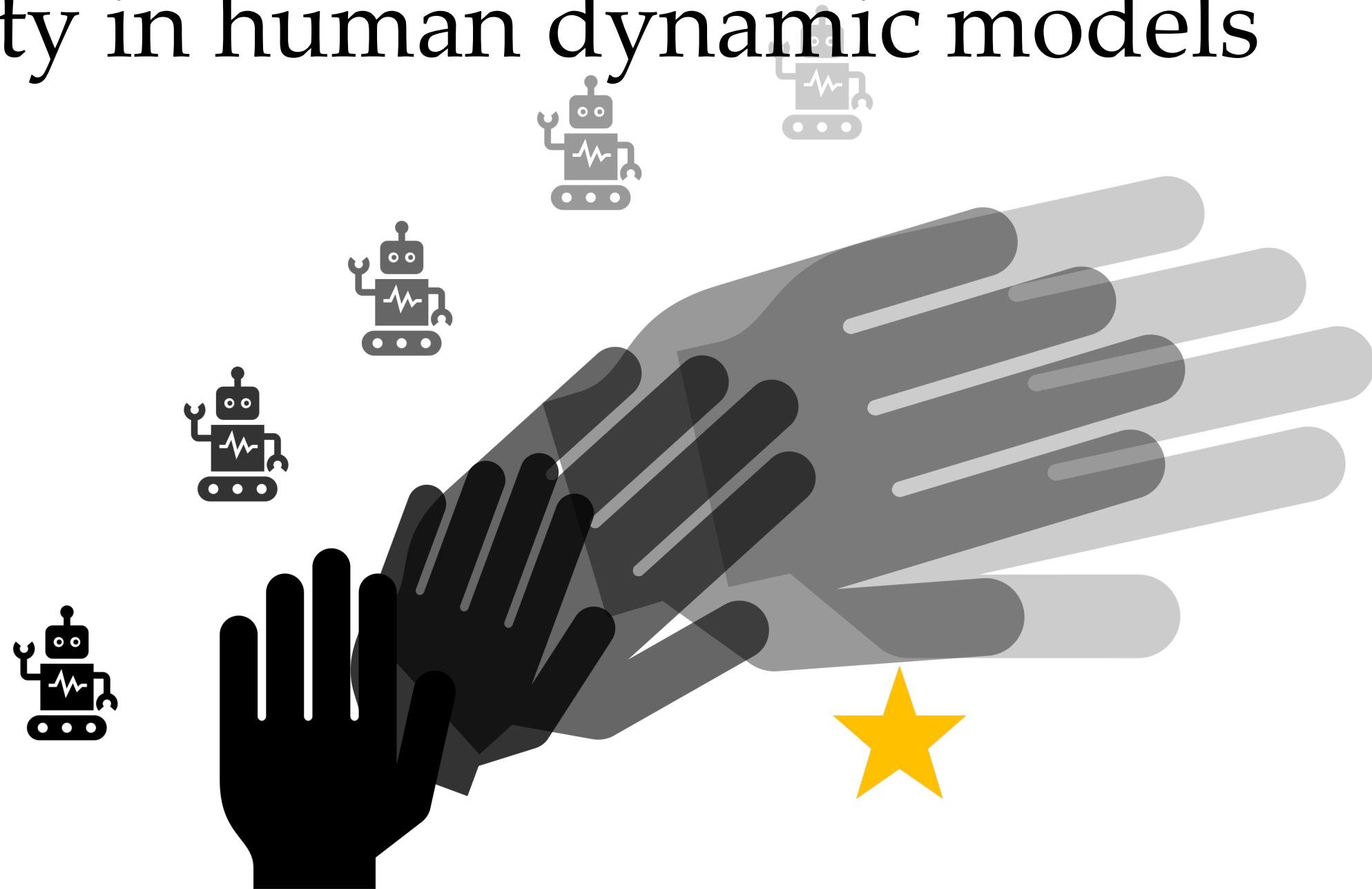
Human-aware motion planners

Safety = collision avoidance





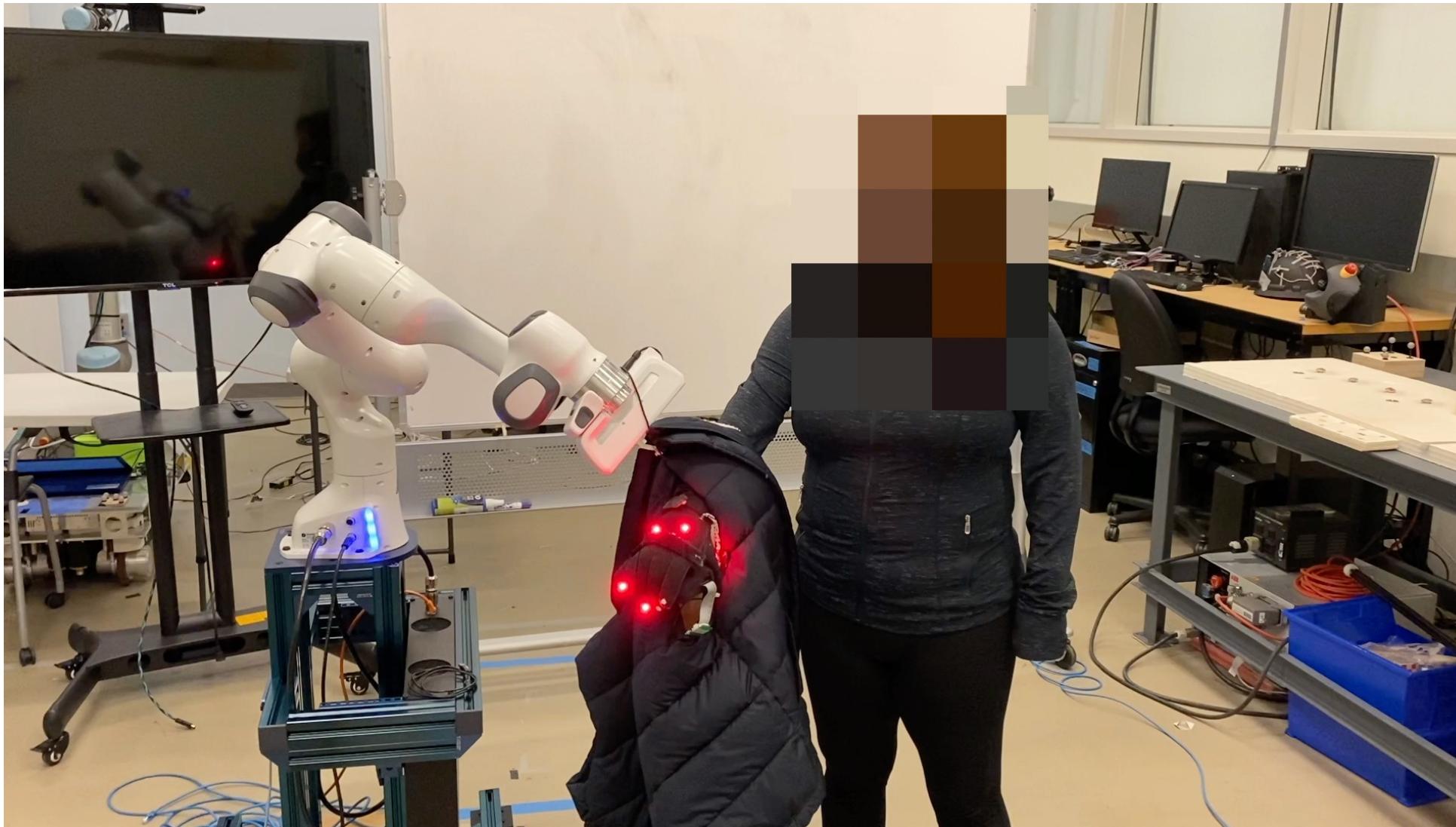
Uncertainty in human dynamic models

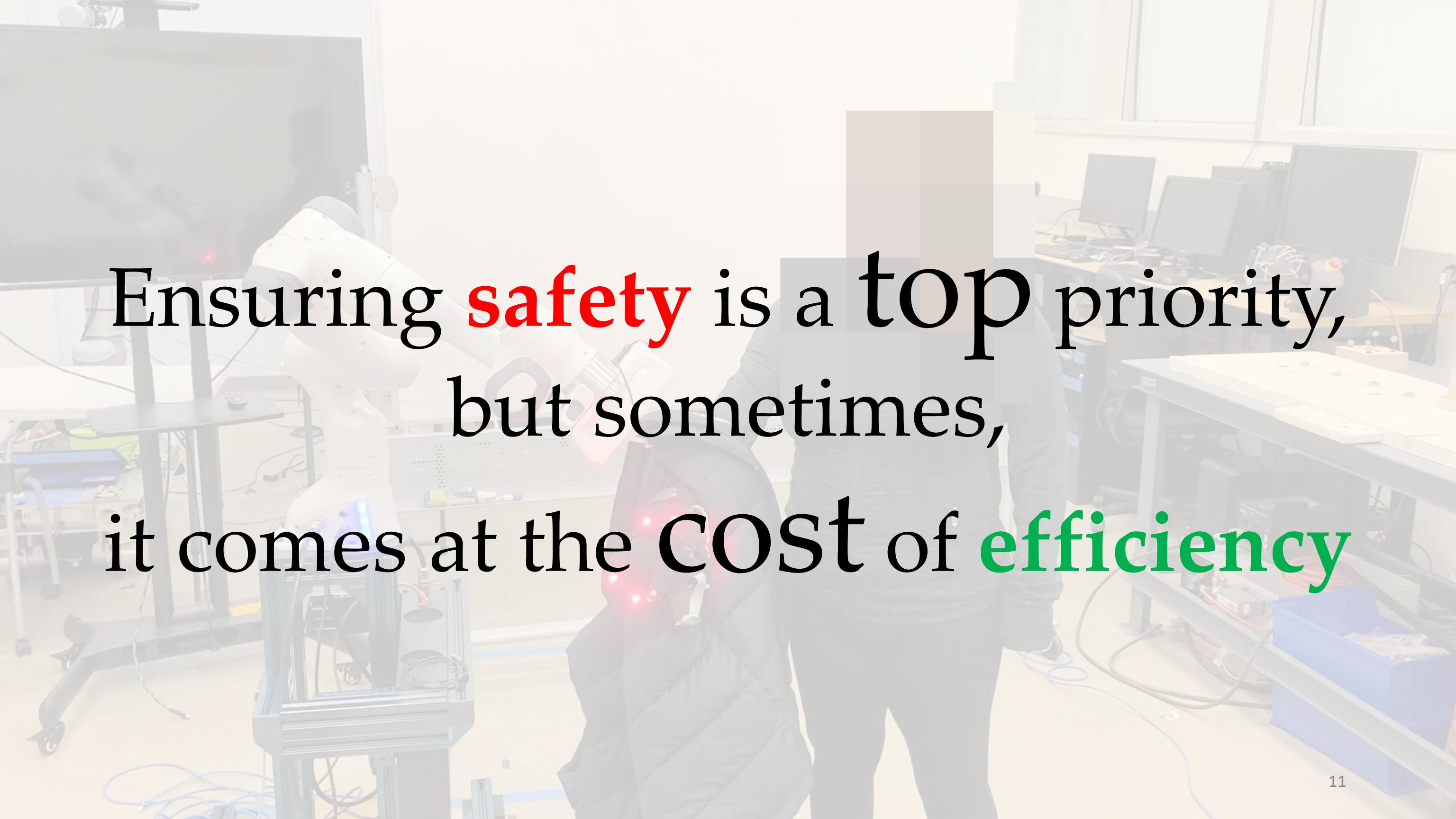


Overly conservative
=> Inefficient



“Freezing robot problem” under uncertainty





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

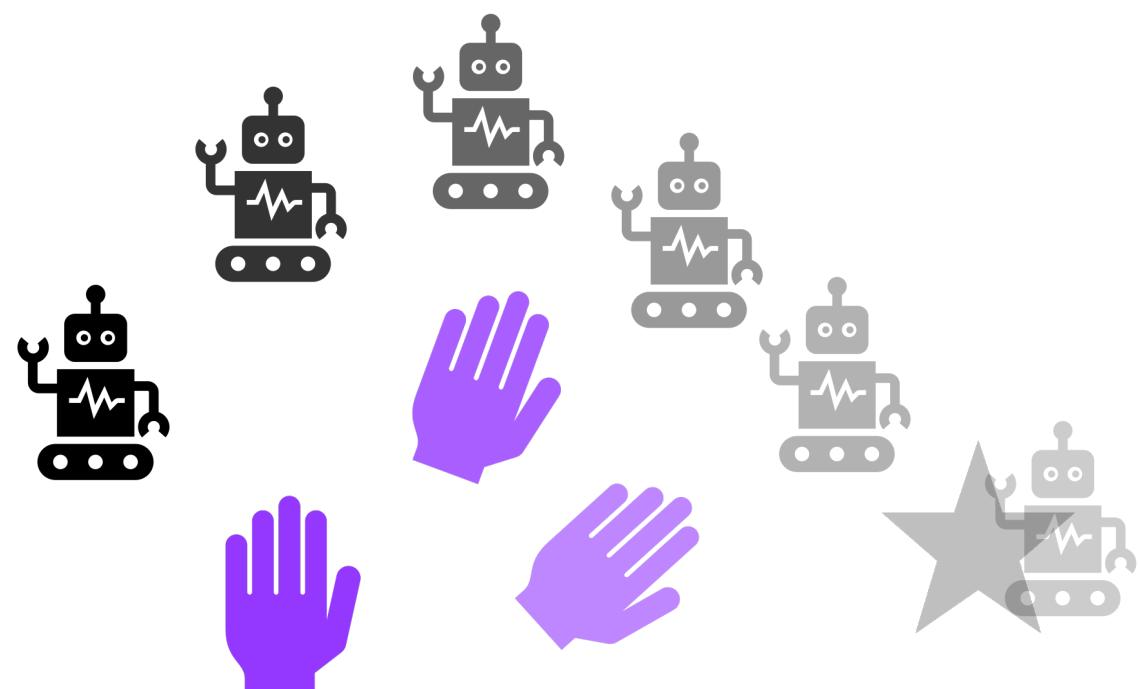
Ensure human safety
&& Improve task efficiency

Ensure human safety
&& Improve task efficiency



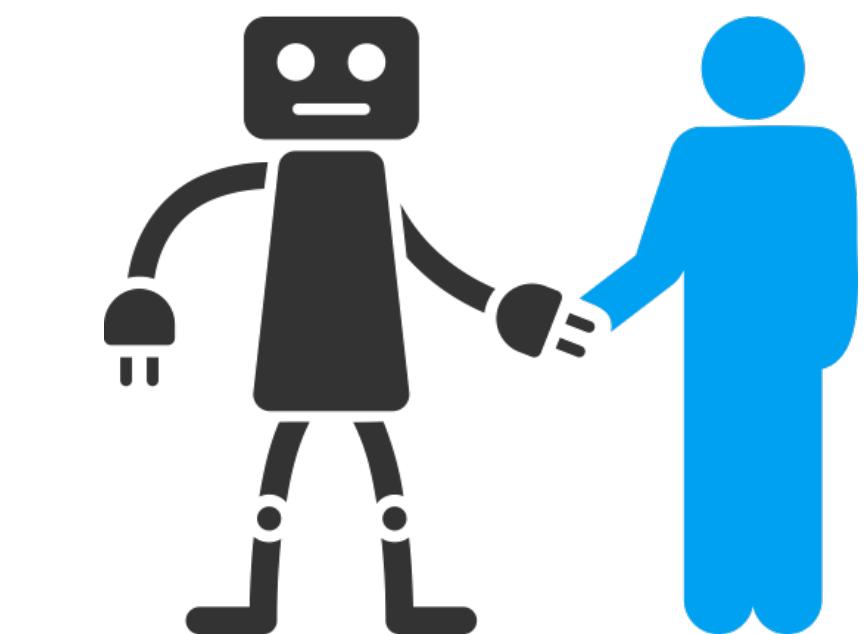
Collision avoidance
OR safe impact

Human-aware motion planners



Collision avoidance

Compliant controllers



Reduce contact force

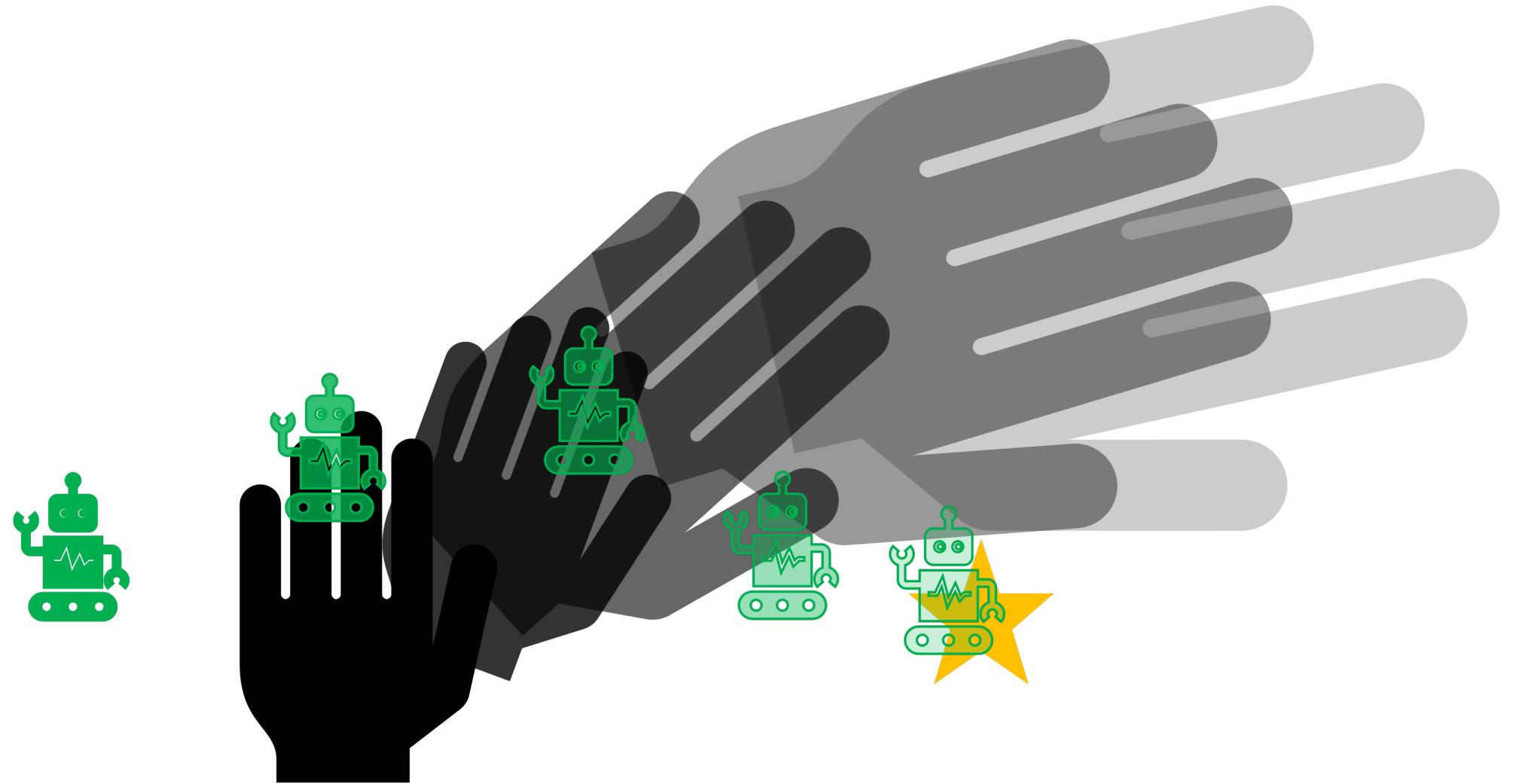
Human-aware motion planners

Collision avoidance

Compliant controllers

Reduce contact force

Collision avoidance **OR** safe impact



Ensure human safety
&& Improve task efficiency



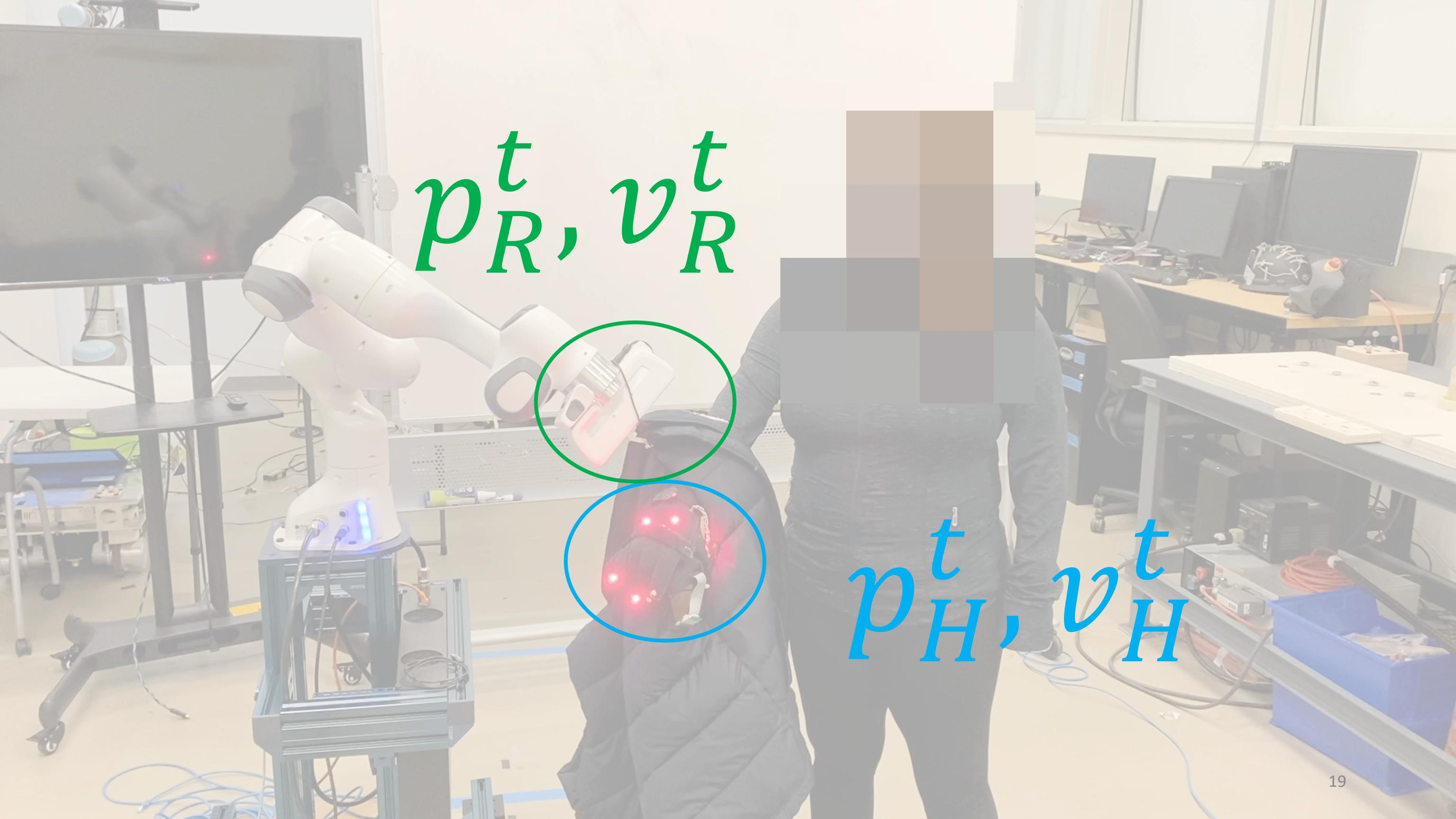
Collision avoidance
OR safe impact

MPC + high probability
safety guarantee

Ensure human **safety**

&& Improve task **efficiency**

Collision avoidance
OR safe impact

 p_R^t, v_R^t p_H^t, v_H^t

Assumption: deterministic && “smooth”

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

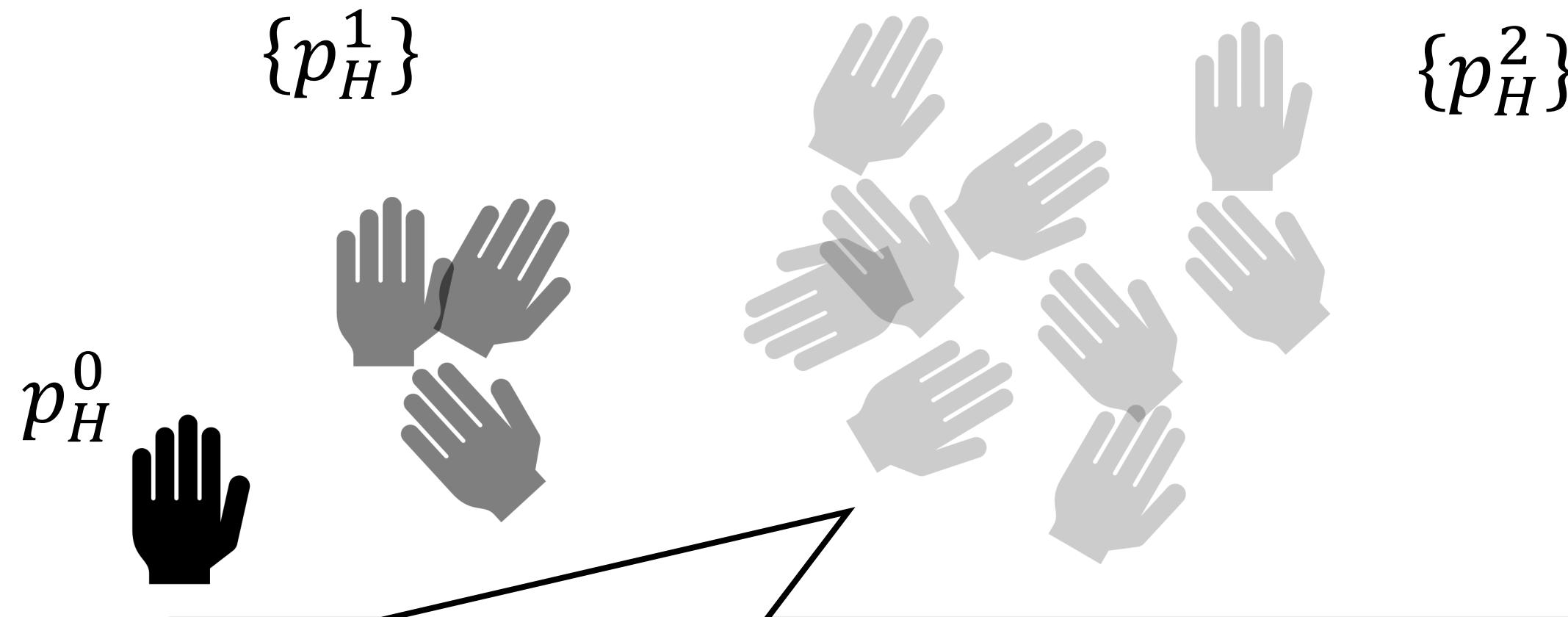
Gaussian Process

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



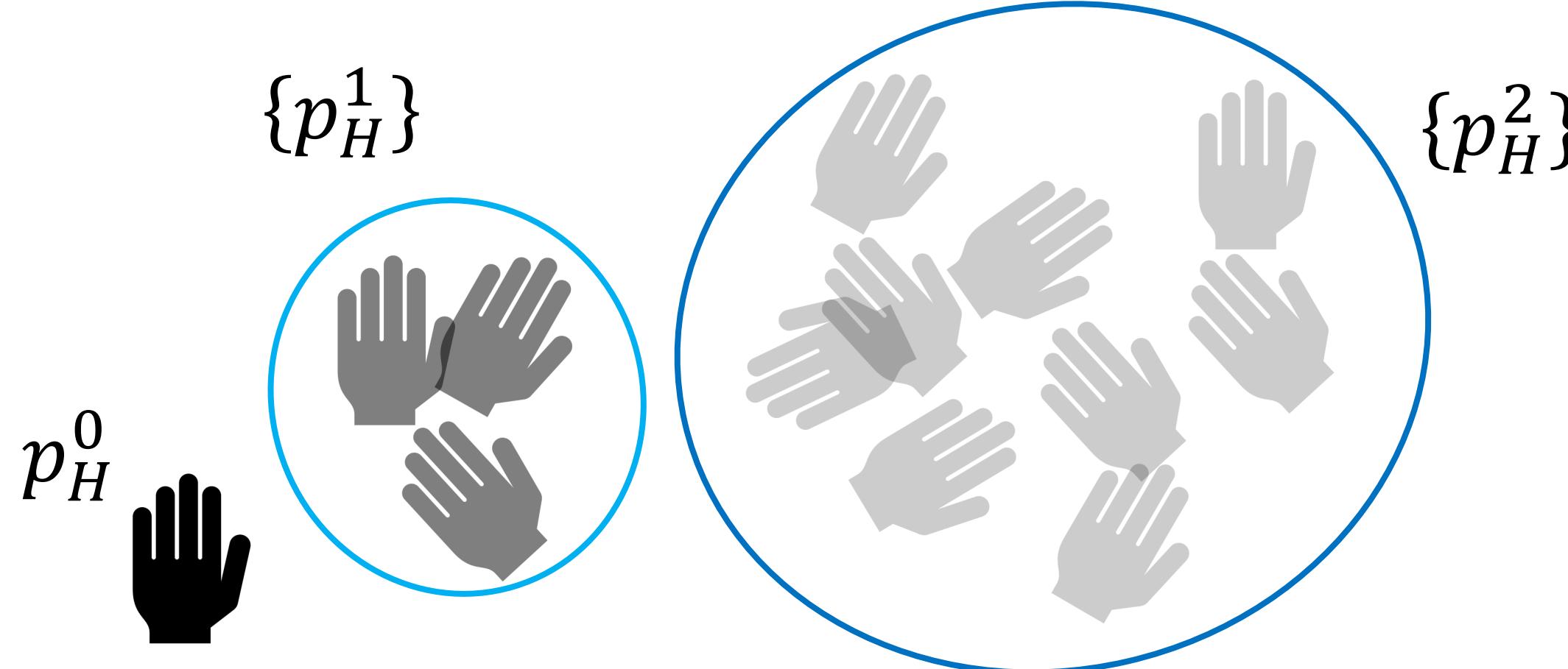
The length of time-steps

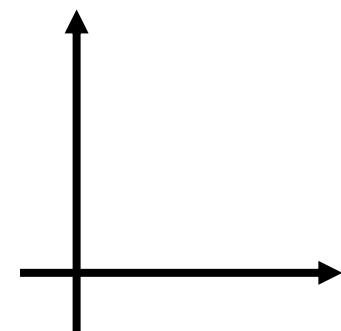
Human motion prediction



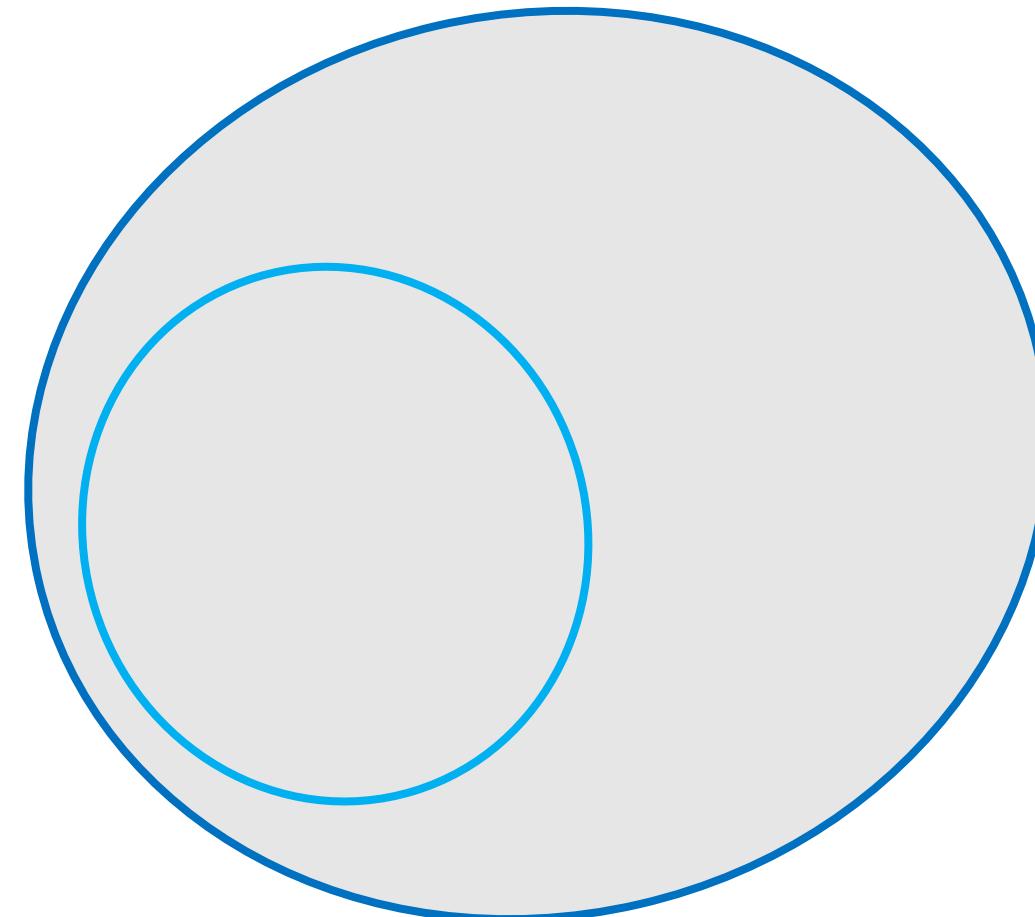
Uncertainty in the human dynamic model:

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





Velocity space



Koller, Berkenkamp, Turchetta, Boedecker, and Krause. Learning-based model predictive control for safe exploration and reinforcement learning. 2019. 27

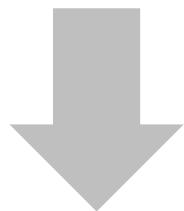
Corollary 1:

.....

With a high probability:

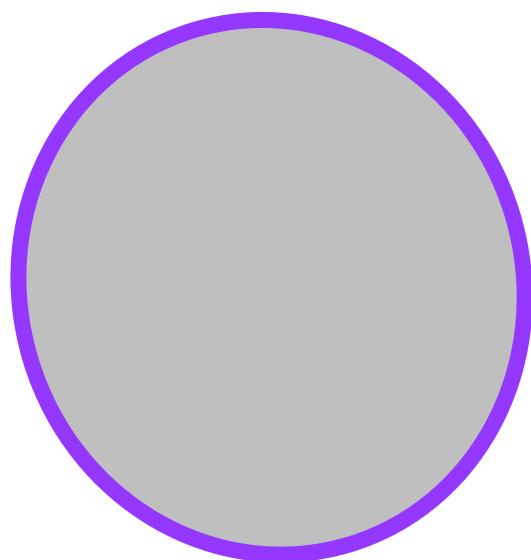
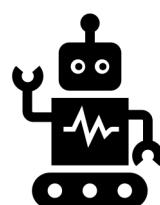
$\forall t \in [1 \dots T]$, human pos, vel \in ellipsoids

Collision avoidance

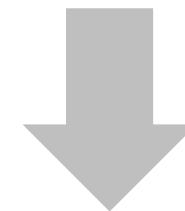


A constraint over

- Robot pos
- Human pos ellipsoid

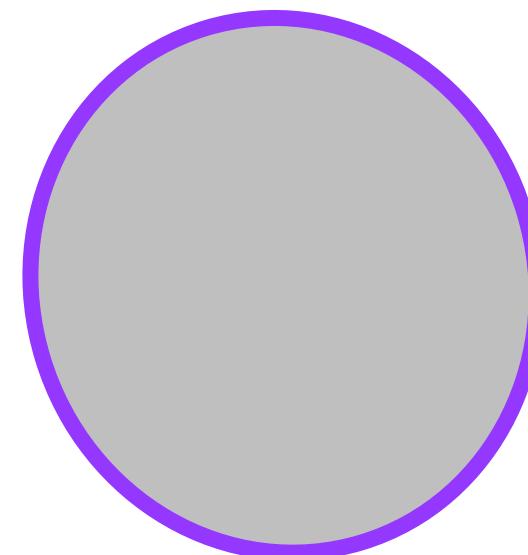
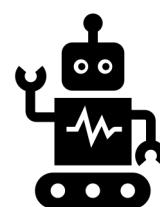


Collision avoidance

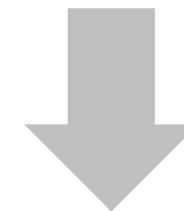


A constraint over

- Robot **pos**
- Human **pos** ellipsoid

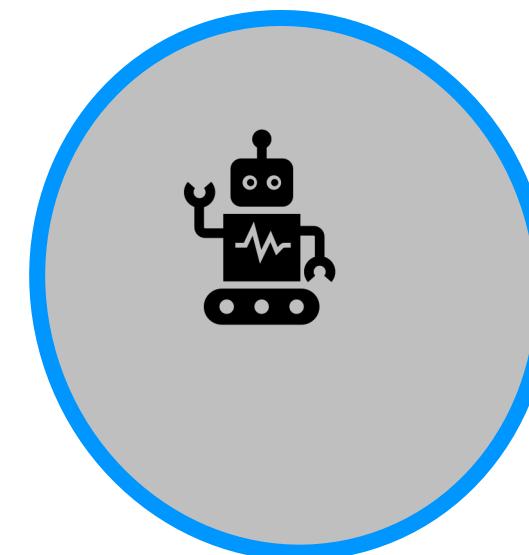
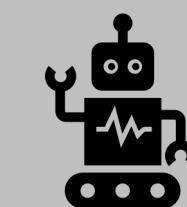


Safe impact

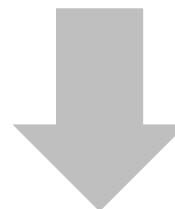


Constraints over

- Robot **vel**
- Human **vel** ellipsoid



Collision avoidance

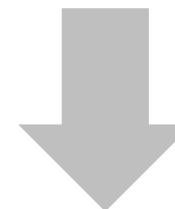


A constraint over

- Robot pos
- Human pos ellipsoid

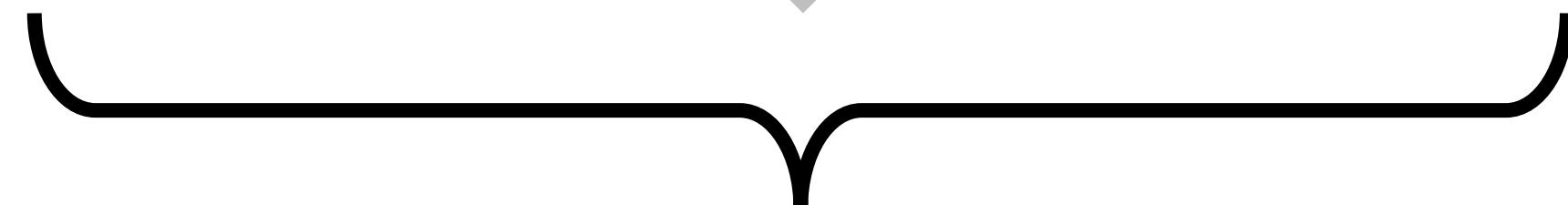
OR

Safe impact

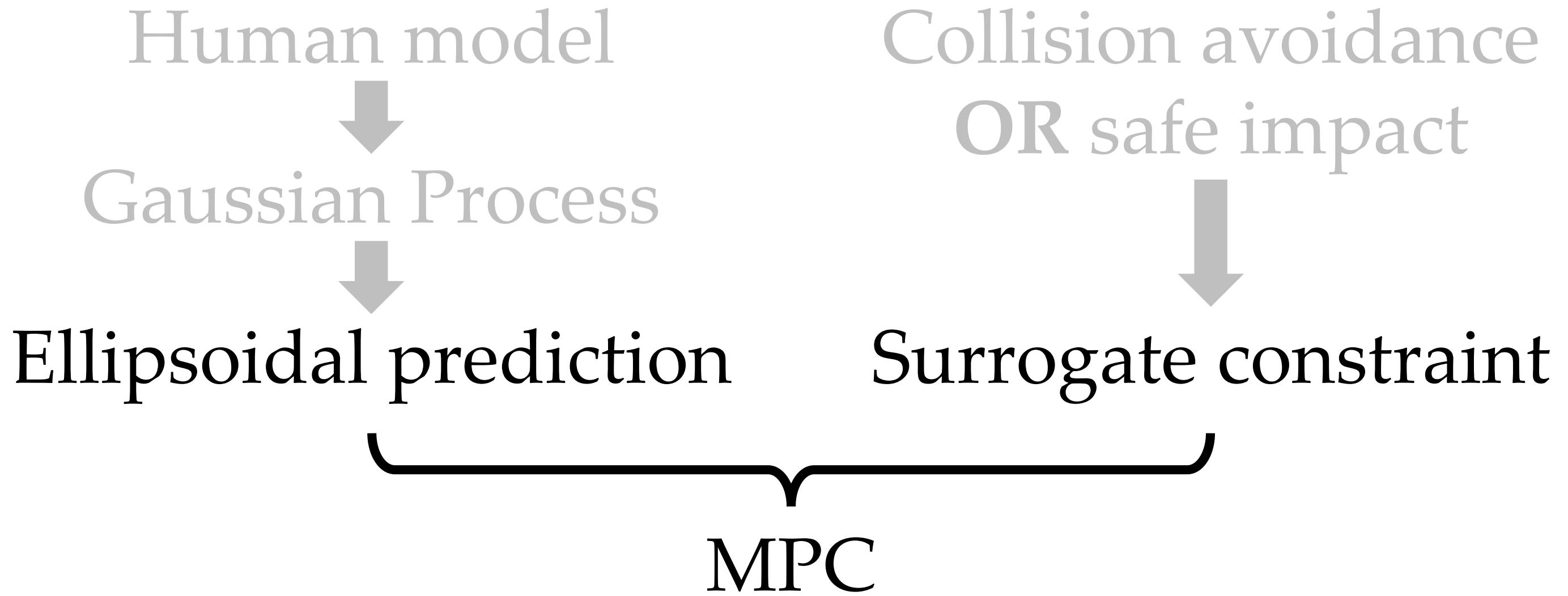


Constraints over

- Robot vel
- Human vel ellipsoid



Surrogate constraints



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

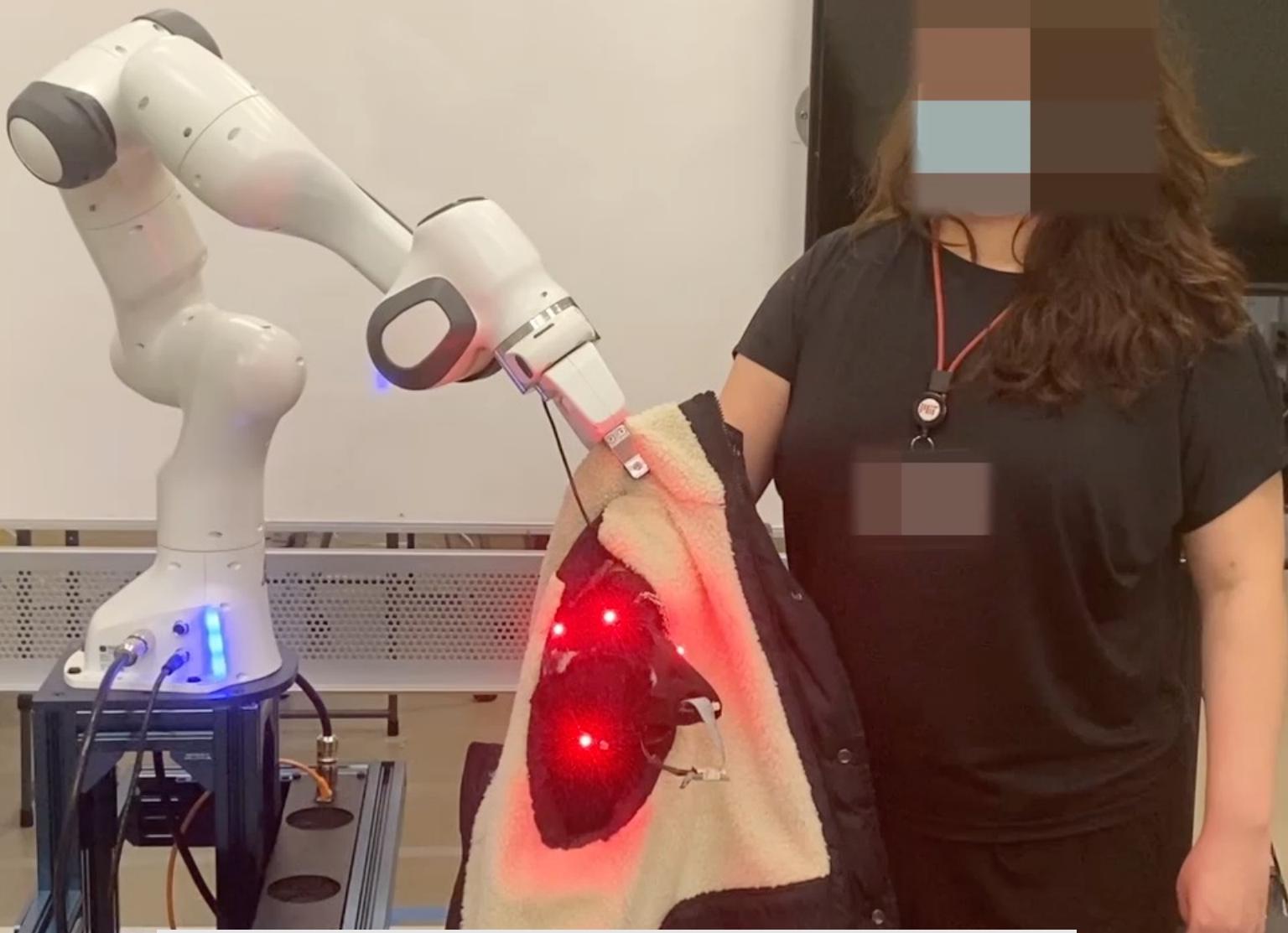
MPC + high probability
safety guarantee

Ensure human **safety**

&& Improve task **efficiency**

Collision avoidance
OR safe impact

$$d_{HR}^{max} = 0.085m$$



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