Regularization for Adversarial Robust Learning

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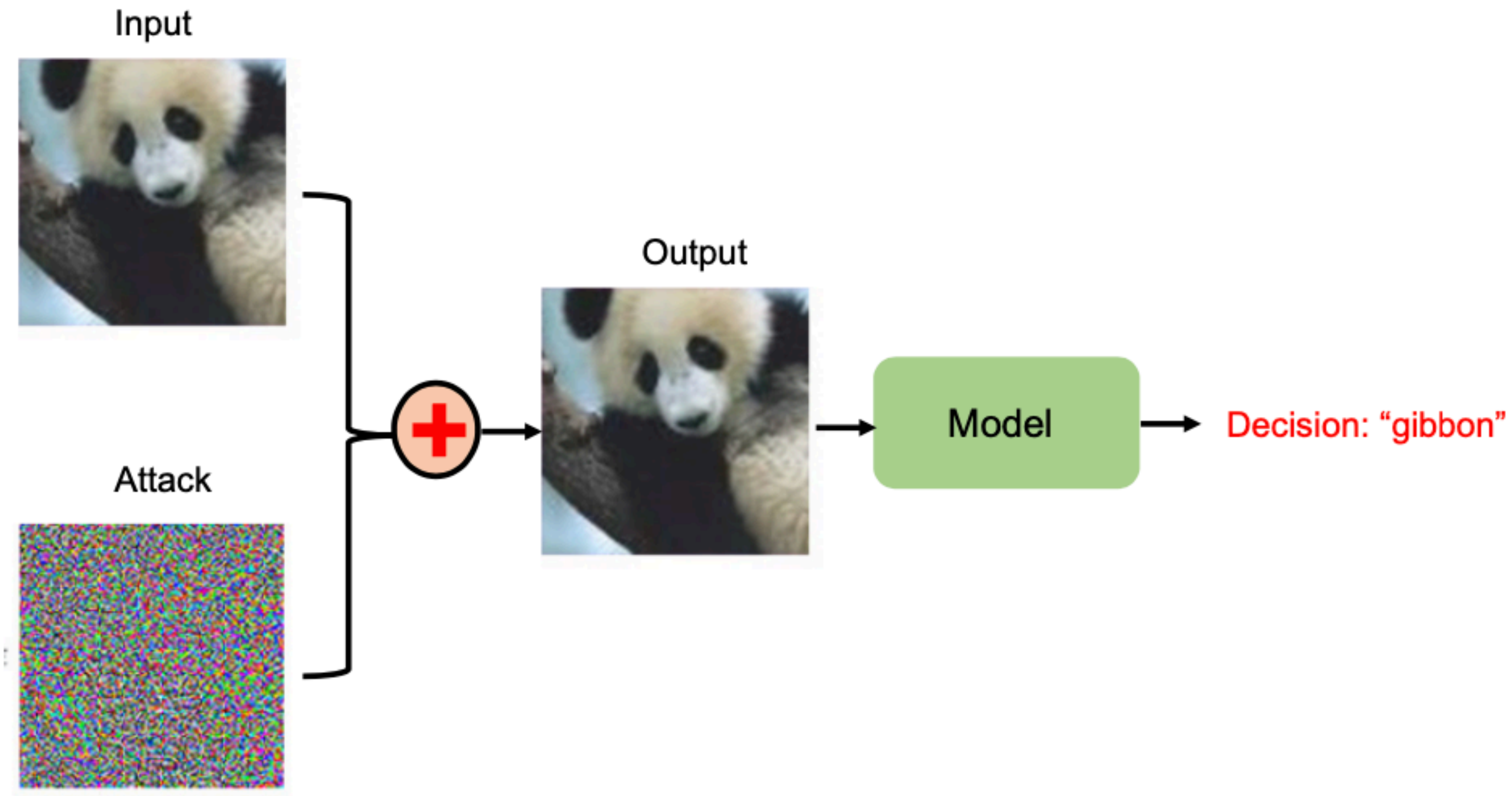
1. Introduction

On the Robustness of ML Models

[Goodfellow et al. 2015]



Adversarial Risk Minimization

Loss Function

$$\min_{\theta \in \Theta} \left\{ \mathbb{E}_{z \sim \mathbb{P}_n} \left[\sup_{\mathbf{d}(z,z') \leq \rho} \ell(z';\theta) \right] \right\}$$

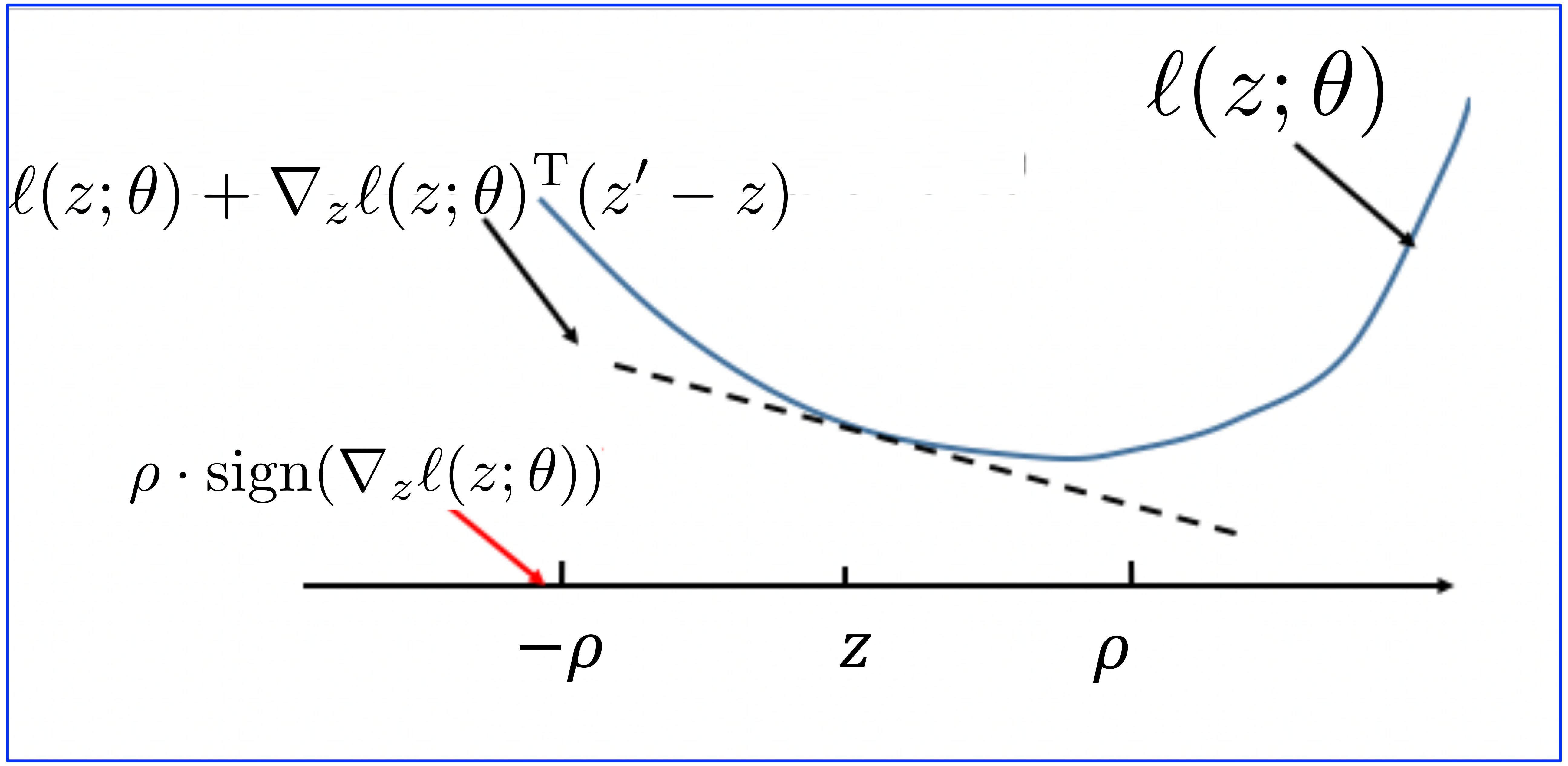
Data (e.g., feature-label pair) following empirical distribution

Perturbation Constriants

Baseline Approach: Linearizing Objective Function

$$\min_{\theta\in\Theta} \left\{ \mathbb{E}_{z\sim\mathbb{P}_n} \left[\sup_{\mathbf{d}(z,z')\le\rho} \ell(z';\theta) \right] \right\}$$

- **Fast Gradient Method (FGM)** [Goodfellow et al. 2015]



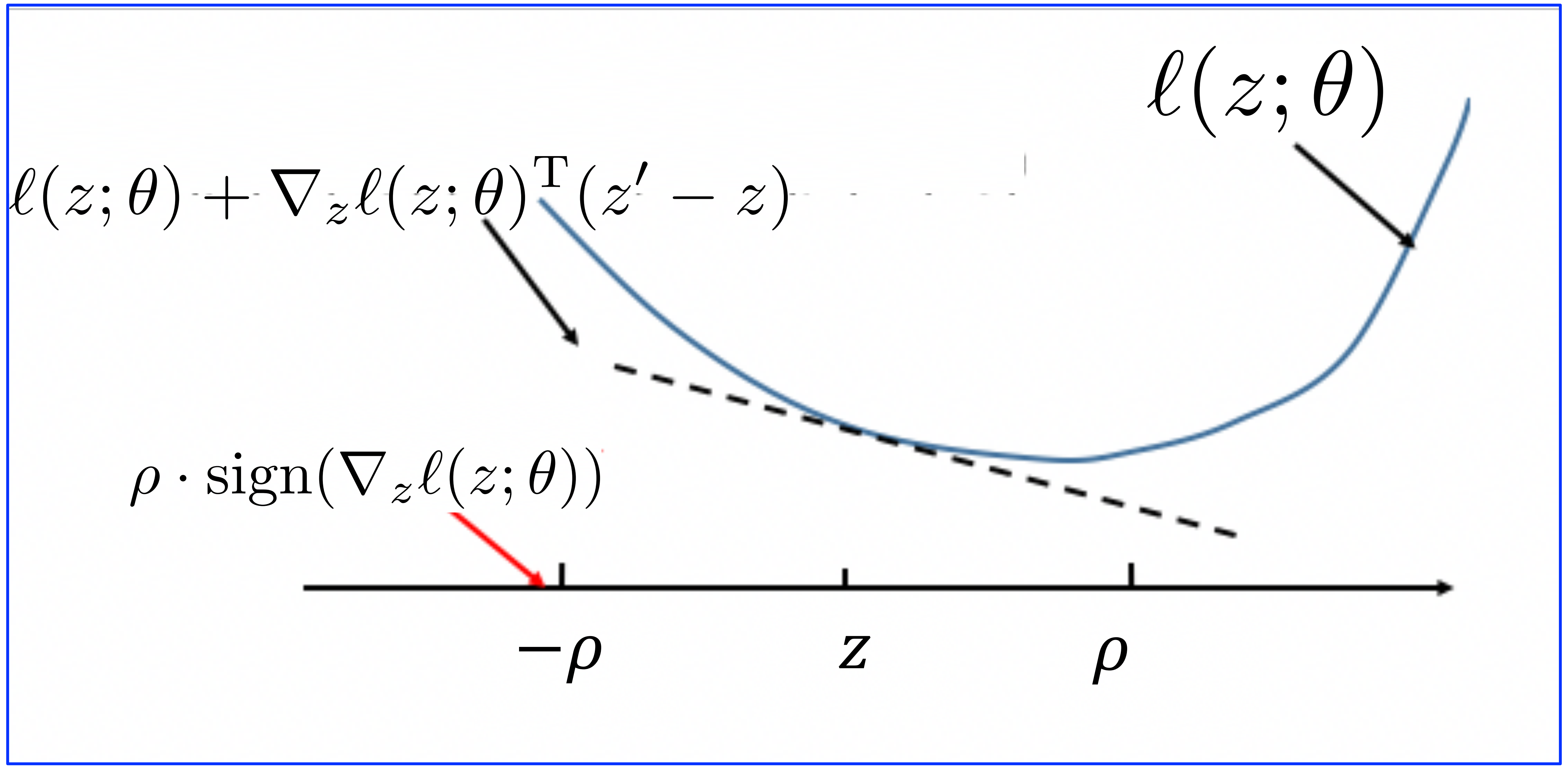
- $z' \approx \underset{\|z-z'\|_\infty\le\rho}{\arg\max} \left[\ell(z;\theta) + \nabla_z \ell(z;\theta)^{\mathrm{T}}(z'-z) \right]$

  $= z + \rho \cdot \mathrm{sign}(\nabla_z \ell(z;\theta))$

Baseline Approach: Linearizing Objective Function

$$\min_{\theta\in\Theta}\left\{\mathbb{E}_{z\sim\mathbb{P}_n}\left[\sup_{\mathbf{d}(z,z')\le\rho}\ell(z';\theta)\right]\right\}$$

- **Iterative Fast Gradient Method (FGM)** [Goodfellow et al. 2015]



- $z^0 = z$
  $$z^k = z^{k-1} + \alpha\cdot\mathrm{sign}(\nabla_z\ell(z^{k-1};\theta)),\quad k=1,\ldots,T-1,\ \alpha=\frac{\rho}{T}$$

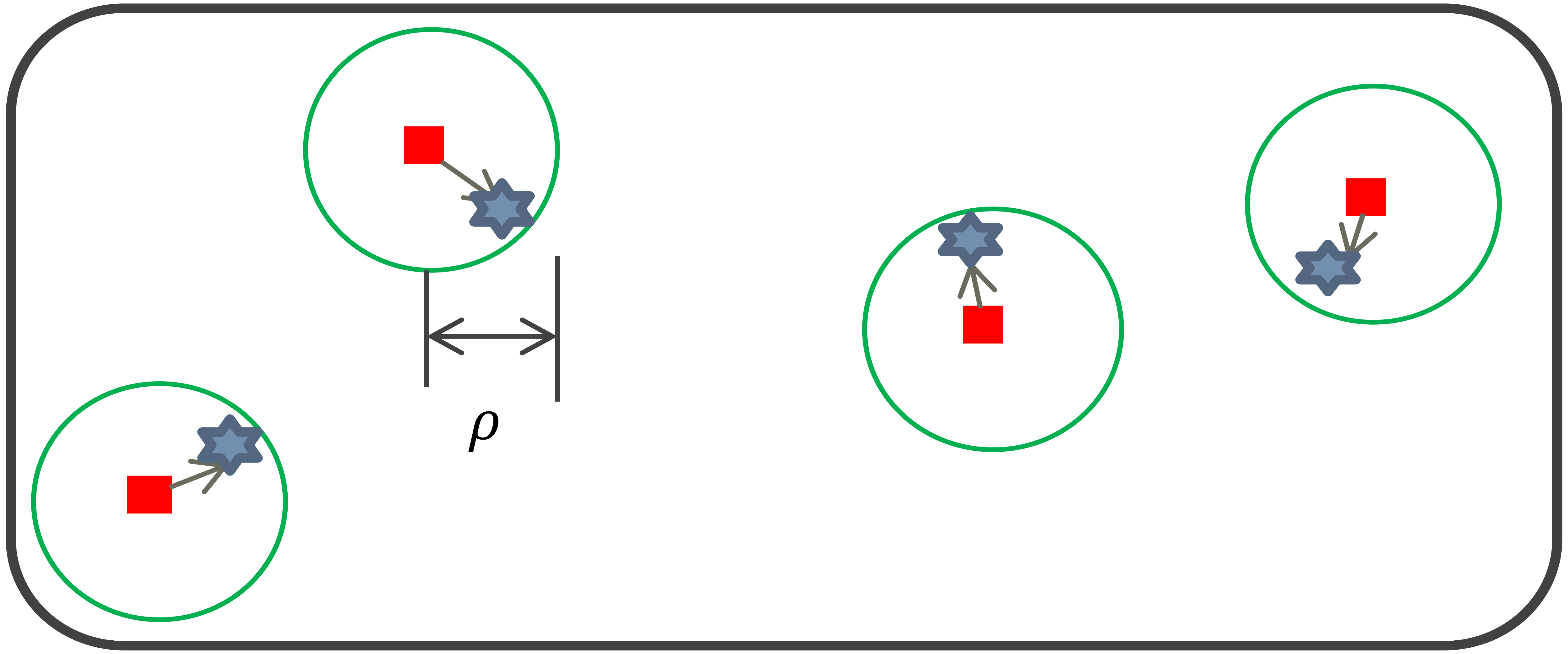
Cons: Optimization error is non-negligible for large ρ!

Connections with Wasserstein Robust Optimization

$$\min_{\theta\in\Theta} \left\{ \sup_{\mathbb{P}:\ \mathcal{W}_\infty(\mathbb{P},\mathbb{P}_n)\le\rho} \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] \right\}$$

$$\mathcal{W}_\infty(\mathbb{P},\mathbb{Q}) = \inf_{\gamma\in\Gamma(\mathbb{P},\mathbb{Q})} \left\{ \gamma\text{-esssup }\mathbf{d}(x,y) \right\}$$

Empirical $\mathbb{P}_n$ Worst-case $\mathbb{P}$



Literature Review

$$\min_{\theta\in\Theta} \left\{ \sup_{\mathbb{P}:\ \mathcal{W}_\infty(\mathbb{P},\mathbb{P}_n)\le\rho} \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] \right\}$$

***p*-Wasserstein DRO Approximation**

[Sinha, Namkoong, Volpi, Duchi, 2020]

$$\min_{\theta\in\Theta} \left\{ \sup_{\mathbb{P}:\ \mathcal{W}_p(\mathbb{P},\mathbb{P}_n)\le\rho} \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] \right\}$$

$$\min_{\theta\in\Theta,\lambda\ge 0} \left\{ \lambda\rho^p + \mathbb{E}_{x\sim\mathbb{P}_n}\left[\sup_z \left\{ \ell(z;\theta) - \lambda\|z-x\|^p \right\} \right] \right\}$$

- Easy to optimize for large choice of λ

$$\mathcal{W}_p(\mathbb{P},\mathbb{Q}) = \inf_{\gamma\in\Gamma(\mathbb{P},\mathbb{Q})} \left\{ \left(\mathbb{E}_{(x,y)\sim\gamma}[\|x-y\|^p] \right)^{1/p} \right\}$$

Literature Review

$$\min_{\theta\in\Theta}\left\{\sup_{\mathbb{P}:\ \mathcal{W}_\infty(\mathbb{P},\mathbb{P}_n)\le\rho}\mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)]\right\}$$

***p*-Wasserstein DRO**

$$\min_{\theta\in\Theta,\lambda\ge 0}\left\{\lambda\rho^p+\mathbb{E}_{x\sim\mathbb{P}_n}\left[\sup_z\left\{\ell(z;\theta)-\lambda\|z-x\|^p\right\}\right]\right\}$$

Entropic Regularized *p*-Wasserstein DRO Approximation

[Wang, Gao, Xie, 2021]

$$\min_{\theta\in\Theta}\left\{\sup_{\mathbb{P}:\ \mathcal{S}_{p,\epsilon}(\mathbb{P},\mathbb{P}_n)\le\rho}\mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)]\right\}$$

$$\mathcal{S}_{p,\epsilon}(\mathbb{P},\mathbb{P}_n)=\inf_{\gamma\in\Gamma(\mathbb{P},\mathbb{P}_n)}\left\{\mathbb{E}_{(x,y)\sim\gamma}[\|x-y\|^p]+\epsilon\mathbb{E}_{(x,y)\sim\gamma}\left[\log\left(\frac{\mathrm{d}\gamma(x,y)}{\mathrm{d}x\mathrm{d}\gamma(y)}\right)\right]\right\}$$

Literature Review

$$\min_{\theta\in\Theta}\left\{\sup_{\mathbb{P}:\ \mathcal{W}_\infty(\mathbb{P},\mathbb{P}_n)\le\rho}\mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)]\right\}$$

How about adding regularization directly?

***p*-Wasserstein DRO**

$$\min_{\theta\in\Theta,\lambda\ge 0}\left\{\lambda\rho^p+\mathbb{E}_{x\sim\mathbb{P}_n}\left[\sup_z\left\{\ell(z;\theta)-\lambda\|z-x\|^p\right\}\right]\right\}$$

Entropic Regularized *p*-Wasserstein DRO Approximation

[Wang, Gao, Xie, 2021]

$$\min_{\theta\in\Theta,\lambda\ge 0}\left\{\lambda\bar{\rho}+\mathbb{E}_{x\sim\mathbb{P}_n}\left[\lambda\epsilon\log\mathbb{E}_{z\sim\mathbb{Q}_{x,\epsilon}}\left[e^{f(z)/(\lambda\epsilon)}\right]\right]\right\}$$

$$\frac{\mathrm{d}\mathbb{Q}_{x,\epsilon}(z)}{\mathrm{d}z}\propto e^{-\|z-x\|^p/\epsilon}$$

1. Entropic regularization brings **computational benefits**
2. Entropic regularization introduces **absolutely continuous worst-case distributions**

Regularized Adversarial Robust Learning

$$\min_{\theta\in\Theta} \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x,y) \le \rho \end{array} \right\}$$

Regularized Adversarial Robust Learning

$$\min_{\theta\in\Theta} \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \eta\mathbb{D}_f(\gamma,\gamma_0) : \begin{array}{l} \gamma\in\Gamma(\mathbb{P}_n,\mathbb{P}) \\ \gamma\text{-esssup}\ \mathbf{d}(x,y)\le\rho \end{array} \right\}$$

- **f-divergence (e.g., KL or χ^2):**

$$\mathbb{D}_f(\gamma,\gamma_0) = \int f\left(\frac{\mathrm{d}\gamma}{\mathrm{d}\gamma_0}\right)\mathrm{d}\gamma_0$$

- **Reference transport γ_0 is uniform:**

For each $z\in\operatorname{supp}(\mathbb{P}_n)$, $\gamma_0(\,\cdot\mid z)$ is uniform on $\mathbb{B}_\rho(z)$

$$\gamma_0(z,z') = \mathbb{P}_n(z)\cdot\mathbb{Q}_{z,\rho}(z')$$

2. Strong Duality

Strong Dual Reformulation

Under mild conditions, $V_{\text{Primal}} = V_{\text{dual}}$:

$$V_{\text{Primal}} = \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{\mathbb{P}}[\ell(z;\theta)] - \eta \mathbb{D}_f(\gamma, \gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x, y) \le \rho \end{array} \right\}$$

By $\gamma_0(z, z') = \mathbb{P}_n(z) \cdot \mathbb{Q}_{z,\rho}(z')$, $\quad \gamma(z, z') = \mathbb{P}_n(z) \cdot \mathbb{P}_z(z')$,

$$V_{\text{Dual}} = \mathbb{E}_{z\sim\mathbb{P}_n} \left[\sup_{\mathbb{P}_z} \underbrace{\left\{ \mathbb{E}_{z'\sim\mathbb{P}_z}[\ell(z';\theta)] - \eta \mathbb{D}_f(\mathbb{P}_z, \mathbb{Q}_{z,\rho}) \right\}}_{\textbf{Penalized } f\textbf{-divergence DRO}} \right]$$

Strong Dual Reformulation

Under mild conditions, $V_{\text{Primal}} = V_{\text{dual}}$:

$$V_{\text{Primal}} = \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{\mathbb{P}}[\ell(z;\theta)] - \eta \mathbb{D}_f(\gamma, \gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x,y) \leq \rho \end{array} \right\}$$

$$V_{\text{Dual}} = \mathbb{E}_{z\sim\mathbb{P}_n} \left[\inf_{\mu\in\mathbb{R}} \left\{ \mu + \mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[(\eta f)^*(\ell(z';\theta) - \mu)] \right\} \right]$$

Divergence $\mathbb{D}_f(\cdot,\cdot)$	**Choice of** $f(x)$	V_{Dual}
KL-Divergence	$x\log x - x + 1$	$\mathbb{E}_{\mathbb{P}_n}\left[\eta \log \mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[e^{\ell(z';\theta)/\eta}]\right]$
χ^2-Divergence	$\frac{1}{2}(x^2 - 1)$	$\mathbb{E}_{z\sim\mathbb{P}_n}\left[\inf_{\mu\in\mathbb{R}} \left\{ \frac{1}{2\eta} \mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[\ell(z';\theta) - \mu]_+^2 + \frac{\eta}{2} + \mu \right\}\right]$

Strong Dual Reformulation

Divergence $\mathbb{D}_f(\cdot,\cdot)$	Choice of $f(x)$	V_{Dual}
KL-Divergence	$x\log x - x + 1$	$\mathbb{E}_{\mathbb{P}_n}\left[\eta \log \mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[e^{\ell(z';\theta)/\eta}]\right]$
χ²-Divergence	$\frac{1}{2}(x^2-1)$	$\mathbb{E}_{z\sim\mathbb{P}_n}\left[\inf_{\mu\in\mathbb{R}}\left\{\frac{1}{2\eta}\mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[\ell(z';\theta)-\mu]_+^2+\frac{\eta}{2}+\mu\right\}\right]$

Strong dual for un-regularized case (η=0) [Gao et al., 2022]:

$$V_{\text{Primal}} = \sup_{\mathbb{P},\gamma}\left\{\mathbb{E}_{\mathbb{P}}[\ell(z;\theta)] : \begin{array}{l}\gamma\in\Gamma(\mathbb{P}_n,\mathbb{P})\\ \gamma\text{-esssup }\mathbf{d}(x,y)\le\rho\end{array}\right\}$$

$$V_{\text{Dual}} = \mathbb{E}_{z\sim\mathbb{P}_n}\left[\sup_{z':\ \mathbf{d}(z,z')\le\rho}\ell(z';\theta)\right]$$

Laplace's Method

Extension of Laplace's Method

Divergence $\mathbb{D}_f(\cdot,\cdot)$	Choice of $f(x)$	V_{Dual}
KL-Divergence	$x\log x - x + 1$	$\mathbb{E}_{\mathbb{P}_n}\left[\eta\log\mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[e^{\ell(z';\theta)/\eta}]\right]$
χ²-Divergence	$\frac{1}{2}(x^2-1)$	$\mathbb{E}_{z\sim\mathbb{P}_n}\left[\inf_{\mu\in\mathbb{R}}\left\{\frac{1}{2\eta}\mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[\ell(z';\theta)-\mu]_+^2+\frac{\eta}{2}+\mu\right\}\right]$

Consistency property (regularized adversarial loss converges to non-regularized one) holds if $\mathrm{dom}(f)=\mathbb{R}_+$

Example: $f(x)=\mathbb{I}\{0\le x\le\alpha^{-1}\}$, $V_{\mathrm{Dual}}=\mathbb{E}_{z\sim\mathbb{P}_n}\left[\mathtt{AV@R}_{\alpha,\mathbb{Q}_{z,\rho}}(\ell(\cdot;\theta))\right]$

Recovery of Worst-case Distribution

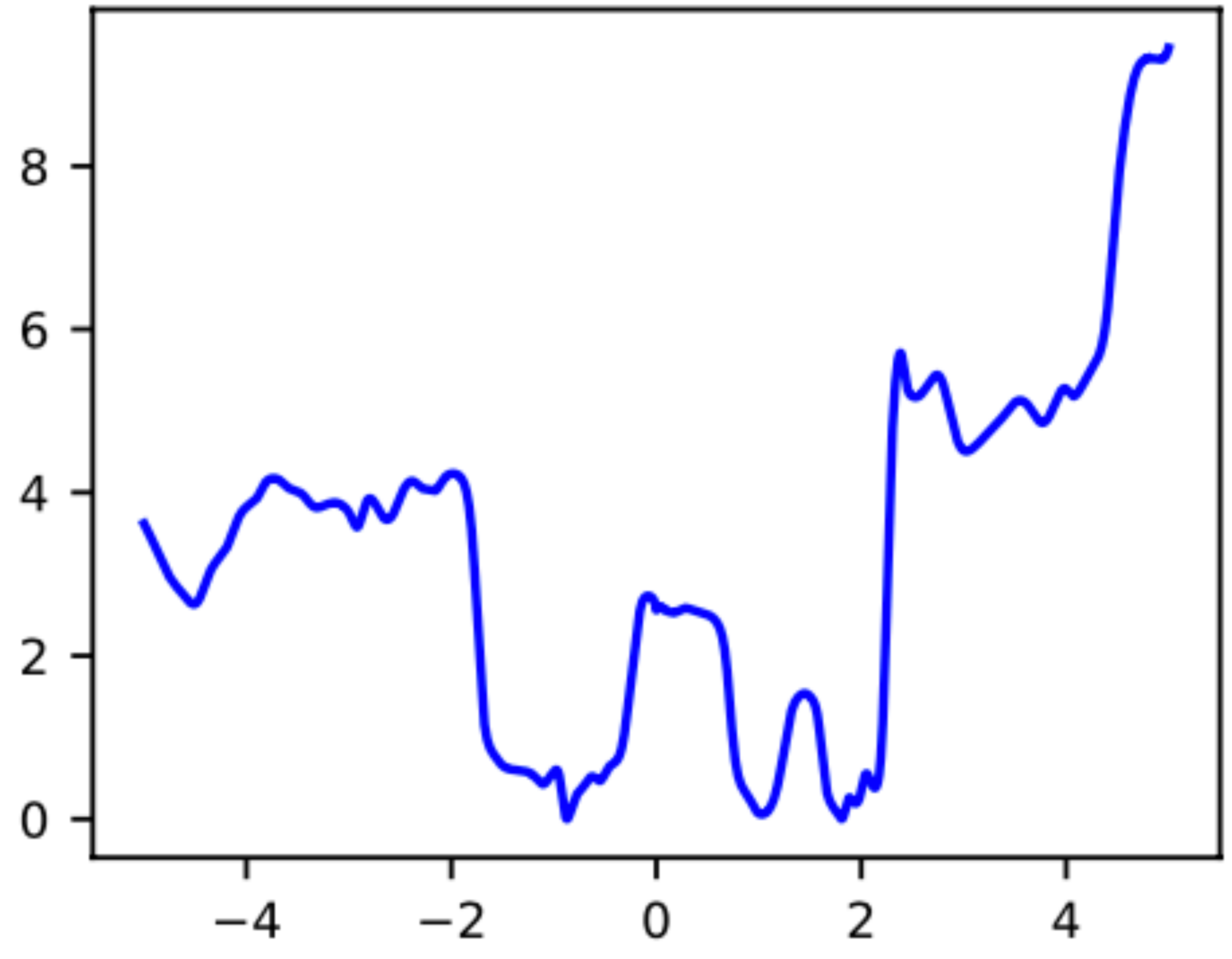
$$(\mathbb{P}^*, \gamma^*) = \operatorname*{argmax}_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \mathbb{D}_f(\gamma,\gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x,y) \le \rho \end{array} \right\}$$

$$\frac{\mathrm{d}\mathbb{P}^*(\omega)}{\mathrm{d}\omega} = \mathbb{E}_{z\sim\mathbb{P}_n}\left[\alpha_z \cdot \mathbf{1}\{\mathbf{d}(\omega,z)\le\rho\} \cdot (\eta f)^{*\prime}(\ell(\omega;\theta)-\mu_z^*)\right]$$

Normalizing Constant **Support Constraint** **Density contributed by z**

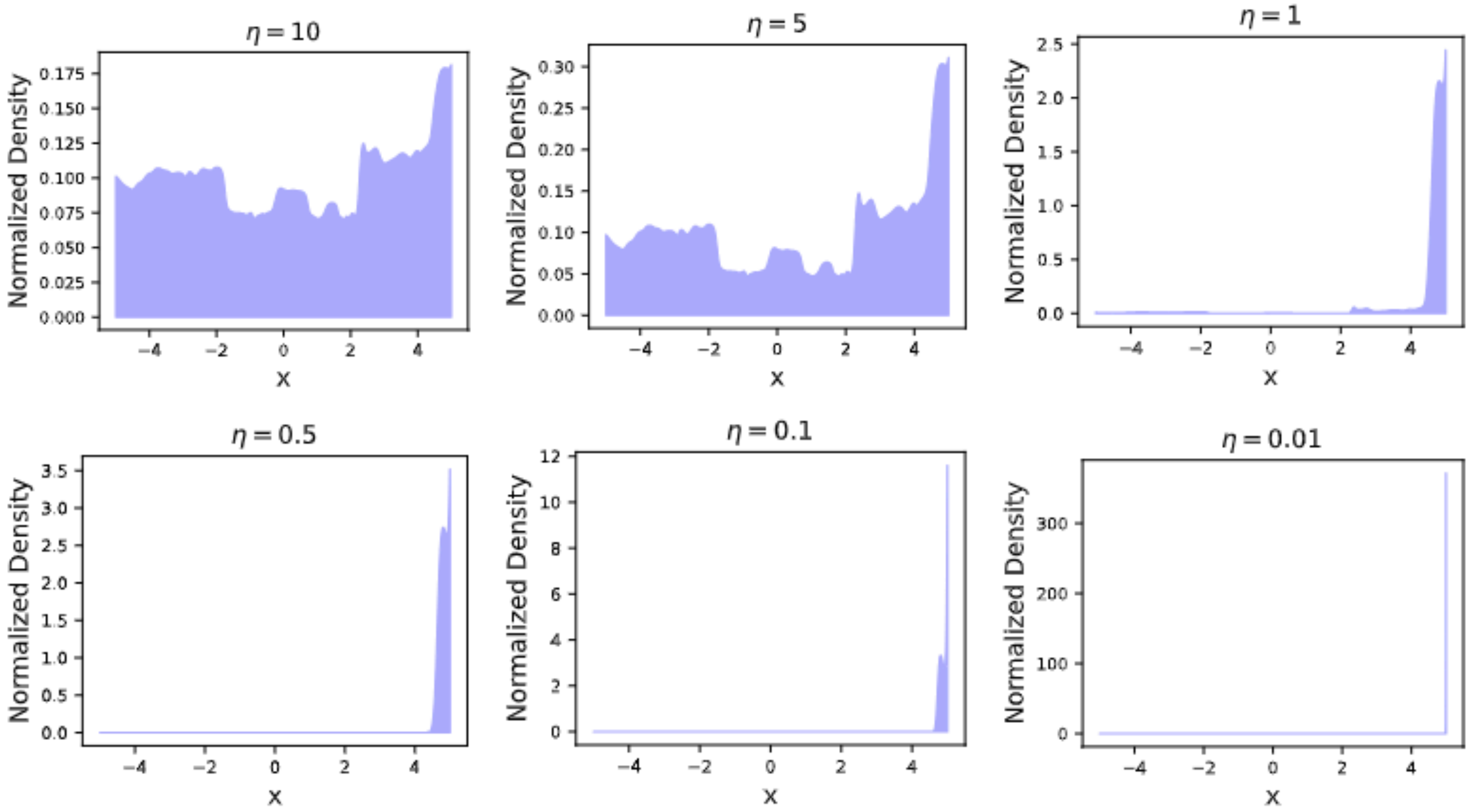
Recovery of Worst-case Distribution

$$(\mathbb{P}^*, \gamma^*) = \operatorname*{argmax}_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \mathbb{D}_f(\gamma, \gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x,y) \le \rho \end{array} \right\}$$



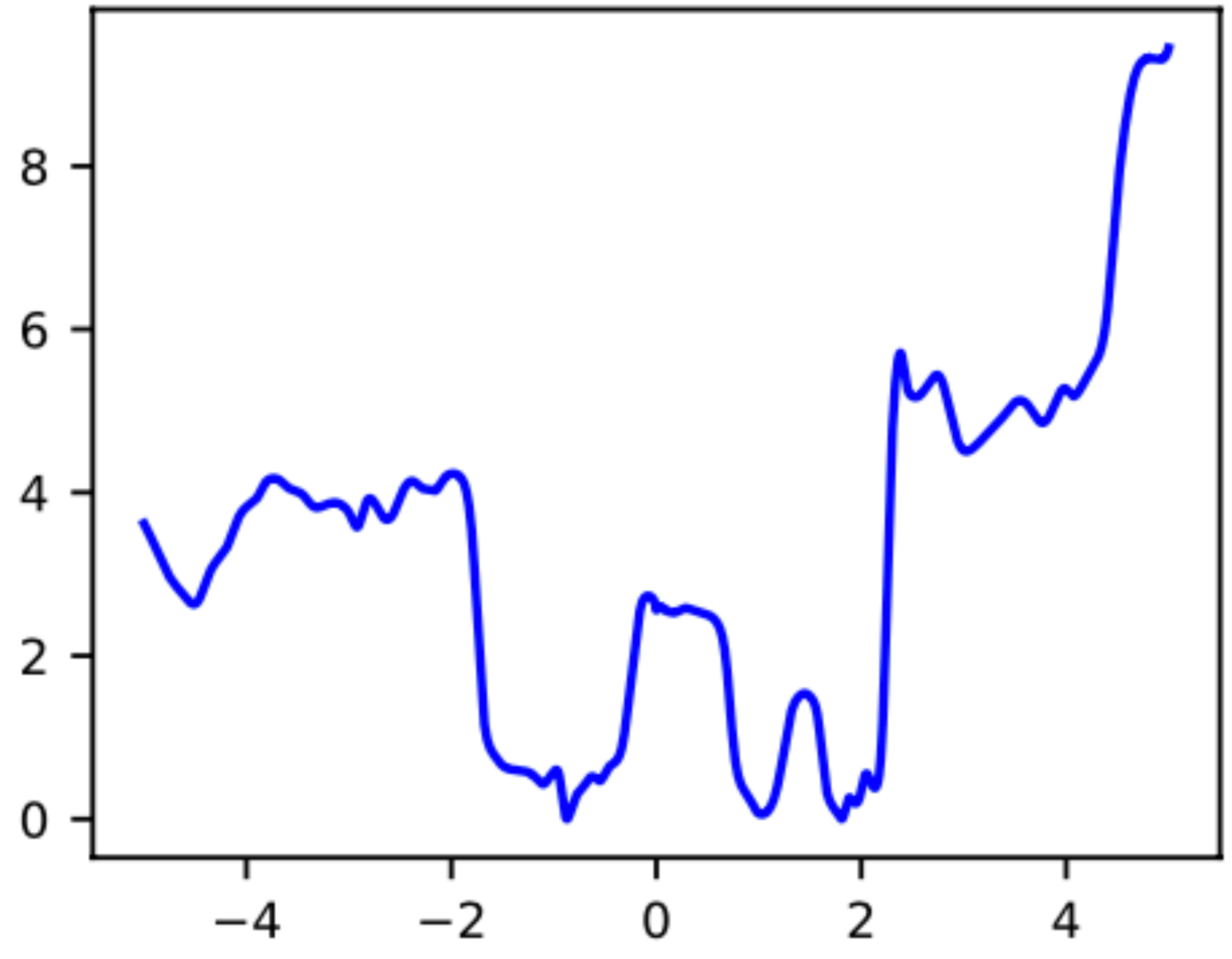
Landscape of 3-layer neural network

Entropic Regularization:



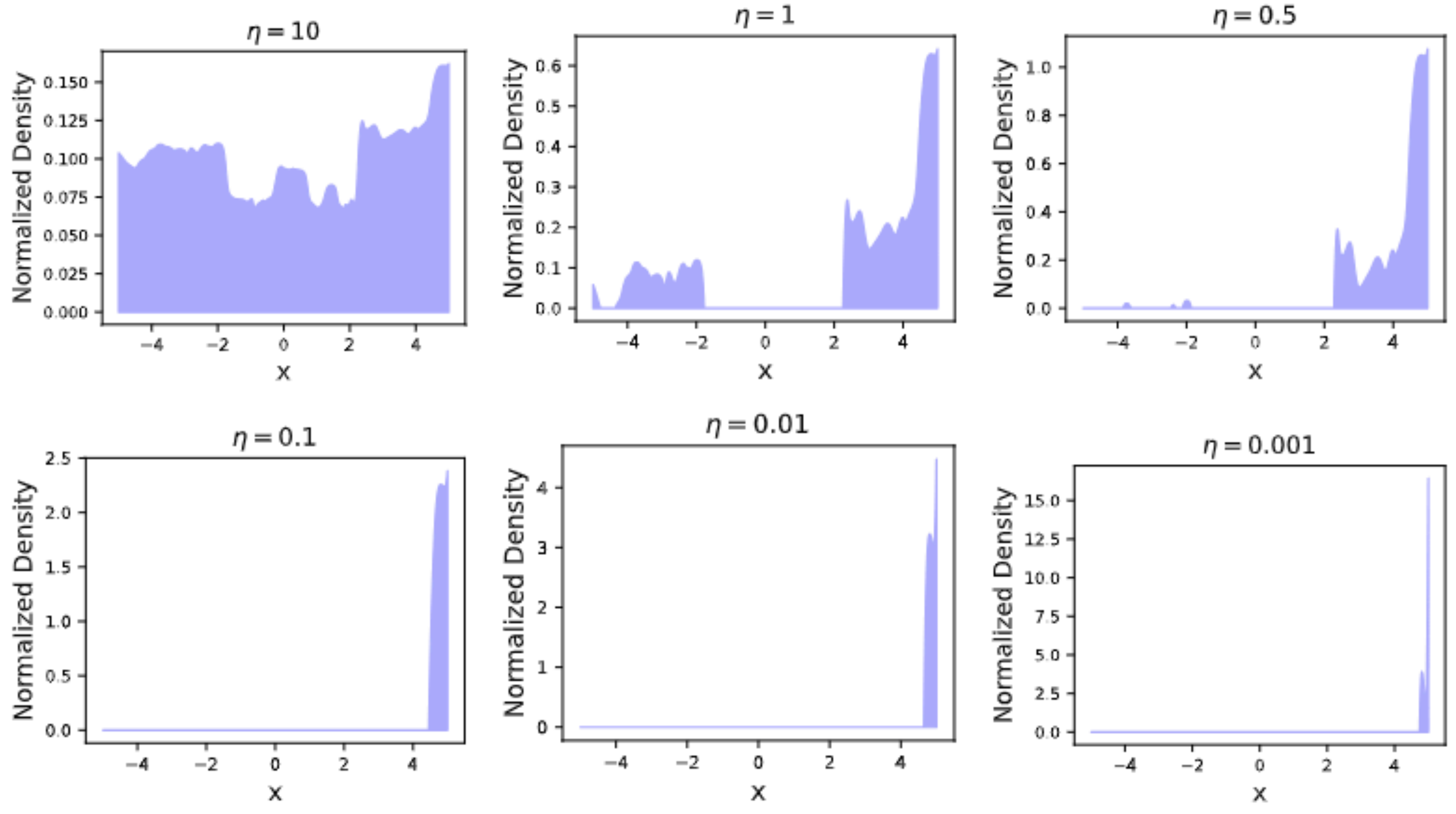
Recovery of Worst-case Distribution

$$(\mathbb{P}^*, \gamma^*) = \underset{\mathbb{P},\gamma}{\text{argmax}} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - {\color{red}\mathbb{D}_f(\gamma,\gamma_0)} : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x,y) \le \rho \end{array} \right\}$$



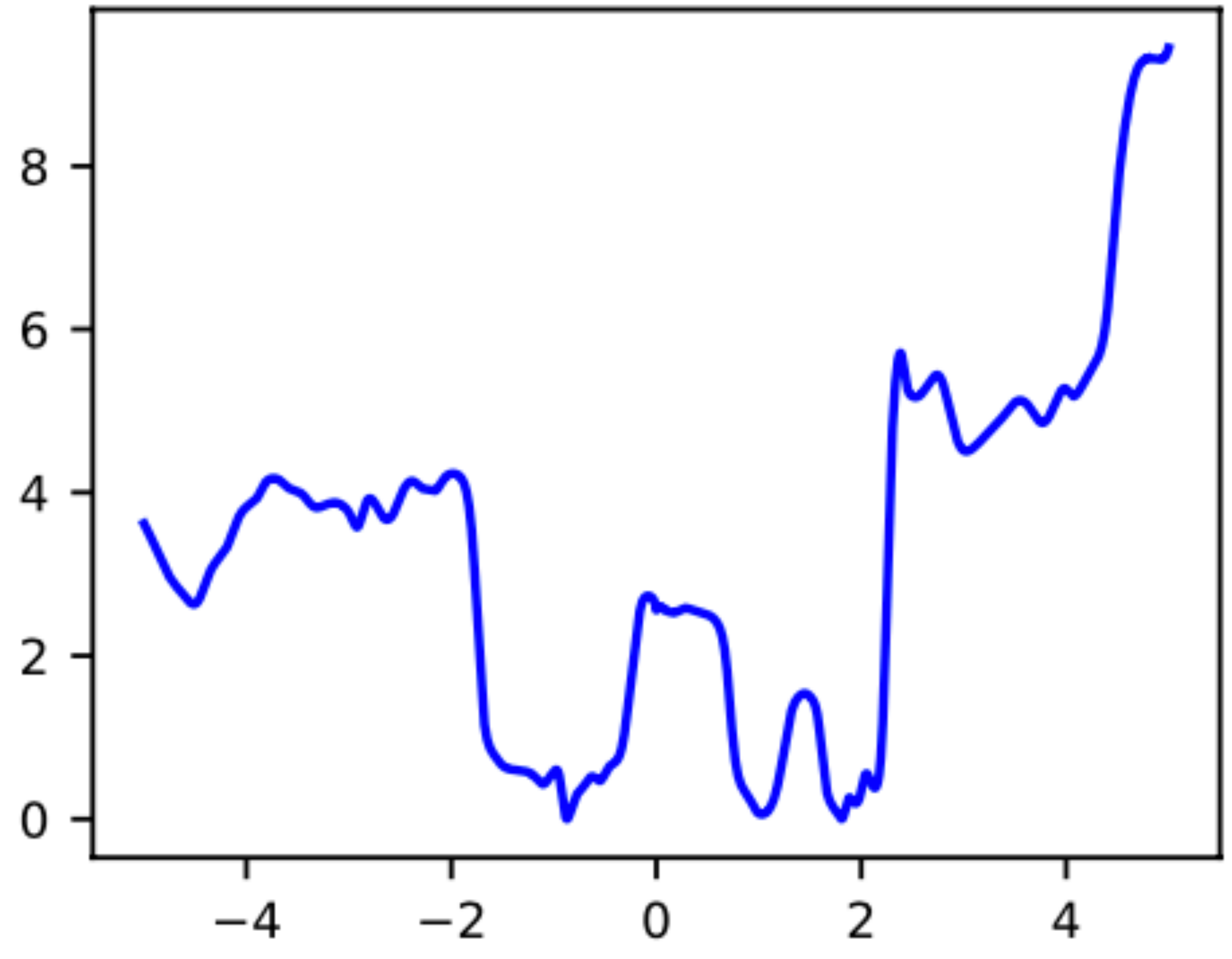
Landscape of 3-layer neural network

Quadratic Regularization:



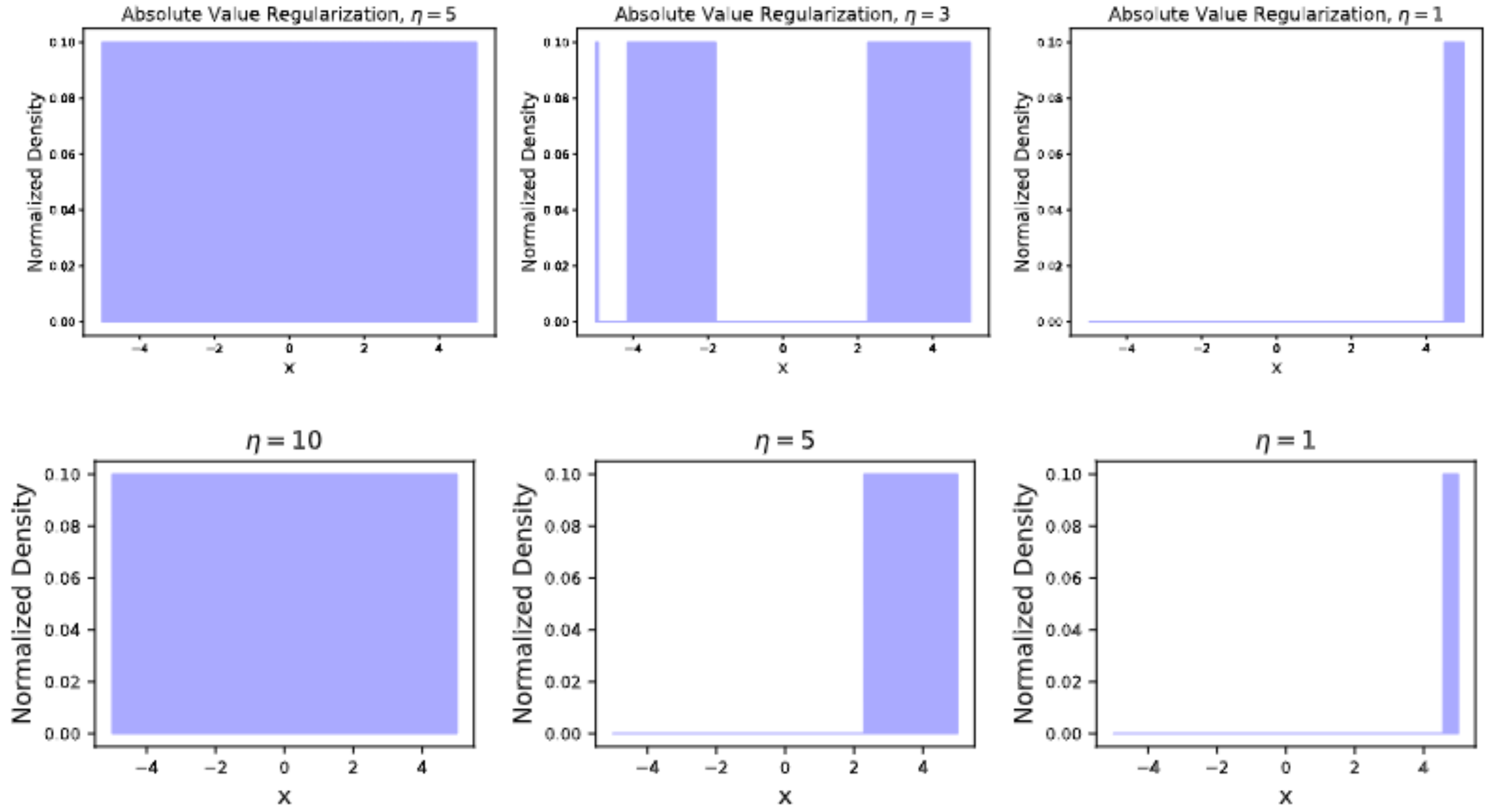
Recovery of Worst-case Distribution

$$(\mathbb{P}^*, \gamma^*) = \operatorname*{argmax}_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \mathbb{D}_f(\gamma, \gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \mathbf{d}(x, y) \le \rho \end{array} \right\}$$



Landscape of 3-layer neural network

Absolute Value/Hinge Loss Regularization:



3. Algorithm Design

Tractable Algorithm

- **Ideal formulation:**

$$\min_{\theta\in\Theta} \mathbb{E}_{z\sim\mathbb{P}_n}\left[\inf_{\mu\in\mathbb{R}}\left\{\mu+\mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[(\eta f)^*(\ell(z';\theta)-\mu)]\right\}\right]$$

Tractable Algorithm

- **Approximation:**

$$\min_{\theta\in\Theta} \mathbb{E}_{\substack{\bullet\ z \sim \mathbb{P}_n \\ \bullet\ \{z_i'\}_{i\in[2^l]} \sim \mathbb{Q}_{z,\rho}}} \left[\inf_{\mu\in\mathbb{R}} \left\{ \mu + \frac{1}{2^l} \sum_{i\in[2^l]} [(\eta f)^*(\ell(z_i';\theta) - \mu)] \right\} \right]$$

Tractable Algorithm

- **Ideal formulation:**

$$\min_{\theta\in\Theta} \boxed{\mathbb{E}_{z\sim\mathbb{P}_n}\left[\inf_{\mu\in\mathbb{R}}\left\{\mu+\mathbb{E}_{z'\sim\mathbb{Q}_{z,\rho}}[(\eta f)^*(\ell(z';\theta)-\mu)]\right\}\right]} \triangleq F(\theta)$$

- **Approximation:**

$$\min_{\theta\in\Theta} \boxed{\mathbb{E}\left[\inf_{\mu\in\mathbb{R}}\left\{\mu+\frac{1}{2^l}\sum_{i\in[2^l]}[(\eta f)^*(\ell(z_i';\theta)-\mu)]\right\}\right]} \triangleq F^l(\theta)$$

- $z\sim\mathbb{P}_n$
- $\{z_i'\}_{i\in[2^l]}\sim\mathbb{Q}_{z,\rho}$

Tractable Algorithm

- **Approximation:**

$$\min_{\theta\in\Theta} \mathbb{E}\left[\inf_{\mu\in\mathbb{R}} \left\{\mu + \frac{1}{2^l}\sum_{i\in[2^l]}\left[(\eta f)^*\left(\ell(z_i';\theta) - \mu\right)\right]\right\}\right] \triangleq F^l(\theta)$$

- $z \sim \mathbb{P}_n$
- $\{z_i'\}_{i\in[2^l]} \sim \mathbb{Q}_{z,\rho}$

SGD with Naive Estimator: Fix large $l \equiv L$,

If converged? → **False** → **Sample $z \sim \mathbb{P}_n$ and $\{z_i'\}_{i\in[2^L]} \sim \mathbb{Q}_{z,\rho}$** → **Generate Sample Estimate of $\nabla F^L(\theta)$ and Update** → (back to **If converged?**)

Tractable Algorithm

- **Approximation:**

$$\min_{\theta\in\Theta} \mathbb{E} \left[\inf_{\mu\in\mathbb{R}} \left\{ \mu + \frac{1}{2^l} \sum_{i\in[2^l]} [(\eta f)^* (\ell(z_i'; \theta) - \mu)] \right\} \right] \triangleq F^l(\theta)$$

- $z \sim \mathbb{P}_n$
- $\{z_i'\}_{i\in[2^l]} \sim \mathbb{Q}_{z,\rho}$

SGD with Random Sampling Estimator:

If converged?

False

Sample $\hat{L}$ with
$P(\hat{L} = i) \propto 2^{-i}, i = 0, \ldots, L$

Sample $z \sim \mathbb{P}_n$ and
$\{z_i'\}_{i\in[2^{\hat{L}}]} \sim \mathbb{Q}_{z,\rho}$

Generate Sample Estimate of
$P(\hat{L})^{-1}(\nabla F^{\hat{L}}(\theta) - \nabla F^{\hat{L}-1}(\theta))$
and Update

Complexity for Optimizing F

- **Ideal formulation:**

$$\min_{\theta \in \Theta} \boxed{\mathbb{E}_{z \sim \mathbb{P}_n} \left[\inf_{\mu \in \mathbb{R}} \left\{ \mu + \mathbb{E}_{z' \sim \mathbb{Q}_{z,\rho}} [(\eta f)^*(\ell(z';\theta) - \mu)] \right\} \right]} \triangleq F(\theta)$$

Algorithm	Naive Estimator		Random Sampling Estimator	
Loss $\ell(z,\cdot)$	Convex	Nonconvex Smooth	Convex	Nonconvex Smooth
Choice of f**-divergence**	Arbitrary	**KL-divergence**	Arbitrary	**KL-divergence**
Complexity	$\tilde{O}(\delta^{-3})$	$\tilde{O}(\delta^{-6})$	$\tilde{O}(\delta^{-2})$	$\tilde{O}(\delta^{-4})$

4. Statistical Analysis

Regularization Effects

- Regularized adversarial learning:

$$\min_{\theta\in\Theta} \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \eta \mathbb{D}_f(\gamma,\gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n.\mathbb{P}) \\ \gamma\text{-esssup } \|x-y\| \leq \rho \end{array} \right\}$$

- Regularization Effects:

$$\boxed{(\text{Regularized Adversarial Learning}) \approx \min_{\theta\in\Theta} \left\{ \mathbb{E}_{z\sim\mathbb{P}_n}[\ell(z;\theta)] + \text{Regularization} \right\}}$$

Regularization Effects

- Regularized adversarial learning:

$$\min_{\theta\in\Theta}\ \sup_{\mathbb{P},\gamma}\ \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \eta\mathbb{D}_f(\gamma,\gamma_0) : \begin{array}{l} \gamma\in\Gamma(\mathbb{P}_n,\mathbb{P}) \\ \gamma\text{-esssup}\ \|x-y\| \le \rho \end{array} \right\}$$

- **Case 1:** $\rho/\eta\to\infty$

$$\text{(Regularized Adversarial Learning)} \approx \min_{\theta\in\Theta}\left\{ \mathbb{E}_{z\sim\mathbb{P}_n}[\ell(z;\theta)] + \rho\cdot \boxed{\mathbb{E}_{z\sim\mathbb{P}_n}[\|\nabla\ell(z;\theta)\|]} \right\}$$

  - Recovers regularization for **∞-type Wasserstein DRO**!
  - Hedge against adversarial attack

Regularization Effects

- Regularized adversarial learning:

$$\min_{\theta\in\Theta} \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \eta \mathbb{D}_f(\gamma,\gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup } \|x-y\| \leq \rho \end{array} \right\}$$

- **Case 2:** $\rho/\eta \to 0$

$$\text{(Regularized Adversarial Learning)} \approx \min_{\theta\in\Theta} \left\{ \mathbb{E}_{z\sim\mathbb{P}_n}[\ell(z;\theta)] + \frac{\rho^2}{2\eta f''(1)} \cdot \mathbb{E}_{z\sim\mathbb{P}_n}[\mathbb{V}\mathrm{ar}_{b\sim\beta}[\nabla \ell(z;\theta)^\top b]] \right\}$$

  - Relates to regularization for ***f*-divergence DRO**!
  - Hedge against white noise attack

Regularization Effects

- Regularized adversarial learning:

$$\min_{\theta\in\Theta} \sup_{\mathbb{P},\gamma} \left\{ \mathbb{E}_{z\sim\mathbb{P}}[\ell(z;\theta)] - \eta\mathbb{D}_f(\gamma,\gamma_0) : \begin{array}{l} \gamma \in \Gamma(\mathbb{P}_n, \mathbb{P}) \\ \gamma\text{-esssup}\, \|x-y\| \le \rho \end{array} \right\}$$

- **Case 3:** $\rho/\eta \to C$

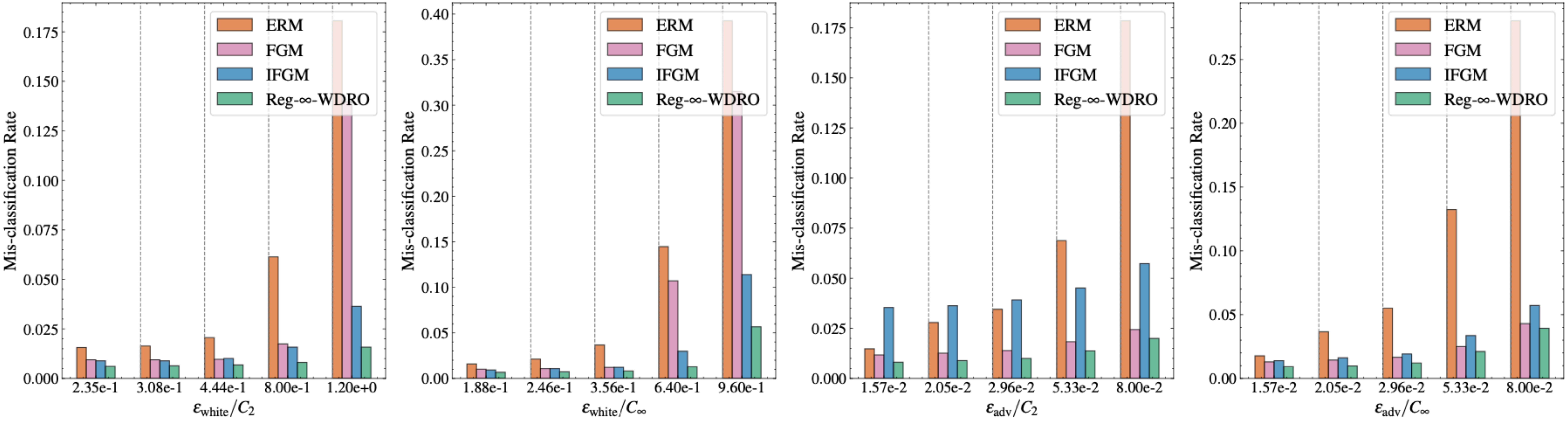
$$\text{(Regularized Adversarial Learning)} \approx \min_{\theta\in\Theta} \left\{ \mathbb{E}_{z\sim\mathbb{P}_n}[\ell(z;\theta)] + \rho\cdot\mathbb{E}_{x\sim\mathbb{P}_n}\left[\inf_{\mu\in\mathbb{R}} \left\{ \mu + \frac{1}{C}\mathbb{E}_{b\sim\beta}[f^*(C\cdot(\nabla\ell(z;\theta)^\top b - \mu))] \right\} \right] \right\}$$

  - Relates to **optimized certainty equivalent regularization**
  - Interpolates between **gradient norm** and **variance regularization**!

5. Numerical Study and Conclusion

Numerical Study: MNIST Classification

- Goal: Classification with $8 \times 8, 6 \times 6$ convolutional network and ELU activation
- Training data: MNIST handwritten digits with $6 \cdot 10^4$ samples
- Testing data: digits with 10^4 samples, perturbed by random/adversarial ℓ_2/ℓ_∞ noise

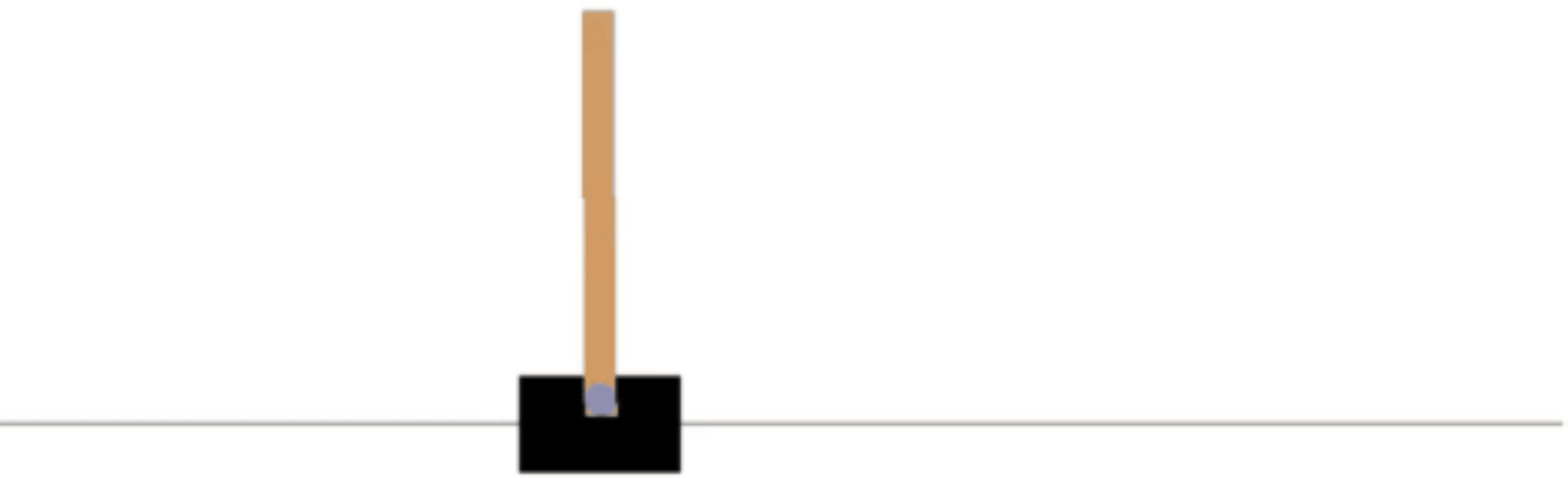


Numerical Study: Reliable Reinforcement Learning

- **Standard Q-learning:** $Q(s^t, a^t) \leftarrow (1-\alpha_t)Q(s^t, a^t) + \alpha_t r(s^t, a^t)$

$$-\gamma\alpha_t \boxed{\min_a \, (-Q(s^{t+1}, a)),} \qquad s^{t+1} \sim \mathbb{P}(\,\cdot \mid s^t, a^t)$$

random agent

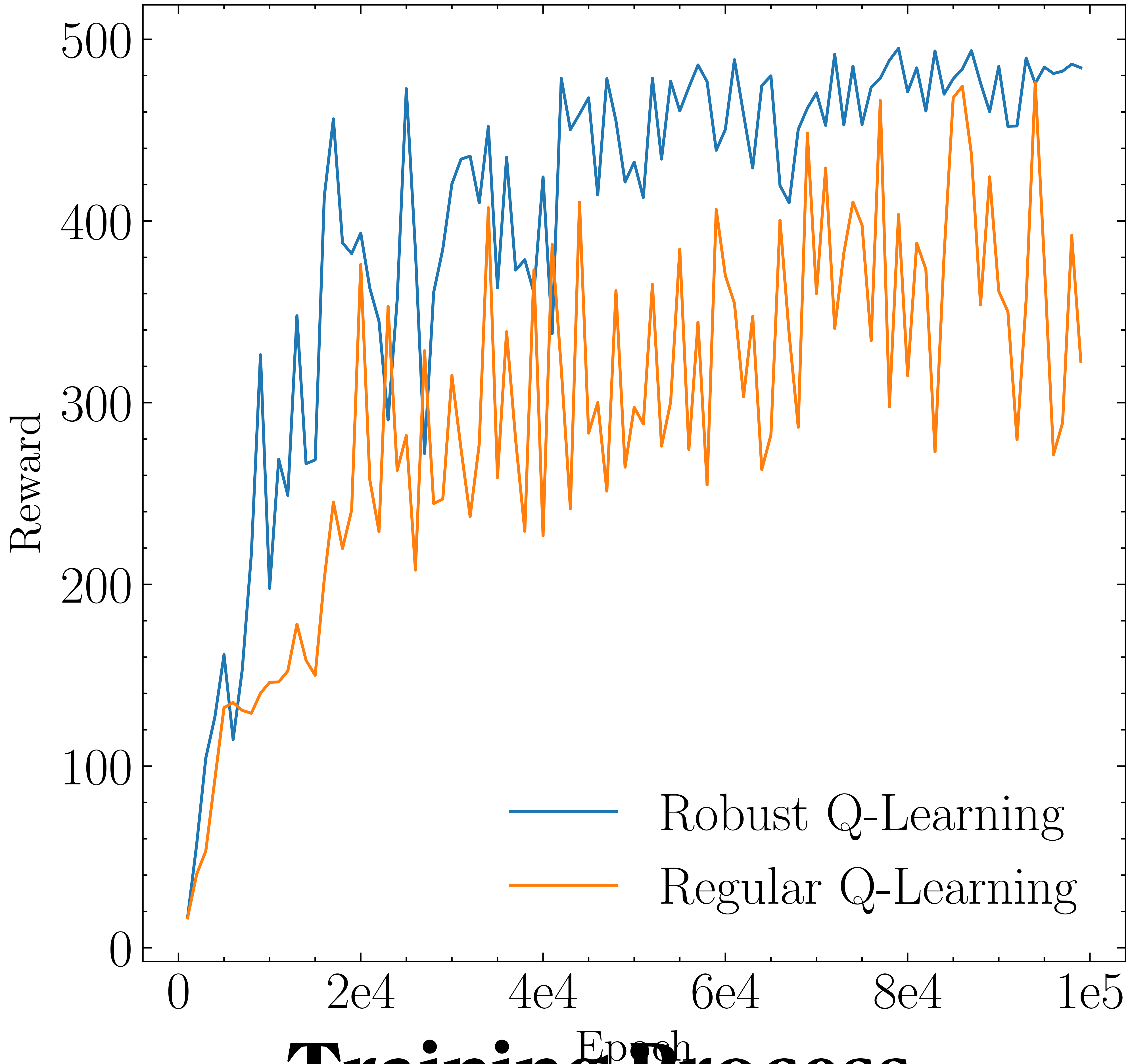


trained agent

Numerical Study: Reliable Reinforcement Learning

Environment	Regular	Robust
Original MDP	469.42±19.03	**487.11±9.09**
Perturbed MDP (Heavy Pole)	187.63±29.40	**394.12±12.01**
Perturbed MDP (Short Pole)	355.54±28.89	**443.17±9.98**
Perturbed MDP (Strong Gravity)	271.41±20.70	**418.42±13.64**

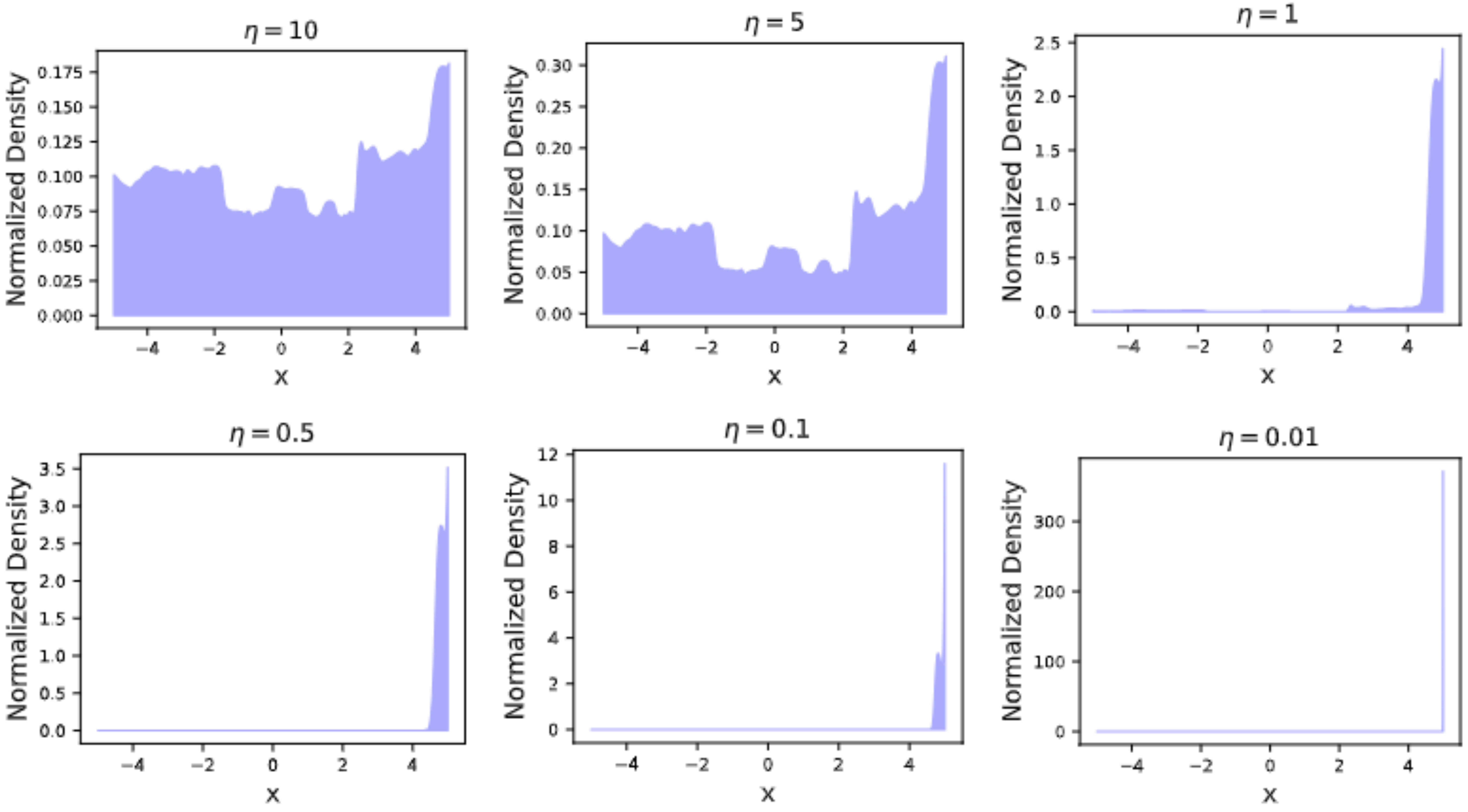
Reward by Regular and Robust Q-Learning

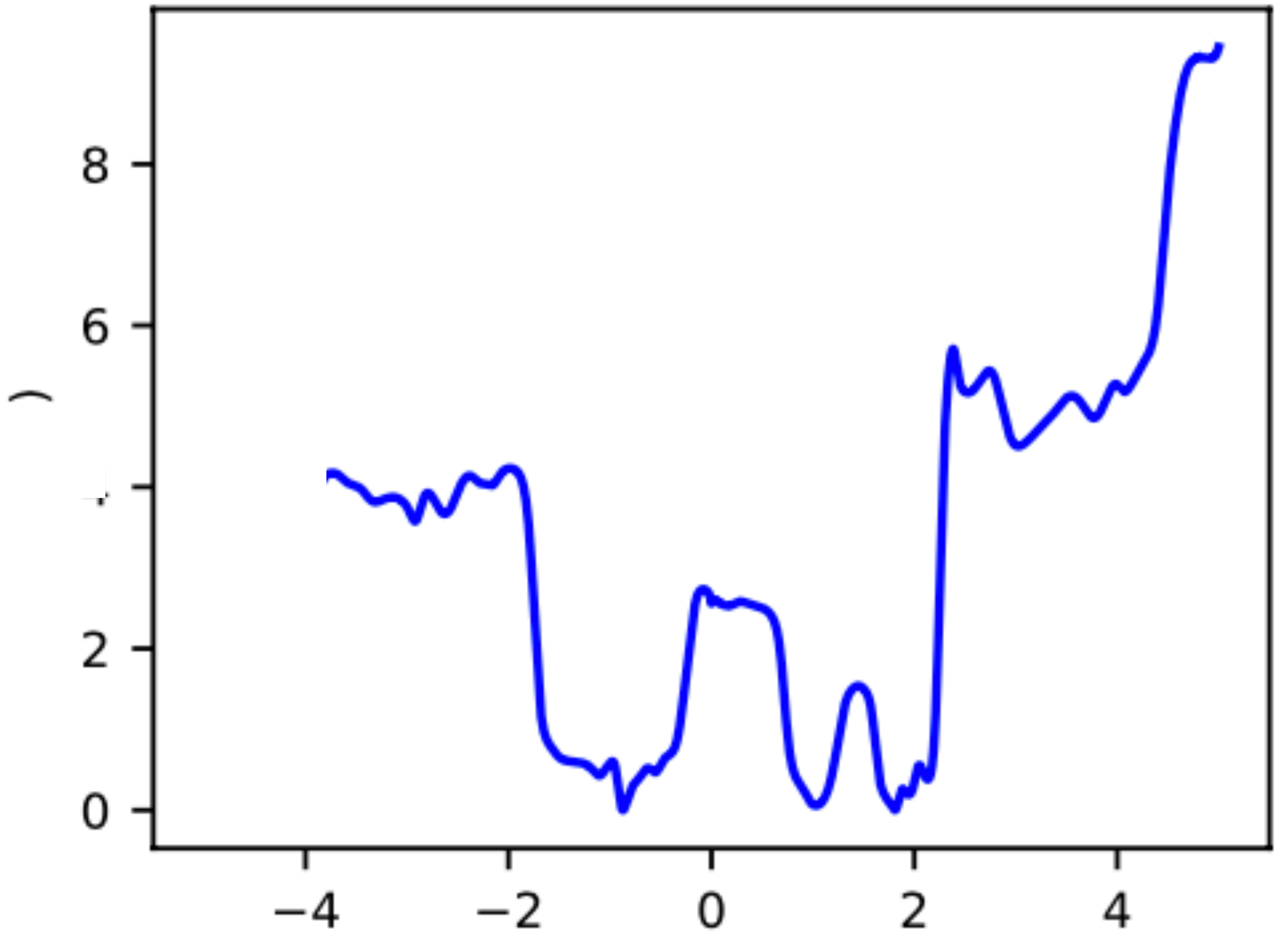


Training Process

Conclusion

- f-divergence regularization for adversarial robust learning (∞-Wasserstein DRO)





Conclusion

- **f-divergence regularization for adversarial robust learning (∞-Wasserstein DRO)**
- **Efficient Algorithm using Multi-level Monte Carlo Sampling**

Algorithm	Loss	Choice of Divergence	Complexity
Random Sampling	Convex/Nonconvex Smooth	Arbitrary/KL-Divergence	$\tilde{O}(\delta^{-2})/\tilde{O}(\delta^{-4})$

Conclusion

- f-divergence regularization for adversarial robust learning (∞-Wasserstein DRO)
- Efficient Algorithm using Multi-level Monte Carlo Sampling
- Regularization effects under different scaling regimes of ρ/η

Related References

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