SIGGRAPH 2024
DENVER+ 28 JUL — 1 AUG

THE PREMIER CONFERENCE & EXHIBITION ON COMPUTER GRAPHICS & INTERACTIVE TECHNIQUES

APERTURE-AWARE LENS DESIGN

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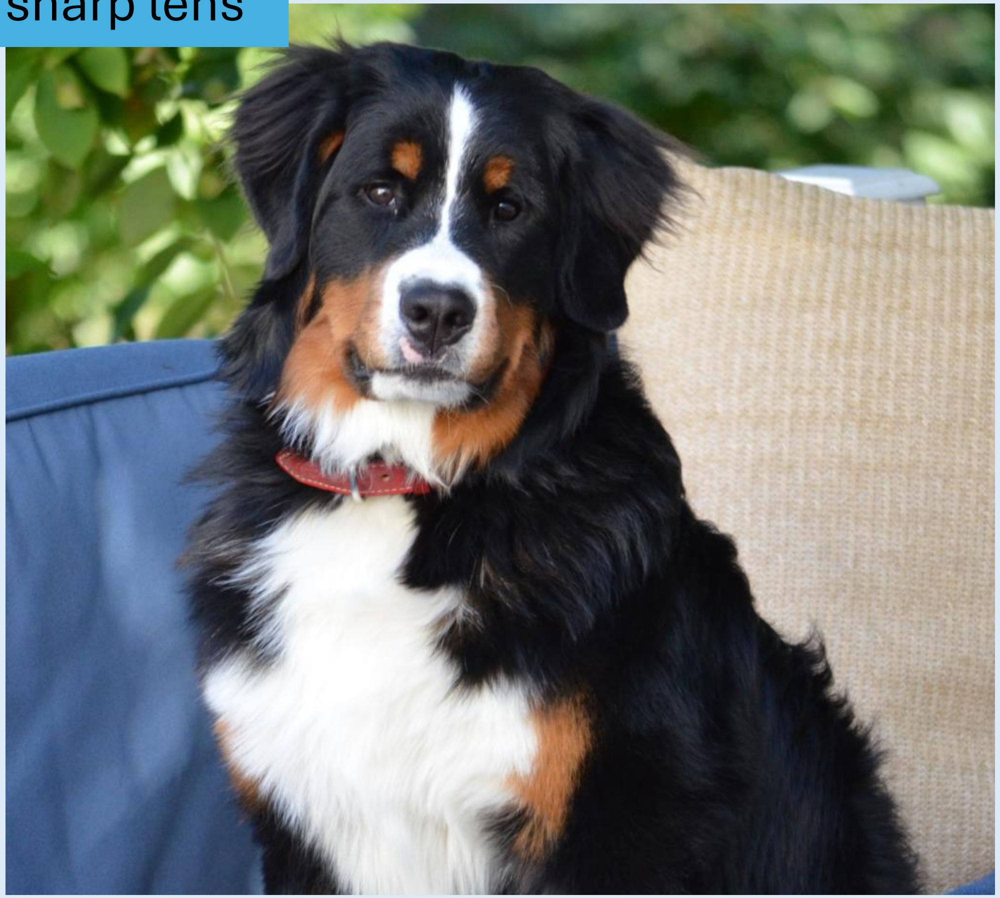
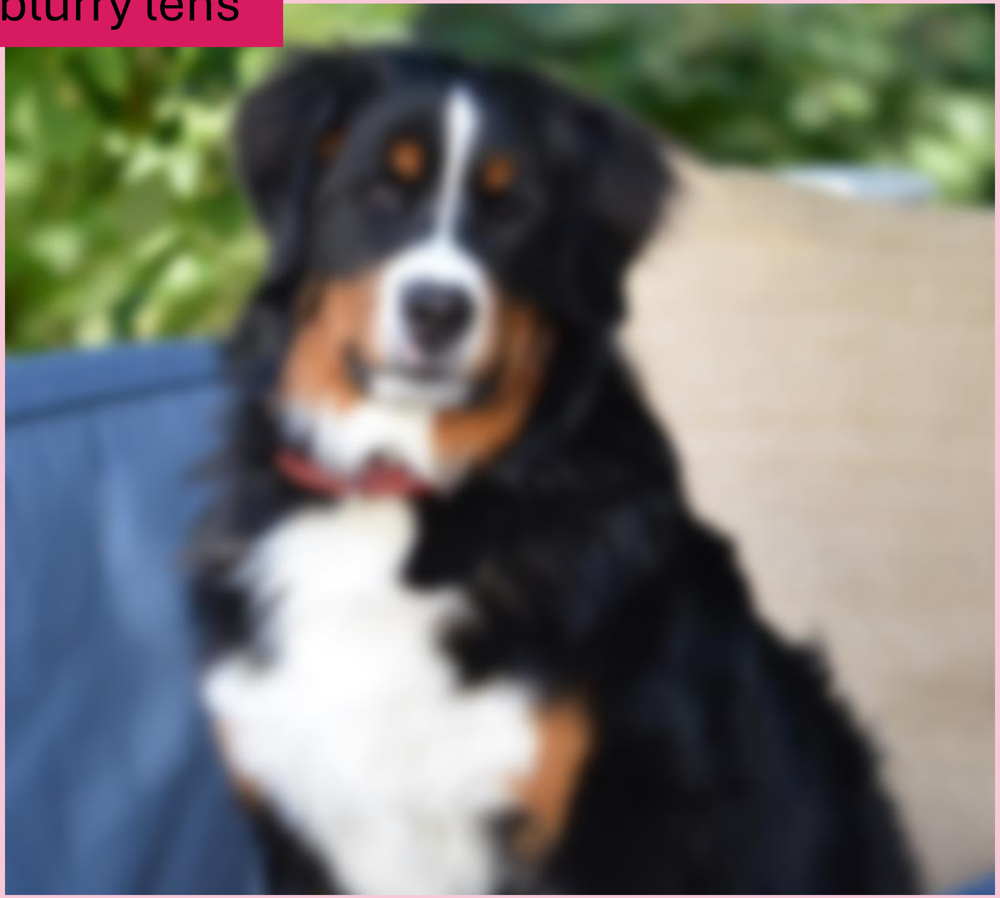
What makes a good lens?

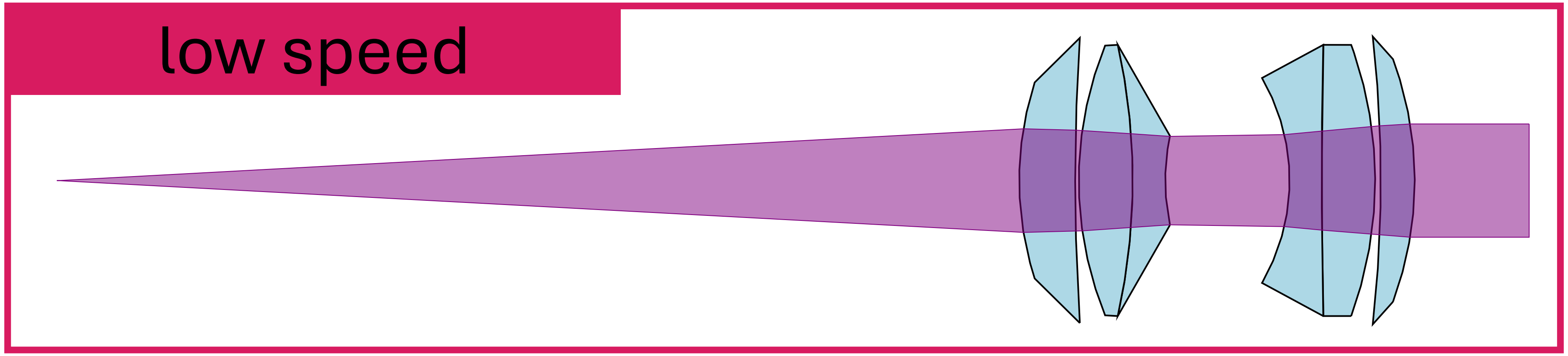
sharp lens

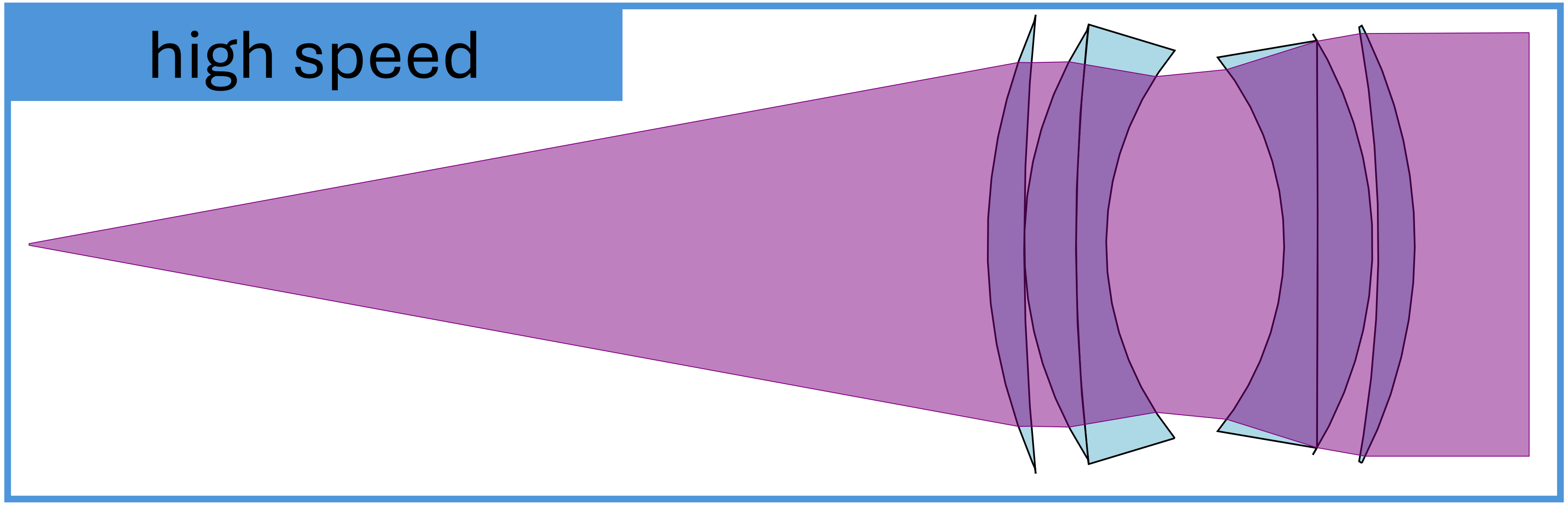


blurry lens



Lens speed is also important



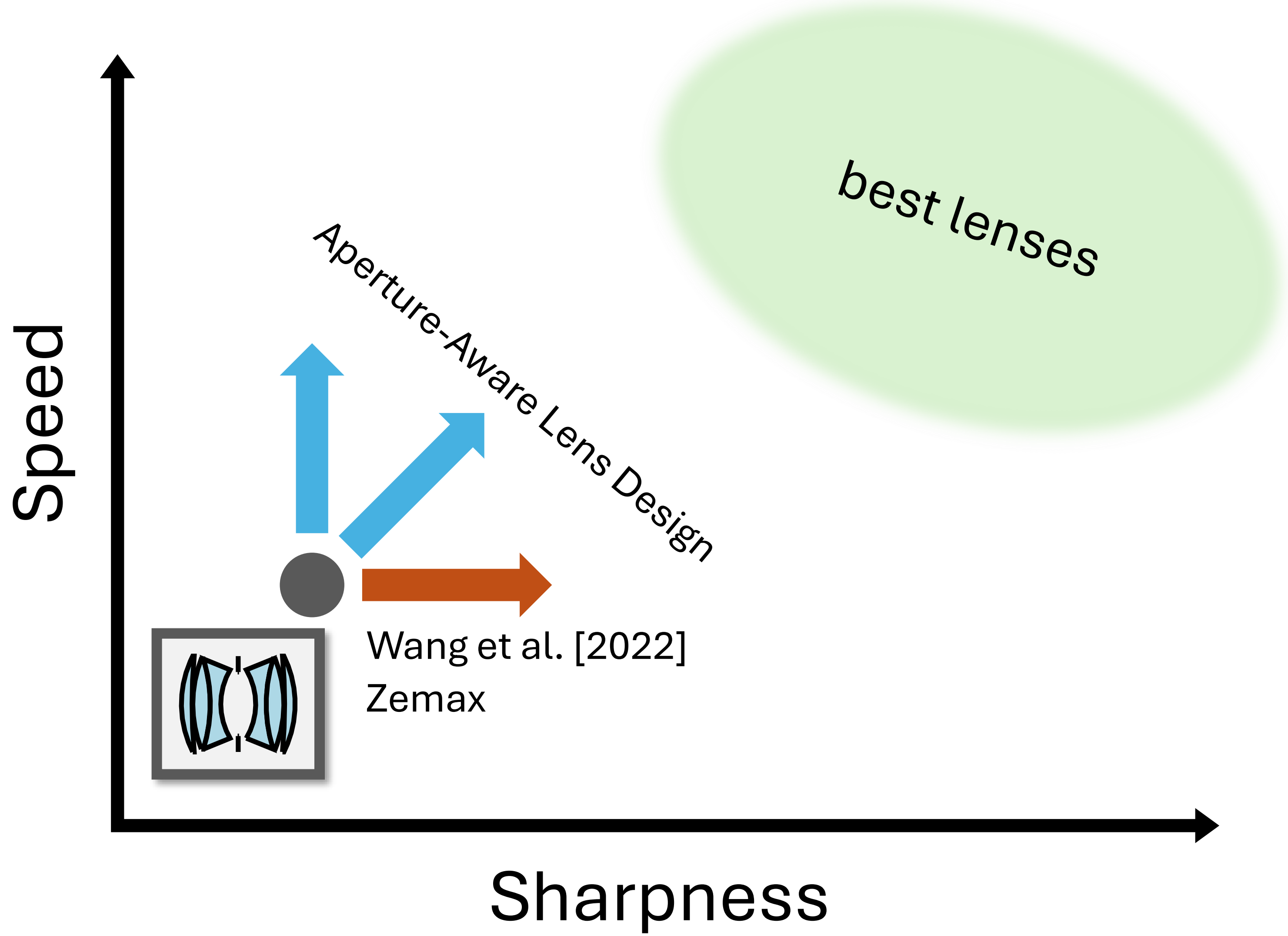


Lens speed is also important

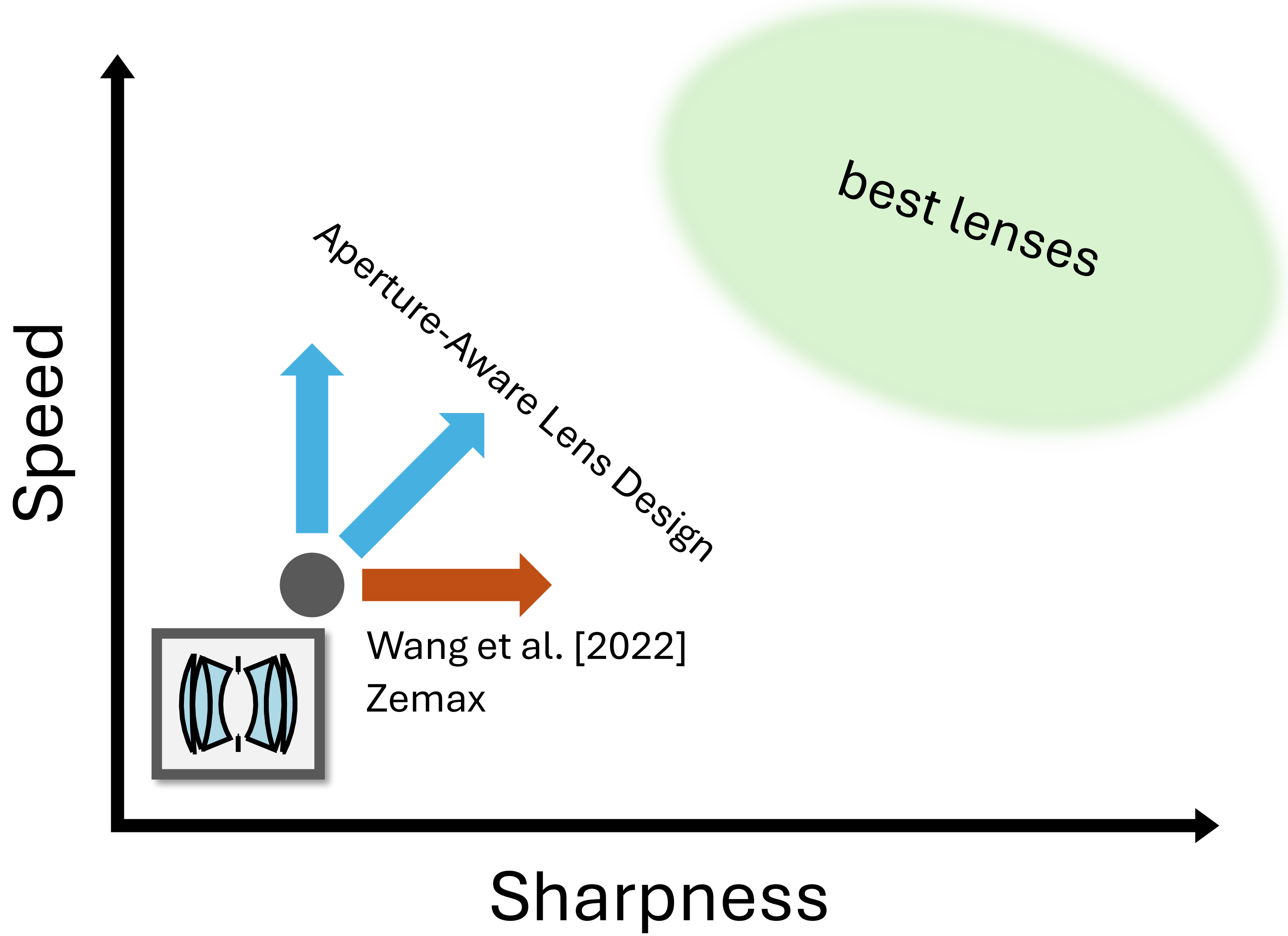
Motion blur

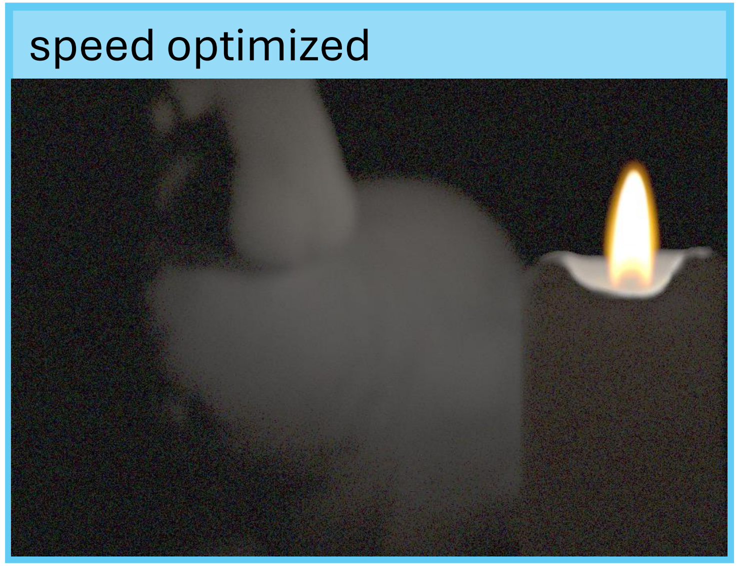
Low light scenes

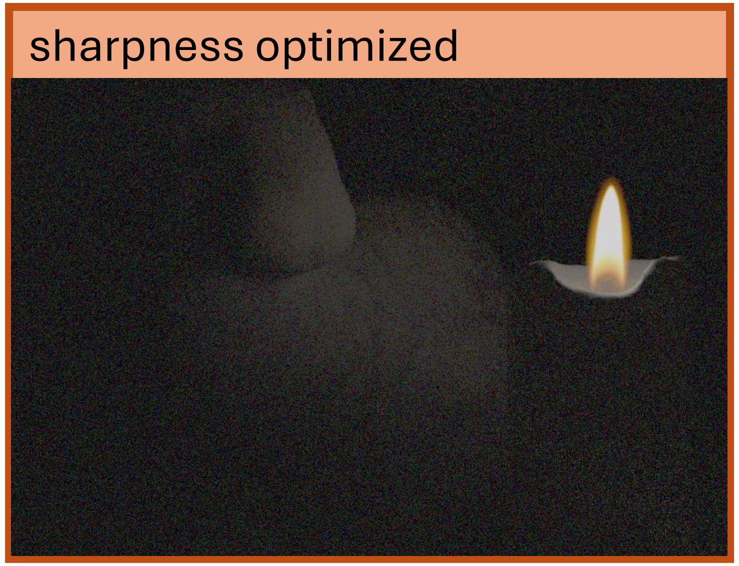
Sharpness vs speed



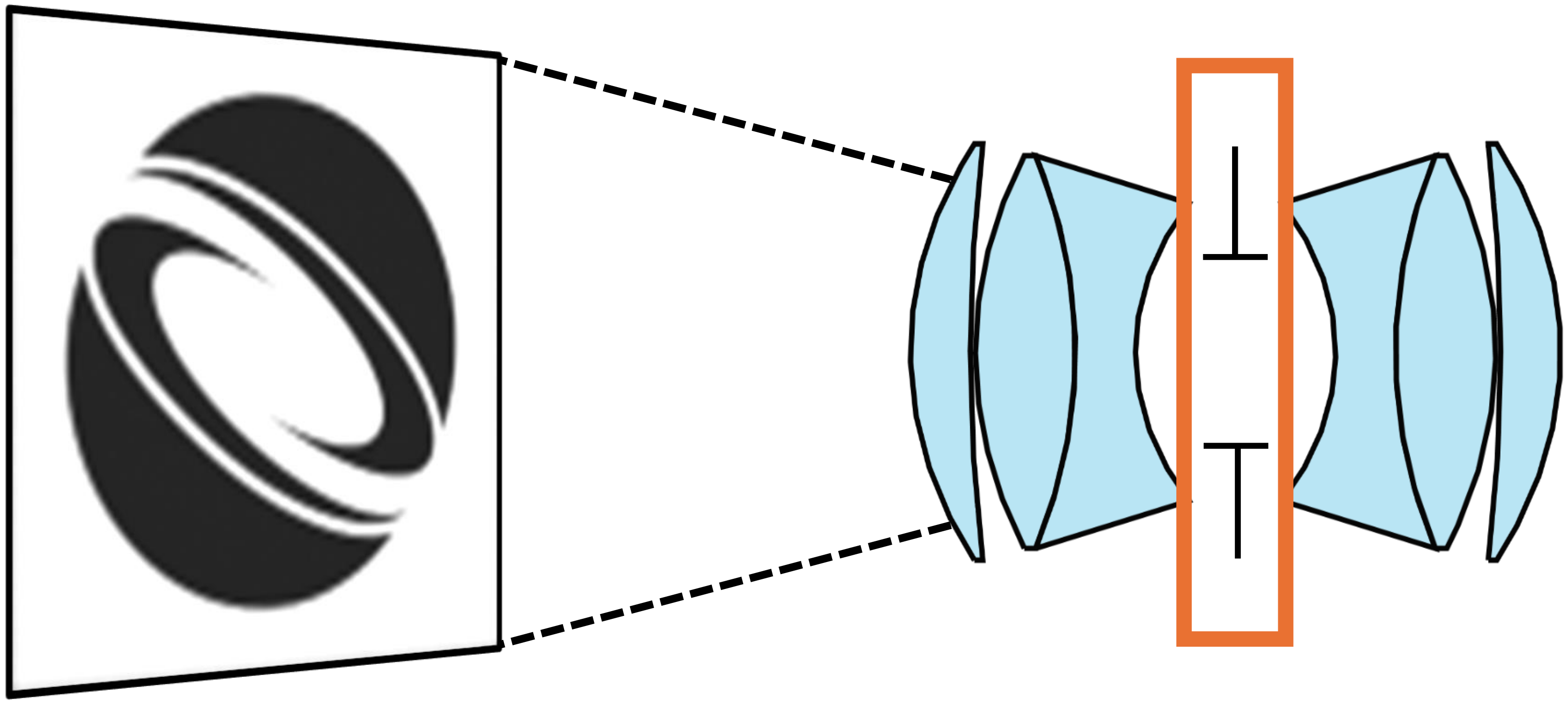
Sharpness vs speed



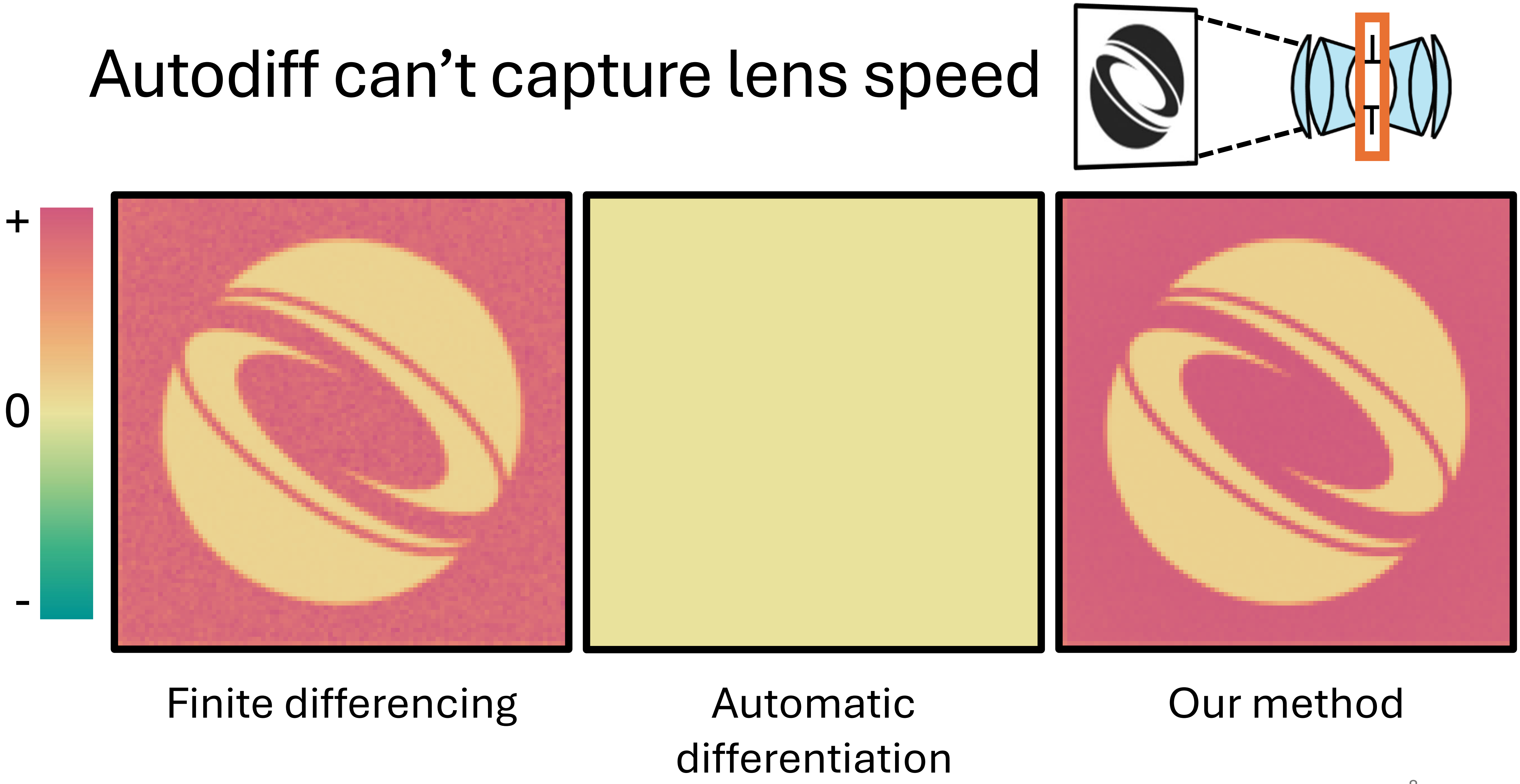




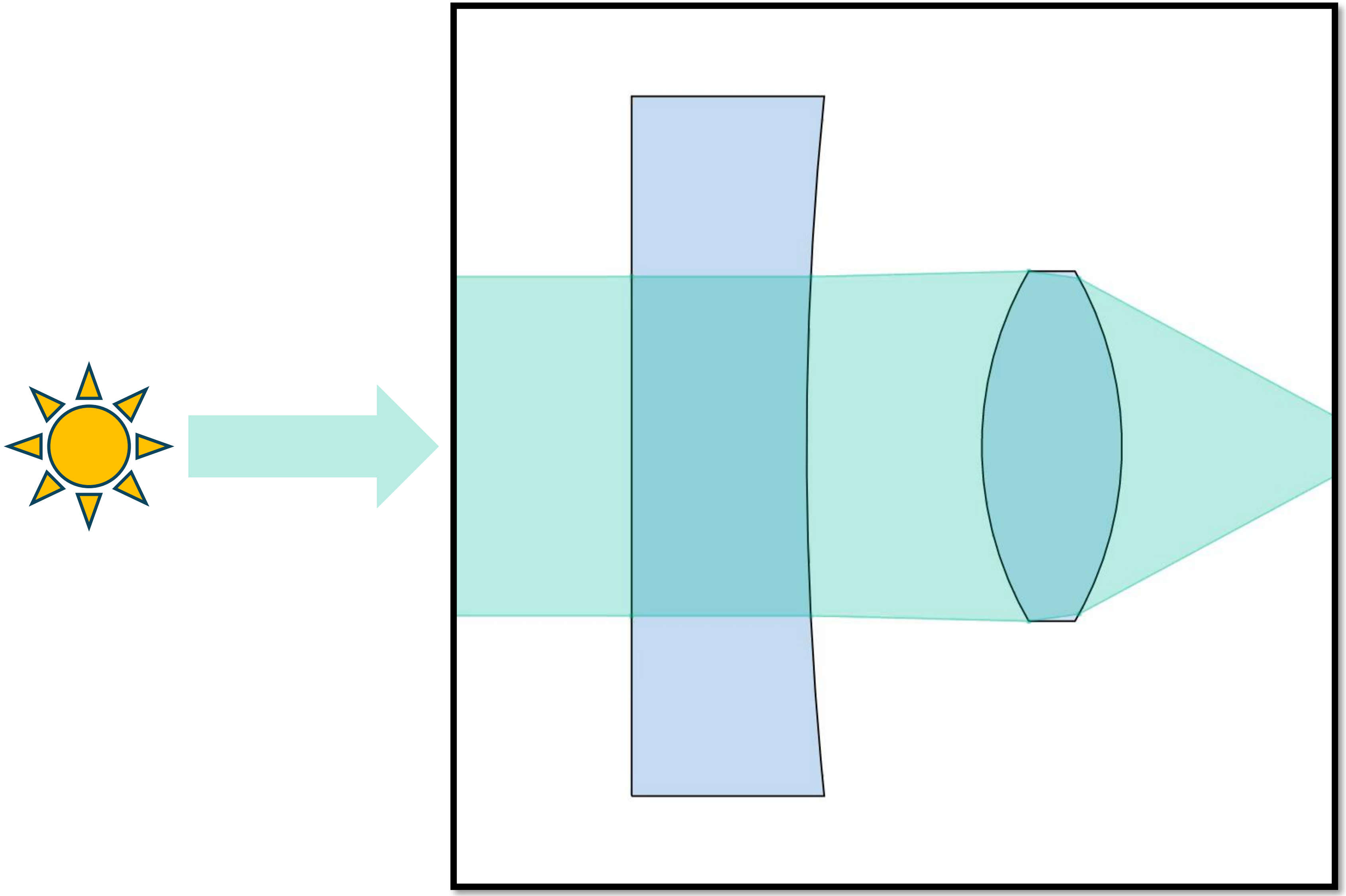
Autodiff can't capture lens speed



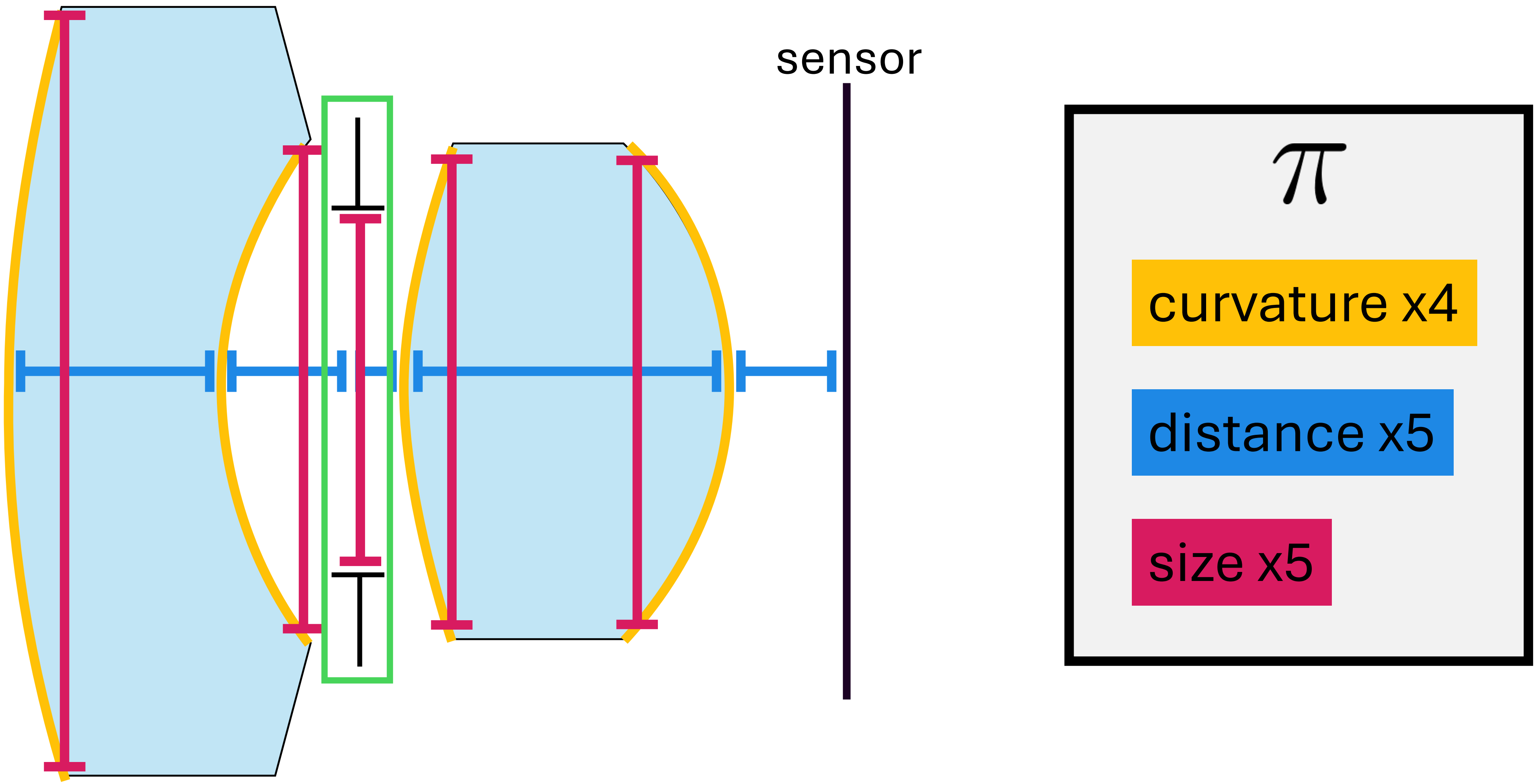
Autodiff can't capture lens speed



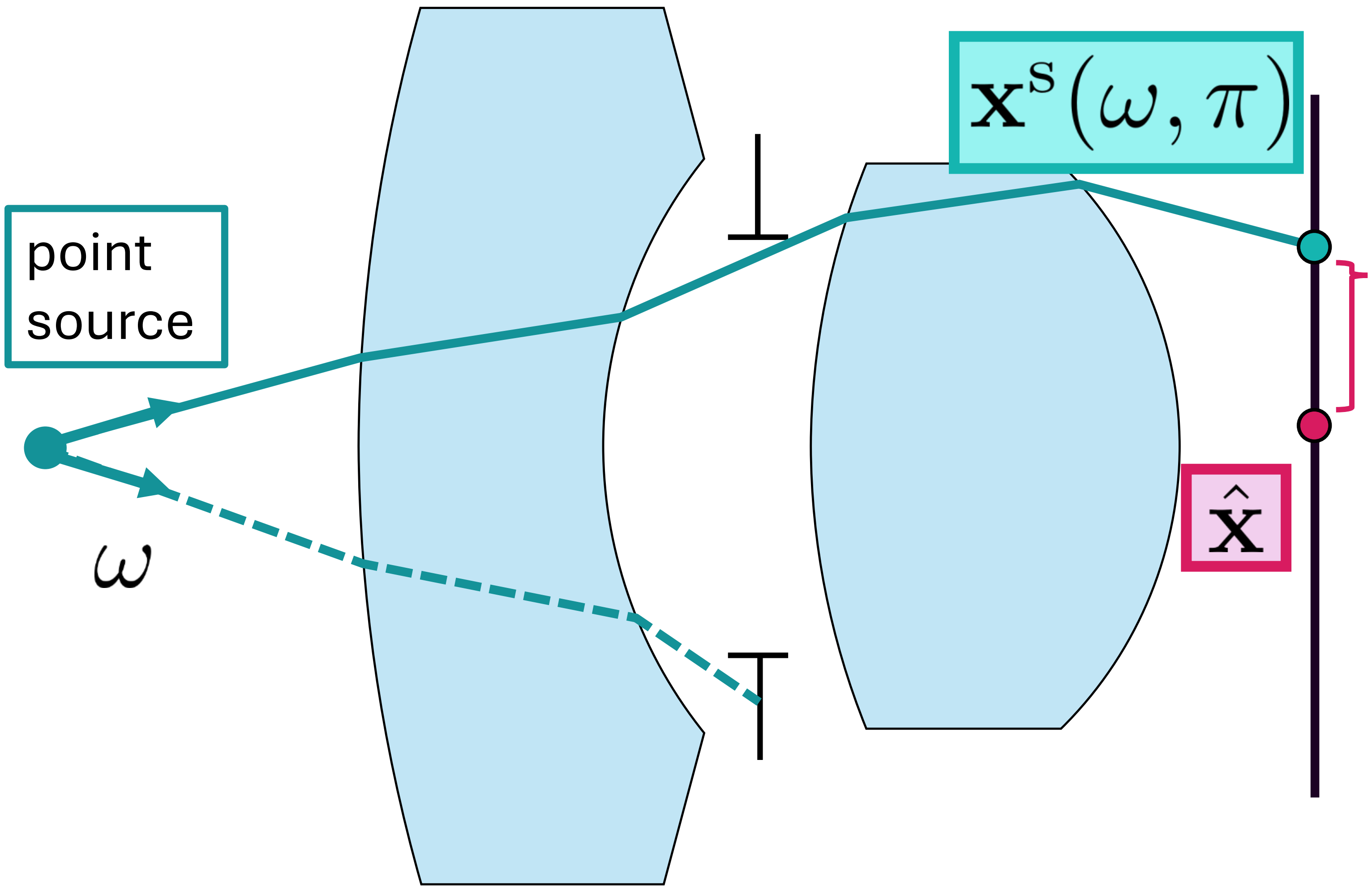
Shape affects speed as well



Representing a lens



Evaluating a lens



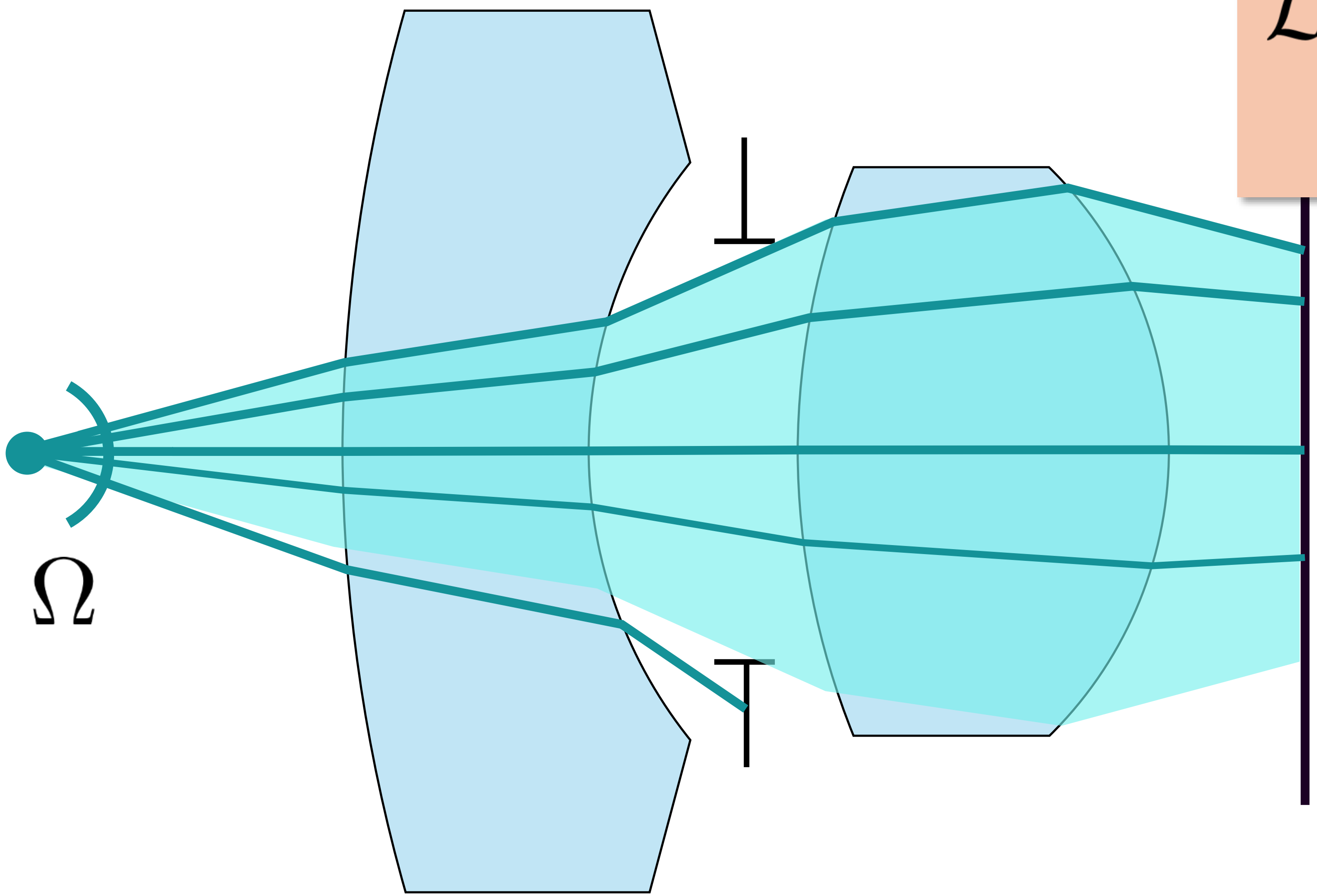
sharpness loss

$$f_{\text{sharpness}} = \|\mathbf{x}^{\mathrm{s}} - \hat{\mathbf{x}}\|^2$$

speed loss

$$f_{\text{speed}} = 1$$

Evaluating a lens



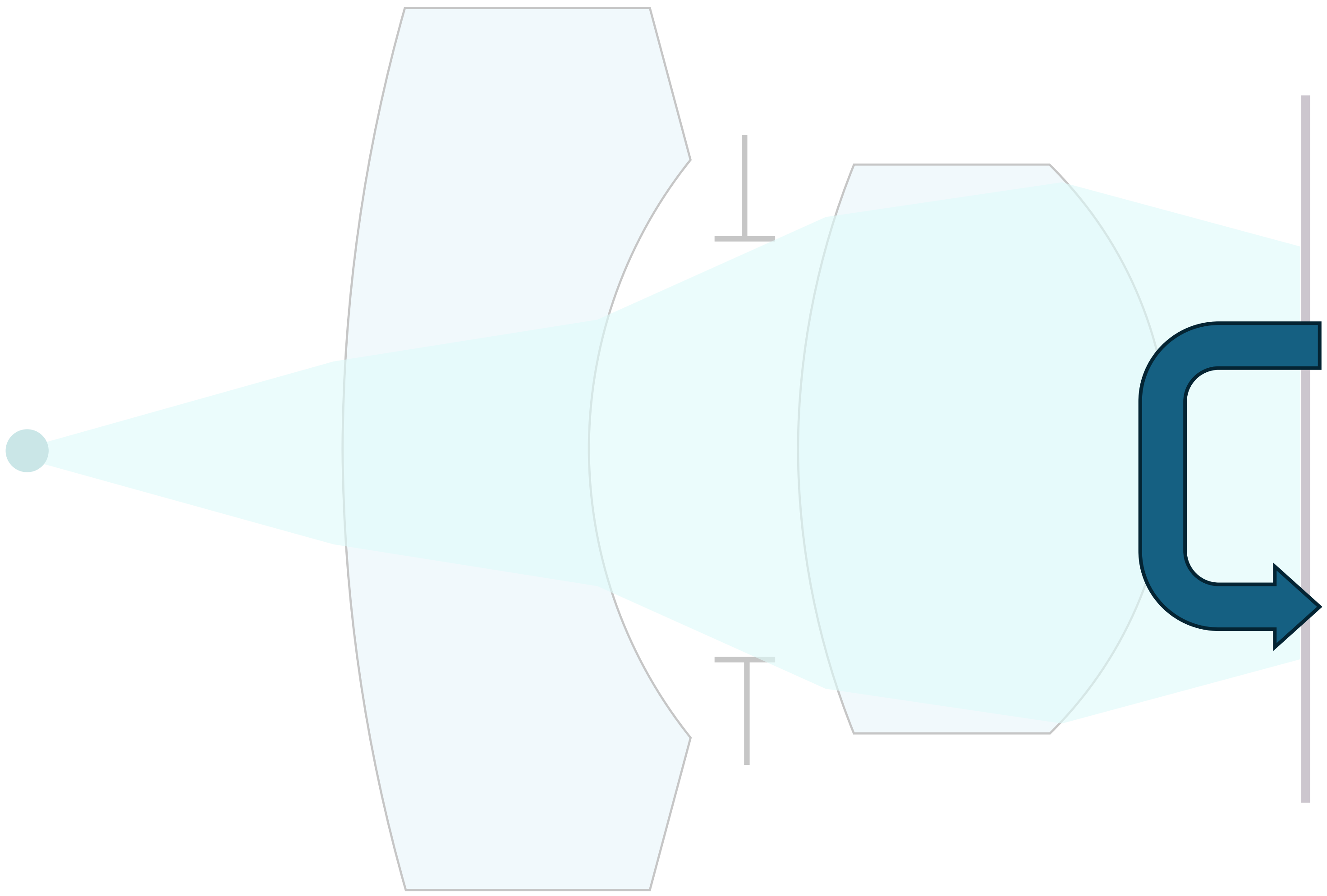
$$\mathcal{L} = \int_{\Omega(\pi)} f(\mathbf{x}^{\mathrm{s}}(\omega, \pi))\, \mathrm{d}\omega$$

$$\approx$$

Monte Carlo estimator

$$\frac{1}{N} \sum_{i=0}^{N} \frac{f\left(\mathbf{x}^{\mathrm{s}}(\omega_i)\right)}{p\left(\omega_i\right)}$$

Optimizing a lens



$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi}$$

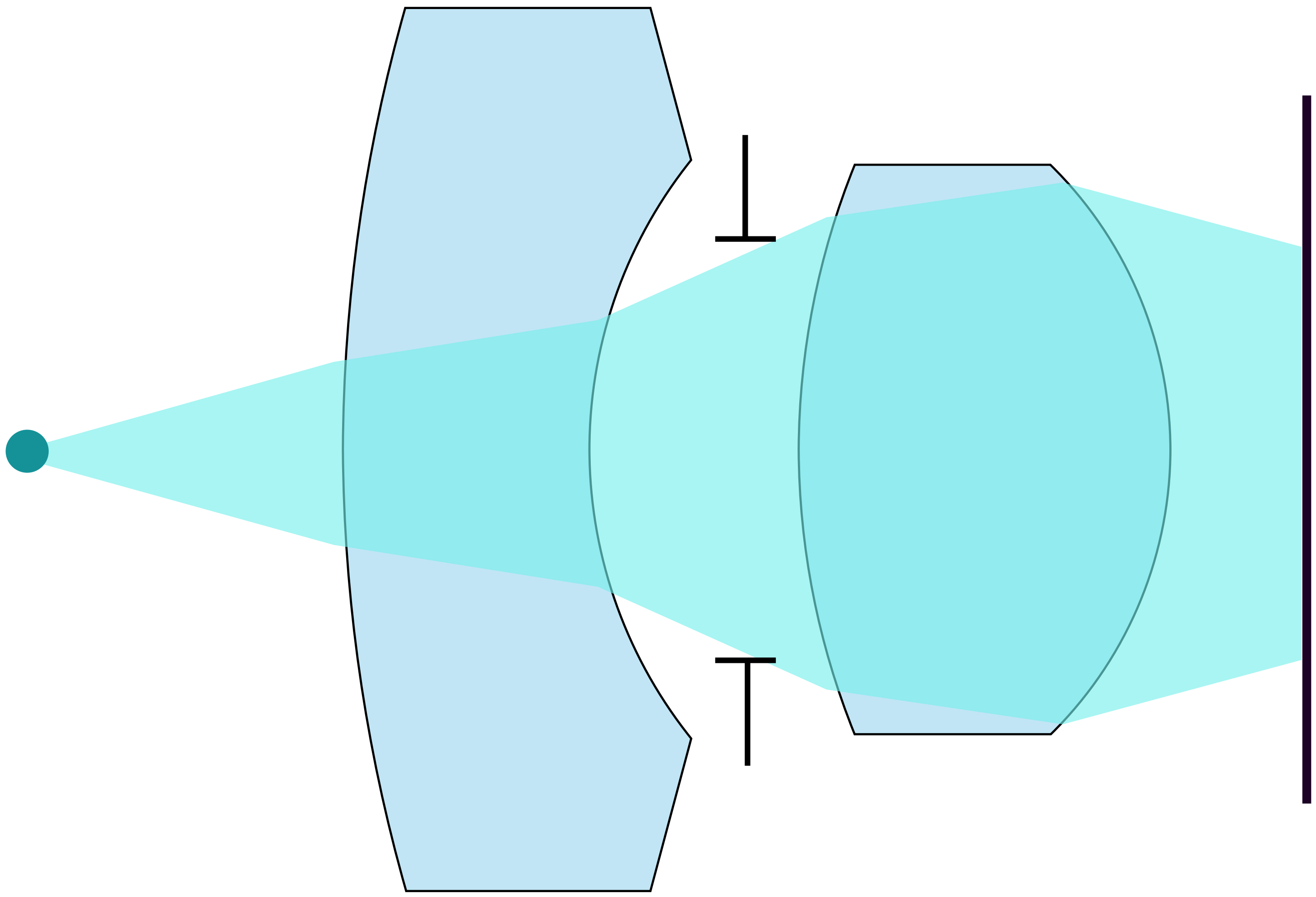
Apply gradient to estimator

$$\frac{\mathrm{d}}{\mathrm{d}\pi}\left(\frac{1}{N}\sum_{i=0}^{N}\frac{f\left(\mathbf{x}^{\mathrm{s}}(\omega_i)\right)}{p\left(\omega_i\right)}\right)$$

Monte Carlo gradient estimator (biased)

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}}\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi}$$

autodiff issue: aperture



Monte Carlo gradient estimator (biased)

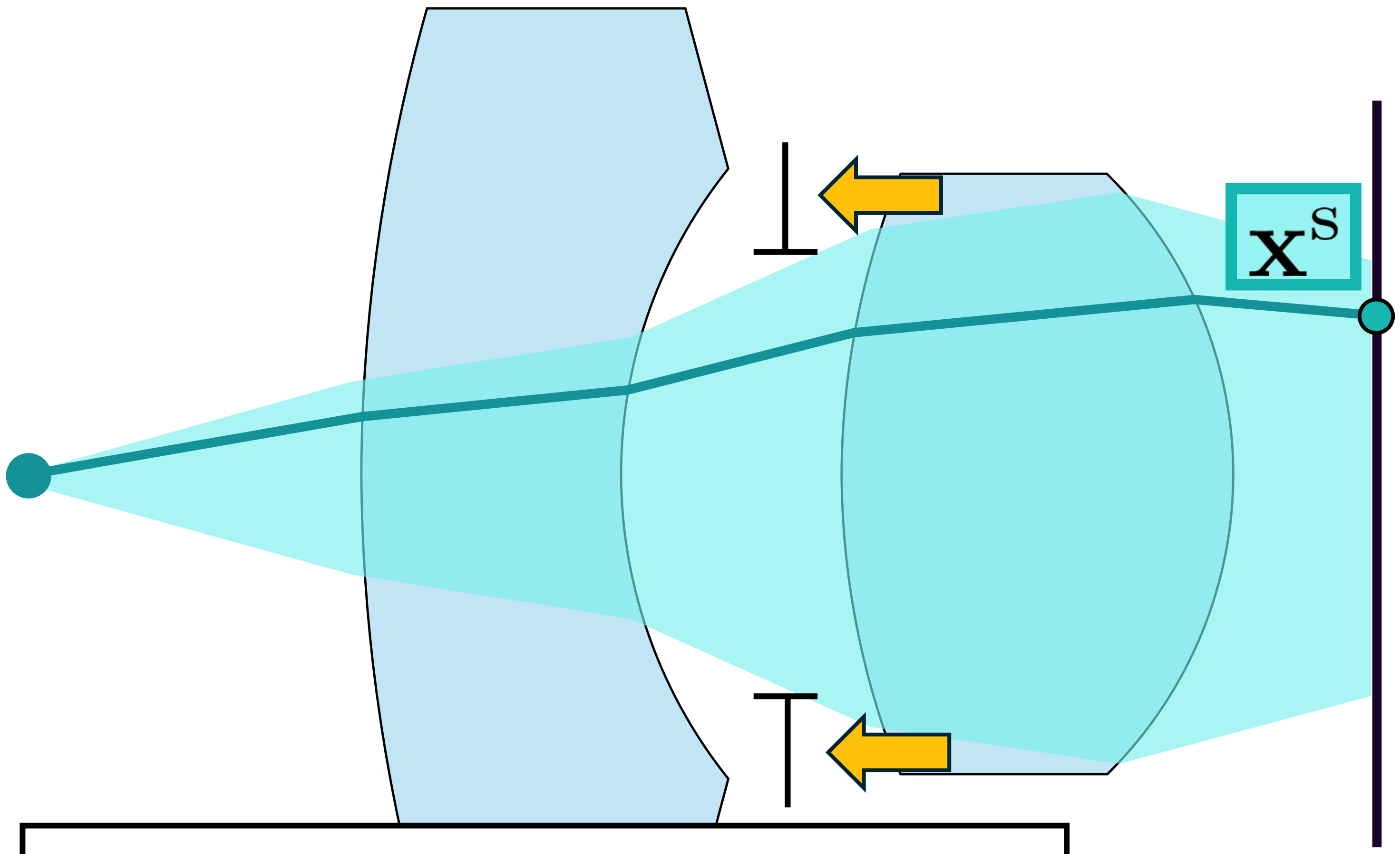
$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}}\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi}$$

$$f_{\mathrm{speed}} = 1$$

$$\Downarrow$$

$$\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}} = 0$$

autodiff issue: aperture



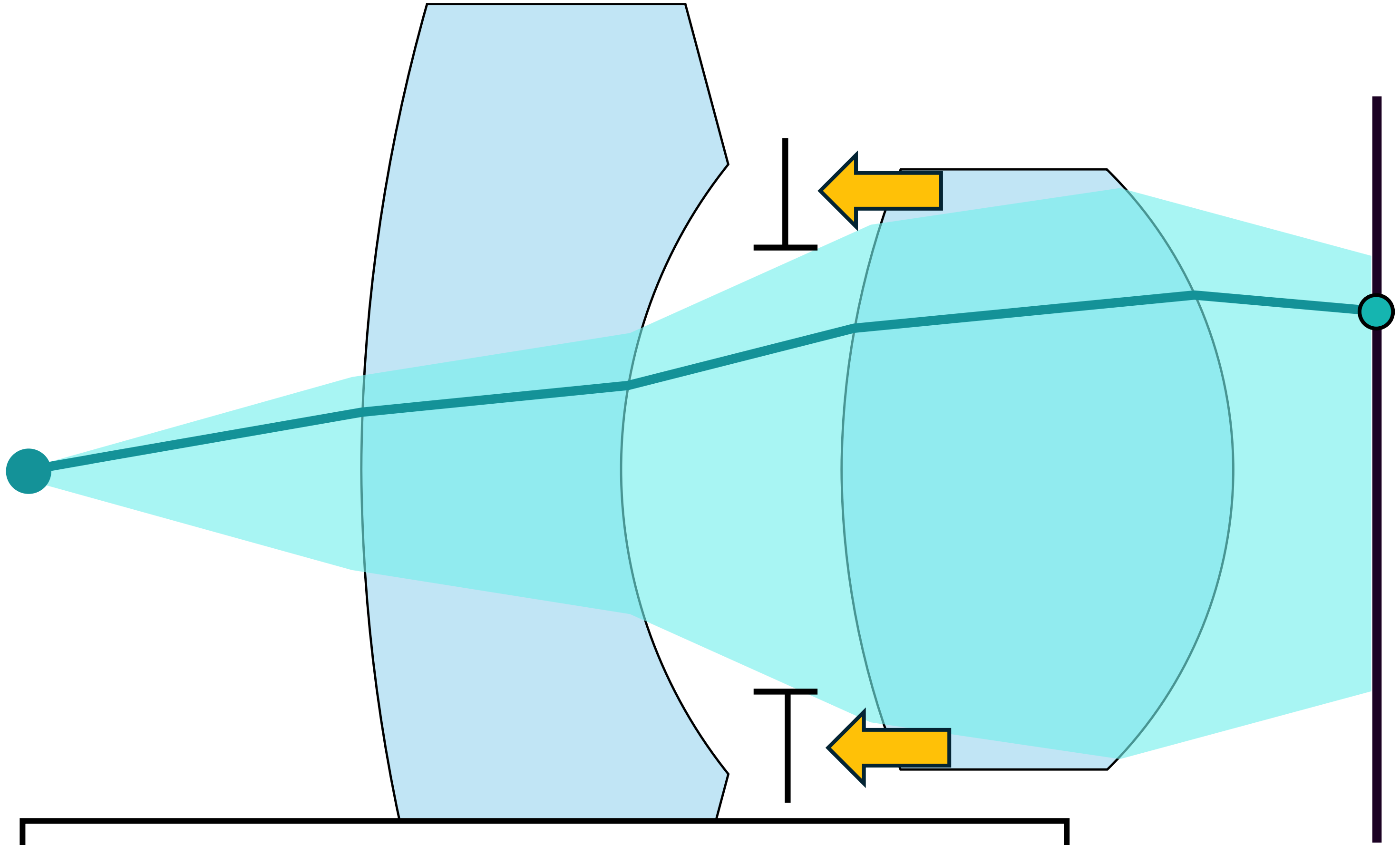
Monte Carlo gradient estimator (biased)

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}}\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi}$$

$$\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi} = 0$$

π : radius of aperture stop

autodiff issue: aperture



π : radius of aperture stop

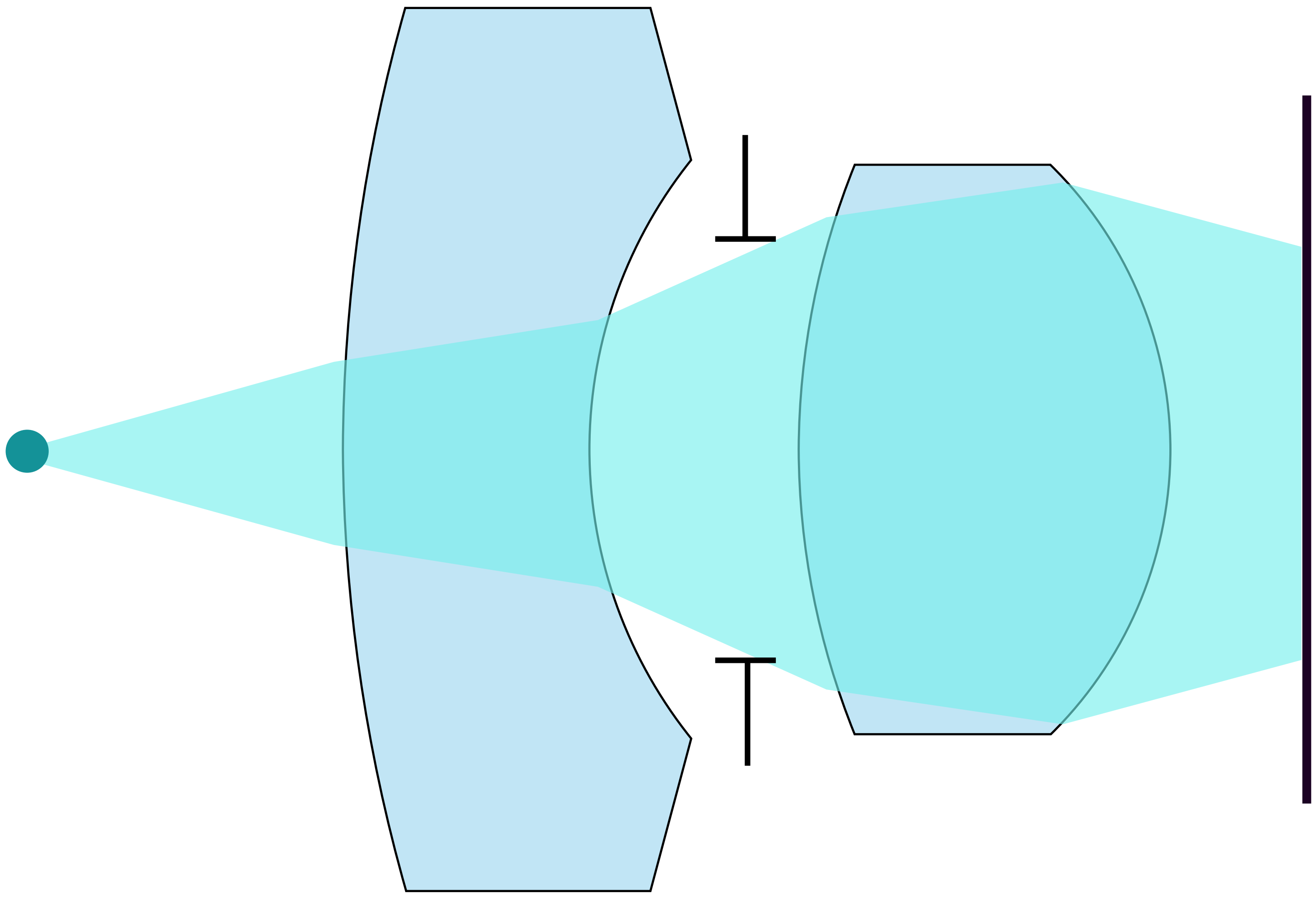
Monte Carlo gradient estimator (biased)

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}}\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi}$$

$$\frac{\mathrm{d}f_{\mathrm{speed}}}{\mathrm{d}\pi}=0$$

$$\frac{\mathrm{d}f_{\mathrm{sharpness}}}{\mathrm{d}\pi}=0$$

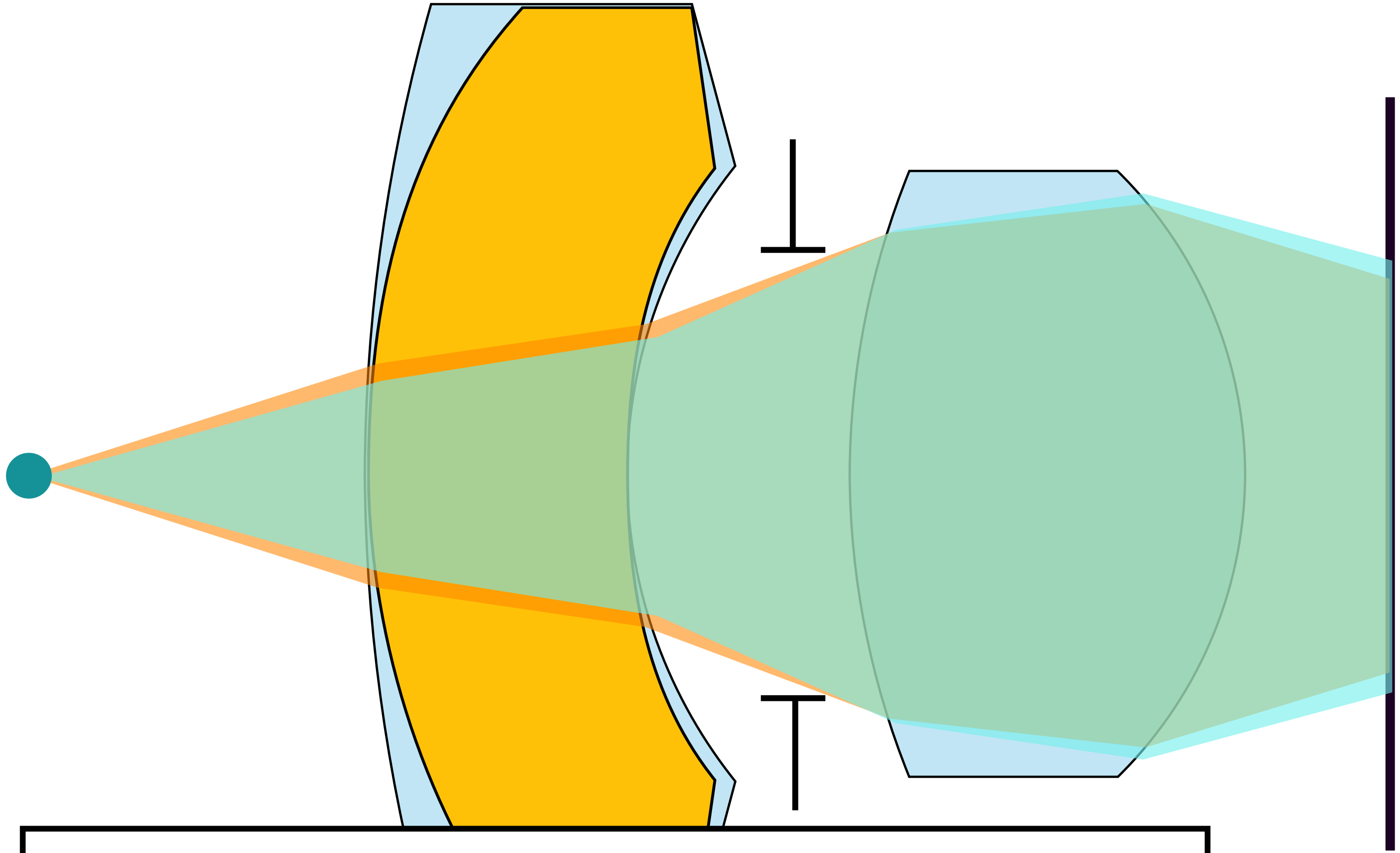
autodiff issue: curvature



Monte Carlo gradient estimator (biased)

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}}\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi}$$

autodiff issue: curvature



π : curvatures of first element

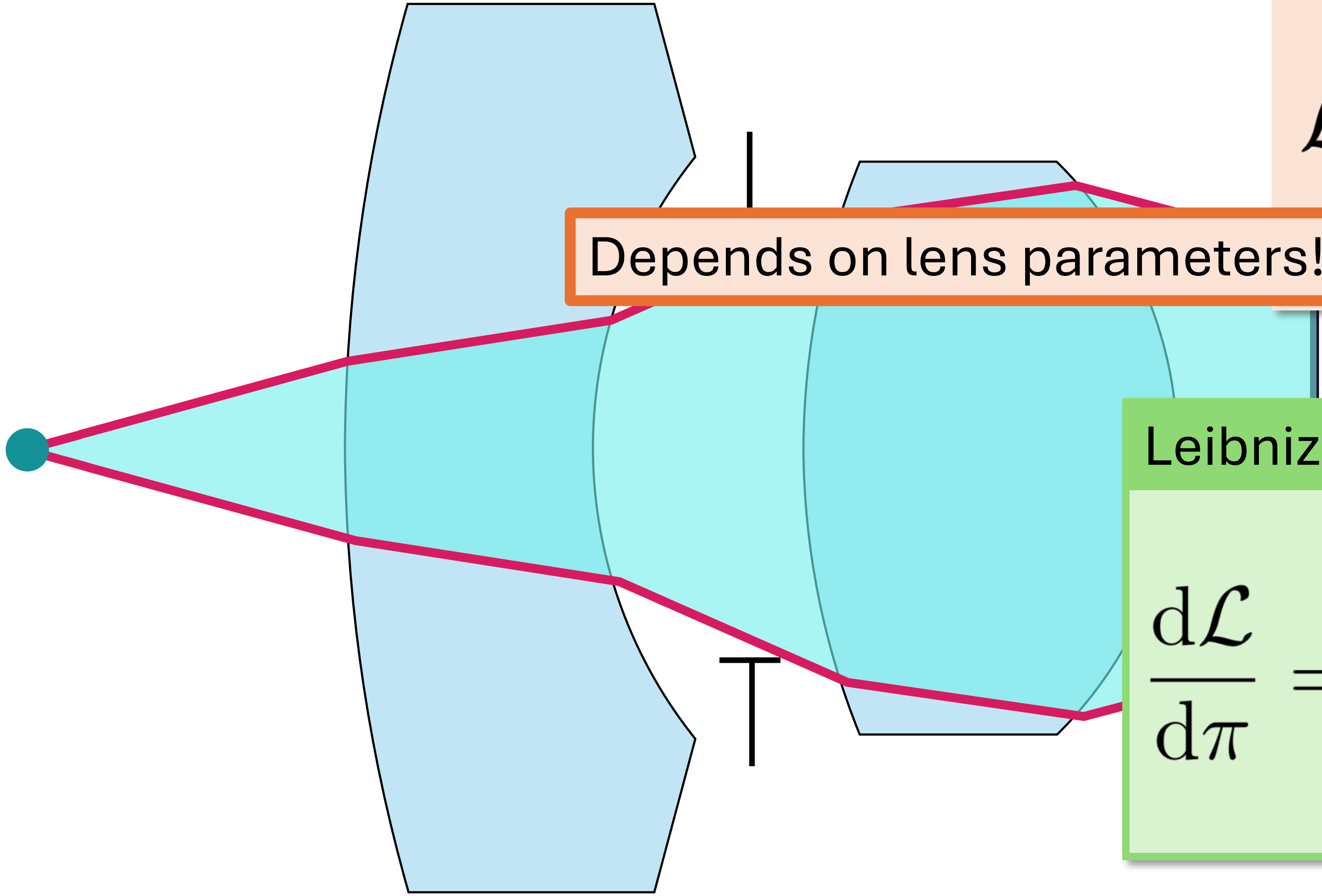
Monte Carlo gradient estimator (biased)

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\mathbf{x}}\frac{\mathrm{d}\mathbf{x}^{\mathrm{s}}}{\mathrm{d}\pi}$$

$$\frac{\mathrm{d}f_{\mathrm{speed}}}{\mathrm{d}\pi} = 0$$

$$\frac{\mathrm{d}f_{\mathrm{sharpness}}}{\mathrm{d}\pi} = \text{biased}$$

Key insight: variable domain of integration



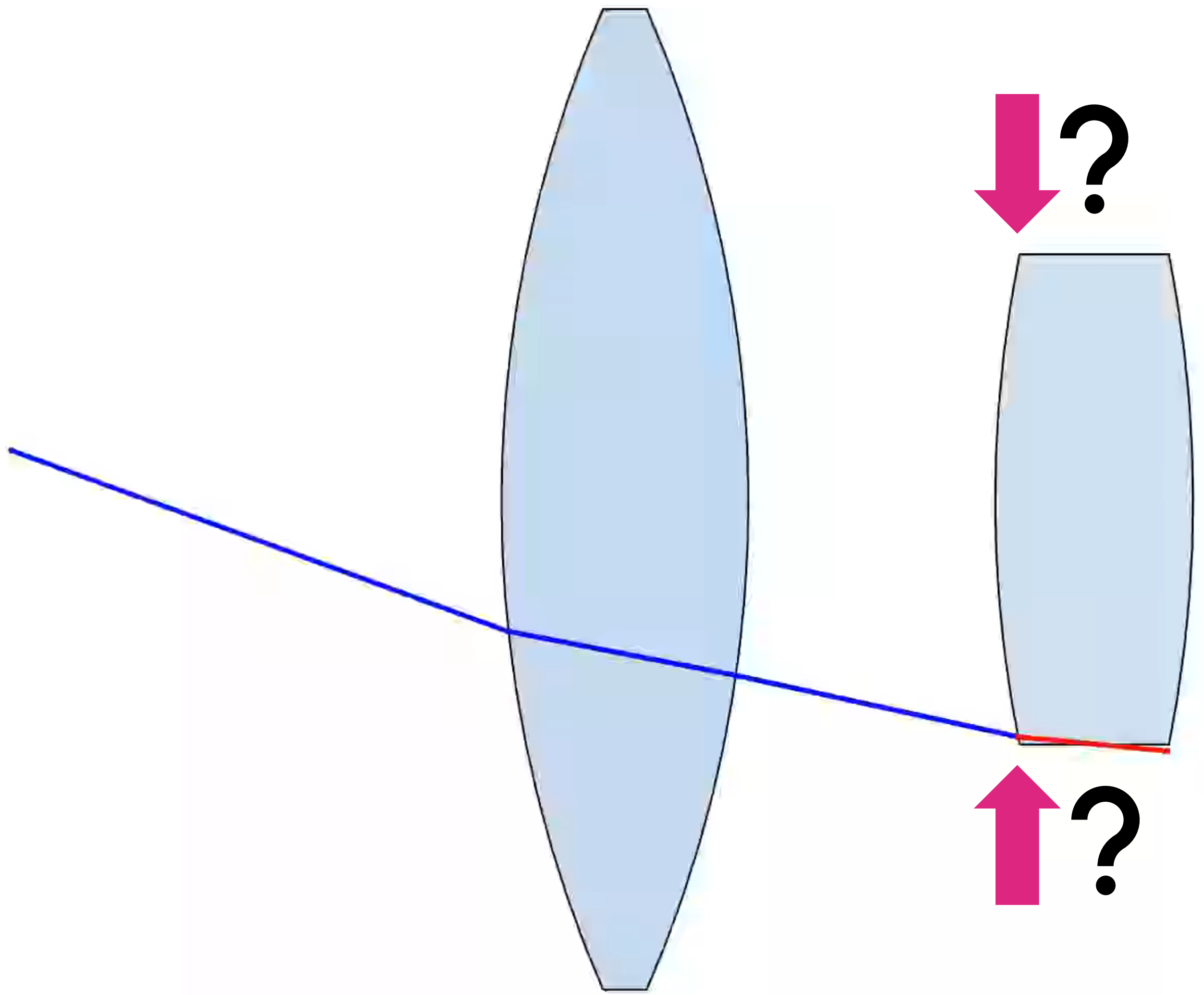
Depends on lens parameters!

$$\mathcal{L} = \int_{\Omega(\pi)} f(\mathbf{x}^{\mathrm{s}}(\omega, \pi))\, \mathrm{d}\omega$$

Leibniz integral rule

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi} = \int_{\Omega(\pi)} \frac{\mathrm{d}f}{\mathrm{d}\pi}\, \mathrm{d}\omega + \int_{\partial\Omega(\pi)} f \frac{\mathrm{d}g}{\mathrm{d}\pi}\, \mathrm{d}\omega$$

Finding the boundary is hard



Leibniz integral rule

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi} = \int_{\Omega(\pi)} \frac{\mathrm{d}f}{\mathrm{d}\pi}\,\mathrm{d}\omega + \int_{\partial\Omega(\pi)} f\,\frac{\mathrm{d}g}{\mathrm{d}\pi}\,\mathrm{d}\omega$$

Use the reparameterization trick

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi} = \int_{\Omega(\pi)} \frac{\mathrm{d}f}{\mathrm{d}\pi}\,\mathrm{d}\omega + \int_{\partial\Omega(\pi)} f\,\frac{\mathrm{d}g}{\mathrm{d}\pi}\,\mathrm{d}\omega$$

Use the reparameterization trick

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi} = \int_{\Omega(\pi)} \frac{\mathrm{d}f}{\mathrm{d}\pi}\, \mathrm{d}\omega + \int_{\partial\Omega(\pi)} f\, \frac{\mathrm{d}g}{\mathrm{d}\pi}\, \mathrm{d}\omega$$

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi} = \int_{\Omega(\pi)} \frac{\mathrm{d}f}{\mathrm{d}\pi}\, \mathrm{d}\omega + \int_{\Omega(\pi)} \nabla \cdot (f \mathcal{V}_g)\, \mathrm{d}\omega$$

Unbiased Monte Carlo estimator

$$\frac{\mathrm{d}\mathcal{L}}{\mathrm{d}\pi} = \int_{\Omega(\pi)} \frac{\mathrm{d}f}{\mathrm{d}\pi}\,\mathrm{d}\omega + \int_{\Omega(\pi)} \nabla \cdot (f\mathcal{V}_g)\,\mathrm{d}\omega$$

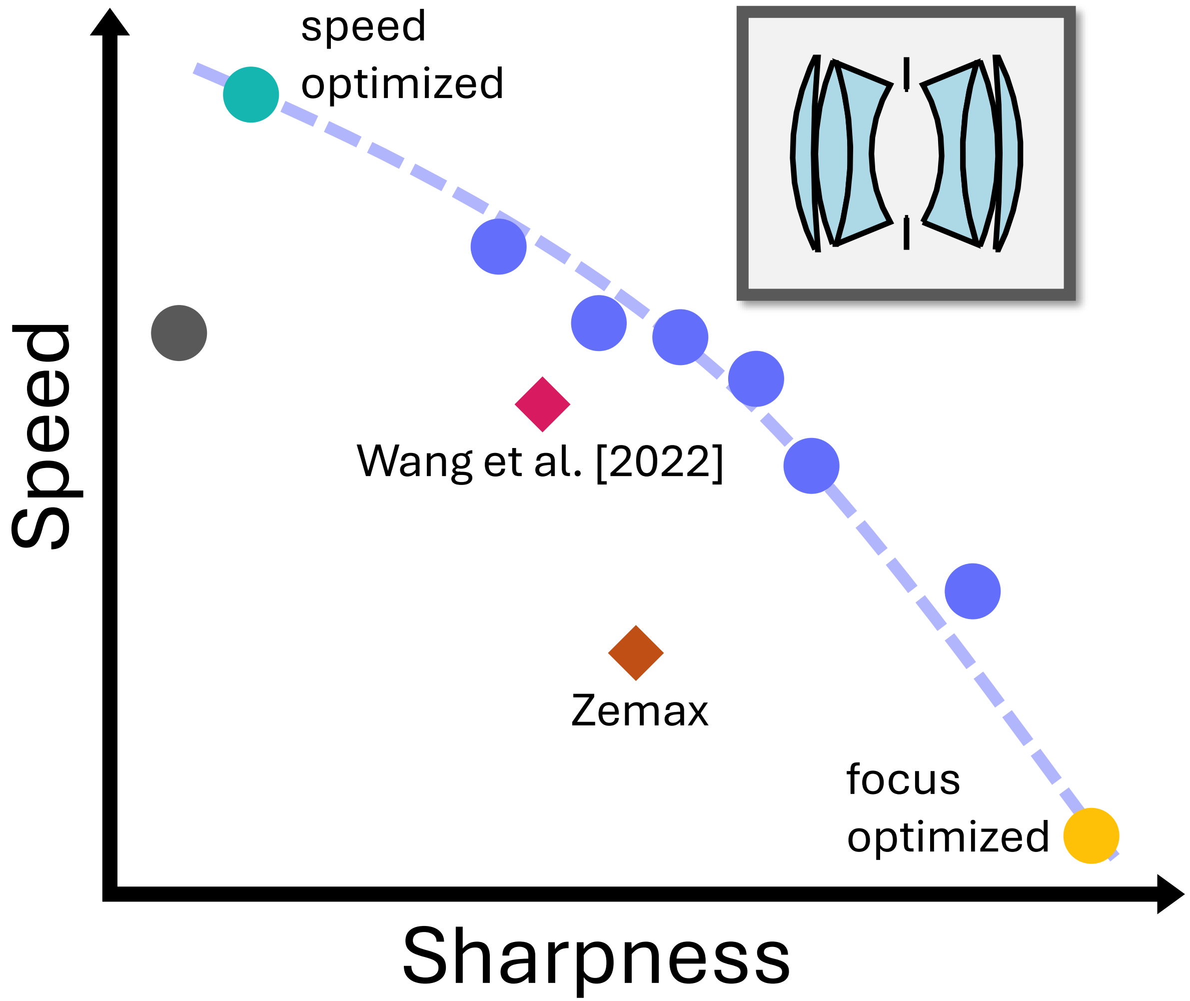
$$\approx$$

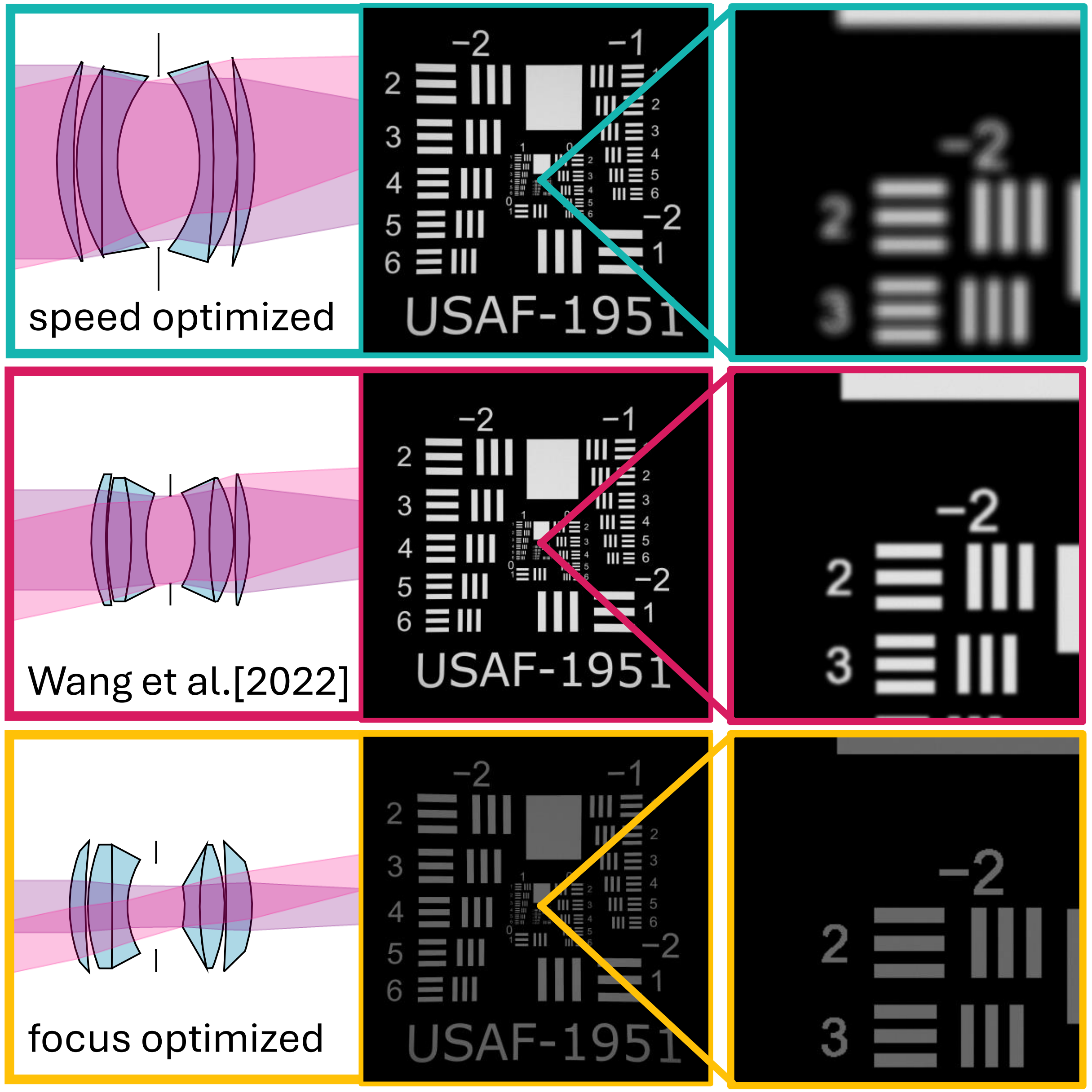
aperture-aware gradient estimator

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\pi} + \nabla \cdot (f\mathcal{V}_g)$$

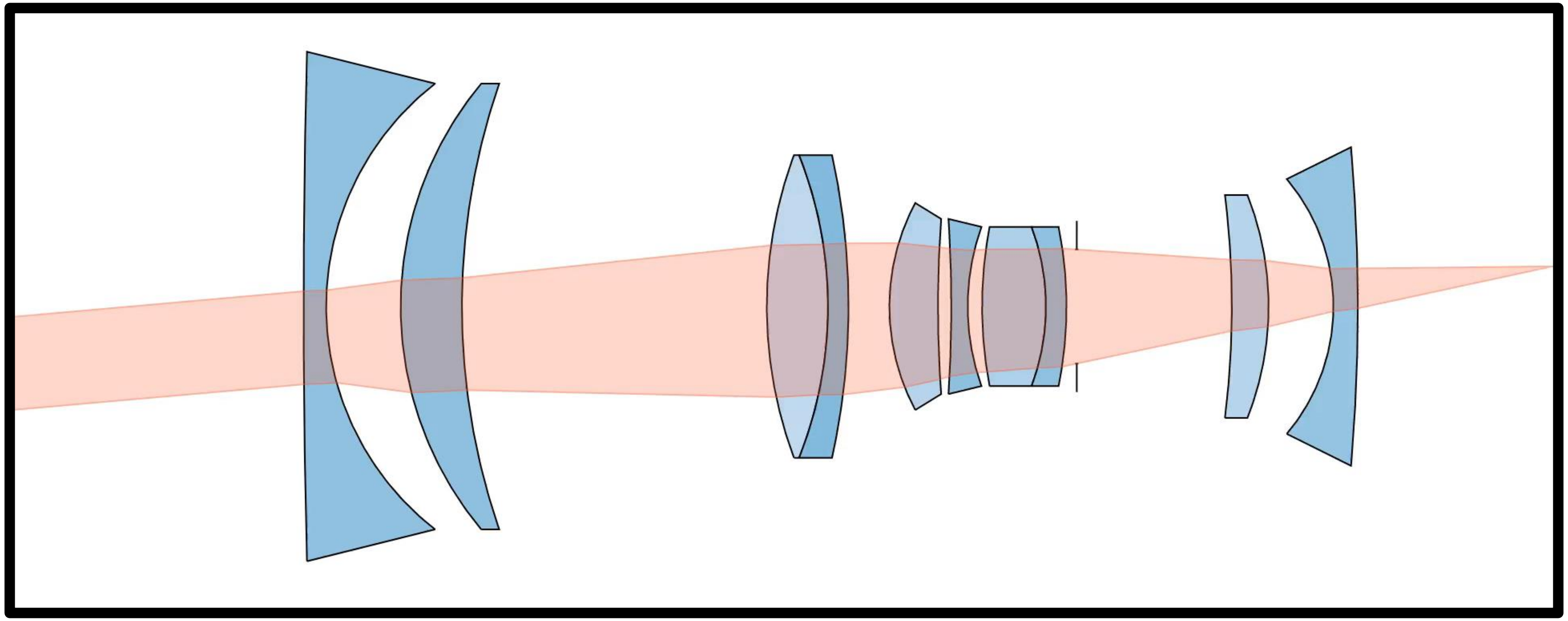
biased gradient estimator

Results

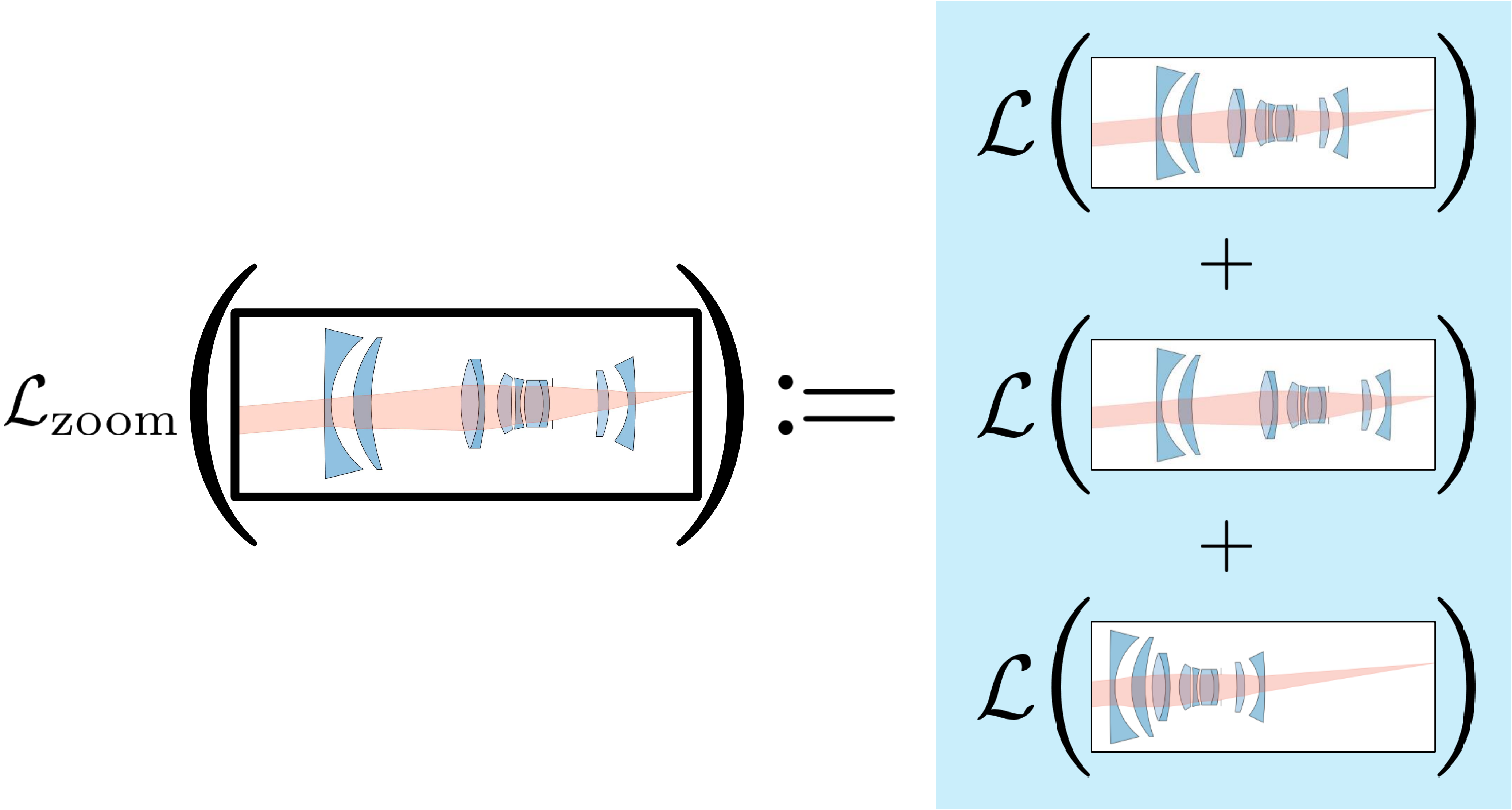

speed
optimized
Speed
Wang et al. [2022]
Zemax
focus
optimized
Sharpness


speed optimized
USAF-1951
Wang et al.[2022]
USAF-1951
focus optimized
USAF-1951

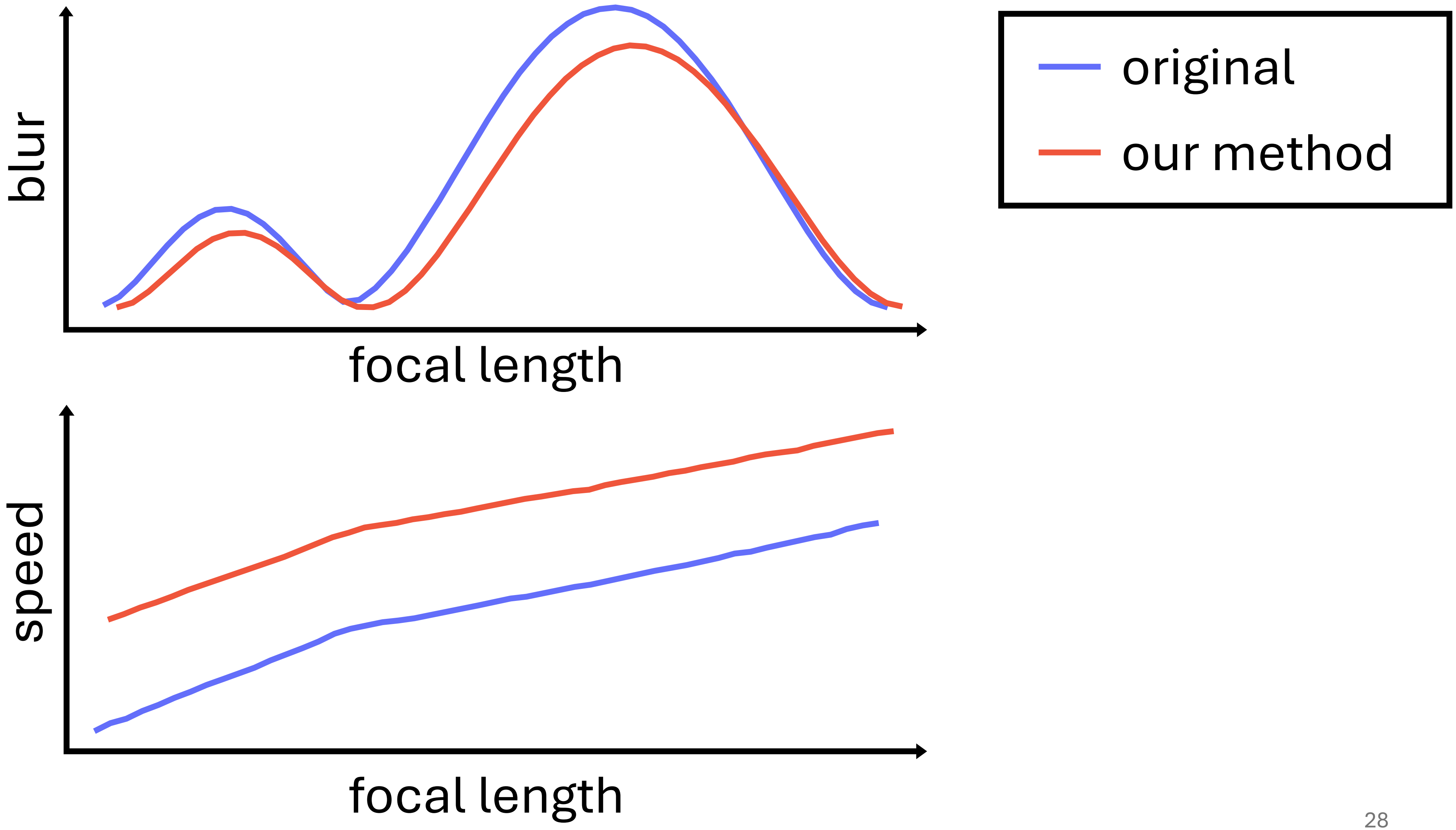
We can also optimize zoom lenses



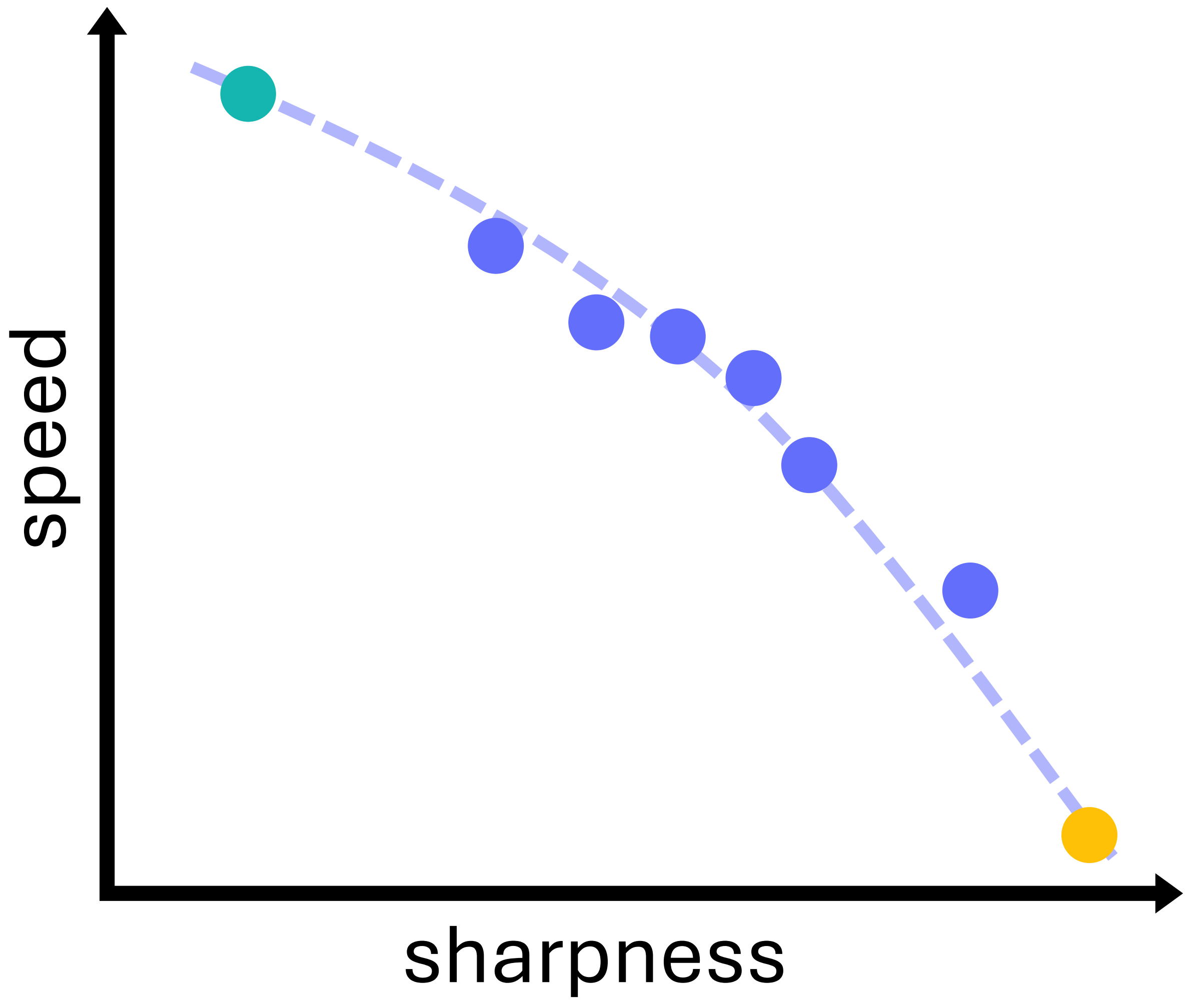
We can also optimize zoom lenses



We get better zoom lenses



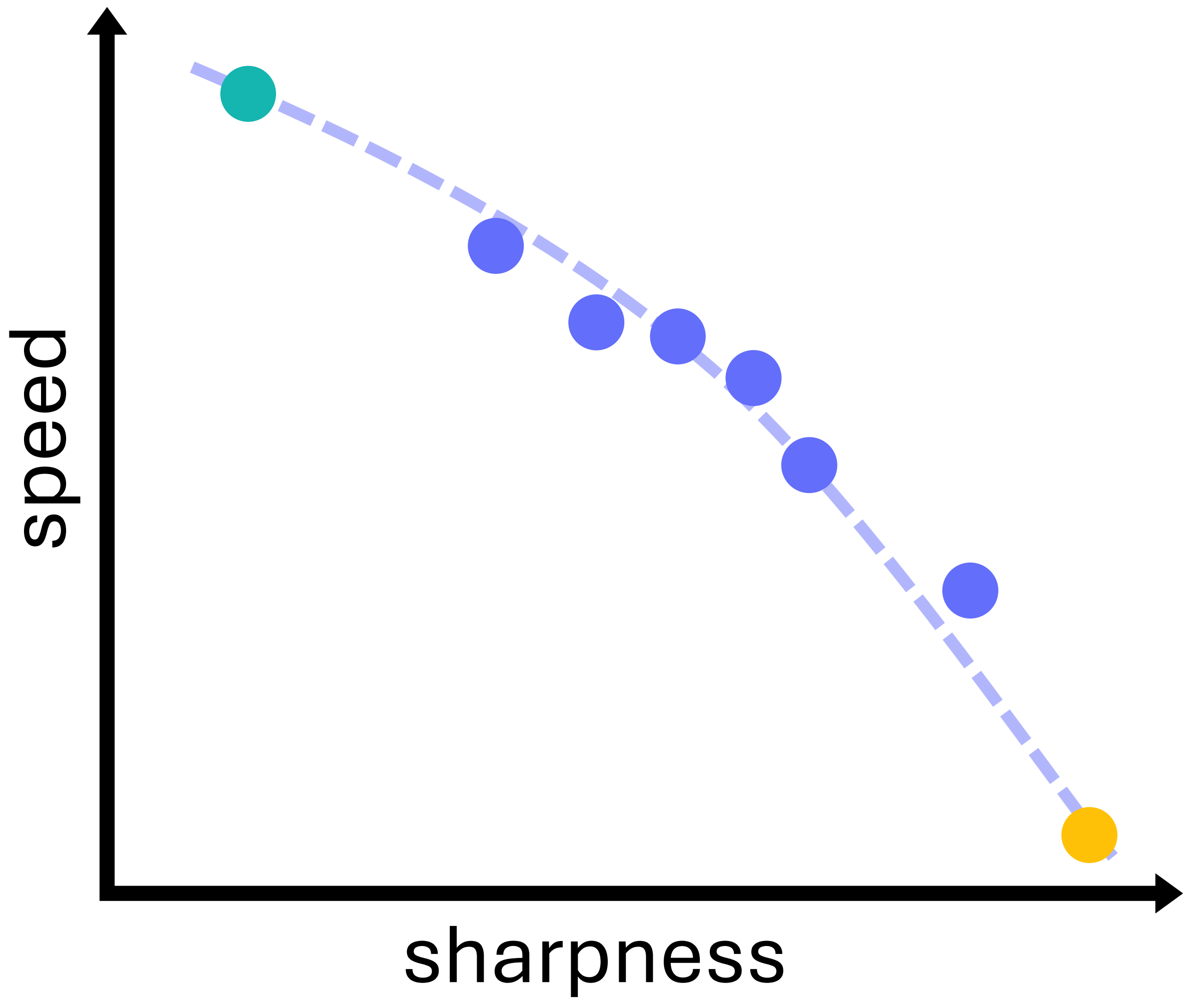
Summary



aperture-aware gradient estimator

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\pi}+\nabla\cdot(f\mathcal{V}_g)$$

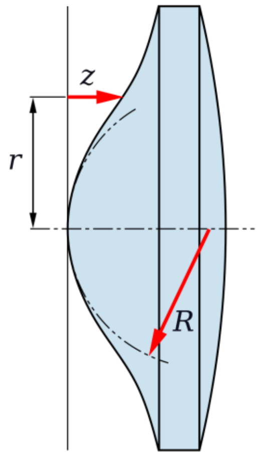
It's possible to optimize other types of lenses



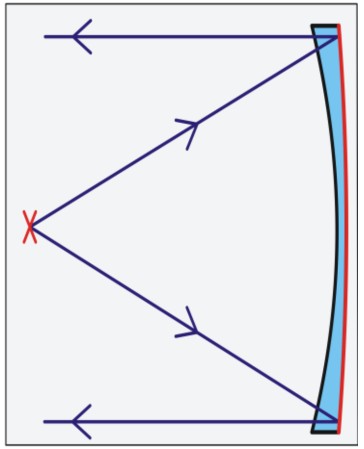
aperture-aware gradient estimator

$$\frac{1}{N}\sum_{i=0}^{N}\frac{1}{p(\omega_i)}\frac{\mathrm{d}f}{\mathrm{d}\pi}+\nabla\cdot(f\mathcal{V}_g)$$

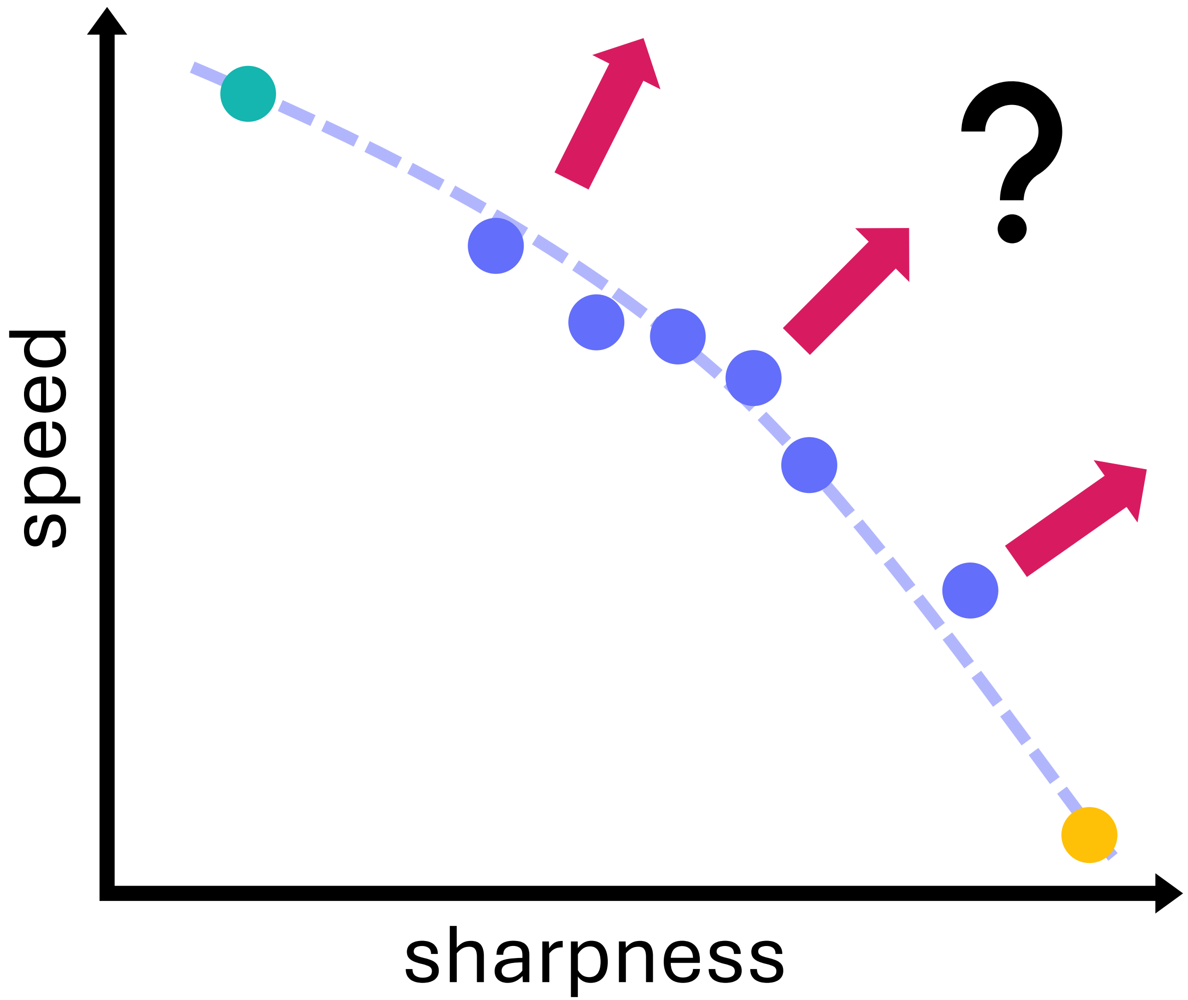
aspherics

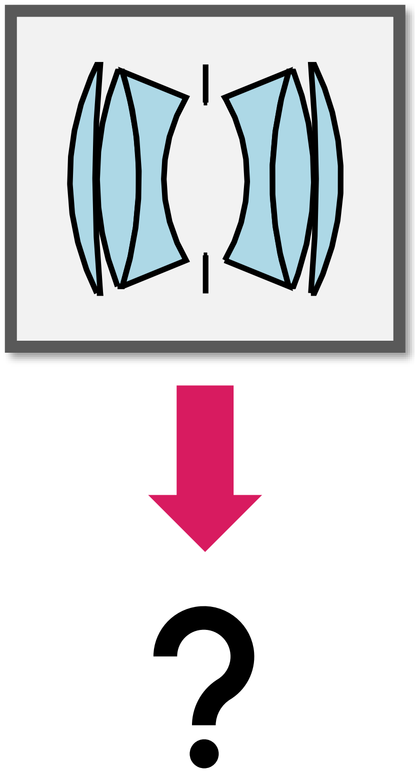


mirrors



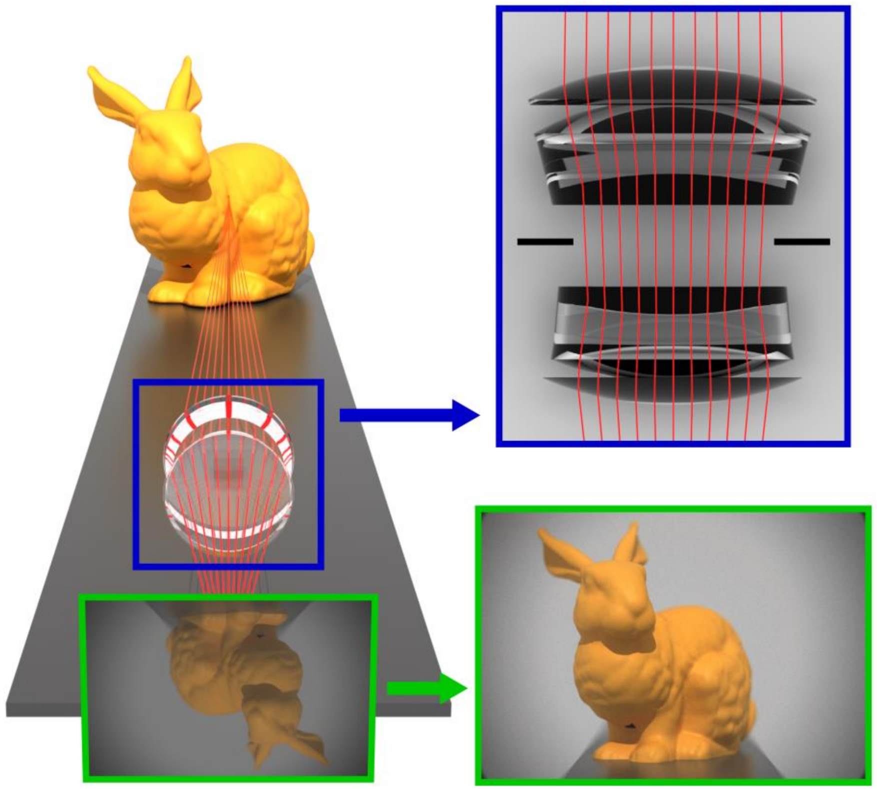
Gradient based methods are limited by the topology of the lens





Aperture-Aware Lens Design

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



code