Enabling smart vision through meta-optics

Dragomir Neshev

ARC Centre of Excellence for Transformative Meta-Optical Systems (TMOS)
Research School of Physics
Australian National University
Canberra, Australia

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Australian National University

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Australian Research Council

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Enabling Smart Vision Through Meta-Optics

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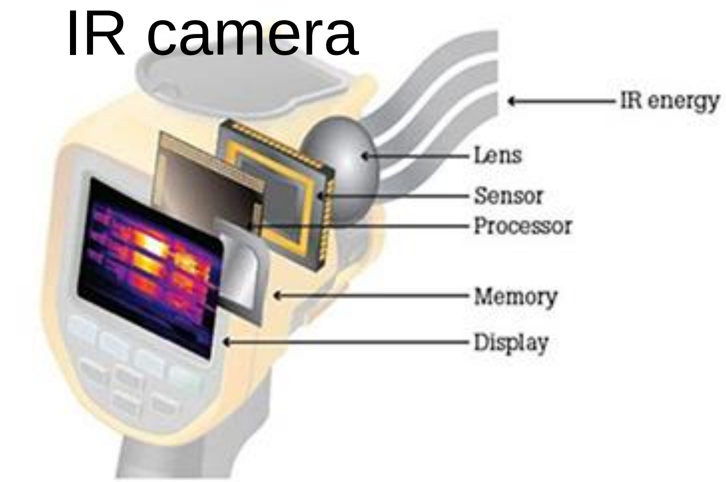
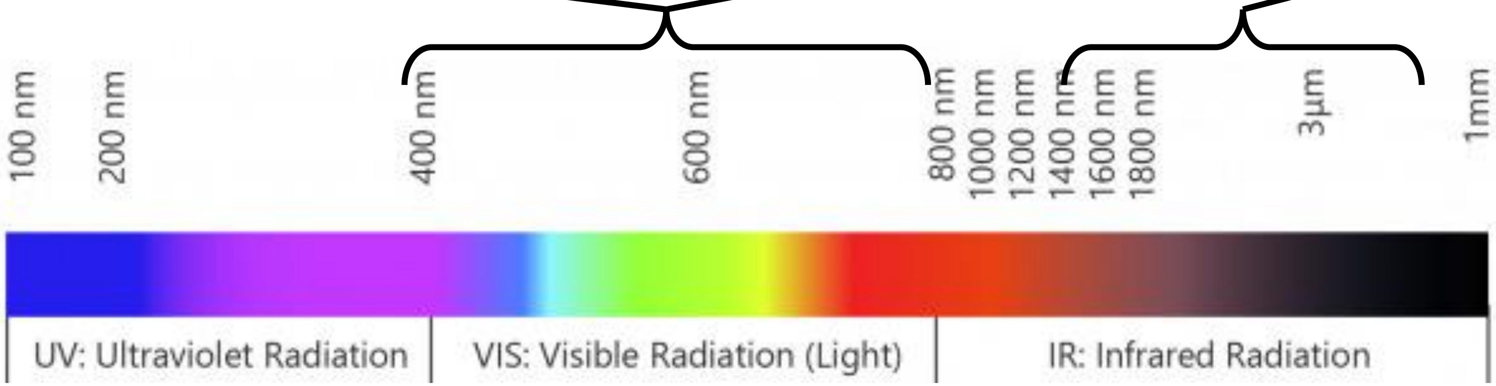
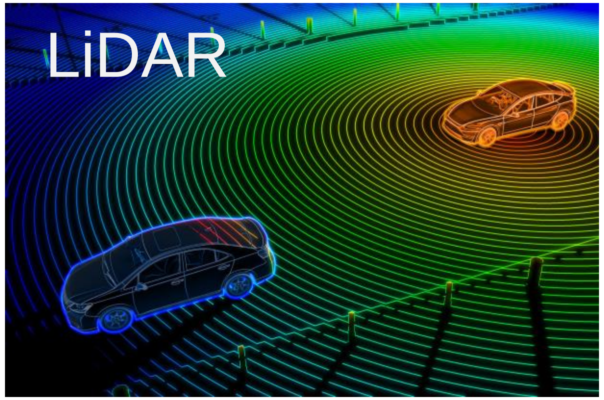
Australian National Fabrication Facility

Vision and vision systems



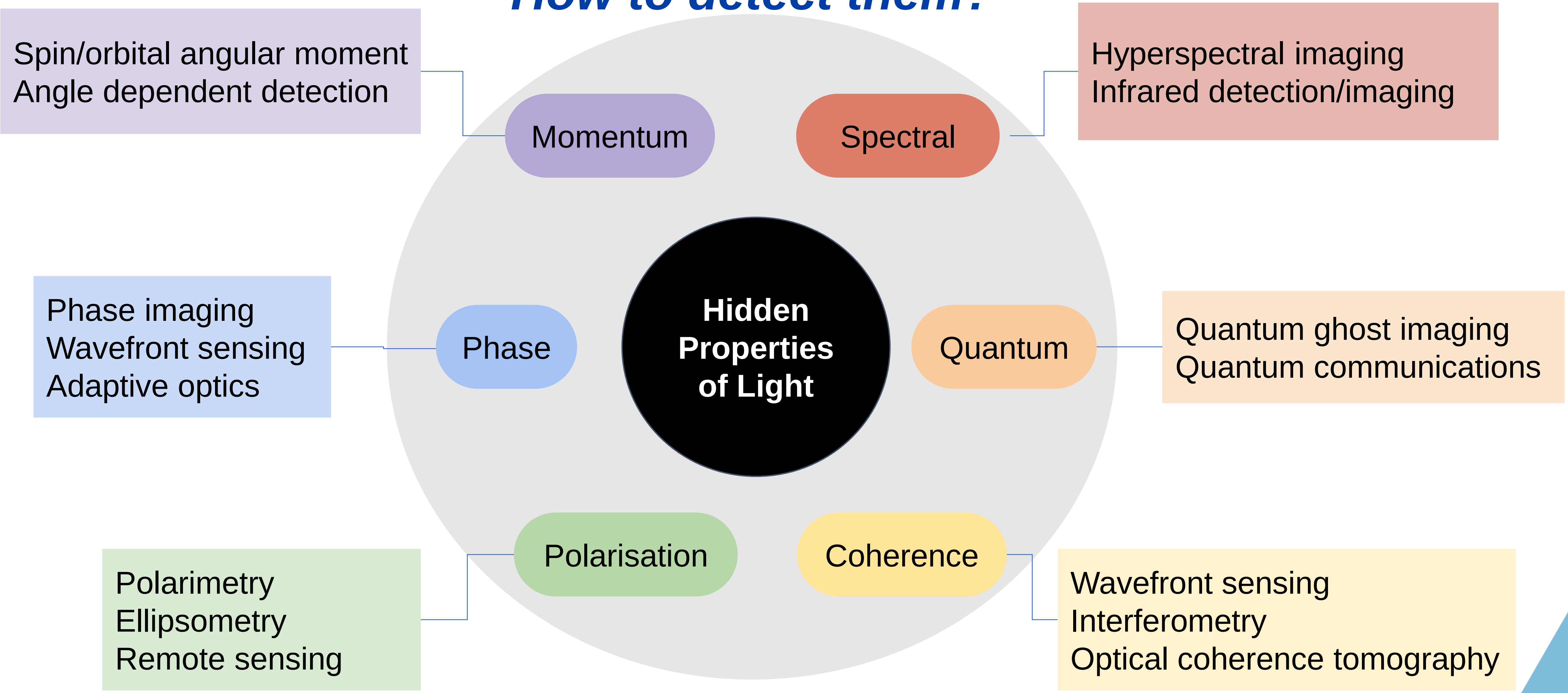




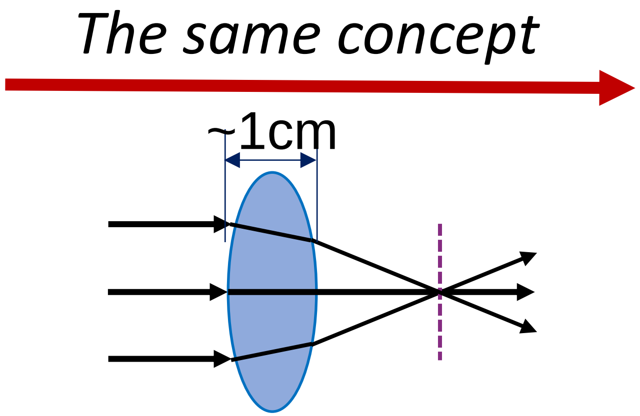
The available systems only measure intensity or timing

Hidden properties of light

How to detect them?



Replacing bulky glass optical elements

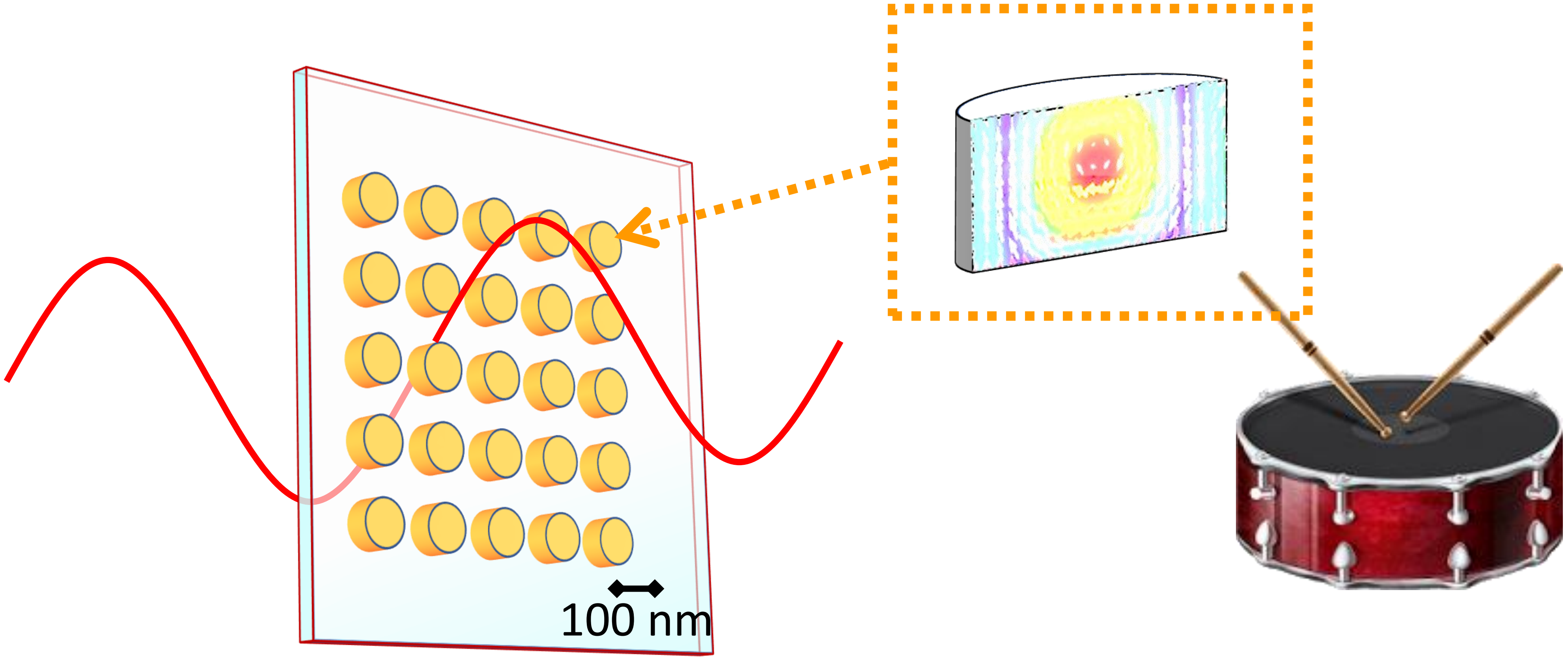


- The lens limits the thickness of OSs
- The number of lenses is limited

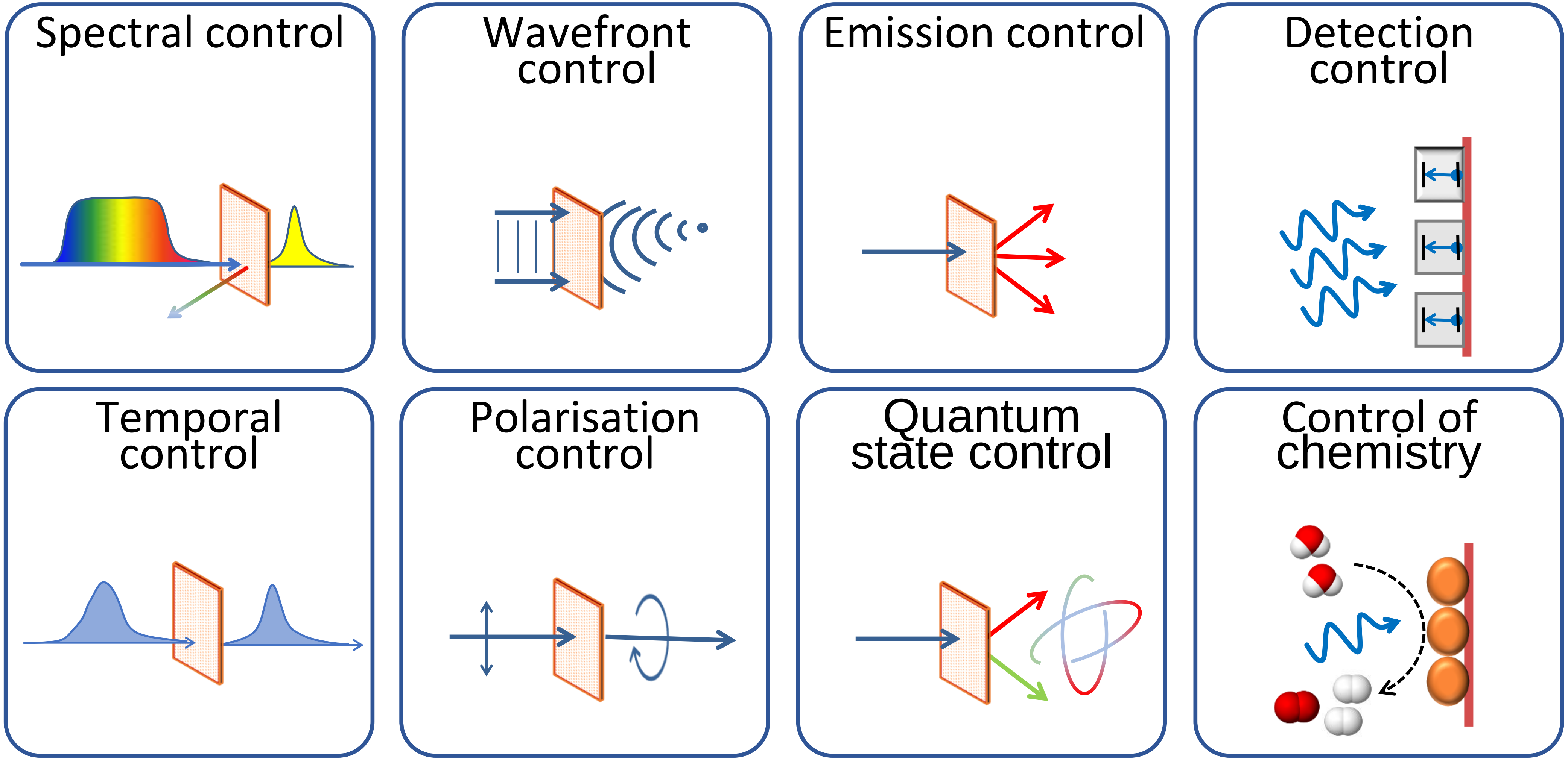
Metasurfaces can miniaturise optical components while adding new functionalities for detection of the hidden properties of light

Metasurfaces: driven by resonances

Metasurfaces are subwavelength arrays of nano-scale optical elements

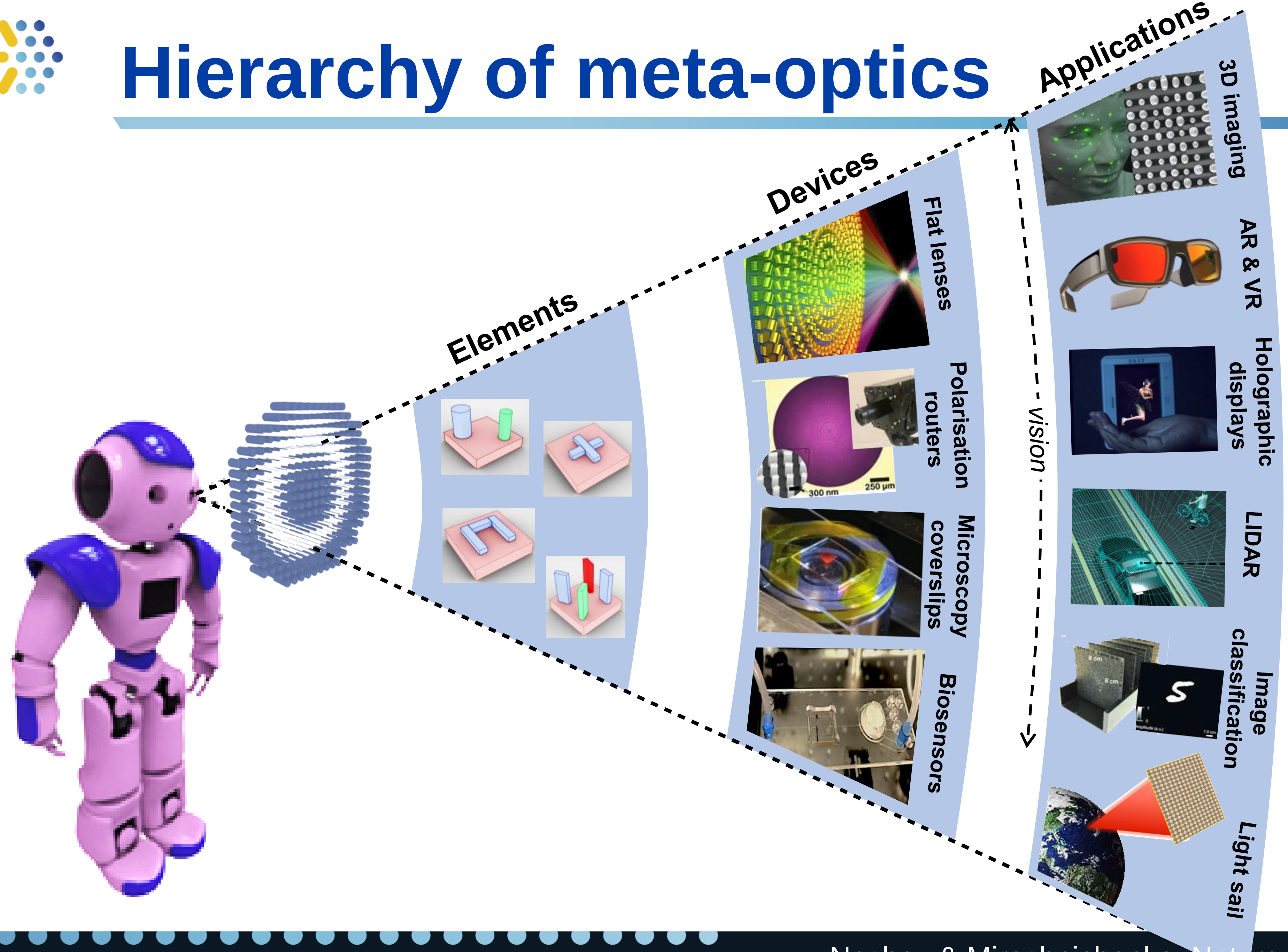


Functions of metasurface



Neshev & Miroshnichenko, Nature Photon. **17**, 26 (2023)

Hierarchy of meta-optics



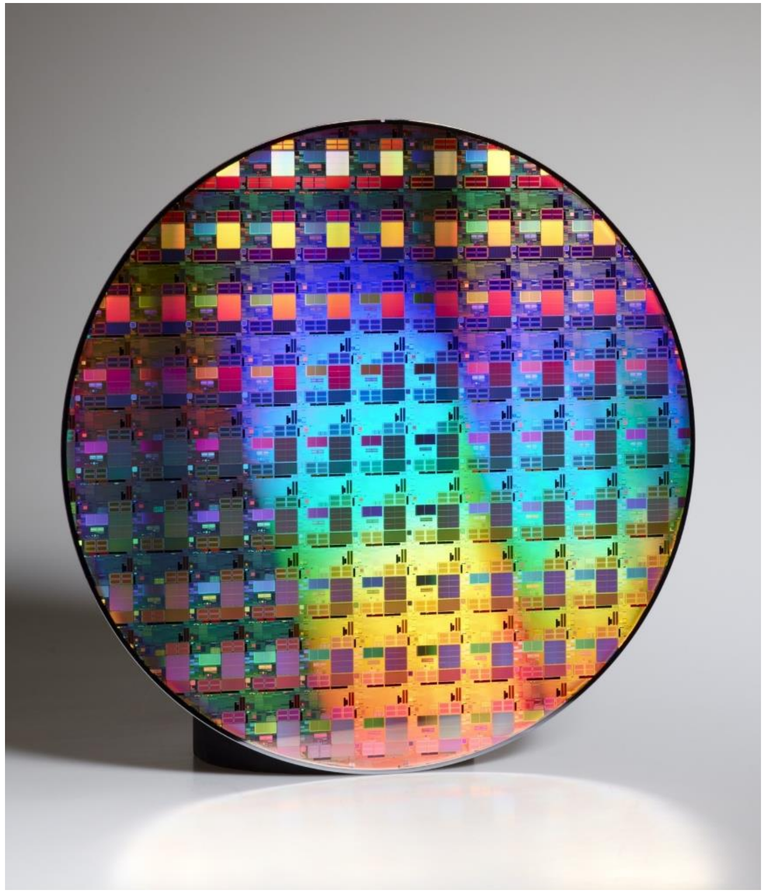
Industrial applications are expanding

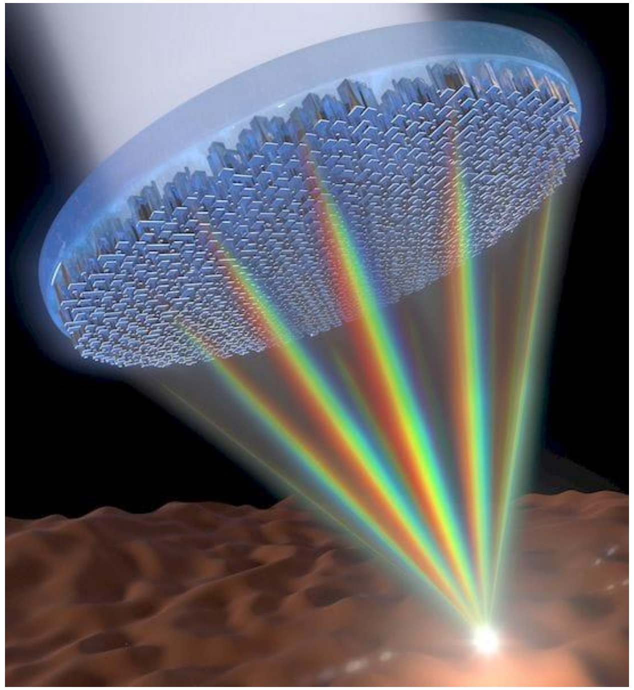
Most applications are vision related, free space optics

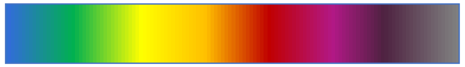
Neshev & Miroshnichenko, Nature Photon. **17**, 26 (2023)

Merging optics and chip-making

***Fabrication of metasurfaces** is compatible and similar to chip making – planar nanofabrication*

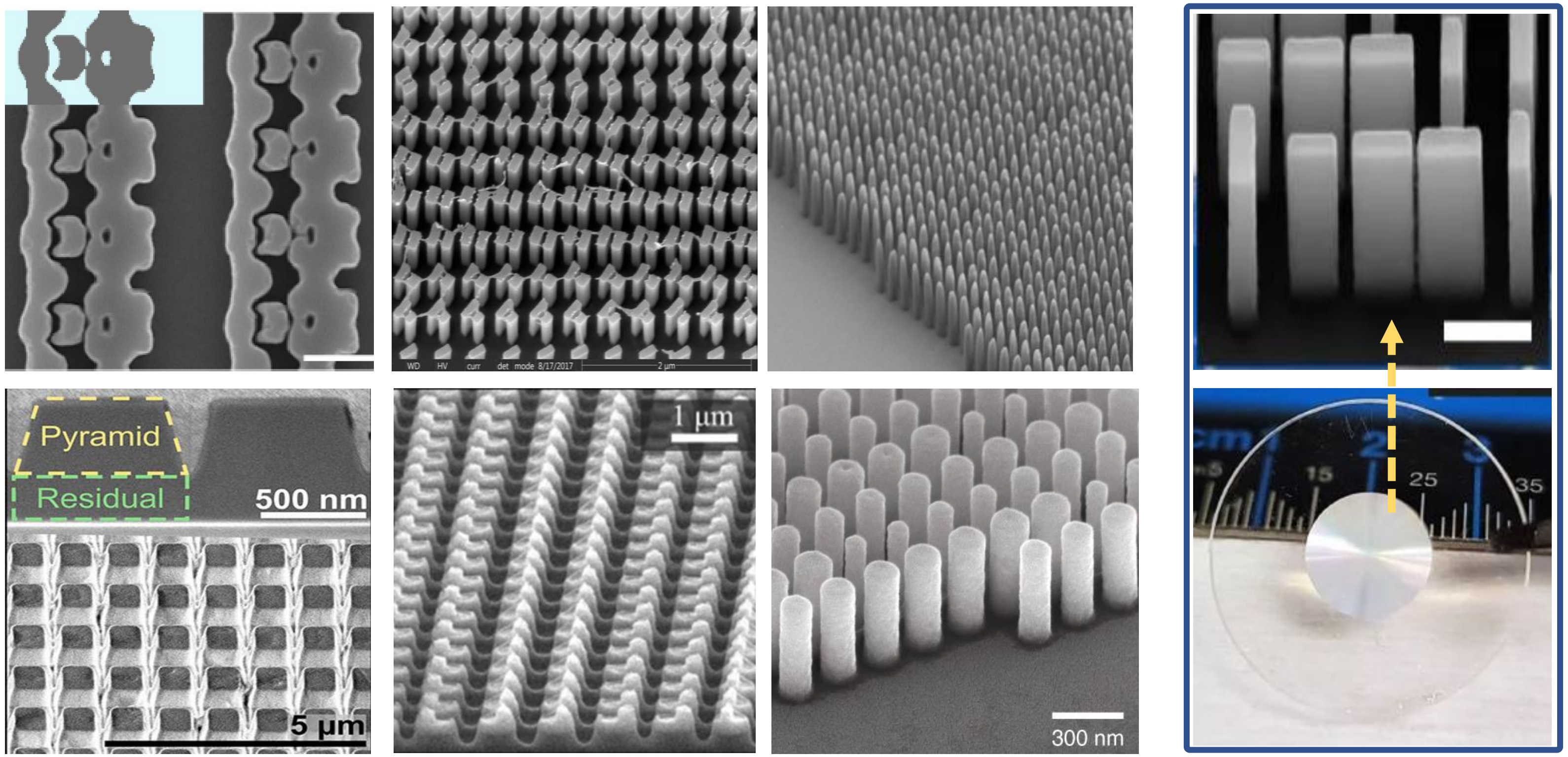






Chen *et al.*, Nature Nanotech. 13, 220 (2018)

Meta-optical elements



$LiNbO_3$ GaAs HfO TiO_2

Metasurfaces of different geometries and different materials

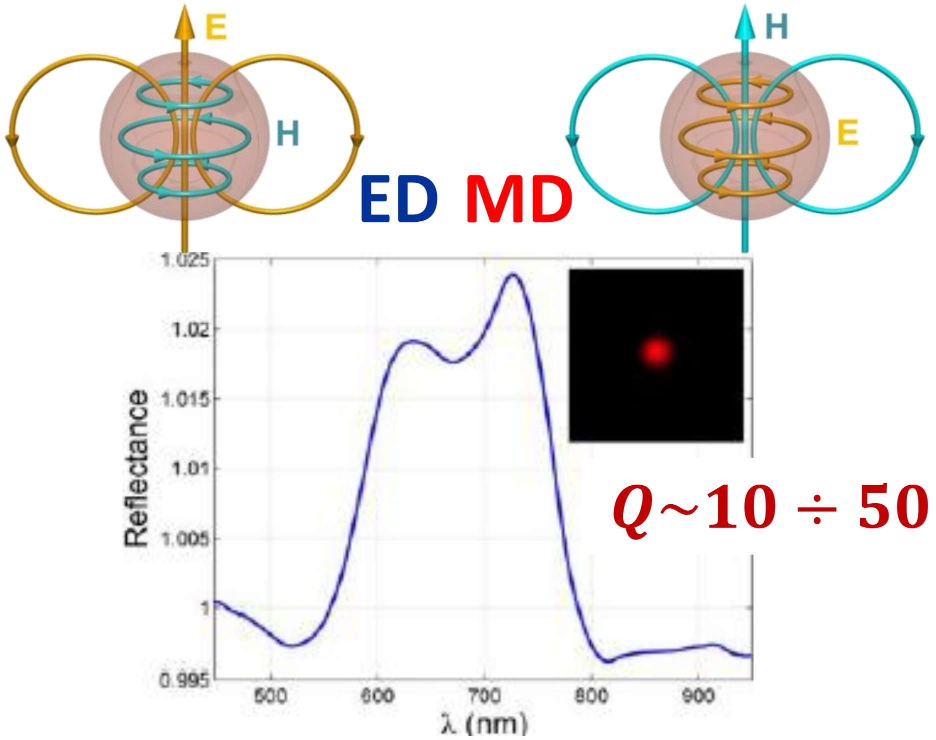
From realism to sur-realism and different materials

Resonances in metasurfaces

localised resonances

Mie-type resonances

localised resonances



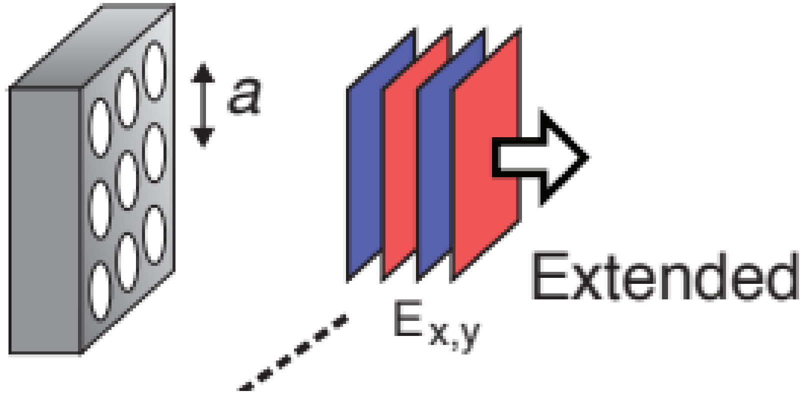
$Q \sim 10 \div 50$

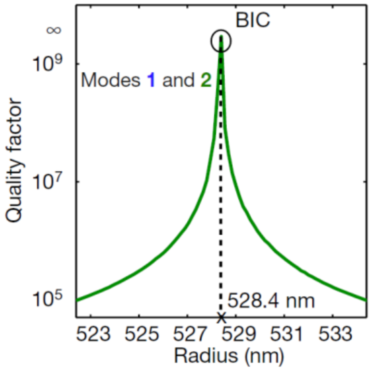
Evlyukhin *et al.*, *Nano Lett.* **12**, 3749 (2012)
Kuznetsov *et al.*, Sci. Rep. **2**, 492 (2012)

lattice resonances

Bound state in the continuum (BIC)

lattice resonances





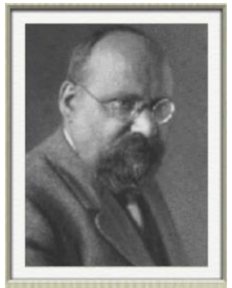
$Q \sim 100 \div 10,000$

Hsu, *et al., Nat. Rev. Mat.*, **1**, 16048, (2016)

Mie resonances in dielectric particles

Light scattering by nanoparticles

Electric type Magnetic type

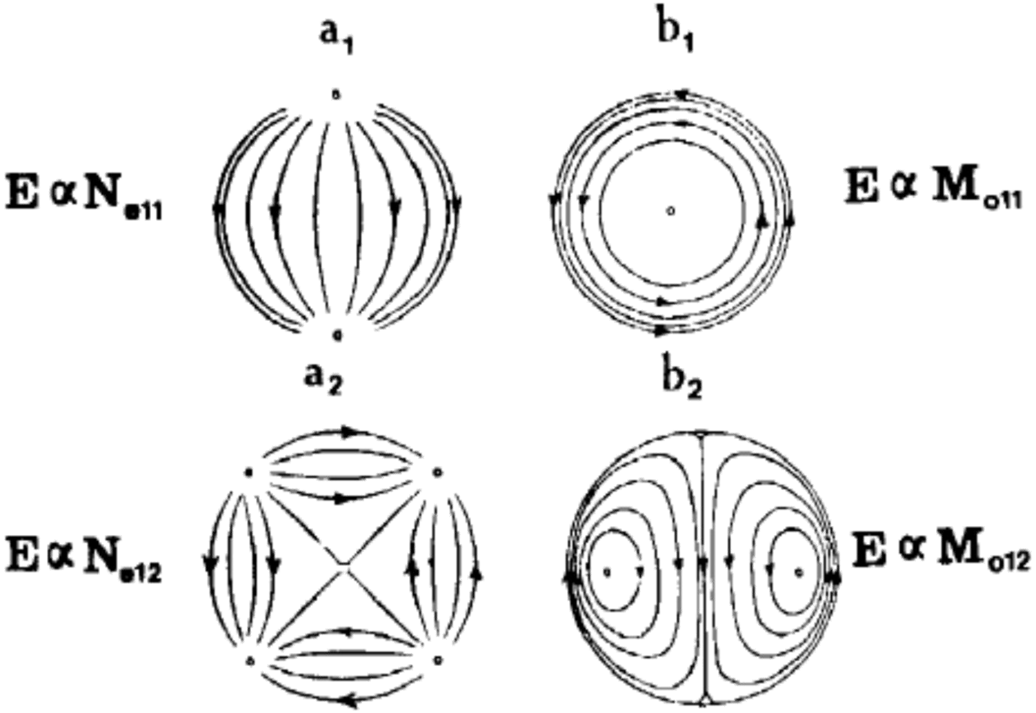


Gustav Mie

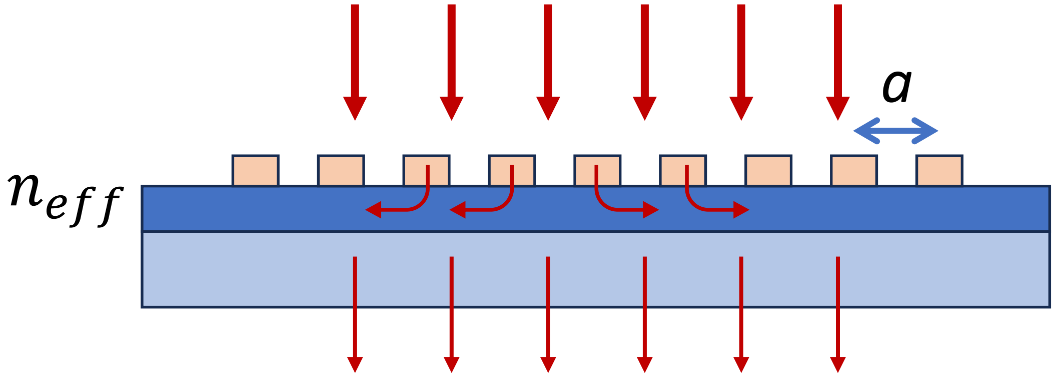
G. Mie, Ann. Phys. **25**, 377 (1908)

$$Q_{sca} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)(|a_n|^2 + |b_n|^2)$$

$$Q_{ext} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)Re(a_n + b_n)$$



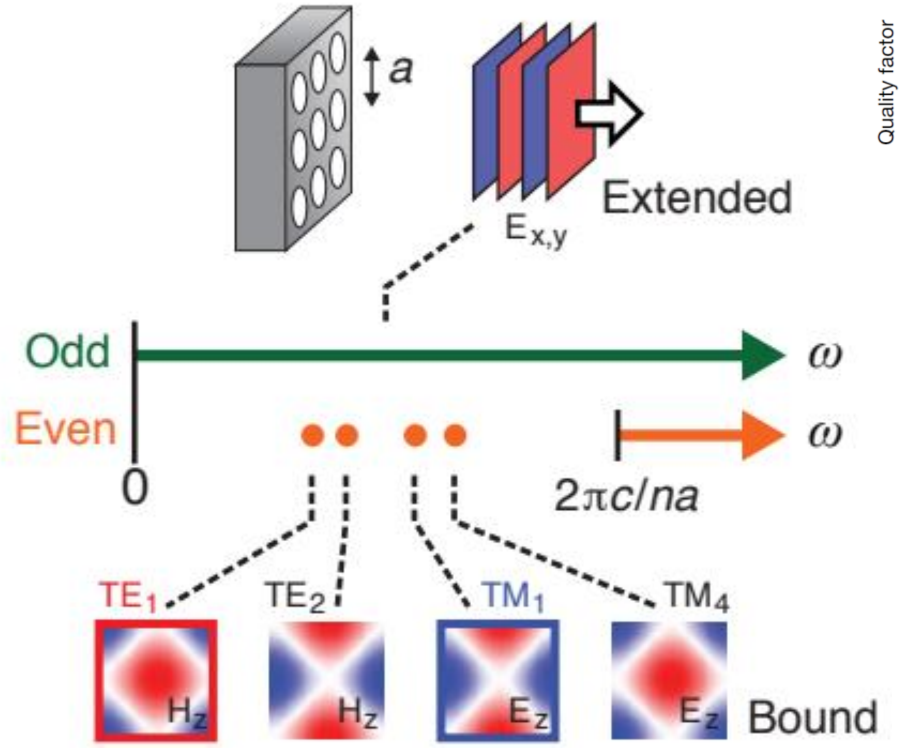
Lattice resonances in metasurfaces

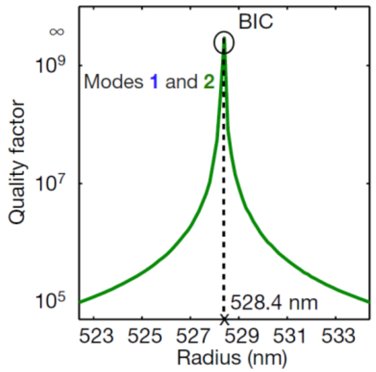


$$\frac{2\pi}{\lambda} n_{eff} = \frac{2\pi}{a}$$

waveguide mode resonance

Bound state in the continuum (BIC)



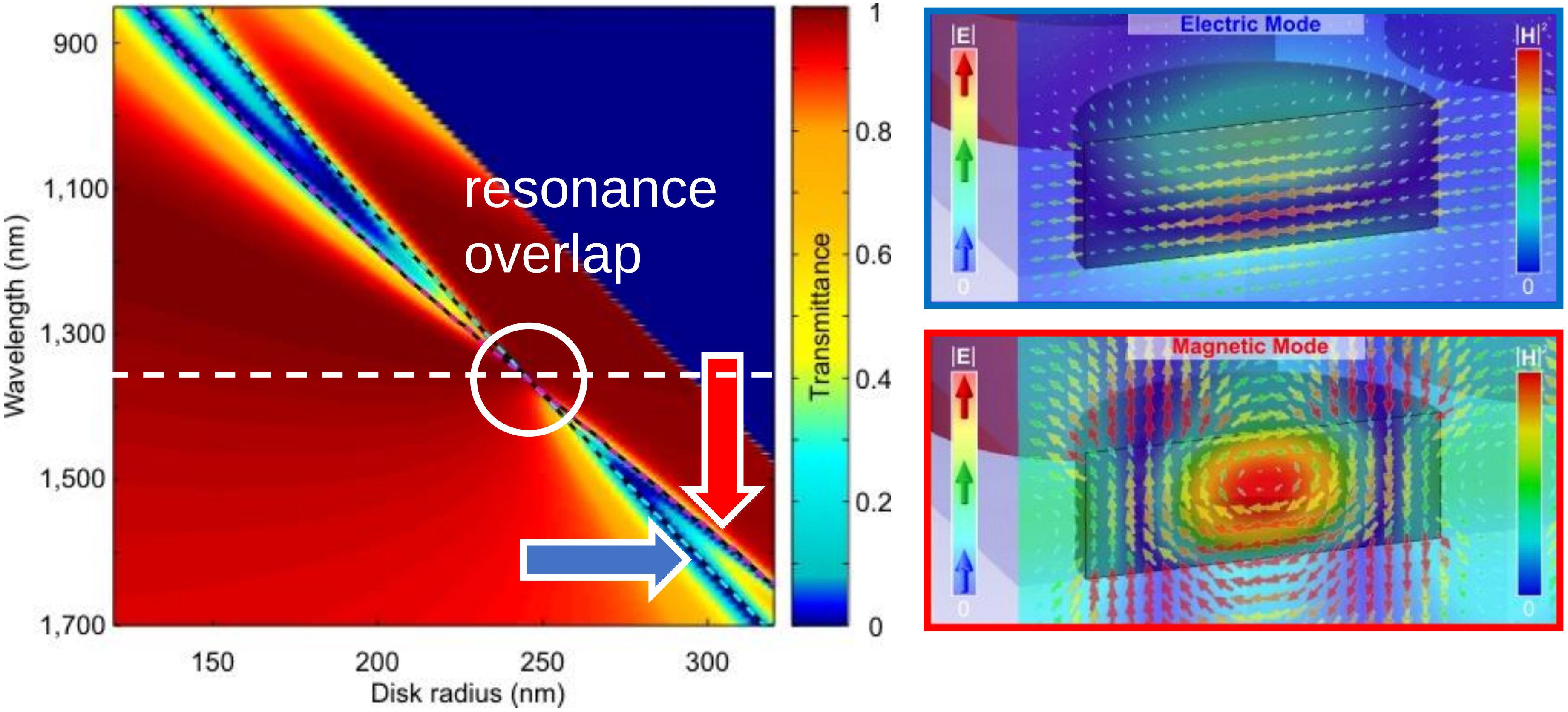


$Q \sim 100 \div 10{,}000$

Hsu, *et al.*, *Nat. Rev. Mat.*, **1**, 16048, (2016)

E&M resonances in dielectric MSs

Silicon nanodisk metasurface (h = 220 nm, variable radius) in n = 1.66 medium.



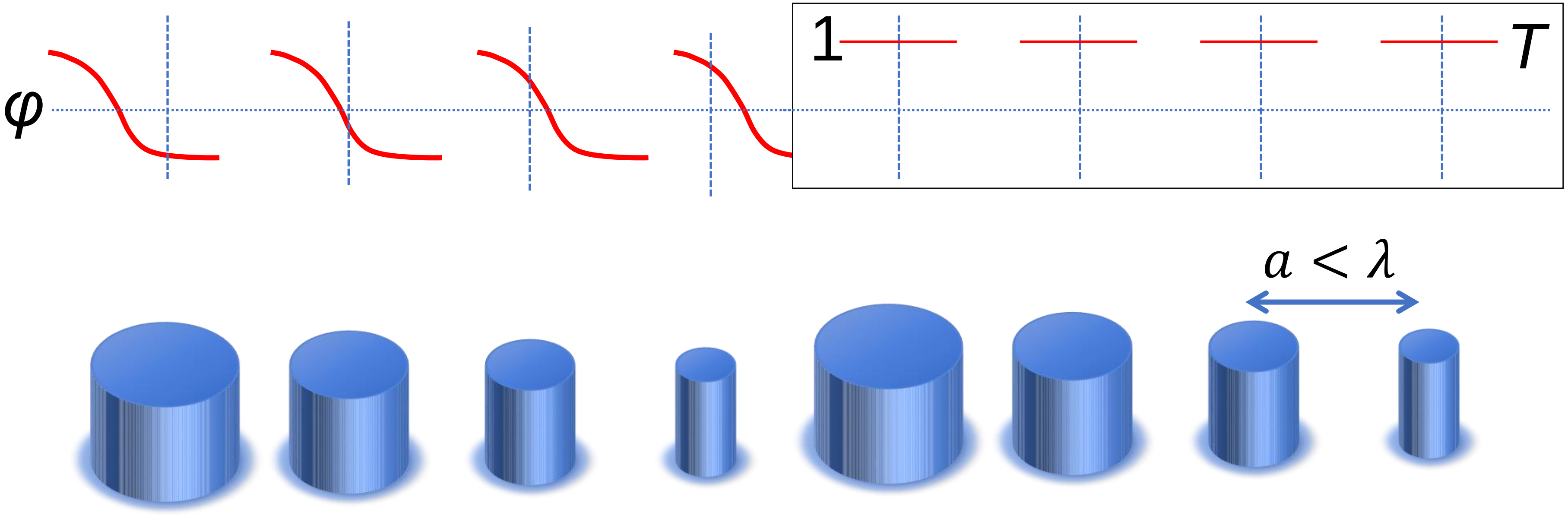
- Complete crossing of electric and magnetic resonances is achieved (Huygens condition)
- Transmittance becomes unity for resonance overlap

Decker *et al*., Adv Opt Mat **13**, 813-820 (2015)

Phase encoding by size scaling

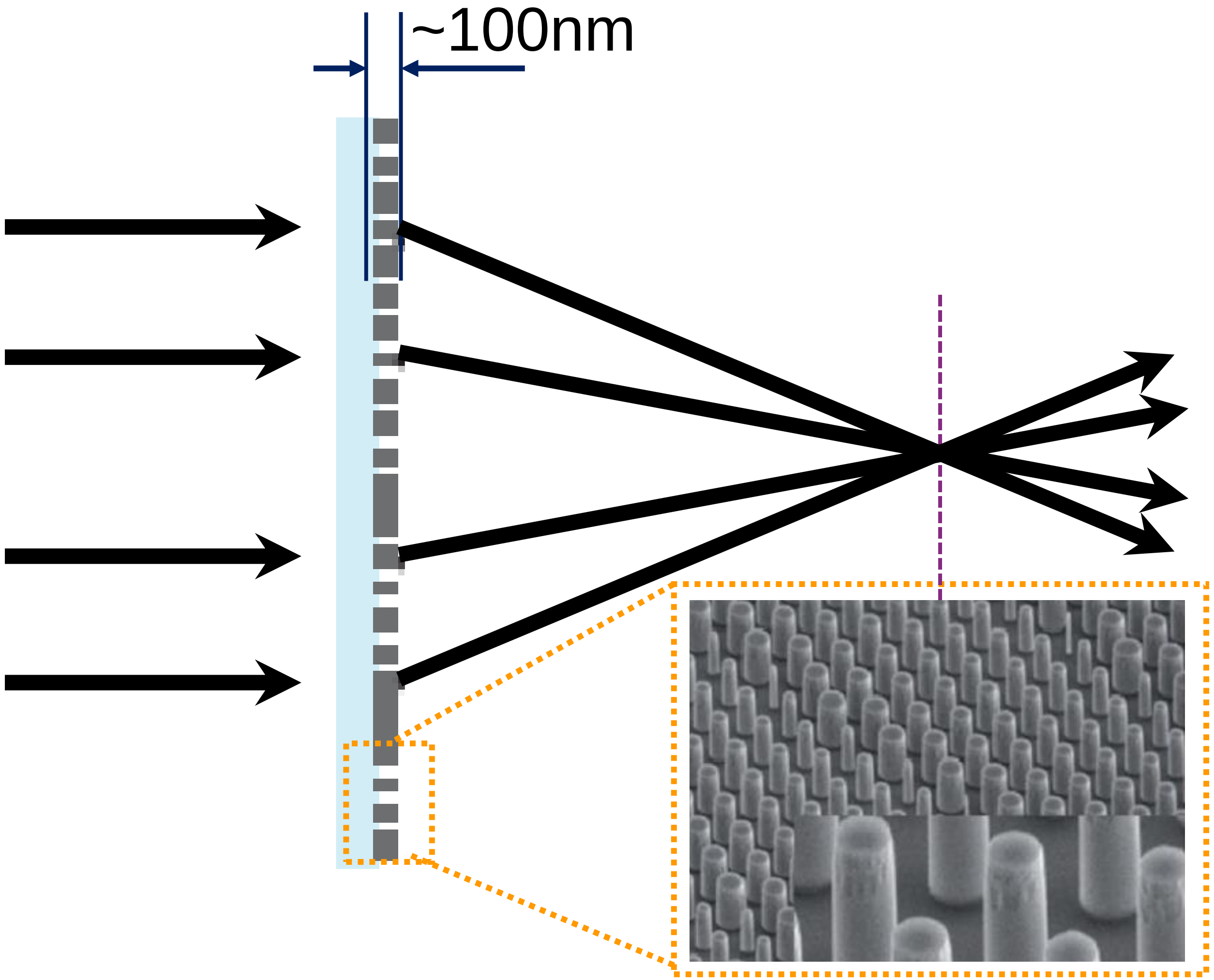
Phase encoding (in x and y) by varying the size at Huygens condition

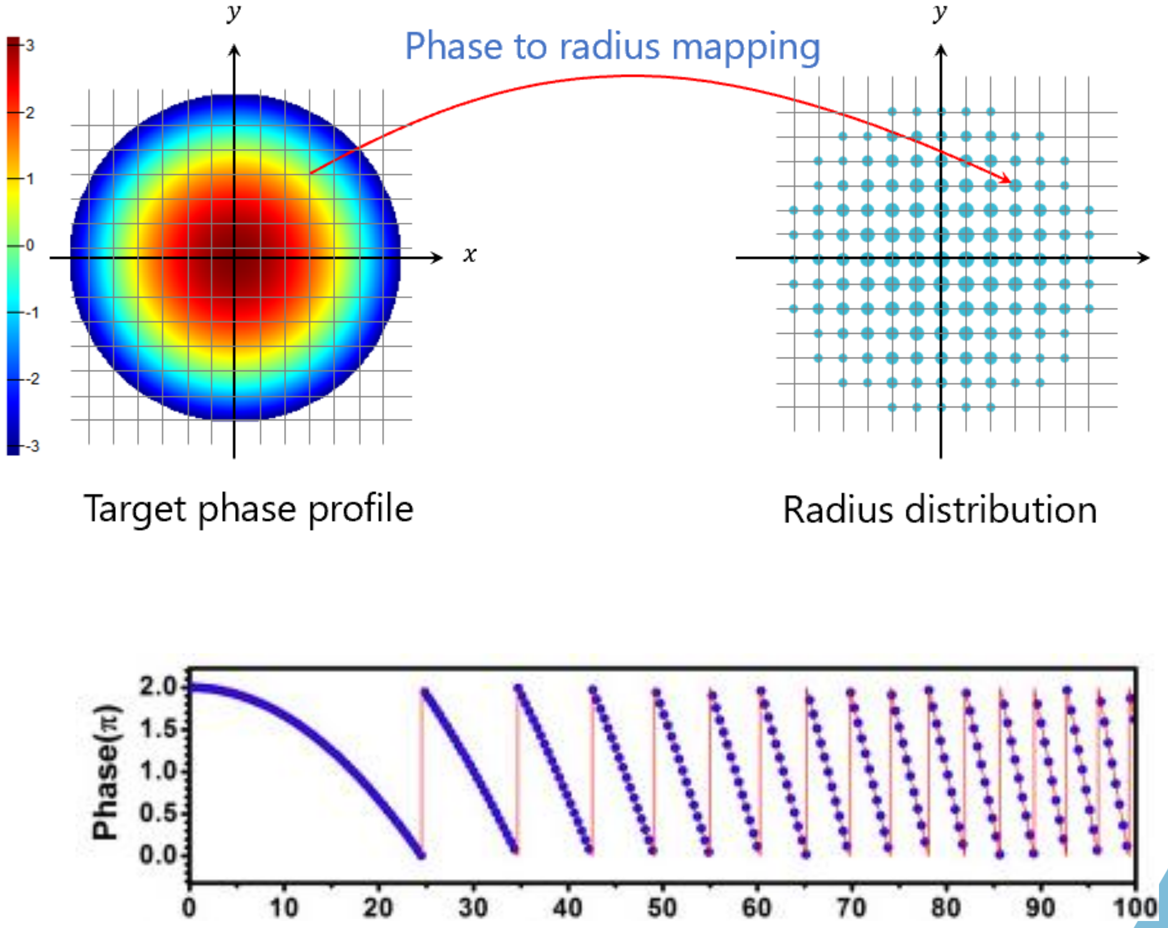
Fixed height



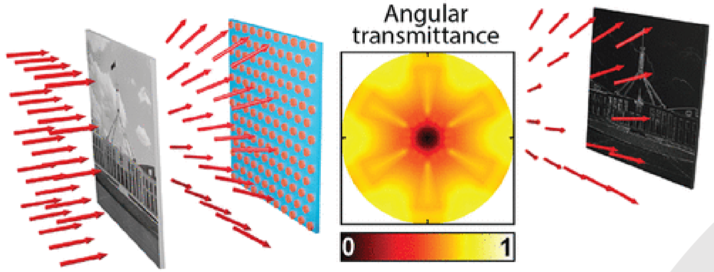
Can encode any phase profile with high transmission

Meta-lens design

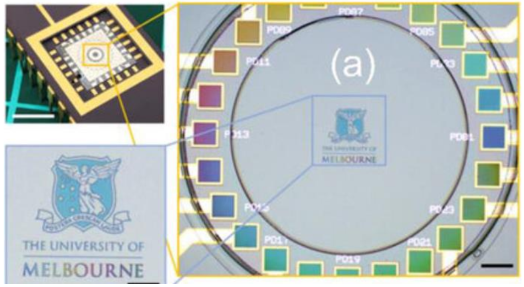




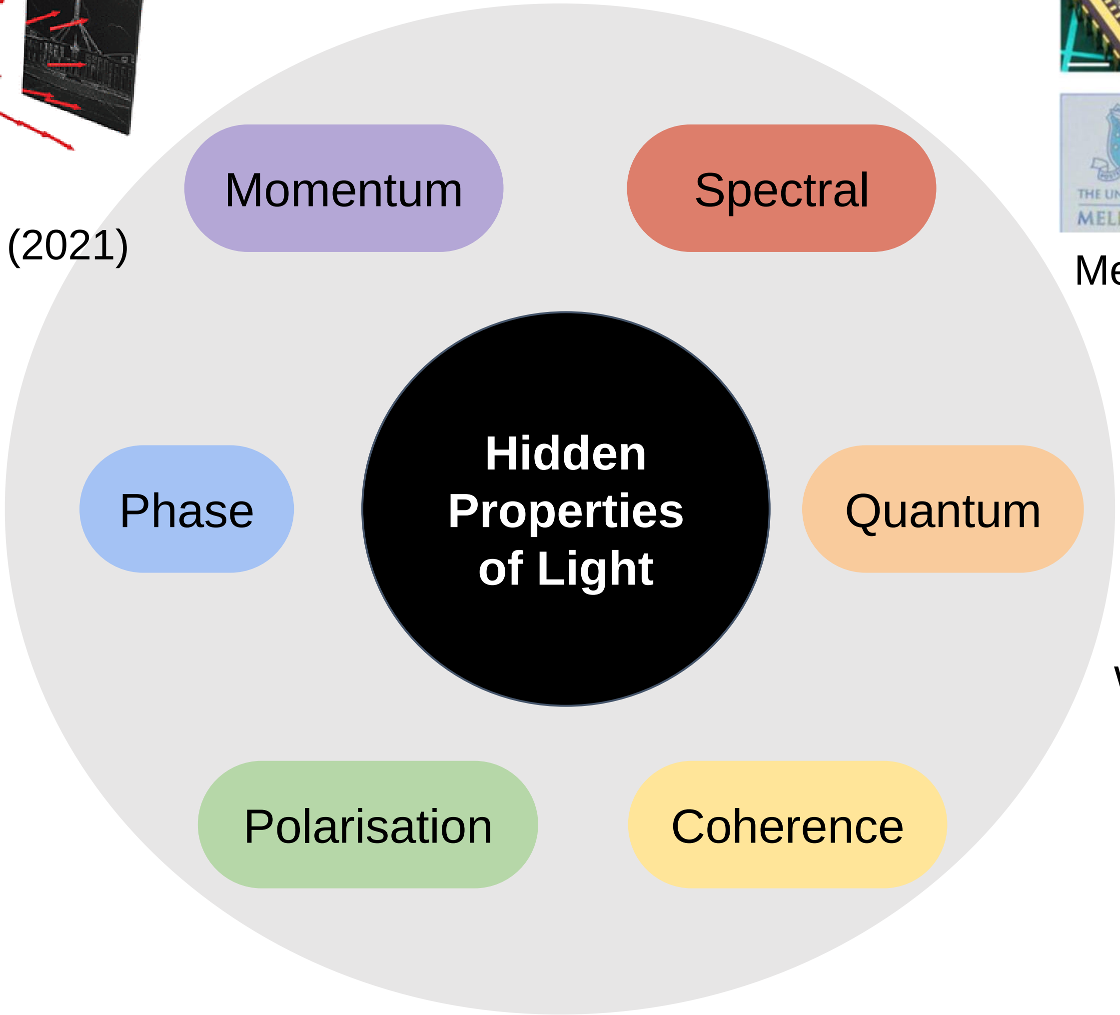
Detection of hidden properties of light

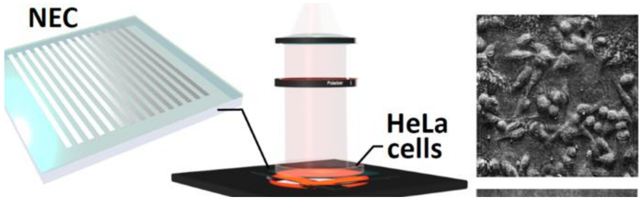


Komar *et al.*, ACS Photon. 8, 864 (2021)

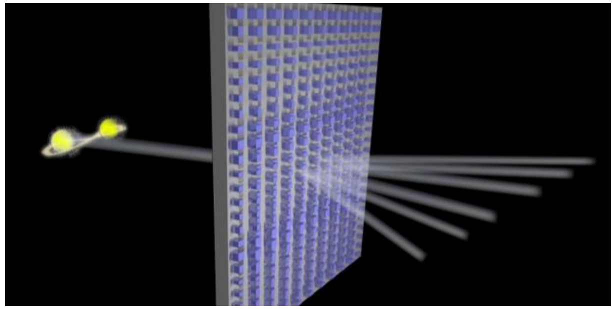


Meng *et al*. Nano Lett 20, 320 (2020)

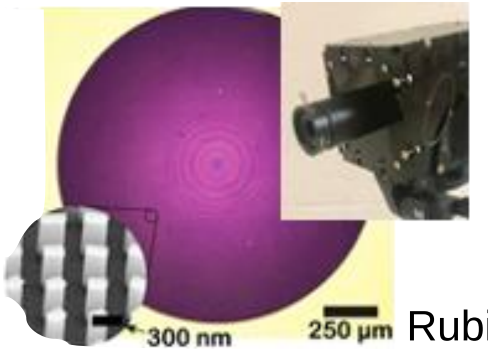




Wesemann *et al.*, Light Sci Appl 10, 98 (2021)



Wang *et al.*, Science 361, 1104 (2018)

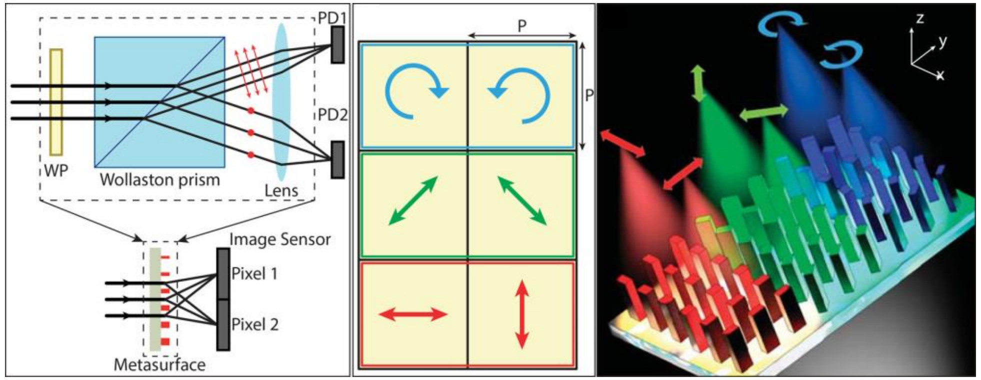


Rubin *et al.* Science 365, 1839 (2019)

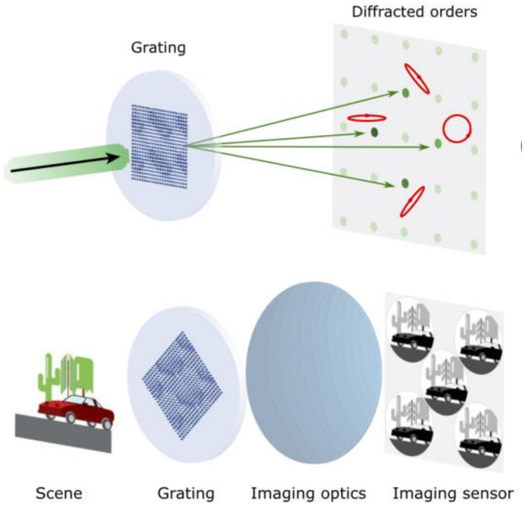
Polarisation imaging for Earth observations

Metasurface polarisation imaging

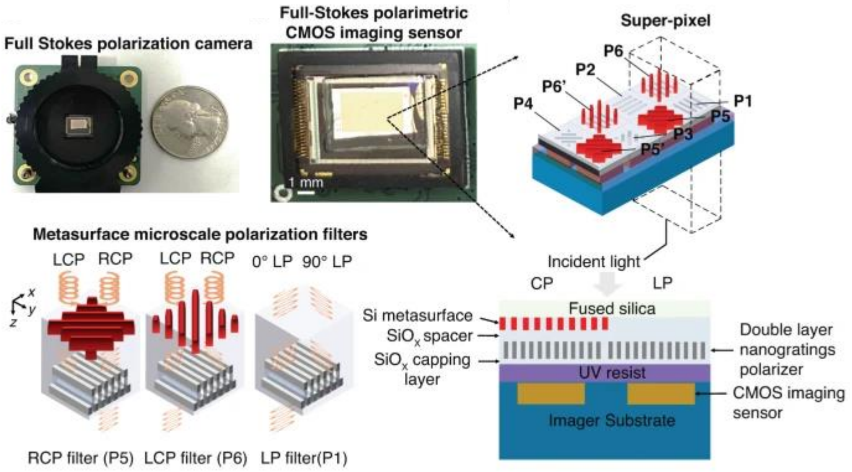
Single-shot polarisation imaging: Capasso (Harvard), Faraon (Caltech), etc.



E. Arabi et. al 2018 (Faraon Group)
https://doi.org/10.1021/acsphotonics.8b00362



N. A. Rubin et al (Capasso Group)
https://doi.org/10.1364/OE.450941



J. Zuo et. al. 2023 (MetaPolarIm)
https://doi.org/10.1038/s41377-023-01260-w

Remote sensing requires additional considerations for satellite movement and field-of-view, low-light imaging, and error accumulation

Polarisation remote sensing

Original

Filtered

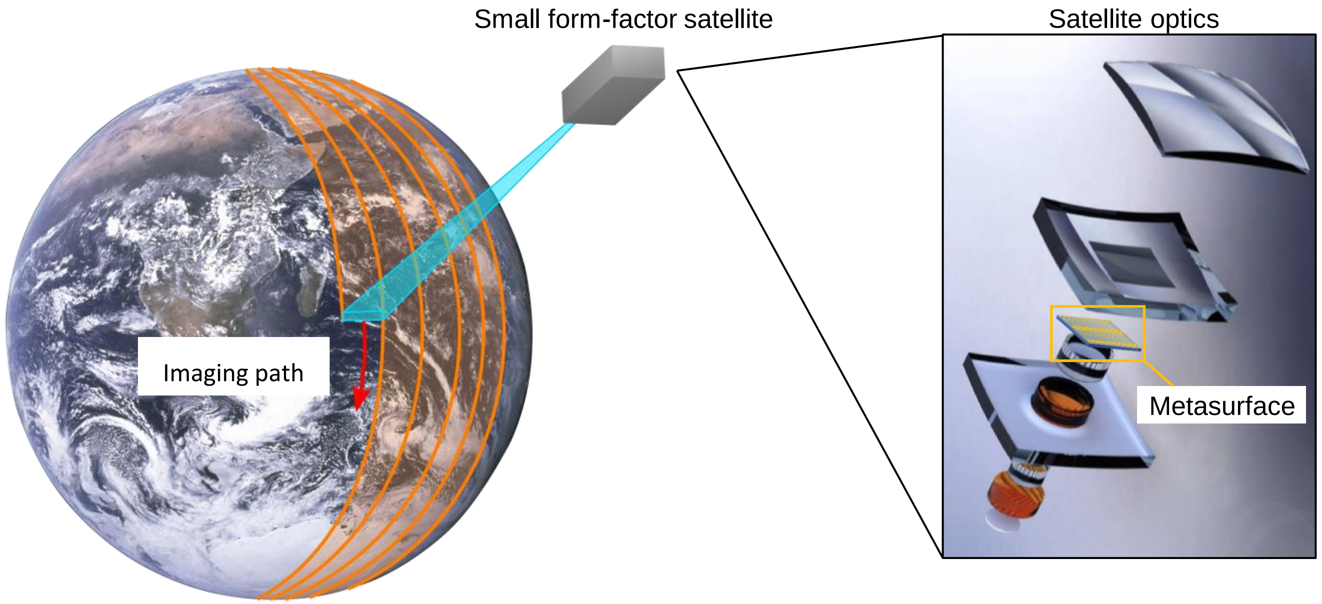
Image: Tektonex https://www.tektonex.com/capabilities/

Image: Polarizing filter (photography). (2021, December 19).
In Wikipedia. https://en.wikipedia.org/wiki/Polarizing_filter_(photography)

- Filtering or extracting water reflections from an image
- Detecting chiral organic aerosols

Polarisation Remote Sensing

In orbiting satellites, we can take advantage of the satellite movement:
a narrow imaging strip is used to form a complete image over time.



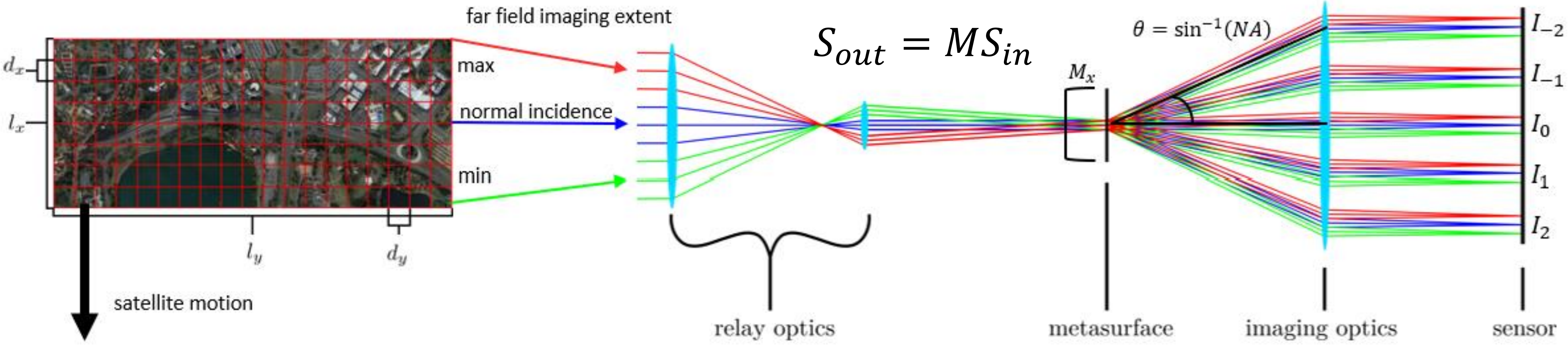
Full-Stokes imaging optics is bulky and heavy, often with moving parts, unsuitable for small form-factor satellites

A metasurface can be placed within an existing small-satellite imaging system, allowing for full polarisation imaging

Images: NASA, image ID AS17-148-22727; Rob Sharp, CHICO hyperspectral sensor.

Satellite imaging design

Metasurface diffracting in one dimension can form polarisation measurements of the imaging strip without losing light to filtering and efficiently using the sensor space

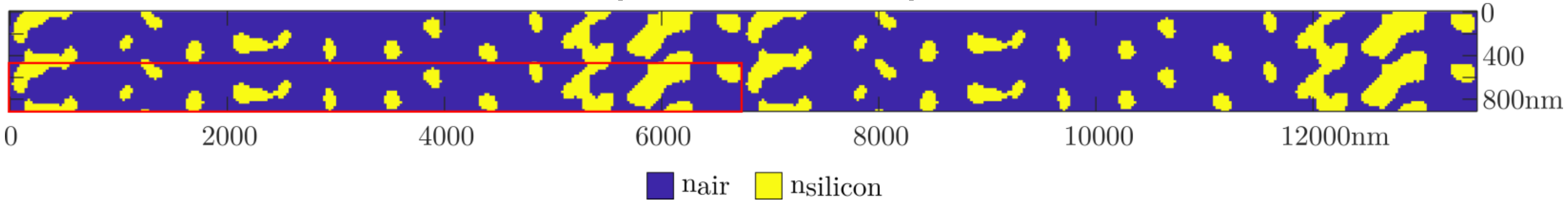


Four polarisation measurements are required to reconstruct the full Stokes polarisation state.

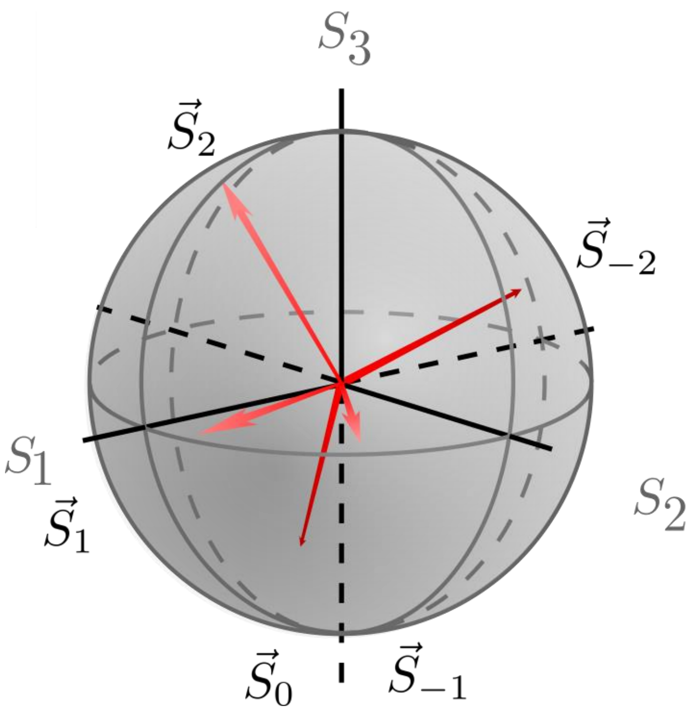
Five measurements allow multiple reconstructions for error monitoring.

Metasurface inverse design (topology optimisation)

840-850nm avoids atmospheric absorption

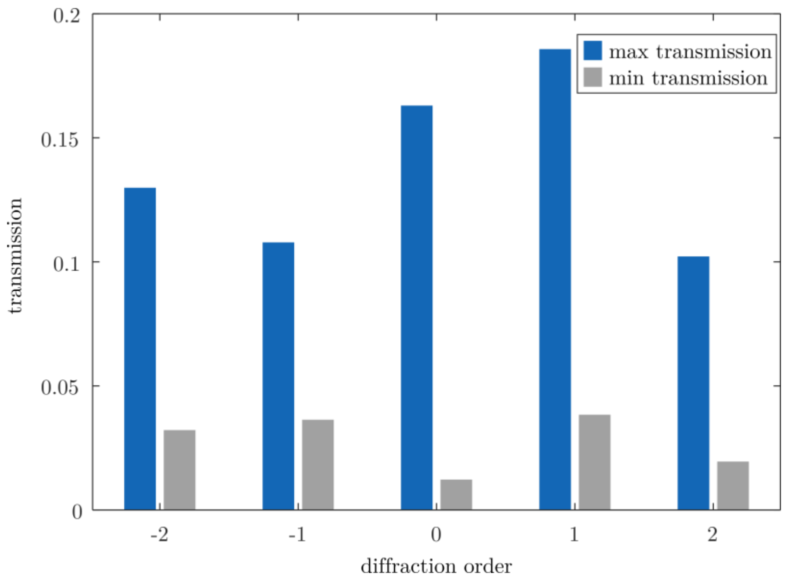


Sub-wavelength patterned silicon

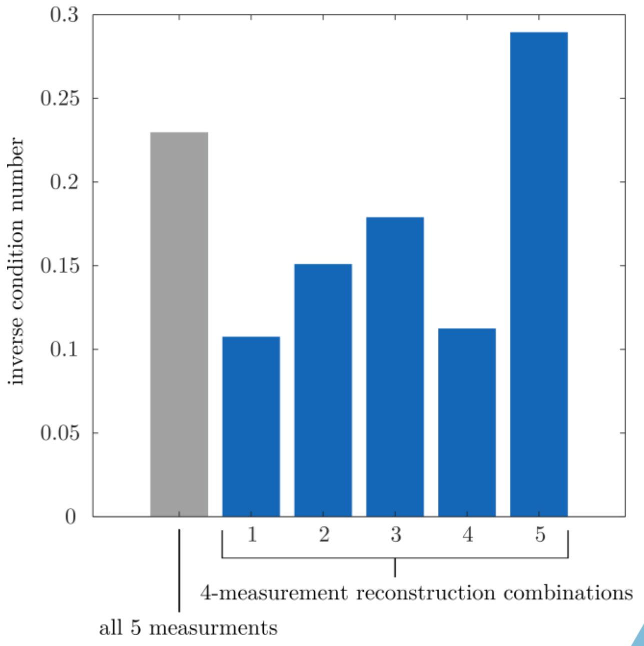


Polarisations corresponding to each diffraction order

The reconstruction performance for different combinations of measurements indicate comparison of reconstructions are possible

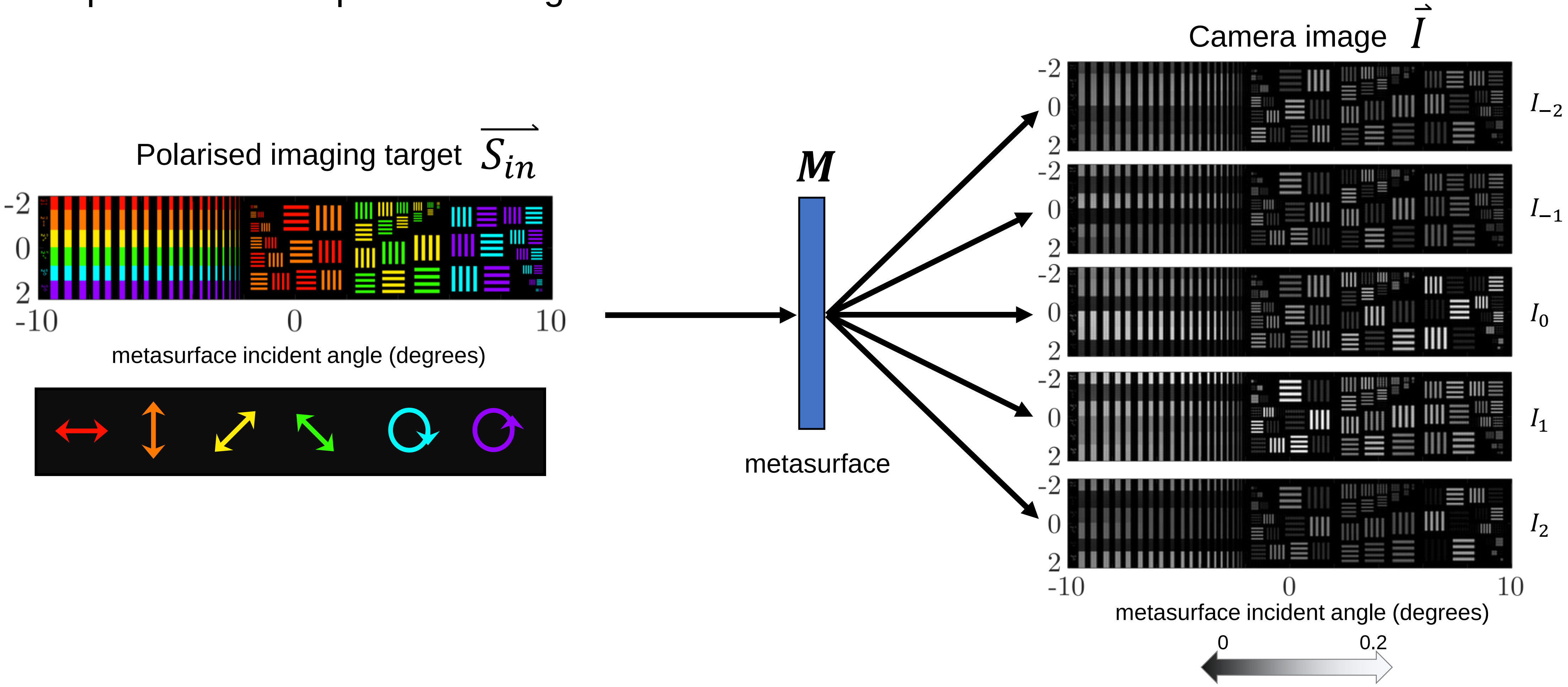


contrast between the orthogonal polarisations for each diffr. order



Polarisation imaging simulation

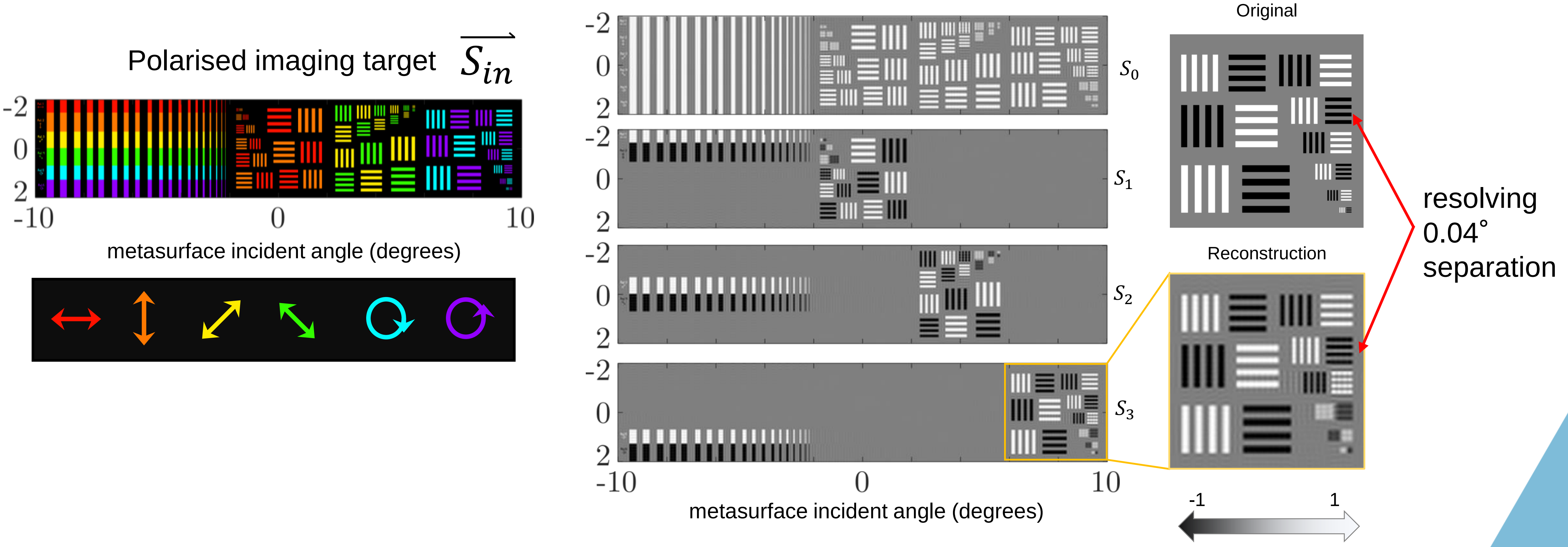
Simulating a 2.23 x 0.44 mm metasurface for a polarised input results in 5 diffraction orders with polarisation-dependent images at the camera sensor



Polarisation imaging simulation

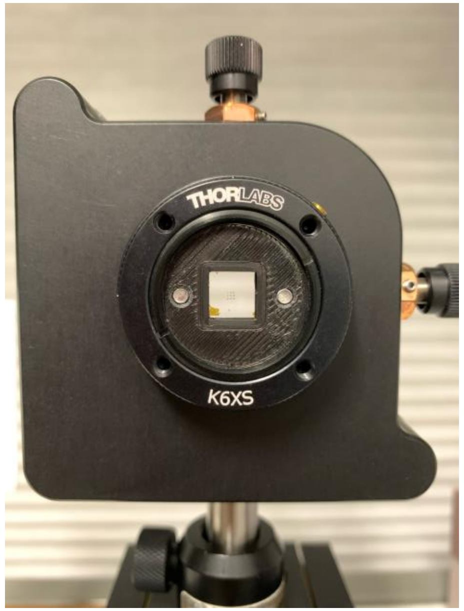
Reconstructing the simulated camera measurements demonstrate the resolution achievable with the 2.23mm by 0.44 mm metasurface

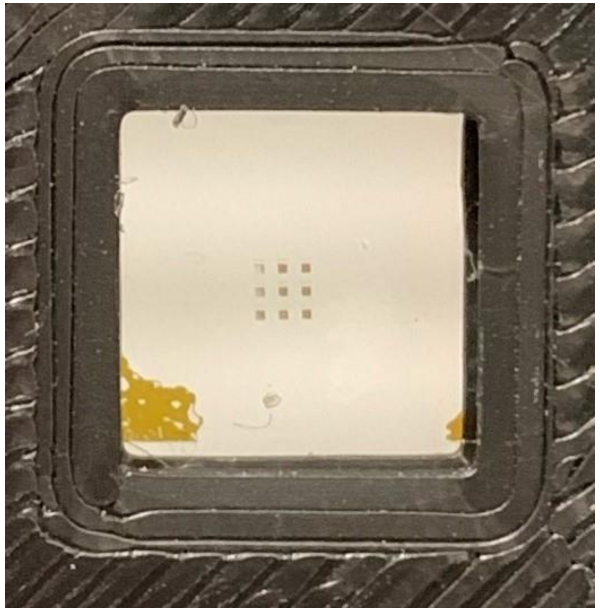
$$\boldsymbol{M}^{-1}\vec{I} = \vec{S}_{reconstructed}$$



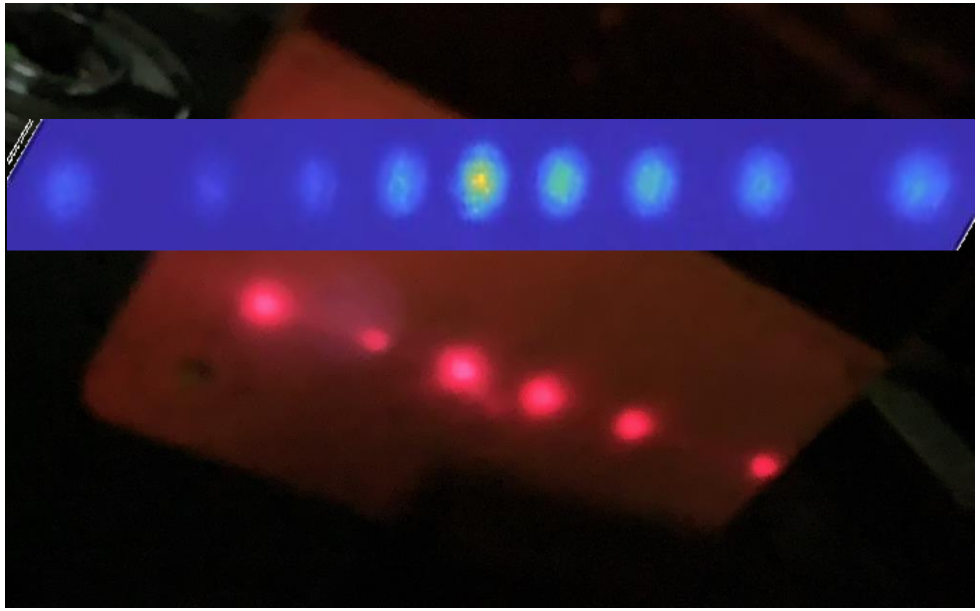
Experimental verifications

Fabricated test samples





Measured test diffraction pattern

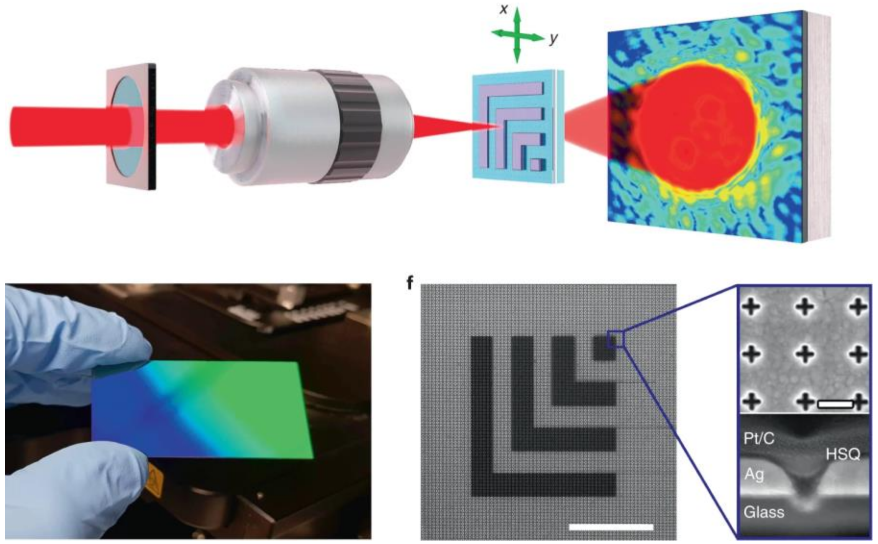


Ongoing …

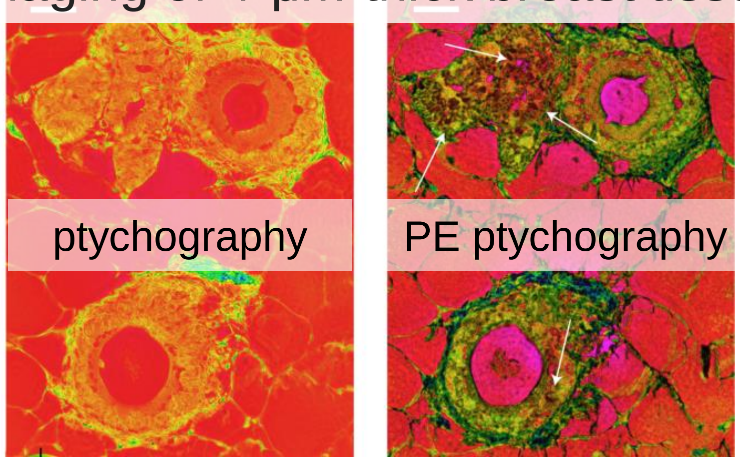
Images: Dr. Josephine Munro

Phase measurements for telescope wavefront correction

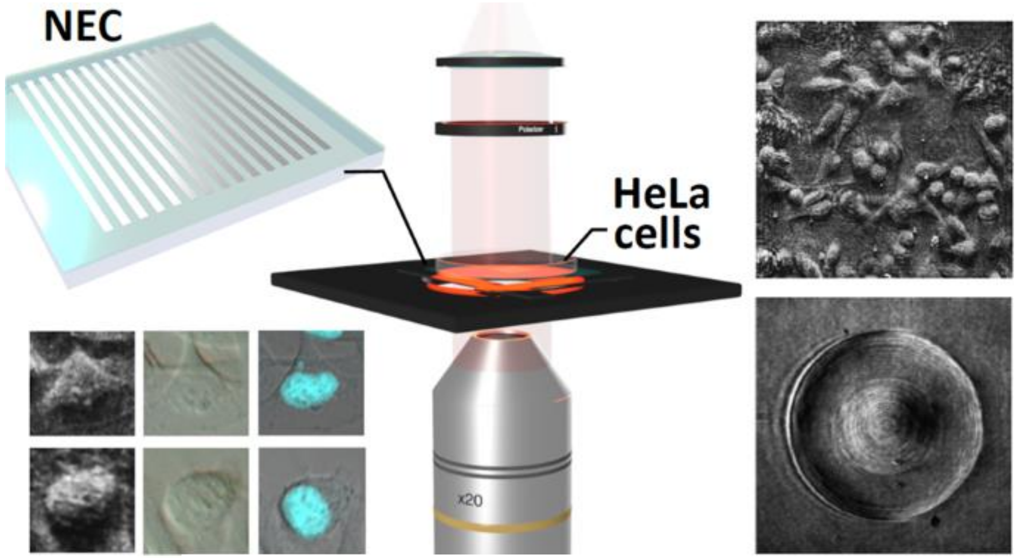
Phase detection with metasurfaces

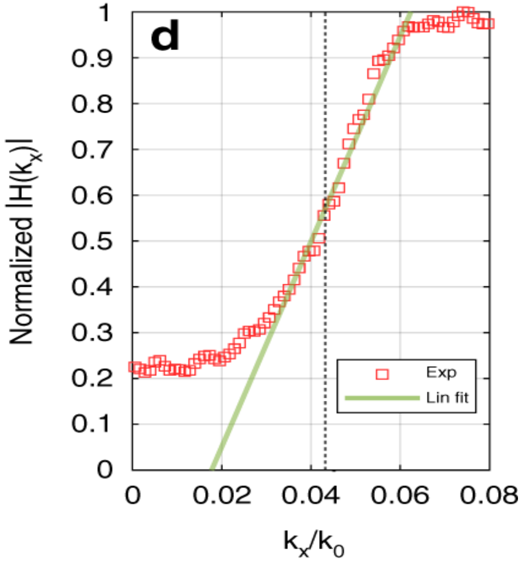


Imaging of 4-μm-thick breast tissue



Balaur et al. *Nat. Photonics* **15,** 222 (2021)

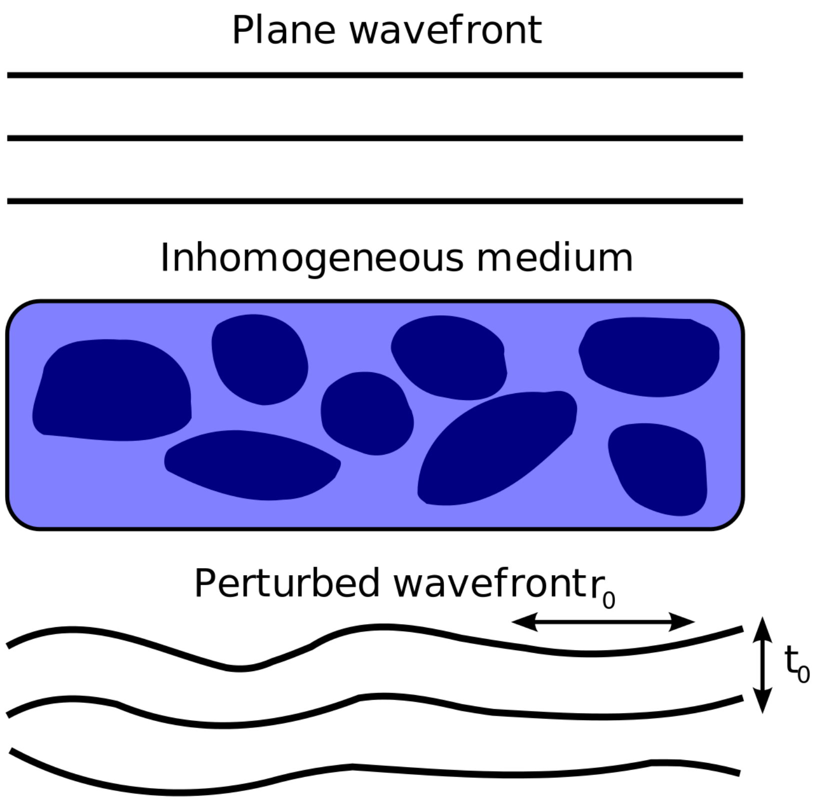




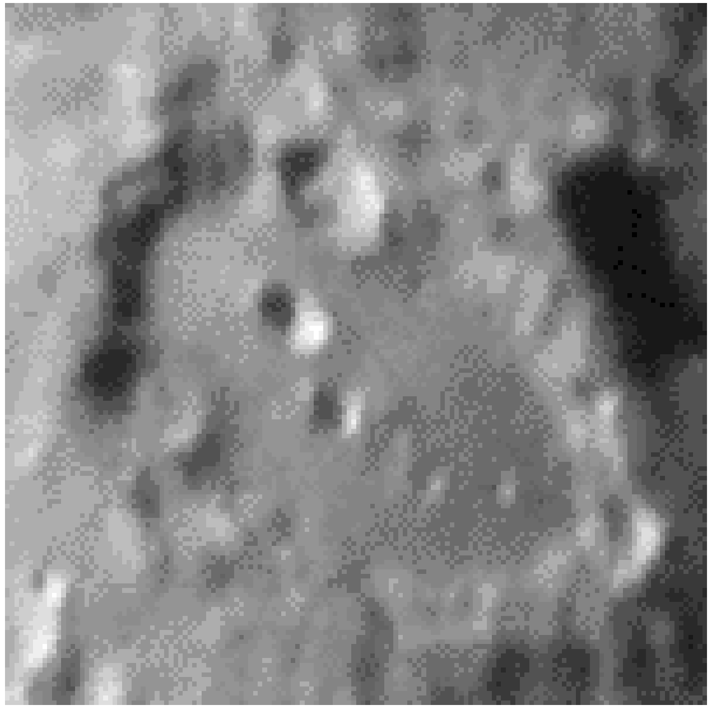
Wesemann et al., Light Sci Appl 10, 98 (2021)

Wavefront distortion by the atmosphere

Atmosphere is an inhomogeneous, due to temperature differentials and wind velocities



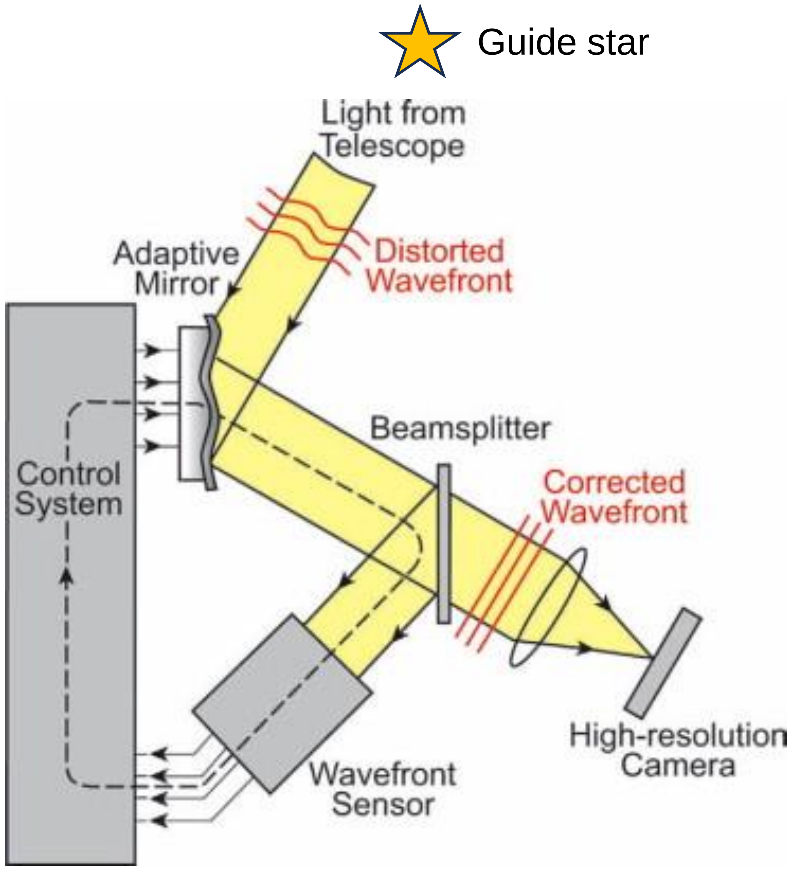
https://commons.wikimedia.org/w/index.php?curid=15279464



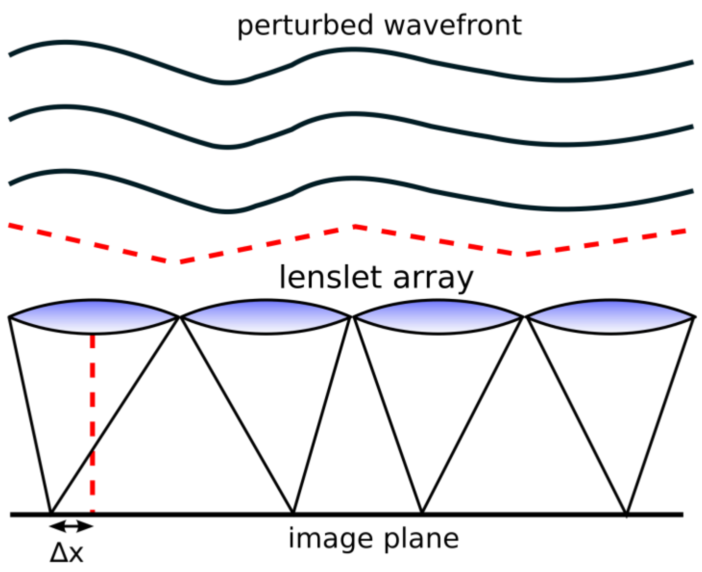
Philipp Salzgeber [1] –
http://salzgeber.at/astro/moon/seeing.html
https://commons.wikimedia.org/w/index.php?curid=483783

Adaptive optics for aberration correction

Adaptive optics system measures and corrects atmospheric aberrations



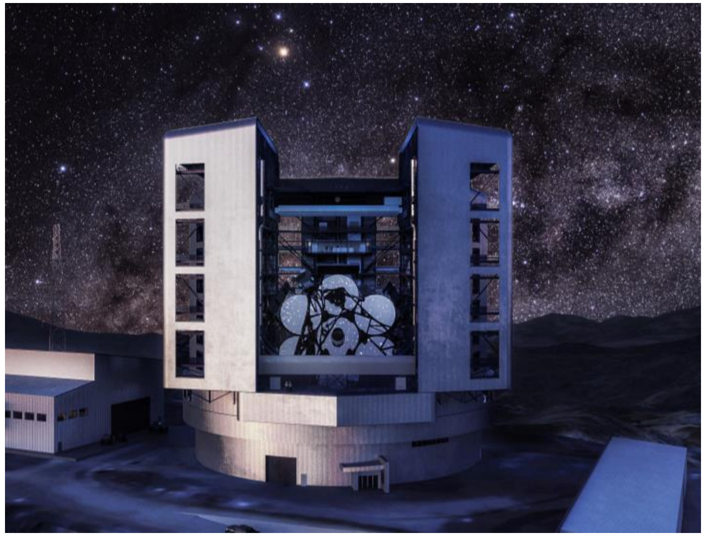
Shack-Hartmann wavefront sensor



Tokunaga, 2014. Chapter 51-New Generation Ground-Based Optical/ Infrared Telescopes. *Encyclopedia of the Solar System (Third Edition)*

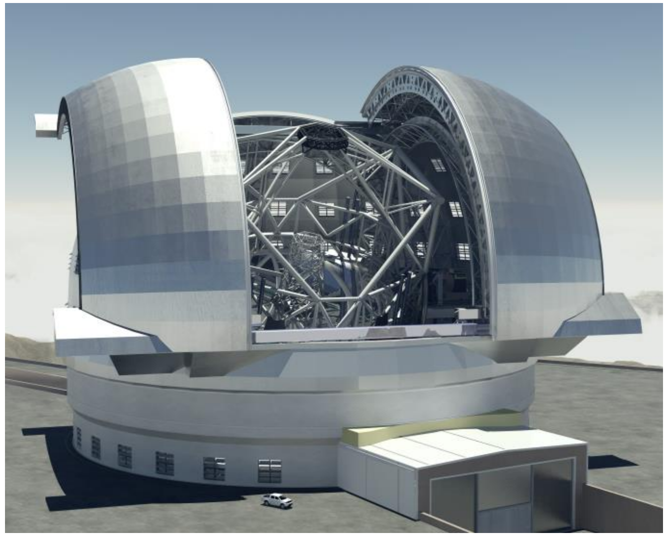
https://commons.wikimedia.org/w/index.php?curid=15278814

Future Extremely Large Telescopes



Giant Magellan Telescope – GMTO Corporation

Giant Magellan Telescope
D = 25.4m
Late 2020s estimated completion



Swinburne Astronomy Productions/ESO - ESO,

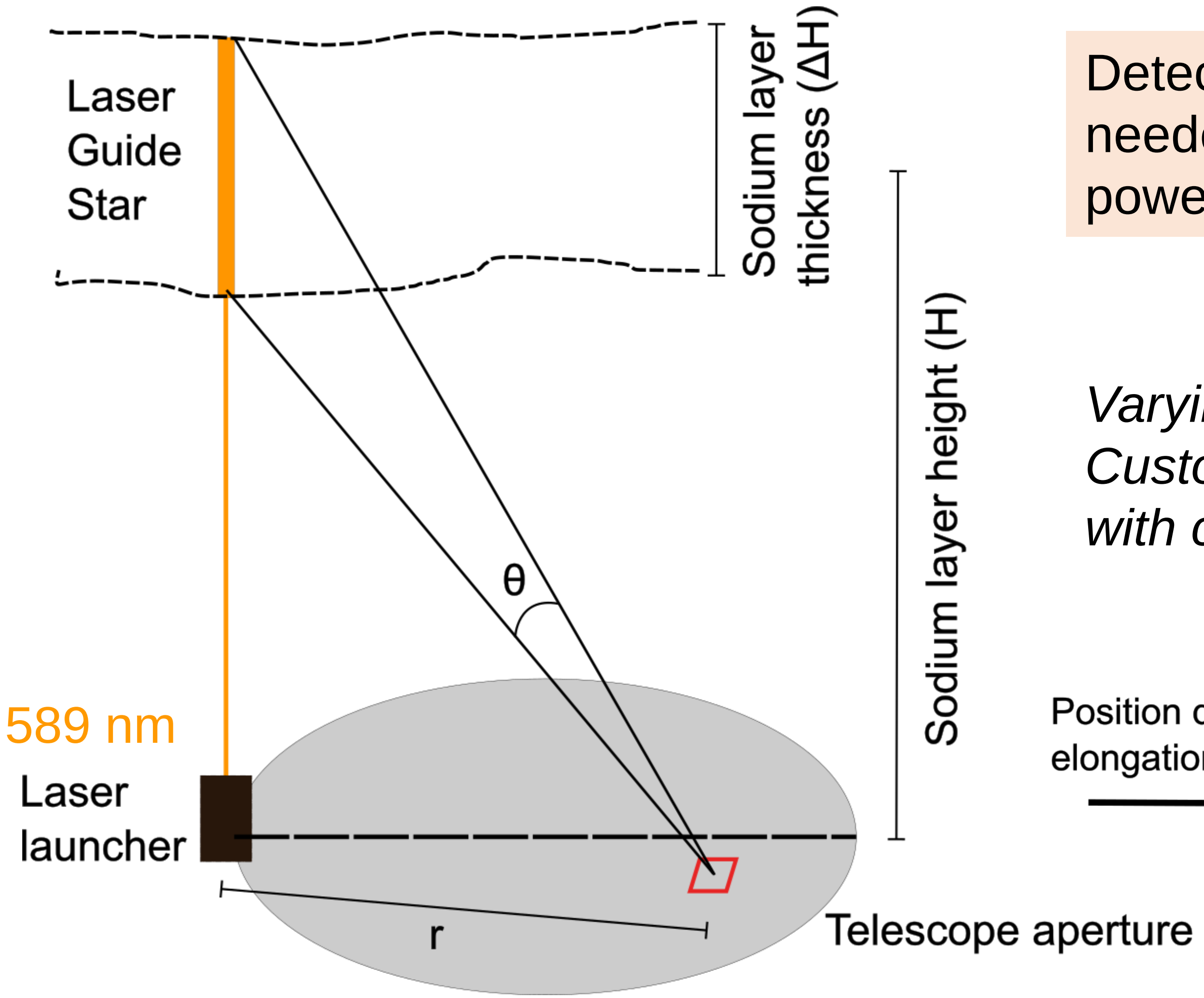
European Extremely Large Telescope
D = 39.3m
2028 estimated completion

TMT Observatory Corporation, Attribution

Thirty Meter Telescope
D = 30m
Significant construction issues

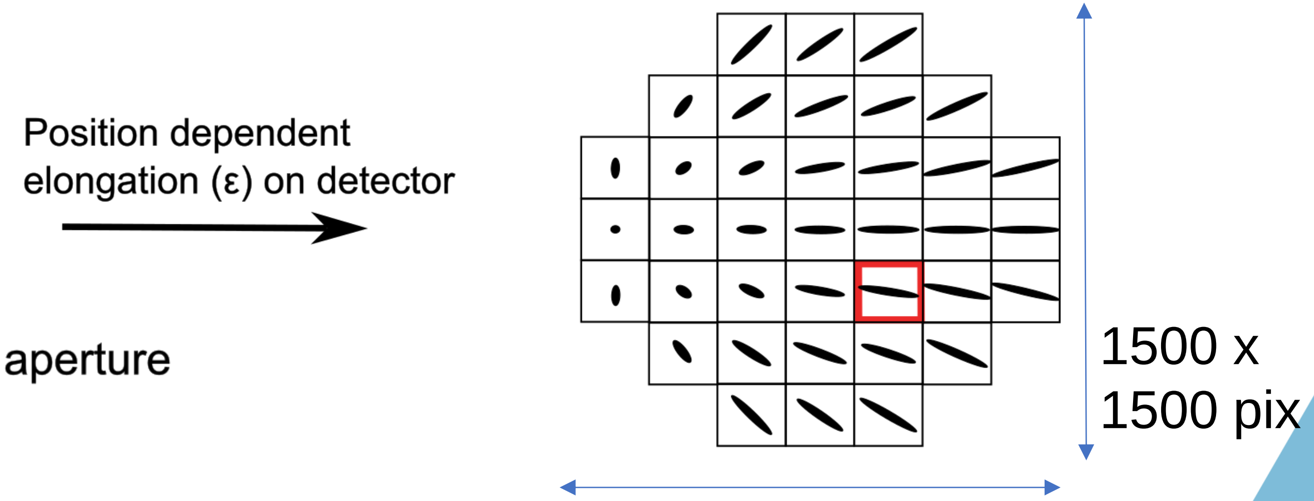
What does extremely large optics have to do with extremely small optics?

Elongations of Sodium laser guide stars

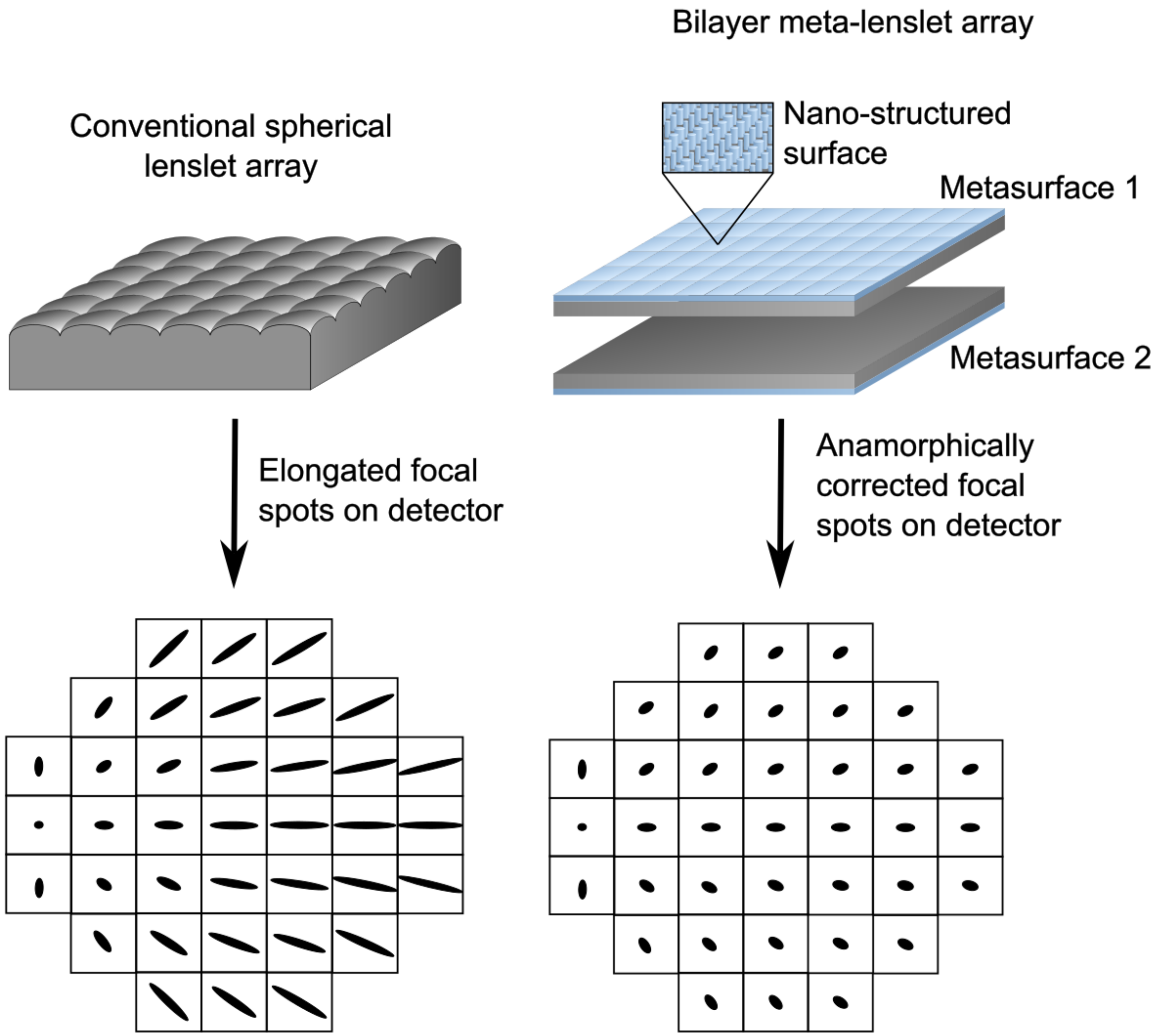


Detectors with a very large number of pixels are needed to avoid truncation; but speed, computation power, and SNRs are compromised

Varying elongation on the wavefront sensor. Custom anamorphic compression extremely difficult with conventional optics



The meta-optics solution



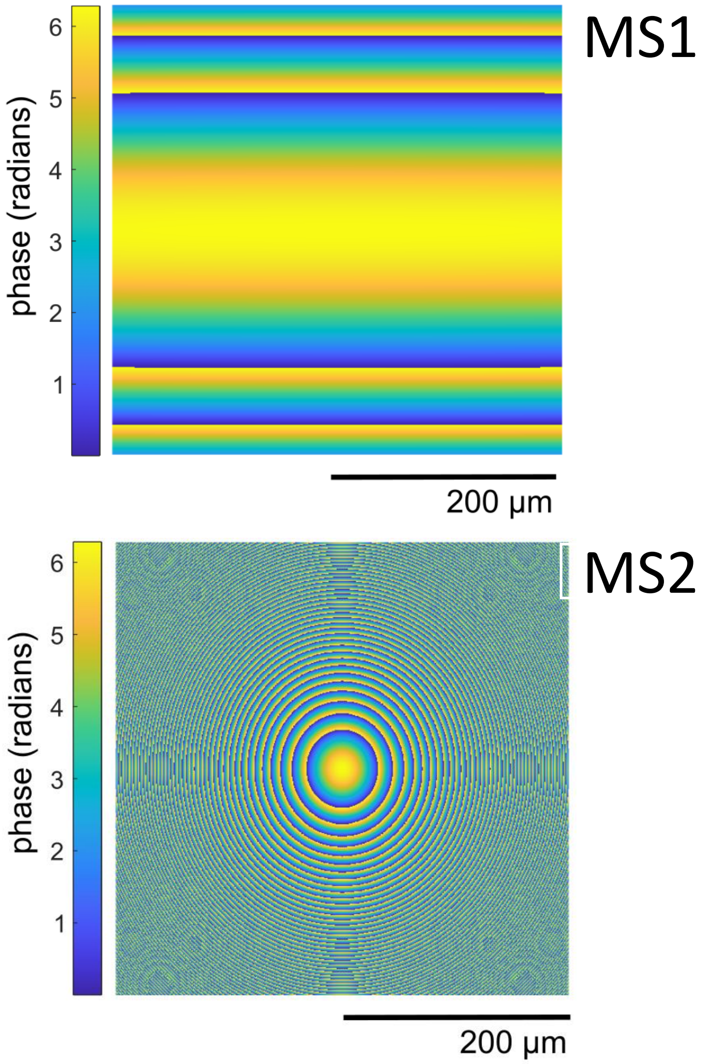
Can a meta-lenslet array be used for laser guide star wavefront sensing?

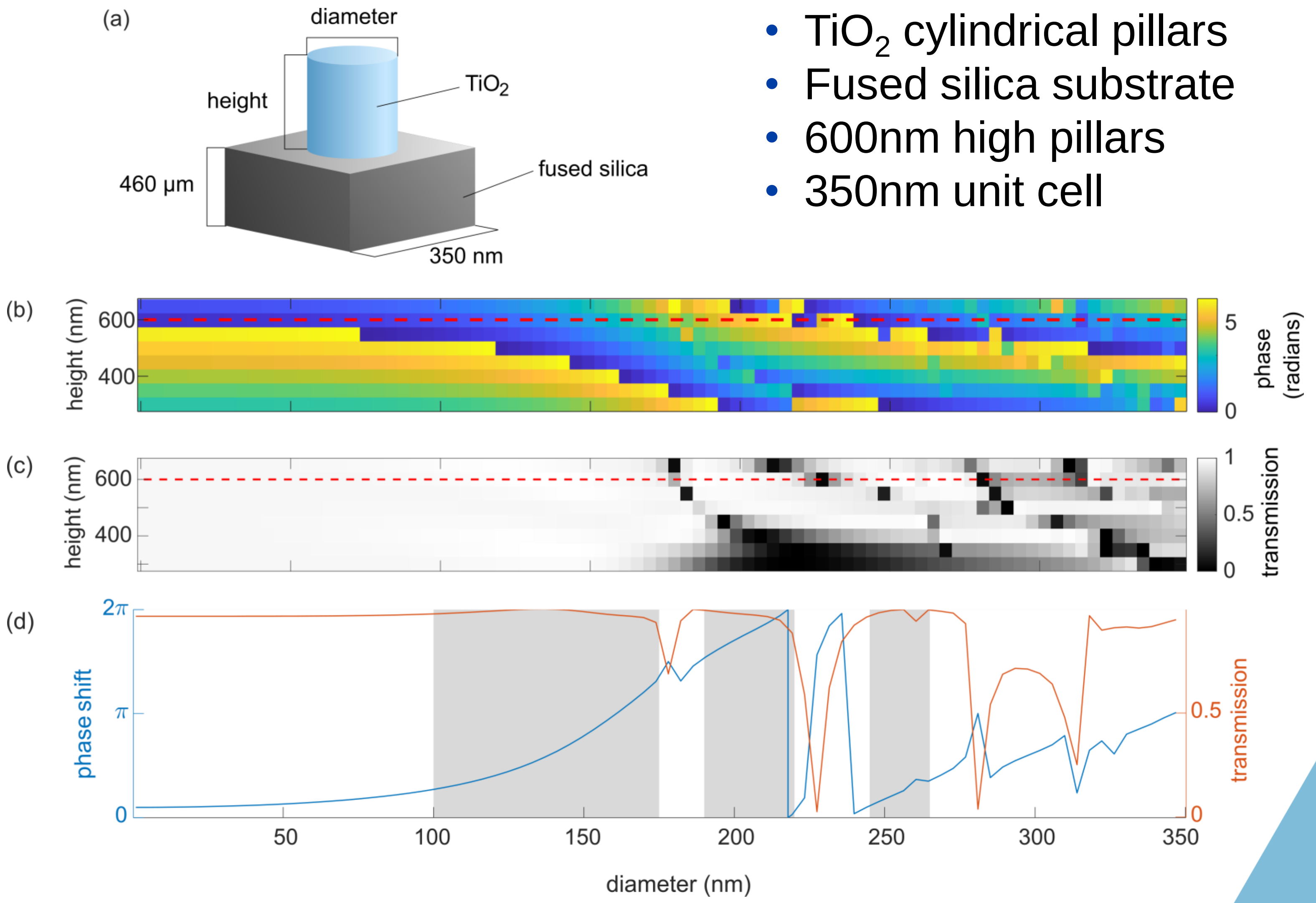
Requirements:

- Anamorphic compression ratios between 1:1 and 1:10
- Wavelength 589 nm
- Subaperture size 150-500µm
- Effective focal length 2-20mm
- Parfocal operation; will require a bilayer (two metasurfaces)

Munro et al, submitted (2024)

Metasurface design and modelling



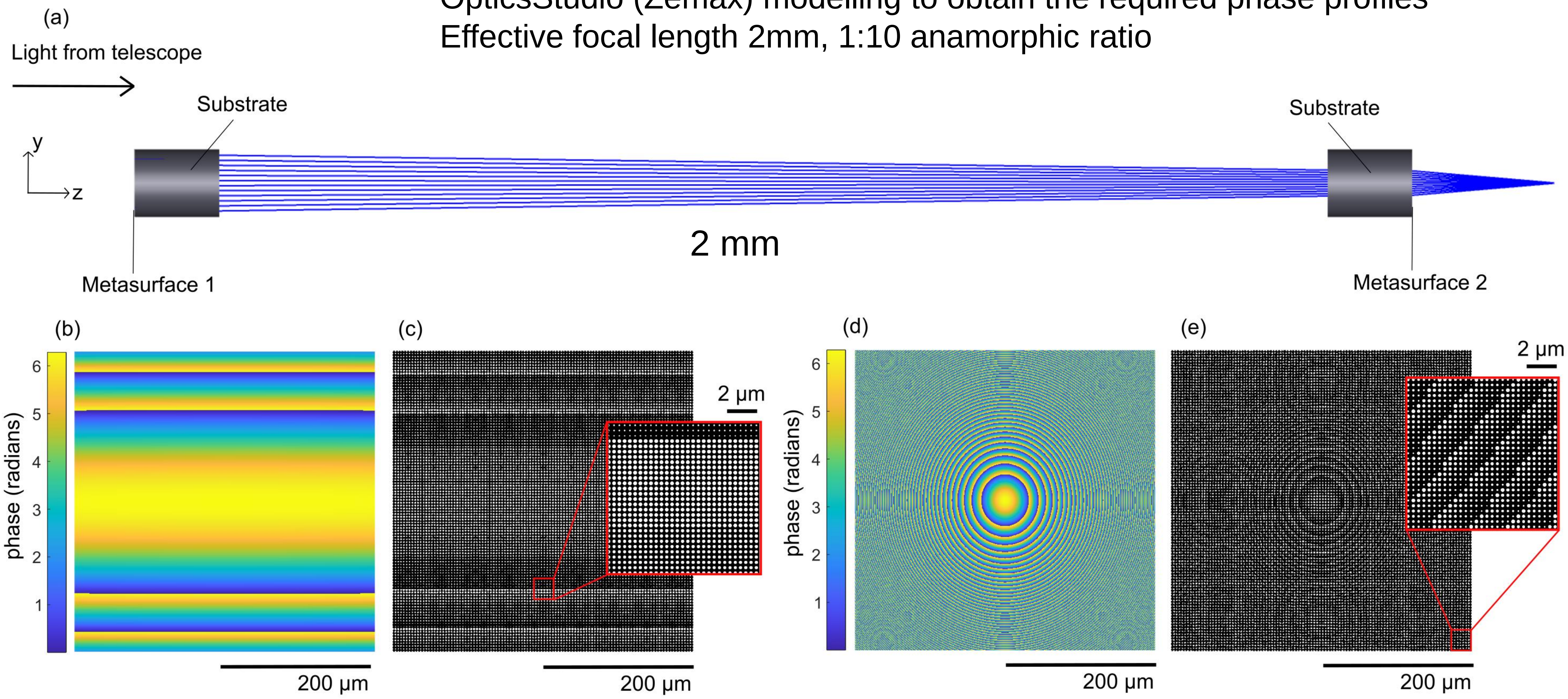


- TiO_2 cylindrical pillars
- Fused silica substrate
- 600nm high pillars
- 350nm unit cell

Munro et al, submitted (2024)

Optical system layout and modelling

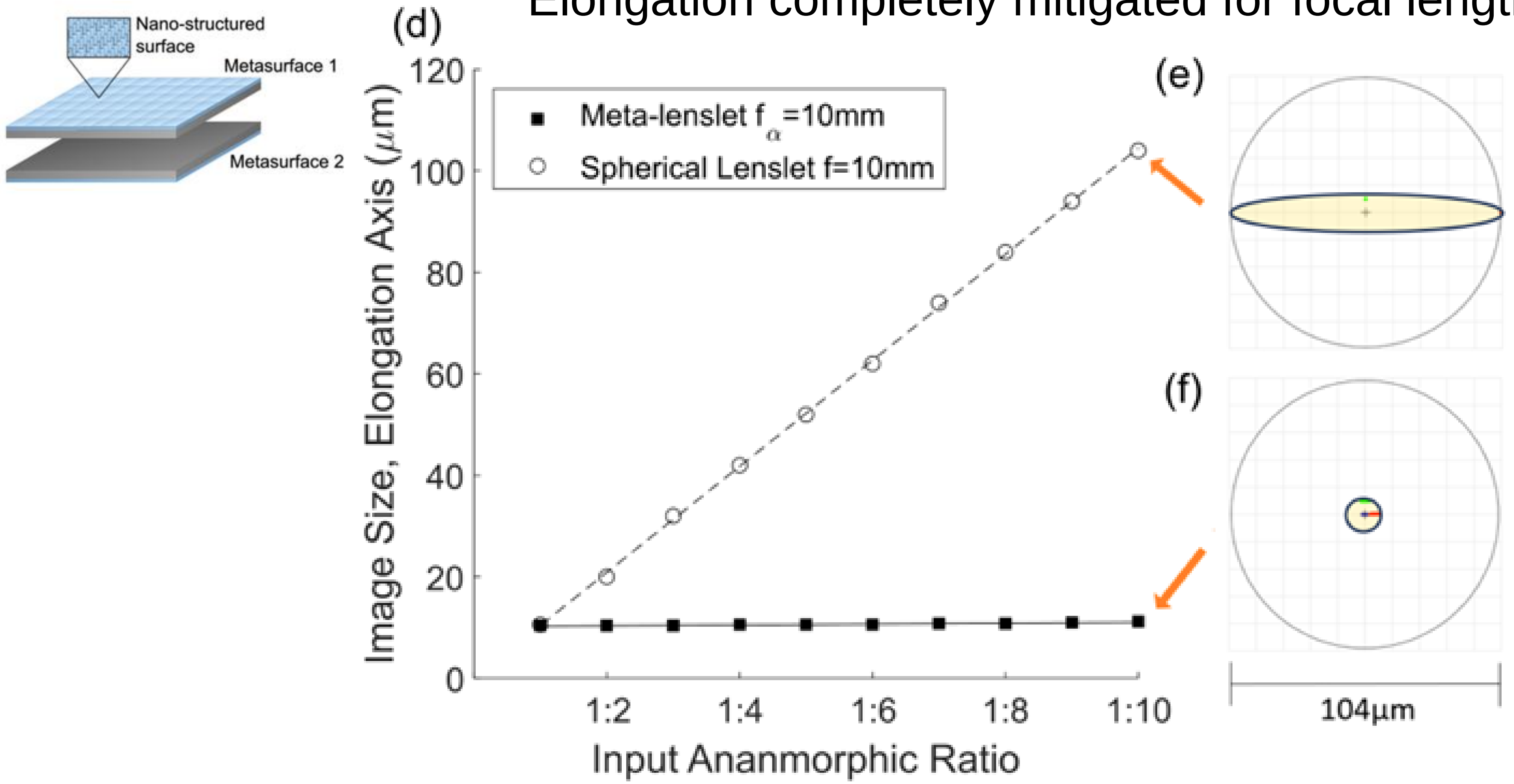
OpticsStudio (Zemax) modelling to obtain the required phase profiles
Effective focal length 2mm, 1:10 anamorphic ratio



Munro et al, submitted (2024)

Anamorphic MS optical performance

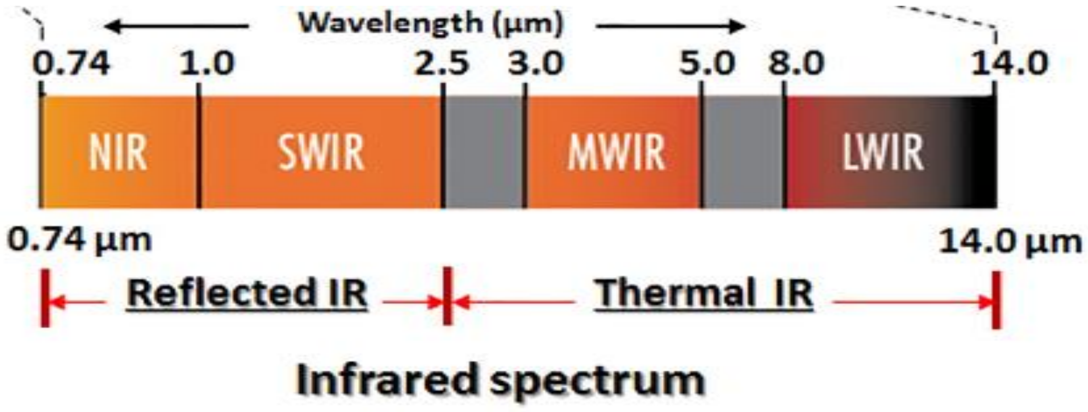
Elongation completely mitigated for focal lengths > 8mm



Elongation reduced by 50% for f = 2 mm

Infrared imaging by up-conversion to visible

Infrared imaging

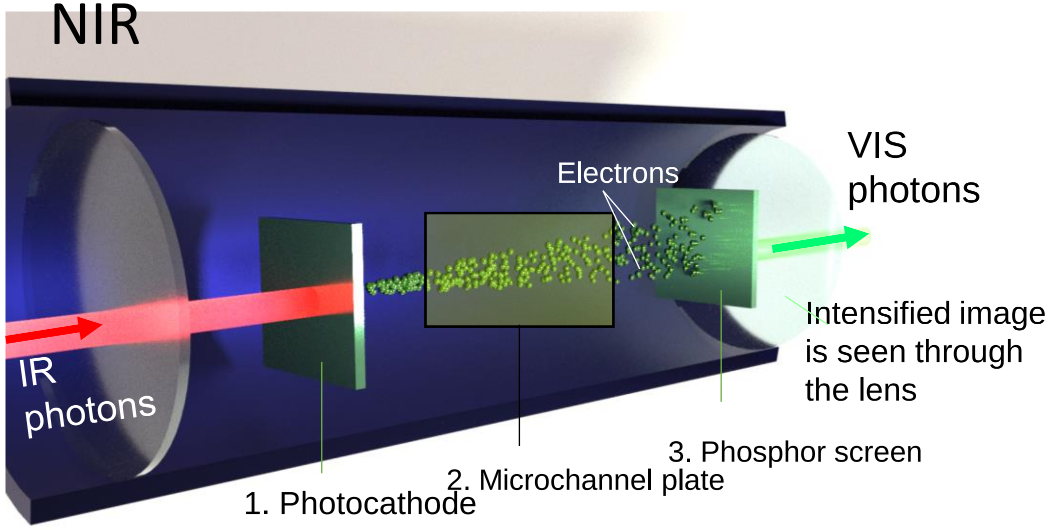


Infrared imaging enables non-destructive analysis of objects and materials, with applications in surveillance, agriculture, and medical diagnosis.

When compared with visible cameras

- *Bulky and expensive*
- *Lower resolution*
- *Environmental interference, high noise*
- *Reduced light range.*

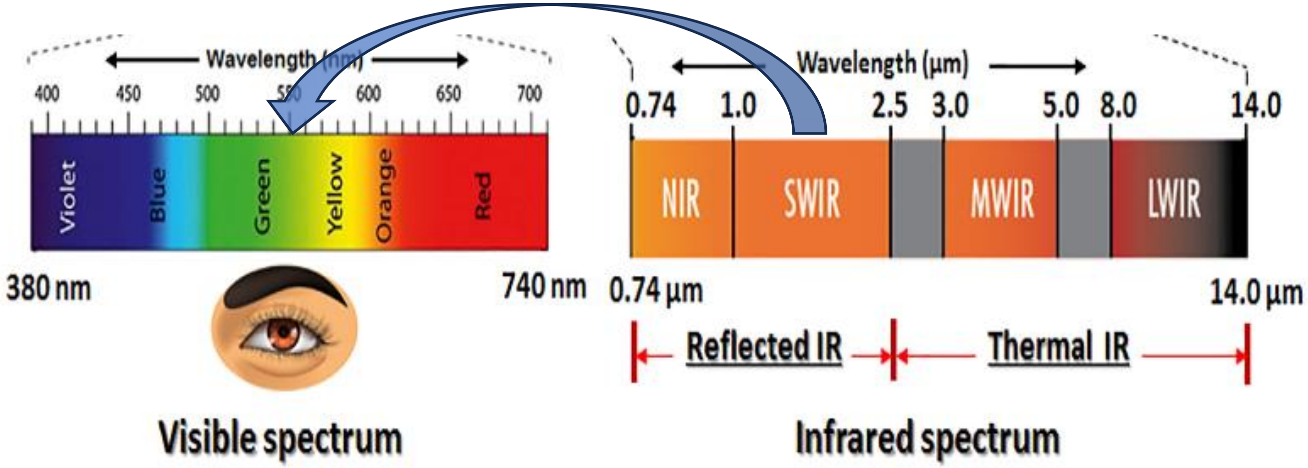
NIR

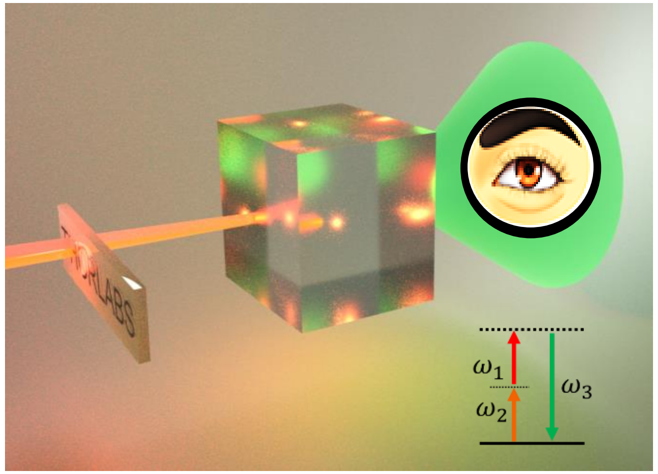


SWIR

LWIR

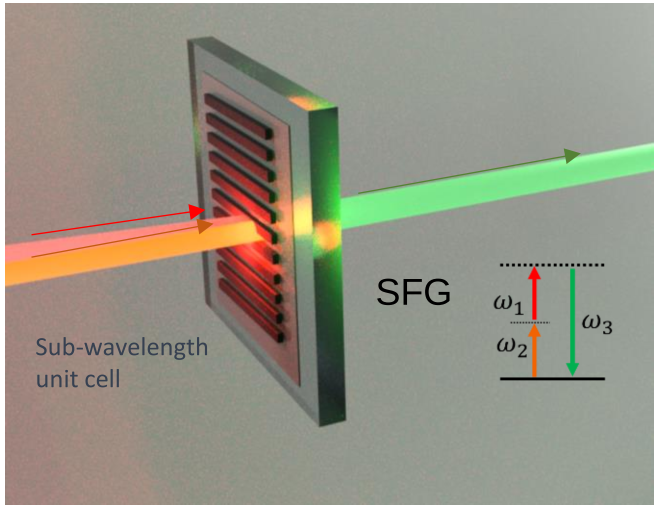
Nonlinear up-conversion and metasurfaces





Use Nonlinear Optics to convert the IR light to visible

- Old idea: Midwinter, Appl. Phys. Lett. 12, 68 (1968)
- Requires bulky NL crystals, high-power lasers, low conversion

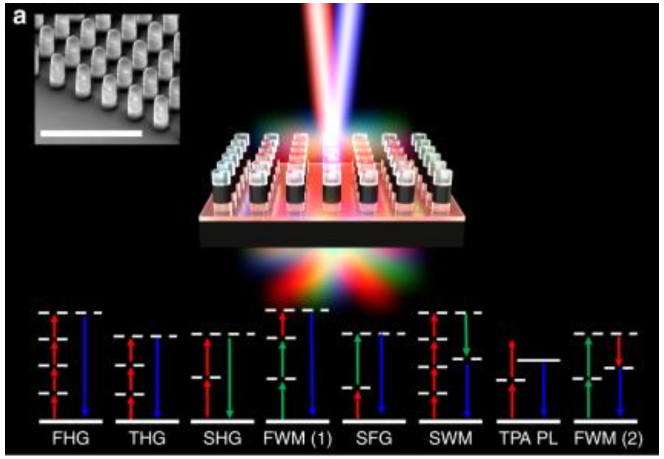


Nonlinear metasurfaces ?

- Ultra-thin and ultra-light
- Fully transparent
- Flexible
- Multicolour IR vision

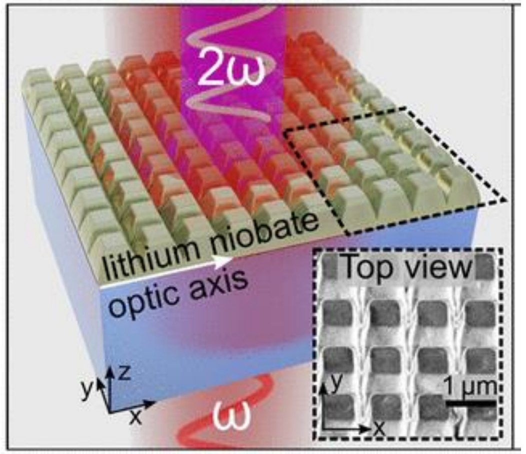
Metasurfaces for nonlinear enhancement

Meta-optical frequency mixer



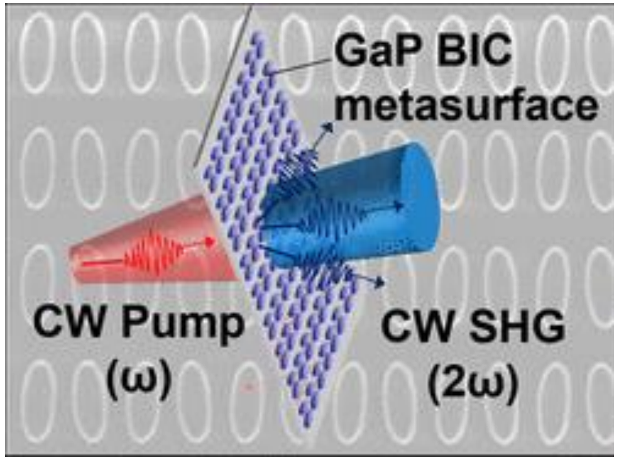
Liu et al., Nat Commun. **9**, 2507 (2018)

Enhanced SHG



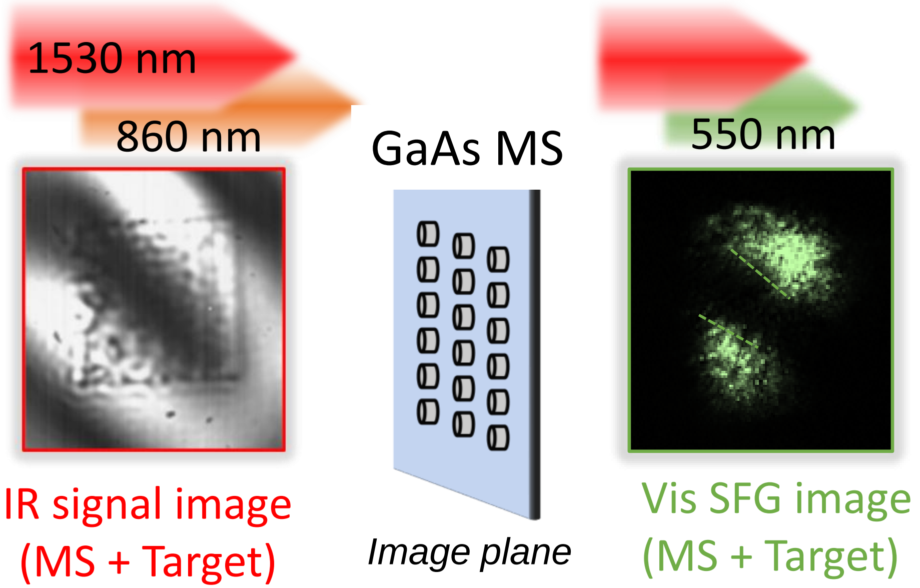
Fedotova et al., Nano Lett. **20**, 8608 (2020)

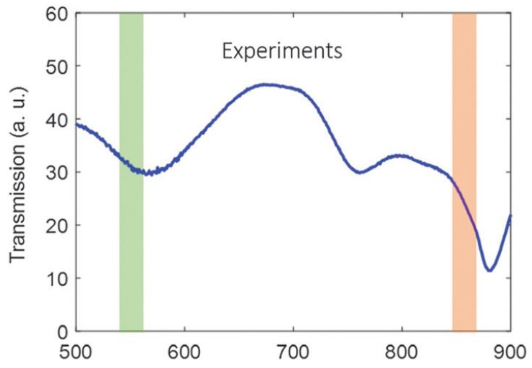
Continuous Wave SHG

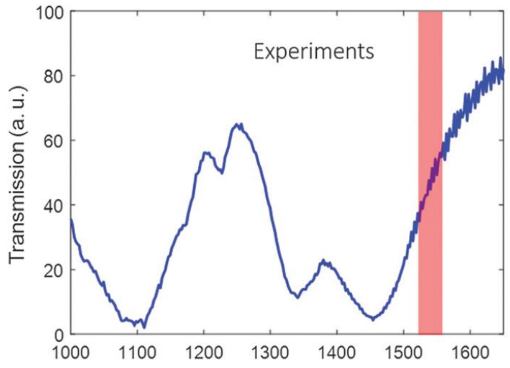


Anthur et al., Nano Lett. **20**, 8745 (2020)

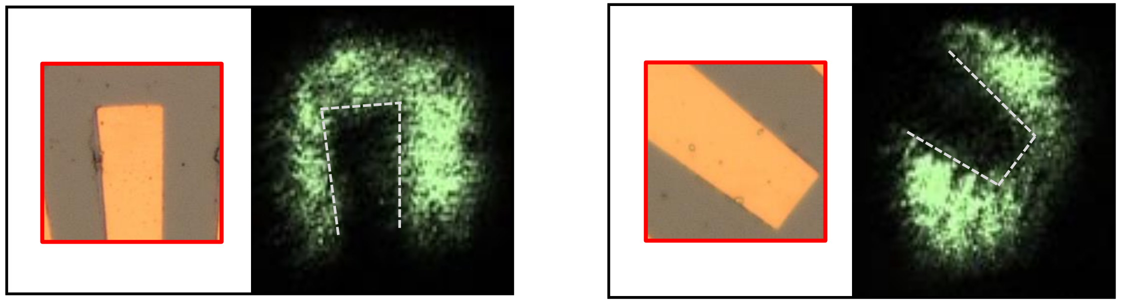
Metasurface up-converted IR imaging







Visible images from target, captured on CCD camera



efficiency 1.6×10^{-6} @ $I_p = 0.78$ GW/cm^2

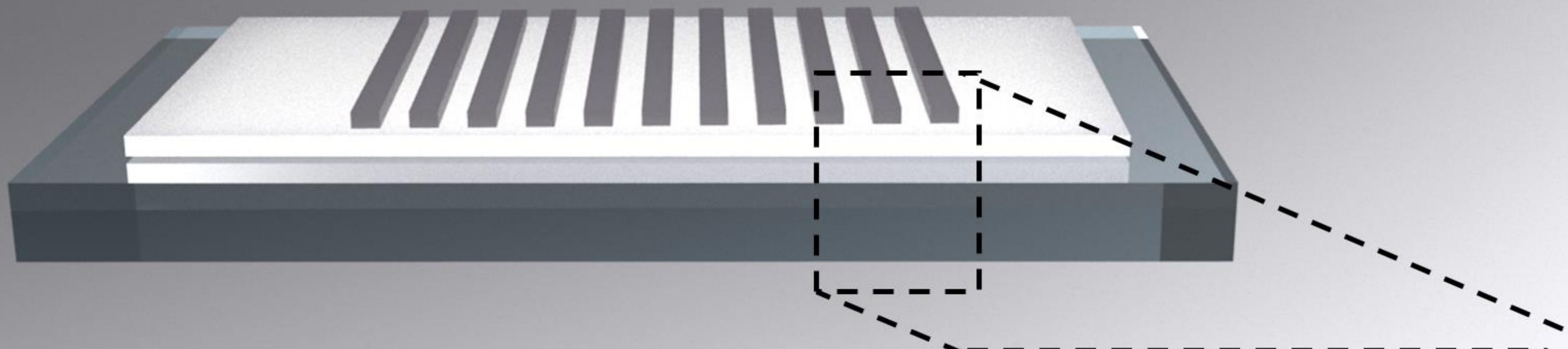
Novel IR imaging at room temperature: potential applications in night vision.

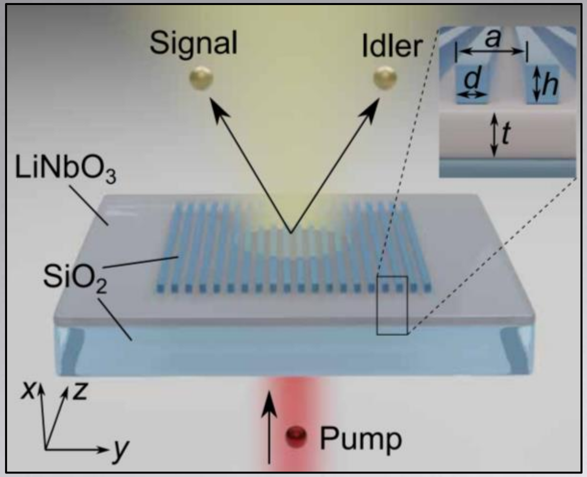
Challenges:

1. Low Q-factor of the resonances
2. High absorption at the visible wvl.
3. Low transparency for the visible

Camacho-Morales *et al*., Advanced Photonics 3, 036002 (2021)

High-Q Lithium Niobate MS for up-conversion





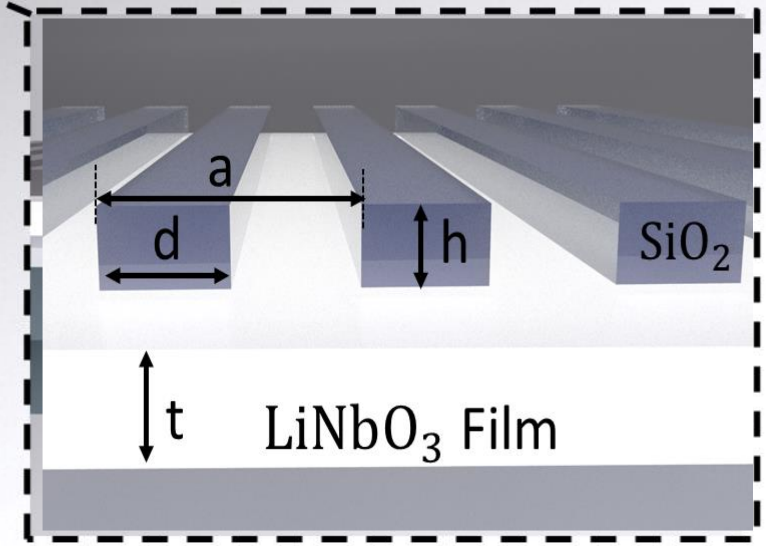
Zhang et al., *Science Adv.* ***8***, *eabq4240* (2022)

Lithium Niobate (**$LiNbO_3$**)

- Broad transparency range
- Large non linear coefficient

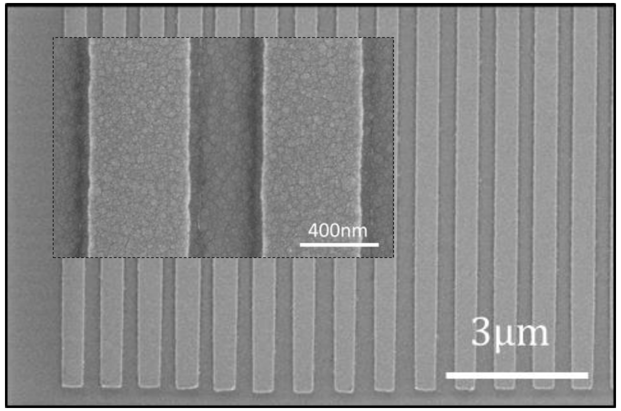
Metasurface (**MS**)

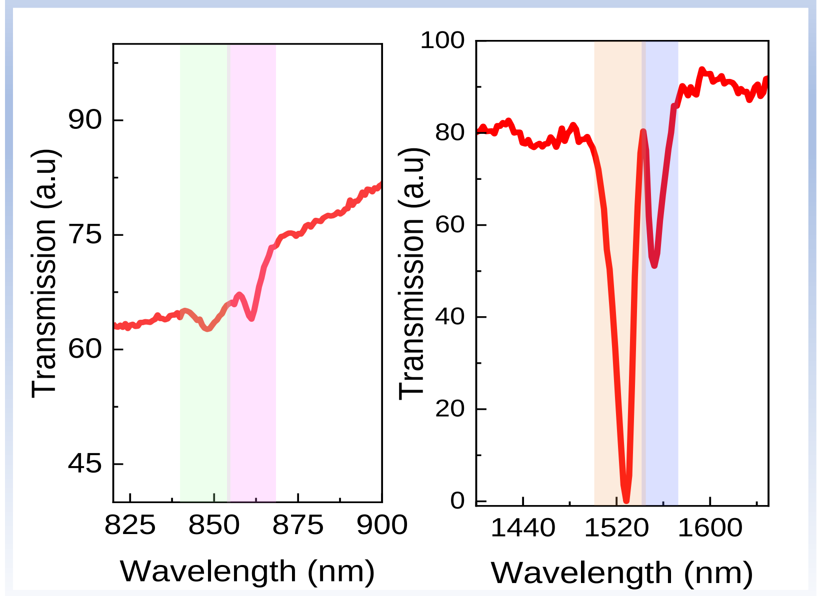
- Amplifies the NL processes
  Q can be > 1000
- Operates at different wavelengths



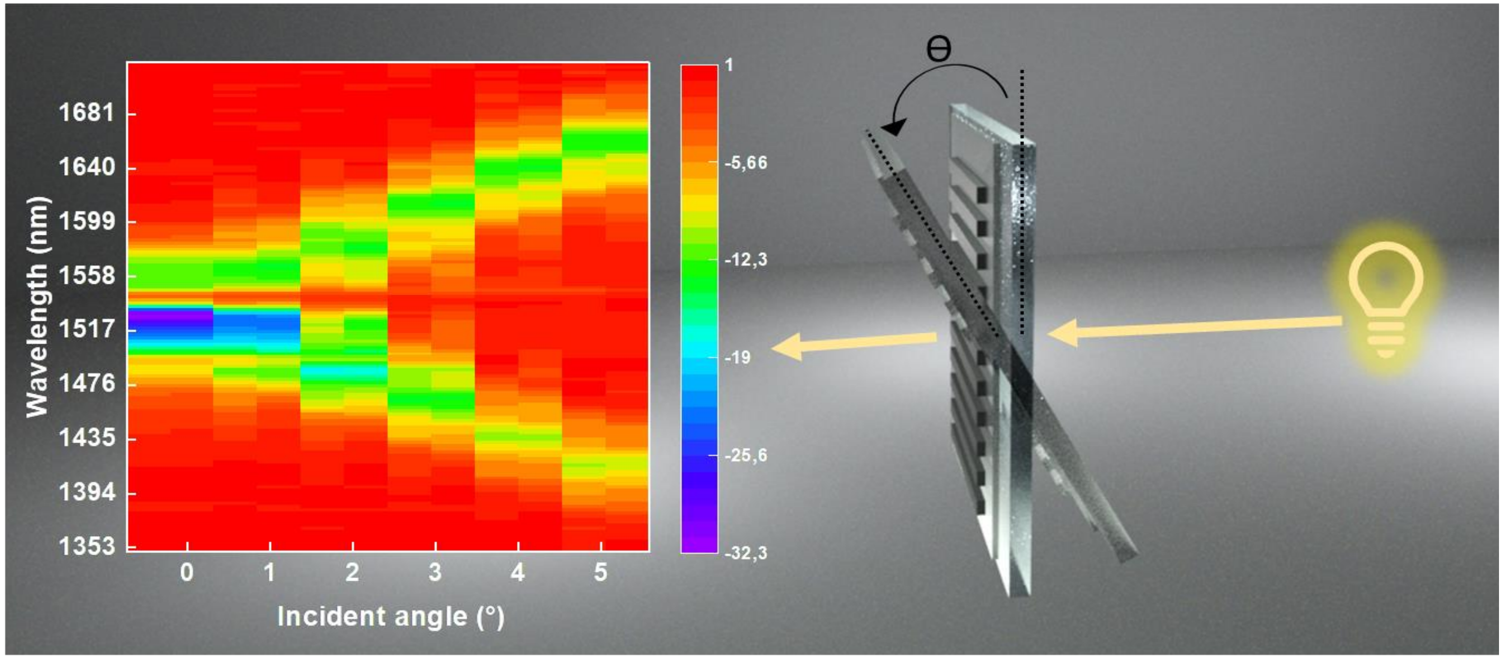
Liner properties of $LiNbO_3$ metasurface

SEM images of the MS



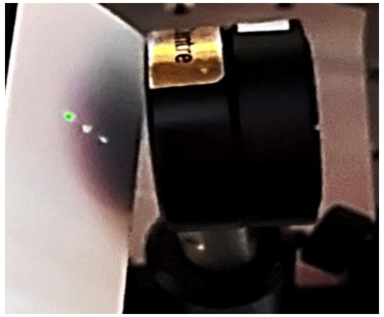


Linear transmission as a function of incident angle and wavelength

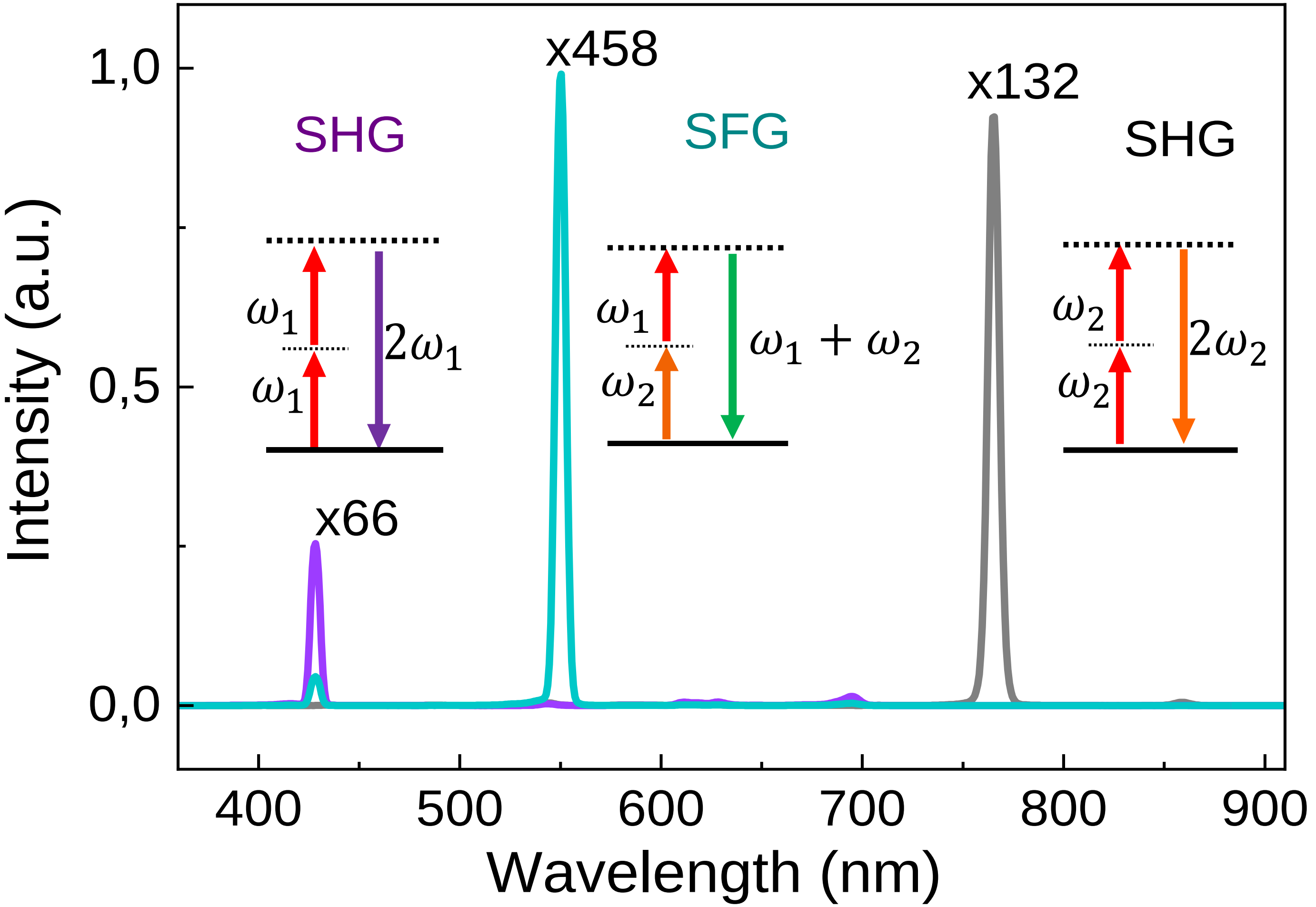


The IR transmission spectrum shows a strong dispersion of the resonance with angle –
How to upconvert different spatial frequencies?

Measured second-order nonlinear emission



Nonlinear spectra from the MS

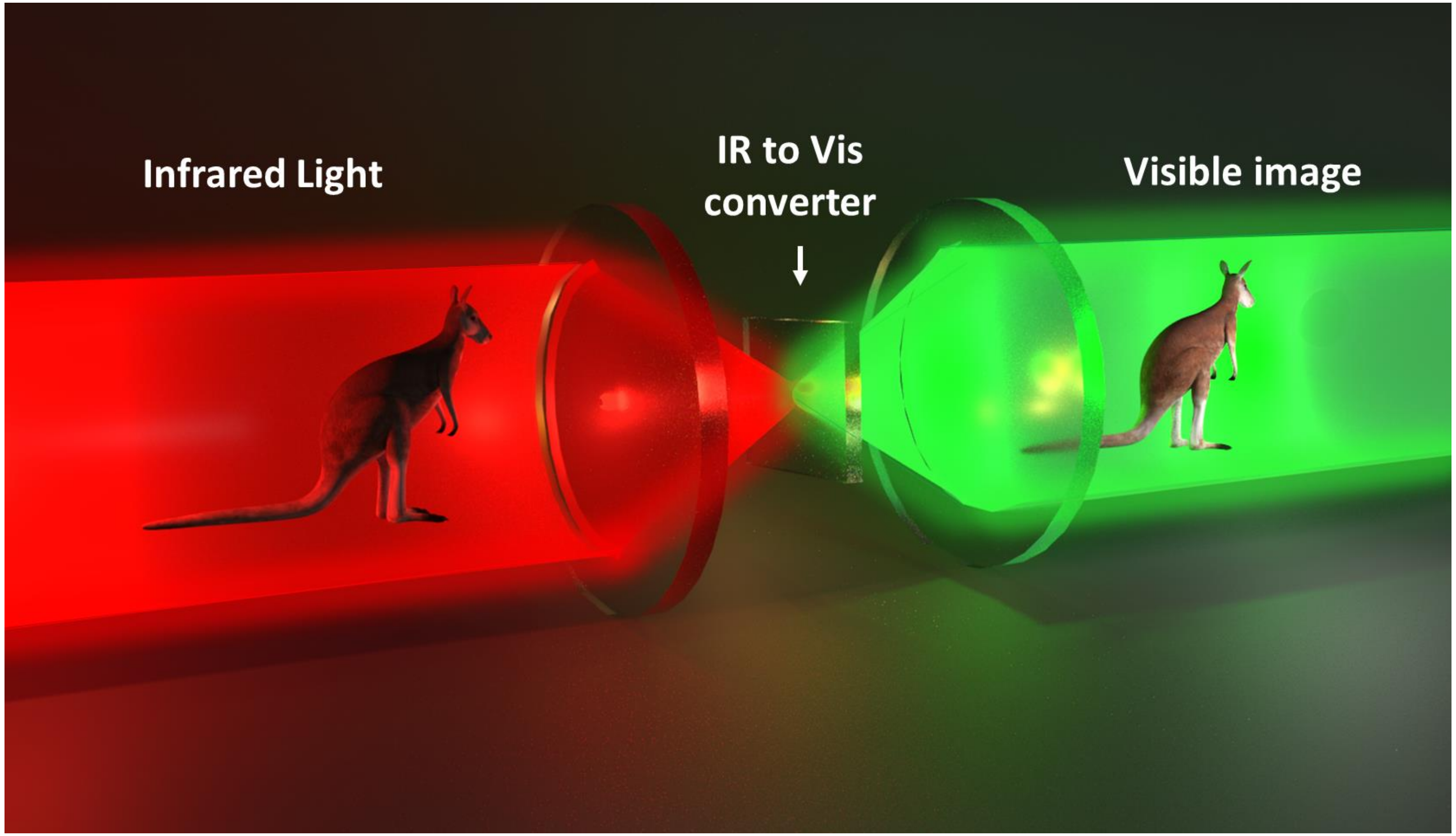


efficiency 0.8 × 10^{-6}
@ I_p = 0.76 GW/cm^2

Ti:Sapp laser with an OPO: pump 860 nm, signal 1530 nm

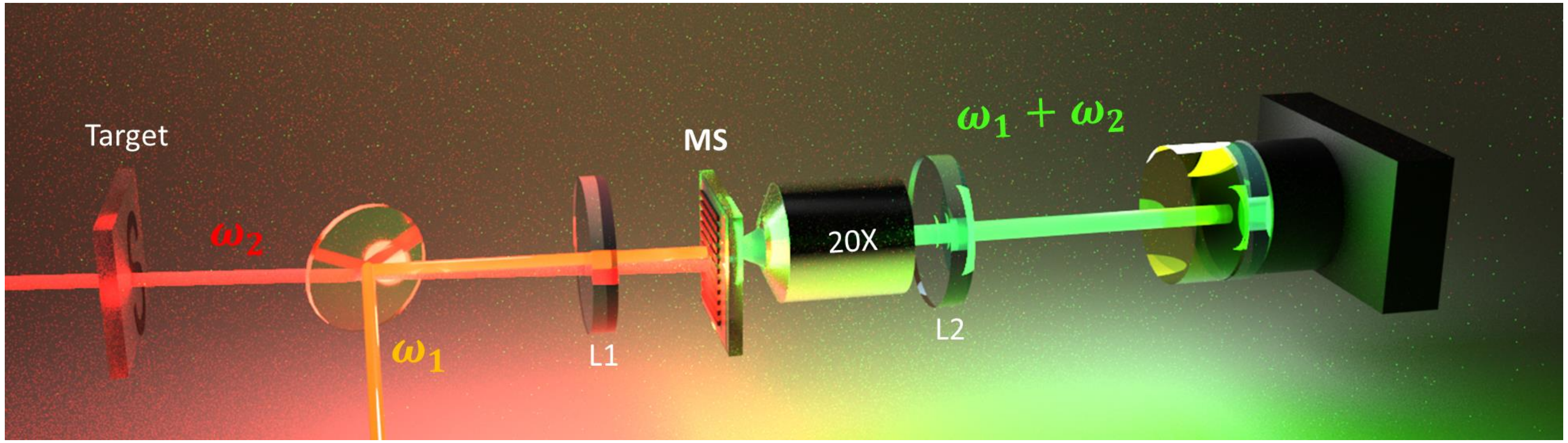
Highly enhanced conversion of SWIR to visible light

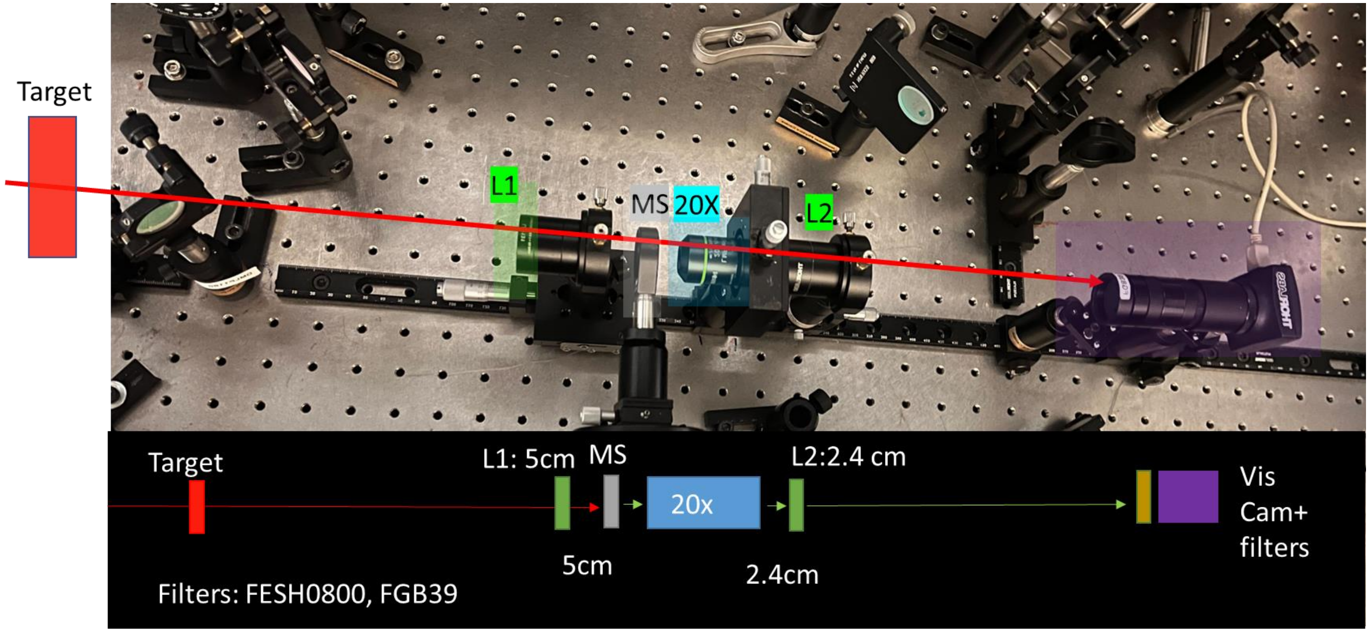
Up-conversion imaging



Valencia Molina et al., Adv. Mater. 2402777 (2024)

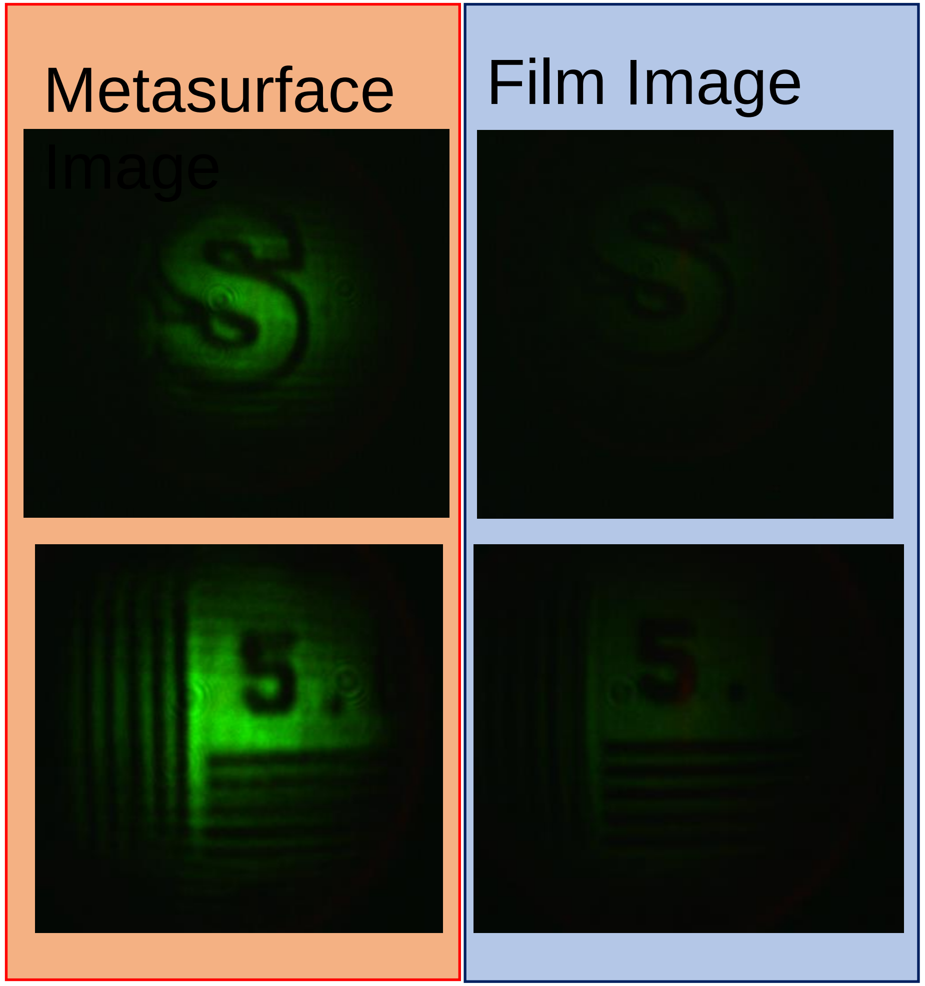
Metasurface up-conversion imaging experiment

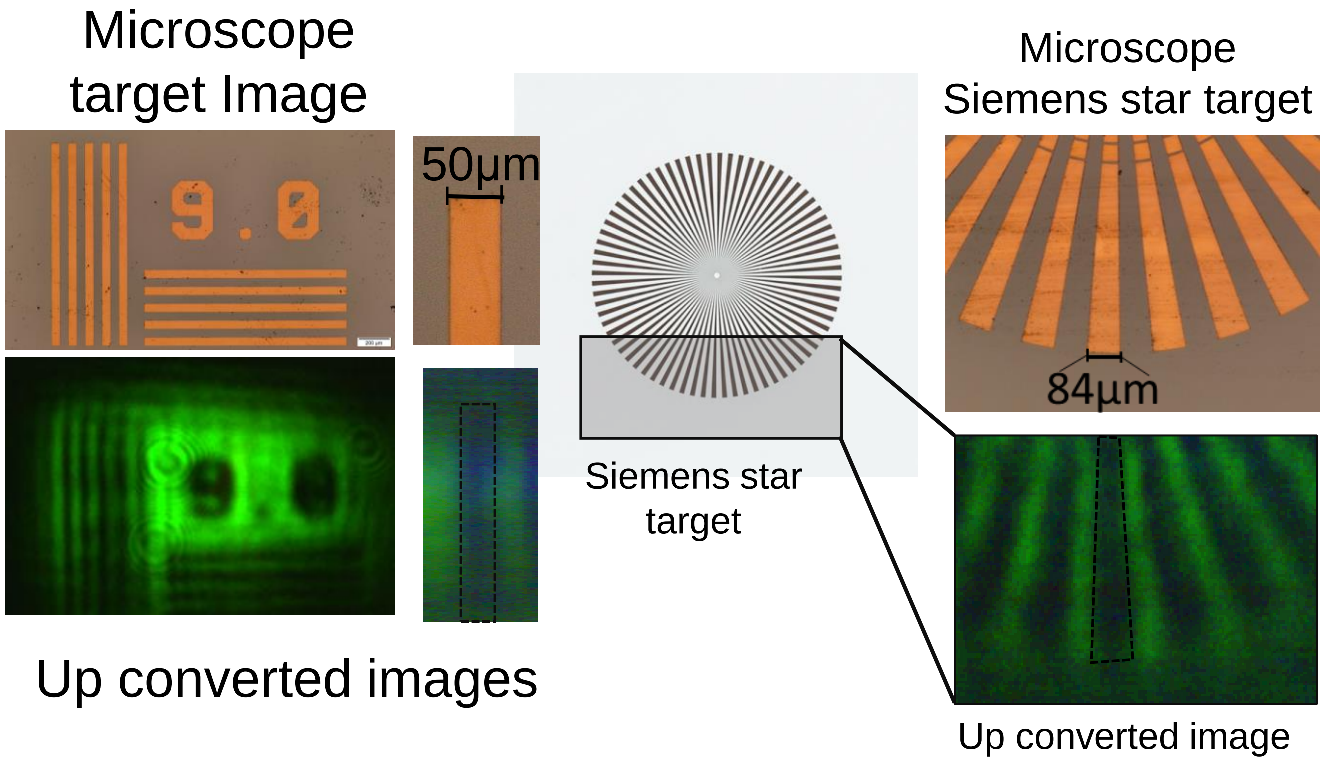




Metasurface is placed in the Fourier plane, allowed due to the coherence of the SFG up-conversion process

Infrared up-conversion imaging by the MS





Up conversion image of IR to visible with a resolution of ~50μm

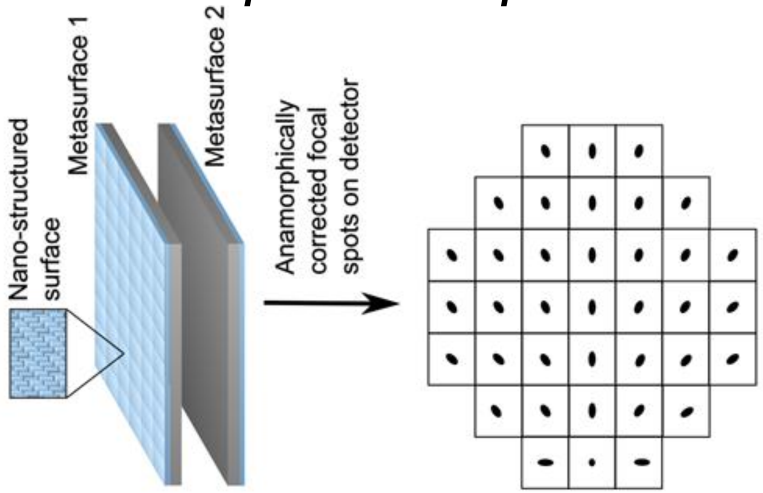
Conclusions and outlook

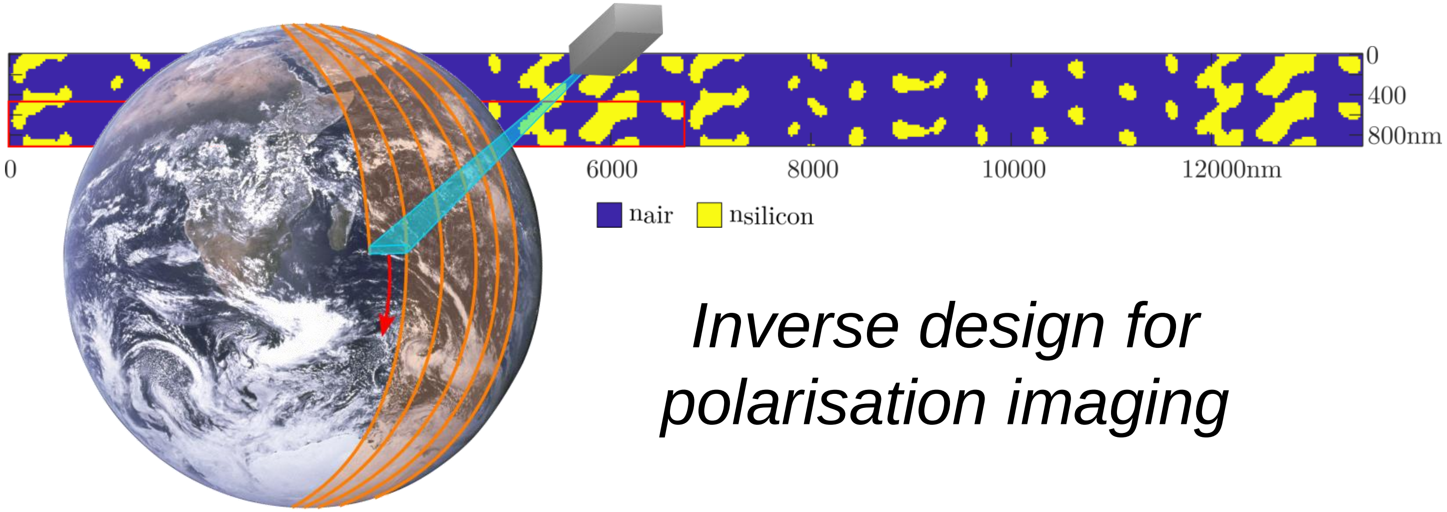
Meta-optics offers new **opportunities over conventional bulk optics**:

- Improved SWaP (Size, Weight and Power)
- Complex functions implemented on a single metasurface

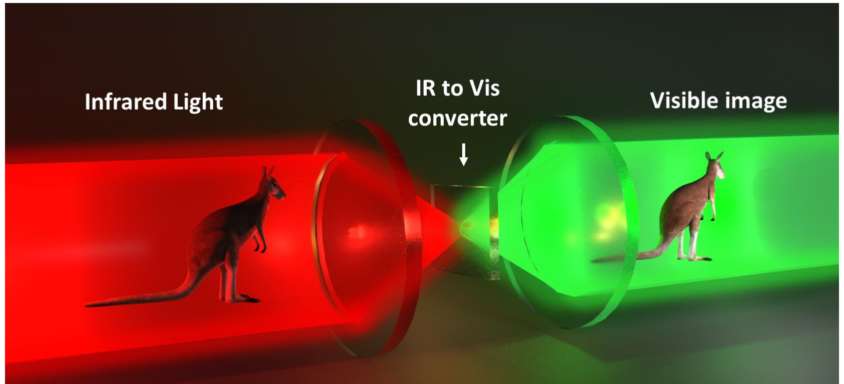
Challenge: limited bandwidth of operation

Anamorphic compression





Inverse design for polarisation imaging



Nonlinear up-conversion

Thanks

Australian National University

TMOS

ANFF