AI^2: Atom Interferometry × Artificial Intelligence
for Quantum Sensing Gravitational Waves & Dark Matter

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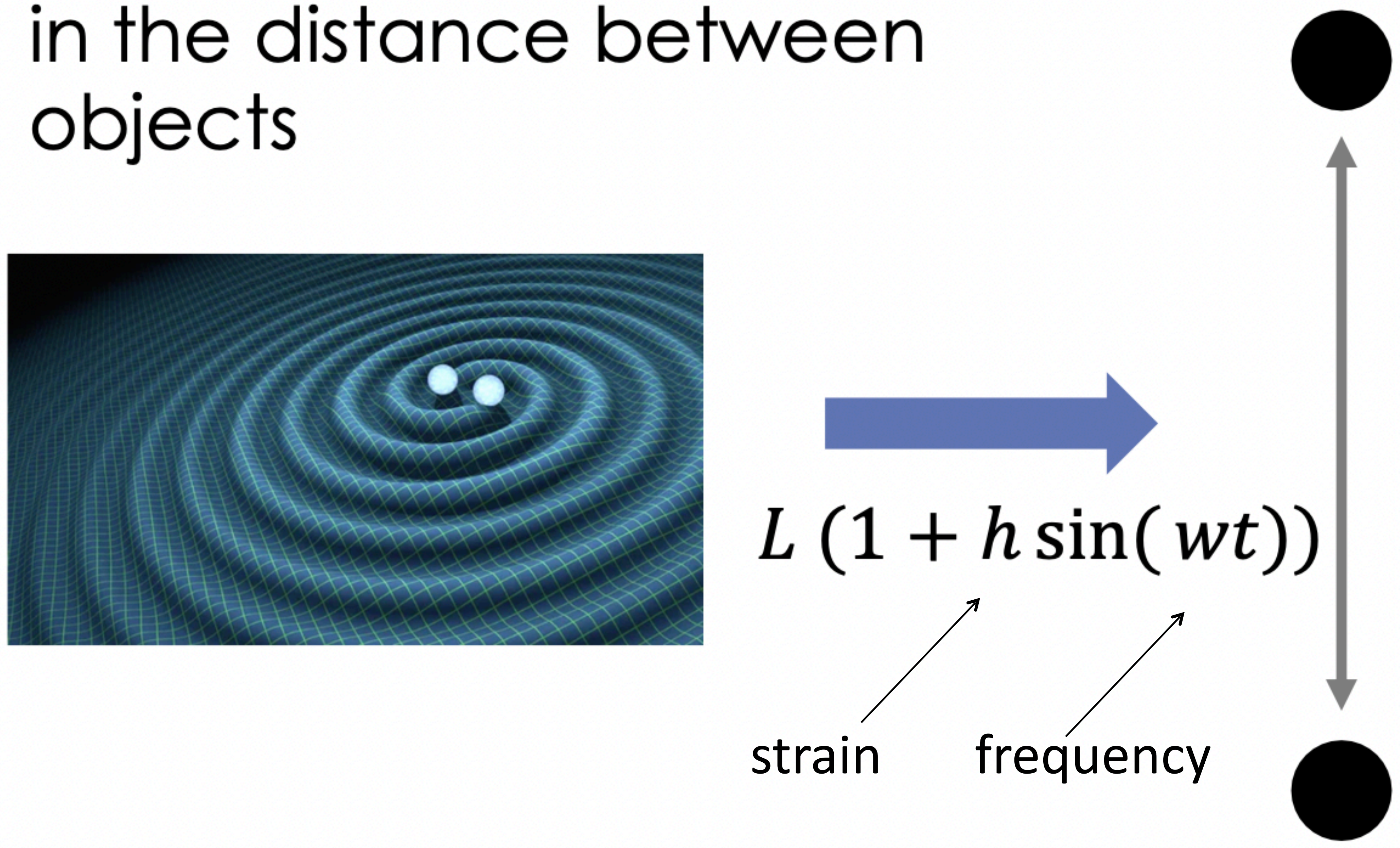
SLAC NATIONAL ACCELERATOR LABORATORY

Stanford University | U.S. DEPARTMENT OF ENERGY

Gravitational Waves and Atomic Sensors

Gravitational waves cause a small modulation in the distance between objects



$$L\,(1 + h\sin(wt))$$

atoms can play two roles

Inertial References

- Freely falling objects, separated by a large baseline
- Must be insensitive to perturbations from non-gravitational forces

Clock

- Monitor separation b/w inertial frames
- Measure time for light to cross baseline

slide credit: A. Schwartzman

Gravitational Waves and Atomic Sensors

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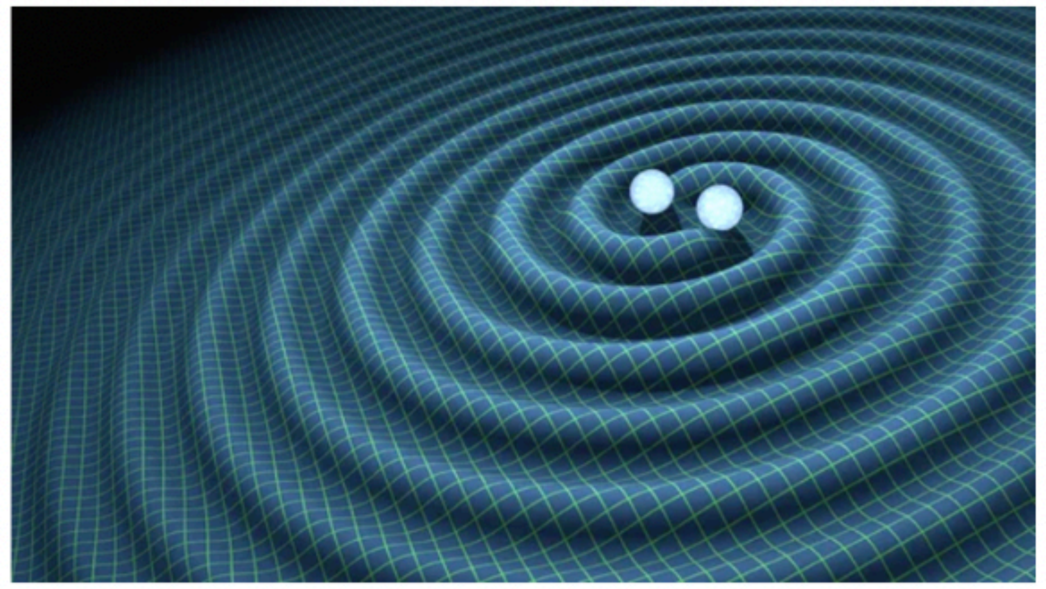
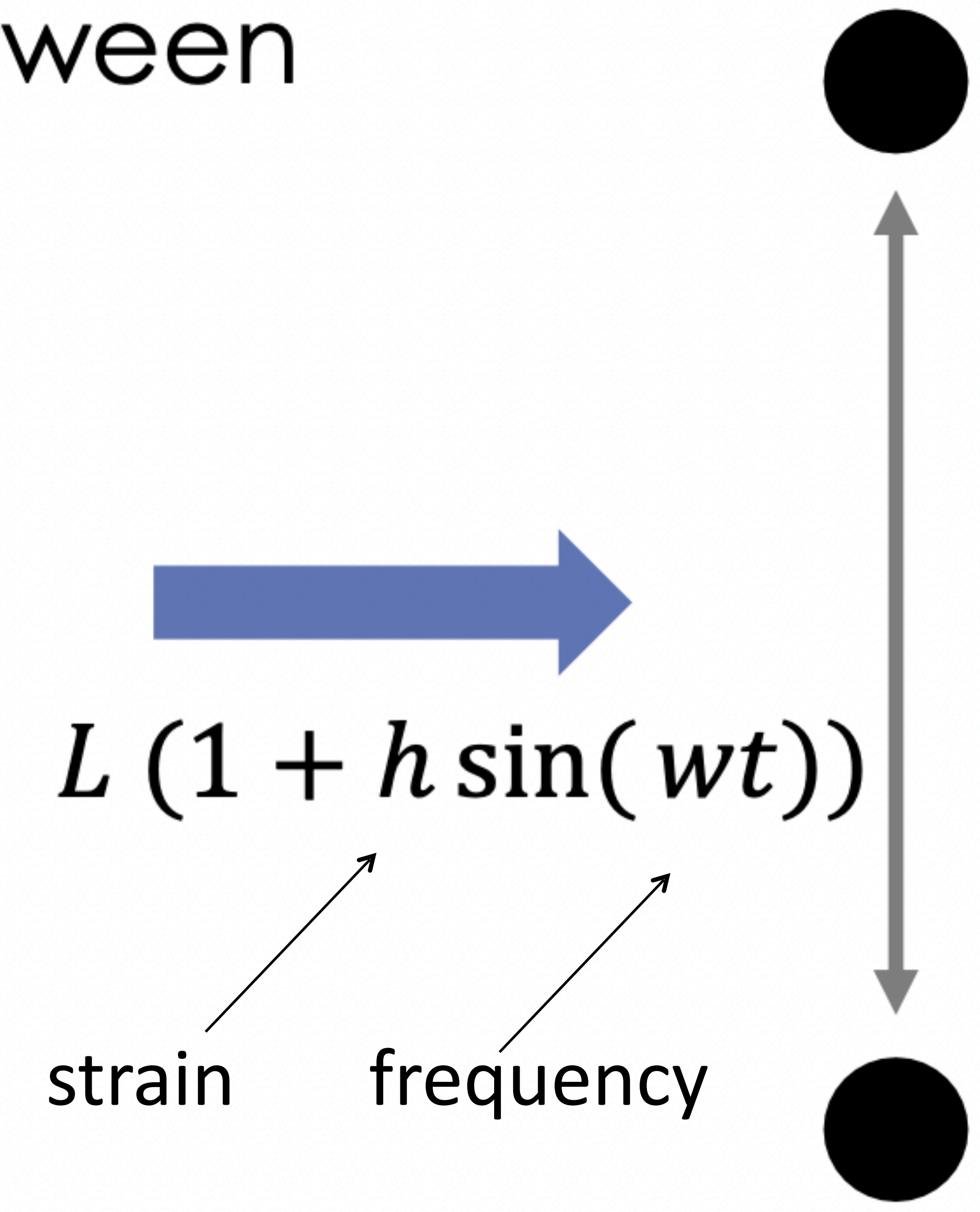


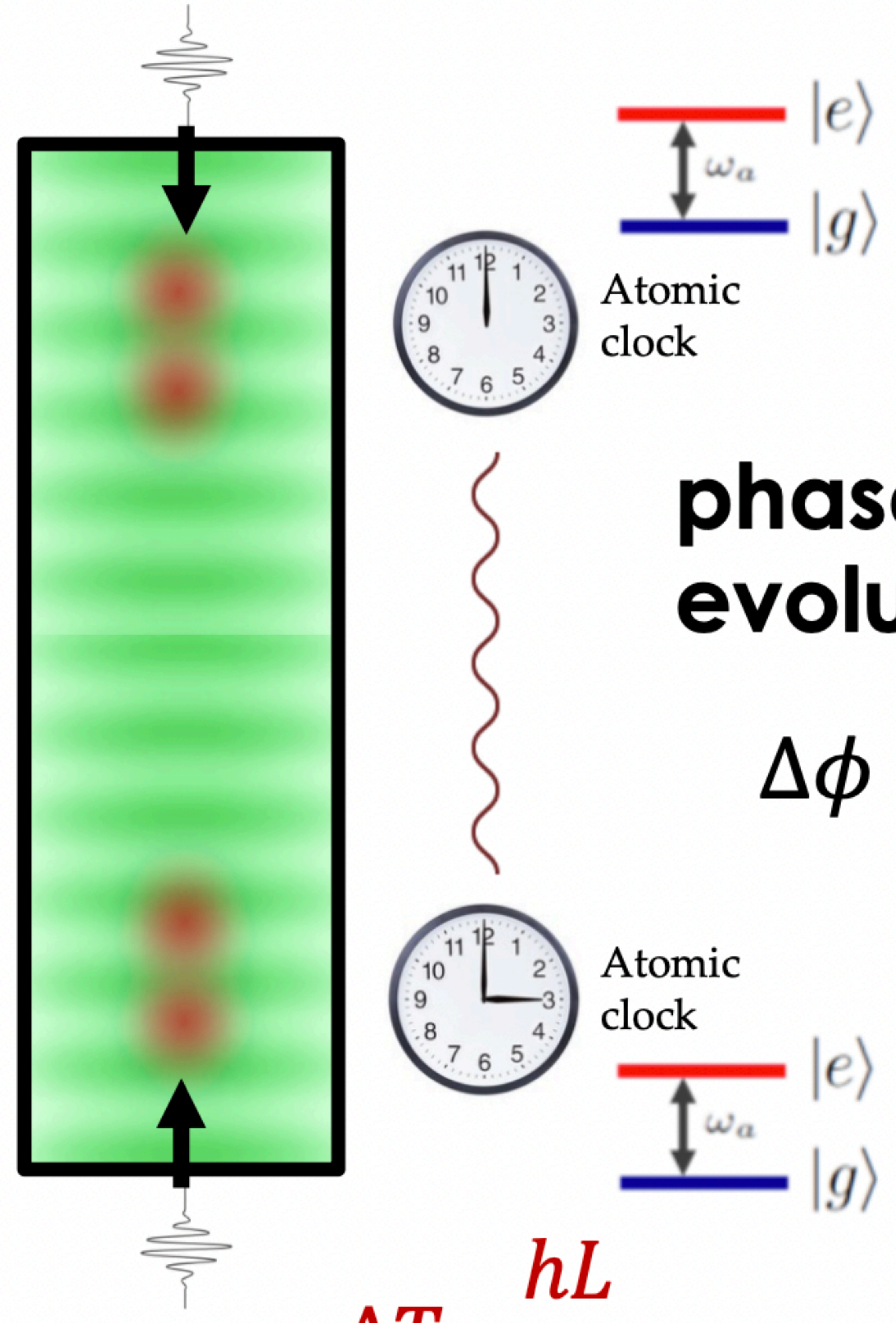


$L\,(1 + h\sin(wt))$

strain

frequency

Quantum



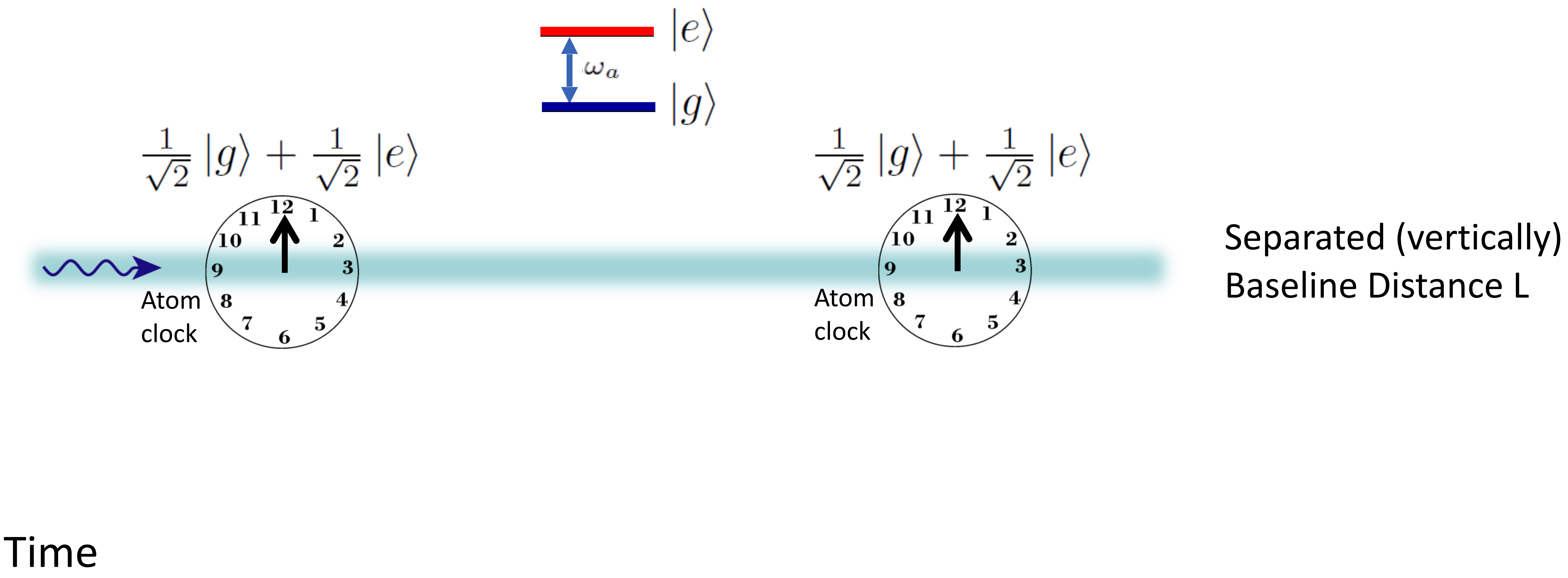
phase evolution:

$$\Delta\phi = w_A\left(\frac{2L}{c}\right)$$

$$\Delta T \sim \frac{hL}{c}$$

slide credit: A. Schwartzman

Simple Example: Two Atomic Clocks



$|e\rangle$

ω_a

$|g\rangle$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$

Atom clock

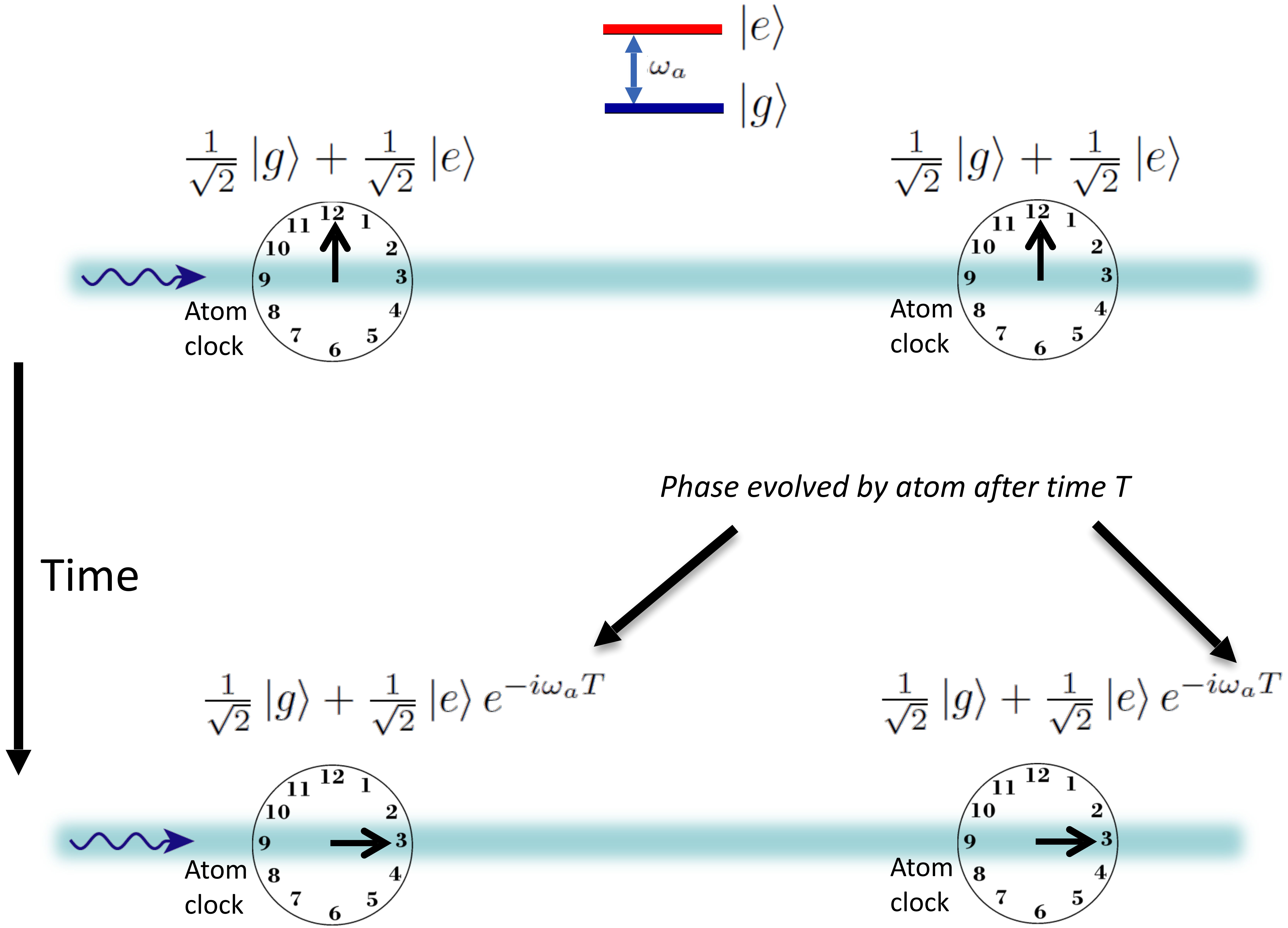
Atom clock

Separated (vertically)
Baseline Distance L

Time

slide credit: J. Hogan

Simple Example: Two Atomic Clocks



$|e\rangle$

ω_a

$|g\rangle$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

Separated (vertically)
Baseline Distance L

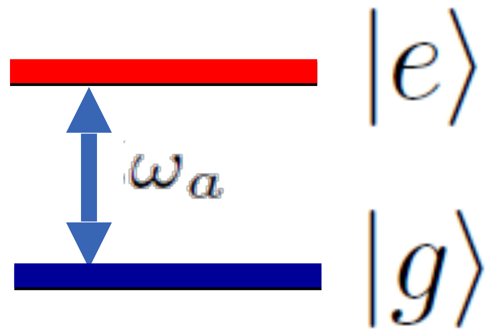
Phase evolved by atom after time T

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$$

$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T}$$

slide credit: J. Hogan

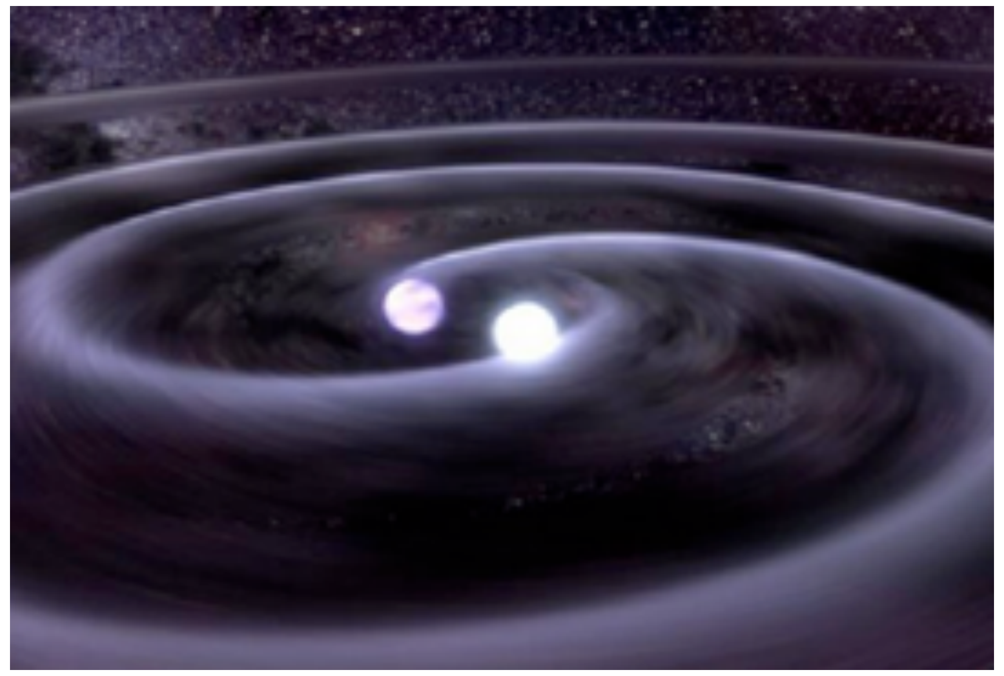
Simple Example: Two Atomic Clocks



$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle$$

Separated (vertically)
Baseline Distance L

Time



GW changes light travel time

$$\Delta T \sim hL/c$$

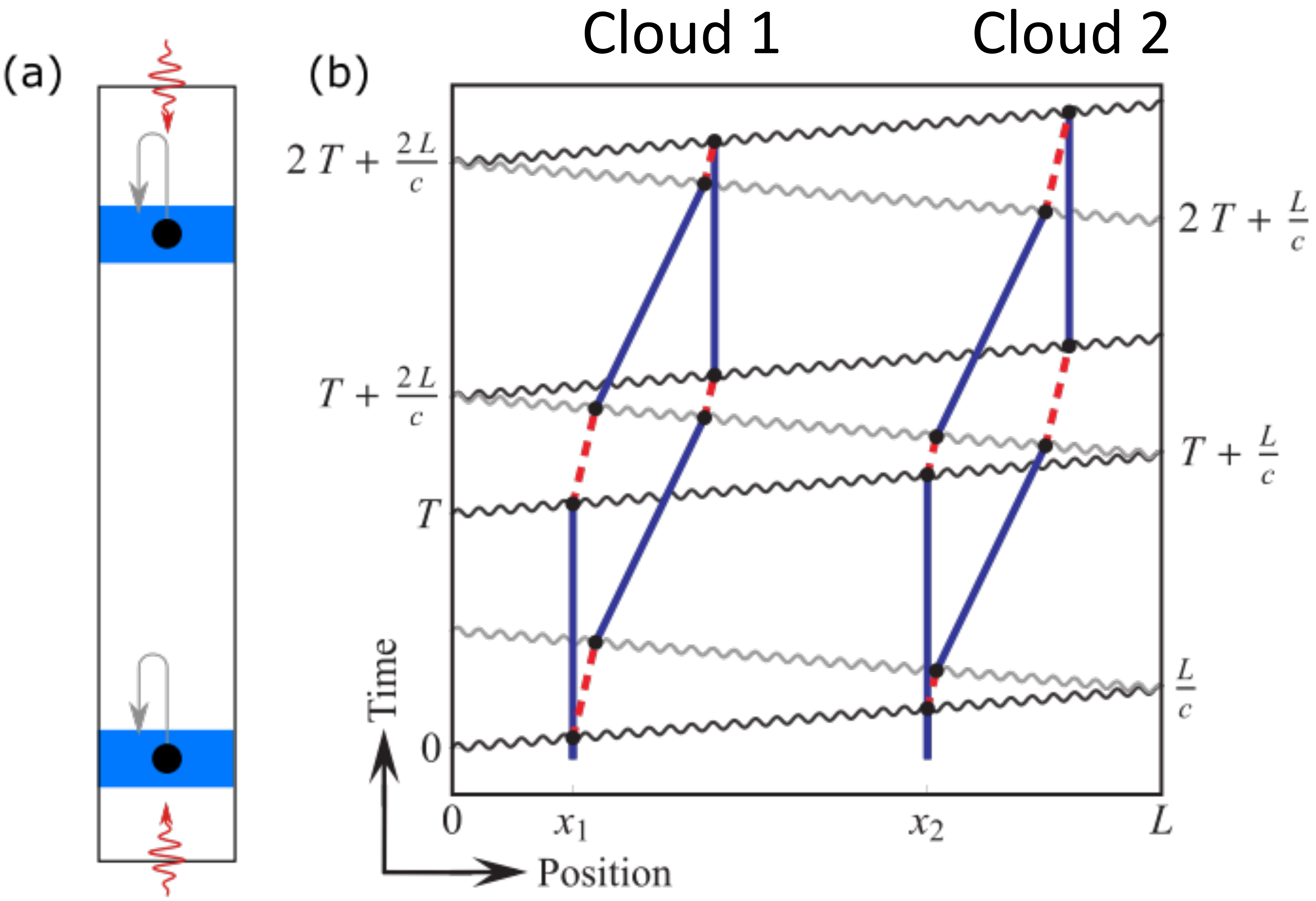
$$\frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a T} \qquad \frac{1}{\sqrt{2}}|g\rangle + \frac{1}{\sqrt{2}}|e\rangle\, e^{-i\omega_a (T+\Delta T)}$$

slide credit: J. Hogan

Clock Gradiometer

Excited state phase evolution difference:

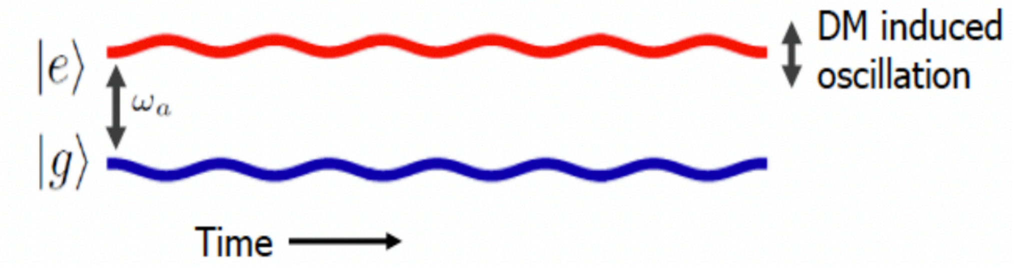
$$\Delta\phi \sim \omega_A \, (2L/c)$$

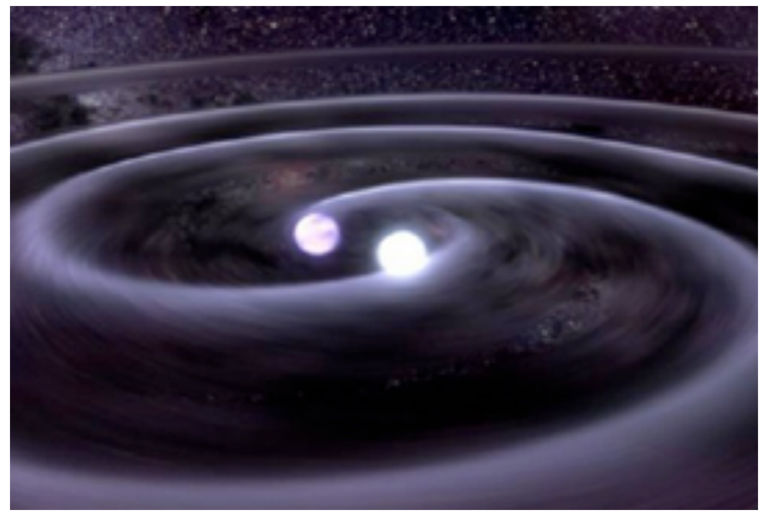


Two ways for phase to vary:

$\delta\omega_A$	*Dark matter*
$\delta L = hL$	*Gravitational wave*

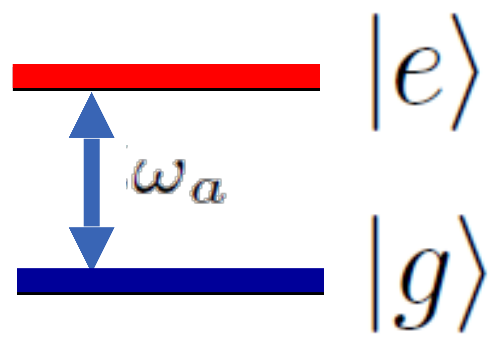
Ultra-light DM coupling causes time-varying atomic energy levels





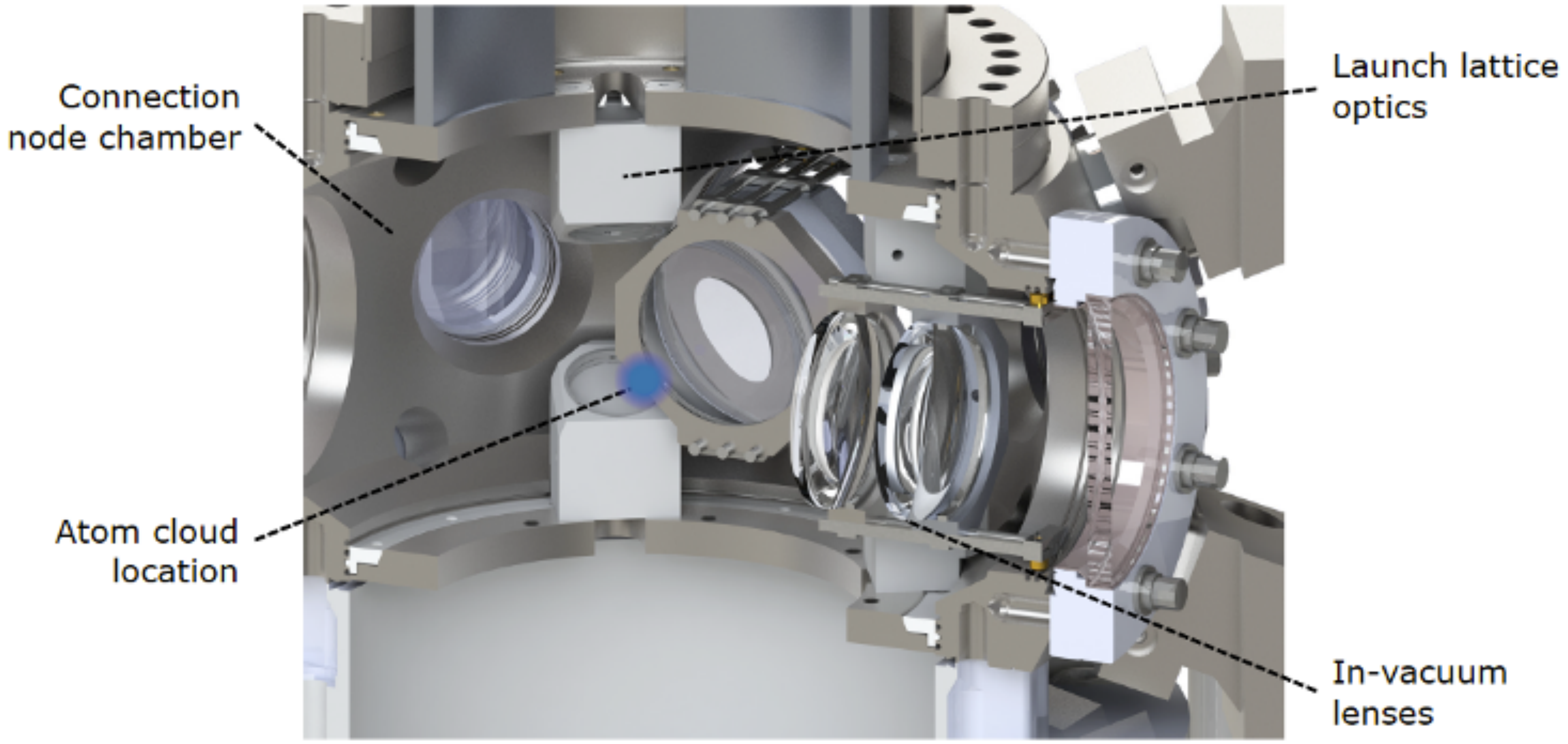
$L\,(1 + h \sin(\omega t\,))$

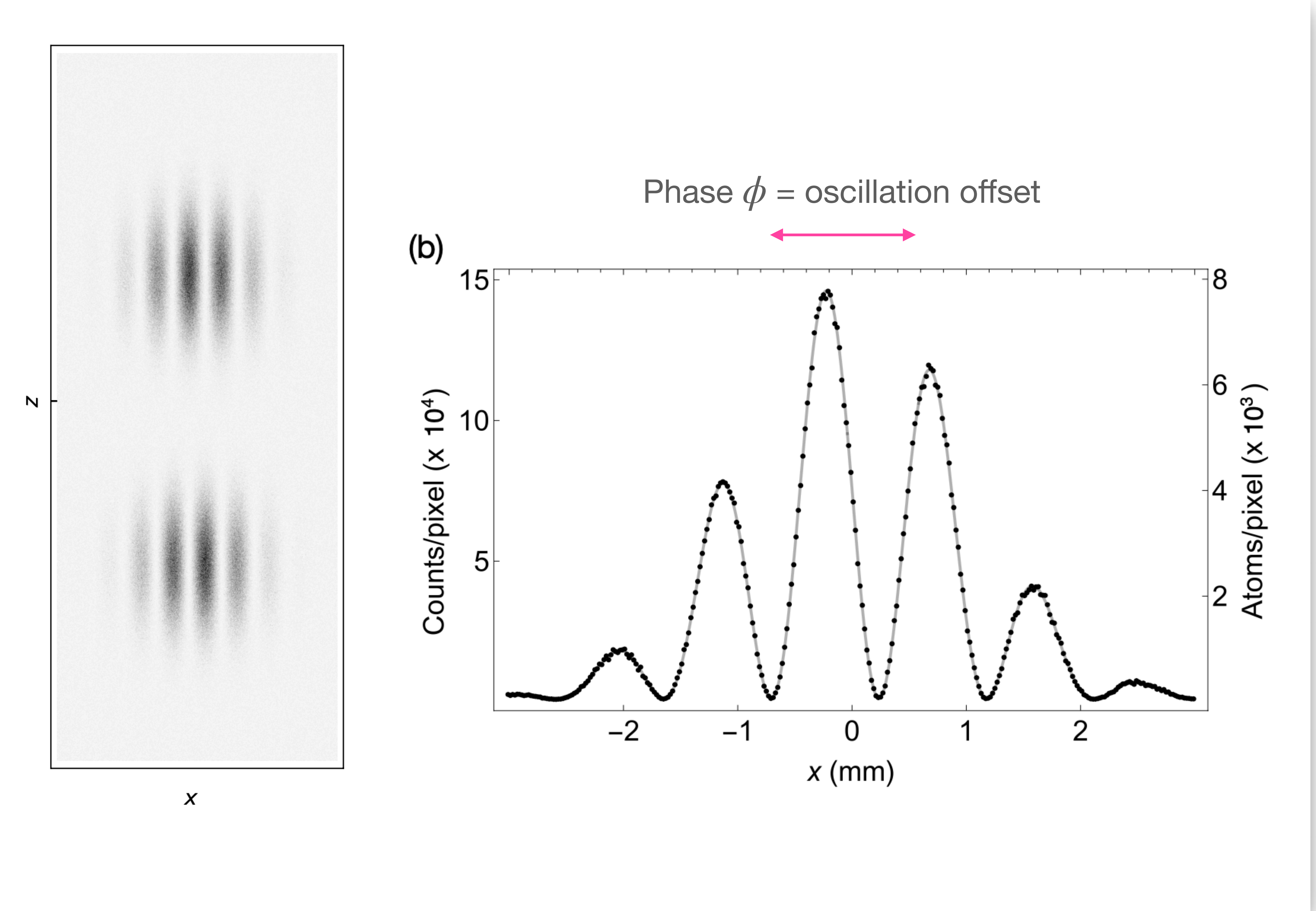
Each interferometer measures the change over time T



Graham et al., PRL **110**, 171102 (2013).
Arvanitaki et al., PRD **97**, 075020 (2018).

Imaging the Cloud

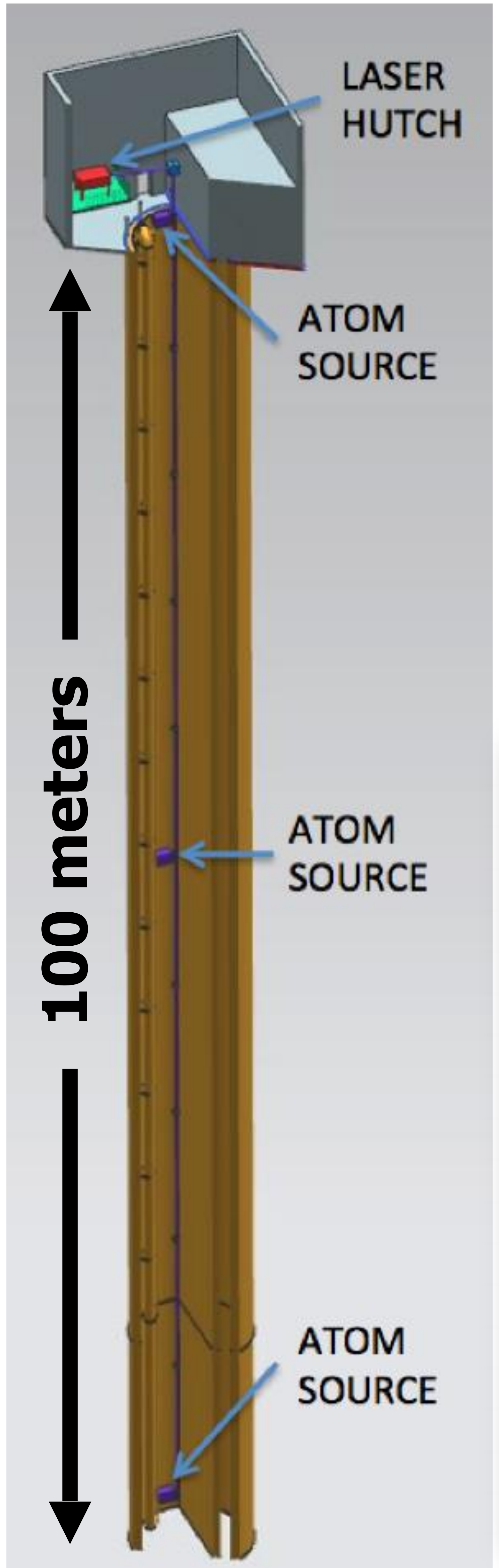




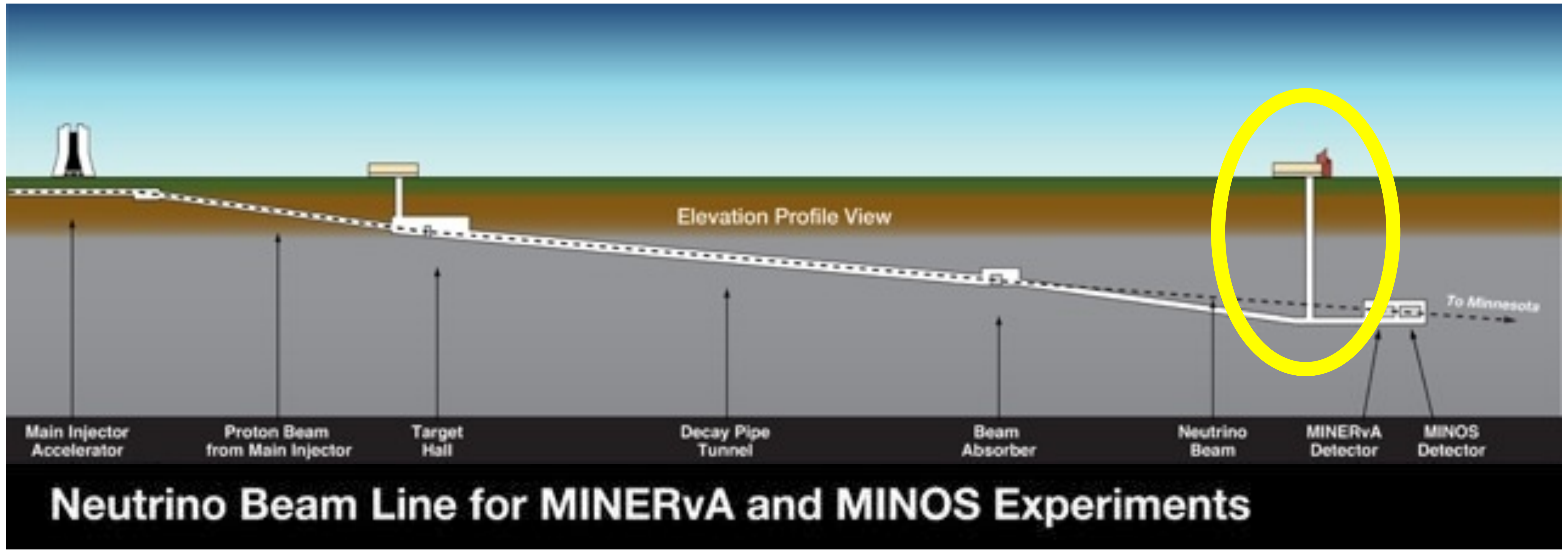
Images: arXiv:2104.02835

MAGIS-100

arXiv:2104.02835



Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



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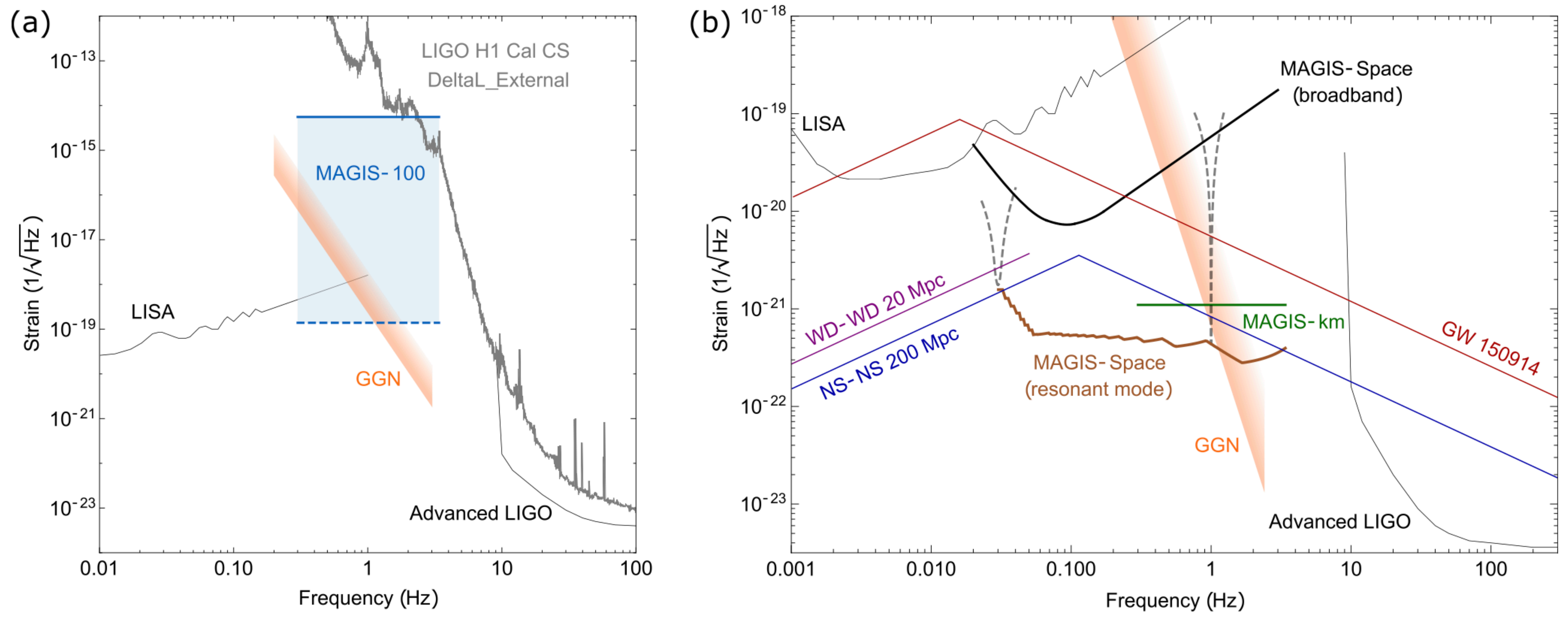
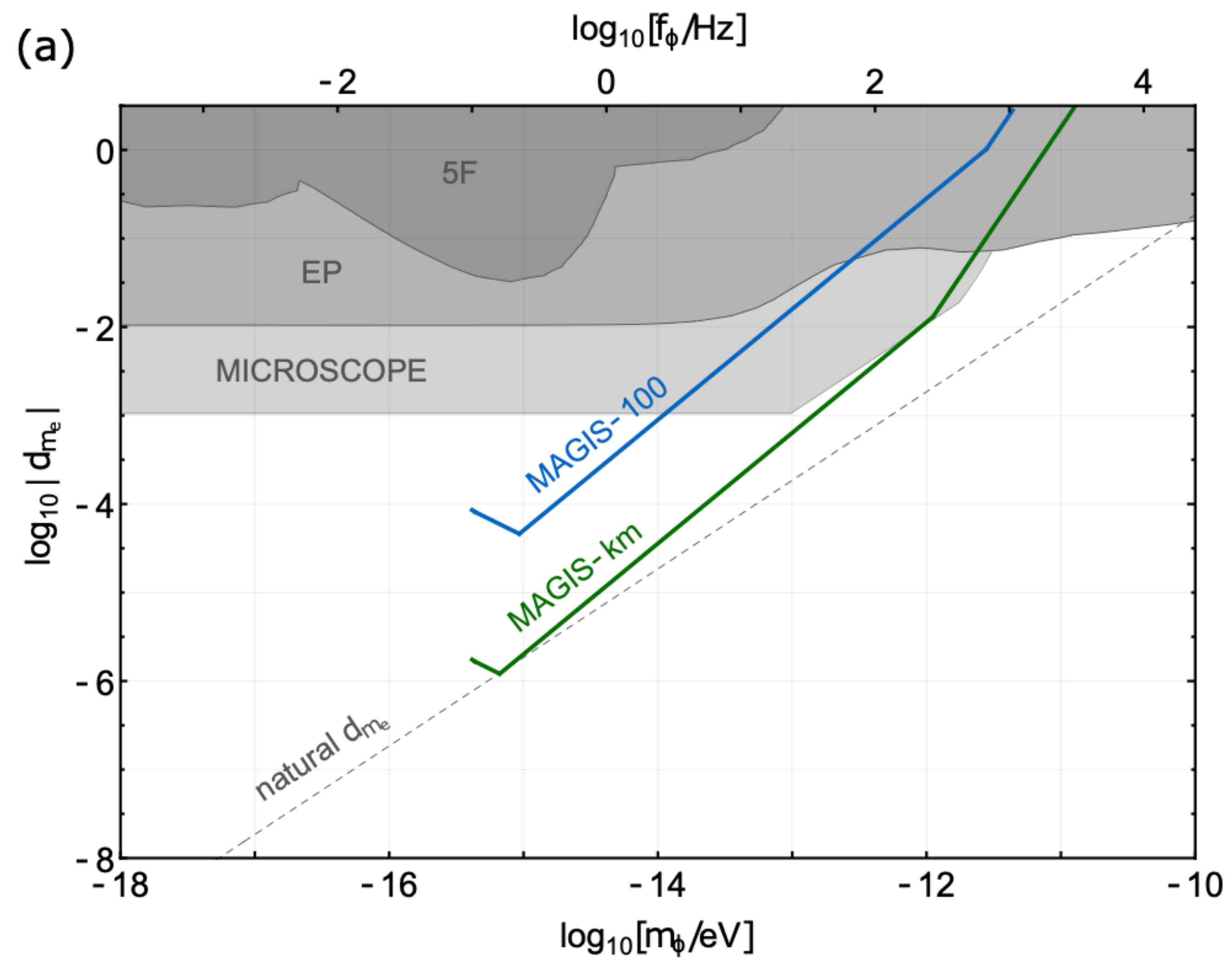
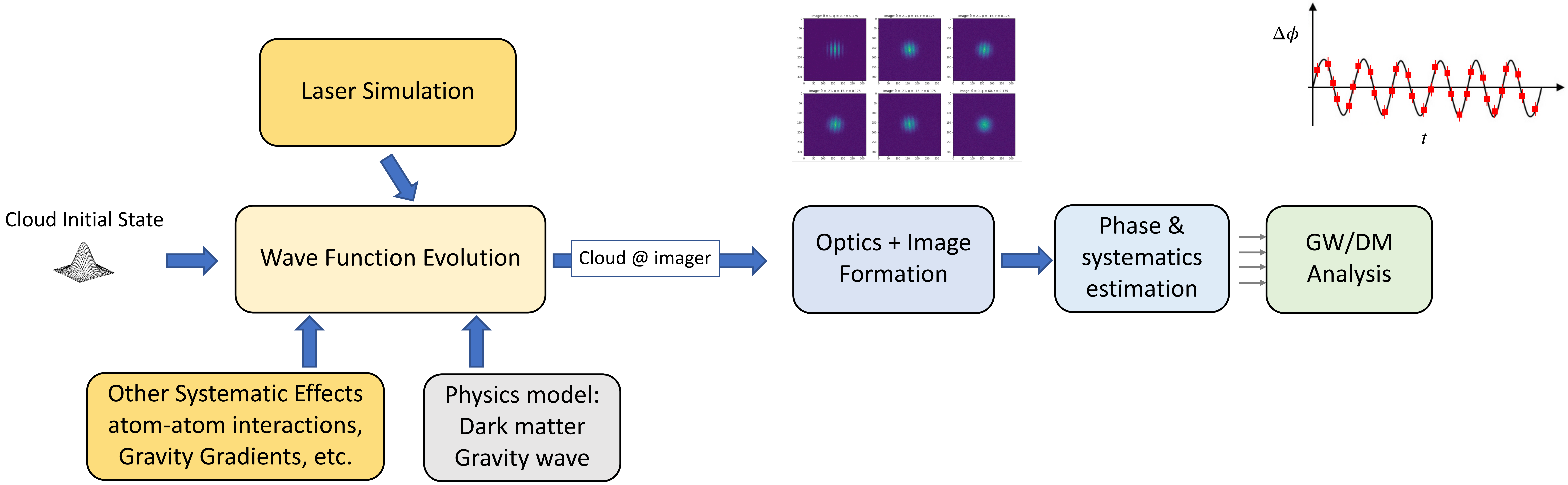
Gravitational Waves



Dark Matter



Simulation and Analysis Chain



Laser Simulation

Cloud Initial State

Wave Function Evolution

Cloud @ imager

Optics + Image Formation

Phase & systematics estimation

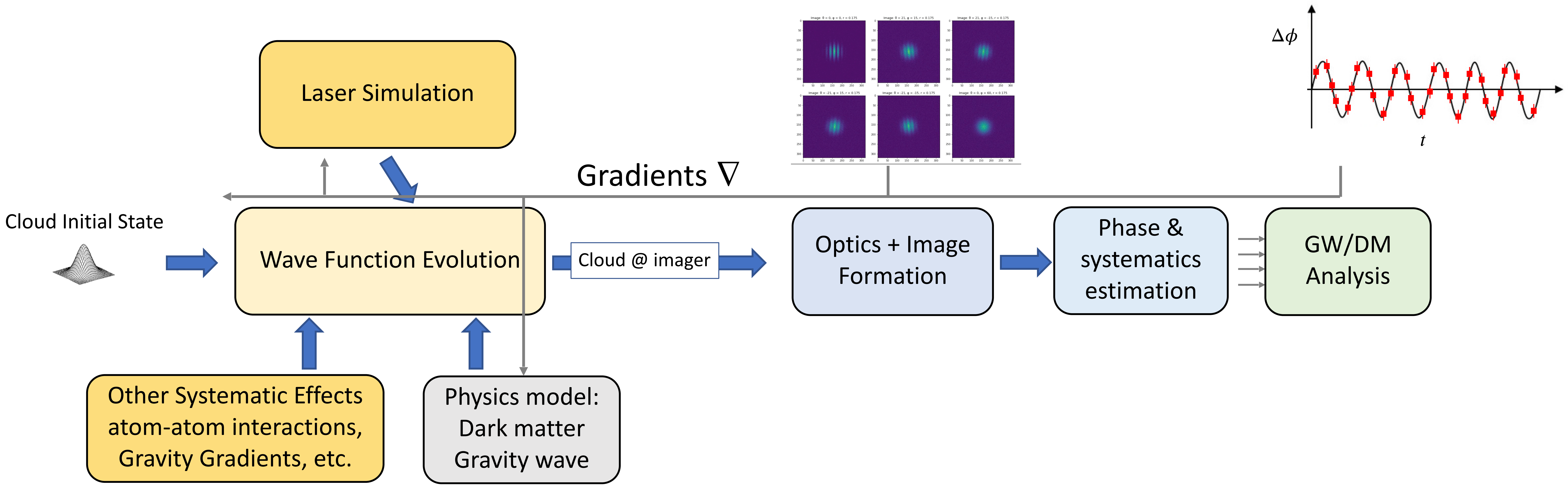
GW/DM Analysis

Other Systematic Effects atom-atom interactions, Gravity Gradients, etc.

Physics model: Dark matter Gravity wave

- 🟨 Cloud evolution
- ⬜ Physics Model
- 🟦 Imaging
- 🟧 Cloud reconstruction
- 🟩 Time series analysis

Differentiable Simulation and Analysis Chain



Laser Simulation

Gradients ∇

Cloud Initial State

Wave Function Evolution

Cloud @ imager

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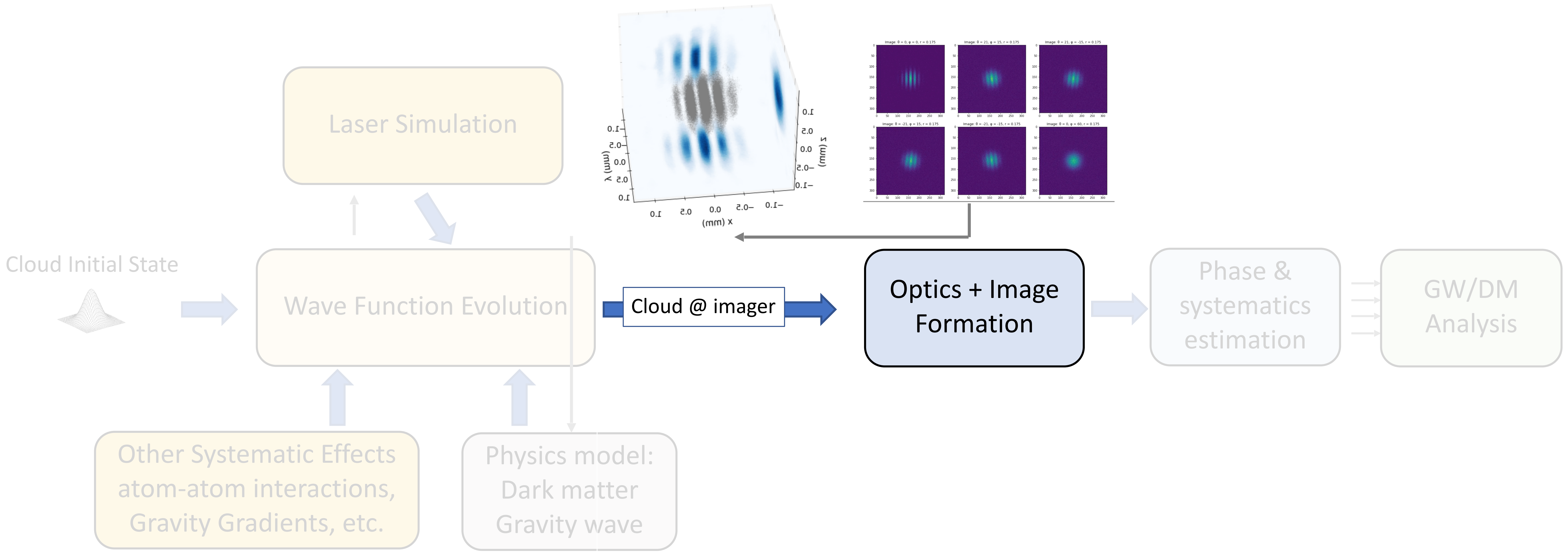
3D Cloud Reconstruction



Laser Simulation

Cloud Initial State

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Physics model: Dark matter Gravity wave

🟨 Cloud evolution

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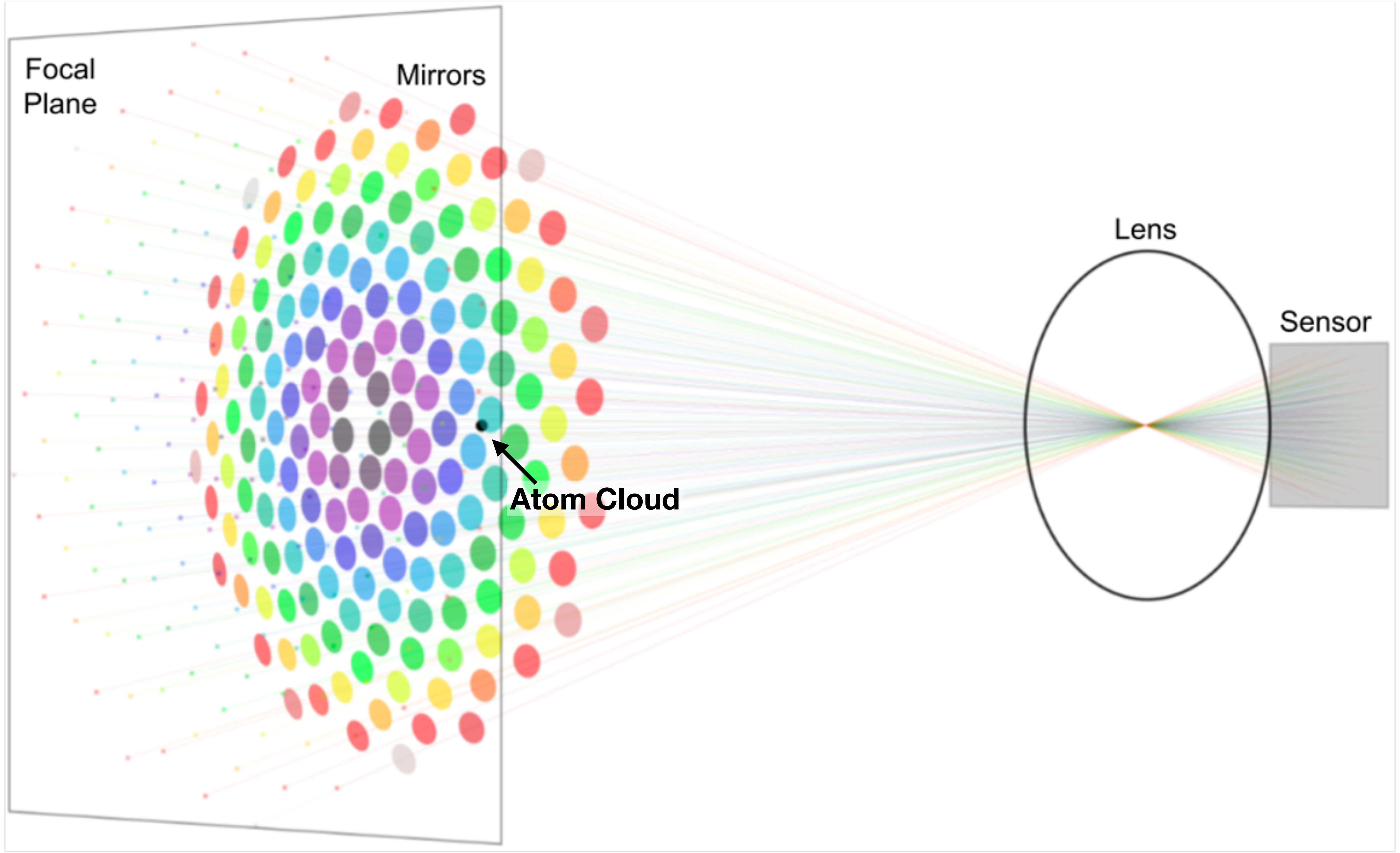
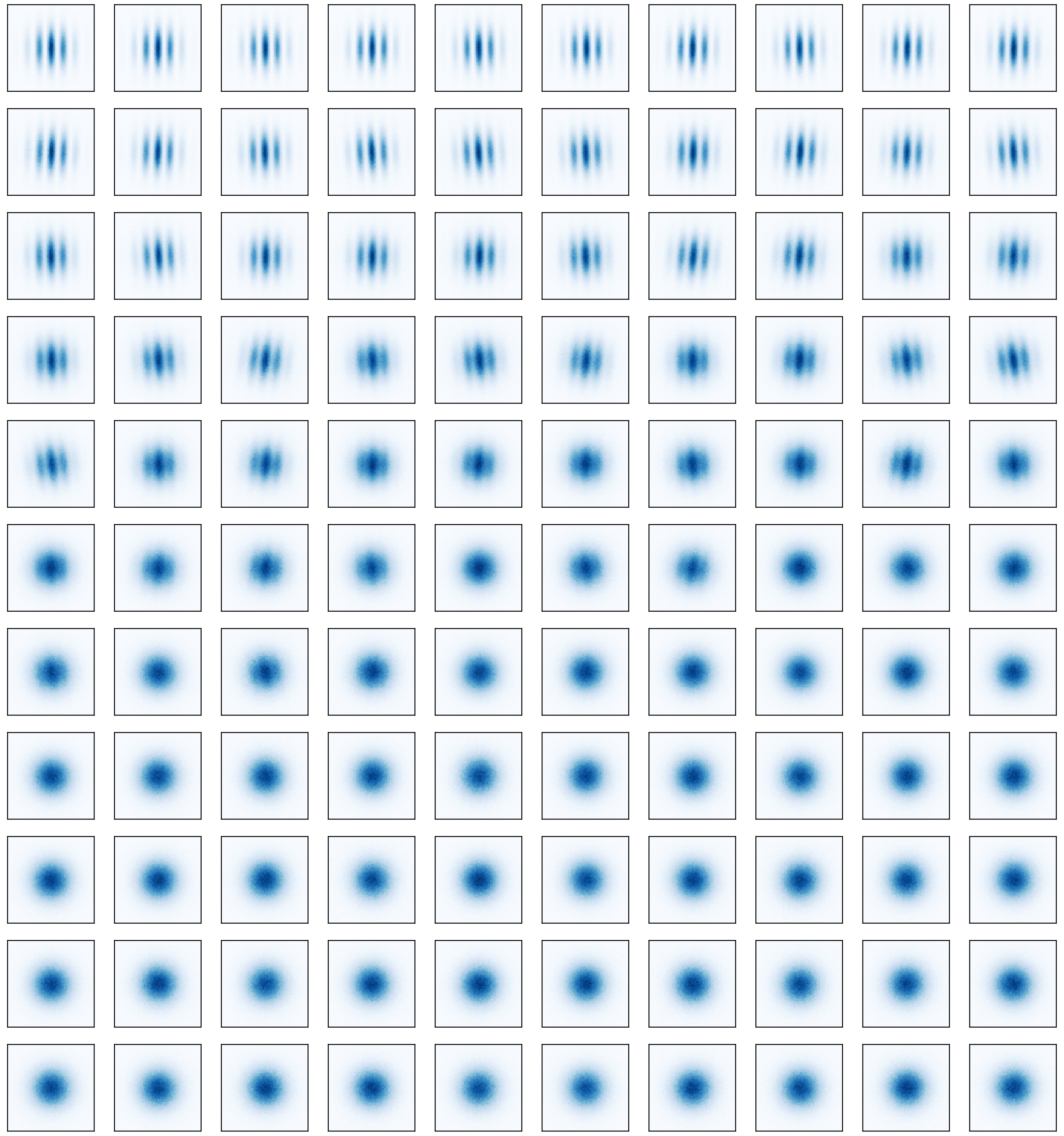
🟩 Time series analysis

S. Cheong, J. Frisch, S. Gasiorowski, J. Hogan, **M. K.**, M. Safari, A. Schwartzman, M. Vandegar
arXiv:2205.11480

Novel Single-Shot Multi-View Imaging for 3D Reconstruction





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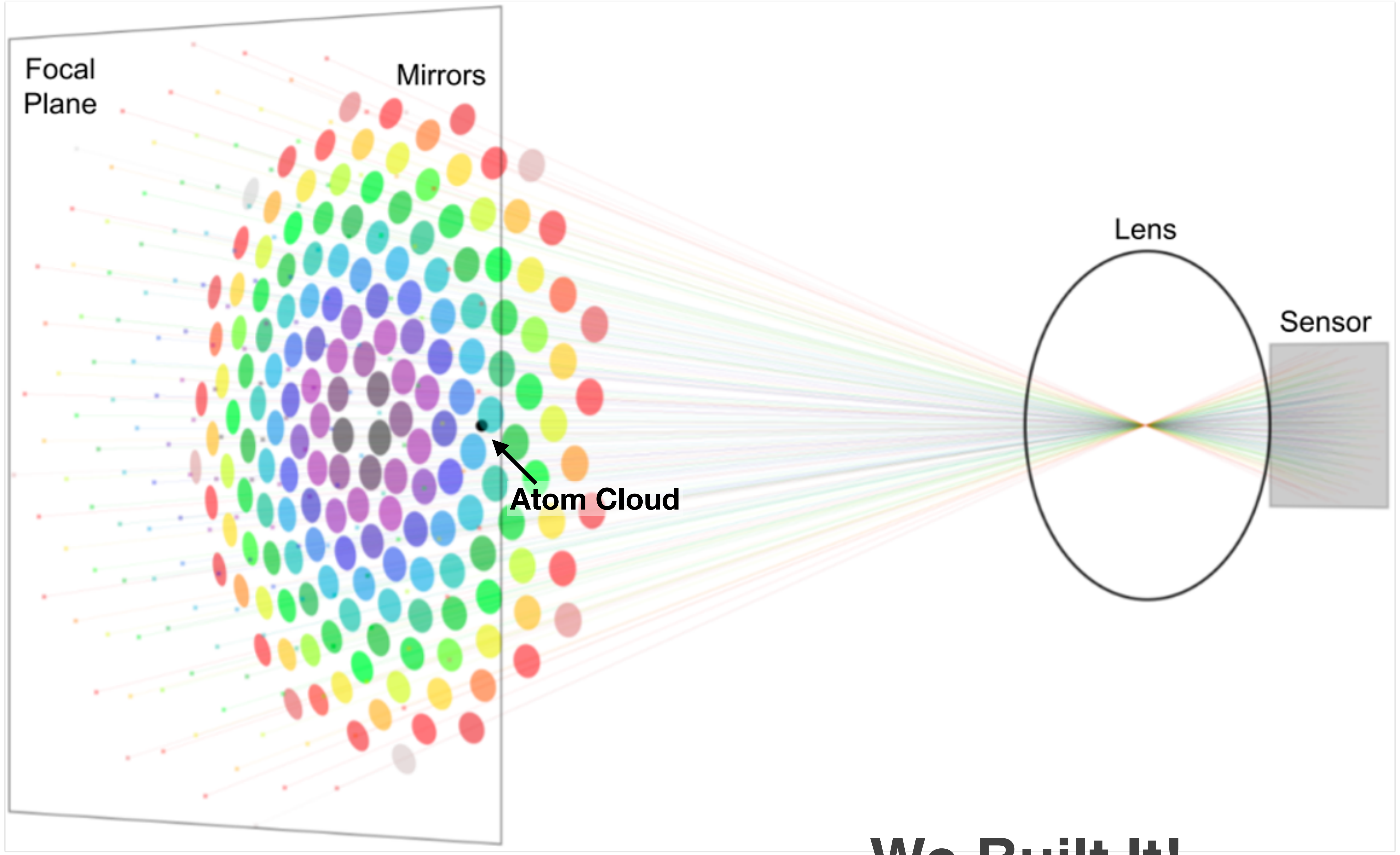

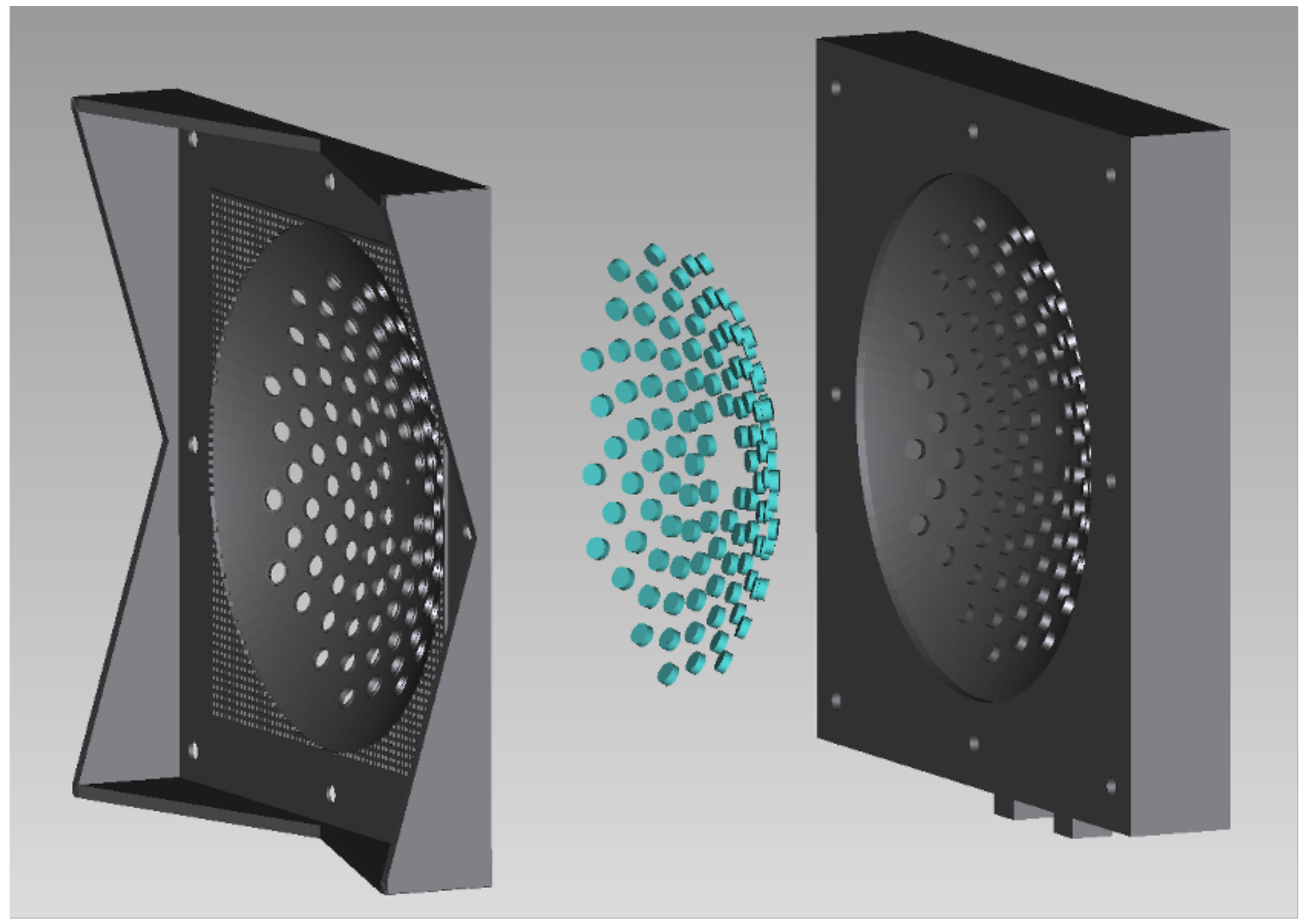

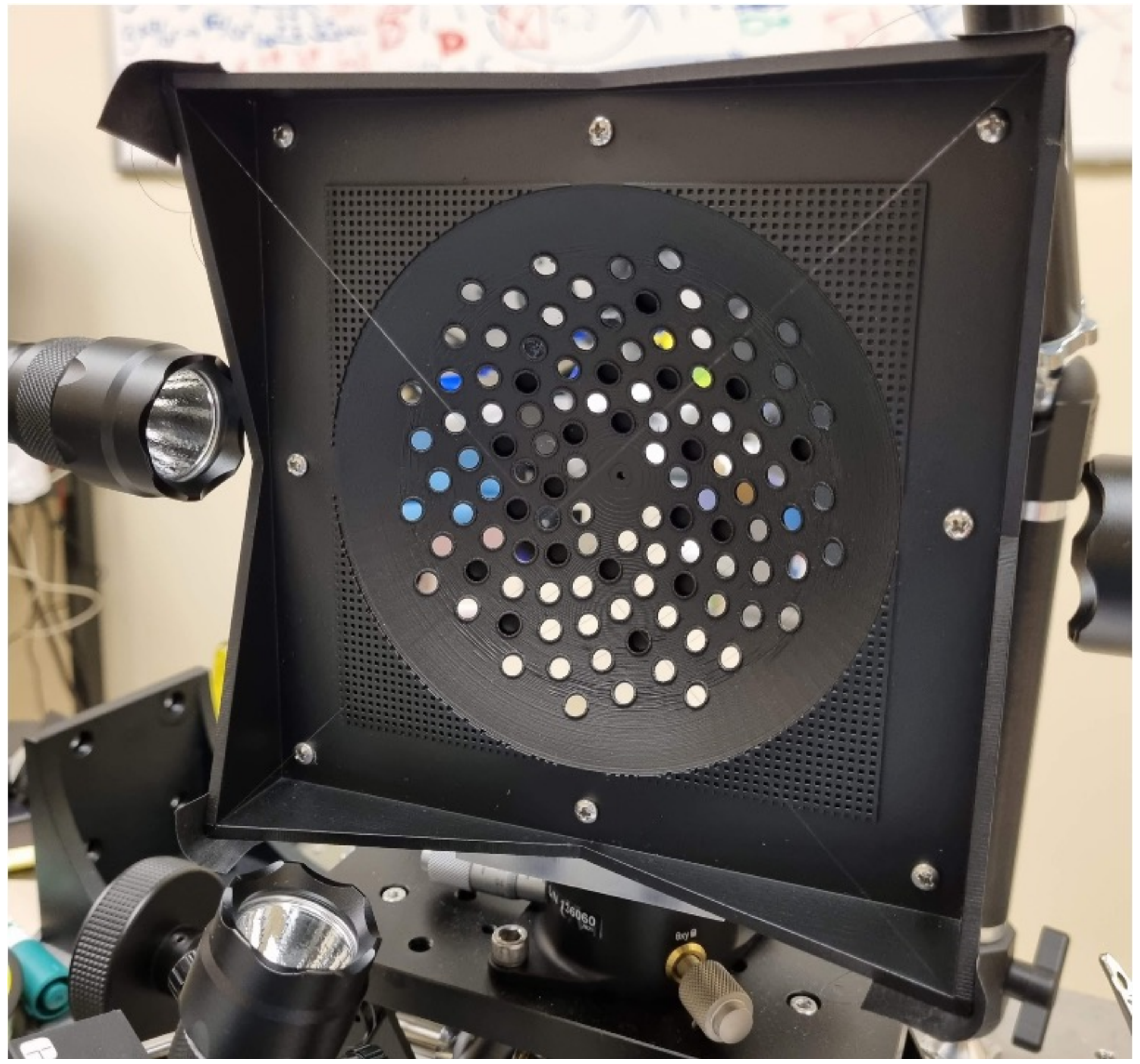

We Built It!

S. Cheong, J. Frisch, S. Gasiorowski, J. Hogan,
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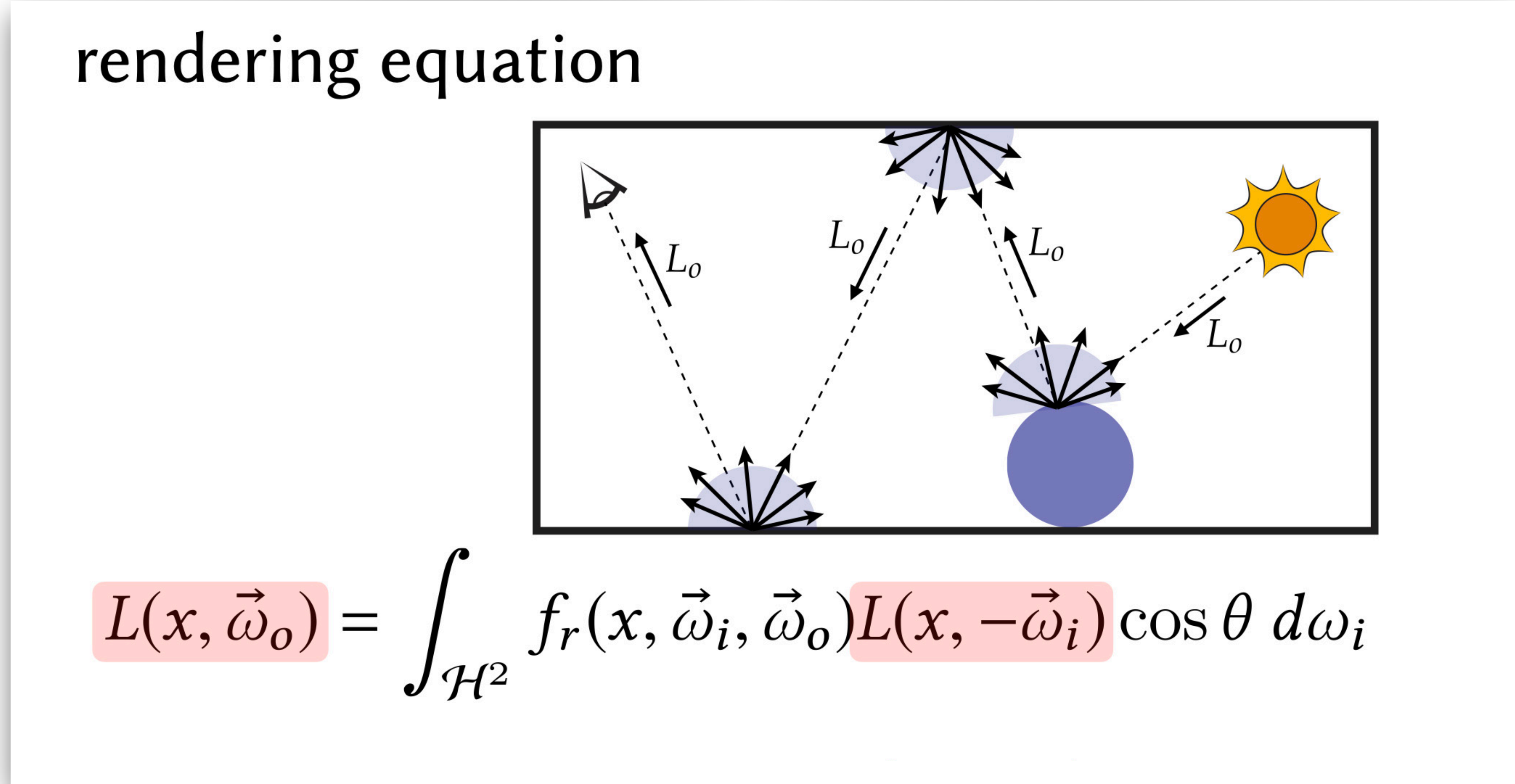
Rendering and Inverse Rendering

Rendering:

From 3D model scene, simulate image on camera at given position and angle

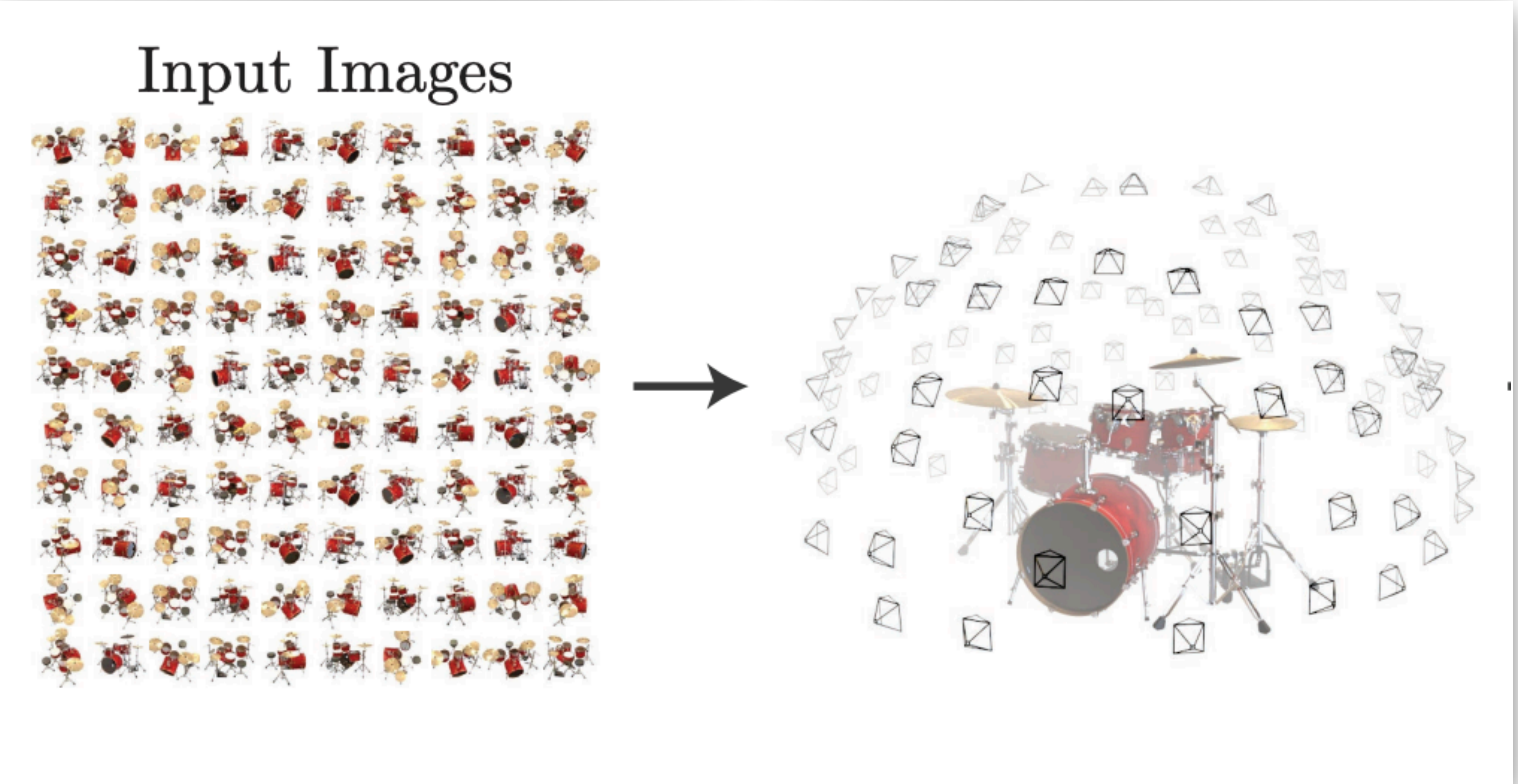


rendering equation

$$L(x, \vec{\omega}_o) = \int_{\mathcal{H}^2} f_r(x, \vec{\omega}_i, \vec{\omega}_o) L(x, -\vec{\omega}_i) \cos\theta \, d\omega_i$$

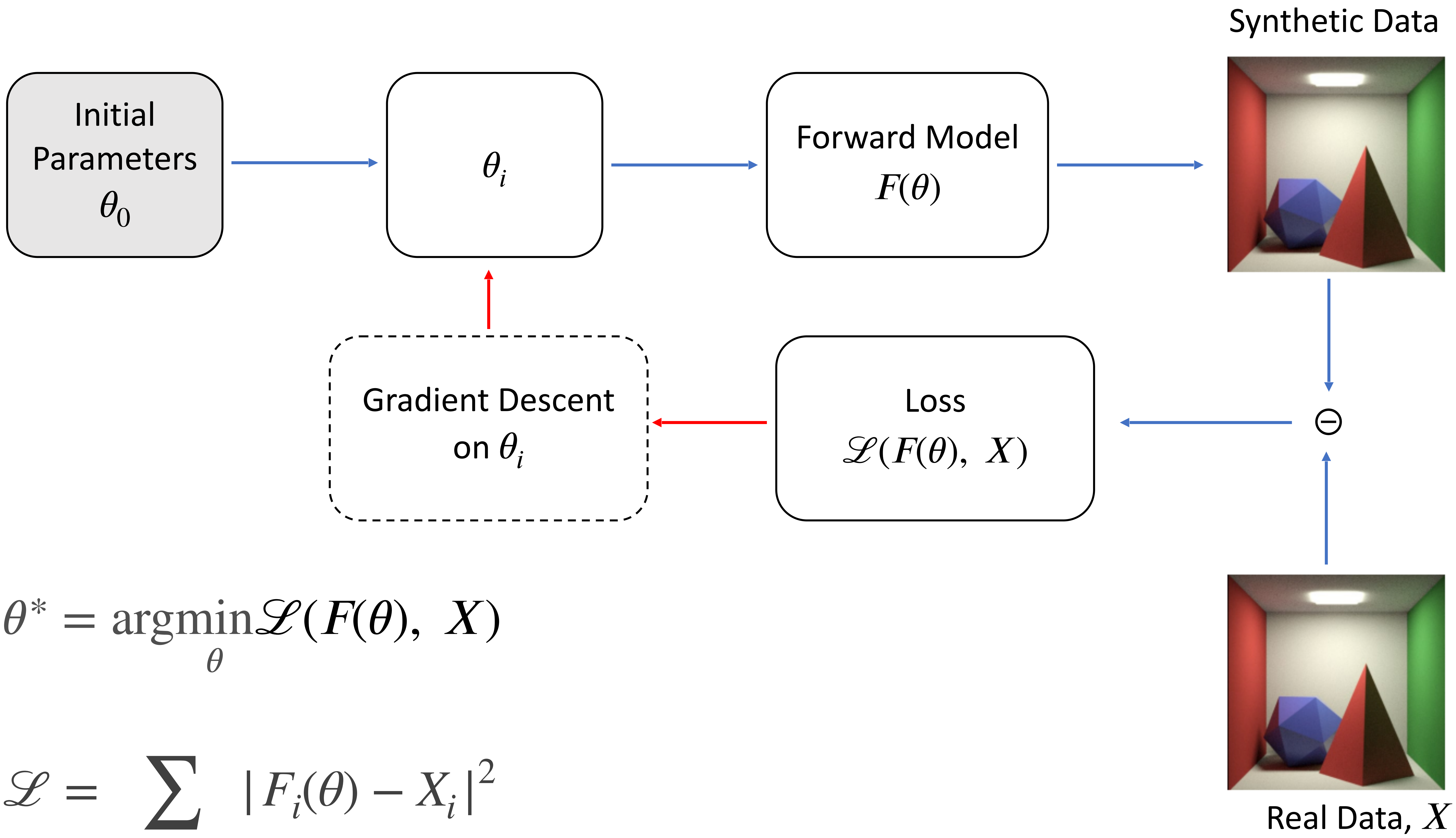
Inverse Rendering:

From multiple 2D images, reconstruct 3D model of scene



Input Images

Inverse Rendering with Analysis-by-Synthesis



Initial Parameters θ_0

θ_i

Forward Model $F(\theta)$

Synthetic Data

$\ominus$

Real Data, X

Loss $\mathscr{L}(F(\theta),\ X)$

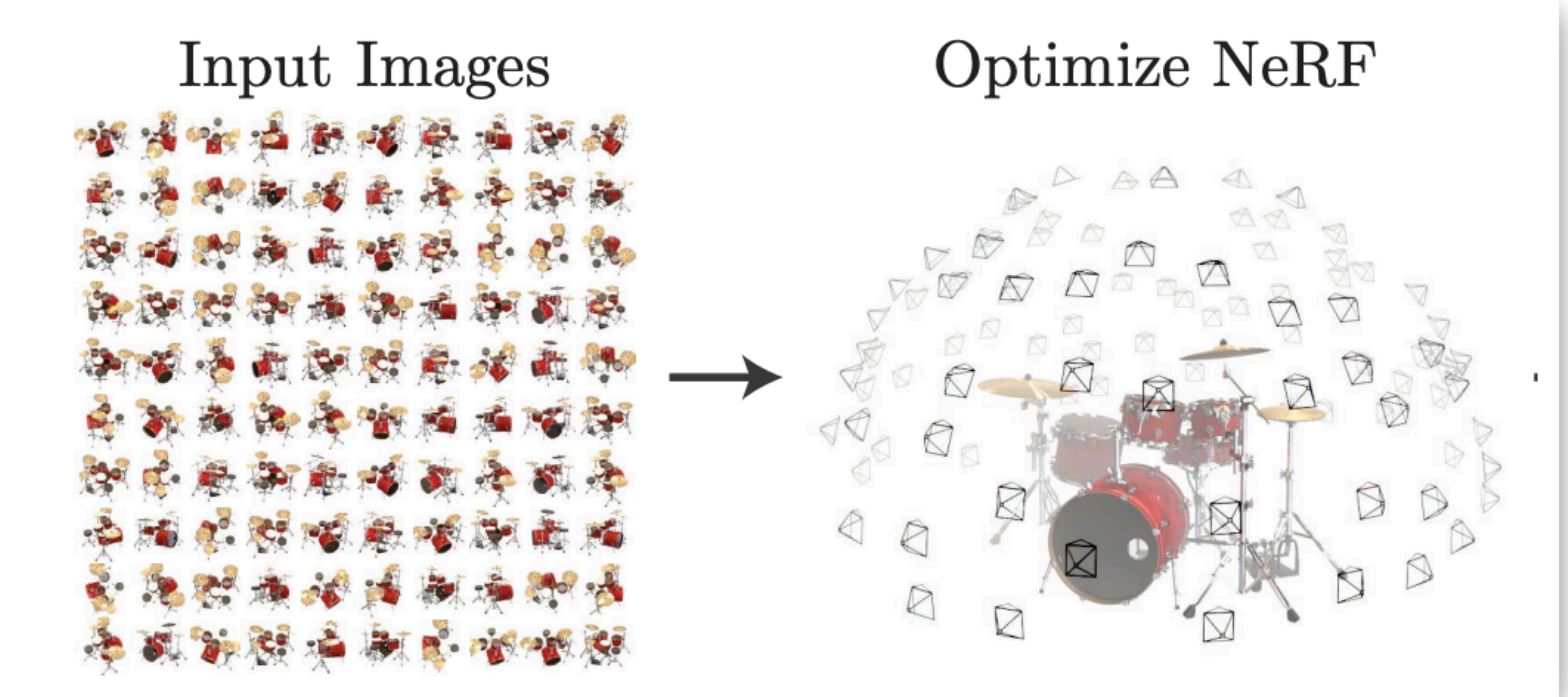
Gradient Descent on θ_i

$$\theta^* = \underset{\theta}{\operatorname{argmin}} \mathscr{L}(F(\theta),\ X)$$

$$\mathscr{L} = \sum_{i \in pixels} |F_i(\theta) - X_i|^2$$

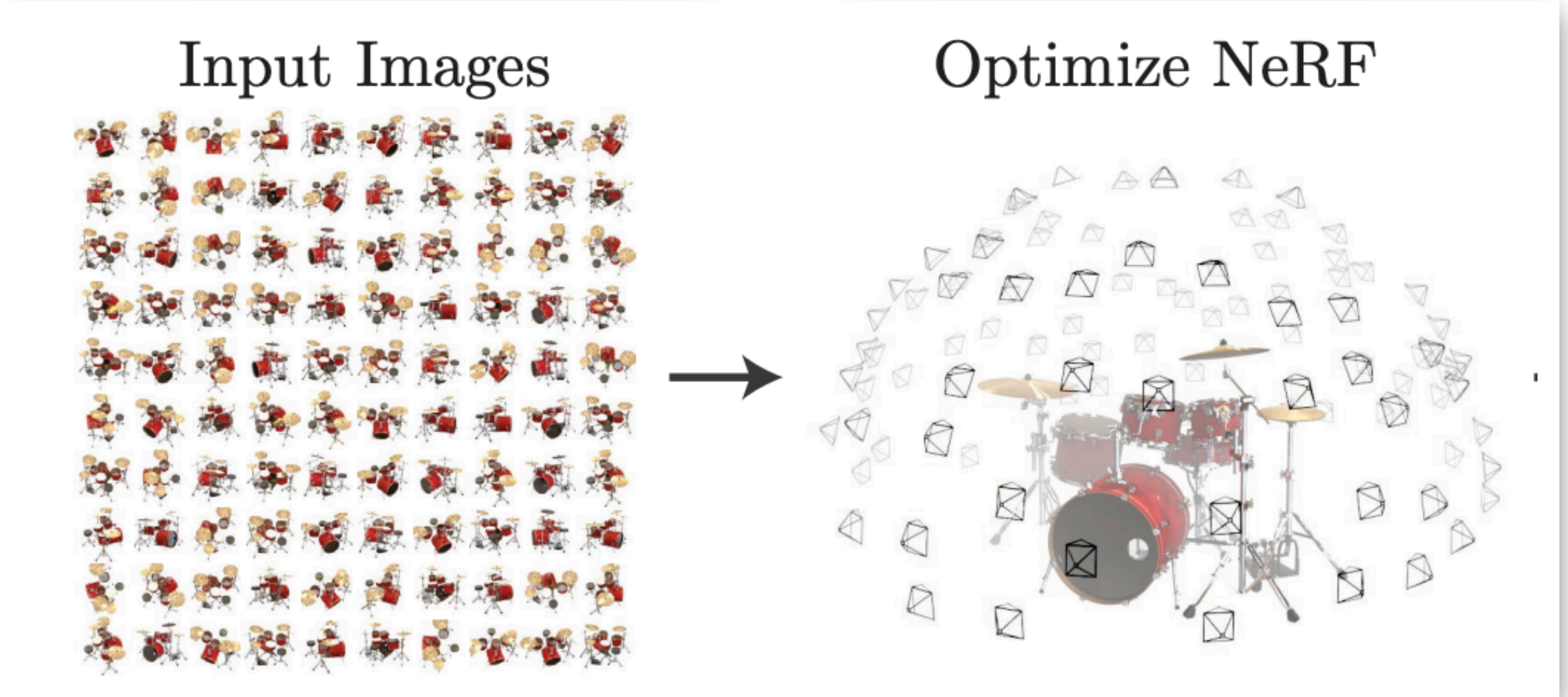
Neural Radiance Fields (NeRF)

arXiv:2003.08934

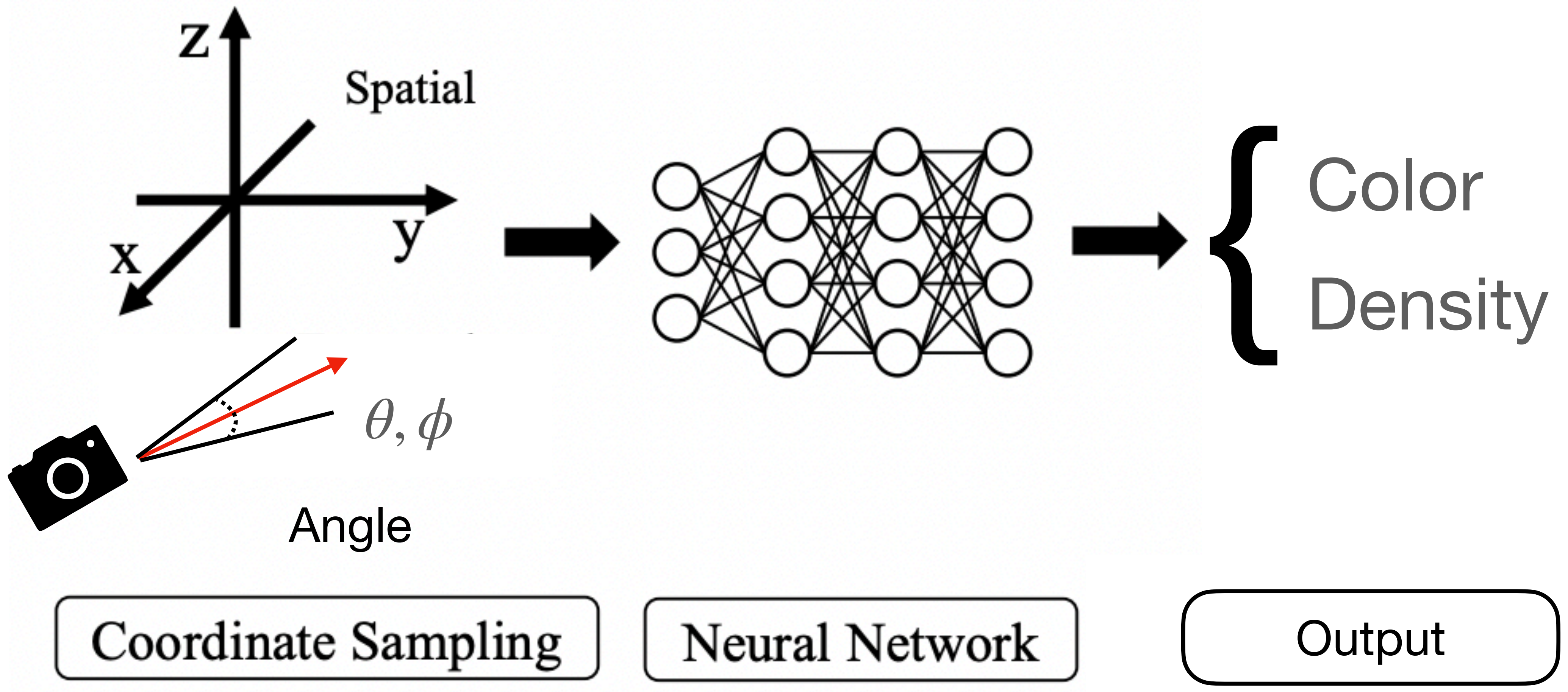


Neural Radiance Fields (NeRF)

arXiv:2003.08934



Represent Scenes using Neural Network



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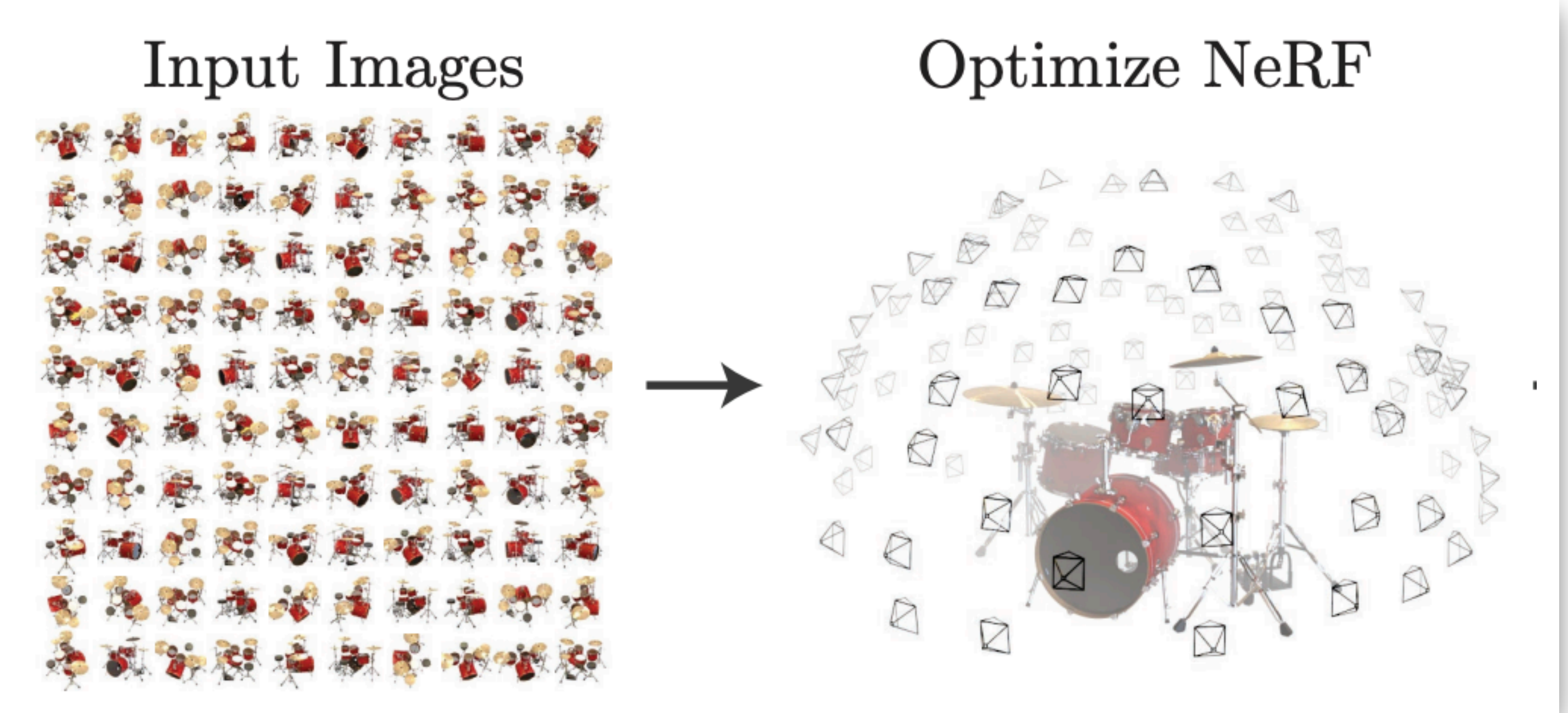

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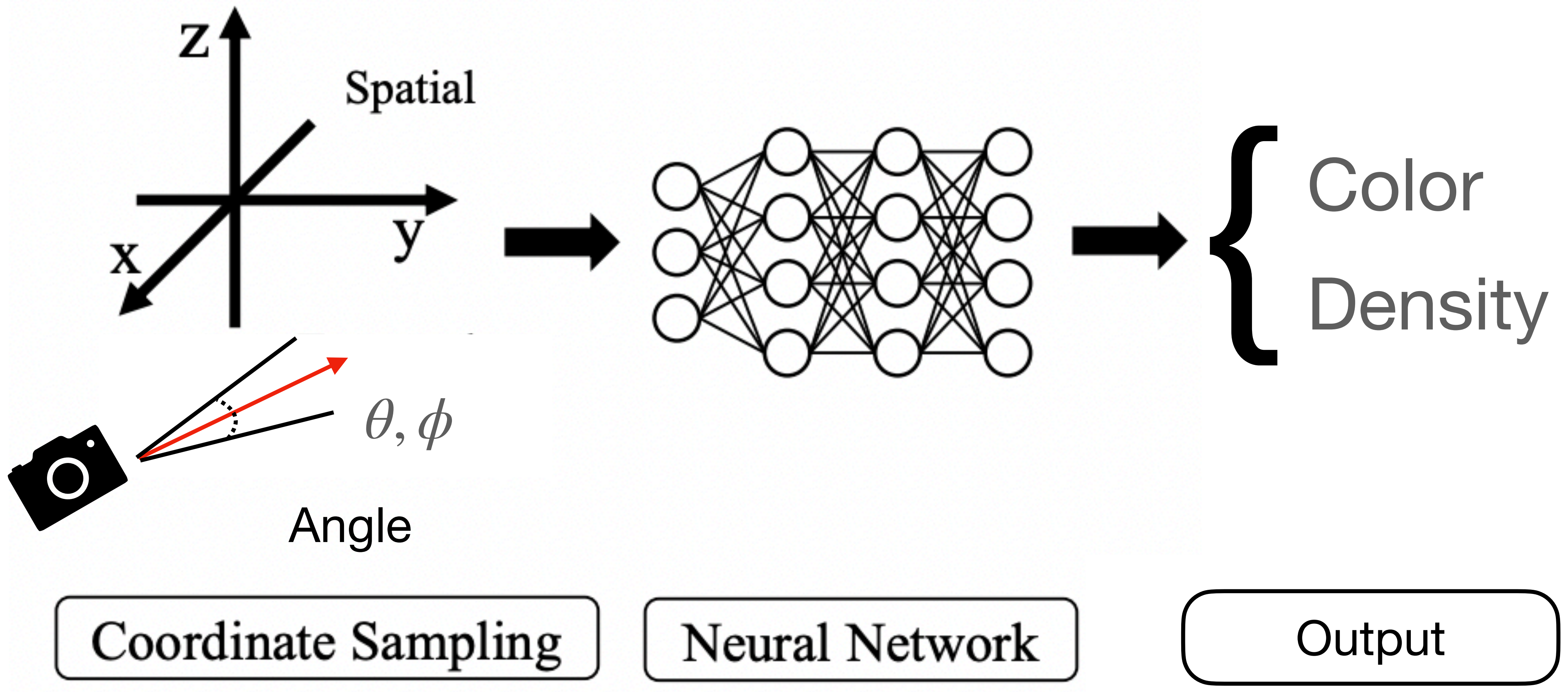
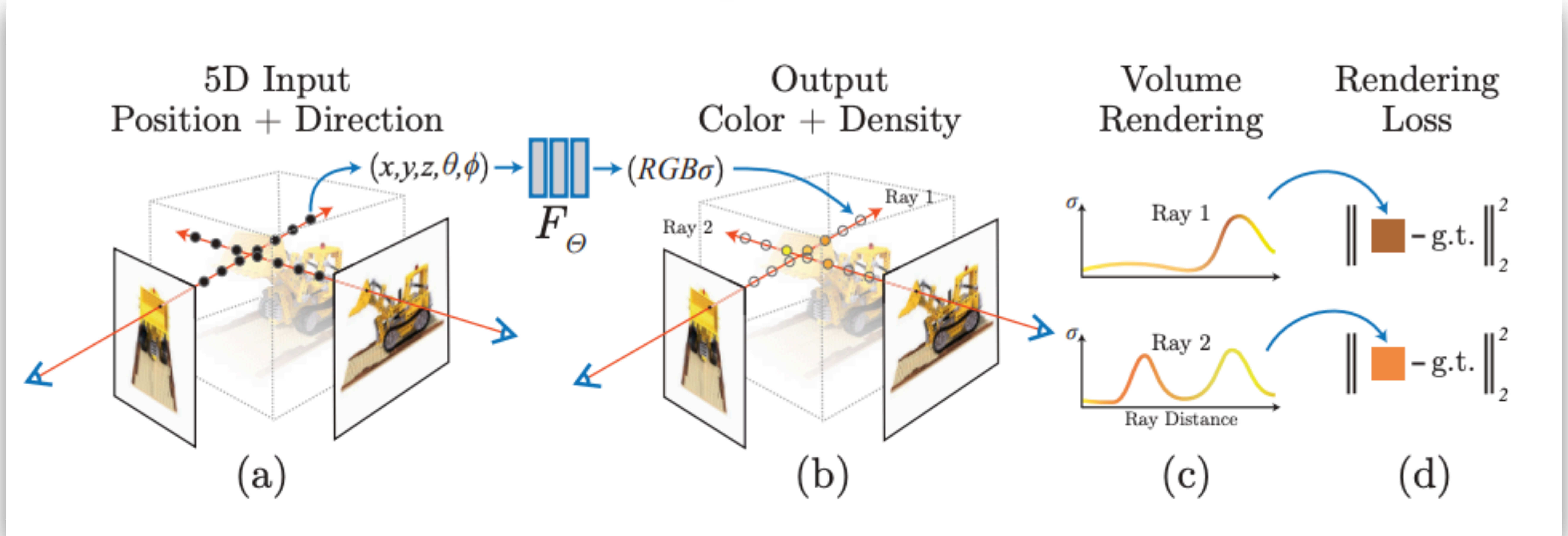
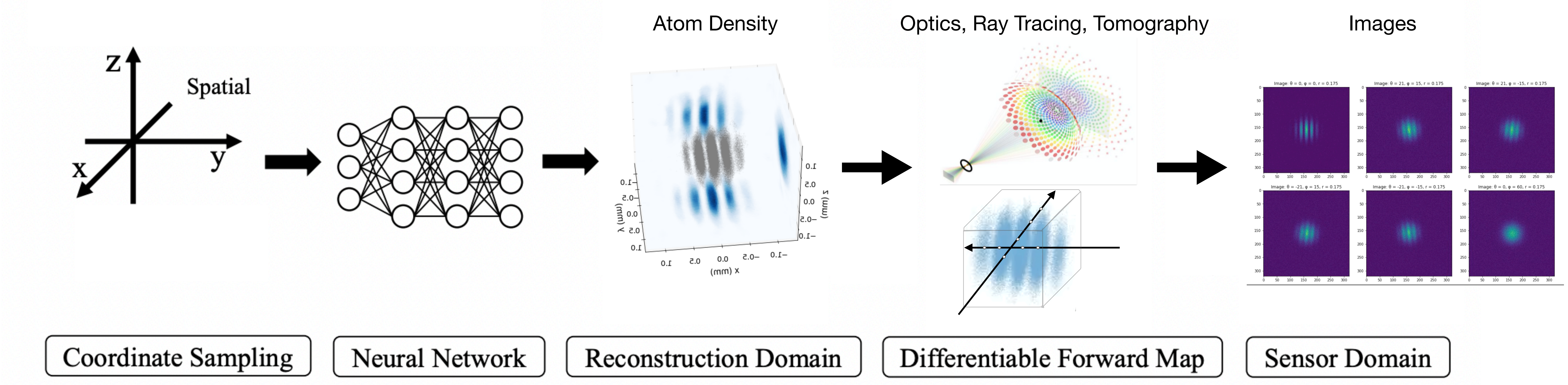




Neural Radiance Fields (NeRF)

arXiv:2003.08934

Neural Fields For Atom Cloud Reconstruction



Atom Density

Optics, Ray Tracing, Tomography

Images

Coordinate Sampling

Neural Network

Reconstruction Domain

Differentiable Forward Map

Sensor Domain

Neural Field models Atom Cloud Density

Forward Model: GradOptics
Differentiable Ray Tracing and Optics simulator

→ Tomographic Imaging

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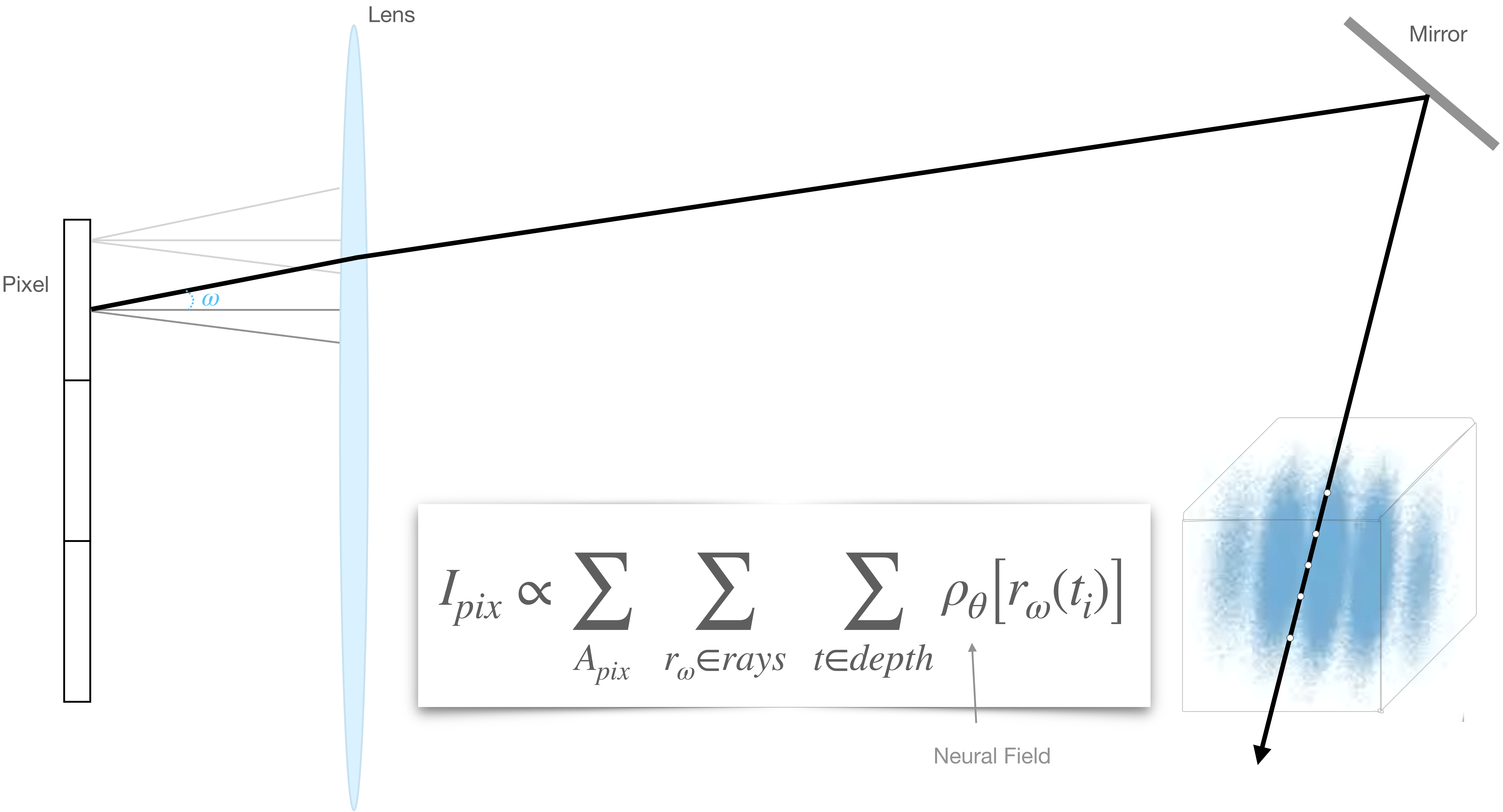
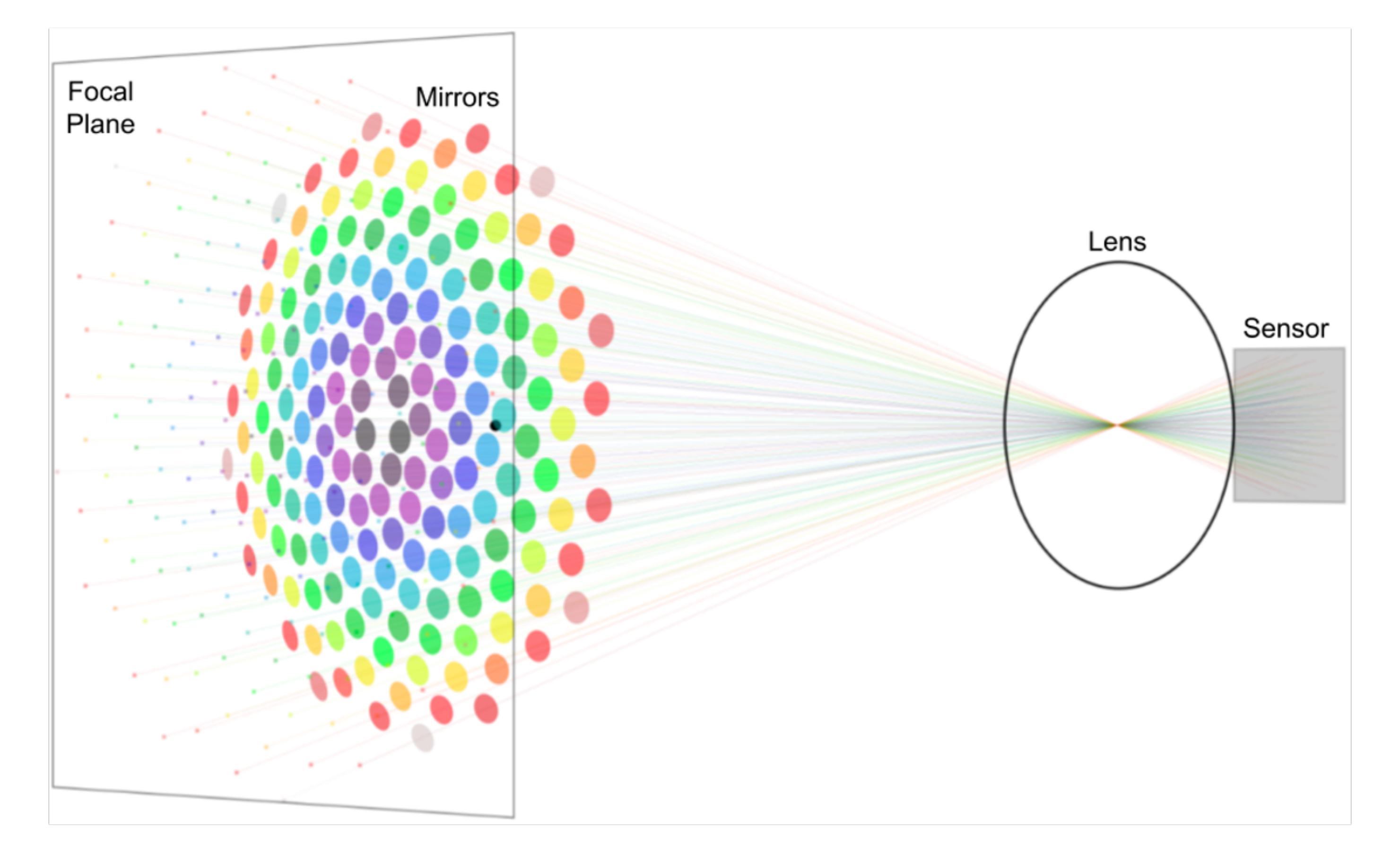
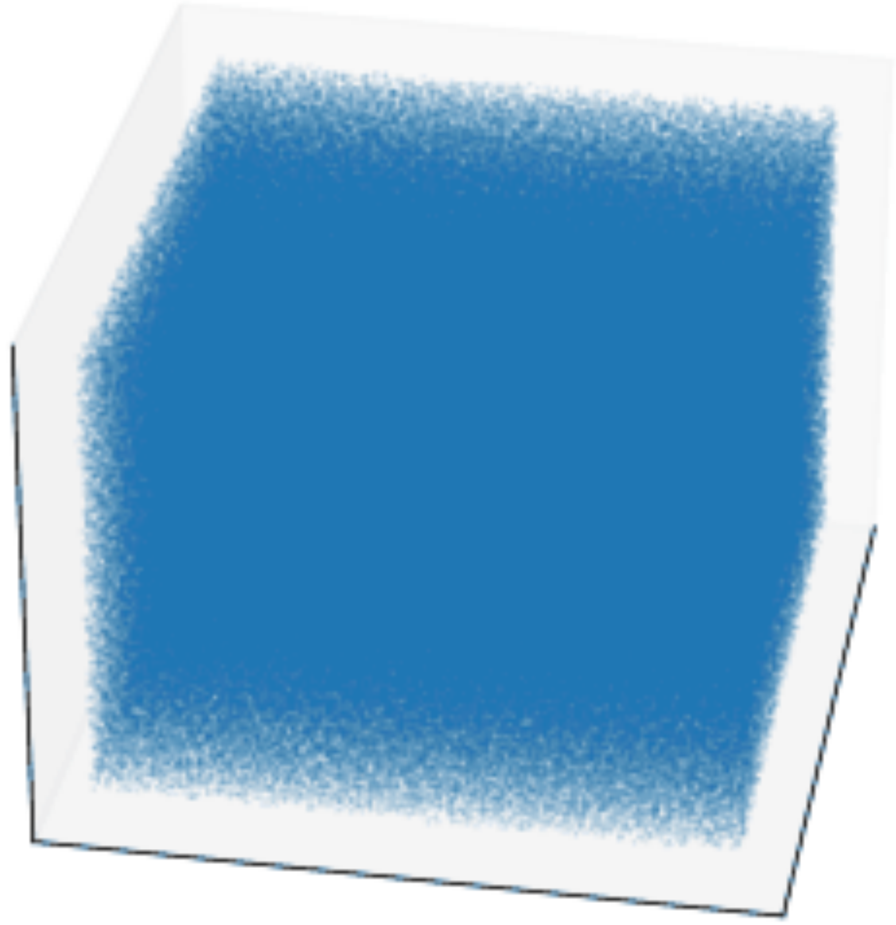
Computing Pixel Intensities

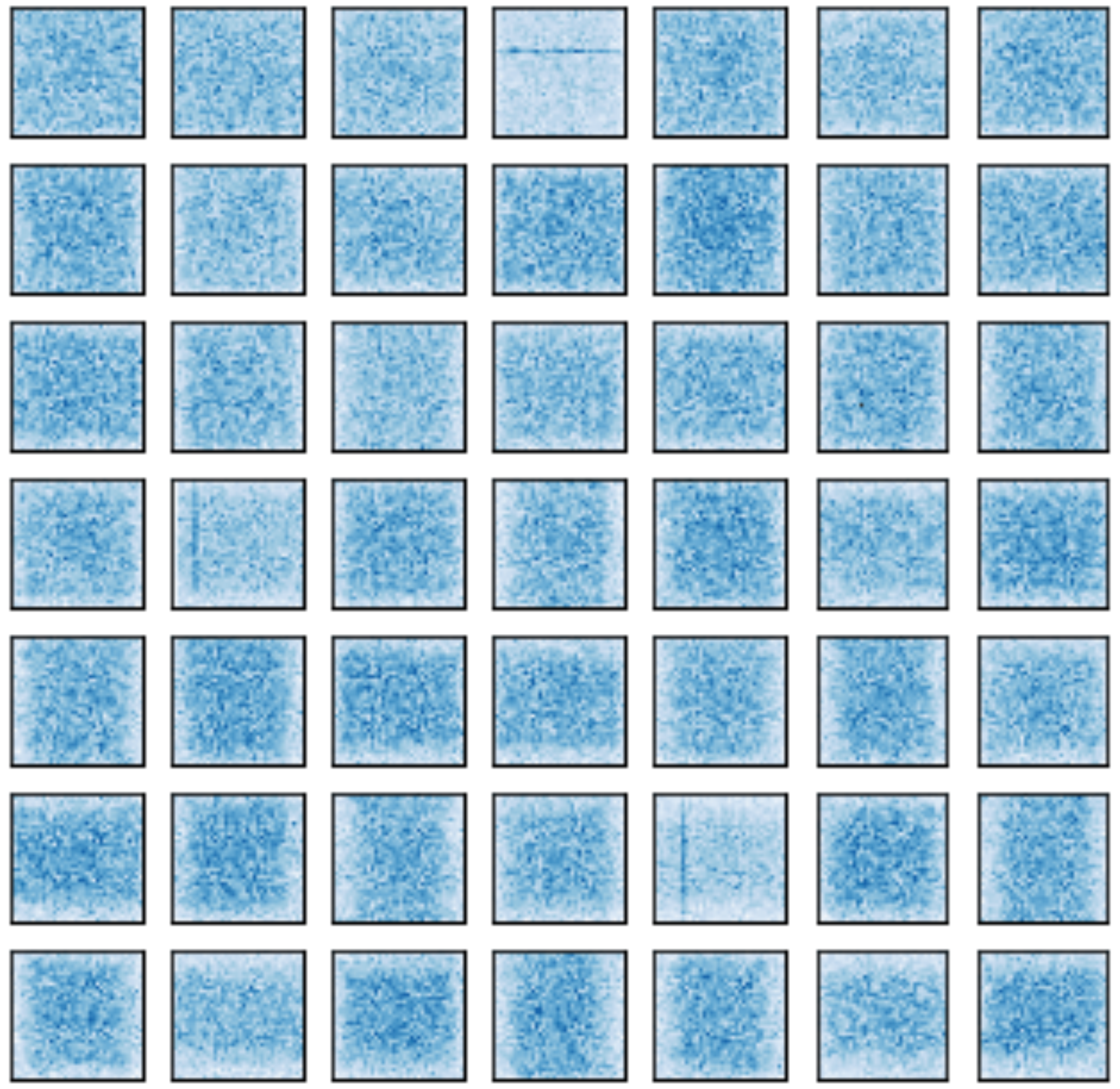


$$I_{pix} \propto \sum_{A_{pix}} \sum_{r_\omega \in rays} \sum_{t \in depth} \rho_\theta\left[r_\omega(t_i)\right]$$

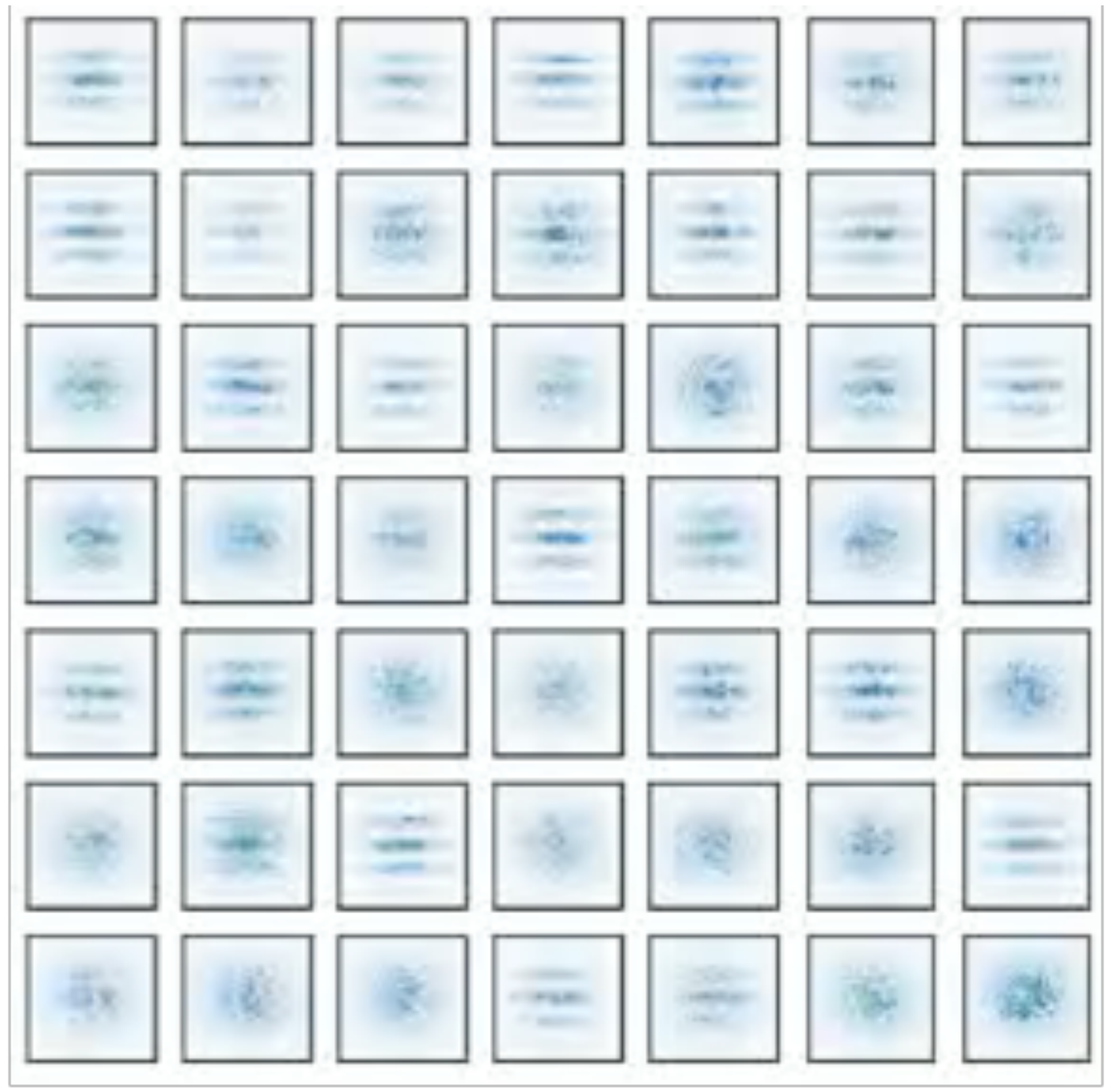
3D Reconstruction of Atom Clouds (in simulation)







Model



Target: Measured Data

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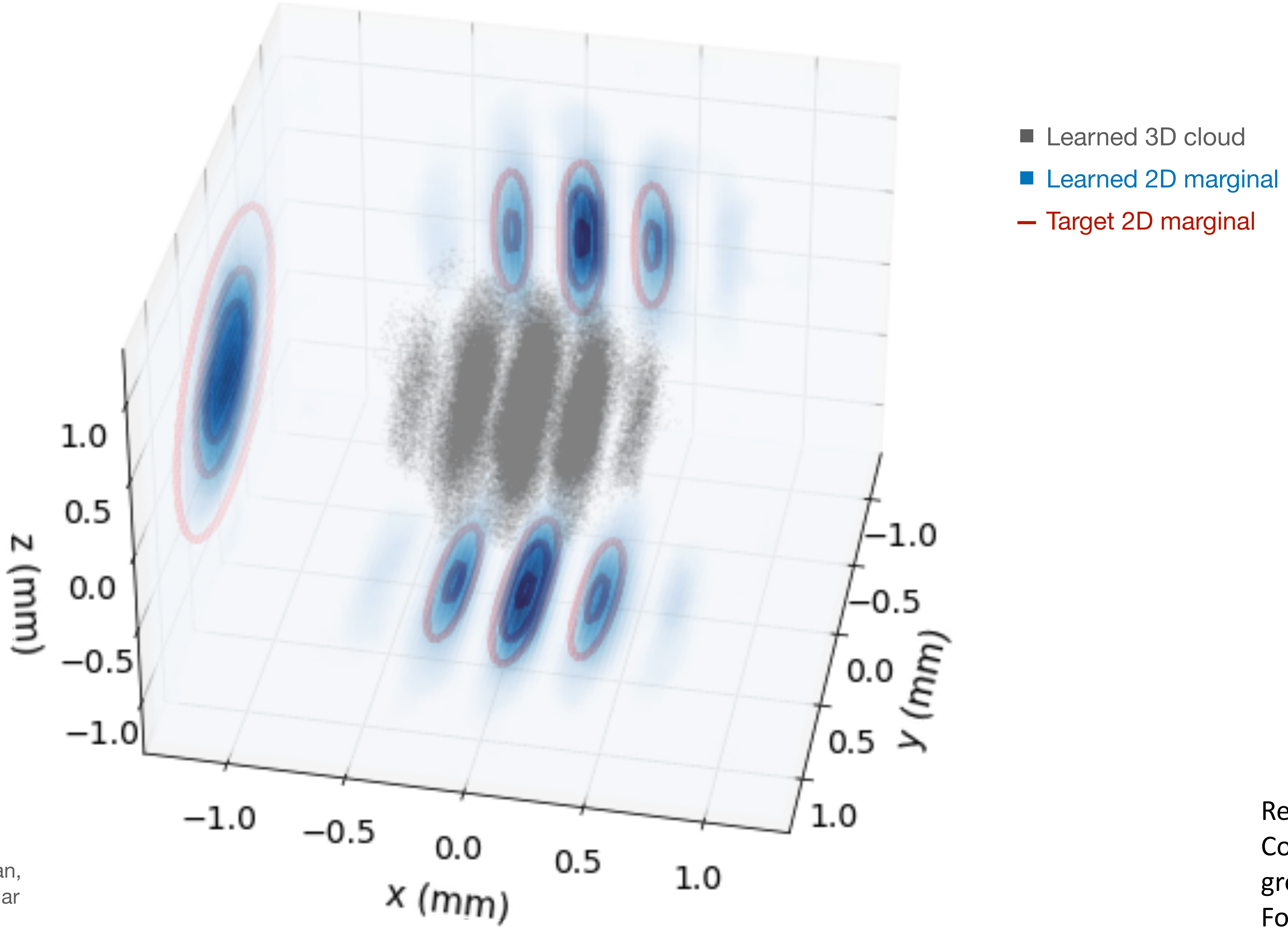
3D Reconstruction of Atom Clouds (in simulation)



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arXiv:2205.11480

Resolution ~ 60μm
Computed comparison to ground truth density with Fourier Shell Correlation

Reconstructing Real Objects

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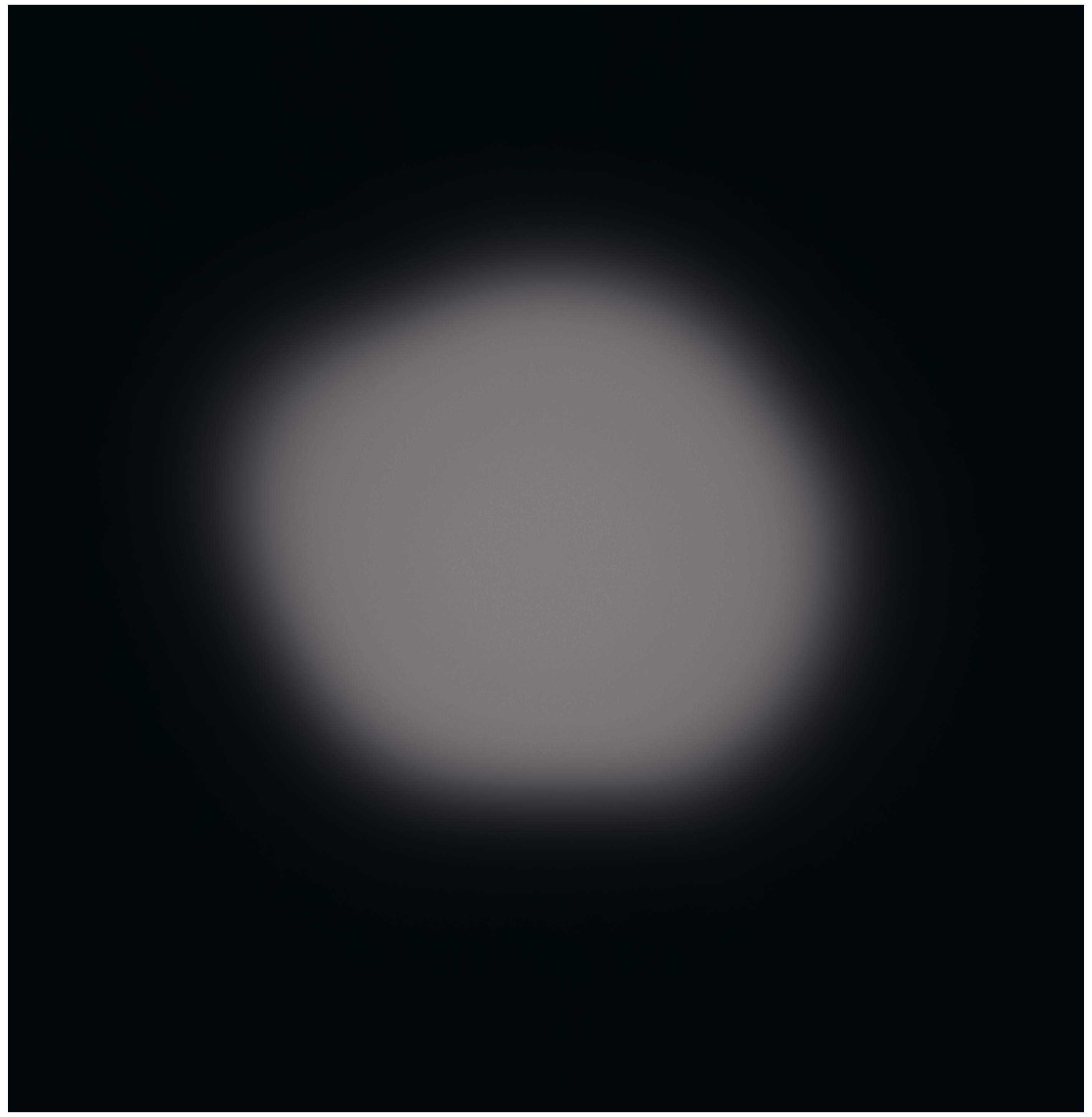
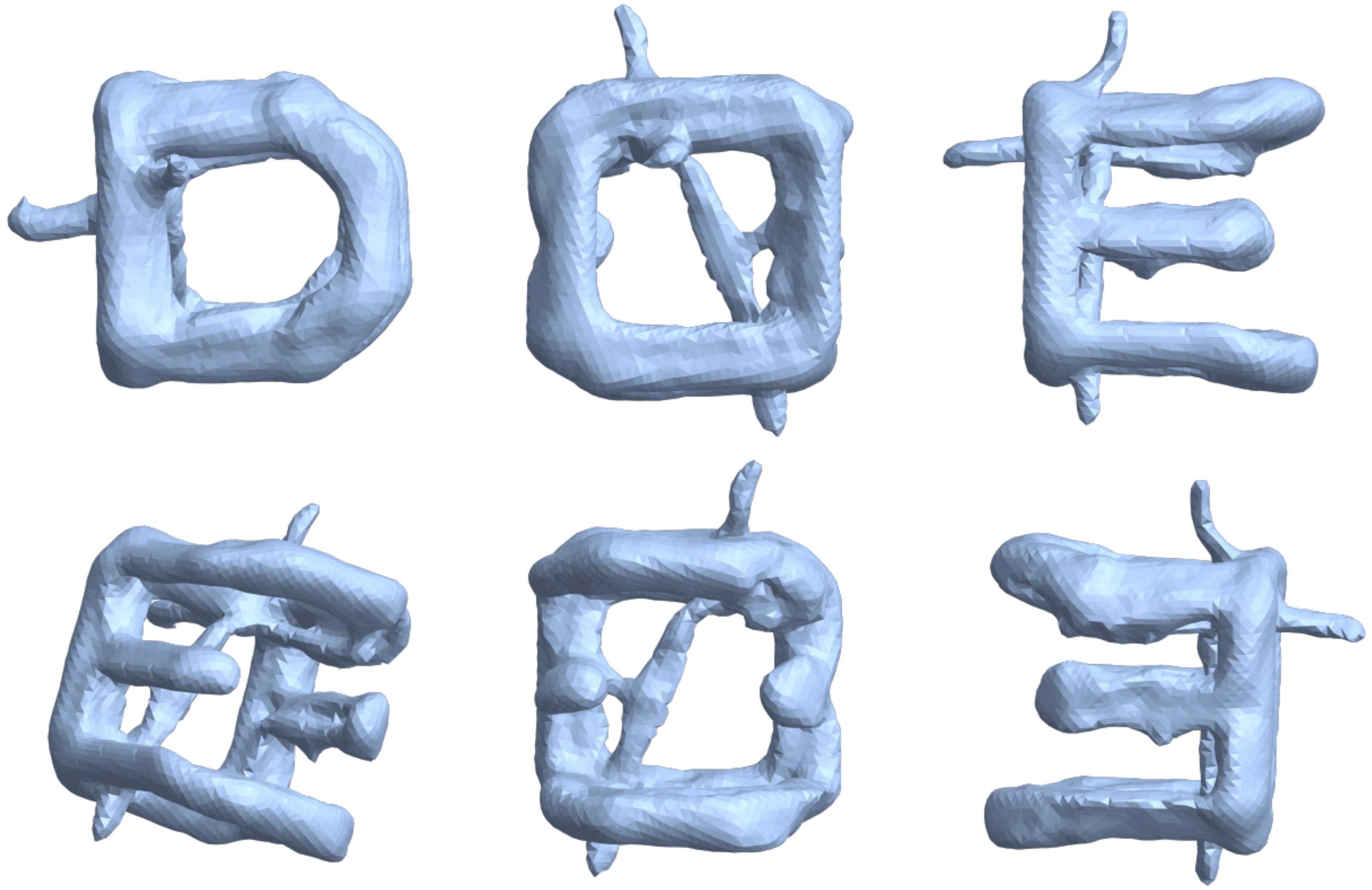
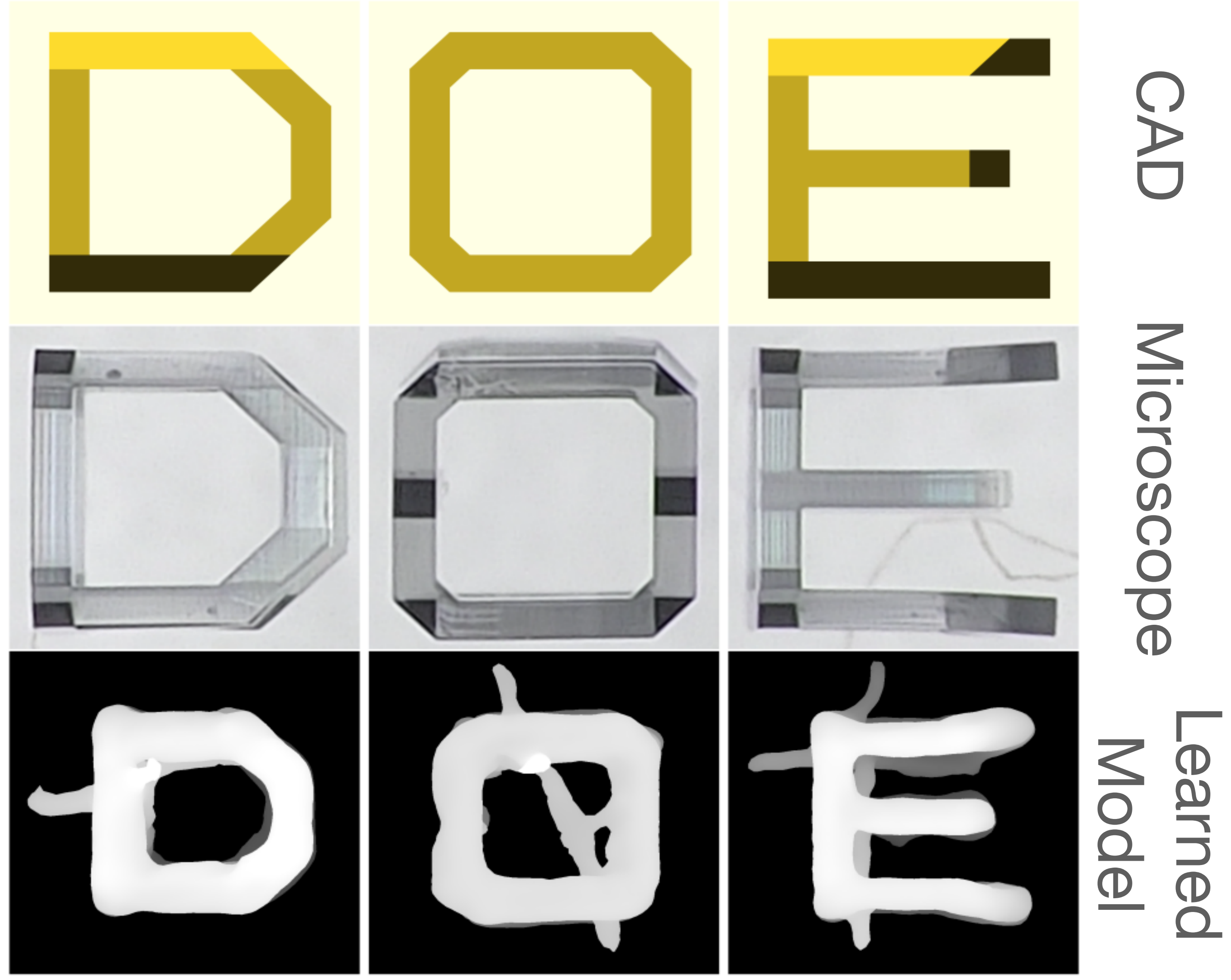
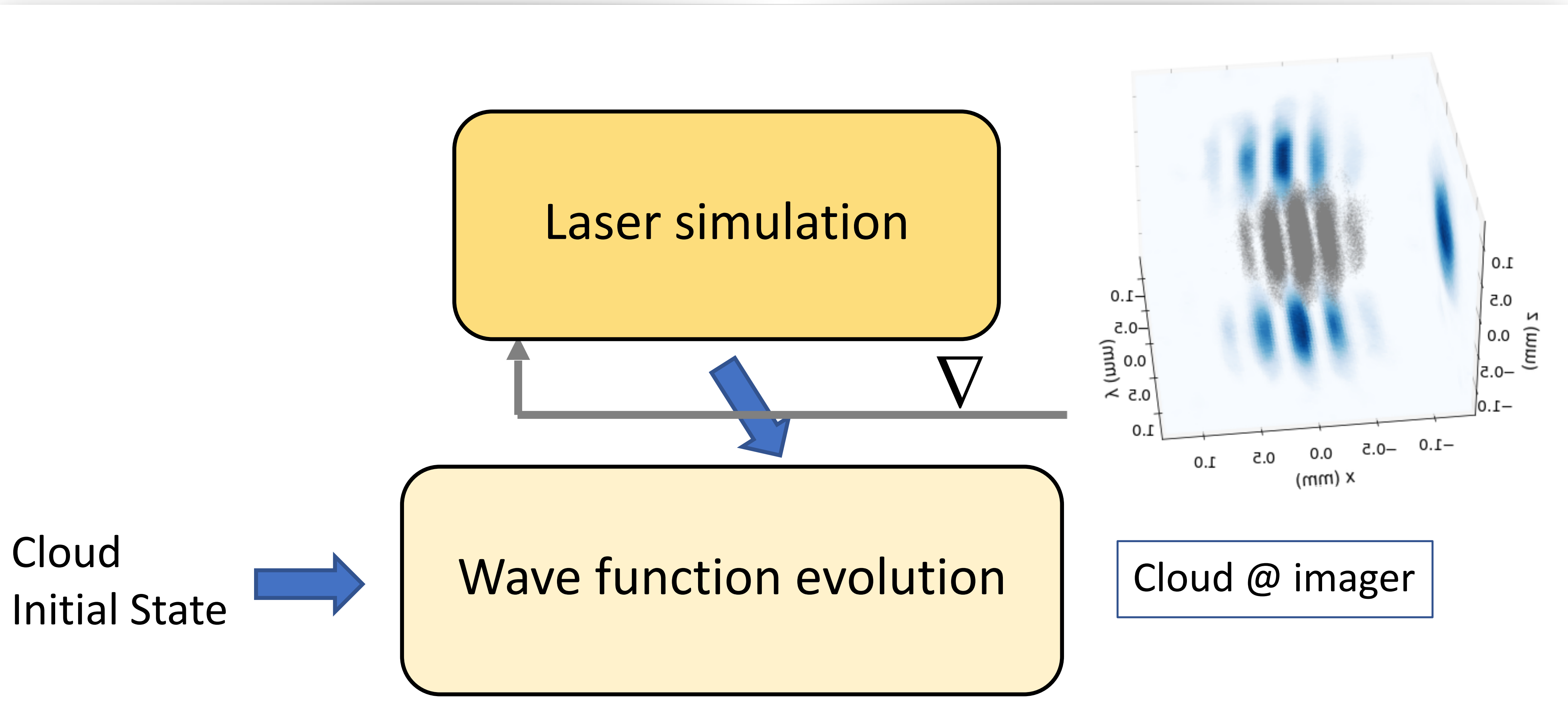




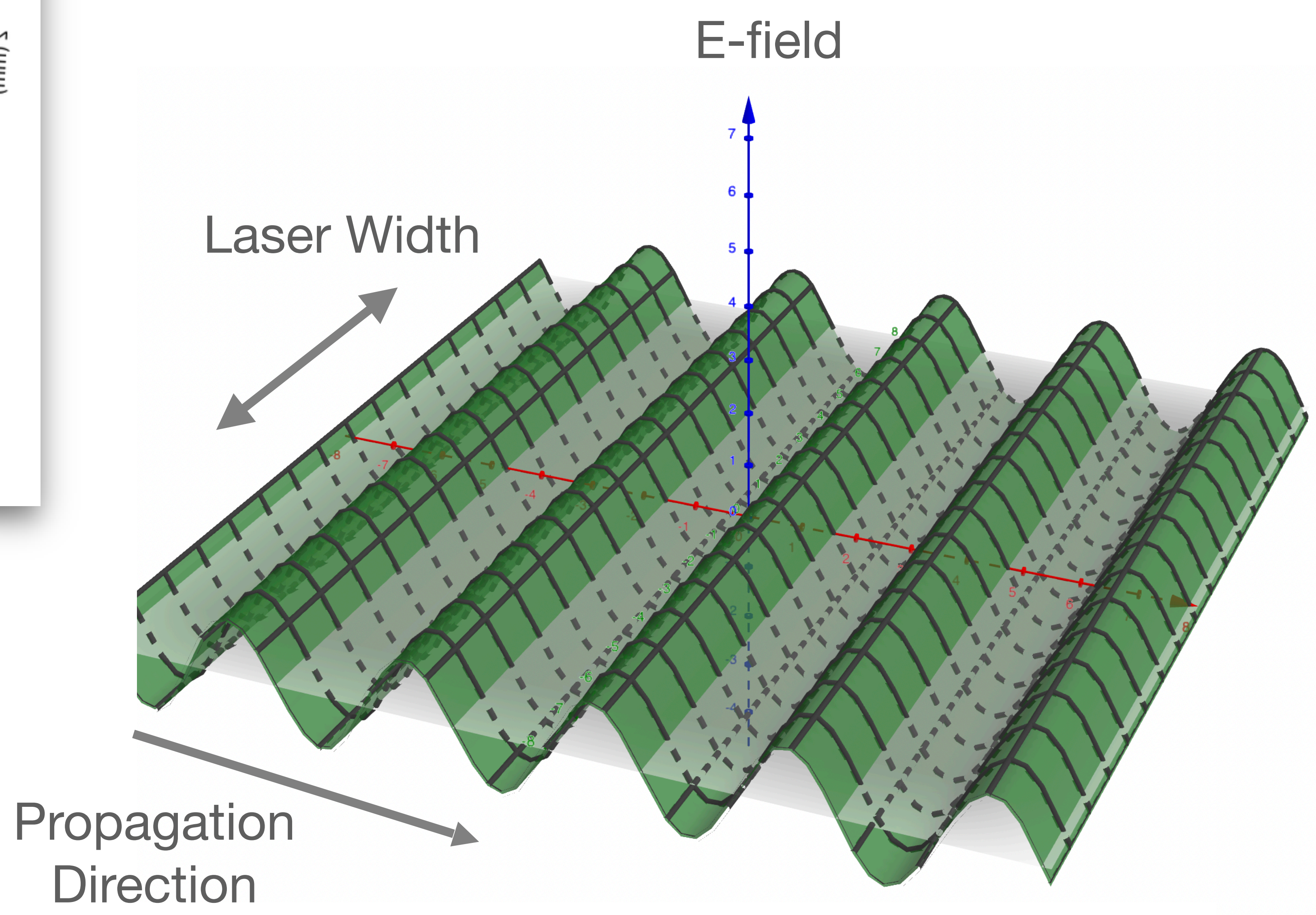


Resolution ~ 70μm
Computed using split-halves
Fourier Shell Correlation

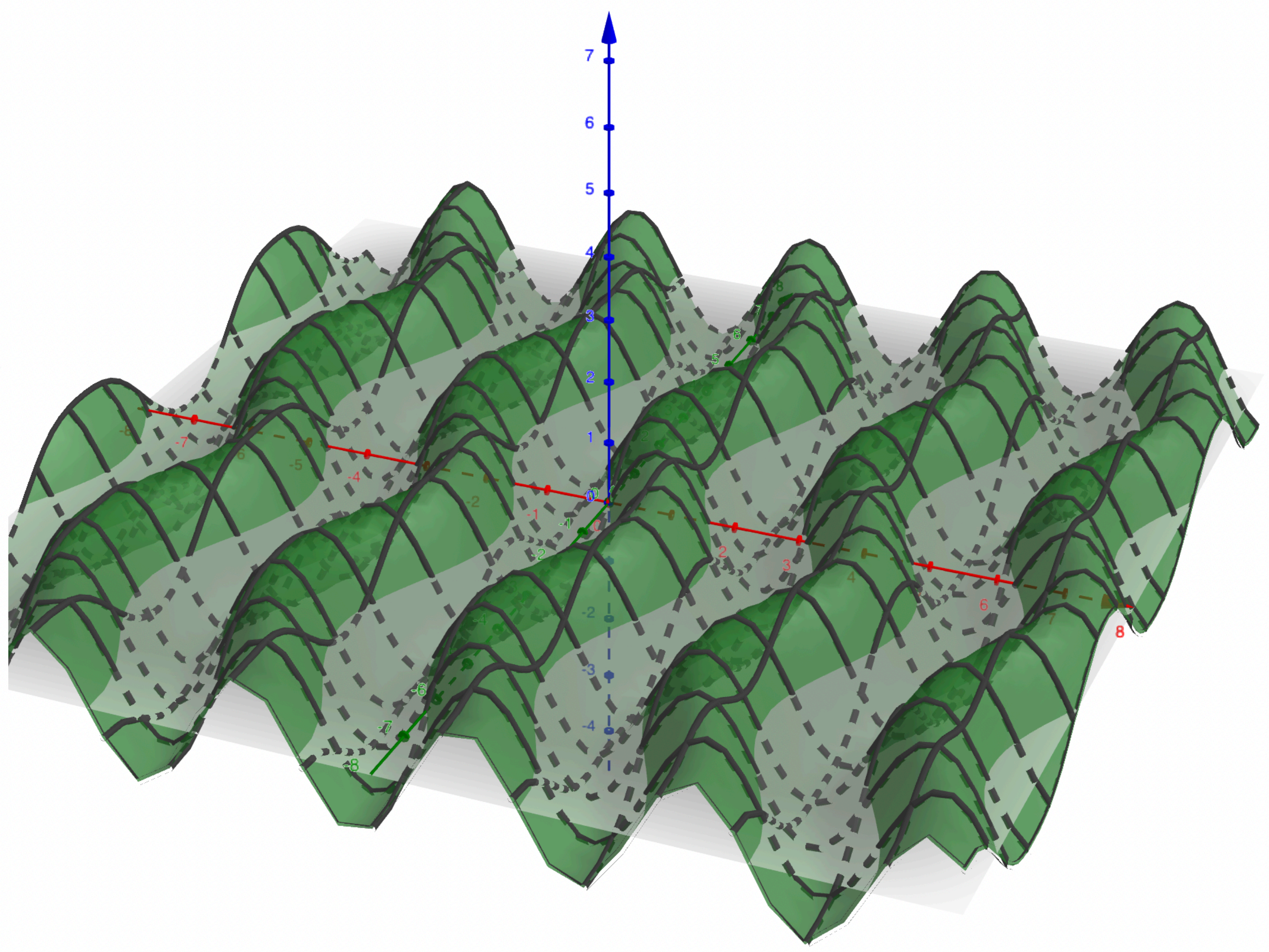
Laser Wavefront Aberrations - Key Noise Source



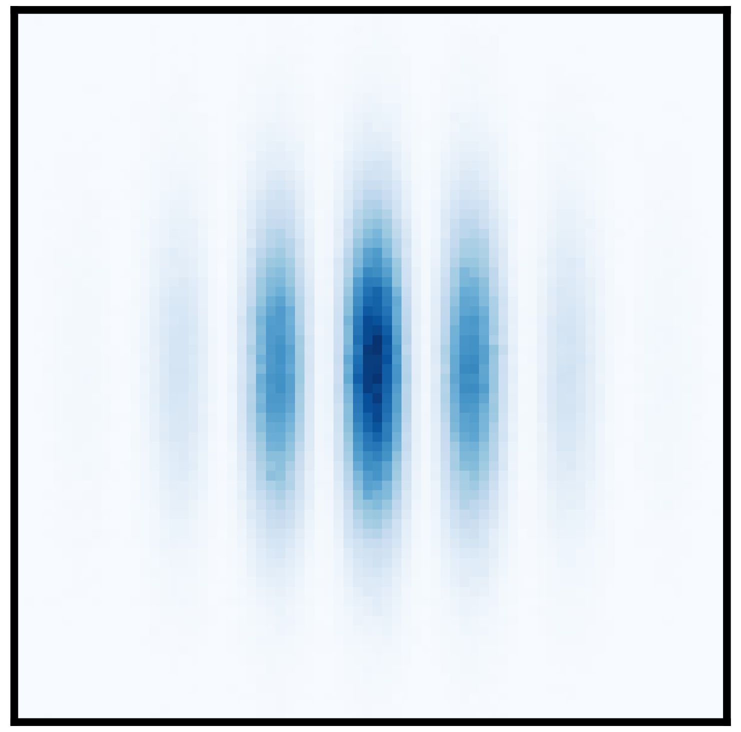
Ideal:
Flat Laser Wavefront



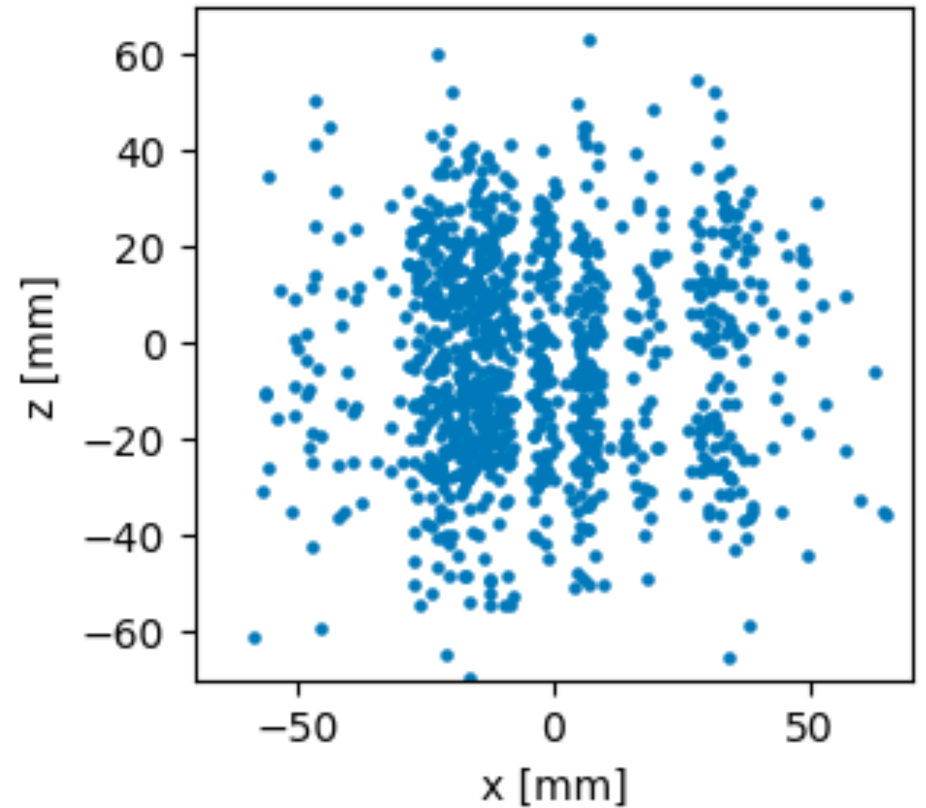
Not Ideal:
With Aberrations



Resulting Fringe Pattern:



Good: visible fringes



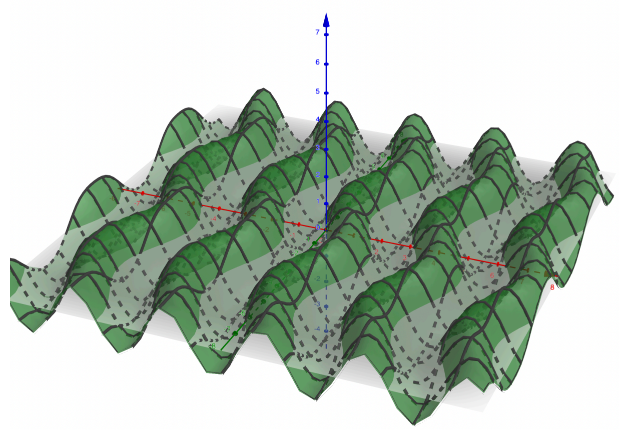
Bad: fringes perturbed

Work in Progress:
S. Gasiorowski, N. Sachdeva, **M.K.**
Y. Wang, O. Rochman, T. Kovachy

Fitting Laser Wavefront Aberrations

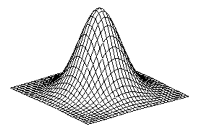
Wavefront Model

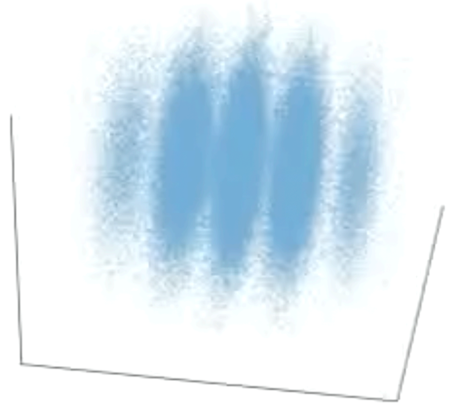
For complex aberrations, model with neural network



Wave function Evolution (ODE Solver)

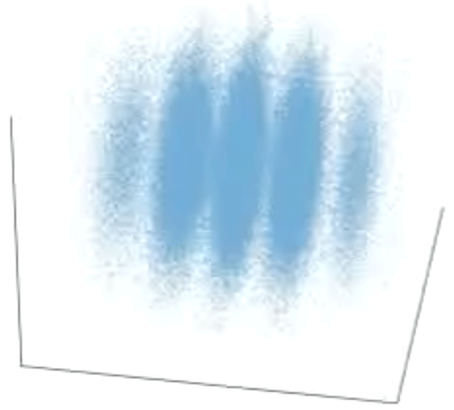
Initial State:



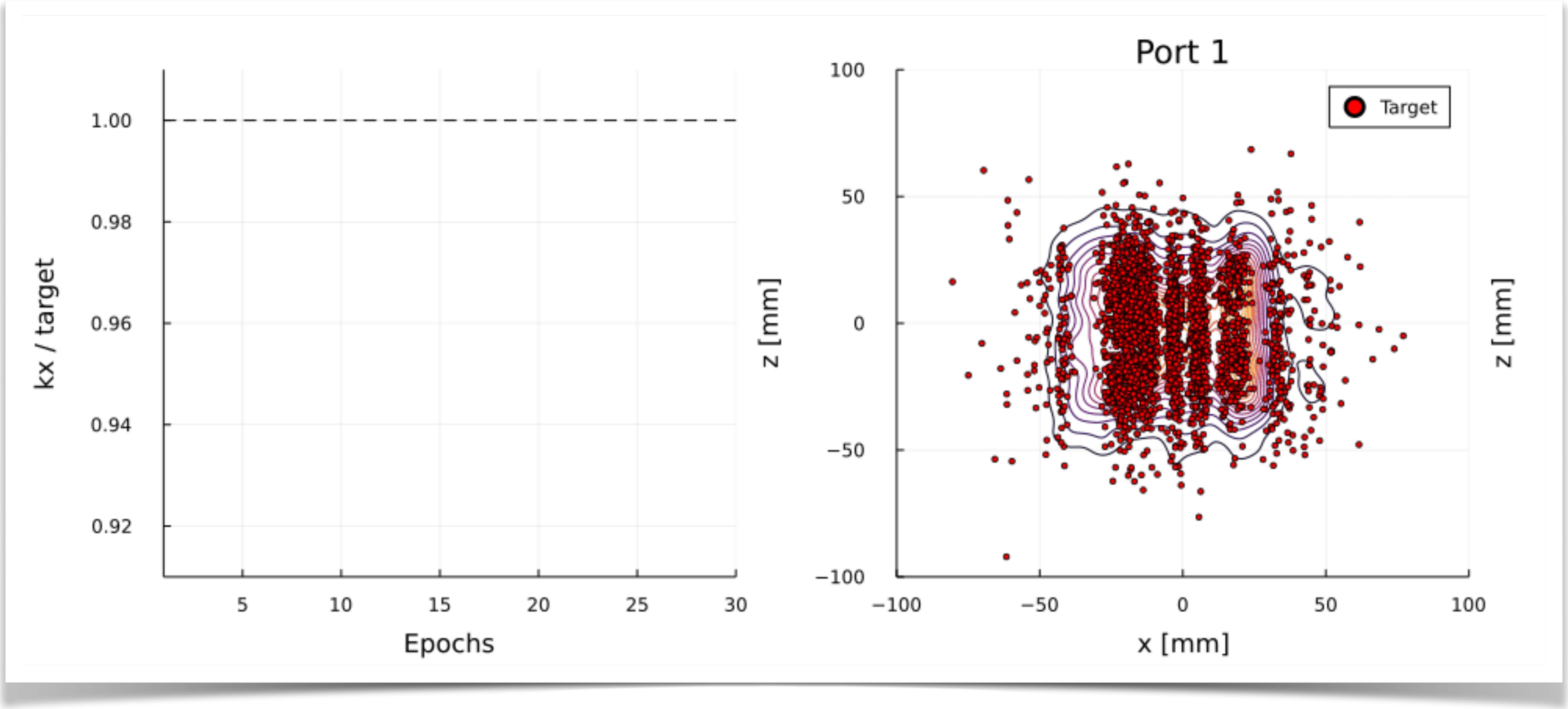


Simulated Data

Compare

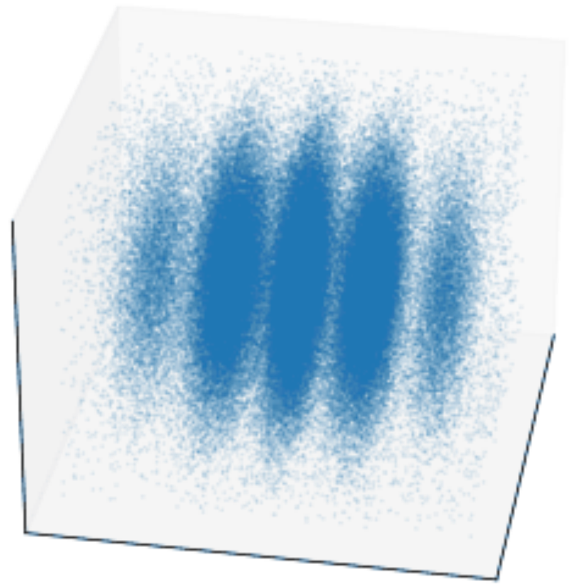


Measured Data



Summary

Atom interferometry: Exciting new frontier for gravitational waves physics and Machine Learning

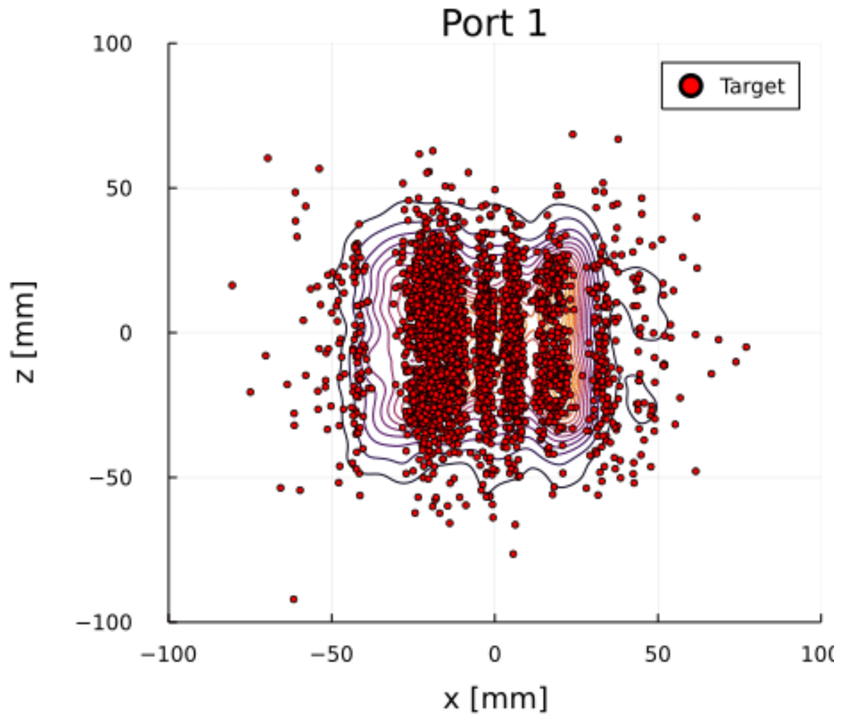


Differentiable Simulators: Open new ways to do analysis

- Significantly easier when building from the ground up

For MAGIS, many exciting challenges ahead:

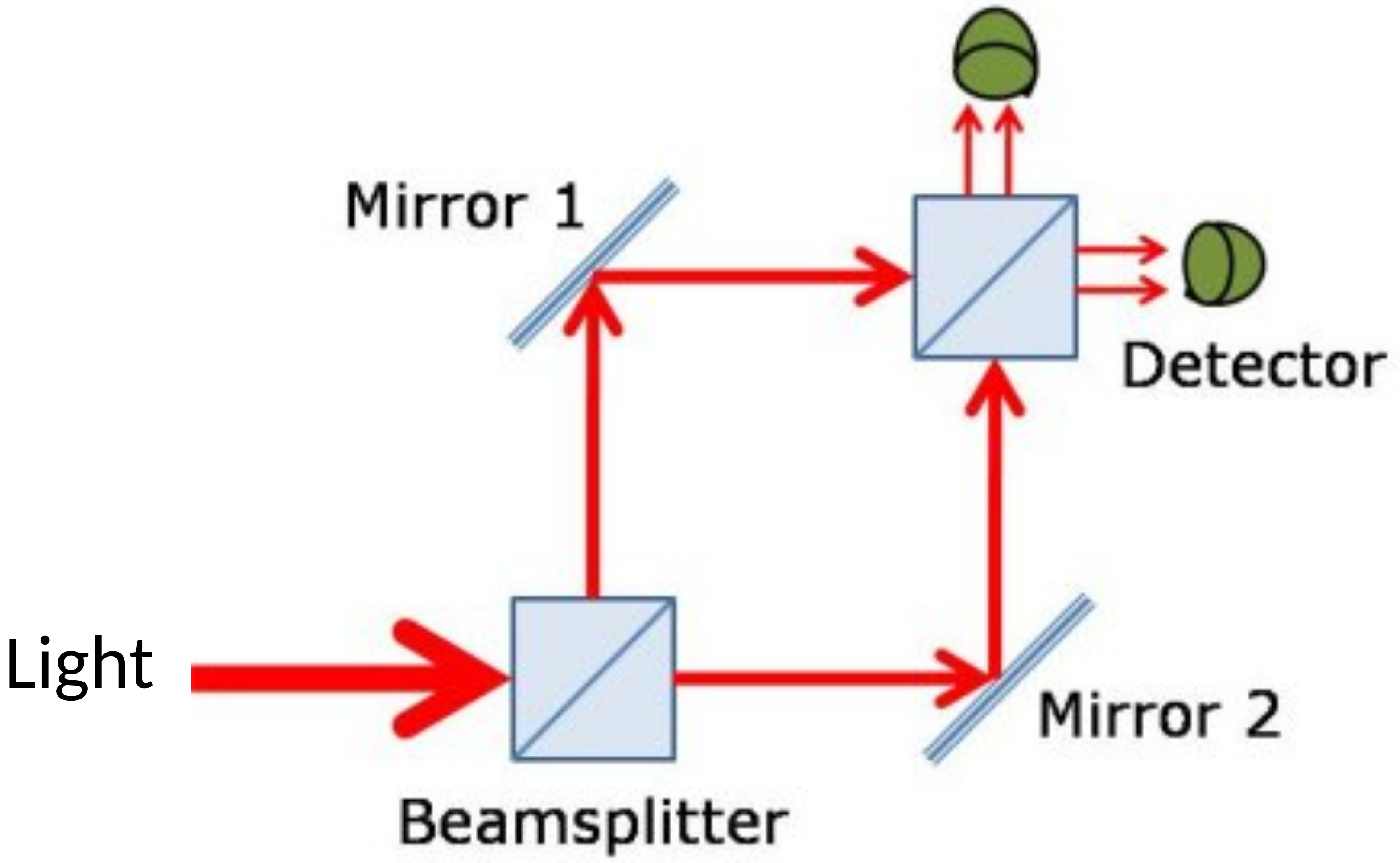
- How to do large scale $O(10^6)$ trajectory simulations fast
- How to perform inference (extract phase) from 3D reconstruction
- Gradient-based system design and calibration
- Solving ODE / PDE directly using neural fields?
- …

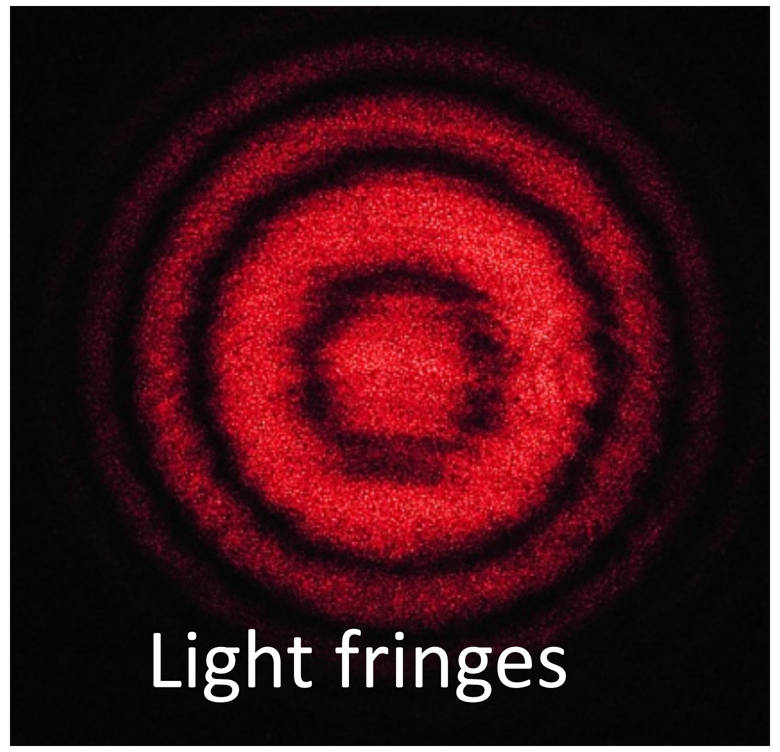


Backup

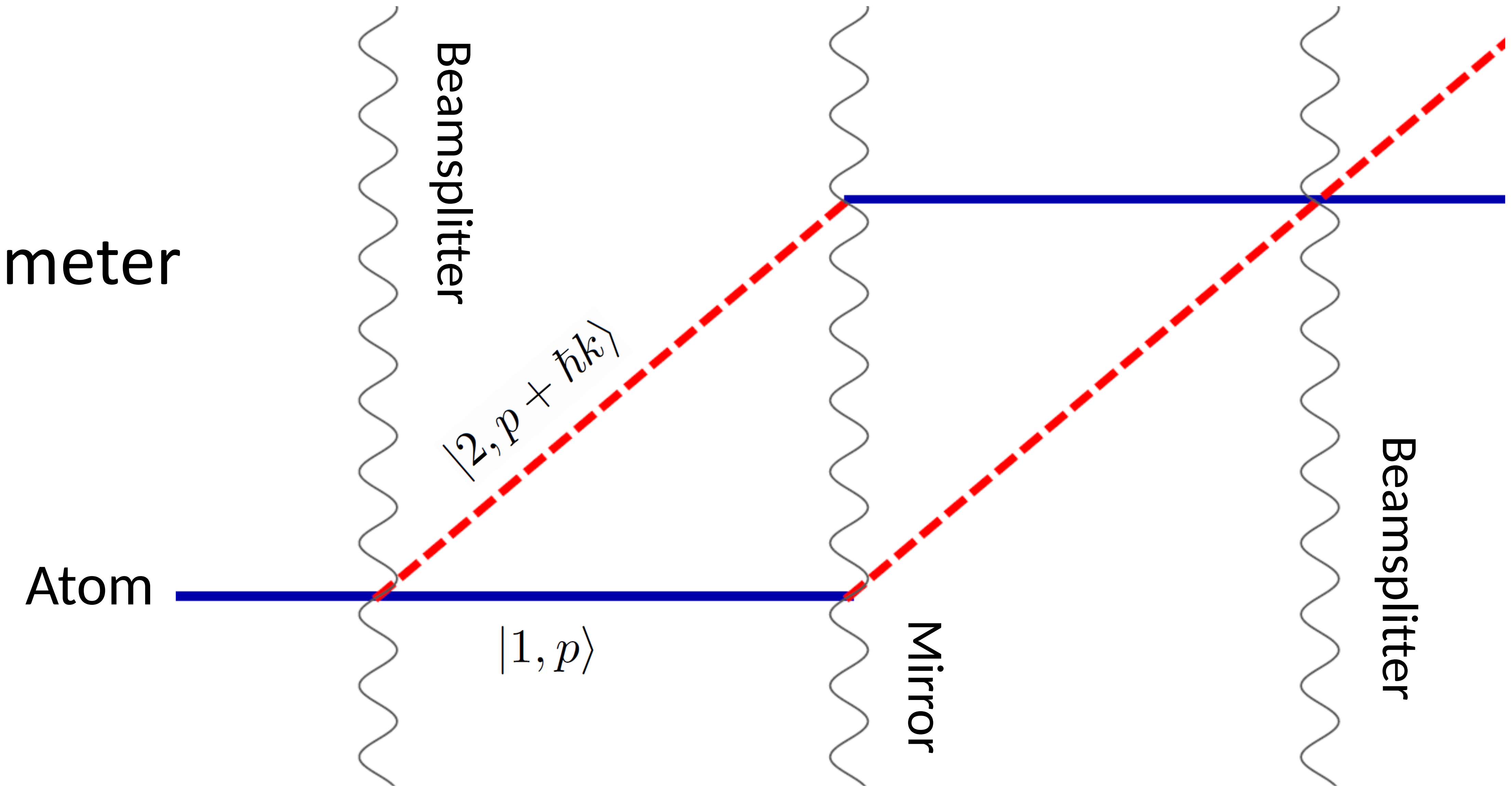
Atom Interference

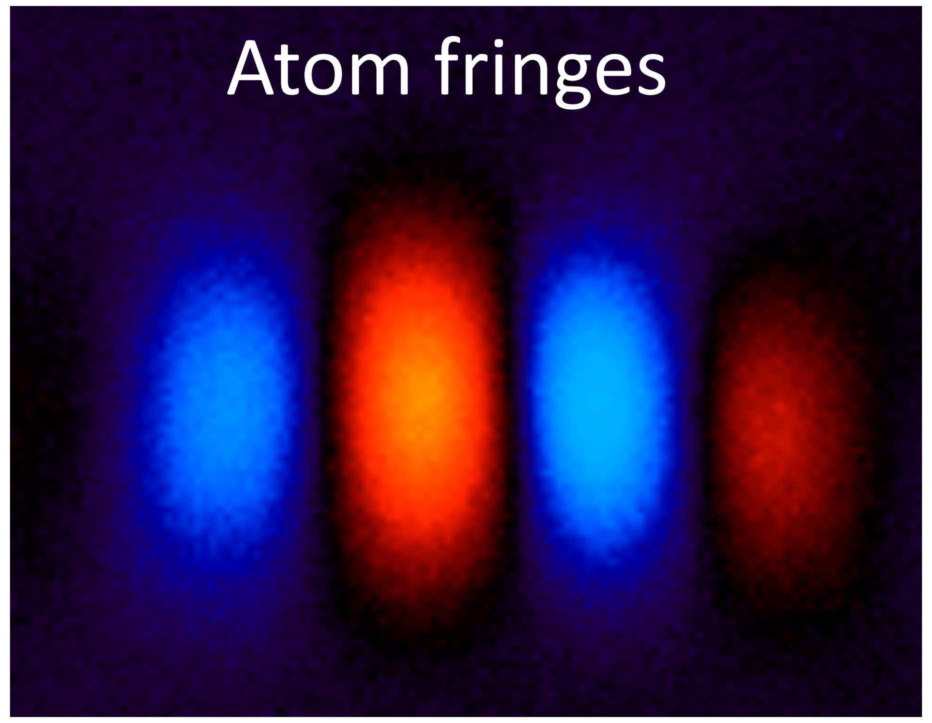
Light interferometer



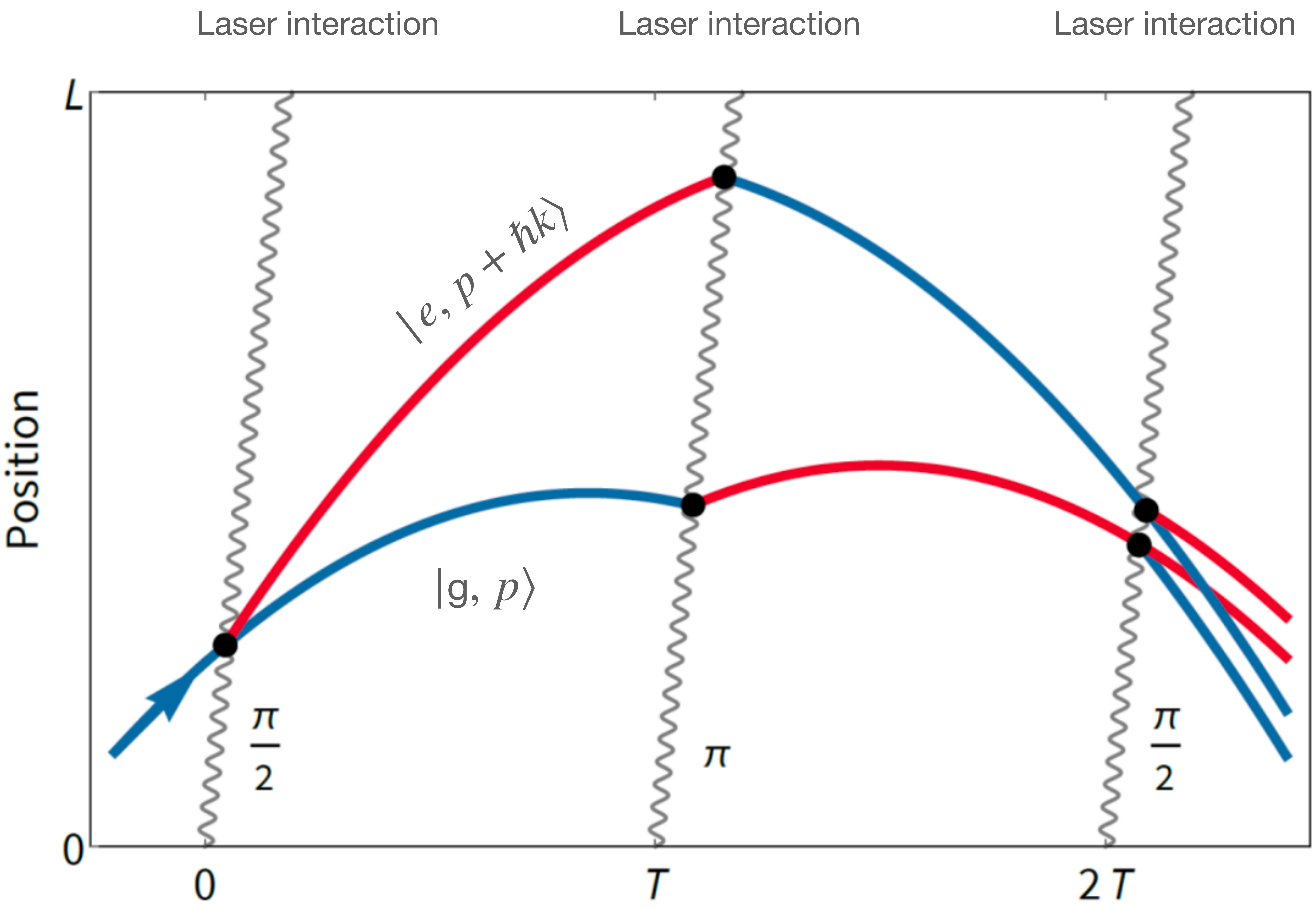

Light fringes

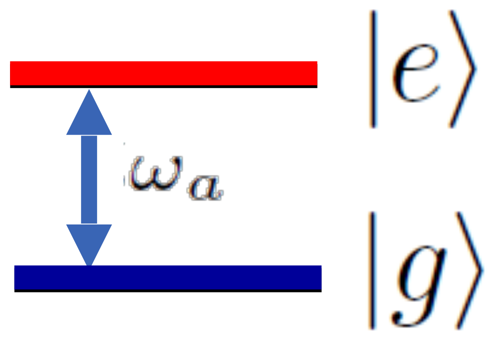
Atom interferometer




Atom fringes

Single Atom Interferometer

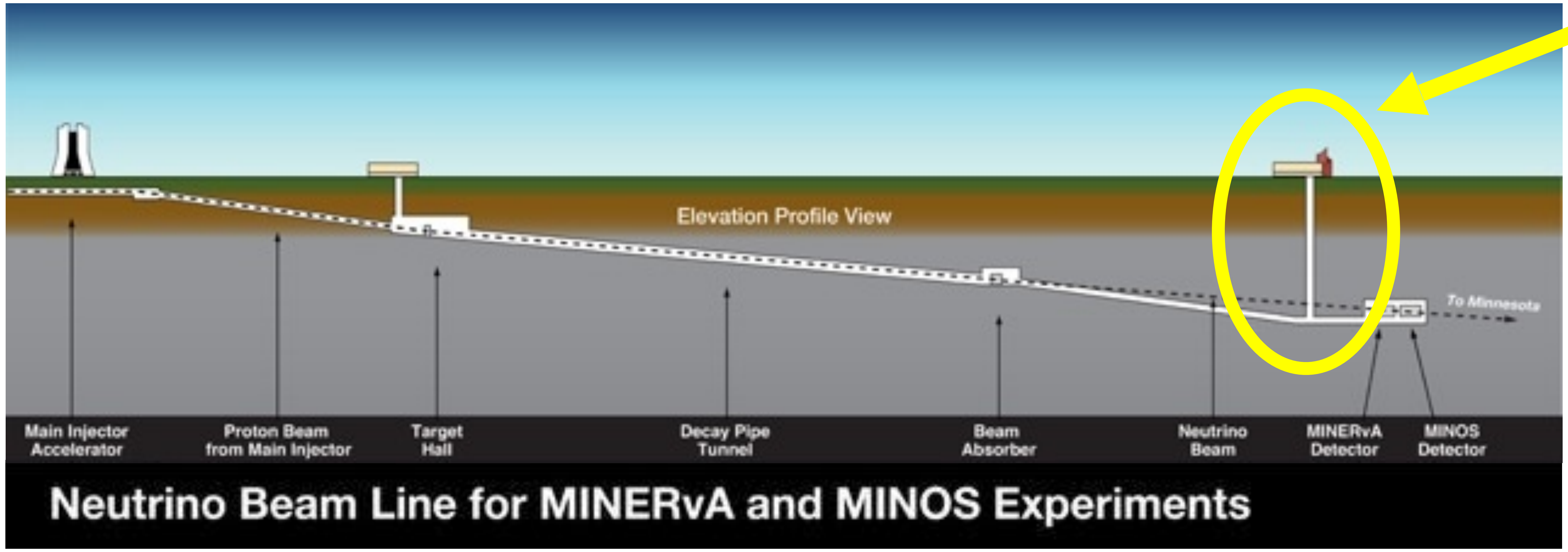




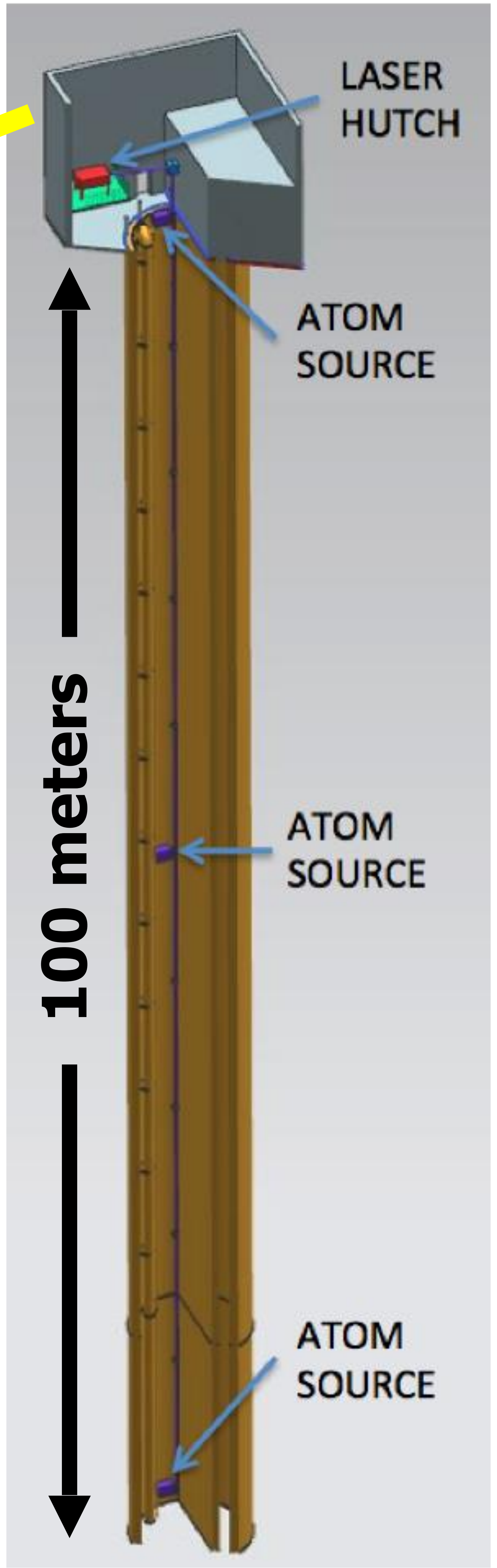
MAGIS-100

arXiv:2104.02835

Matter wave **A**tomic **G**radiometer **I**nterferometric **S**ensor



Neutrino Beam Line for MINERvA and MINOS Experiments



- 100-meter baseline atom interferometry in existing shaft at Fermilab
- Intermediate step to full-scale (km) detector for gravitational waves
- Clock atom sources (Sr) at three positions to realize a gradiometer
- Extreme quantum superposition states: several meter separation, up to 9 s duration
- Launch rate ~1Hz

STANFORD
JOHNS HOPKINS UNIVERSITY
Northwestern University
Fermilab
SLAC
UNIVERSITY OF CAMBRIDGE
Northern Illinois University
UNIVERSITY OF OXFORD
UNIVERSITY OF LIVERPOOL

Phase Extraction & Uncertainties

Many systematic effects can be sources of noise in phase measurements

- Especially laser wavefront variations – i.e. laser phase varying spatially

Goal: 3D Cloud Reconstruction

Why:

- Increased light detection
- Model spatially varying systematic effects

How: Single-Shot Multi-View Imaging System

Challenge: How to reconstruct the cloud in 3D?

- Tomographic imaging with complex geometry

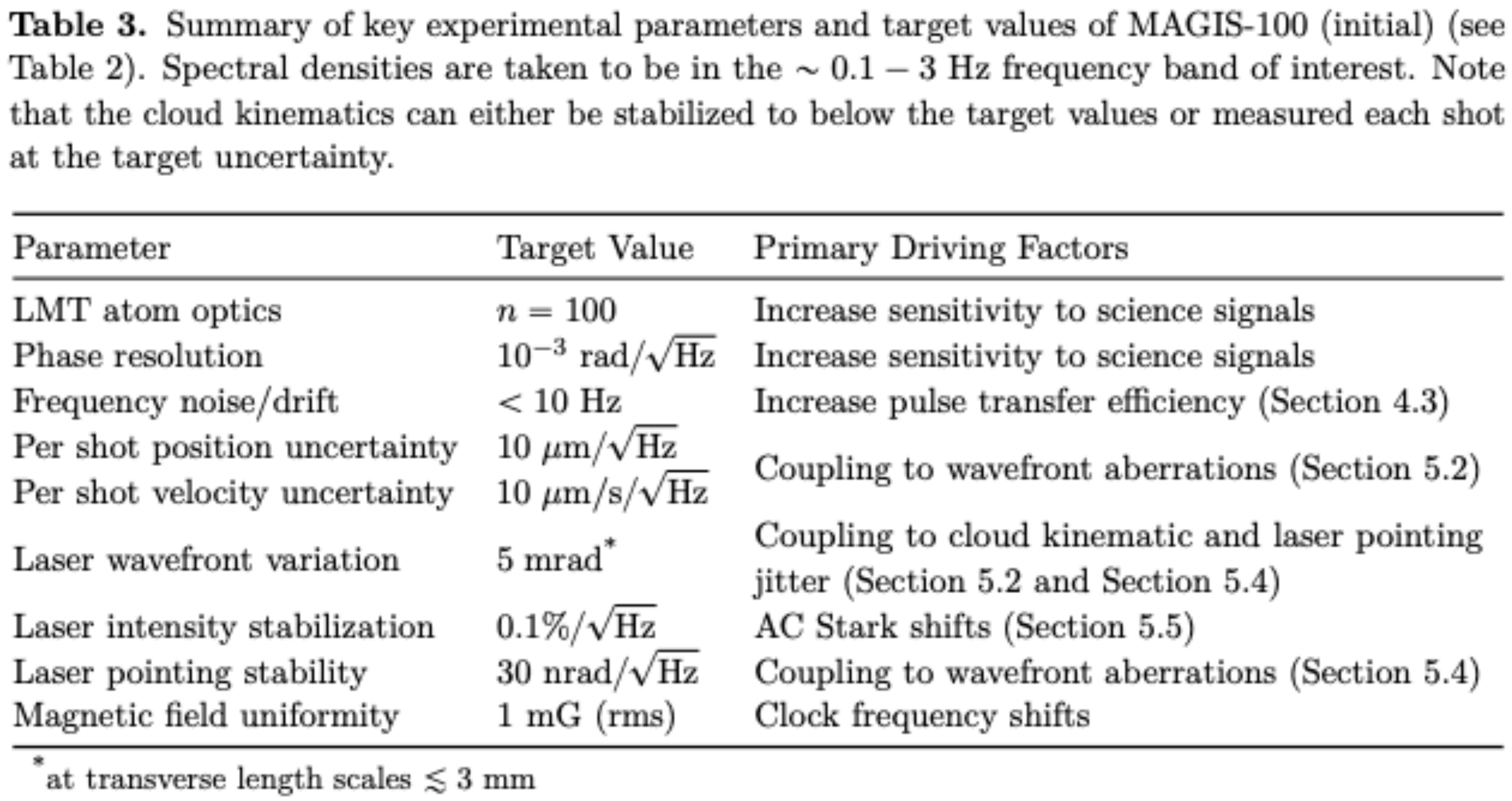


Table 3. Summary of key experimental parameters and target values of MAGIS-100 (initial) (see Table 2). Spectral densities are taken to be in the $\sim 0.1 - 3$ Hz frequency band of interest. Note that the cloud kinematics can either be stabilized to below the target values or measured each shot at the target uncertainty.

Parameter	Target Value	Primary Driving Factors
LMT atom optics	$n = 100$	Increase sensitivity to science signals
Phase resolution	10^{-3} rad/$\sqrt{\text{Hz}}$	Increase sensitivity to science signals
Frequency noise/drift	< 10 Hz	Increase pulse transfer efficiency (Section 4.3)
Per shot position uncertainty	10 μm/$\sqrt{\text{Hz}}$	Coupling to wavefront aberrations (Section 5.2)
Per shot velocity uncertainty	10 μm/s/$\sqrt{\text{Hz}}$	
Laser wavefront variation	5 mrad*	Coupling to cloud kinematic and laser pointing jitter (Section 5.2 and Section 5.4)
Laser intensity stabilization	0.1%/$\sqrt{\text{Hz}}$	AC Stark shifts (Section 5.5)
Laser pointing stability	30 nrad/$\sqrt{\text{Hz}}$	Coupling to wavefront aberrations (Section 5.4)
Magnetic field uniformity	1 mG (rms)	Clock frequency shifts

*at transverse length scales $\lesssim 3$ mm

Neural Fields (aka Implicit Neural Representations / Coordinate Networks)

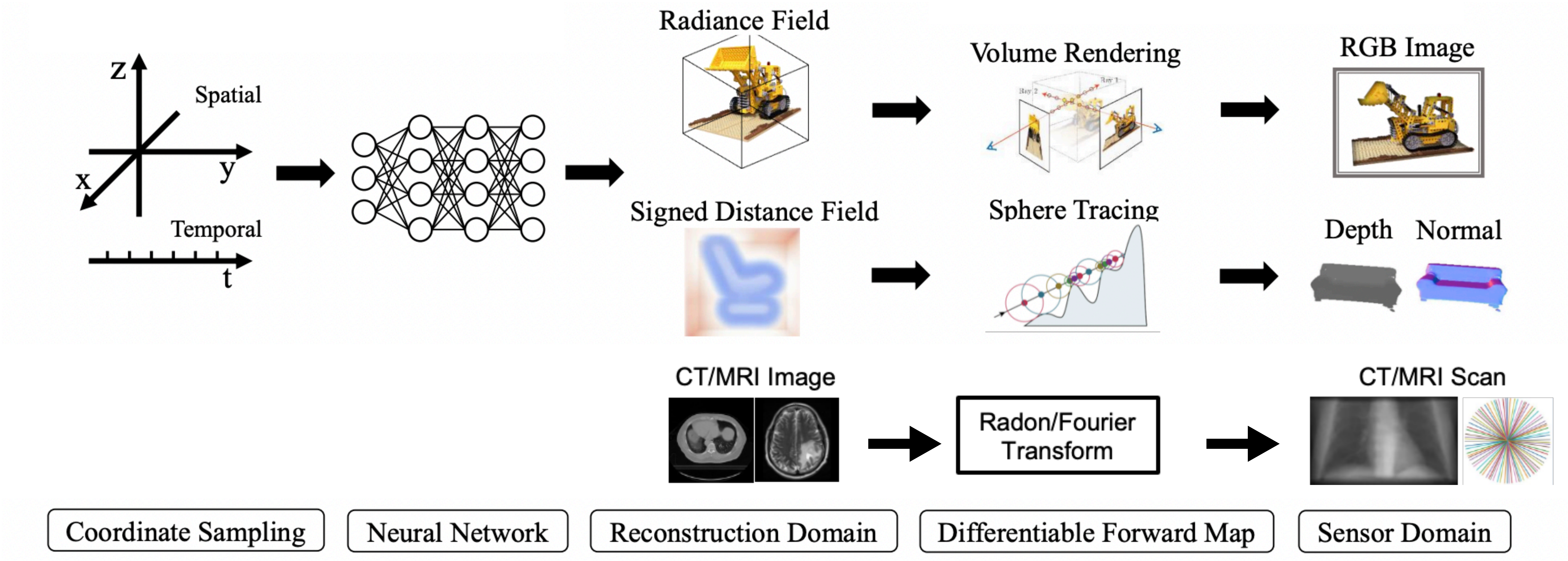
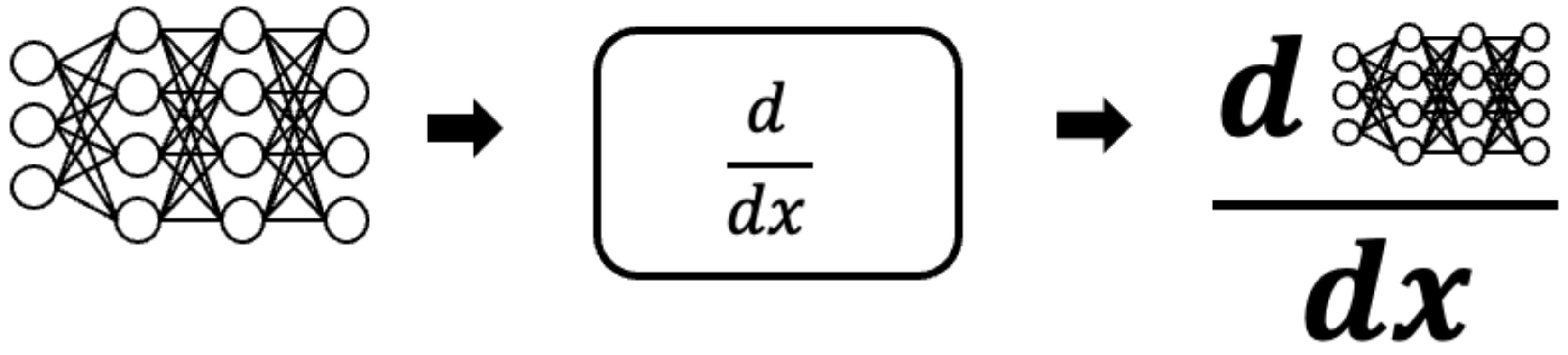


Image Credit: arXiv:2111.11426

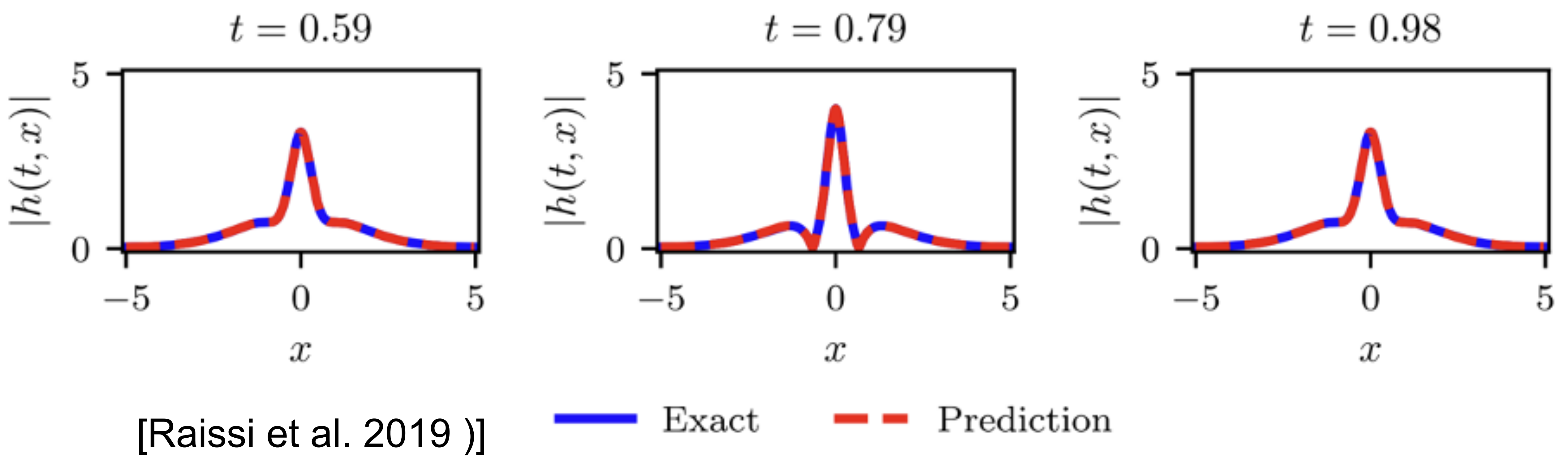
Neural Fields in Science

Physics Informed Neural Networks (PINN)

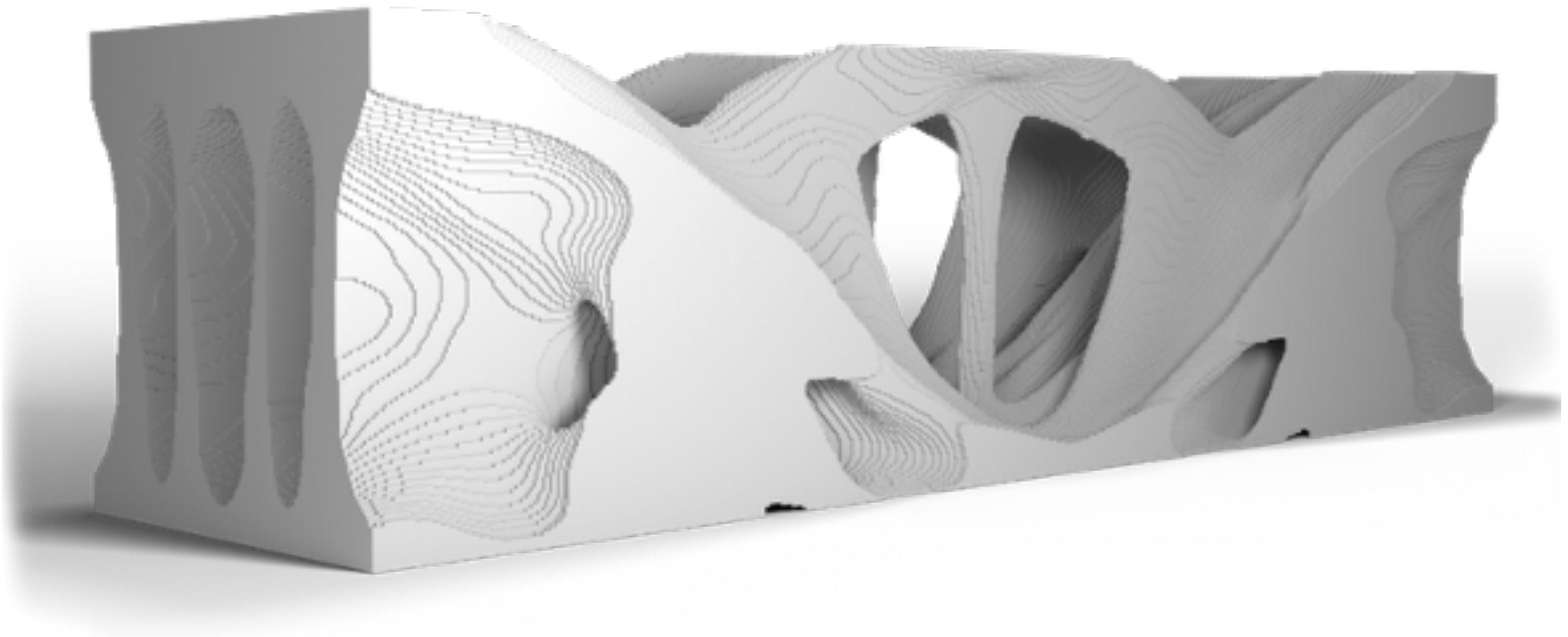


Schrödinger's Equation

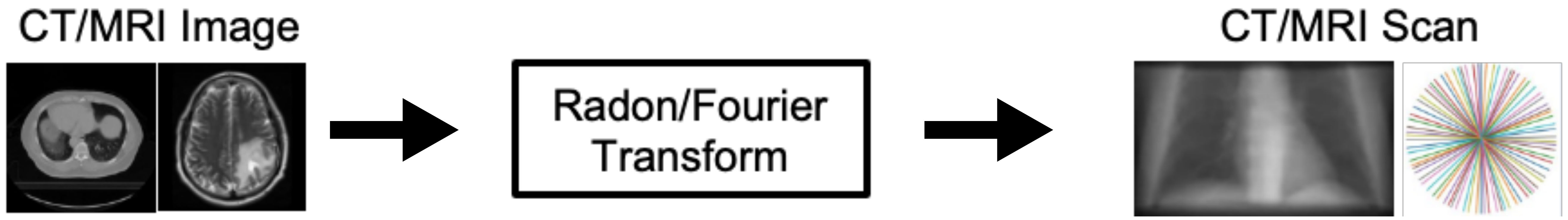
$$-\frac{\hbar^2}{2m}\nabla^2\psi + V\psi = E\psi$$



[Raissi et al. 2019)]



Material Strutural Topology Optimization
SFC 21 [Doosti et al.]



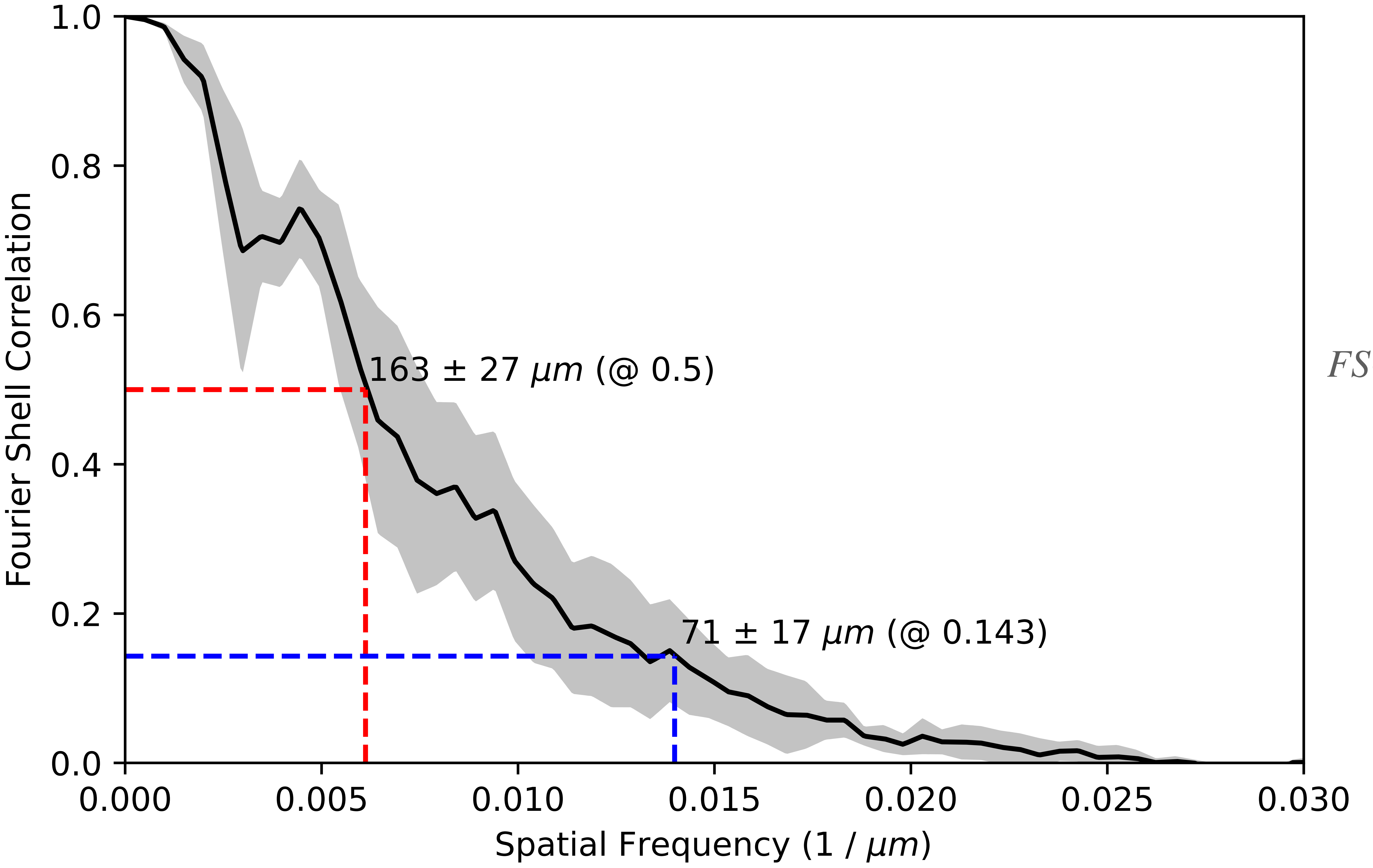
CT/MRI Image

Radon/Fourier Transform

CT/MRI Scan

arXiv:2108.10991

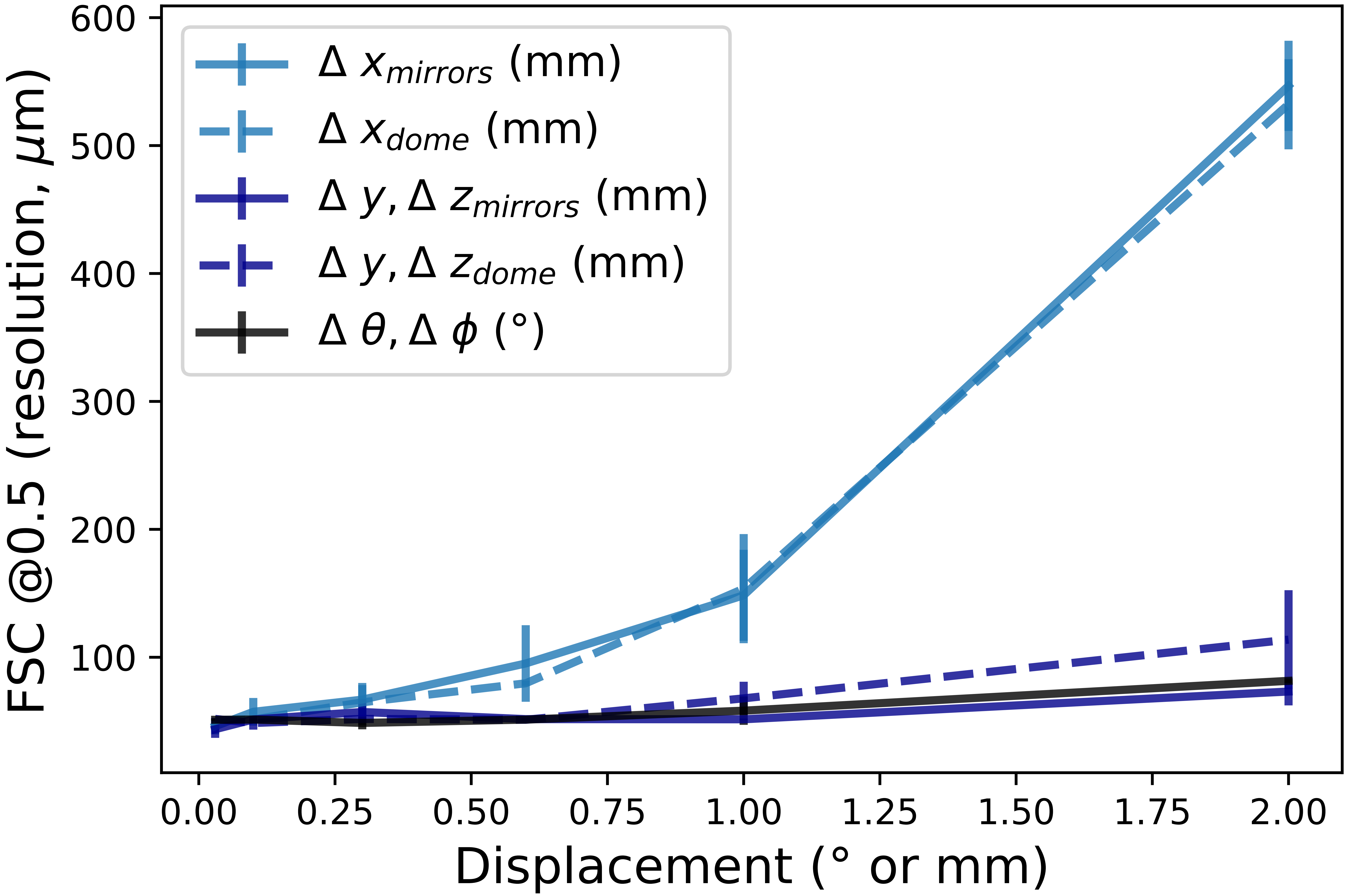
Also some examples (non-exhaustive) of neural fields in Astronomy [2105.13031][2205.11767], Cryo-EM [1909.05215], Sonar image restoration [2112.08539], …



$$FSC(s) = \frac{\sum_{|\mathbf{g}|\in s}\left(F_1(\mathbf{g})\overline{F_2(\mathbf{g})}\right)}{\sqrt{\left(\sum_{|\mathbf{g}|\in s}|F_1(\mathbf{g})|^2\right)\left(\sum_{|\mathbf{g}|\in s}|F_2(\mathbf{g})|^2\right)}}$$

F_1= Fourier Transform of Volume 1
F_2= Fourier Transform of Volume 2
s = Shell in Fourier Space

Split Halves Method:
Split number of views in half
Reconstruct two volumes, one with each half
Compare with FSC



$$FSC(s) = \frac{\sum_{|\mathbf{g}|\in s}\left(F_1(\mathbf{g})\overline{F_2(\mathbf{g})}\right)}{\sqrt{\left(\sum_{|\mathbf{g}|\in s}|F_1(\mathbf{g})|^2\right)\left(\sum_{|\mathbf{g}|\in s}|F_2(\mathbf{g})|^2\right)}}$$

F_1= Fourier Transform of Volume 1
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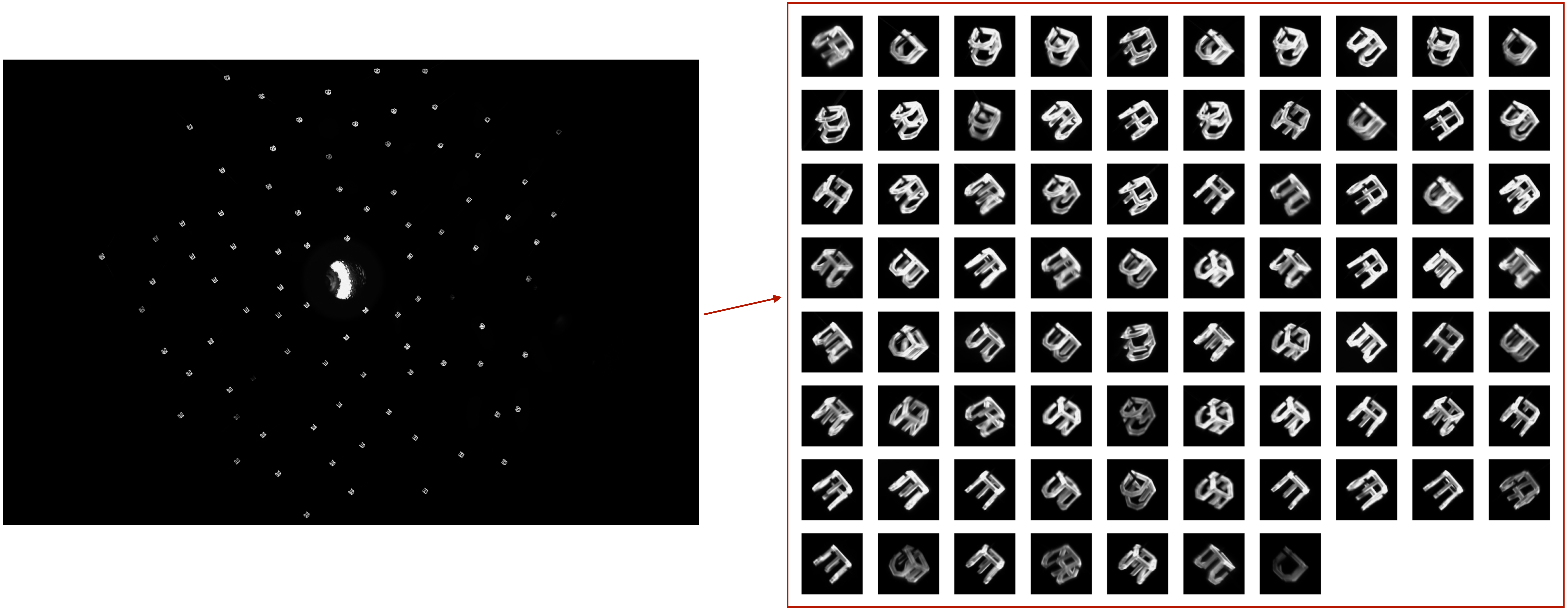
s = Shell in Fourier Space

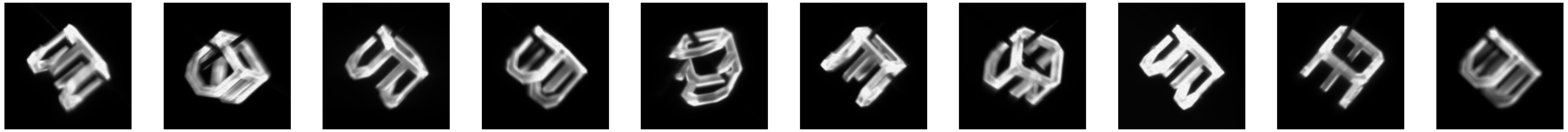
Raw Images



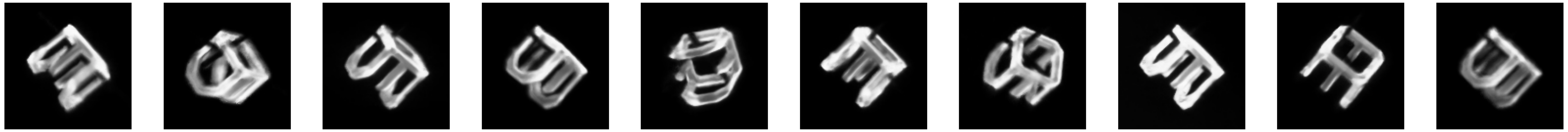
Rendering New Views

S. Cheong, J. Frisch, S. Gasiorowski, J. Hogan,
M. K., M. Safari, A. Schwartzman, M. Vandegar
arXiv:2205.11480

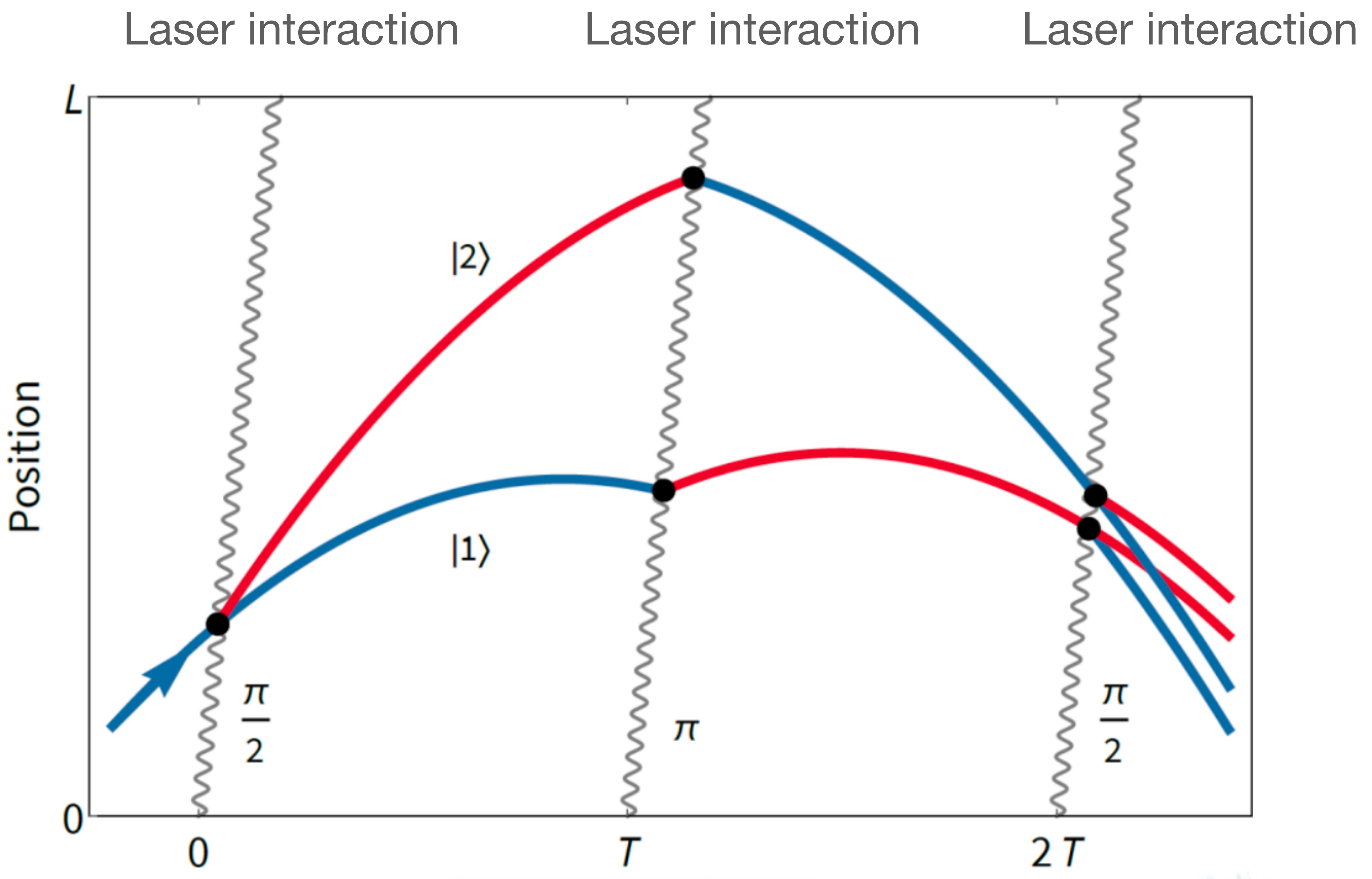
Real Views

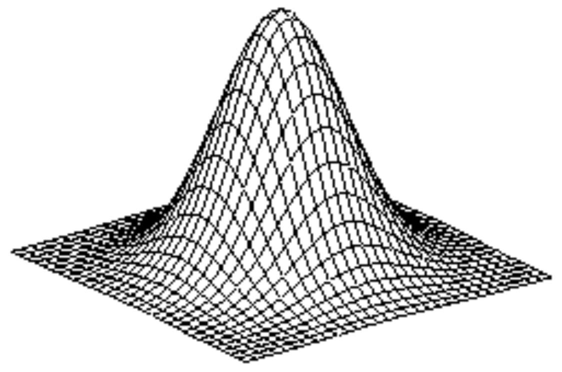


Generated Views

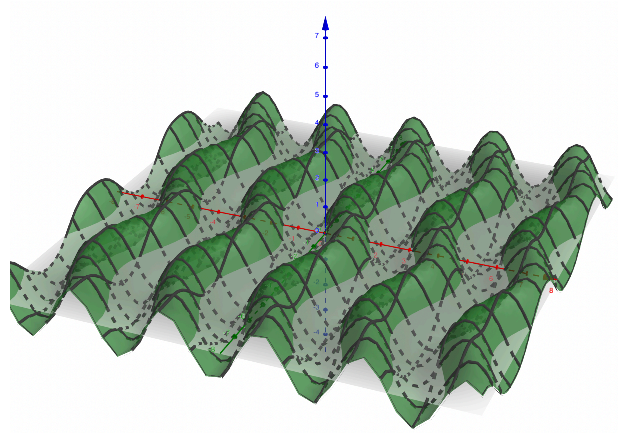


Laser Wavefront Aberrations → Inverse Problem with ODE

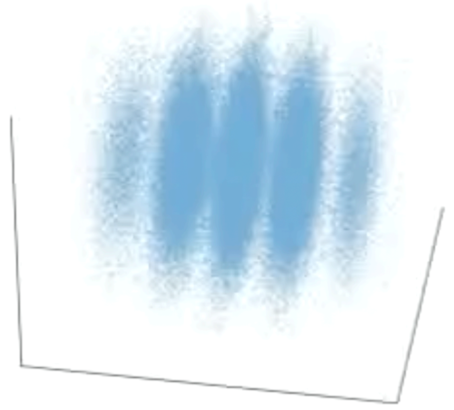




Initial State:
Known



Wavefront Aberrations:
Unknown



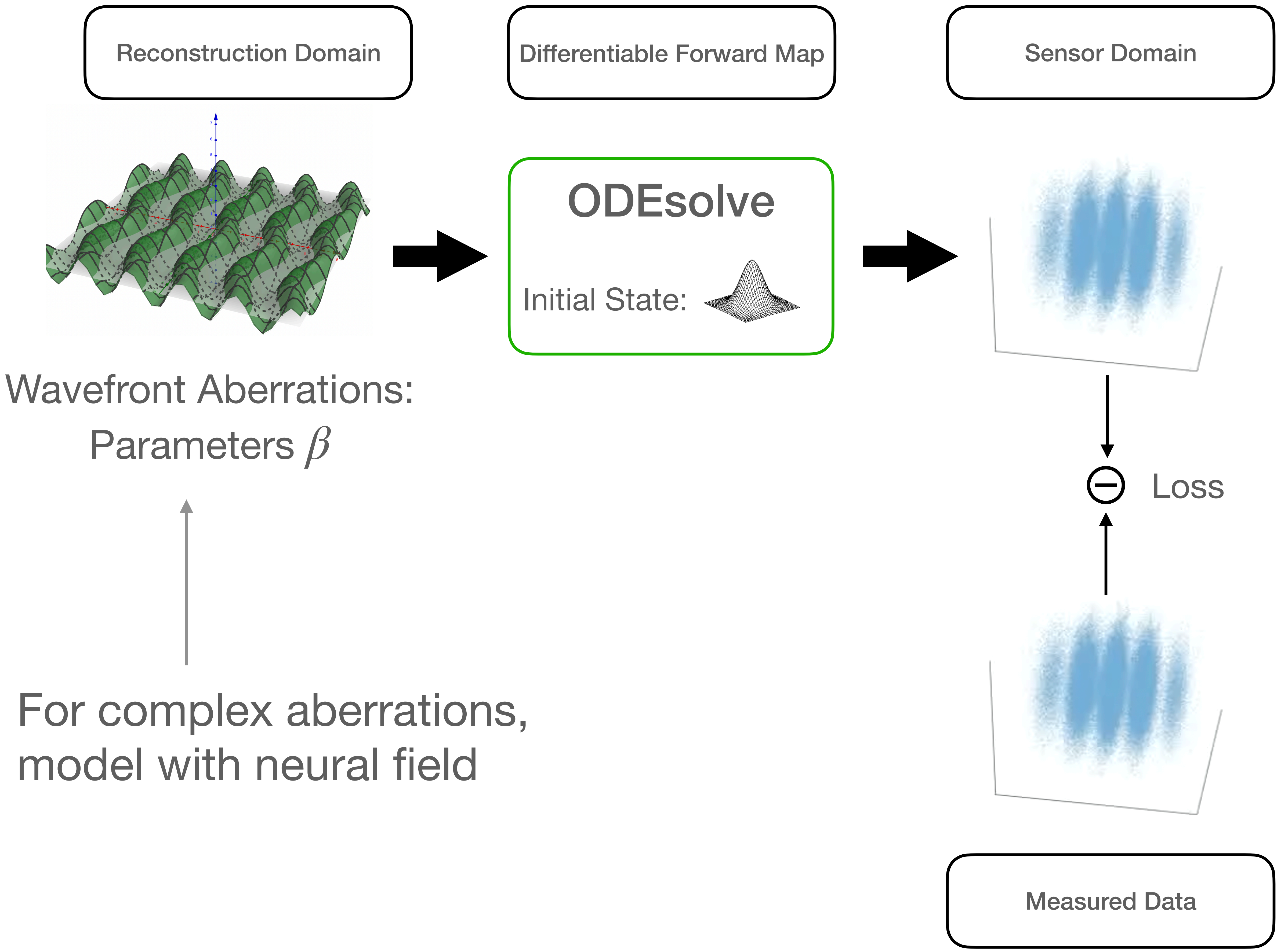
Final State:
Reconstructed

Semi-classical approximation of S.E.

- Atoms follow classical equations of motion
- Simulate trajectories with numerical ODE solver
- Compute phase using trajectories

Work in Progress:
S. Gasiorowski, N. Sachdeva, **M.K.**
Y. Wang, O. Rochman, T. Kovachy

Laser Wavefront Aberrations → Inverse Problem with ODE



Reconstruction Domain

Differentiable Forward Map

Sensor Domain

ODEsolve

Initial State:

Wavefront Aberrations:
Parameters β

Loss

Measured Data

For complex aberrations,
model with neural field

Semi-classical approximation of S.E.

- Atoms follow classical equations of motion
- Simulate trajectories with numerical ODE solver
- Compute phase using trajectories

Analysis by synthesis

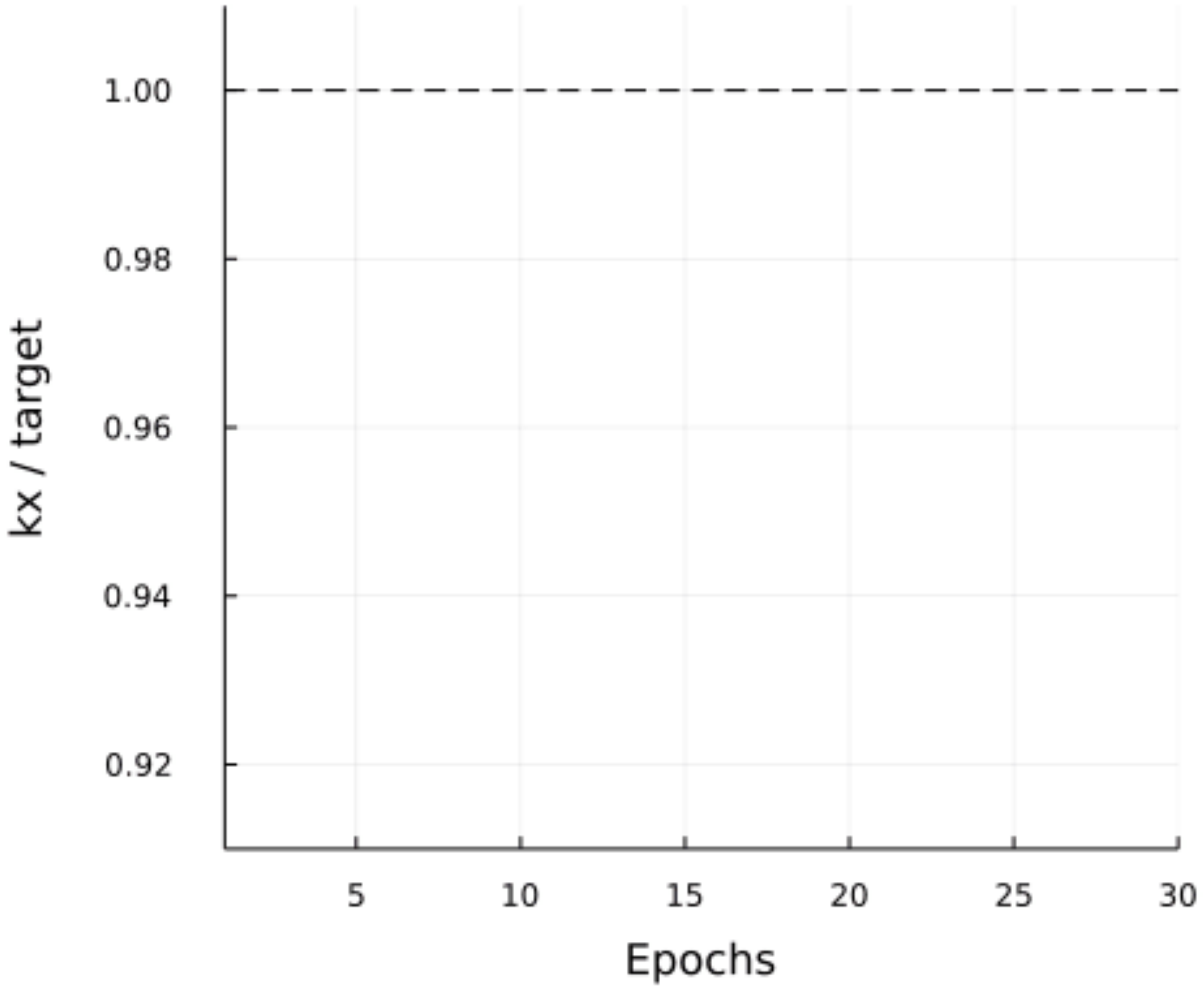
1. Simulate trajectories with ODEsolve & calculate phase
2. Compare trajectories to measured density → likelihood
3. Gradient descent on laser parameters $\beta \rightarrow$ adjoint method

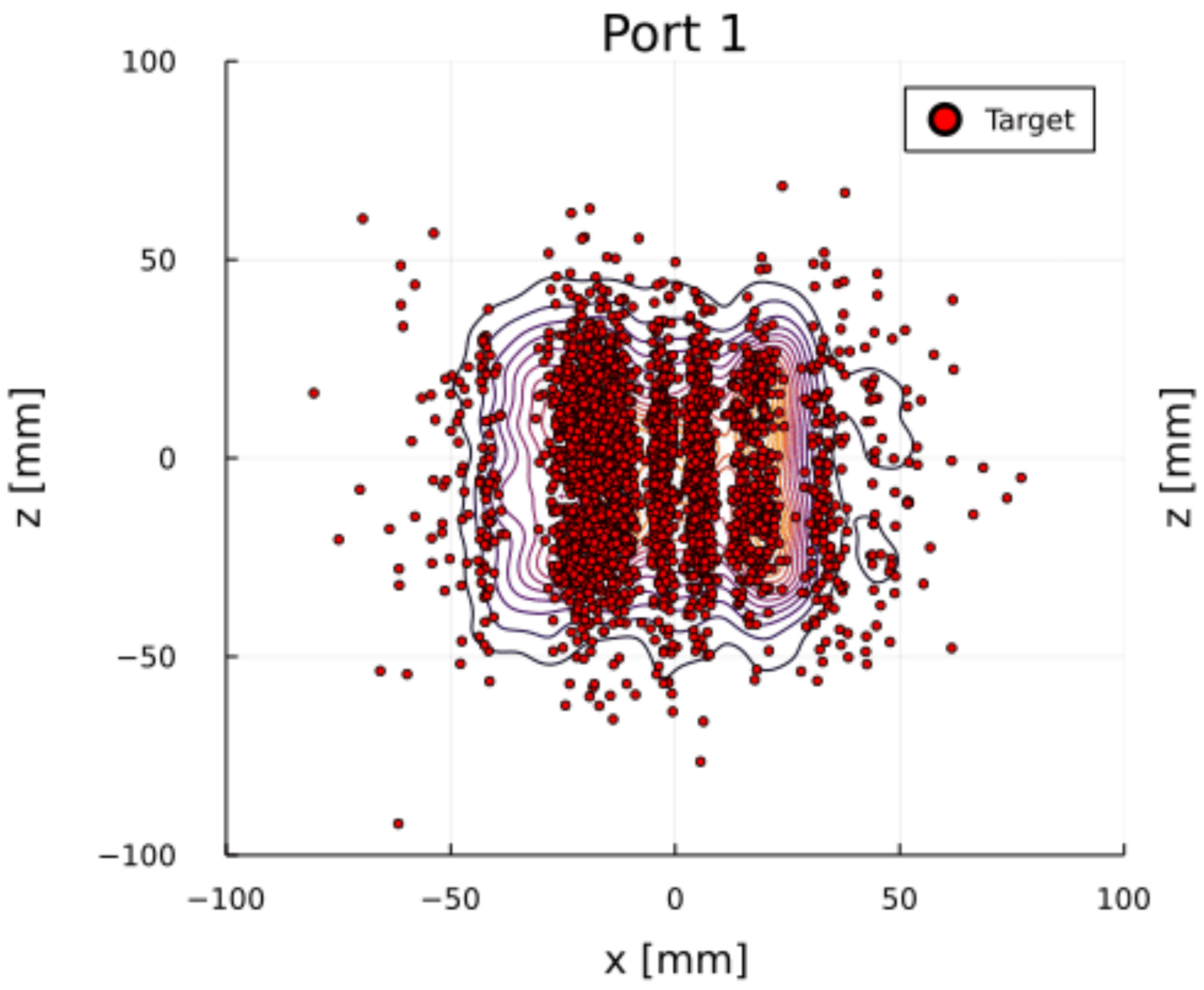
Work in Progress:
S. Gasiorowski, N. Sachdeva, **M.K.**
Y. Wang, O. Rochman, T. Kovachy

Work in Progress: Differentiating through Evolution to fit Laser Parameters

Toy Example:
- Target = Single frequency aberration
- Fit model with unknown single frequency aberration

julia Julia DiffEq Zygote





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