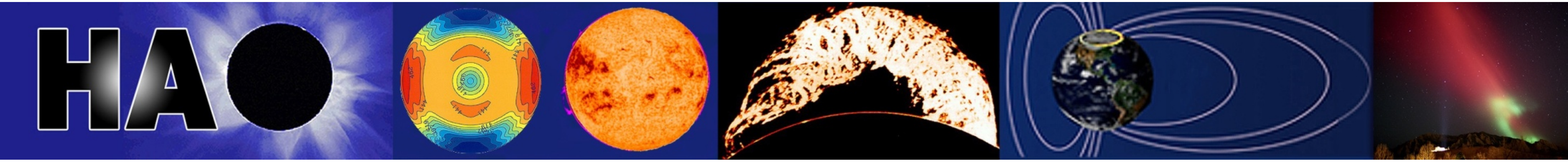


Efficient Wavelength-Diverse Polarimetric Modulators

Alfred G. de Wijn, Roberto Casini, Steve Tomczyk

High Altitude Observatory (HAO) – National Center for Atmospheric Research (NCAR)

NCAR

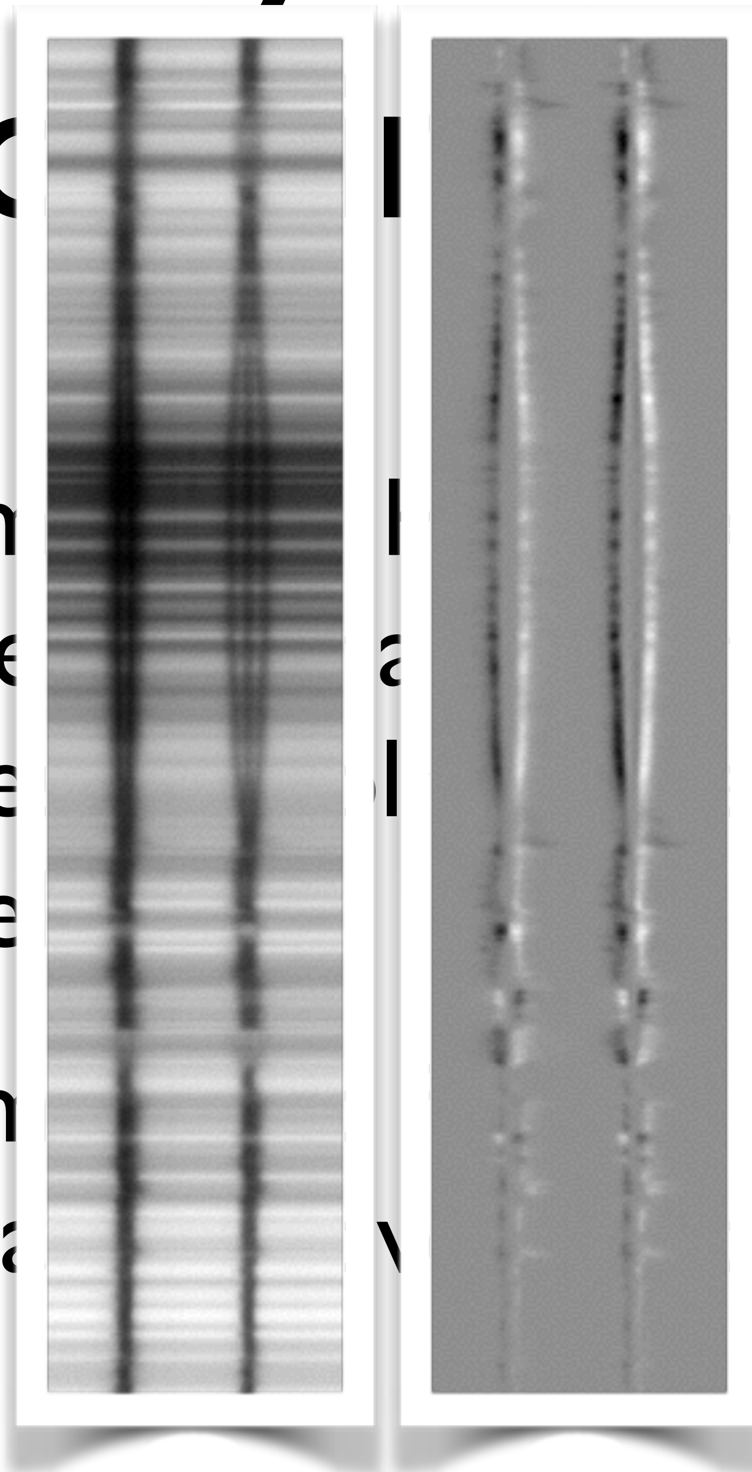
Terminology, etc.

- I'm using the Stokes formalism
  - Intensity I, linear Q & U, circular V
- Sensitivity: ability to detect a signal
- Accuracy: ability to know what that signal is
- Pathetic: 10^{-2} or worse
- Respectable: 10^{-4} or bigger

History of Solar Polarimetry

- Pieter Zeeman and Hendrik Lorentz discover the "Zeeman effect" in 1896: spectral lines are split in the presence of magnetic field.
- Hale finds magnetic field in sunspots in 1908 using a primitive spectro-polarimeter.

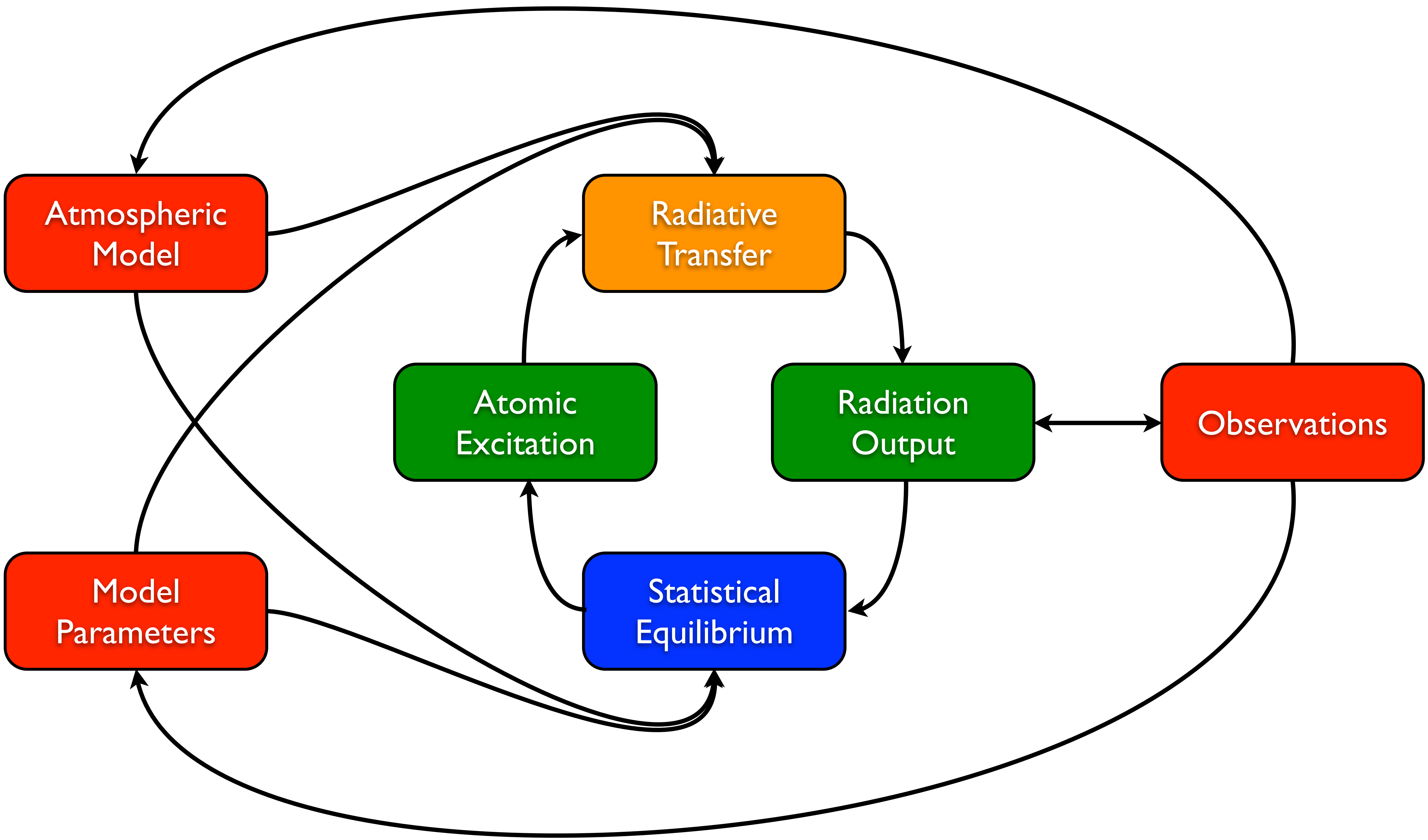
History of Solar Po ry



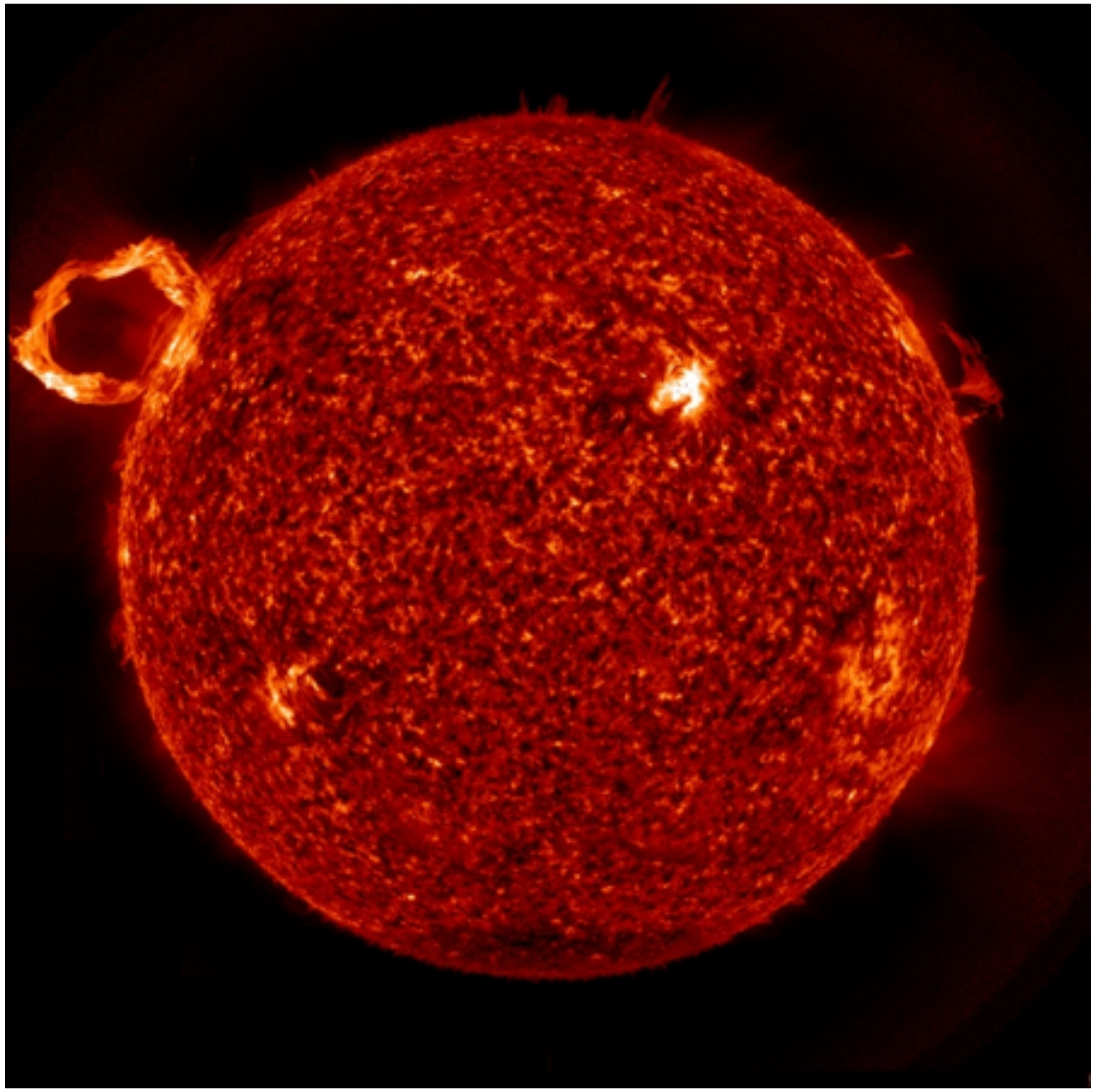
- Pieter Zeem Lorentz discover the ” in 1896: spectral line presence of magnetic fie
- Hale finds n sunspots in 1908 using a ro-polarimeter.

Interpretation for Solar Physics Applications

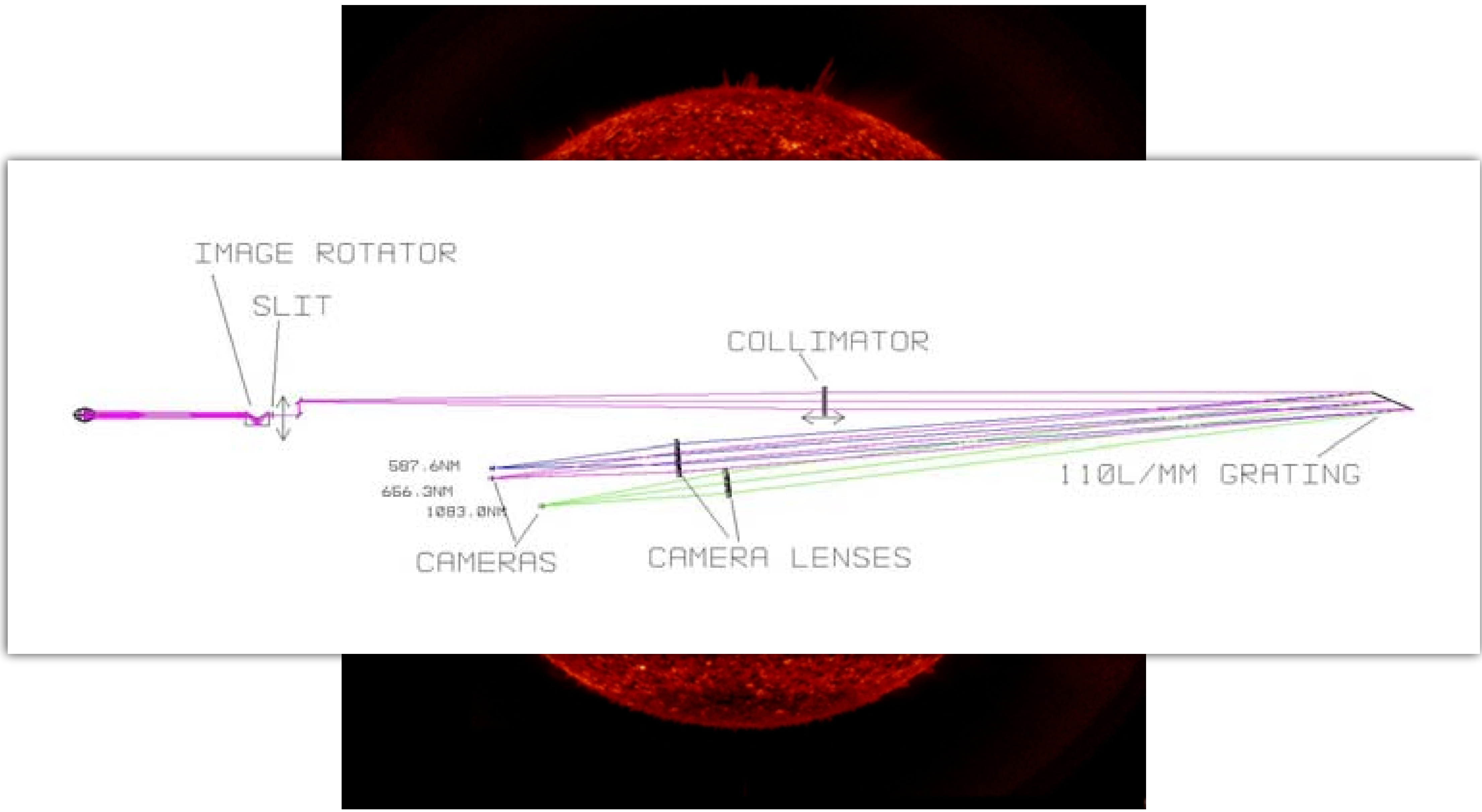
- We measure the Stokes 4-vector as a function of wavelength in spectral lines for remote sensing of plasma parameters.
- Apply an “inversion” process: synthesize, compare, repeat. (That’s really a forward model, actually.)
- We need a model atmosphere, and calculate polarized radiative transfer.


Atmospheric Model
Radiative Transfer
Atomic Excitation
Radiation Output
Observations
Model Parameters
Statistical Equilibrium

How instrument development works



How instrument development works

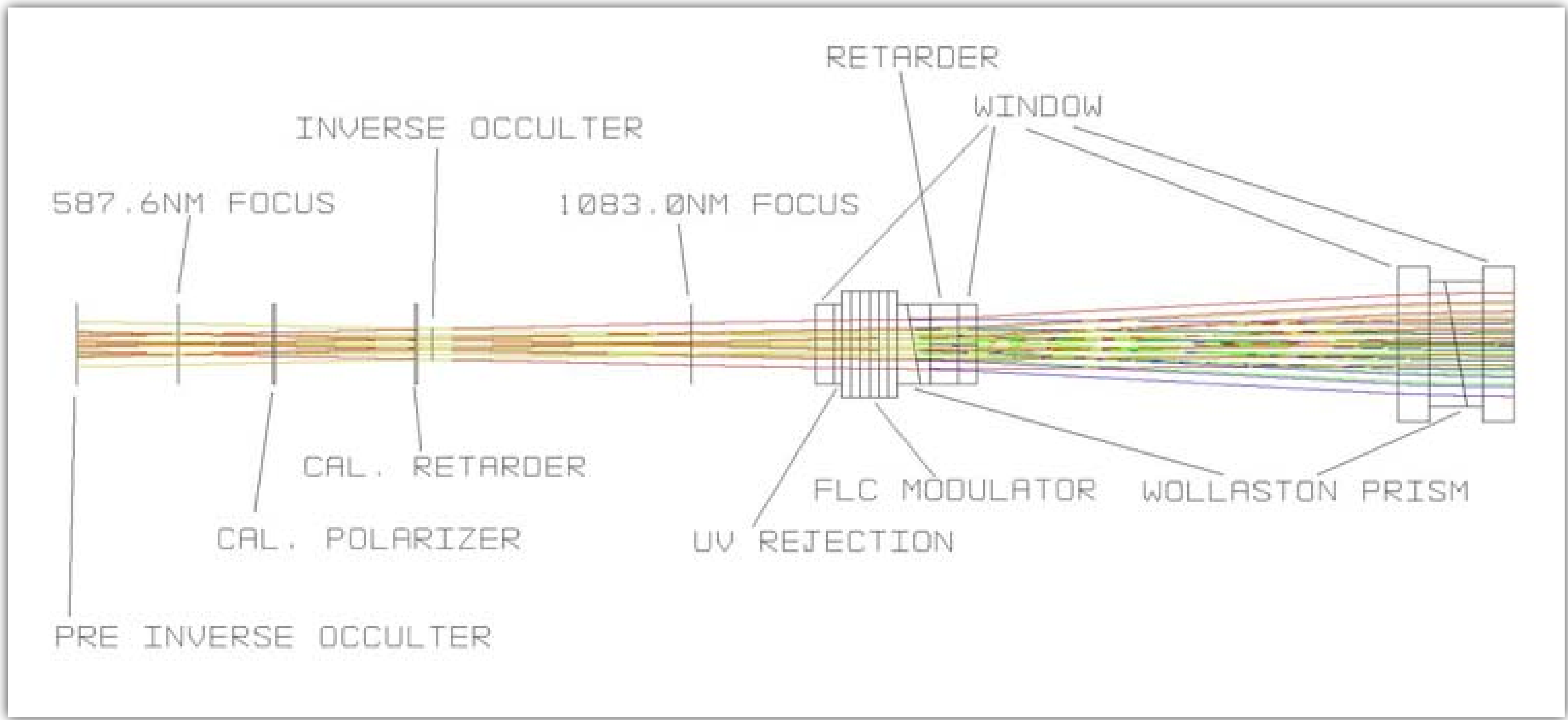


How instrument development works

- A spectro-polarimeter to measure magnetic field in prominences and filaments
- Traditional eschelle spectrograph
- He I 587.6 nm (D3) or Hα 656.3 nm, and He I 1083.0 nm

How instrument development works

- Built and deployed, but… it didn't work



What's a Modulator?

- Detectors are sensitive to intensity
- Use optical components to change the input Stokes vector in a known way, i.e., "modulate"
- Use an "analyzer" that selects usually Q
- Demodulate the measured intensities to find the Stokes vector

Modulator Anatomy

- Retarder: constant retardance and fast axis
  - Birefringent crystal or polymer
- Constant retarder with variable fast axis
  - Rotating retarder, Liquid Crystal
- Variable retarder with constant fast axis
  - Liquid Crystal, PEM, Pockels Cell

The Modulation Matrix

- For each state *i* of the modulator, the measured intensity can be written as the product of the Stokes vector with a 'modulation vector': $I_i = \mathbf{M}_i \cdot \mathbf{S}$
- The modulation matrix **O** is composed of rows $\mathbf{M}_i$: $O_{i,j} = (\mathbf{M}_i)_j$.
- The measured intensities are now given by $\mathbf{I} = \mathbf{O} \cdot \mathbf{S}$.

Two Example Modulators

Type	Fast axis angle	Retardance	Modulation Vector
LCVRs	(0°, 45°)	(180°, 360°)	(1,+1,0,0)
		(180°, 180°)	(1,–1,0,0)
		(90°, 90°)	(1,0,+1,0)
		(90°, 270°)	(1,0,–1,0)
		(180°, 90°)	(1,0,0,+1)
		(180°, 270°)	(1,0,0,–1)

Type	Retardance	Fast axis angle	Modulation Vector
FLCs	(180°, 102.2°)	(0°, –18.1°)	$(1,+1/\sqrt{3},+1/\sqrt{3},-1/\sqrt{3})$
		(0°, +18.1°)	$(1,+1/\sqrt{3},-1/\sqrt{3},+1/\sqrt{3})$
		(45°, –18.1°)	$(1,-1/\sqrt{3},+1/\sqrt{3},+1/\sqrt{3})$
		(45°, +18.1°)	$(1,-1/\sqrt{3},-1/\sqrt{3},-1/\sqrt{3})$

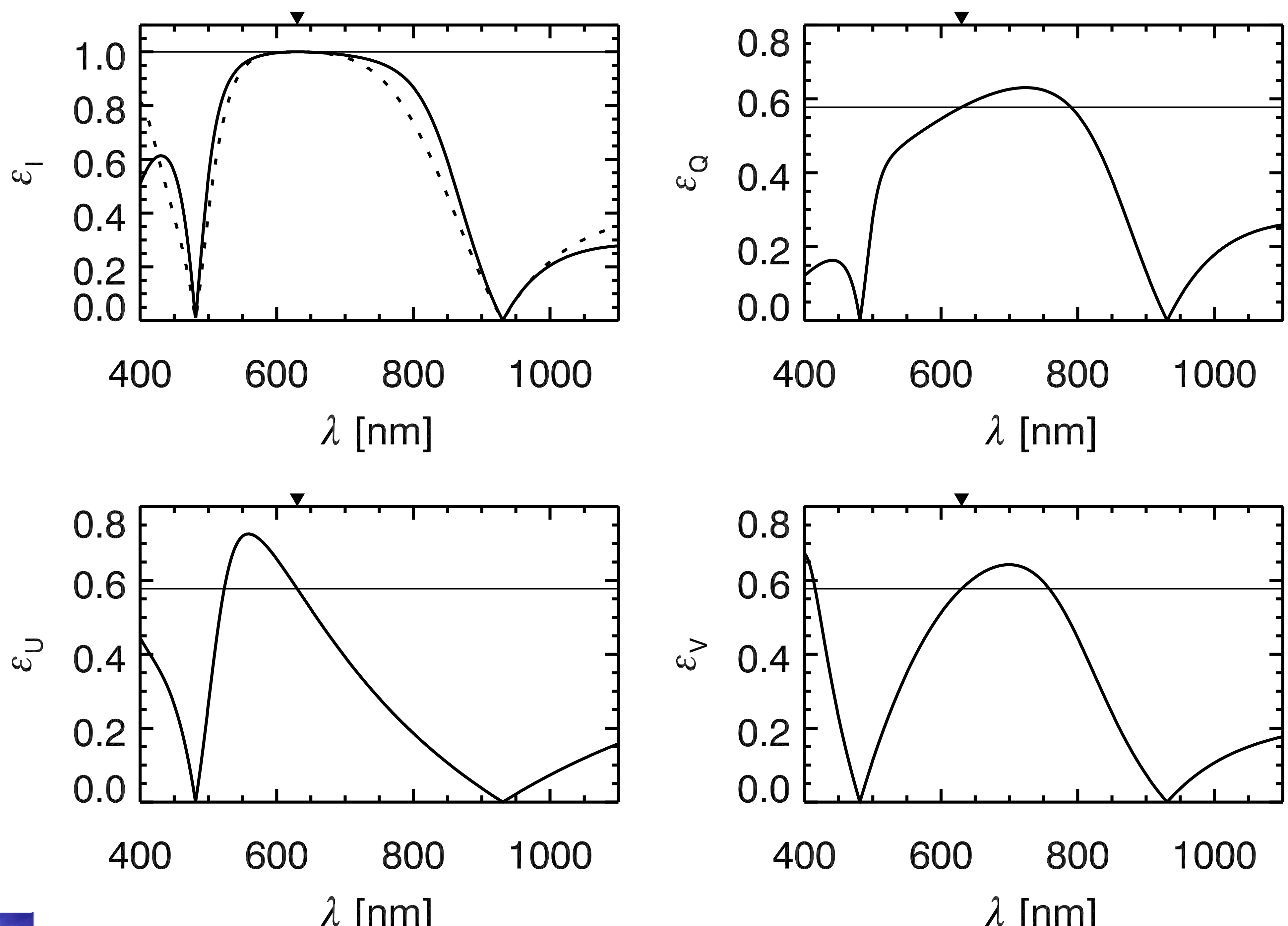
What makes a good modulator?

- Some pre-determined modulation states that I like for some reason? Not really…
- I'd like:
  - A simple, manufacturable design
  - Broad spectral coverage
  - Near-optimal performance at all wavelengths of interest

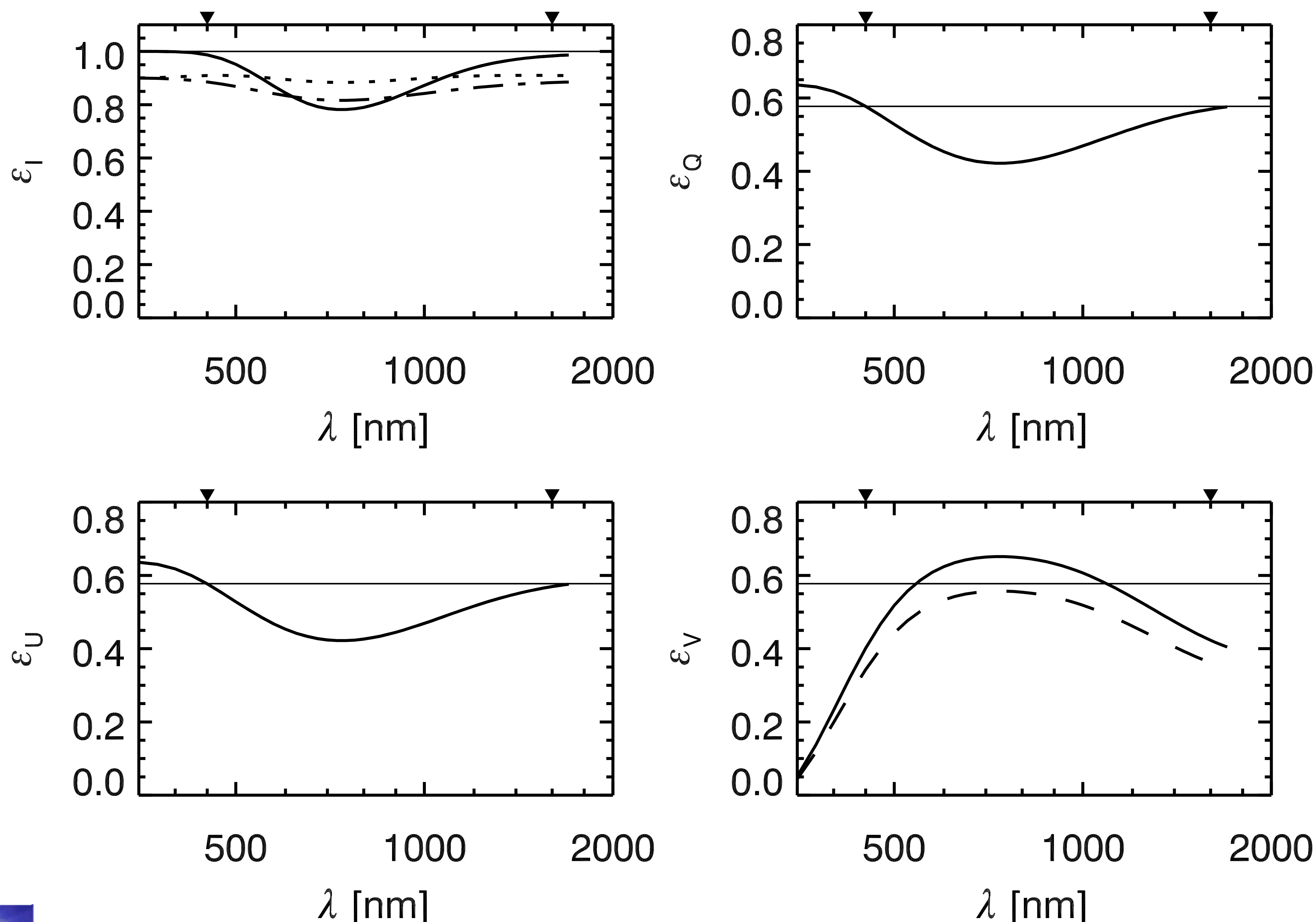
Efficiency

- See Del Toro Iniesta & Collados 2000 (2000ApOpt..39.1637D)
- After a lot of math, they find the *efficiencies*: $\epsilon_i = (n(\mathbf{O}^T\mathbf{O})^{-1}{}_{ii})^{-1/2}$
- $\epsilon_I{}^2 \leq 1$ and $\epsilon_Q{}^2 + \epsilon_U{}^2 + \epsilon_V{}^2 \leq 1$
- Notice that $\sigma_i = n^{-1/2}\,\sigma / \epsilon_i$, where σ is the error on a single measurement

Example Modulator



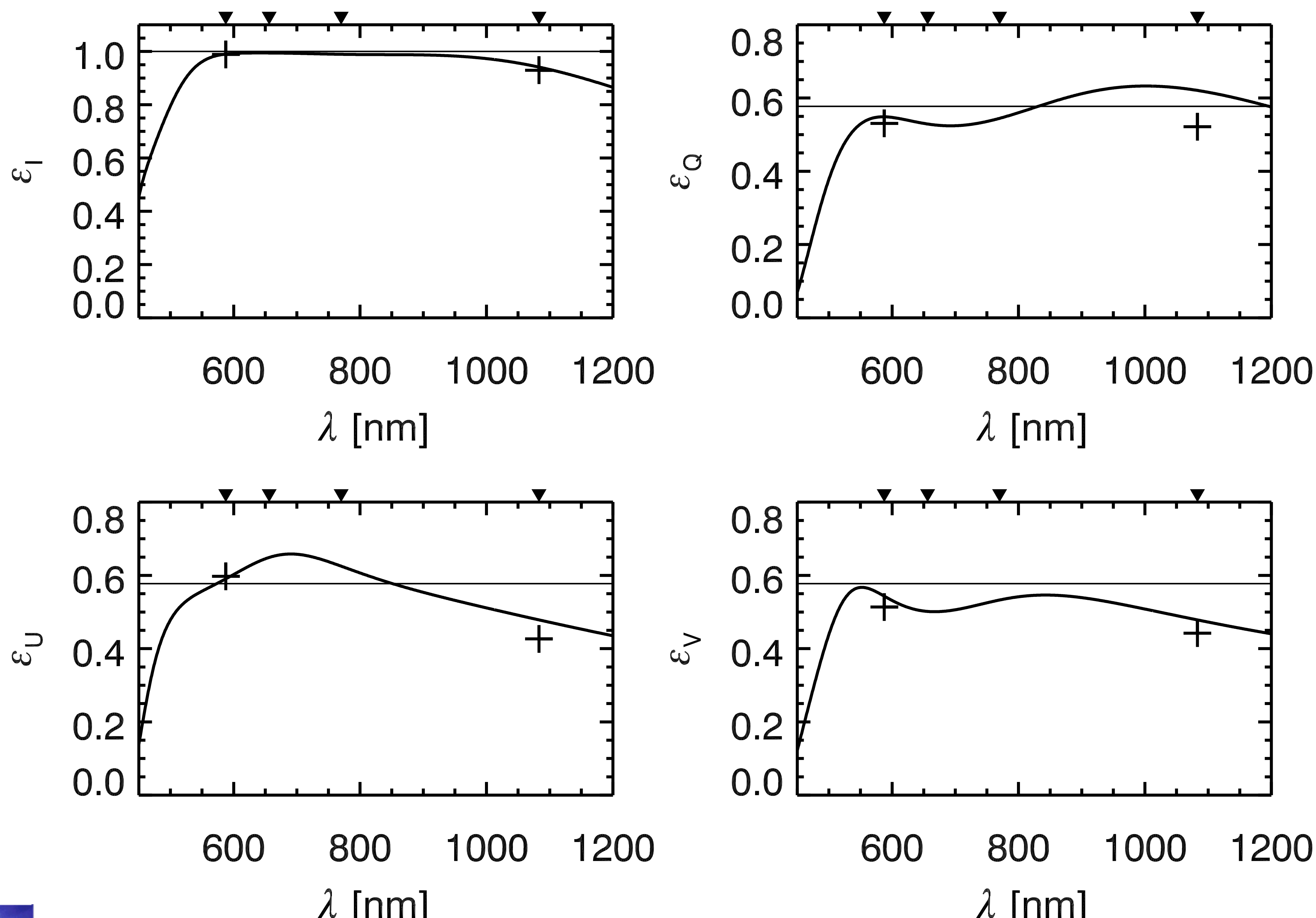
Achromaticity



Polychromatic

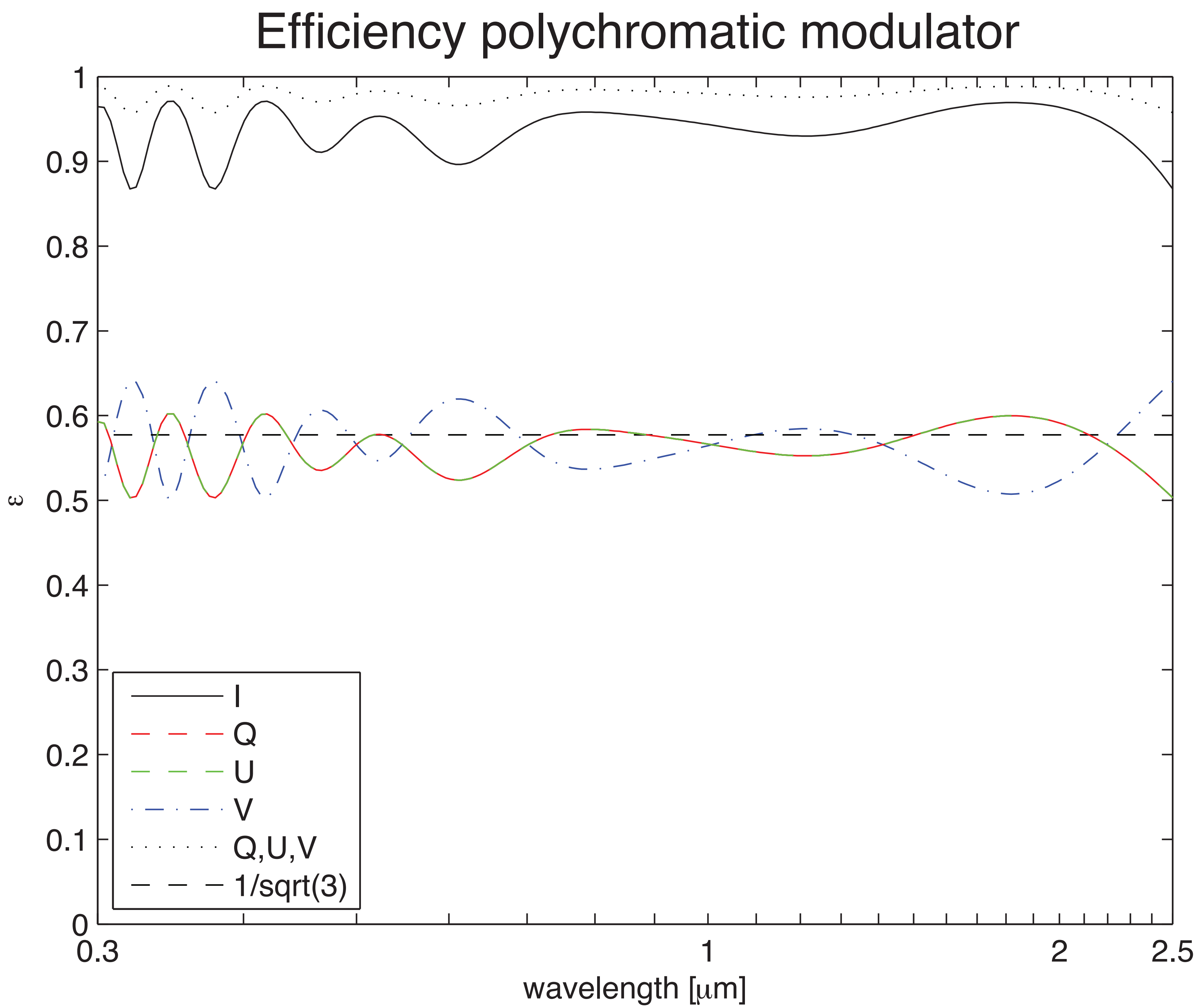
- Poly-: from πολύς, many
- Achromatization of the *efficiency* of the modulator
- Difficult to design manually, so employ a computer to optimize
- We use a Monte-Carlo-like method

Examples



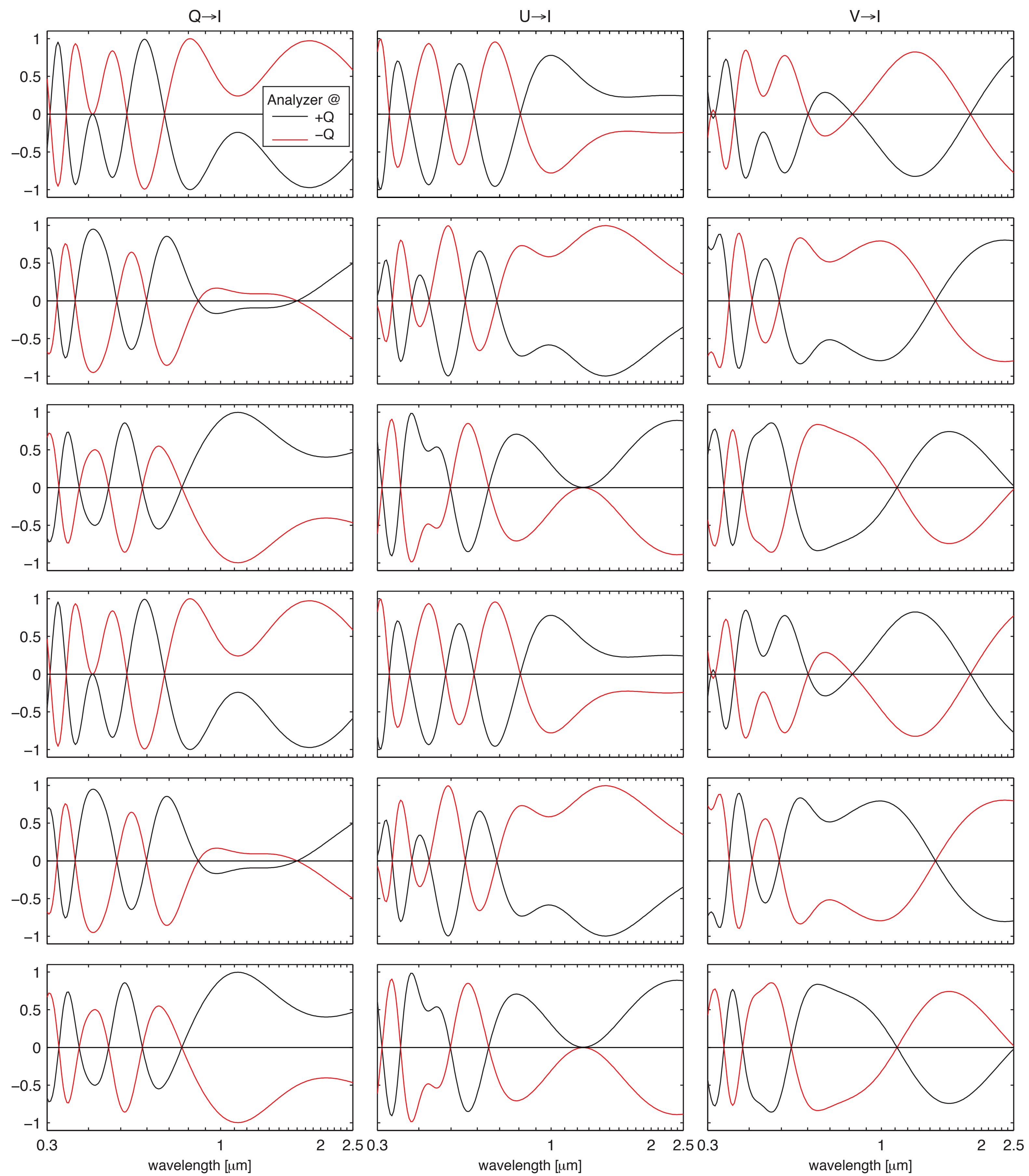
ε_I
ε_Q
ε_U
ε_V
0.0
0.2
0.4
0.6
0.8
1.0
600
800
1000
1200
λ [nm]

XShooter



Efficiency polychromatic modulator
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
ε
0.3
1
2
2.5
wavelength [μm]
I
Q
U
V
Q,U,V
1/sqrt(3)

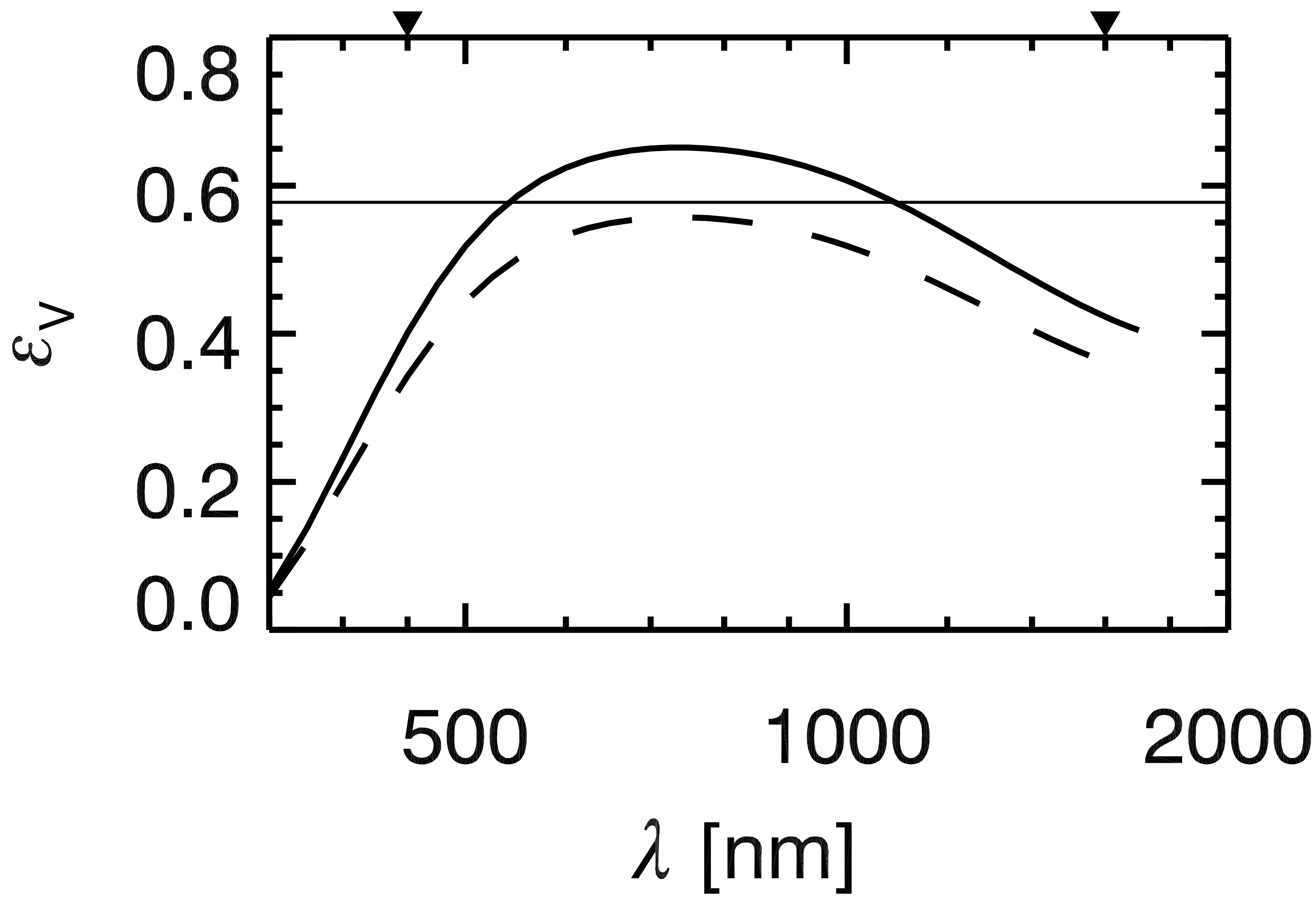
Modulation matrix



Summary

- Achromatization of the modulation matrix may be an unnecessary constraint on the design of spectrally-diverse modulators
- A modulator needs to be efficient at all wavelengths of interest
- Polychromatic modulators can be found using numerical exploration of the parameter space using computer codes

A word about demodulation



A word about demodulation

- You do not get to choose how you demodulate
- With 4 states, there is only one way
- With more than 4 states, there are infinitely many ways but only one way that optimizes the retrieval of the Stokes parameters from the observed intensities