THE UNIVERSITY OF ARIZONA
Wyant College of Optical Sciences

Application of LWIR Spectro-Polarimetry for Ice-Water Discrimination

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Comprehensive Oral Exam

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Outline

- **Ice-Water Discrimination**
  - Applications
- **Background: Optical Physics**
  - Polarization in LWIR
  - Blackbody Radiation
  - Optical Constants of Water
- **Design of Channeled Polarimeters: Optical Engineering**
  - High Order Retarder
  - Diffraction Grating
  - Polarimetric Efficiency
- **Data Reduction: Image Science**
  - Fourier Transform
  - Sources of Noise
  - Retrieve Polarization Information from Intensity Values

Applications

ICESat-2

ICE, CLOUD, AND LAND ELEVATION SATELLITE-2

- Monitoring Earth's cryosphere
- Differentiating thermodynamic phase of clouds
- Safety mitigation: detecting ice buildup on aircrafts and roads
- Detecting melt ponds on glacial ice

- Current methods: microwave radiometers

<u>Advantage of LWIR Spectro-Polarimetry:</u>

Discriminate in the phase transition between water and ice while they are at the same kinetic temperature

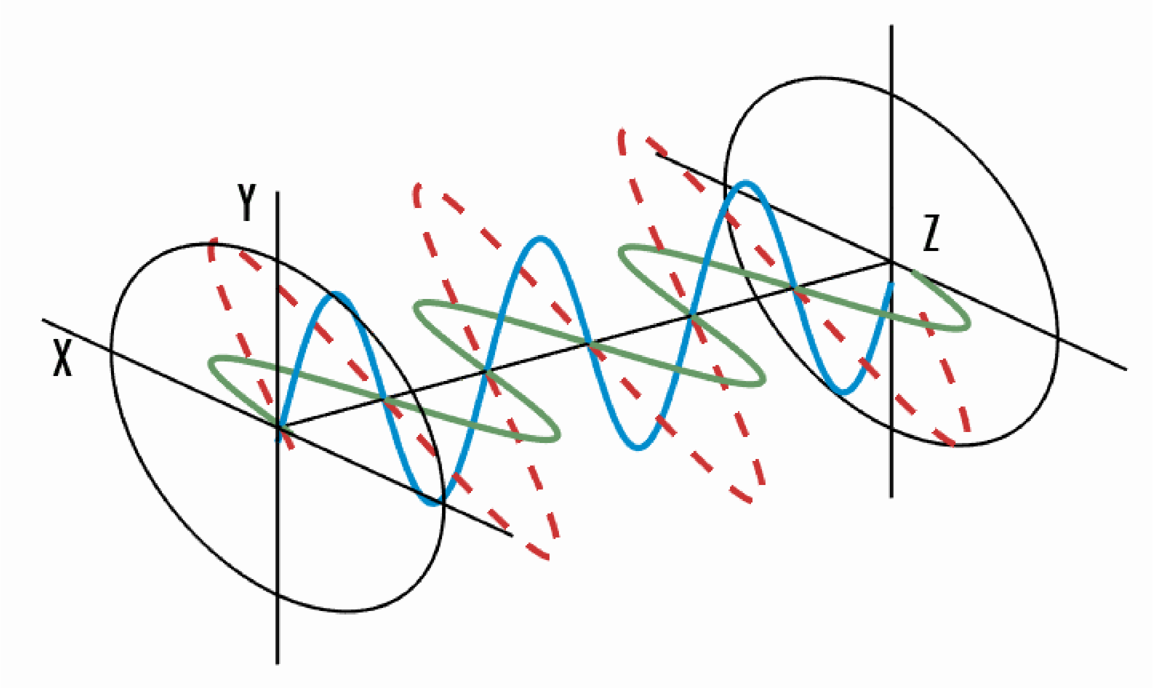
Polarization

- Polarization is the preferential direction of electric field oscillation
- Two linear Stokes parameters, Q and U, quantify linear polarization states

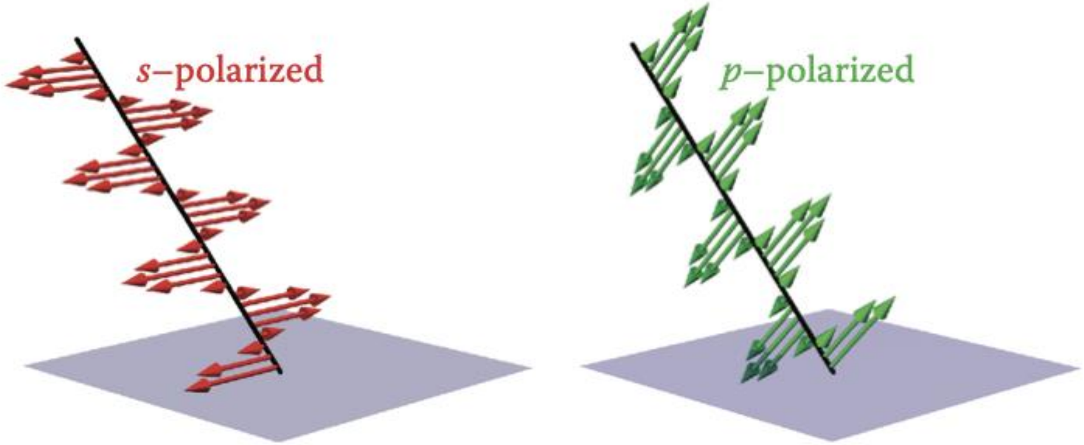
$$\mathbf{S}\,(I,\rho,\theta) = I\begin{bmatrix}1\\ \rho\cos(2\theta)\\ \rho\sin(2\theta)\end{bmatrix} = \begin{bmatrix}I\\ Q\\ U\end{bmatrix} = \begin{pmatrix}P_{0^\circ}+P_{90^\circ}\\ P_{0^\circ}-P_{90^\circ}\\ P_{45^\circ}-P_{135^\circ}\end{pmatrix}$$

ρ- Degree of Linear Polarization (DoLP)

θ- Angle of Linear Polarization (AoLP)



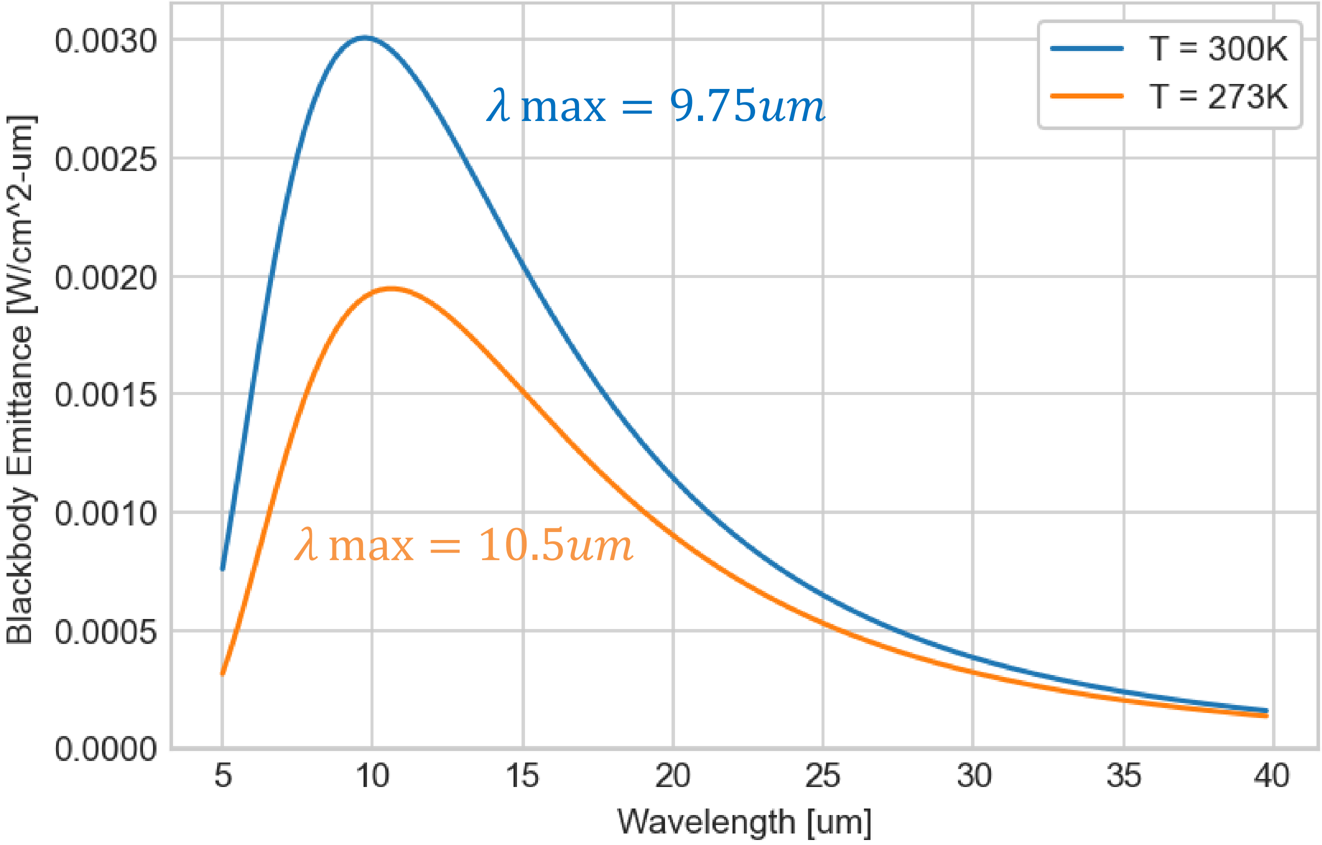
- Fresnel reflection is higher for s-polarized
- Fresnel transmission is higher for p-polarized



135° polarization: combination of two linear components, equal amplitude and phase

Blackbody Radiation

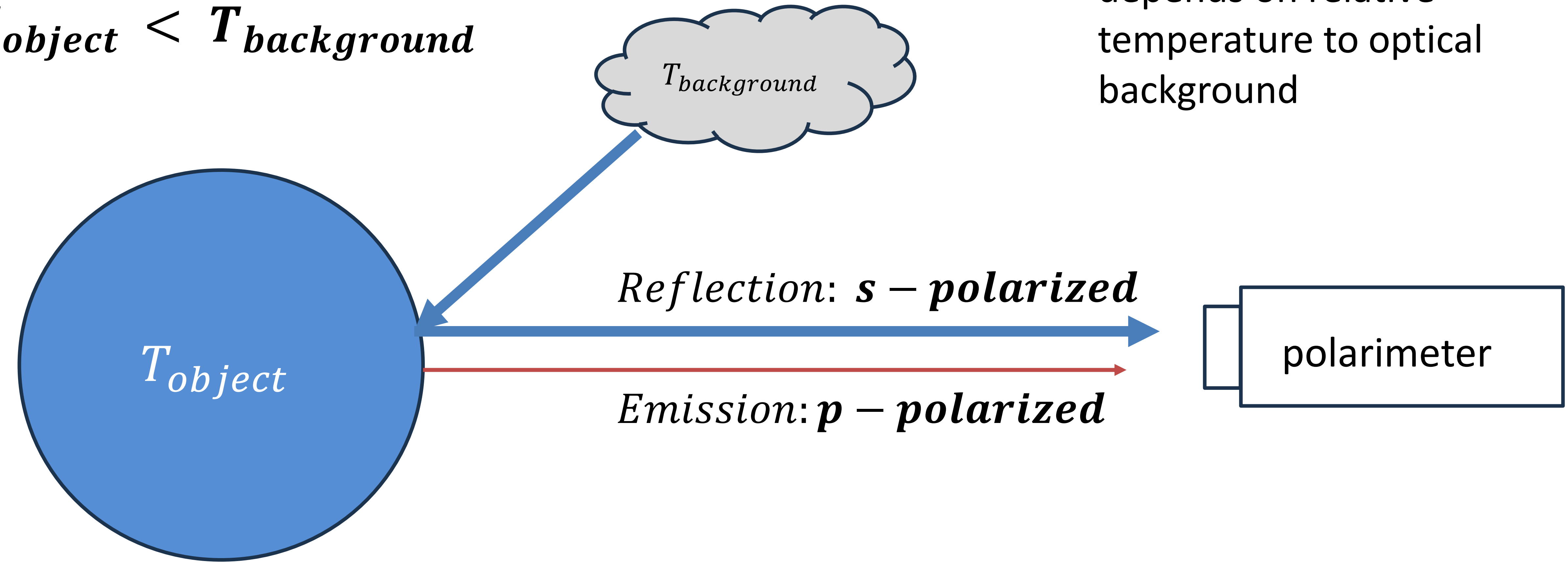
- A blackbody is an idealized material that absorbs all radiation incident upon it
- **All thermal equilibrium** , a blackbody will:
  - have a spectral emittance described by Plank's law
  - have an emissivity of 1
  - be unpolarized
- Graybodies with $\varepsilon < 1$ will be partially polarized
- Rougher surfaces will have decreased polarized emission but higher emissivity
- **Brightness temperature**: the temperature at which an ideal blackbody would need to be to have an equivalent radiance of a graybody at a given wavelength



Polarized Reflection

$$Case\ 1: Cold\ Target$$
$$\boldsymbol{T_{object} < T_{background}}$$

- Polarization measurement depends on relative temperature to optical background

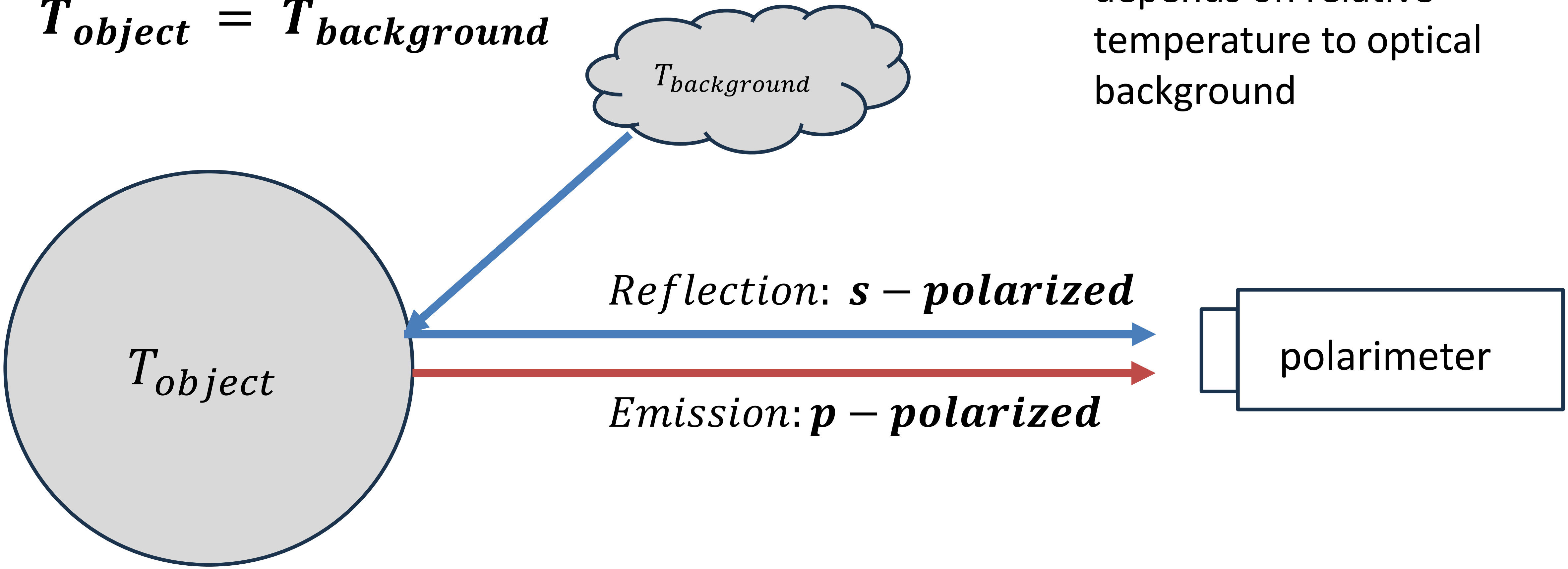


Unpolarized Thermal Equilibrium

Case 2: Thermal Equilibrium

$$T_{object} = T_{background}$$

- Polarization measurement depends on relative temperature to optical background

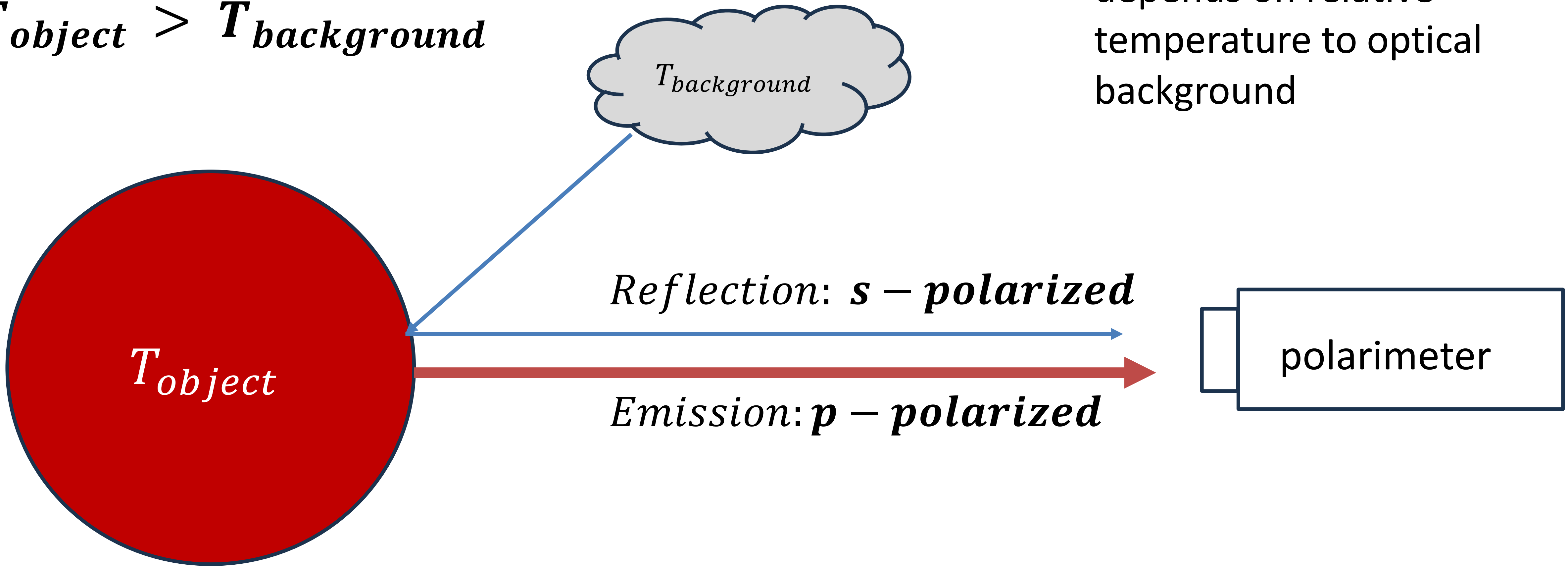


Polarized Emission

Case 3: Hot Target

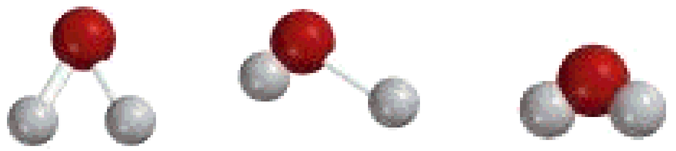
$$\boldsymbol{T_{object} > T_{background}}$$

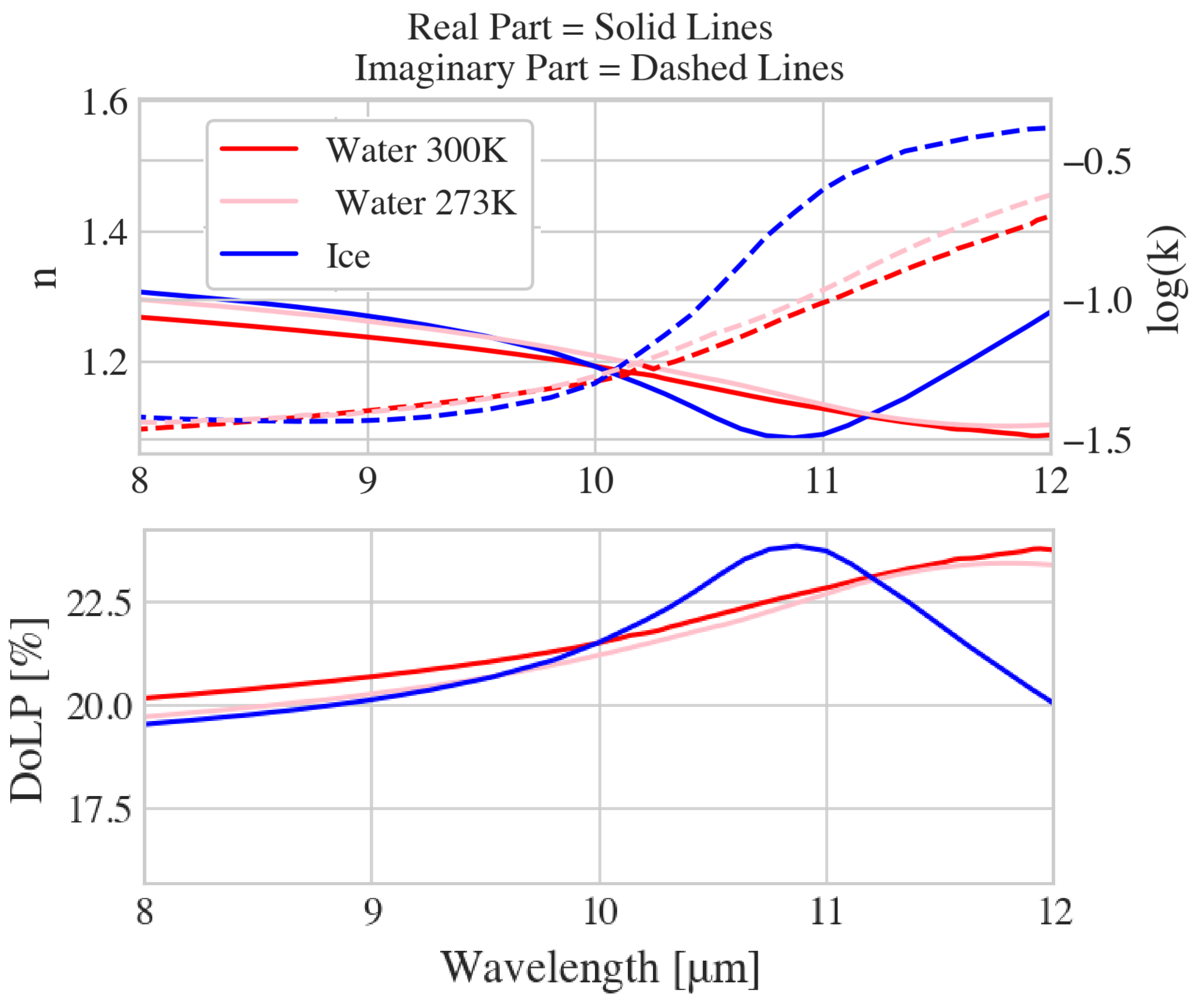
- Polarization measurement depends on relative temperature to optical background



Optical Constants of Water

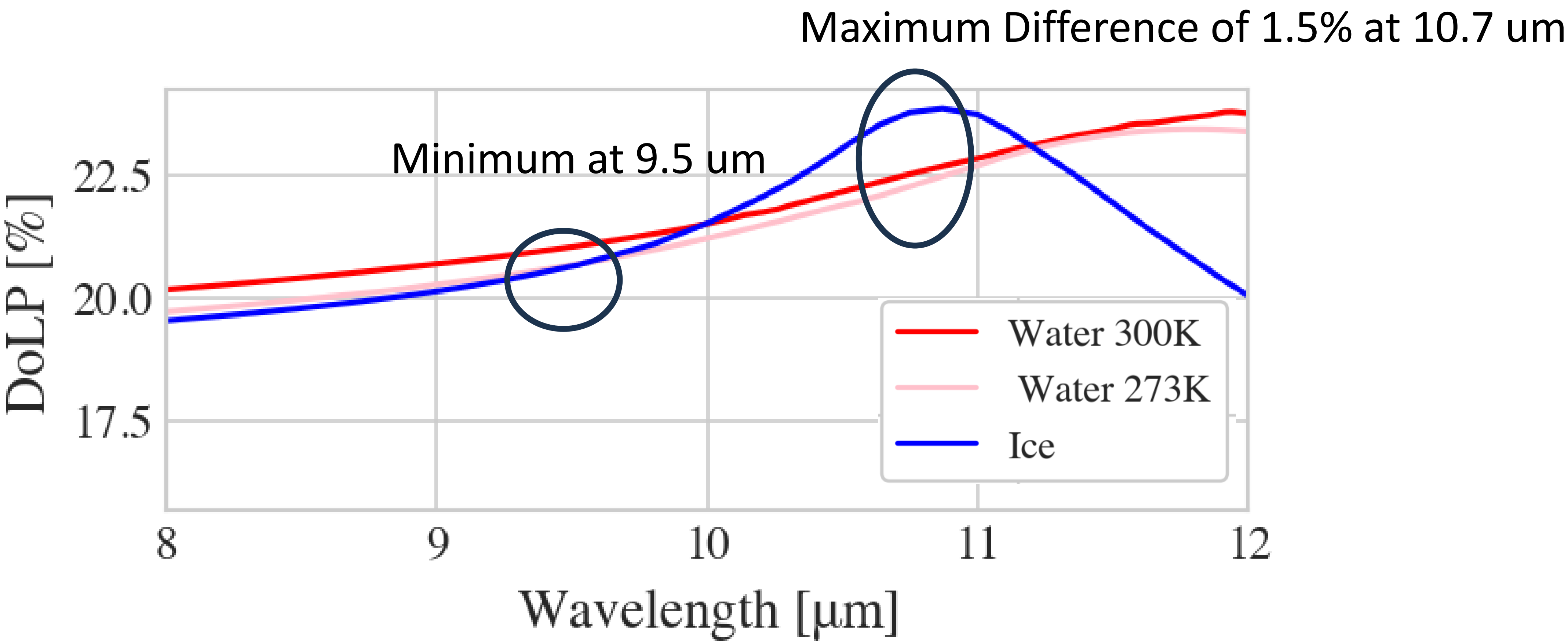
- Molecular vibrations are a dominant absorption mechanism in the LWIR
- Fundamental vibrational modes of the H_2O molecule occur at different frequencies
- Ice and water have different vibrational frequencies, and thus different spectral regions of anomalous dispersion
- Therefore, the refractive index is dependent on kinetic temperature and thermo-dynamic phase





Polyanskiy. Refractive Index Database (2008)

Polarization Simulation at 20° view angle



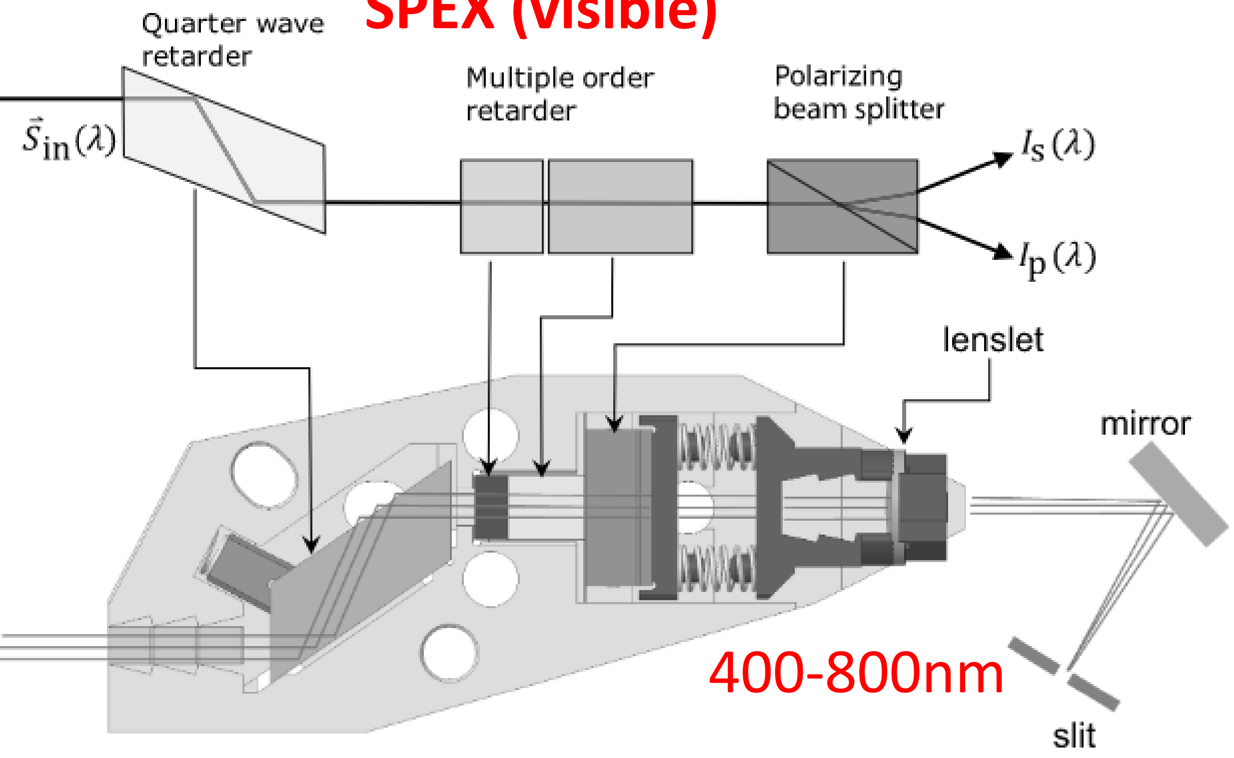
<u>For ice-water discrimination:</u>

Polarimetric Precision: Resolve a 1.5% Difference in DoLP

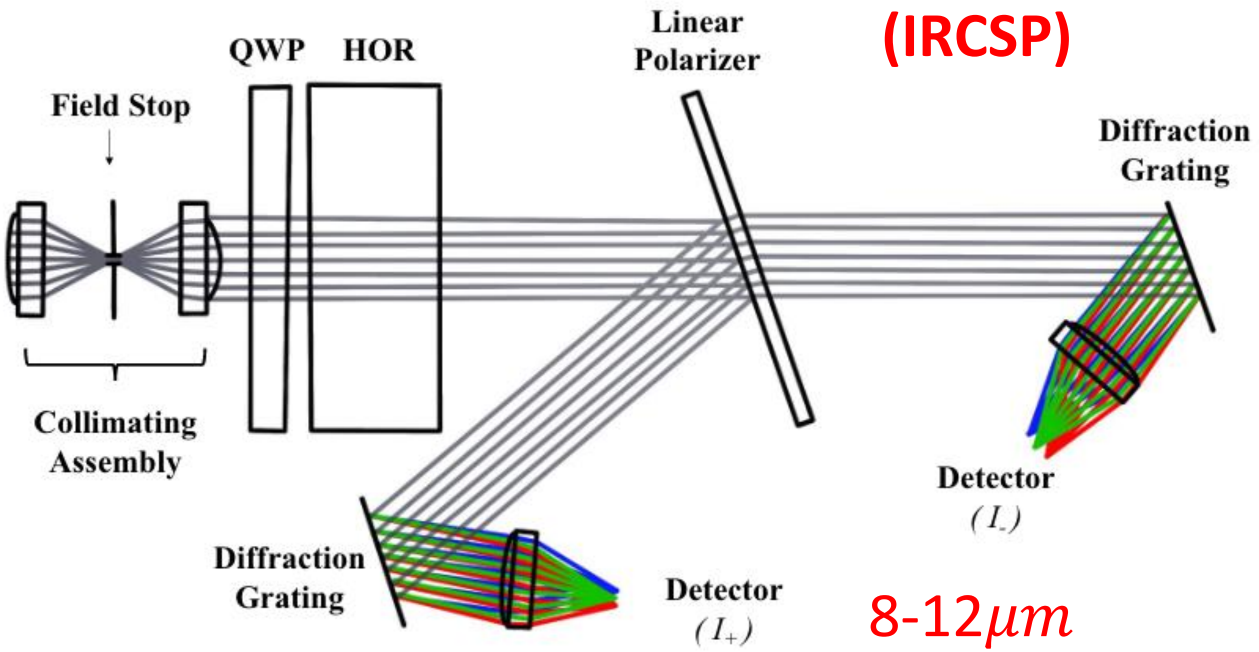
Spectral Resolution: 1.2 microns

Spectropolarimeter Instrument Concept

SPEX (visible)



Infrared Channeled Spectro-Polarimeter (IRCSP)



1. Wavelength dependent polarization modulation
   - Quarter wave plate and high order retarder
   - **Thickness of HOR effects Nyquist sampling**

2. Split orthogonal polarization states
   - Polarized beam splitter

3. Spectrally resolve the intensity on the focal plane
   - **Dispersion of diffraction grating, detector pitch, and focal length effects Nyquist sampling**

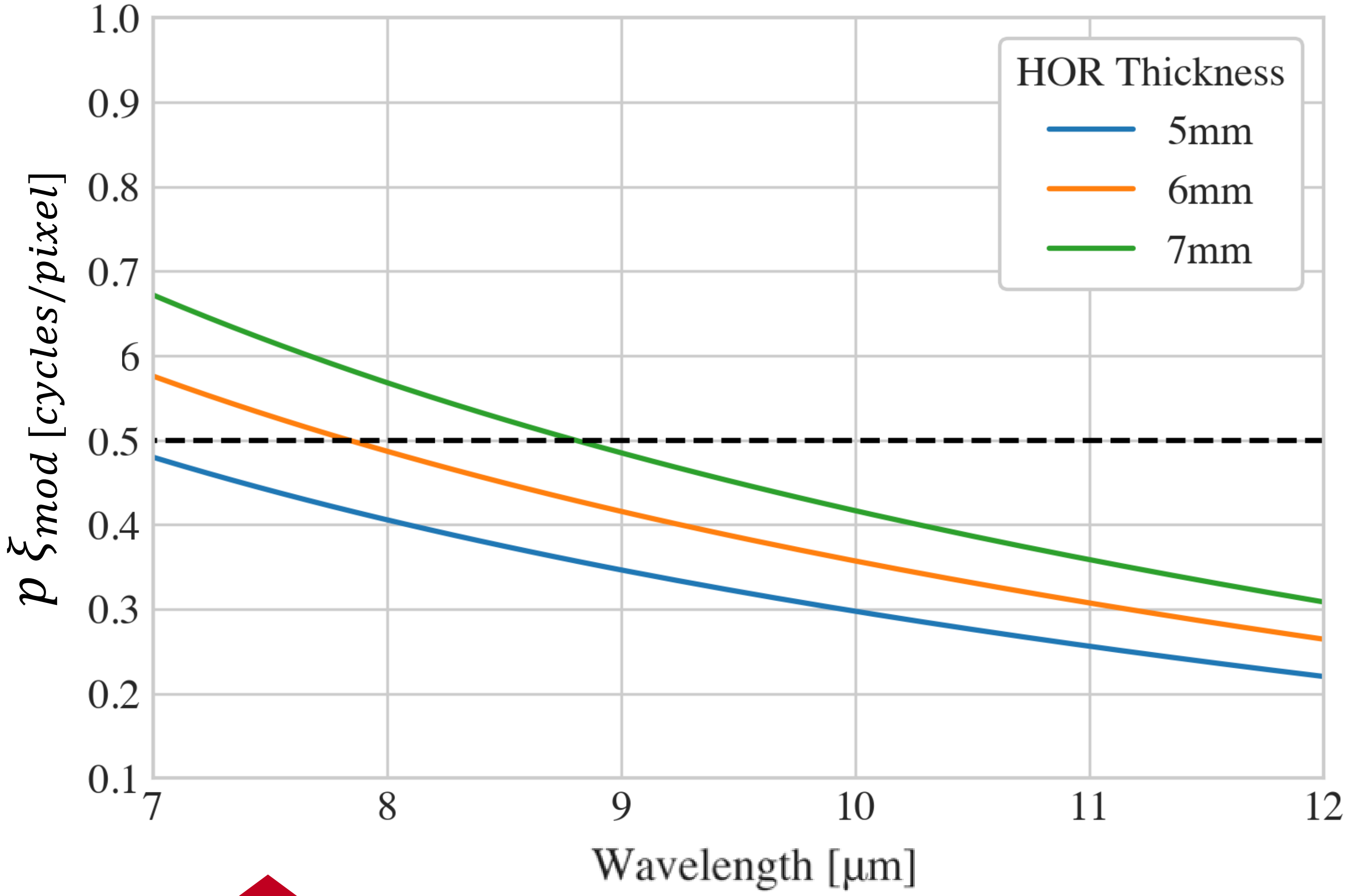
Nyquist Sampling

- Modulation frequency at the focal plane must be less than half the sampling frequency
- Sampling frequency limited by pixel pitch
- Modulation frequency (ξ_{mod}) is the retardance multiplied by the linear dispersion of the grating

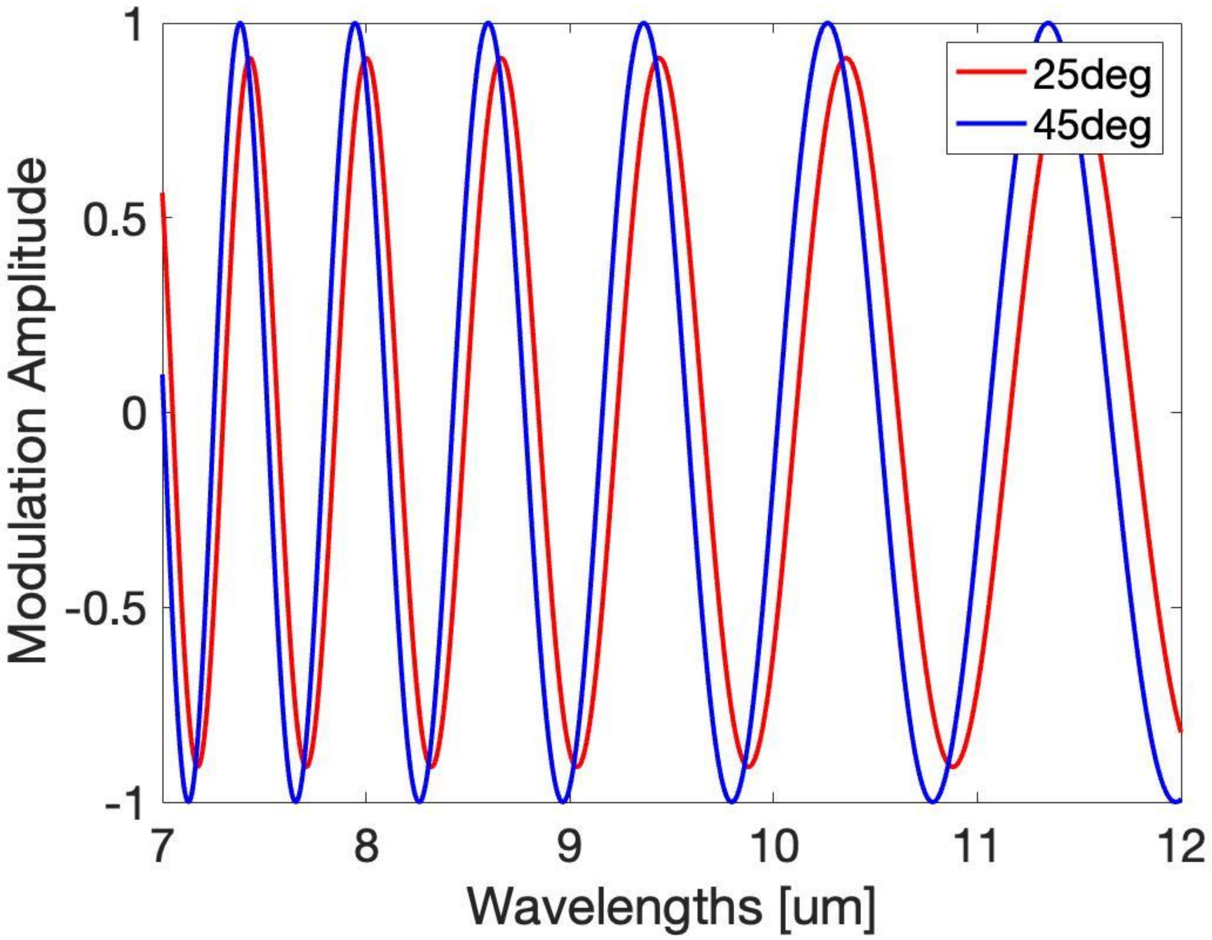
$$\frac{\cos(\theta_d) d_G}{f} \delta(\lambda)\, p \leq 0.5$$

Grating Period, d_G = 20μm
Focal Length, f = 6.3mm

Pixel Pitch p = 12μm.



Crystal Alignment



$$M = \frac{I_s - I_p}{I_s + I_p}$$

- QWP and HOR must have their fast axis oriented 45 degrees with respect to each other for unit modulation amplitude

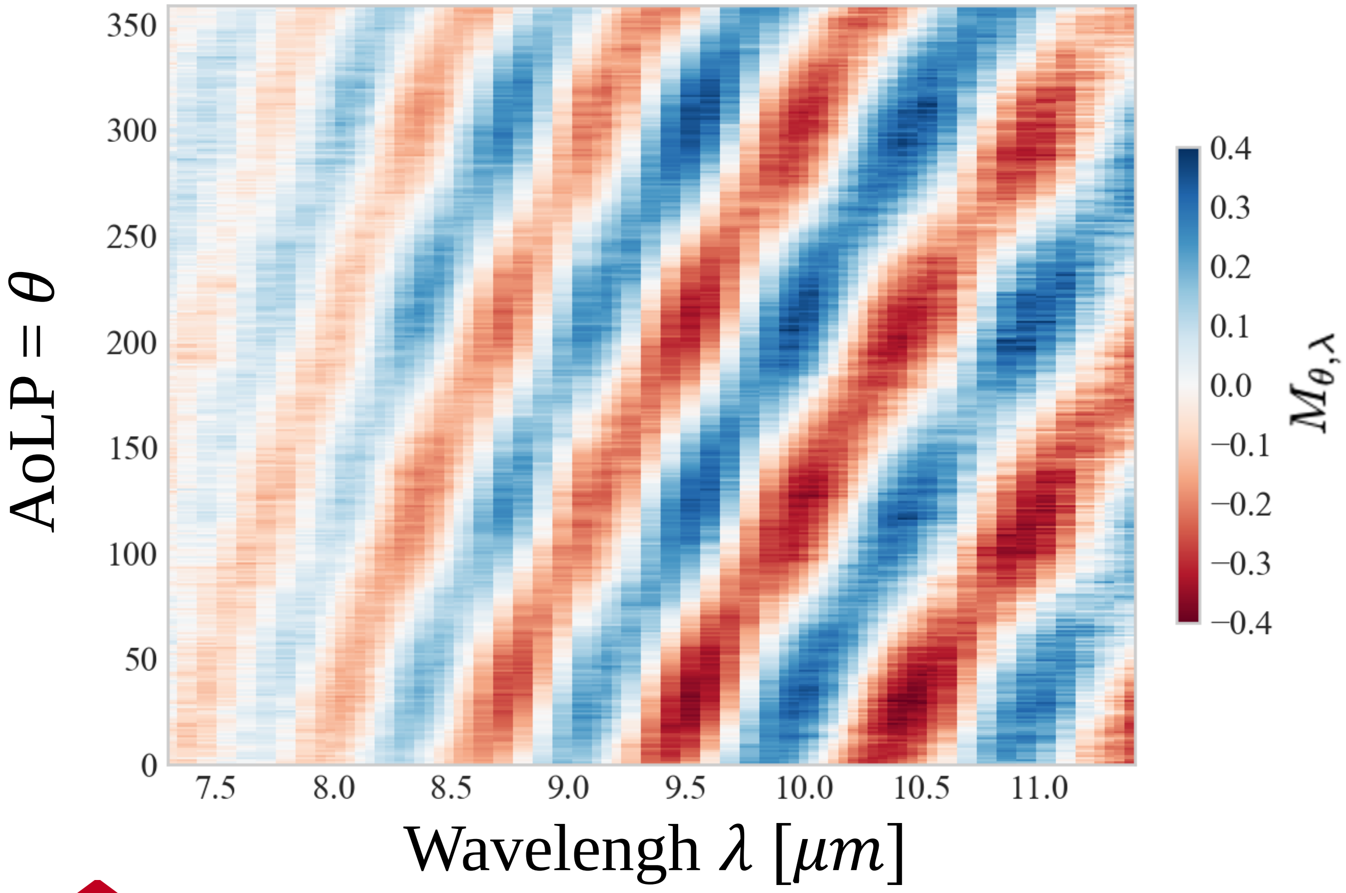
Polarimetric Efficiency

$$M_{\theta,\lambda} = W_{\theta,\lambda}\left[Q\sin\left(\frac{2\pi\delta(\lambda)}{\lambda}\right) + U\cos\left(\frac{2\pi\delta(\lambda)}{\lambda}\right)\right]$$

Efficiency Term = Amplitude of modulation with fully polarized input

What affects the efficiency?:

- Alignment of QWP and HOR
- Path contrast of polarized beam splitter
- Polarization dependent transmission
- Blurring of point spread function
- Spectral resolution
- Pixel pitch
- Detector noise



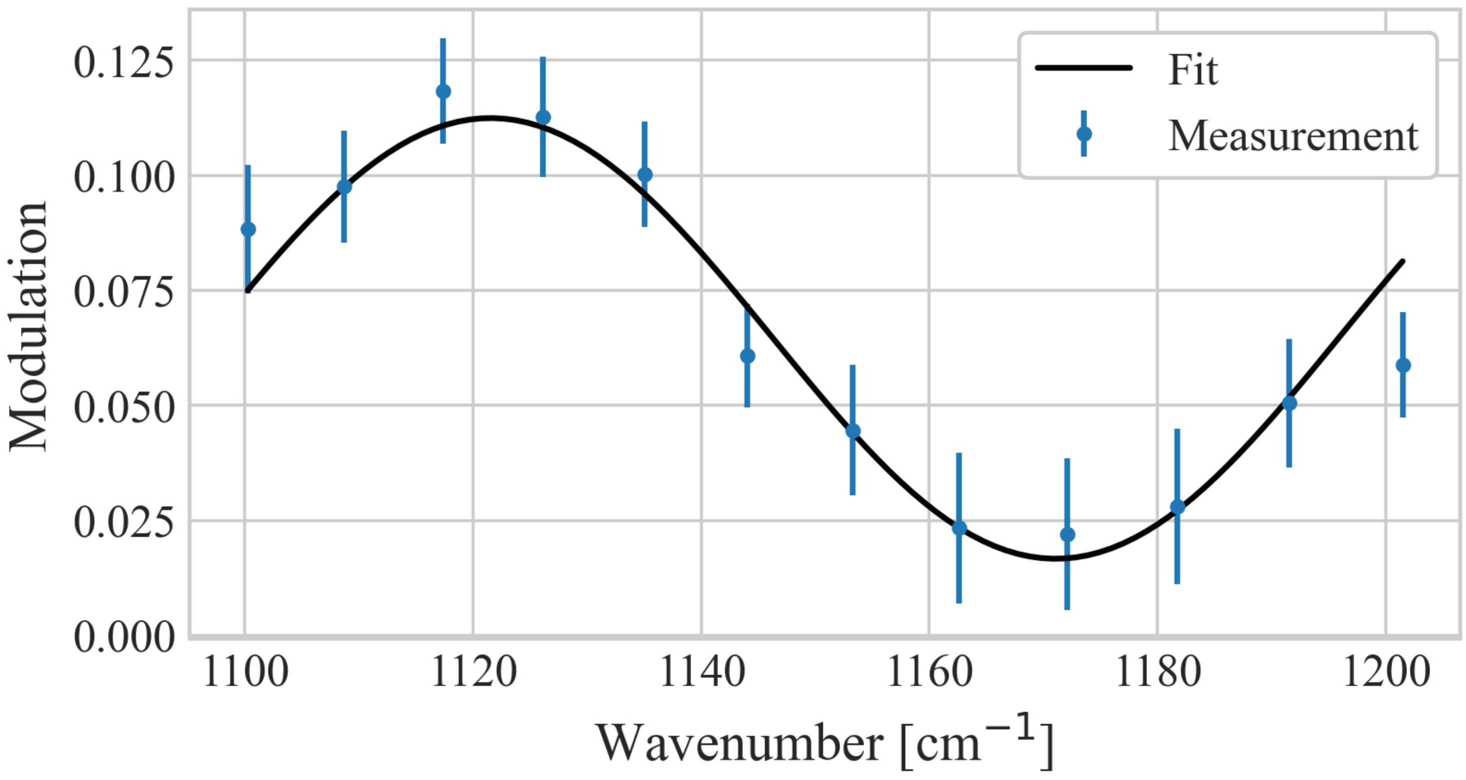
Johnson Noise

- IRCSP detectors are FLIR Boson uncooled microbolometers
- Most prevalent source of noise: Johnson noise
  - Caused by random movement of charge carriers
  - Detector response changes with small temperature fluctuations
- Current FLIR Bosons have a Noise Equivalent Differential Temperature (NEDT) of 20mK at room temperature

Data Reduction

Demodulation: process of extracting Q and U from discrete camera counts

- SPEX uses a linear regression to retrieve Q and U as fit parameters
- IRCSP does demodulation in Fourier space to minimize the effect of noise



Fit:

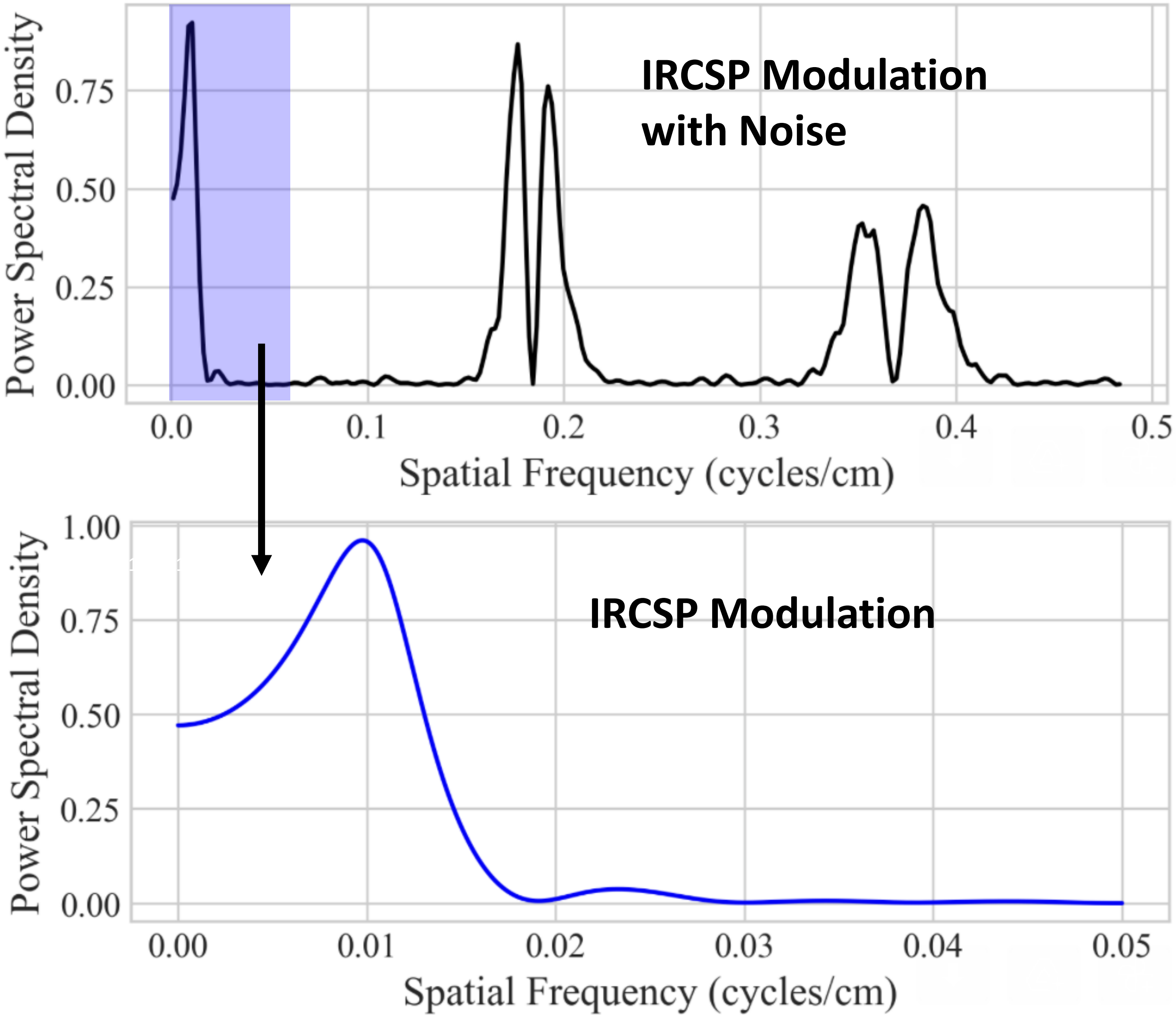
$$M_{\theta,\lambda} = W_{\theta,\lambda}\left[Q\sin\left(\frac{2\pi\delta(\lambda)}{\lambda}\right) + U\cos\left(\frac{2\pi\delta(\lambda)}{\lambda}\right)\right]$$

Measurement:

$$M = \frac{I_s - I_p}{I_s + I_p}$$

Demodulation in Fourier Space

- A Fourier transform is a method that converts a spatial signal into its frequency components
- A power spectrum, the modulus squared of a Fourier transform, identifies the frequency content
- Johnson noise has a wider power spectrum than the IRCSP modulation because the noise content has a higher spatial frequency



Summary and Conclusion

– Ice and water at the same kinetic temperature is expected to have different polarization signatures in the LWIR because of differences in their refractive indices. A LWIR spectro-polarimeter can be specified to measure this difference.

– The modulation function is a merit of performance of spectropolarimeters. Design considerations to maximize the amplitude of modulation include:
  - Thickness of HOR, diffraction grating period, and detector to meet Nyquist requirement
  - Selection of polarized beam splitter