Phase Space Reconstruction from Accelerator Beam Measurements Using Neural Networks and Differentiable Simulations

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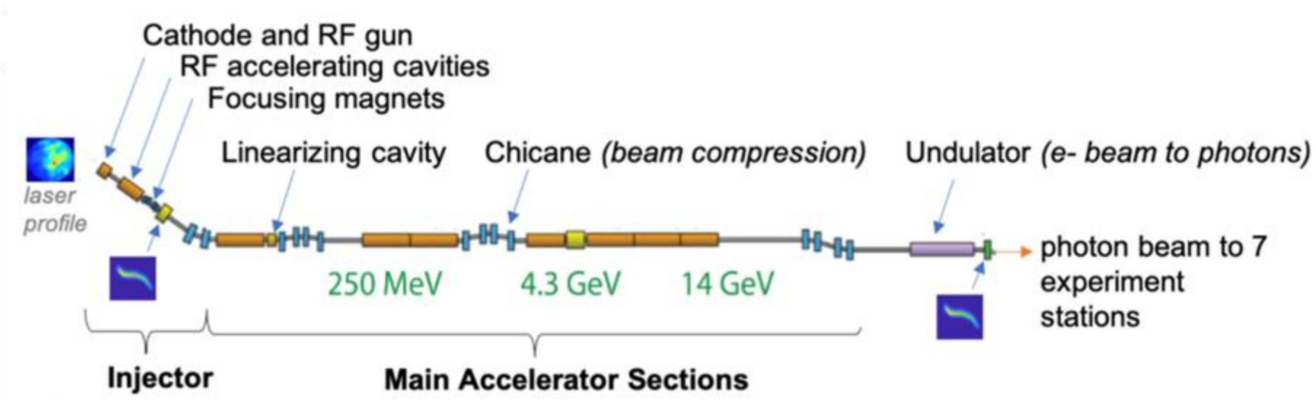
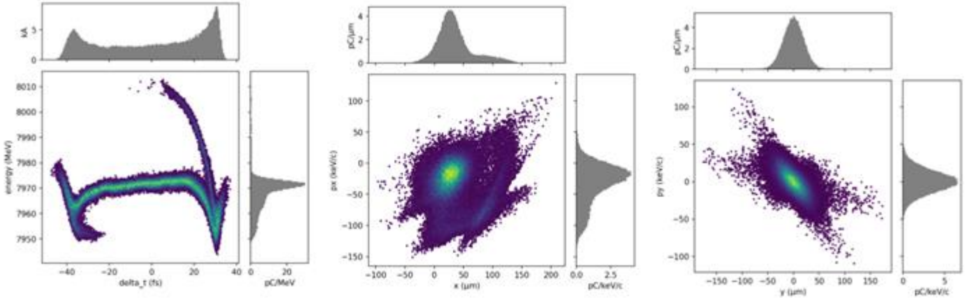
Manipulating Beams in Phase Space



A. Edelen



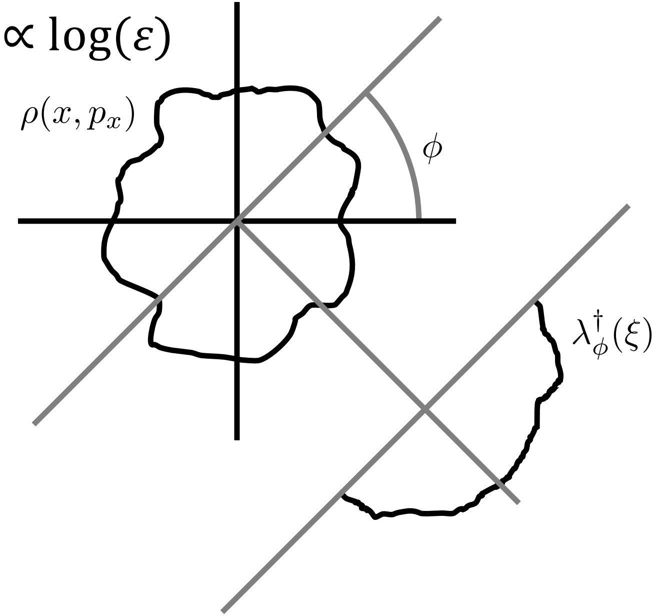
How do we measure particle beam distributions in 6D phase space?

$$\rho(x, p_x, y, p_y, z, \delta)$$

Maximum Entropy Tomography (MENT)

Rotate phase space and reconstruct the distribution from 1D projections +
maximize the beam distribution entropy

Note: $H \propto \log(\varepsilon)$

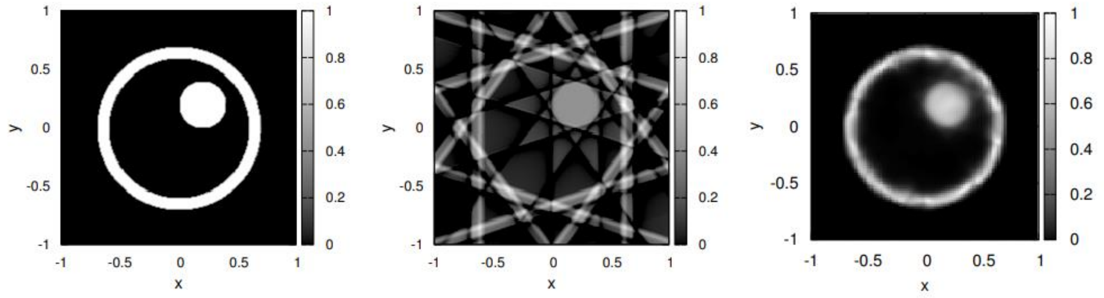


Lagrange multiplier

$$\rho^* = \arg\min\{-H(\rho) + \lambda f(\rho)\}$$

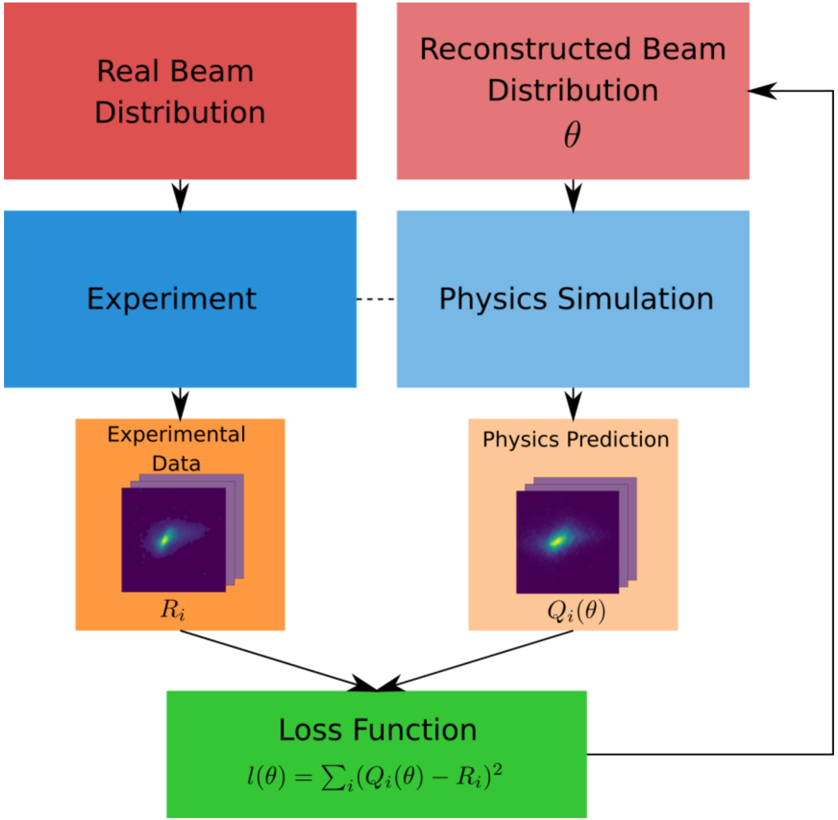
Distribution entropy

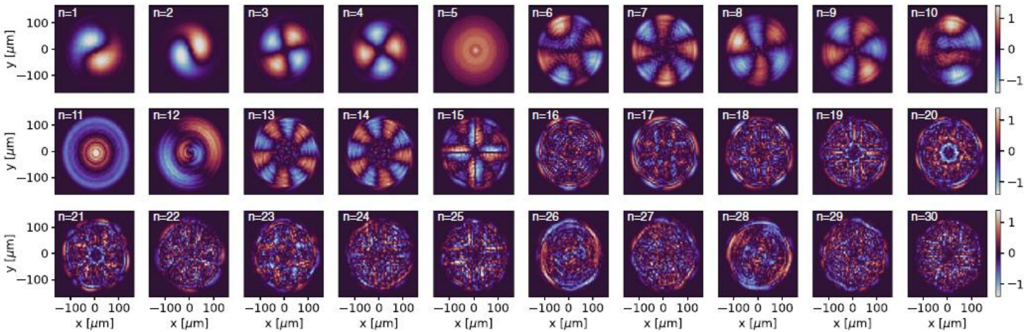
Measurement reconstruction



Hock K. and Ibison M., JINST, 2013

Inferring Beam Distributions Using Optimization

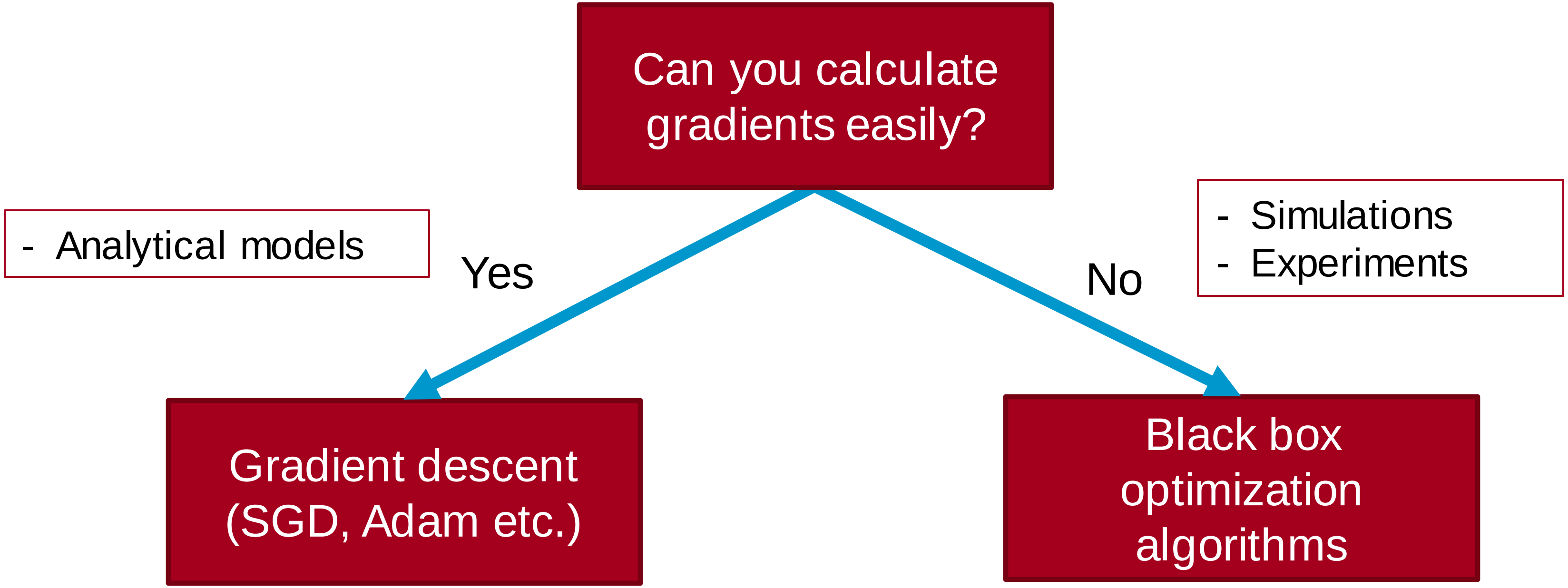




Scheinker, Alexander, et al *Scientific reports* 11.1 (2021): 1-11.

Represent beam distribution with principal component analysis (PCA) and optimize weights to fit experimental measurements

Optimization Strategies for Inference

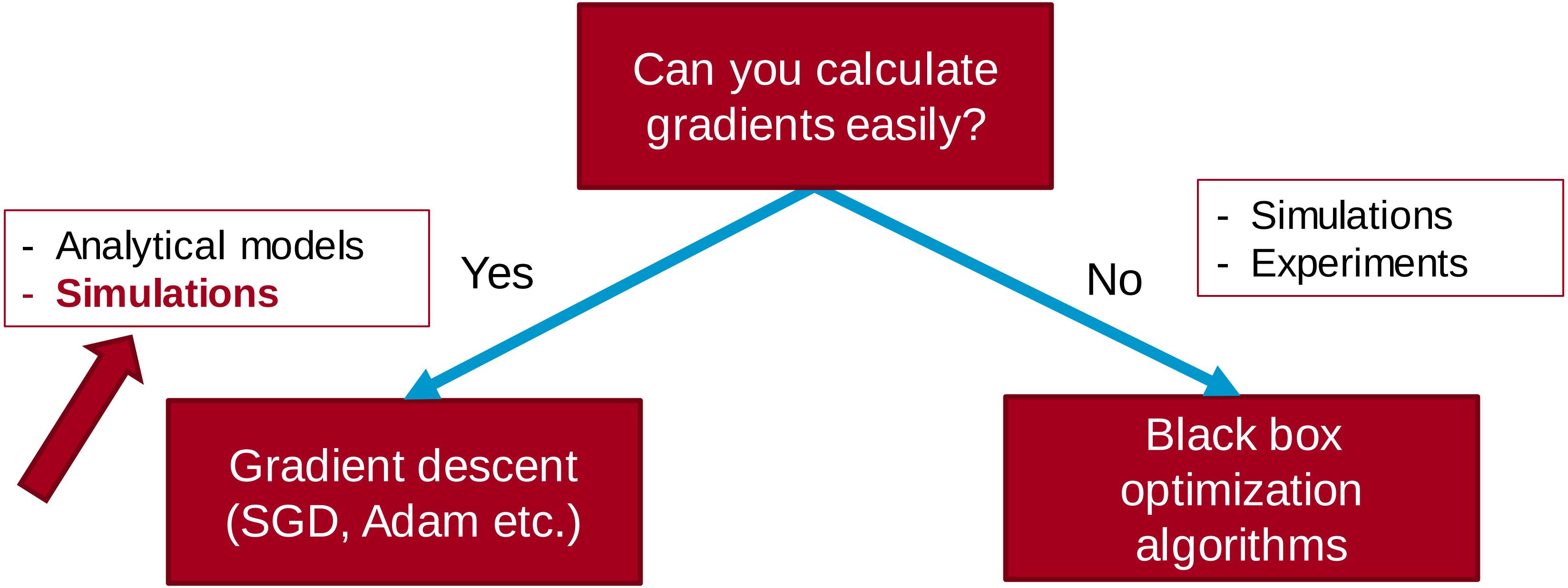


Scales to >10k parameters
(ML training)

Scales poorly with
input dimension if not unimodal

Go ahead, try it with simplex…

Optimization Strategies for Inference



Scales to >10k parameters (ML training)

Scales poorly with input dimension if not unimodal

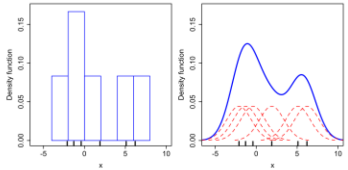
Go ahead, try it with simplex…

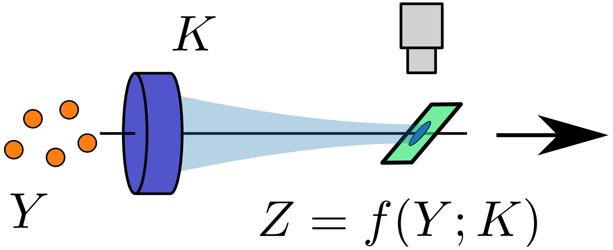
Differentiable Simulations

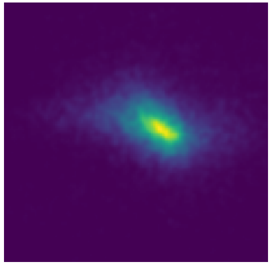
Keep track of derivative information during **every** calculation step.

Enables **gradient based optimization** of model error with respect to all free parameters using the chain rule.

Easily optimize models with >10k free parameters.







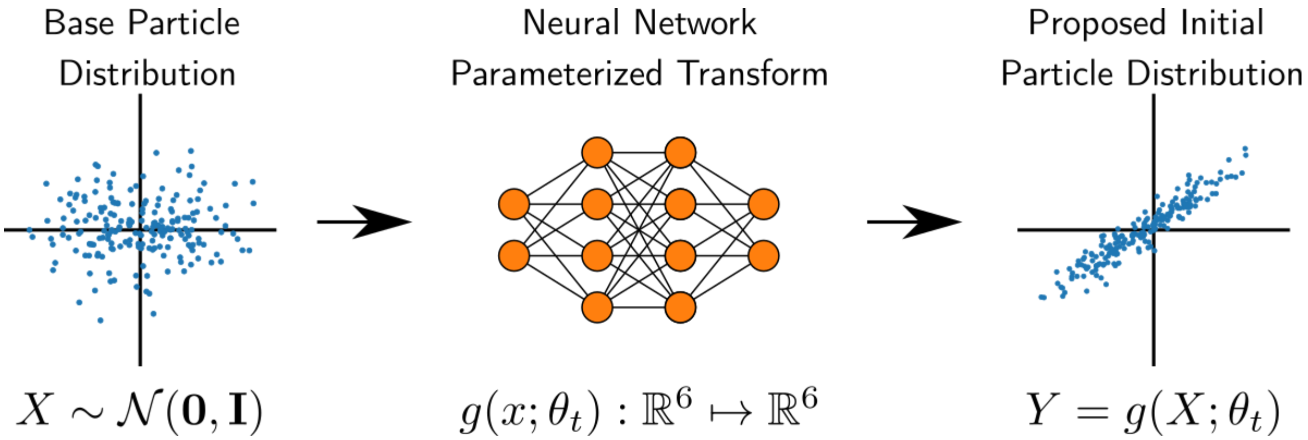
$$Q^{(i,j)} = \mathrm{KDE}(Z)$$

$$\frac{\partial Z}{\partial Y}, \frac{\partial Z}{\partial K}, \frac{\partial \sigma_Z}{\partial K}, \dots$$

$$\frac{\partial Q^{(i,j)}}{\partial Y}, \frac{\partial Q^{(i,j)}}{\partial K}$$

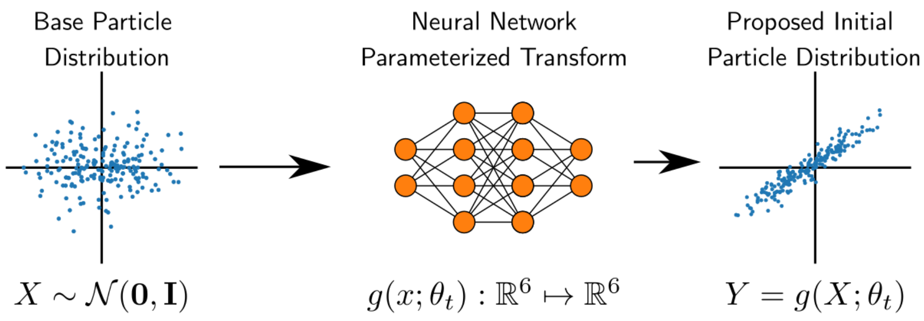
Neural Network Parameterization of Beam Distributions

Want to parameterize 6D phase space distributions with a function that is **flexible** and **learnable**.

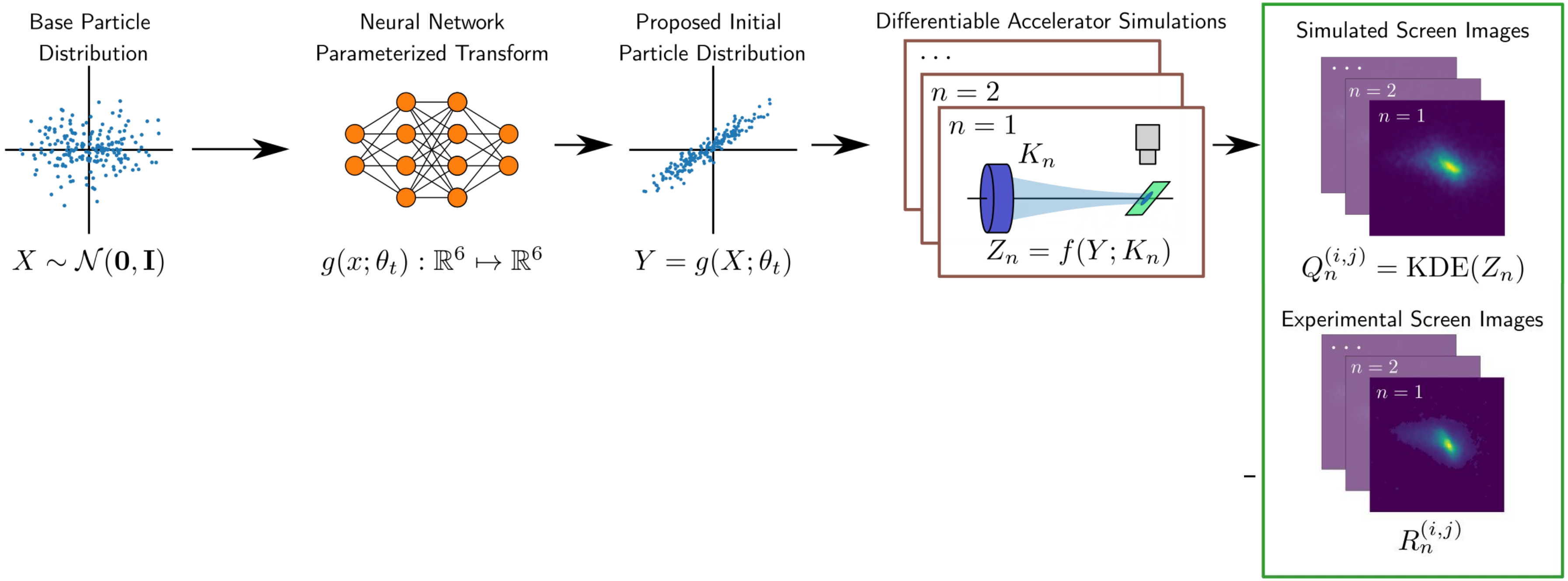


Fully connected NN with ~O(1k) parameters

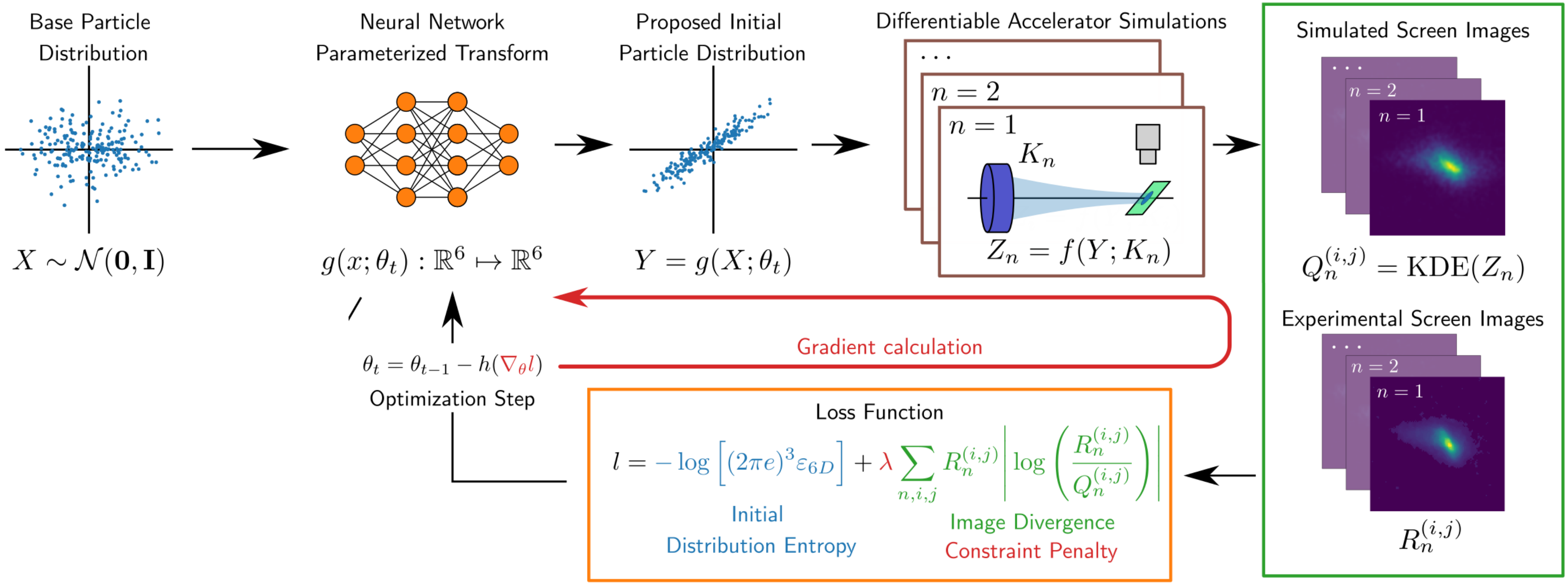
Phase Space Reconstruction Pipeline



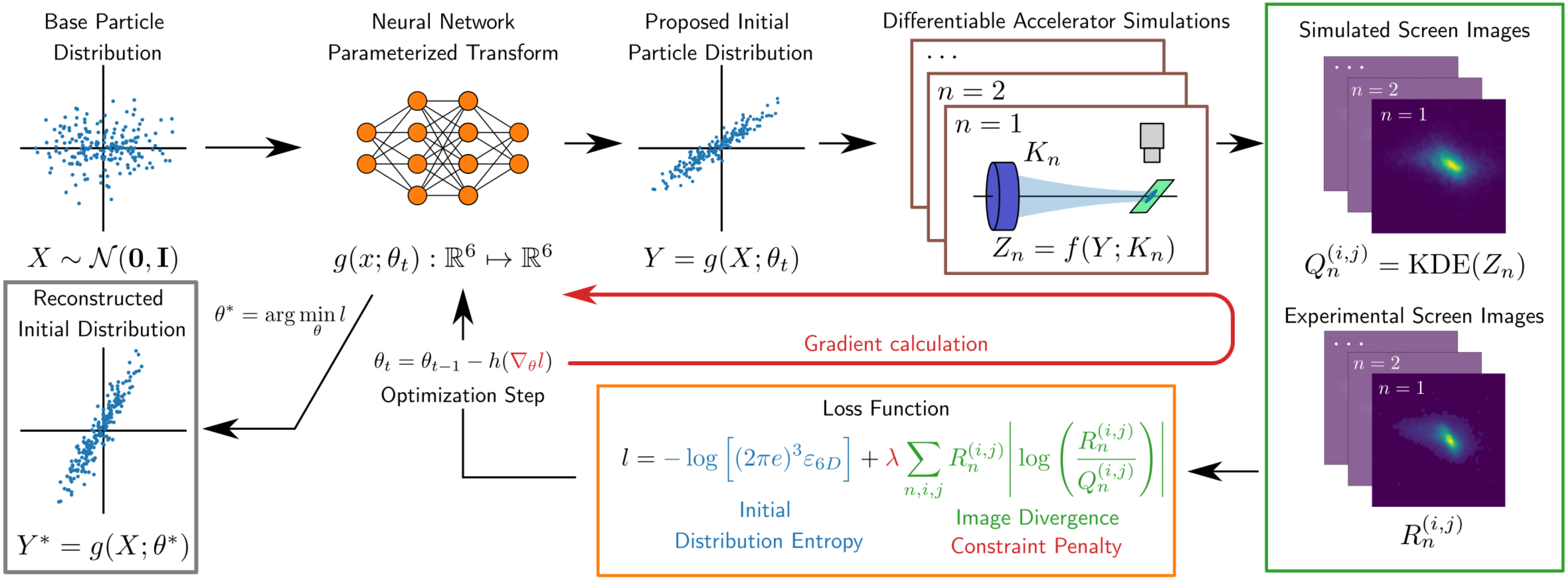
Phase Space Reconstruction Pipeline



Phase Space Reconstruction Pipeline



Phase Space Reconstruction Pipeline

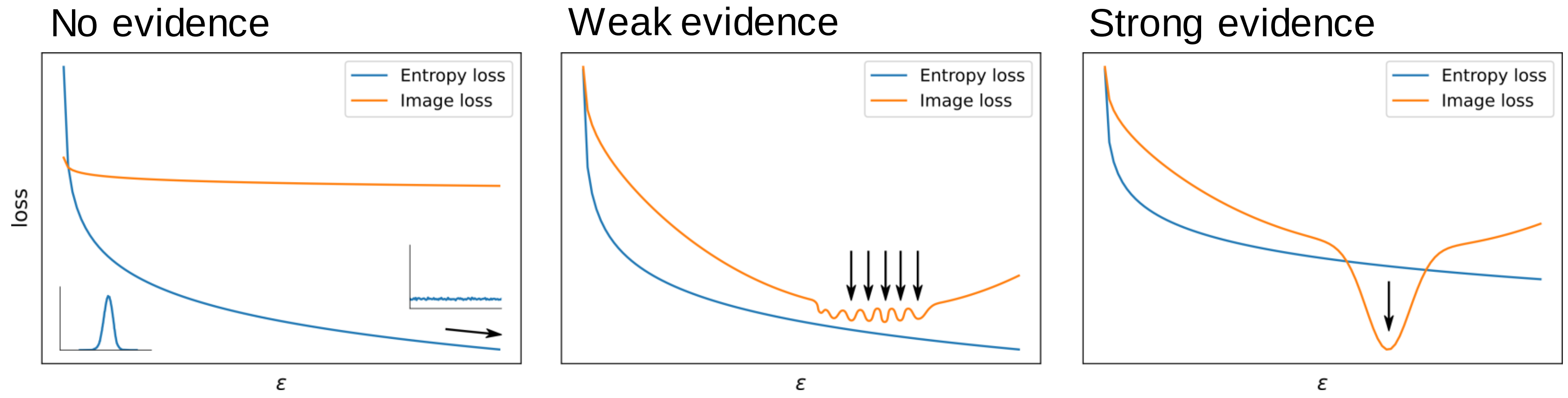


Maximum Entropy Loss Function

$$l = -\log\left[(2\pi e)^3 \varepsilon_{6D}\right] + \lambda \sum_{n,i,j} R_n^{(i,j)} \left| \log\left(\frac{R_n^{(i,j)}}{Q_n^{(i,j)}}\right)\right|$$

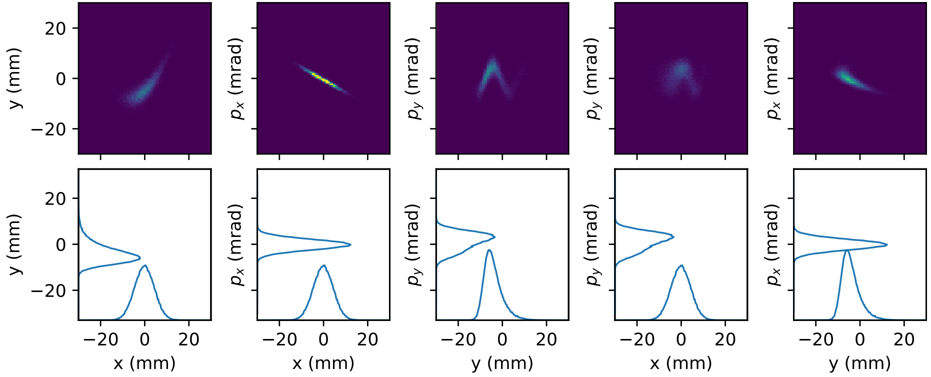
Initial
Distribution Entropy

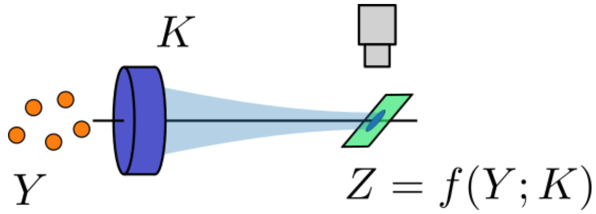
Image Divergence
Constraint Penalty



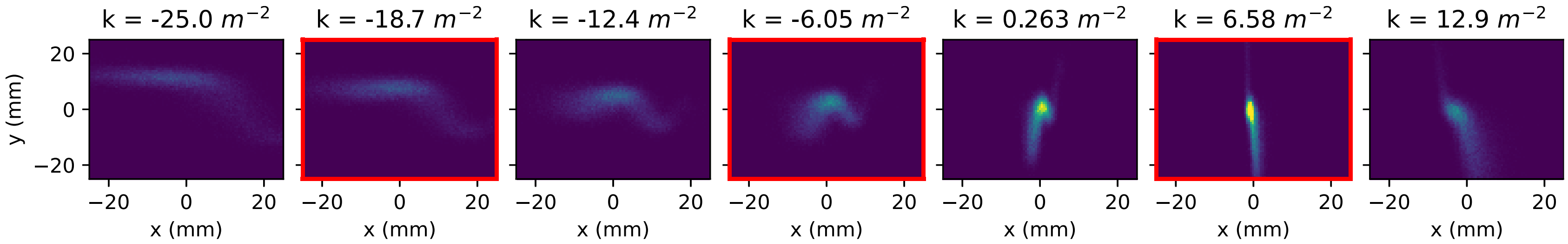
Synthetic Example

Synthetic beam distribution in simulation

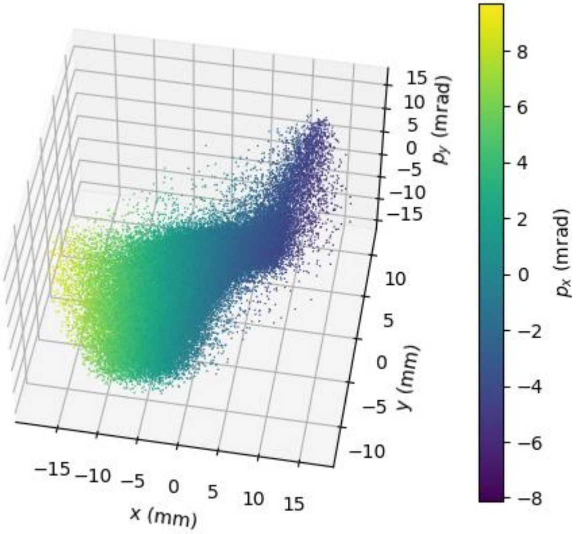


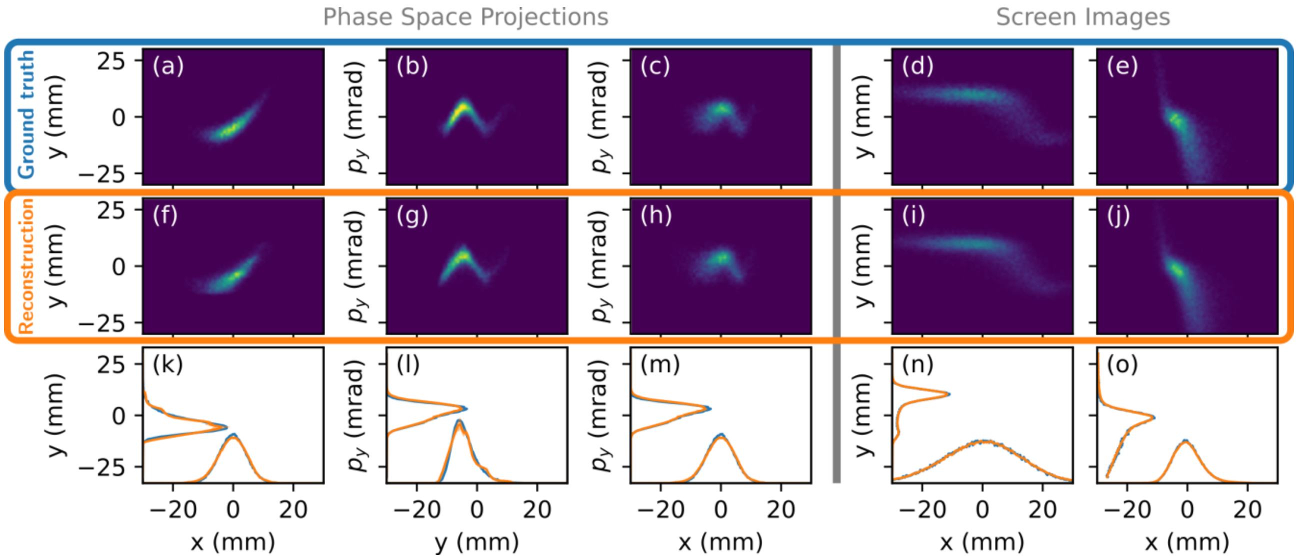


Screen images



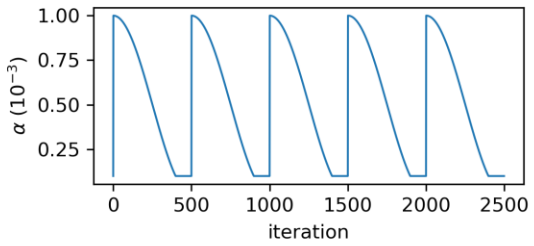
Synthetic Example Reconstruction

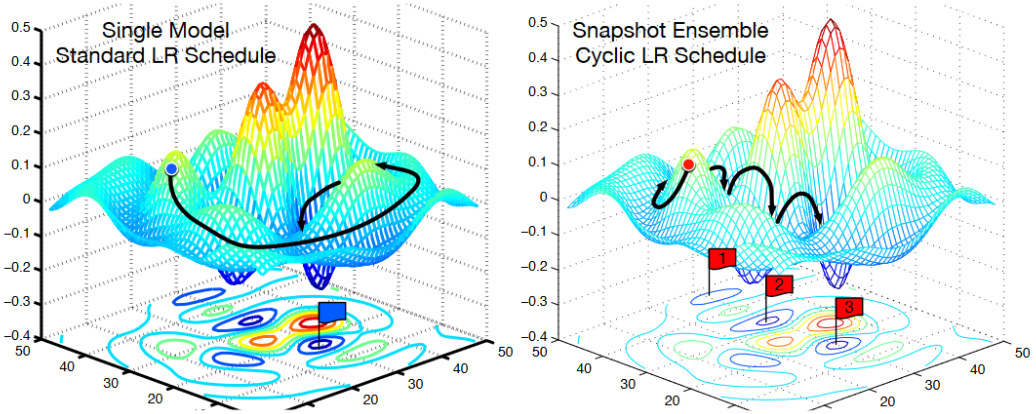




Measuring Model Uncertainty

Create a snapshot ensemble to measure uncertainty by cycling the learning rate





Huang G. et al., ICLR 2017

Measuring Model Uncertainty and Convergence

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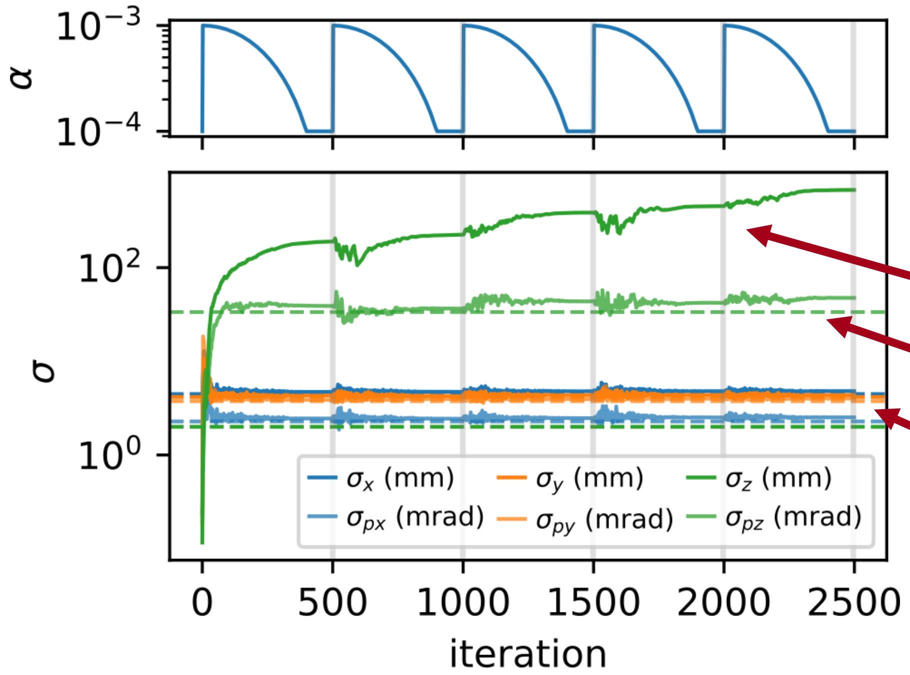


Loss Function

$$l = -\log\left[(2\pi e)^3 \varepsilon_{6D}\right] + \lambda \sum_{n,i,j} R_n^{(i,j)} \left| \log\left(\frac{R_n^{(i,j)}}{Q_n^{(i,j)}}\right) \right|$$

Initial Distribution Entropy

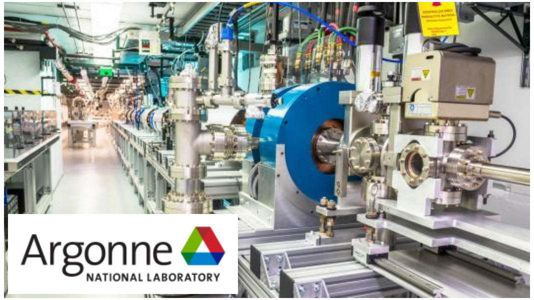
Image Divergence Constraint Penalty

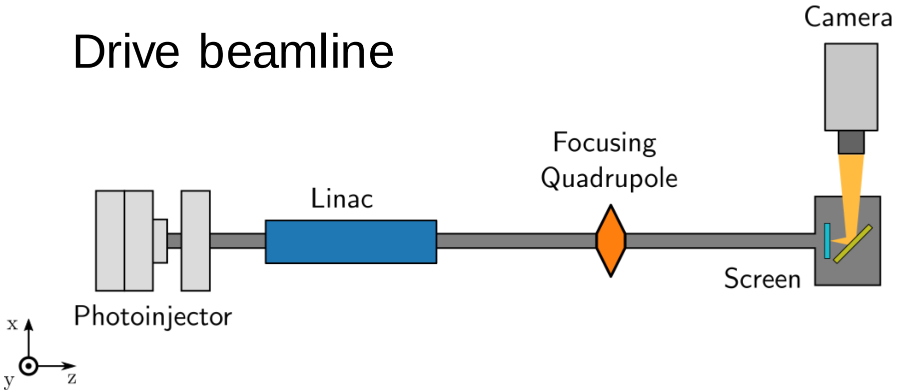
No information

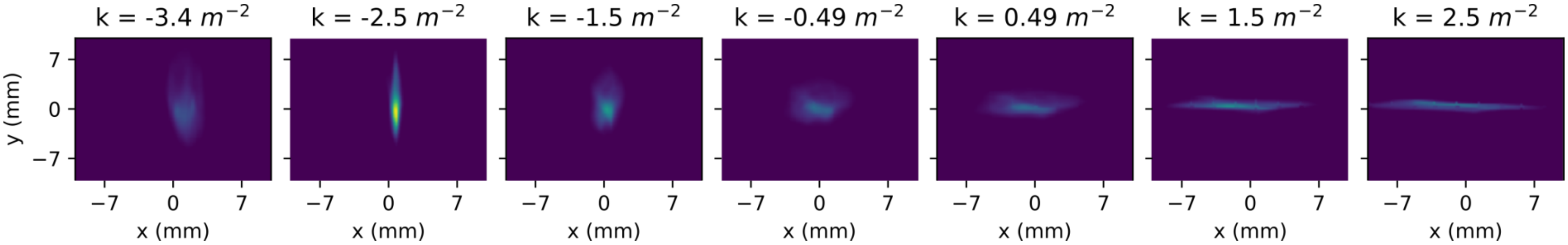
Some information

Lots of information

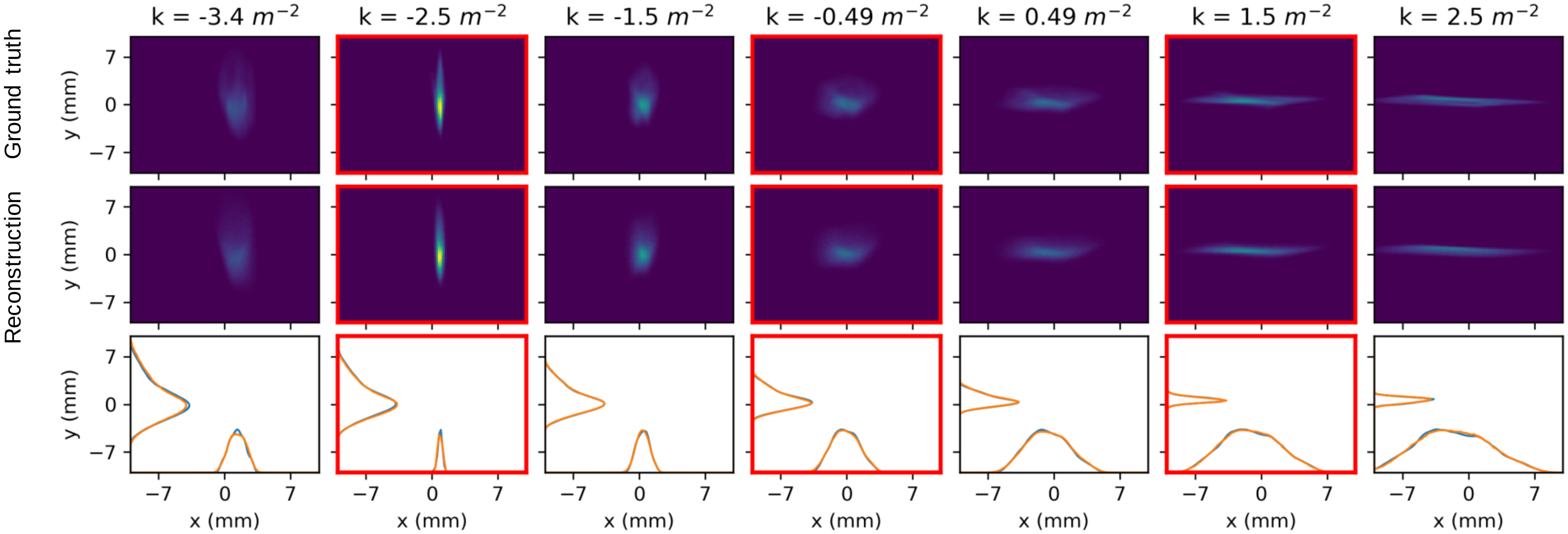
Tomography Example from AWA





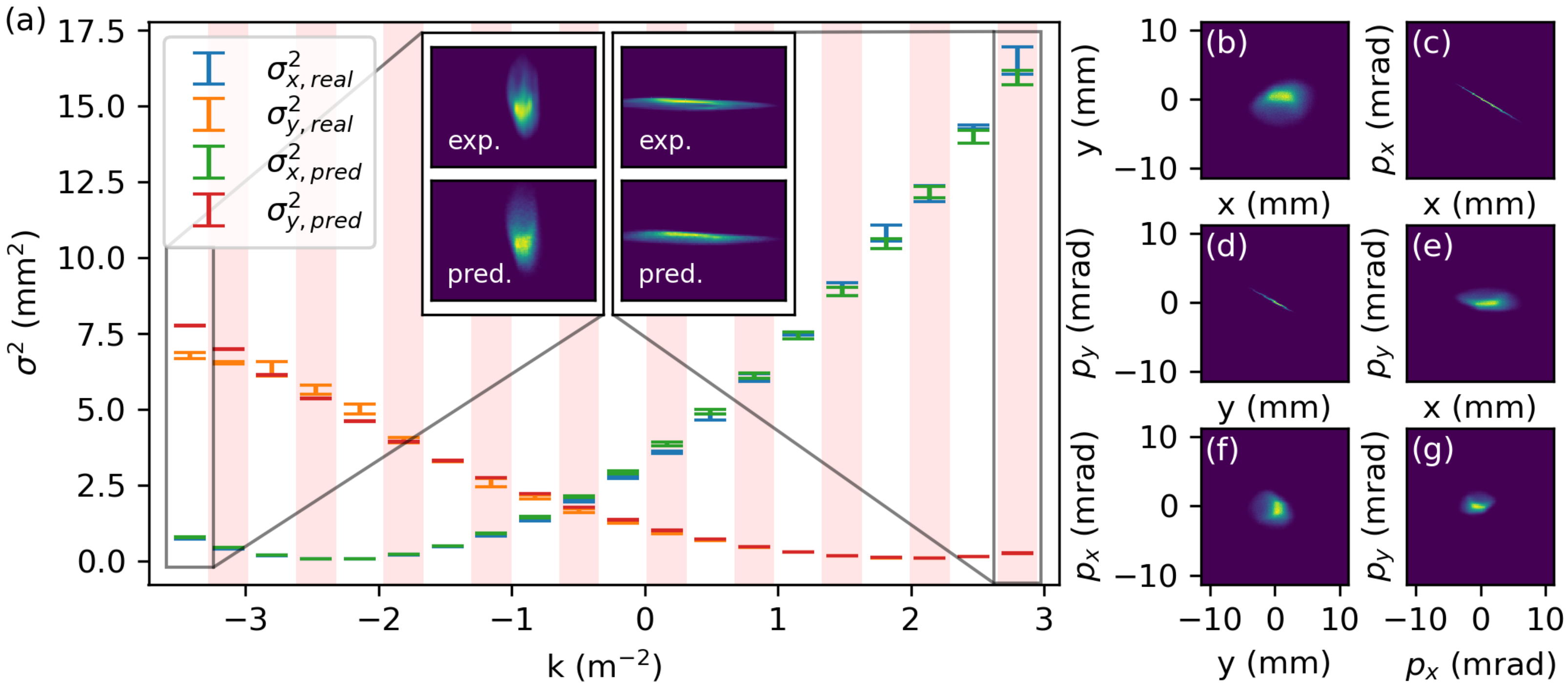


AWA Reconstruction Results



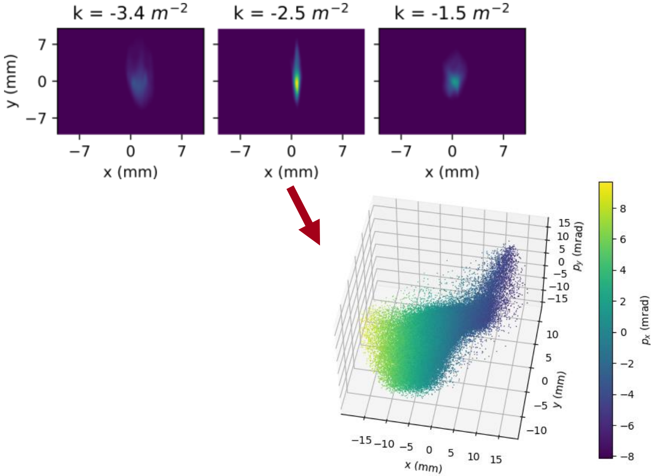
Red border denotes test samples

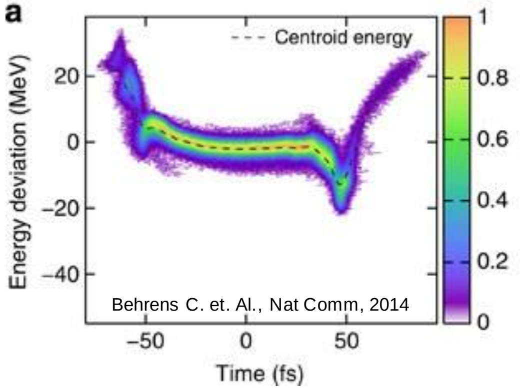
AWA Reconstruction Results



Conclusions

- We can create **detailed reconstructions of beam phase spaces** from simple tomographic accelerator measurements without special diagnostics
- Reconstructions from differentiable simulations **are not limited** by analytical tractability, number of free parameters
- Theoretically we are only limited by model detail and accuracy, **need further investment in differentiable simulations**
- Need to expand our idea of what can be used as a diagnostic





Behrens C. et. Al., Nat Comm, 2014

Details https://arxiv.org/abs/2209.04505

Thanks!

SLAC

- Auralee Edelen
- Chris Mayes
- Daniel Ratner

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Argonne Wakefield Accelerator

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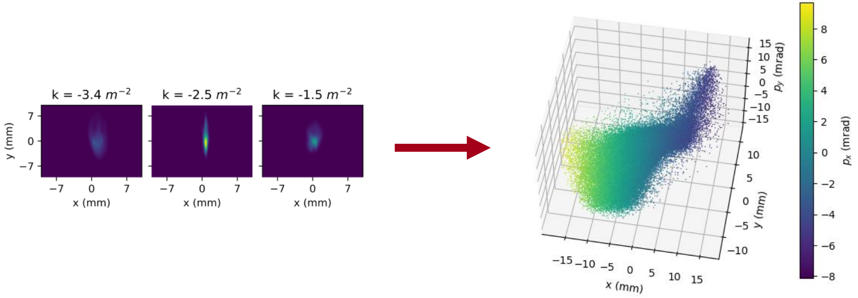
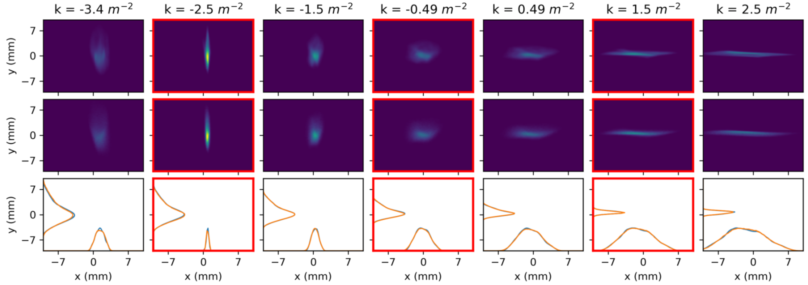
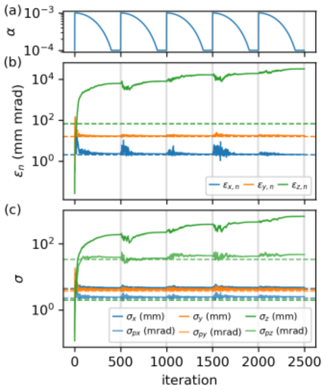
- John Power
- Eric Wisniewski







Questions?