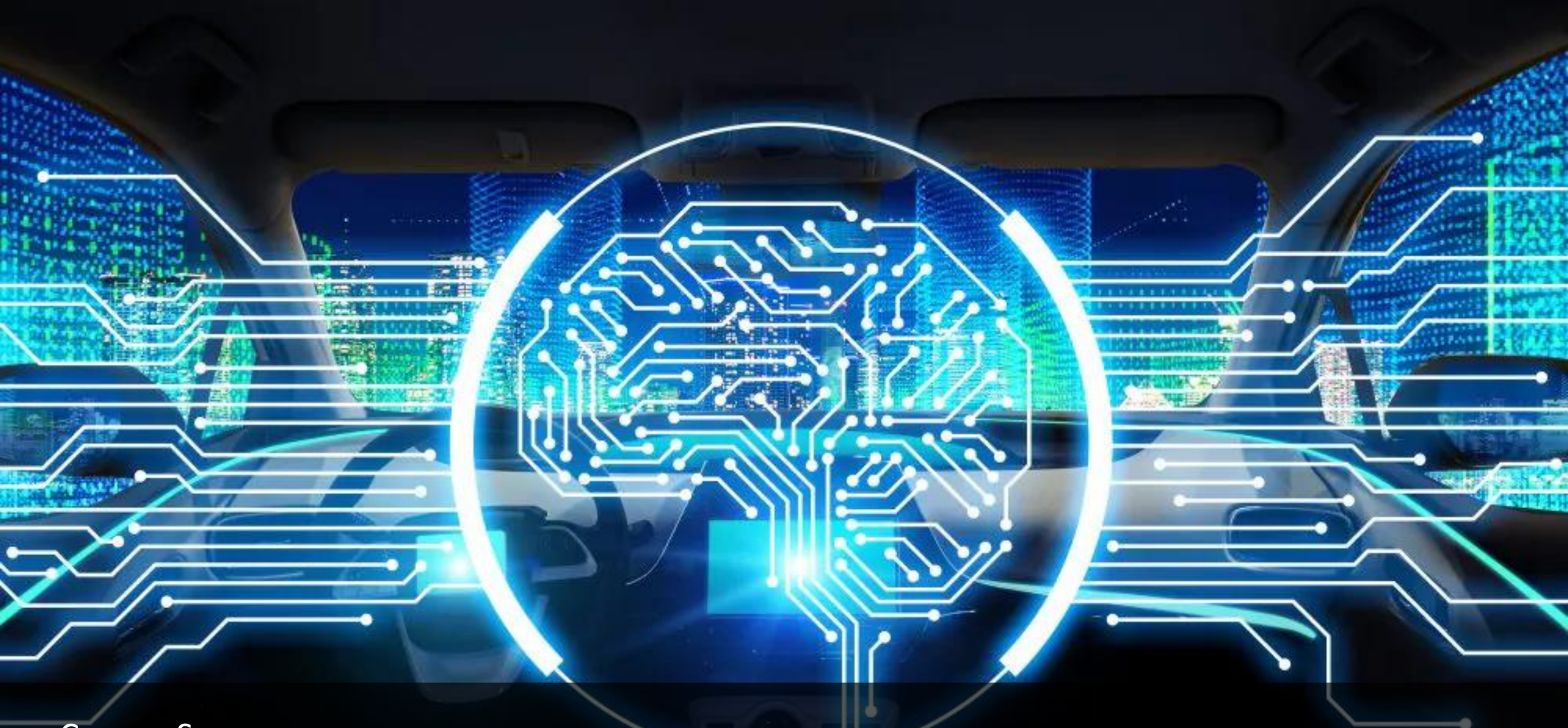
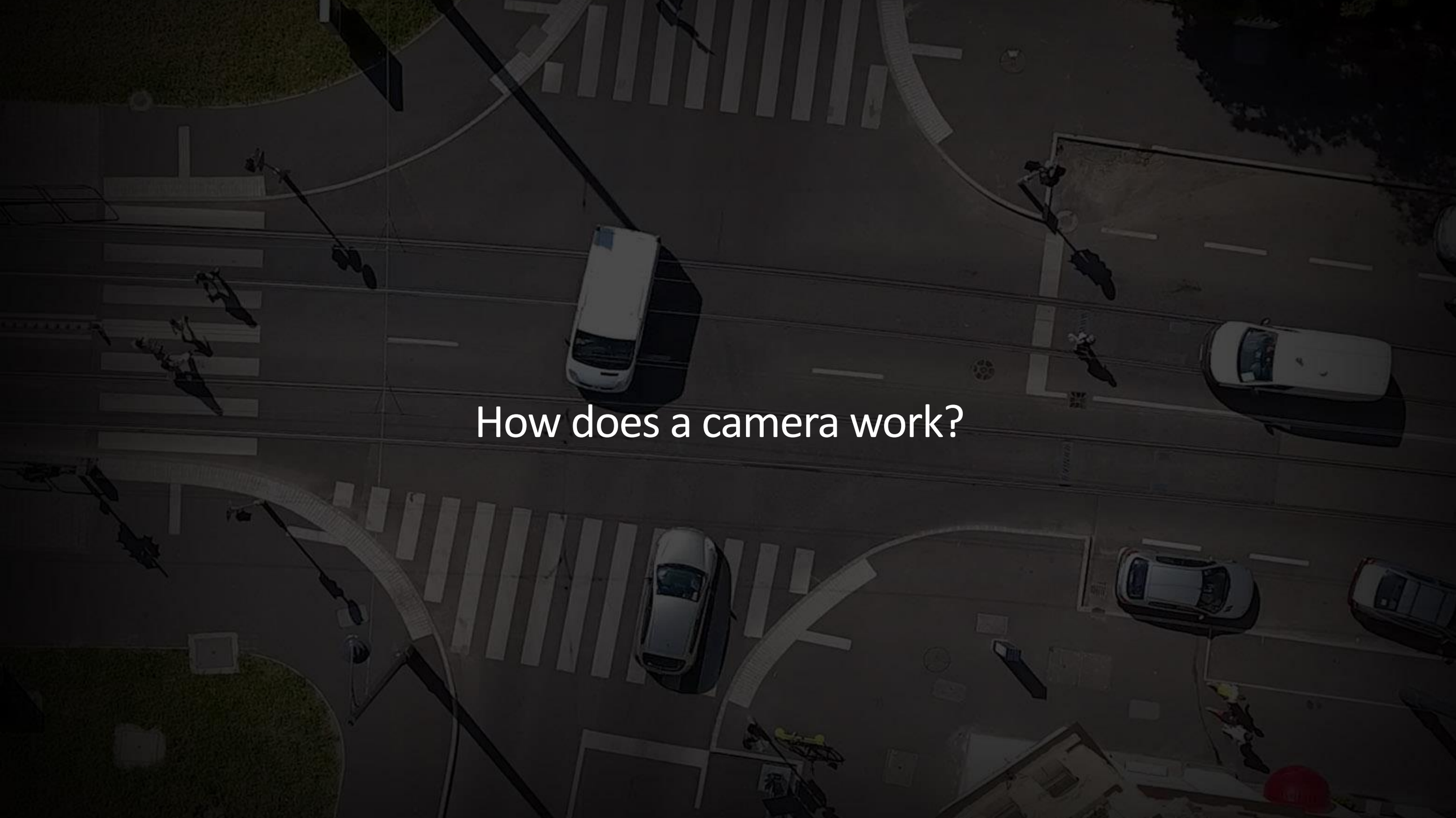


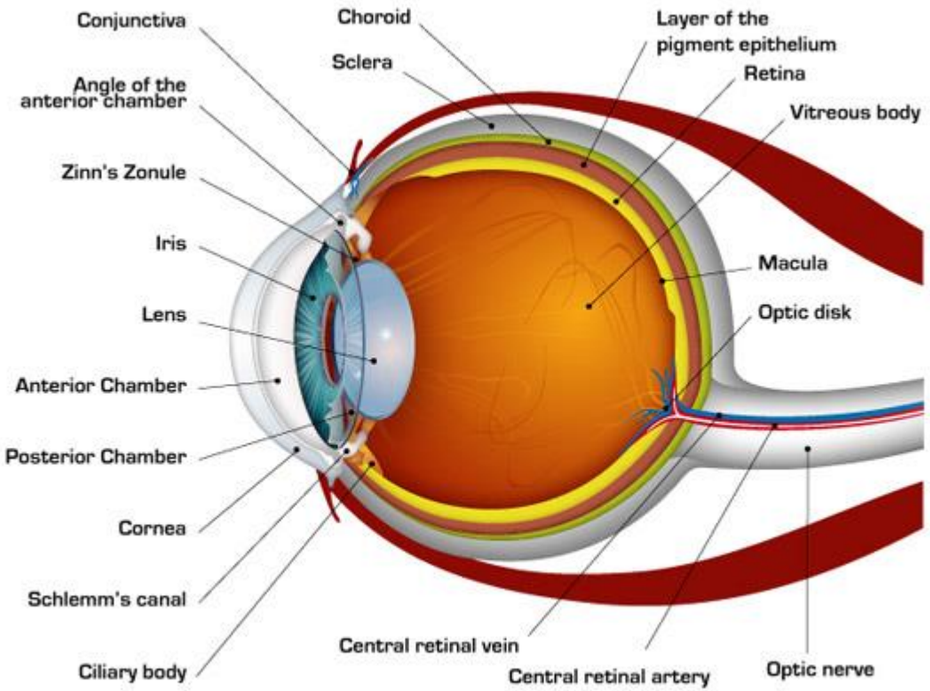
# Camera Sensors

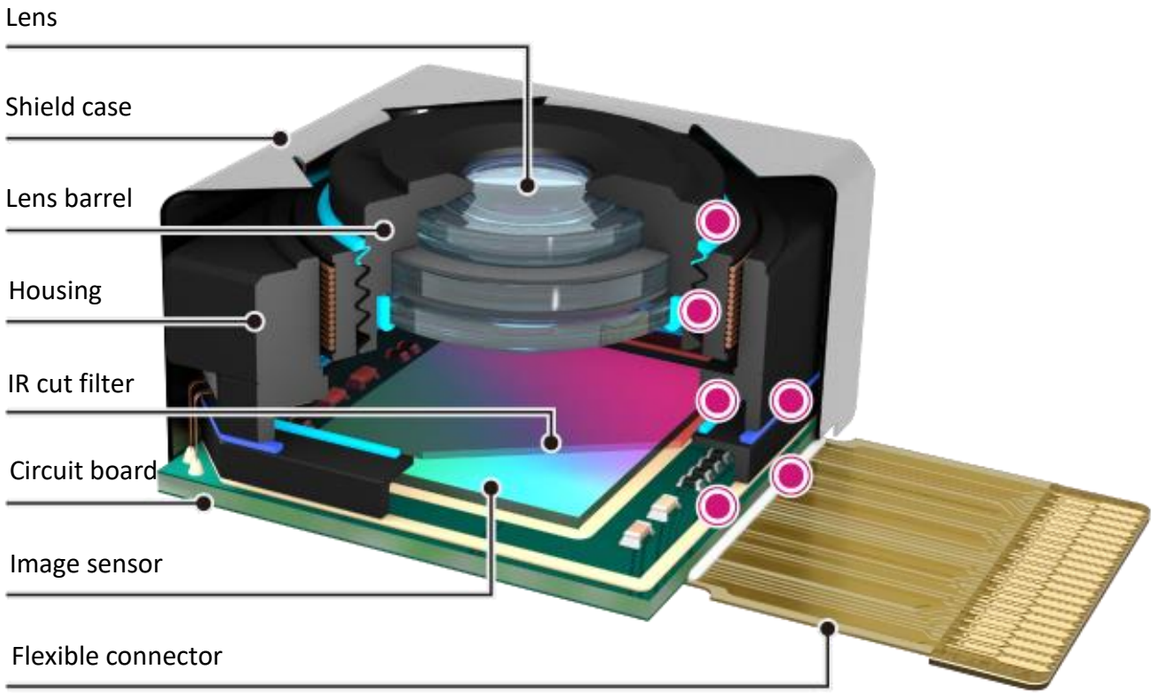
Peter D. Kozma – ELTE IK

# Content overview

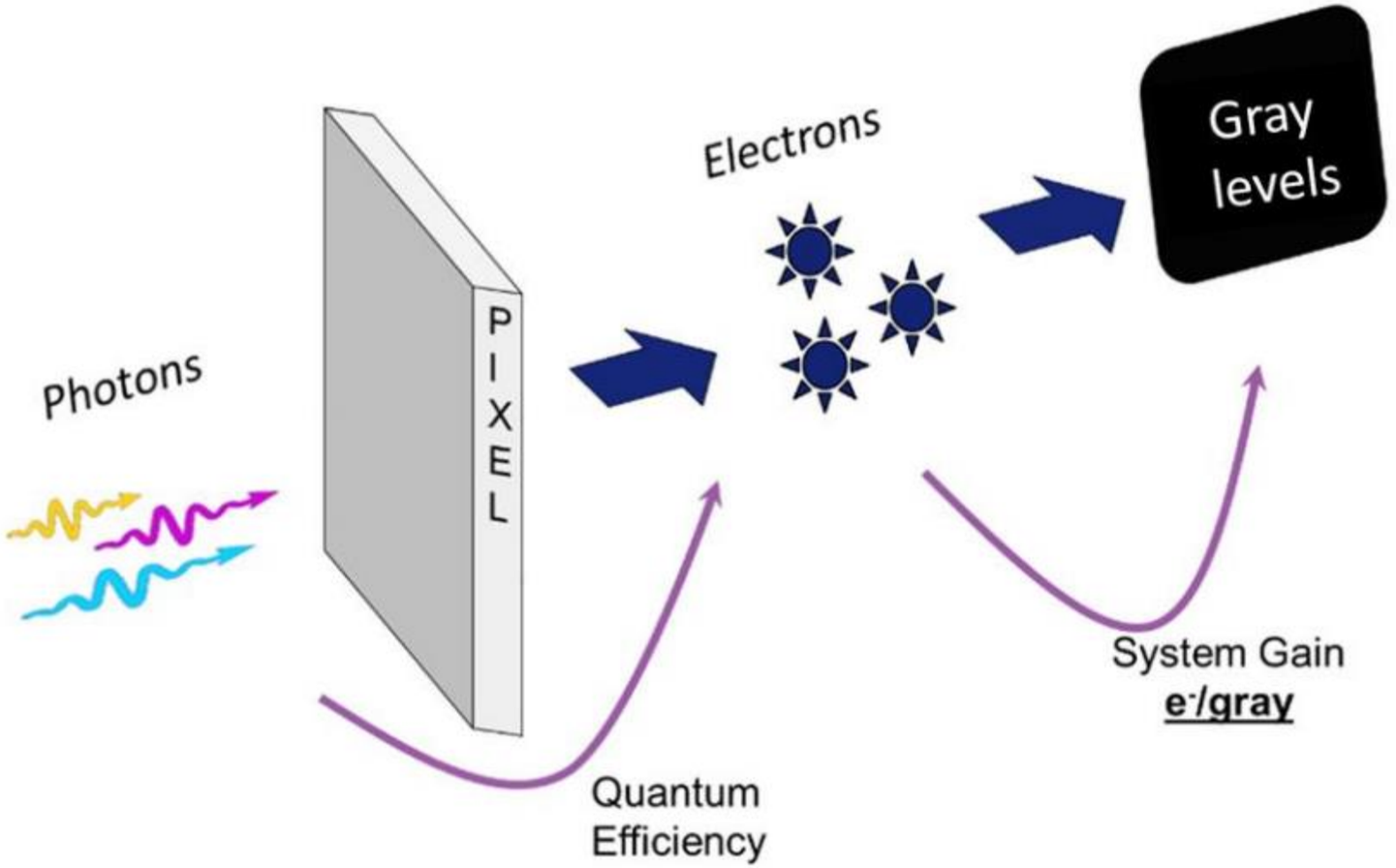

How does a camera work?

# Human eye and camera sensor

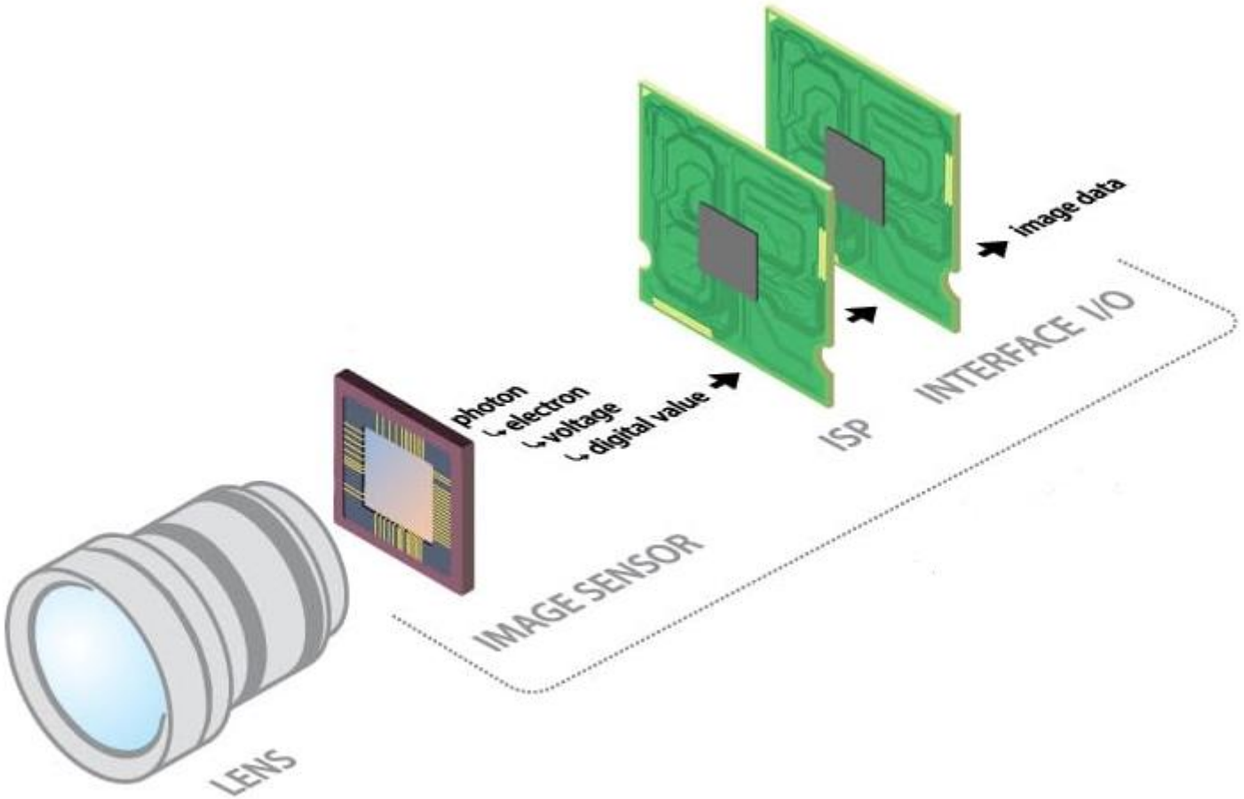


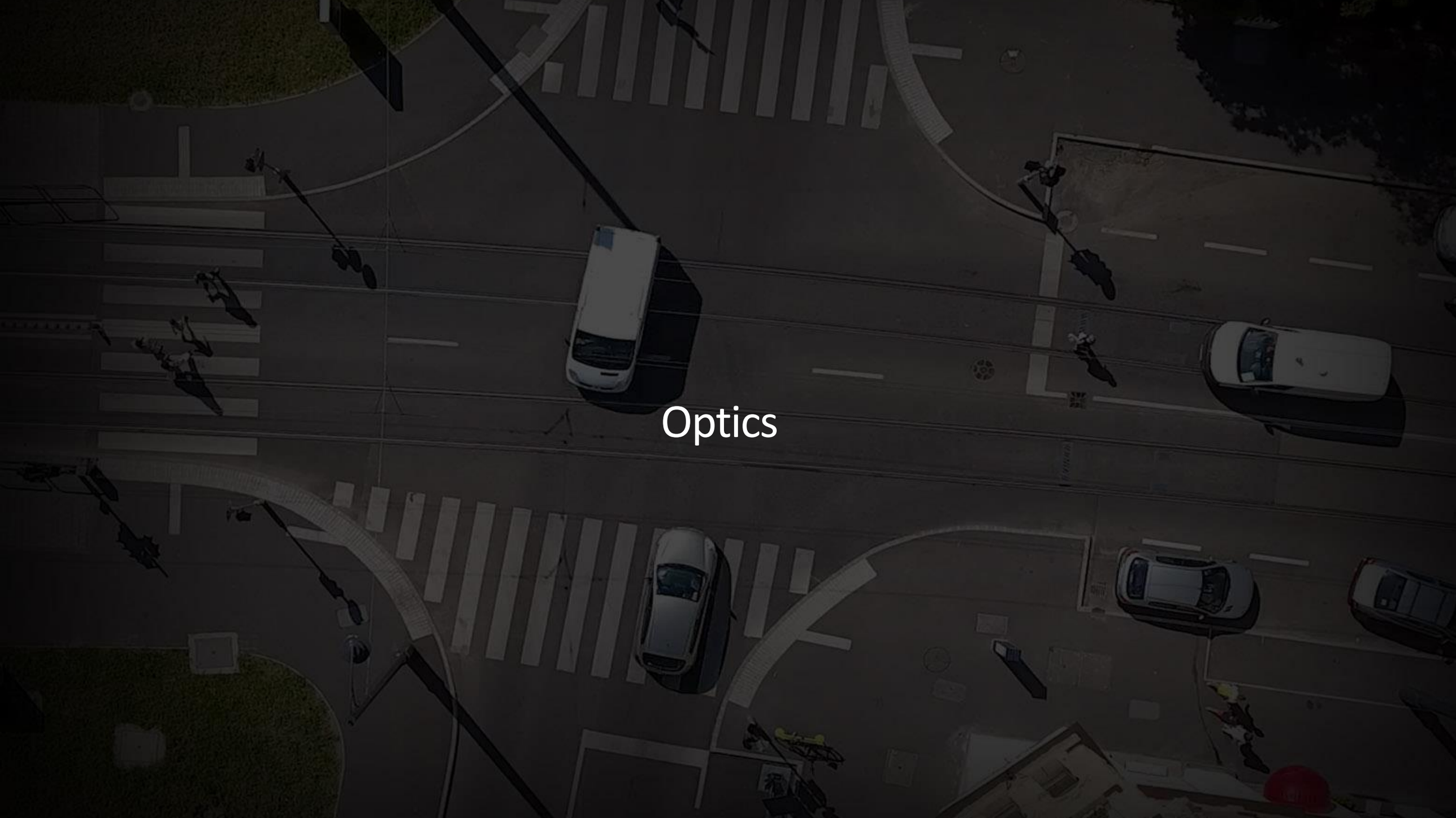



# We all know that



# Camera components

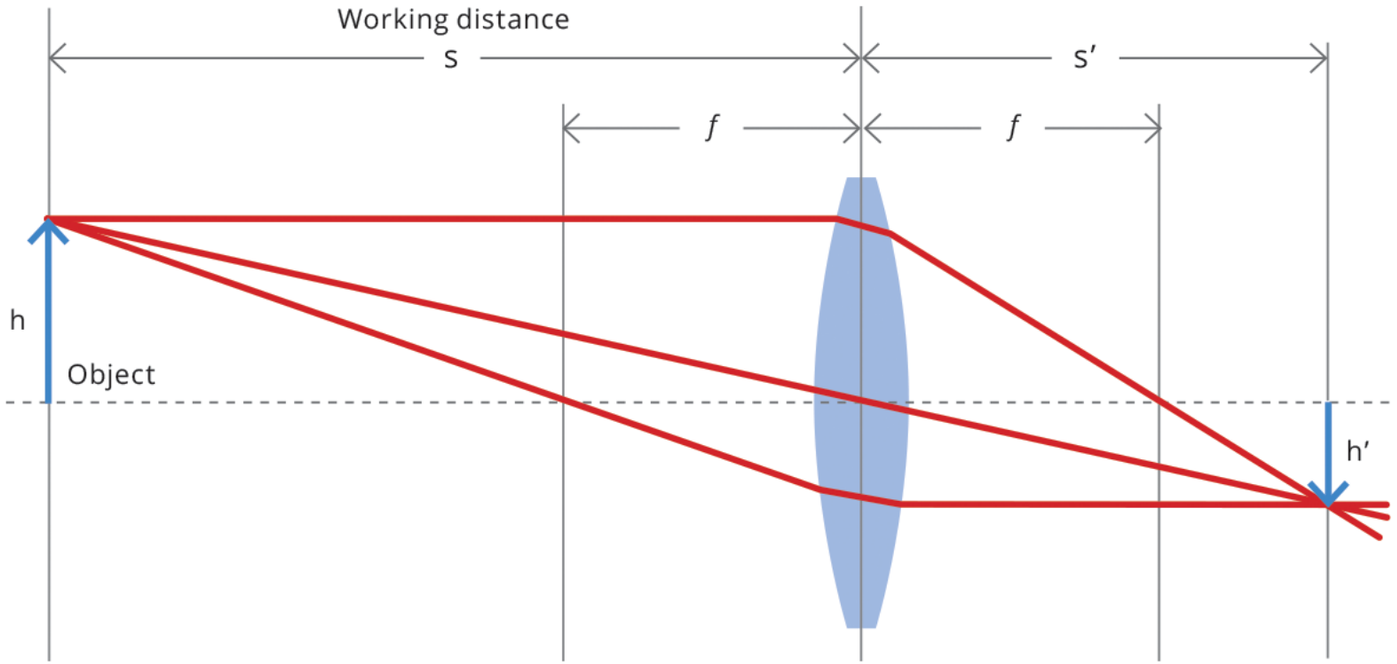




# Optics

# Thin lens- and paraxial approximation

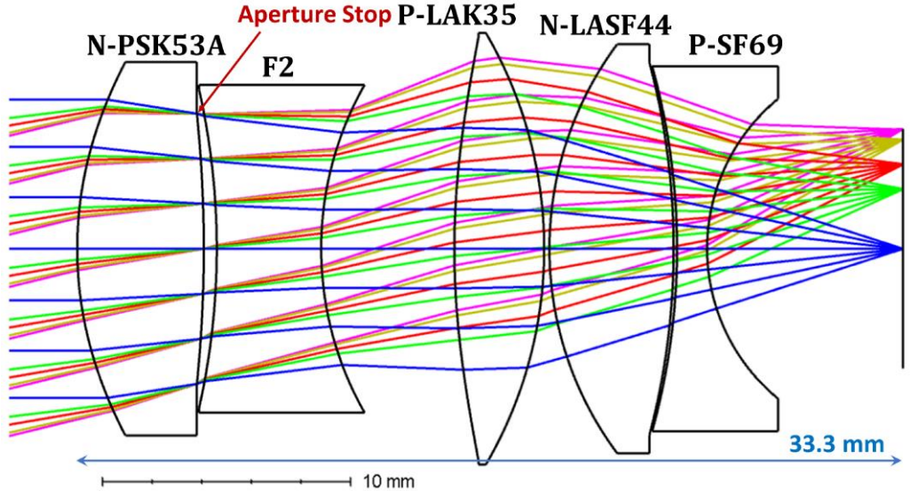
- **Focal lenght (f):** the distance from the center of the lens to the principal foci (or focal points) of the lens
- **Working distance (s):** object to lens distance where the image is at its sharpest focus
- **Focal distance (s'):** lens to sensor distance where the image is at its sharpest focus
- **Depth of Field (DoF):** maximum range where the object appears to be in acceptable focus
- **Magnification (M):** ratio between object (h) and its image (h')
- **Resolution:** minimum distance between two points that can still be distinguished as separate points
- **Field of View (FoV):** total area that can be viewed by the lens and imaged onto the camera sensor
- **F-number (F/#):** the ratio of the focal length (f) to the diameter (d) of the aperture

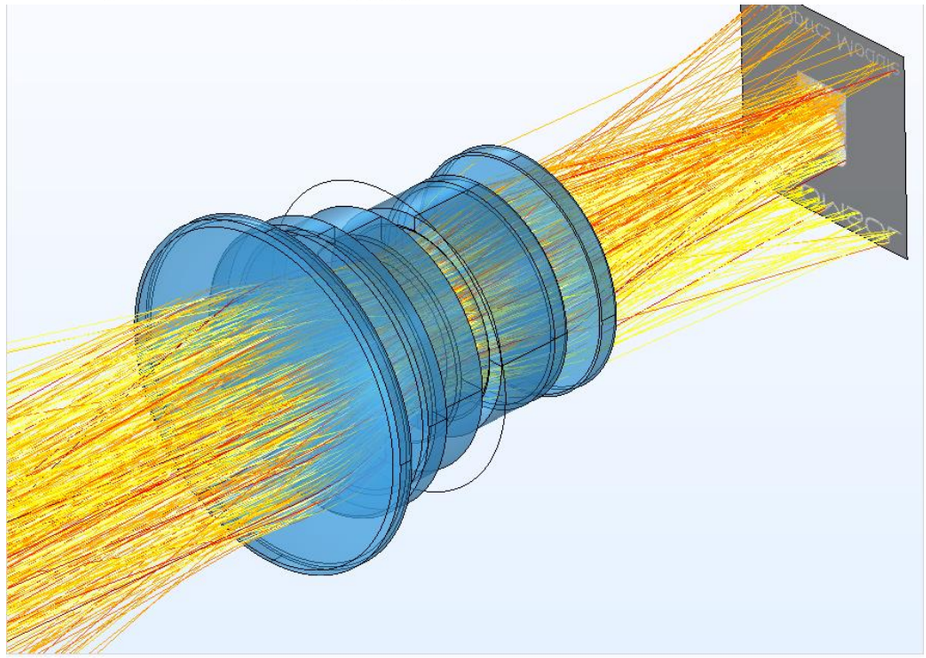



$$\frac{1}{s'} - \frac{1}{s} = \frac{1}{f} \qquad s = \frac{f(M-1)}{M} \qquad F/\# = \frac{f}{d}$$

# Real world optics

- **Ray tracing: design analysis and optimization**
  - Zemax OpticStudio: zemax.com
  - Code V: synopsys.com/optical-solutions/codev.html
  - OSLO: lambdares.com/oslo
  - TracePro: lambdares.com/tracepro
  - Comsol Multiphysics: comsol.com/ray-optics-module



# Why is it so complex?

- **Difficult requirements**
  - High resolution
  - Special working distance
  - Special wavelength
  - Variable focal distance
  - High FoV
  - Large DoF
  - Miniaturization
  - Cost optimization

**Careful design**

**Special materials**

**Difficult manufacturing**

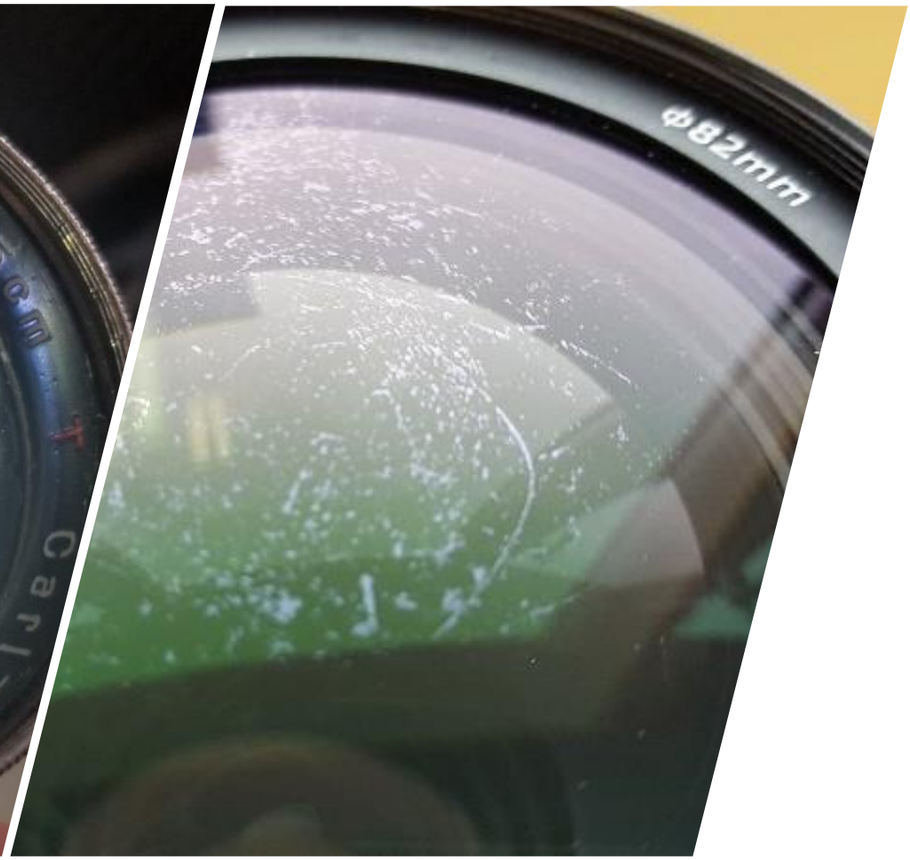
**Complex assembly**

- **Potential aberrations**
  - Physical aberrations
  - Spherical aberrations
  - Chromatic aberrations
  - Astigmatism
  - Coma
  - Field curvature
  - Distortion
  - Low contrast and resolution
  - Vignetting

# Physical aberrations

- Effects
  - Stray light (flare)
  - Loss of sharpness (blurring)
  - Reduced contrast (haze)
  - Washed-out colors
- Correction possibilities
  - Cleaning
  - Repair
  - Replacement
  - Preventive measures
  - Software correction

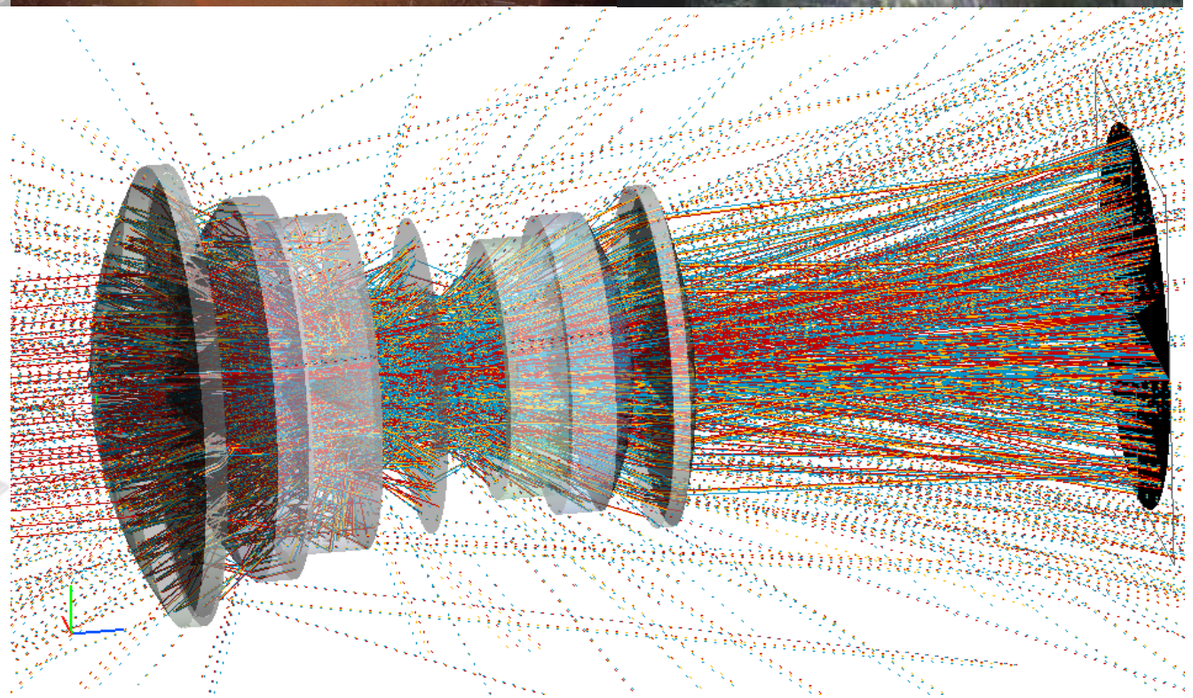

Dirt, dust, scratches, inhomogeneities




Damaged optical coating

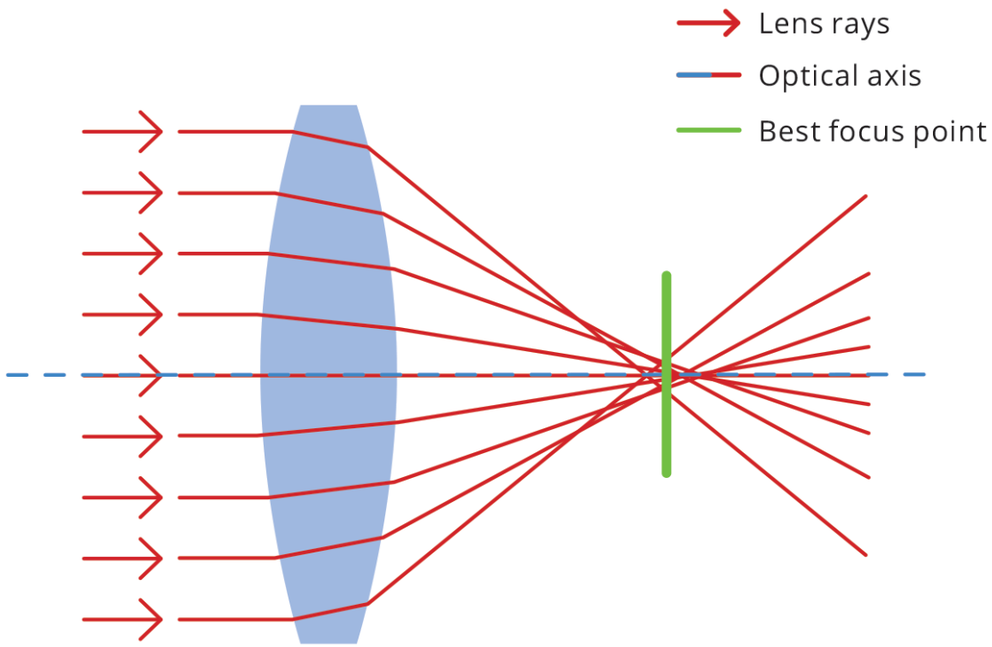
# Physical aberrations





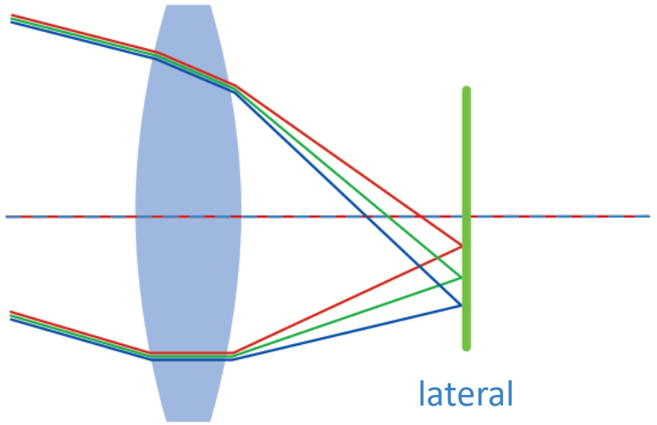
# Spherical aberrations

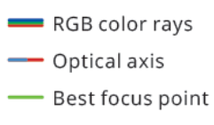
- Effects
  - Loss of sharpness (blurring)
  - Reduced contrast (haze)
  - Halo around bright objects
- Correction possibilities
  - Aperture reduction
  - Replacement to aspheric lens
  - Correction lens
  - Software correction

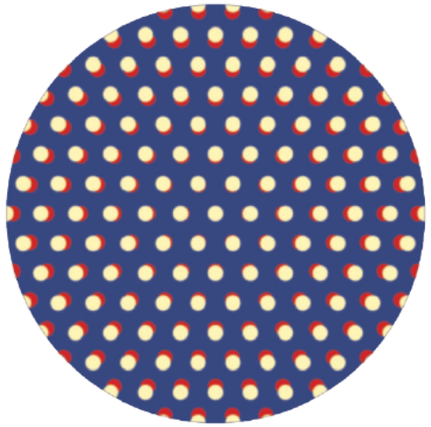


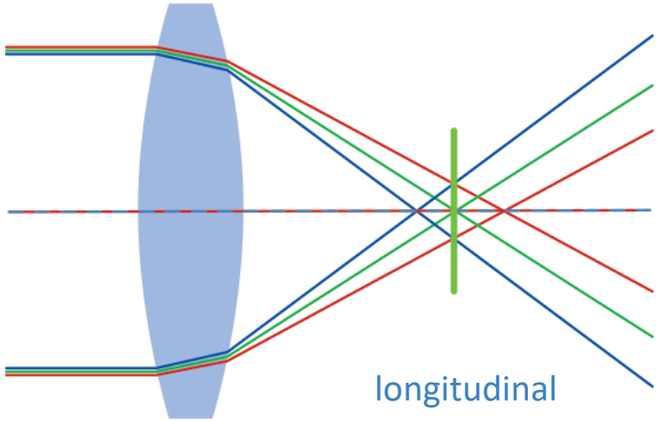
# Chromatic aberration

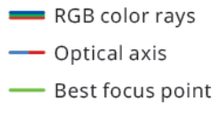
- Effects
  - Color fringing
  - Loss of sharpness (blurring)
  - Reduced contrast (haze)
- Correction possibilities
  - Aperture reduction
  - Replacement to achromatic lens
  - Correction lens
  - Software correction

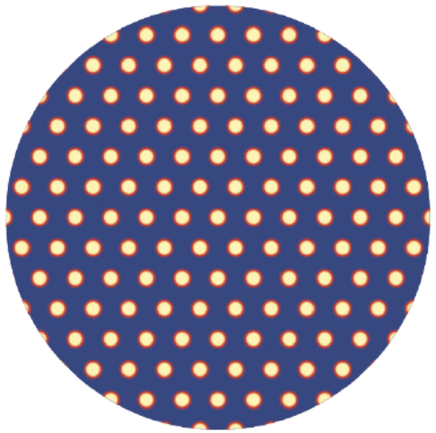


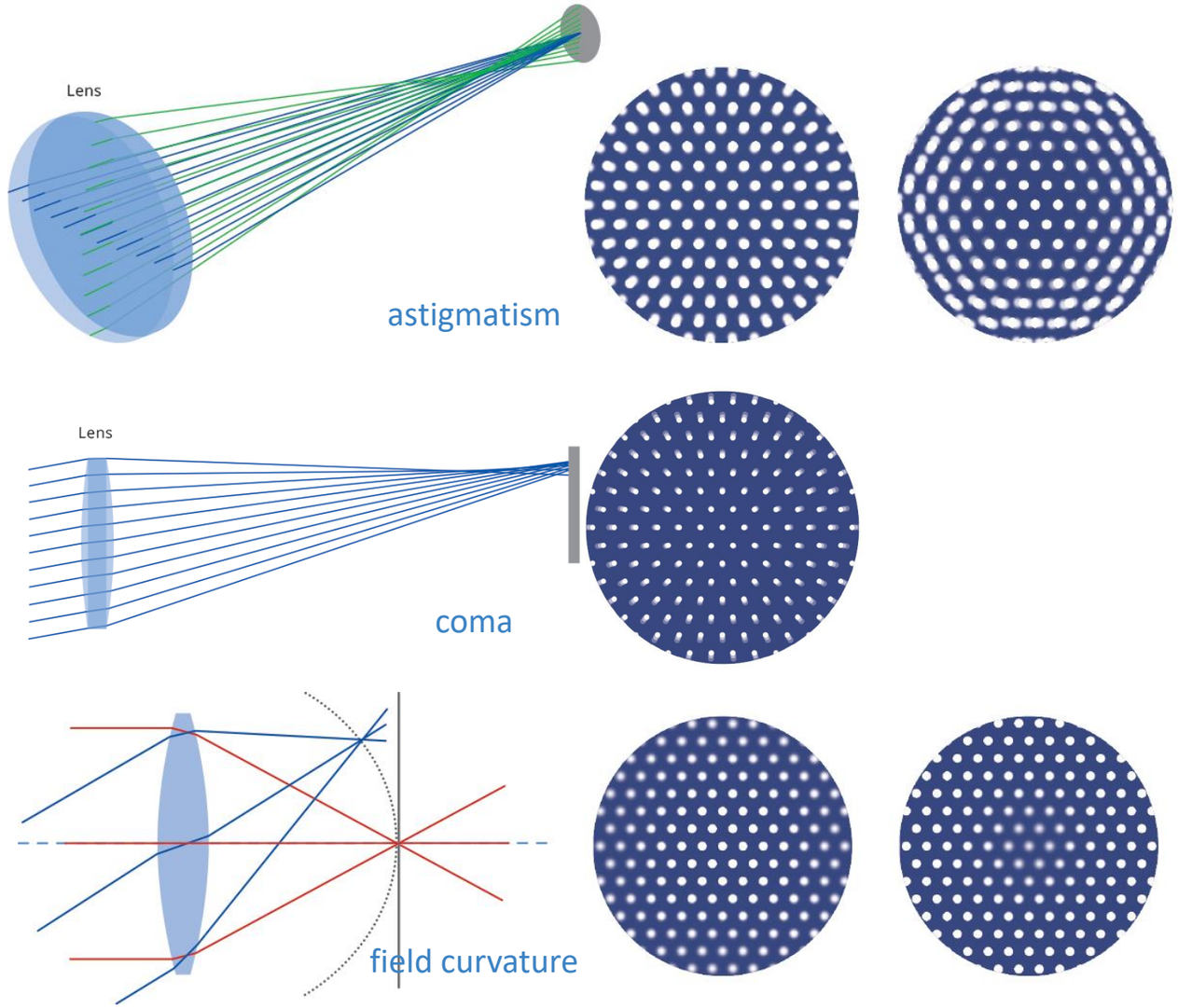


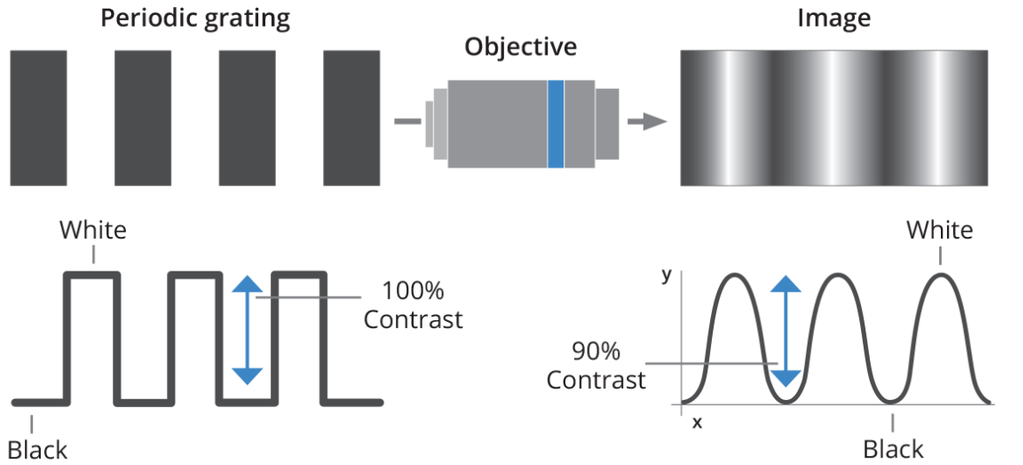
# Astigmatism, coma, field curvature

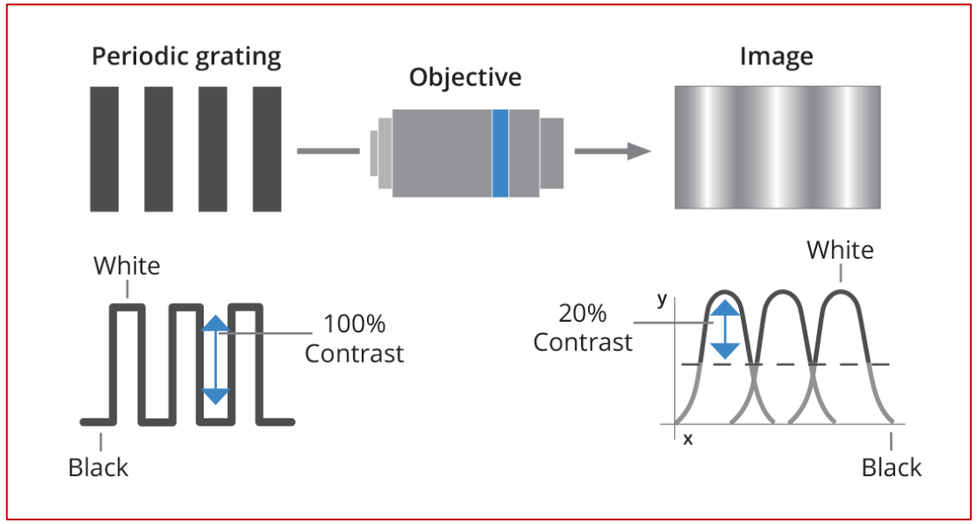
- Effects
  - Loss of sharpness (blurring)
  - Reduced contrast (haze)
- Correction possibilities
  - Aperture reduction
  - Replacement of lens
  - Correction lens
  - Software correction



# Reduced contrast, reduced resolution

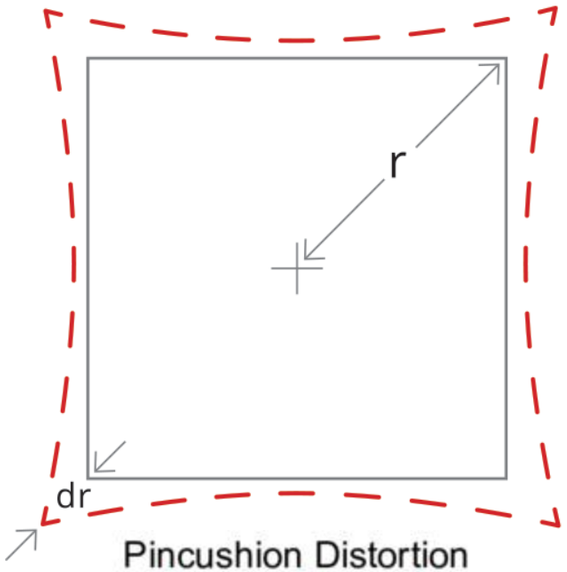
- Effects
  - Loss of sharpness (blurring)
  - Reduced contrast (haze)
  - Washed-out colors
- Correction possibilities
  - Aperture reduction
  - Replacement of lens
  - Software correction



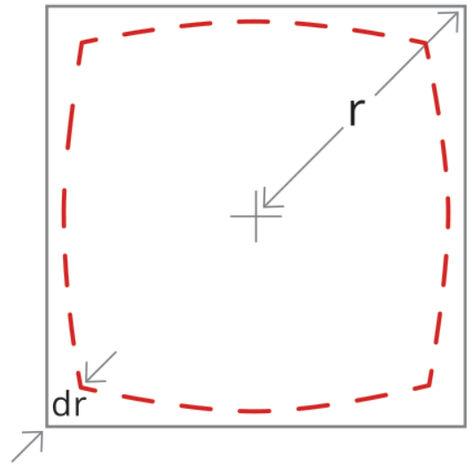



# Distortion

- Effects
  - Image deformation
- Correction possibilities
  - Replacement of lens
  - Correction lens
  - Software correction



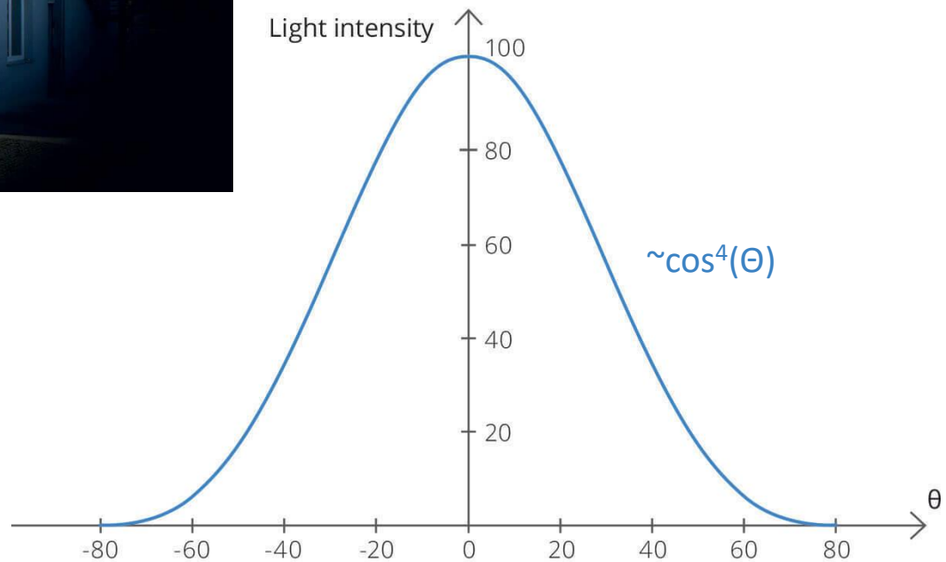

Pincushion Distortion




Barrel Distortion

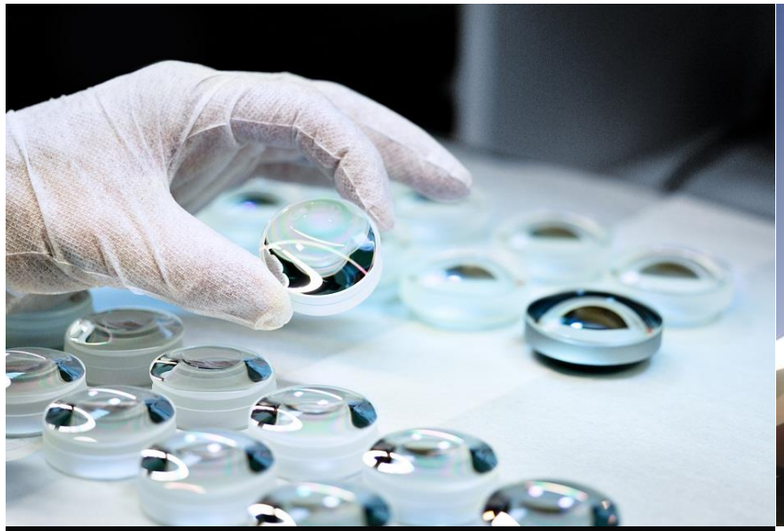
# Vignetting

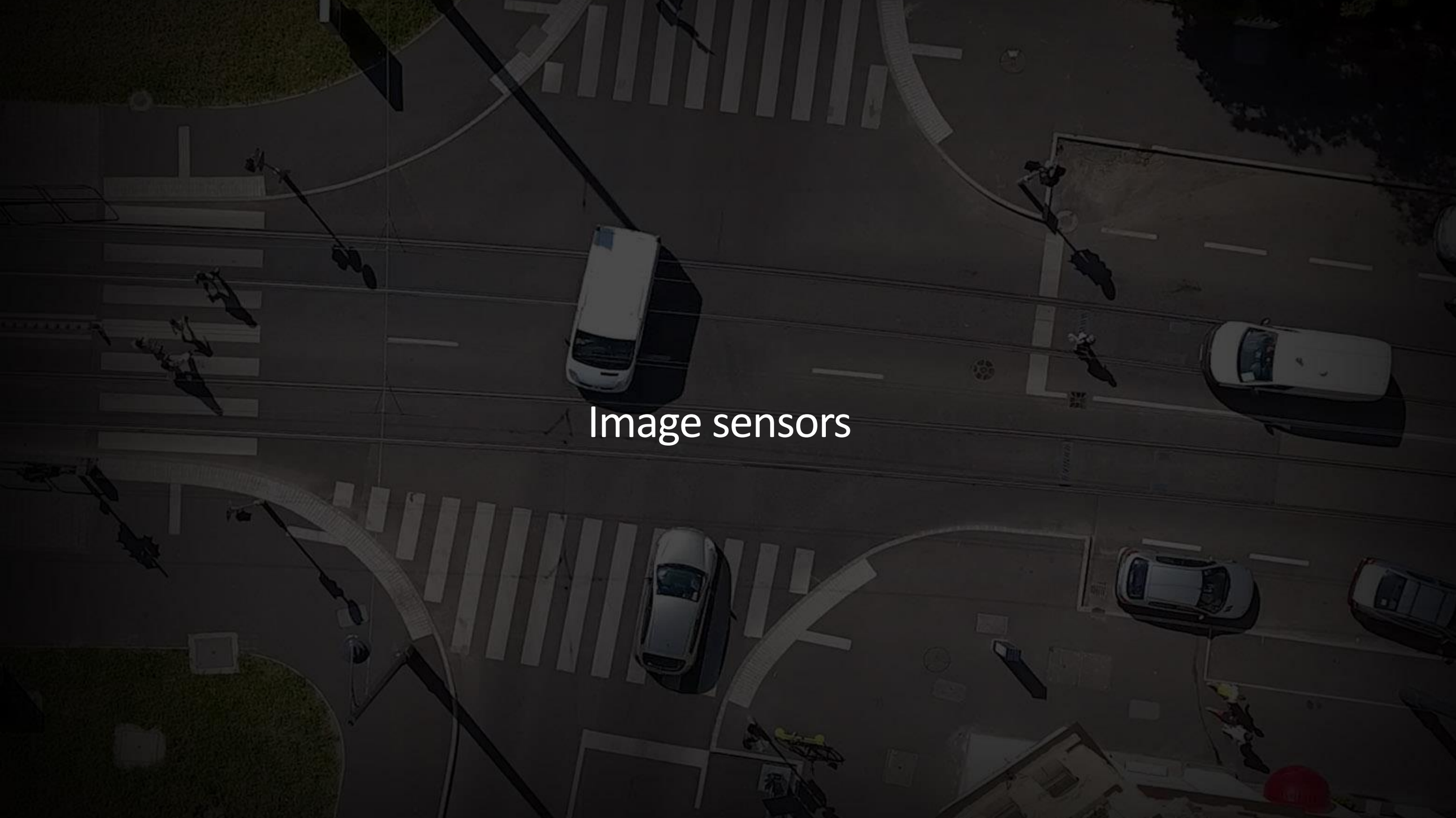
- Effects
  - Decreasing intensity by angle of incidence
- Correction possibilities
  - Aperture increase
  - Decreased FoV
  - Software correction



# Optics manufacturers

- **Some relevant optics manufacturers**
  - Carl Zeiss AG: zeiss.com
  - Nikon Corporation: nikon.com
  - Thorlabs, Inc.: thorlabs.com
  - Edmund Optics: edmundoptics.com
  - Schott AG: schott.com
  - Corning Incorporated: corning.com
  - Jenoptik AG: jenoptik.com
  - Olympus Corporation: olympus-global.com
  - Leica Microsystems: leica-microsystems.com
  - Canon Inc.: global.canon.com

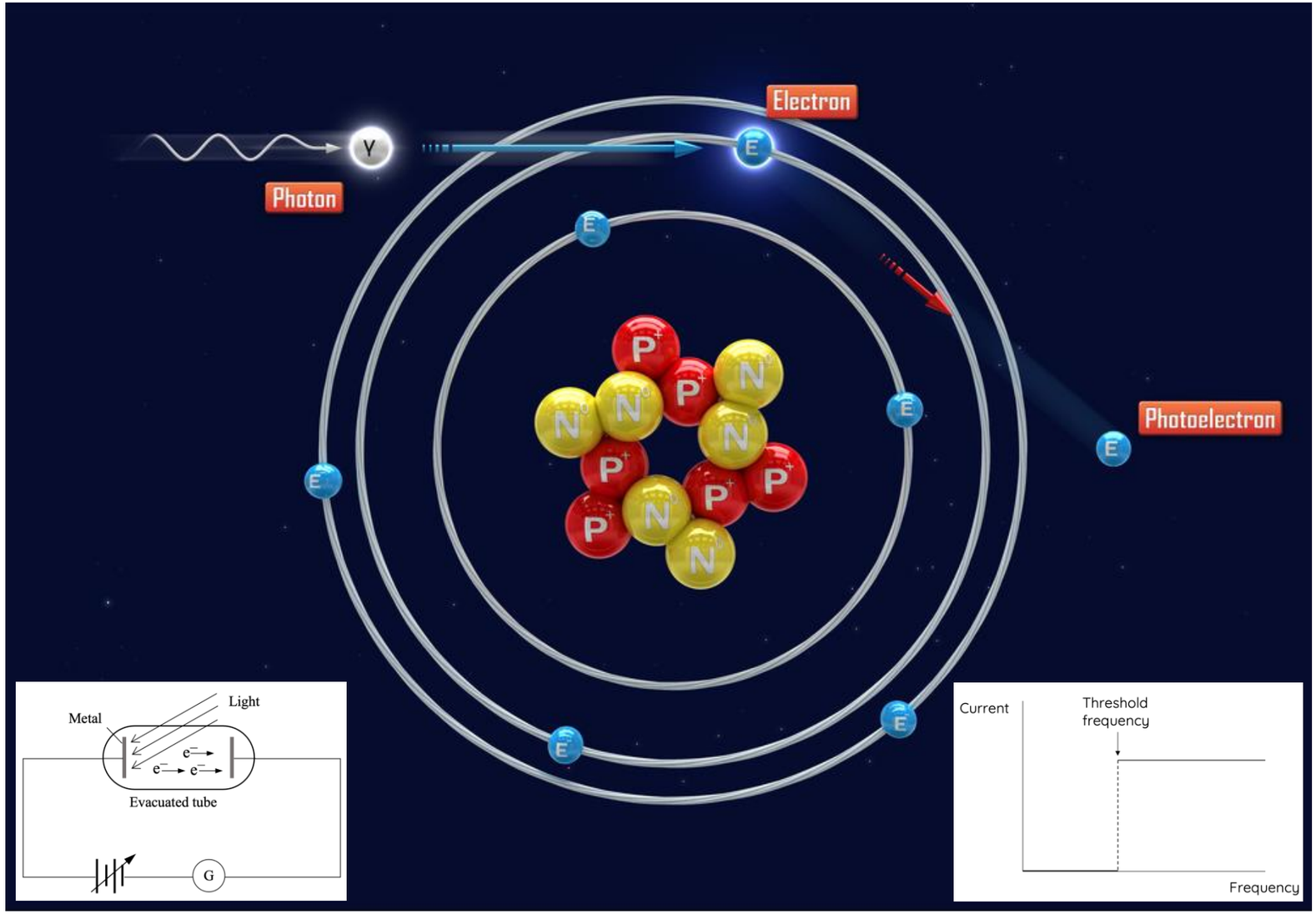


# Image sensors

# The photoelectric effect

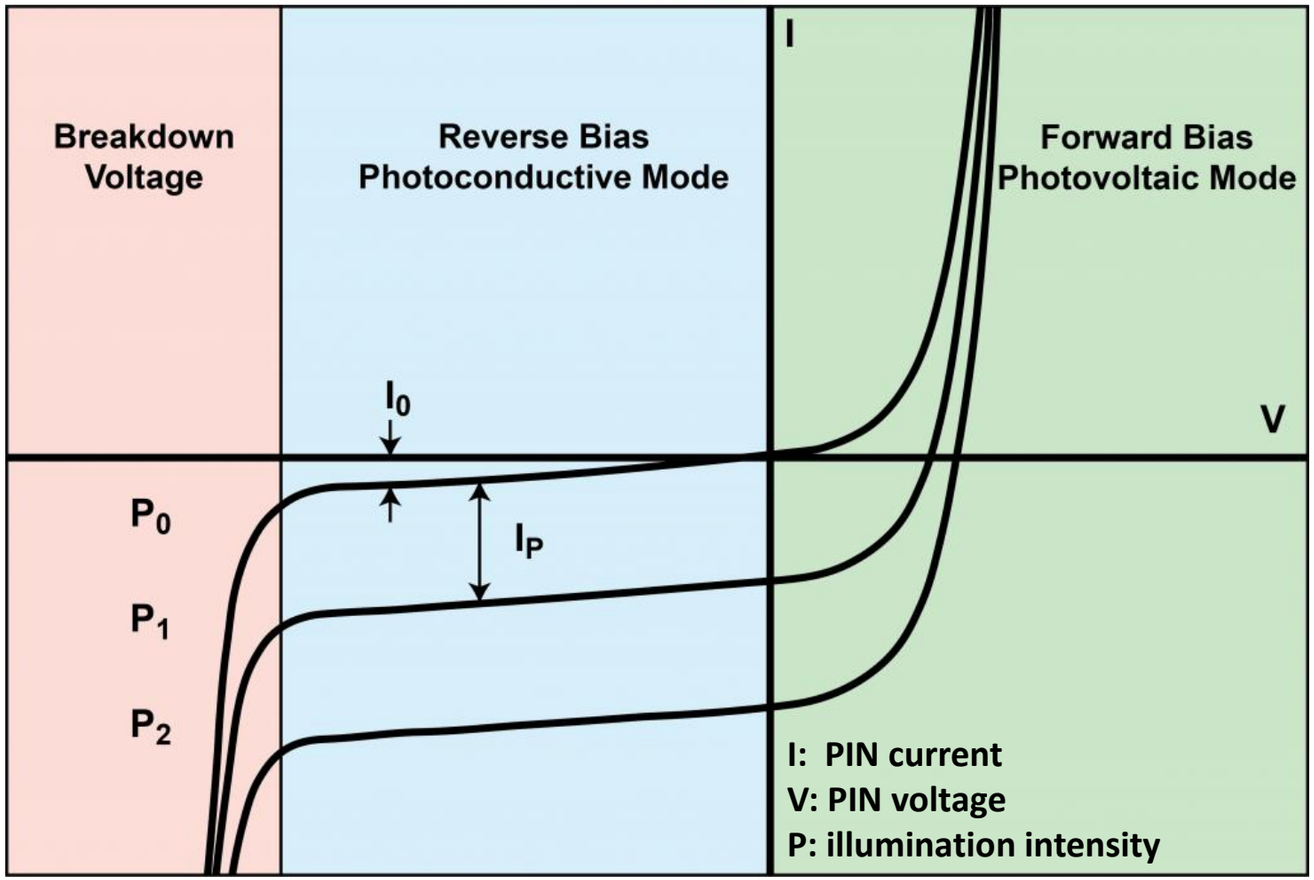
- Electromagnetic radiation can cause electron emission (H. Hertz)
- P. Lenard's experiment results disagreed with classical electromagnetism
- The phenomenon is frequency dependent
- A. Einstein's quantum model of light Nobel Price (1921)
- Material absorbs photons ($E=hv$) and emits (photo)electrons, if E > work function



# Photodetector

- Semiconductor device to transform optical signal to electrons, a kind of diode
- PN junction of large area & shallow junction depth
- Operating under reverse voltage
- No light → low reverse current = dark current
- Photons generate electron-hole pairs
- Reverse current = photocurrent ~ light intensity (not voltage)

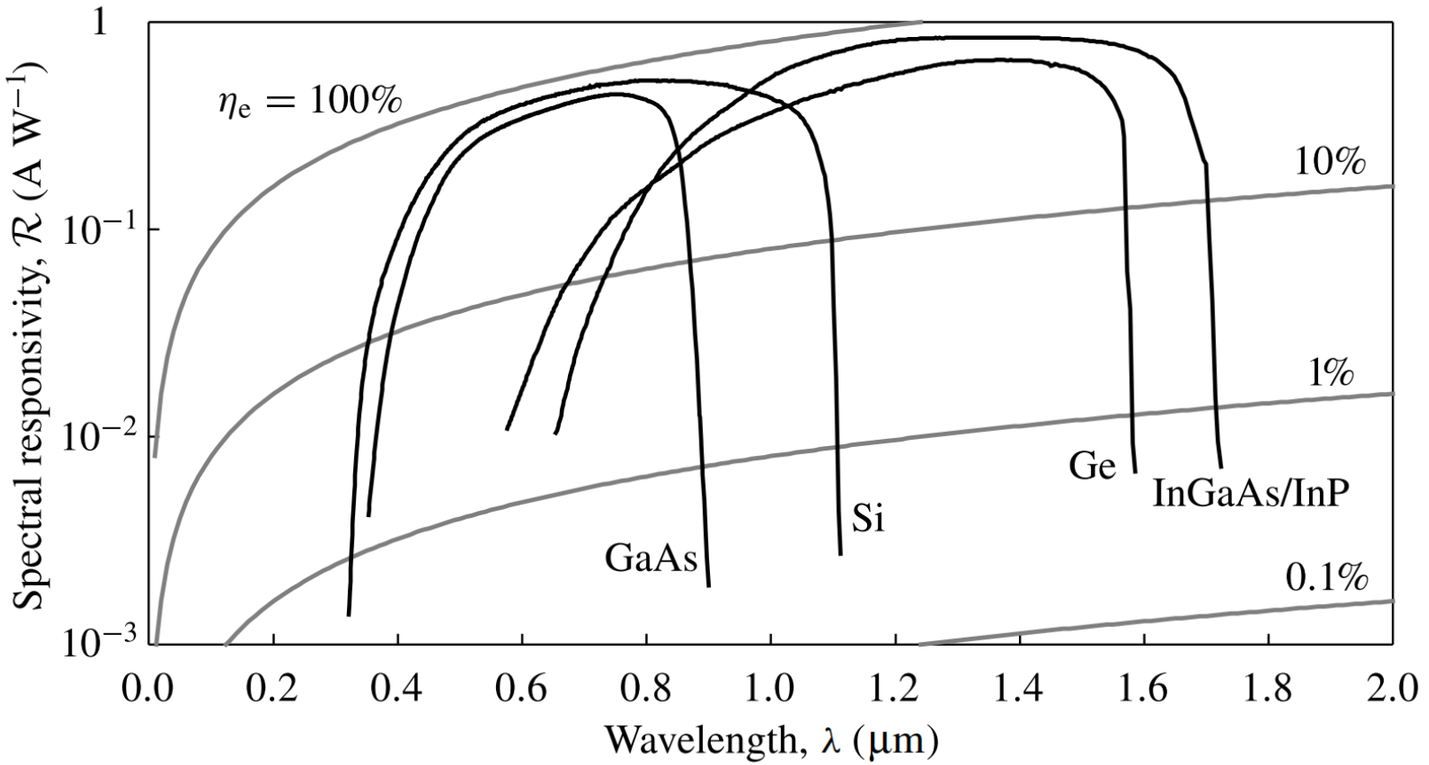
- Theory




PIN photodiode

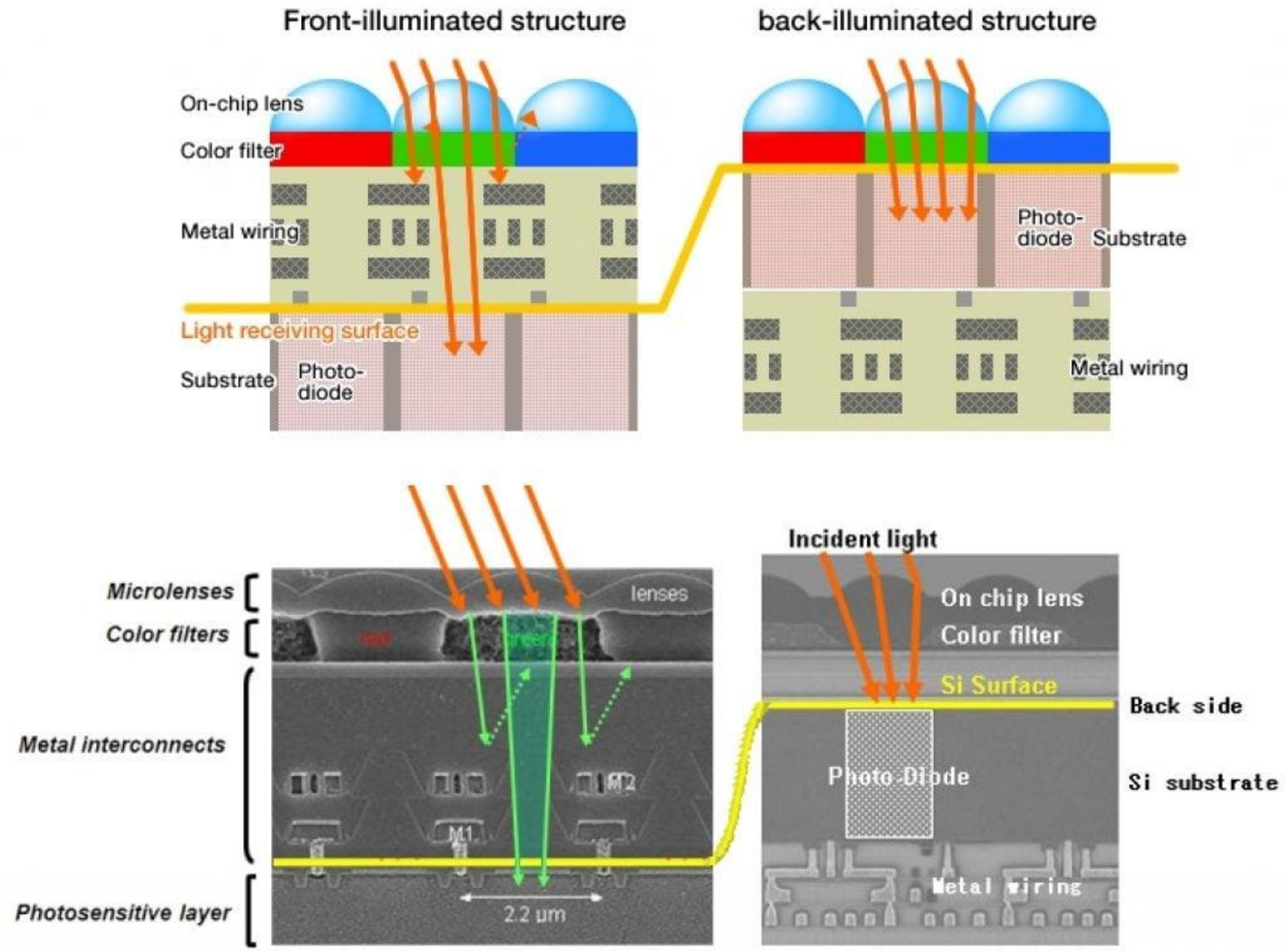
# Quantum efficiency

- Different materials for different applications
  - Silicon (Si)
  - Germanium (Ge)
  - Indium Gallium Arsenide (InGaAs)
  - Gallium Arsenide (GaAs)
  - … and many others
- Spectral responsivity (*R*): [A/W]
  - Intensity to current conversion
- Quantum efficiency ($\eta$): [ ]
  - Photon to photoelectron conversion



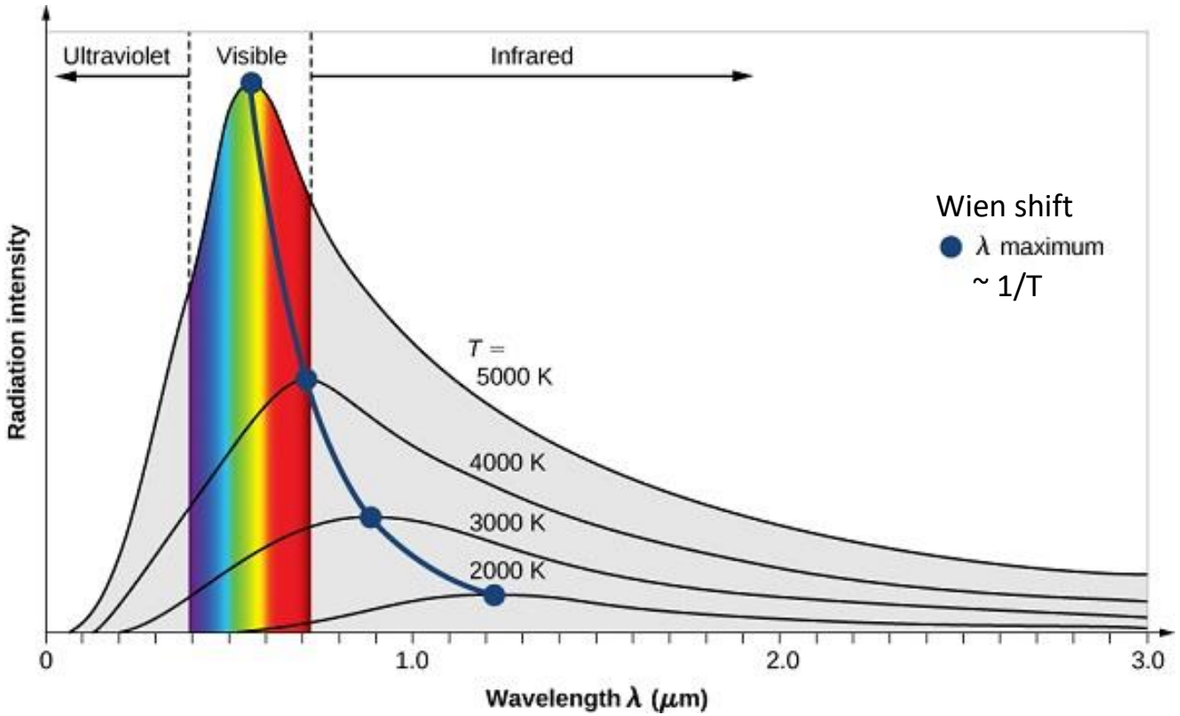
# Image sensor

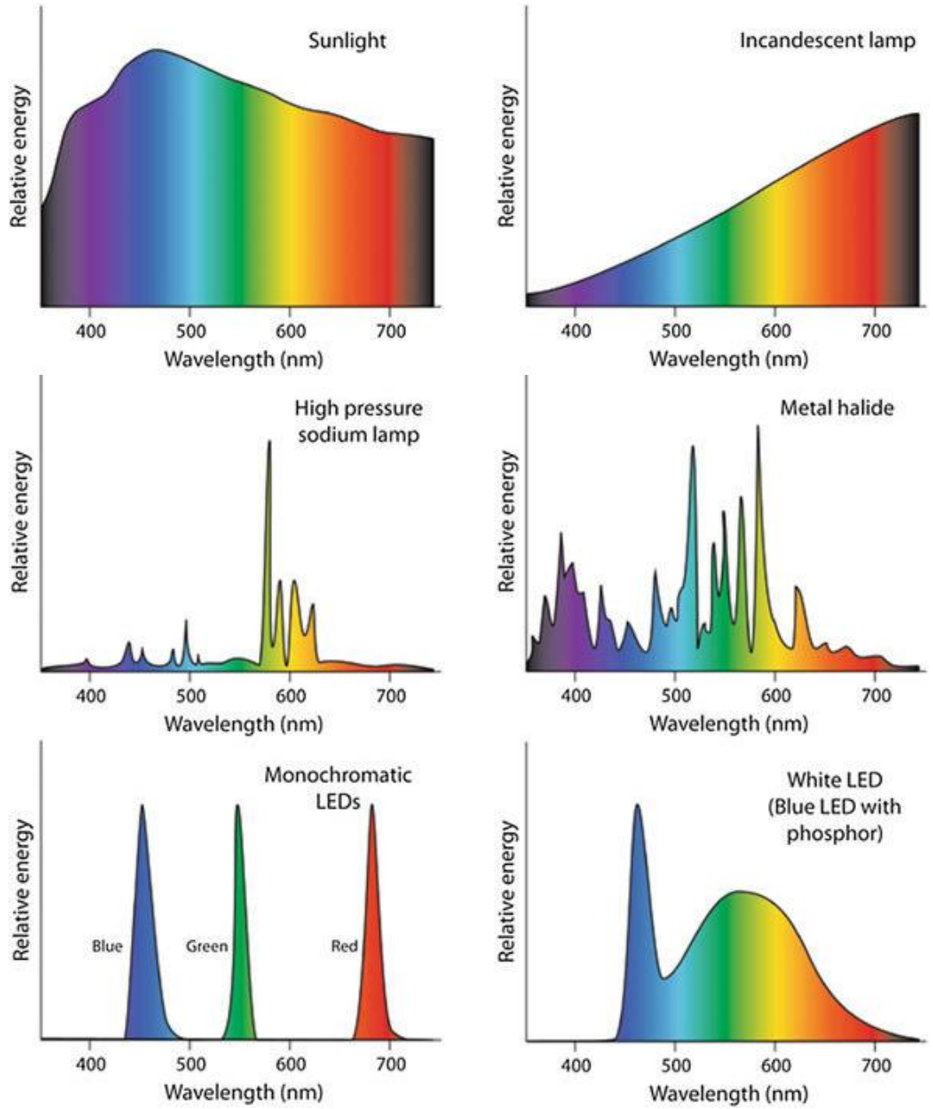
- Main components of a pixel
  - Microlens array
  - Color filter
  - Photodiode
  - Electronics
- Sensor Architecture
  - Front-side illuminated
  - Back-side illuminated
- Sensor technology
  - Charge coupled device
  - Complementary metal-oxide semiconductor



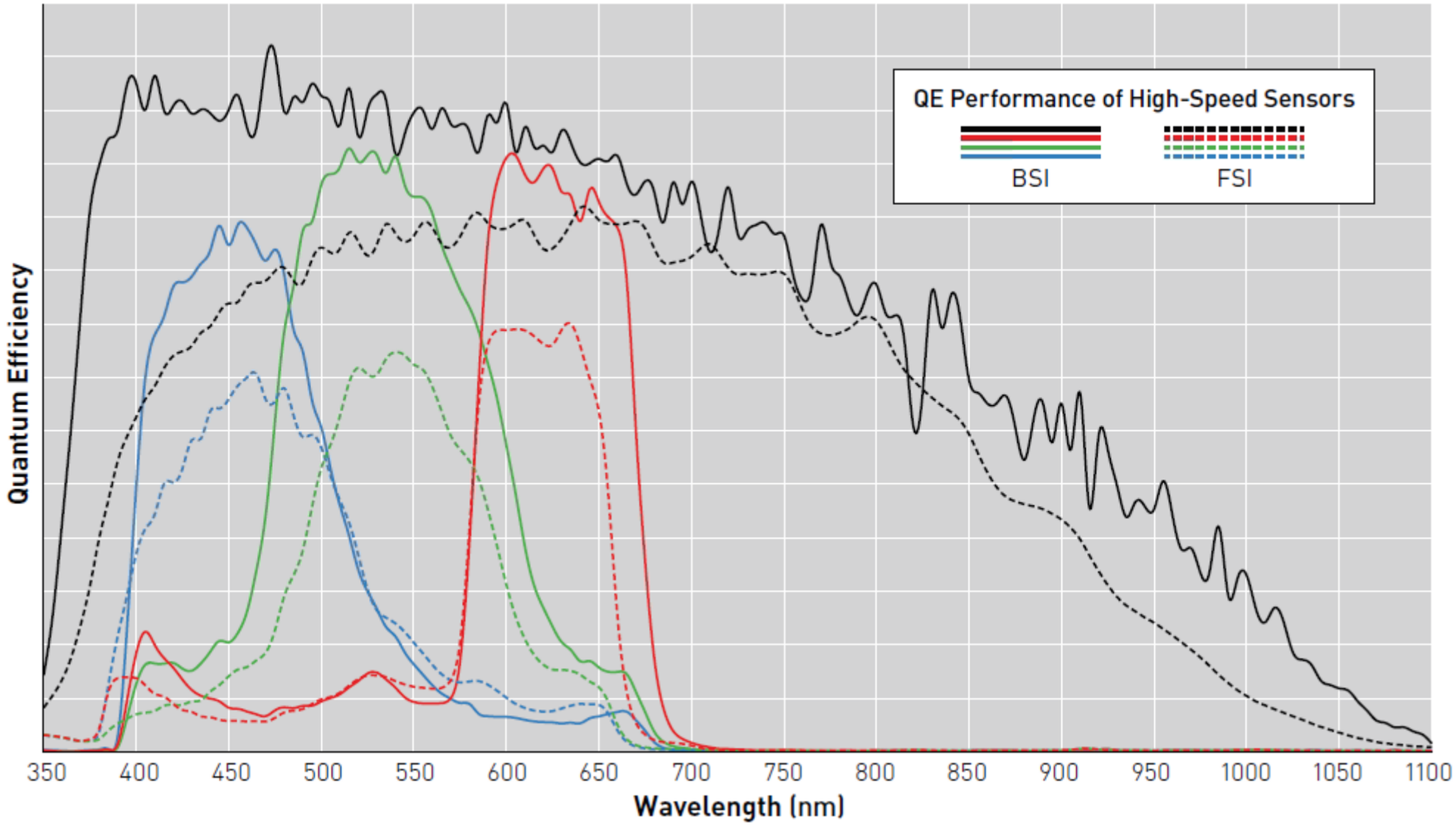
# Illumination spectrum

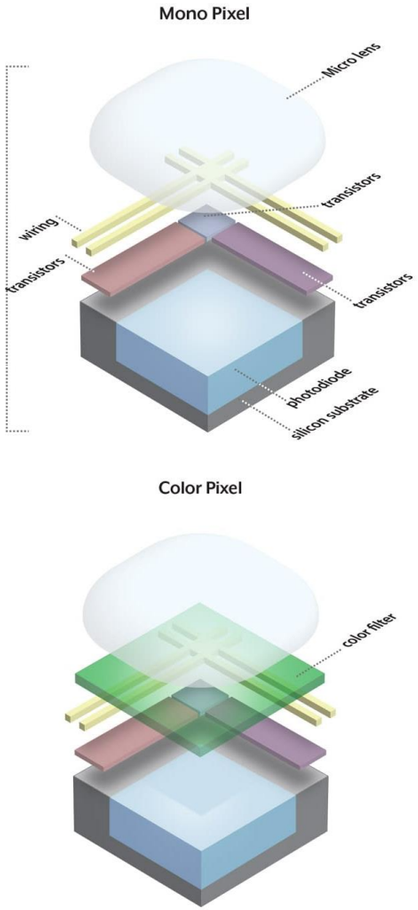
Black-body radiation



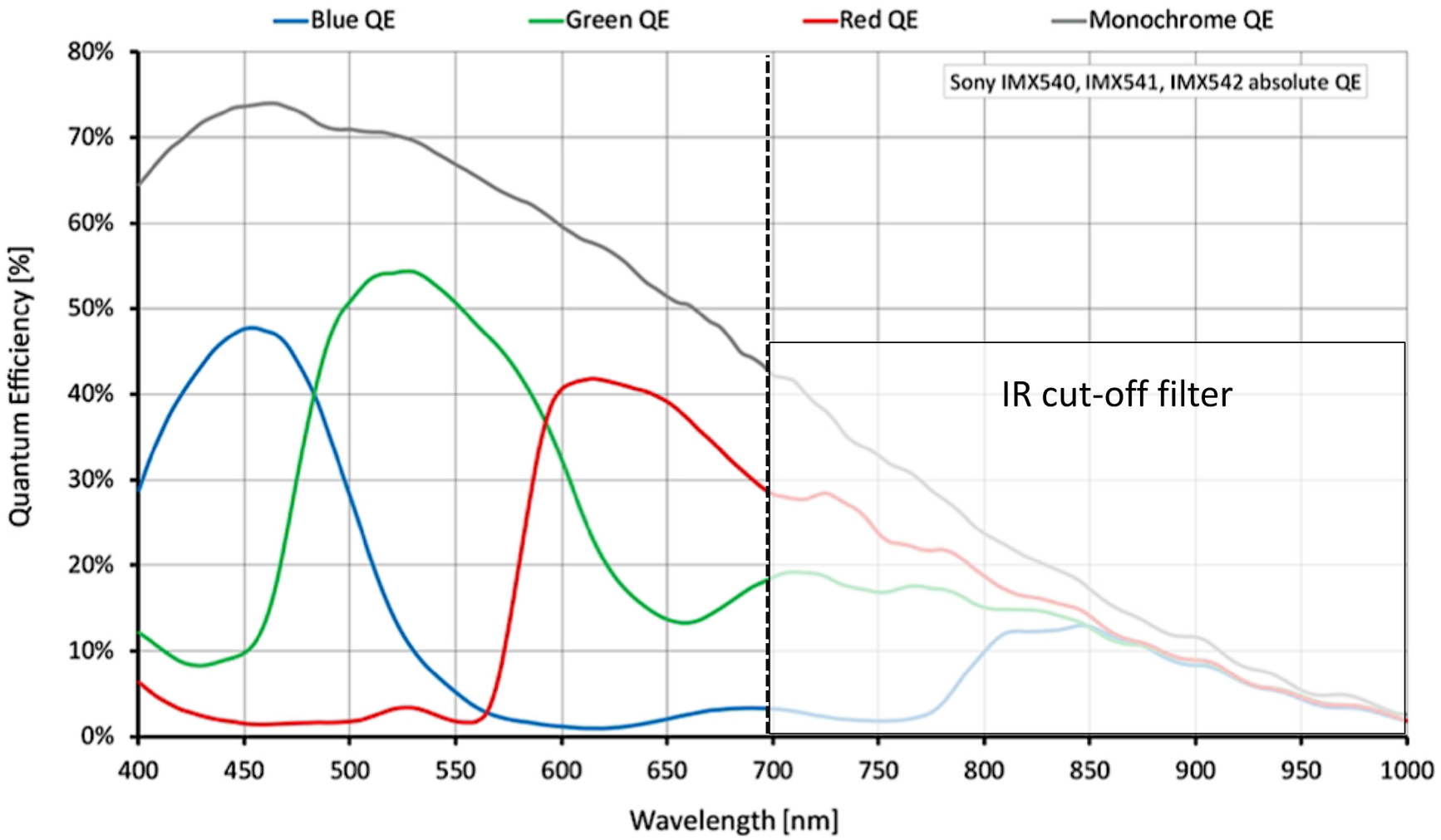



# Quantum efficiency plot



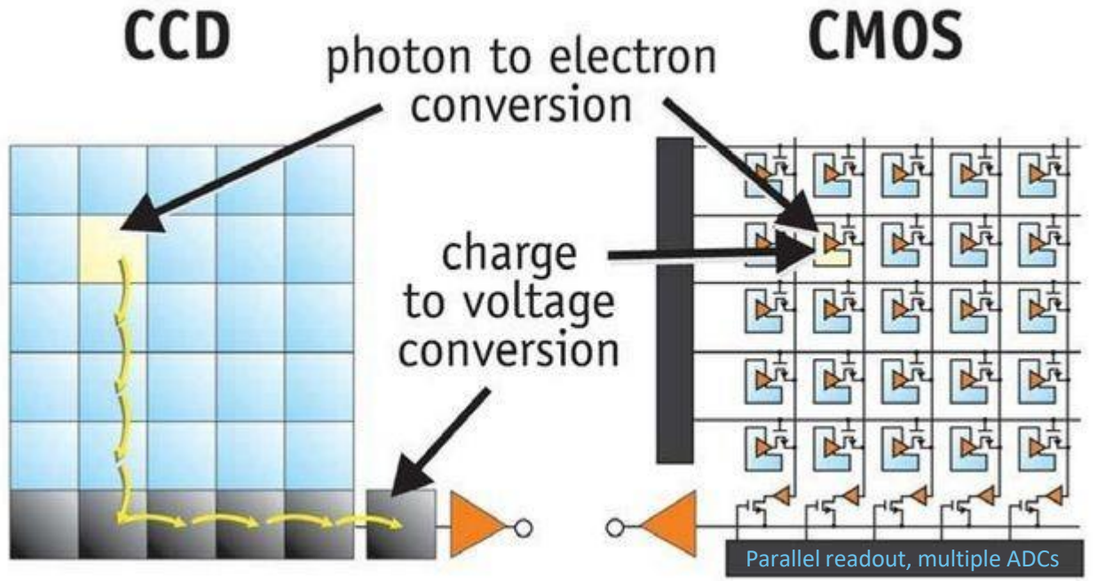
# Quantum efficiency plot

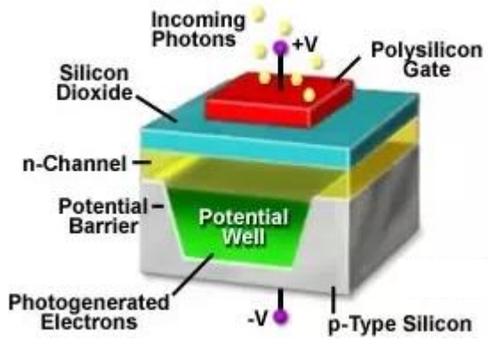


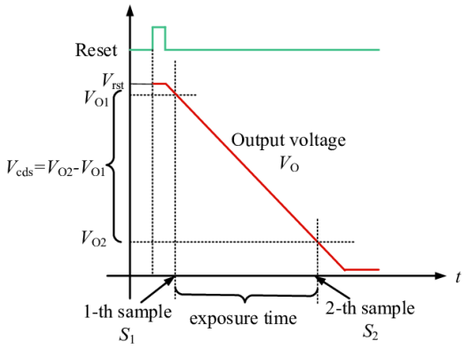
# Image sensors

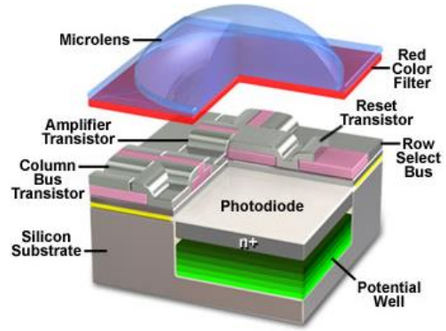
- Charge coupled device (CCD)
  - Higher sensitivity
  - Higher uniformity
- Complementary metal-oxide semiconductor (CMOS)
  - Faster readout and ROI
  - Higher integrability (SoC)
  - Lower power consumption
  - Lower manufacturing cost

- Video



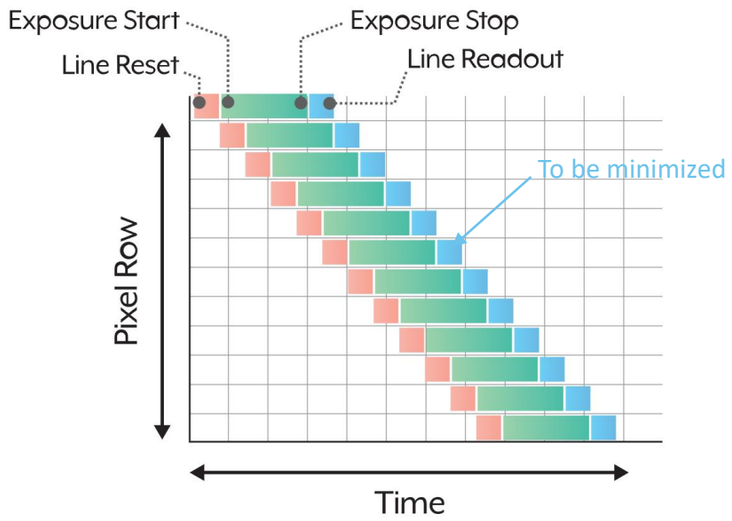



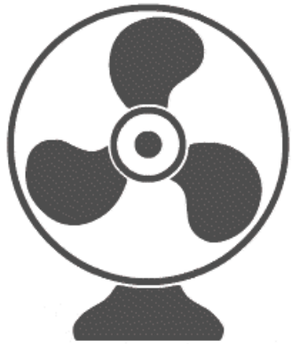



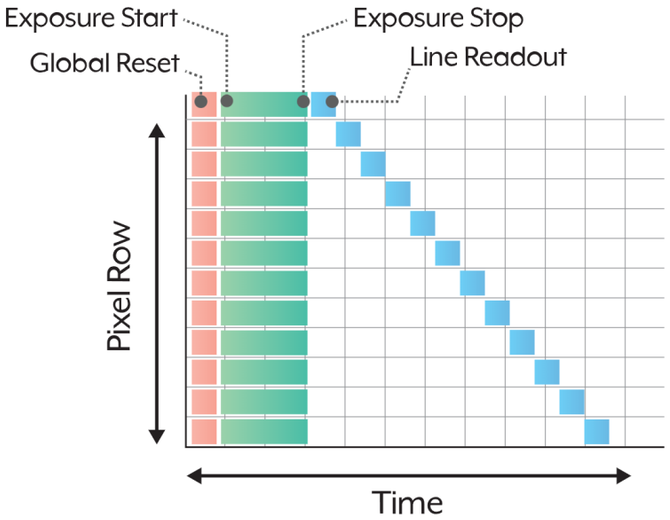



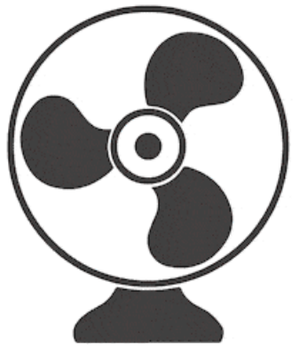
# Shutter types

- Shutter types
  - Rolling shutter
    - Typically CMOS
    - Motion artifacts
    - Synchronization issues
  - Global shutter
    - Typically CCD
    - Lower frame rates
    - Higher power consumption

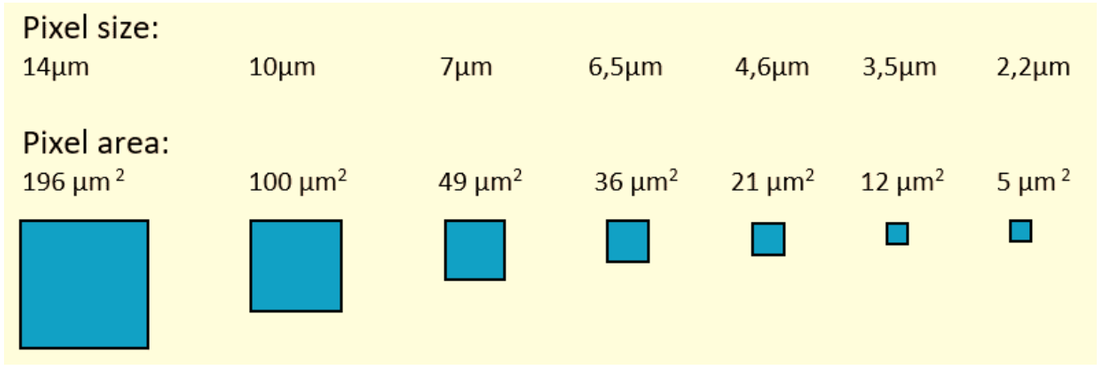


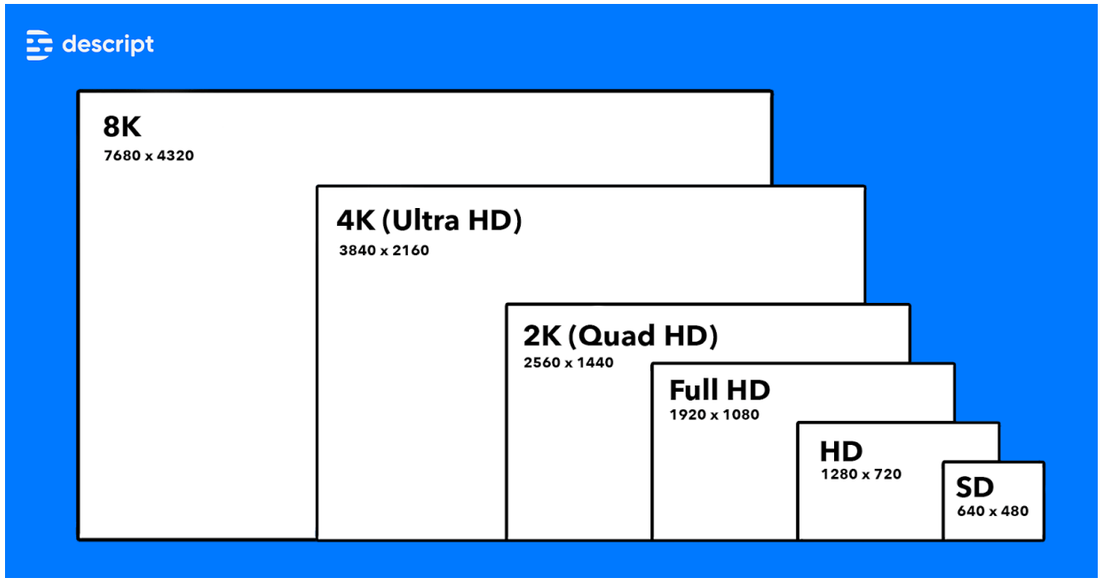



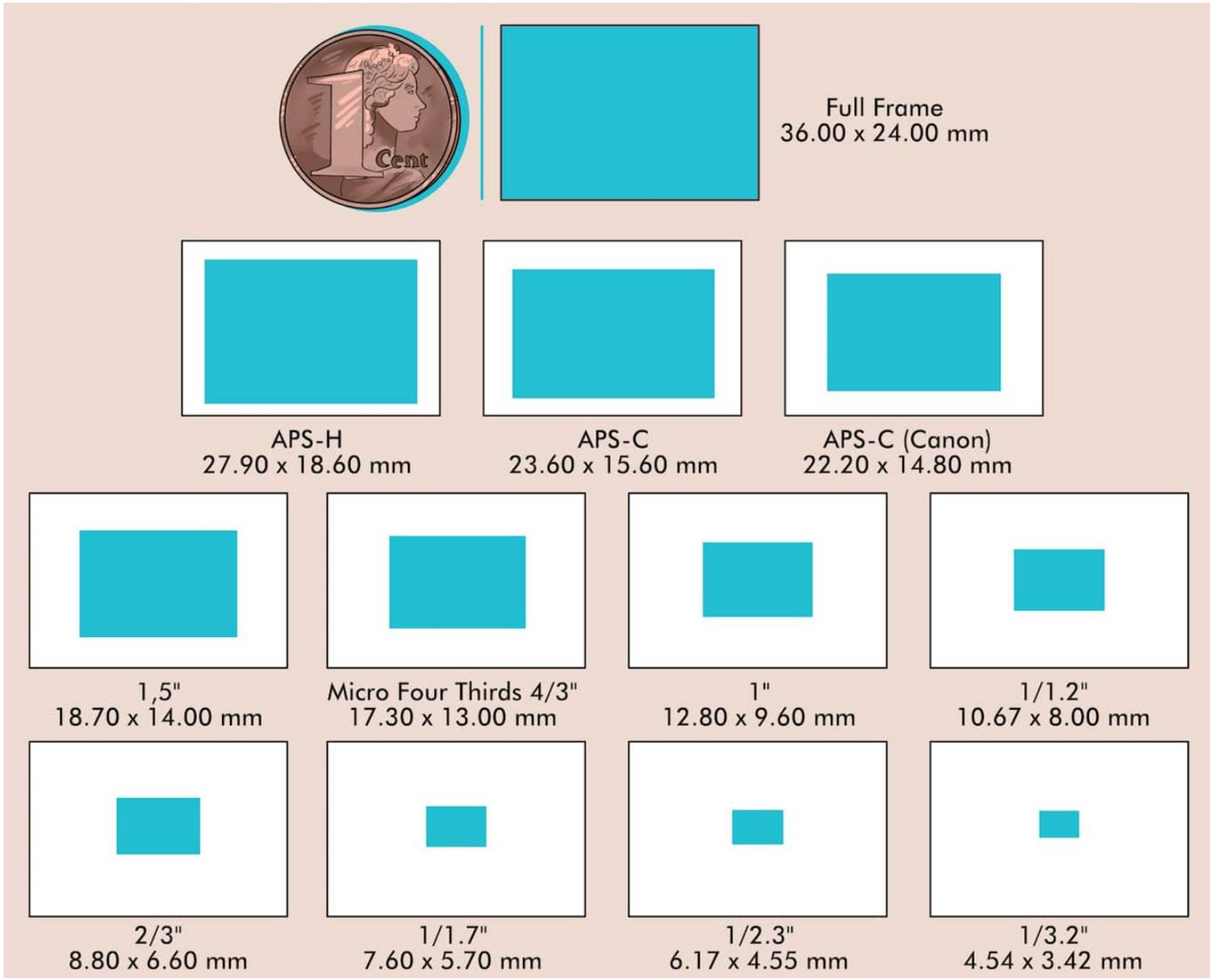


# Typical image sensor sizes

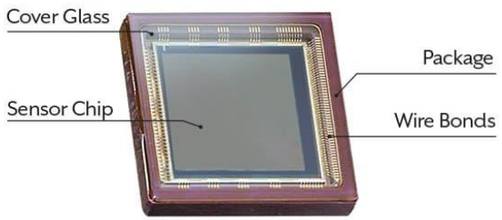


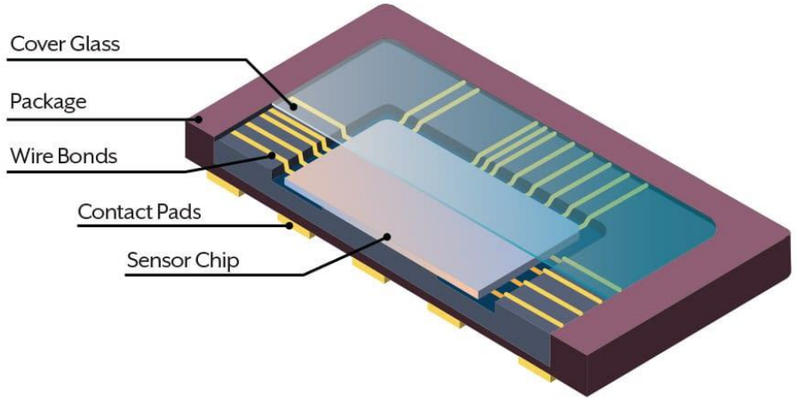



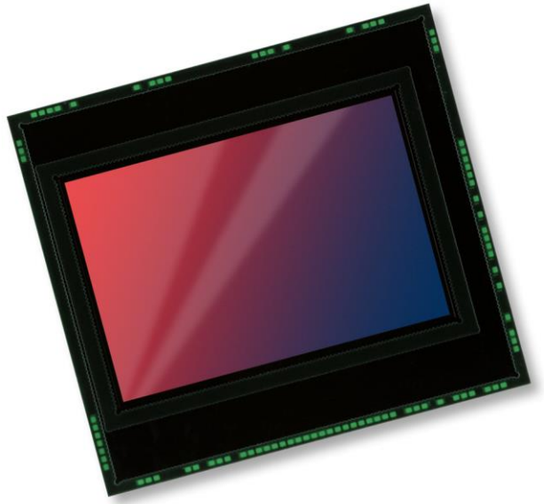



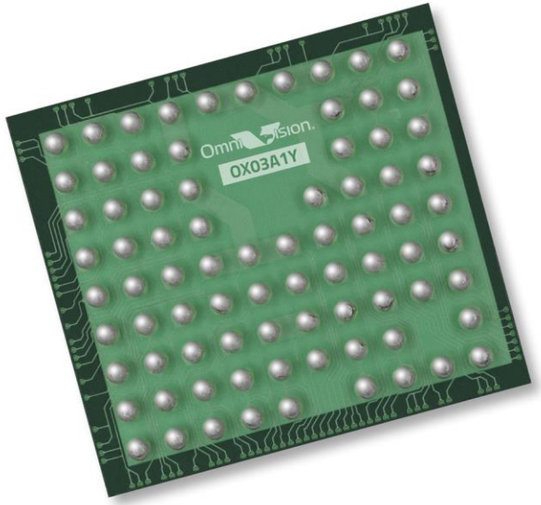
# Image sensor providers

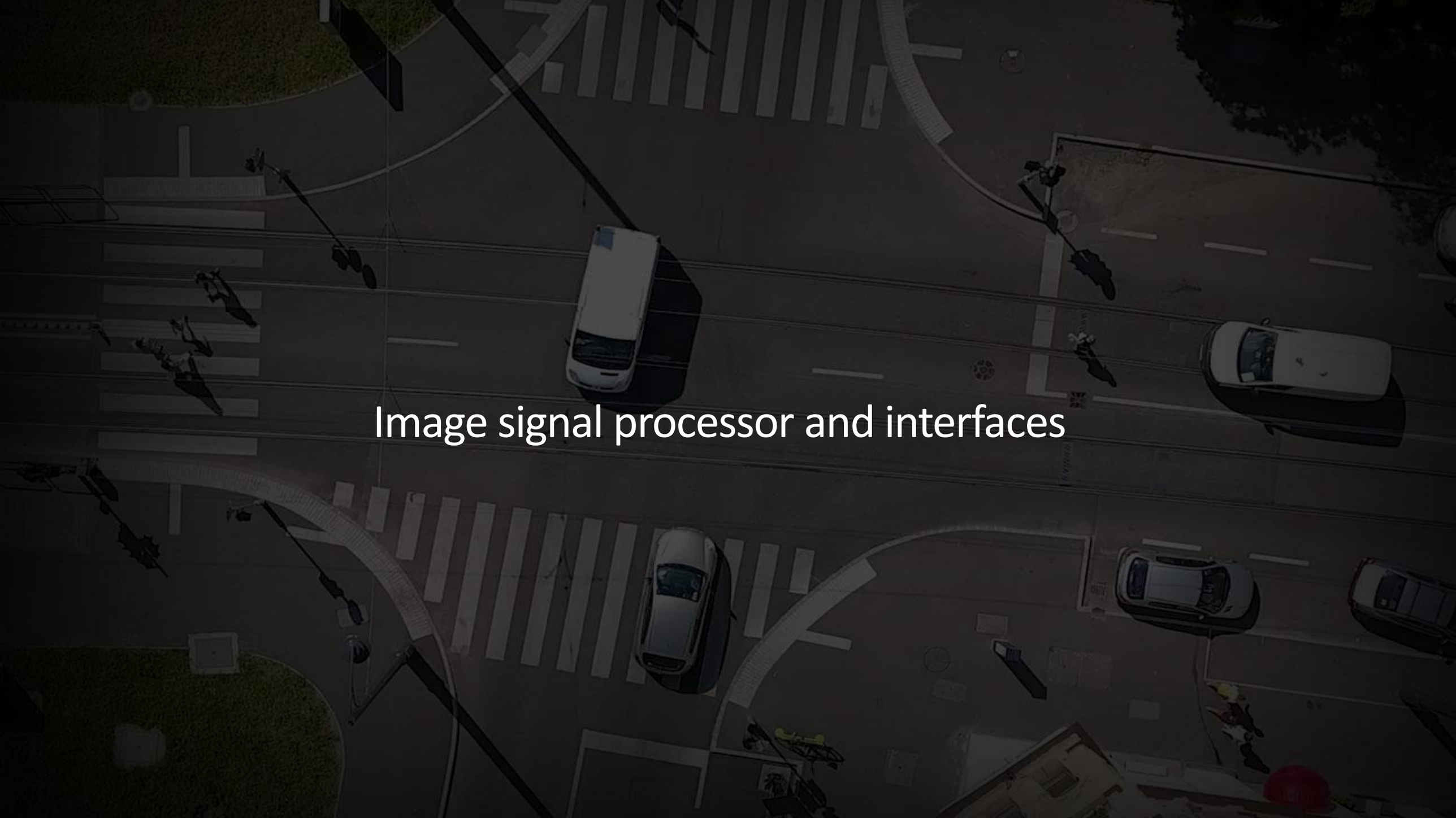
- **Some relevant image sensor providers**
  - Sony: sony-semicon.co.com *
  - Samsung: samsung.com *
  - OmniVision: ovt.com *
  - ON Semiconductor: onsemi.com *
  - Panasonic: panasonic.com *
  - STMicroelectronics: st.com *
  - Canon: canon.com
  - Toshiba: teli.com.jp
  - Himax Tech: himax.com.tw
  - Teledyne e2v: teledyne-e2v.com
  - Pixart Imaging: pixart.com



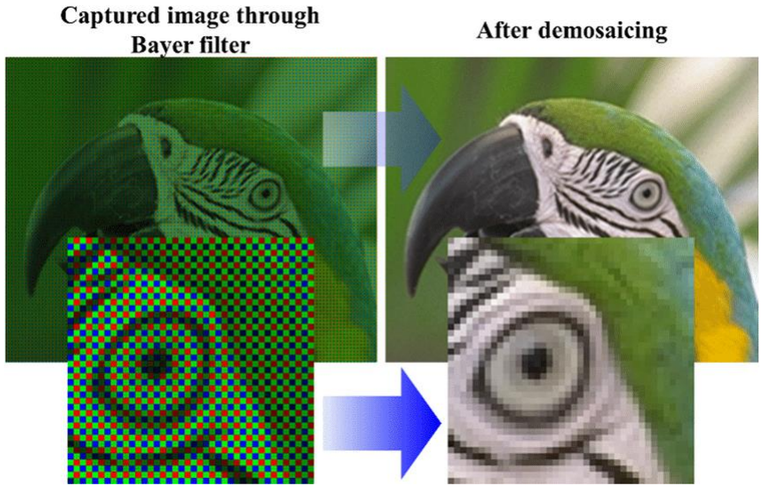




# Image signal processor and interfaces

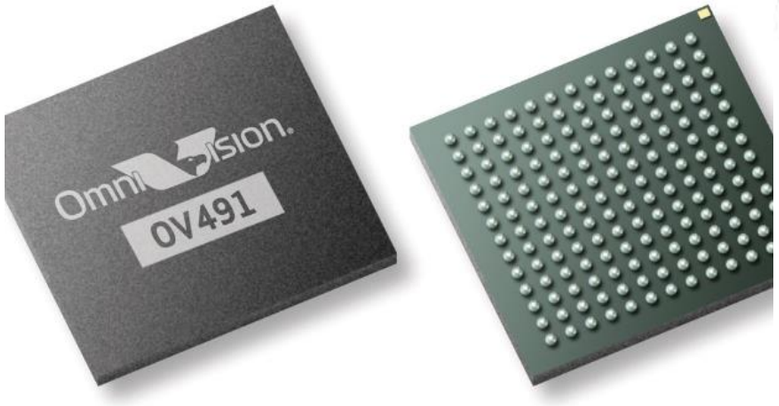
# Image signal processor

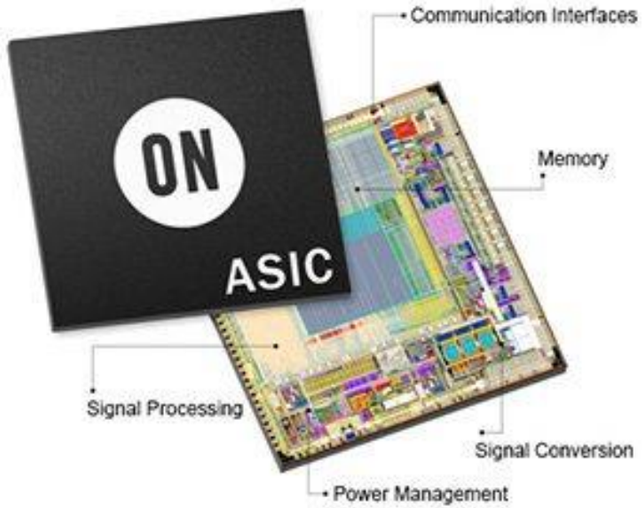
- **Most important features of ISP**
  - Sensor data acquisition
  - Black level correction
  - Noise reduction
  - Defective pixel correction
  - White balance
  - Demosaicing
  - Color correction
  - Color denoising
  - Gamma correction
  - Vignetting correction
  - Distortion correction
  - Edge enhancement
  - Auto focus
  - High dynamic range (HDR) processing
  - Image scaling
  - Color space conversion
  - Image compression
  - Final image formatting
  - Metadata generation




# Image signal processor manufacturers

- **Some relevant ISP providers**
  - Qualcomm: qualcomm.com *
  - Sony: sony-semicon.co.jp *
  - Samsung: samsung.com *
  - OmniVision: ovt.com *
  - Apple: apple.com
  - Intel: intel.com
  - Huawei: huawei.com
  - Nvidia: nvidia.com *
  - Ambarella: ambarella.com *
  - ST Microelectronics: st.com *
  - ON Semiconductor: onsemi.com *
  - Texas Instruments: ti.com *



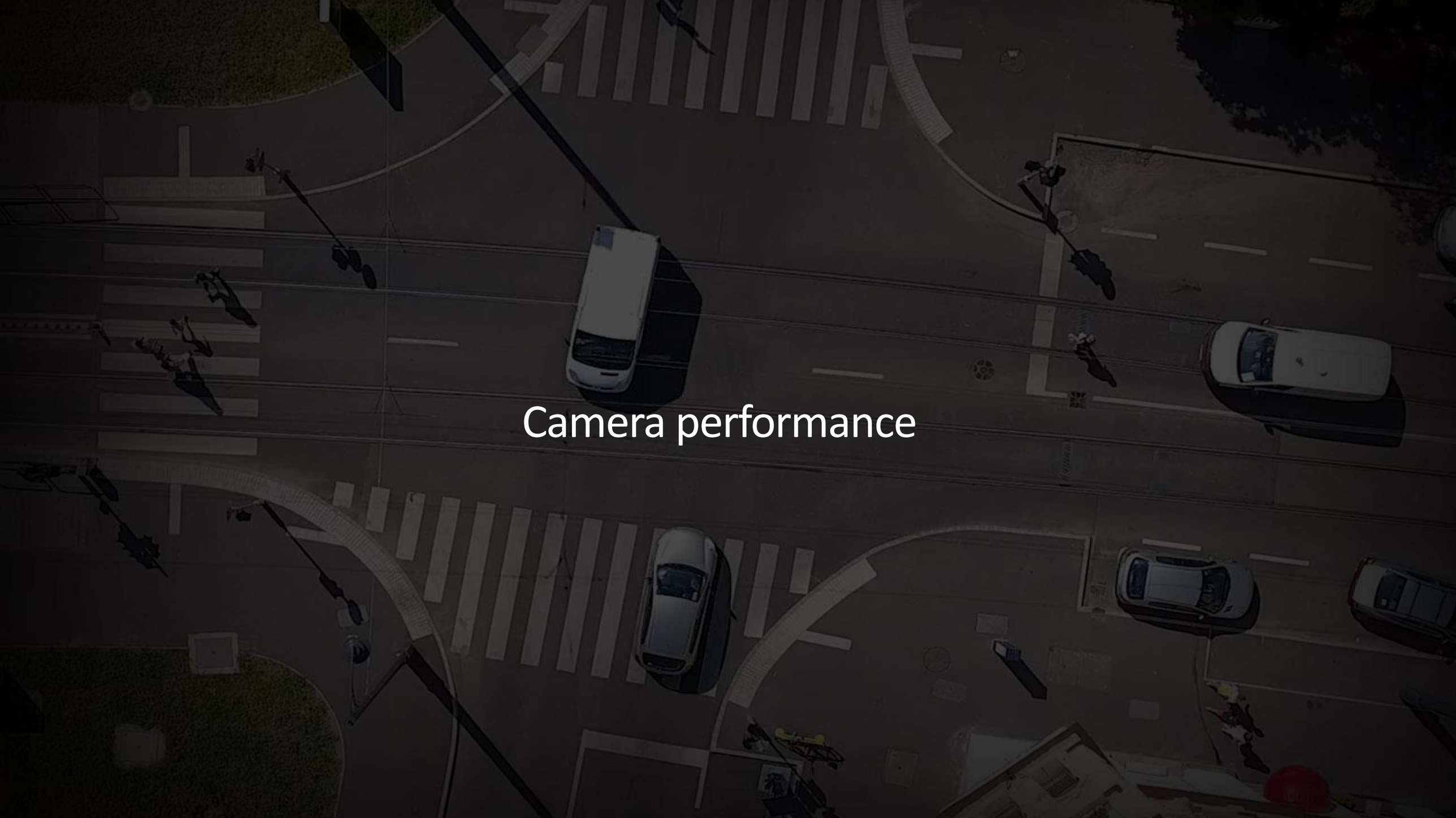





# Interfaces and connectors

- **Most common protocols**
  - MIPI CSI-2 *
  - USB
  - LVDS *
  - Ethernet *
  - PCIe
  - CoaXPress
  - HDMI/Display port
  - Camera Link
  - FPD-Link III *
  - FireWire (IEEE 1394)
  - SDI
  - $I^2C$
  - SPI

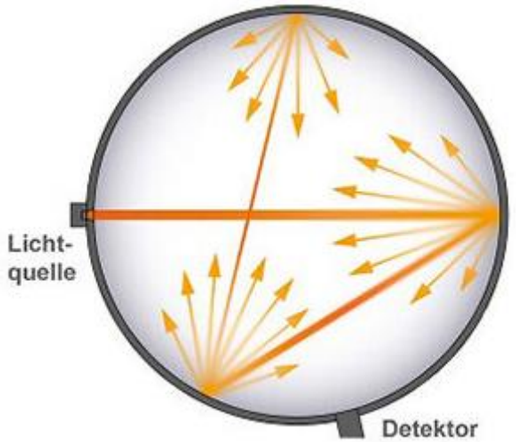
- **Most common connectors**
  - FPC
  - MIPI *
  - USB
  - FAKRA *
  - Board-to-Board *
  - Coaxial *
  - Hirose
  - PCIe
  - Ethernet (RJ45)
  - Automotive Ethernet *
  - HDMI/DisplayPort
  - FireWire

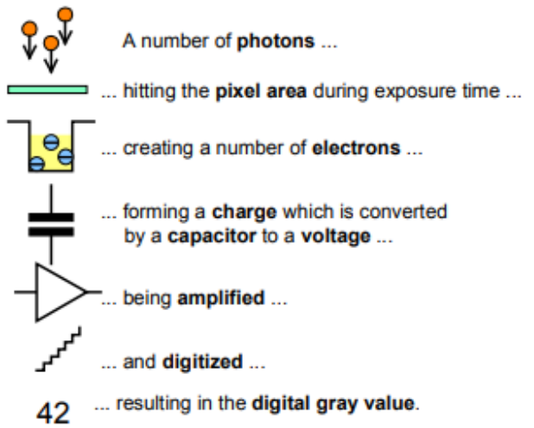


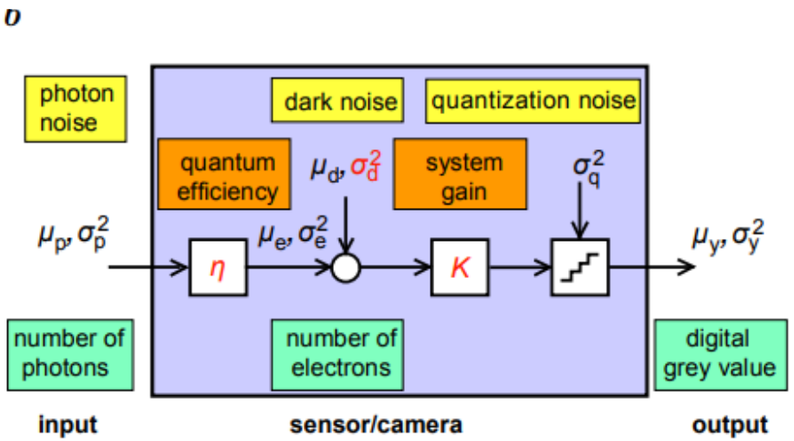
# Camera performance

# EMVA 1288

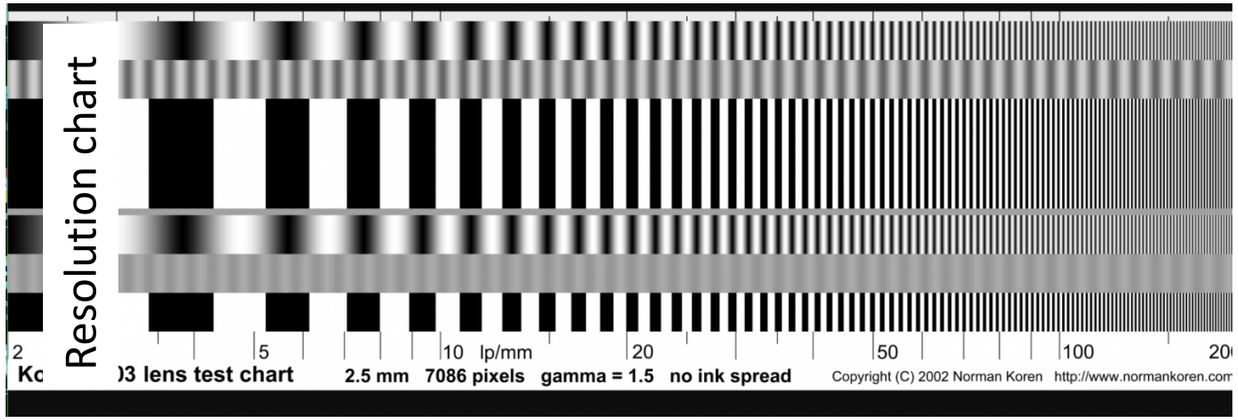
- **EMVA 1288**
  - Standard for characterization of image sensors and cameras
    - Linear characteristics
    - General characteristics
  - Measurements for
    - Quantum efficiency
    - Gain
    - Dark noise
    - Signal to noise ratio
    - Absolute sensitivity ratio
    - Saturation capacity
    - Dynamic range
    - Dark signal nonuniformity
    - Photo response nonuniformity
    - Non-linearity error
    - Dark current
  - Companies are following the standard: Link

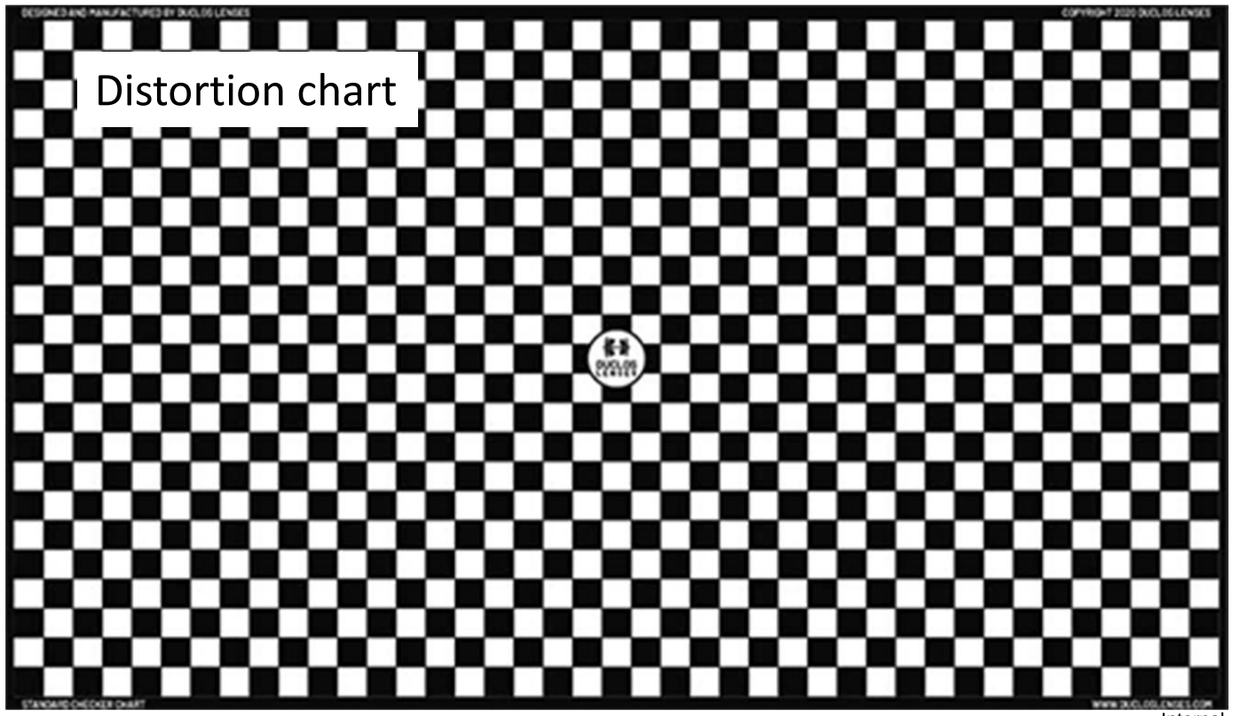


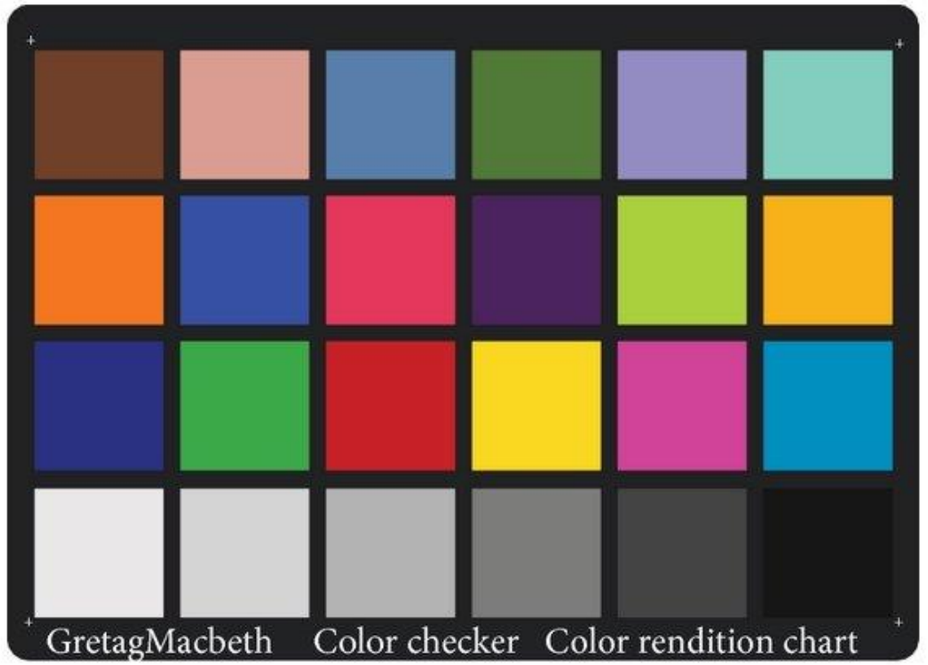



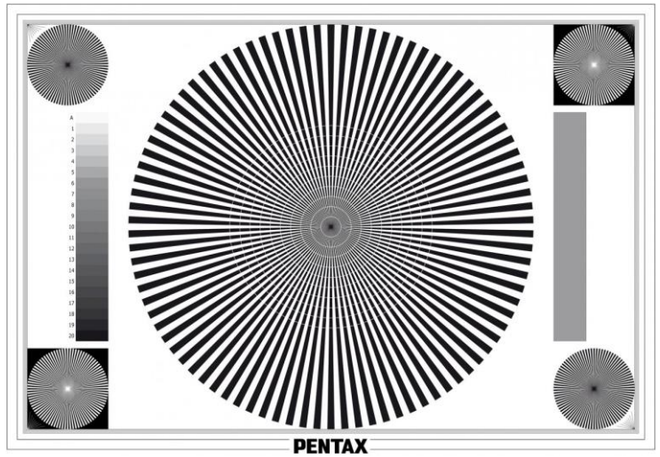



# Test charts



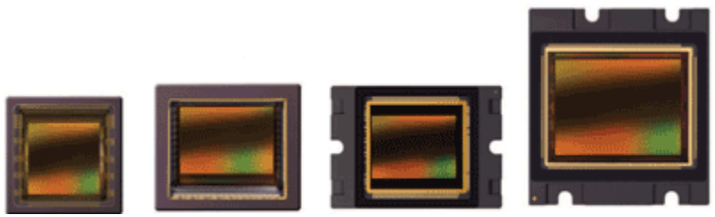




Focus chart

# Important camera parameters

- **Some important imaging parameters**
  - Sensor- and pixel size
  - Resolution
  - Bit depth
  - Color filter array
  - Quantum efficiency
  - Sensitivity
  - Signal-to-noise ratio
  - Dynamic range
  - Shutter type
  - Frame rate
  - Readout speed
  - Temperature sensitivity
  - Power consumption
  - Price
  - etc



**Automotive grade requirements**

**Careful component selection**

**Extensive component testing**

**Accurate assembly**

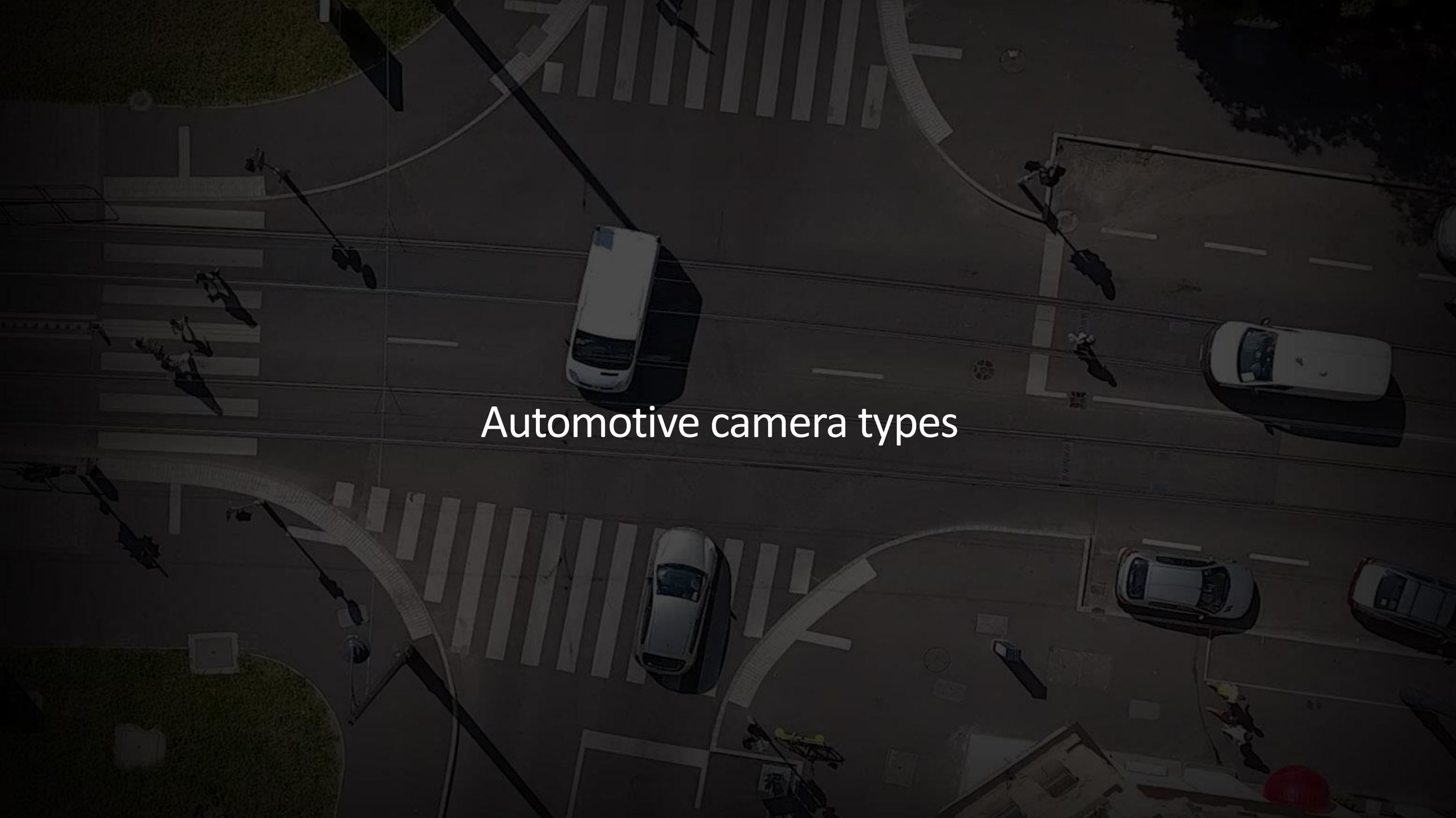
**Product validation**

**Proper handling**

- **Some important optics parameter**
  - Focal length
  - Aperture
  - Field of view
  - Resolution
  - Optical coatings
  - Optics quality (aberrations)
  - Build quality and material
  - Size and weight
  - Environmental resistance
  - Mount type
  - Compatibility with image sensor
  - Price
  - etc

# Product tests

- **Product testing before release**
  - Image quality testing
  - Environmental testing
  - Mechanical and durability testing
  - Electrical and signal integrity testing
  - Functional testing
  - Reliability and lifespan testing
  - Compliance and certification testing
  - Performance testing in real-world



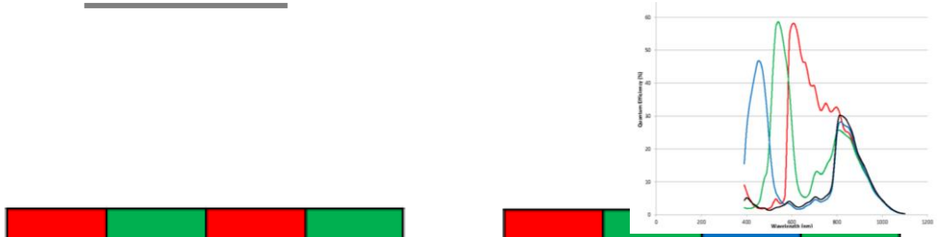
# Automotive camera types

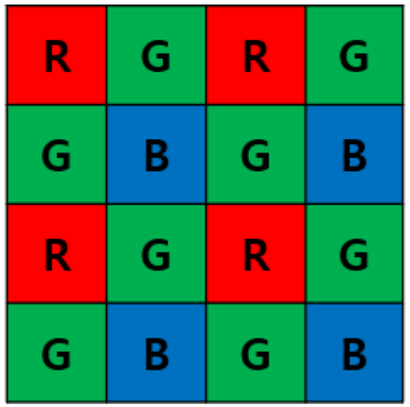
# Camera optics

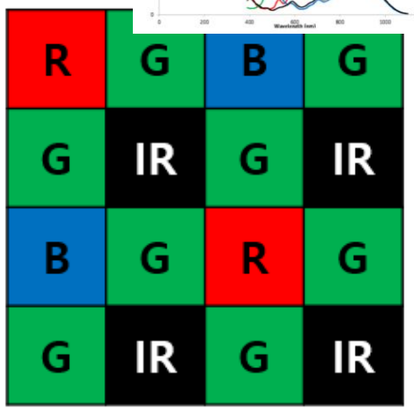
- **Typical camera optics in autonomous vehicles**
  - Long-range cameras
    - FoV: 30 – 60°
    - Long-range
    - Pinhole camera model
  - Wide-angle cameras
    - FoV: 90 – 120°
    - Mid-range
    - Wide-angle camera model
  - Surround cameras
    - FoV: > 180°
    - Close-range
    - Fisheye or ocam camera model

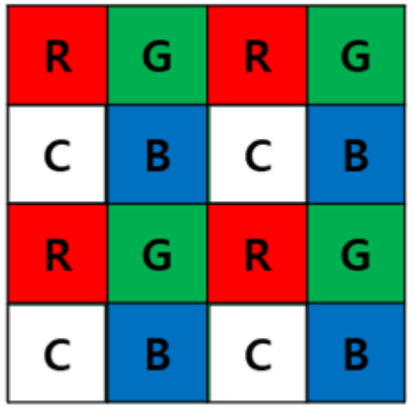
# Color filter arrays

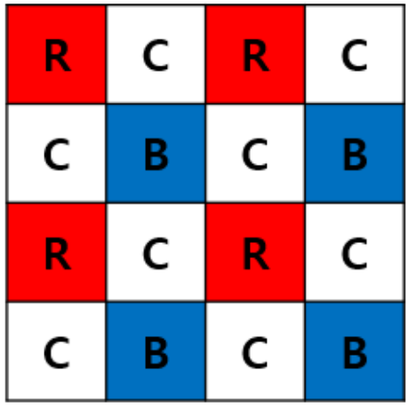
- **Typical CFAs in autonomous vehicles**
  - RGGB (Bayer filter)
    - Standard for color accuracy
  - RGBIr
    - Color + enhanced low-light perf.
  - RGCB (Panchromatic)
    - Color + enhanced low-light perf.
  - RCCB
    - Balance between sens. and color inf.
  - RCCC
    - Sensitivity with minimal color inf.
  - CCCC (Monochrome)
    - Maximizes sensitivity

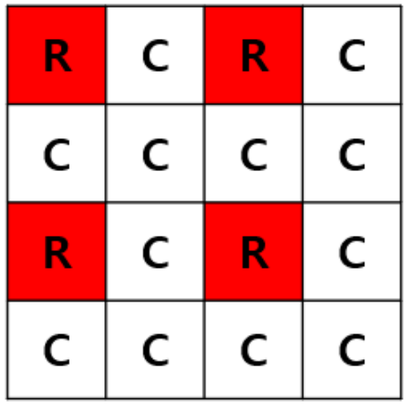


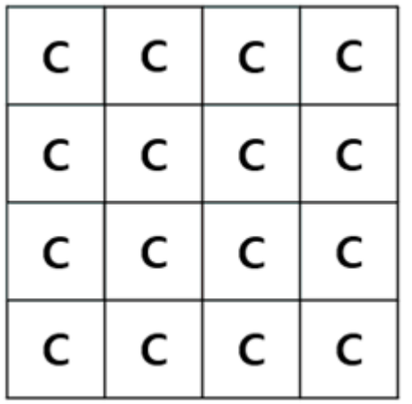


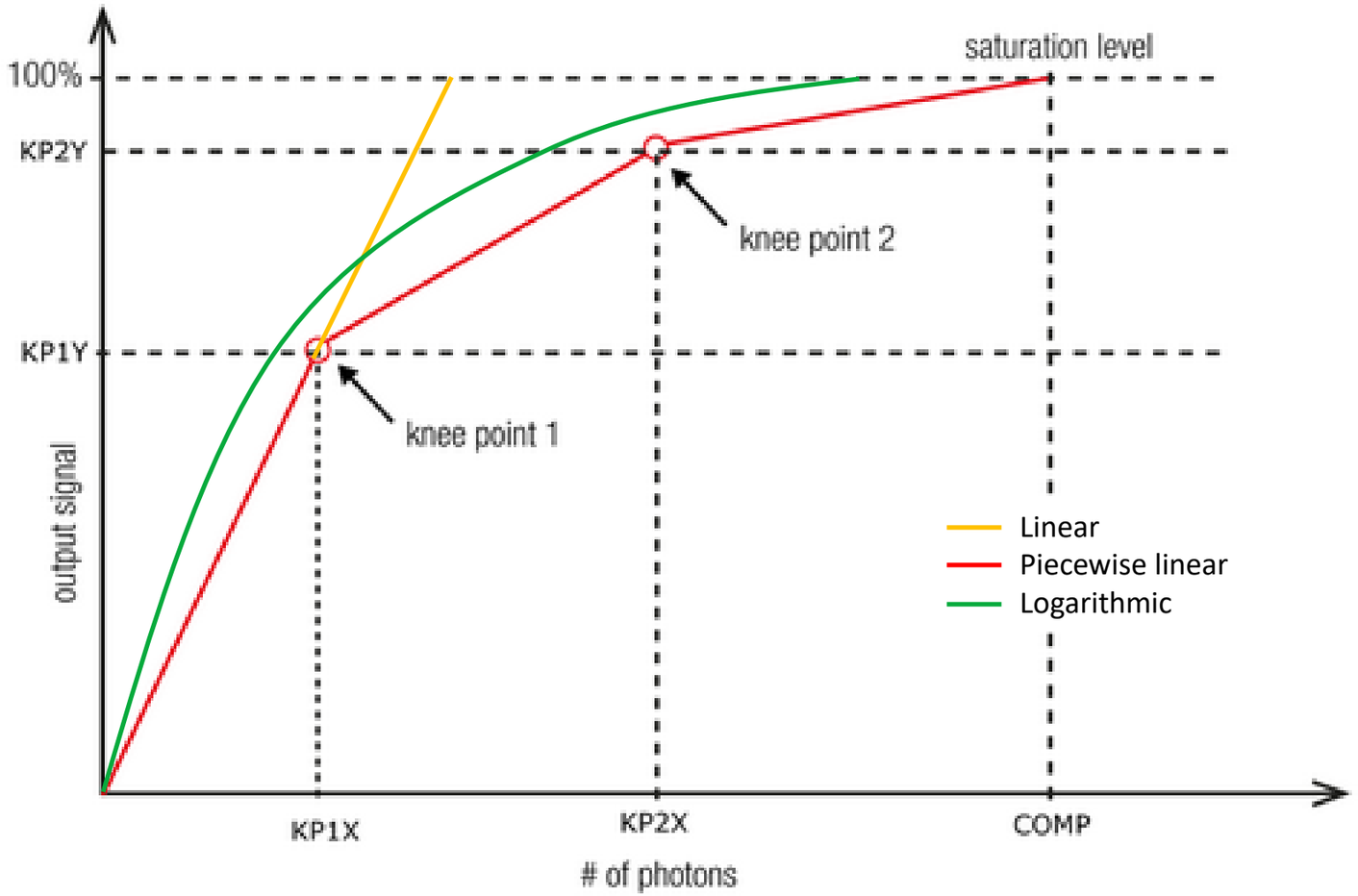



# High dynamic range

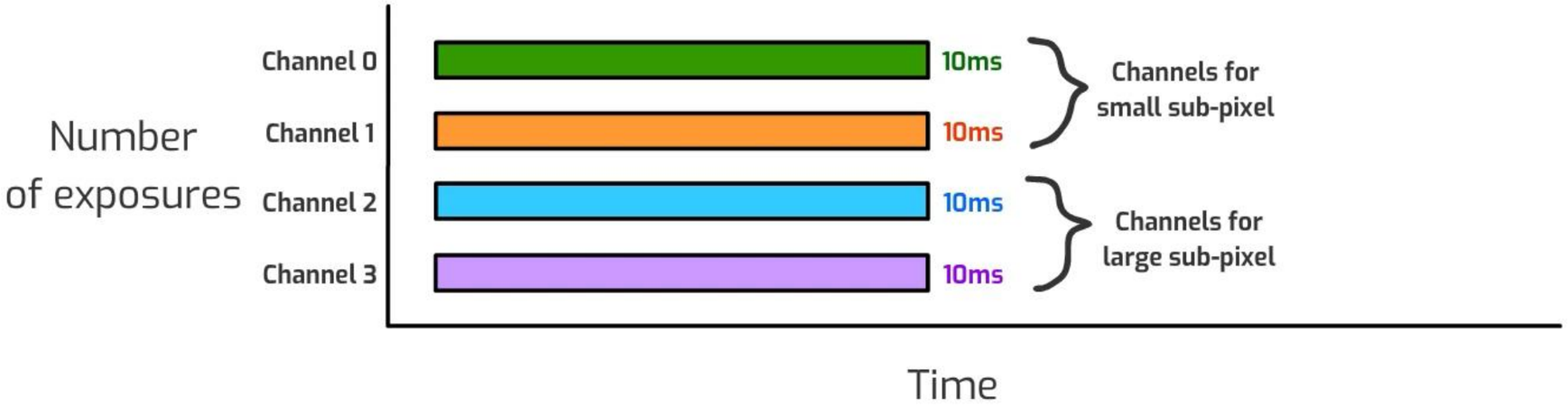
- **HDR image generation**
  - High well depth
    - Single exposure
    - Linear characteristics
    - 70 – 90 dB
  - Multi-exposure method
    - Typically 3 – 4 exposures
    - Piecewise linear characteristics
    - 120 – 140 dB
  - Nonlinear image sensor
    - Single exposure
    - Logarithmic characteristics
    - 100 – 120 dB



# High dynamic range

# High dynamic range

## IMX490 HDR
## Simultaneous Exposure




**HDR Image**
**No motion artifacts**

# LED flicker mitigation

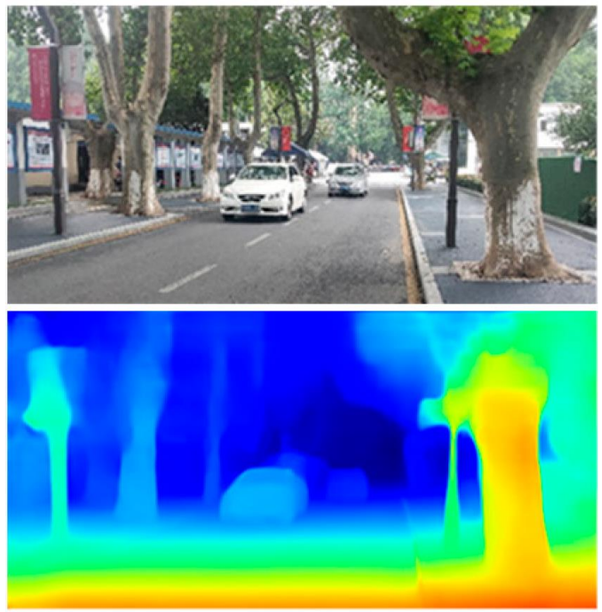
# LED flicker mitigation

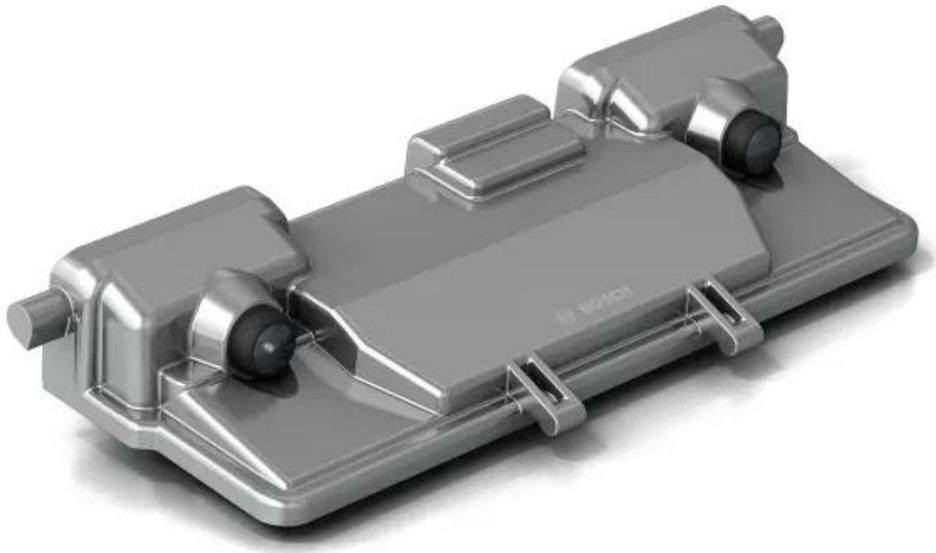
# Cameras

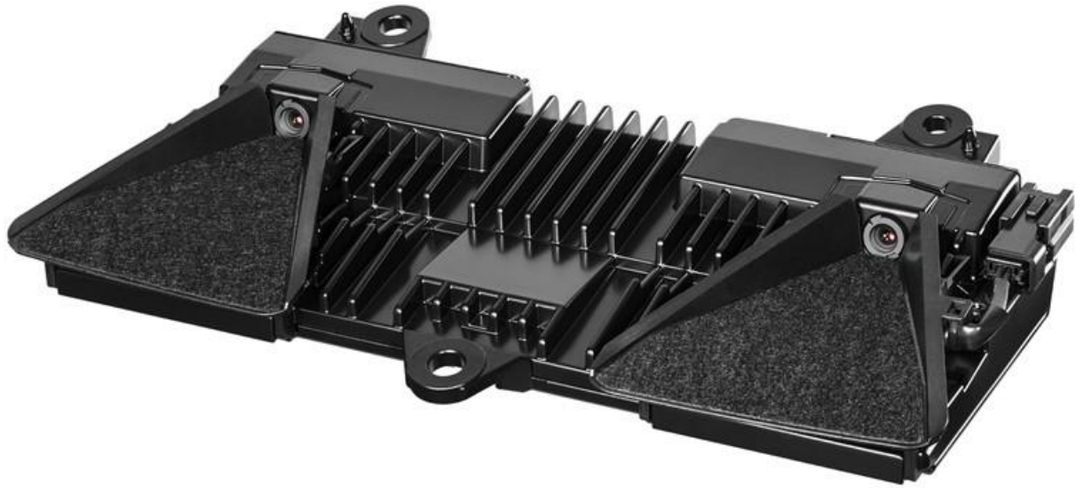
- **Some relevant automotive camera manufacturers**
  - Bosch
  - Continental
  - Magna
  - ZF Friedrichshafen
  - Valeo
  - Autoliv / Veoneer
  - Mobileye
  - Sony
  - Aptiv
  - Denso


# Stereo cameras

- **Some relevant automotive stereo camera manufacturers**
  - Bosch
  - Continental
  - Autoliv / Veoneer
  - Denso

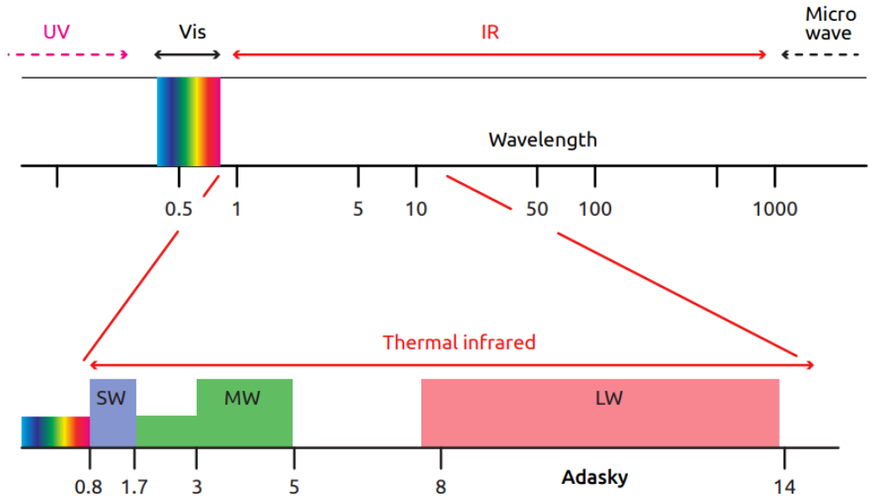






# Infrared cameras

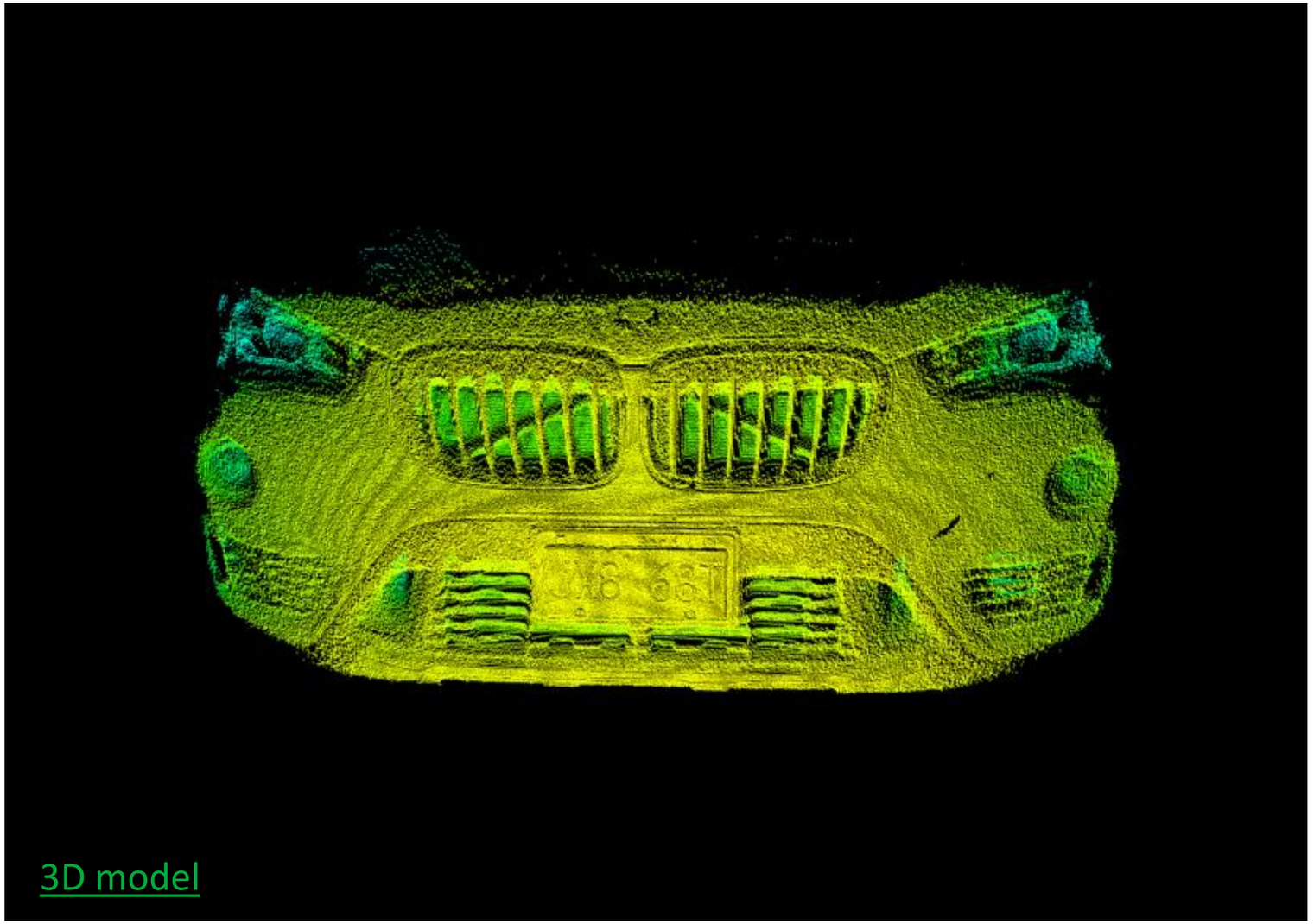
- **Some relevant infrared camera manufacturers for autonomous vehicles**
  - Teledyne FLIR
  - Adasky
- How to apply in bad weather conditions?



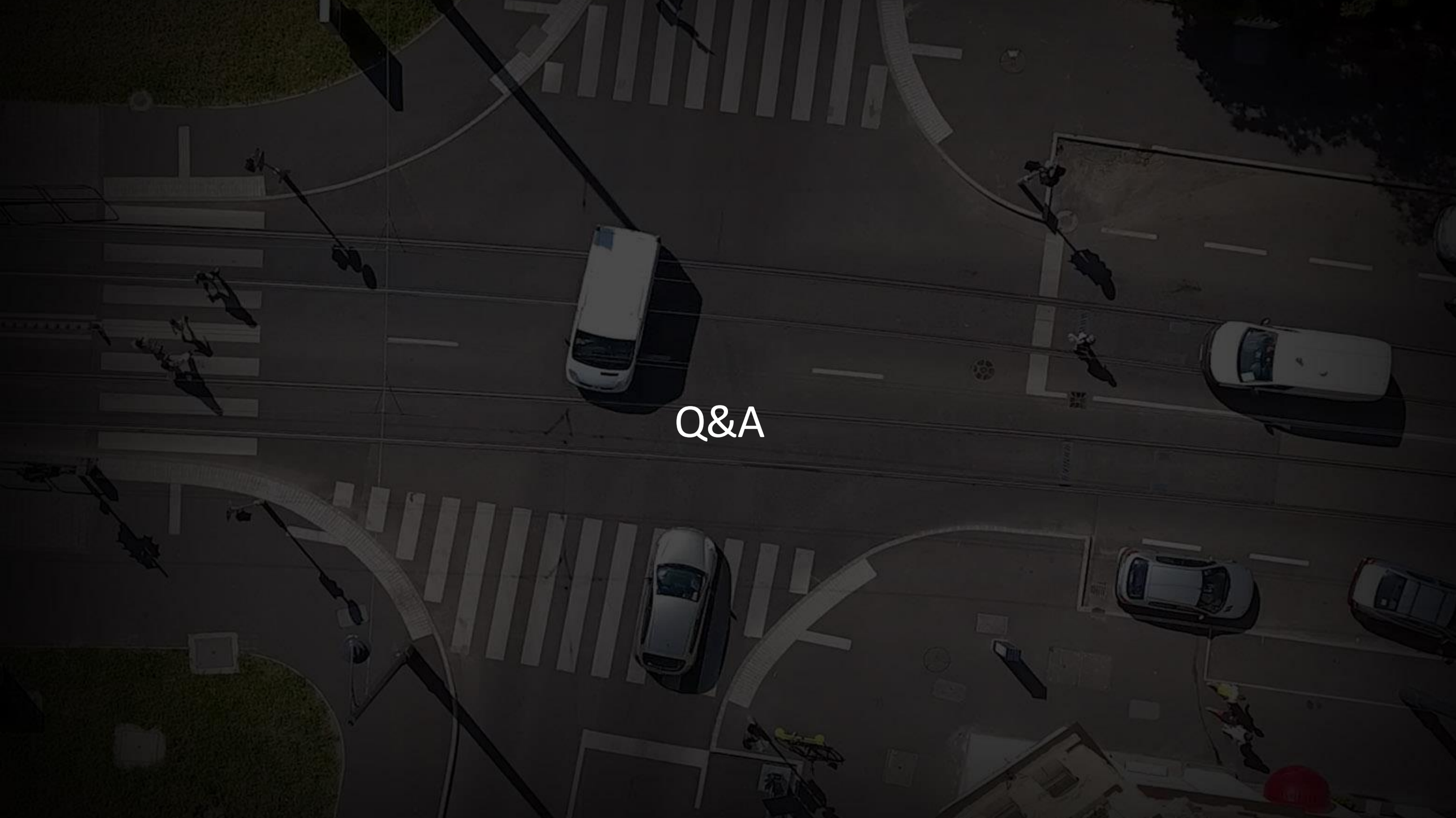



# Time of flight cameras

- **Time of flight cameras**
  - Time of flight image sensors
  - Infrared light source
  - Very limited range
  - Very limited outdoor performance
  - Not for automotive applications
  - Video



3D model


Q&A