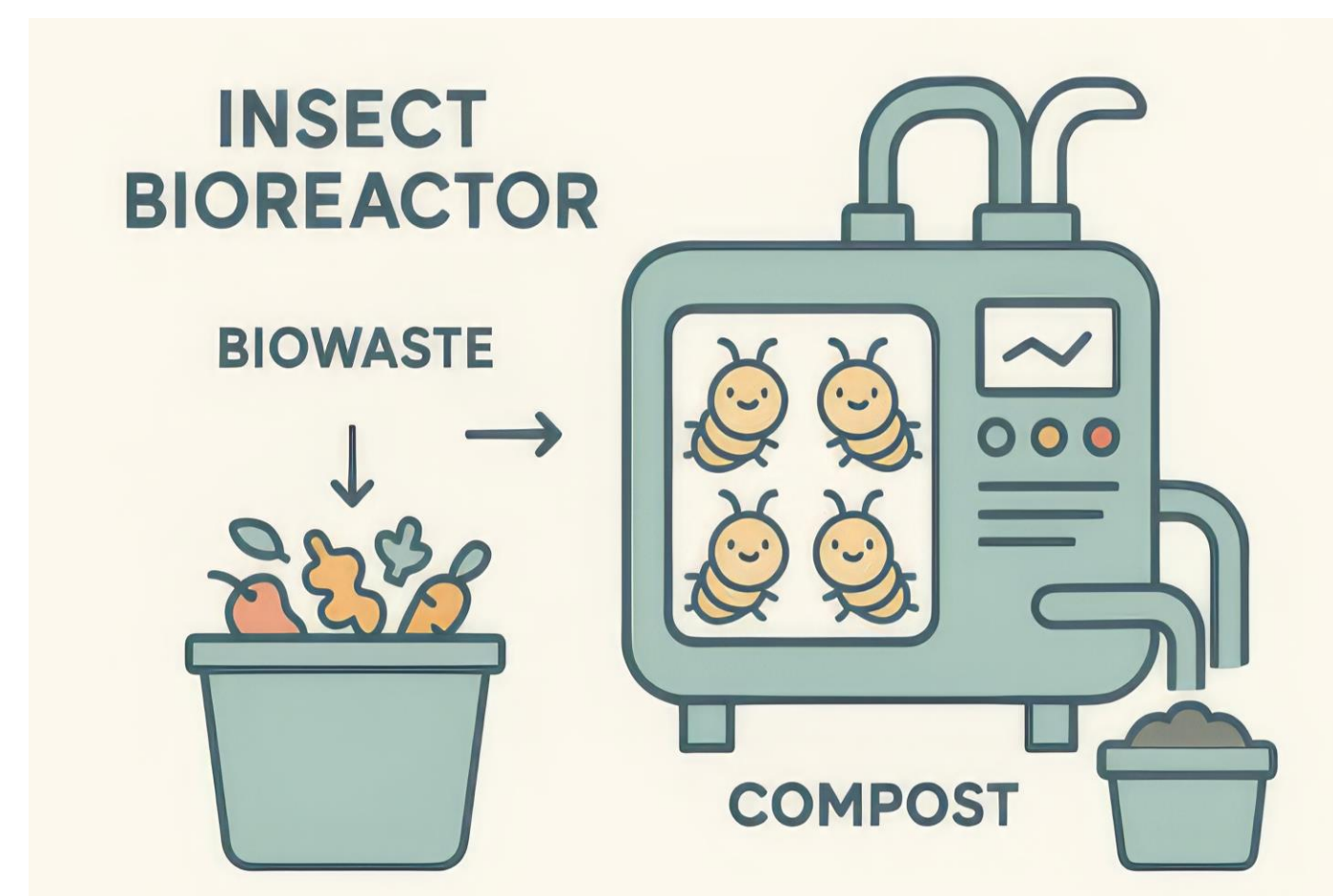


# Bioreactor Digital Twin

## Introduction

### What are Bioreactors?



- **Bioreactors** are optimal environments for organisms to convert raw materials into desired products
- **Insect Bioreactors** convert biowaste into nutrient-dense compost
  - Benefit: Capture economic value from biowaste that would otherwise be discarded
  - Ex: Beer brewing fermentation

### Digital Twins



- **Digital model:** isolated representation of physical system that predicts how it might behave (e.g. CAD files, 3D models in game design)
- **Digital shadow:** digital model that updates with input from real physical system
- **Digital twin:** digital shadow that can be modified to alter the physical system

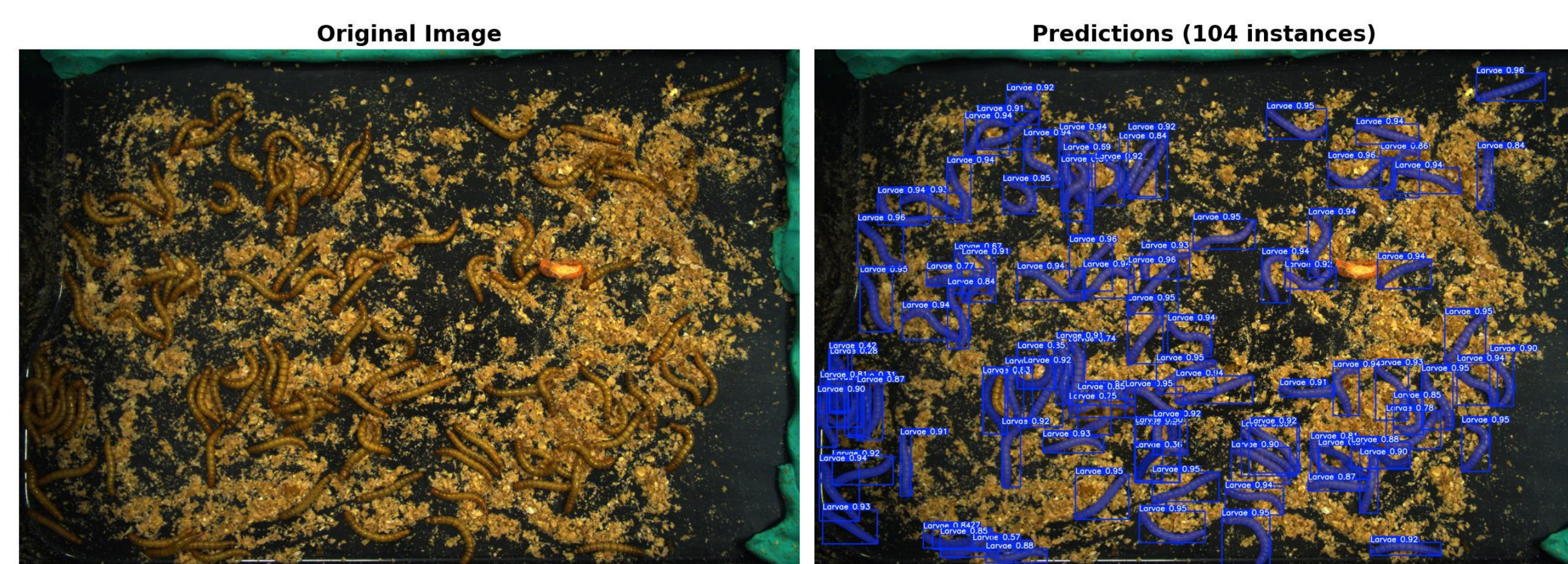
## Objectives

### Perception Monitoring System



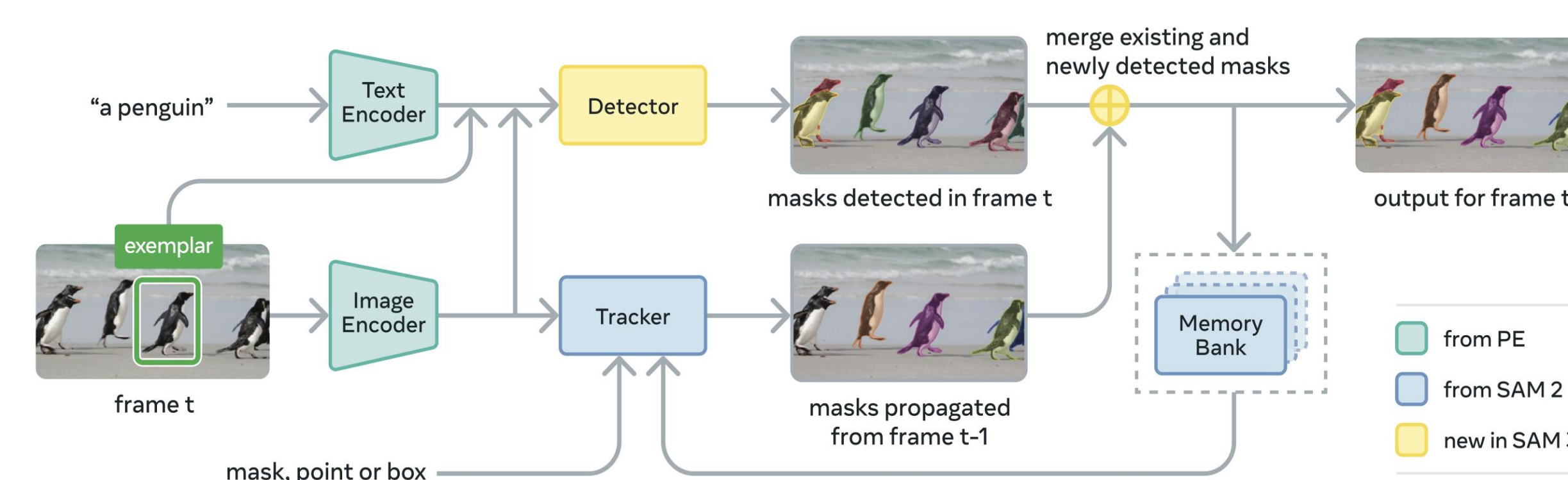
- **Segmentation:** count individual insects, estimate population size
- **Pose estimation:** track insect movement, classify alive vs. dead, precursor to behavior analysis
- **Phenotyping:** determine insect size, growth stage
- **Behavior analysis:** classify more complex insect behaviors combining segmentation and pose tracking

## Lit Review: TenebrioVision [1]



- Relevant dataset with high density (10-100) annotations per image
  - 53,600+ total annotated instances with bounding boxes and instance segmentation masks
- High-resolution frames: 3088 x 2076 pixels
- Diverse images with 30-second interval sampling

## Lit Review: Segment Anything Model 3 [2]

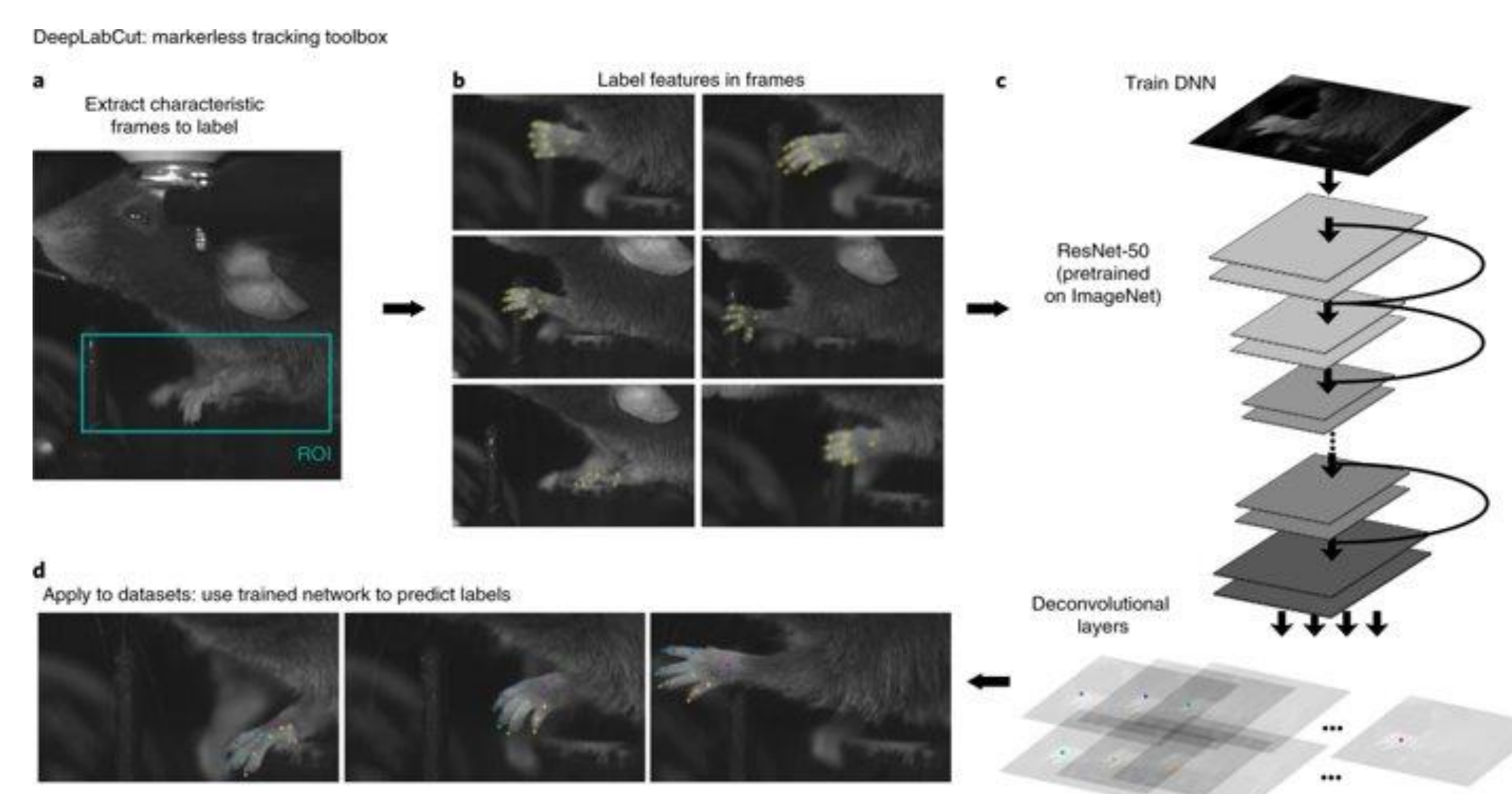


- SAM: foundation segmentation model with click-to-segment usage
- SAM2: added consistent object segmentation tracking across video
- SAM3: added multimodal prompts and concept recognition
- Introduced combined embedding space with text and image
- Separated recognition and localization into separate heads

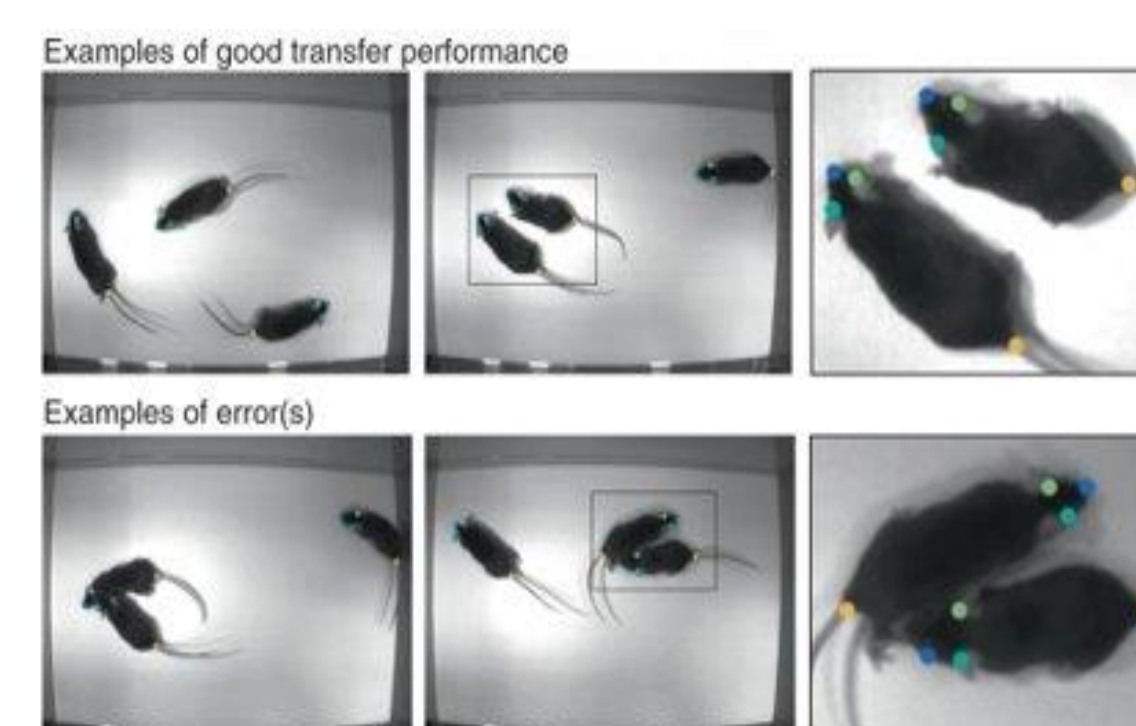


## Lit Review: DeepLabCut [3]

- Markerless pose estimation for non-human animals
- Inspiration from neuroscience focuses on mice and fruit flies
  - Open-source project success expanded to many other animals
- DeepCut: joint model for person detection and body part proposal
- DeeperCut: image-conditioned pairing of body part proposals
- DeepLabCut: transfer learning with minimal (~200-800) images

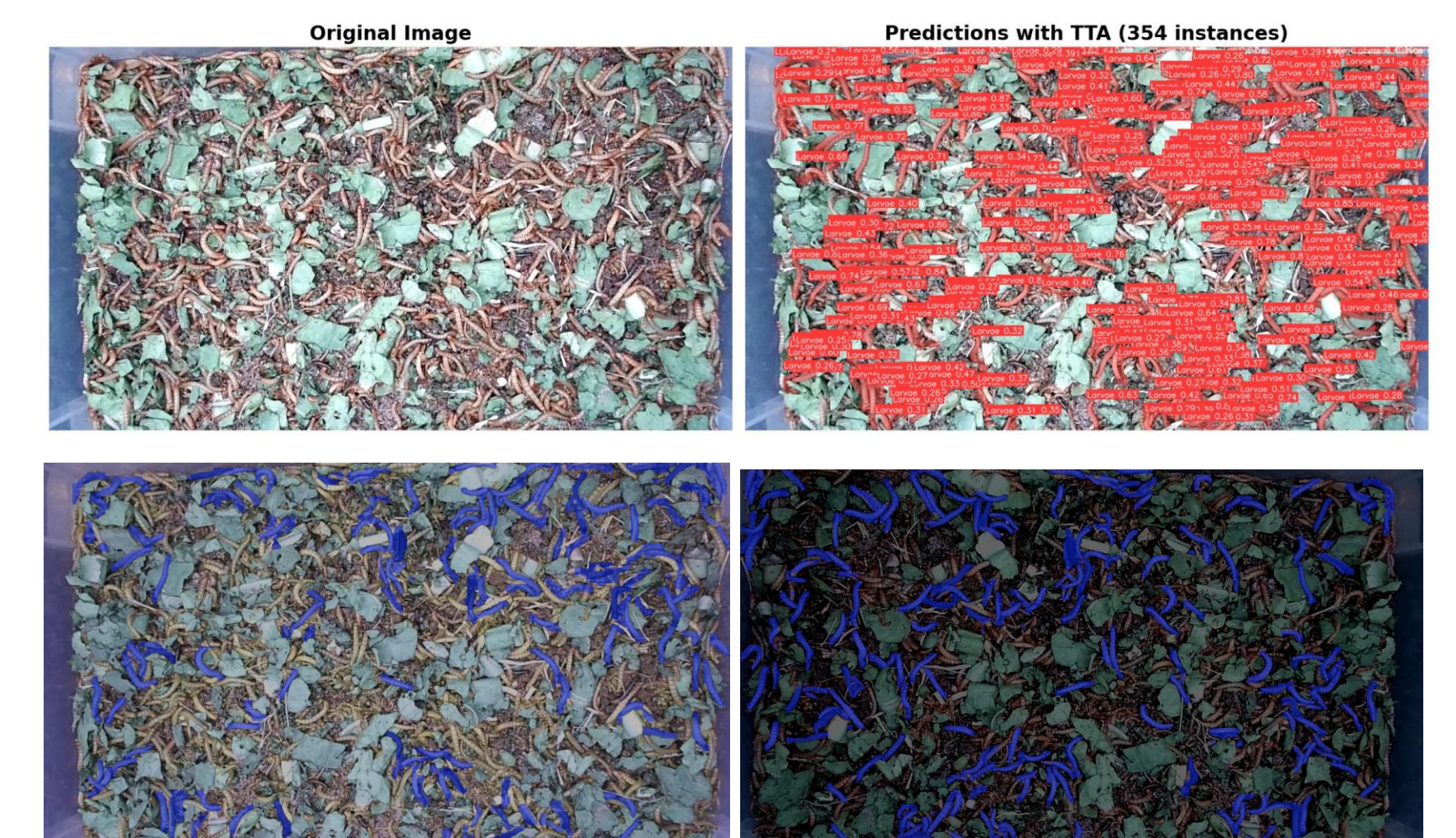


- Trained on single-animal images but generalizes to multi-animal
- SuperAnimal foundation models perform well on 40+ animals
  - Excludes insects



## Technical Progress: Segmentation

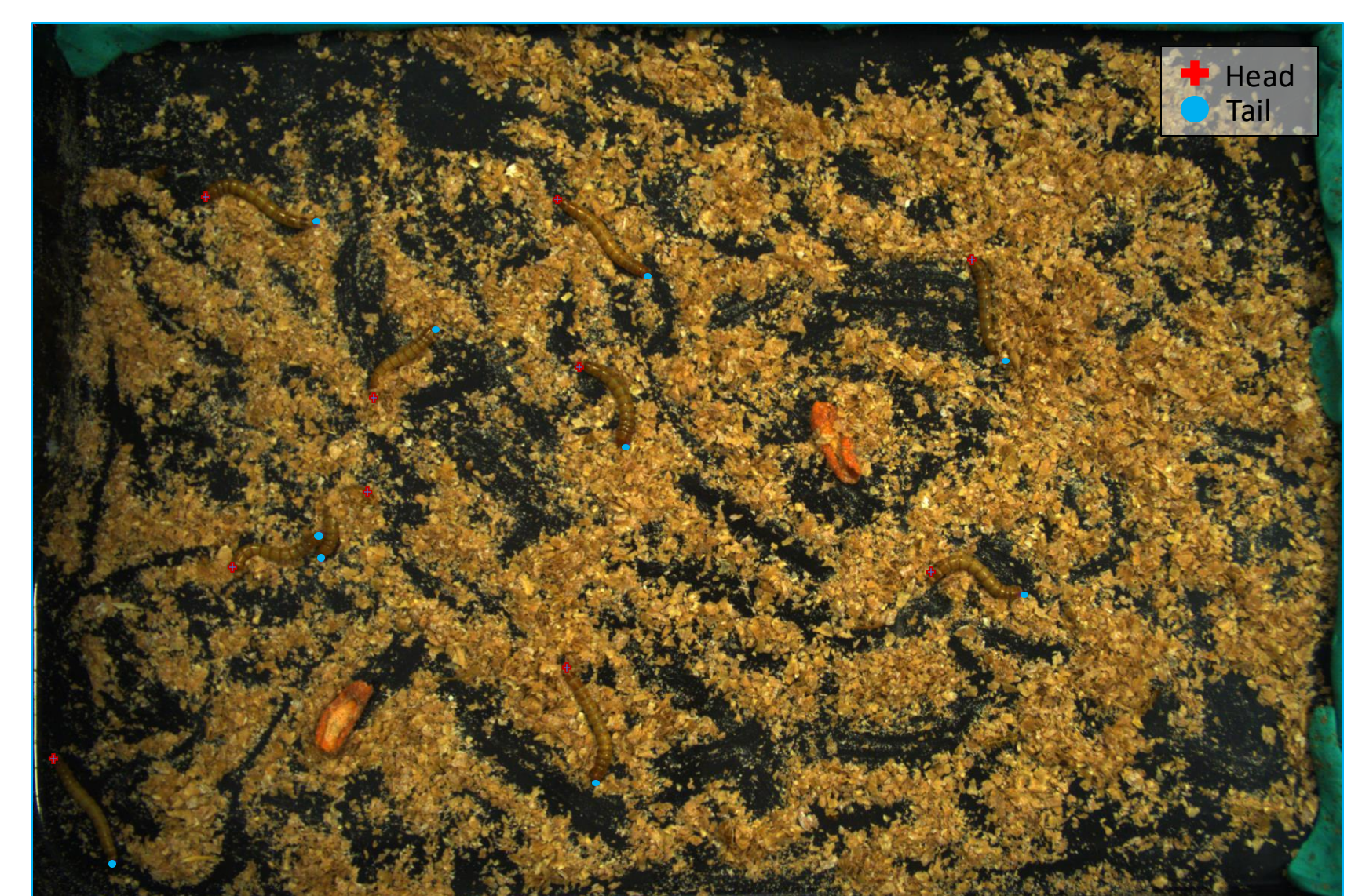
- Reproduced TenebrioVision experiments
- |             | mAP   | mAP@75_bbox | mAP_mask | mAP@75_mask |
|-------------|-------|-------------|----------|-------------|
| #YOLO_v8_IS | 0.880 | 0.965       | 0.729    | 0.830       |
| SAM3        | 0.663 | 0.790       | 0.512    | 0.520       |
| DART        | 0.740 | 0.884       | 0.548    | 0.628       |
- Fixed quick memory exploration for SAM3 when there are hundreds of instances.
  - Explored test-time augmentation for YOLO models adaptation to our data.



- Explored DART, a more efficient variant of SAM3

## Technical Progress: Pose Estimation

- Fine-tuned DeepLabCut ResNet50 model with TenebrioVision



## Next Steps

- Finish the domain adaptation method and evaluate it.
- Adapt DART into our pipeline for real time monitoring.
- Fine-tune TenebrioVision using more annotations per worm. Try morphological models to better approximate worm shape
- Collect a greater variety of worm data and verify prediction stability
- Classify behaviors using tracking

## Acknowledgements

Dr. Laszlo Jeni and CUBE Lab

## References

- [1] Papadopoulos, Angelos-Michael, et al. "TenebrioVision: A Fully Annotated Dataset of Tenebrio Molitor Larvae Worms in a Controlled Environment for Accurate Small Object Detection and Segmentation." *Icpram*. 2024.
- [2] Carion, Nicolas, et al. "Sam 3: Segment anything with concepts." *arXiv preprint arXiv:2511.16719* (2025).
- [3] Mathis, Alexander, et al. "DeepLabCut: markerless pose estimation of user-defined body parts with deep learning." *Nature neuroscience* 21.9 (2018): 1281-1289.