



Bio-inspired Multispectral-Polarization Imaging Devices with Perovskite Nanocrystals for UV and Visible Spectral Sensing

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University of Illinois Urbana Champaign

FA9550-24-1-0112



Accomplishments



- **Synthesis of UV-fluorescent Perovskite nanocrystals for wavelength resolved UV imaging.**
- **Bioinspired UV-color-NIR imaging sensor**
- **Geolocalization in GPS denied environment**



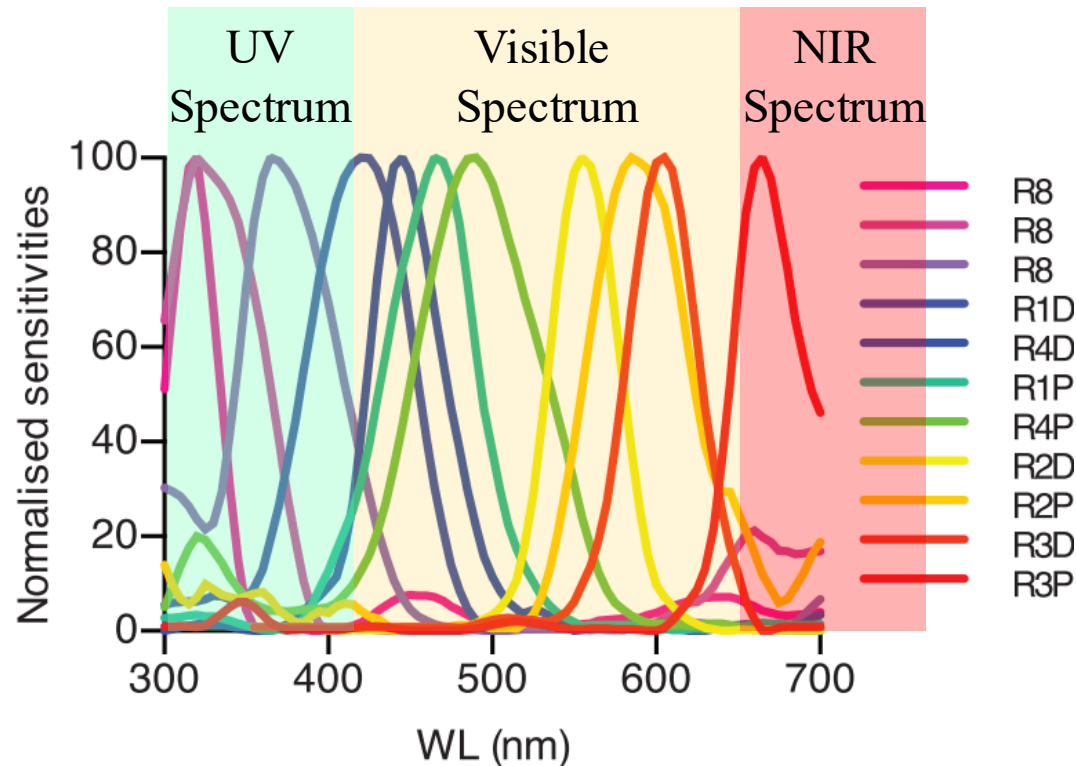
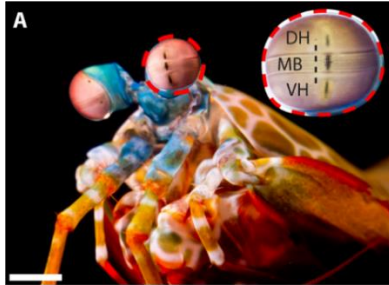
Accomplishments



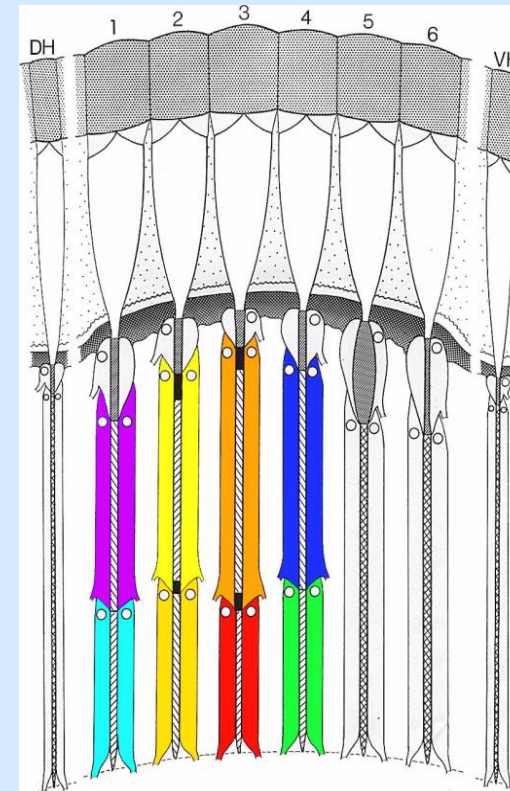
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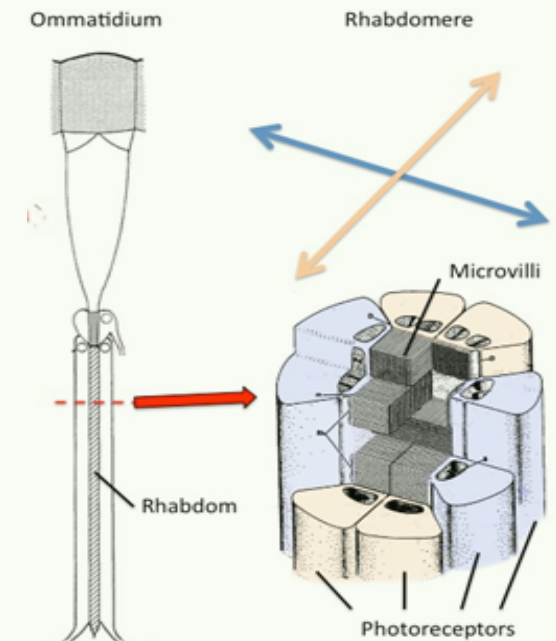
Mantis Shrimp Visual System



Multispectral Sensitivity



Polarization Sensitivity

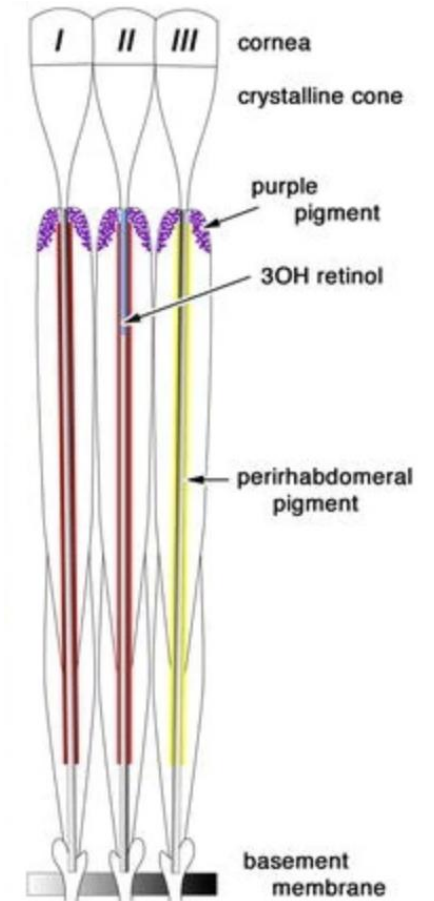
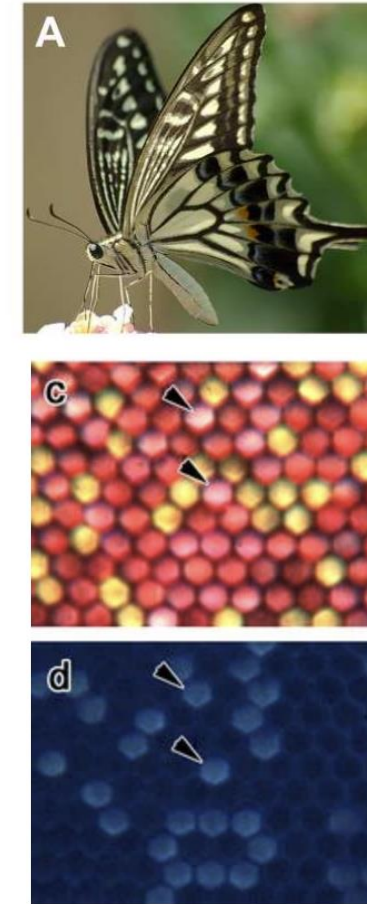
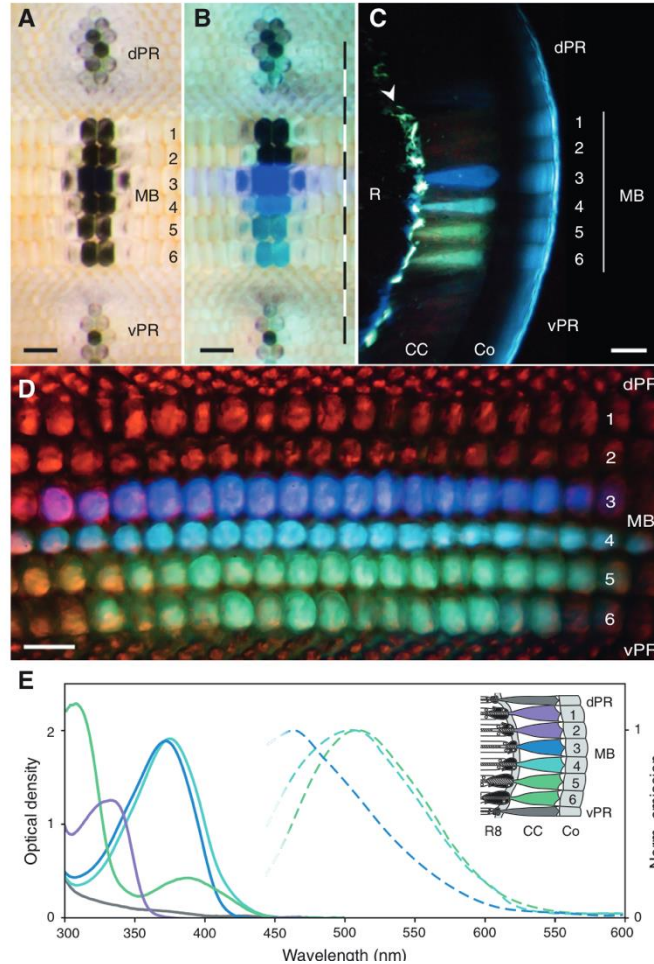
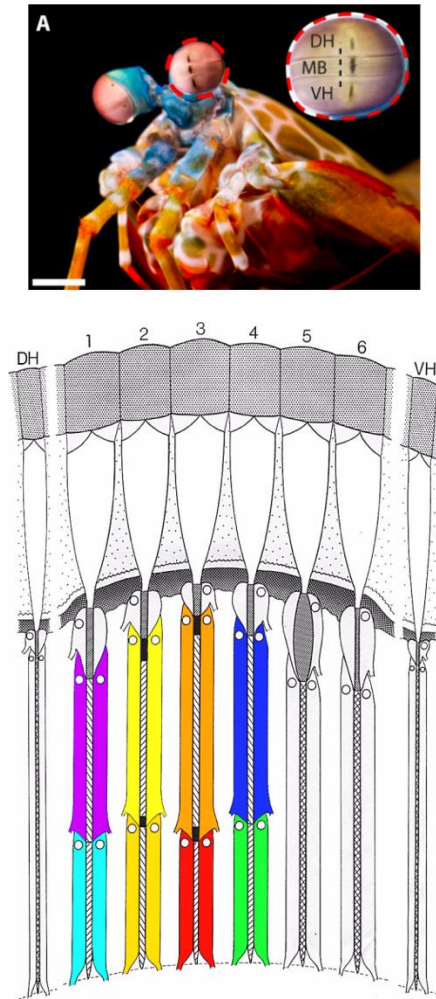


Cronin TW and Marshall NJ. "A retina with at least ten spectral types of photoreceptors in a mantis shrimp," **Nature**, 1989.

Thoen H., et al., "Different Type of Color Vision in Mantis Shrimp," **Science**, 2014.



UV Sensitivity: Absorption and Fluorescence



Bok MJ, Porter ML, Place AR, Cronin TW. "Biological sunscreens tune polychromatic ultraviolet vision in mantis shrimp," **Current Biology**. 2014.

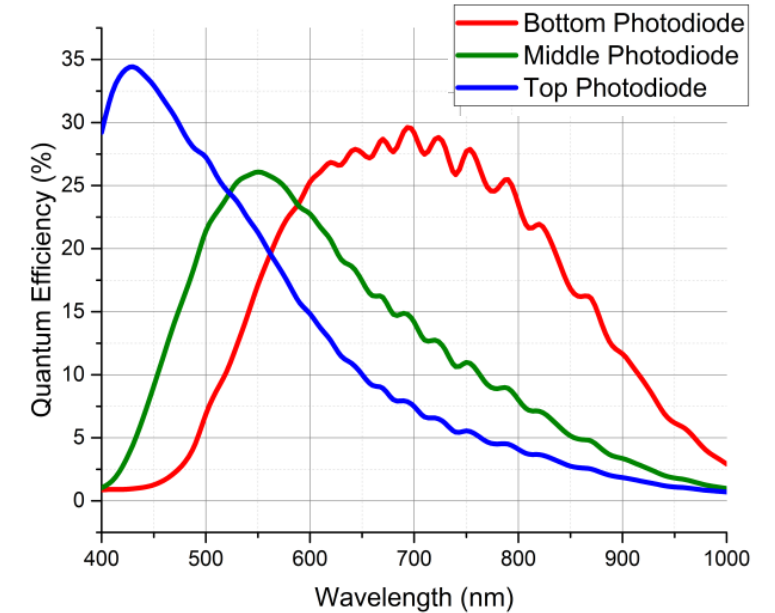
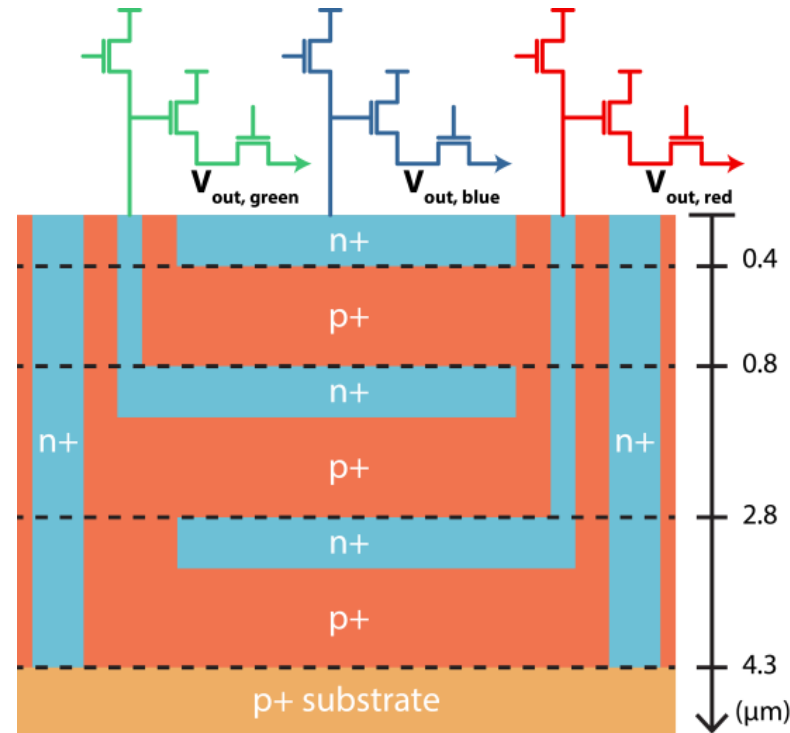
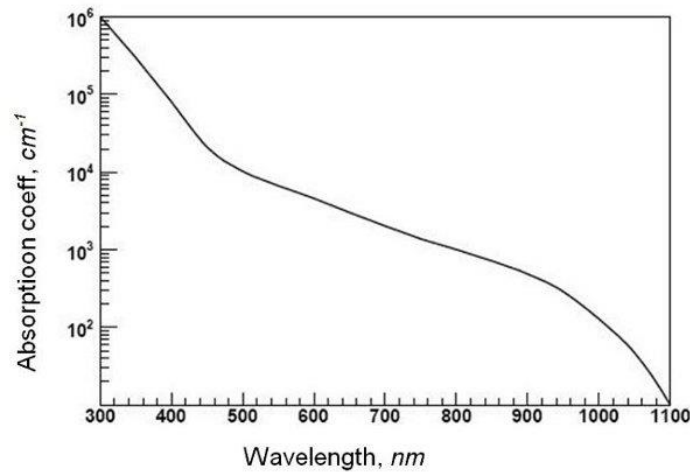
Arikawa K. "The eyes and vision of butterflies," **The Journal of physiology**. 2017.



Vertically Stacked Photodiodes in CMOS



Silicon Absorption Coefficient



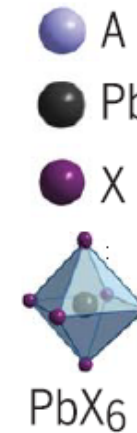
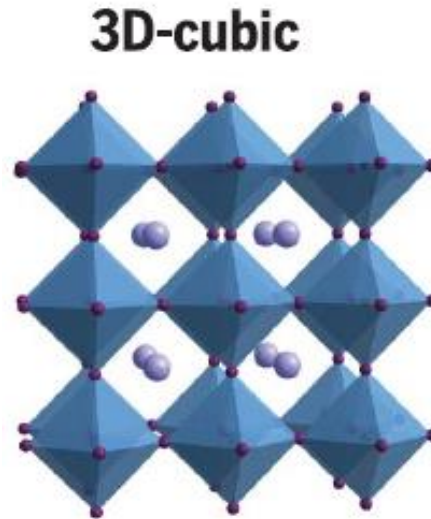
- Kodak and Foveon IP
- M. Garcia, R. Marinov and A. Vail and V. Gruev, *Optica*, 2017.
- S. Powell, R. Garnett, J. Marshall, C. Rizk and V. Gruev, **Science Advances**, 2018.



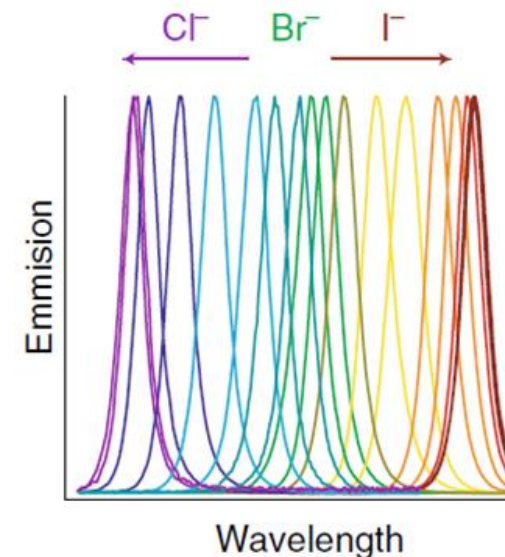
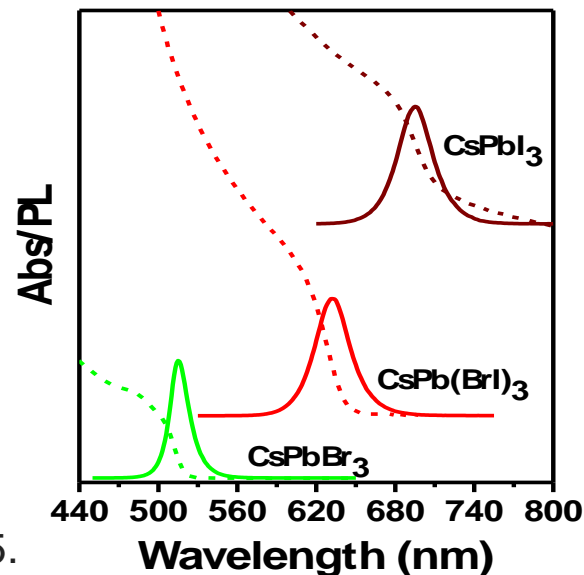
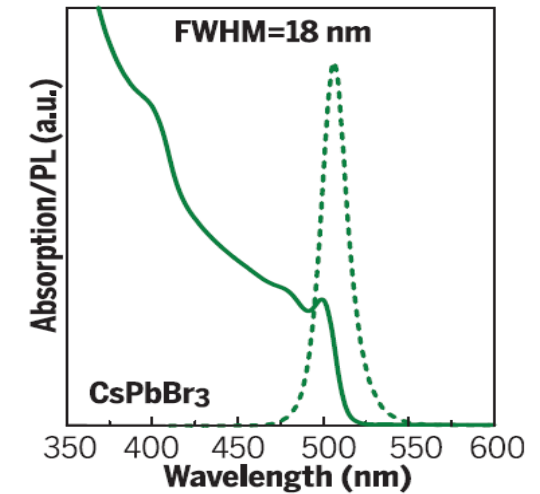
Perovskite Nanocrystals for UV sensing



- Cesium lead halide perovskite: CsPbX_3 ($\text{X}=\text{Cl}, \text{Br}, \text{I}$)
- Large PLQY (~100%)
- Broad absorption spectrum
- Small FWHM
- Tunable emission wavelength

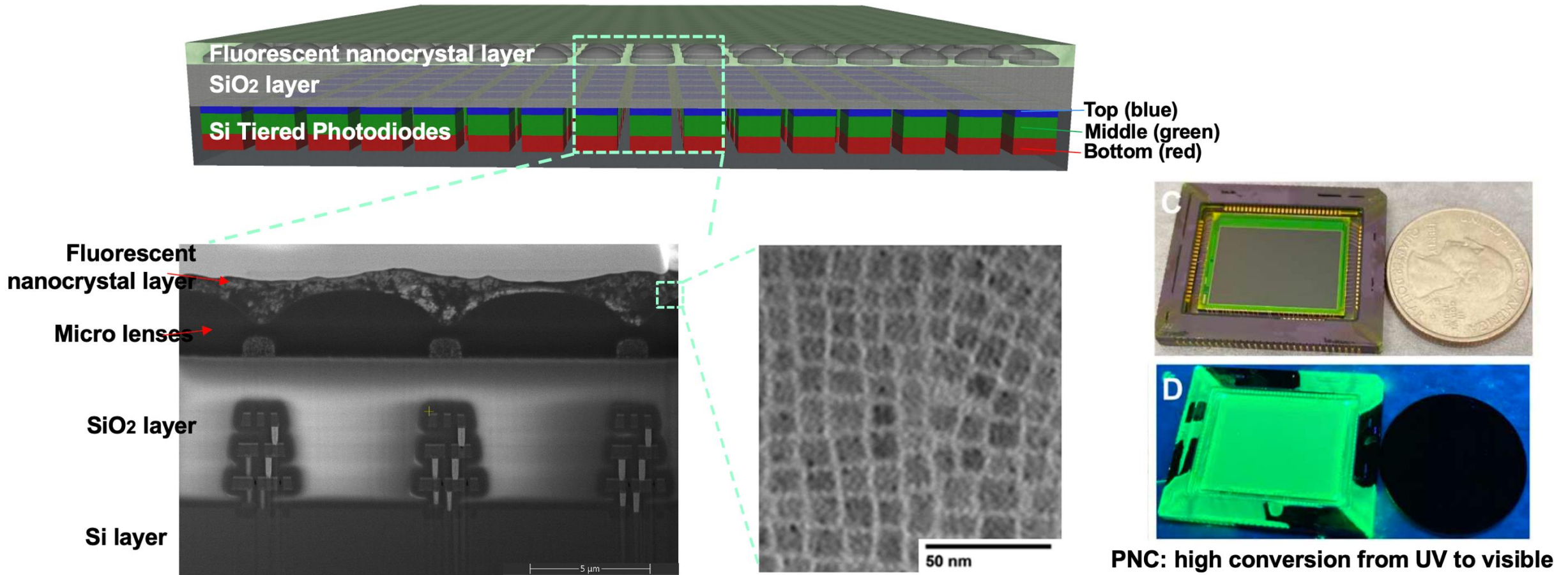


Anion exchange





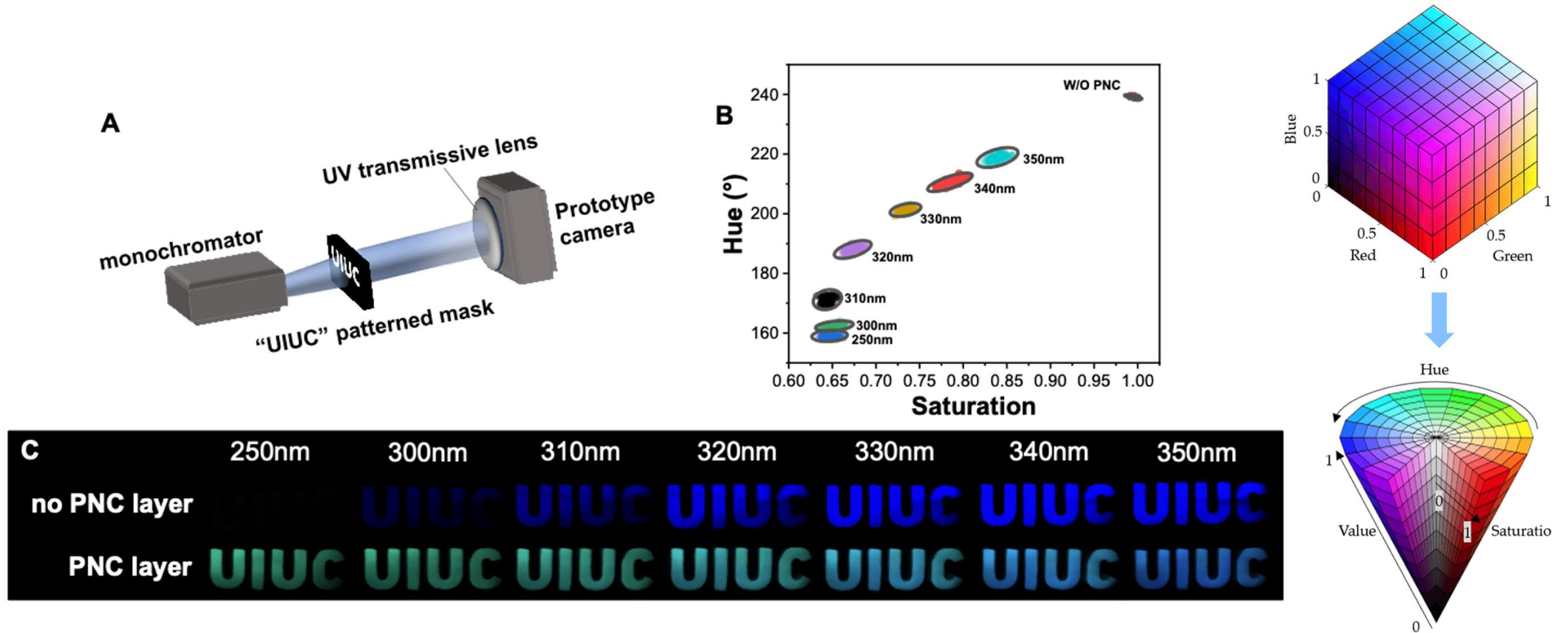
Bioinspired Wavelength Resolved UV Sensor



Chen C, et al. "Bioinspired, vertically stacked, and perovskite nanocrystal-enhanced CMOS imaging sensors for resolving UV spectral signatures". **Science Advances**, 9(44), 2023.

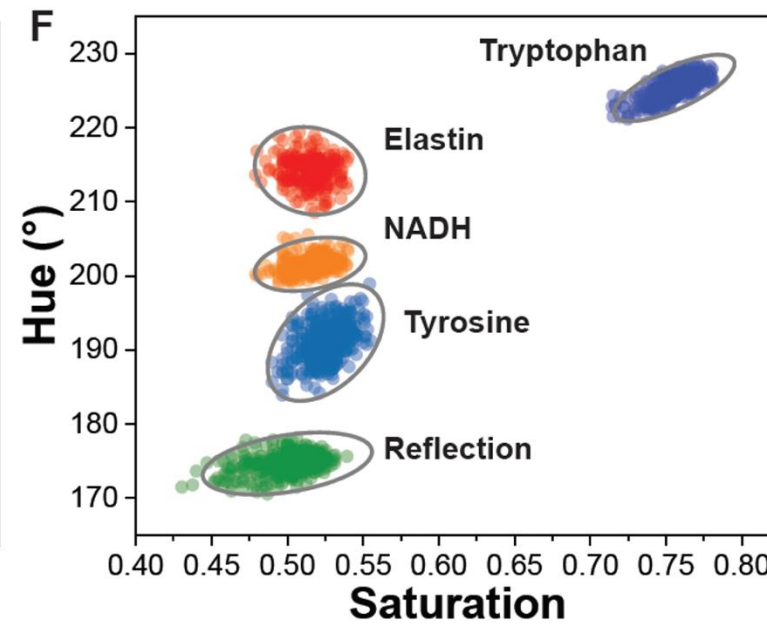
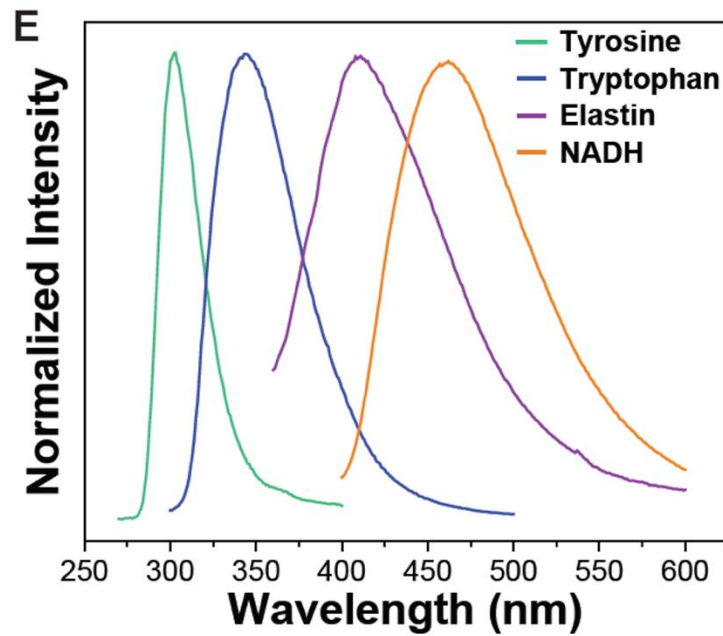
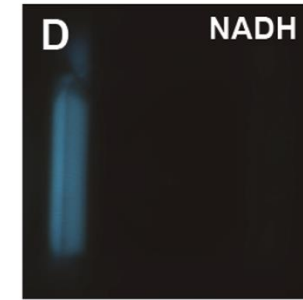
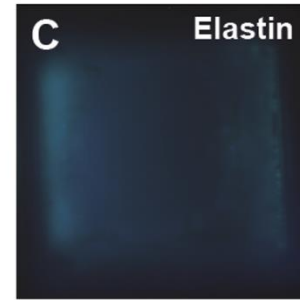
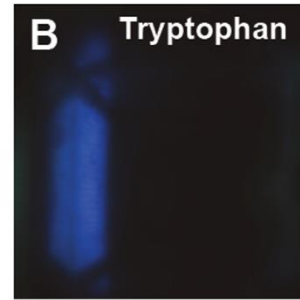
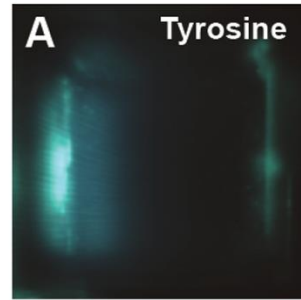


Wavelength Resolved UV Sensing





UV Autofluorescence Imaging of Biomolecules





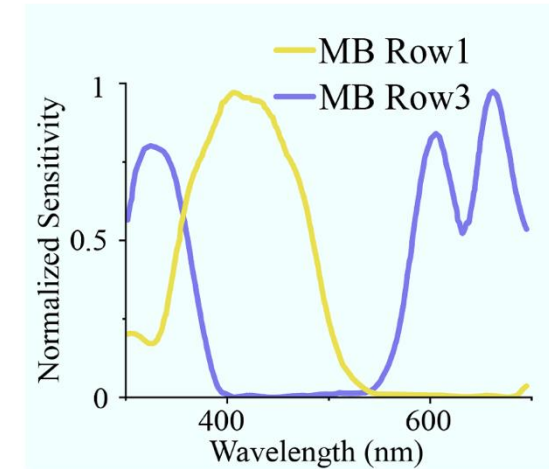
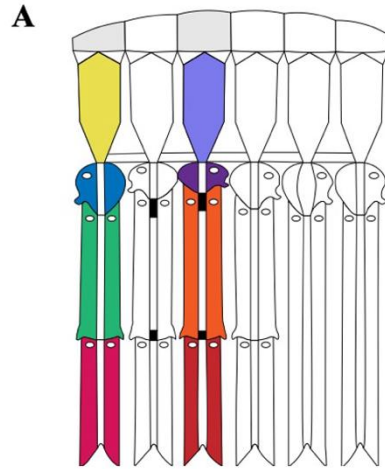
Accomplishments



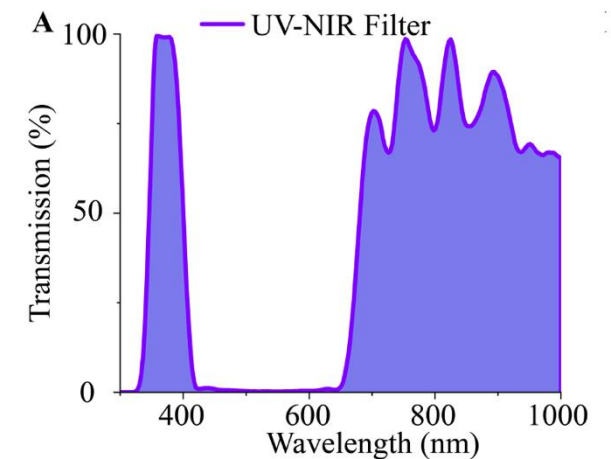
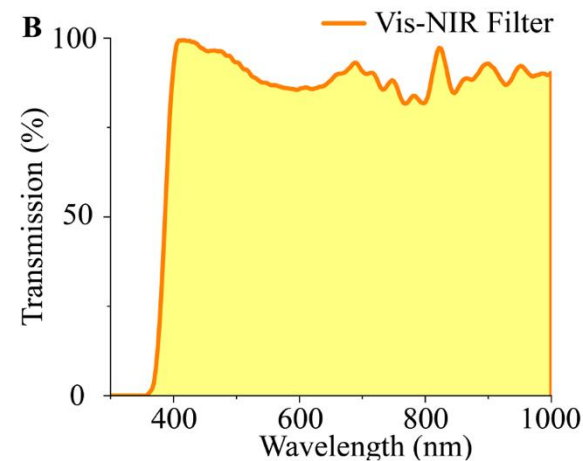
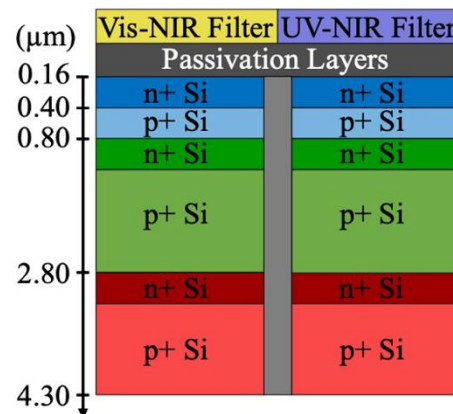
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From Nature To UV-Color-NIR Vision

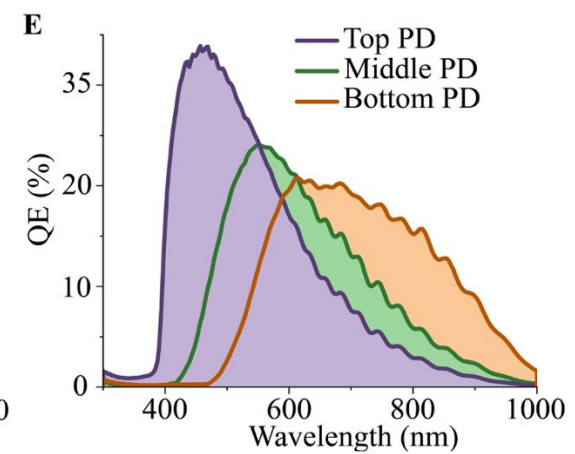
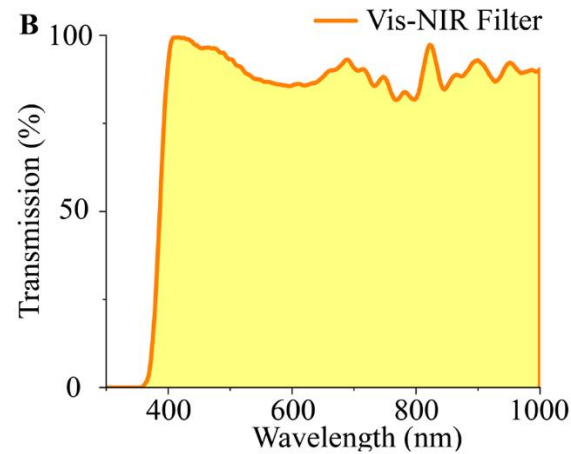
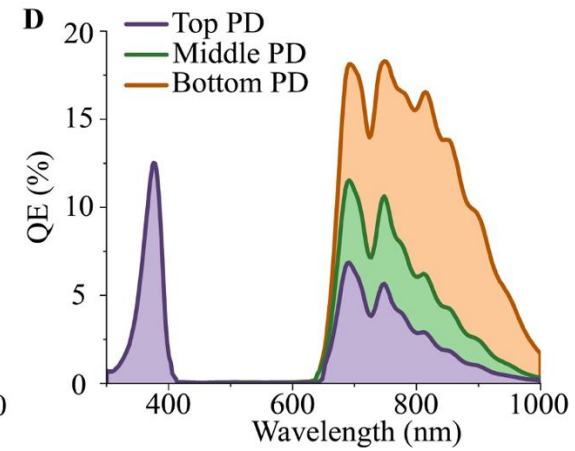
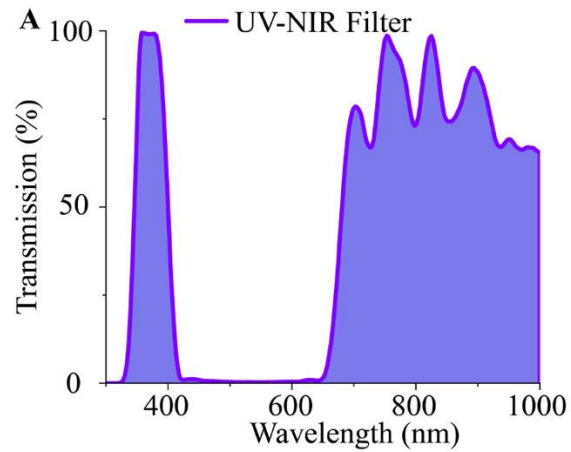


Cronin TW, Bok MJ. "Photoreception and vision in the ultraviolet," **Journal of Experimental Biology**, 2016.

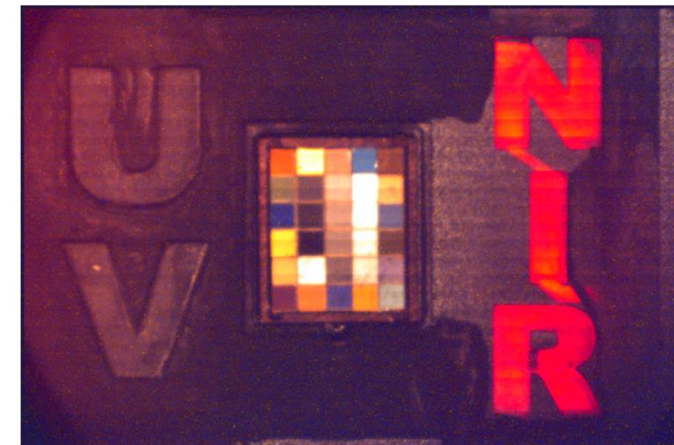




UV-NIR Discrimination



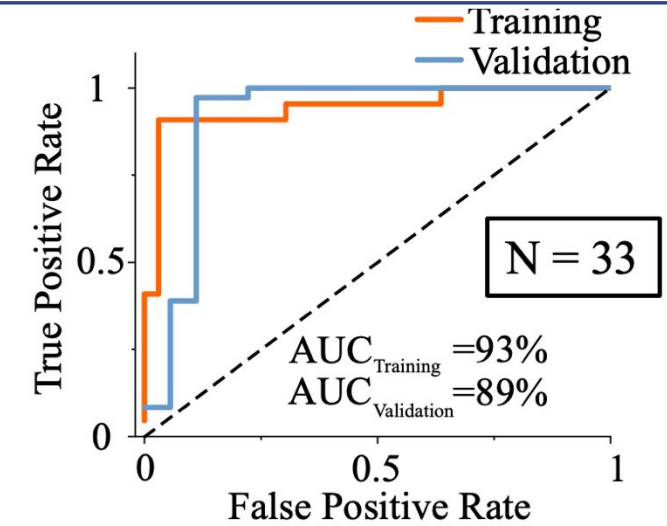
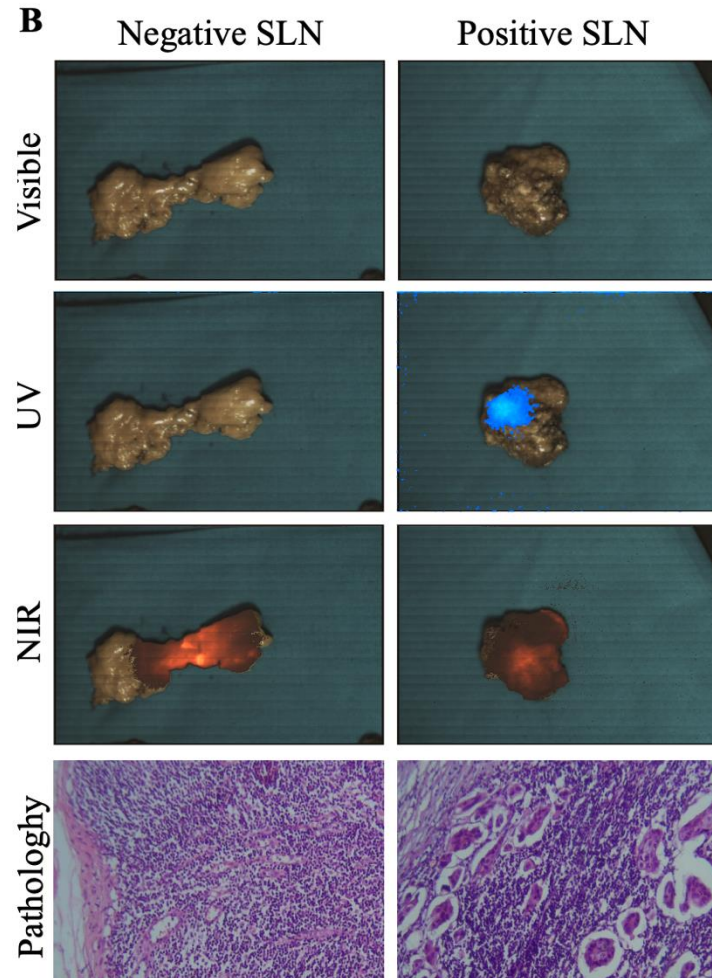
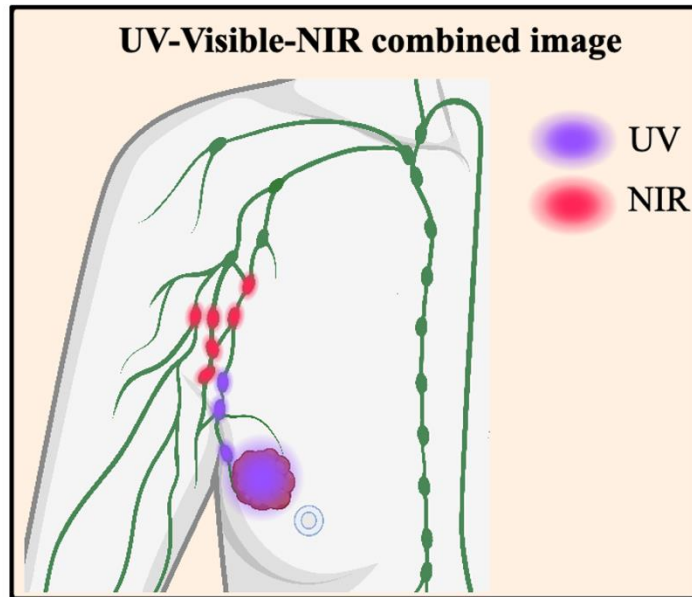
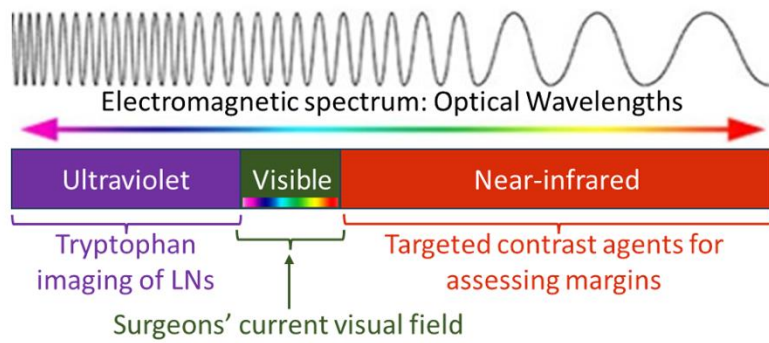
UV-NIR Simultaneous Image



Visible-NIR Simultaneous Image



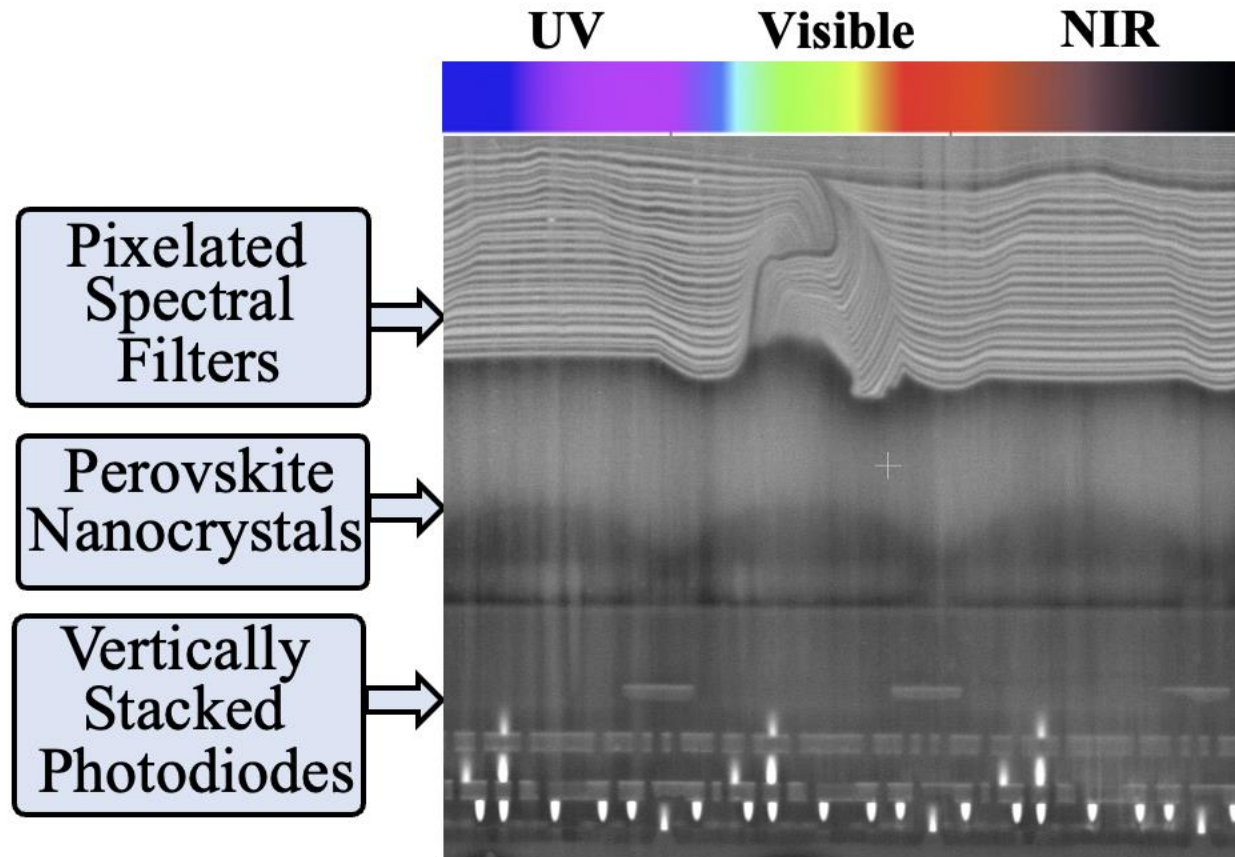
Clinical Validation



Y. Jin, Z. Zhu, ... ,V. Gruev, "Biomimetic Image Sensor for Intraoperative Metastatic Lymph Node Detection" (*in review*).



Next Step: Adding Multispectral UV+Color+NIR





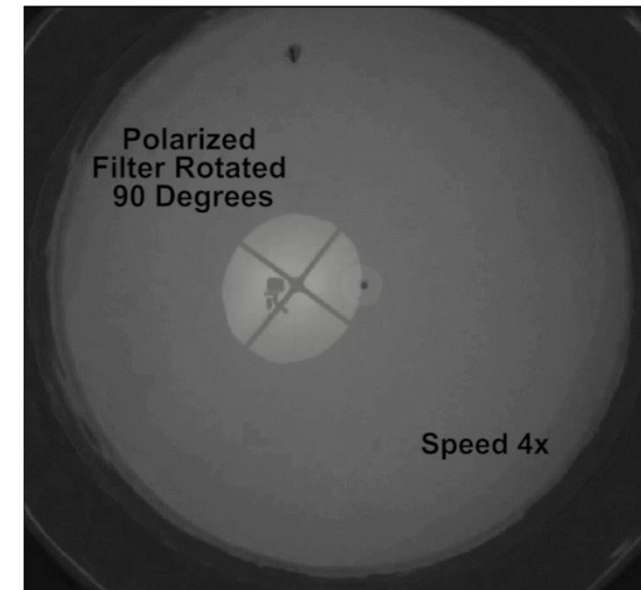
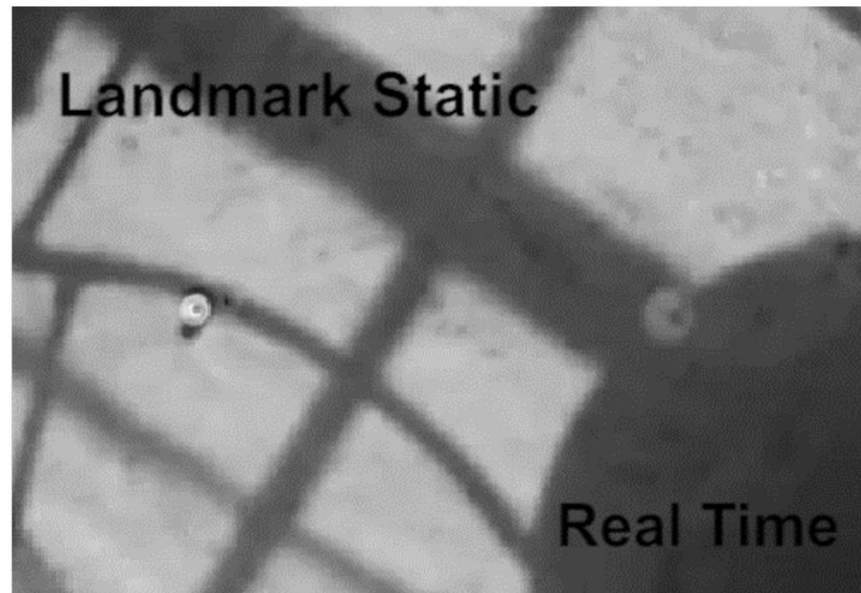
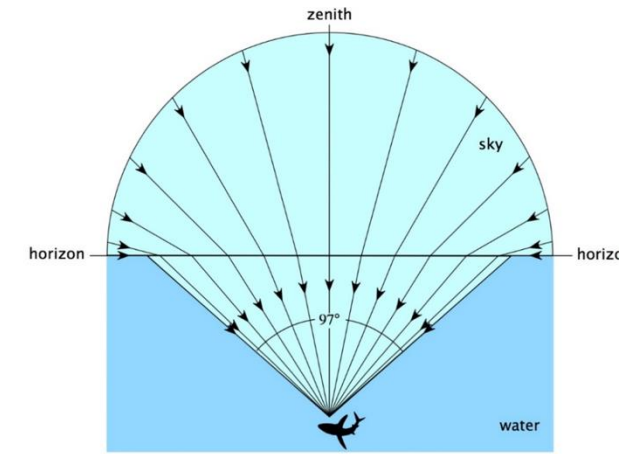
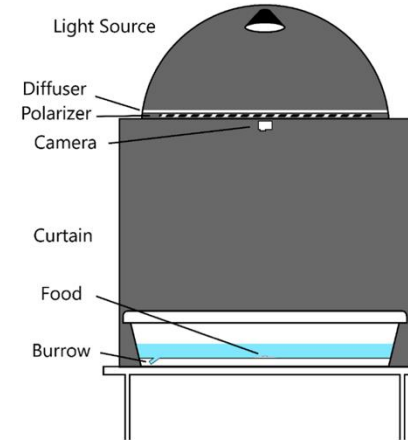
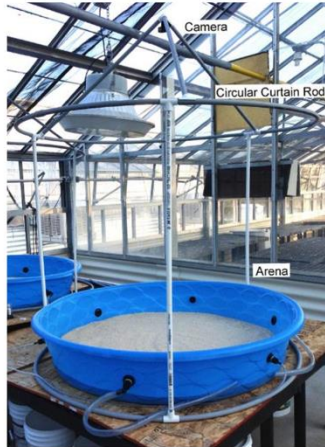
Accomplishments



- Synthesis of UV-fluorescent Perovskite nanocrystals for wavelength resolved UV imaging.
- Bioinspired UV-color-NIR imaging sensor
- **Geolocalization in GPS denied environment**



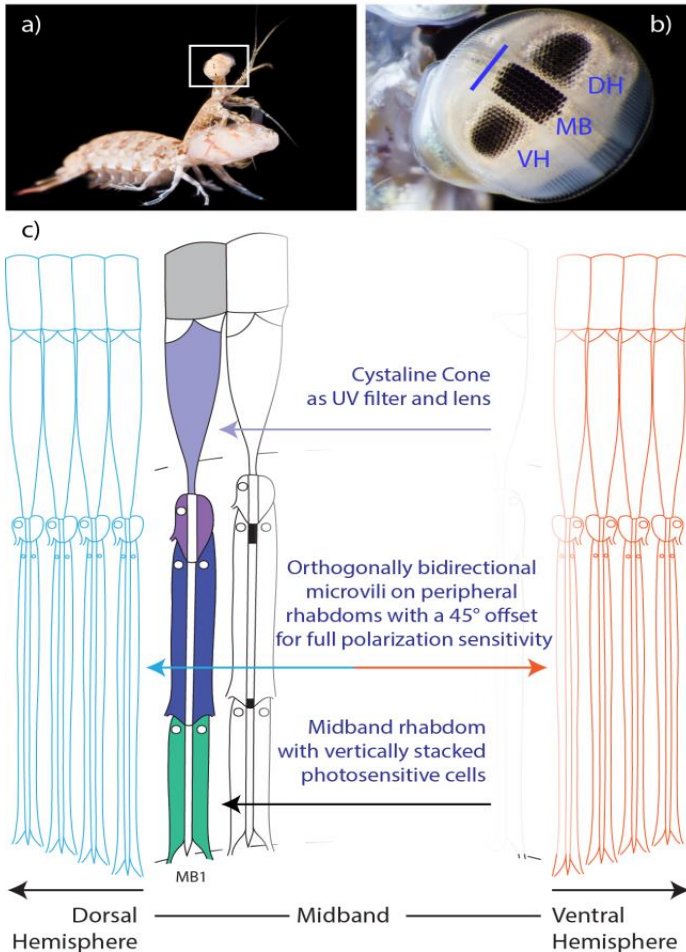
Mantis Shrimp Navigation





Bioinspired Color Polarization Imager

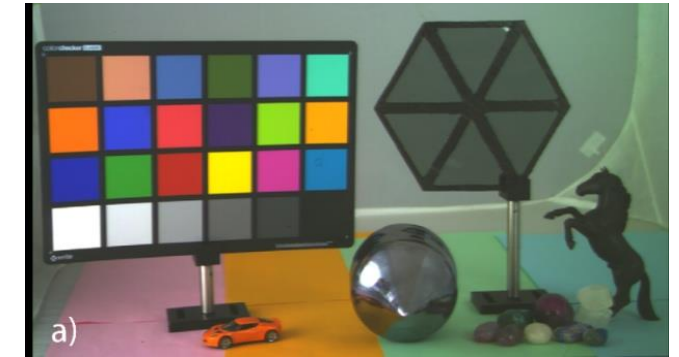
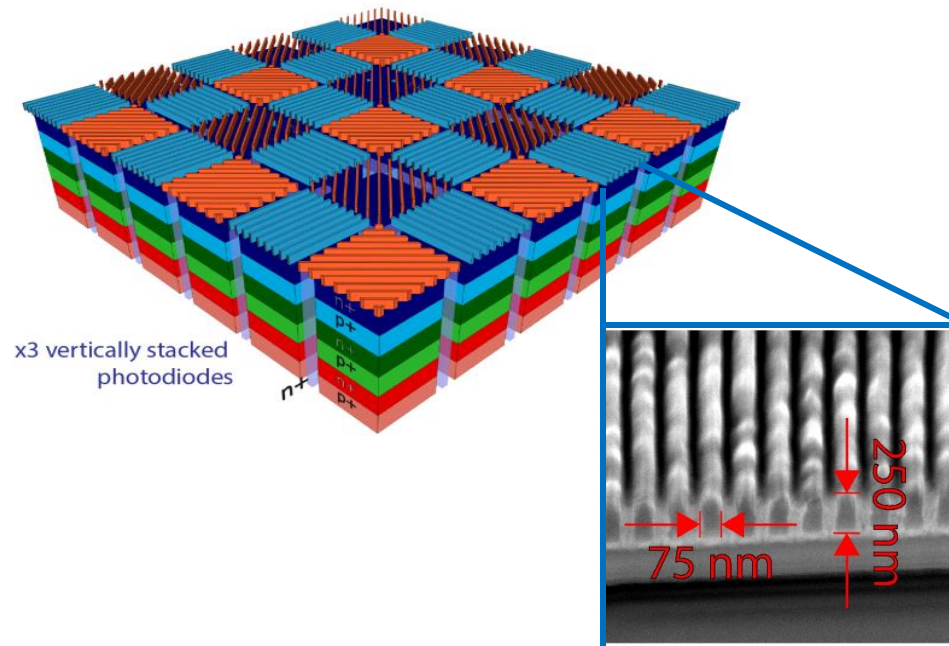
Mantis shrimp's compound eye



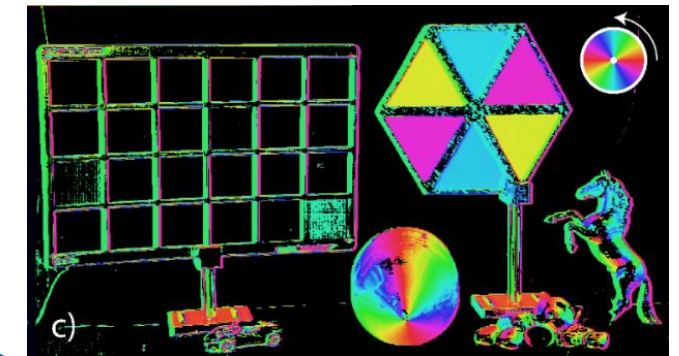
Bio-inspired color-polarization imager



2 pairs of orthogonal linear polarization filters with a 45° offset



Color



Angle of Polarization

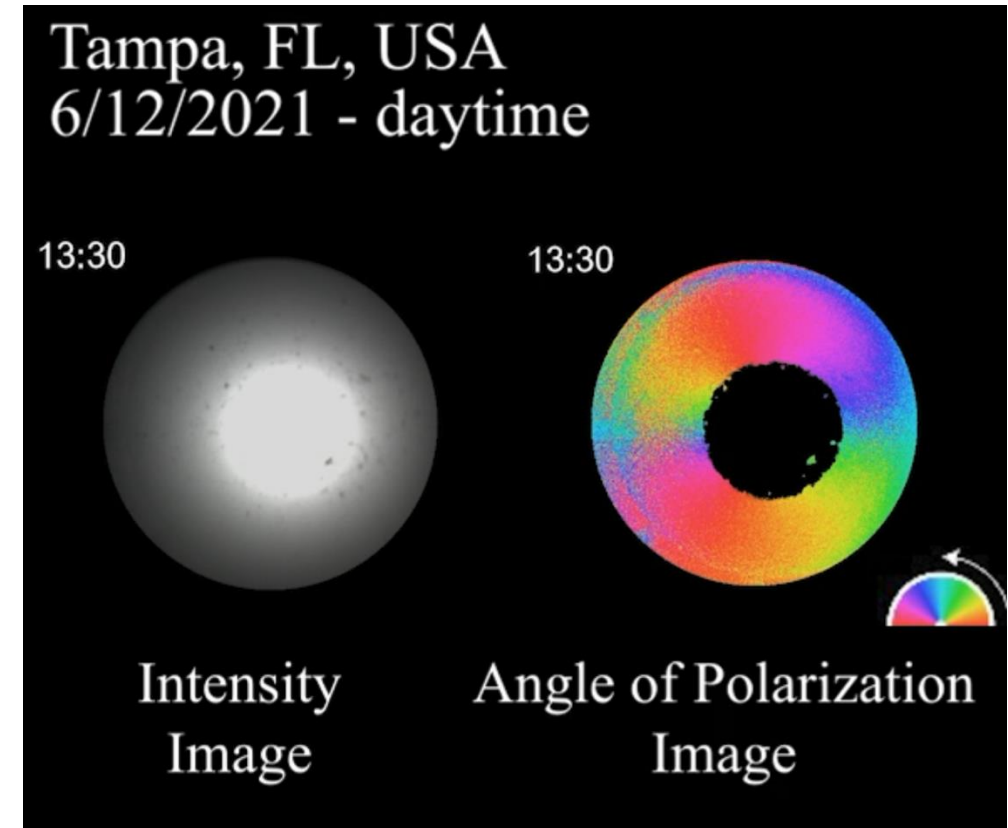
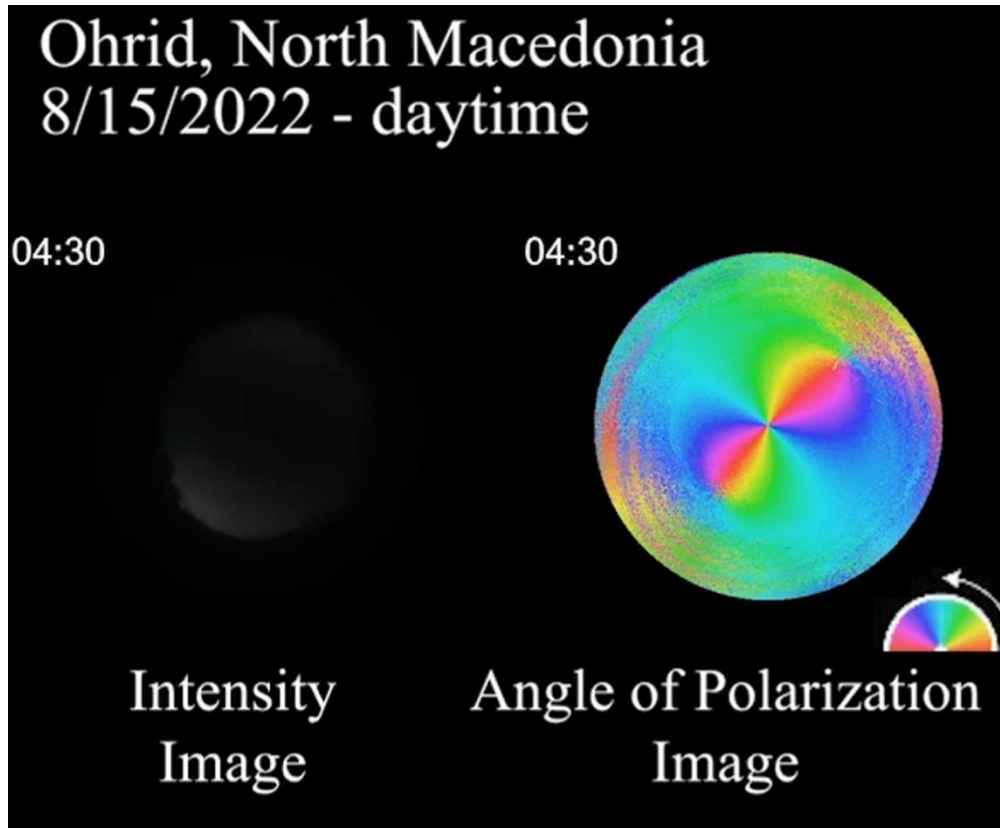


Underwater Polarization Timelapse



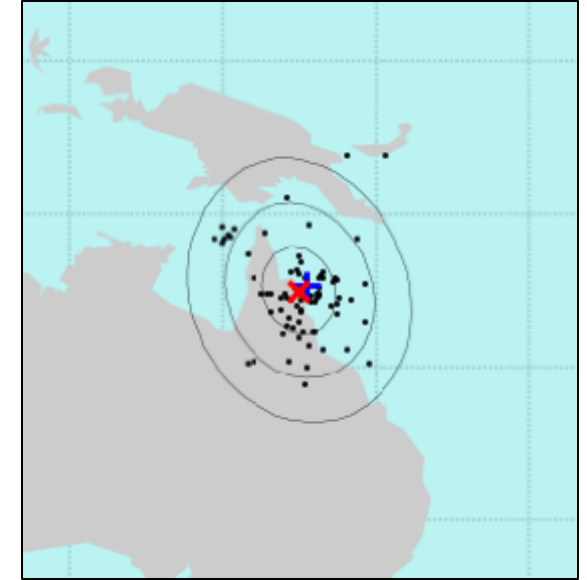
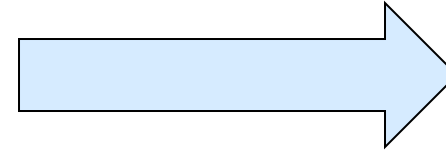
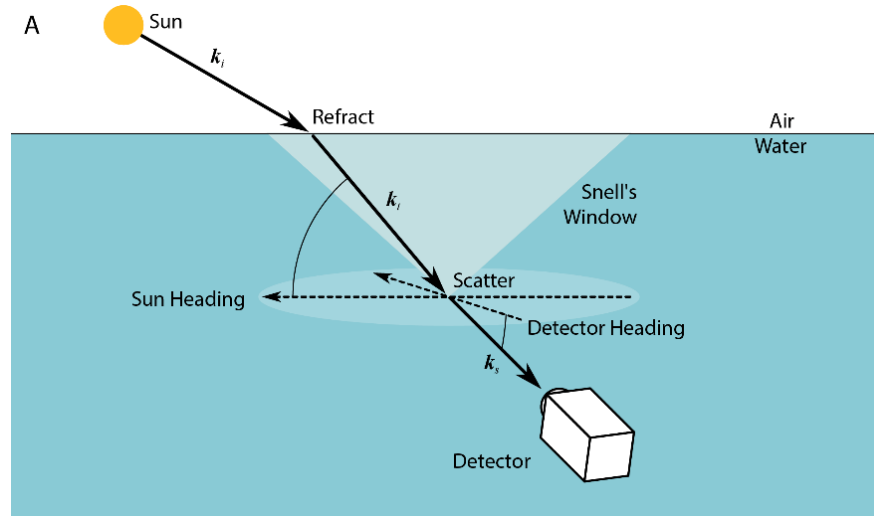
High Visibility Waters

Low Visibility Waters





Underwater Polarization Patterns



$$S_d = M_{S \rightarrow D} M_S M_{R \rightarrow S} M_R S_i$$

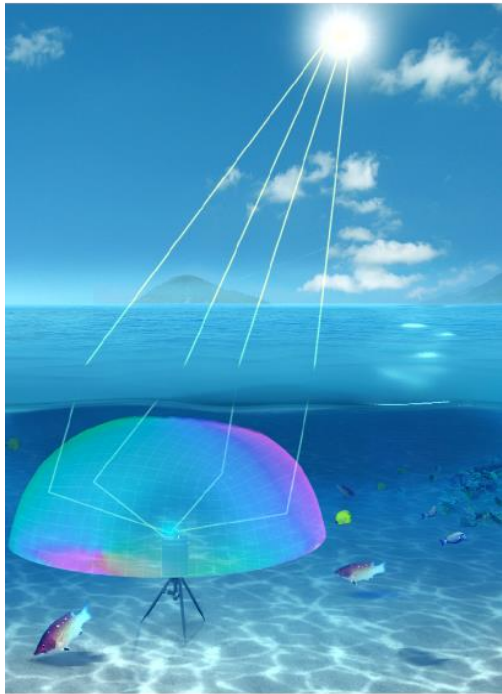
$$M_R = \frac{1}{2} \begin{pmatrix} t_s^2 + t_p^2 & t_s^2 - t_p^2 & 0 & 0 \\ t_s^2 - t_p^2 & t_s^2 + t_p^2 & 0 & 0 \\ 0 & 0 & 2t_s t_p & 0 \\ 0 & 0 & 0 & 2t_s t_p \end{pmatrix}$$

$$M_S = \frac{\beta_{FF}(\theta)}{c_\theta^2 + 1} \begin{pmatrix} c_\theta^2 + 1 & c_\theta^2 - 1 & 0 & 0 \\ c_\theta^2 - 1 & c_\theta^2 + 1 & 0 & 0 \\ 0 & 0 & 2c_\theta & 0 \\ 0 & 0 & 0 & 2c_\theta \end{pmatrix}$$

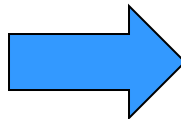
~2,000km RMS
underwater geolocation



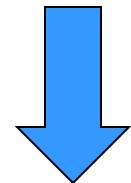
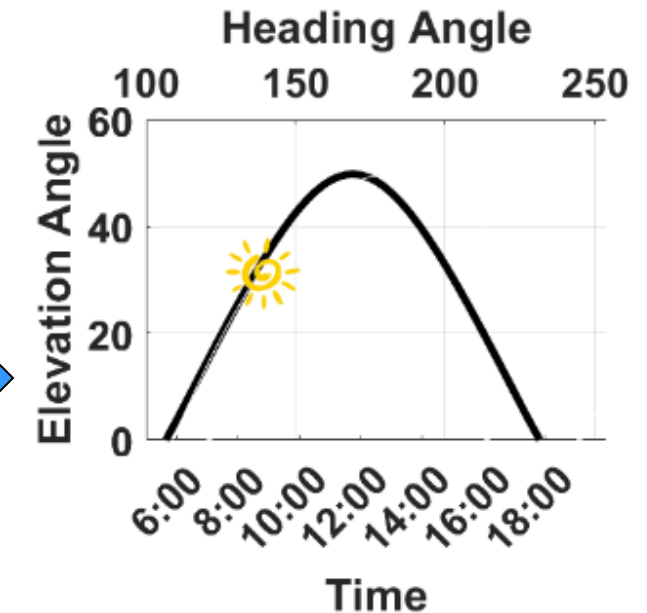
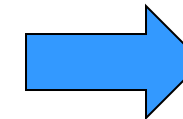
Objective: Geolocalization in GPS Denied Areas



Bio-inspired imaging sensor for underwater polarization.



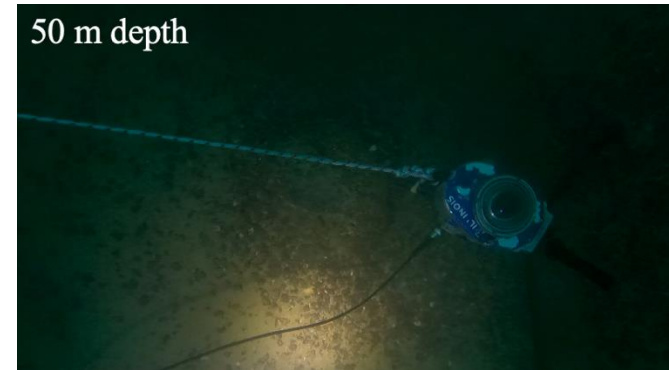
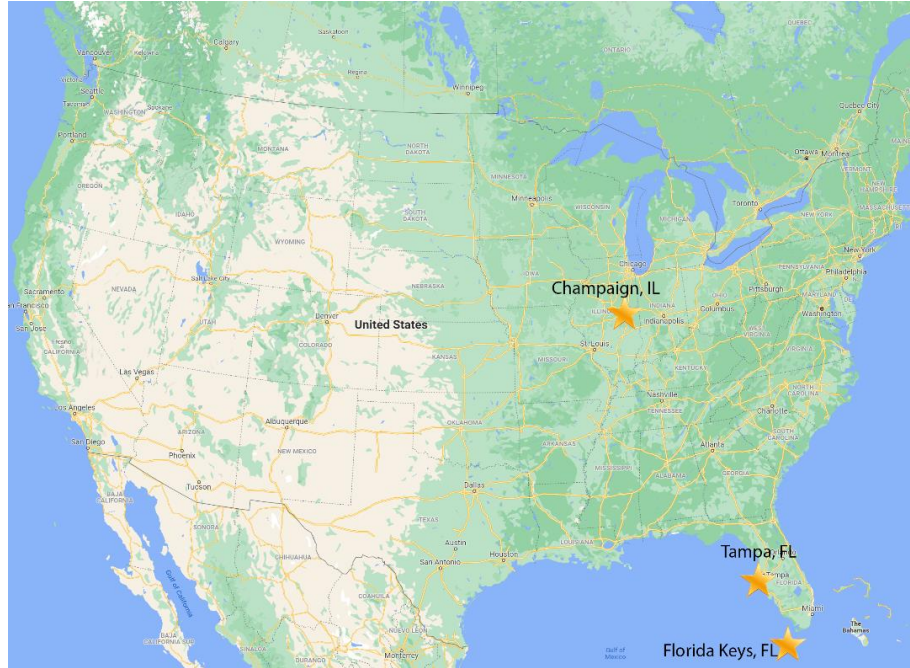
Time and geo-position specific underwater polarization pattern



Geolocation:
longitude and latitude



Data Collection Around the Globe



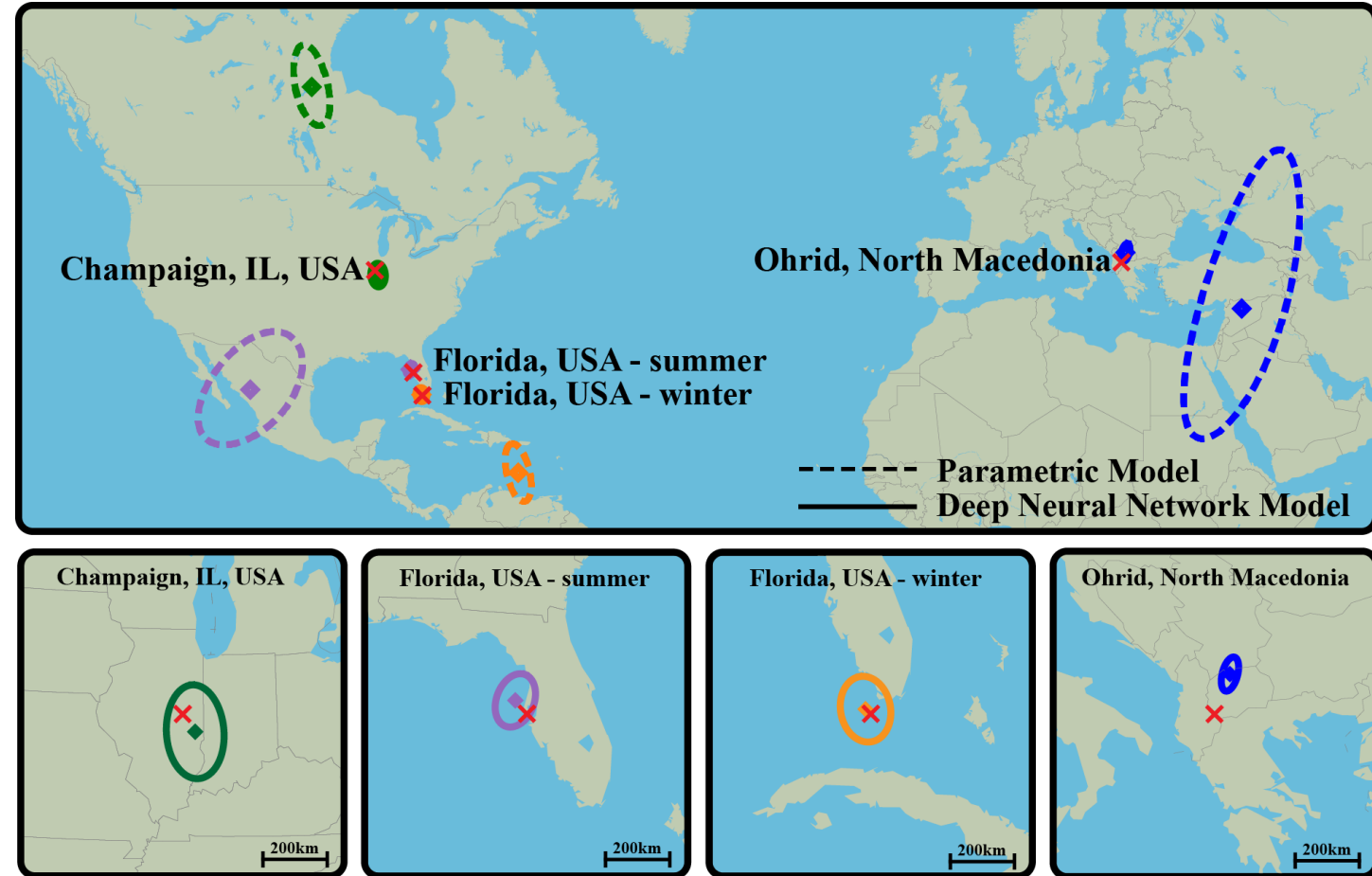
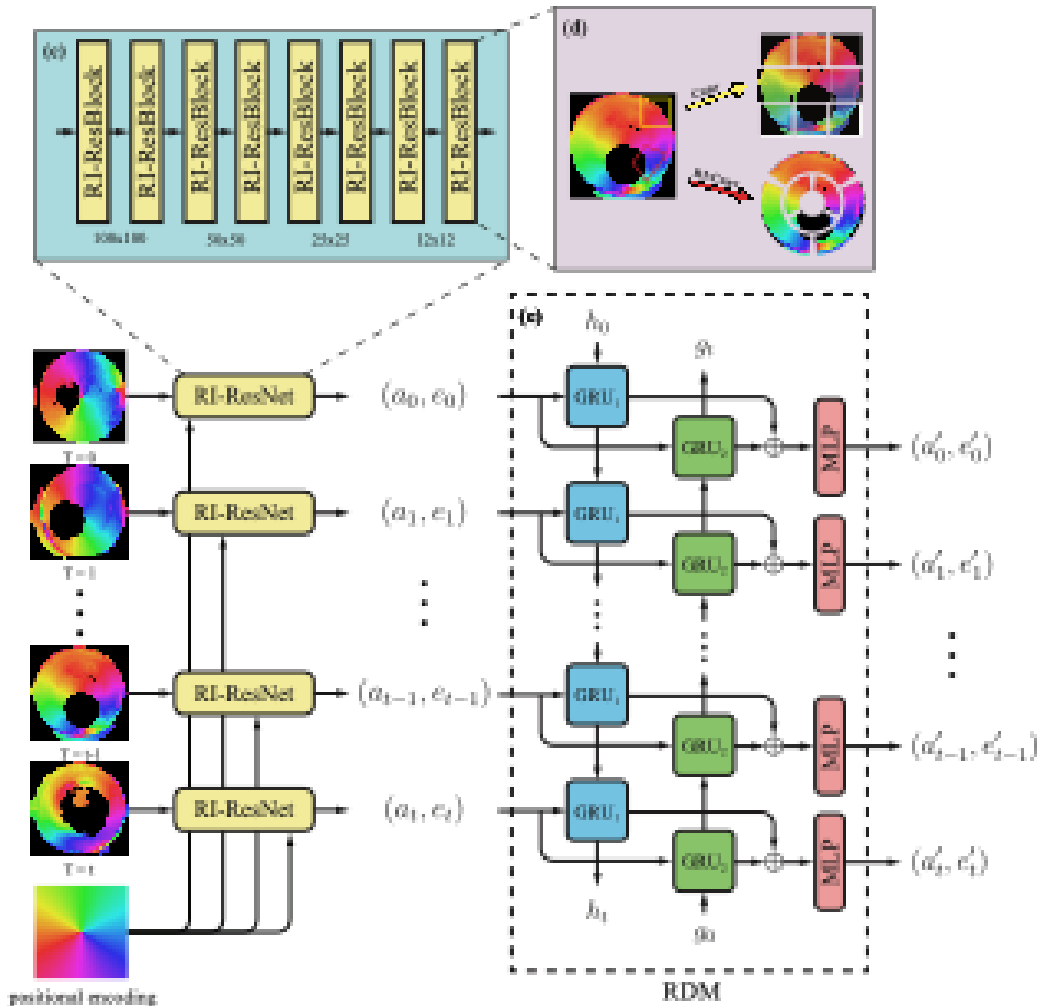
~1 PByte of underwater data collection from four sites:

- **Champaign, IL** (September - November 2020)
- **Florida Keys, FL** (December 2020)
- **Tampa, FL** (May and June 2021)
- **Ohrid, North Macedonia** (July 2021 - Dec 2023)
- **Hawaii, HW** (January 2022)
- **Cordoba, Argentina** (January 2022)





Machine Learning Framework for Geolocalization



~ 60 km geolocalization accuracy

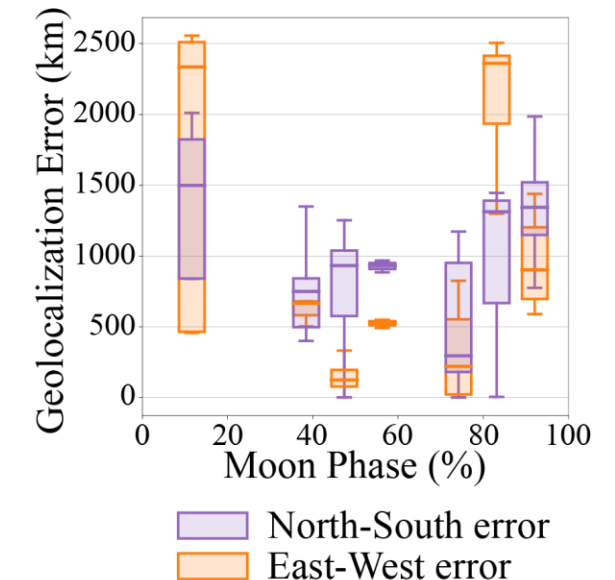
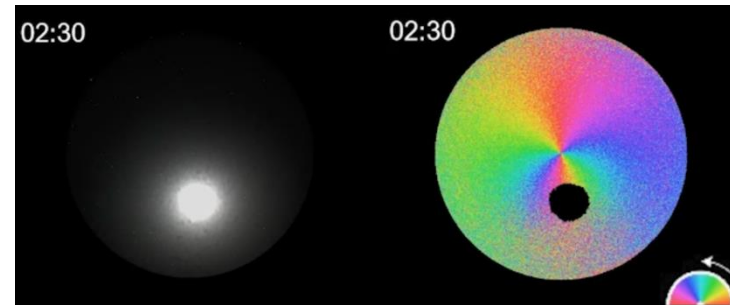
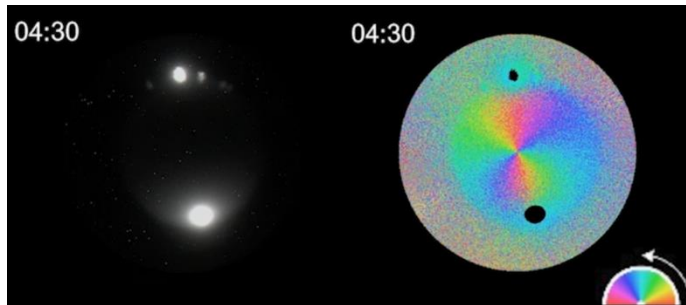
X. Bai, Z. Liang, Z. Zhu, A. Schwing, D. Forsyth and V. Gruev, "Polarization-Based Underwater Geolocalization with Deep Learning", **eLight**, (2023).



Nighttime Geolocalization

High visibility:
Ohrid, North Macedonia

Low visibility:
Champaign, IL



X. Bai, Z. Liang, Z. Zhu, A. Schwing, D. Forsyth and V. Gruev, "Polarization-Based Underwater Geolocalization with Deep Learning", **eLight**, (2023).

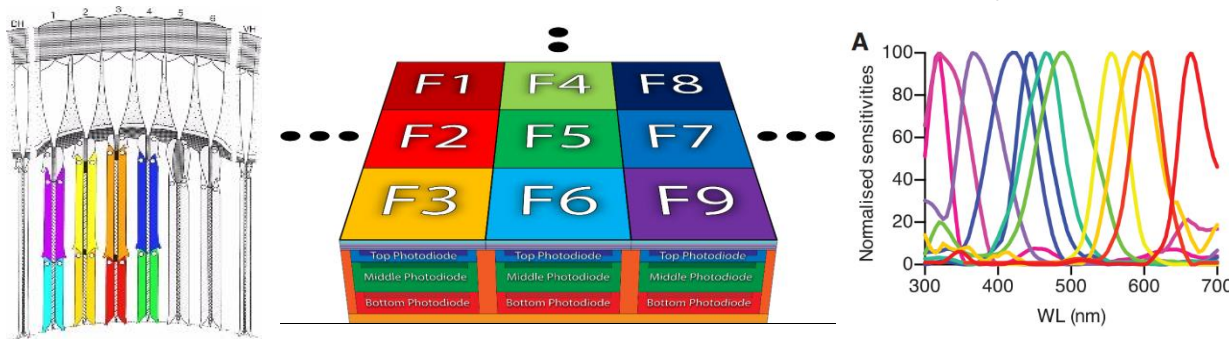


Bio-inspired Multispectral-Polarization Imaging Devices with Perovskite Nanocrystals for UV and Visible Spectral Sensing

Viktor Gruev and Shuming Nie

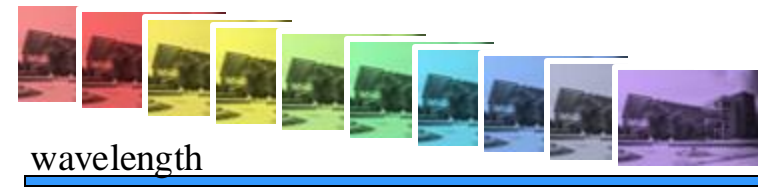
Objectives:

- Mimic the mantis shrimp visual system to design next generation of low power, compact, snap shot, multispectral and polarization sensitive cameras.
- Understand the mechanisms behind Perovskite nanocrystals



Technical Approach:

- Synthesized all inorganic perovskite crystals for UV imaging. Perovskite nanocrystals are integrated with silicon vertically stacked photodetectors to enable multispectral UV detection.
- Monolithic integration of perovskite nanocrystals, pixelated optical filters and silicon vertically stacked photodiodes for UV-visible-NIR and polarization imaging

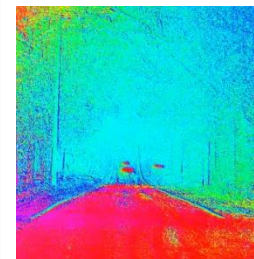


Accomplishments:

- Chemical synthesis of perovskite nanocrystals with different colors.
- Integration of PNCs with CMOS imaging technology
- Develop data driven framework for polarization based geolocation in GPS denied areas.
- Filed one patent and obtained approval for another

DoD Benefit: Compact, low power, highly sensitive multispectral and polarization imagers for target recognition in adverse conditions.

polarization



multispectral target detection

