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Automated design of compound lenses with discrete-continuous optimization

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Carnegie Mellon University and Google

Sponsored by acm

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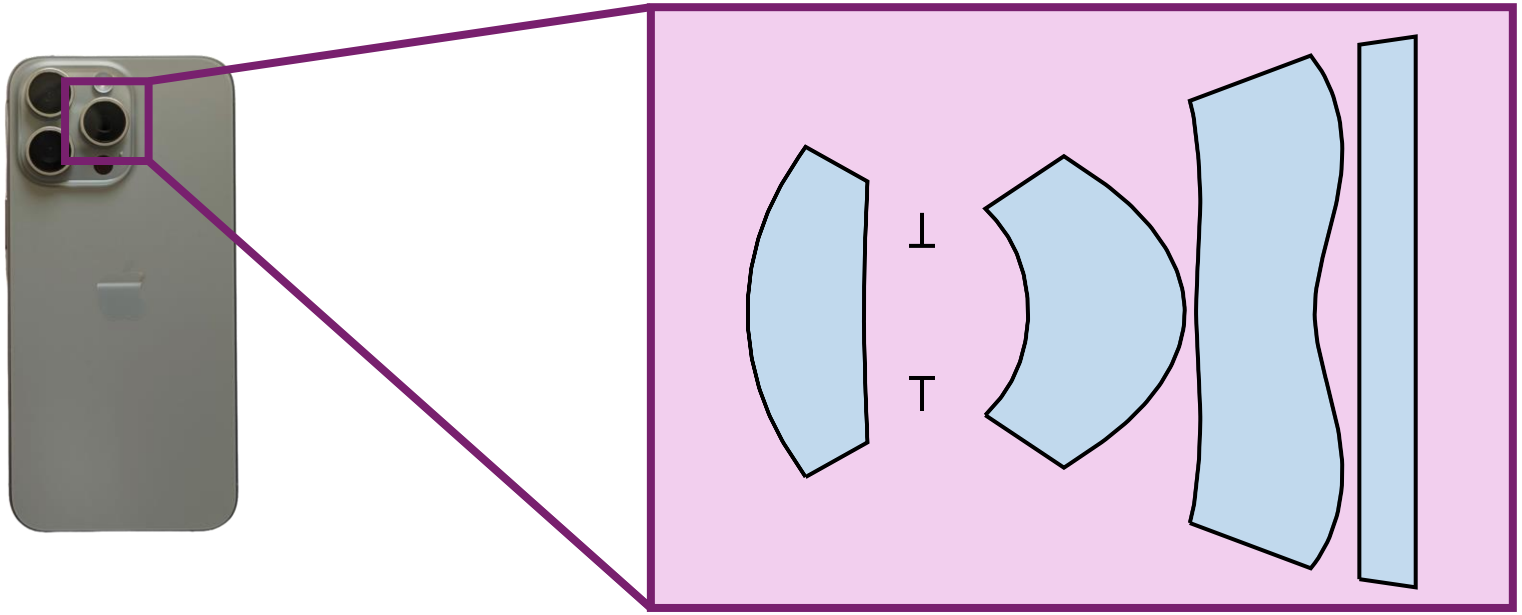
Lenses are everywhere

Many kinds of designs

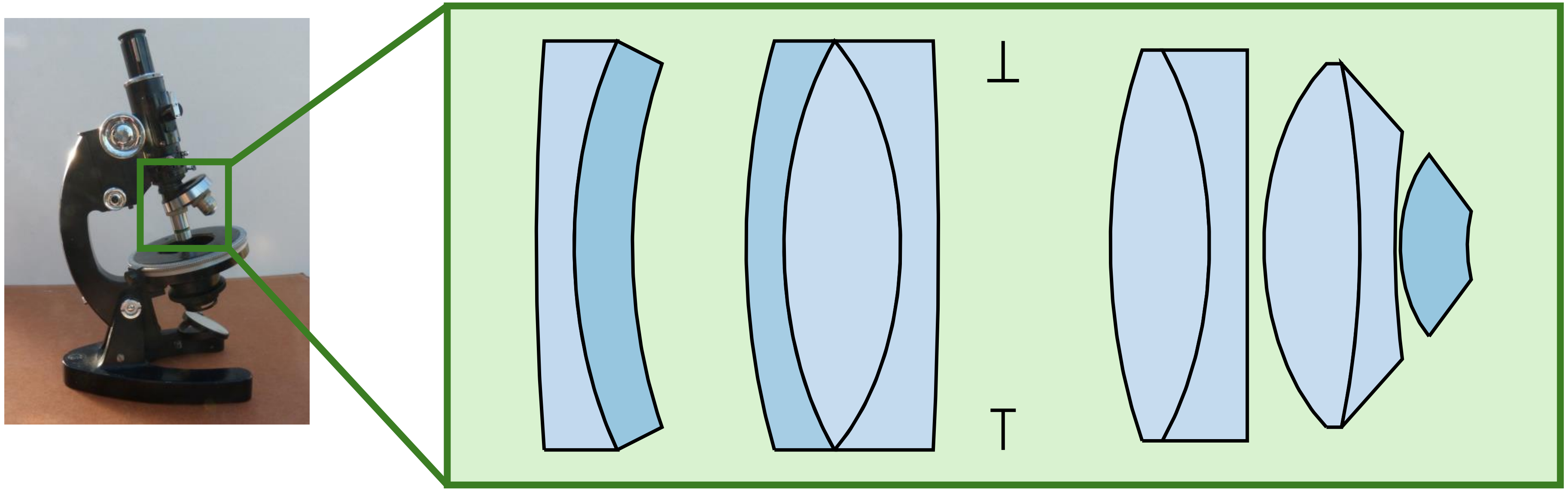
wide angle

fast



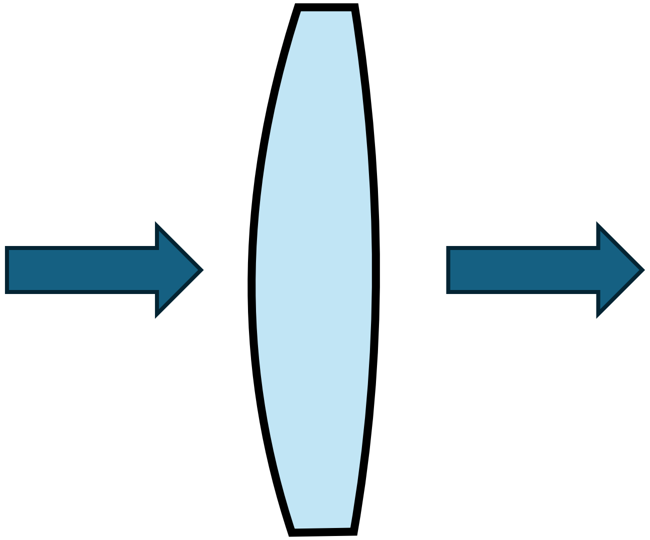
high resolution

no aberrations



Simple lenses aren’t enough

scene

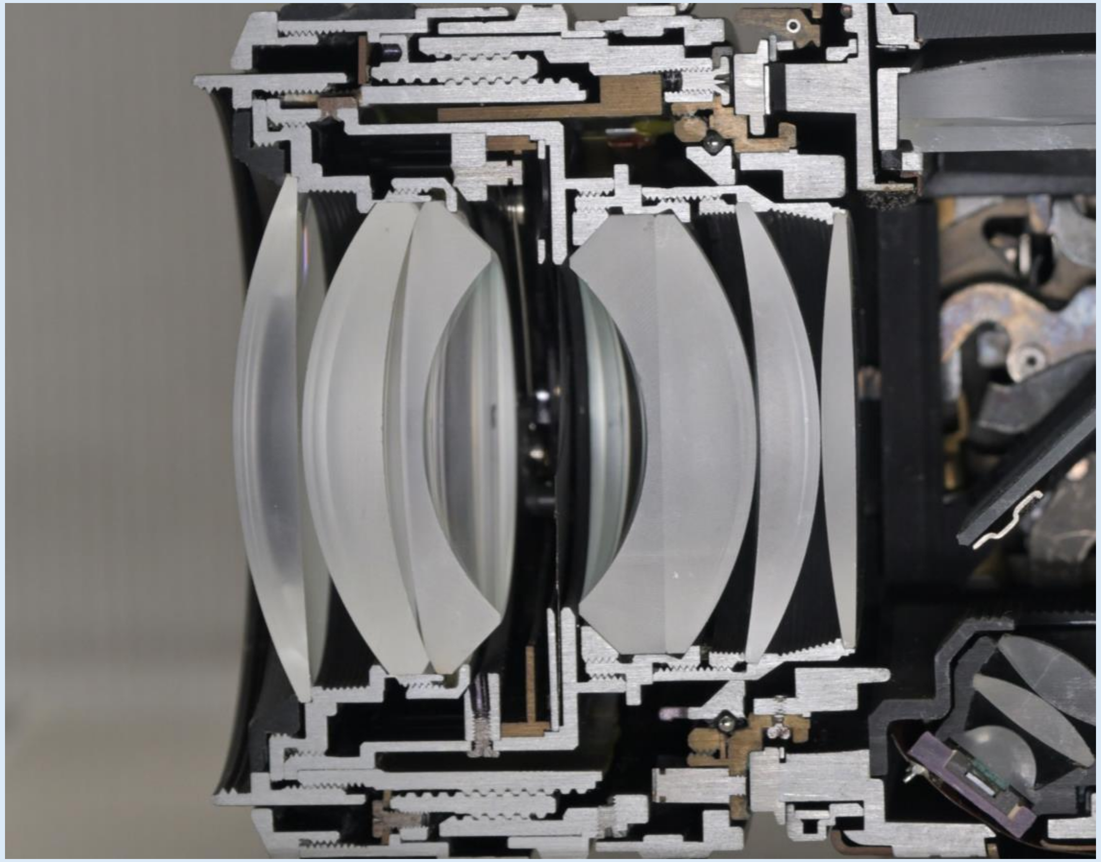


singlet lens

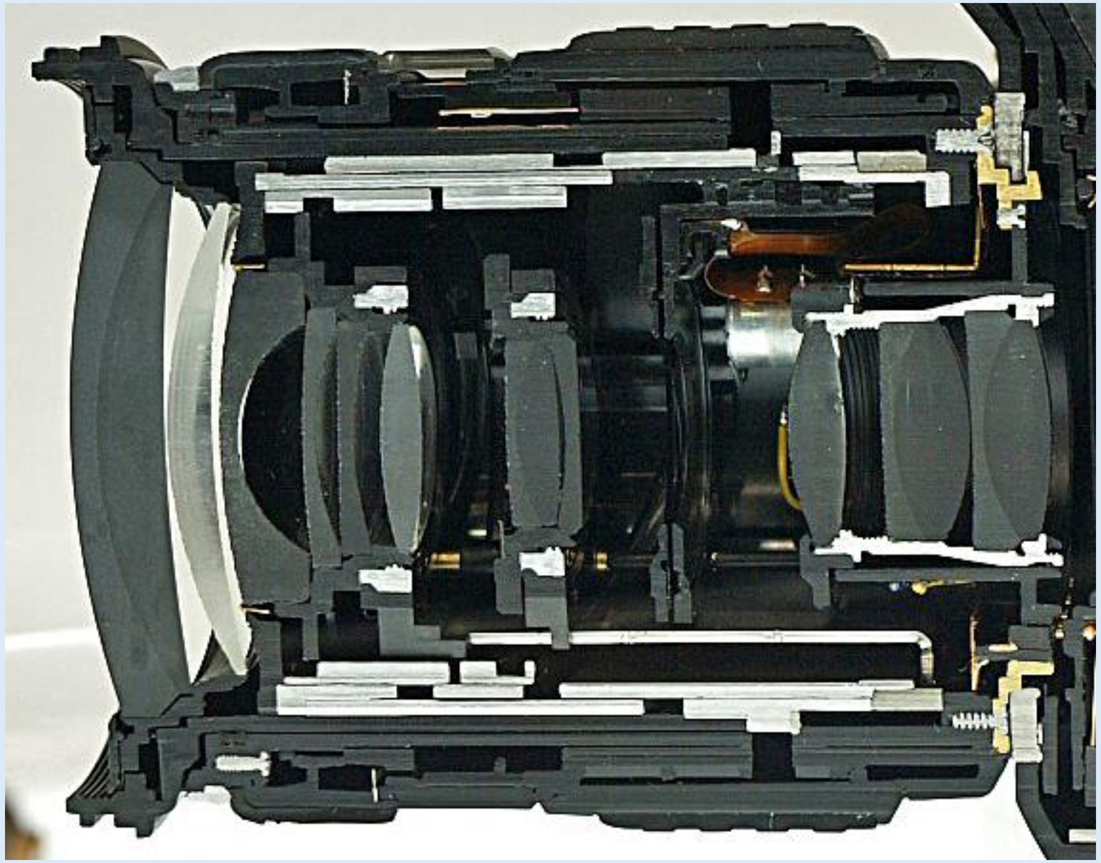
result

Modern lenses are complicated

Nikon F3 Cutaway

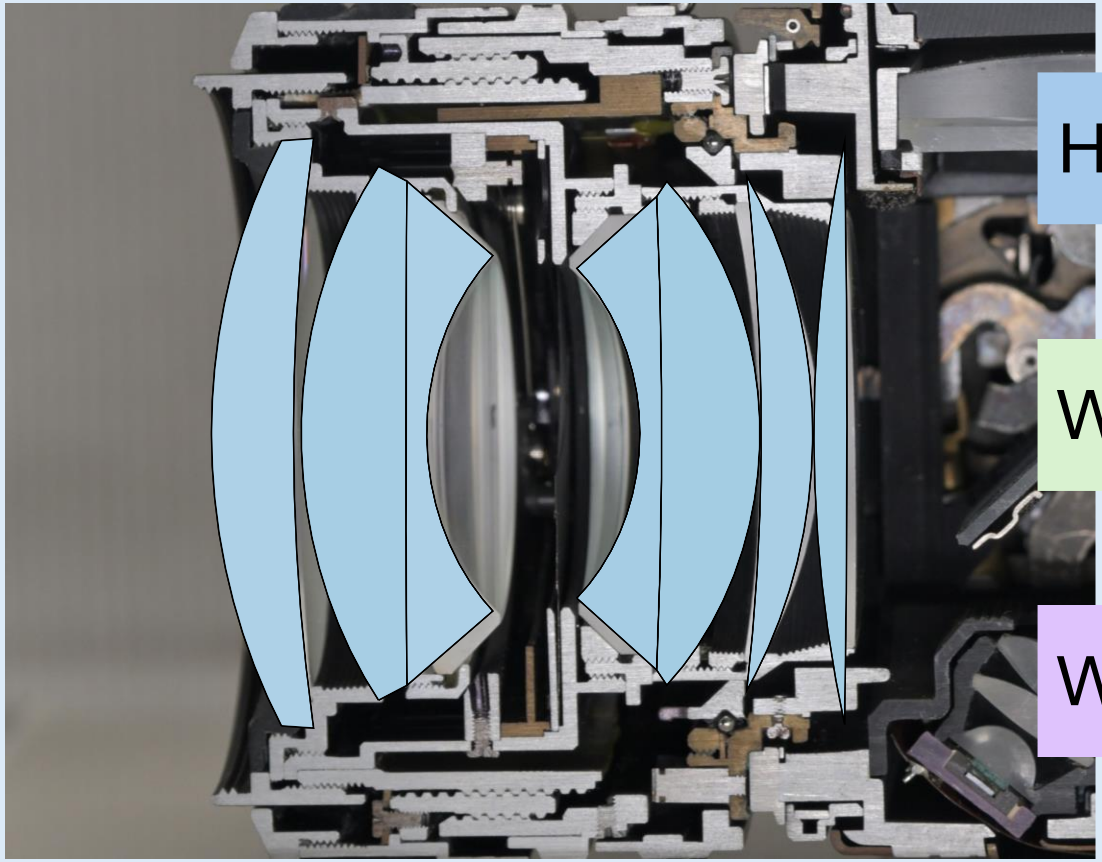


Olympus E-30 Cutaway



Combinatorially many discrete options

Nikon F3 Cutaway

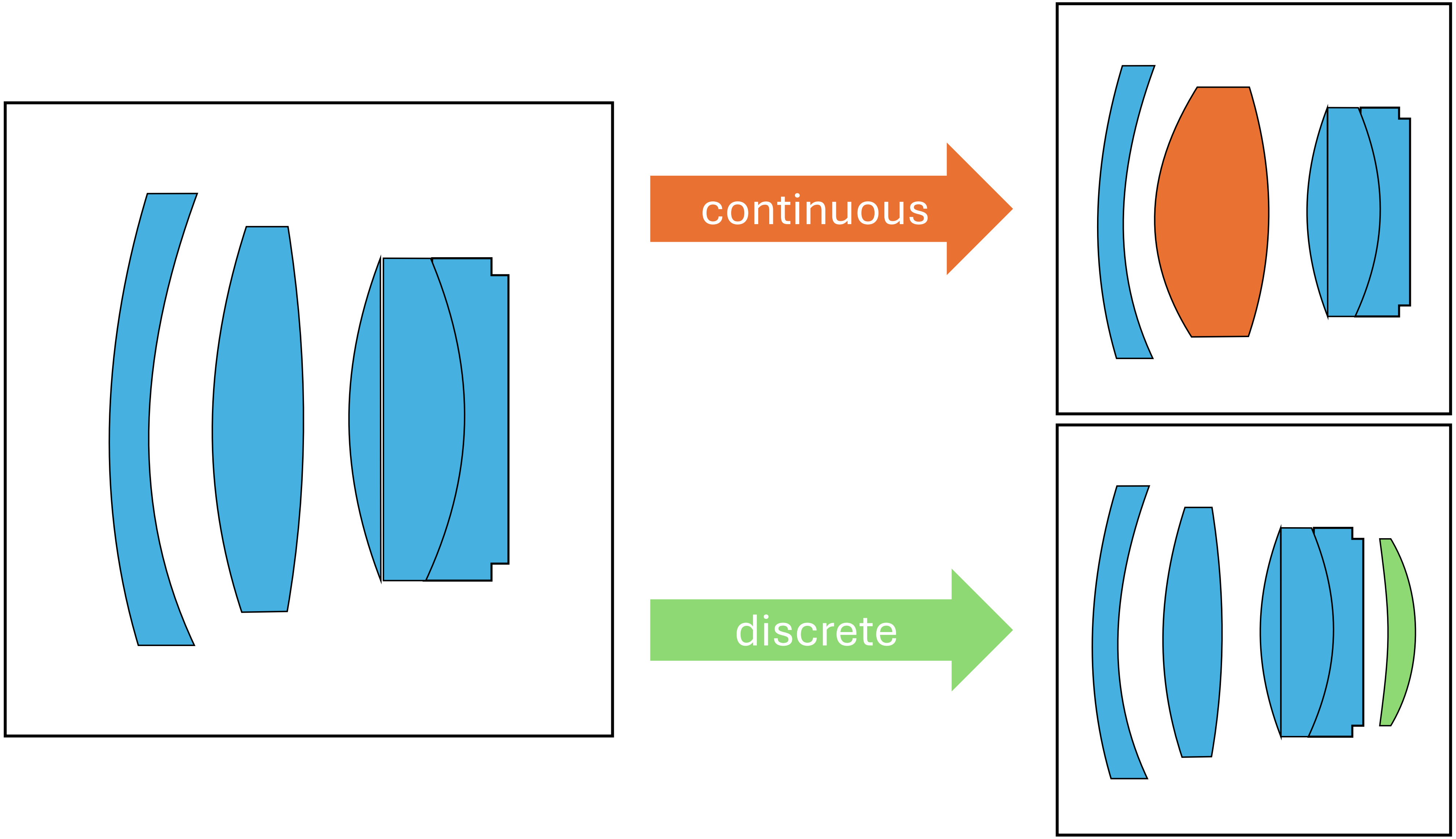


How many elements?

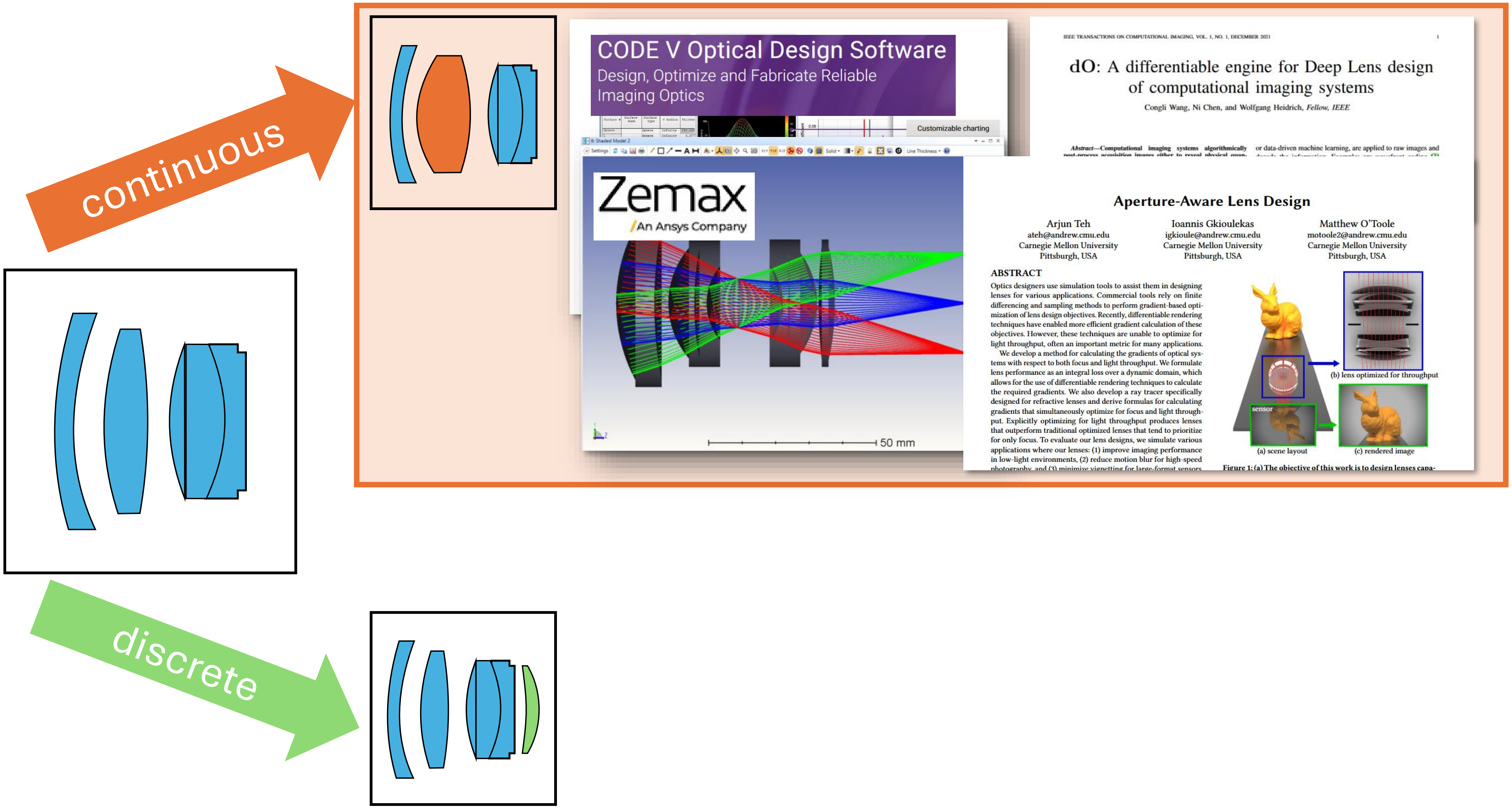
Which elements are glued together?

What order and orientation?

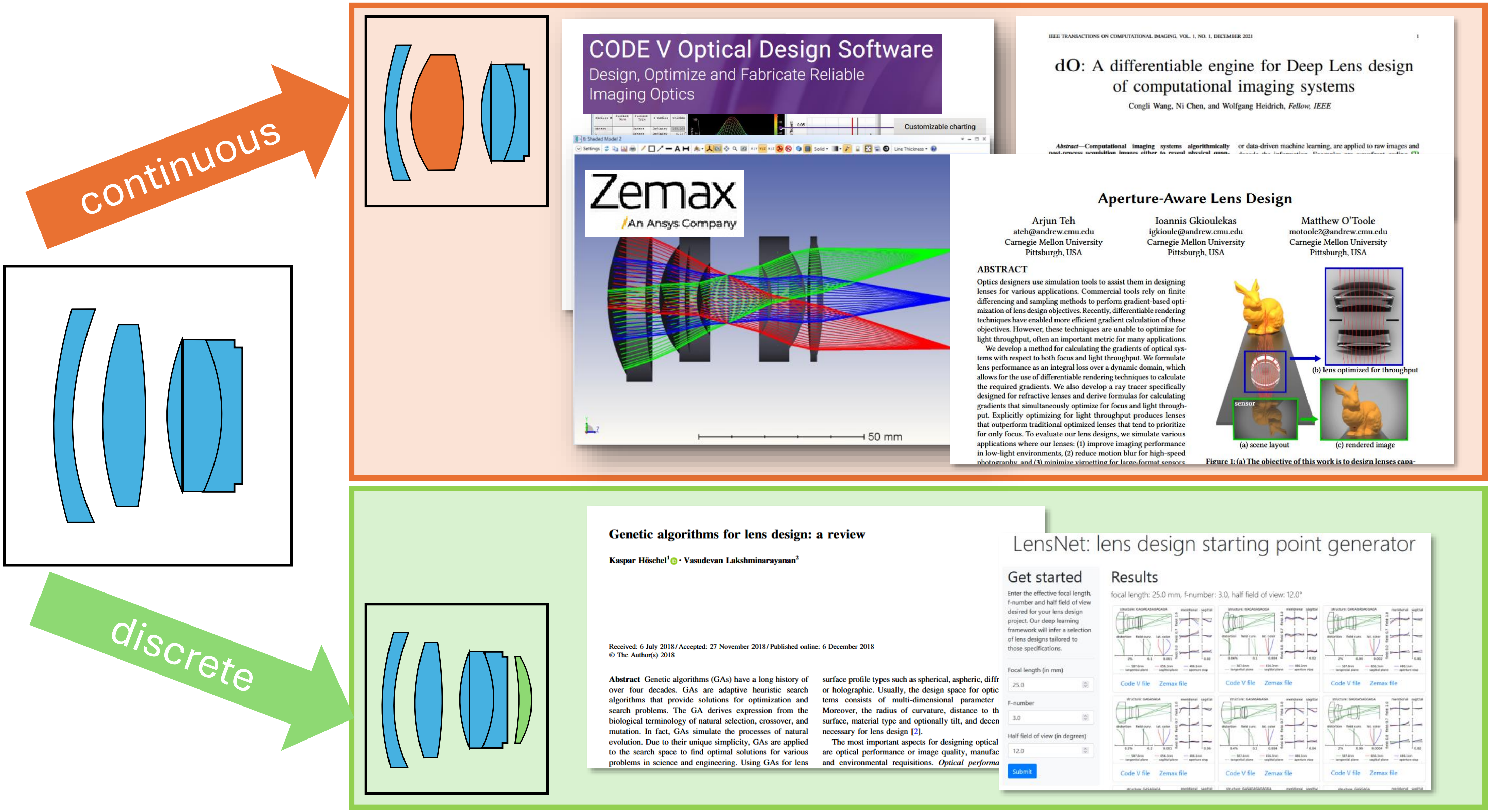
Two types of parameters



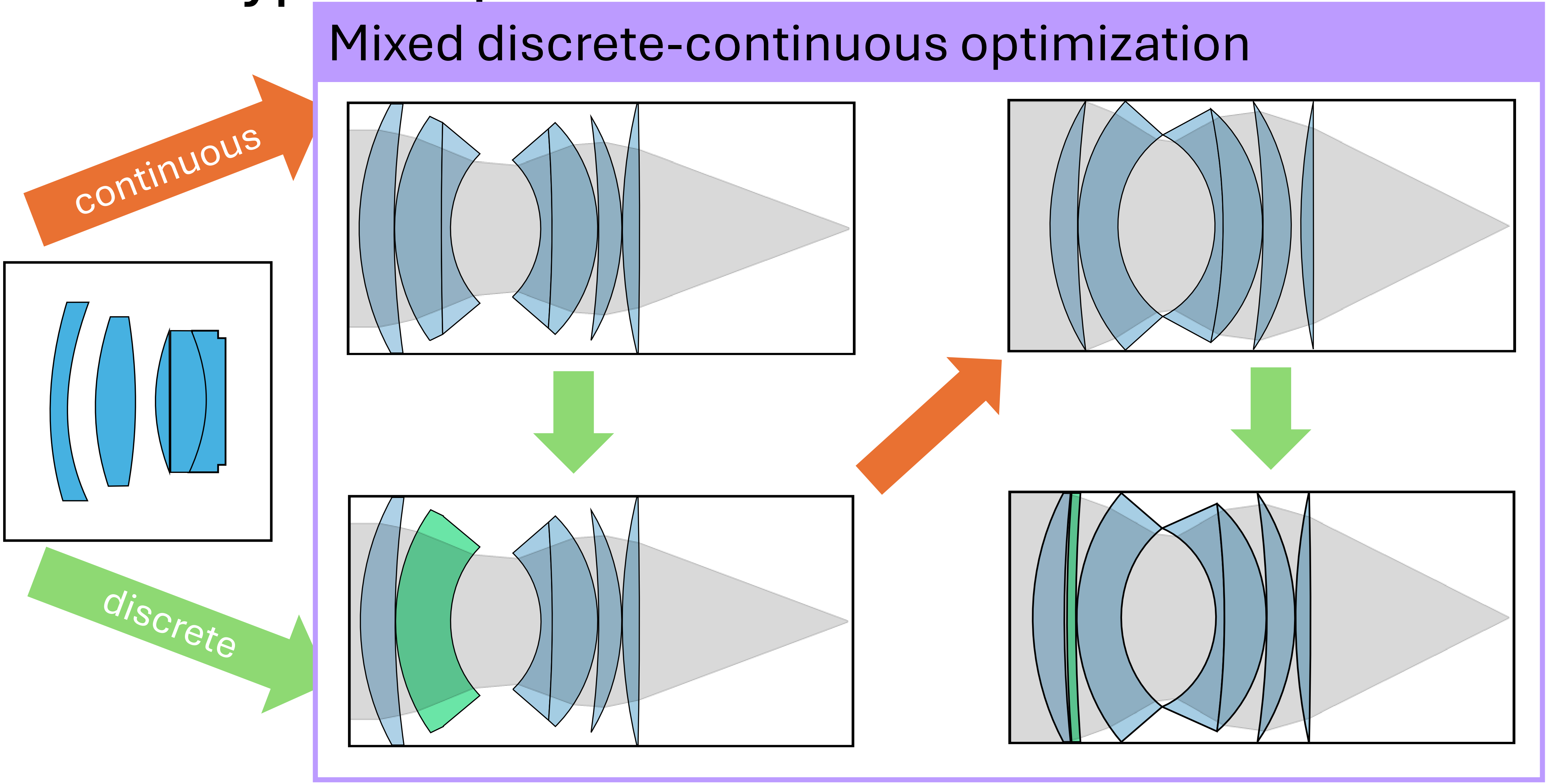
Two types of parameters



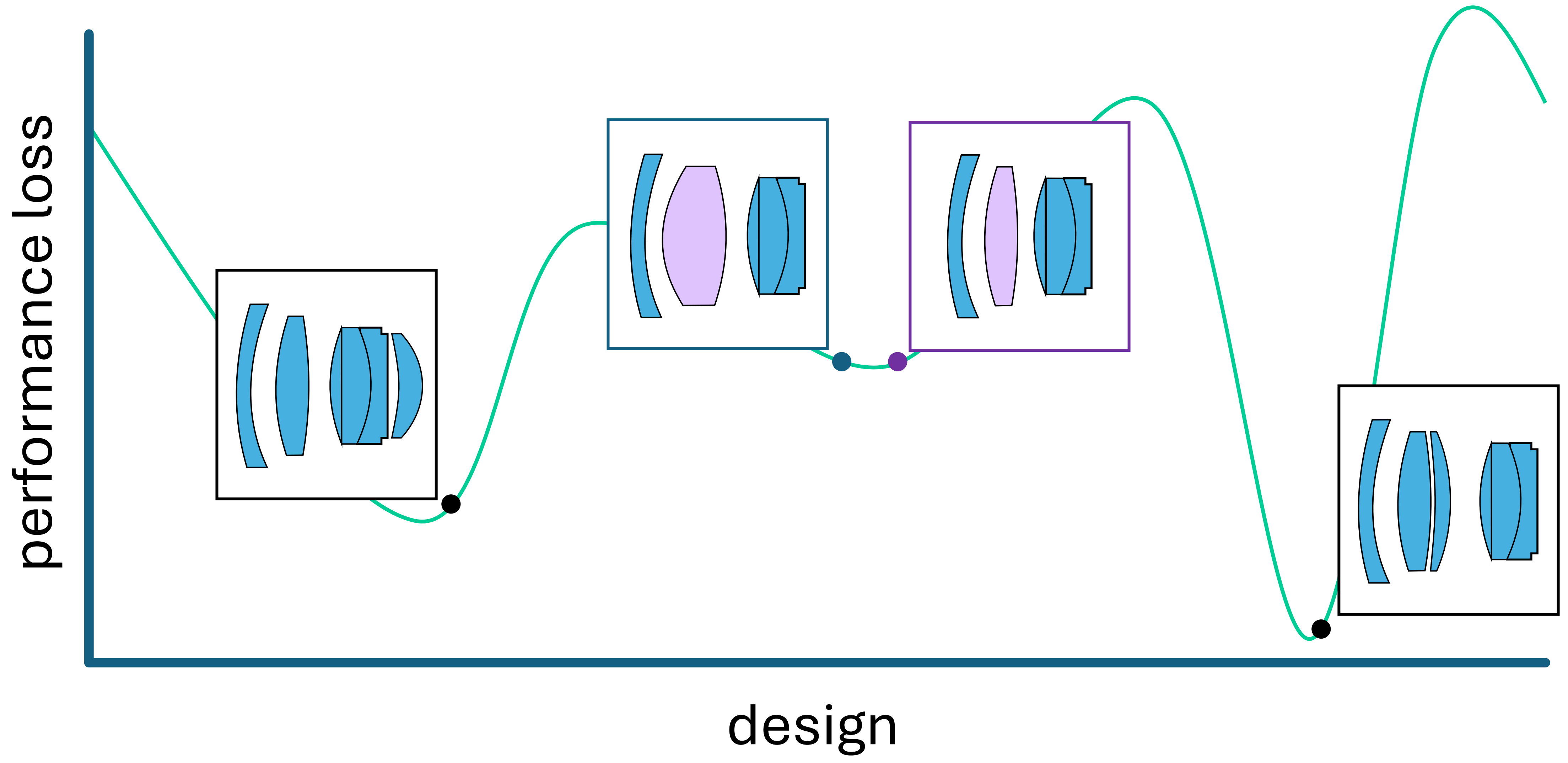
Two types of parameters



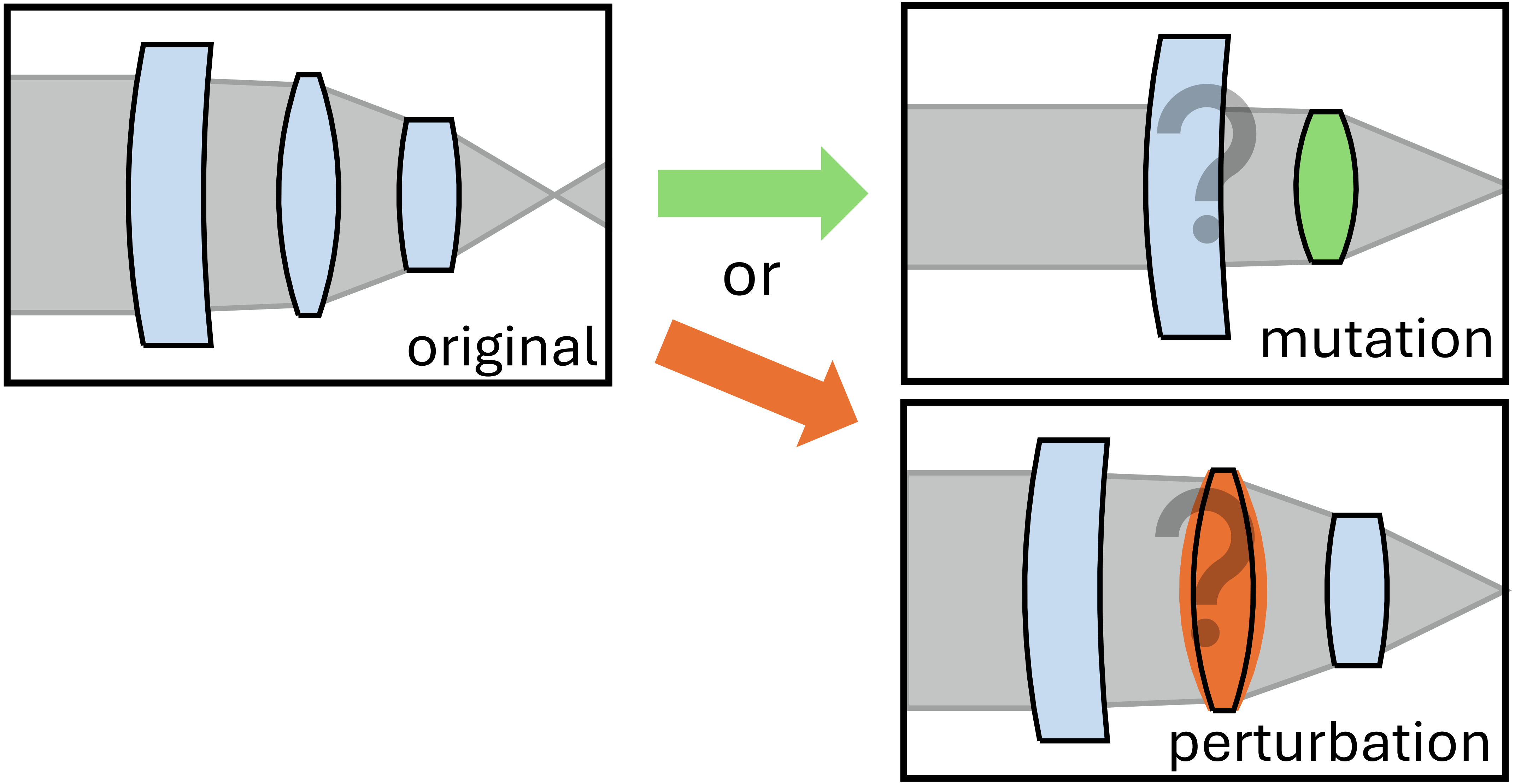
Two types of parameters



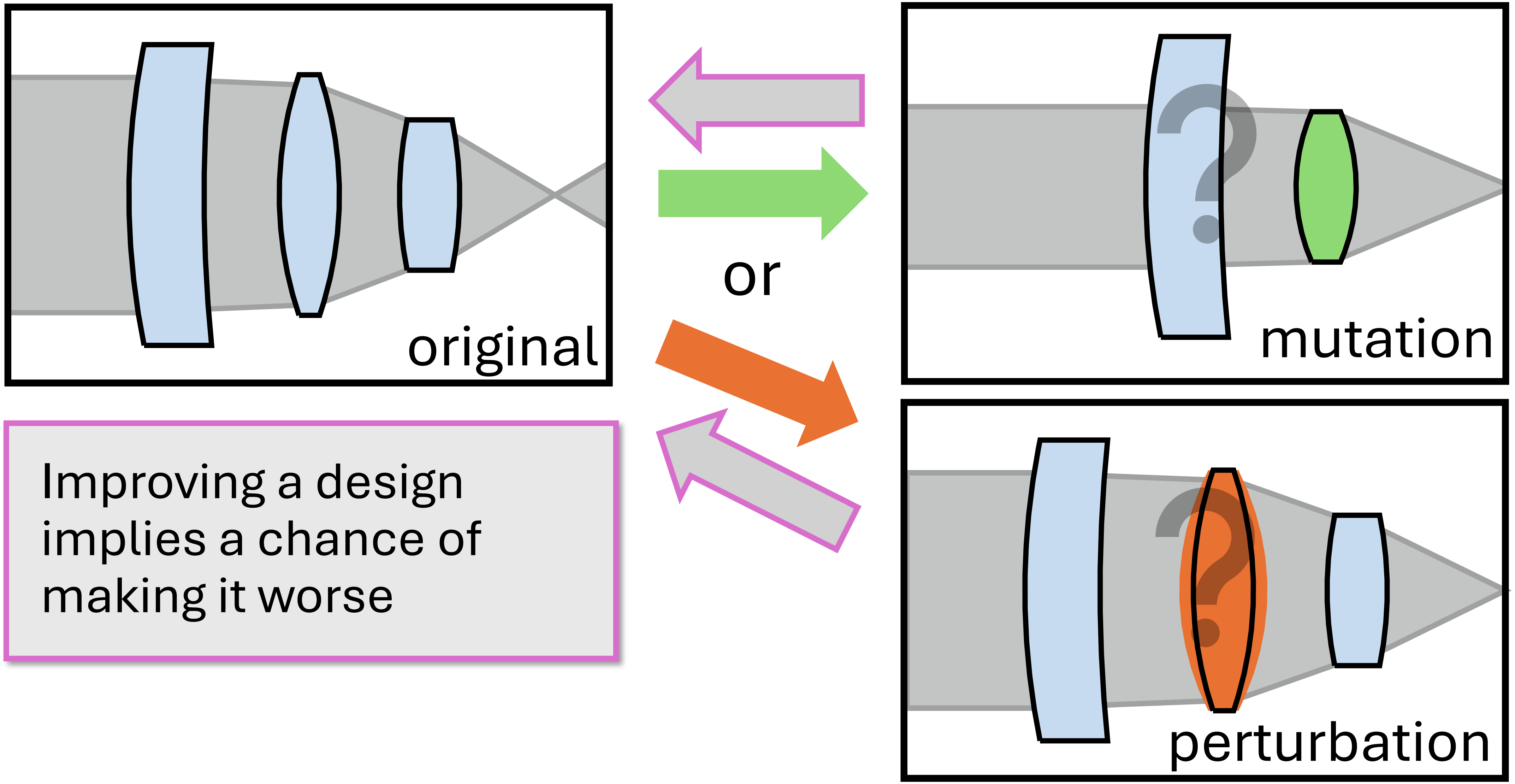
Key idea: sample the space of designs



Metropolis-Hastings



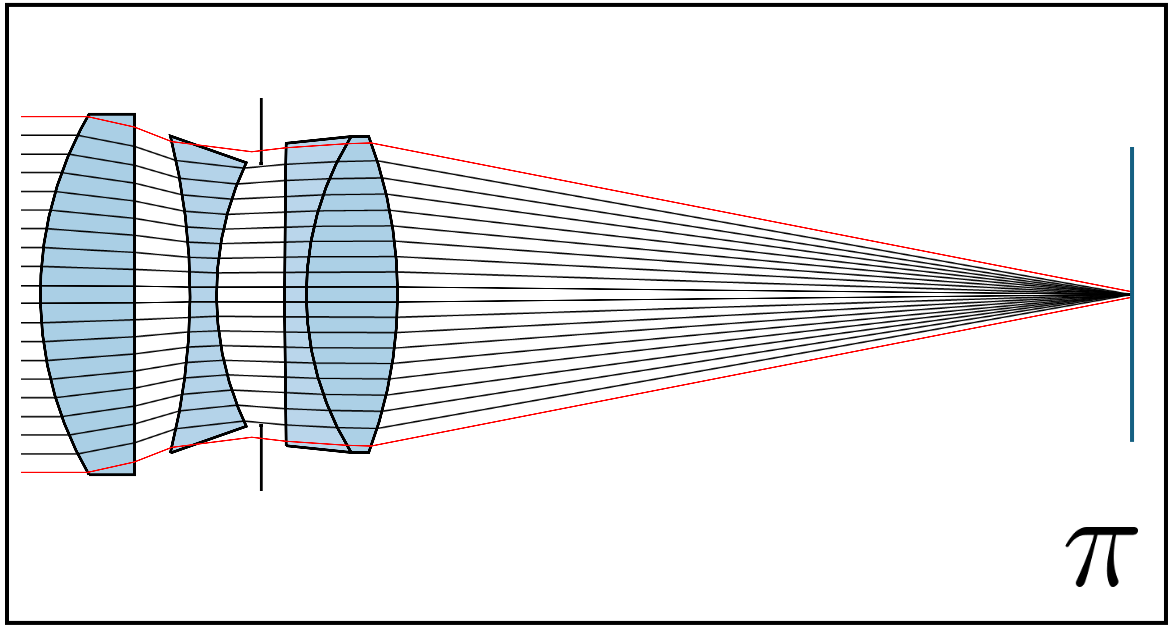
Metropolis-Hastings requires reversibility

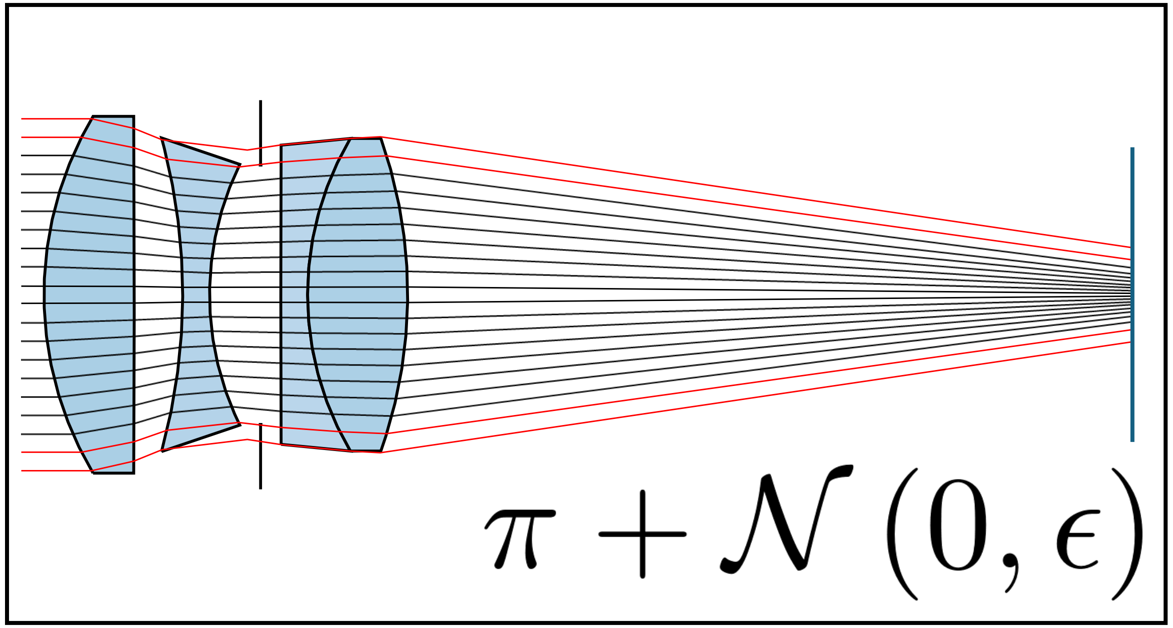


Improving a design implies a chance of making it worse

Metropolis-Hastings requires noise

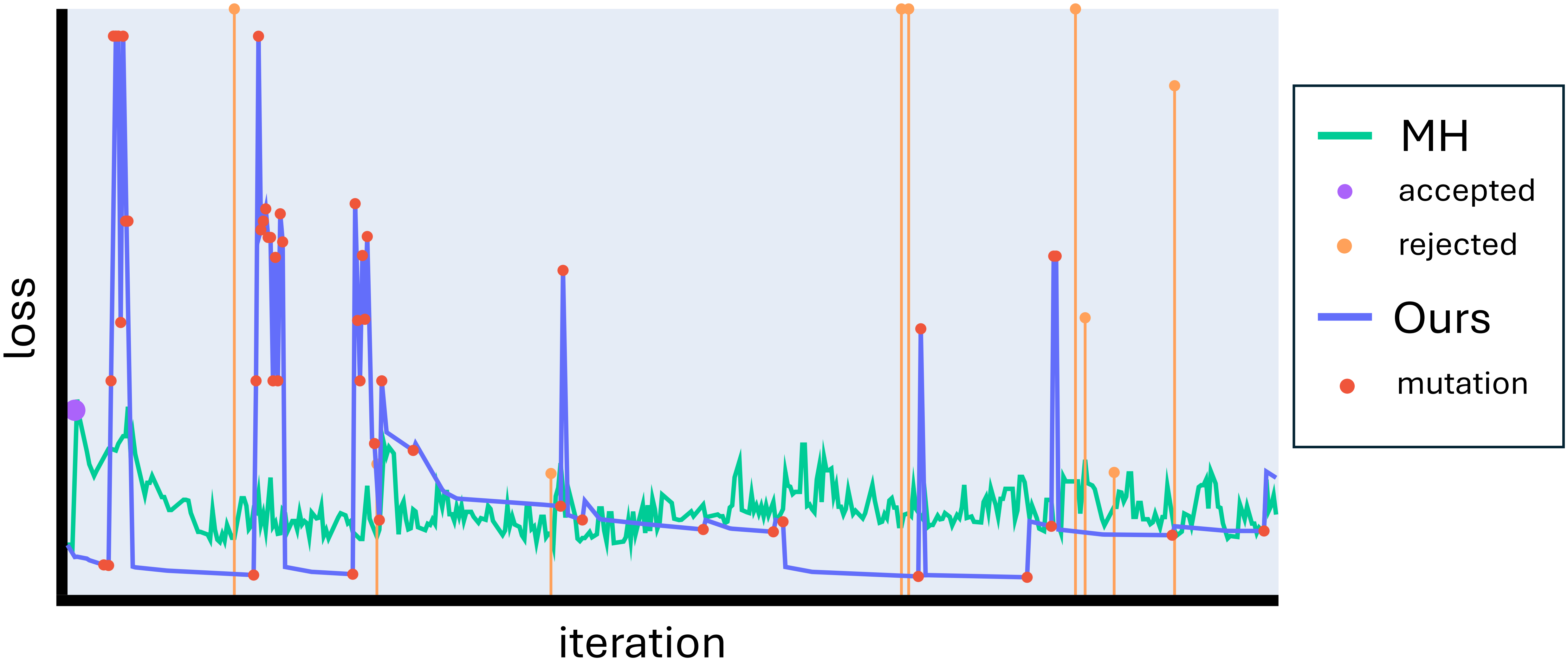
Langevin Monte Carlo (gradient descent) requires noise



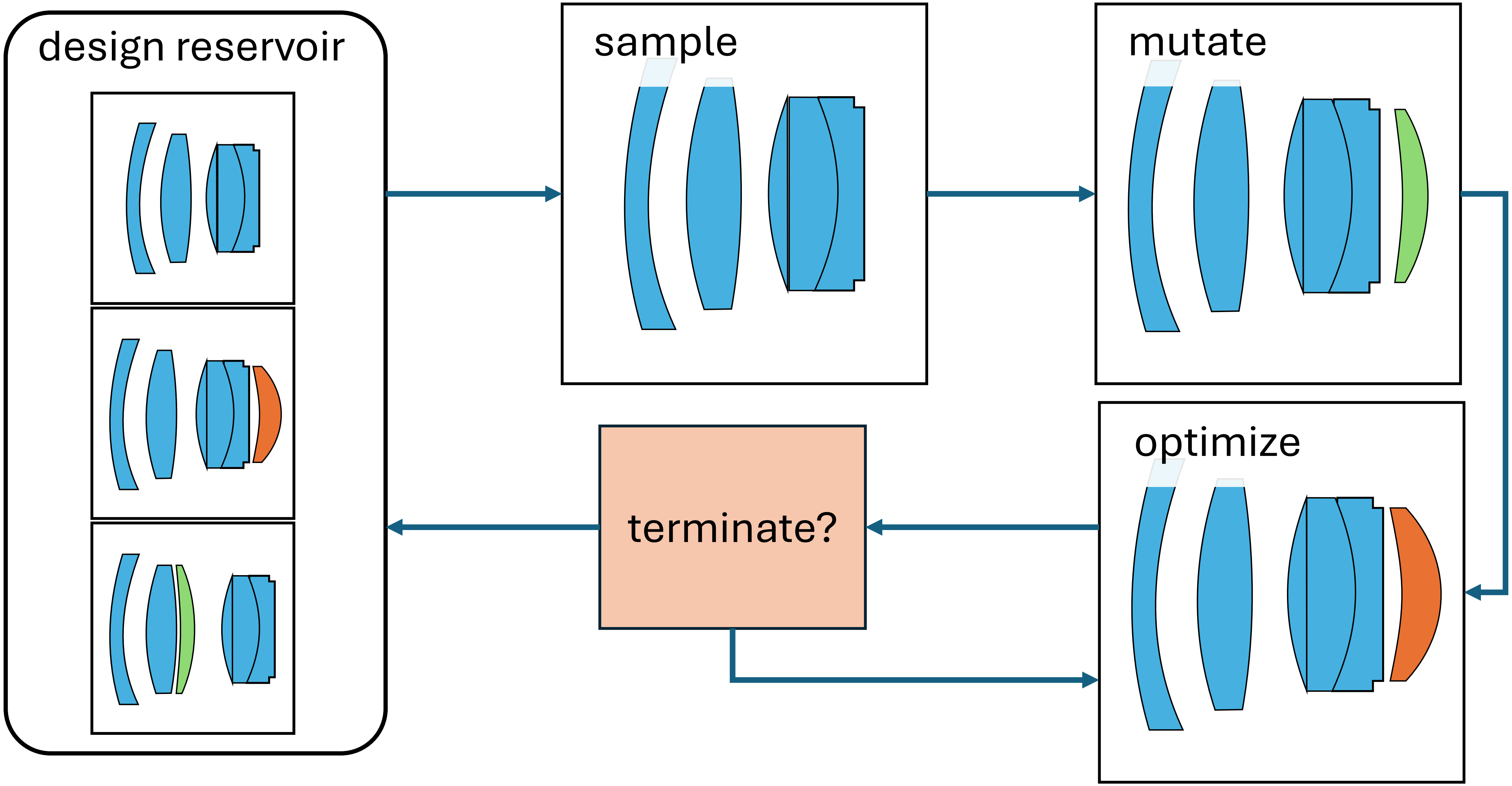


Lenses are sensitive to small changes

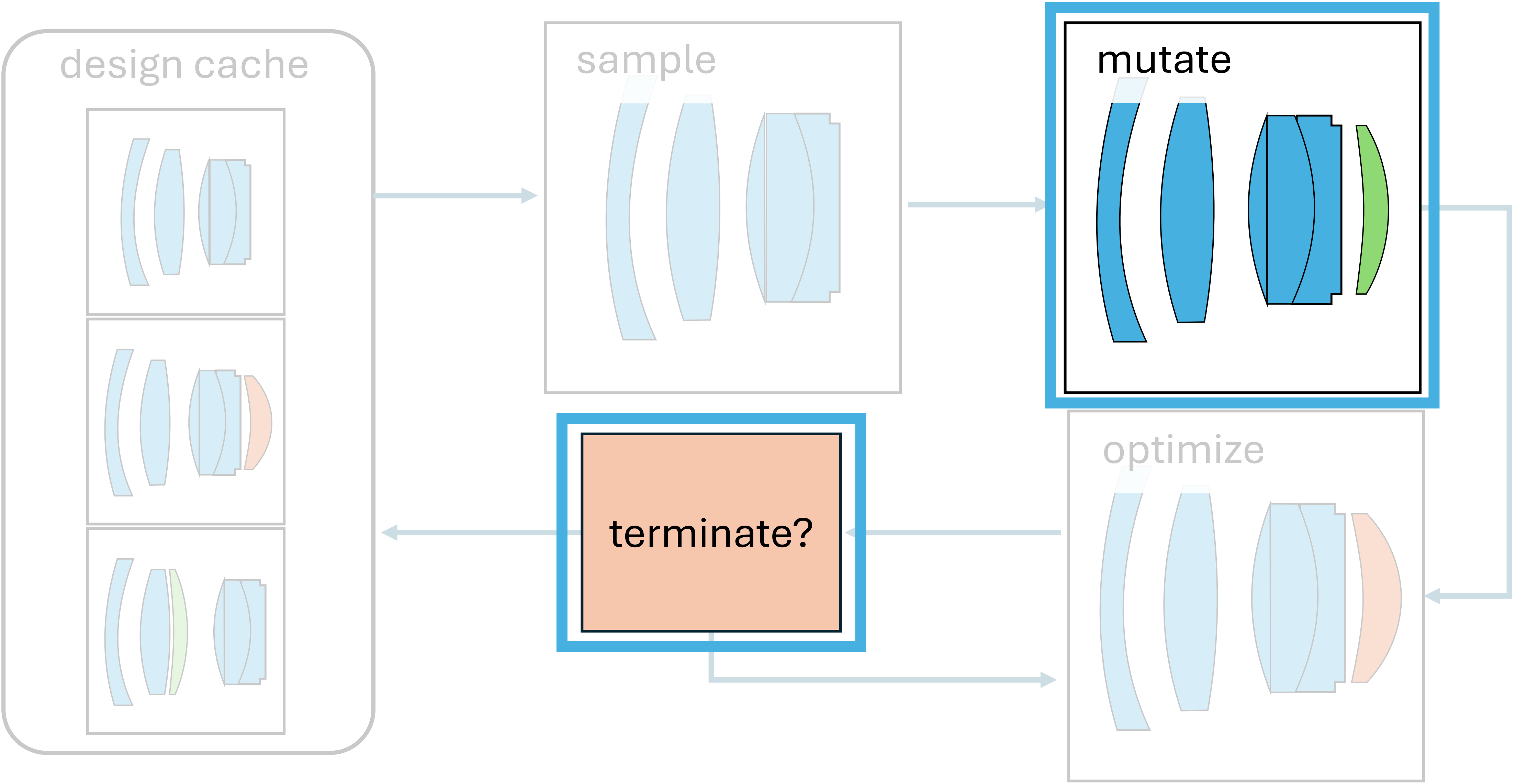
Comparison to Metropolis-Hastings



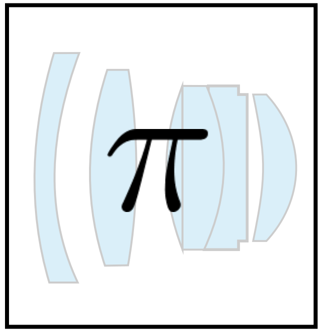
Quasi-stationary Monte Carlo (QSMC)



Quasi-stationary Monte Carlo (QSMC)



Stochastic termination

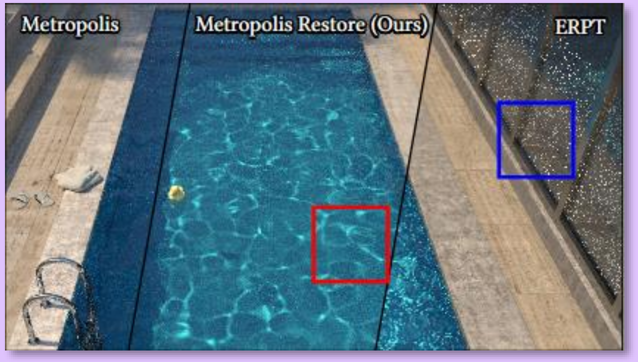
$L($  $)$

Boltzmann distribution

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

RESTORE

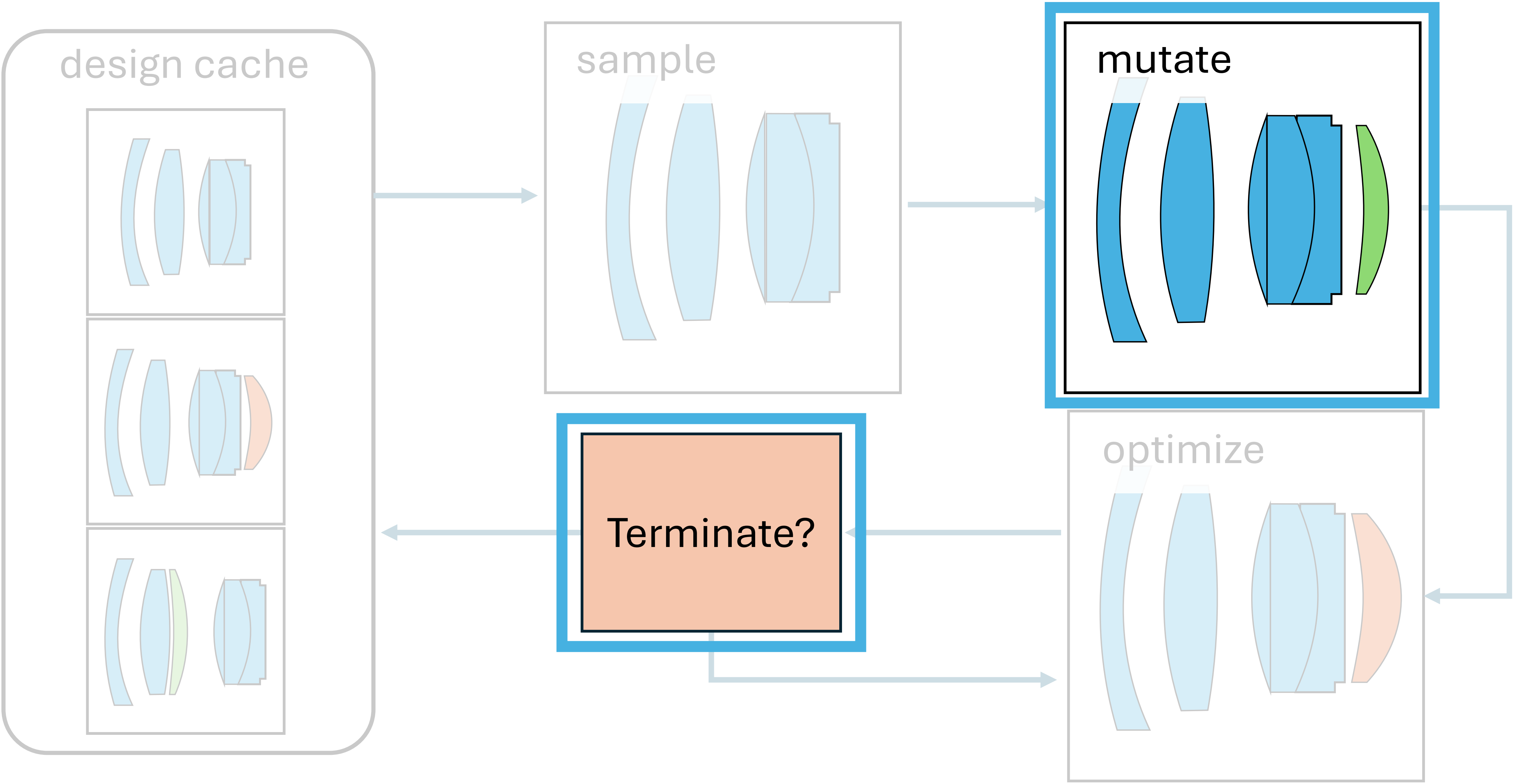
Jump Restore Light Transport [Holl et al. 2025]



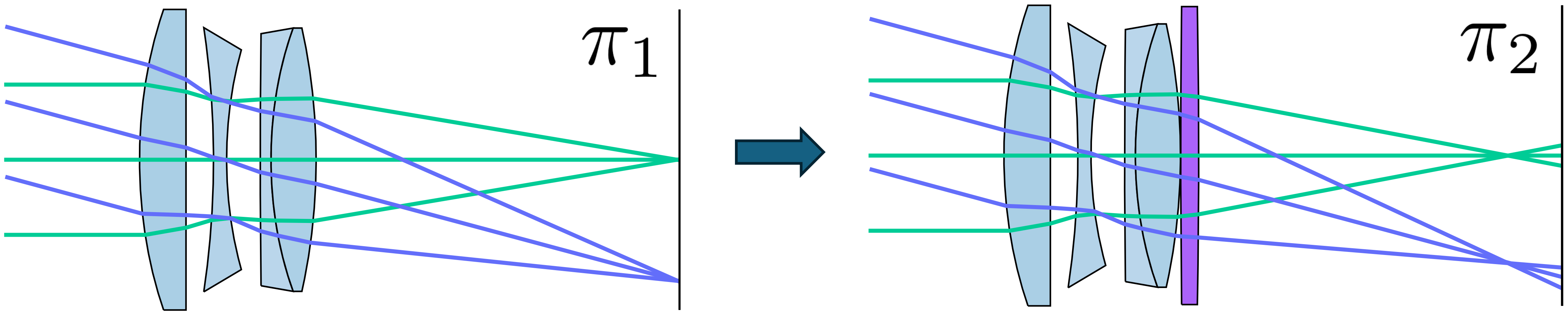
Probability of termination

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

Quasi-Stationary Monte Carlo (QSMC)



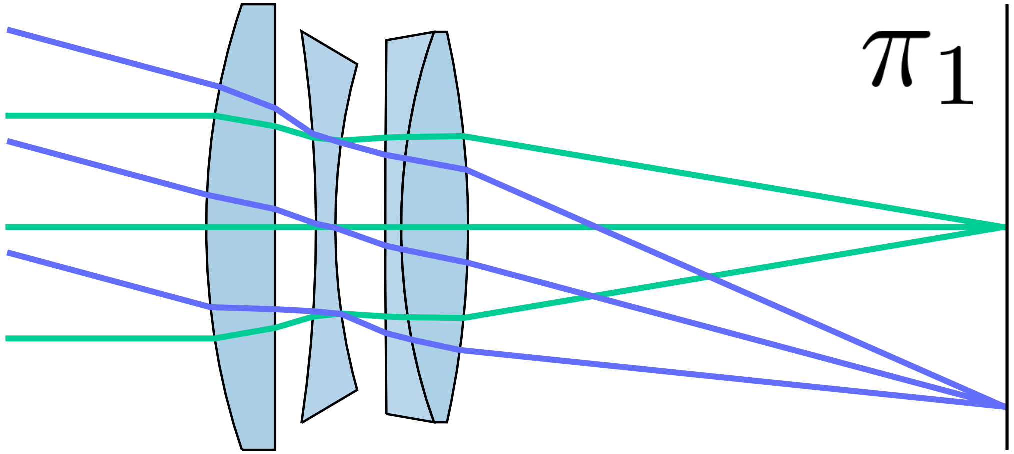
Simple mutations are problematic

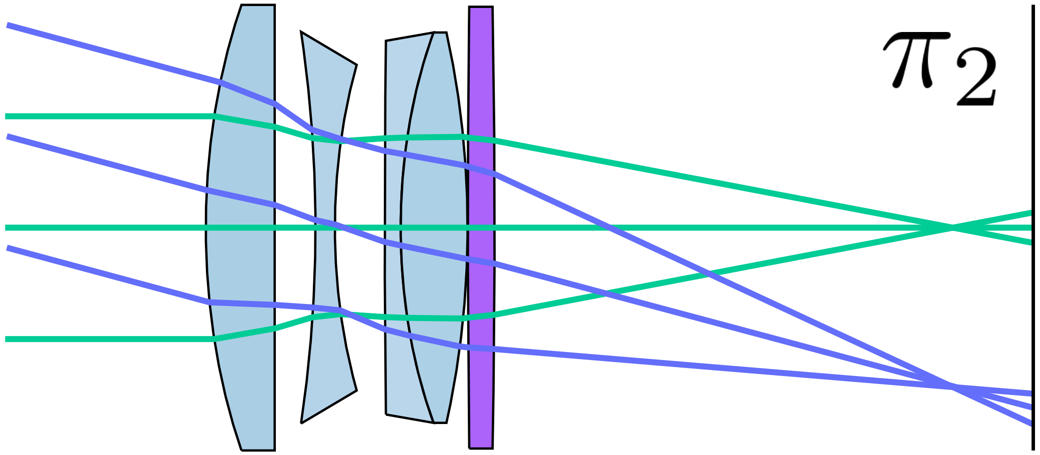


High chance of being a **worse** design

Most likely **terminated**

Key idea: paraxial optics as a proxy





Ray transfer matrix

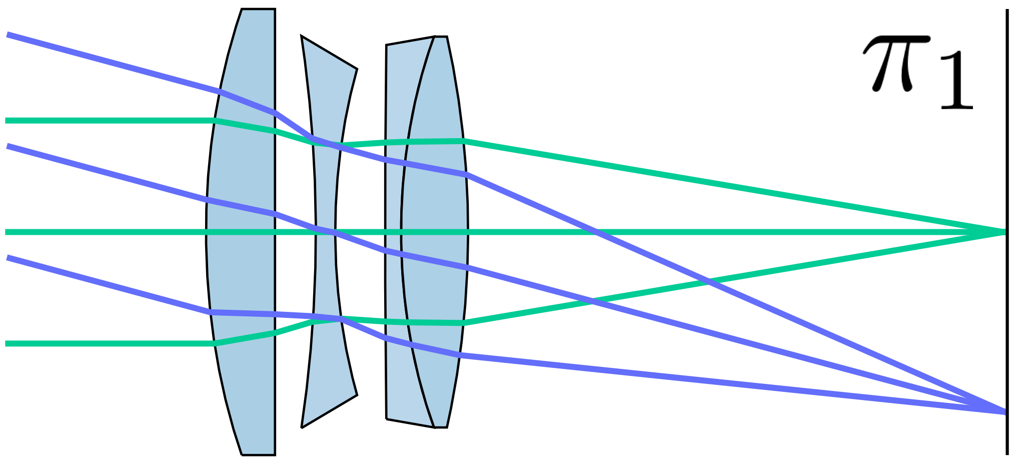
$$\mathbf{M}(\pi_1) = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

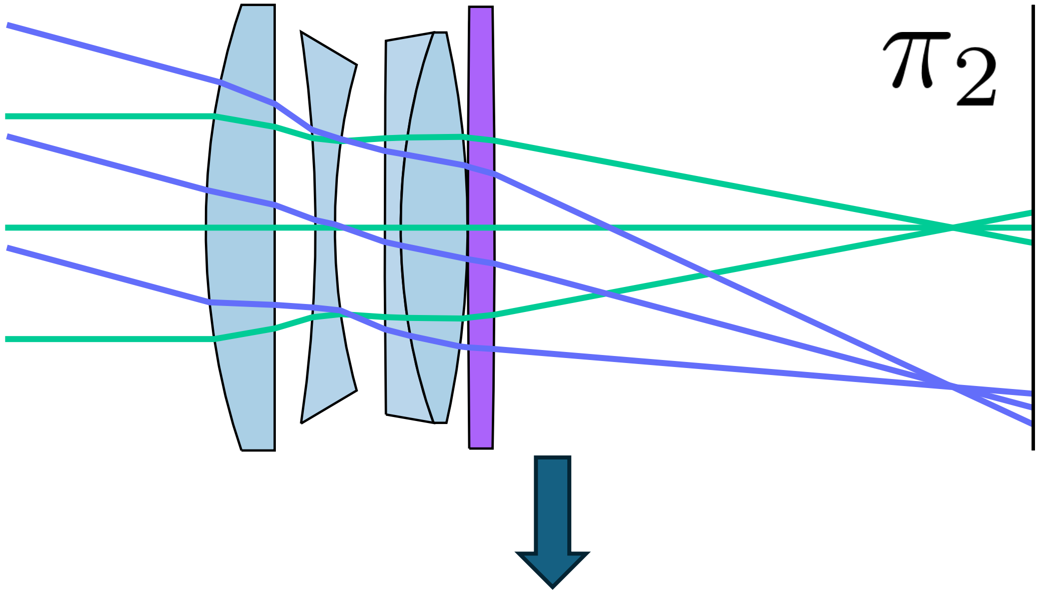
$\neq$

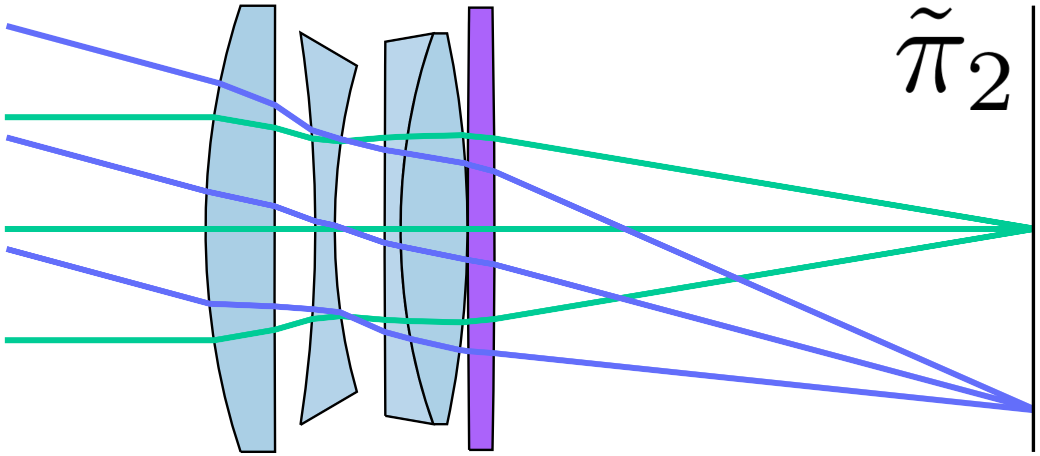
Ray transfer matrix

$$\mathbf{M}(\pi_2) = \begin{bmatrix} a' & b' \\ c' & d' \end{bmatrix}$$

Key idea: paraxial optics as a proxy





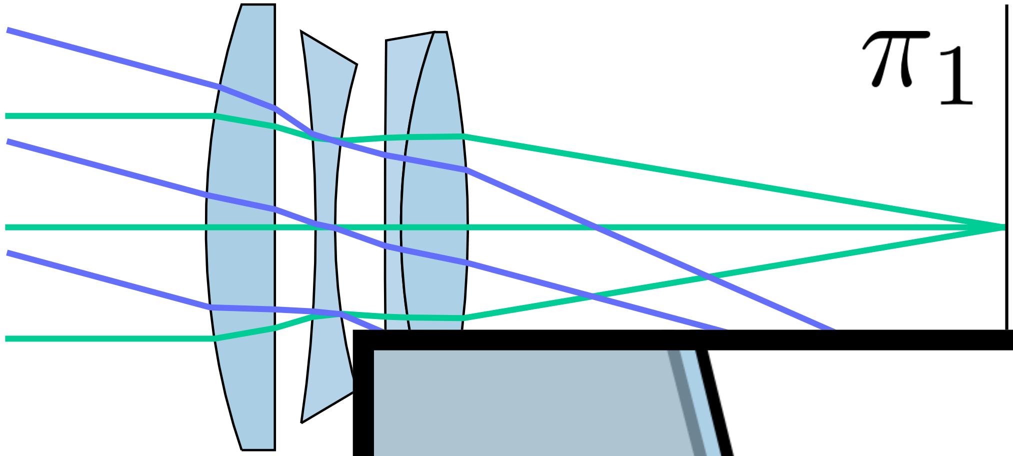


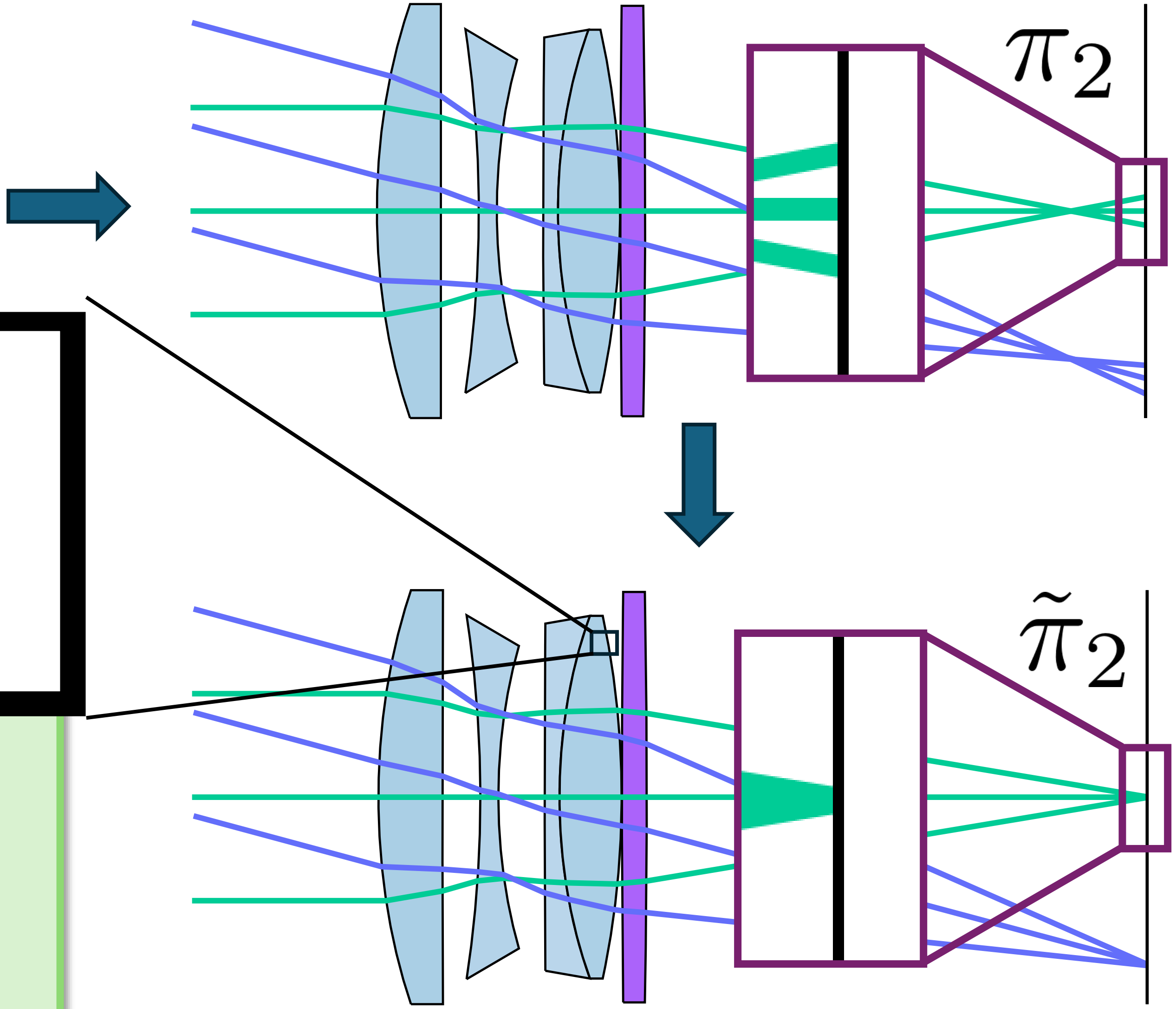
Paraxial projection

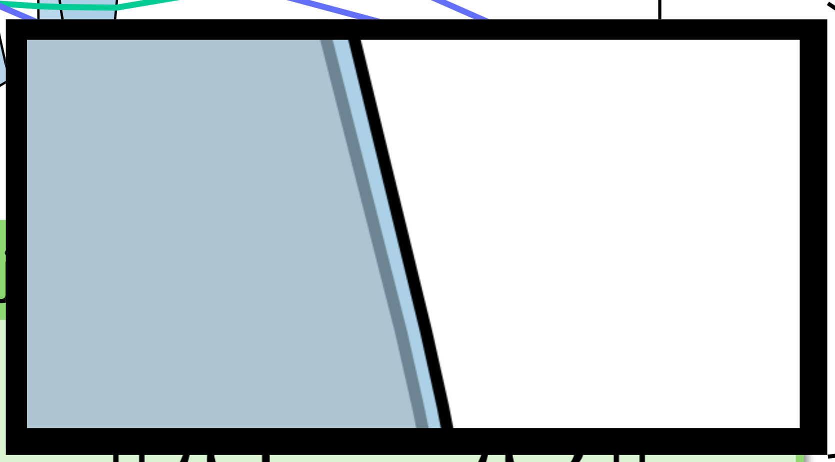
$$\min_{\pi_2} \quad \|\pi_1 - \pi_2\|^2$$

$$s.t. \quad \mathbf{M}(\pi_1) = \mathbf{M}(\pi_2)$$

Key idea: paraxial optics as a proxy





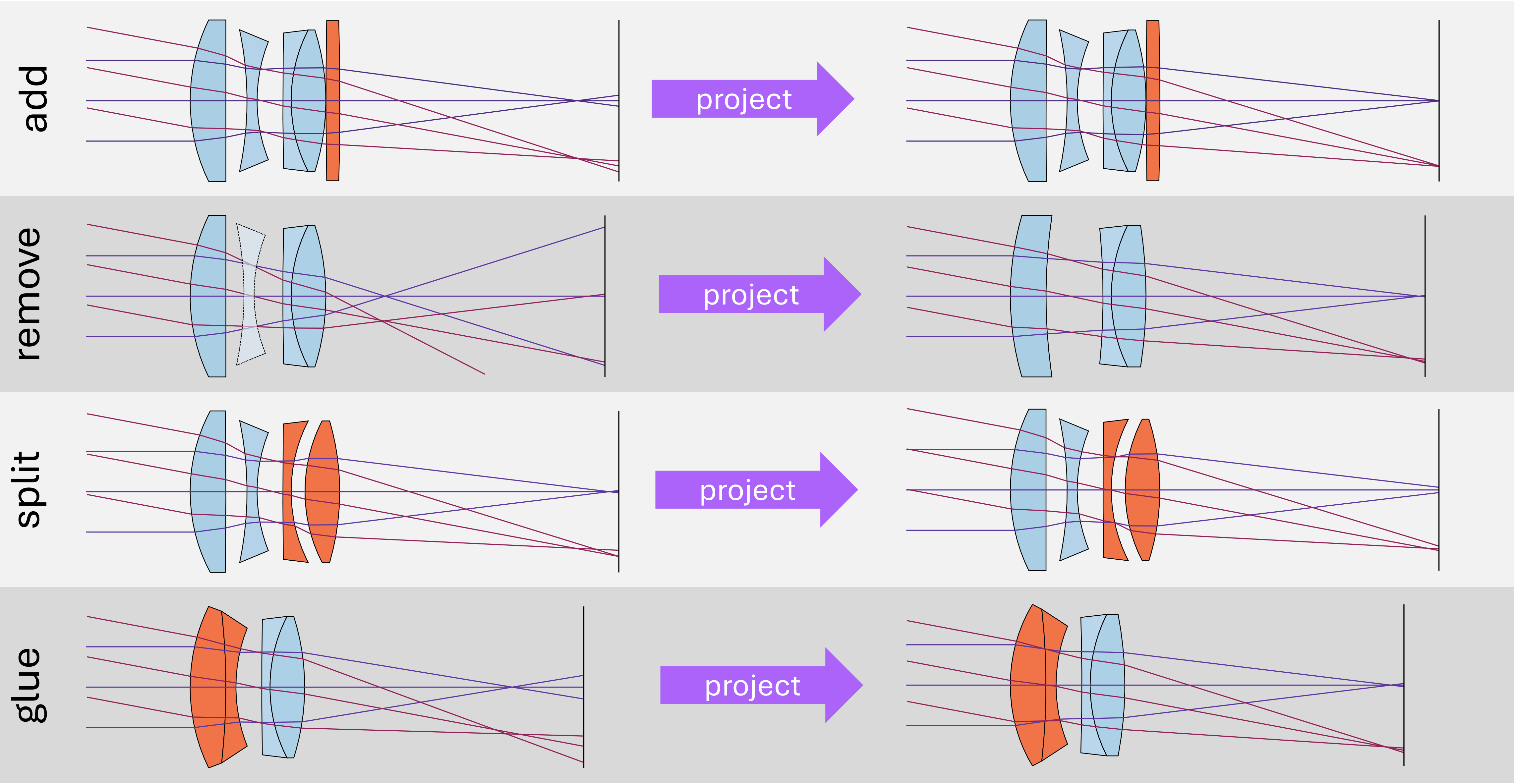


Paraxial proj

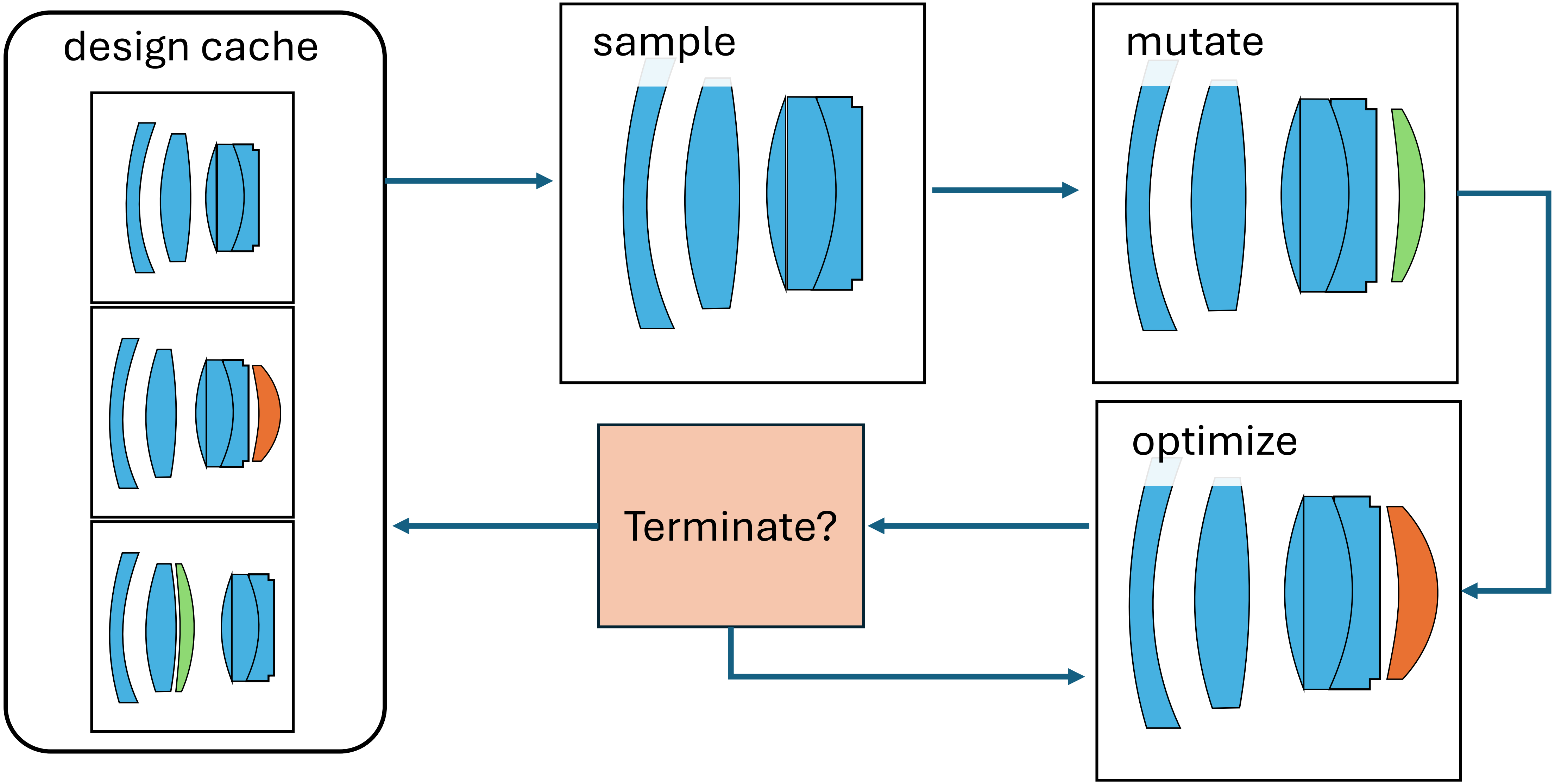
$$\min_{\pi_2} \quad \|\pi_1 \ldots \pi_2\|$$

$$s.t. \quad \mathbf{M}\left(\pi_1\right) = \mathbf{M}\left(\pi_2\right)$$

Paraxial projection

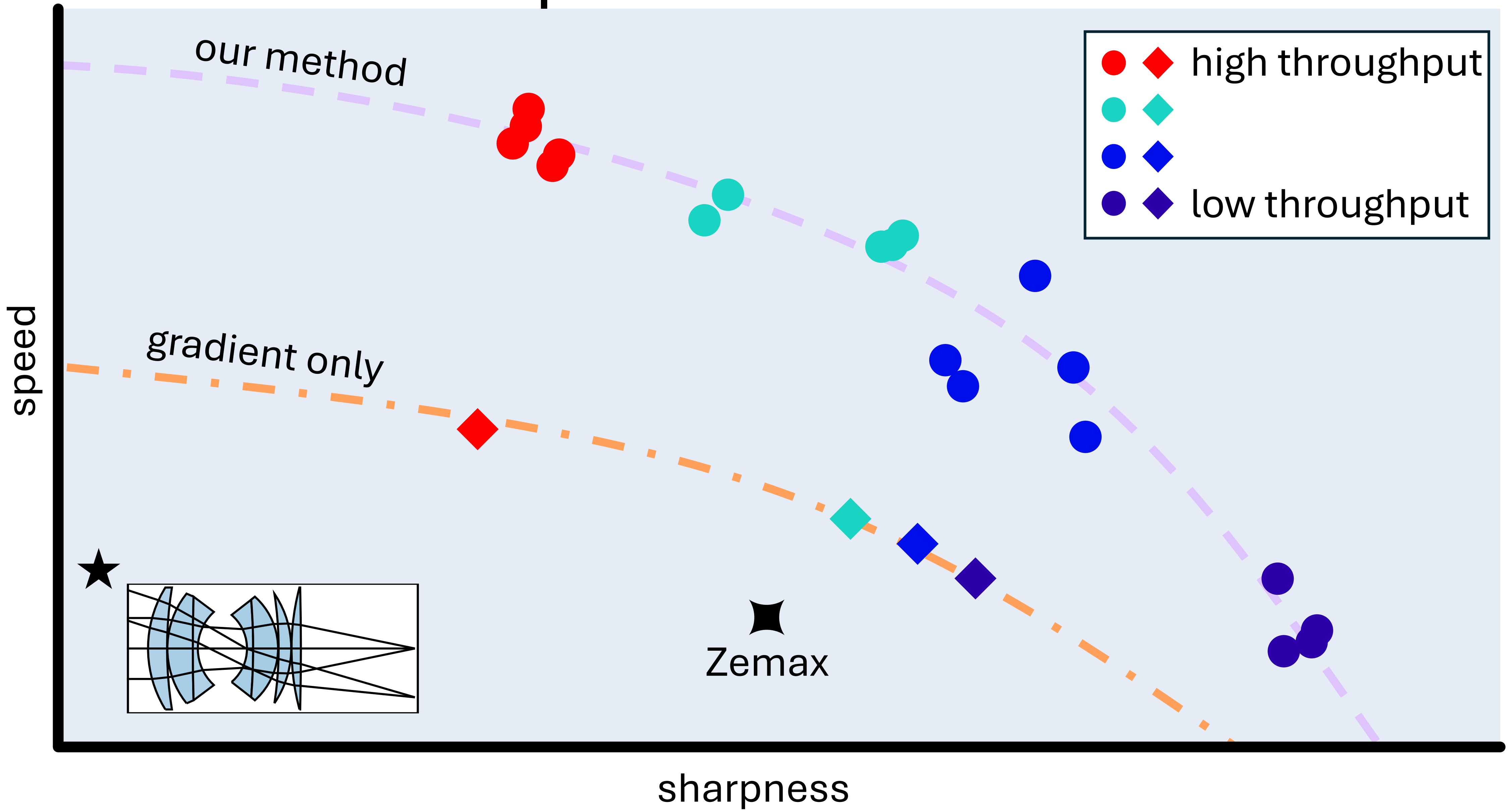


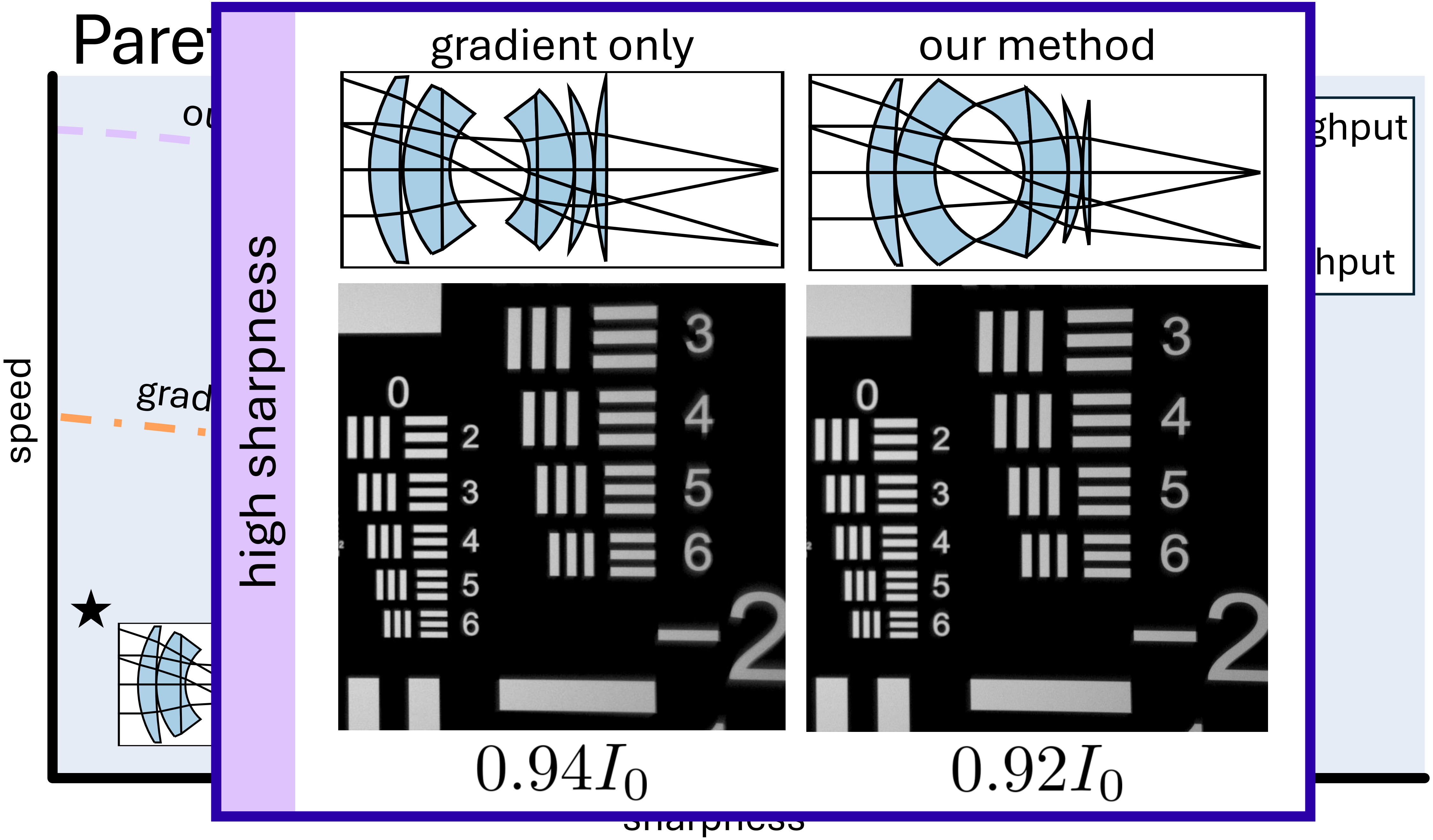
Quasi-Stationary Monte Carlo (QSMC)

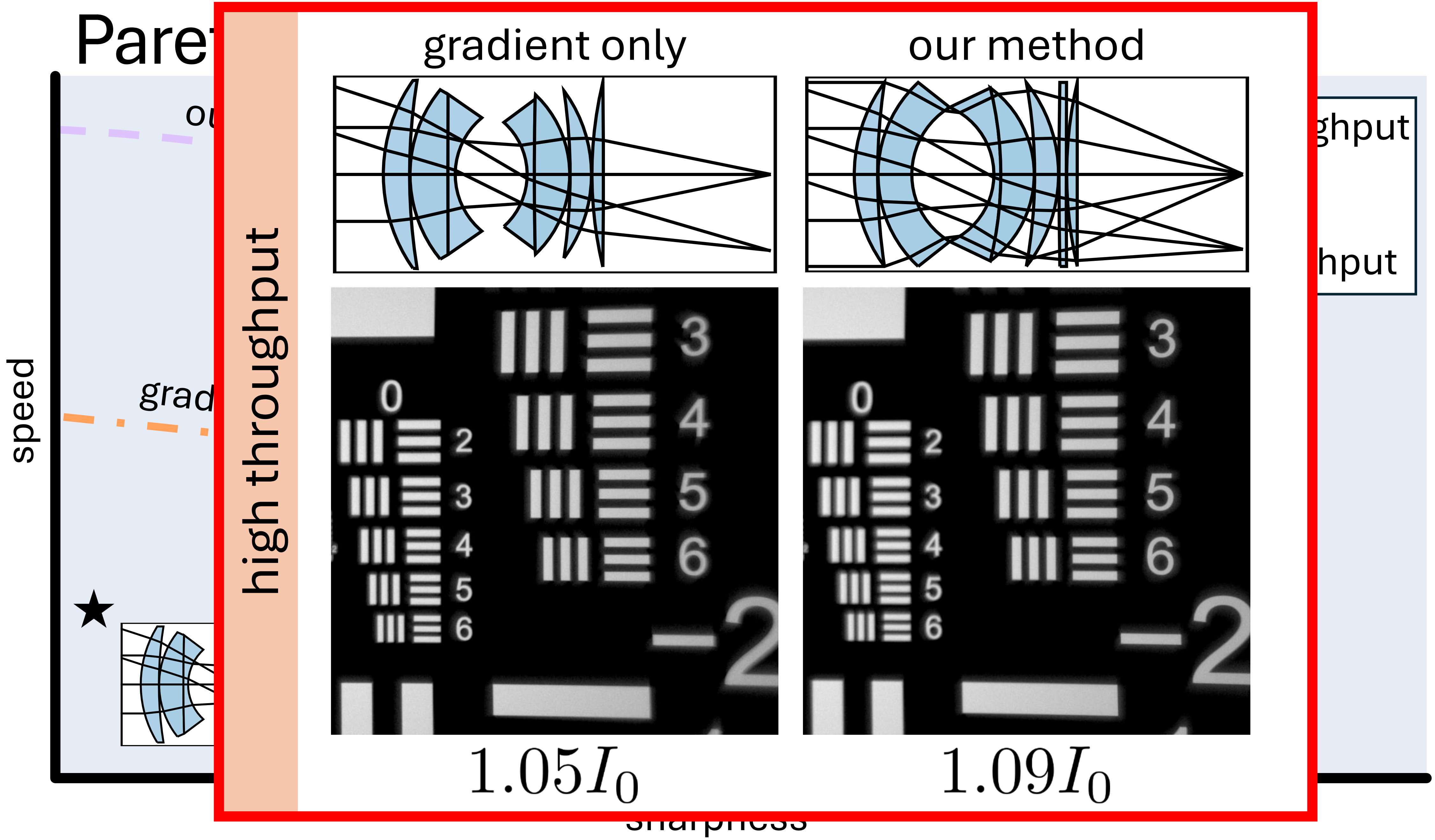


Pareto front expansion

Pareto front expansion

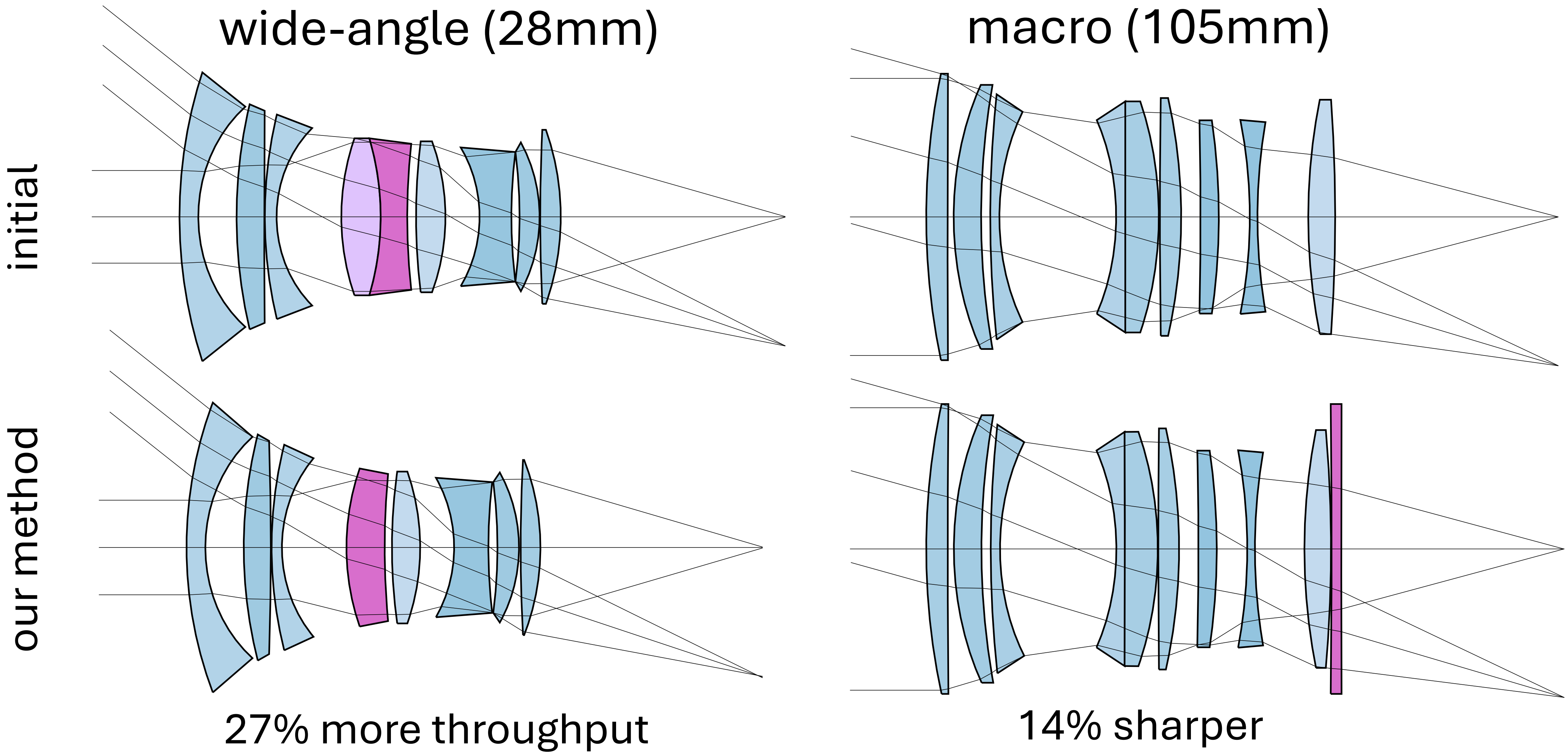



Paret
ou
grad
speed
ghput
hput
high sharpness
gradient only
our method
$0.94 I_0$
$0.92 I_0$

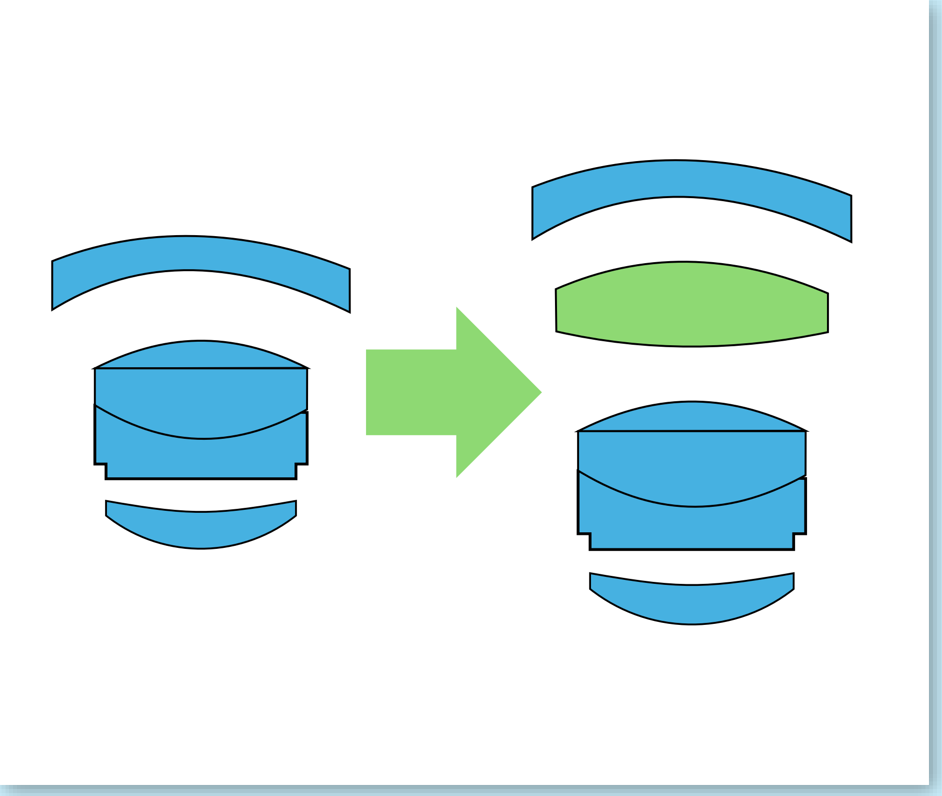


Pare
speed
ou
grad
ghput
hput
high throughput
gradient only
our method
1.05I0
1.09I0

Can improve other lens types as well



Discrete-continuous optimization

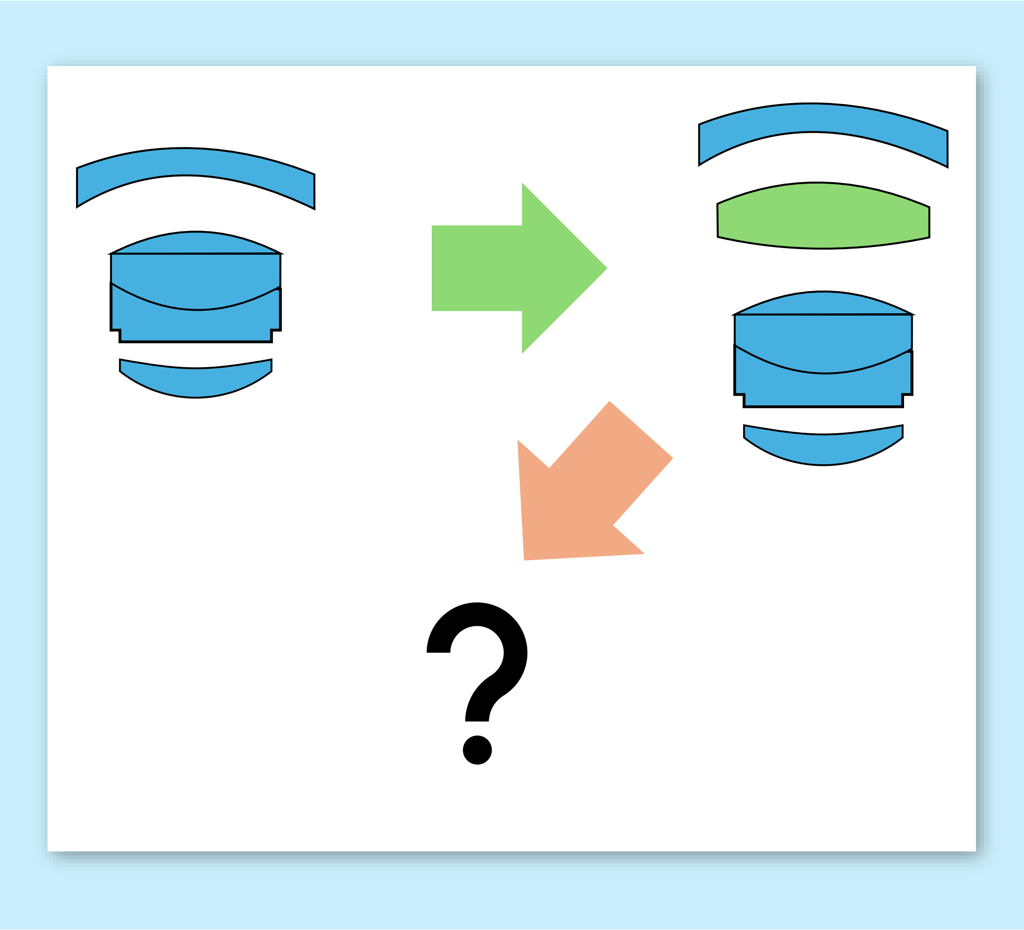


Optimization as a sampling problem

QSMC allows for optimization without noise

Better mutations with paraxial projection

Our method is extendable



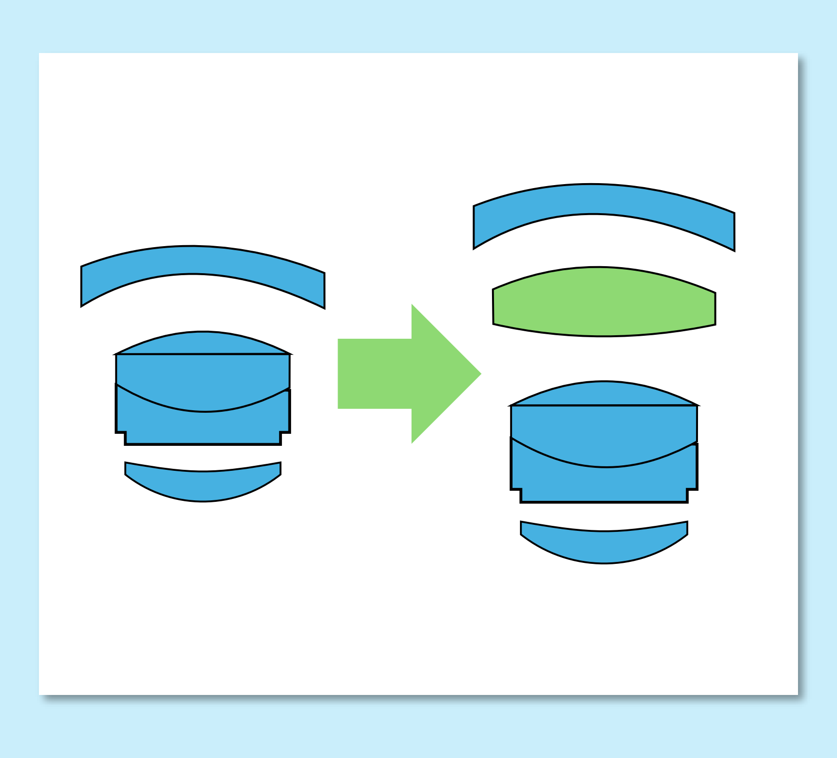
add aspheric, cylindrical, and other types of optics

new design objectives to target specific aberrations

manufacturing and tolerance aware design

Automated design of compound lenses with discrete-continuous optimization

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



Website + Code

ALFRED P. SLOAN FOUNDATION

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