

Defense of Master's Thesis

Exploring Predator-Prey Dynamics from Videos using Generative Adversarial Imitation Learning

Jannik Wirtheim

Konstanz, 23.02.2026

Motivation



Reference: „The hunt from above“ – Angela Albi : <https://www.campus.uni-konstanz.de/uni-leben/die-kunst-der-haie>

Modelling of Multi-Agent Systems

Behavior is modeled using hand-crafted interaction rules.

→ requires domain knowledge from the designer.

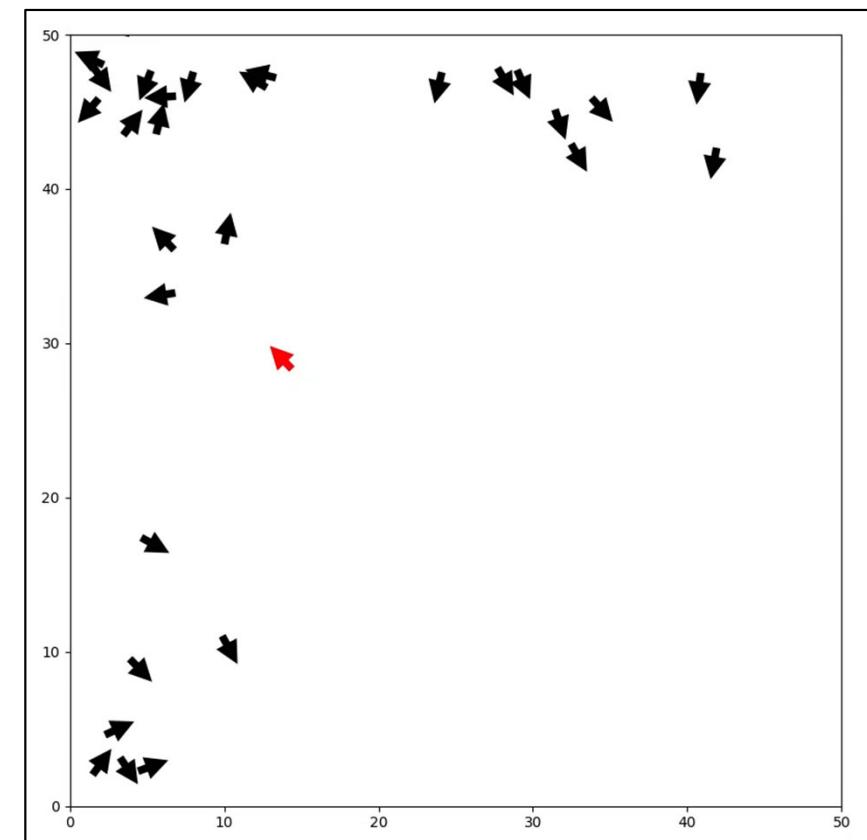
Pros/Cons:

- + Simple rules
- + Reasonable behavior
- Expert knowledge
- Oversimplified dynamics

Hand-crafted rules

Examples:

- Reynolds Boids (1987)
- Vicsek Model (1995)
- Couzin Model (2002)
- (Reinforcement Learning (RL))



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Hand-crafted rules

Behavior is learned by imitation from expert demonstrations.

→ desired behavior is implicitly represented in the data.

Pros/Cons:

- + No manual rule design
- + Complex dynamics
- Data dependency
- Computational problems

Data-driven approaches

Examples:

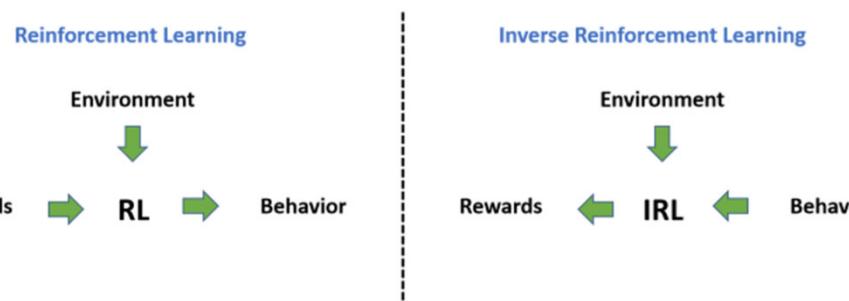
- Reynolds Boids (1987)
- Vicsek Model (1995)
- Couzin Model (2002)
- (Reinforcement Learning (RL))

Examples:

- Behavioral Cloning (BC)
- Inverse RL
- Generative Adversarial Imitation Learning (GAIL)

Data-driven Methods

https://skandavaidyanath.github.io/post/inverse-rl-paper/the_problem.png



Behavioral Cloning:

- Supervised learning
- Training on states s
- Learning of actions a

→ *Large amount of data*
→ *Compounding errors*

Inverse RL:

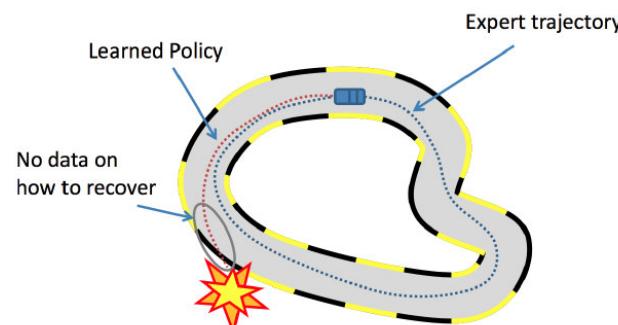
- Recovers reward from expert behavior
- Learns policy from reward
- Avoids manual reward design

→ *Reward ambiguity*
→ *Computational cost*

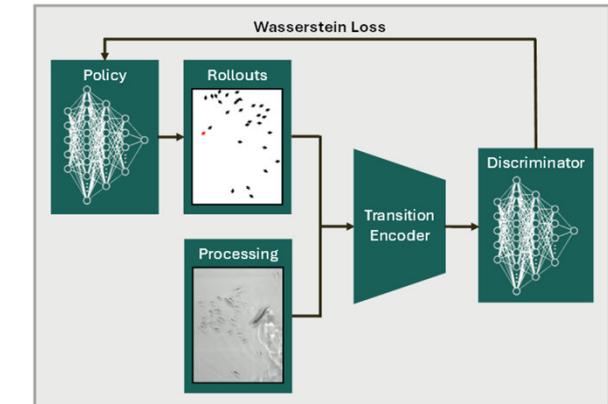
GAIL:

- Adversarial learning (policy vs. discriminator)
- Distribution matching
- Scales to multi-agent imitation

→ *Imbalance*
→ *Mode collapse*



<https://smartlabai.medium.com/a-brief-overview-of-imitation-learning-8a8a75c44a9c>



Modelling of Predator-Prey Systems

Predator–prey systems represent a specific form of multi-agent systems in which heterogeneous groups pursue contrasting objectives.

Prey strategies:

- Cooperative behavior
- Coordinated motion
- Synchronized directional changes
- Confuse predator & increase survival chance

Predator strategies:

- Dispersion tactics
- Isolated prey
- Separate individuals from swarm

Challenge: Imitation is driven by a survival-based interplay between cooperative prey and a attack-oriented predator.

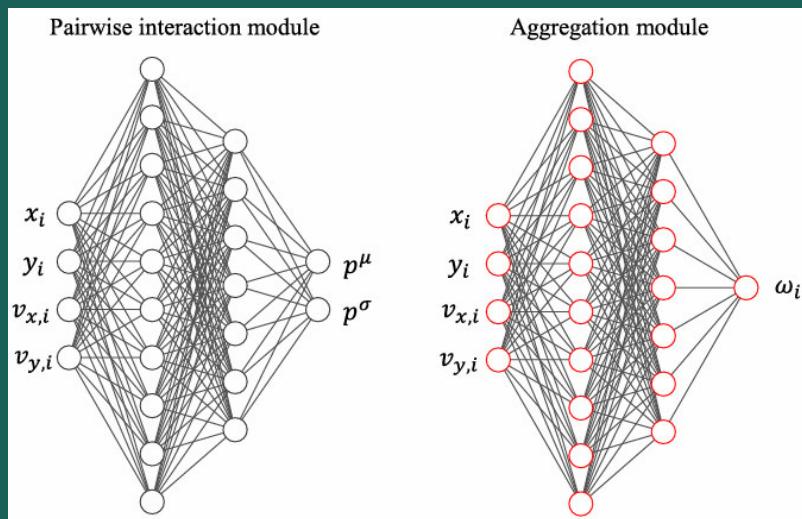


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Related Research

Adversarial imitation learning with deep attention network for swarm systems (Yapei Wu et al., 2025)

- GAIL with shared individual policy
- Couzin-based swarm demonstrations
- Same policy & tensor structure
- Limited to single-species imitation



(Yapei Wu et al., 2025, p.4)

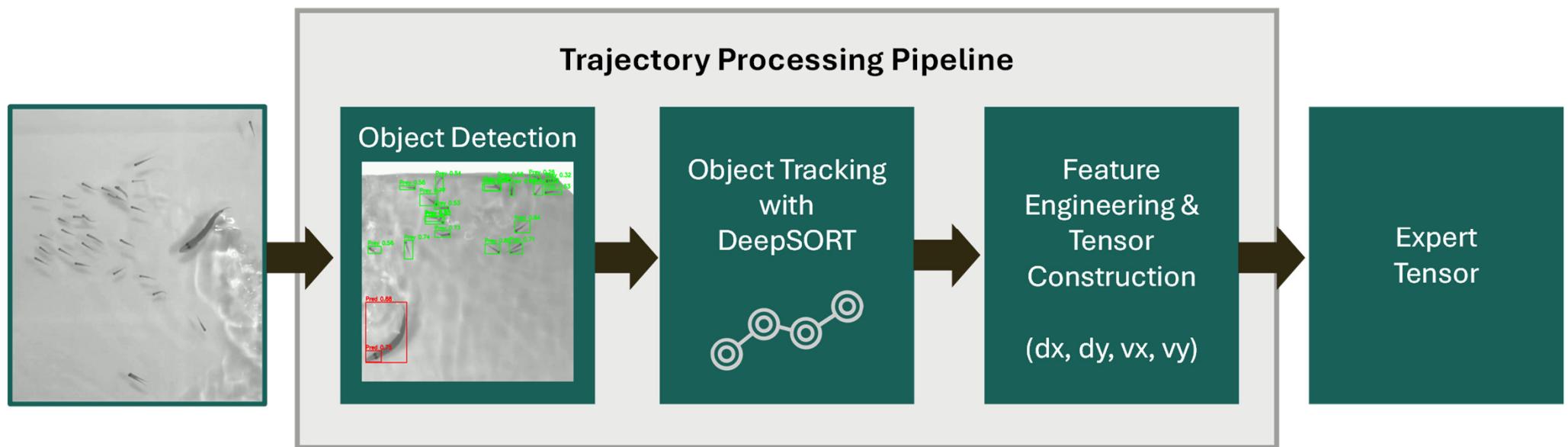
CBIL: Collective Behavior Imitation Learning for Fish from Real Videos (Yifan Wu et al., 2025)

- GAIL on latent video representations
- Transition Encoder
- Feature clustering & reward shaping
- Imitated predation with multi-instance single policy



(Yifan Wu et al., 2025, p.9)

Data Collection & Processing



Data Collection & Processing

Recording of predator-prey aquarium:

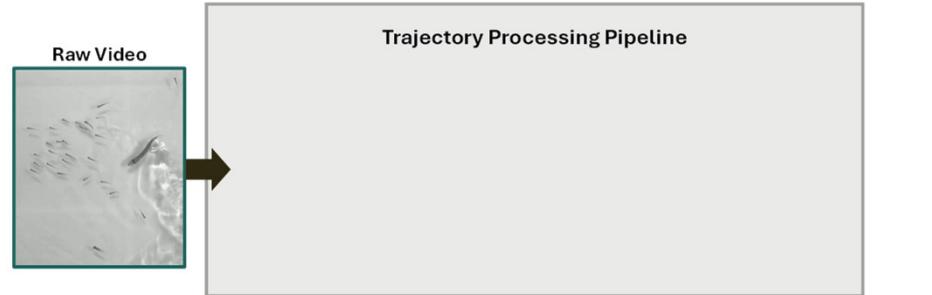
- Setup & recordings by MPI
- Sunbleak (*Leucaspis delineatus*)
- Northern pike (*Esox lucius*)

Video-related overview:

- 35 recordings (1 predator, 32 prey)
- total duration 16:42:49 h
- 151.695 frames

Predator-related overview:

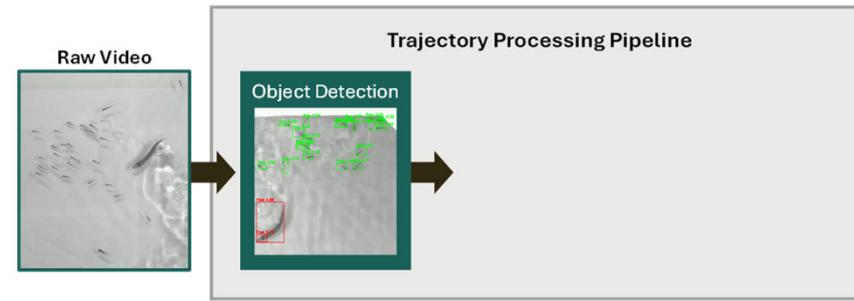
- 32 attacks
- 18.9 seconds
- 0.12% of total recordings



Data Collection & Processing

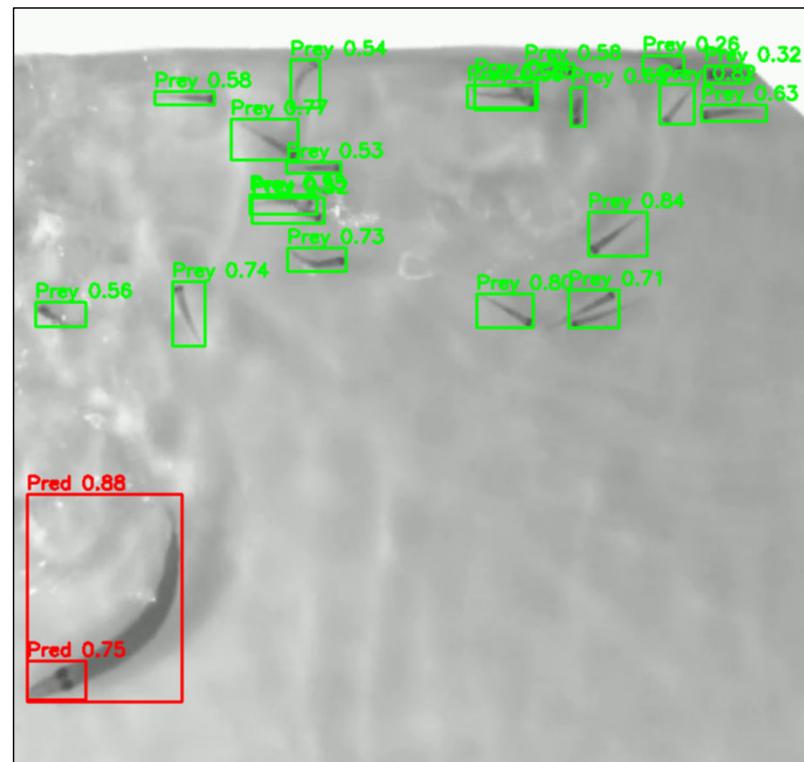
Object-detection:

- Custom YOLOv11
- fine-tuned on 100 hand-labeled frames
- extract positions



Detection error:

- Predator: MAE ± 0.03
- Prey: MAE ± 3.11



Error causes:

- Dense groups
- Occlusions
- Predation success

→ Attack scenes manually labeled

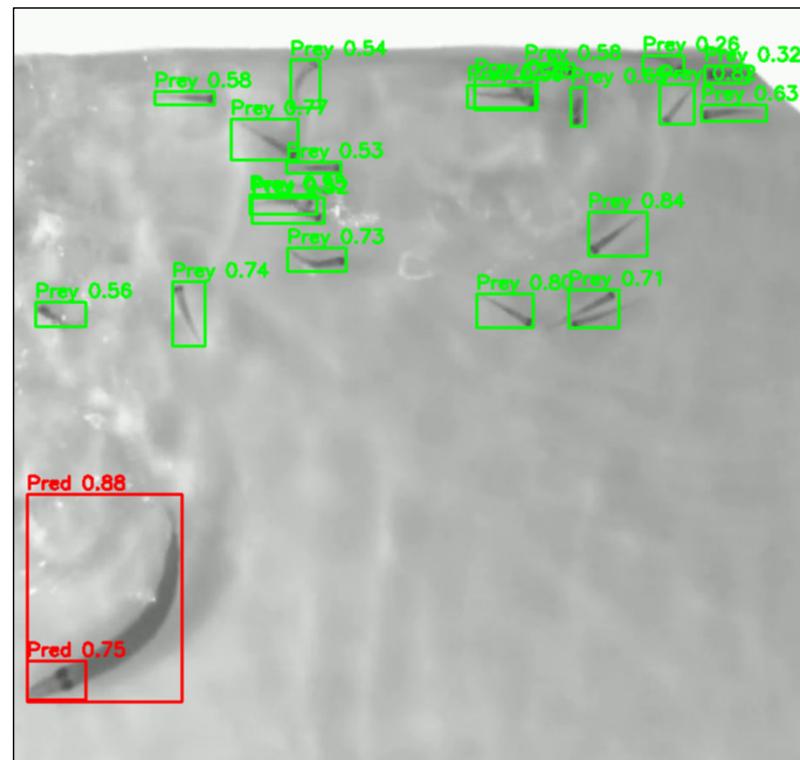
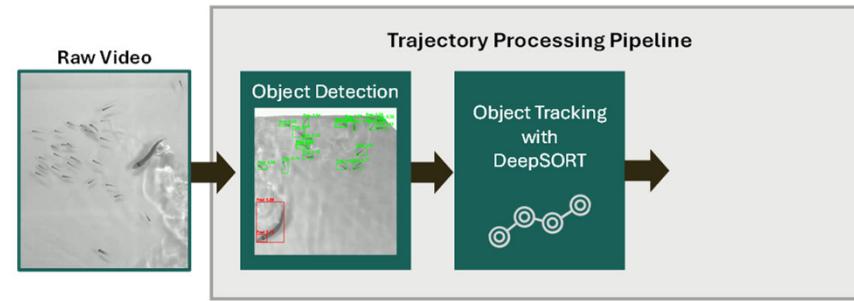
Data Collection & Processing

Object tracking (DeepSORT):

- Data association via Hungarian algorithm
- Kalman filter for state estimation and missed detections
- Produces consistent track IDs over time

Results:

- 793 valid 10-frame windows
- 7.79% of all frames retained



Data Collection & Processing

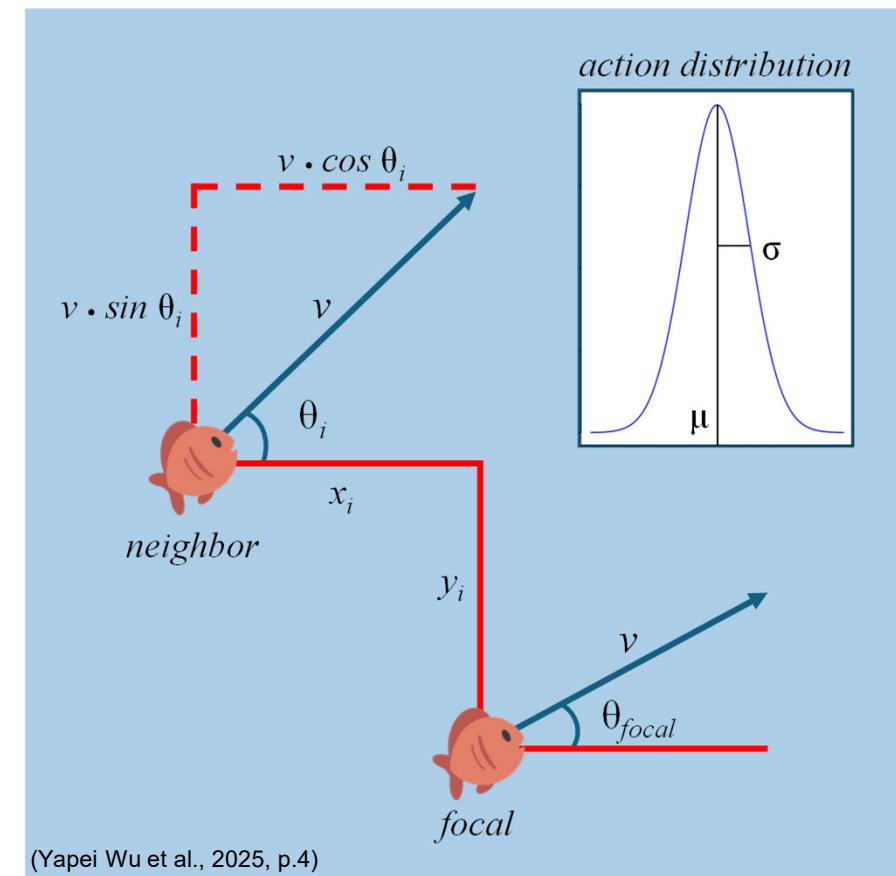
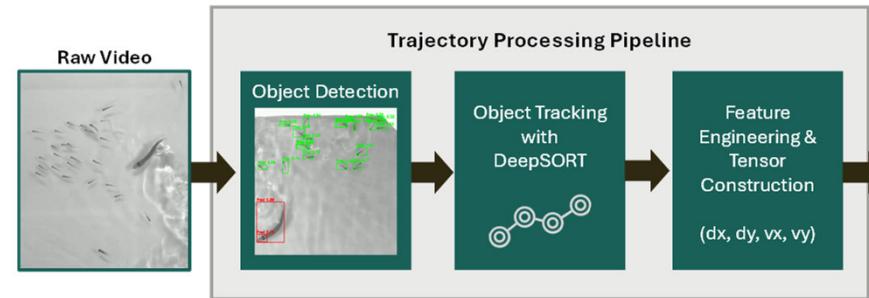
State / action representation:

- Pairwise distances (dx, dy)
 - Relative velocities (vx, vy)
 - Action $\Delta\theta$
- $[dx, dy, vx, vy, \theta]$

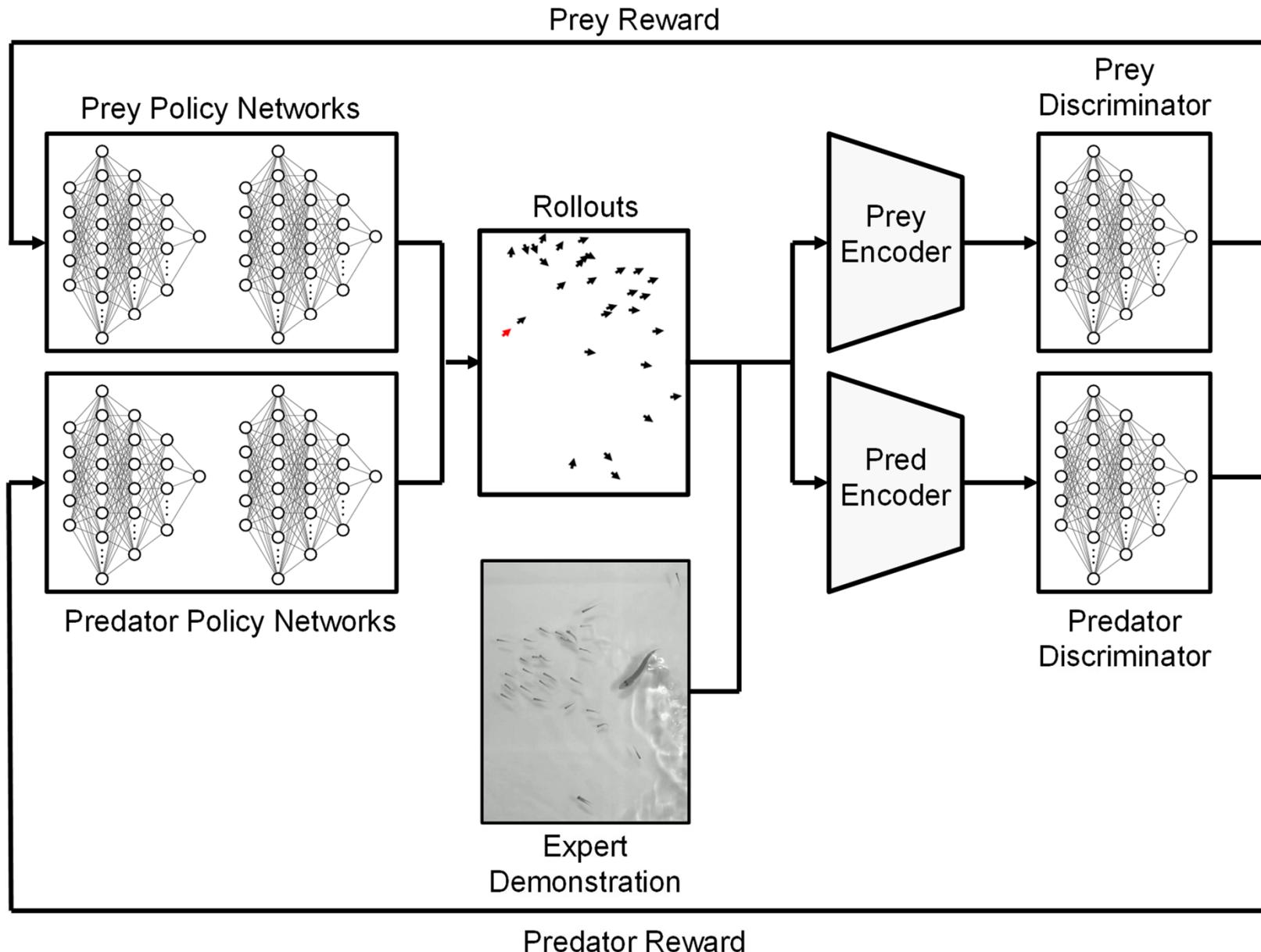
Tensor: [batch, windows, agents, neigh, features]

Prey Tensor $\in \mathbb{R}^{793 \times 10 \times 32 \times 32 \times 6}$

Predator Tensor $\in \mathbb{R}^{793 \times 10 \times 1 \times 32 \times 5}$

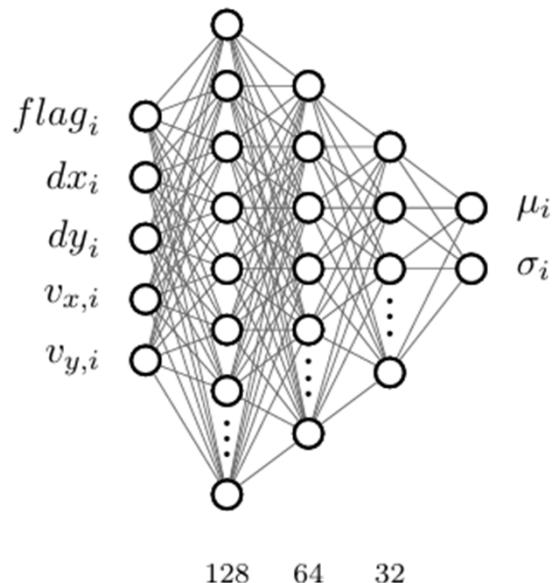


Methodology: GAIL

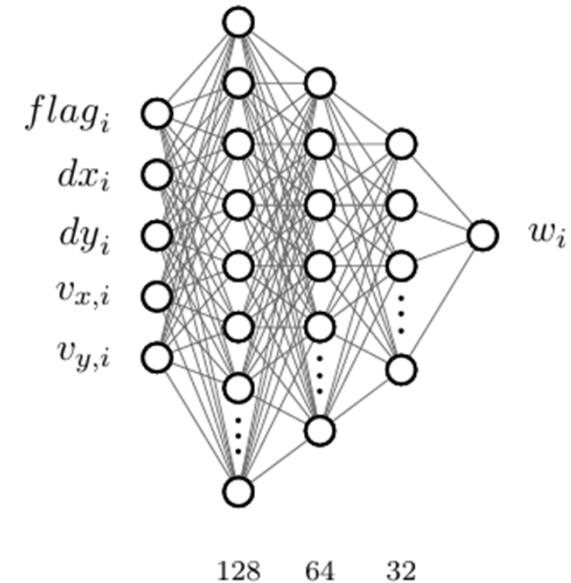


Modular Policy

Pairwise Interaction Network



Attention Network



Pairwise Interaction Network:

- Input: [dx, dy, vx, vy]
- Output: μ , σ
- Parameters of a Gaussian action distribution

→ stochastic individual response

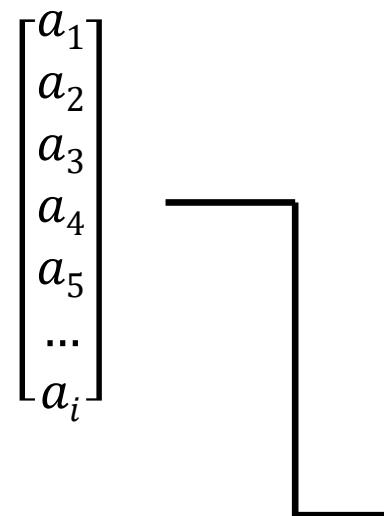
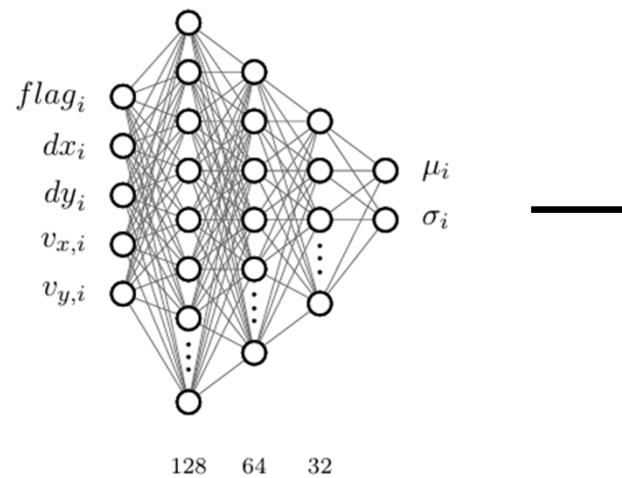
Attention Network:

- Input: [dx, dy, vx, vy]
- Output: w
- Relative influence of each neighbor

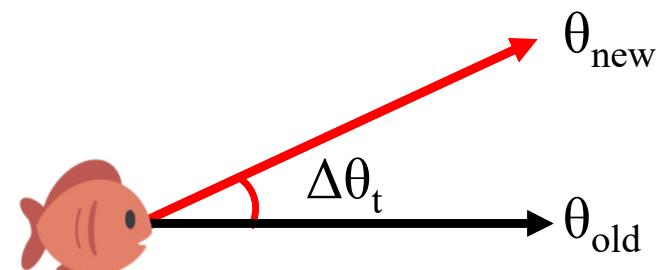
→ interpretable interaction structure

Modular Policy

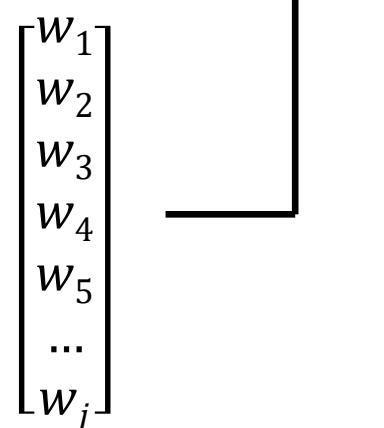
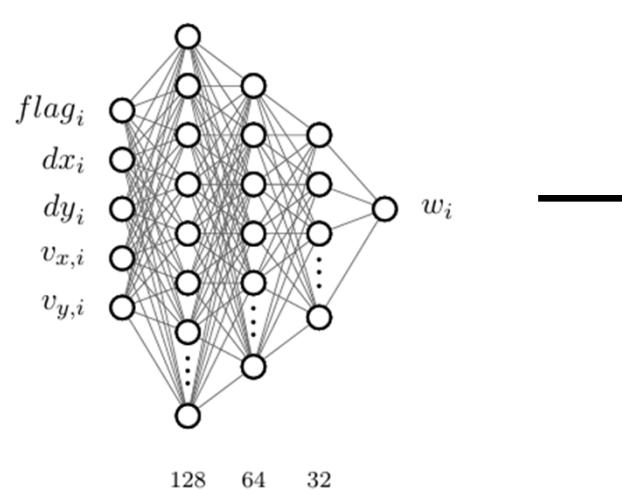
Pairwise Interaction Network



$$a = \sum_{i \in \mathcal{I}} a_i \frac{\omega_i}{\sum_{j \in \mathcal{I}} \omega_j}$$



Attention Network



Modular Policy – Evolutionary Strategy

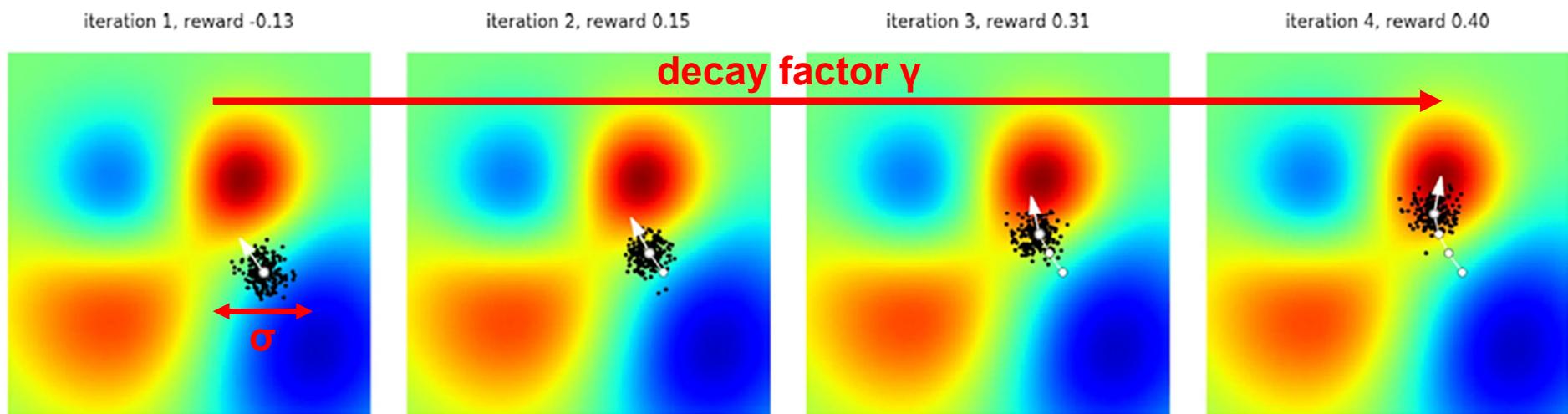
"At every iteration ("generation"), a population of parameter vectors ("genotypes") is perturbed ("mutated") and their objective function value ("fitness") is evaluated"
(Salimans et al., 2017, p.2).

1. Stage:

- Sample perturbation noise
- Apply perturbations to parameters
- Collect rollout rewards

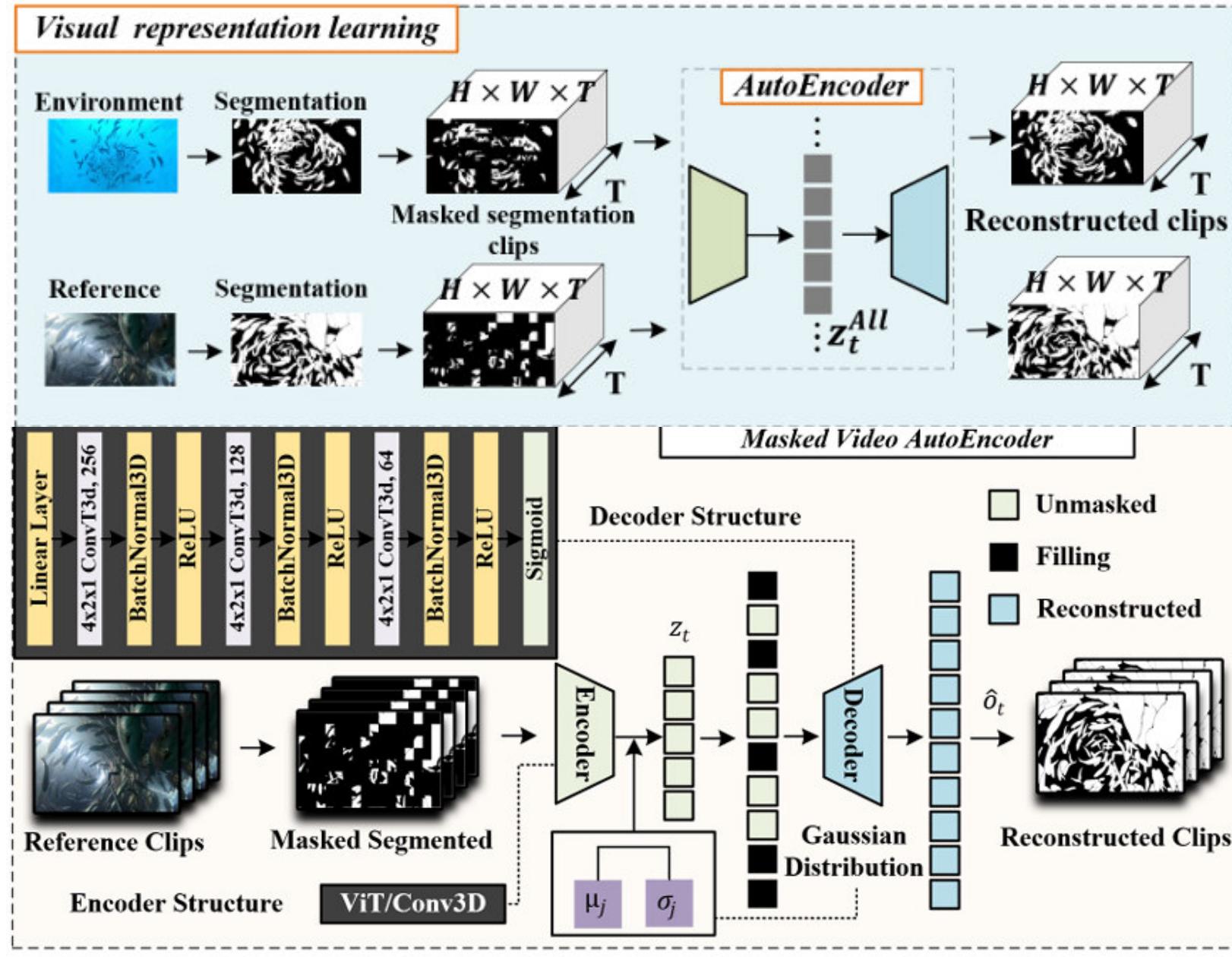
2. Stage:

- Weight perturbations by obtained rewards
- Higher-reward = higher update influence



<https://images.ctfassets.net/kftzwdyauwt9/d5acb8a0-a1a1-4772-09f9e1a6550b/e7bccd4dd7532331595032ac7b9e3f14/evo.png>

CBIL Transition Encoder

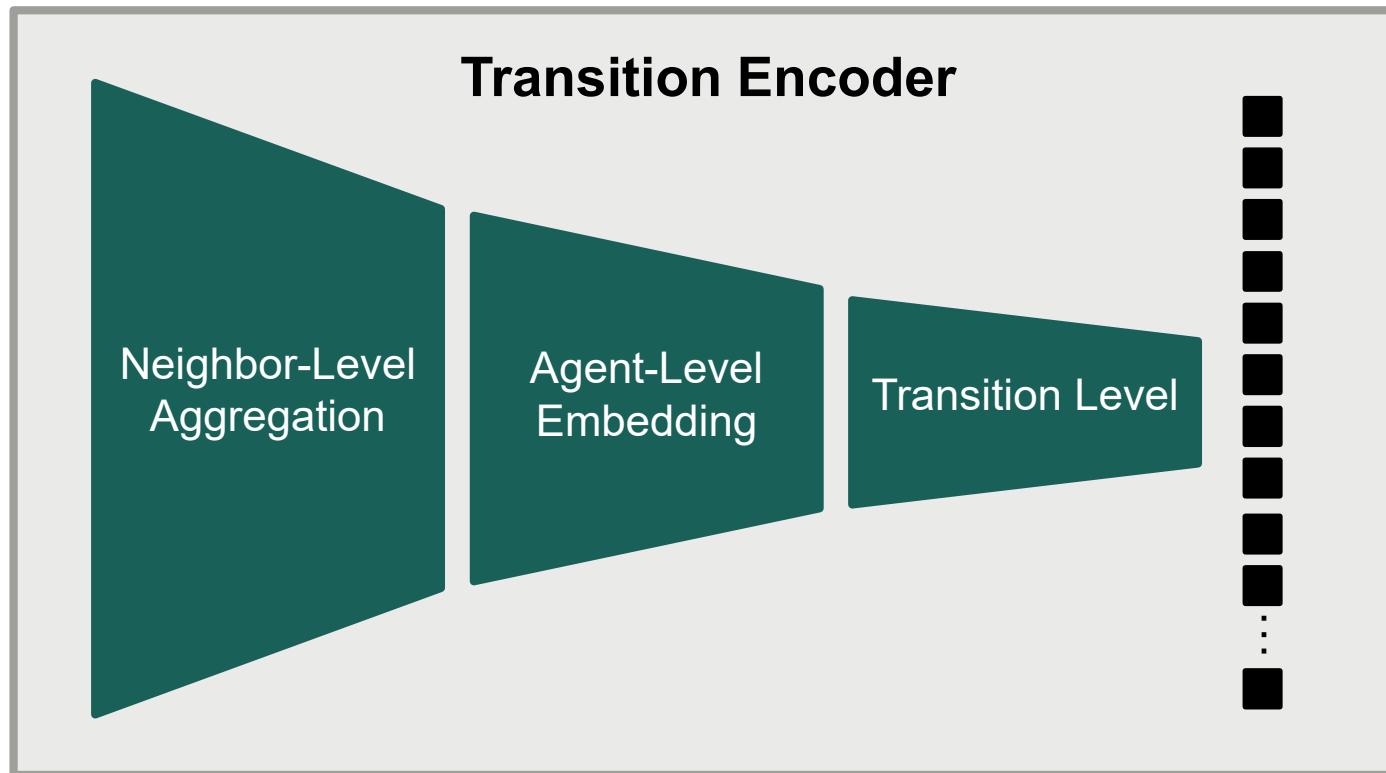


(Yifan Wu et al., 2025, p.4)

Transition Encoder

Input tensor:

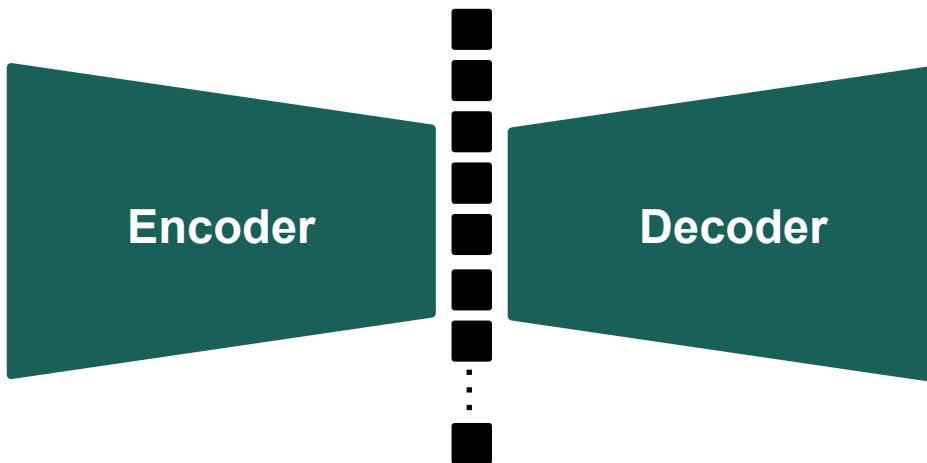
[batch = 10, windows = 10, agents = 33, neigh = 32, feat = 4]



Output tensor: [batch, windows-1, agents, 2z]

Transition Feature (2z) = $[z_t, \Delta z_t]$

Transition Encoder - Training

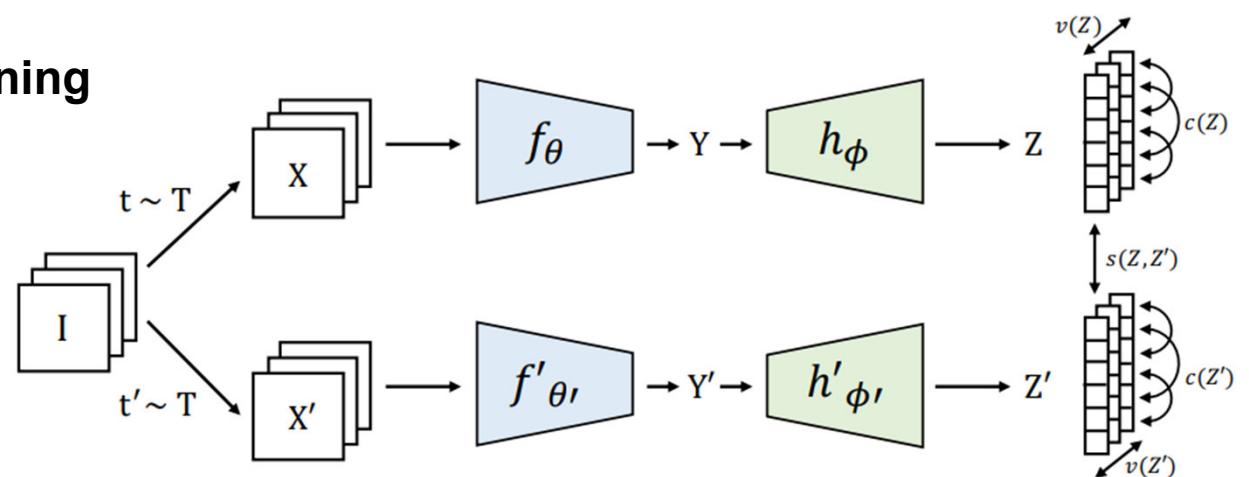


Problems with reconstruction-based training

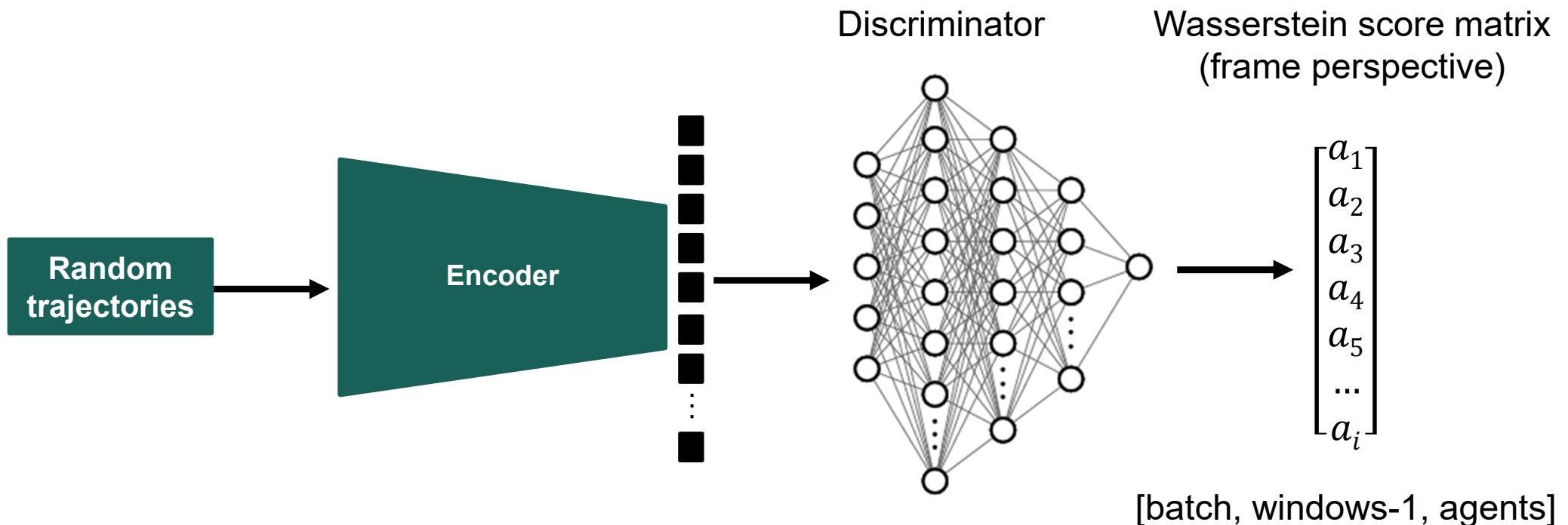
- Poor reconstruction loss \rightarrow weak latent?
- Decoder not required for GAIL
- Question: Training possible without reconstruction? \rightarrow VICReg

Self-supervised representation learning

- No decoder, direct latent training
- Prevents representation collapse
- Augmentation:
 - State noise
 - Neighbor dropout
 - Feature dropout



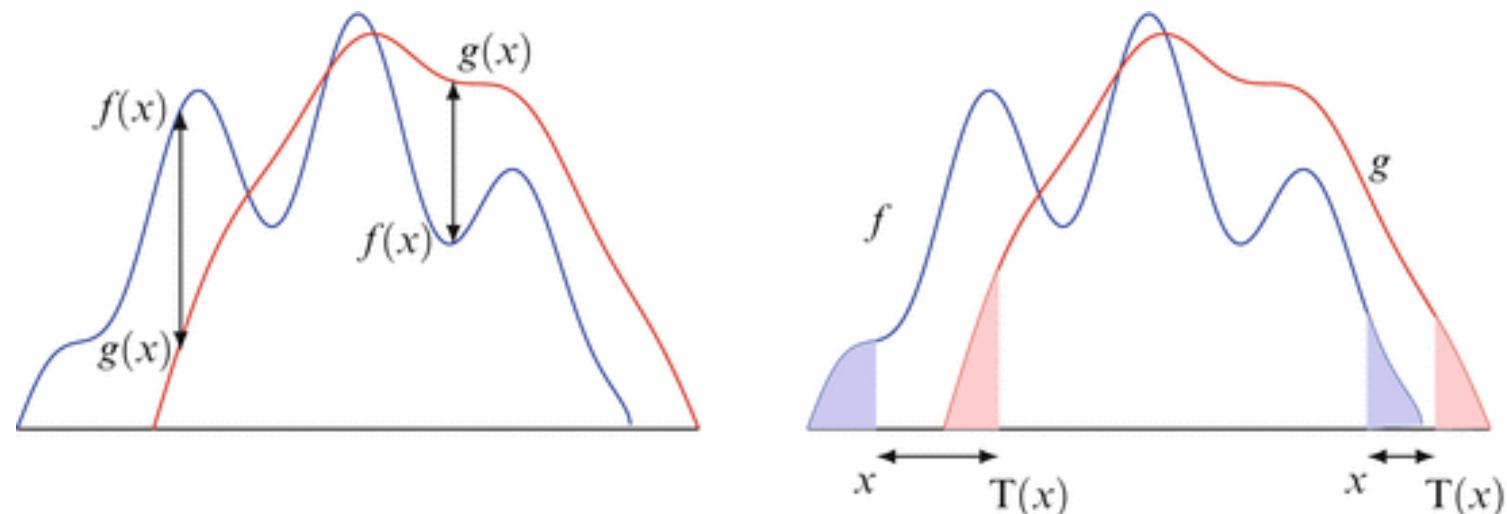
Discriminator



Wasserstein Loss & Earth-Mover Distance

$$W(\mathbb{P}_E, \mathbb{P}_\pi) = \inf_{\gamma \in \Pi(\mathbb{P}_E, \mathbb{P}_\pi)} \mathbb{E}_{(\tau_E, \tau_\pi) \sim \gamma} [\|\tau_E - \tau_\pi\|]$$

"Intuitively, $\gamma(\tau_E, \tau_\pi)$ indicates how much "mass" must be transported from τ_E to τ_π in order to transform the distributions P_E into the distribution P_π (Arjovsky et al., 2017, p. 4)".



https://link.springer.com/chapter/10.1007/978-3-319-20828-2_5

Environment

Base Environment

Analysis and visualization of trained policy networks.

Properties:

- Non-vectorized
- Slower

Used for:

- Policy evaluation
- Metric computation
- Visualization

Vectorized Environment

Efficient and fast ES training

Properties:

- Fully vectorized batch simulation
- Tightly coupled to ES rollouts
- GPU-accelerated execution

Used for:

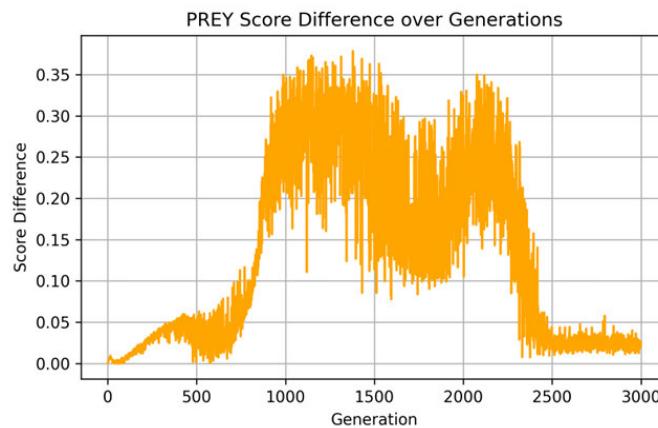
- Parallel evaluation of policy perturbations

Both:

- Initialized through expert states
 - Bouncing at walls

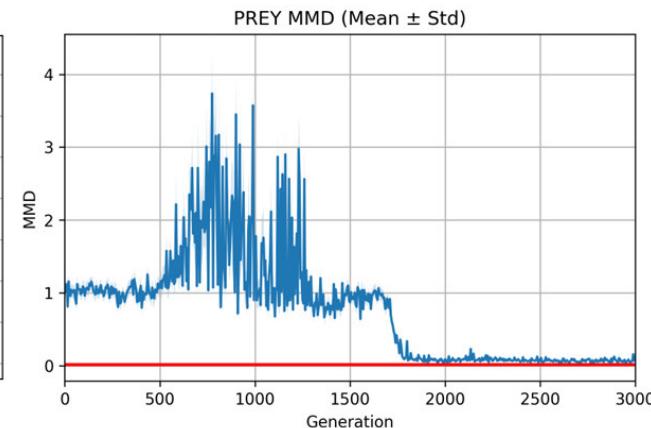
Performance Evaluation

Wasserstein proxy



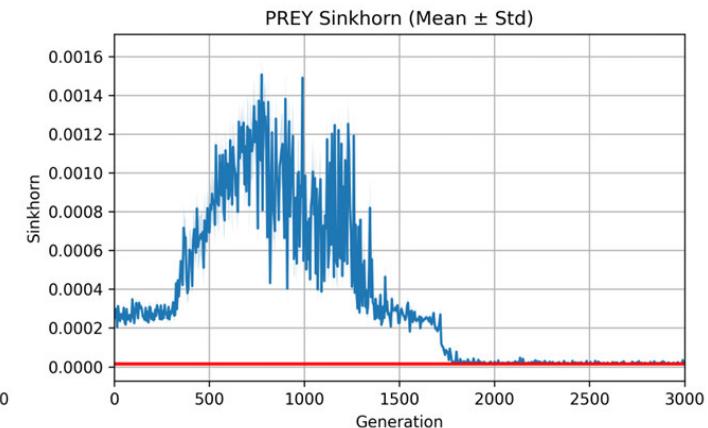
Discriminator
score differences

Maximum Mean Discrepancy (MMD)



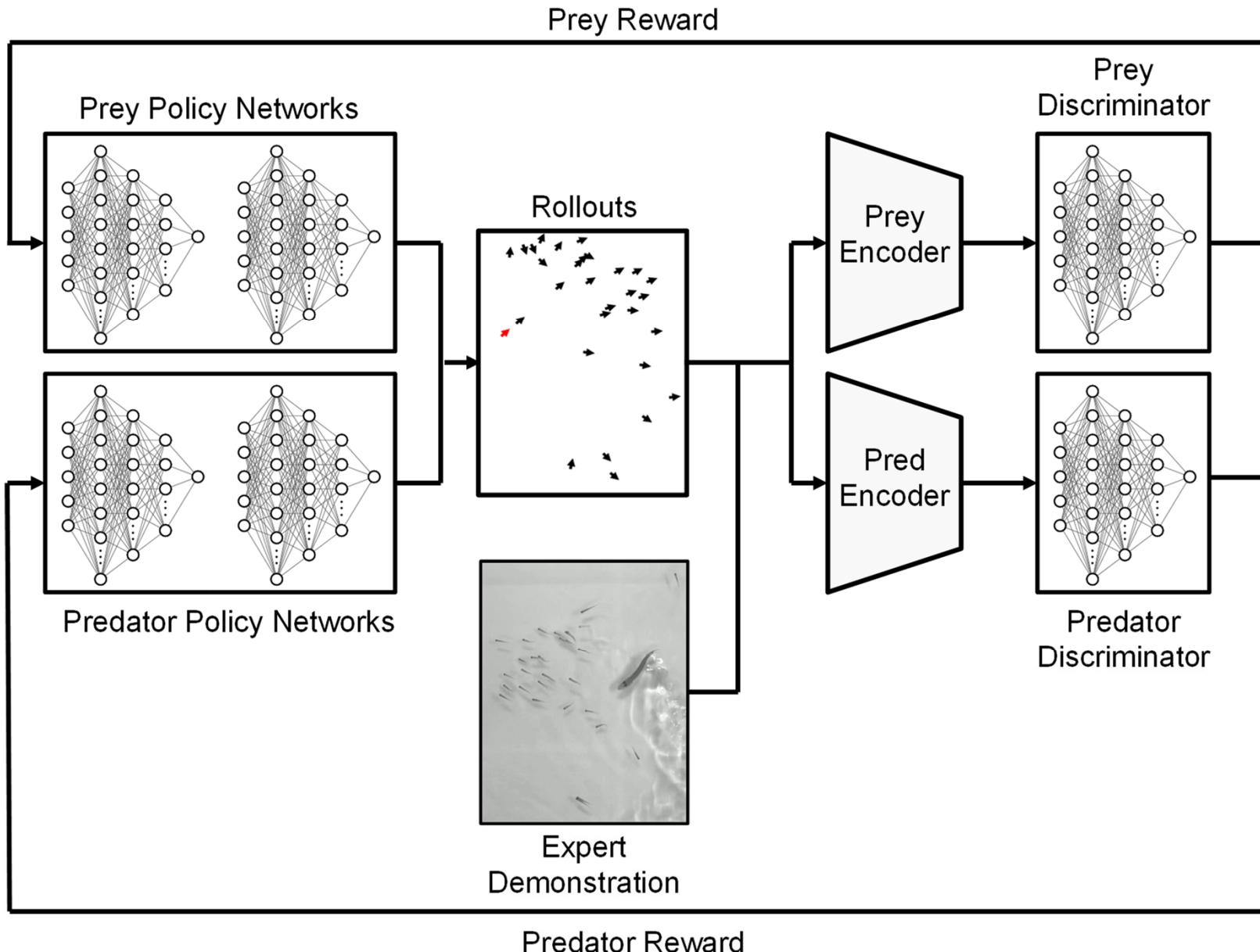
Distance between
sampled batches

Sinkhorn distance

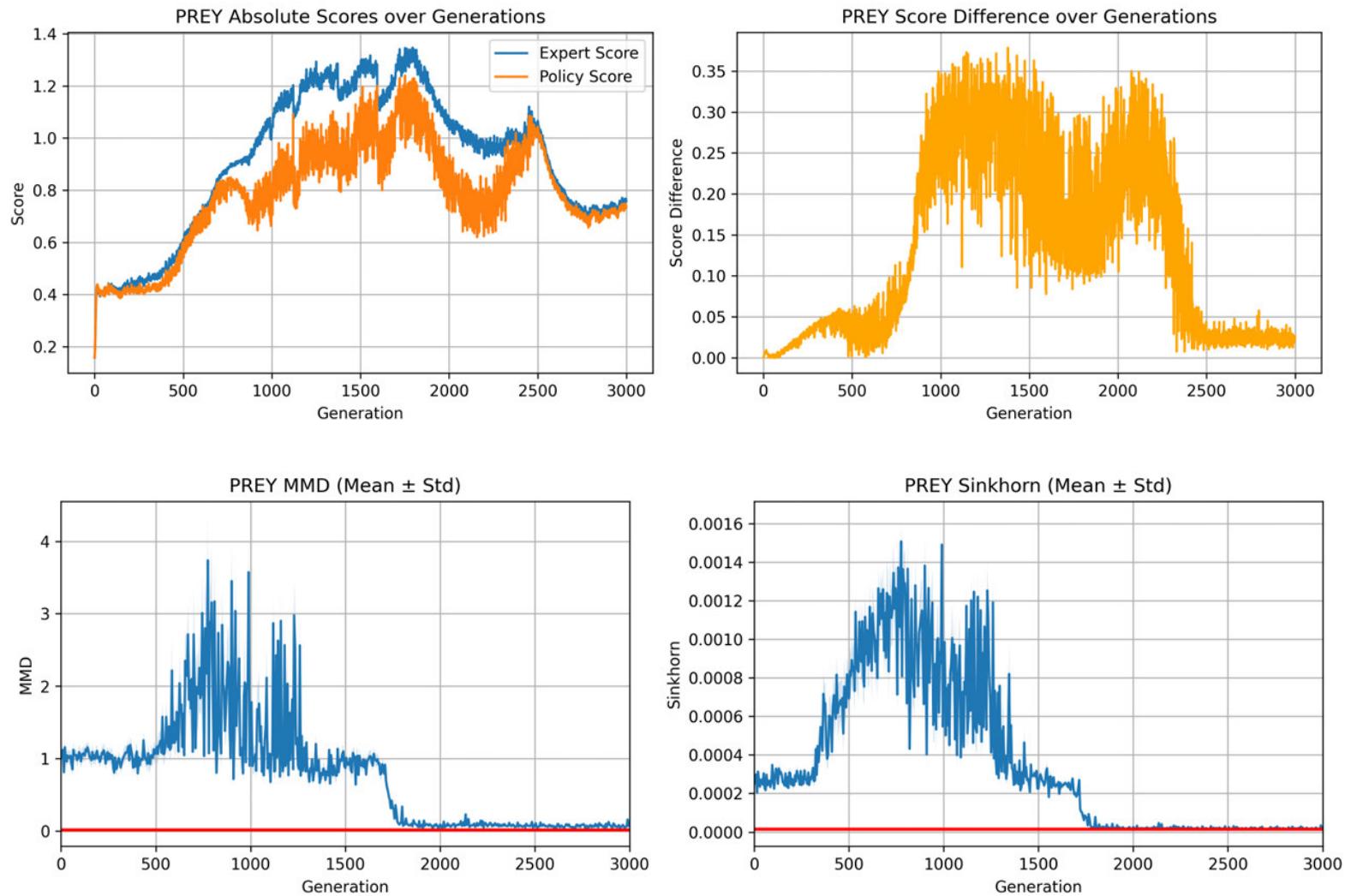


Distance between
transition features

Training Procedure

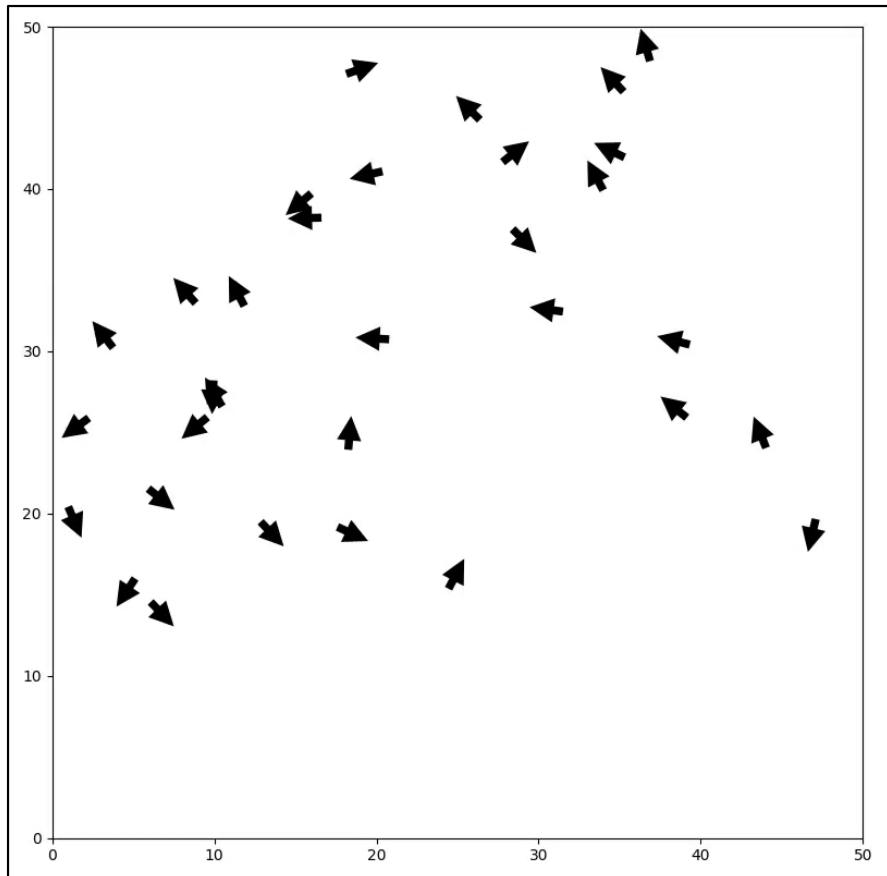


Prey-Only Model

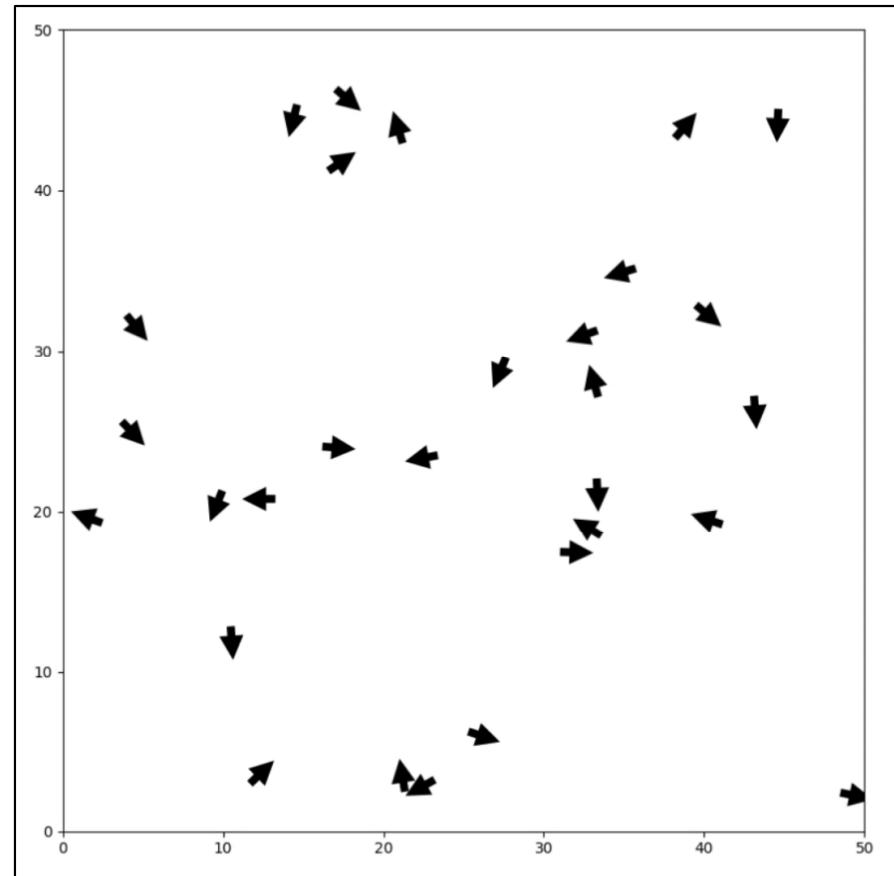


Prey-Only Model

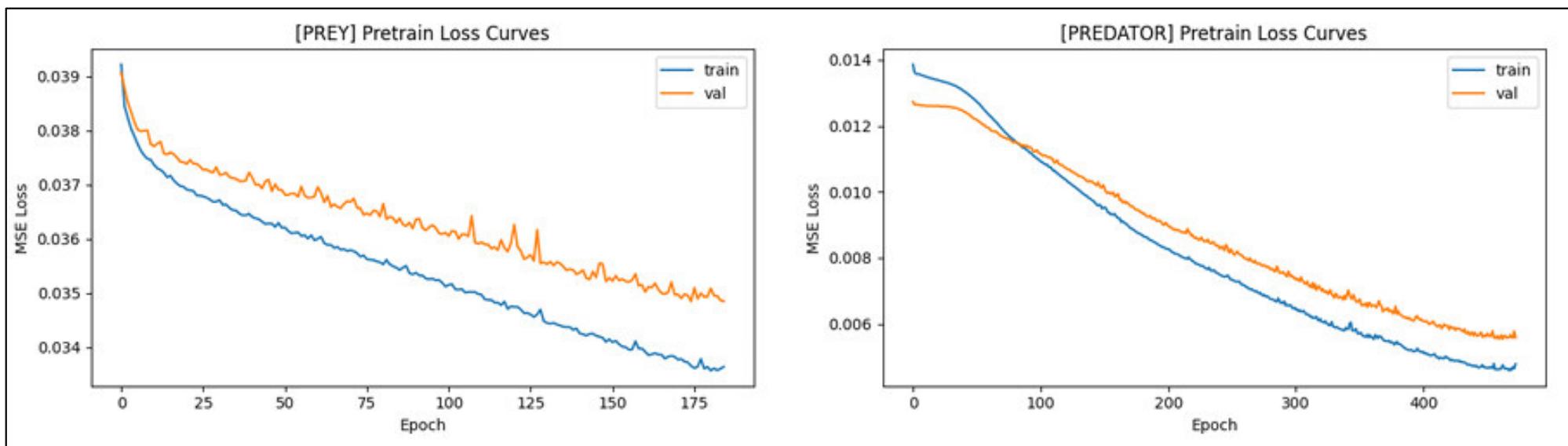
Expert demonstrations
Couzin model



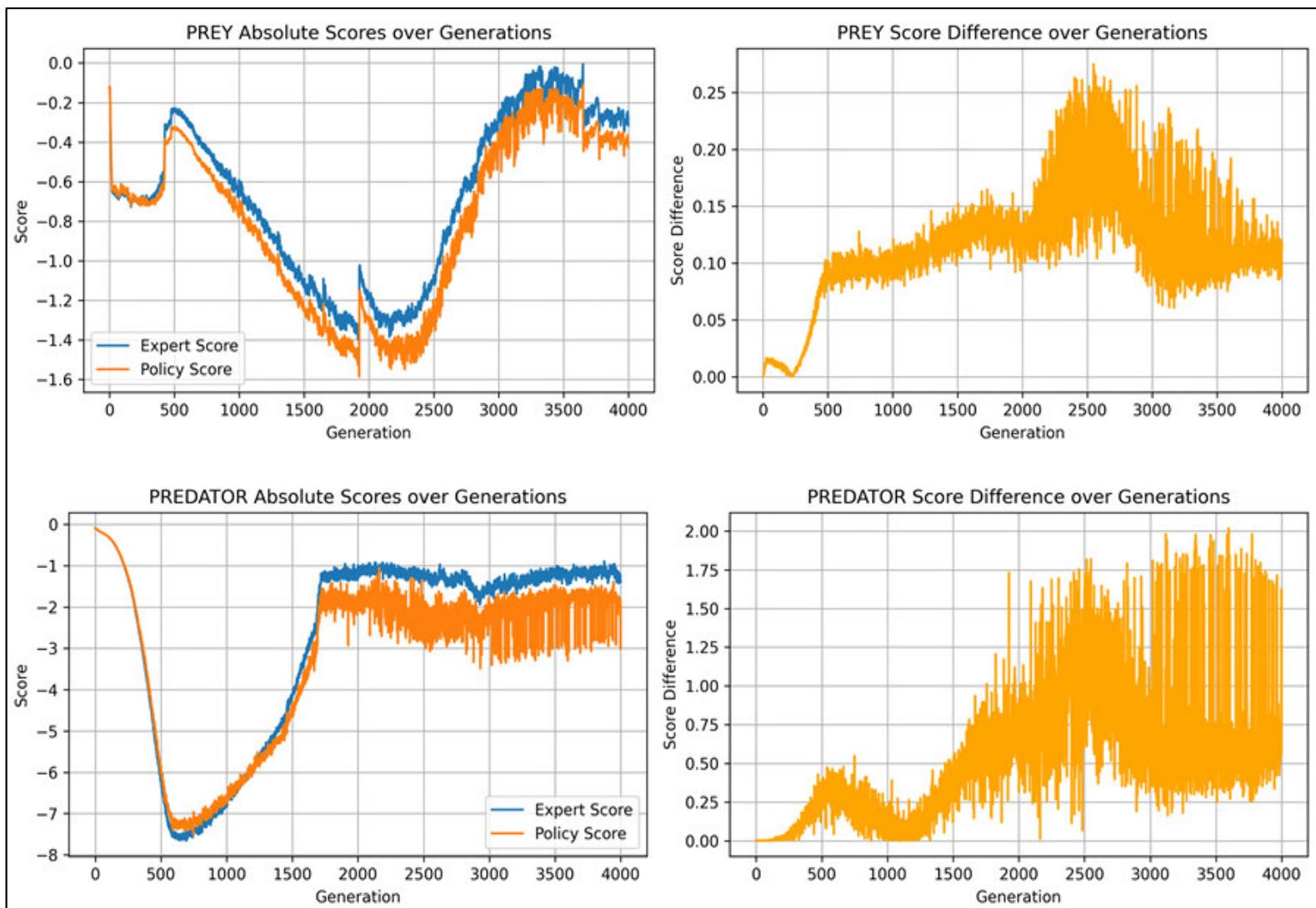
Policy-generated
Prey-only GAIL model



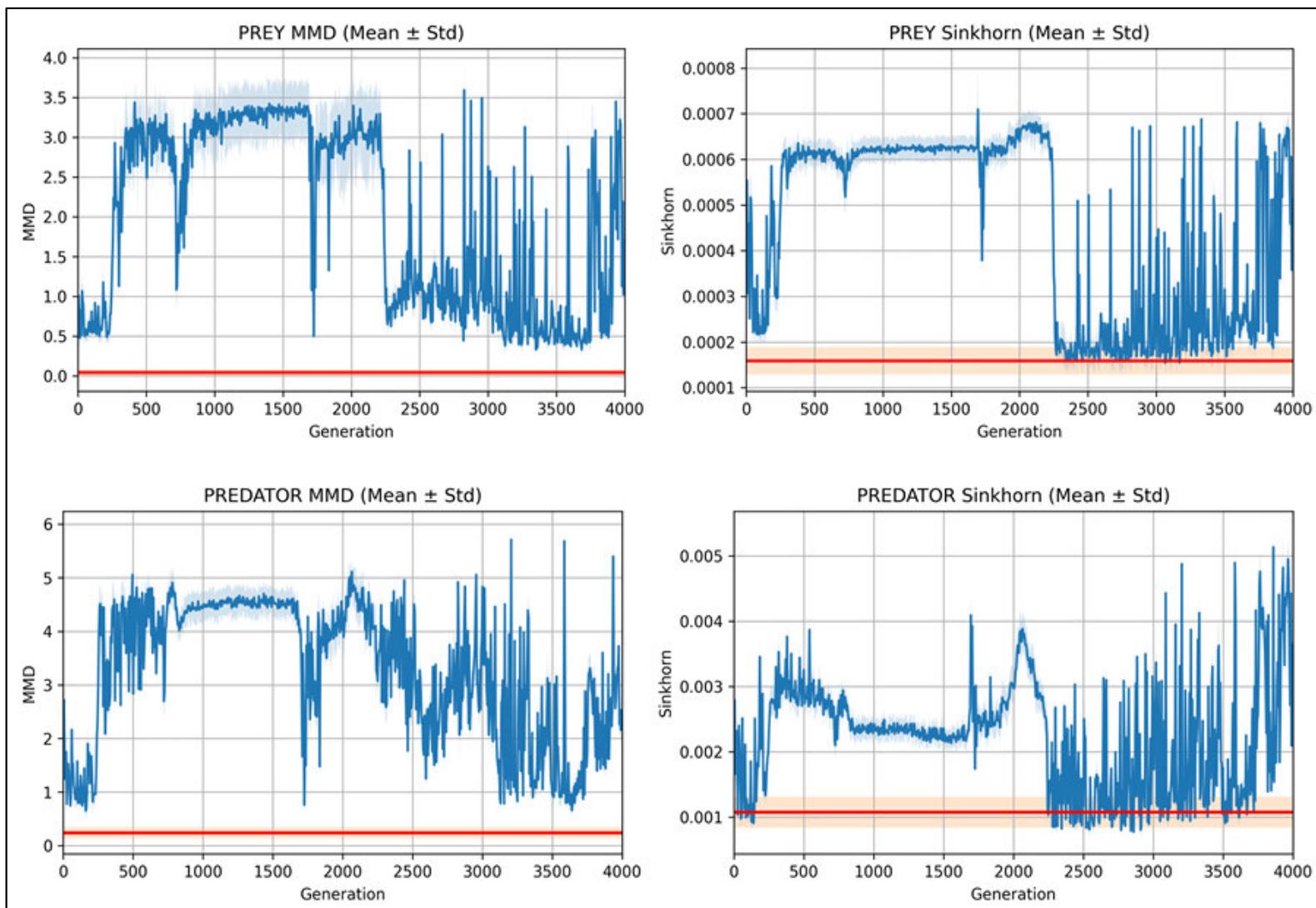
Video Predator-Prey Model



Video Predator-Prey Model

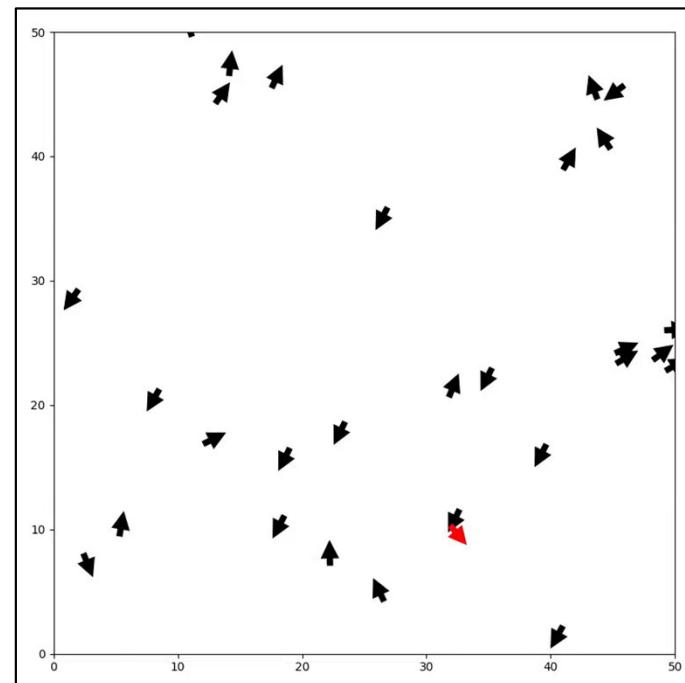
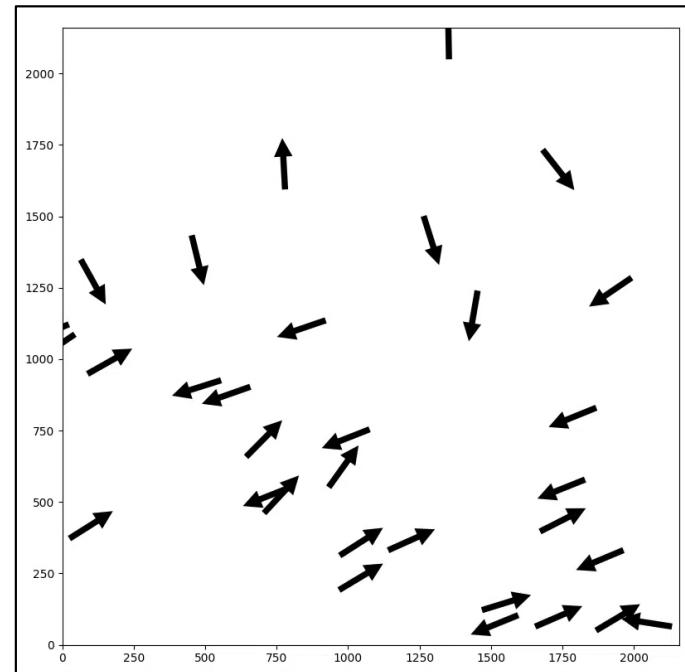


Video Predator-Prey Model

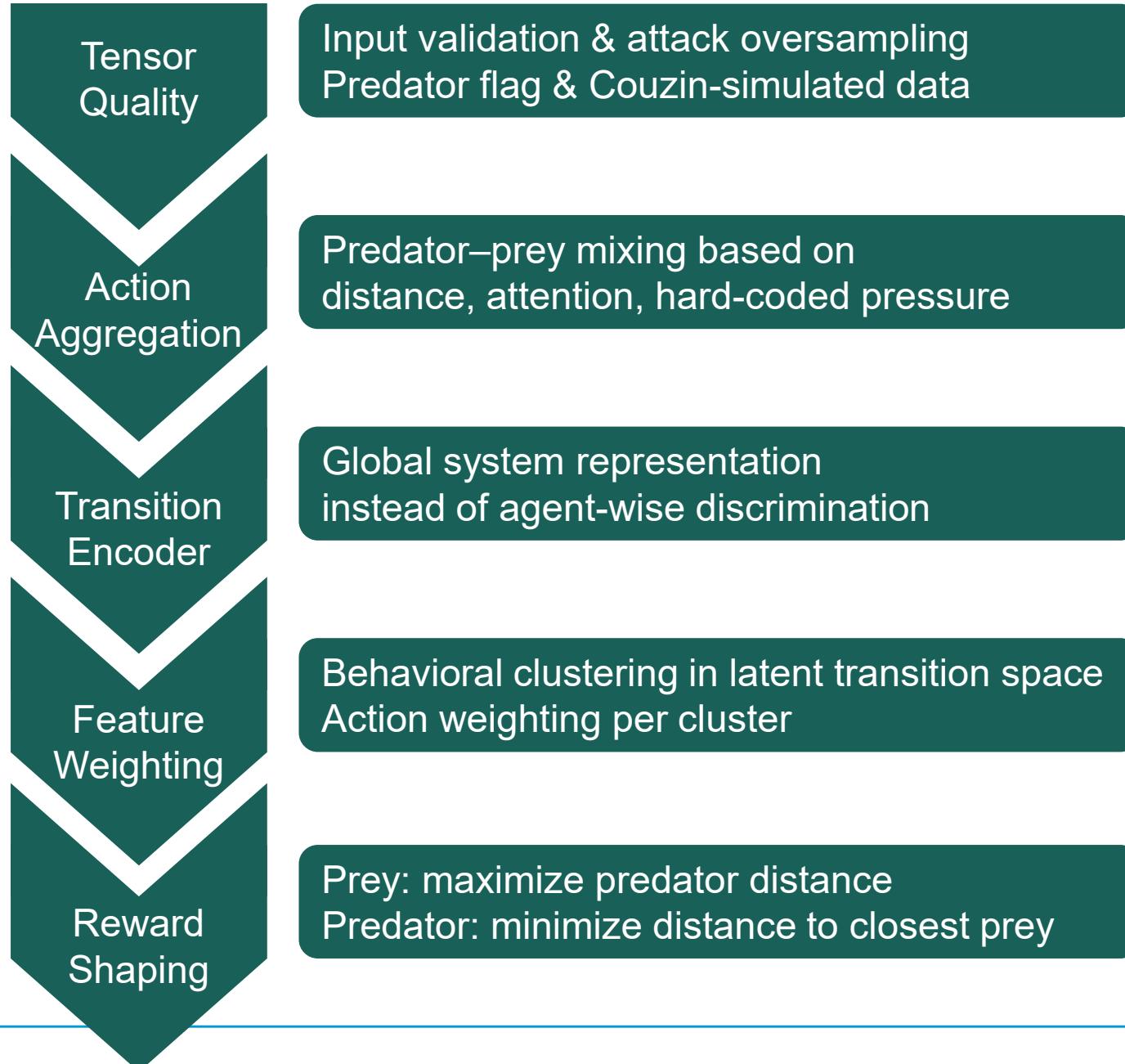


Video Predator-Prey Model

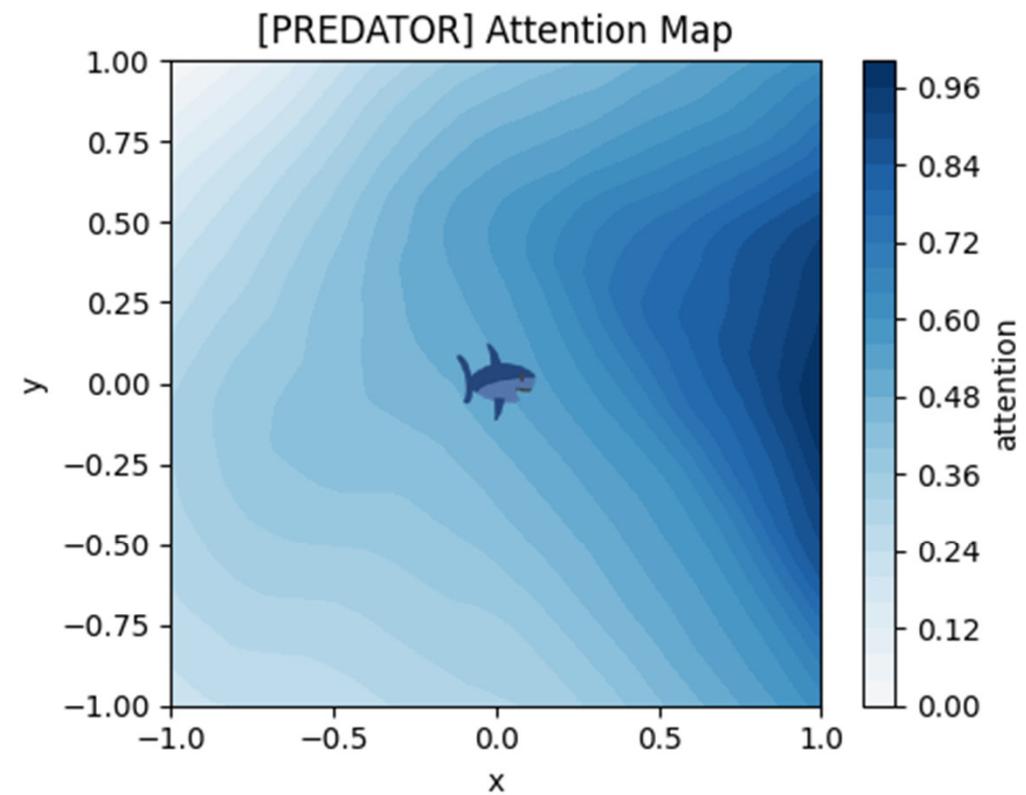
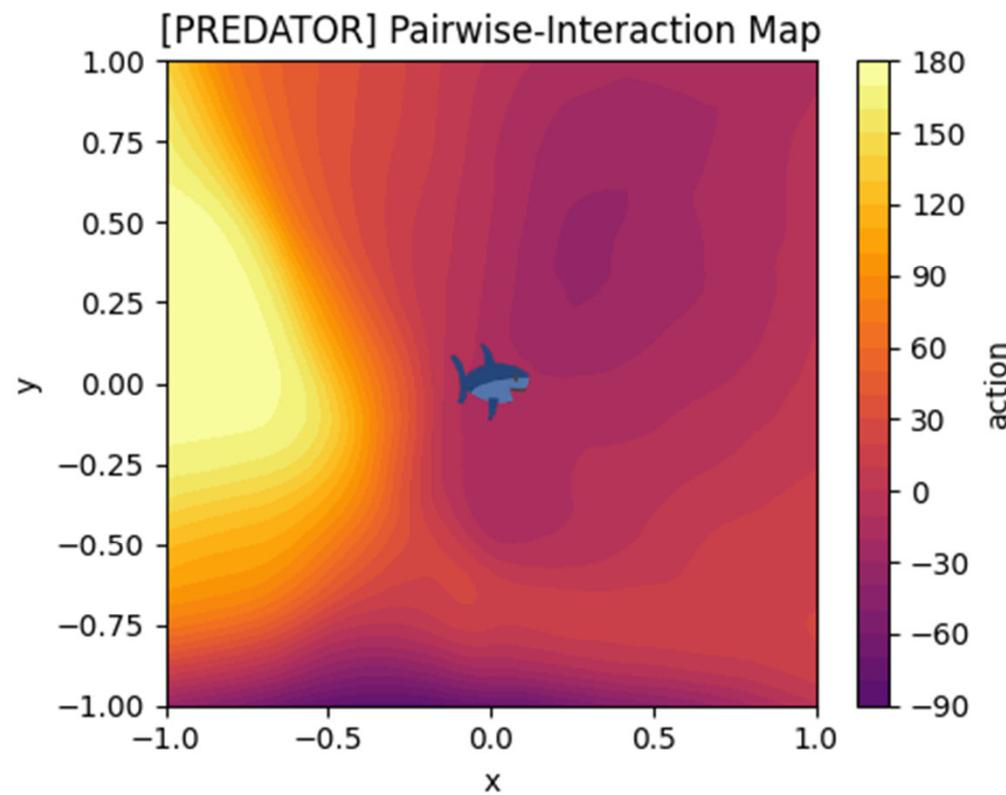
Expert demonstrations



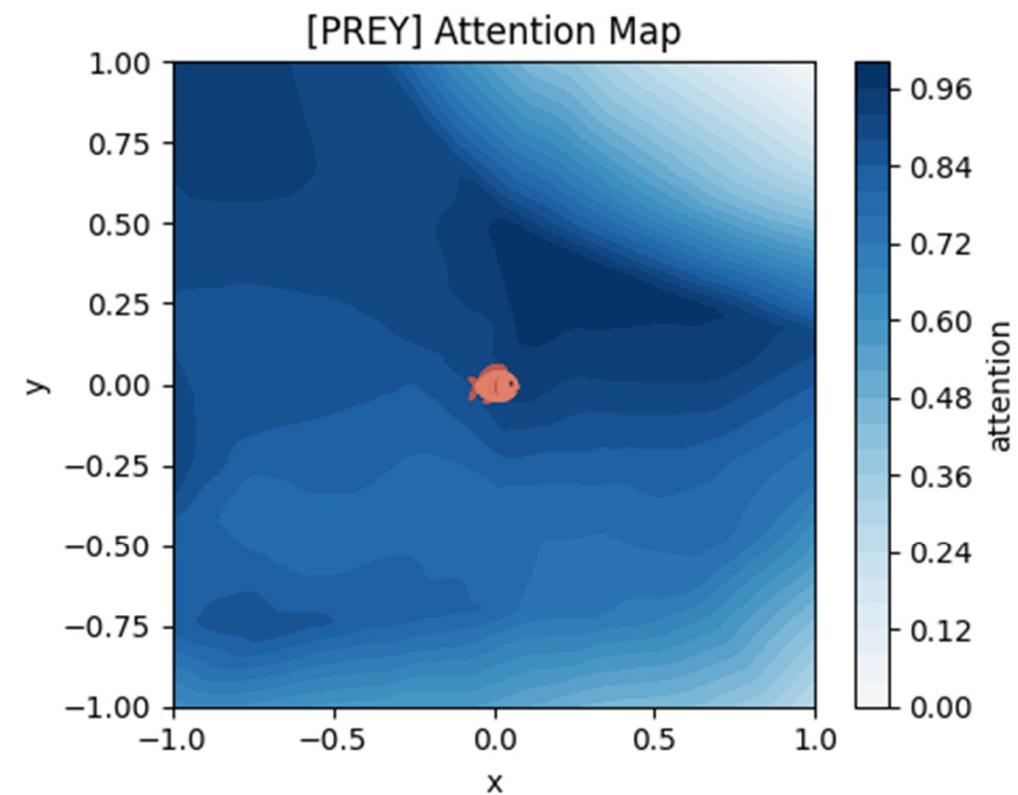
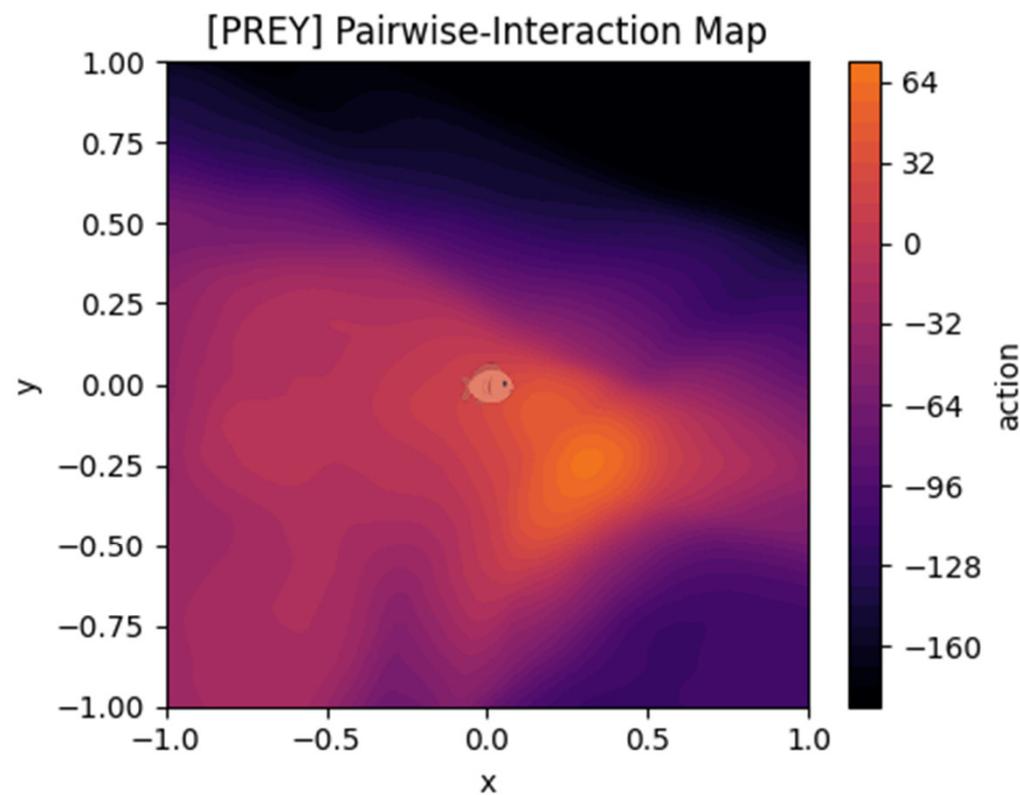
Recovery of missing inter-group dynamics



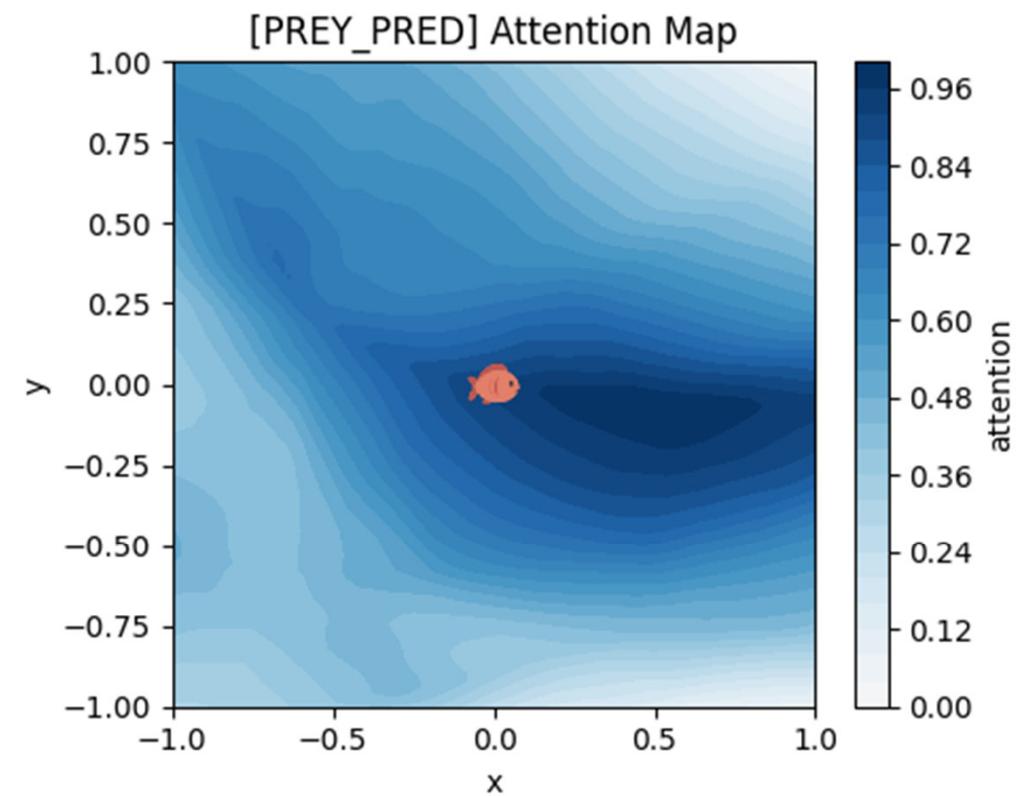
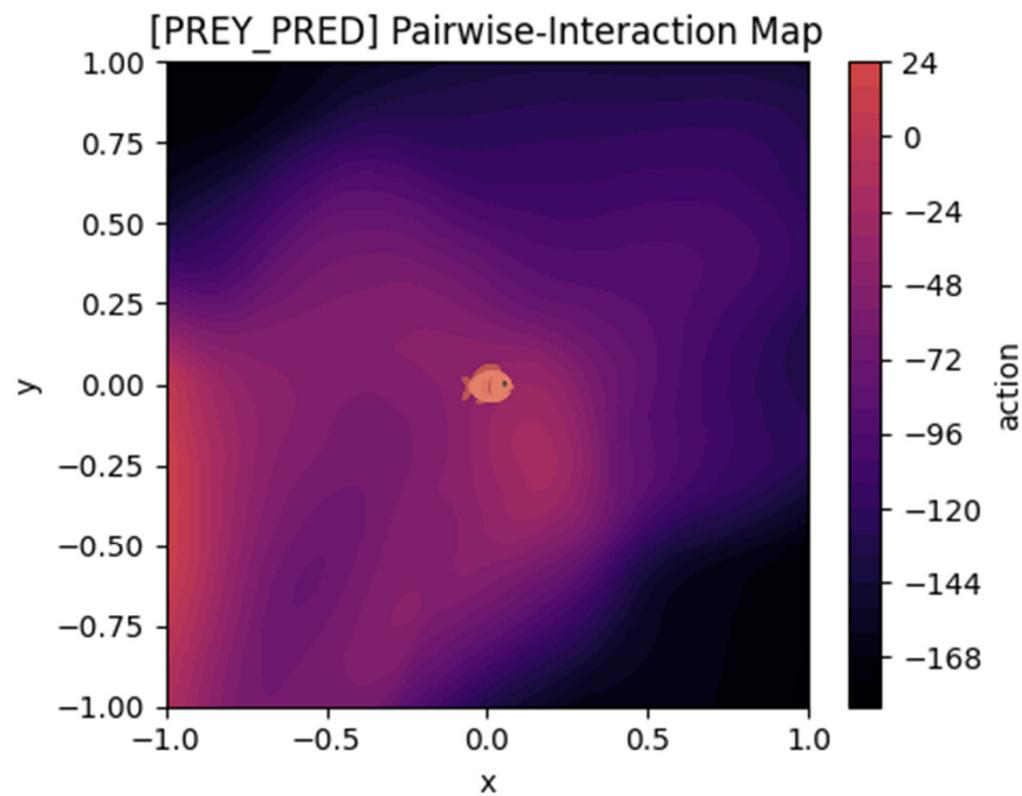
Experiment: Policy Maps



Experiment: Policy Maps

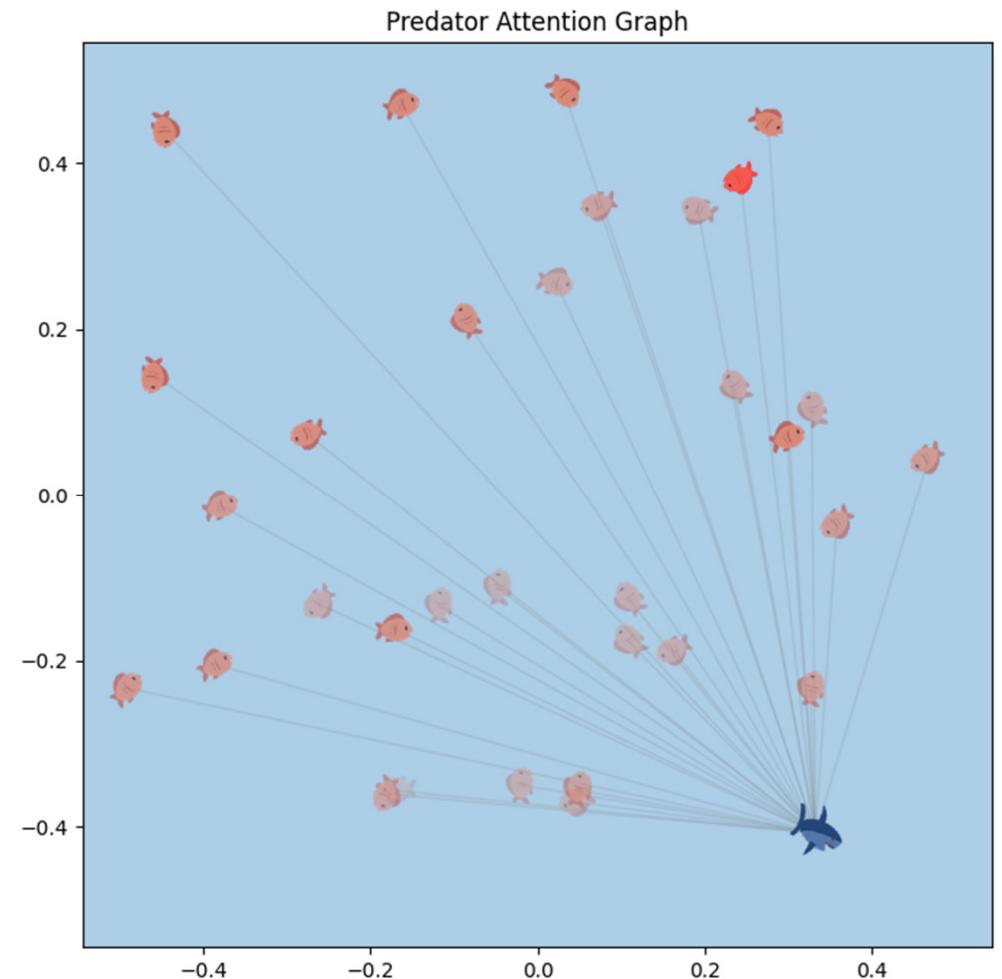
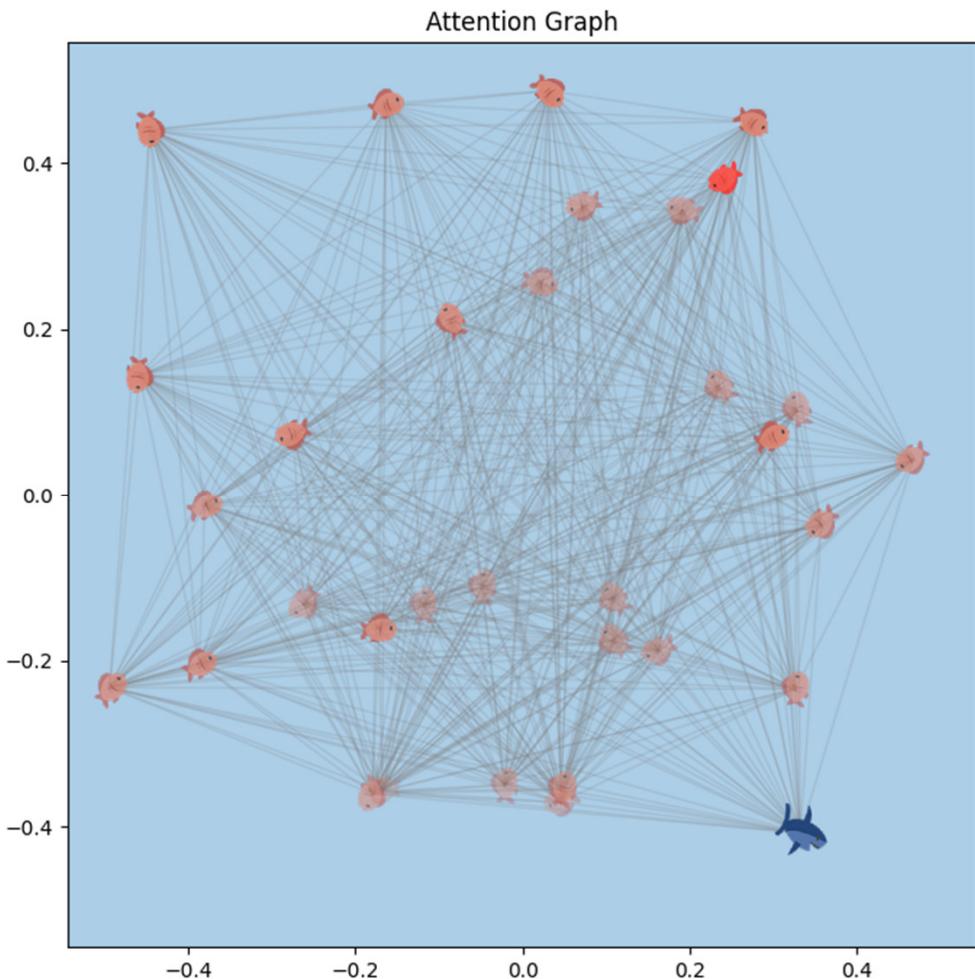


Experiment: Policy Maps



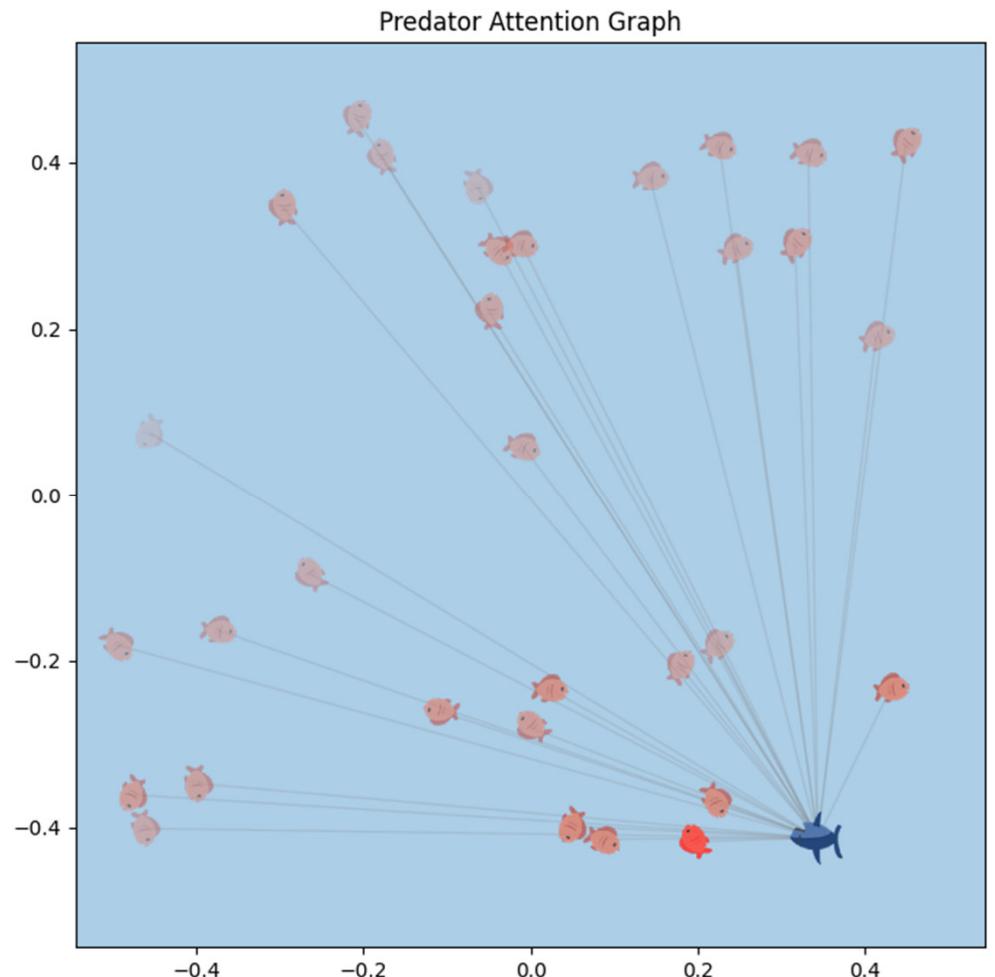
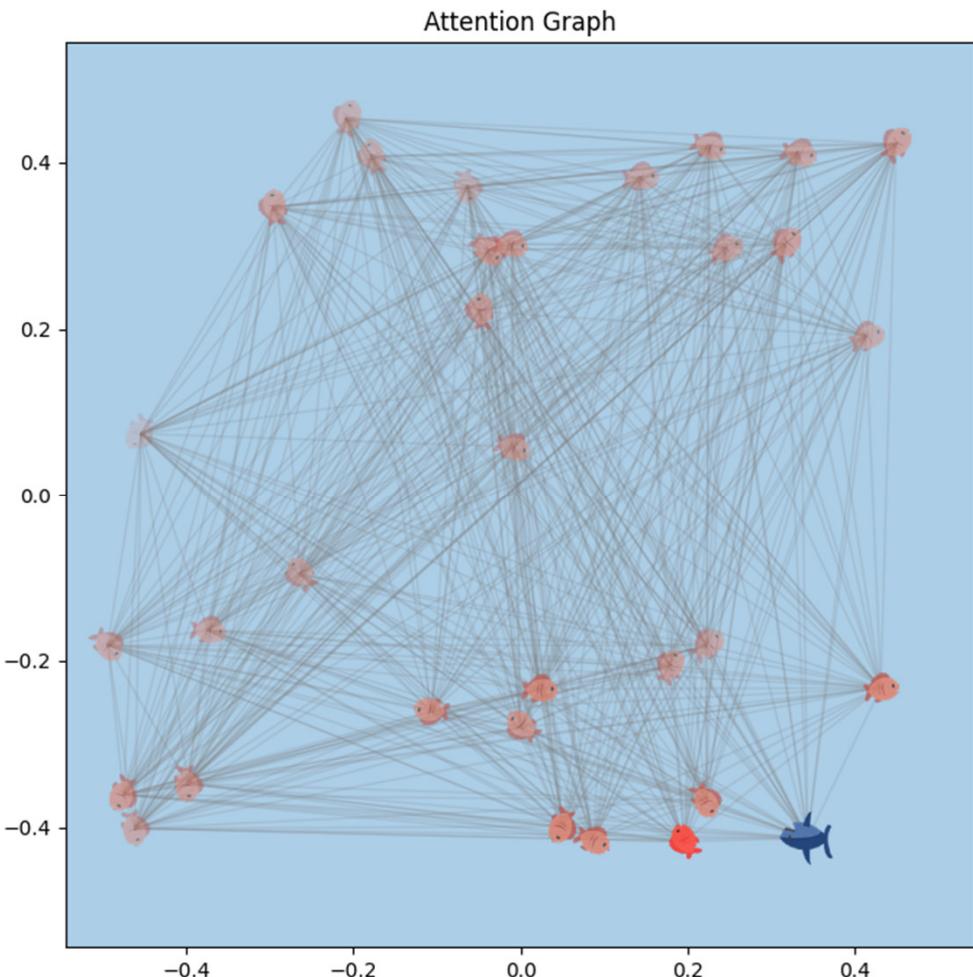
Experiment: Leadership Analysis

GAIL policies:

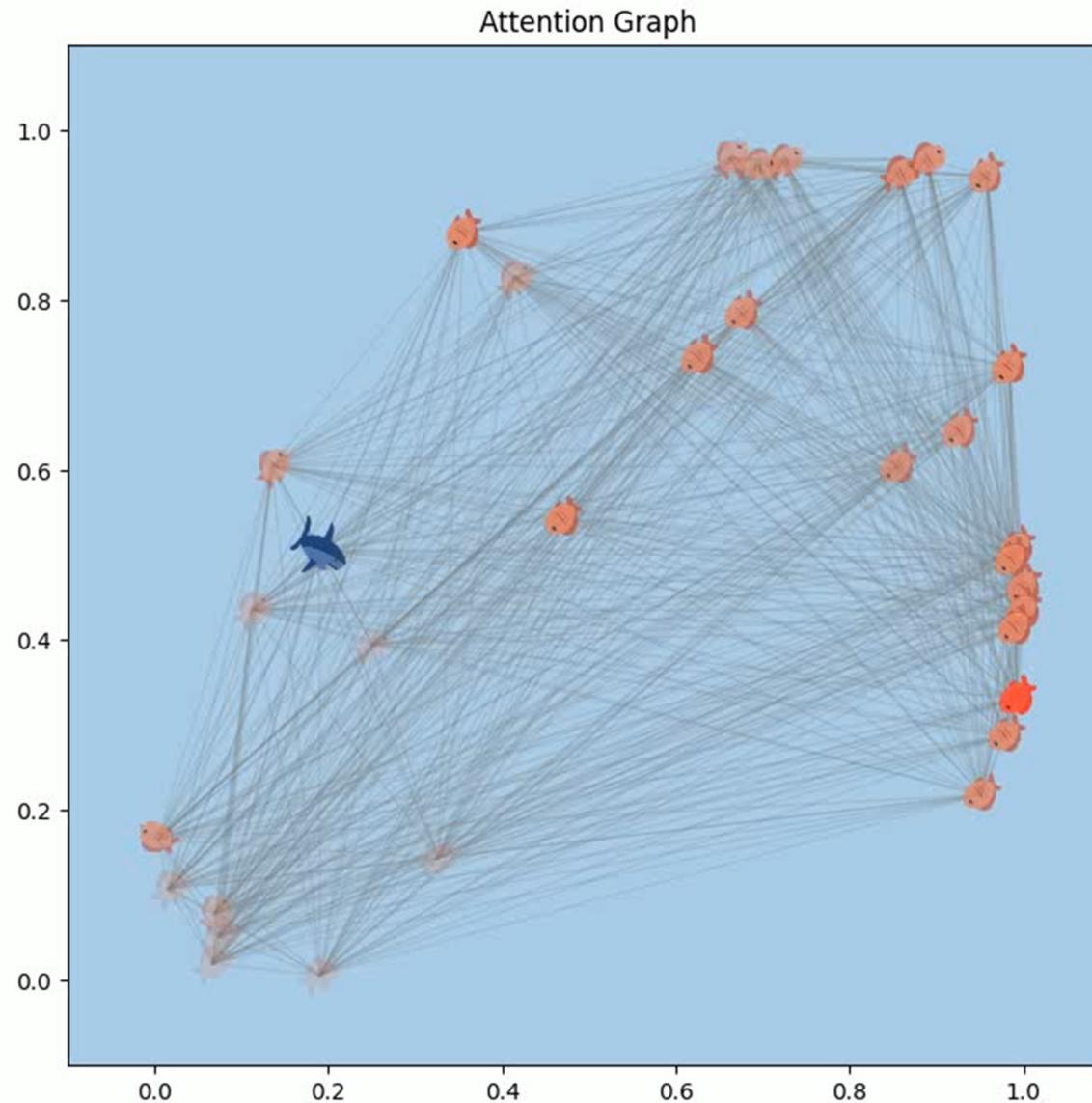


Experiment: Leadership Analysis

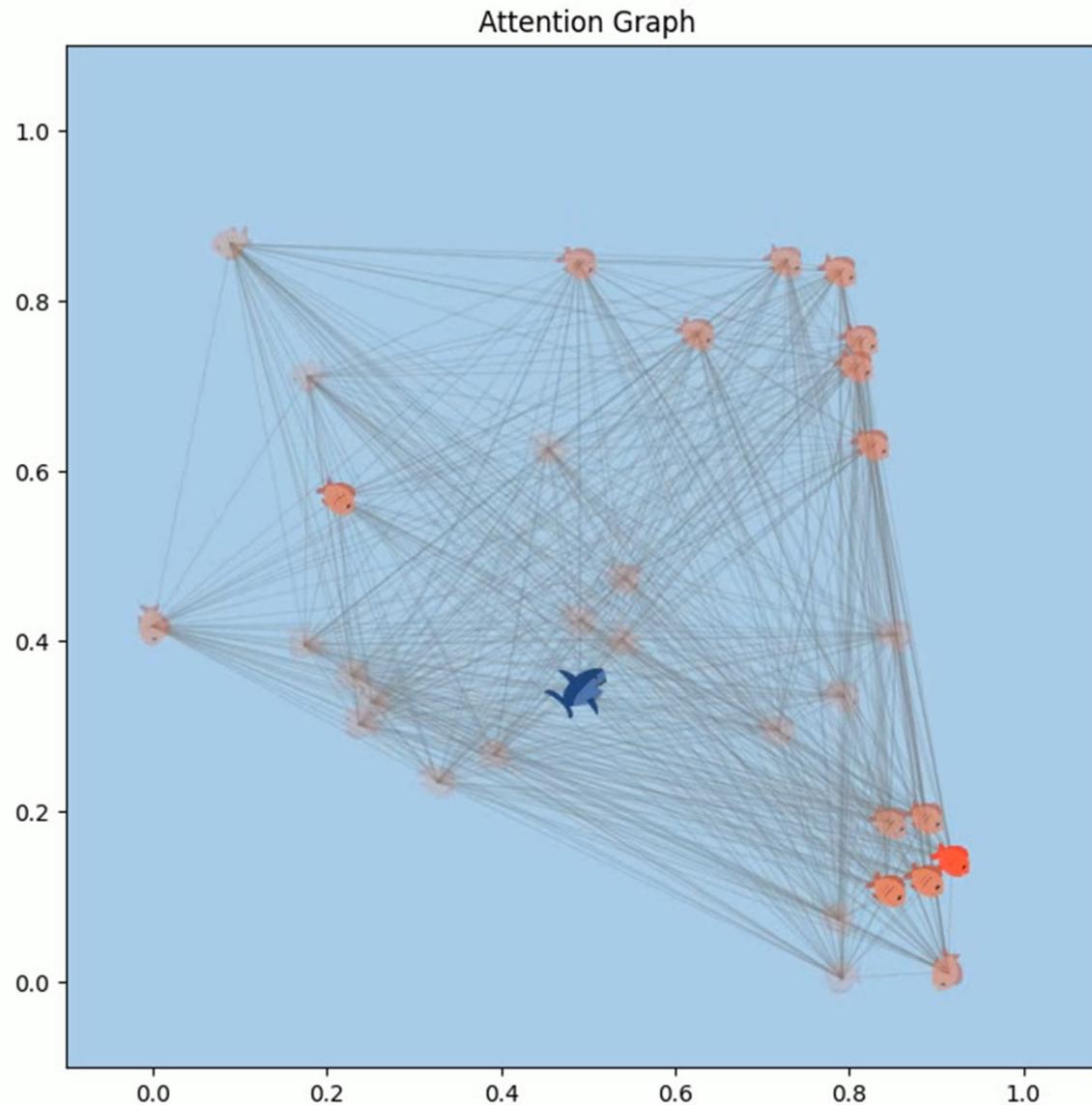
BC policies:



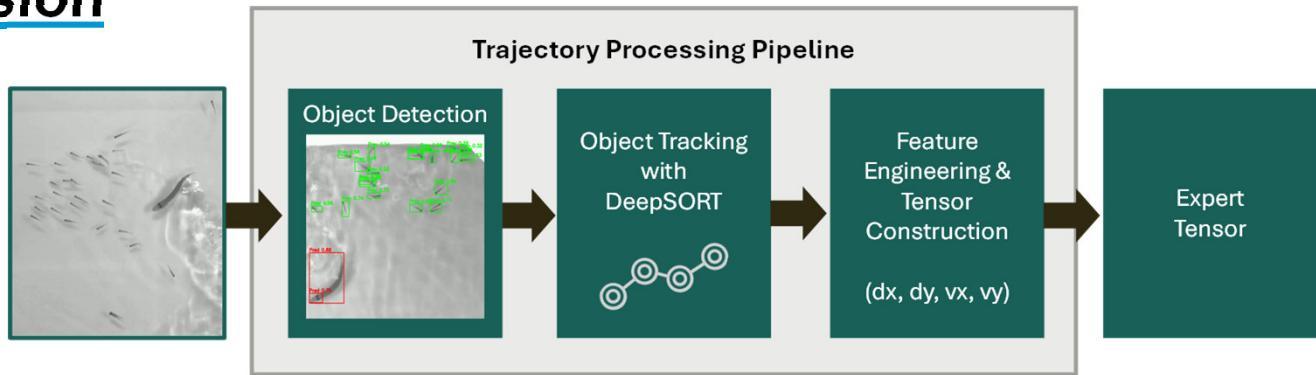
Experiment : Leadership Analysis



Experiment : Leadership Analysis



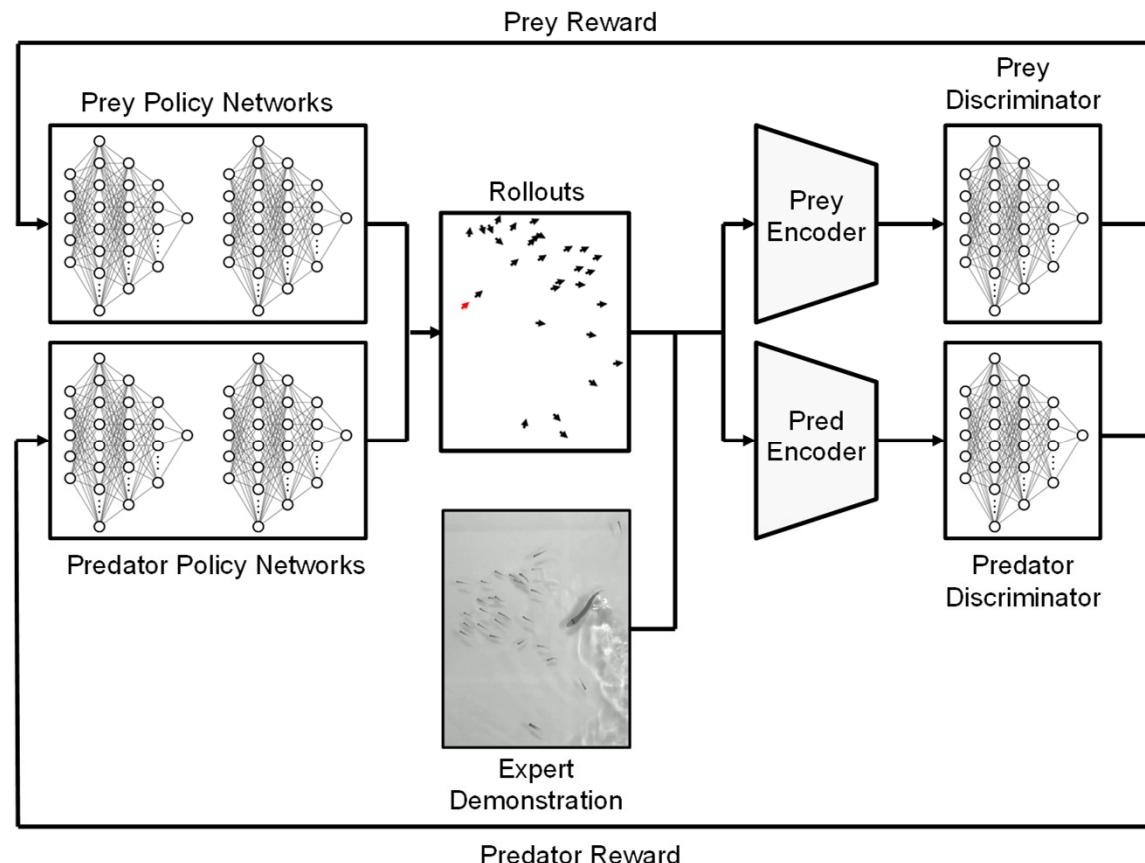
Summary & Discussion



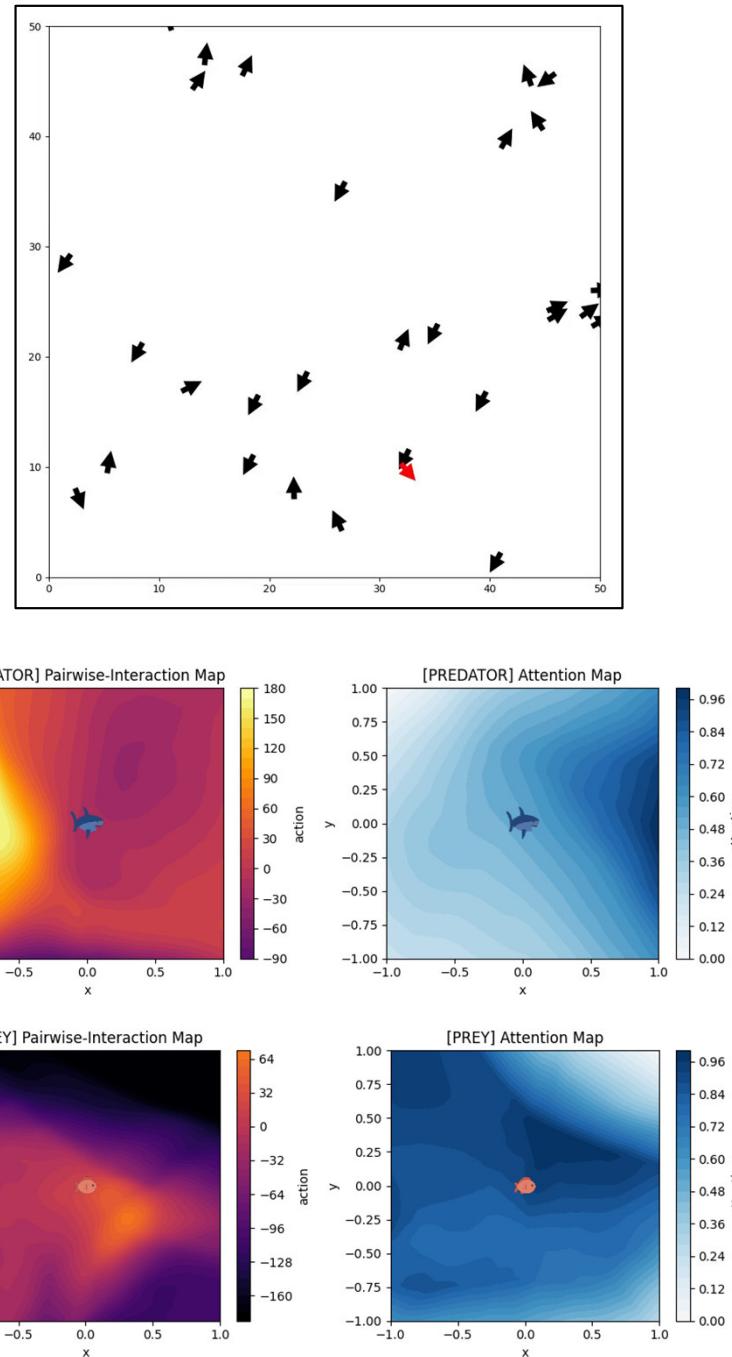
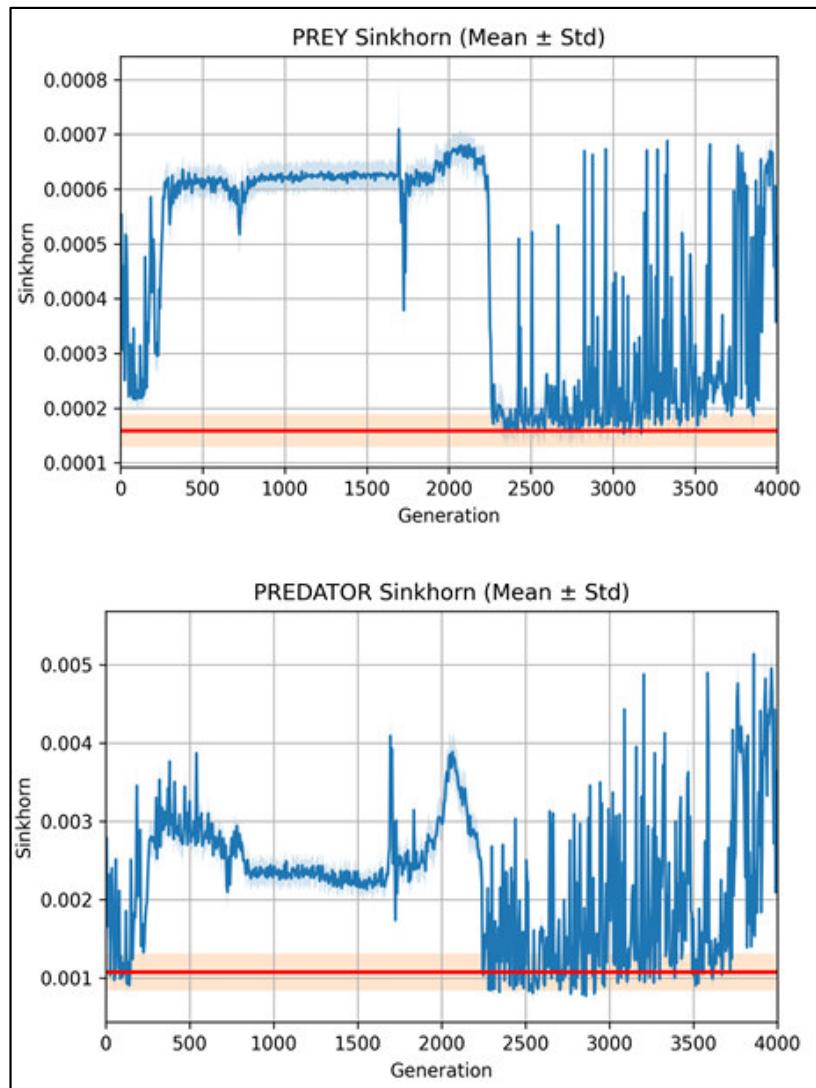
General GAIL pipeline works!
→ Prey-only model

Partial imitation of predator-prey models

But: missing inter-group dynamics



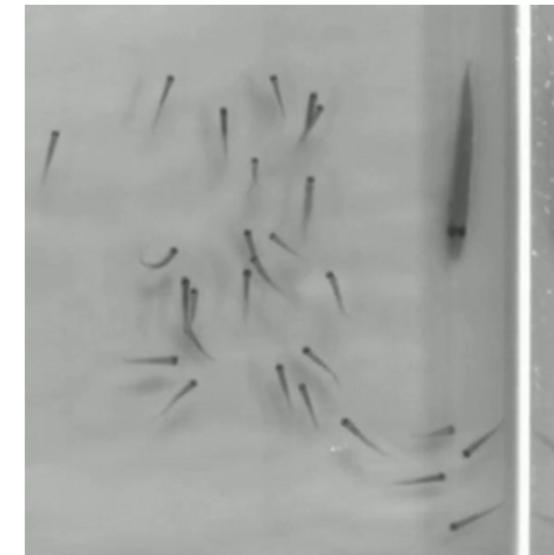
Summary & Discussion



Limitations & Future Work

Data processing:

- Large fraction of data remains unused (92.81%)
- Improve tracking continuity and missing detections
- Train on longer temporal contexts and varying group sizes

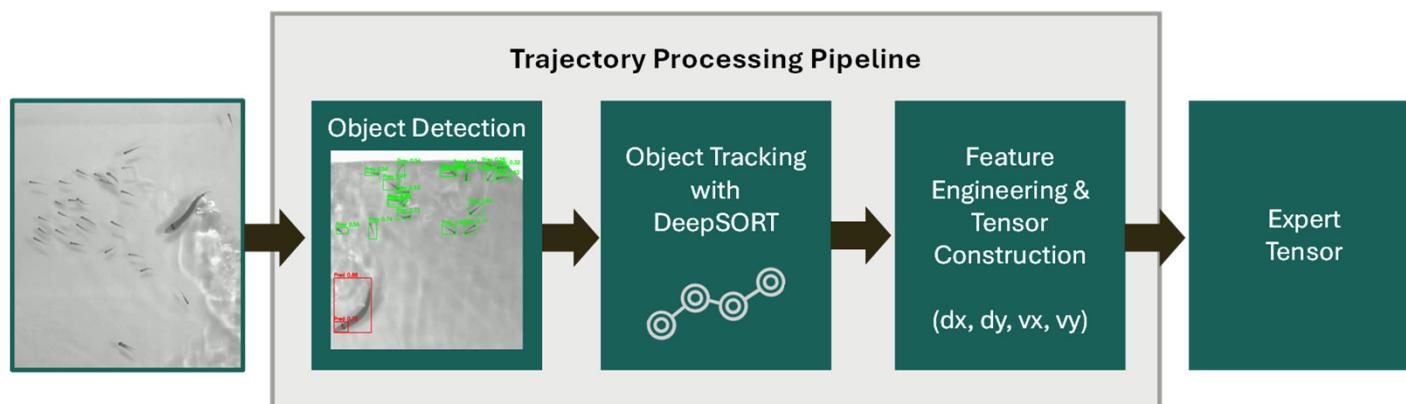


Predator attacks:

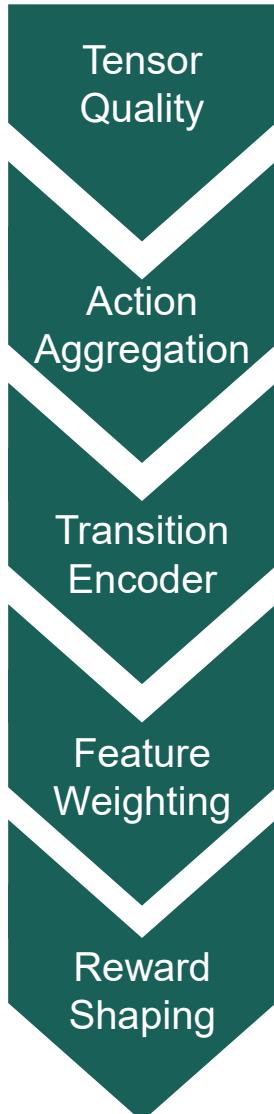
- Increase number of attack sequences
- Definition of attack behavior (hectic movements, ...)

Input features:

- Extend policy features with acceleration

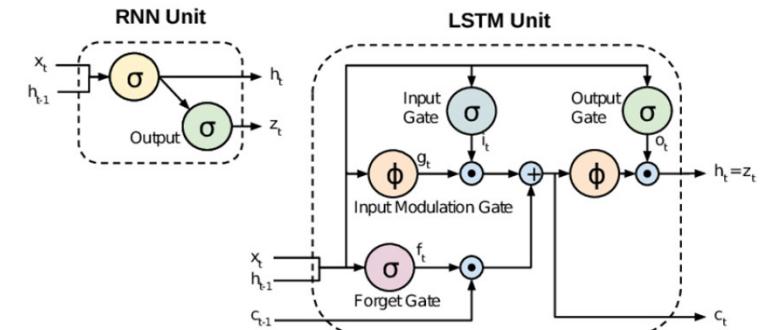


Limitations & Future Work



Sequence processing discriminator

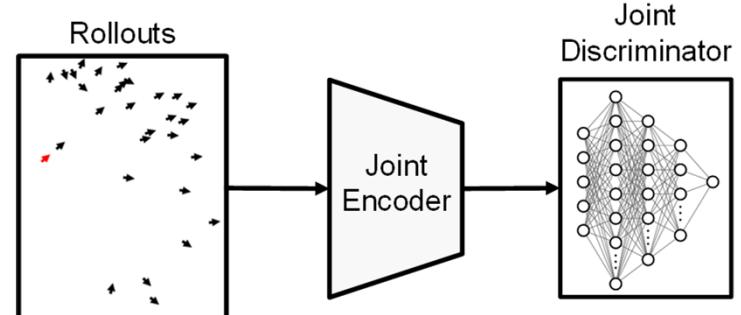
- Modelling temporal dependencies
- Train on longer temporal contexts
- RRN or LSTM

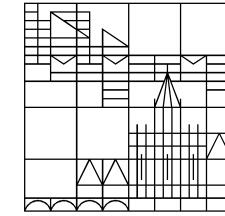


<https://ashutoshtripathi.com/2021/07/02/what-is-the-main-difference-between-rnn-and-lstm-nlp-rnn-vs-lstm/>

Missing inter-group dynamics

- CBIL's multi-instance single policy
- Joint encoder and discriminator
- 2-stage-setup





**Thank you
for your
Attention!**

Jannik Wirtheim
Konstanz



Reference: „The hunt from above“ – Angela Albi: <https://www.campus.uni-konstanz.de/unileben/die-kunst-der-haie>