Improving light collection efficiency of silicon photomultipliers through the use of metalenses

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CPAD

Madison, Wisconsin
December 8, 2019

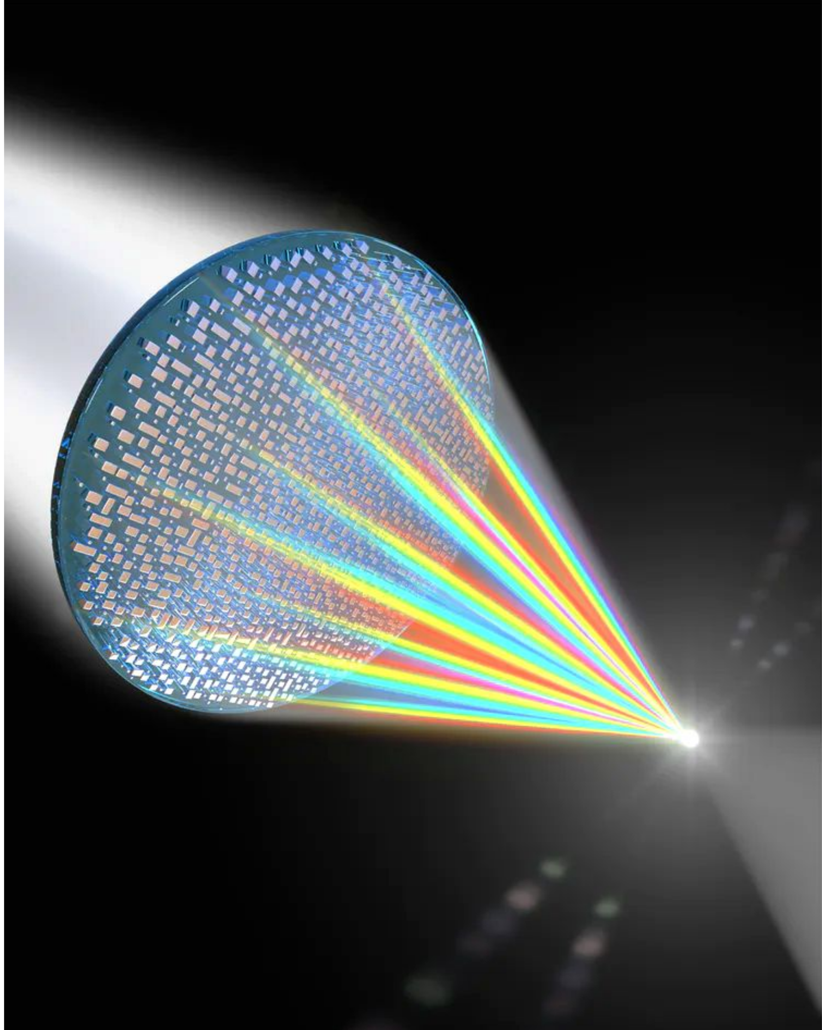


Image: Capasso Group, Harvard University

Outline

- ➢ Motivation
  - SiPM coverage in particle detectors
- ➢ Metalenses
  - introduction - what and why
  - working principle
- ➢ SiPMs with metalenses
  - experimental design
  - beam profiling and metalens efficiency
- ➢ Results and Outlook

Motivation

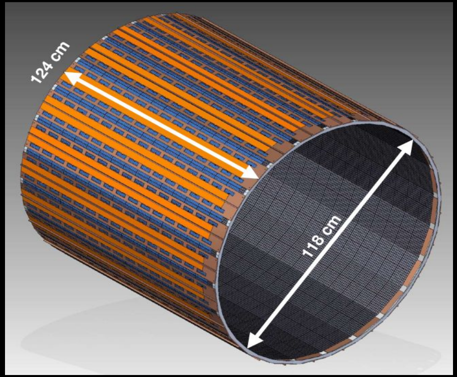
Particle detectors with SiPMs

- Many experiments could benefit from increase in light collection by SiPMs
  - 0$\nu\beta\beta$, dark matter, event neutrino, etc.

DarkSide-20k

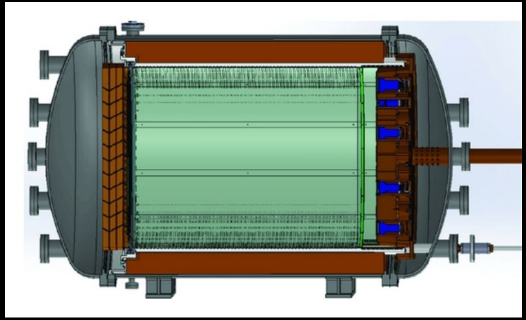
G. Giovanetti, CPAD 2018

nEXO



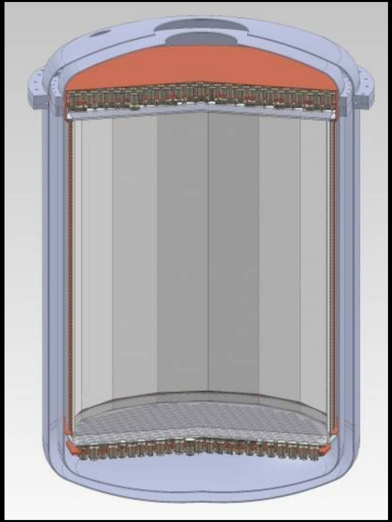
arXiv:1806.02220

NEXT



arXiv:11307.3914

DARWIN



DARWIN Collaboration

Light collection of SiPMs

Why SiPMs?

- single p.e. resolution
- low voltage + high gain
- compact (radiopurity)
- improving VUV sensitivity

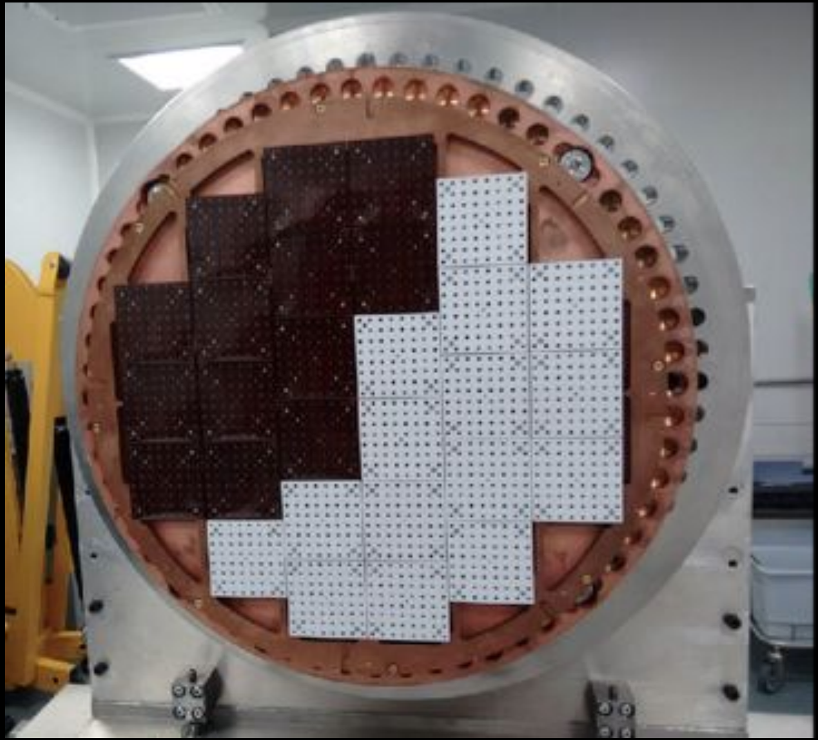
Why fewer/smaller SiPMs?

- cost
- simpler electronics
- fewer readout channels
- recycle existing infrastructure

Why increase light collection of SiPMs?

- track/position reconstruction
- energy resolution/ threshold
- trigger efficiency

~ 1% area coverage by SiPMs in NEXT



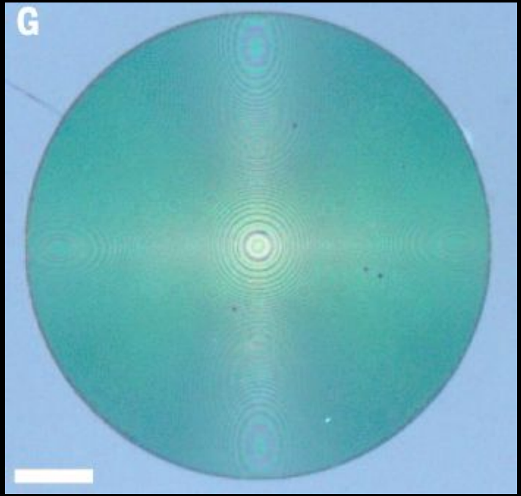
Metalenses

What are Metalenses?

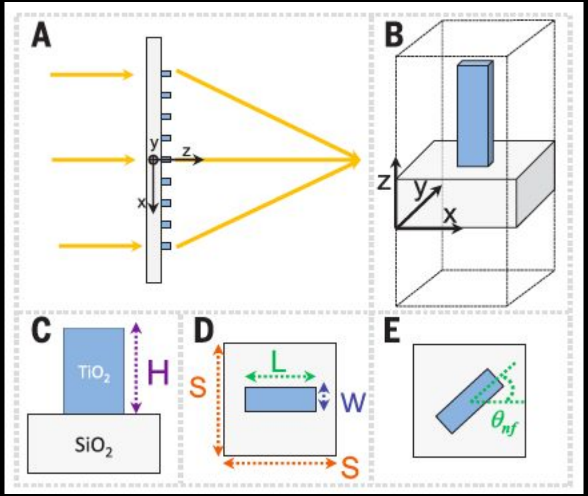
- multifocal diffractive lenses
- optimized for specific/ multiple wavelength(s)
- nanostructures on thin substrate

click here for a video introduction!

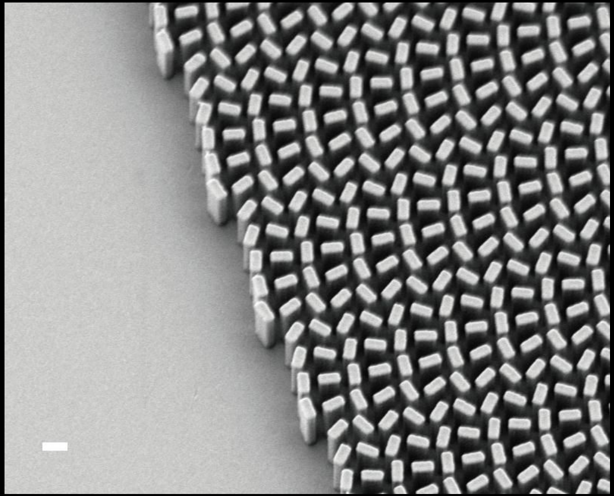
optical image of single metalens



schematic of metalens nanostructures



SEM image of nanofins (metasurfaces)



Images: Khorasaninejad et al., Science **352**, 6290 (2016)

Why use metalenses?

Advantages

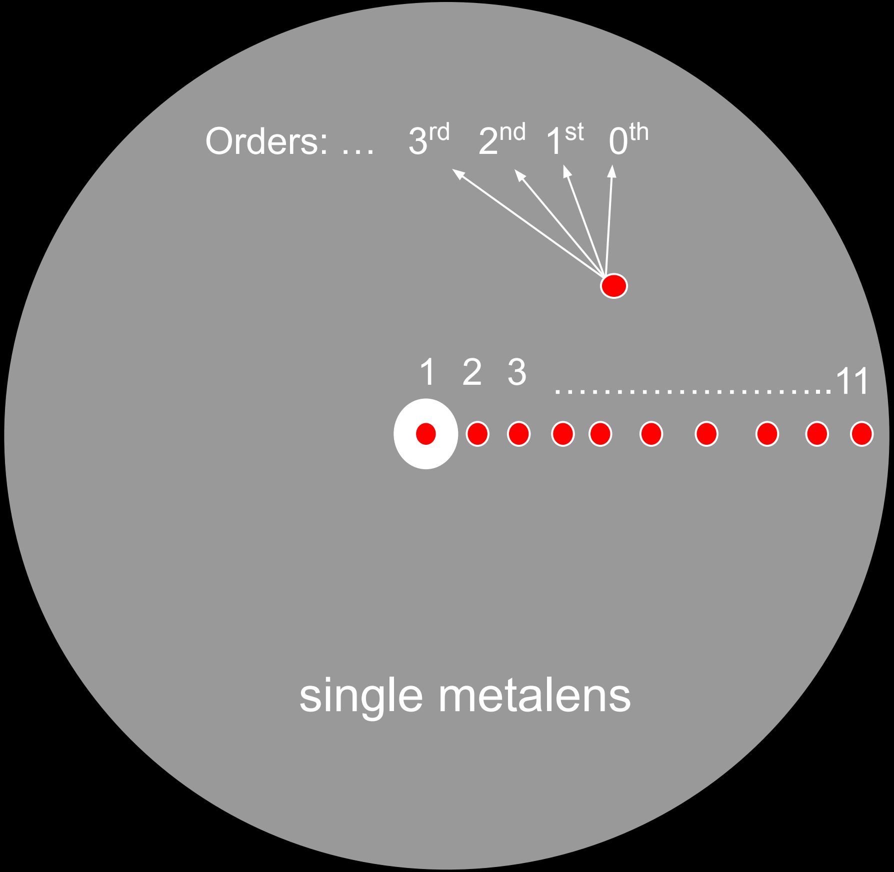
- low cost
  - currently < $10 each
  - smaller SiPM + metalens < larger sipm (3 to 5X)
- compact
  - radiopurity
  - simple mechanical integration
- simple fabrication
  - single layer lithography
  - mass production ok

Potential applications

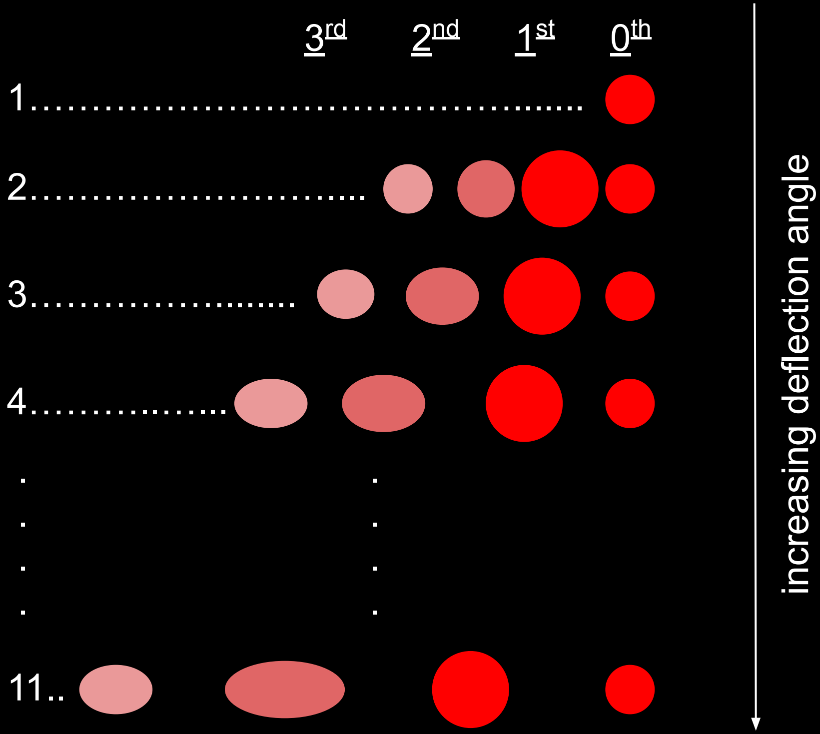
- replacement of refractive lenses
- **particle detectors!**

array of 1 cm diameter metalenses
λ_d = 632 nm (this work)

Light diffraction by metalenses

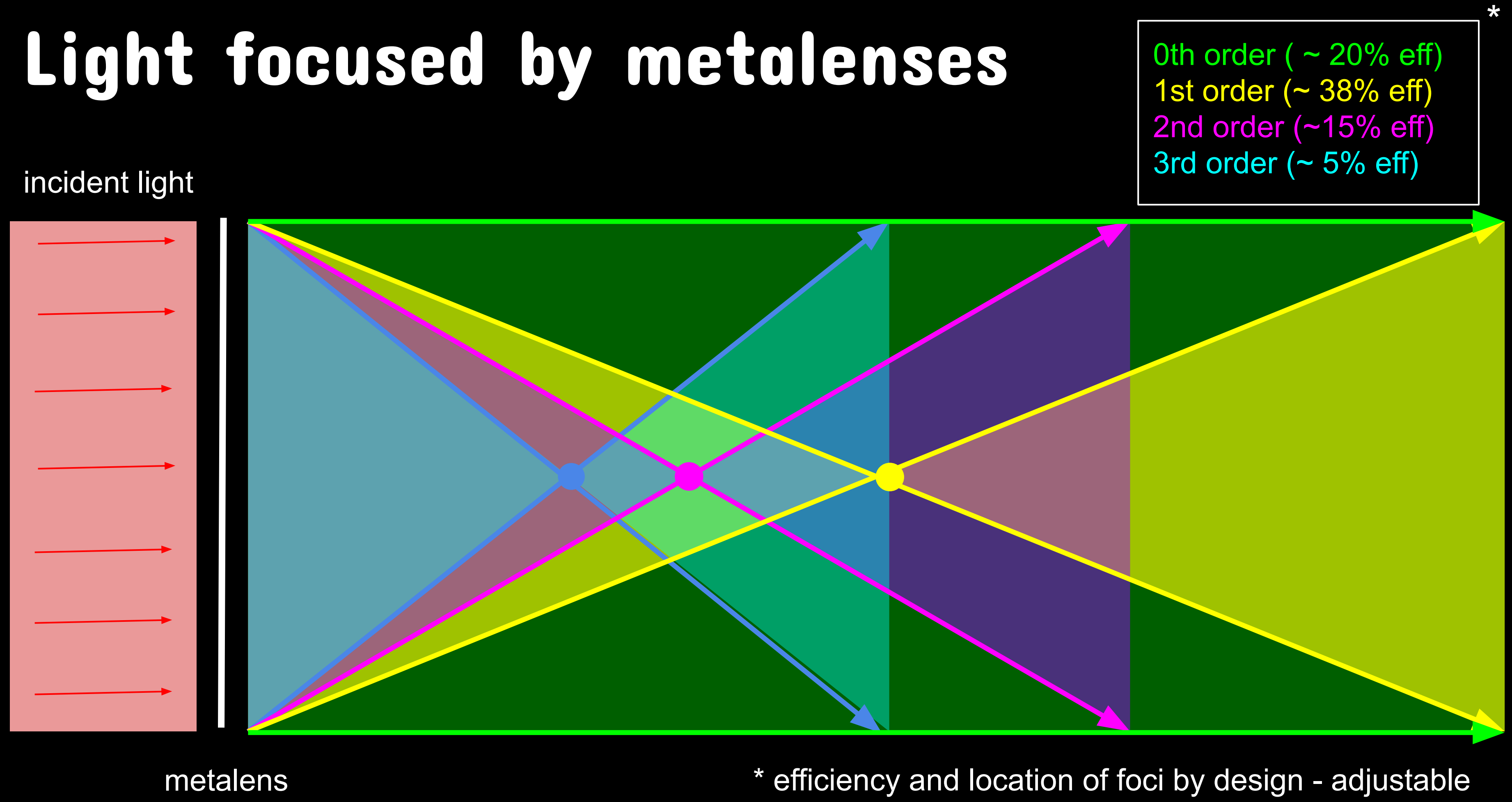


diffraction order projections



Further details: Yu et al., Science **334**, 333 (2011)

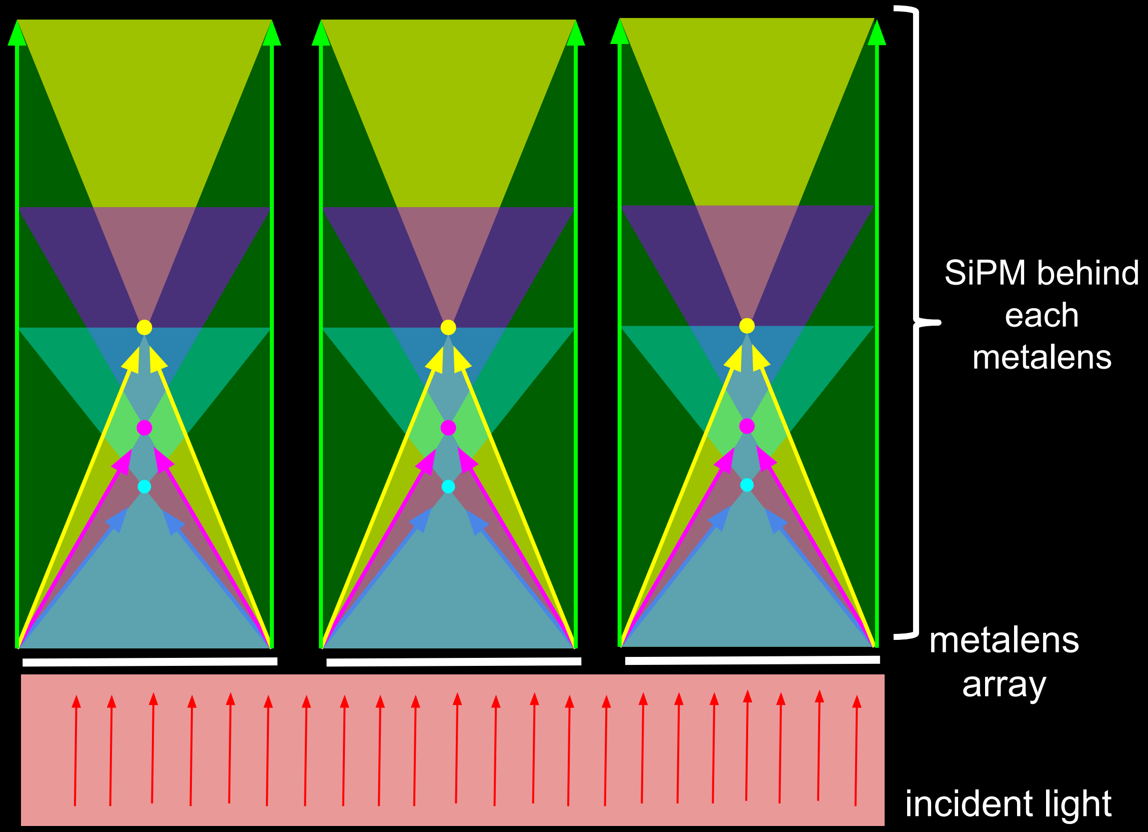
Light focused by metalenses



SiPMs with Metalenses

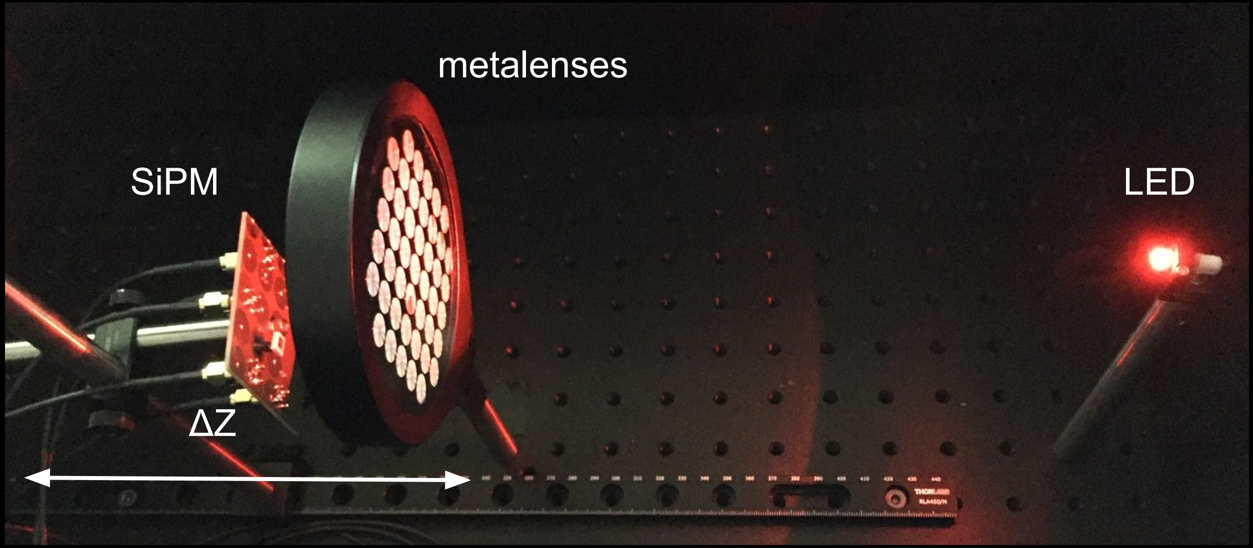
Concept & questions

- concept
  - large photodetection area coverage by metalenses projected onto (small) SiPMs
- questions
  - optimal SiPM location?
  - dependence on SiPM size?
  - how much can the light collection be increased?
  - what influences this increase?
  - what is the light transmission efficiency of the metalenes?

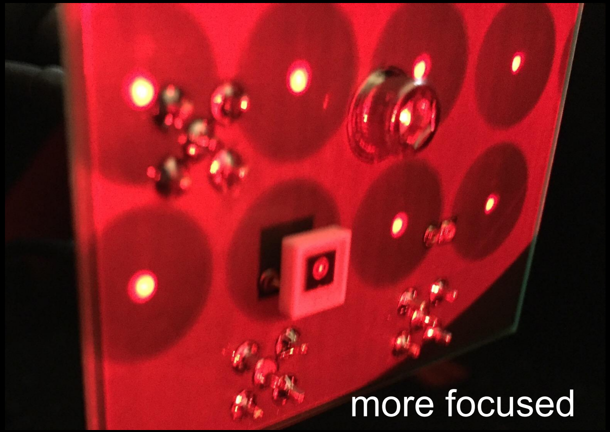


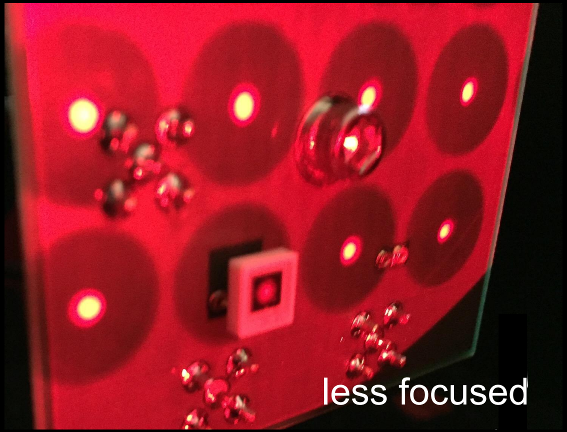
Experimental design

- 1.3 x 1.3, 3 x 3 and 6 x 6 mm^2 SiPMs (Hamamatsu S13370)
- signal as a function of distance from the metalens location
  - with and without metalens in place



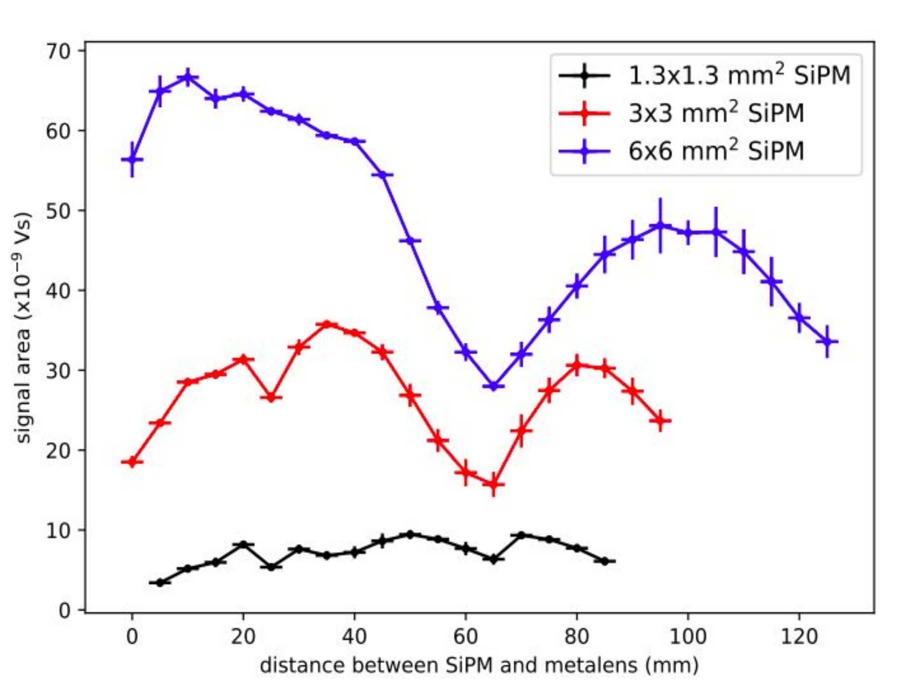
1st order focal point



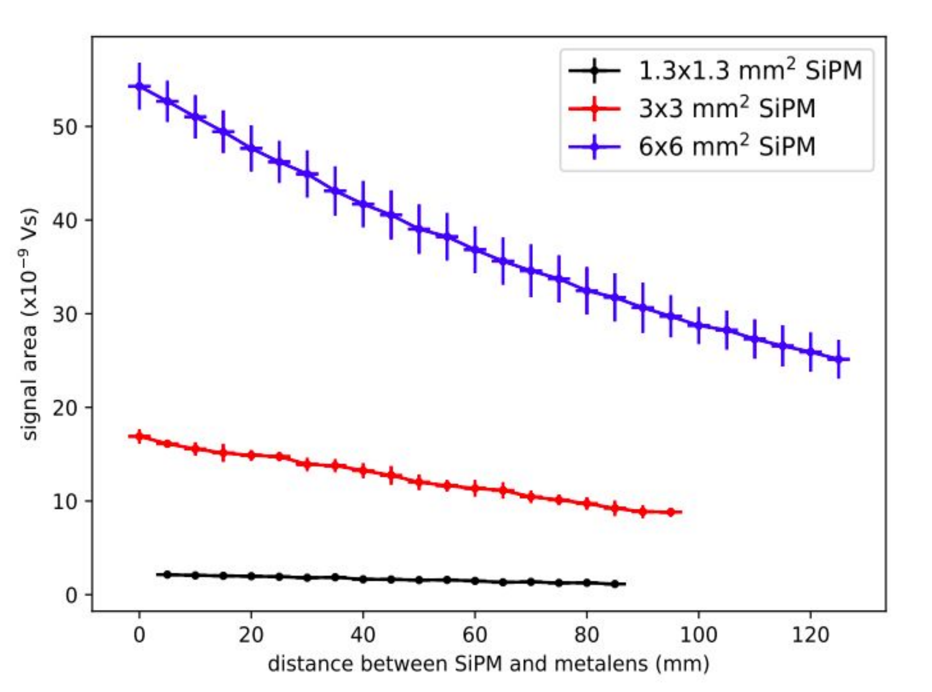


SiPMs' signals

SiPM signals with metalens

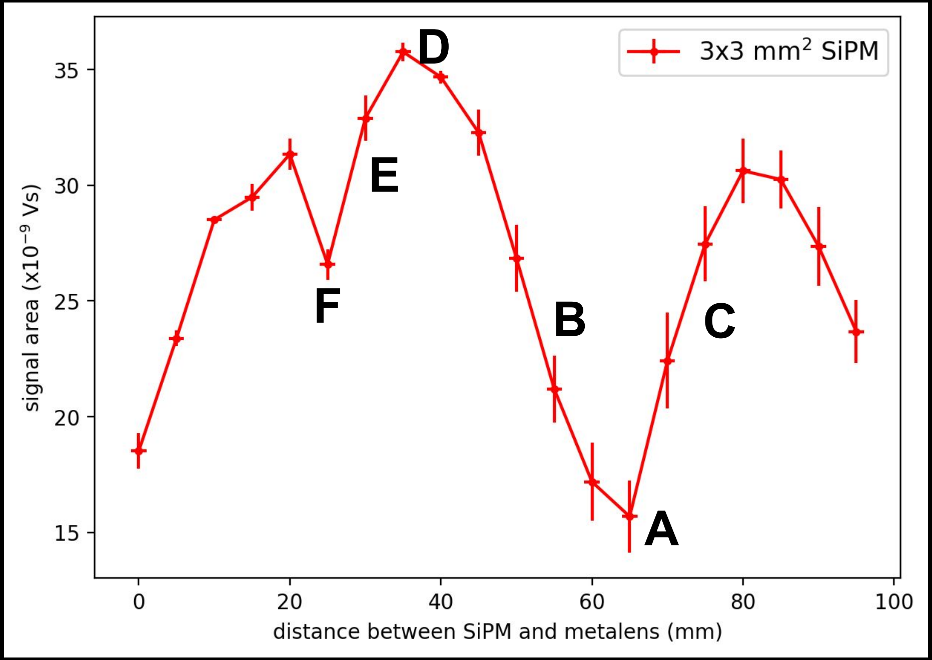


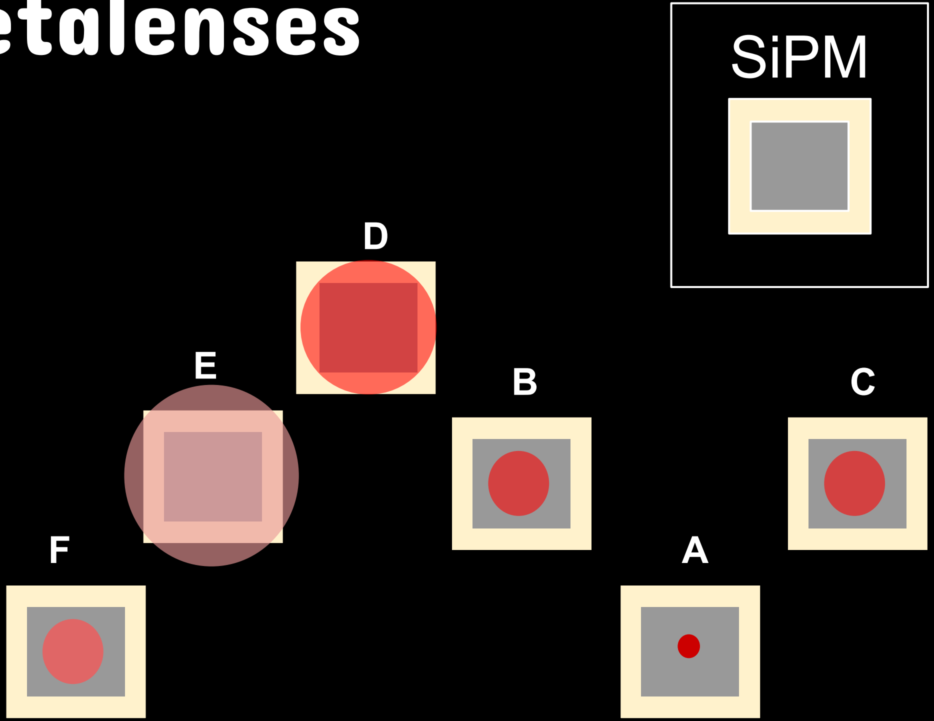
SiPM signals without metalens



- signal shape with metalens
  - projected beam profile + metalens efficiency
- signal shape without metalens
  - $1/r^2$ dependence

Signal shape with metalenses

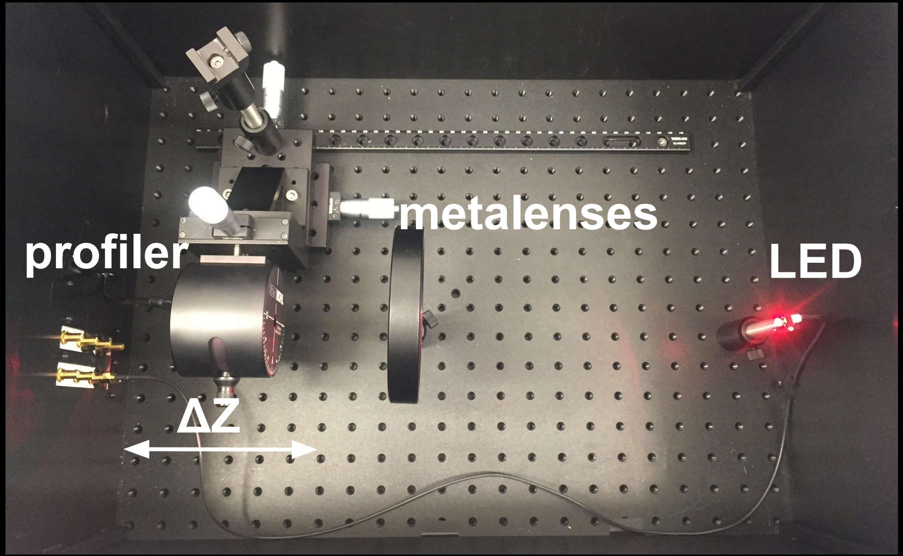


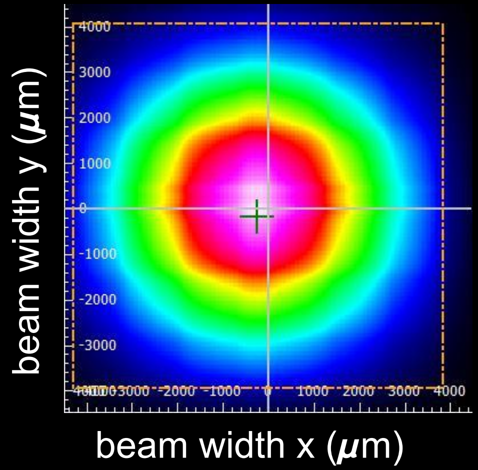


signal (beam diameter, intensity)

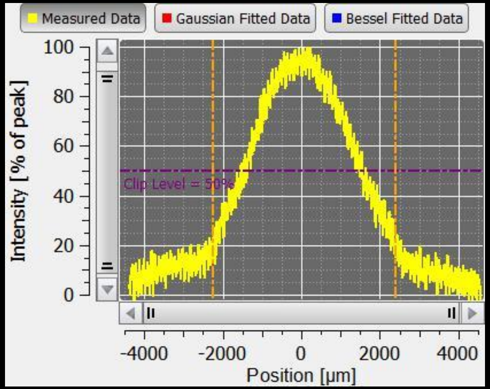
Beam profiling

- Thorlabs BP209
  - beam width (> 13.5% of max intensity)

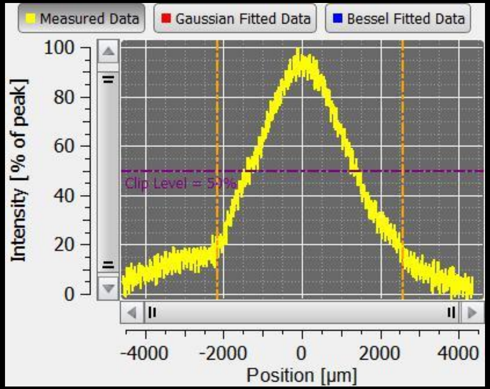




x-profile

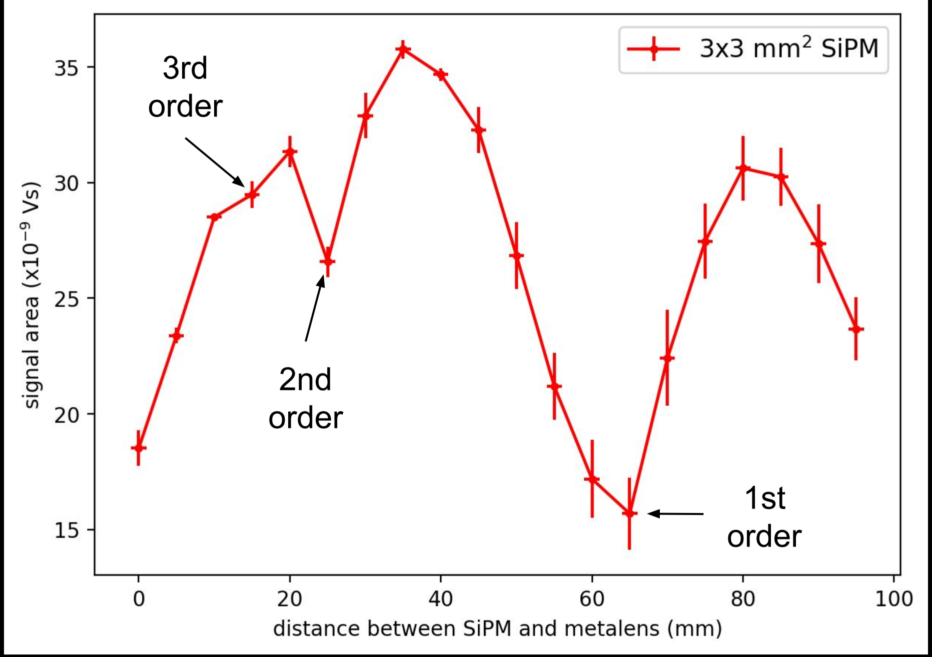


y-profile

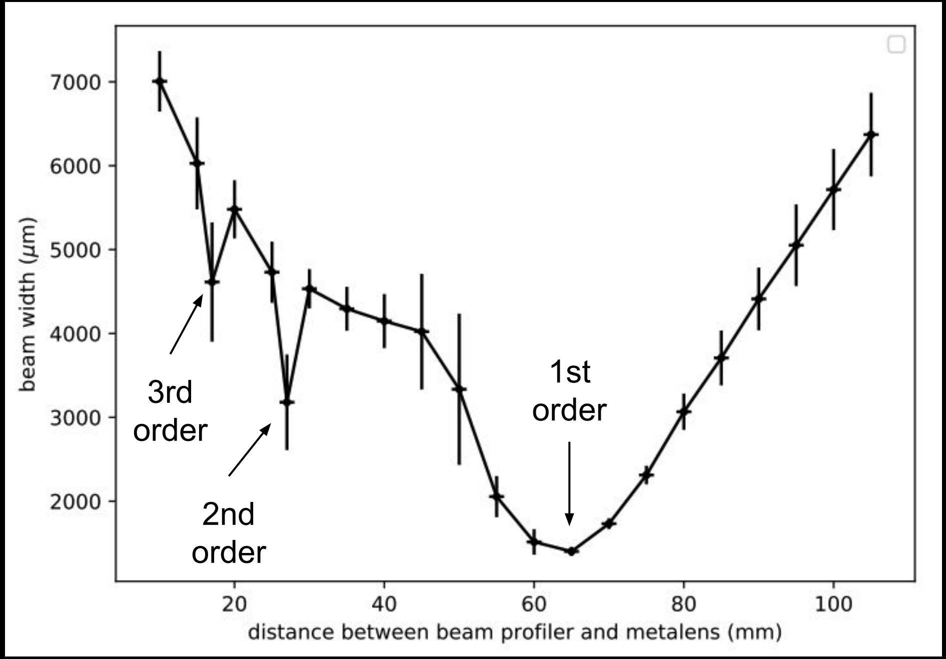


Signal shape and beam width

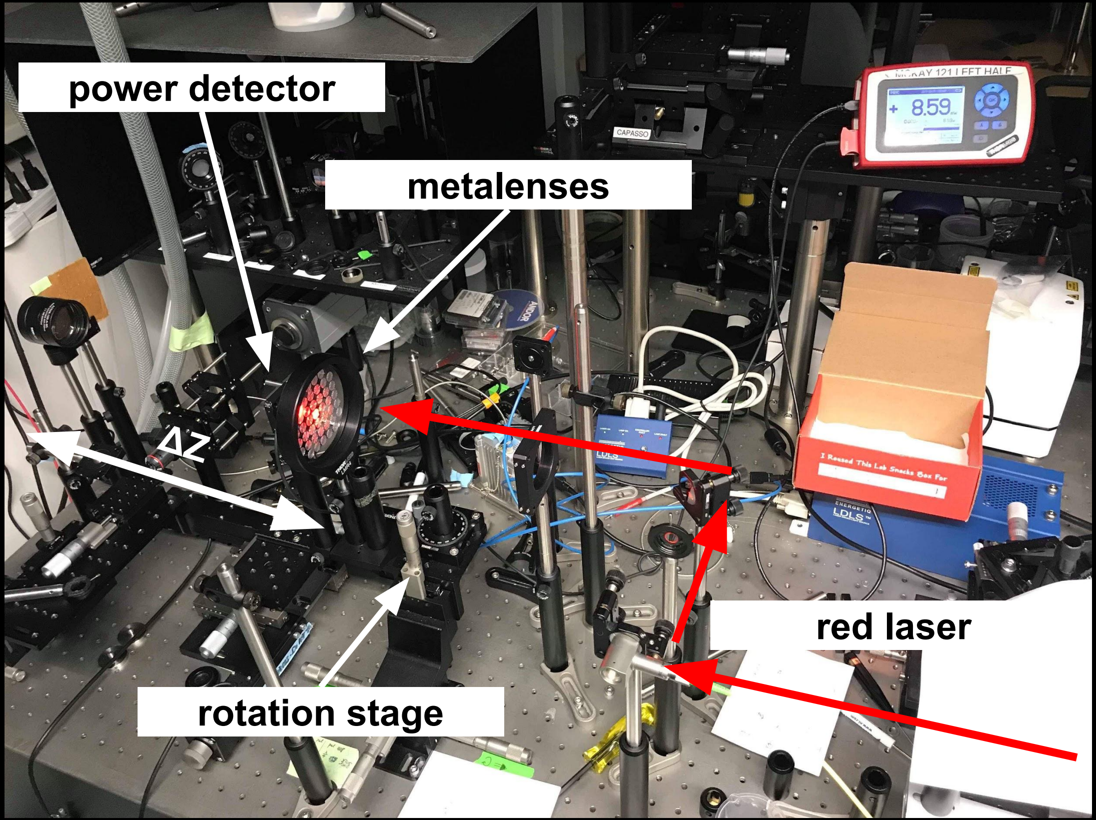
SiPM signal with metalens



measured beam width



Metalens efficiency measurements



normal incidence efficiency

- 10 mm diameter beam, variable aperture power detector
- measure transmitted power as a function of distance from the metalens

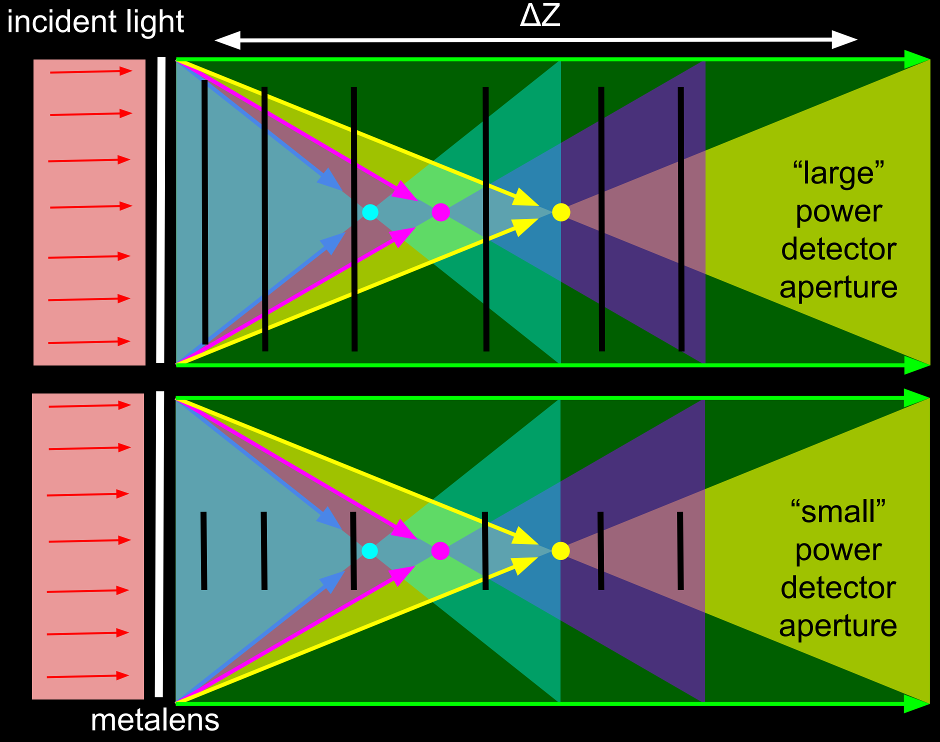
angular efficiency

- 2 mm diameter beam centered on metalens, 10 mm aperture power detector fixed at 5mm from metalens
- measure transmitted power as a function of metalens rotation angle

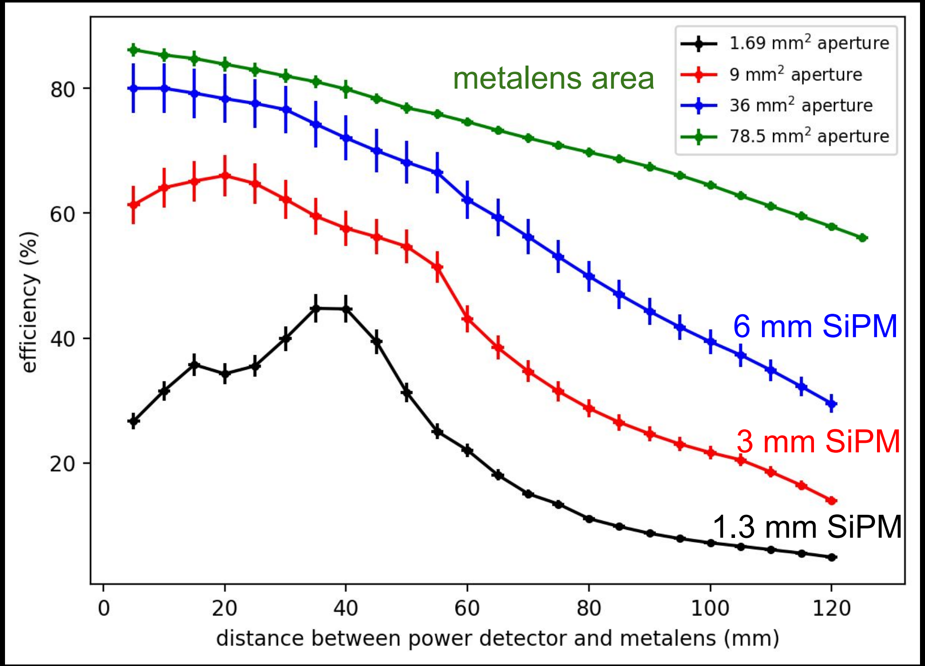
$$\varepsilon = \frac{P_{\text{through metalens}}}{P_{\text{at metalens}}}$$

Linear efficiency results

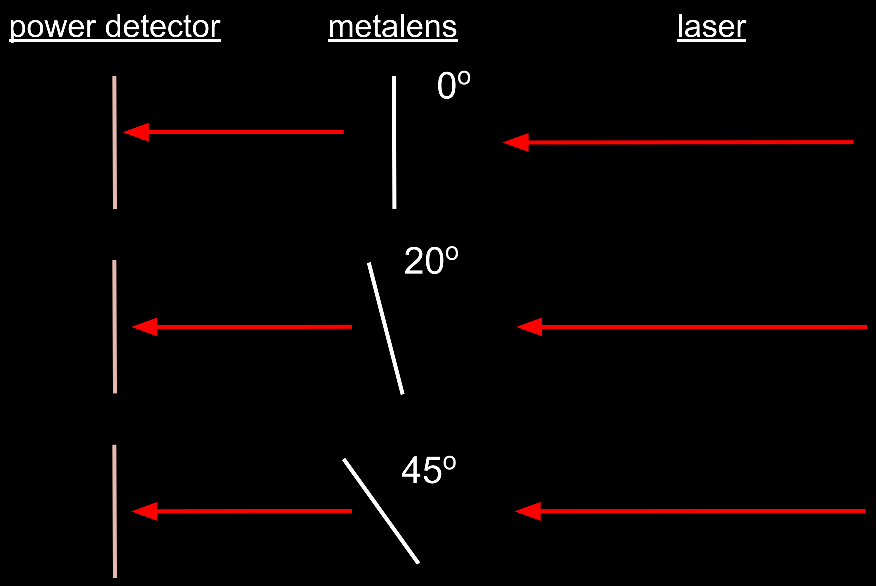
- consequence of combined foci contributions



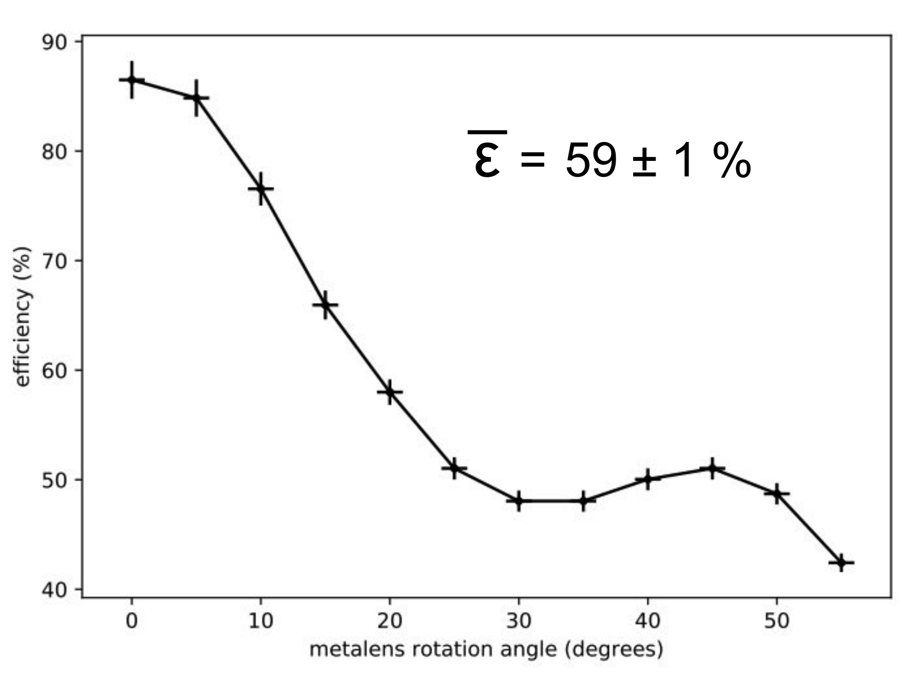
normal incidence efficiency



Angular efficiency results



angular efficiency

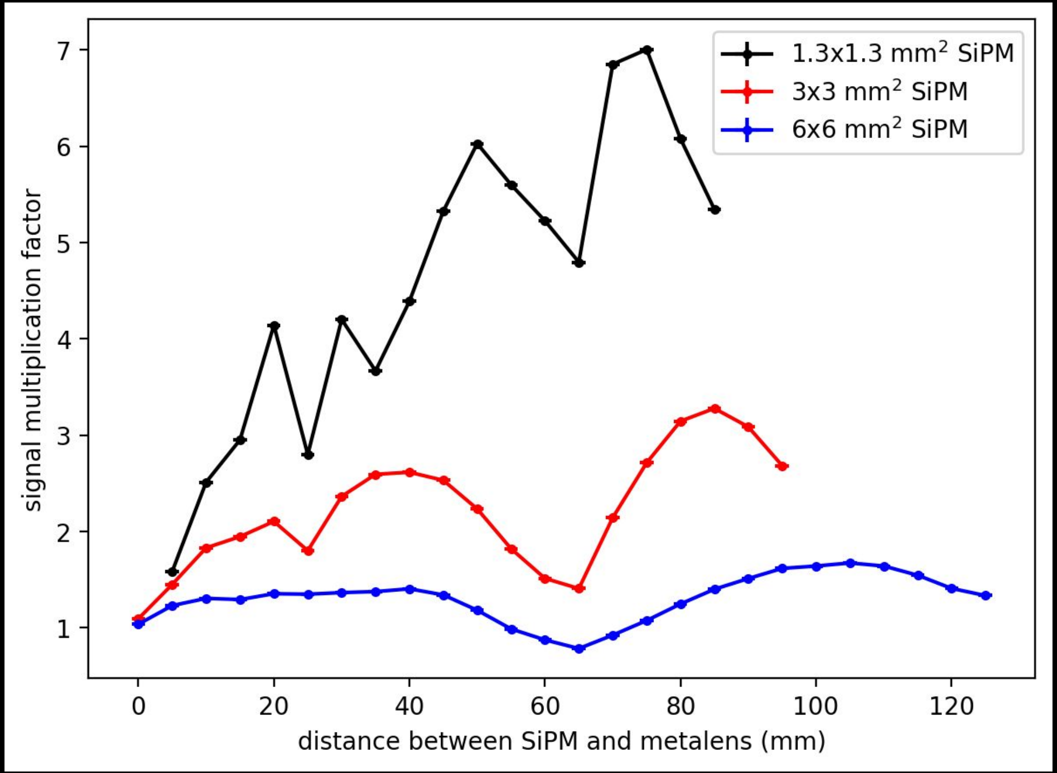


- **F**inite **D**istance **T**ime **D**oming (FDTD) simulation in progress

Signal increase

- signal multiplication factor = signal with metalens divided by signal without metalens
- signal increase improves with decreasing SiPM area
  - increased area coverage (metalens area/ SiPM area)

6-7X signal increase for smallest SiPM!



Conclusions and outlook

Conclusions

- Increasing light collection would benefit several experiments
- Metalenses are a practical and cost-effective solution
- Metalenses are most effective when coupled with SiPMs of small active area, providing an increase of 6-7X in light collection at ~630 nm
  - similar expected at ~430 nm

Outlook

- Detector optimization/ implementation
  - size/shape of metalenses
  - location and spacing of metalenses and SiPMs
  - saturation effects
  - low temperature performance
- Design and fabrication of metalenses
  - VUV (currently down to ~260 nm, wavelength shifting substrate, other nanomaterials)
  - converging foci to maximize light collection

Bonus Material

Metalens Equations

$$\varphi_{nf}(x,y) = \frac{2\pi}{\lambda_d}\left(f - \sqrt{x^2 + y^2 + f^2}\right)$$

$$\frac{d\phi}{dr} = \frac{N}{p} = \frac{2\pi}{\lambda_d}\sin\theta_N$$

$\Phi = \phi$ = phase profile

θ_N = deflection angle of N order

f = focal point N; N = 1,2,3,..

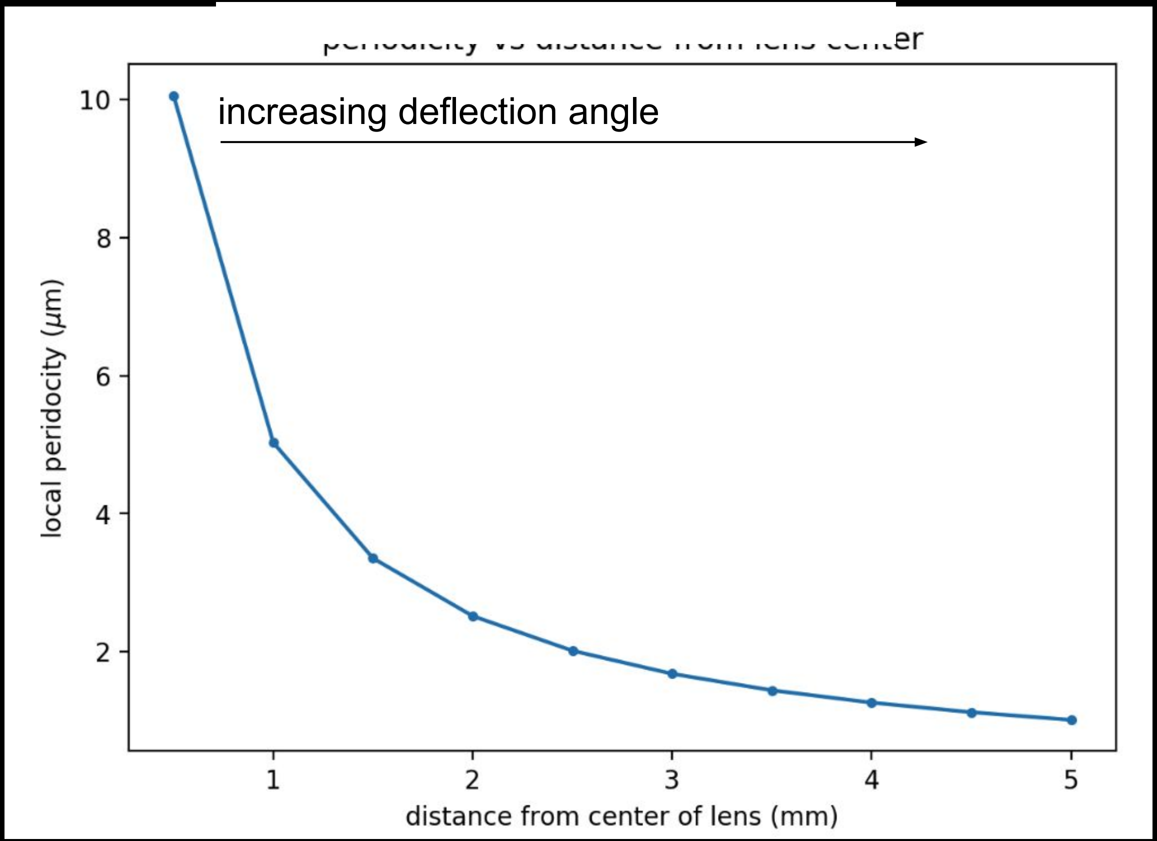
λ_d = design wavelength

p = local periodicity on metalens

Further details: Yu et al., Science **334**, 333 (2011)

Local periodicity of metalens

$$\gamma_{\vec{p}} \;\alpha\; \frac{1}{\text{periodicity}}$$



SEM image of nanofins
with 11um periodicity

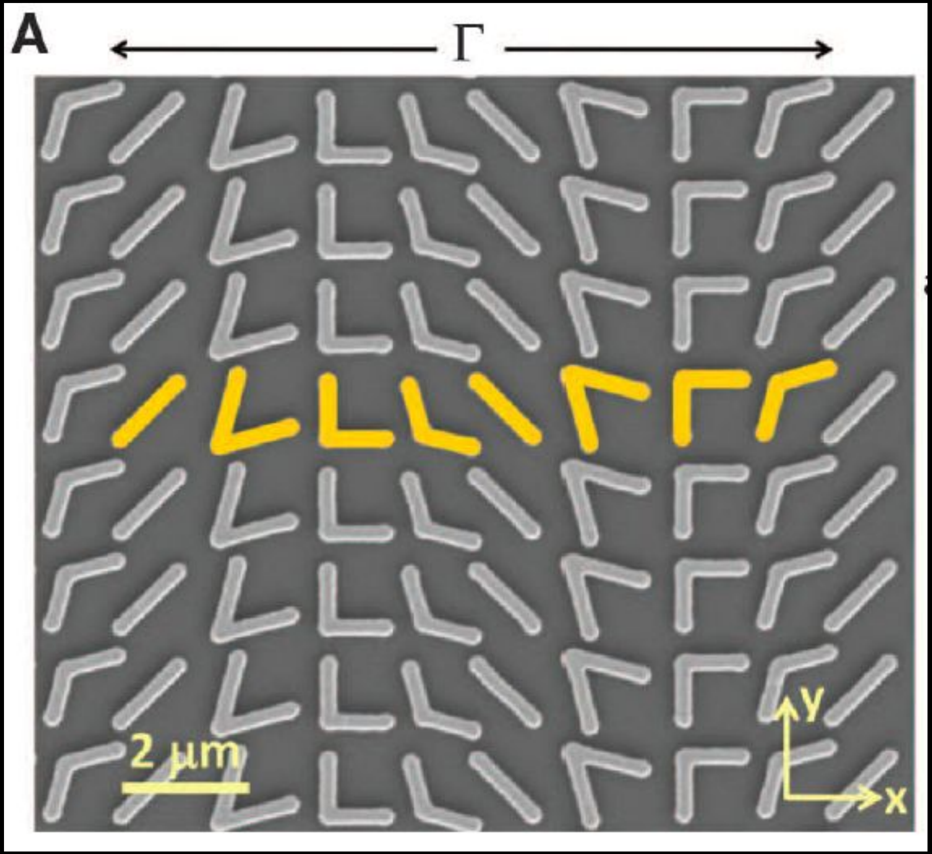


Image: Yu et al., Science **334**, 333 (2011)

Metalens vs ordinary lenses

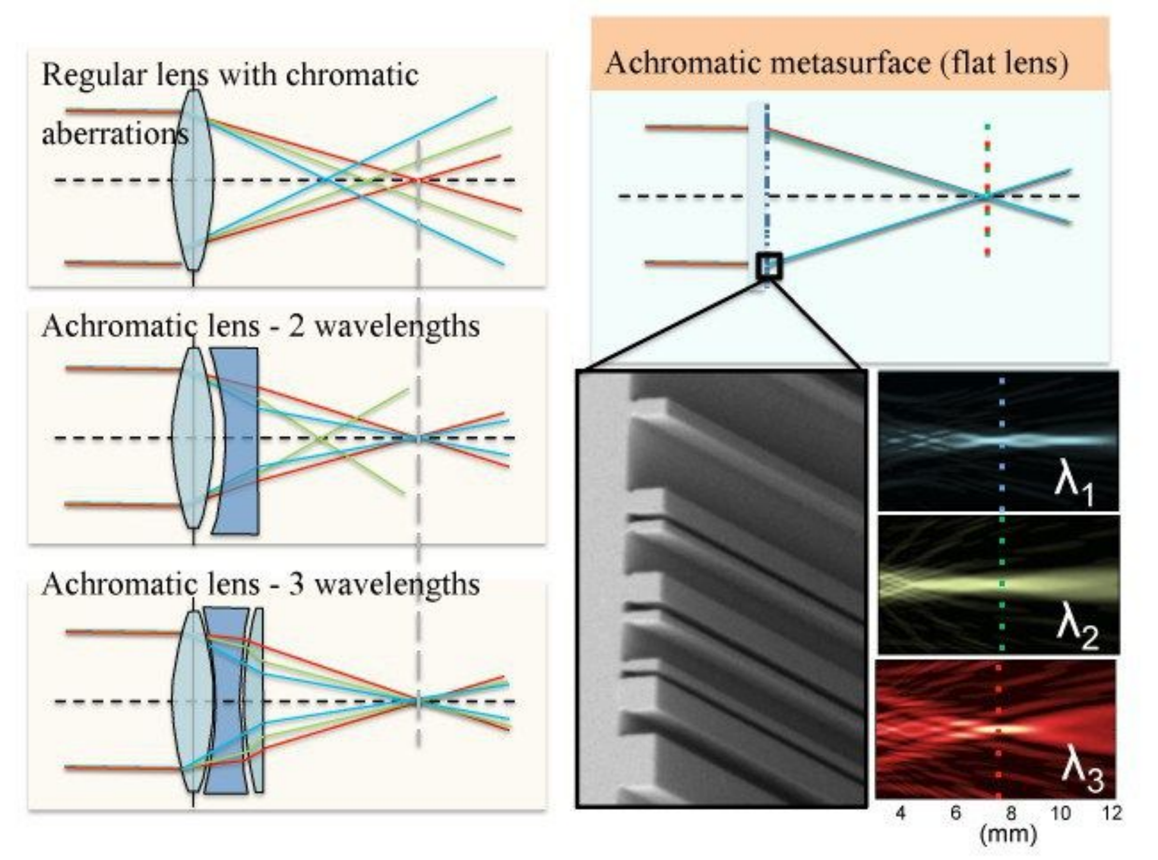
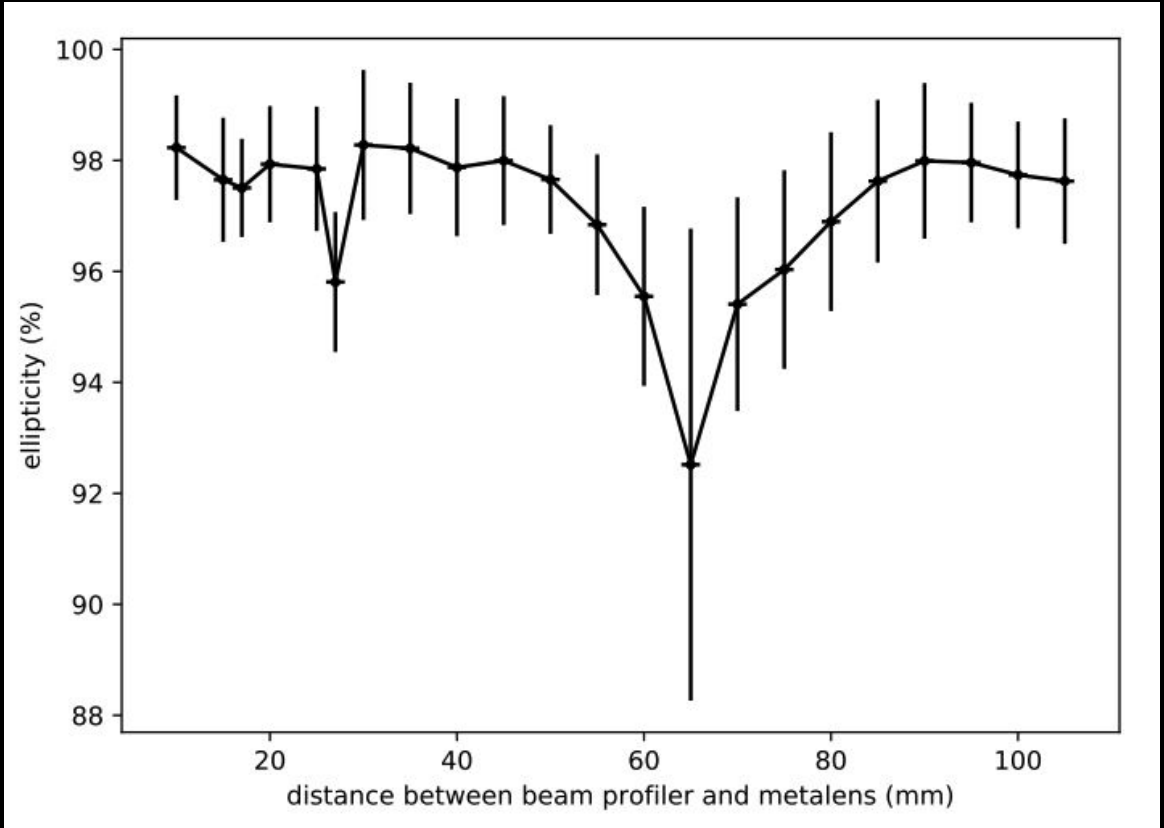


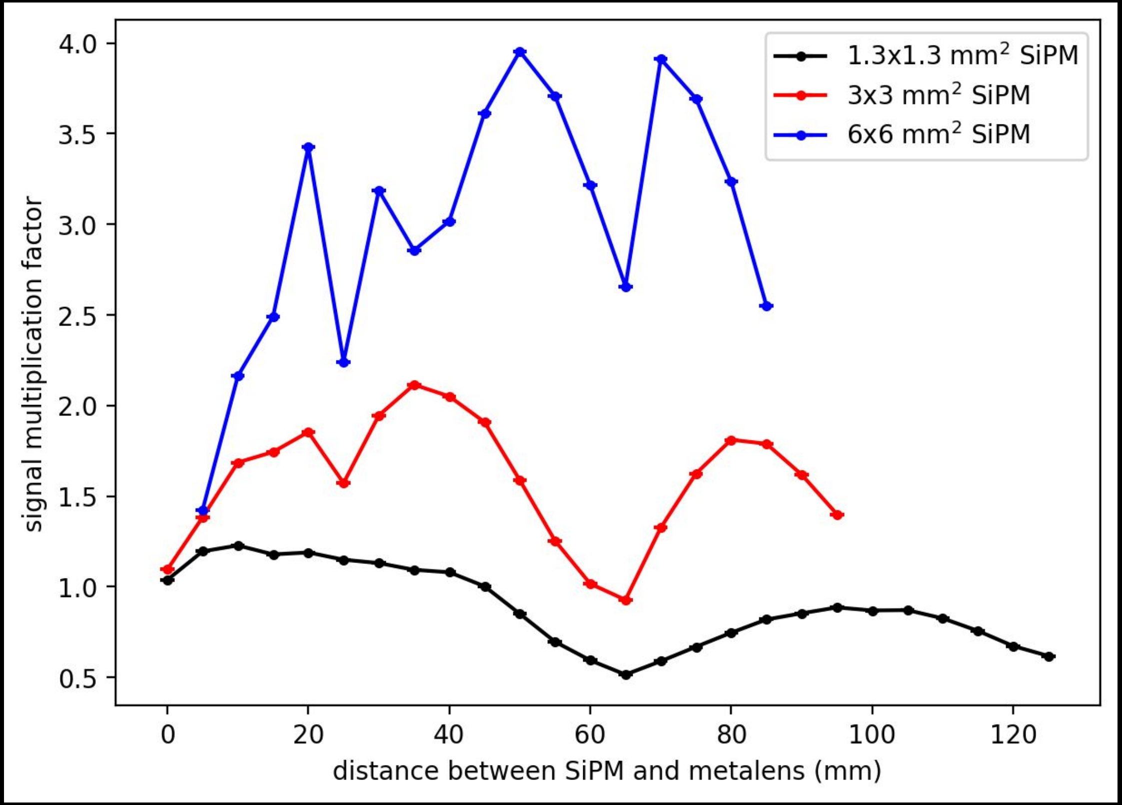
Image: [Laptop Media]

Image: roadtovr.com

Projected beam ellipticity



Signal increase dividing all signals with metalens by signal without metalens at metalens location



Light focused by metalenses