Novel Light-Field Imaging Device with Enhanced Light Collection for Cold Atom Clouds

JINST 17 P08021

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Session WG4: Quantum and Superconducting Detectors
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SLAC NATIONAL ACCELERATOR LABORATORY

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Stanford University | U.S. DEPARTMENT OF ENERGY

Atom Interferometers

Atom Interferometer

- Optical interferometer “flipped”
- De-localized matter-wave over two paths
- Lasers for excitation, momentum transfer, etc.
- Phase sensitive to spacetime area, properties of two states, etc.

Gradiometer or “Differential” Interferometer

- Two atom interferometers separated by some distance
- Driven by a common laser ⇒ Laser noises cancel
- **Differential phase sensitive to baseline length and energy splitting**

$$\Delta\phi \sim \omega_A L/c$$

Image from
Hogan Lab Website

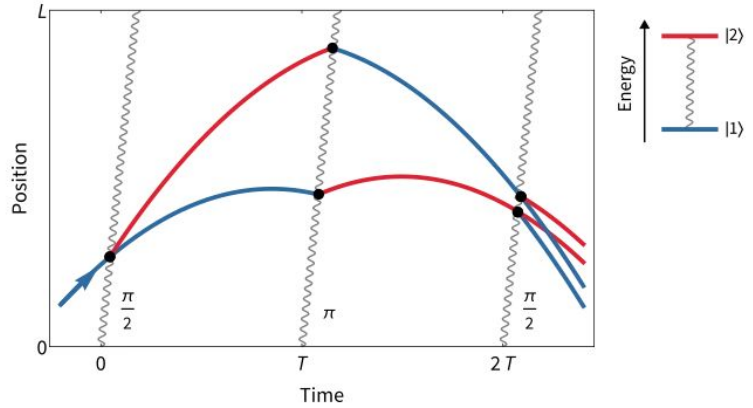

Figure 1: *Space-time diagram of an atom interferometer. A laser beam resonant with an atomic transition manipulates the internal state of the atom. The associated recoil generates a symmetric interferometer.*

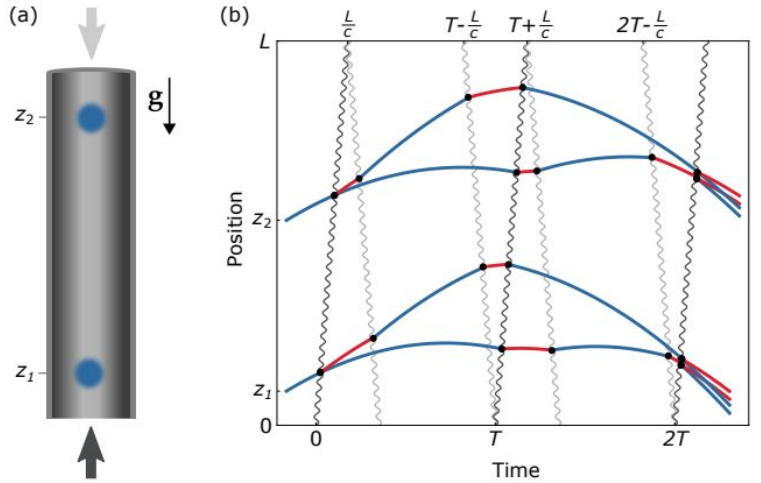

Image from
arXiv:2104.02835

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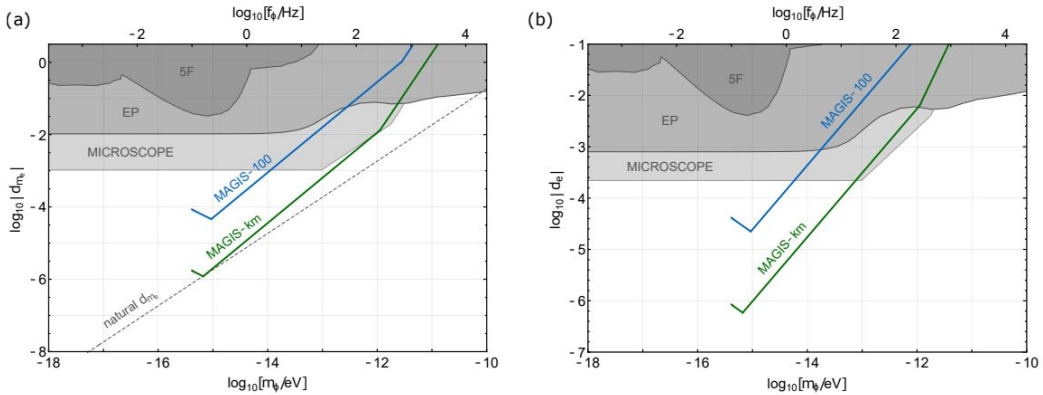
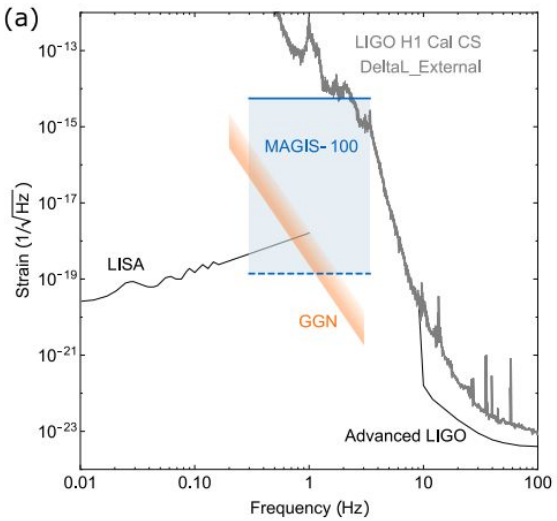
MAGIS Concept

MAGIS Experiment

- Sr clock gradiometer separated by large baseline
- Sensitive to photon- or electron-coupling ultra-light dark matter
- Sensitive to mid-band GW
- **100m experiment currently under construction @ Fermilab**
- Science paper: arXiv:2104.02835
- Also highlighted in Snowmass CF2 whitepaper recently

$$\Delta\phi \sim \omega_A L/c$$





3. **Initiate robust detector R&D program** on the detection of scalar and vector UDM with a broad range of technologies described in this review and novel detection strategies and ensure construction of detectors that are projected to improve sensitivities to UDM by many orders of magnitude. Example projects could include the development and continued support for the MAGIS program (both MAGIS-100 and its future upgrades) and nuclear clocks.

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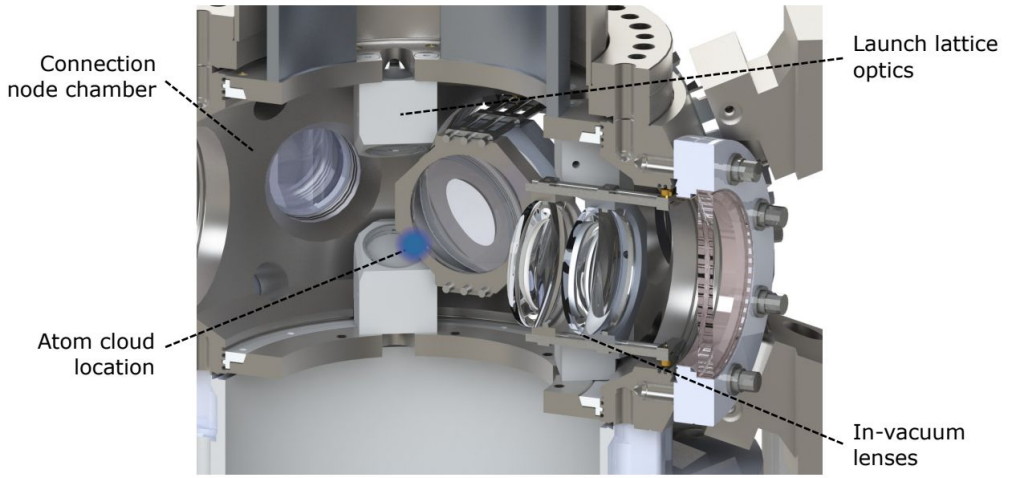
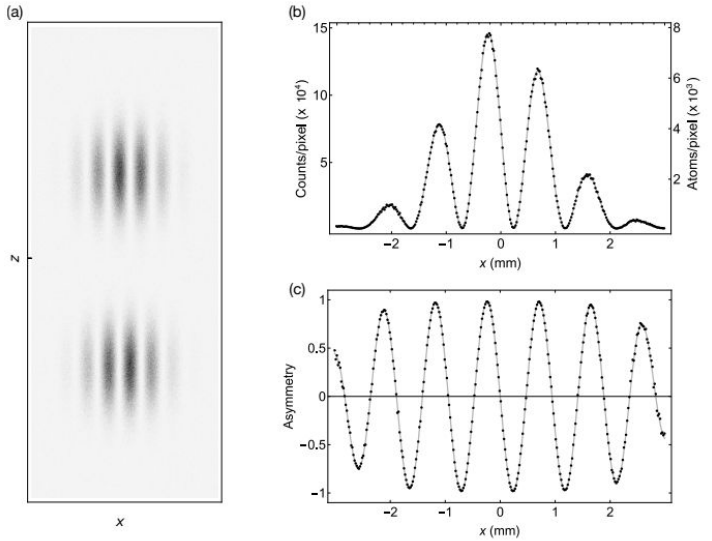
Imaging Requirements at Atom Interferometers

Expected for MAGIS and typical for many atomic experiments:

- Fluorescing cold atom clouds
  - *O*(mm) in overall size
  - *O*(100 μm) feature sizes
- **Capturing 3D light field**
  - Intensity + direction approach to imaging
  - Increase the light gathering ability of imaging
- Challenges
  - Limited number of viewports in experiments
  - More light → larger lens → shallow depth of field
  - **Common limitation in many atomic experiments**





arXiv:2203.14915

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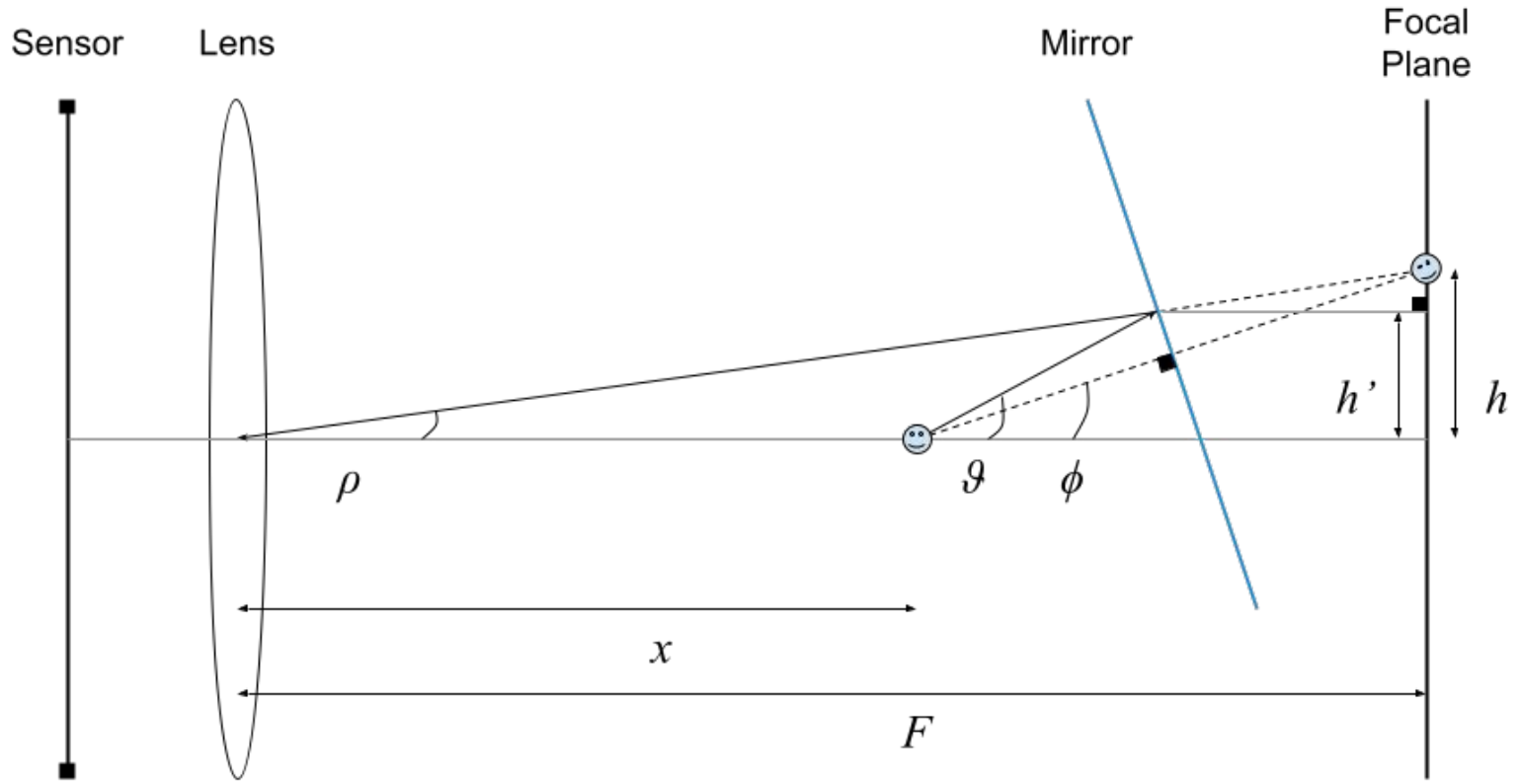
Mirrors to the Rescue

Geometry of a single “view”

Redirect light that is not traveling to the lens with mirrors

Each view direction from the object is mapped to a unique point on the sensor



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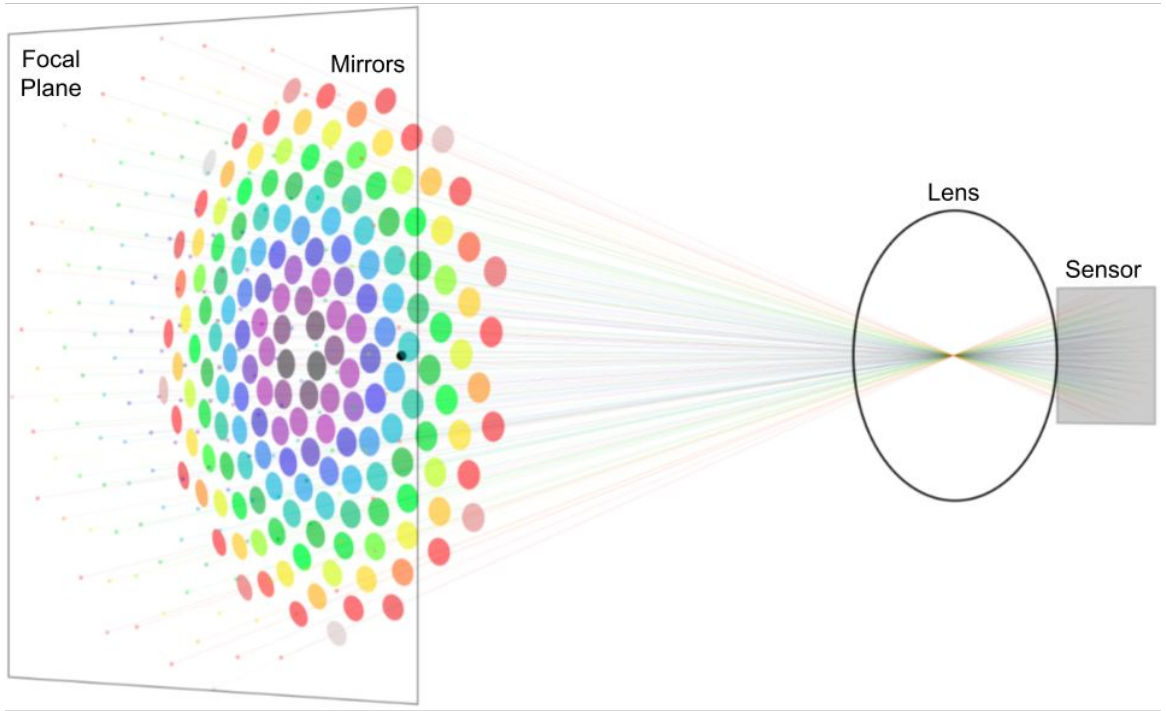
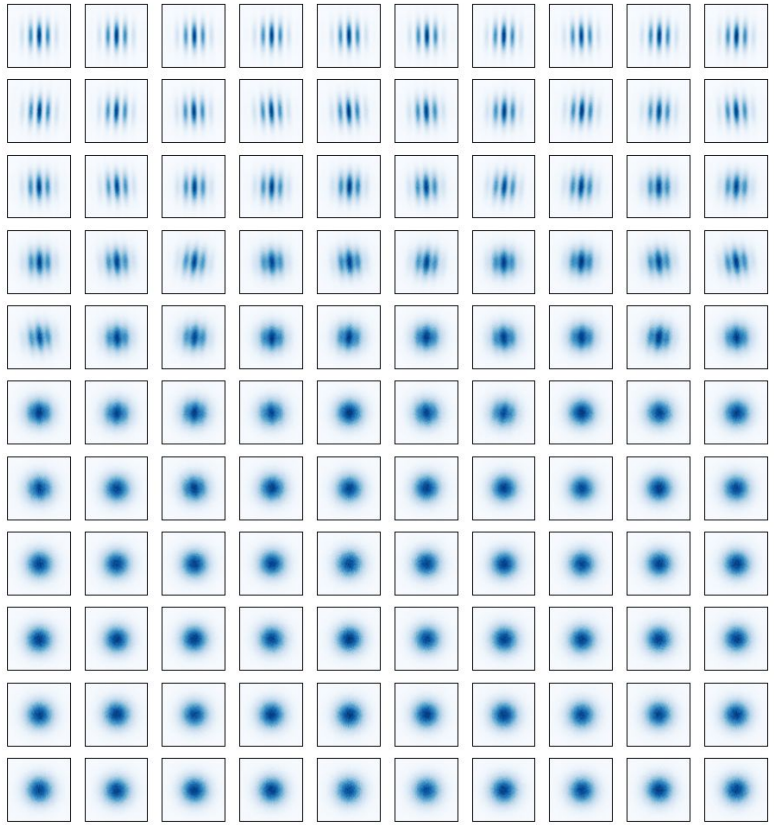
Spatially Multiplexed Light Field Imaging

Array of mirrors around the atom cloud

- Place virtual objects on the focal plane
- Design to capture light from one hemisphere



Capture 3D information & collect more light



Images of different views through different mirrors

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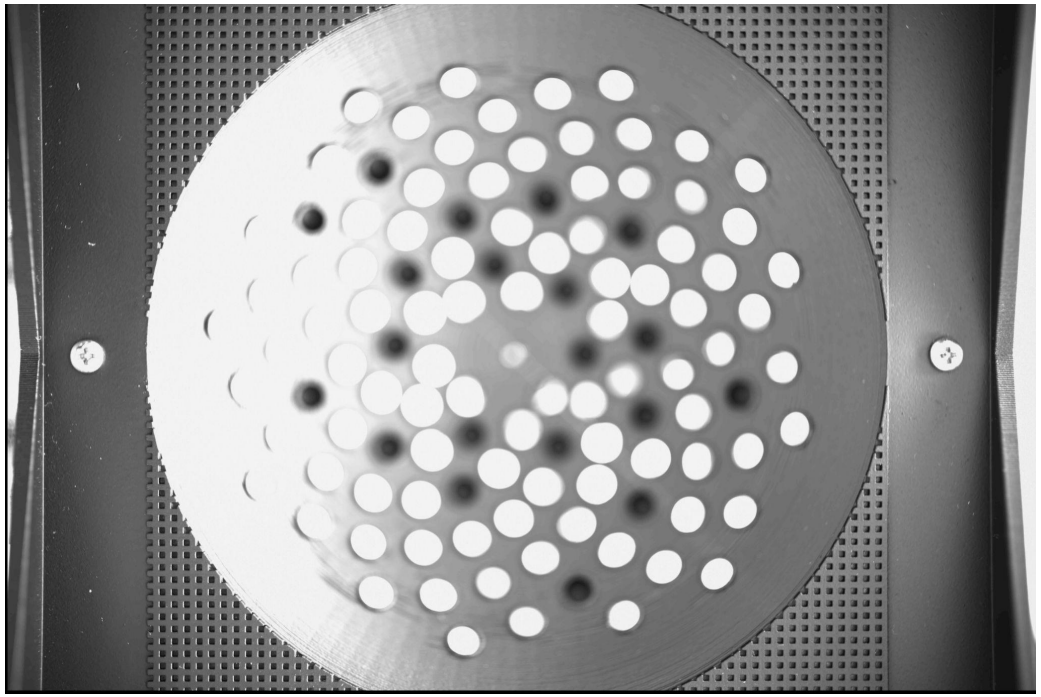
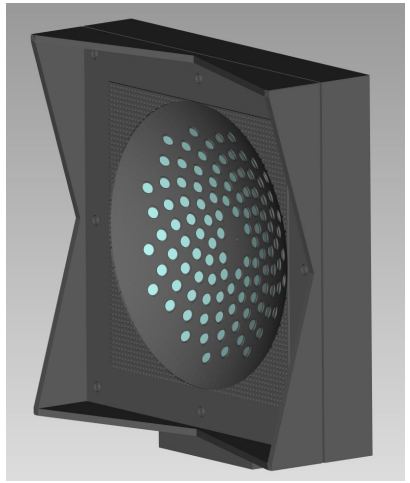
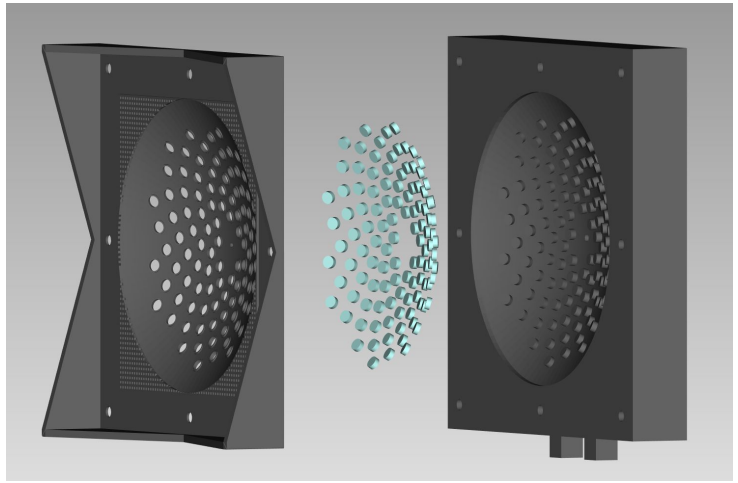
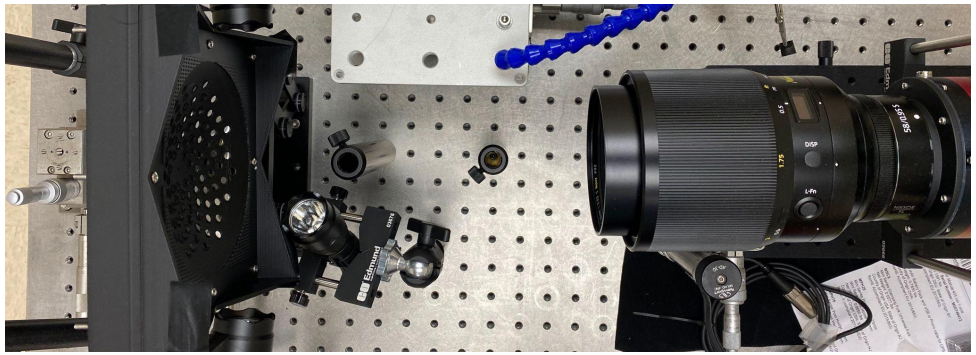
Demonstrator

- 3D printed mechanical support for 5mm mirrors
- Target held with 100 µm fibers
- Optical alignment with In-situ grid ~ 1°









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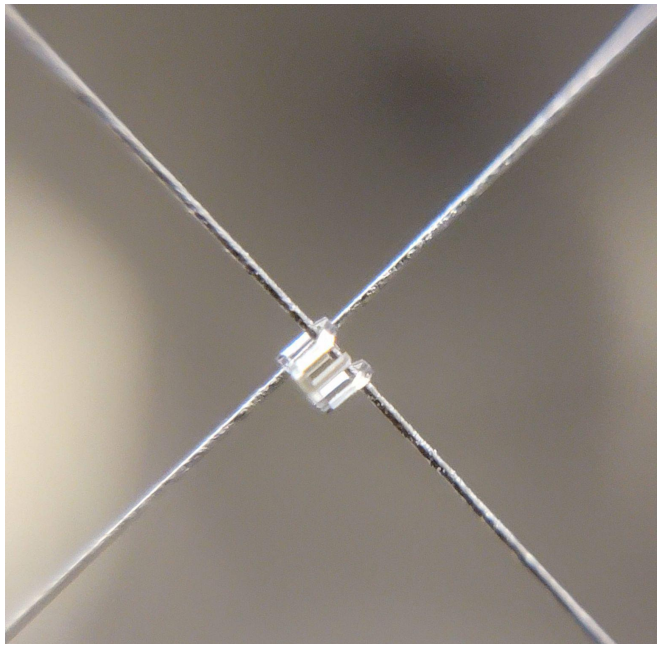
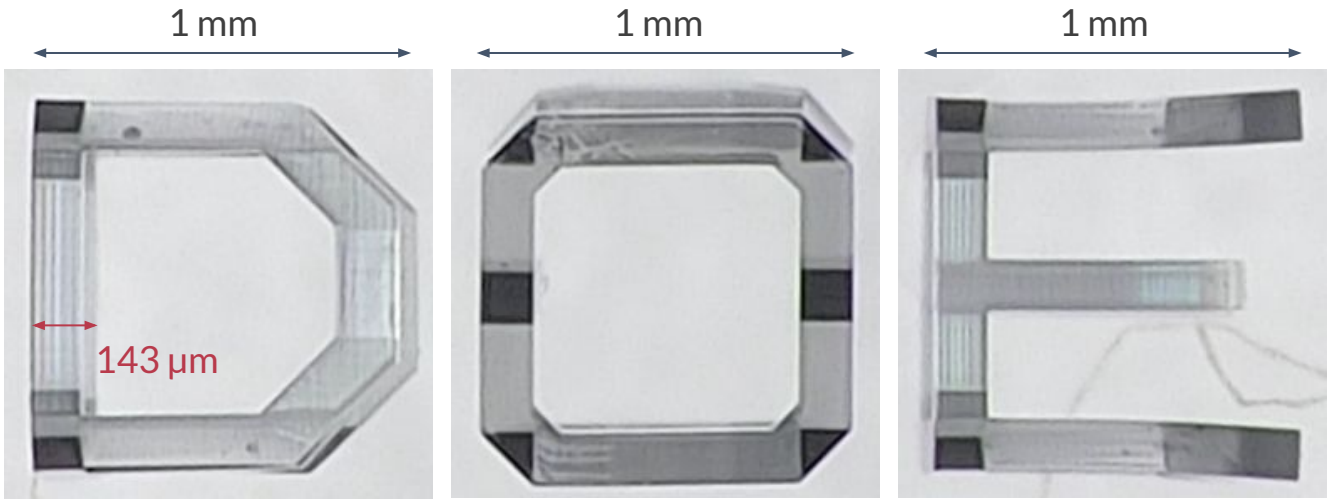
Test Object: DOE Cube

- 3D printed test object

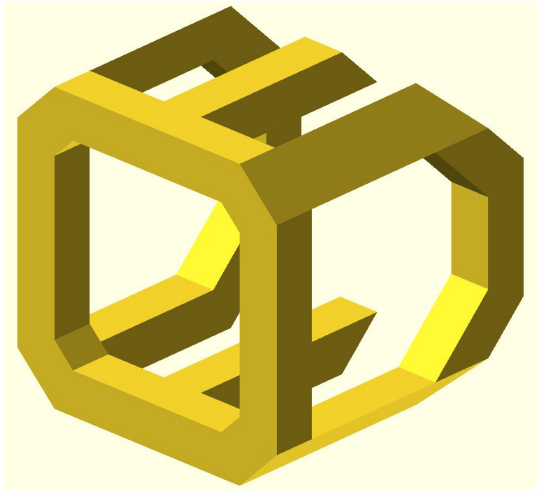
  (projection micro-stereolithography)
- Absorbs at 405 nm
- Fluoresces at 430 - 550 nm



(This is 150 µm thread, final images taken with 100 µm threads)



Microscope images of each face



CAD model

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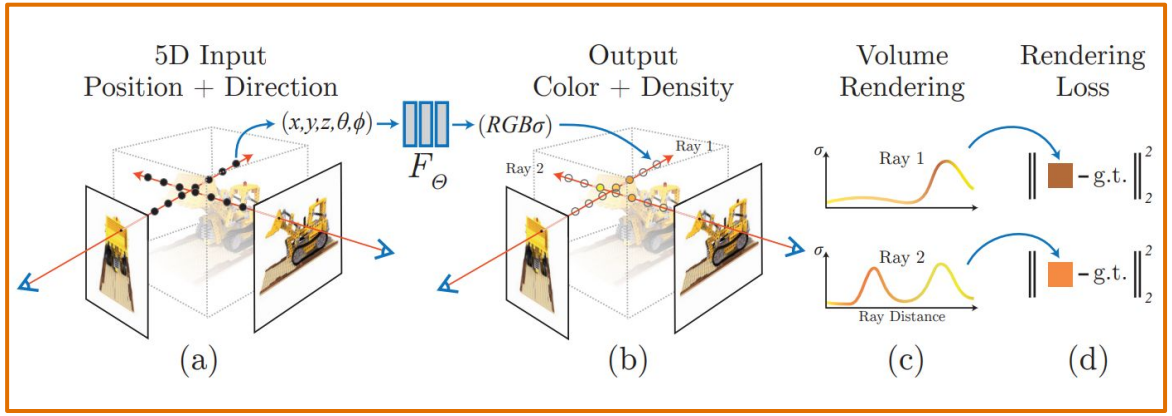
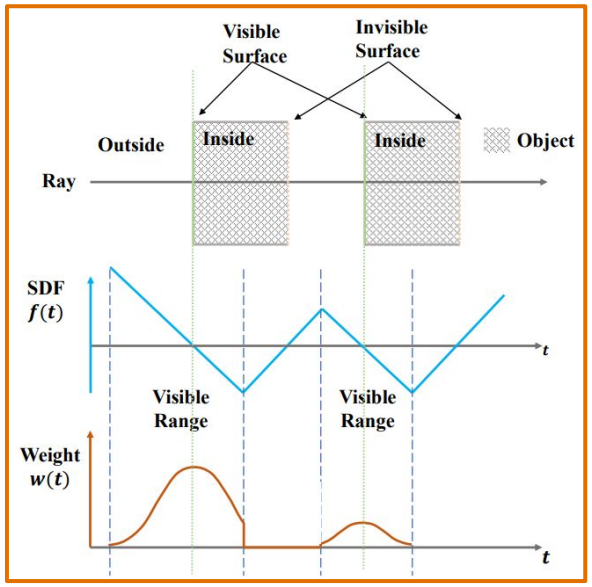
3D Reconstruction & View Synthesis

- Very popular in computer vision/graphics community
  - Take multiple views from different angles
  - Learn underlying scene/volume
  - Generate new views @ different angles
- NeRF: Neural Radiance Fields
  - NN to encode radiance field over volume
- NeuS: Neural Implicit Surfaces
  - Uses “signed distance function”
  - Focuses on surface reconstruction





3D Reconstruction Demo Examples

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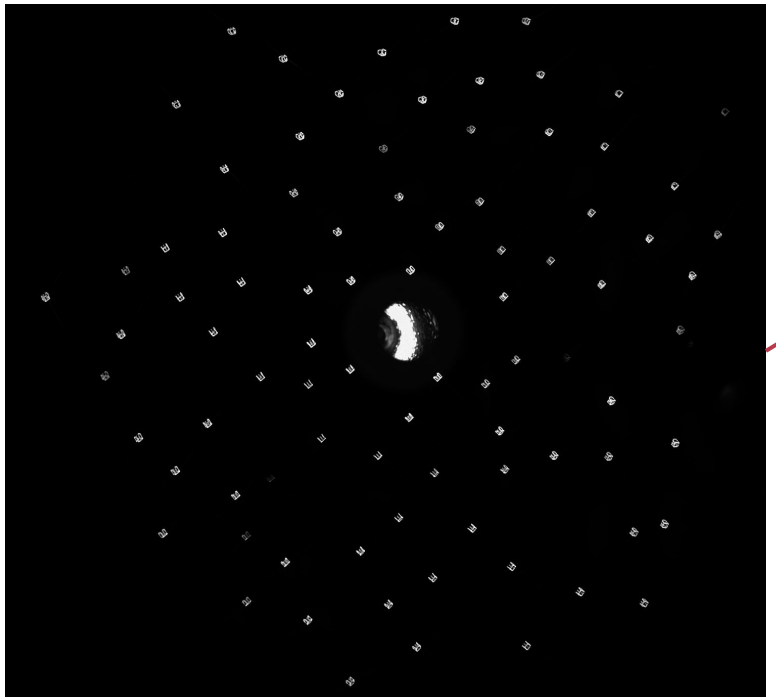
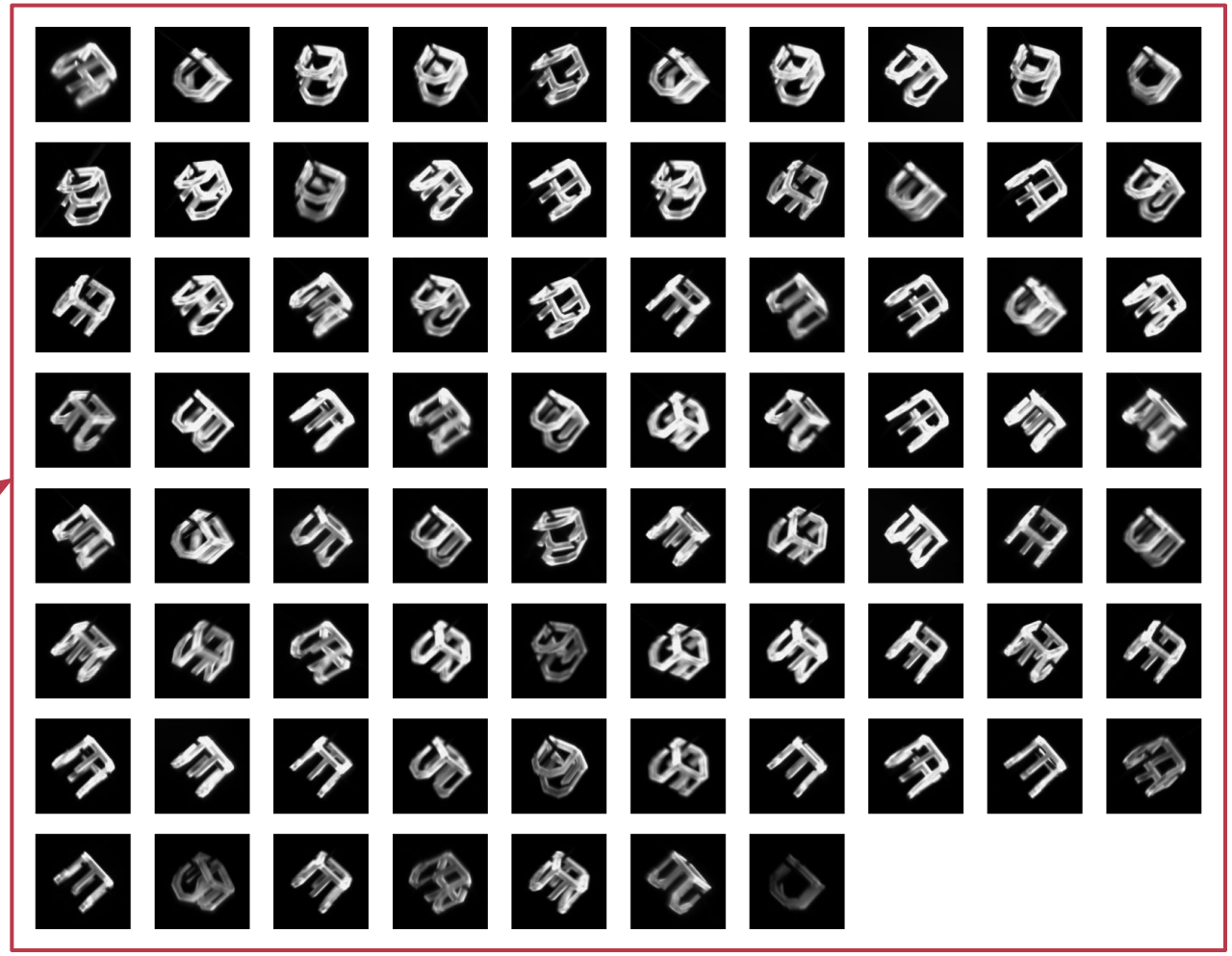
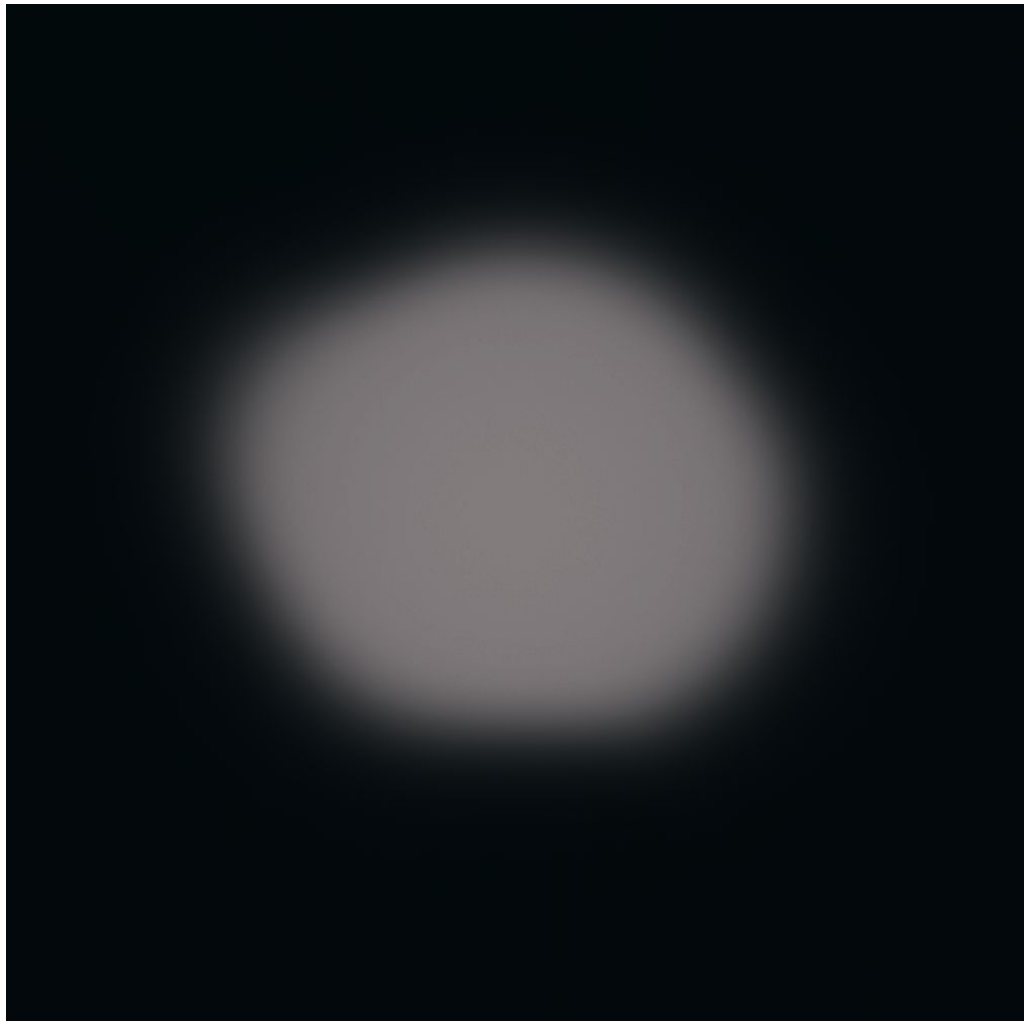
Results: Raw Images

- Patch extraction of each view
- Select good alignment and illumination
  - 77/90 selected





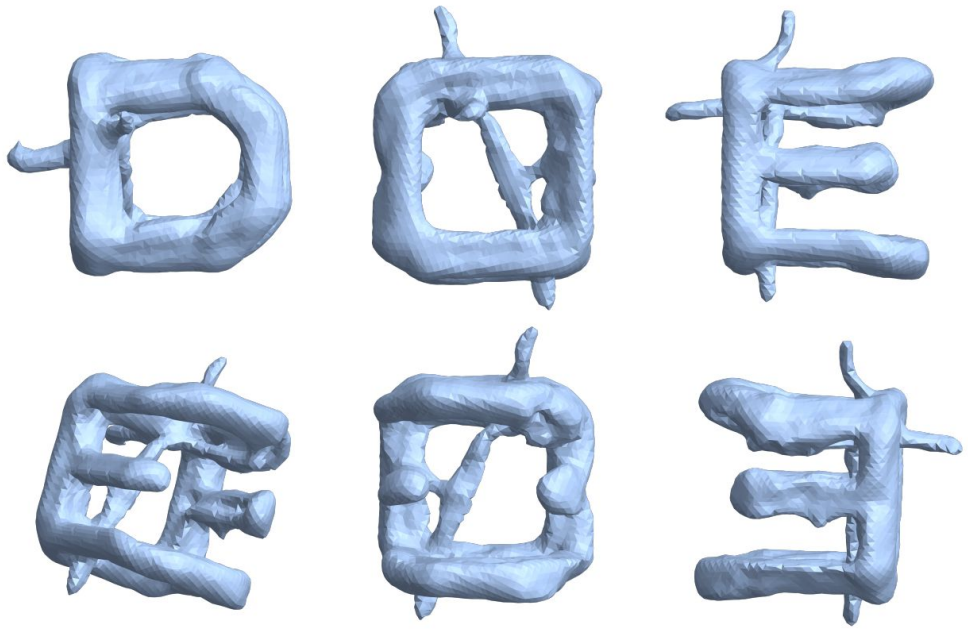
Results: Learning 3D Structure via NeuS



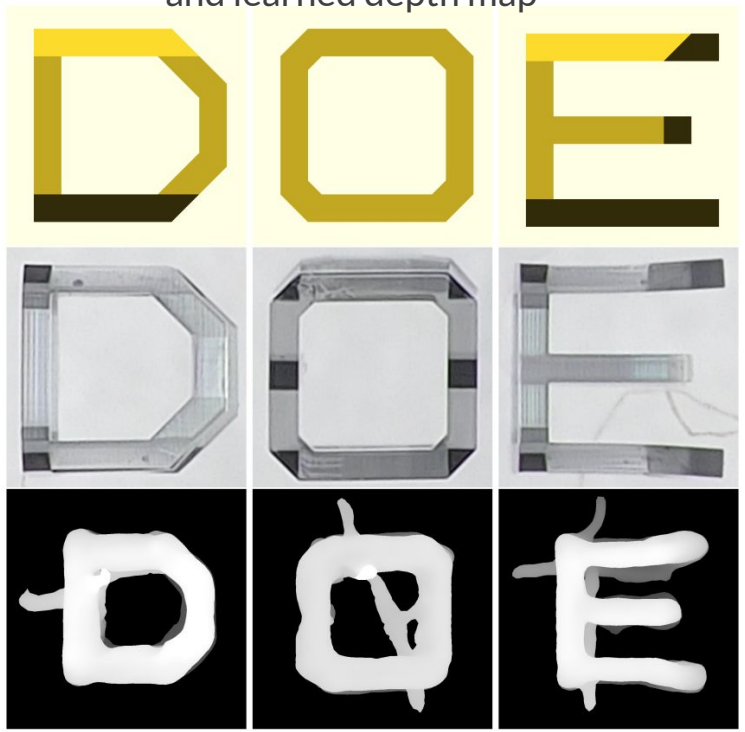
Results: 3D Reconstruction

- 90 mirrors, 77 views selected for reconstruction
- Reconstruction using NeuS

Reconstructed mesh surface



Comparison of CAD, microscope, and learned depth map



Interpolated views (SDF + Color)

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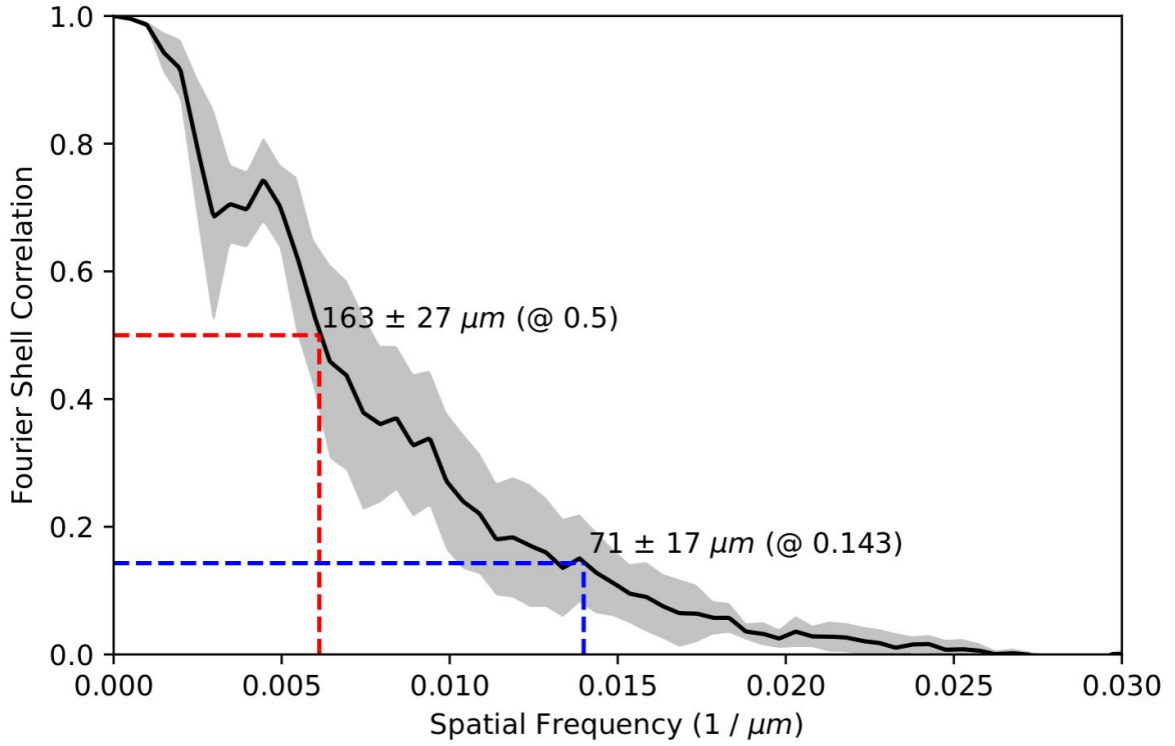
Results: Reconstruction Performance

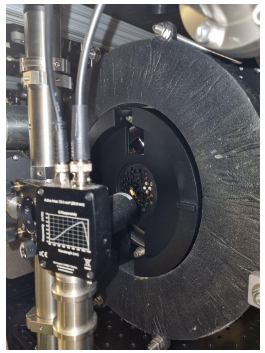
- Fourier Shell Correlation (FSC) as a measure of 3D reconstruction performance
  - Correlation between two density distributions
- Comparison between two independent reconstructions (using half of the dome)
- **System achieves design specifications!**

$$FSC(r) = \frac{\sum_{r_i \in r} F_1(r_i) \cdot F_2(r_i)^*}{\sqrt{\sum_{r_i \in r} |F_1(r_i)|^2 \cdot \sum_{r_i \in r} |F_2(r_i)|^2}}$$



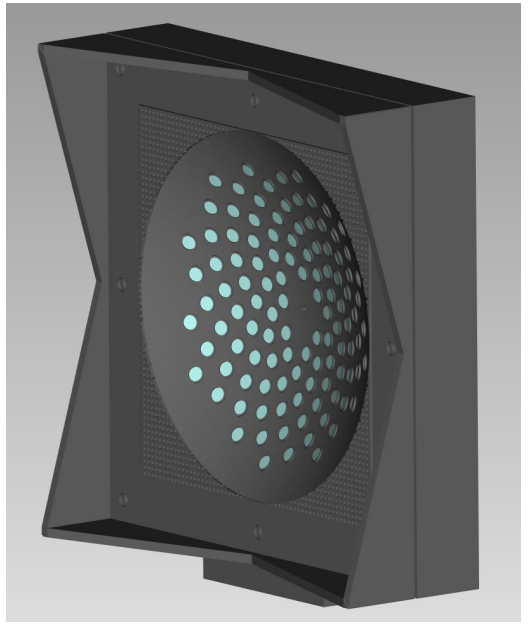
Summary

- **Successful demonstration of spatially multiplexed light-field imaging** for 1mm^3 object with 100 μm features
- Paper published at ***JINST* 17 P08021**
- Broad applicability to atom interferometry and beyond
- Ongoing / Future works
  - Installing at Stanford lab and imaging real atom clouds
  - Full 3D reco. of MOT and dipole traps



  - Laser phase aberration studies using 3D atom clouds

(collaboration with Kovachy lab @ Northwestern)



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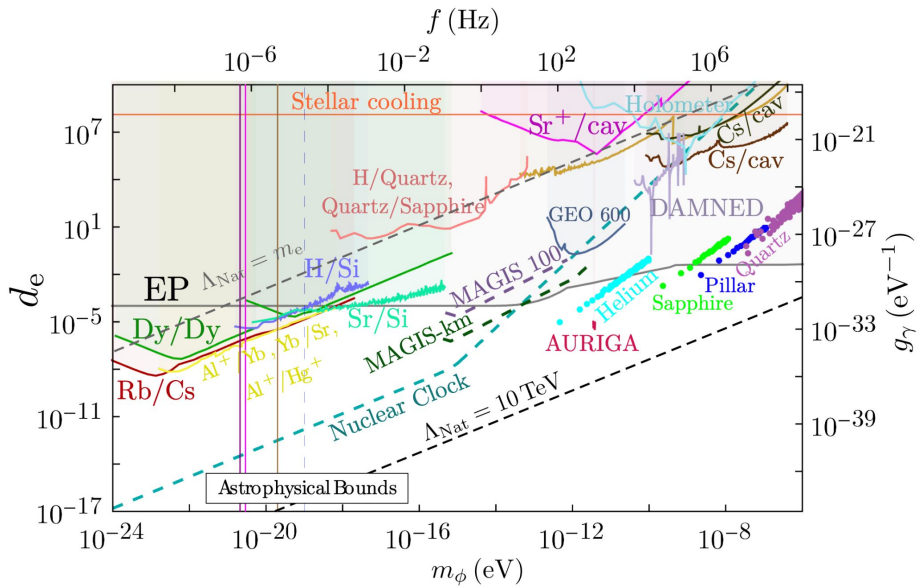
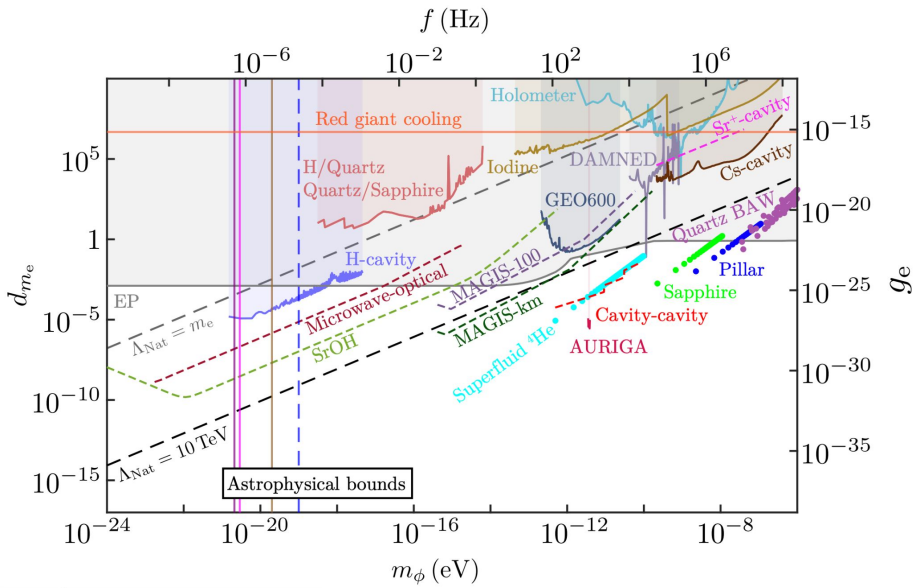
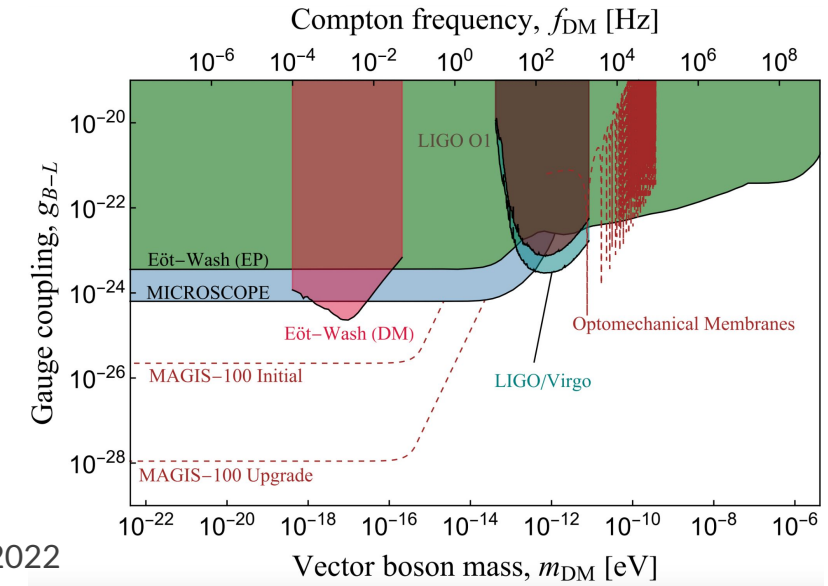
Maxime Vandegar

Joseph Frisch

MAGIS-100 - BSM Physics Potential







https://arxiv.org/abs/2203.14915

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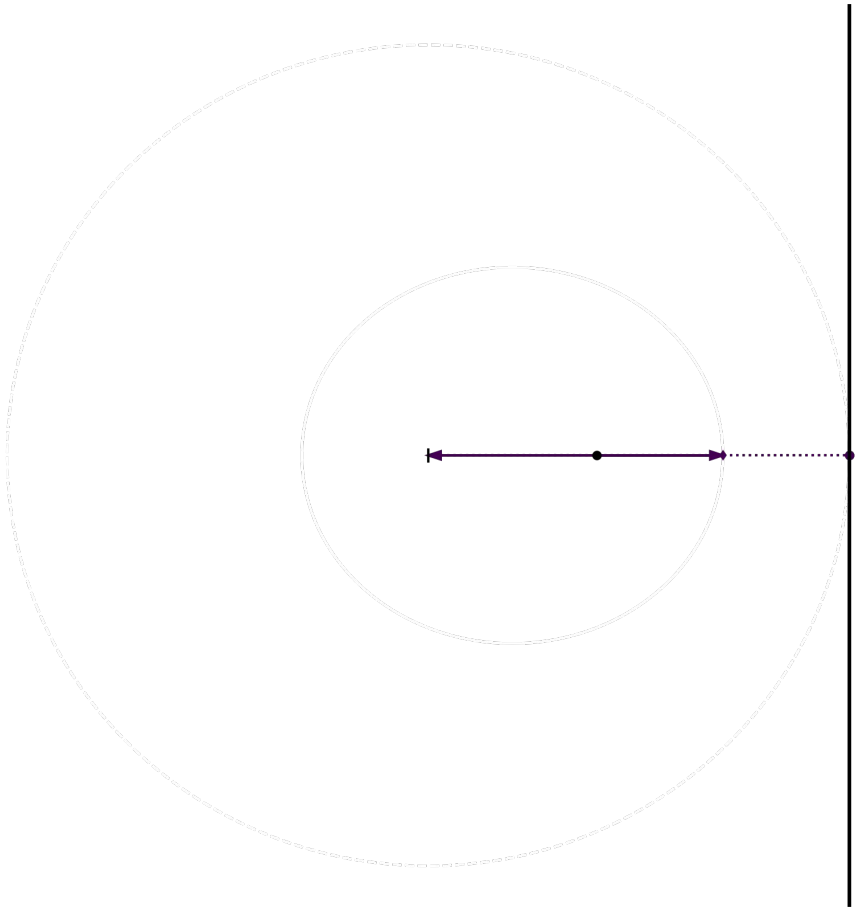
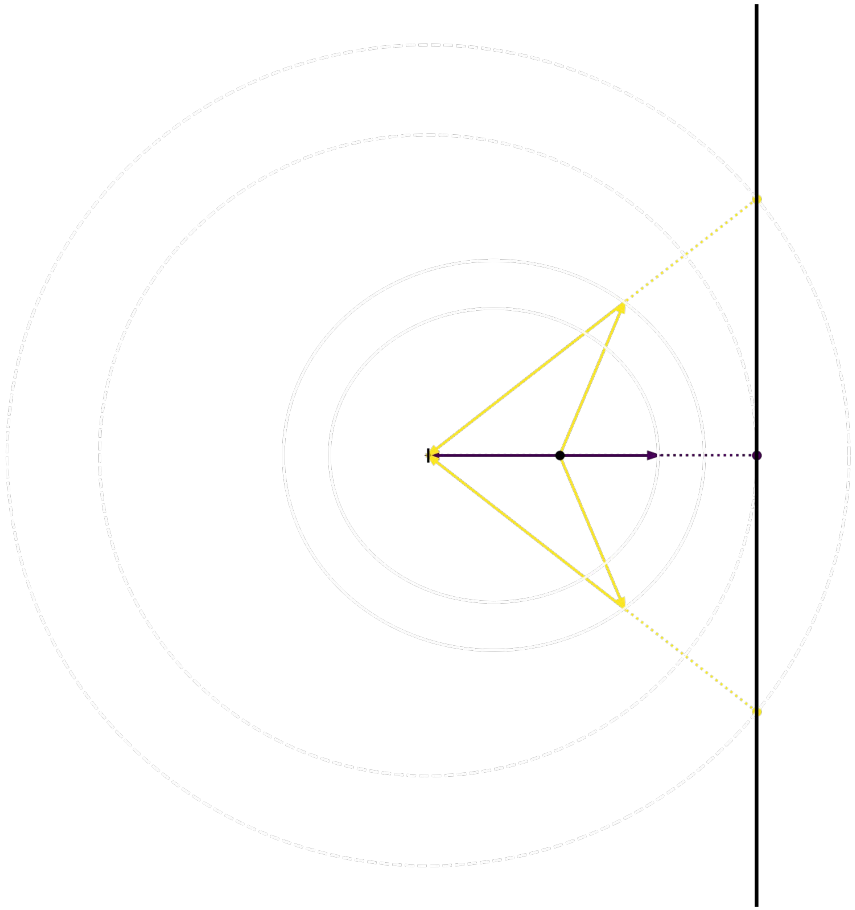
Determining Mirror Parameters

On Axis View



Off Axis View



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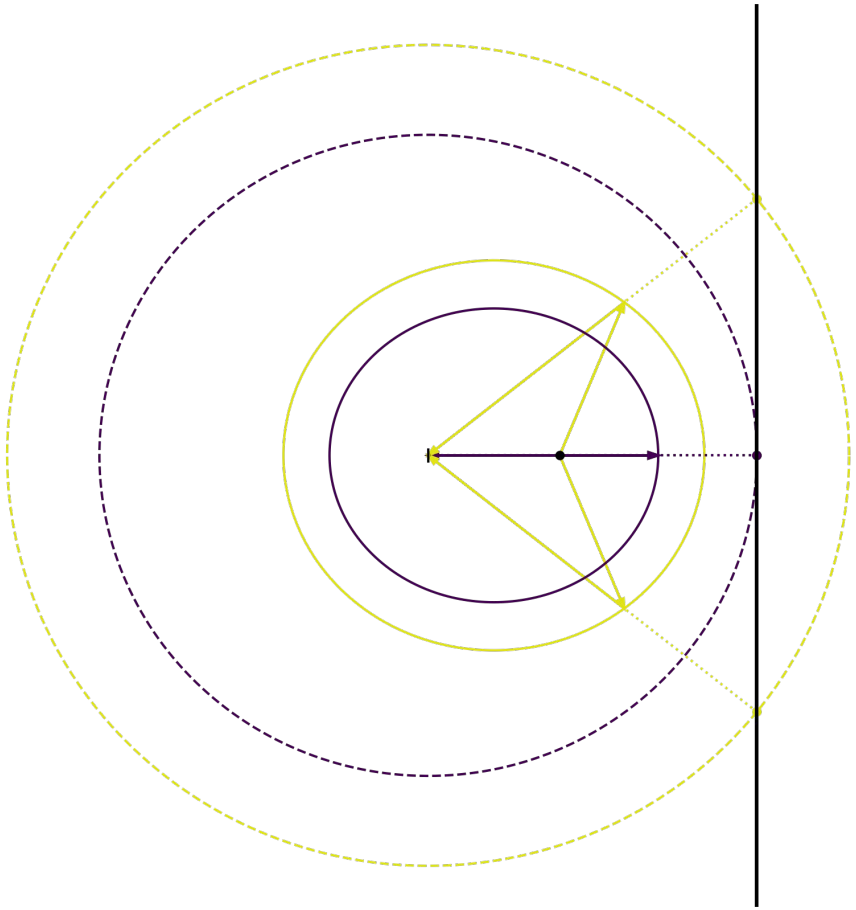
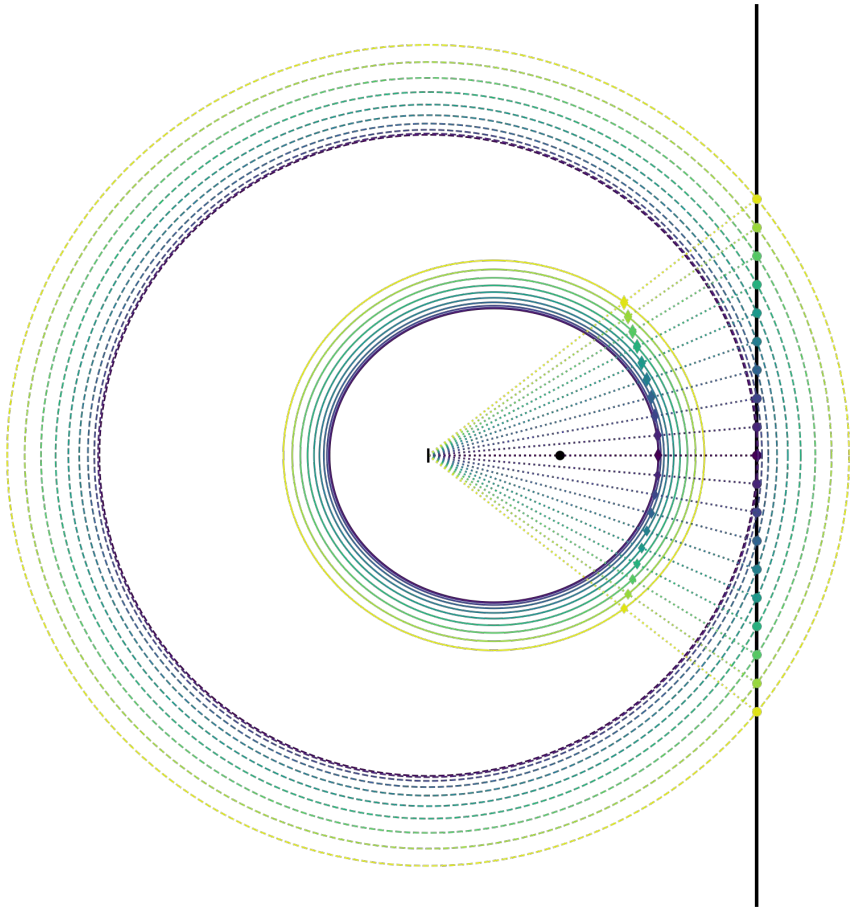
Mirror Parameters - Using The Magic of Ellipses!

Reflections, Directrix, Rays



Working Example



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Results: Alignment Tolerance

- Fourier Shell Correlation (FSC) as a measure of 3D reconstruction performance
- Simulation study with tomographic atom cloud density
- 100 um resolution possible with upto 0.6 mm or 2° alignment errors