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Conference 15 – 18 December 2025

Exhibition 16 – 18 December 2025

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**Automated design of
compound lenses with
discrete-continuous
optimization**

Arjun Teh, Delio Vicini, Bernd Bickel,
Matthew O'Toole, Ioannis Gkioulekas

Carnegie Mellon University and Google

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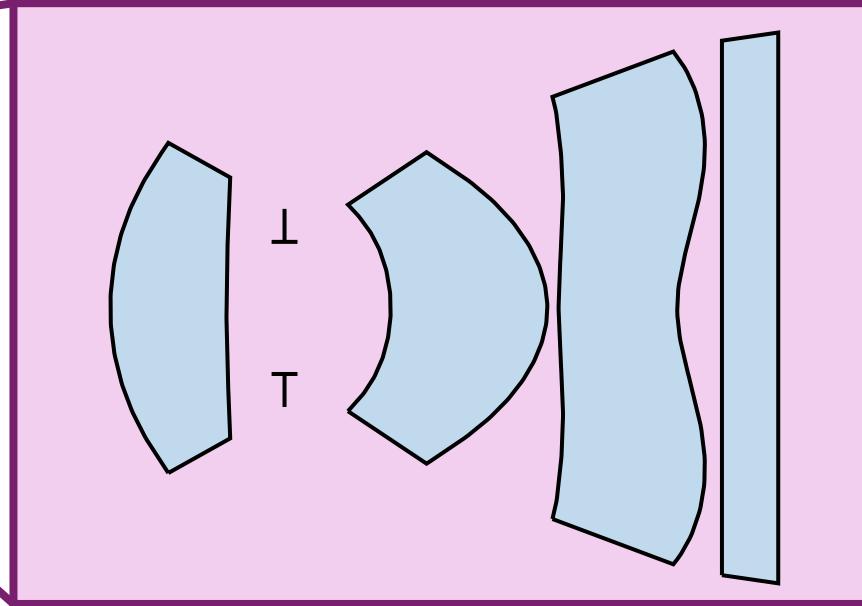
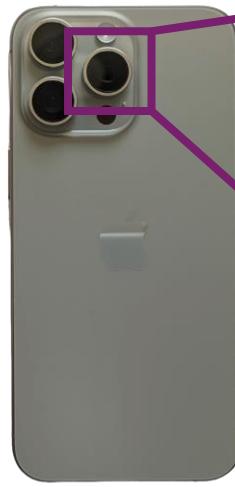
Lenses are everywhere



Many kinds of designs

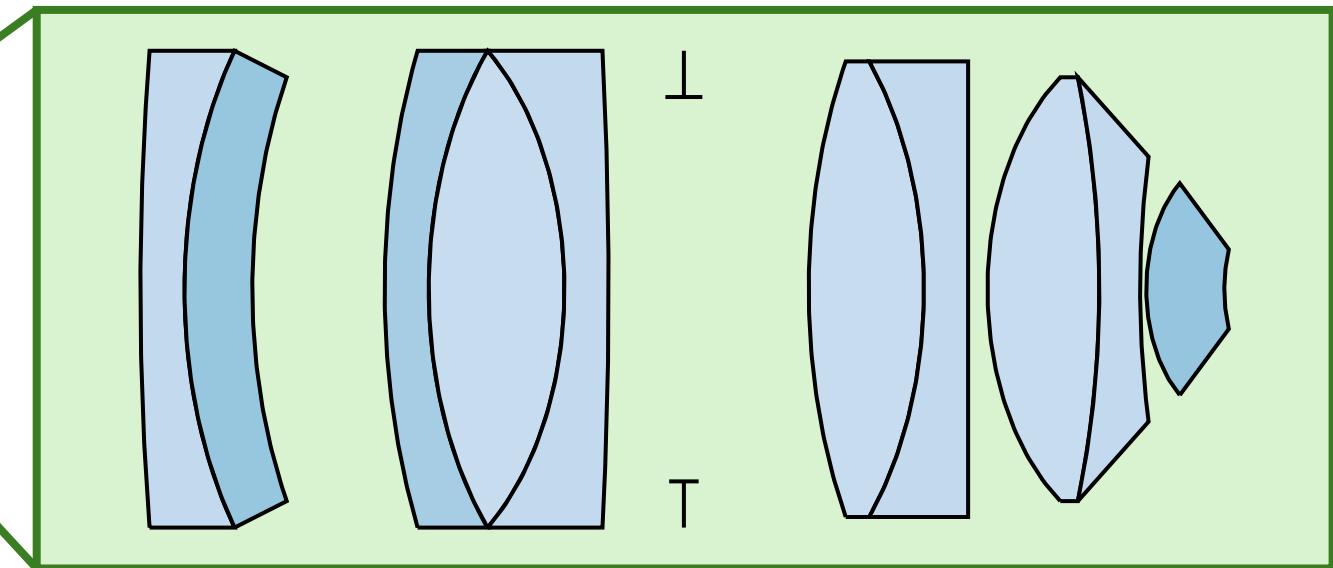
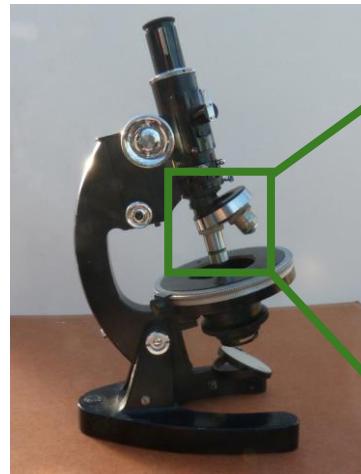
wide angle

fast



high resolution

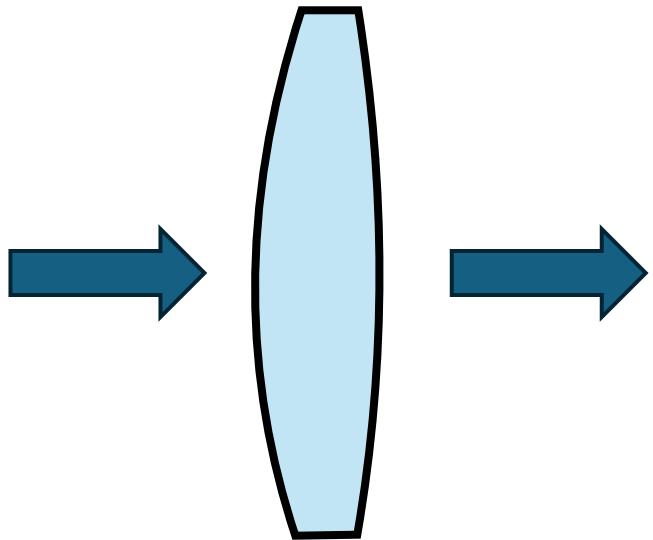
no aberrations



Simple lenses aren't enough



scene



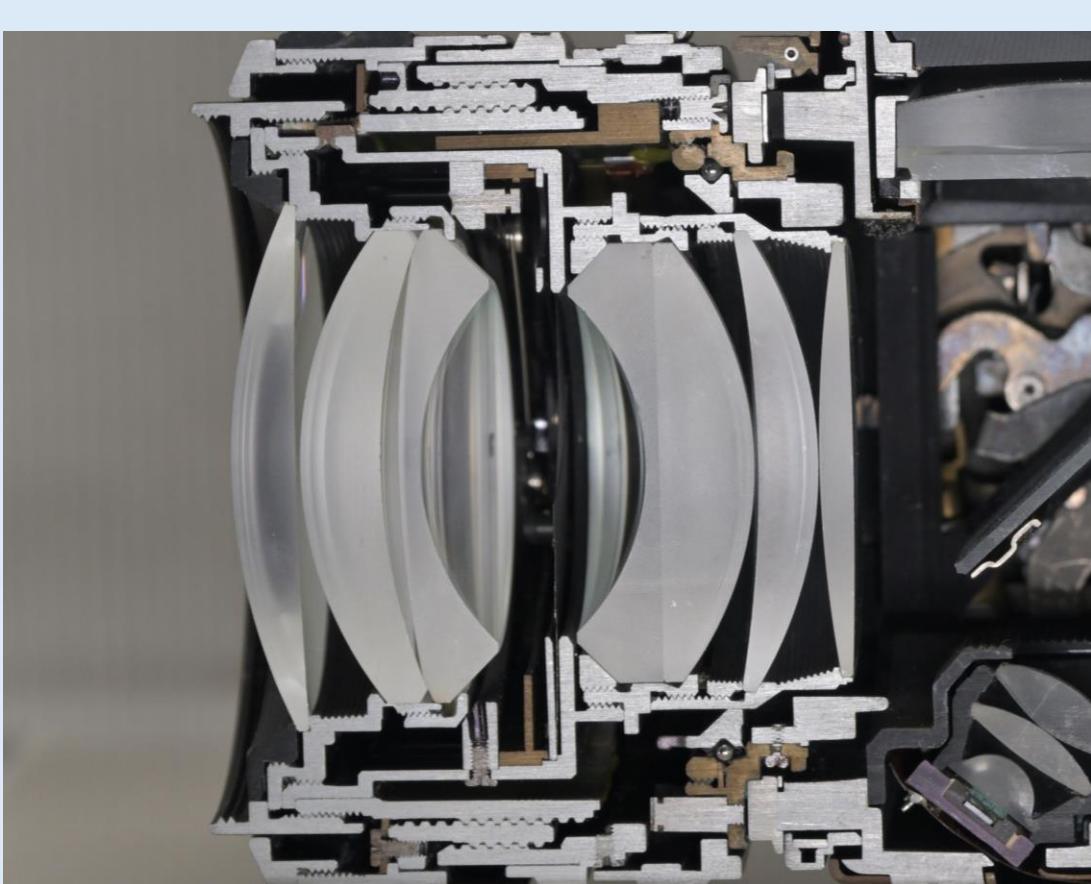
singlet lens



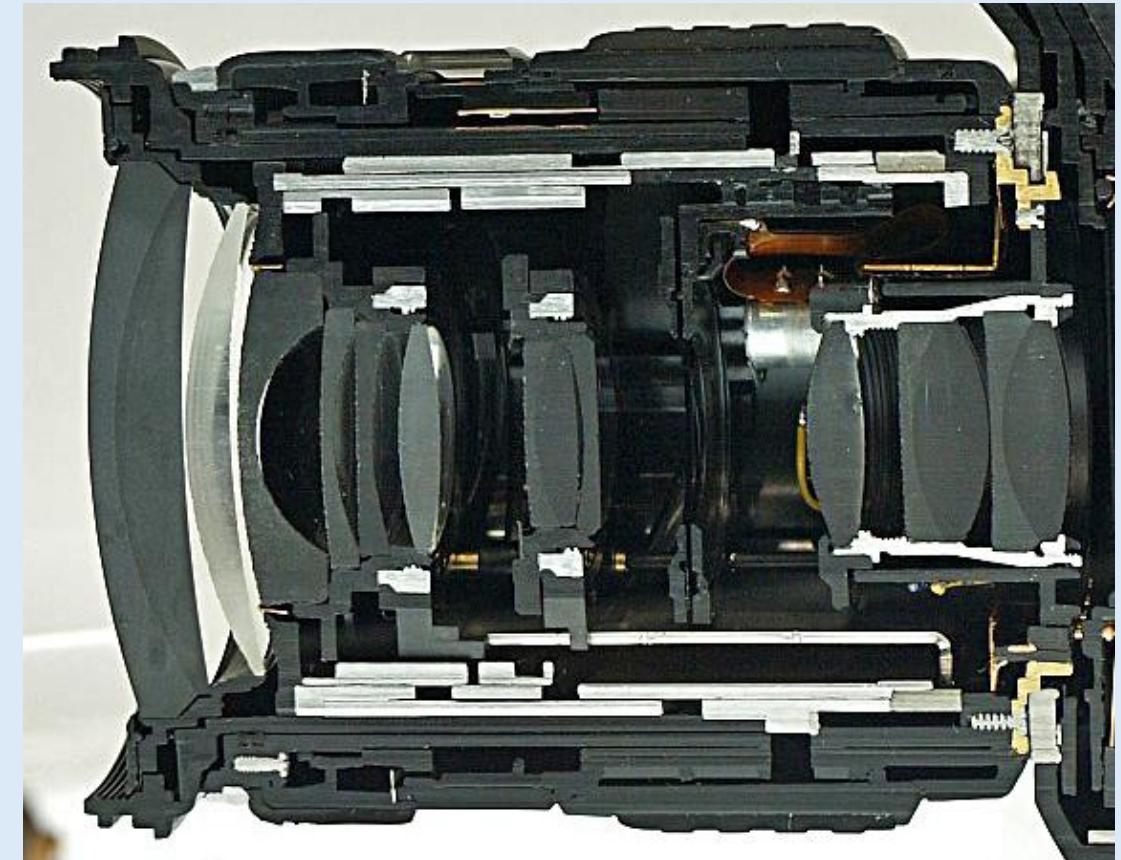
result

Modern lenses are complicated

Nikon F3 Cutaway

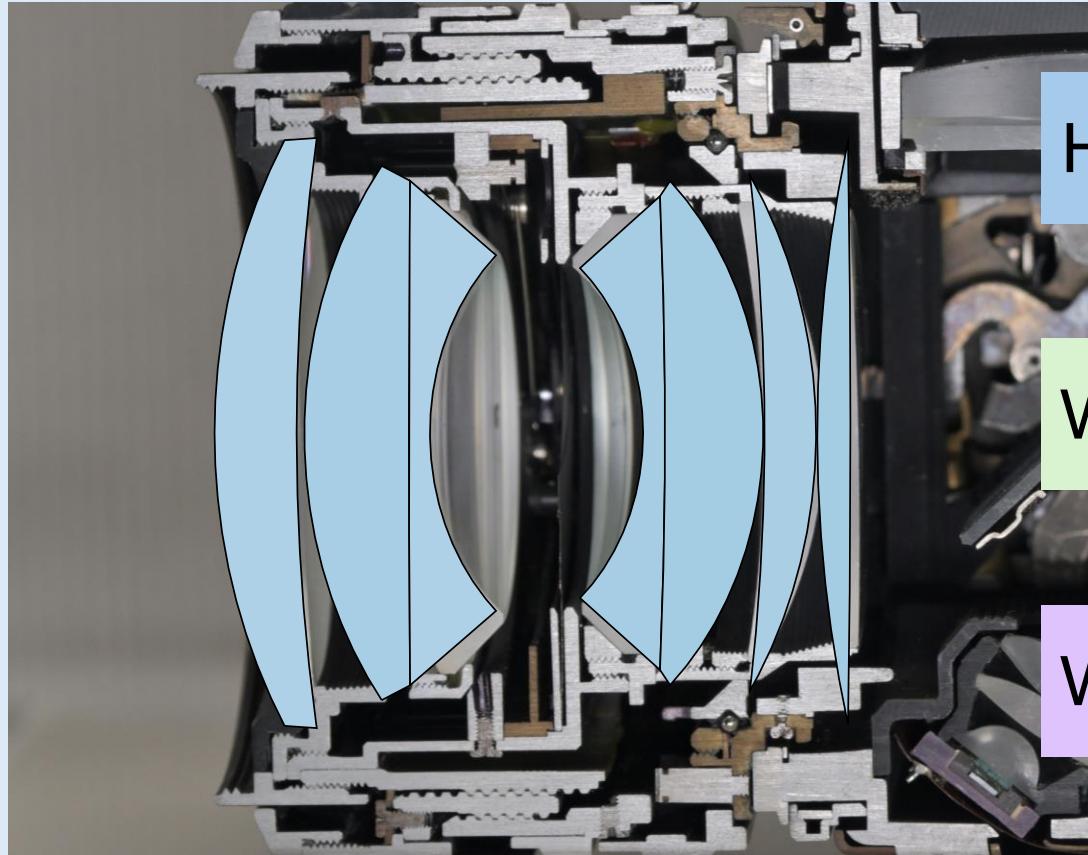


Olympus E-30 Cutaway



Combinatorially many discrete options

Nikon F3 Cutaway

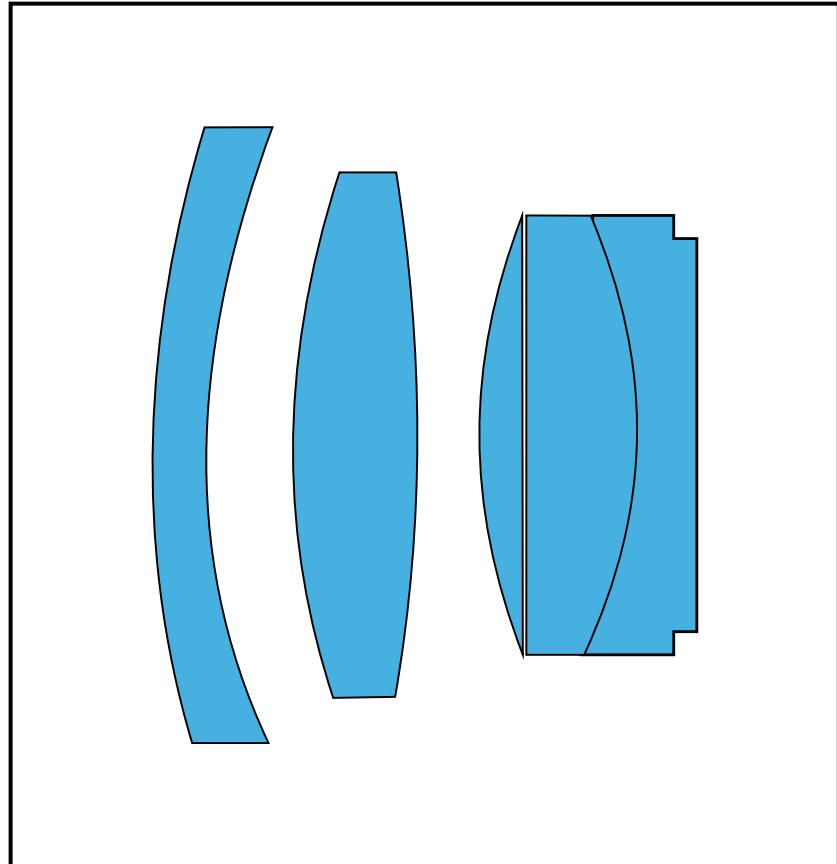


How many elements?

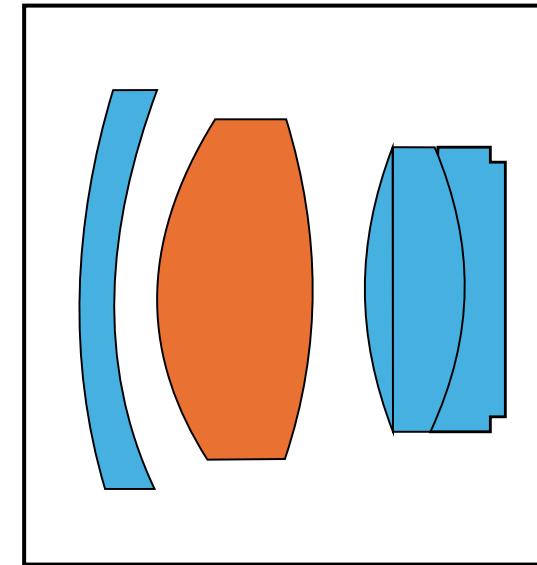
Which elements are glued together?

What order and orientation?

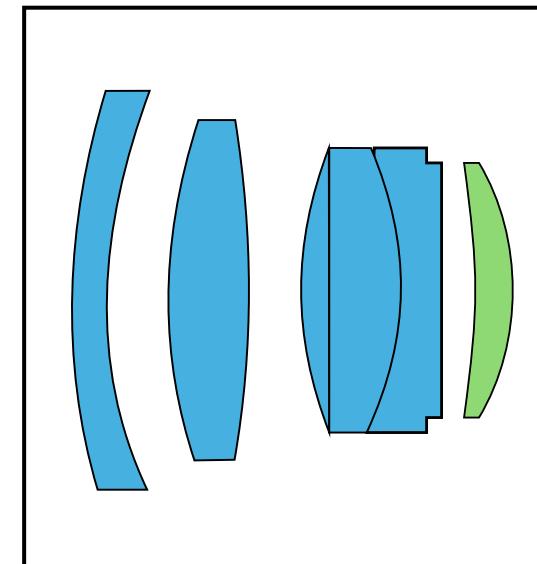
Two types of parameters



continuous



discrete



Two types of parameters

The diagram illustrates two types of lens parameter sets. On the left, a black arrow labeled "continuous" points to a set of three blue lenses. On the right, a green arrow labeled "discrete" points to a set of four lenses, with the fourth lens being green.

CODE V Optical Design Software
Design, Optimize and Fabricate Reliable Imaging Optics

Zemax
An Ansys Company

Ray diagram showing light rays passing through a lens system, with a 150 mm scale bar.

IEEE TRANSACTIONS ON COMPUTATIONAL IMAGING, VOL. 1, NO. 1, DECEMBER 2021

dO: A differentiable engine for Deep Lens design of computational imaging systems

Congli Wang, Ni Chen, and Wolfgang Heidrich, *Fellow, IEEE*

Abstract—Computational imaging systems, algorithmically or data-driven machine learning, are applied to raw images and process images either to reveal physical or data-driven machine learning, are applied to raw images and process images either to reveal physical

Aperture-Aware Lens Design

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ABSTRACT

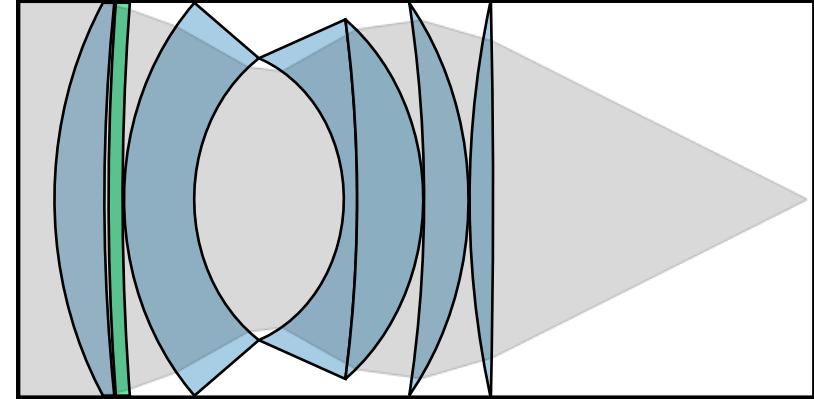
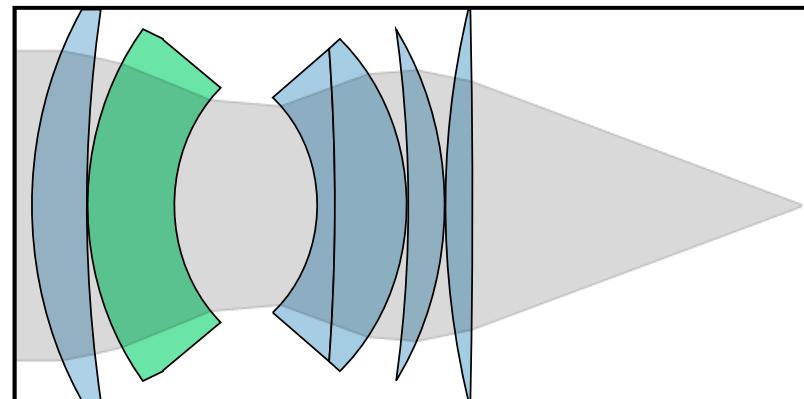
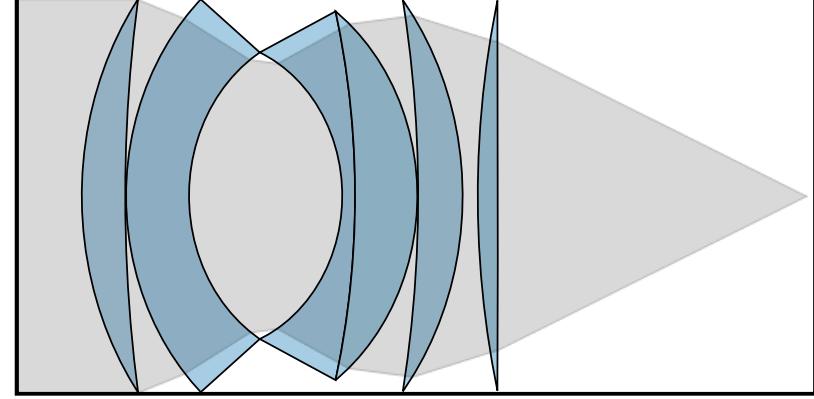
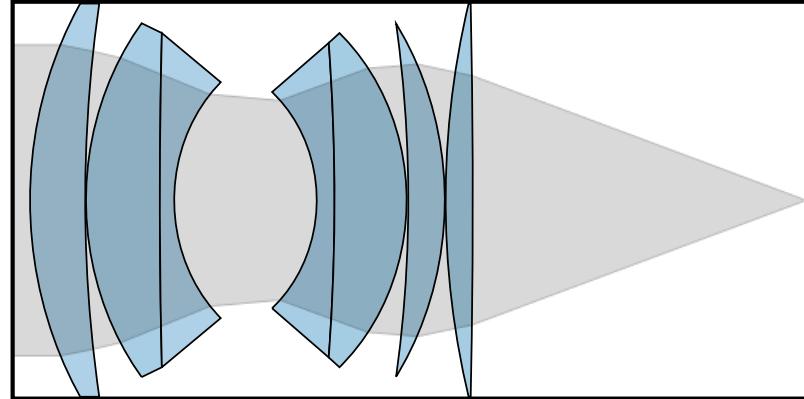
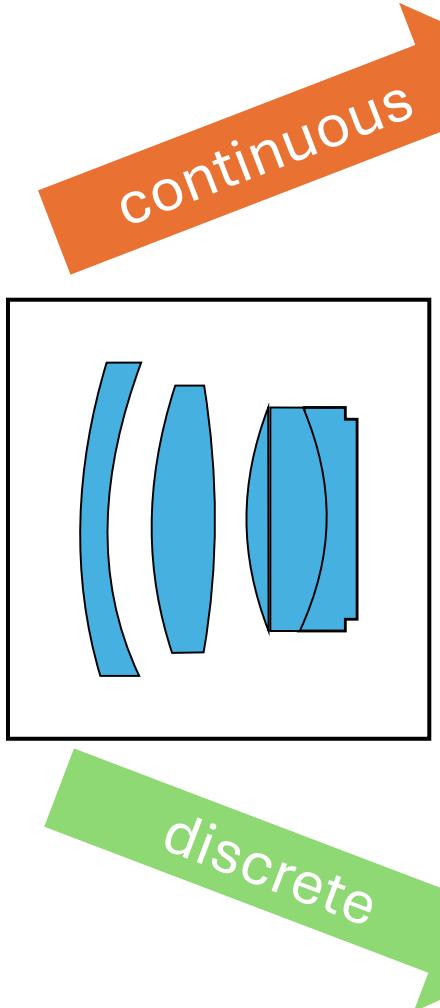
Optics designers use simulation tools to assist them in designing lenses for various applications. Commercial tools rely on finite differencing and sampling methods to perform gradient-based optimization of lens design objectives. Recently, differentiable rendering techniques have enabled more efficient gradient calculation of these objectives. However, these techniques are unable to optimize for light throughput, often an important metric for many applications.

We develop a method for calculating the gradients of optical systems with respect to both focus and light throughput. We formulate lens performance as an integral loss over a dynamic domain, which allows for the use of differentiable rendering techniques to calculate the required gradients. We also develop a ray tracer specifically designed for refractive lenses and derive formulas for calculating gradients that simultaneously optimize for focus and light throughput. Explicitly optimizing for light throughput produces lenses that outperform traditional optimized lenses that tend to prioritize for only focus. To evaluate our lens designs, we simulate various applications where our lenses: (1) improve imaging performance in low-light environments, (2) reduce motion blur for high-speed photography, and (3) minimize vignetting for large-format sensors

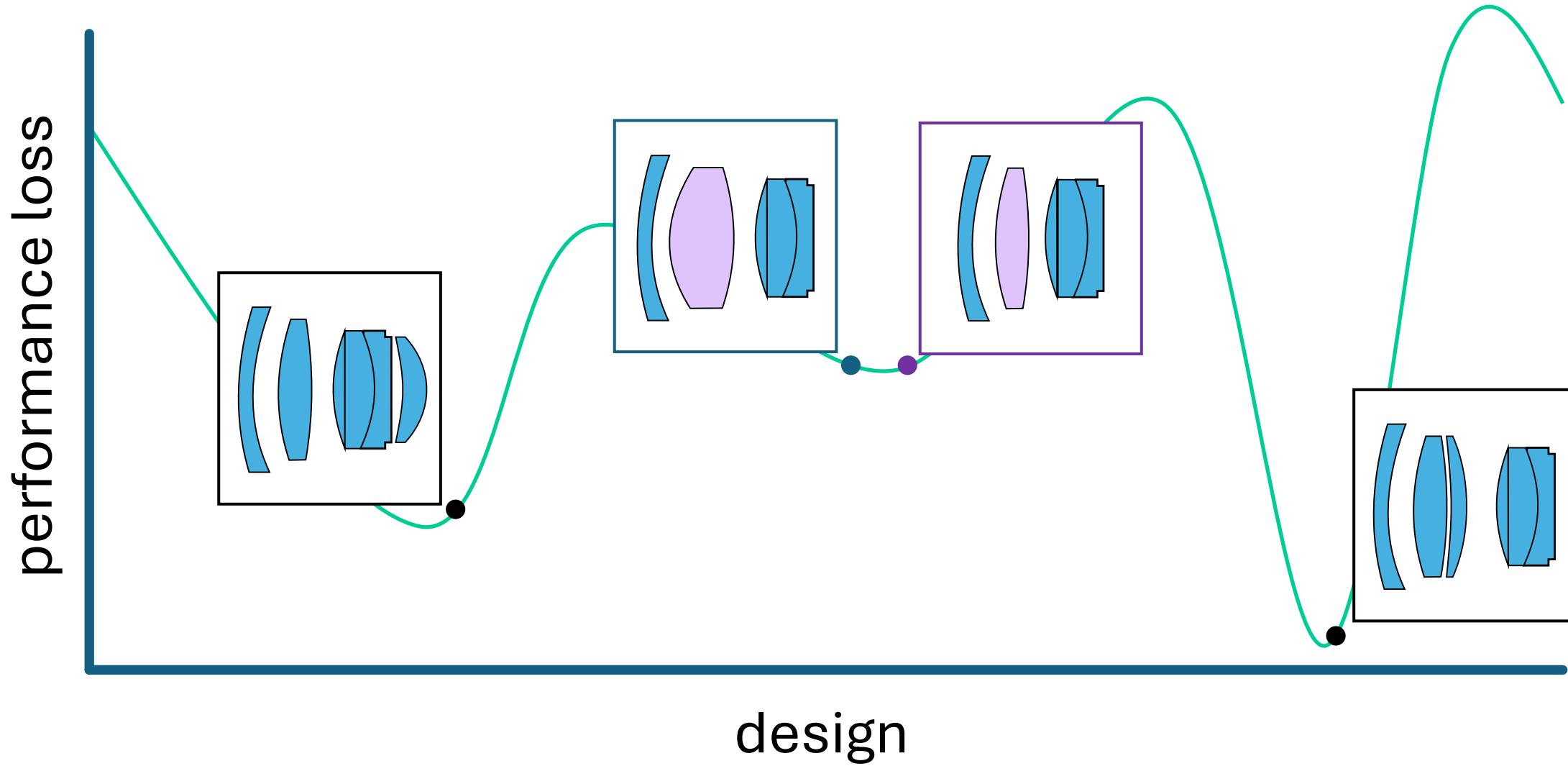
Figure 1: (a) The objective of this work is to design lenses capable of simultaneously optimizing for focus and light throughput. (b) lens optimized for throughput. (c) rendered image.

Two types of parameters

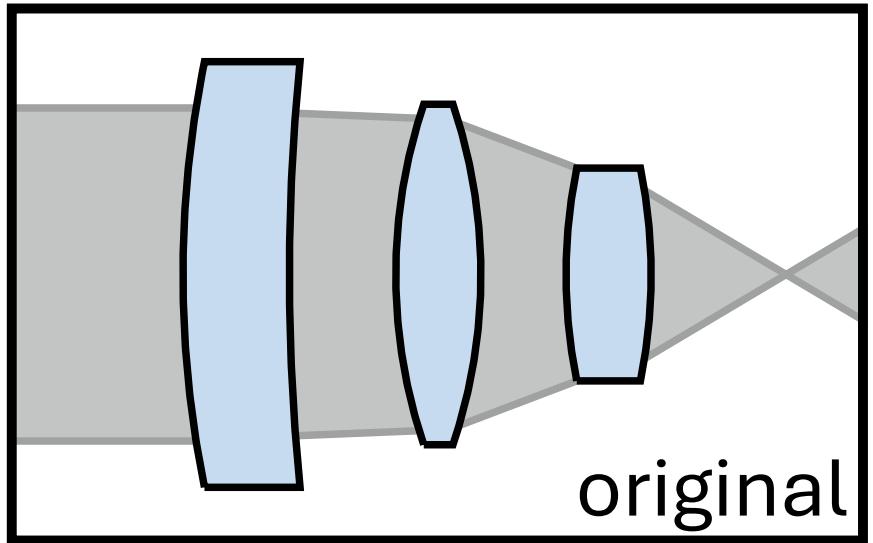
Mixed discrete-continuous optimization



Key idea: sample the space of designs

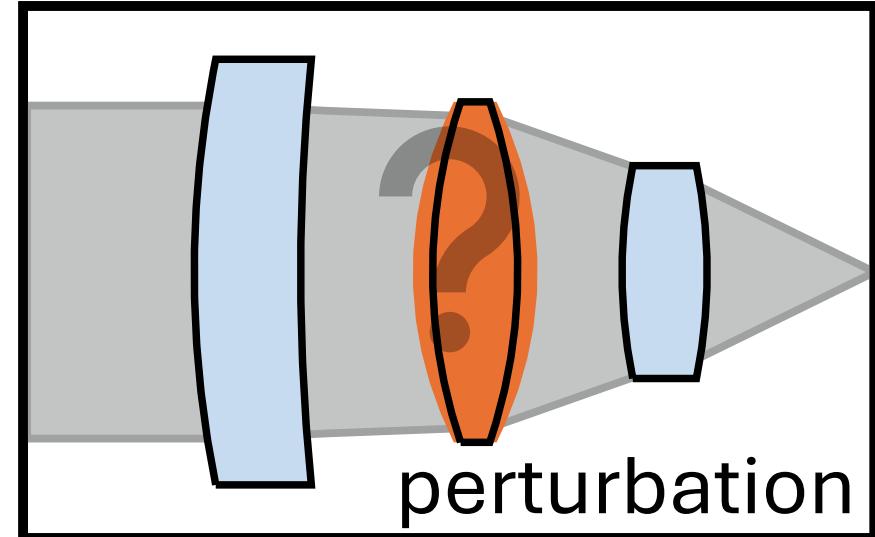
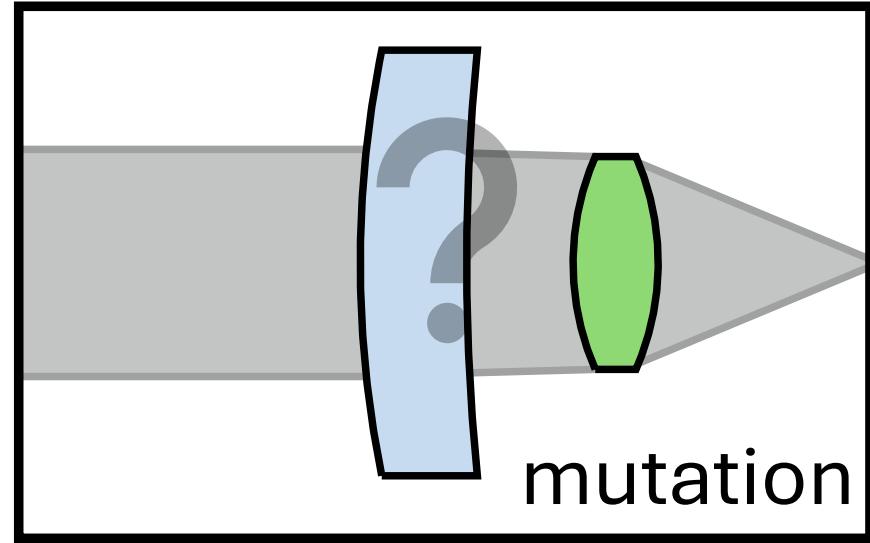


Metropolis-Hastings

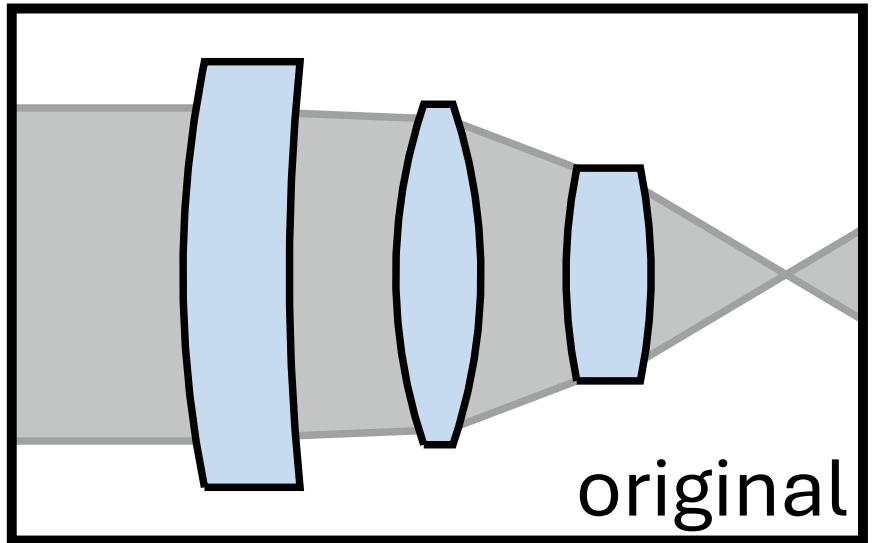


or

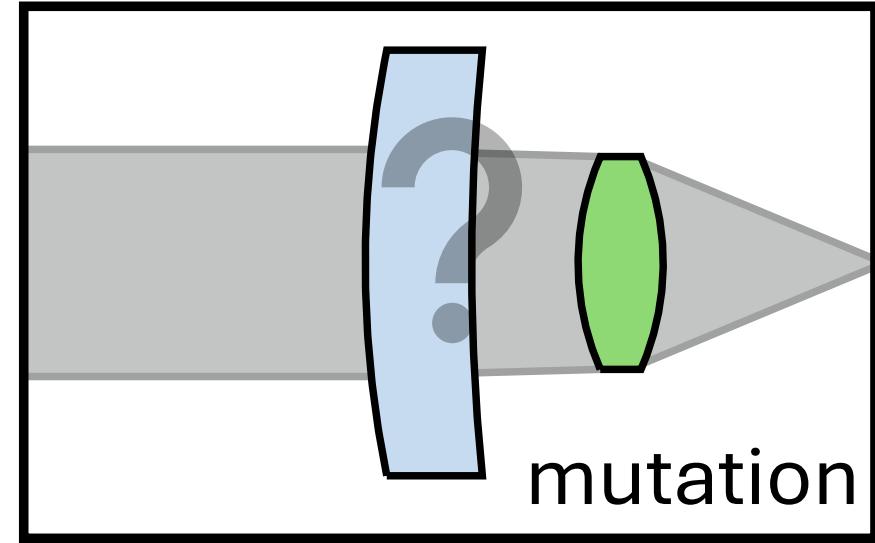
Two arrows originate from the right side of the "original" diagram. A green arrow points to the right, and an orange arrow points downwards, both pointing towards the "mutation" and "perturbation" diagrams.



Metropolis-Hastings requires reversibility

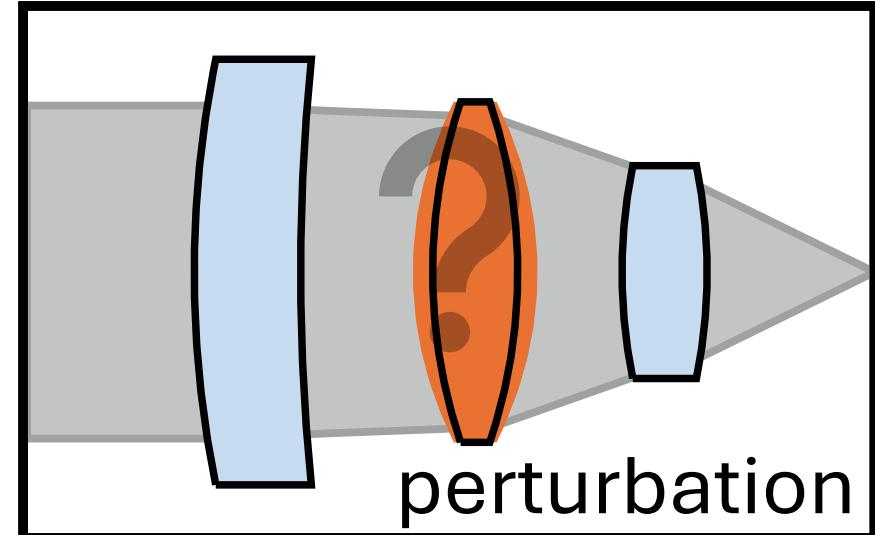


← →
or



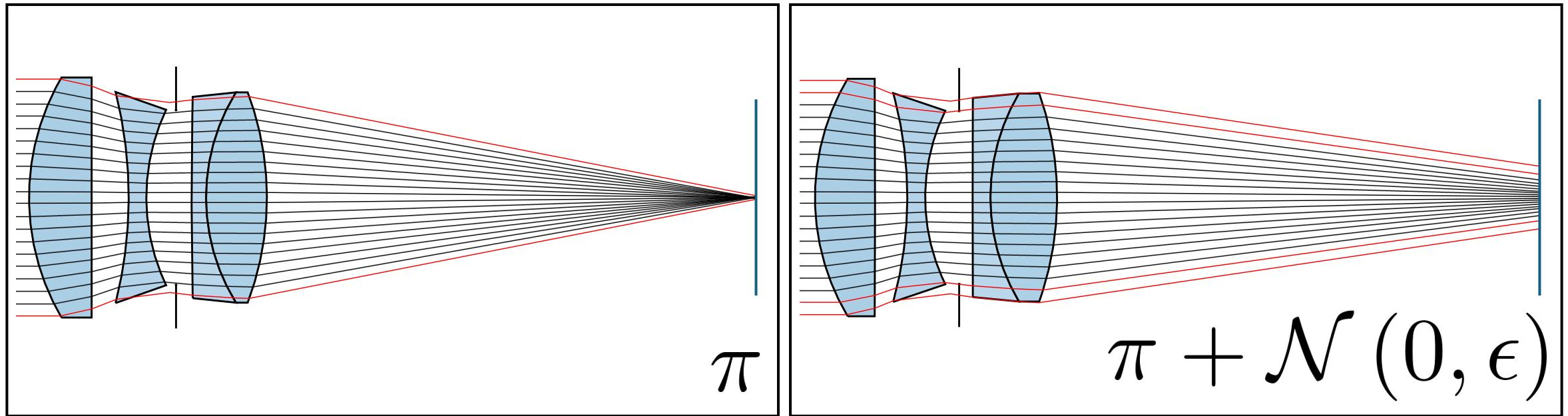
Improving a design
implies a chance of
making it worse

↑ ↘



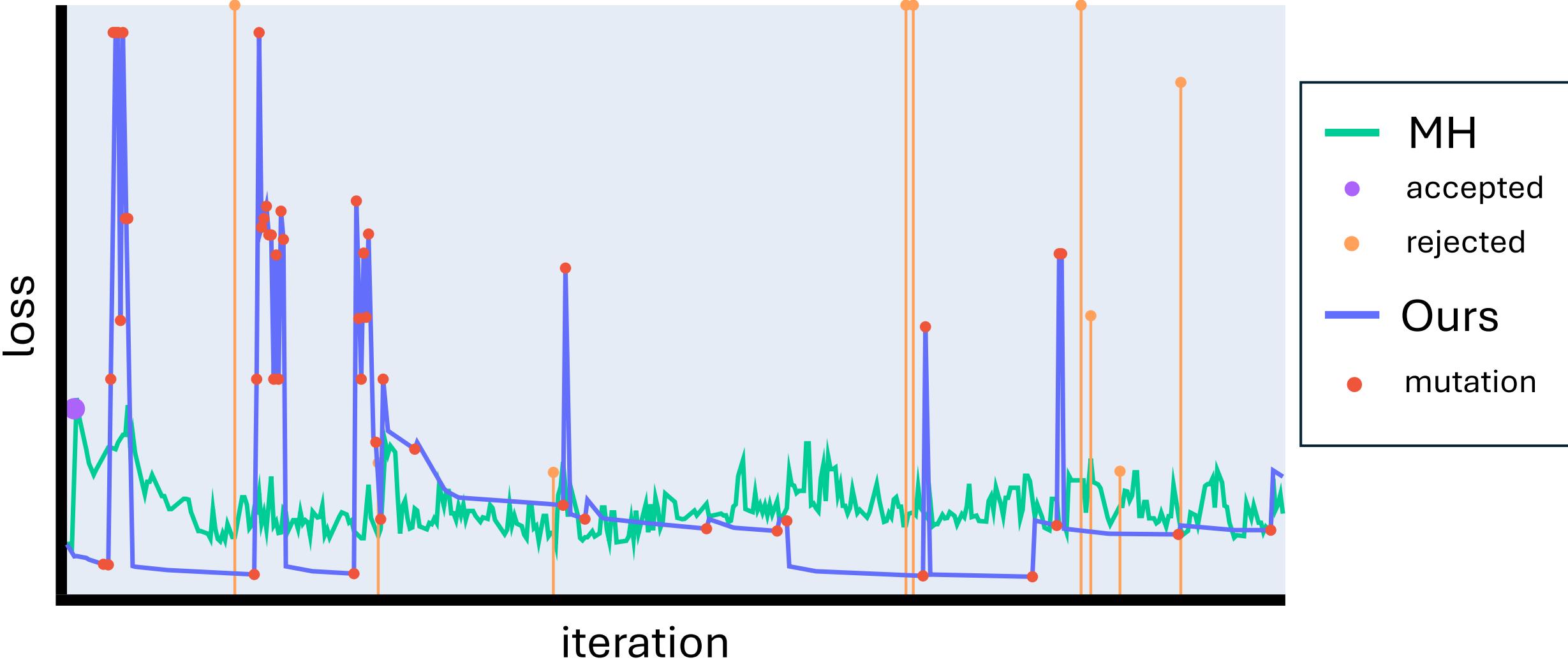
Metropolis-Hastings requires noise

Langevin Monte Carlo (gradient descent) requires noise

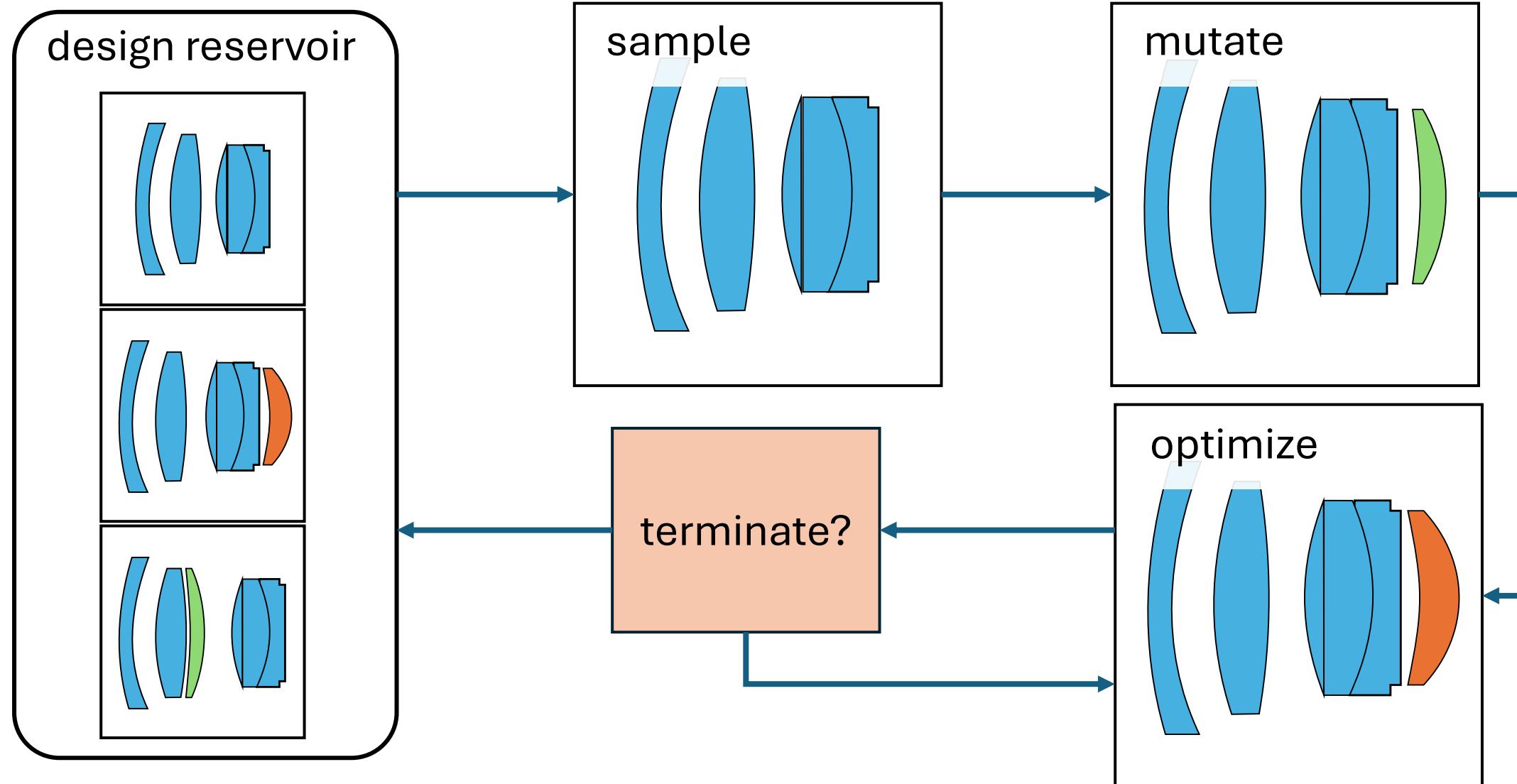


Lenses are sensitive to small changes

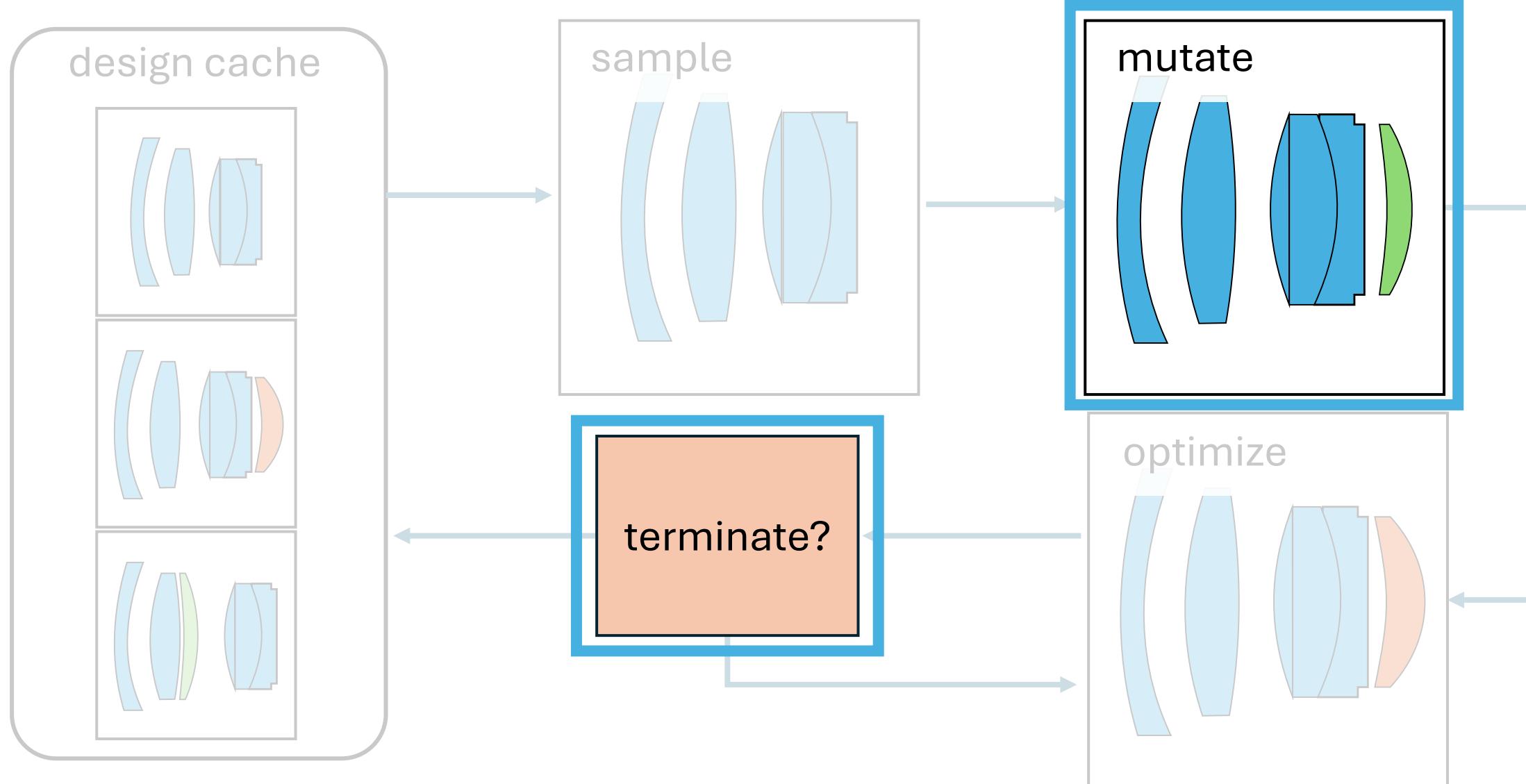
Comparison to Metropolis-Hastings



Quasi-stationary Monte Carlo (QSMC)



Quasi-stationary Monte Carlo (QSMC)



Stochastic termination

$$L(\pi)$$

Boltzmann distribution

$$\rho(\pi) = e^{-L(\pi)}$$

RESTORE

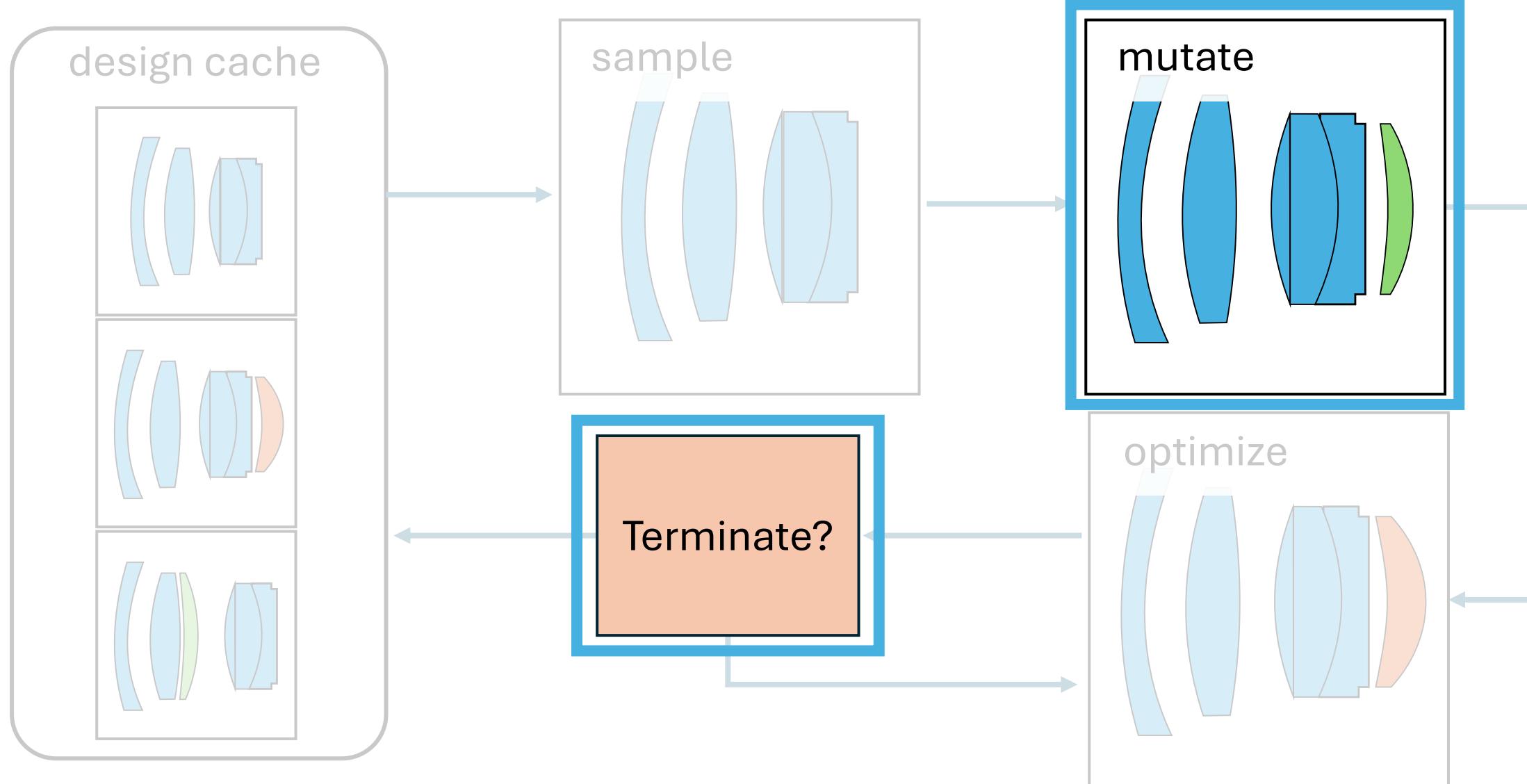
Jump Restore Light Transport
[Holl et al. 2025]



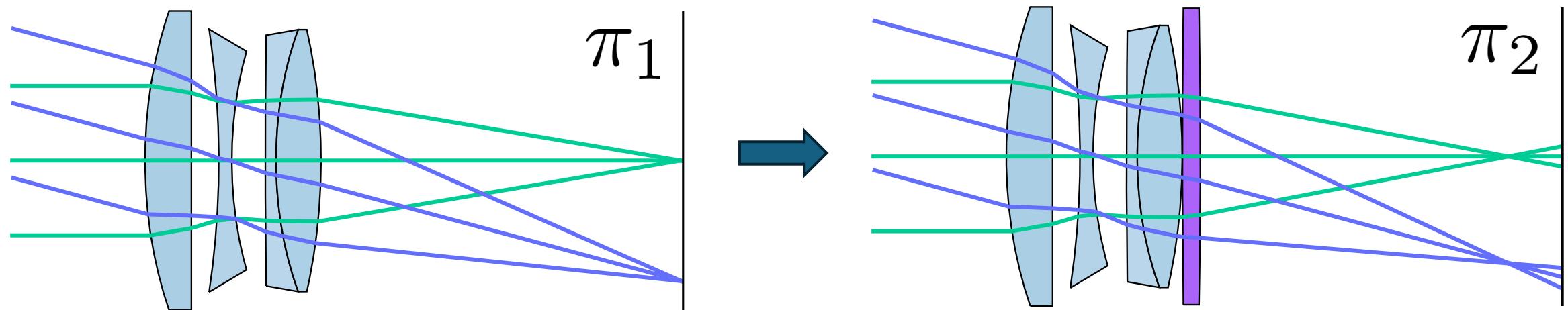
Probability of termination

$$\frac{\rho(\pi_{\text{prev}}) - \rho(\pi) + C}{\rho(\pi) + C}$$

Quasi-Stationary Monte Carlo (QSMC)



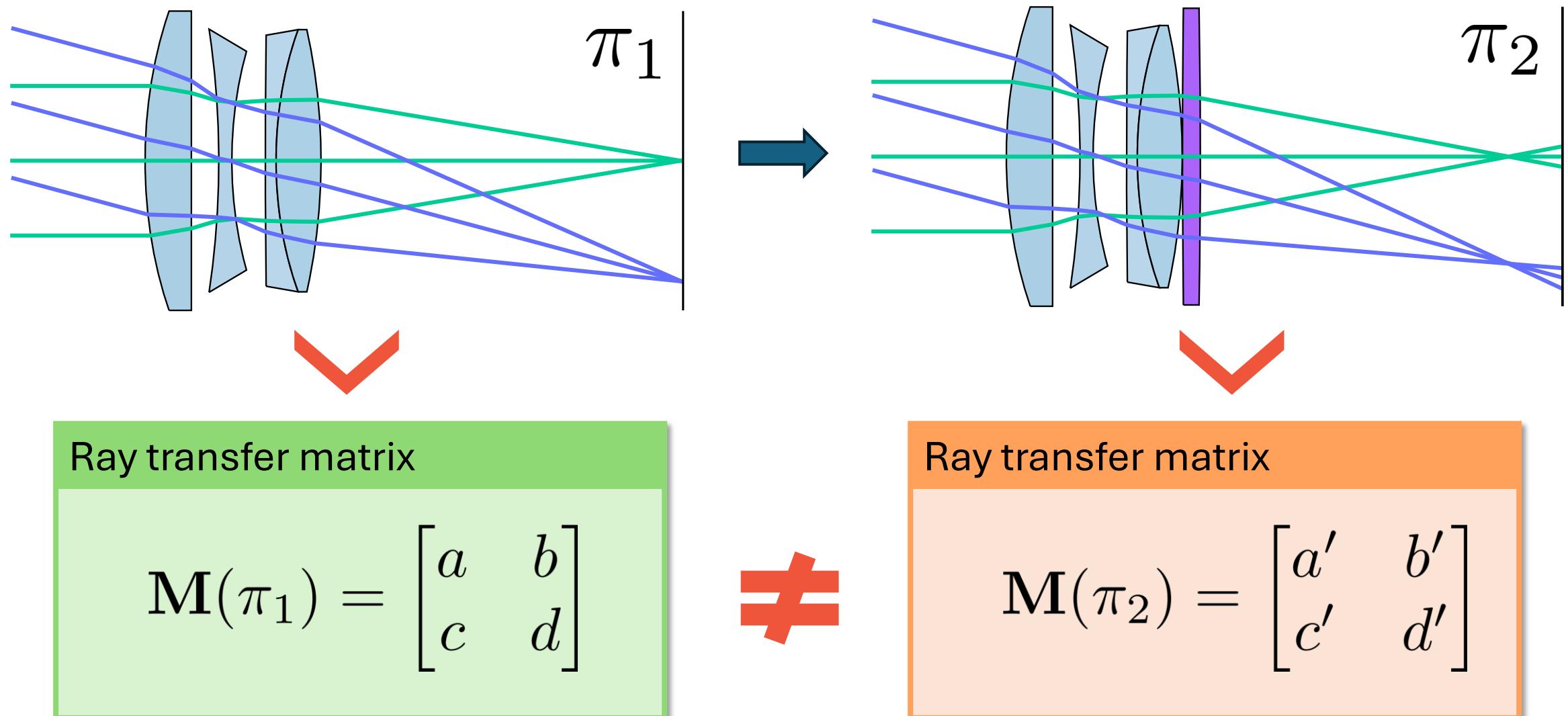
Simple mutations are problematic



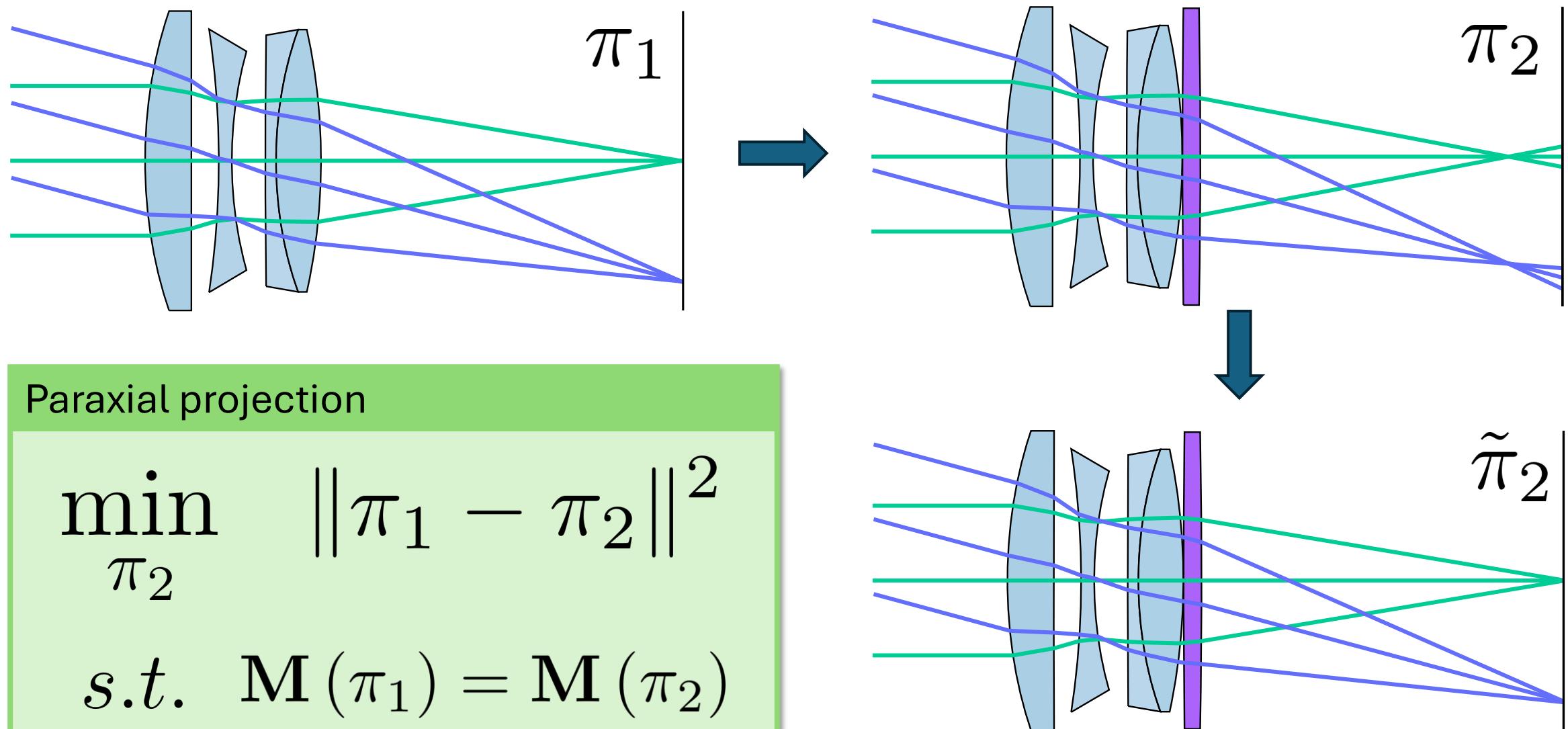
High chance of being a **worse** design

Most likely **terminated**

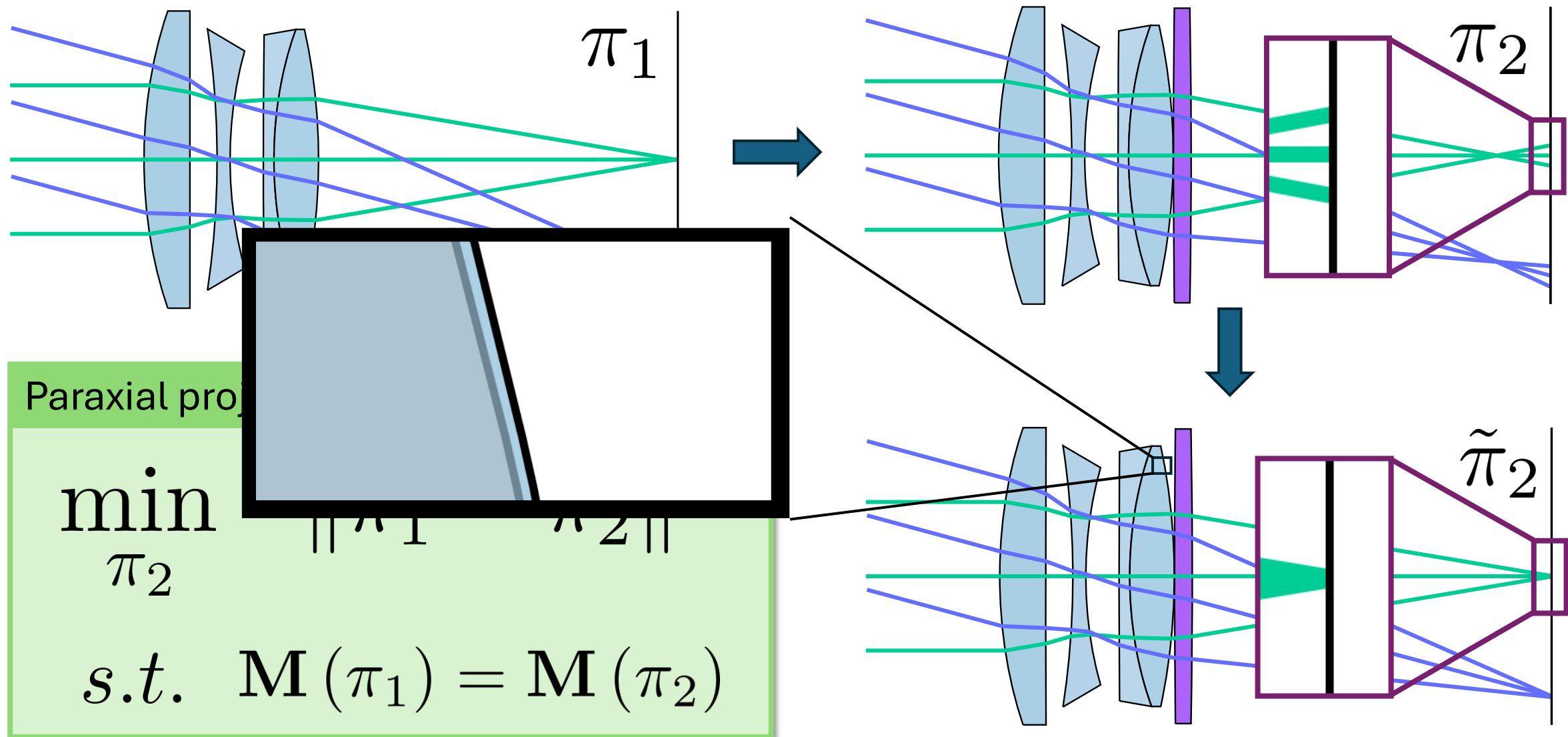
Key idea: paraxial optics as a proxy



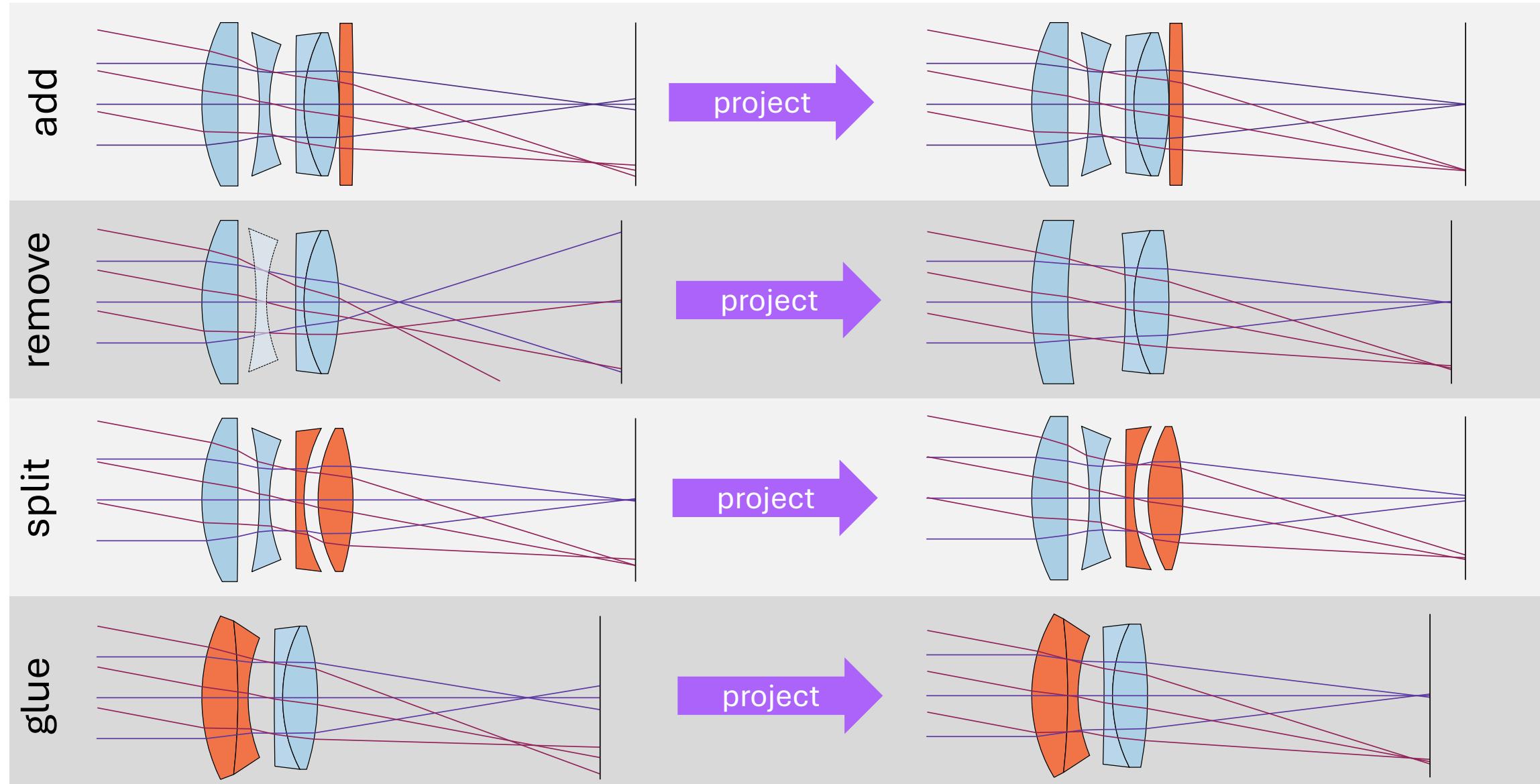
Key idea: paraxial optics as a proxy



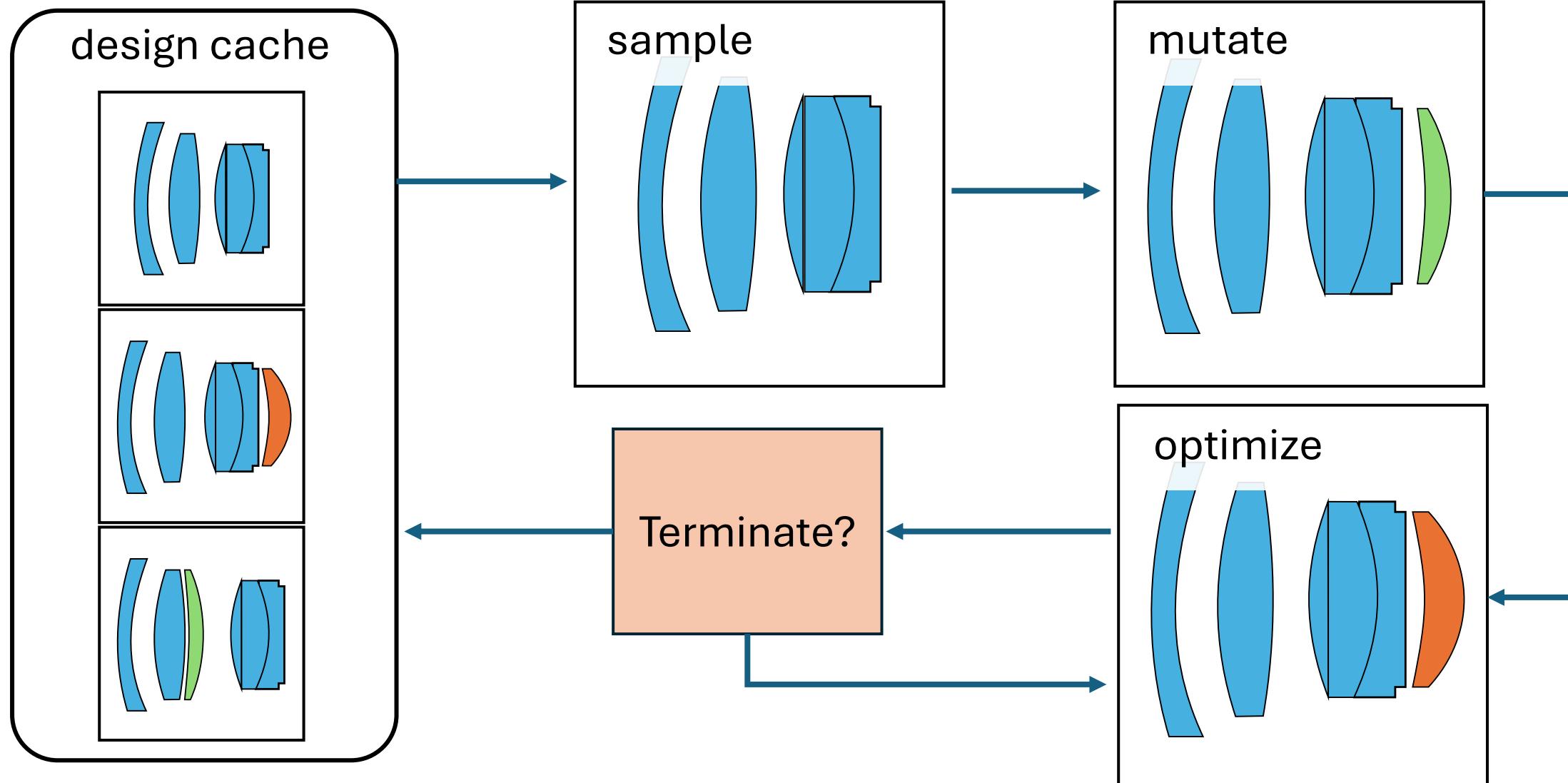
Key idea: paraxial optics as a proxy



Paraxial projection

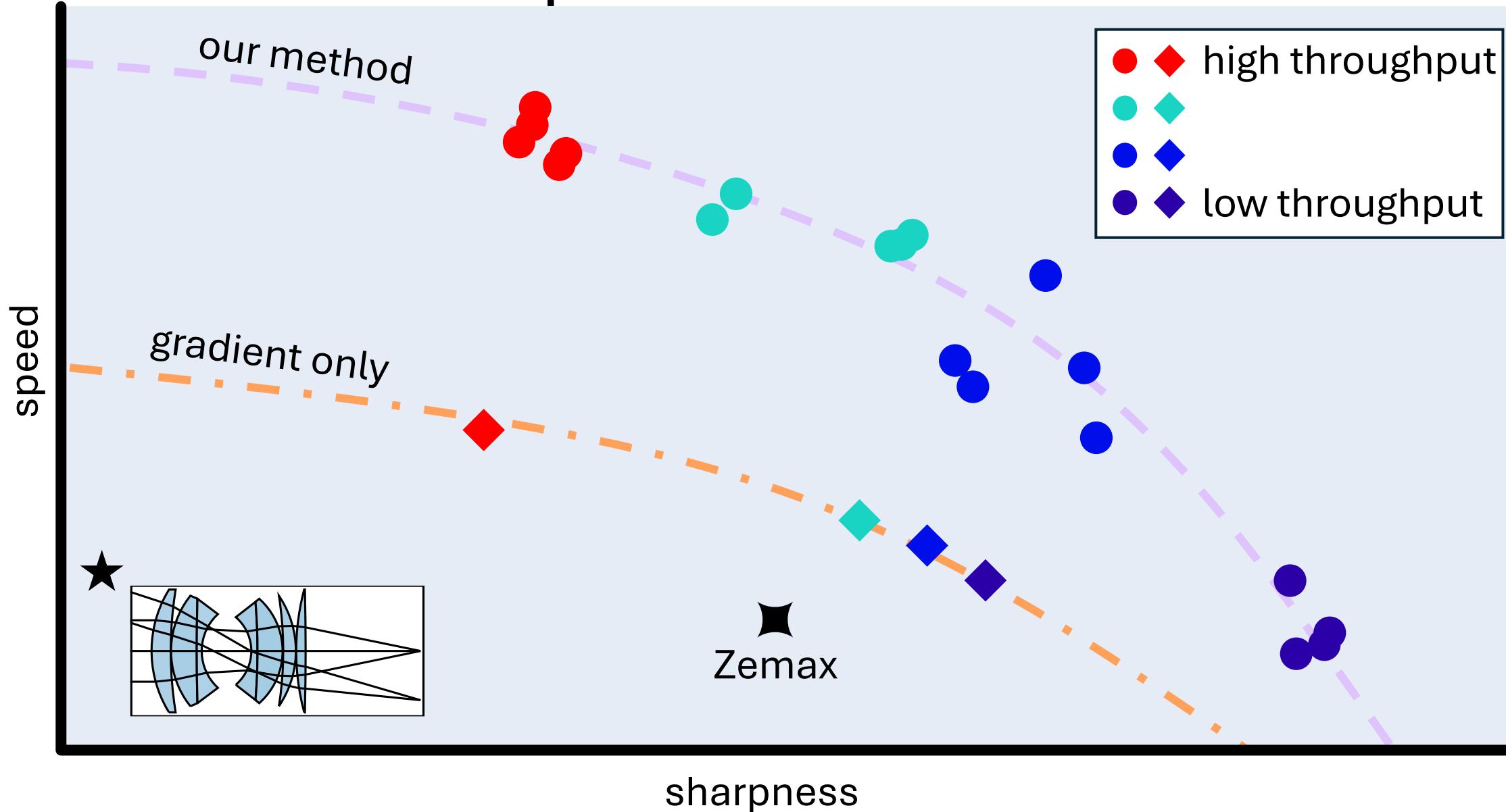


Quasi-Stationary Monte Carlo (QSMC)

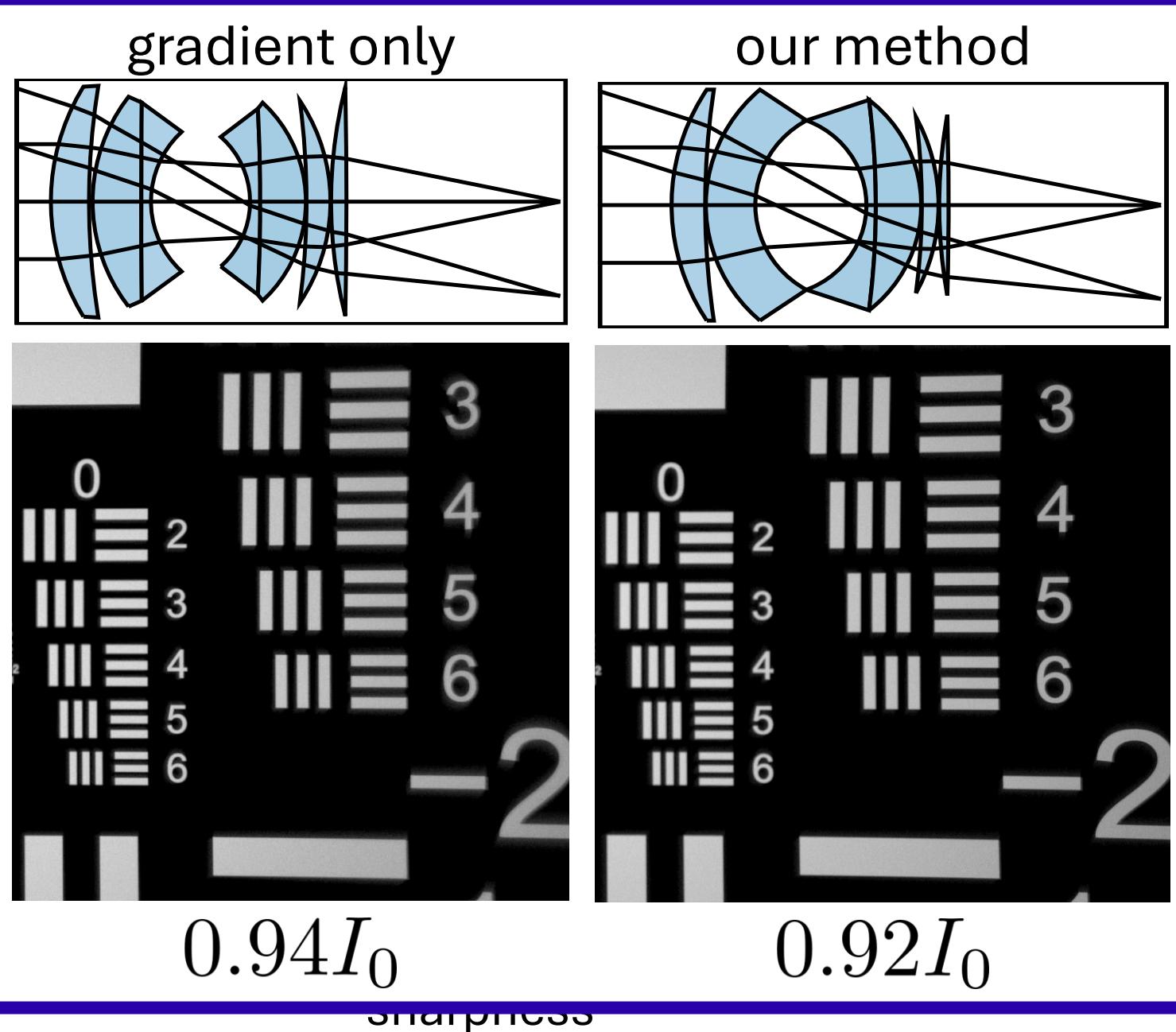
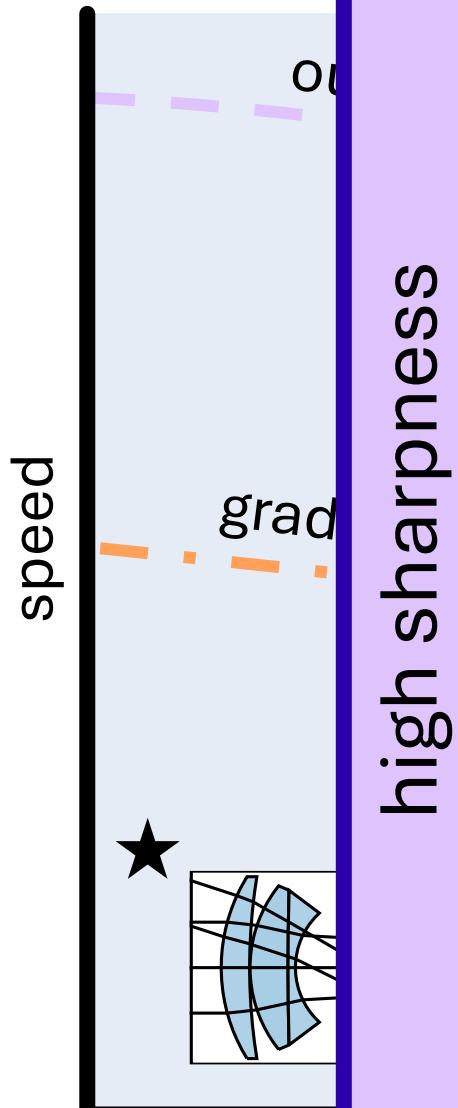


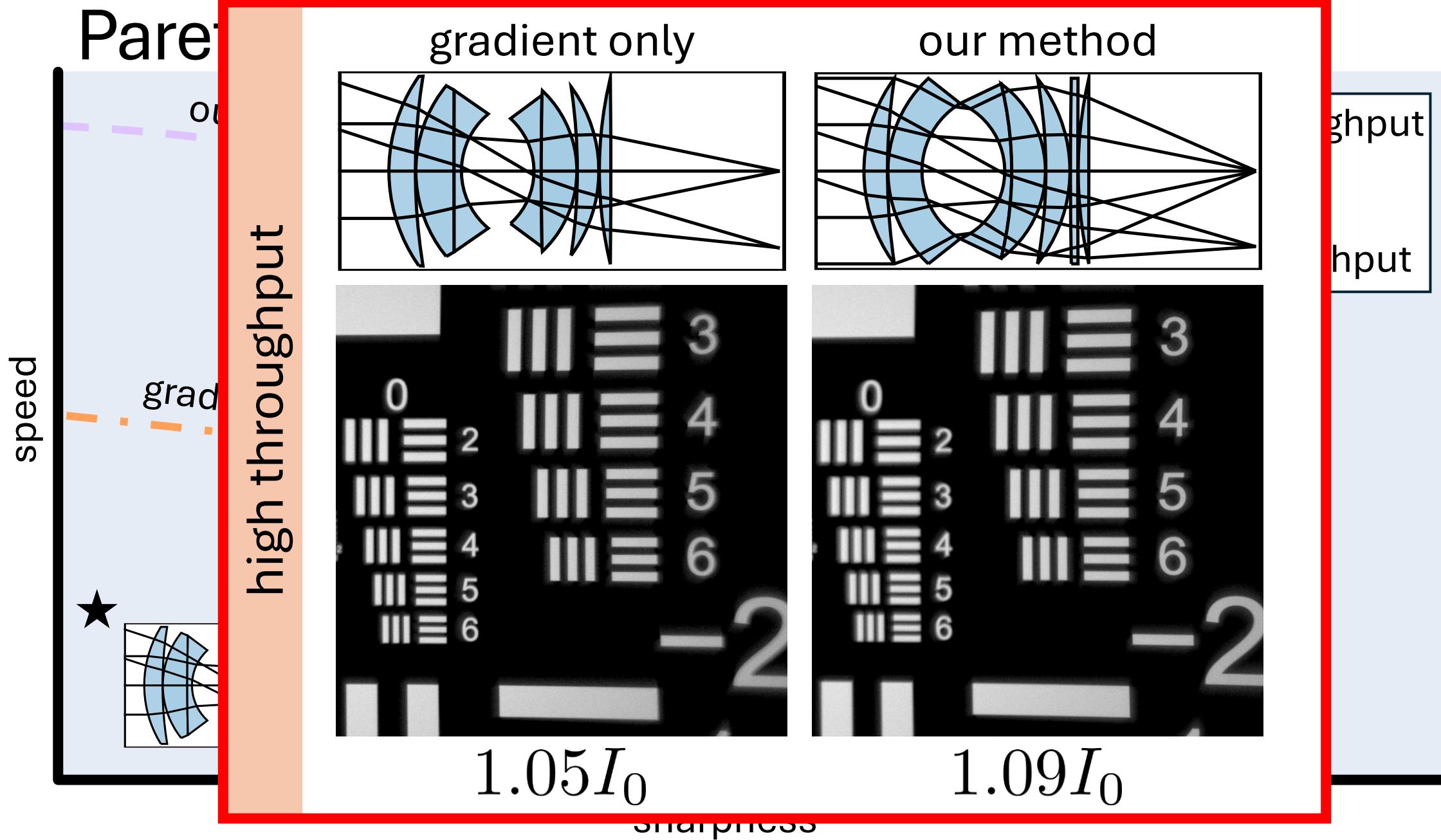
Pareto front expansion

Pareto front expansion

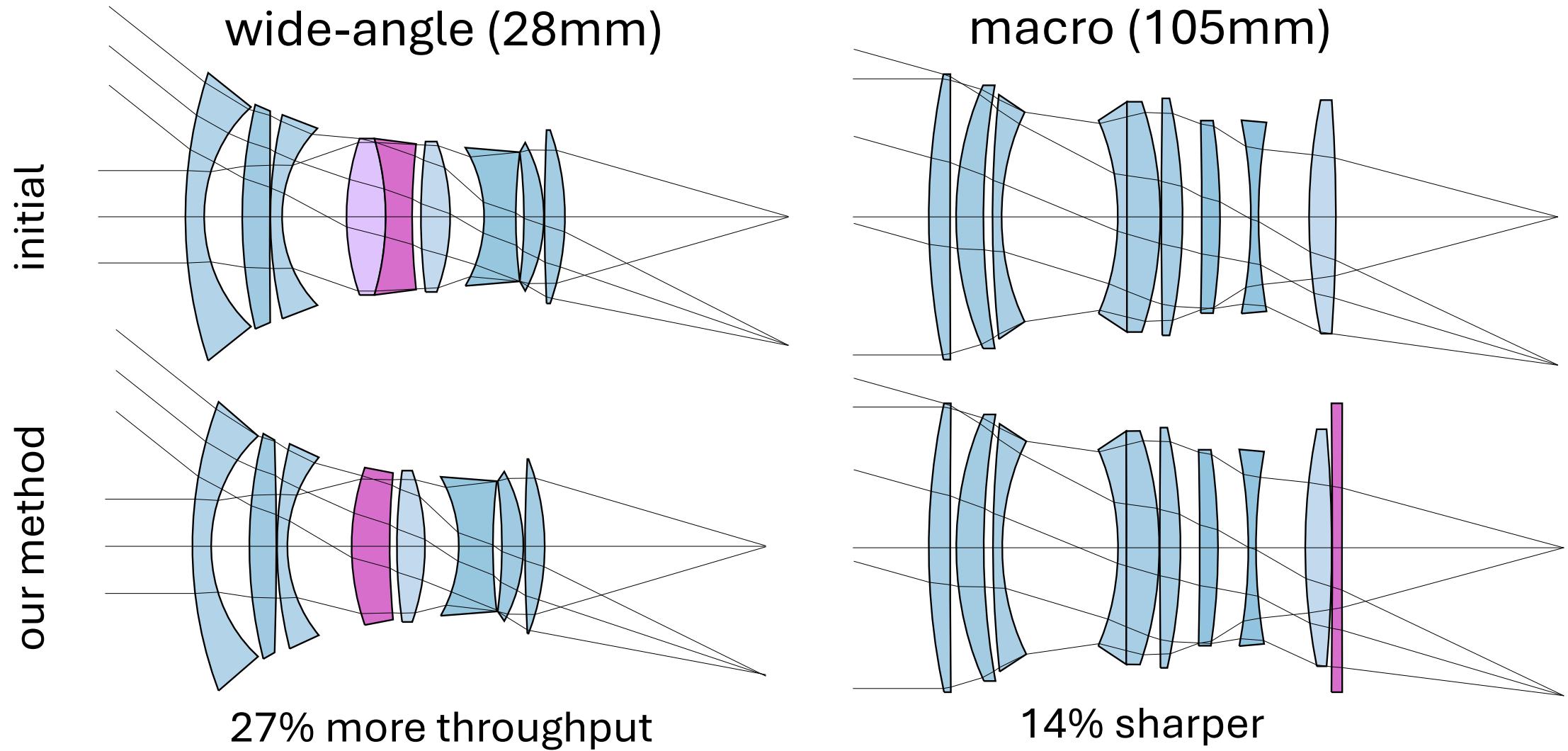


Pareto front

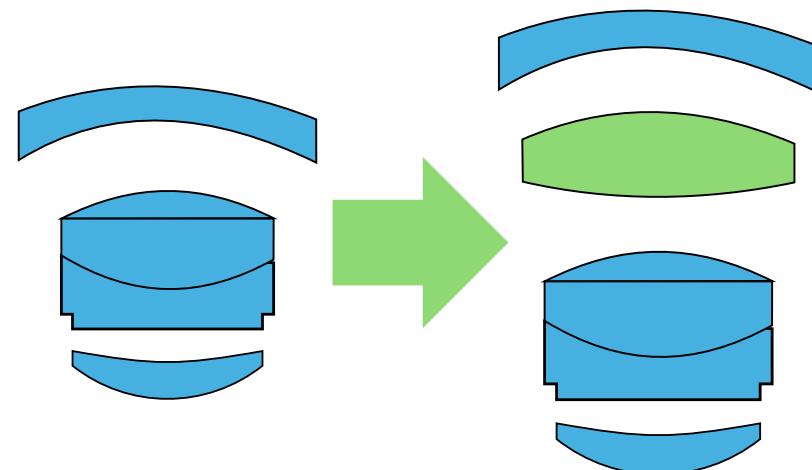




Can improve other lens types as well



Discrete-continuous optimization

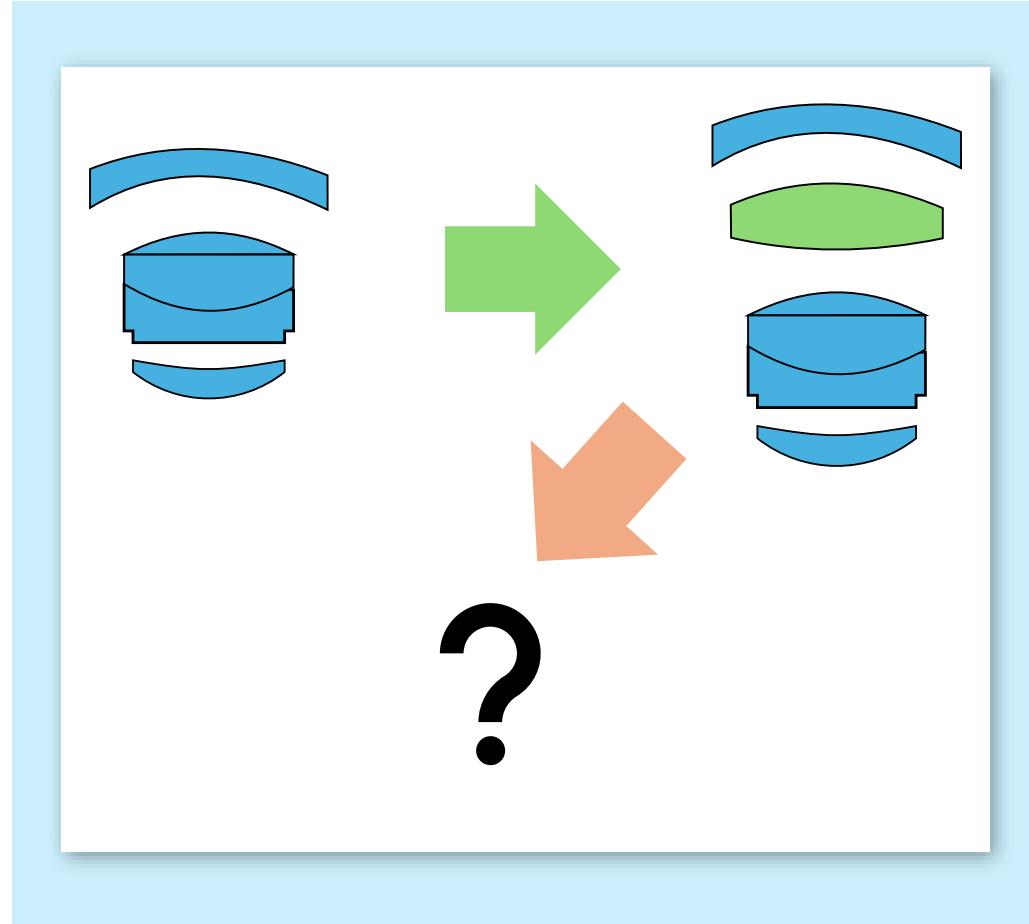


Optimization as a sampling problem

QSMC allows for optimization without noise

Better mutations with paraxial projection

Our method is extendable



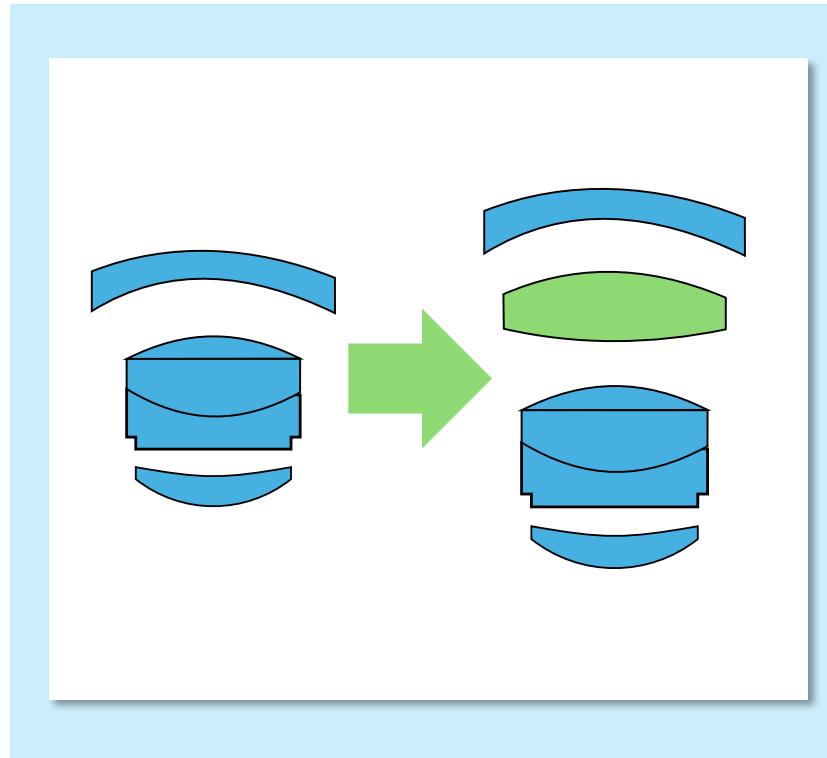
add aspheric, cylindrical, and other types of optics

new design objectives to target specific aberrations

manufacturing and tolerance aware design

Automated design of compound lenses with discrete-continuous optimization

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https://imaging.cs.cmu.edu/automated_lens_design/