Max-Planck Institut
für Plasmaphysik

Possible 2D Current Measurements at ASDEX Upgrade using Coherence Imaging.

O. P. Ford,[1] J. Howard,[2] R. König,[1] J. Svensson,[1] R. Wolf [1]

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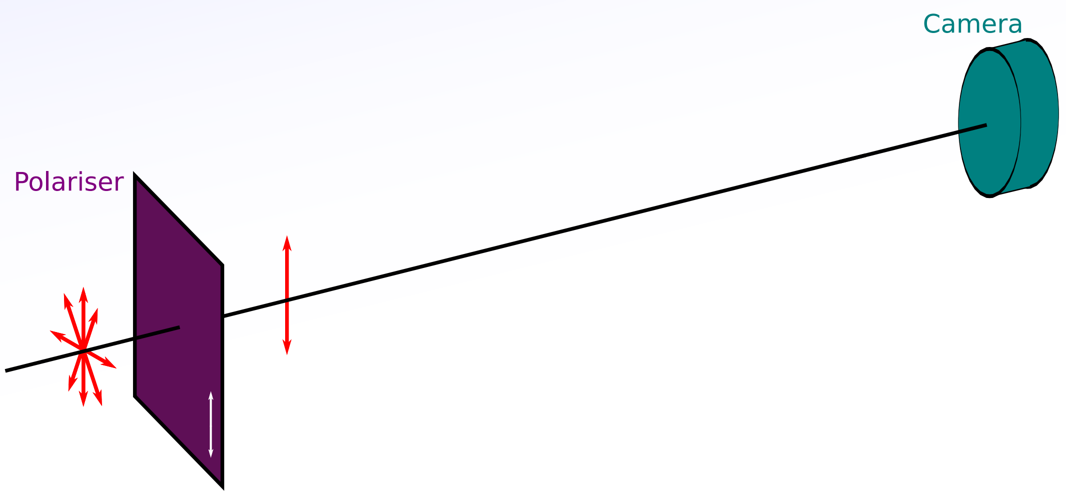
Special thanks to
René Reimer

Talk Outline

- Coherence Imaging Spectroscopy.
- Spectro-Polarimetric Imaging.
- MSE and application of CIS.
- MSE Modelling.
- Findings of MSE modelling so far.
- Another possiblity: Zeeman / Lithium Beam CIS.

Coherence Imaging I

1) Linearly polarise light.



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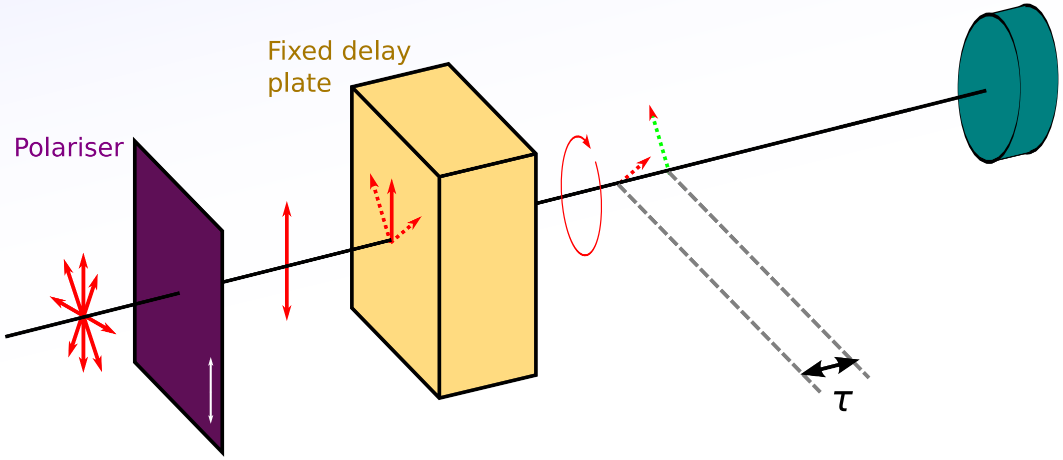

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2) Shift 1 component by τ.
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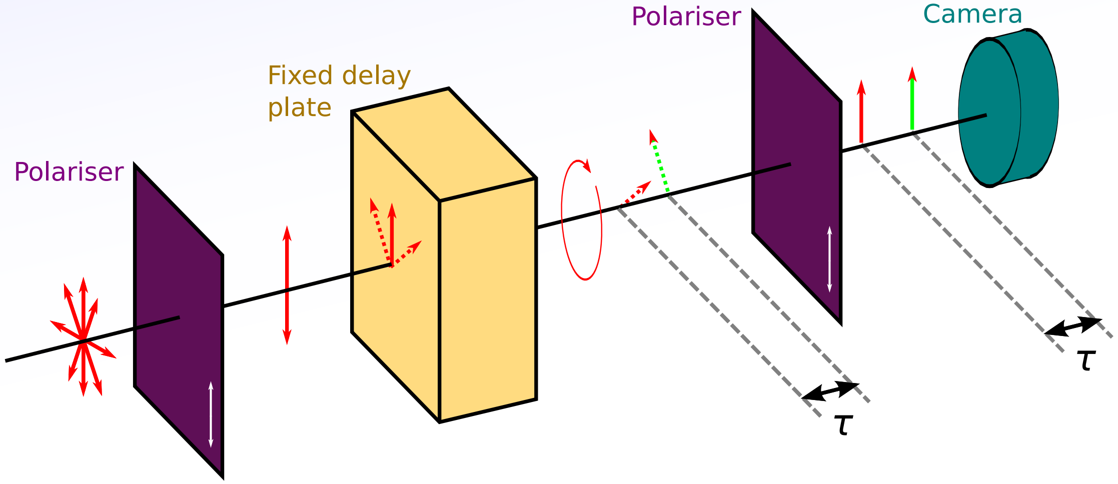

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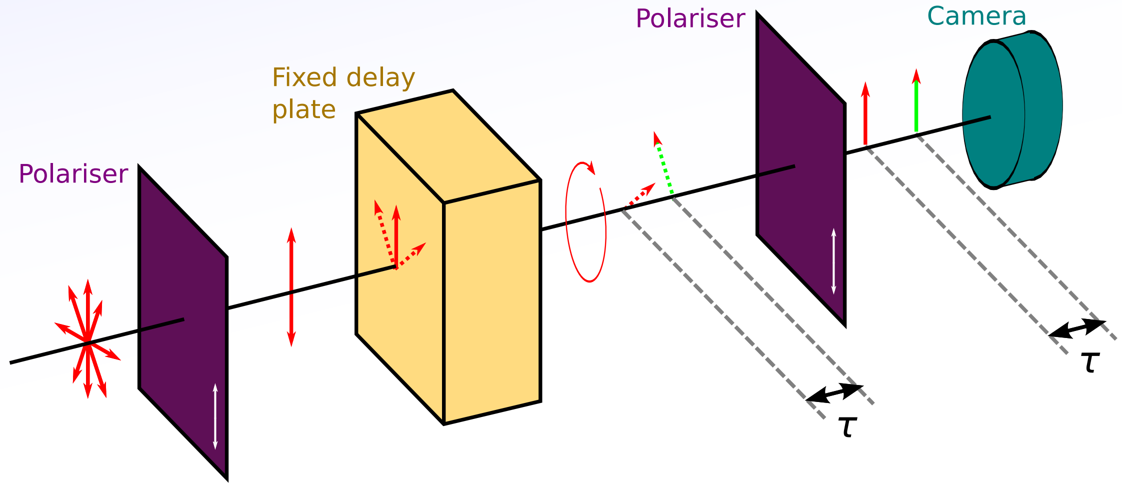

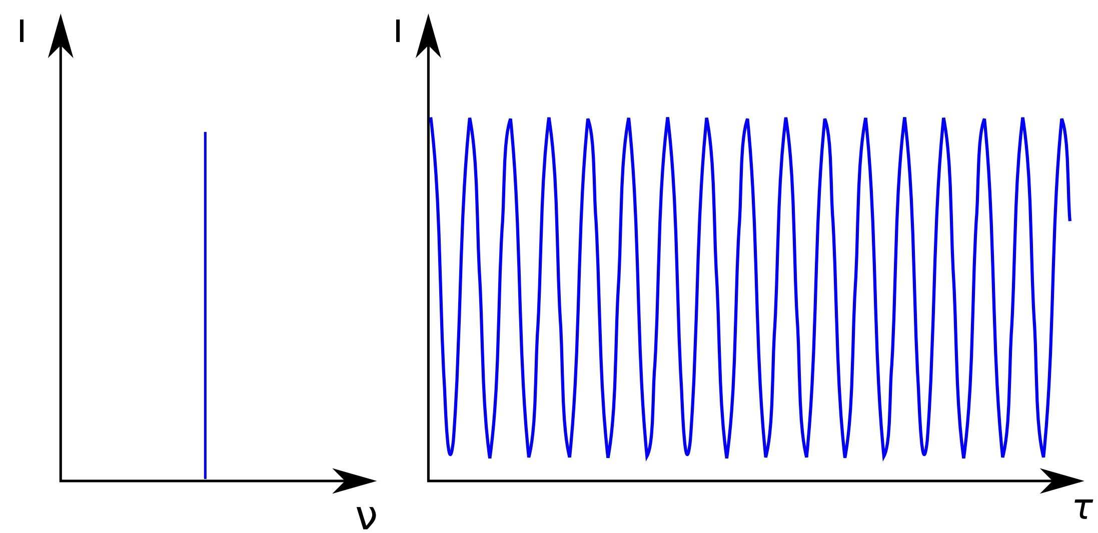

$$I = \frac{I_0}{2}\left(1 + cos\ \tau\right)$$

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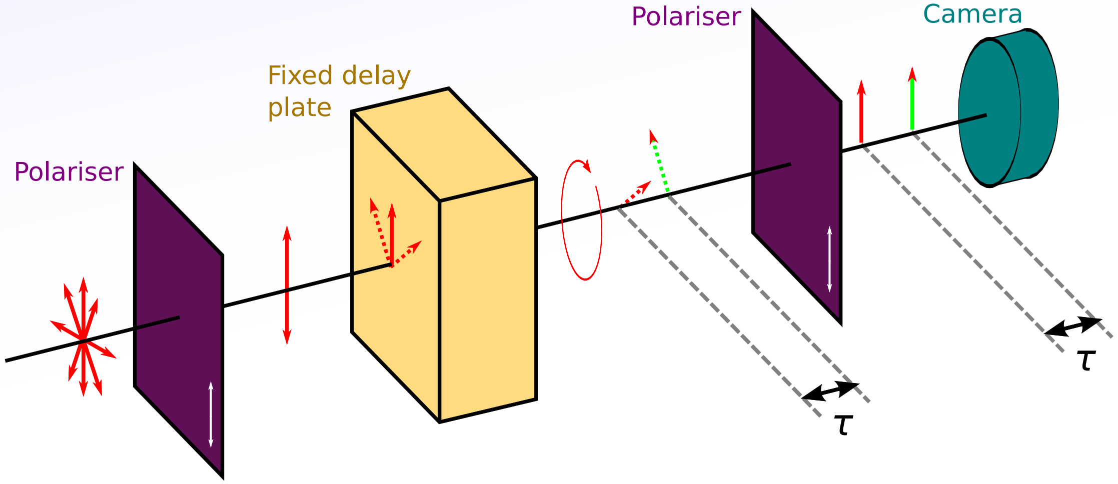

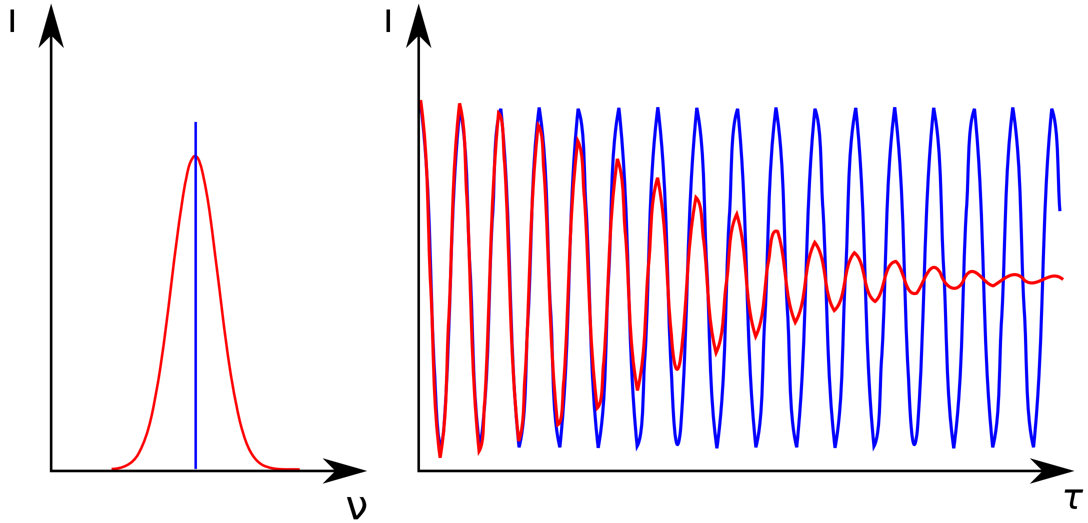

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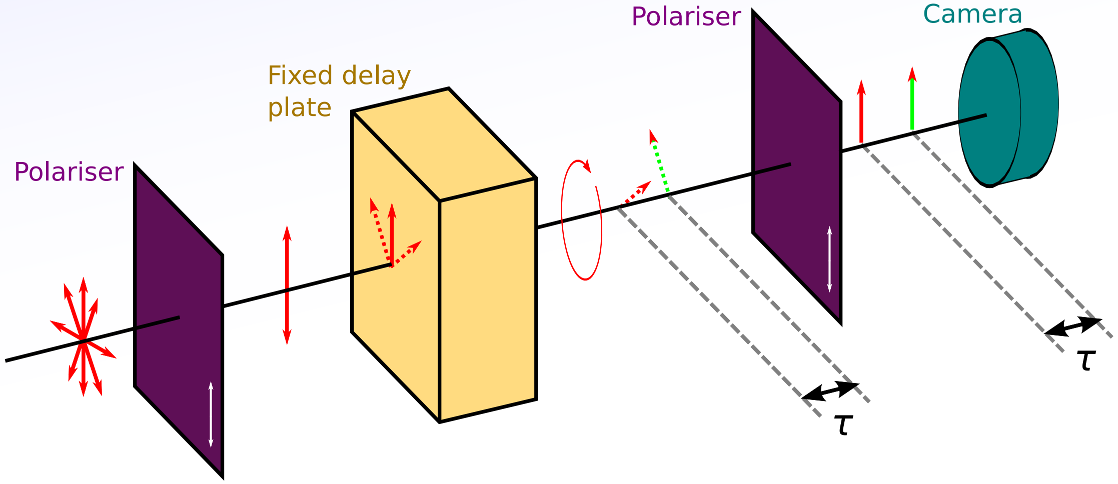
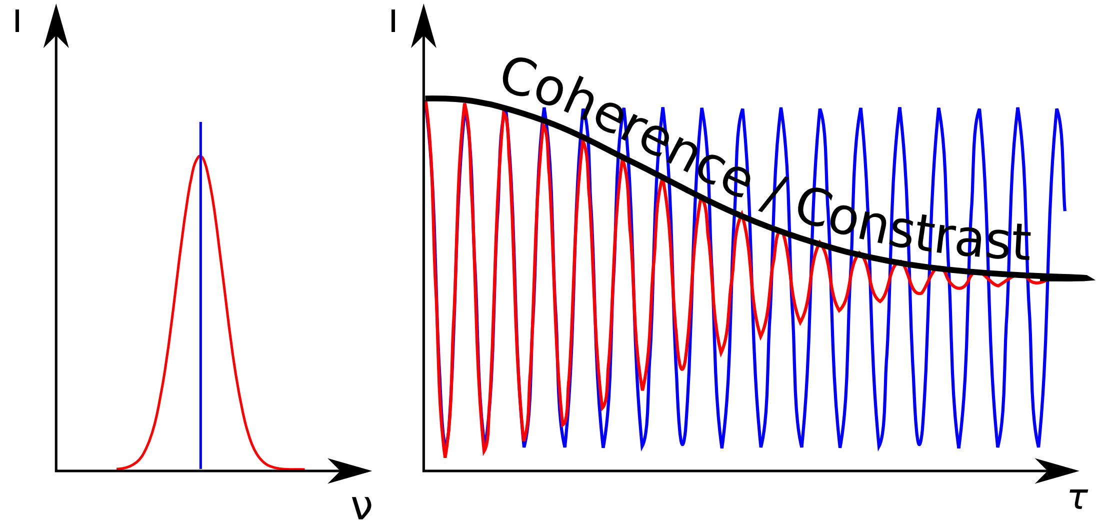


Contrast vs τ gives information about line broadening etc.



$$I = \frac{I_0}{2}\left(1 + \zeta\, cos\, \tau\right) \qquad \zeta(\tau) = Re\left[FT\left[I(\nu)\right]\right]$$

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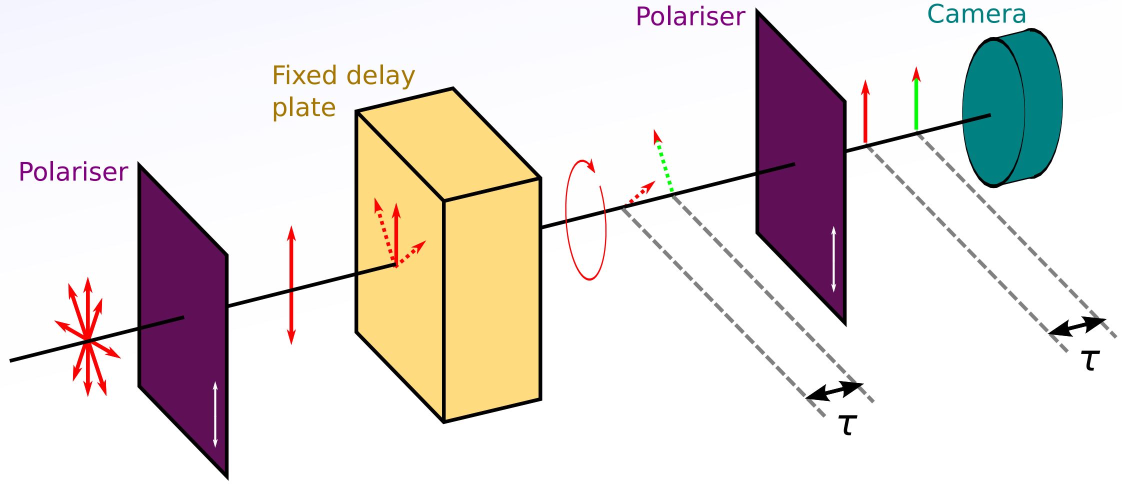
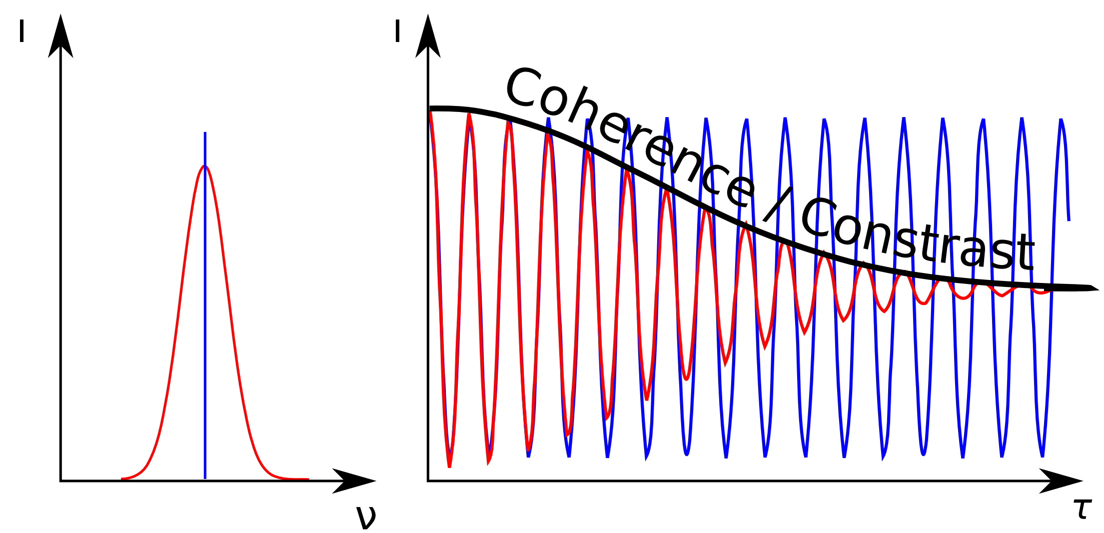


Contrast vs τ gives information about line broadening etc.

Also possible to extract line position (for Doppler shift).

All in 2D.

But we need information from multiple values of τ.



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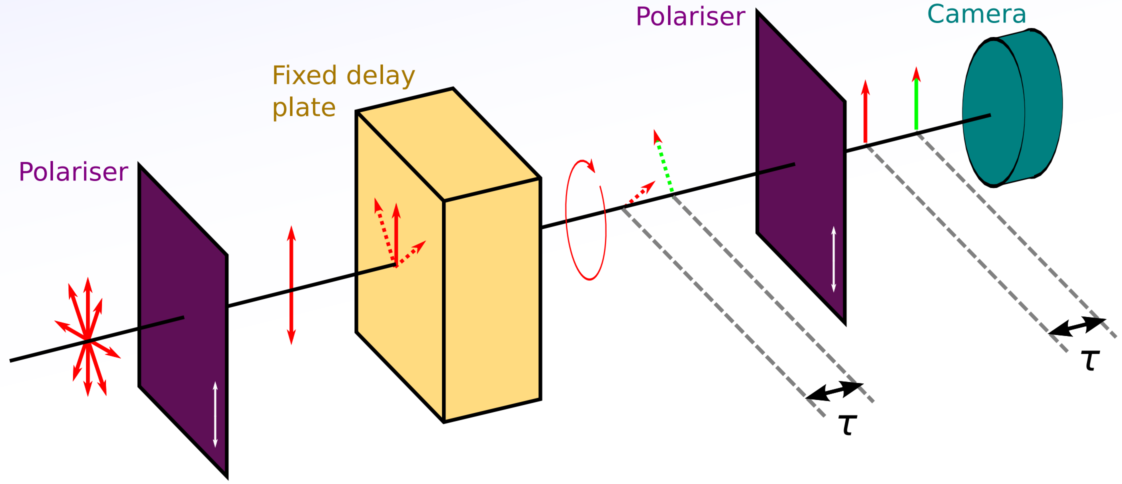

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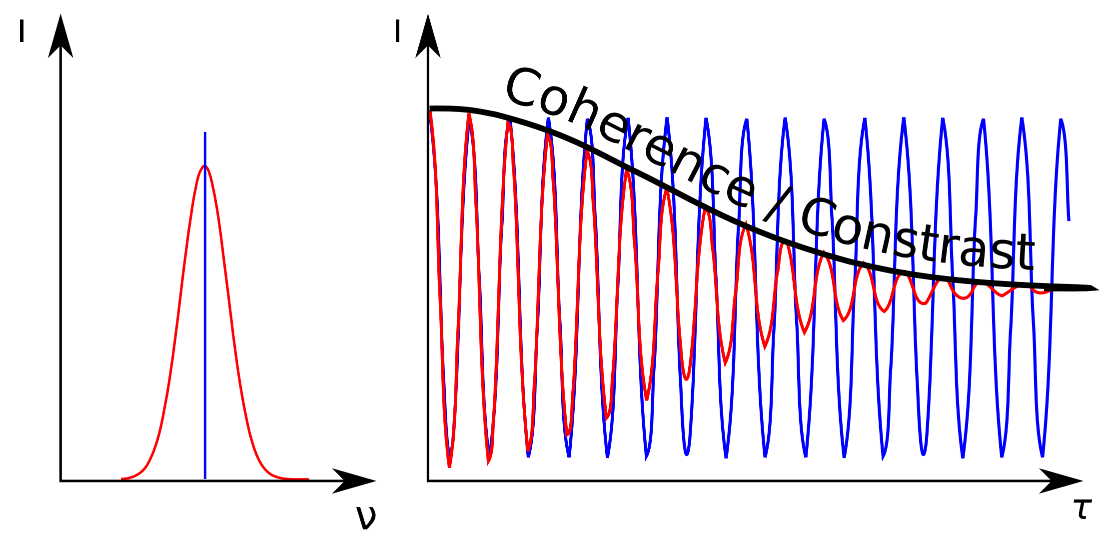

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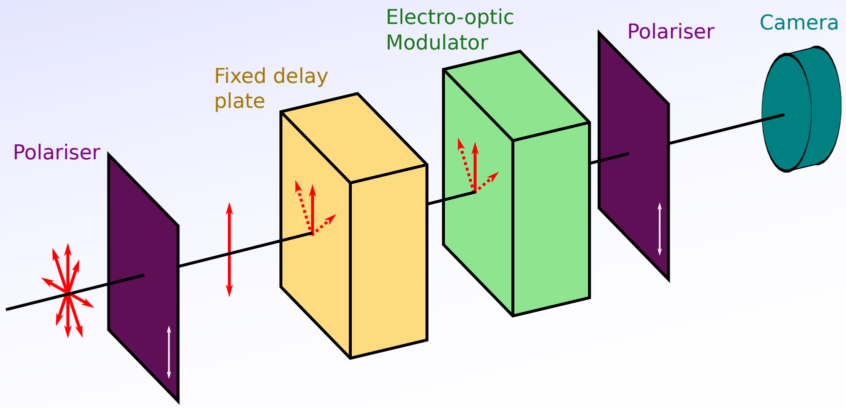
Coherence Imaging II

Two of the possible methods:



Temporal Modulation - vary τ in time,
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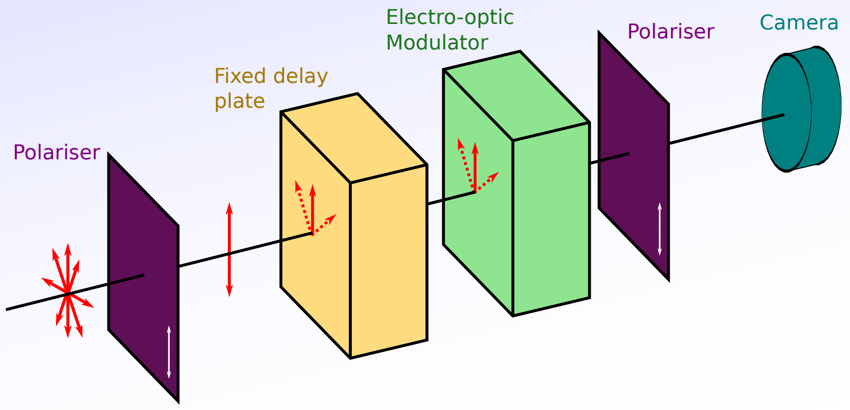

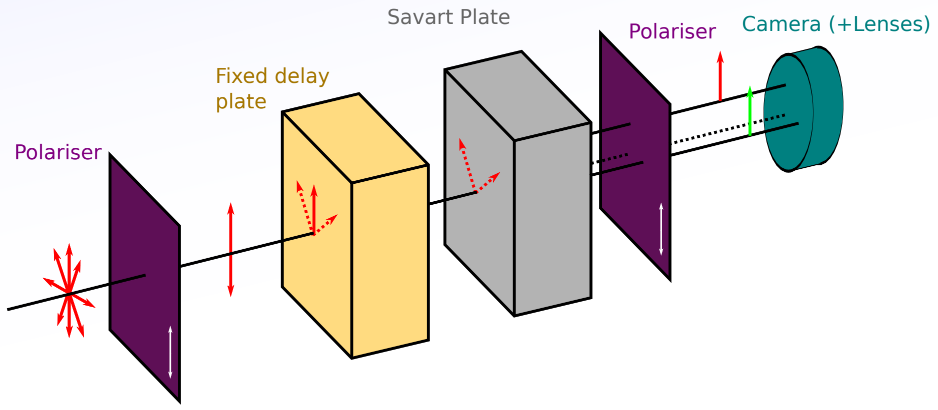

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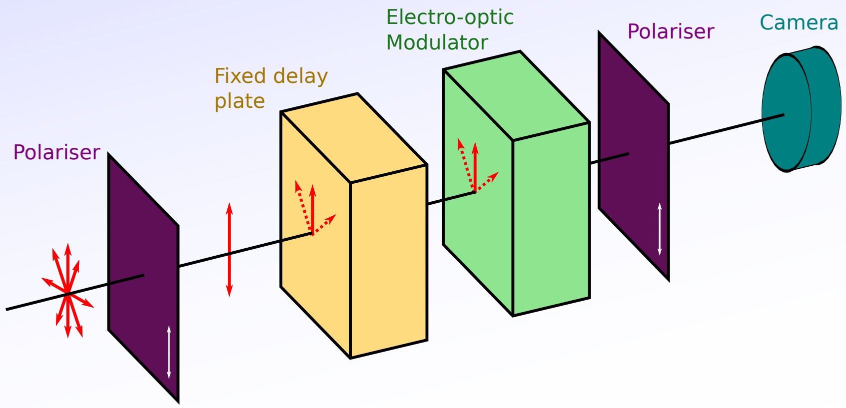

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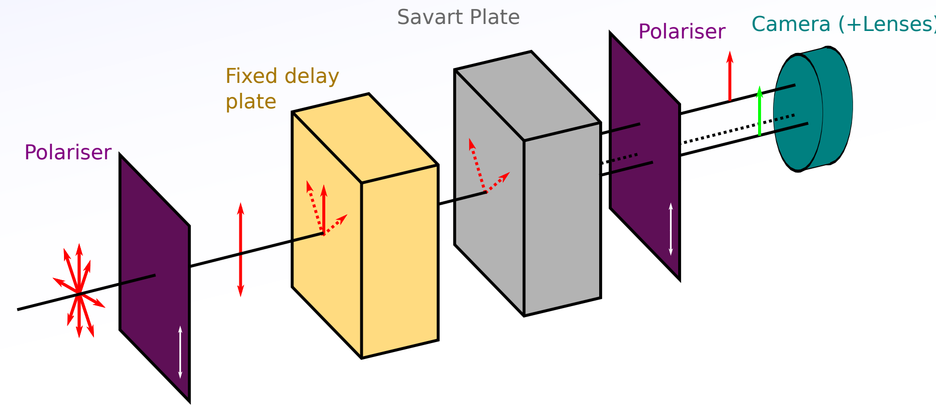

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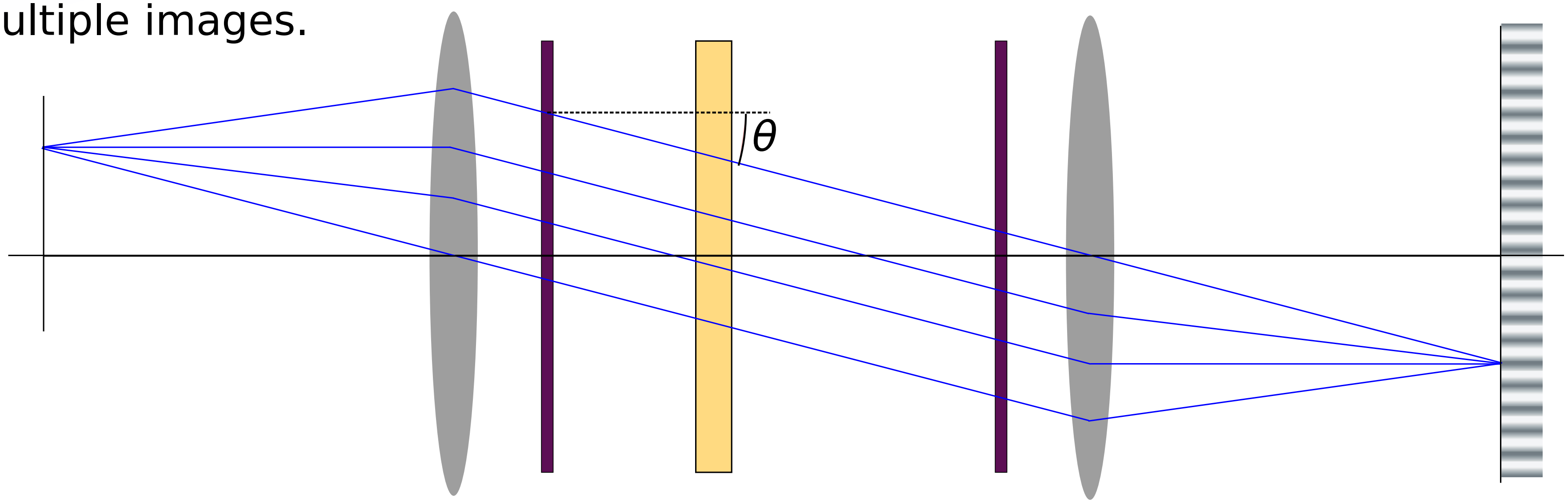

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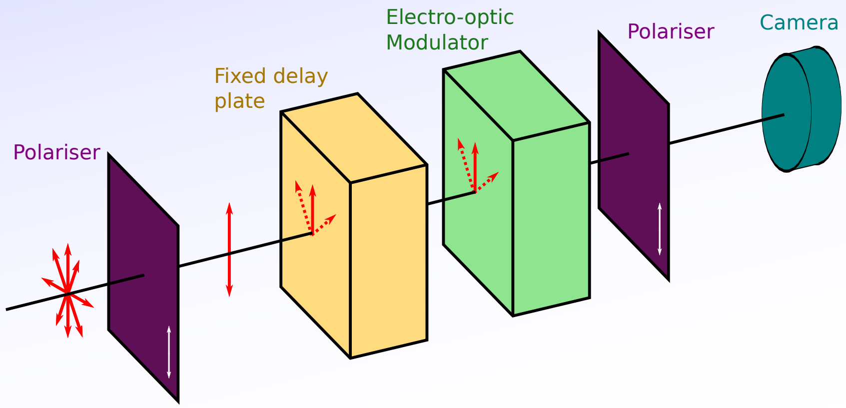

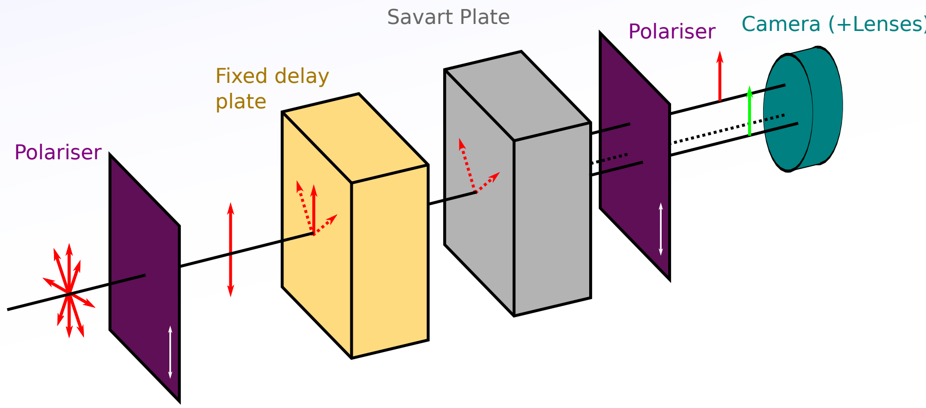

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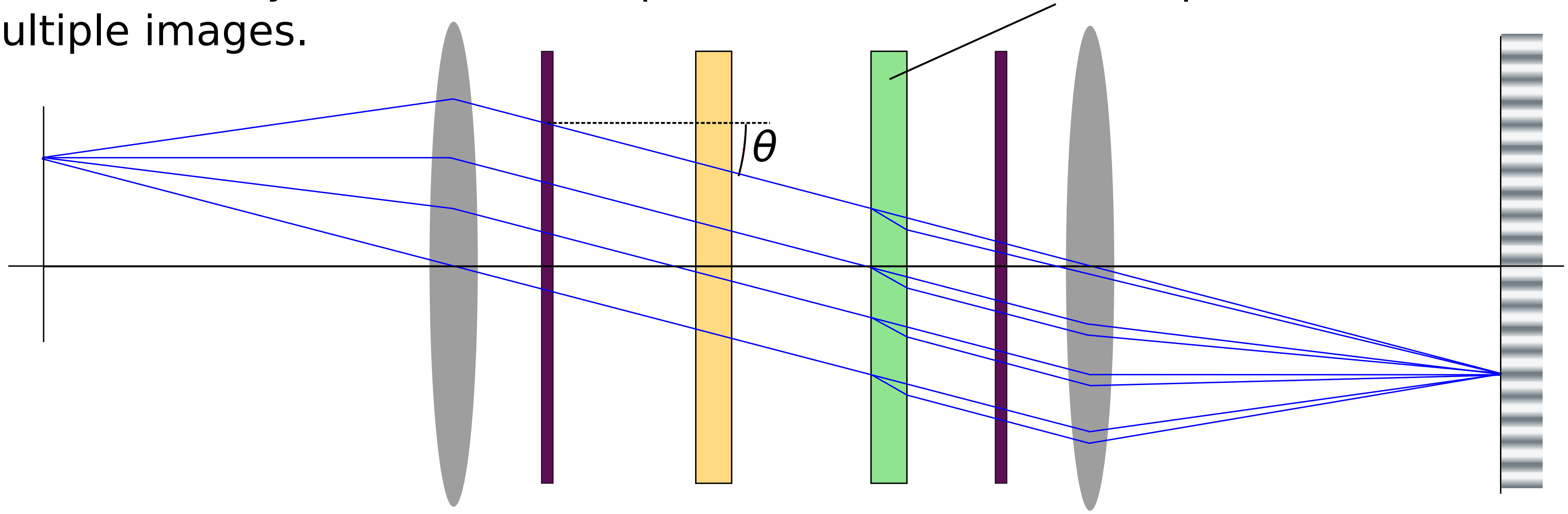

Spatially separates into two components.
One delayed by $\tau(\theta)$. [θ in splitting plane only]

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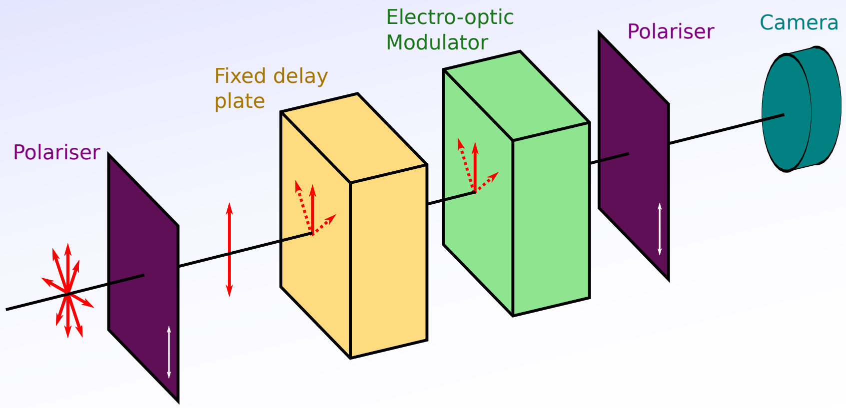

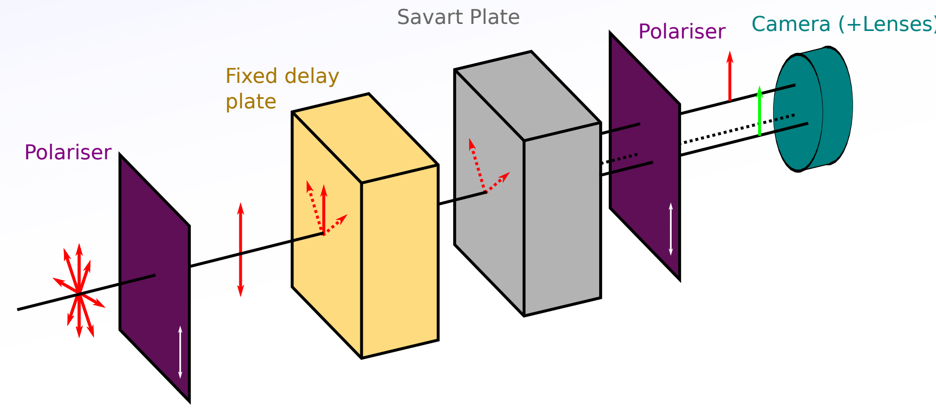

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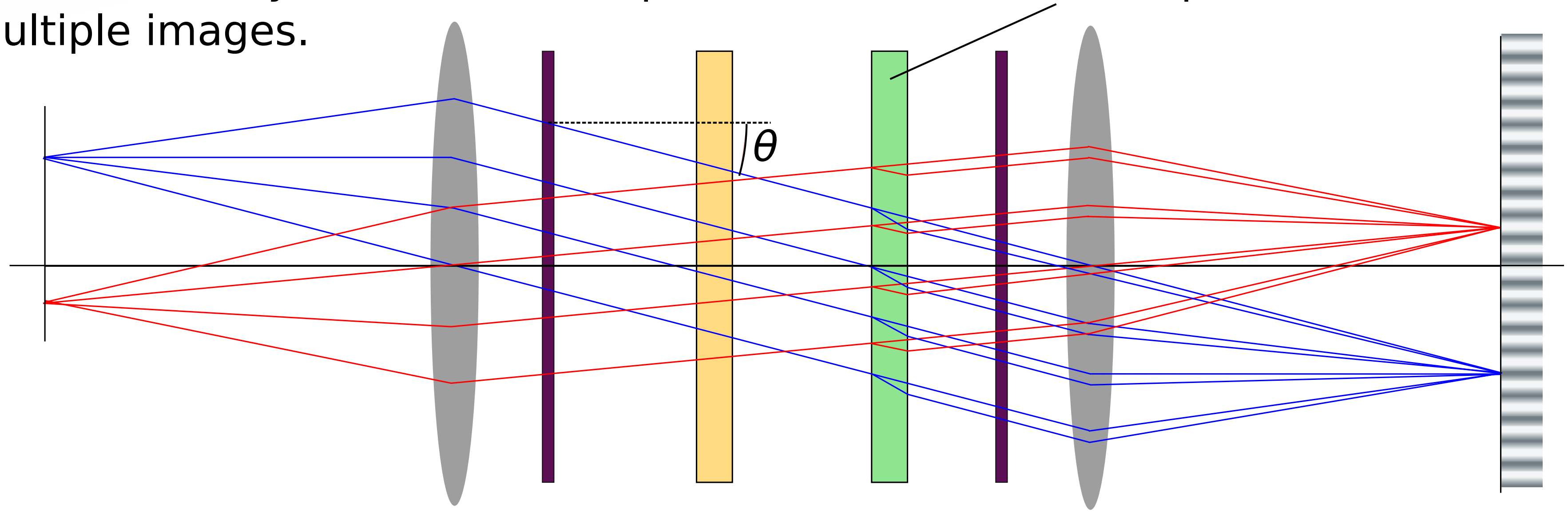

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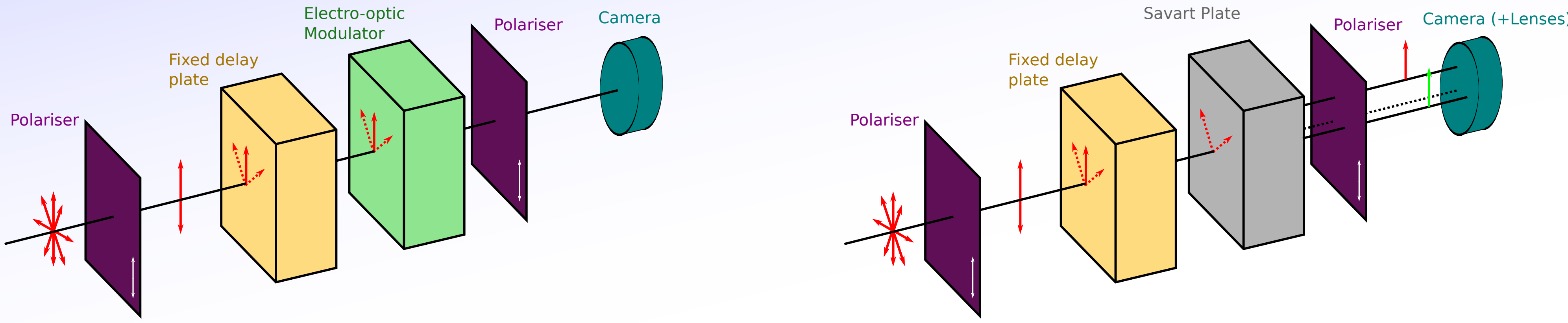

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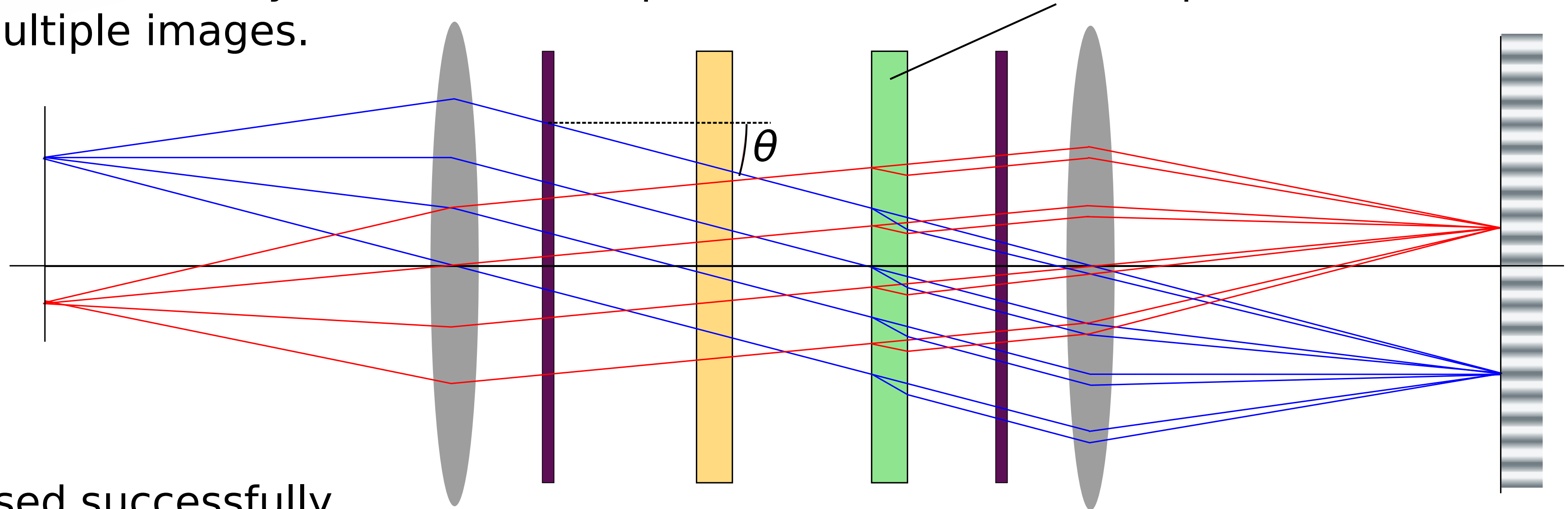

CIS has been used successfully for Doppler spectroscopy e.g. on: DIII-D, H1, WEGA, W7-AS etc.

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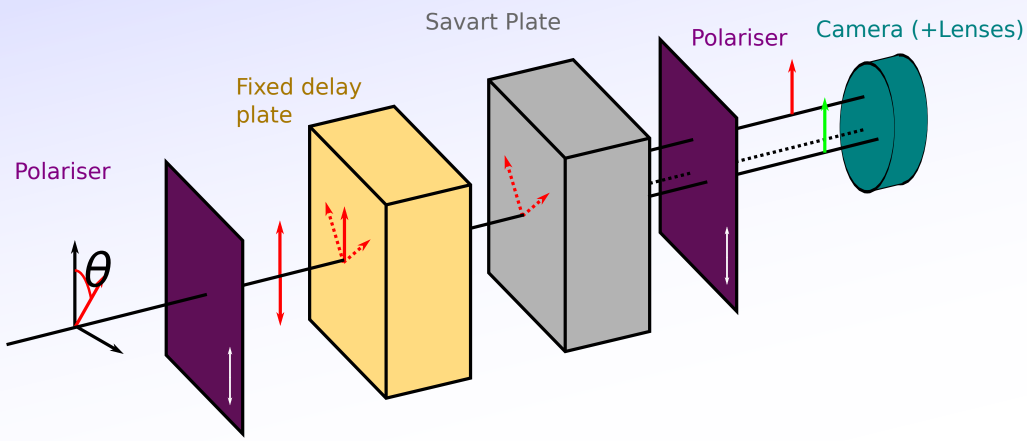
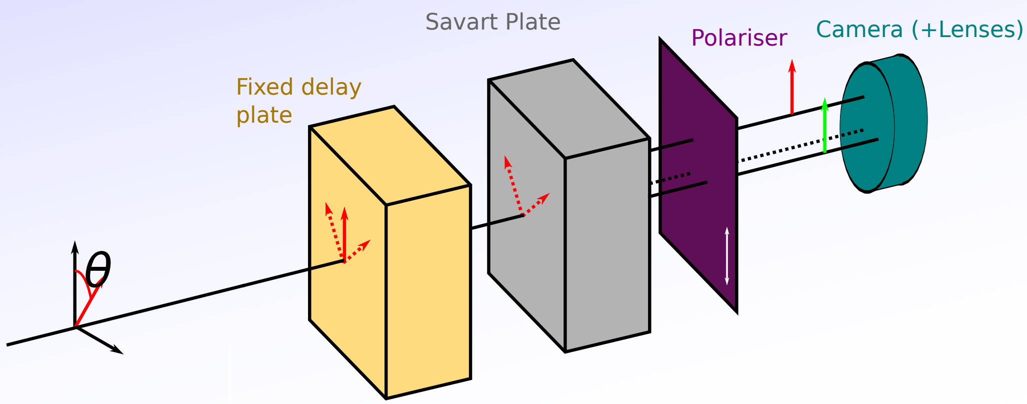
Spectro-Polarimetric Imaging



Spectro-Polarimetric Imaging

Remove first polariser



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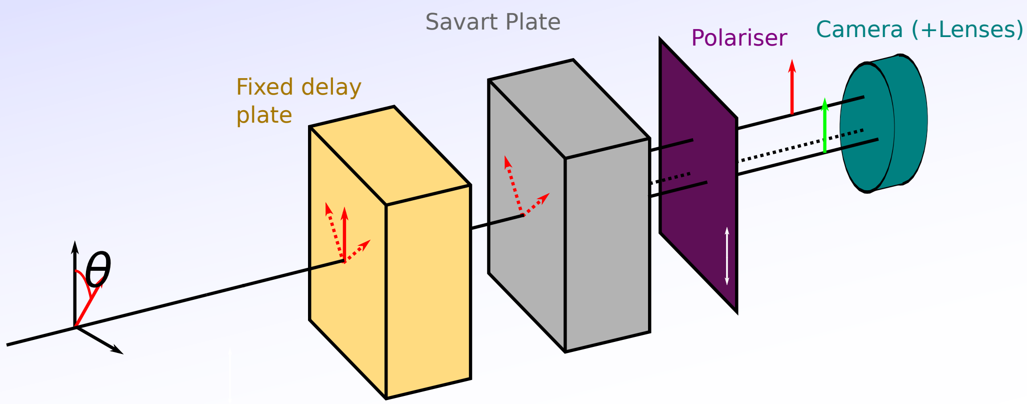

Interference contrast now
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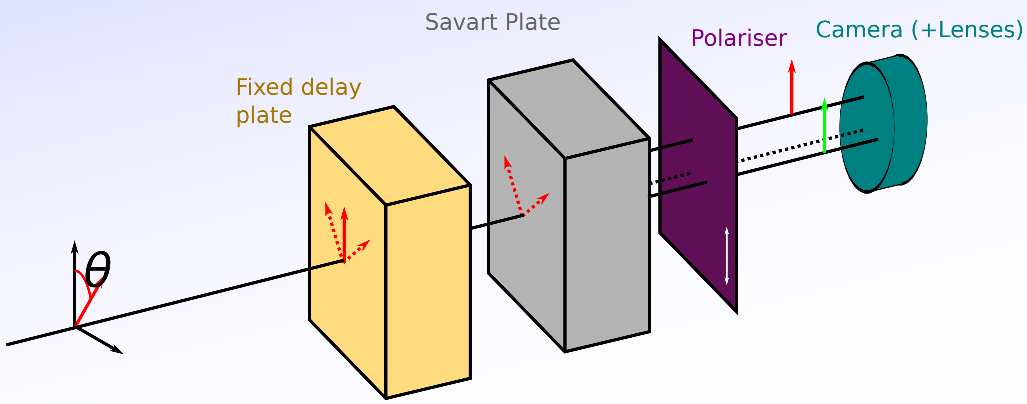

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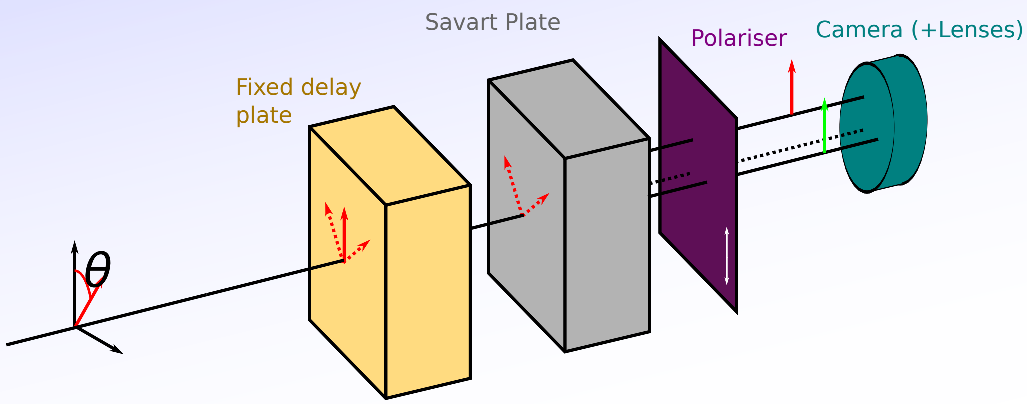

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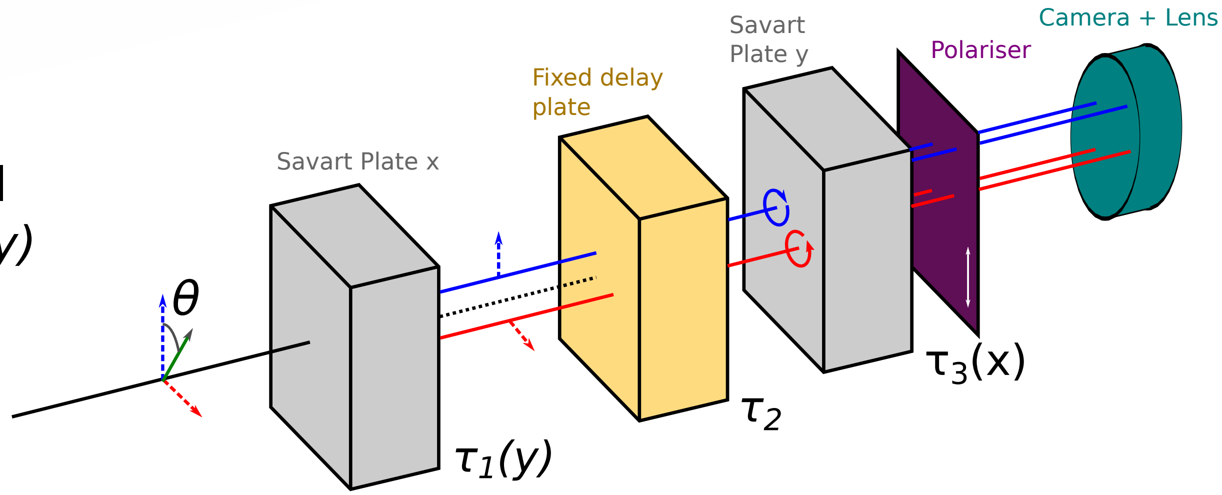
Add primary Savart plate orthogonal to second. This introduces delay $\tau_1(y)$ between orthogonal components.



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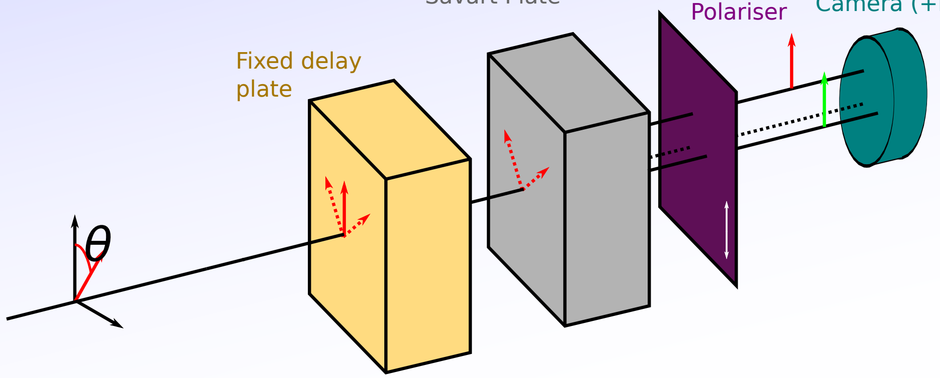

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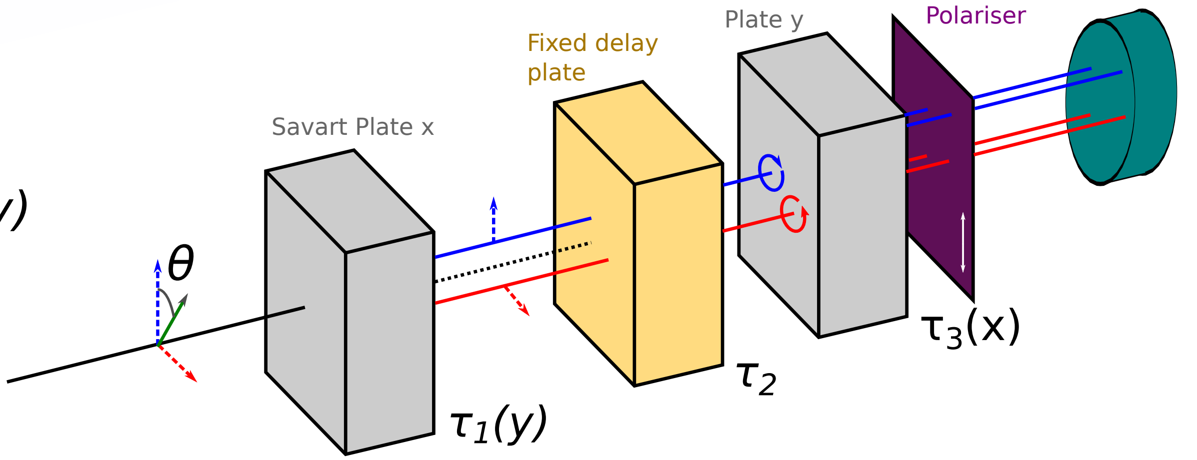

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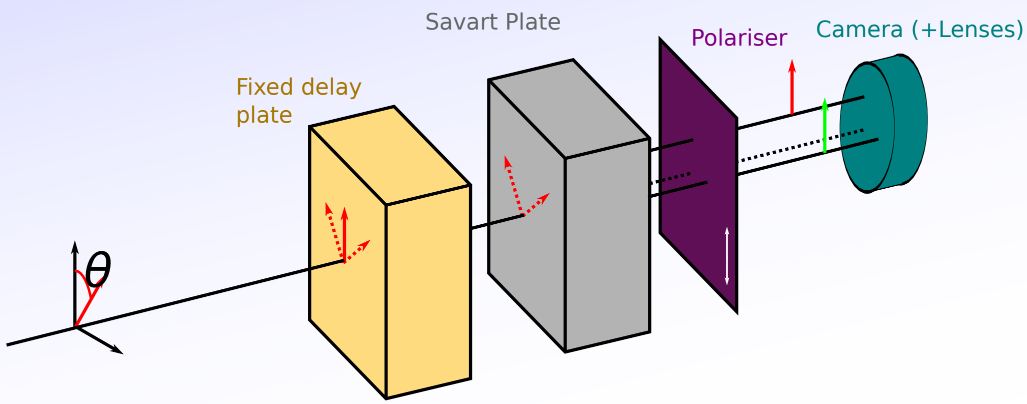

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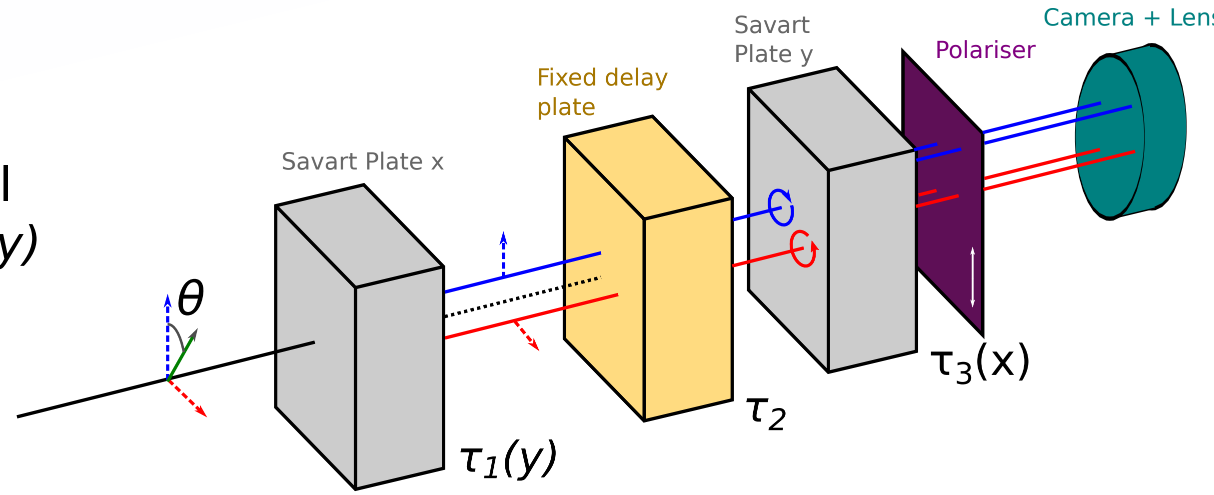

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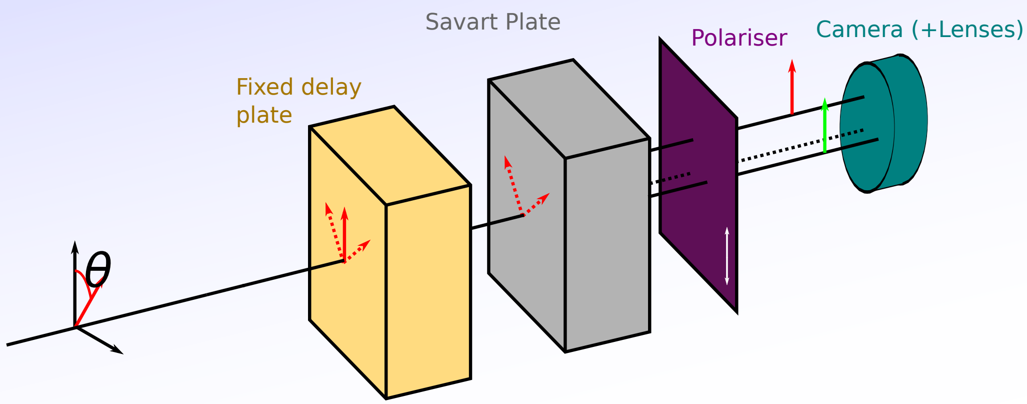

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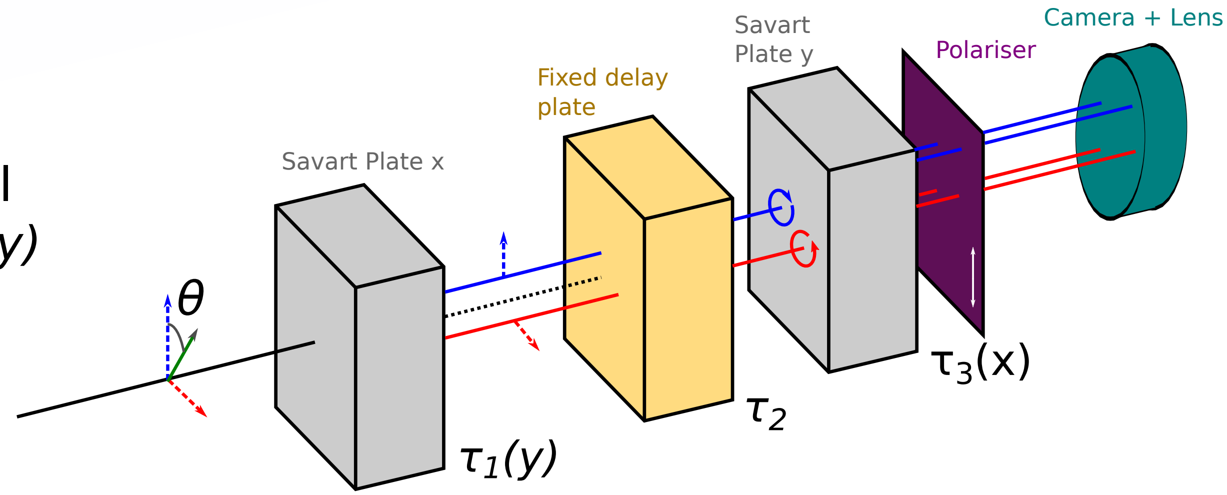

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By demodulating the image in x and y, we can find θ, I_0 and ζ.

This is the '*Double Spatial Hetrodyne*' system. We can instead replace one Savart plate with a Ferro-electric crystal - (No fringes in one direction, but need multiple time slices)

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Observe D_α emission from neutral beam atoms.

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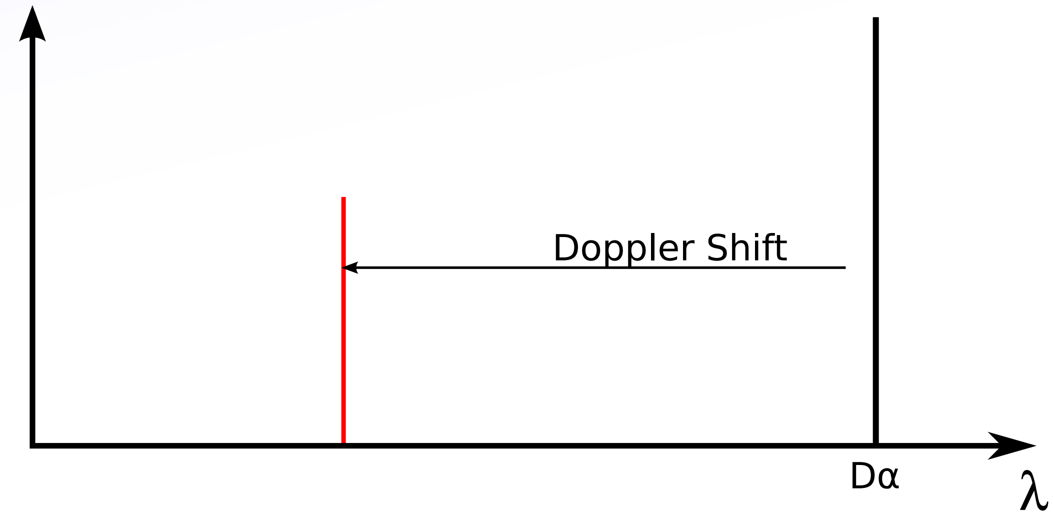
Doppler shifted by velocity toward/away from observer.



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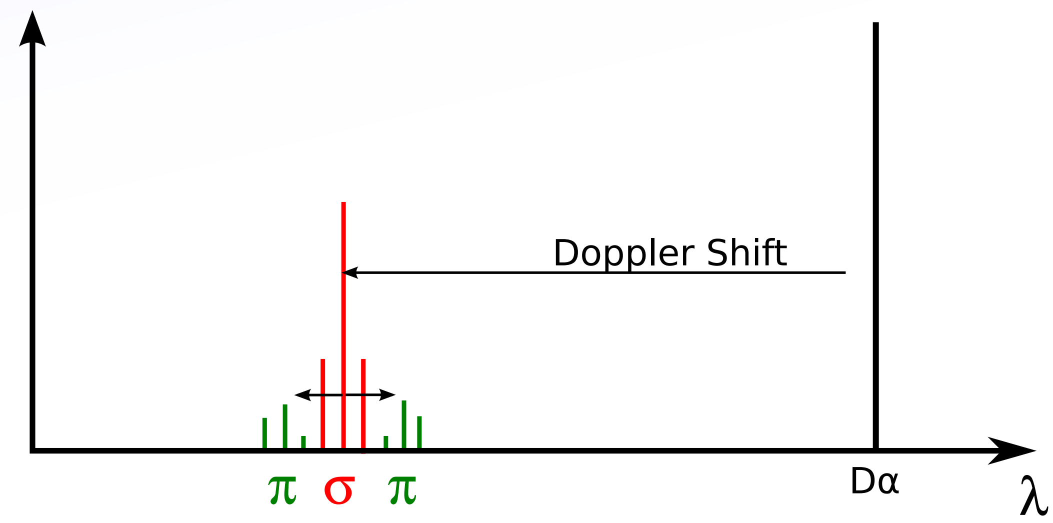
Stark split by electric field in rest frame of atom: $E = v \times B$



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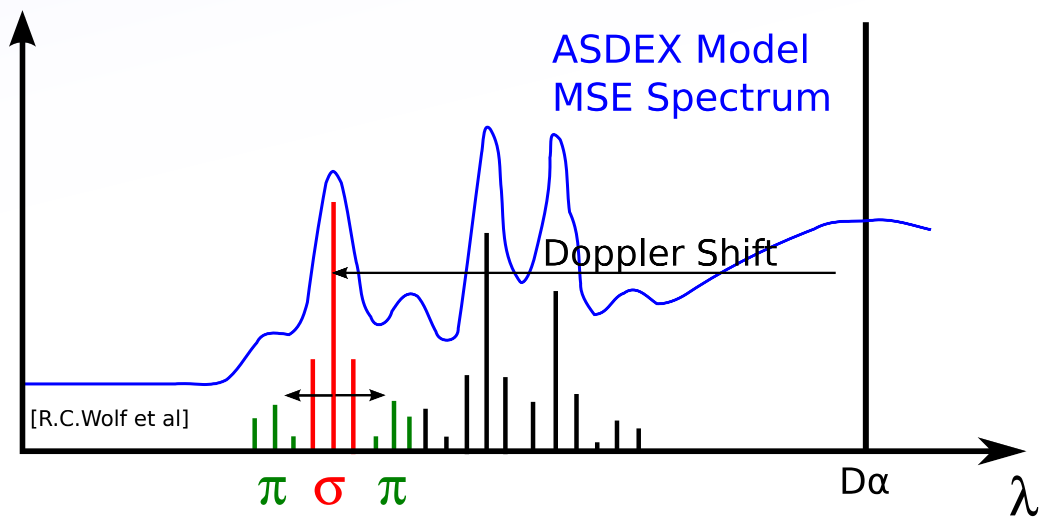

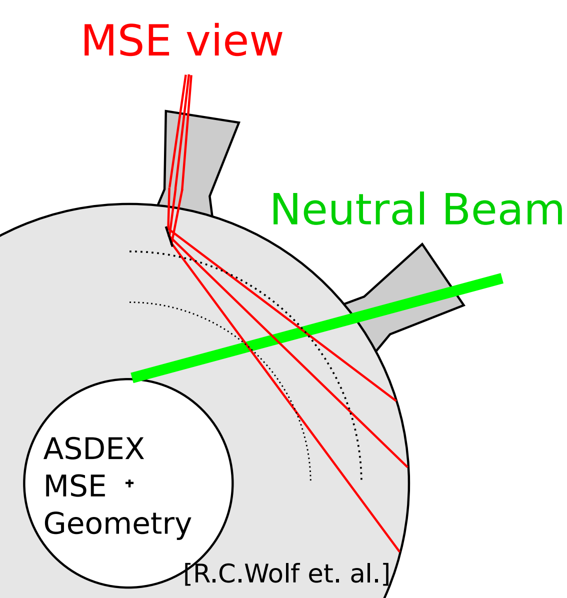

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View perp to E: π polarised parallel to E.
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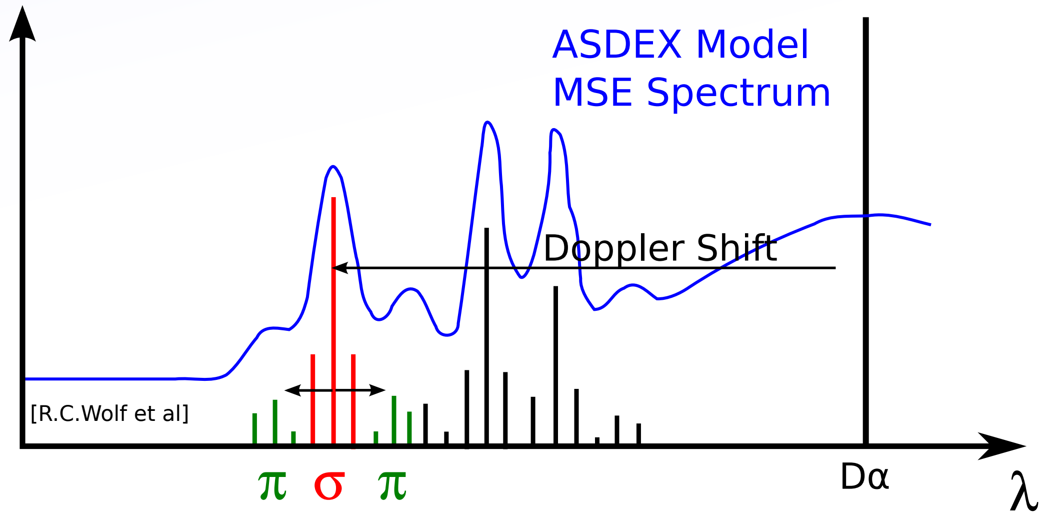

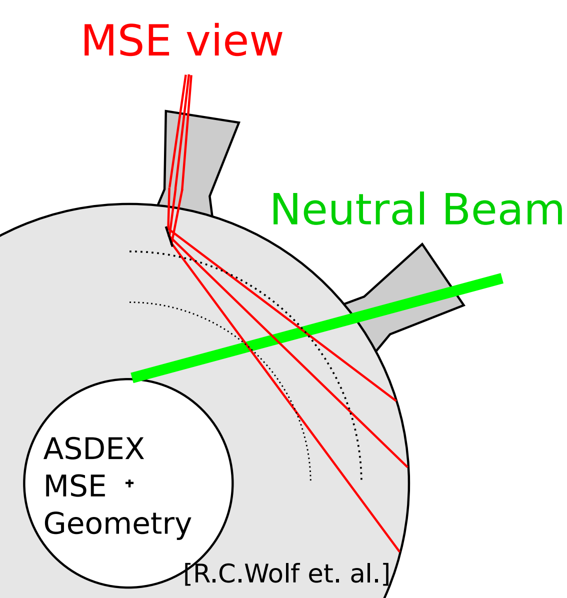

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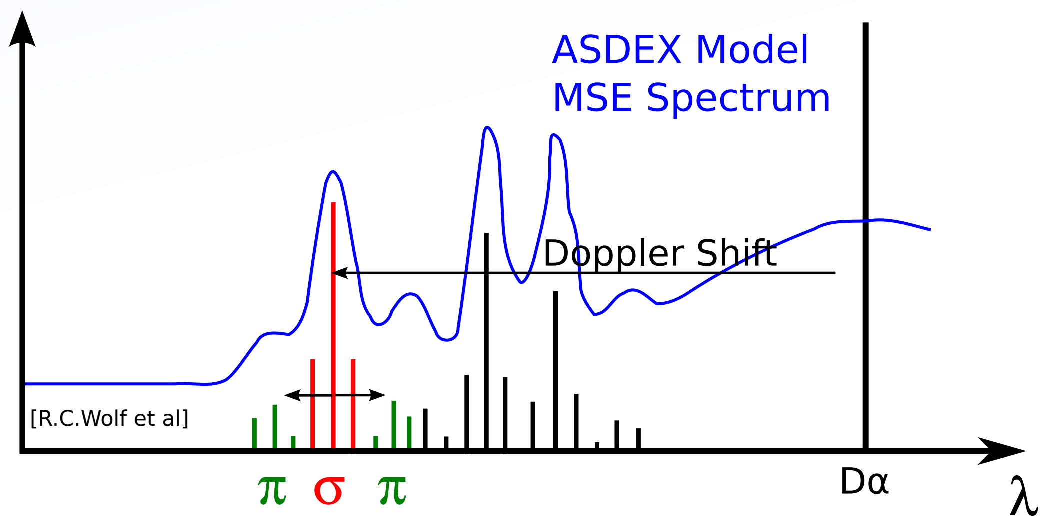
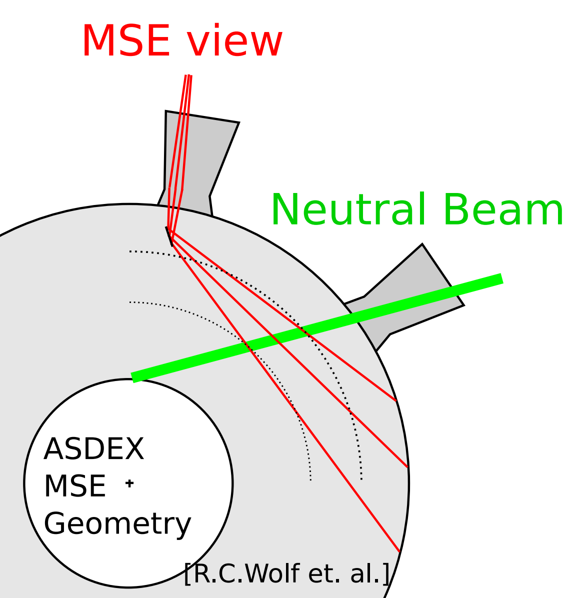
Polarised intensity scales with $\sin^2 \gamma$ for both π and σ with always 90° between them.



Together, whole multiplet is always net unpolarised.



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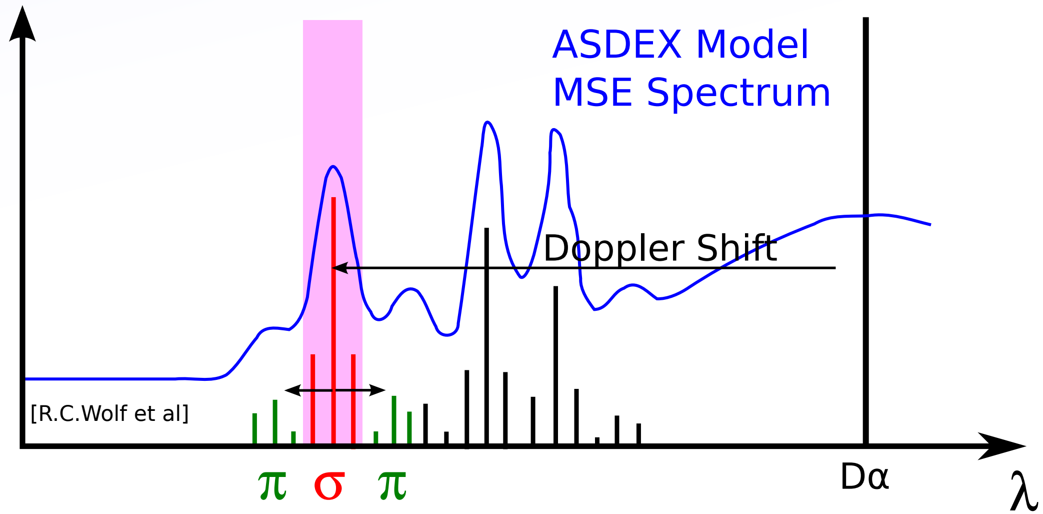
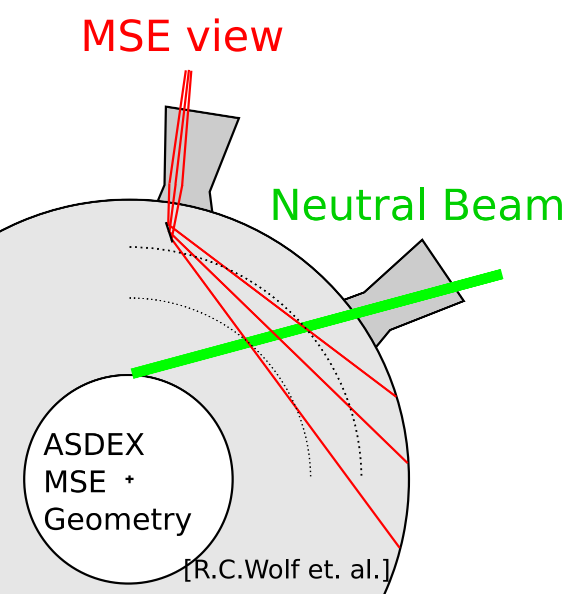




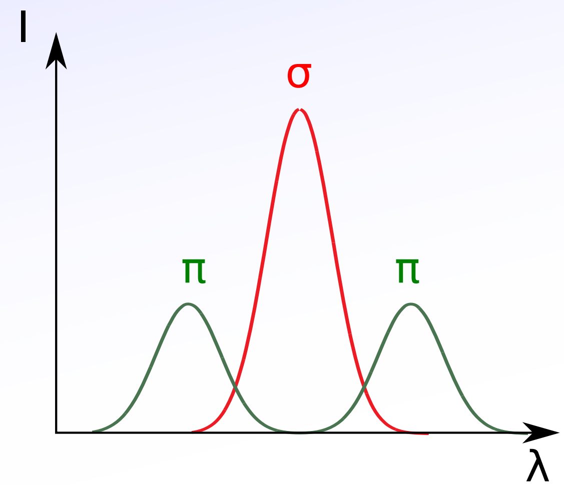
Together, whole multiplet is always net unpolarised.

Conventional systems often:
- Select only σ from spectrum and measure degree of polariastion.
- Select only π or σ and measure polarisation angle.
- Measure ratio of π to σ instensity with spectrometer.

Complex hardware - requires separate filter for each channel.
Low light levels - filter removes large part of light.

Motional Stark Effect Imaging

MSE π and polarised σ are orthogonal and always the same intensity, but they have different spectral profiles, and hence different *ζ:*



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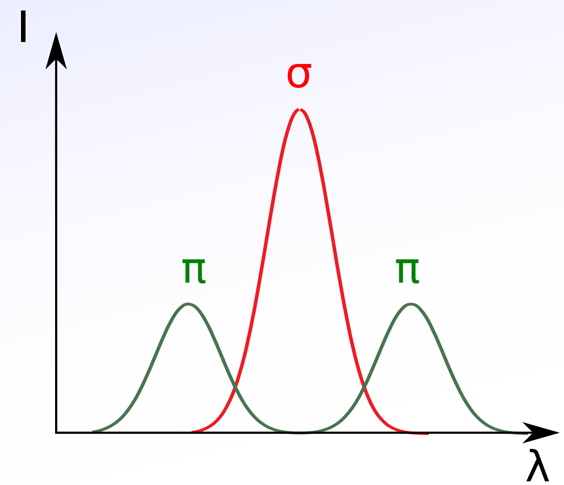

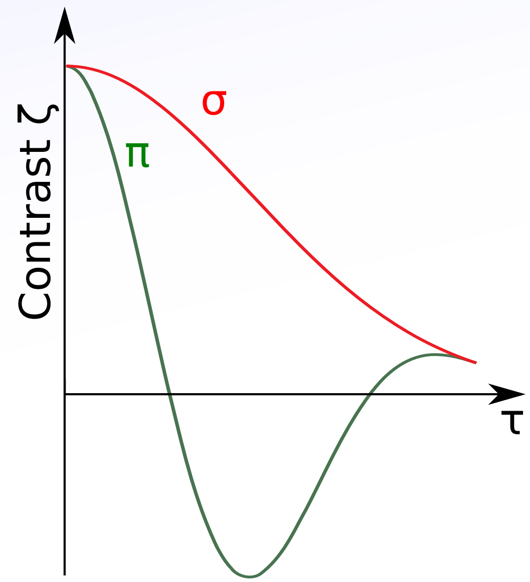

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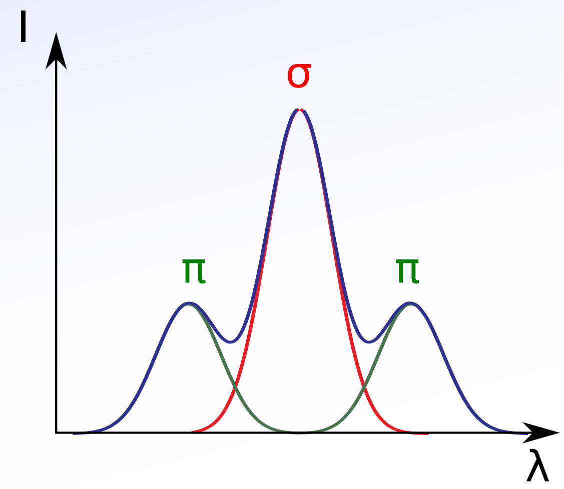
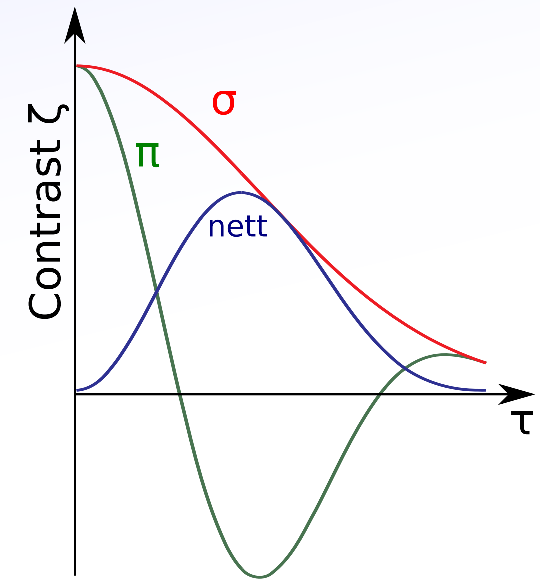
$$\zeta_{nett} = \frac{I_\sigma \zeta_\sigma - I_\pi \zeta_\pi}{I_\sigma + I_\pi}$$





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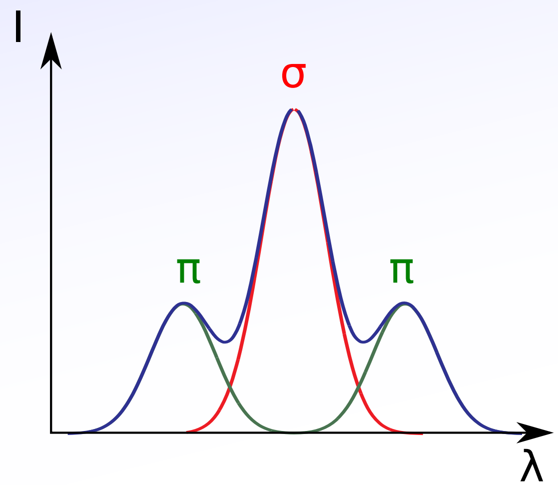

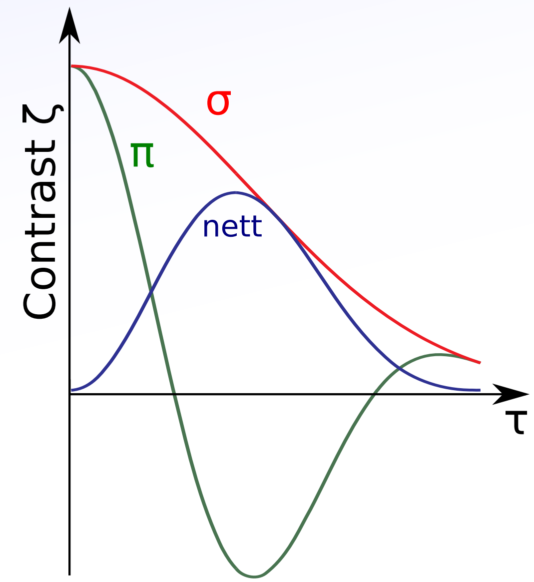

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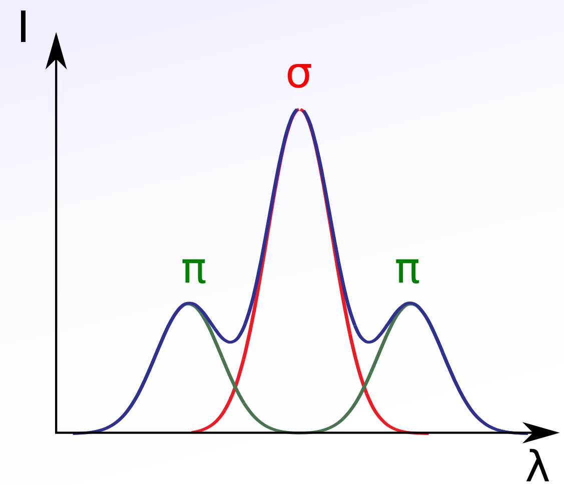

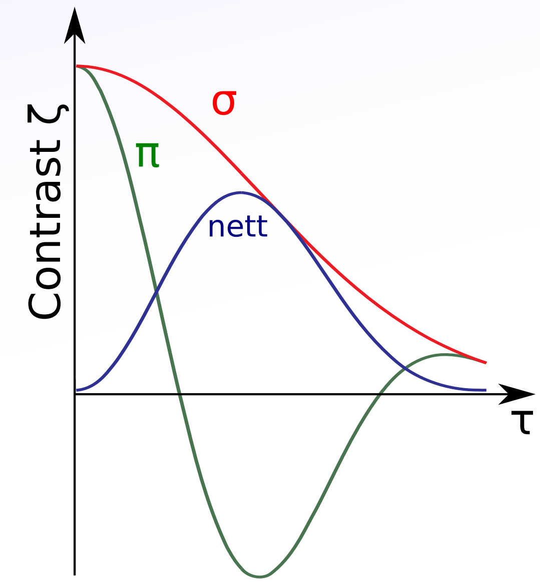

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Whole multiplet (and possibly other energy components) can be included.
--> more light --> better signal to noise.

No need for individual filters for different dopper shift, so we can capture a complete 2D image.

Modelling for AUG: Beams and MSE

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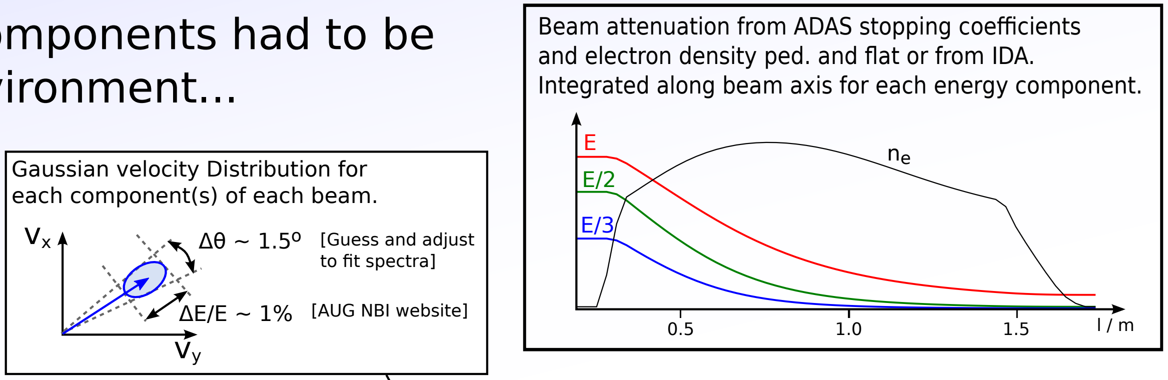

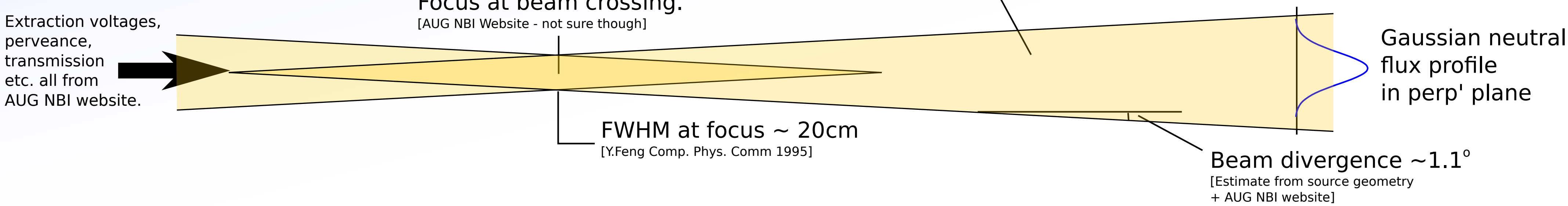

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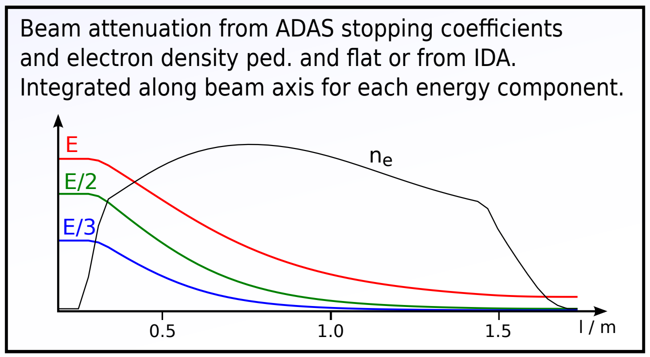

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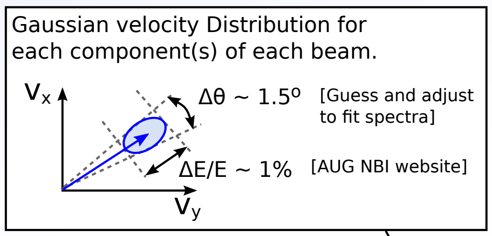

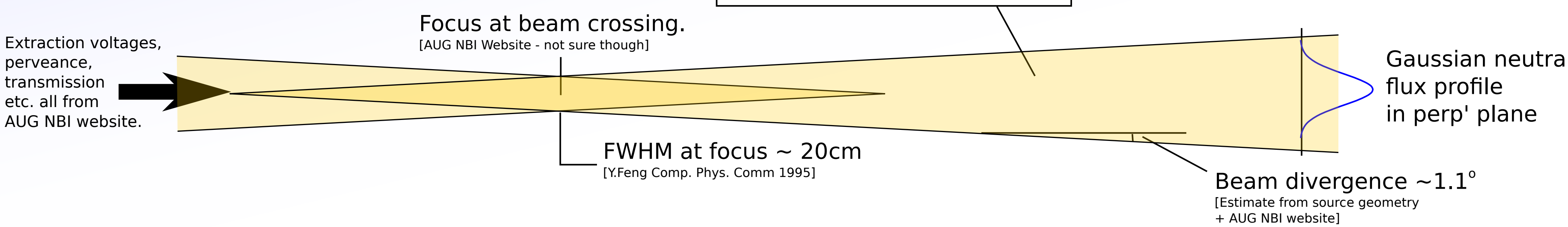

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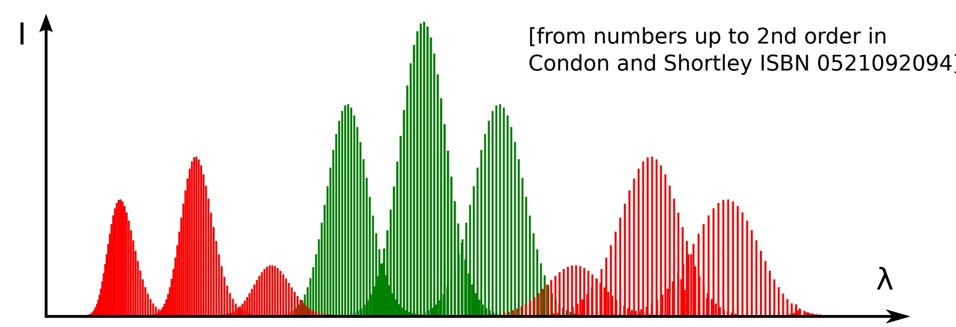
Lists of stokes vectors with Guassian spectral distribution along any given line of sight.

Absolute intensitites calculated using ADAS effective emission coefficients.



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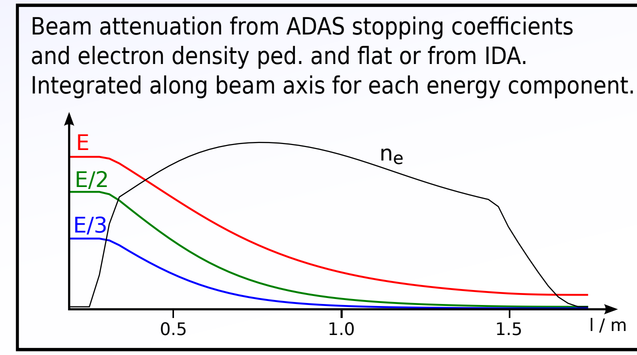

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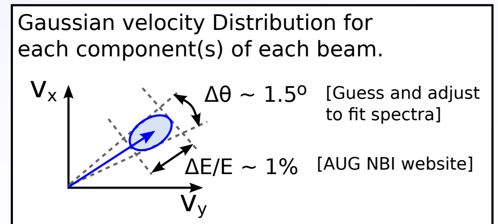

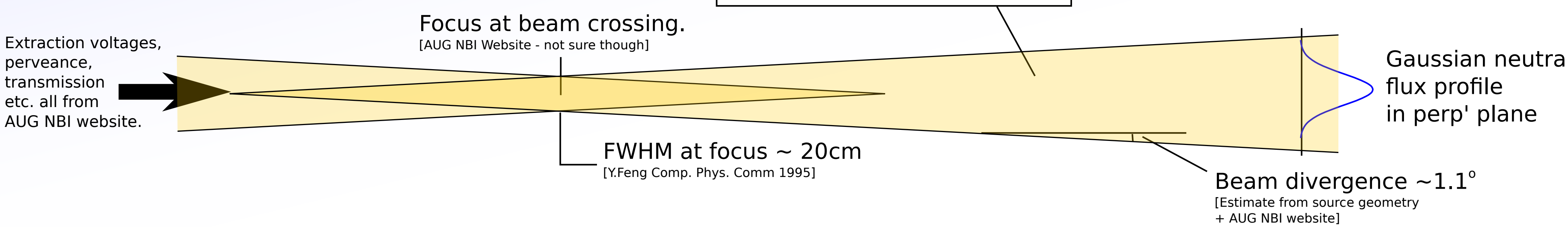

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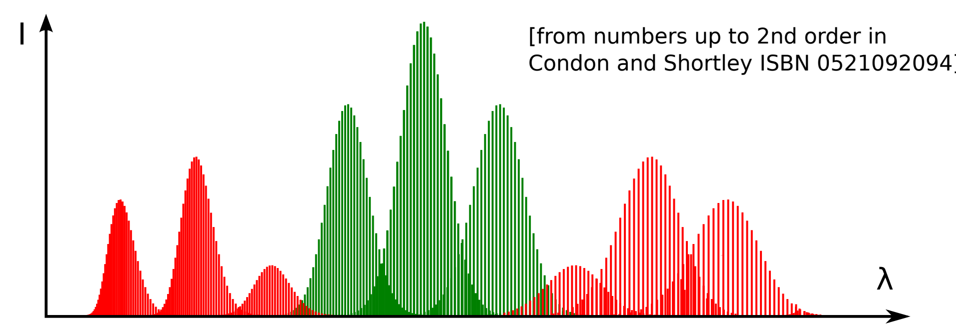
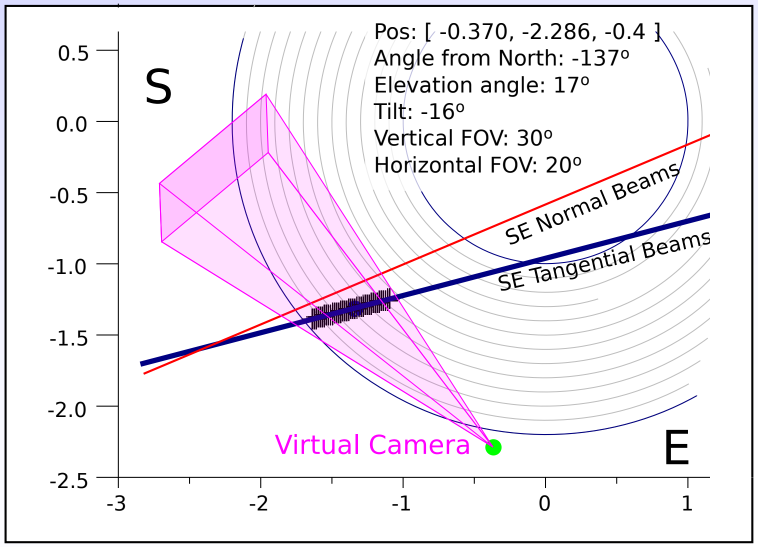


3) Very simple camera base model (optics):
2D fan of lines of sight over given field of view.
This part probably needs the most work to make the model realistic (optical effects)

Modelling for AUG: Geometry and spectrum.



Initial modelling with MSE CIS 'virtual camera' placed at location of mirror in current MSE system.

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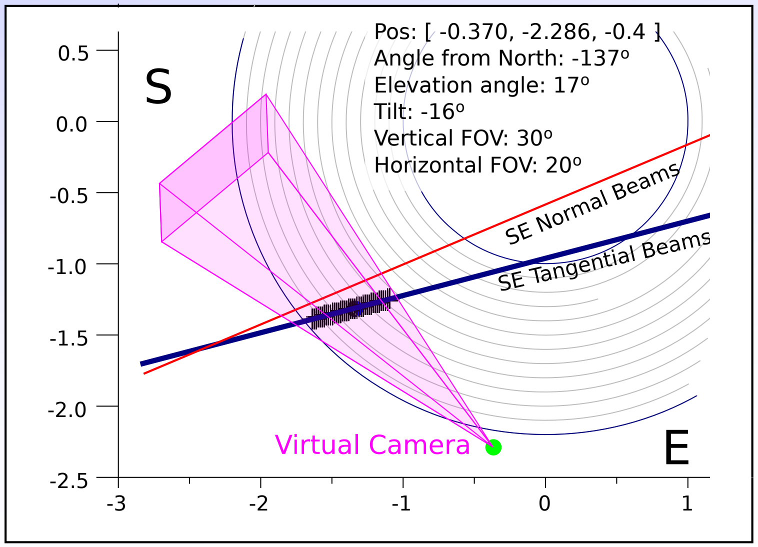

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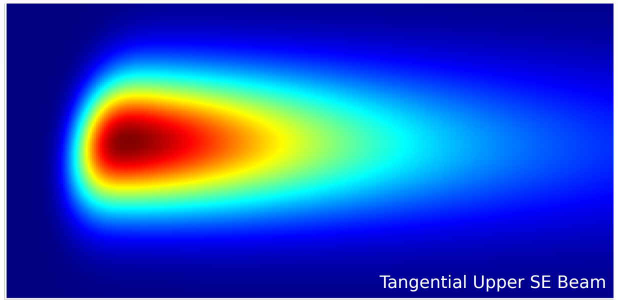

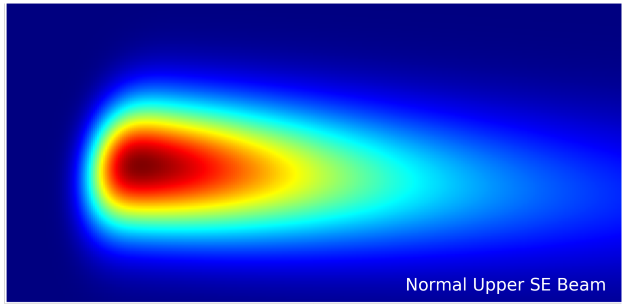

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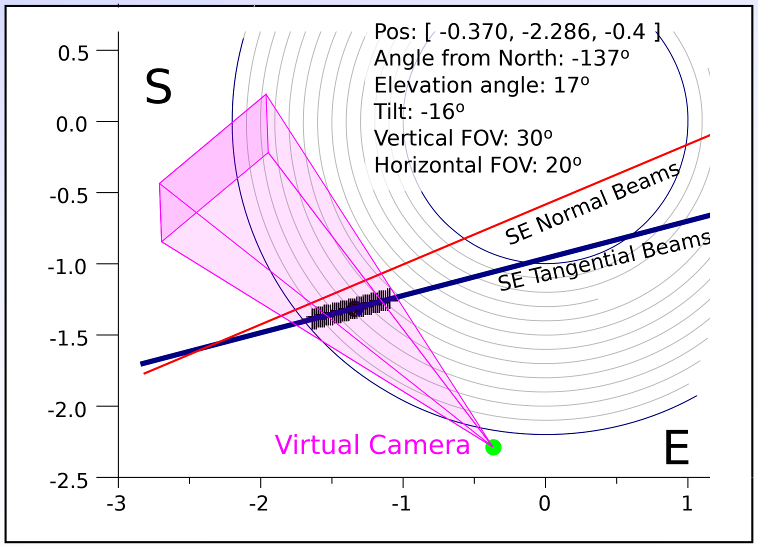

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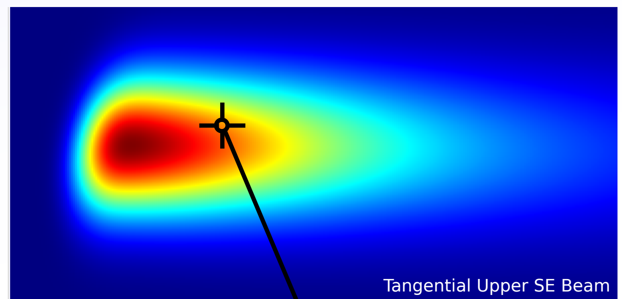
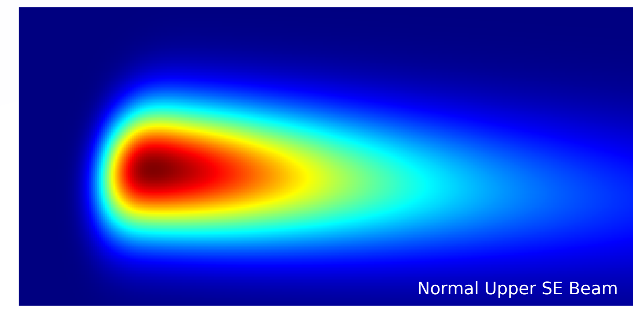
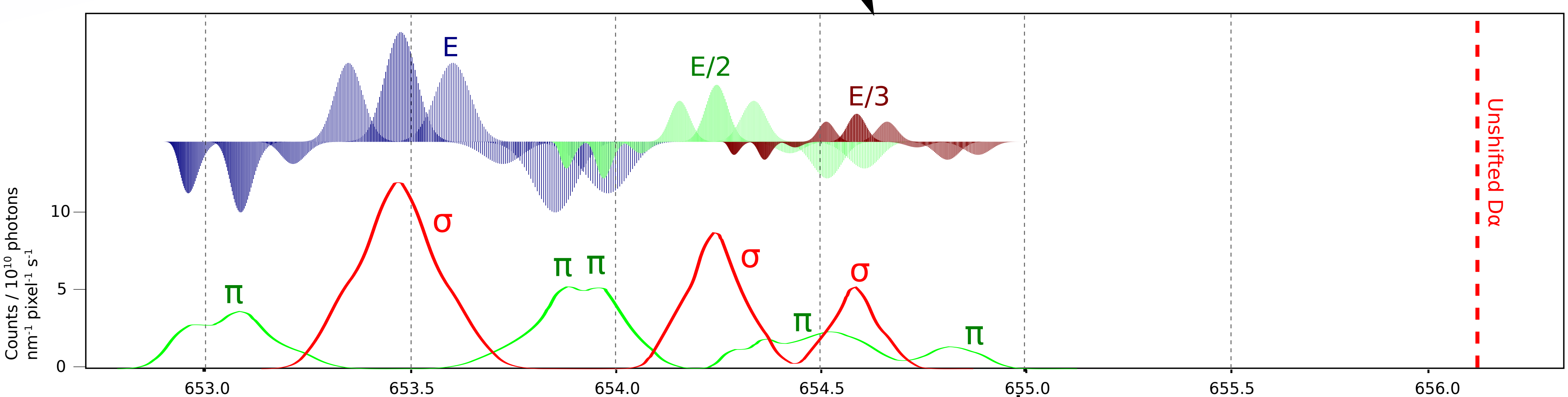




Examination of the spectrum from a single pixel:



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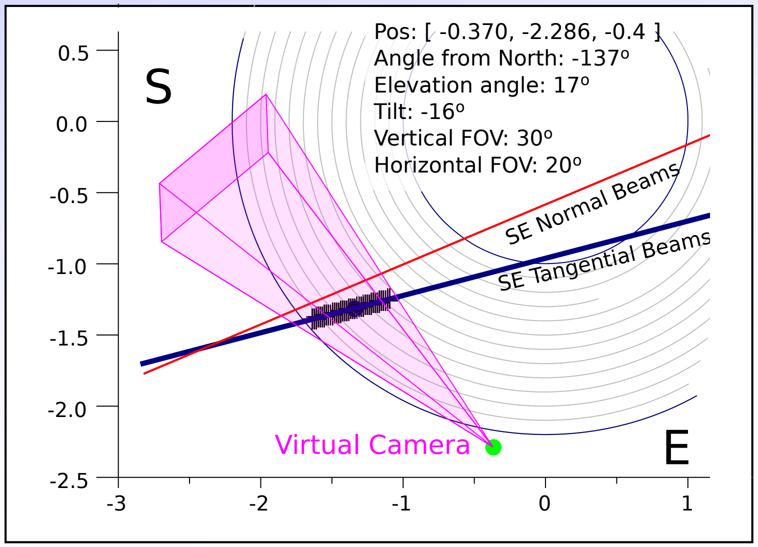

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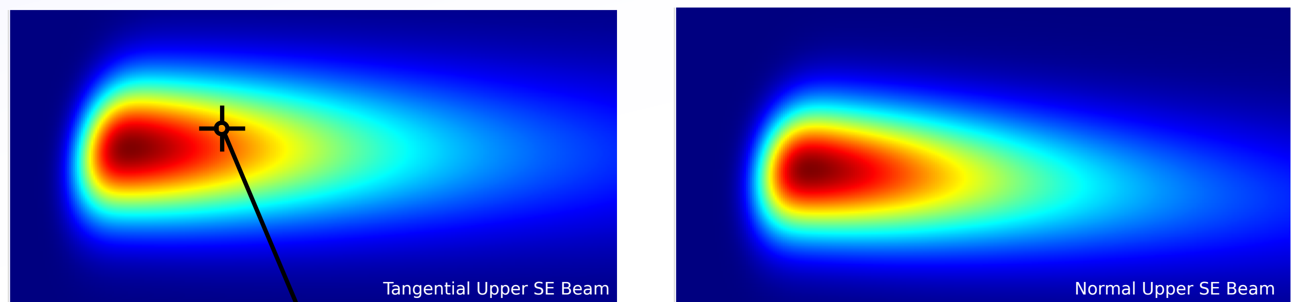

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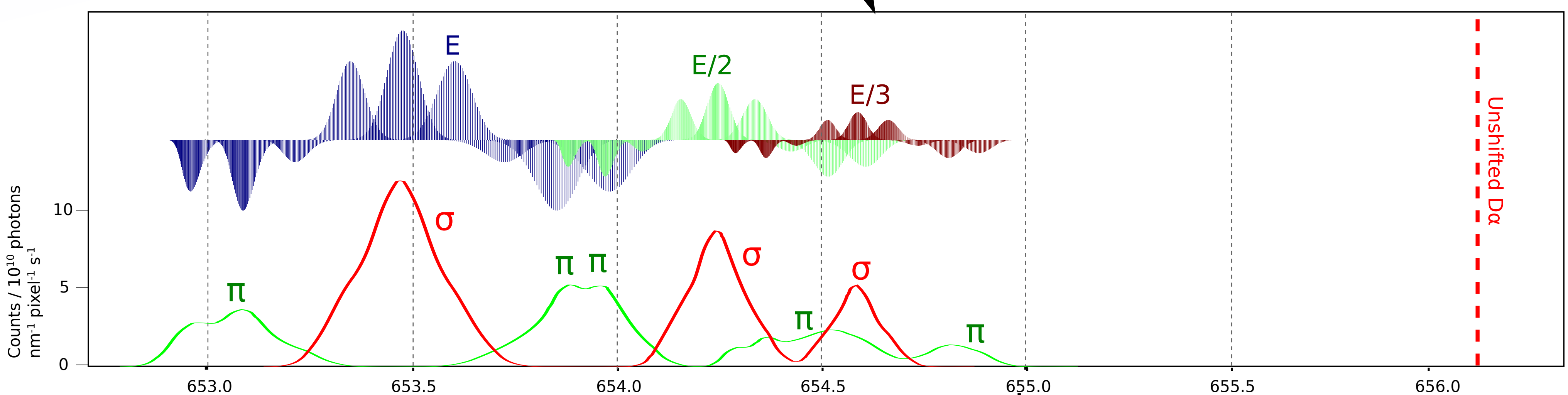
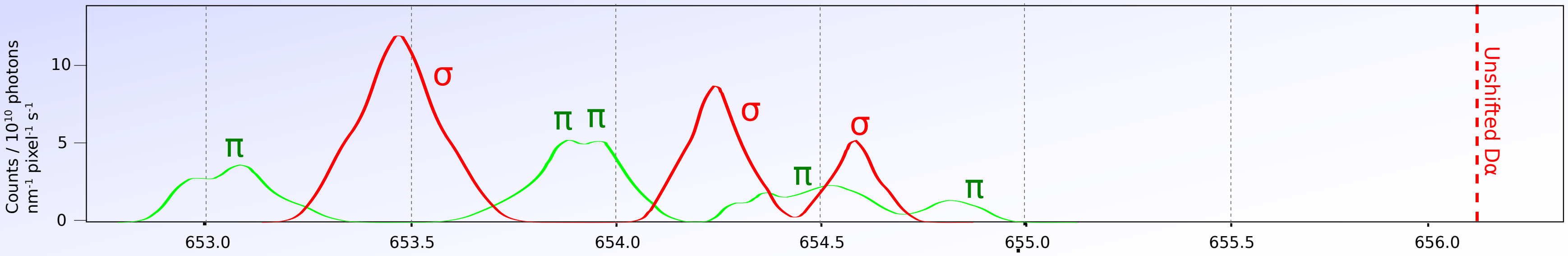


π wings of *E* and *E/2* overlap but this just improves the fringe contrast here.
We can in principal take the light from all the energy components together.

Modelling for AUG: MSE Spectrum



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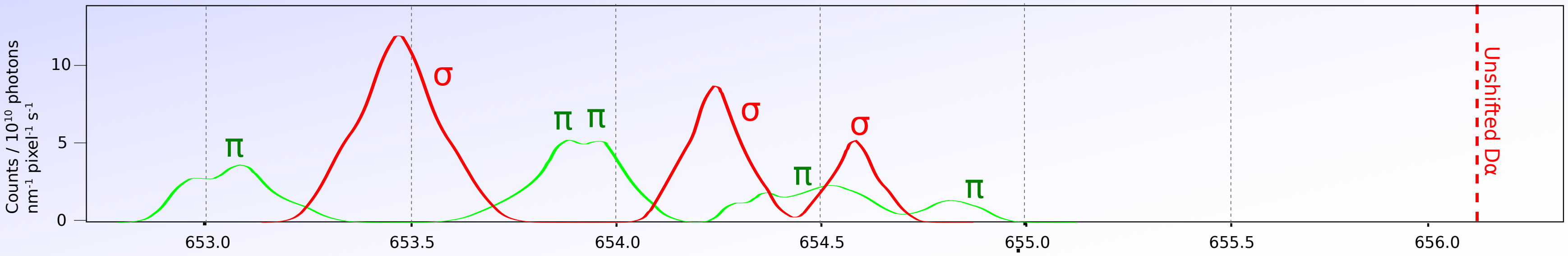
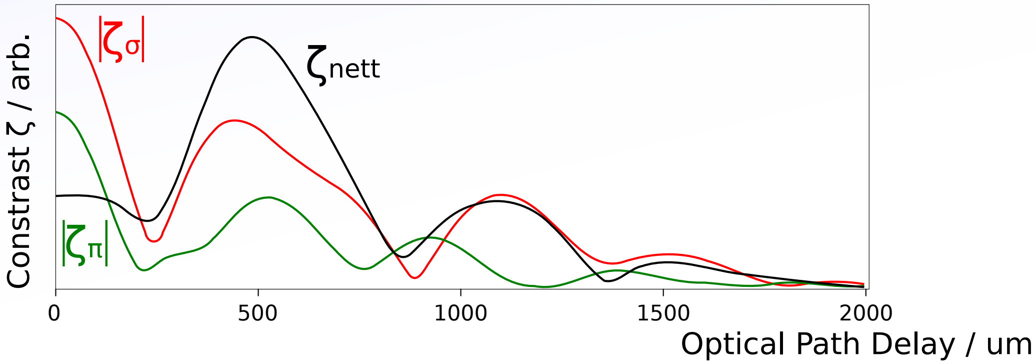


We can also calculate the nett contrast:



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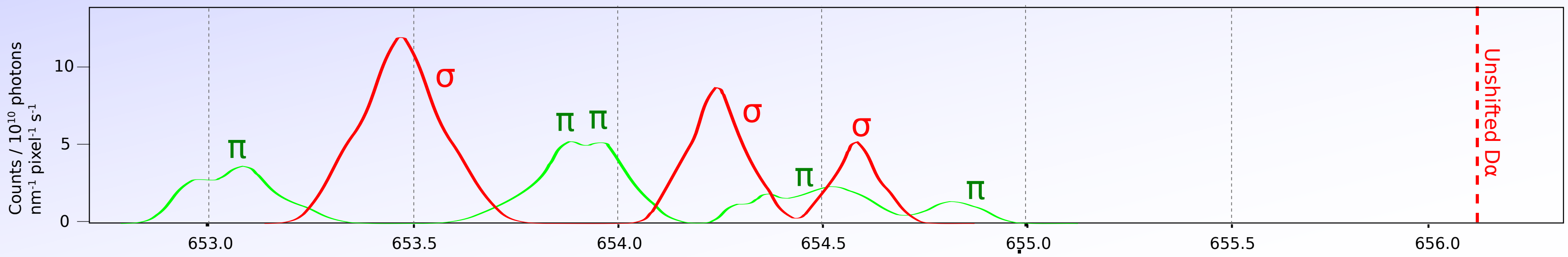

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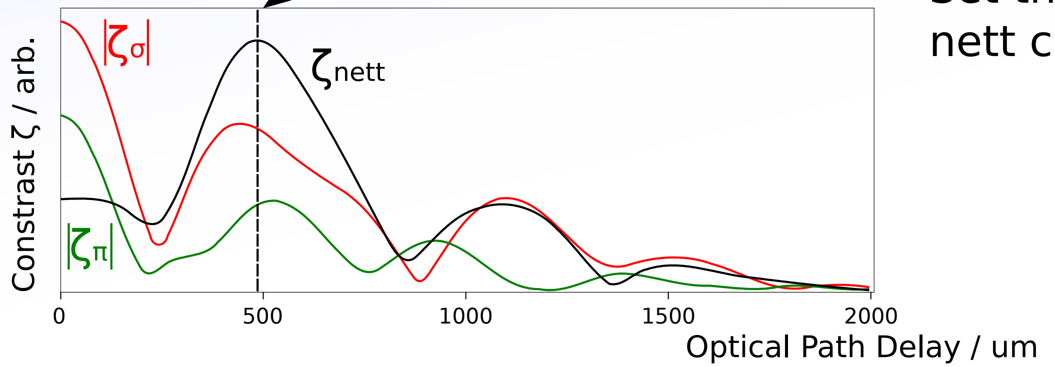

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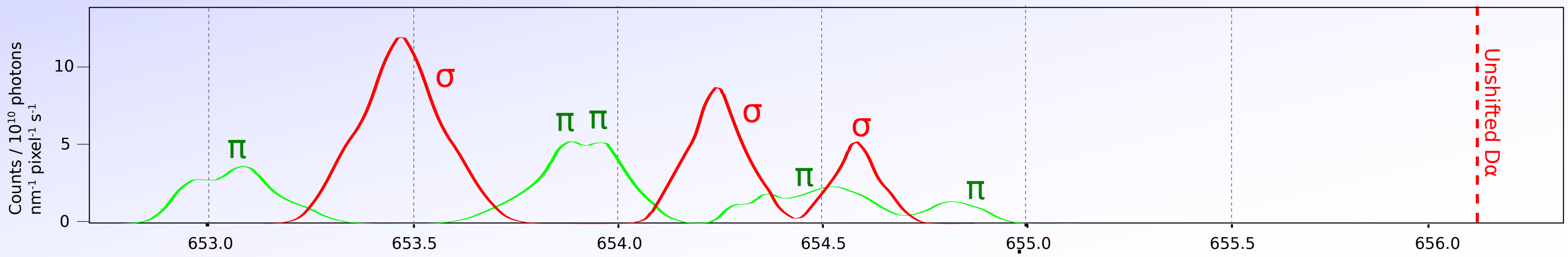

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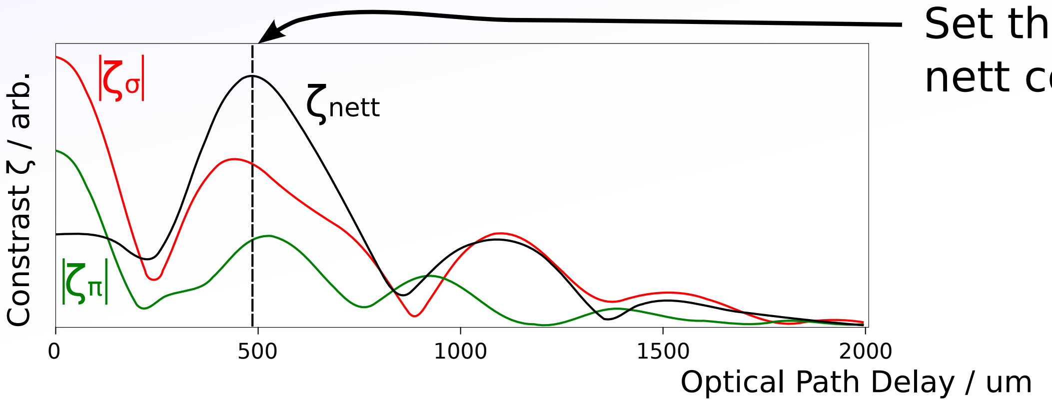

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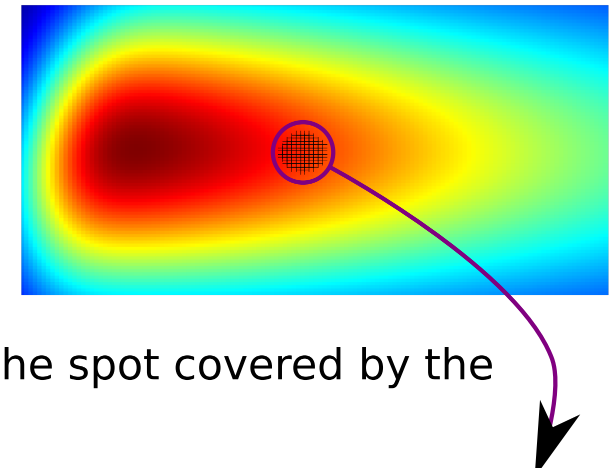
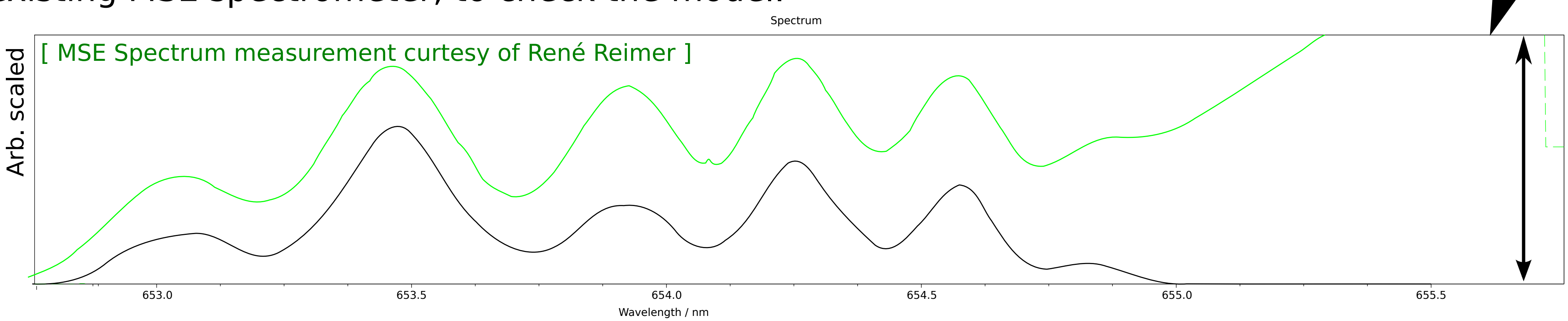


We can also integrate up the spectrum of the pixels that look at the spot covered by the existing MSE spectrometer, to check the model.



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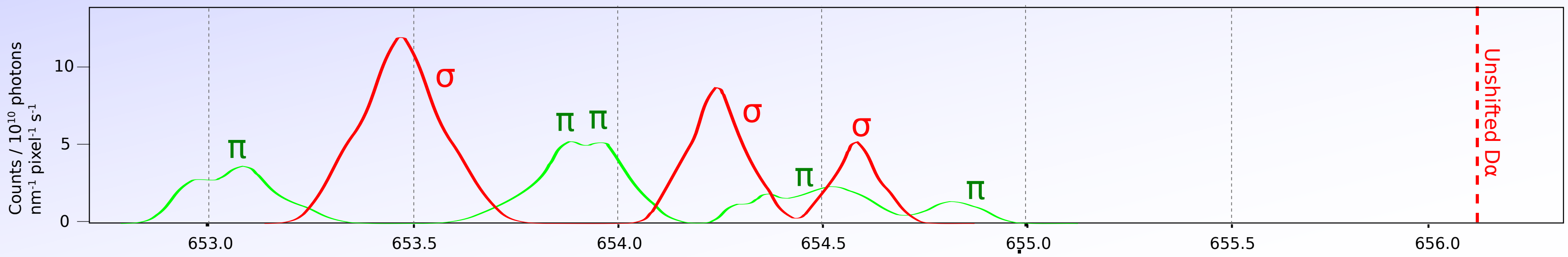

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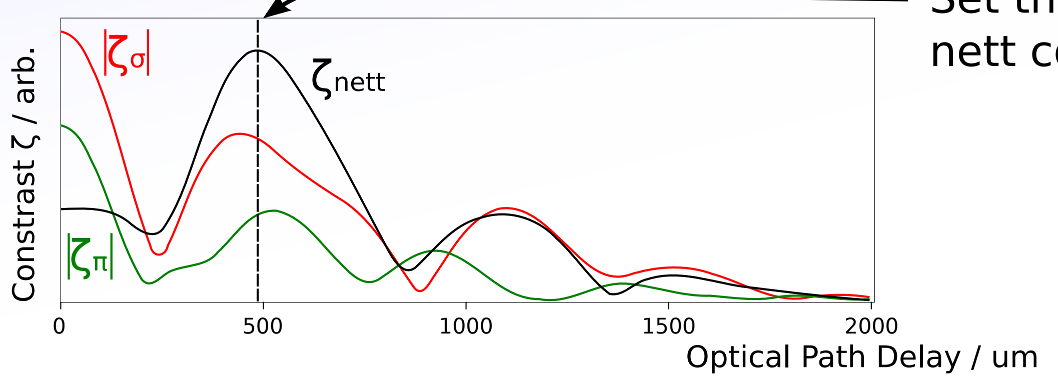

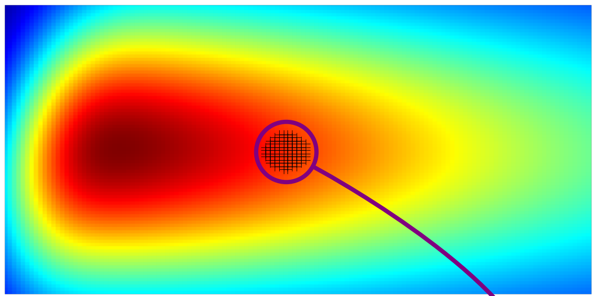

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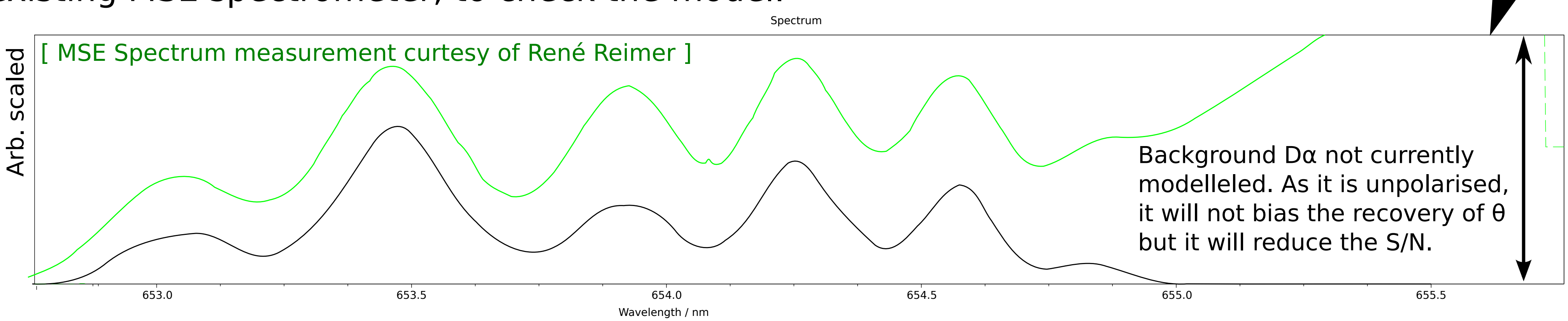

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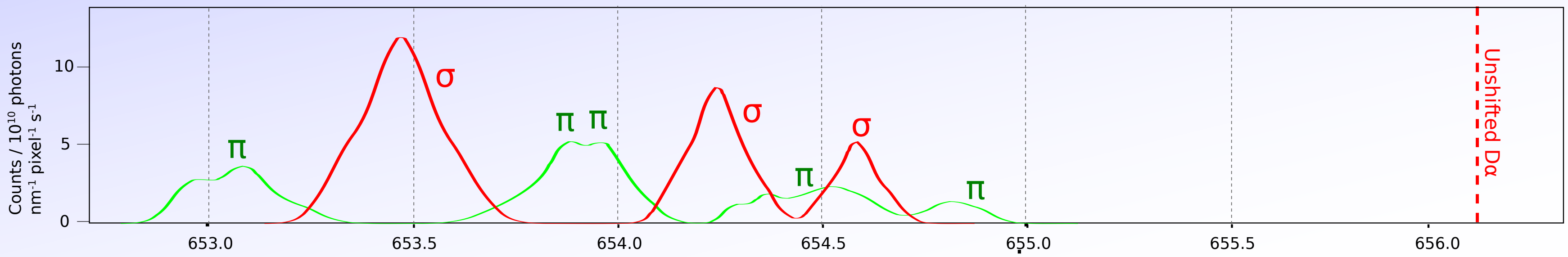

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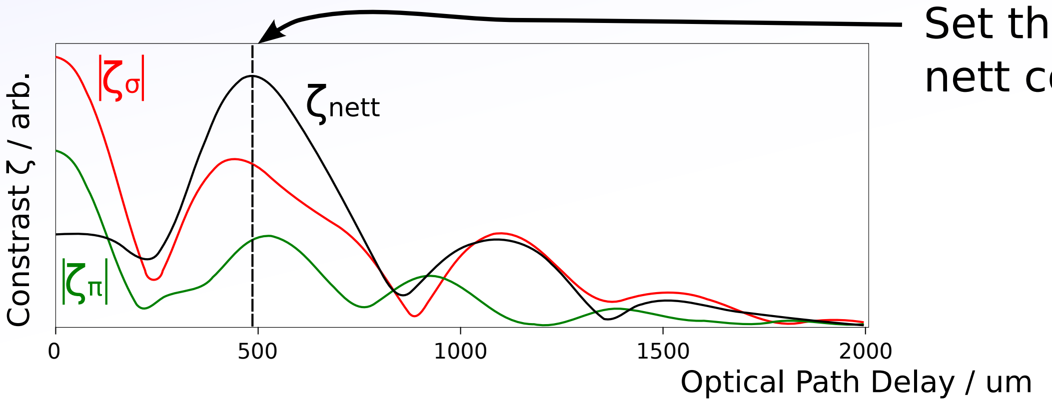

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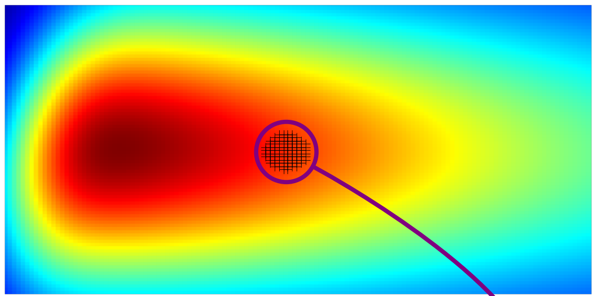

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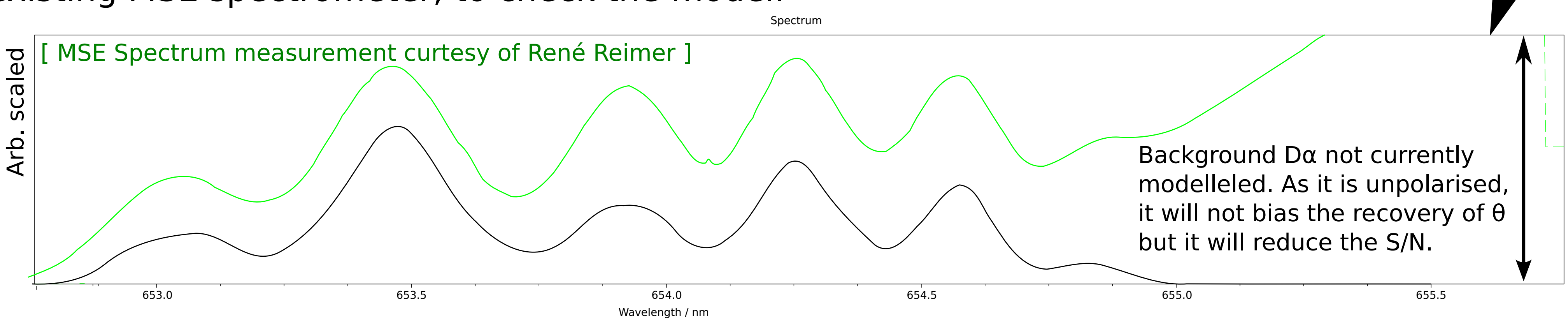

Generally a good match in spectrum. Absolute values match within an order of magnitude.

Double Spatial Heterodyne Model

Thickness of Savart plates sets fringe period in each direction.
Roughly: Shorter fringes = better spatial resolution.
Longer fringes = better S/N.

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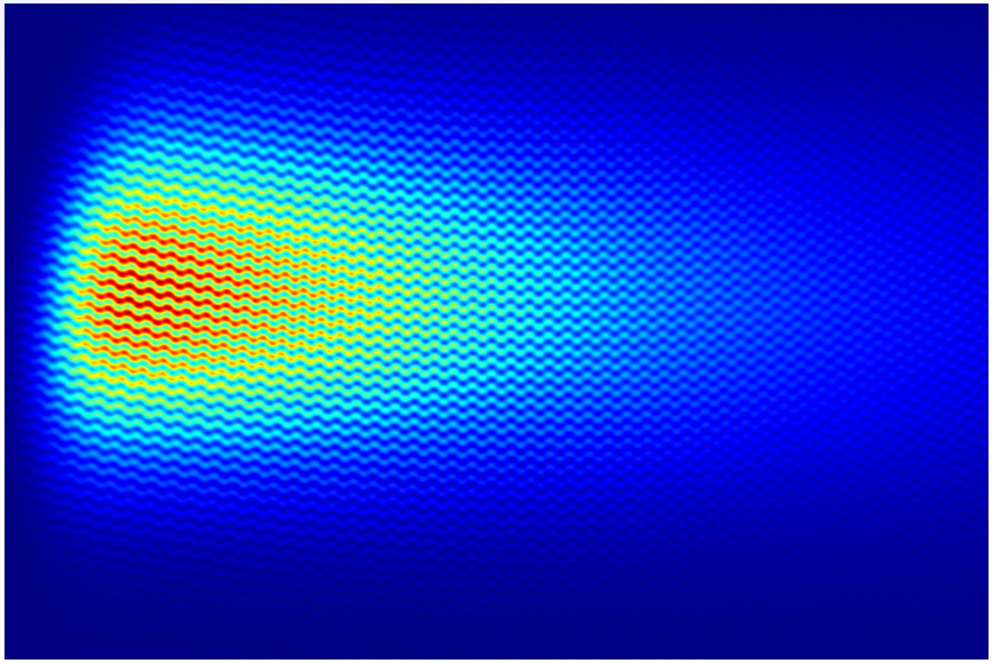

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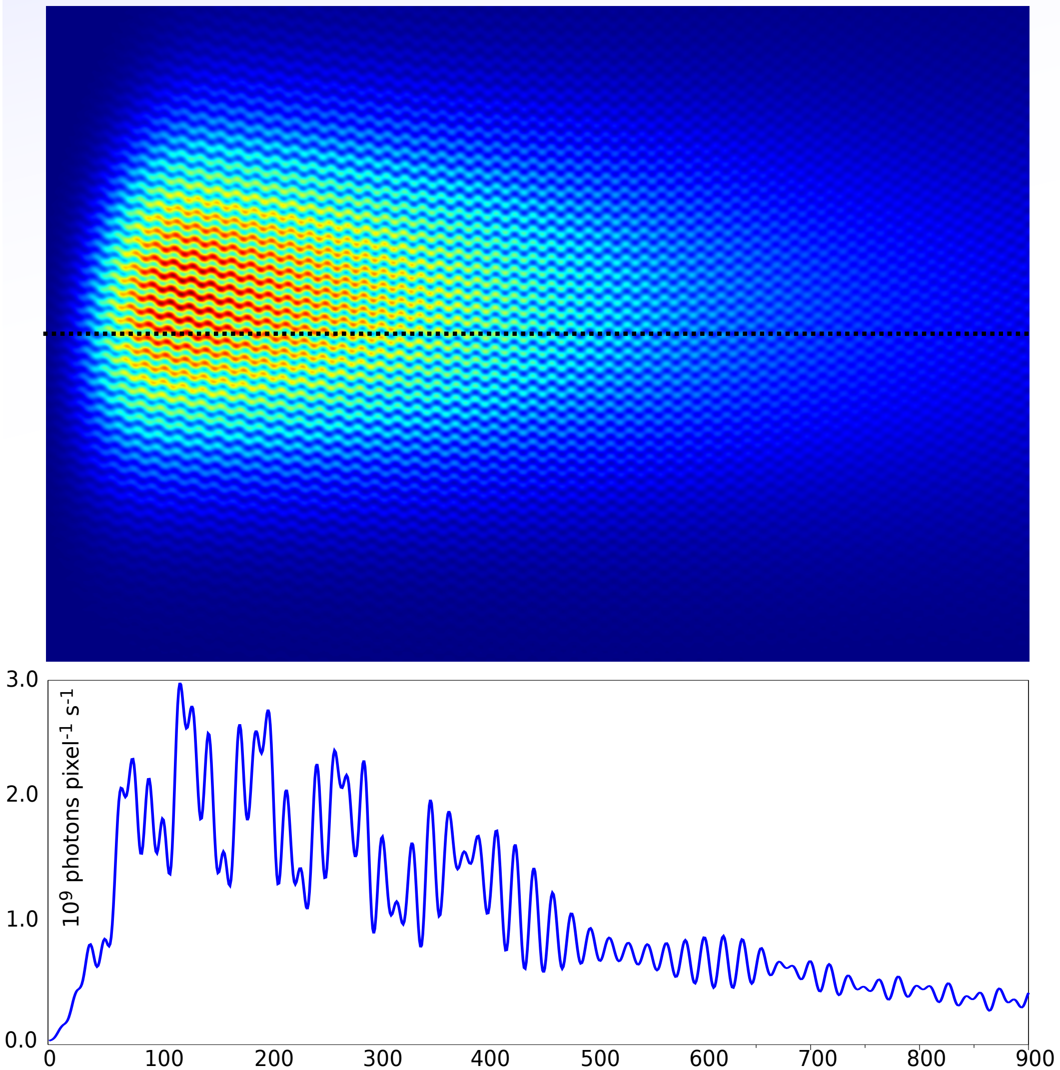

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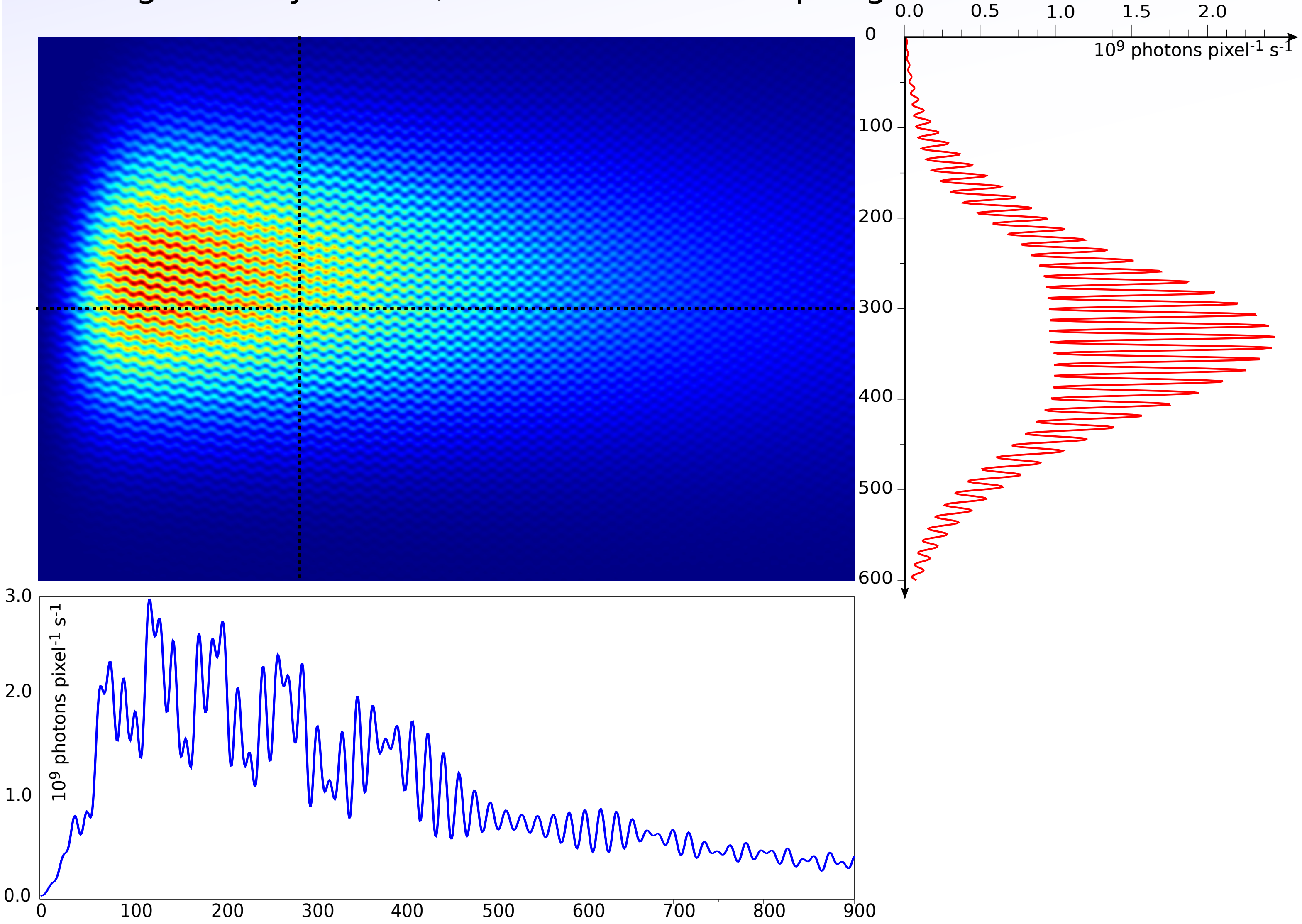

Simple Demodulation

Simple attempt at recovering polarisation projection angle θ from image (with photon noise)

$$I = \frac{(I_\pi + I_\sigma)}{2}\left[1 + \zeta_{nett}\left(\, cos2\theta \; cos(x) + sin2\theta \; sin(x) \; sin(y) \,\right)\right]$$

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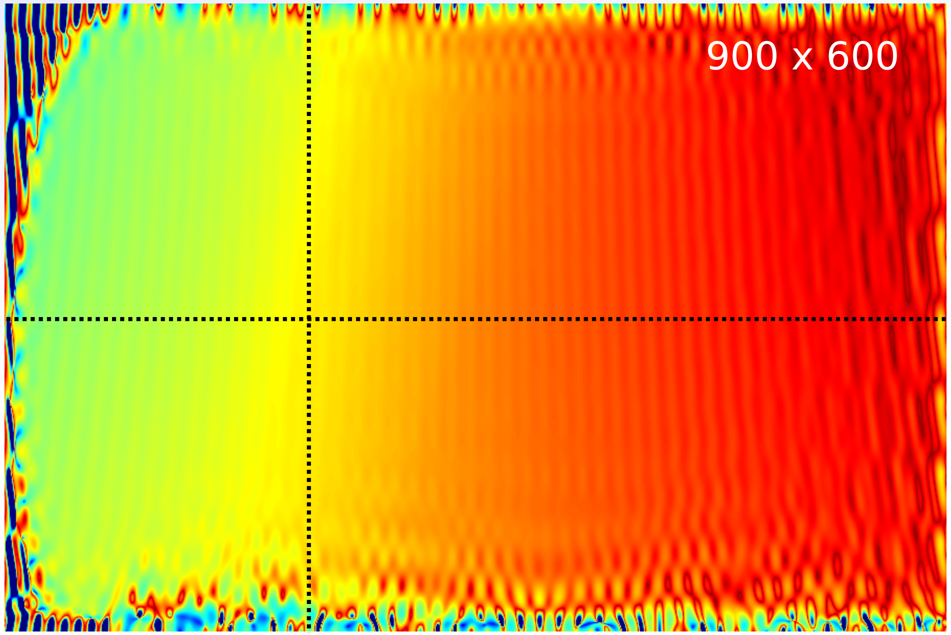

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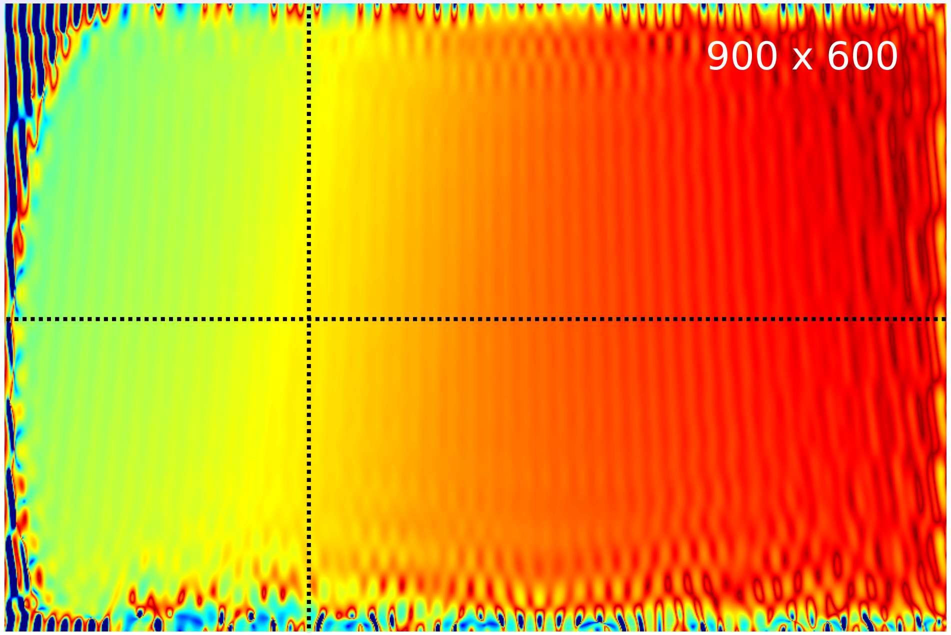

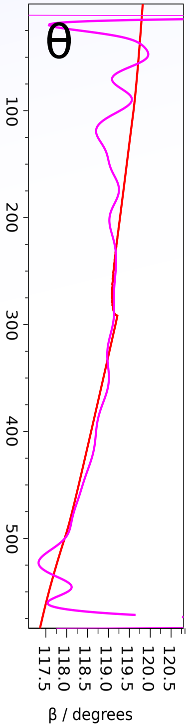

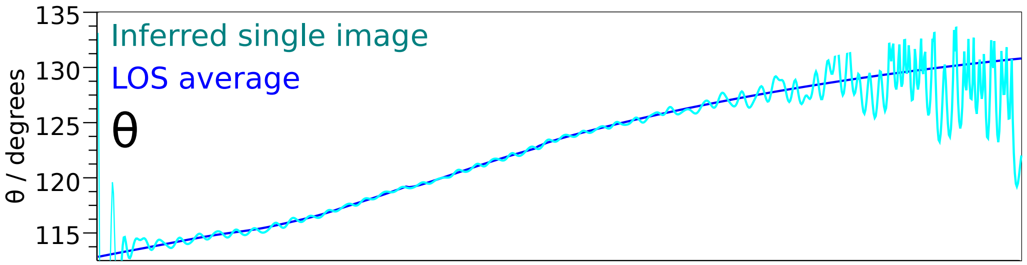

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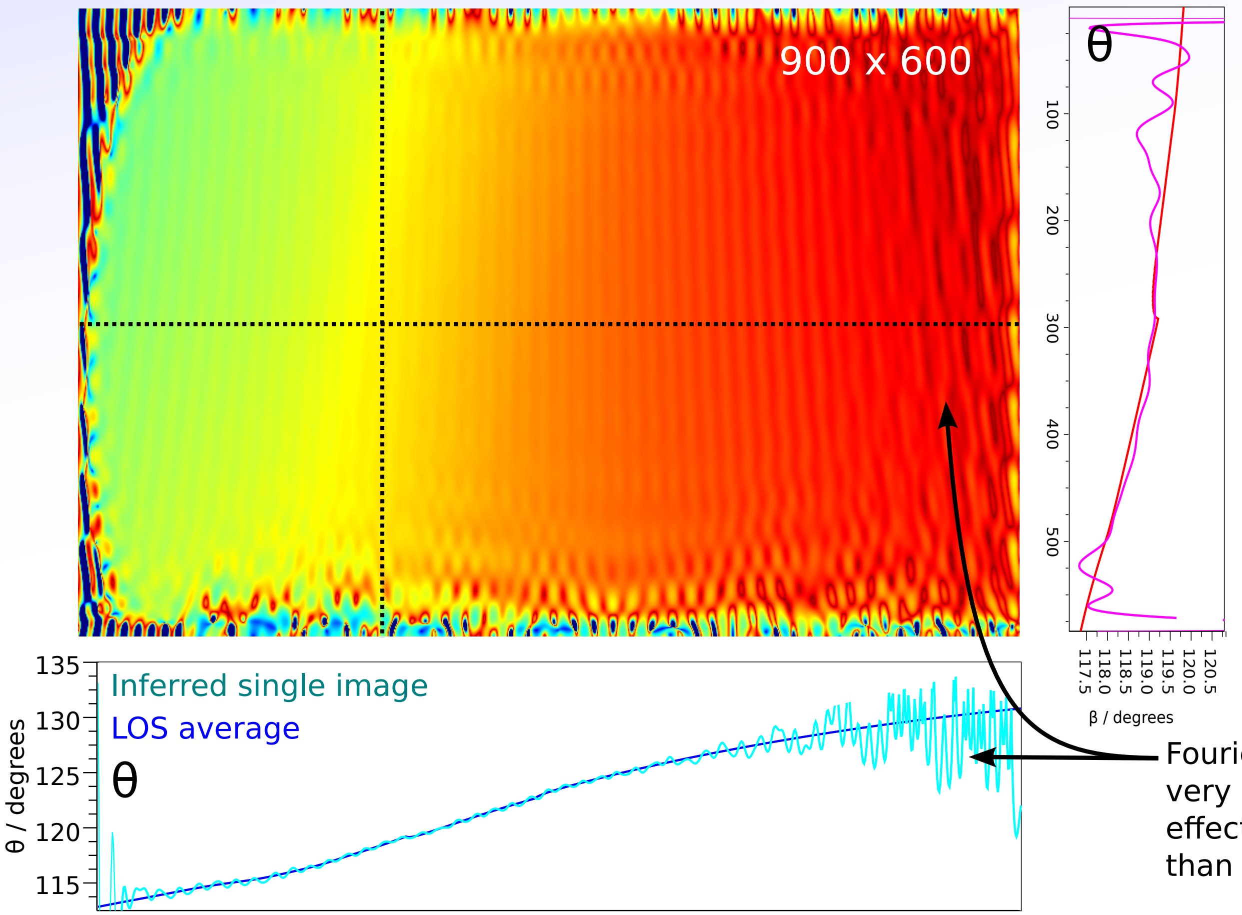

Fourier demodulation very sensitive to edge effects. We can do better than this.

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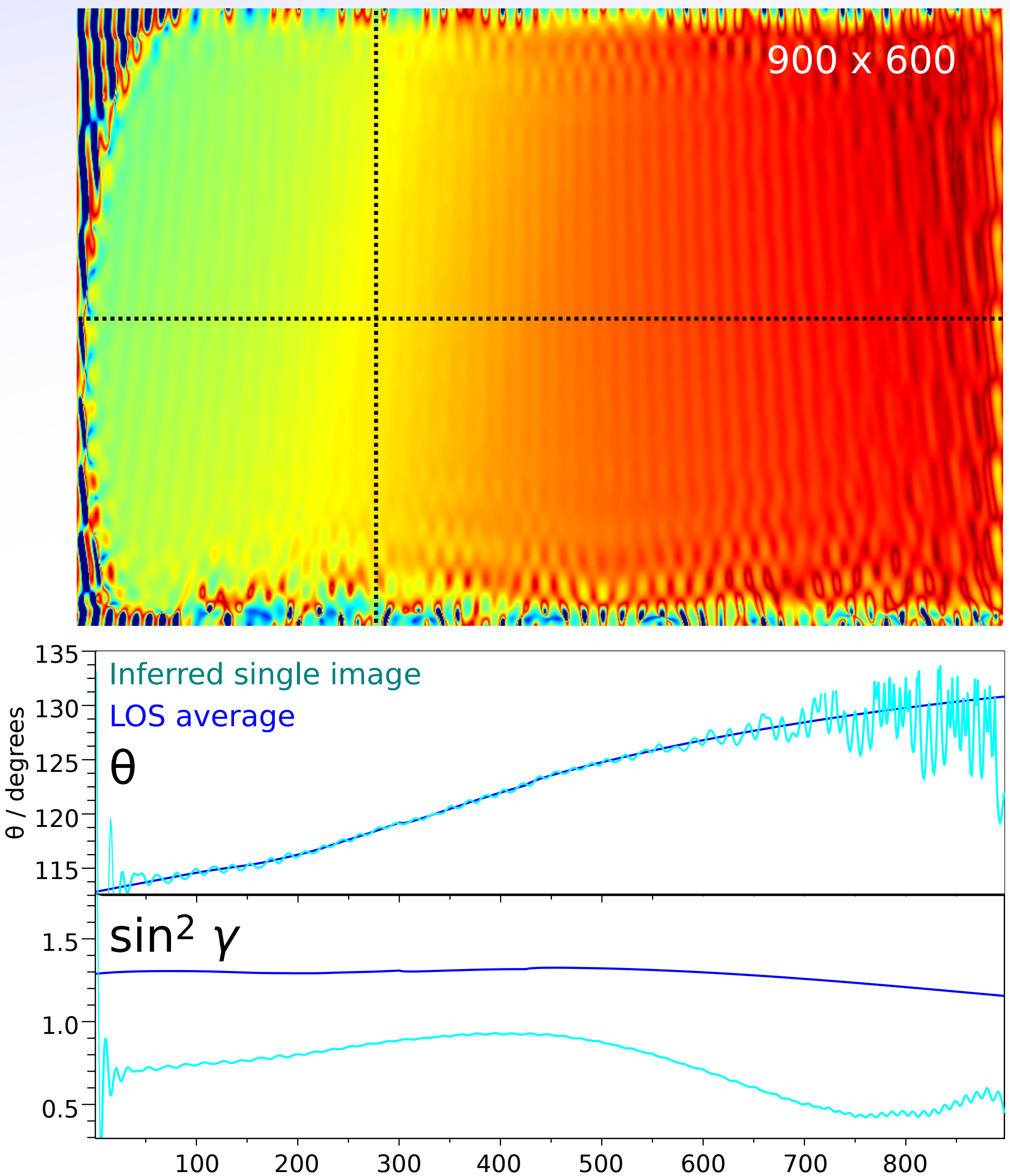

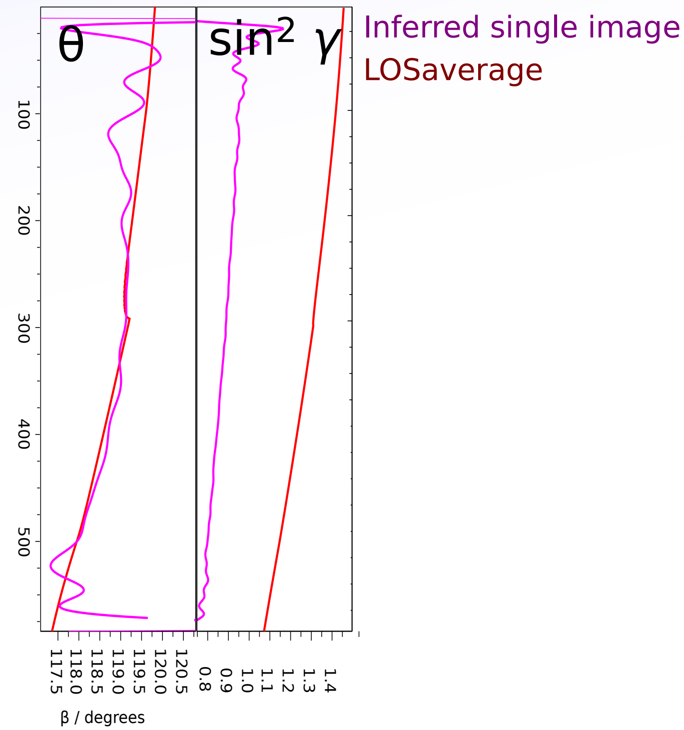

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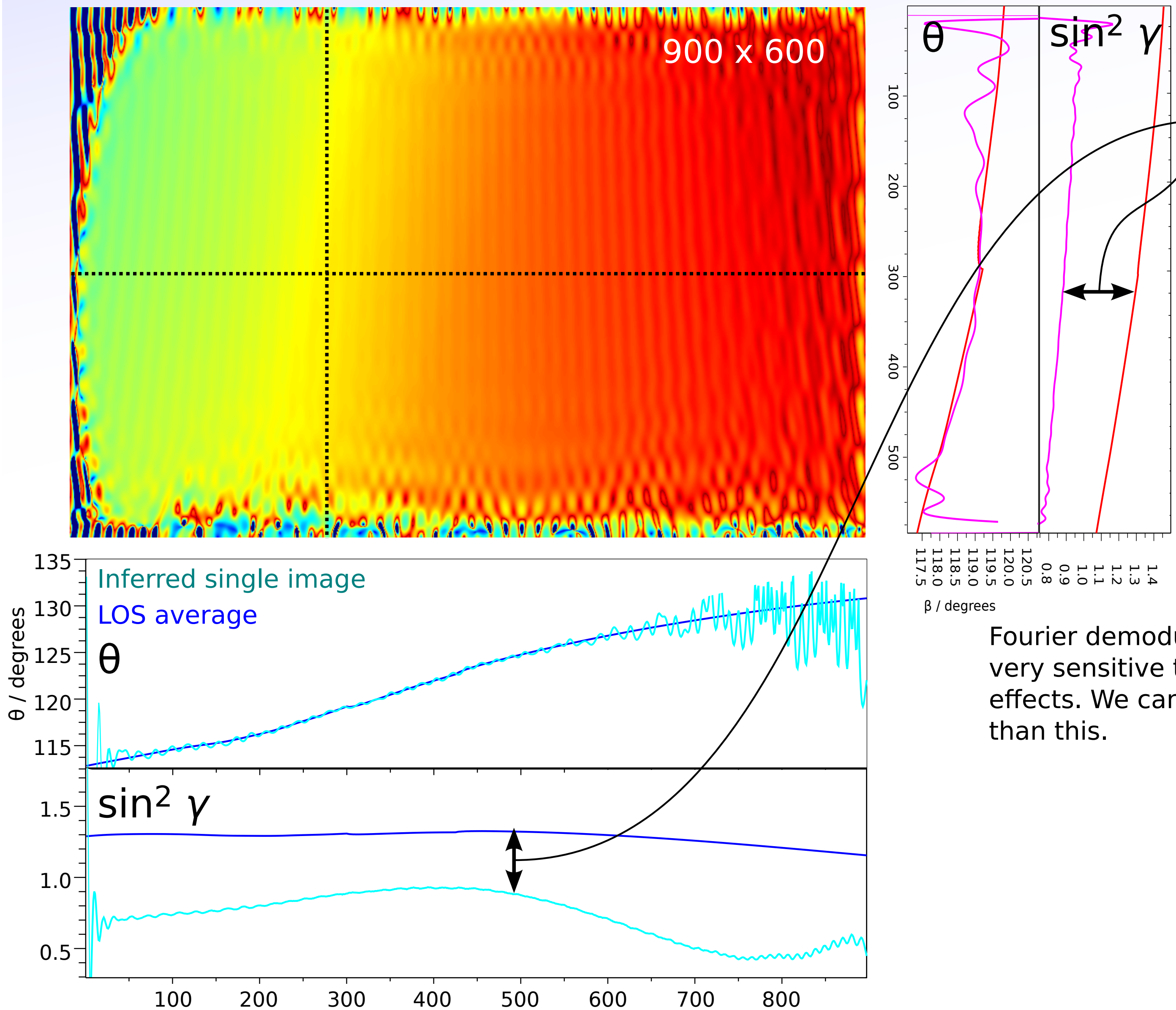

ζ_{nett} also contains the angle γ of E toward/away from camera. LOS integration effects make it difficult but with full Bayesian analysis we may be able to get some more information from this (This is effectively the $I\pi/I\sigma$ method).

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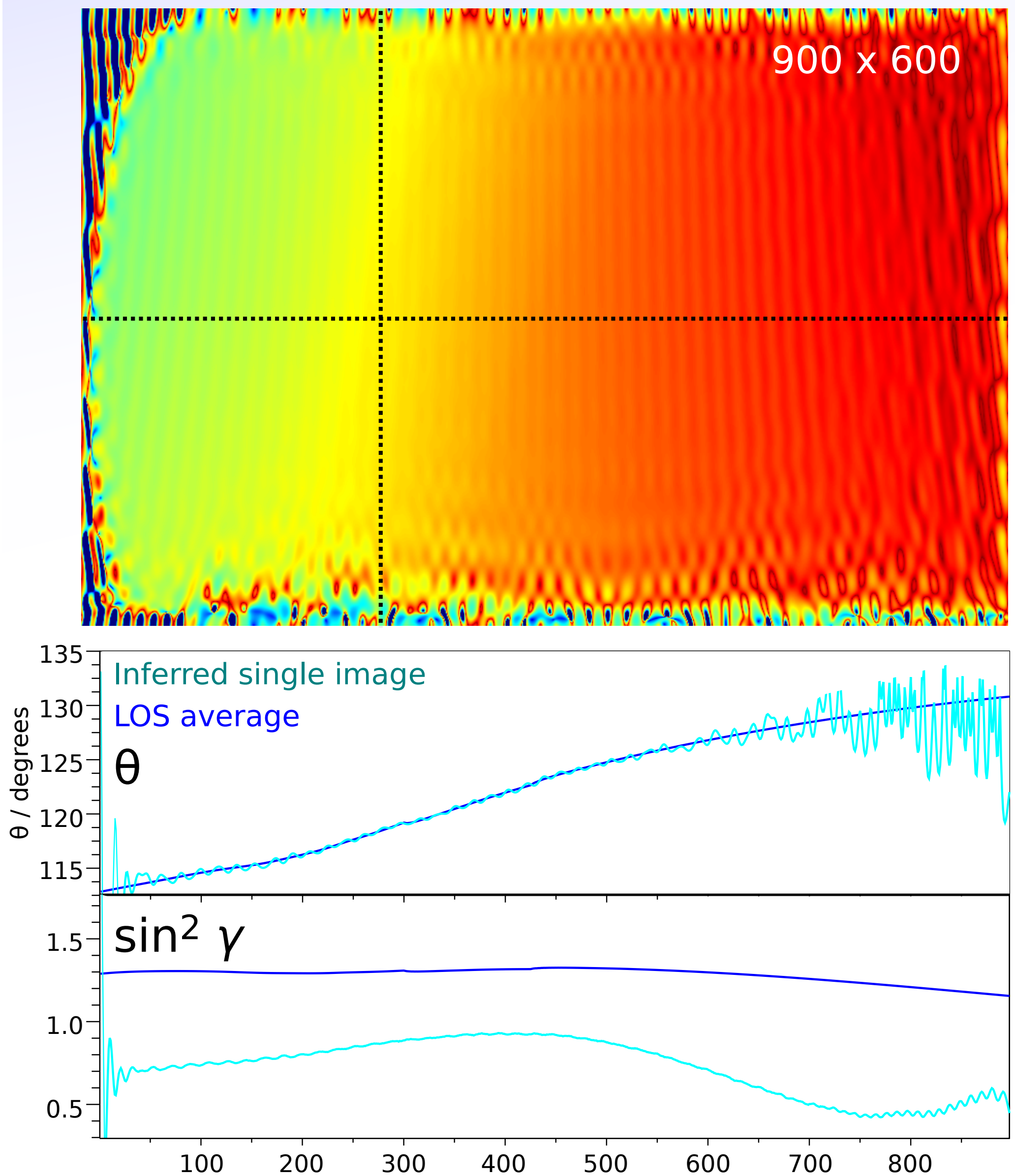

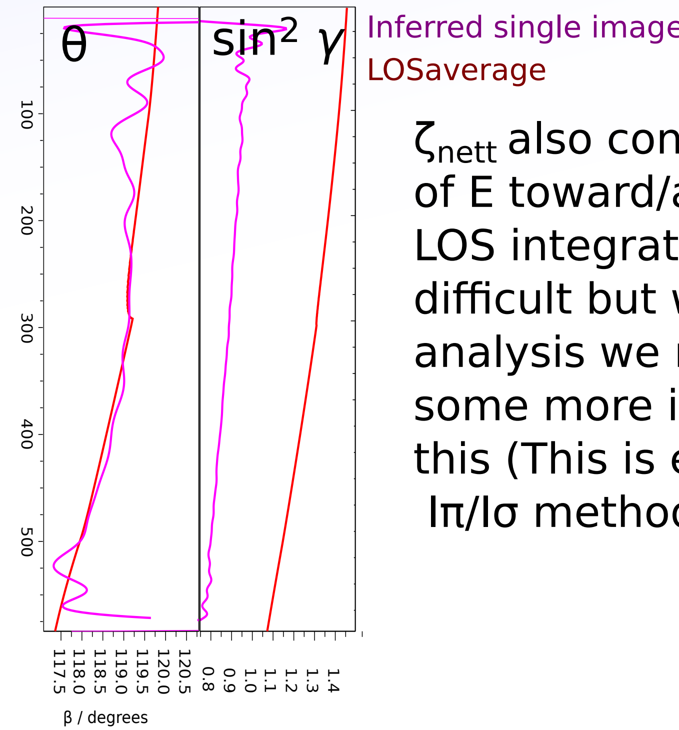

ζ_{nett} also contains the angle γ of E toward/away from camera. LOS integration effects make it difficult but with full Bayesian analysis we may be able to get some more information from this (This is effectively the Iπ/Iσ method).

Fourier demodulation very sensitive to edge effects. We can do better than this.

Simple Demodulation

Simple attempt at recovering polarisation projection angle θ from image (with photon noise)

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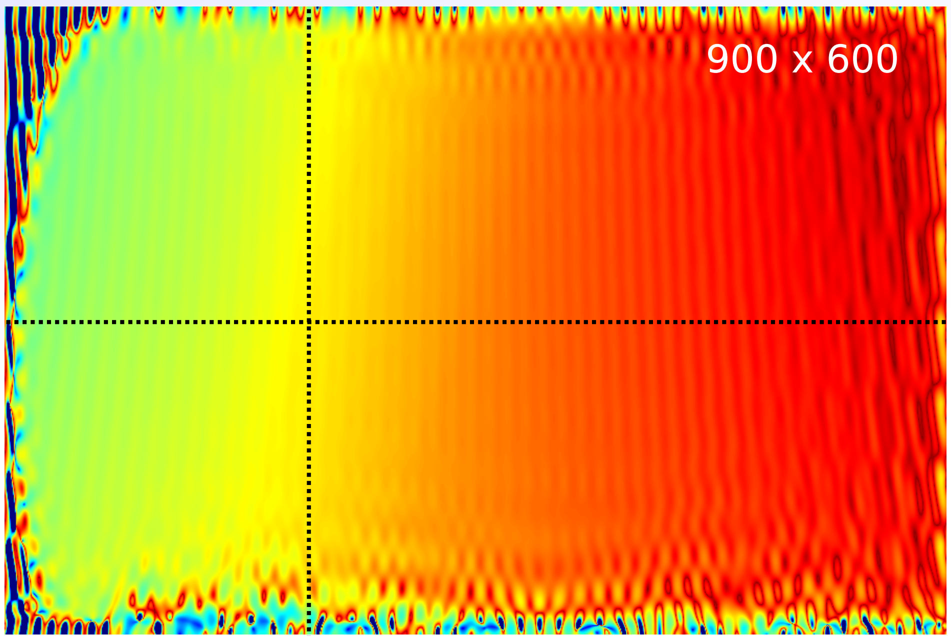

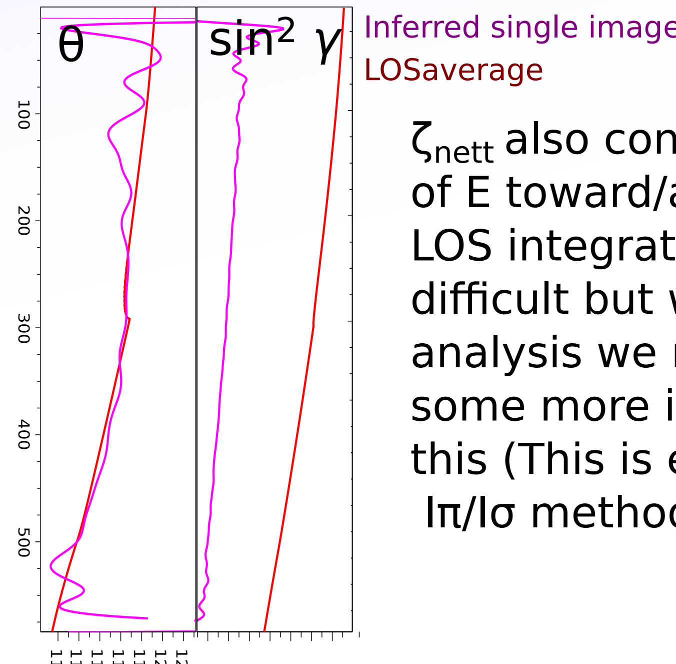

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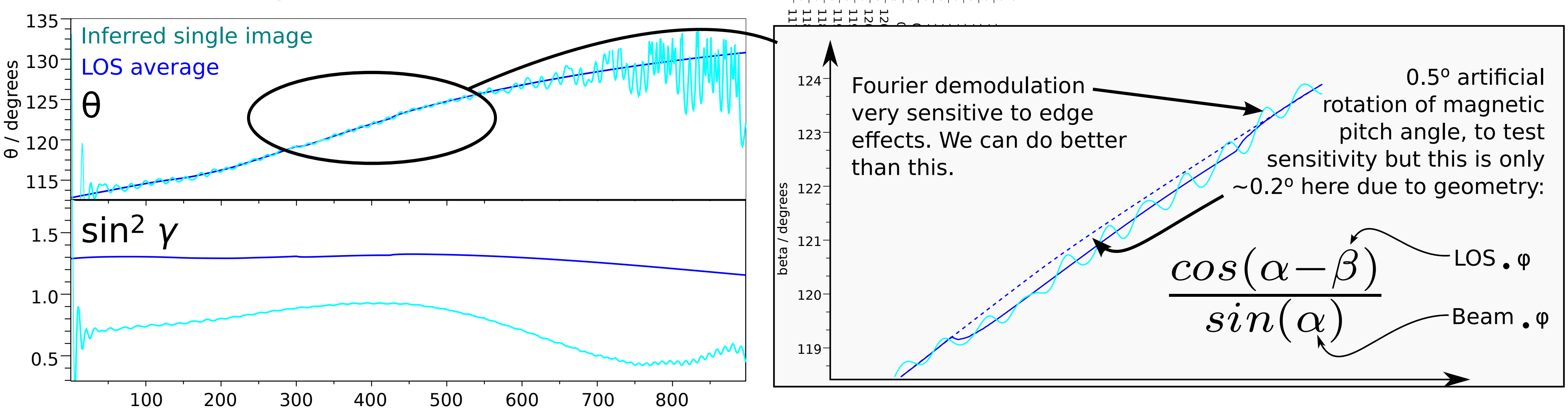
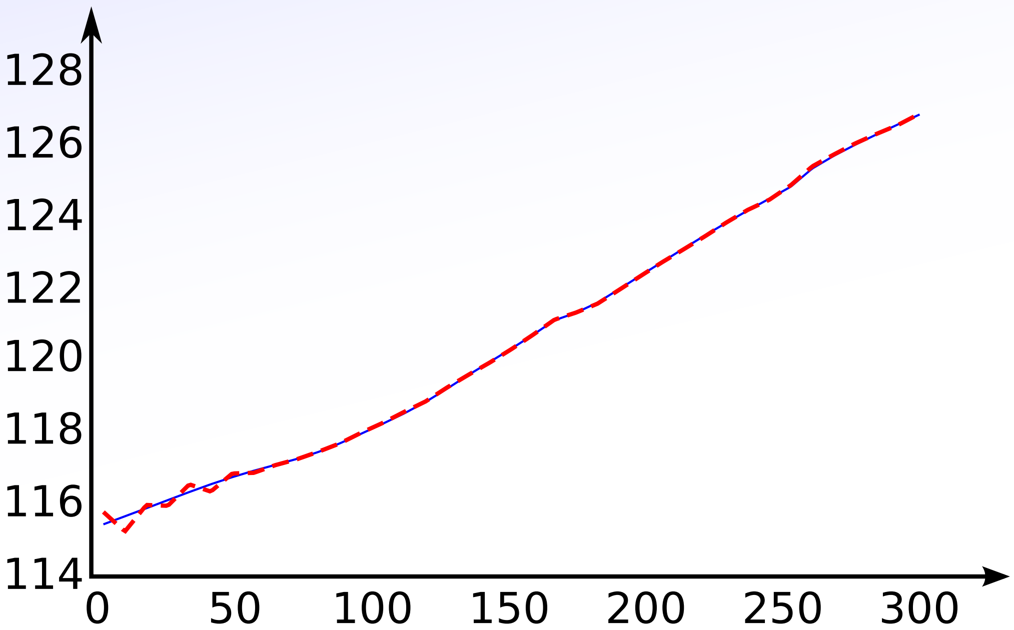


Inference with forward model (Preliminary)

One of the forward modelling/Bayesian techniques (from my PhD work) is very promising.
Will easily handle edge effects, optics/fibre defects, LOS integration etc.



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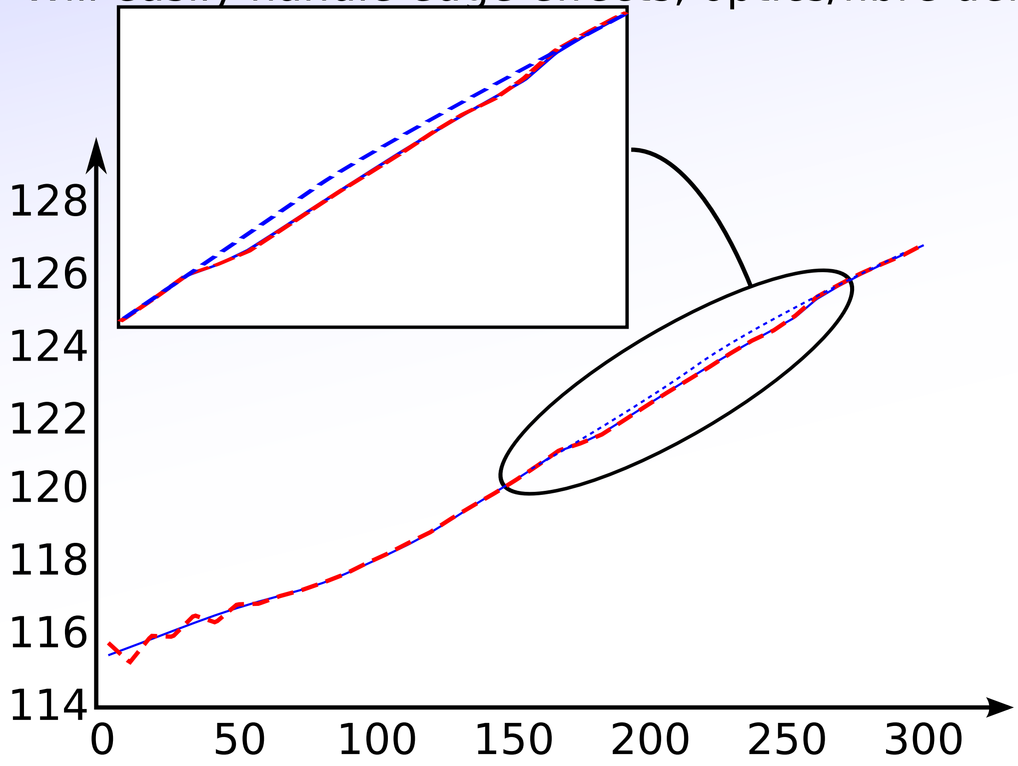

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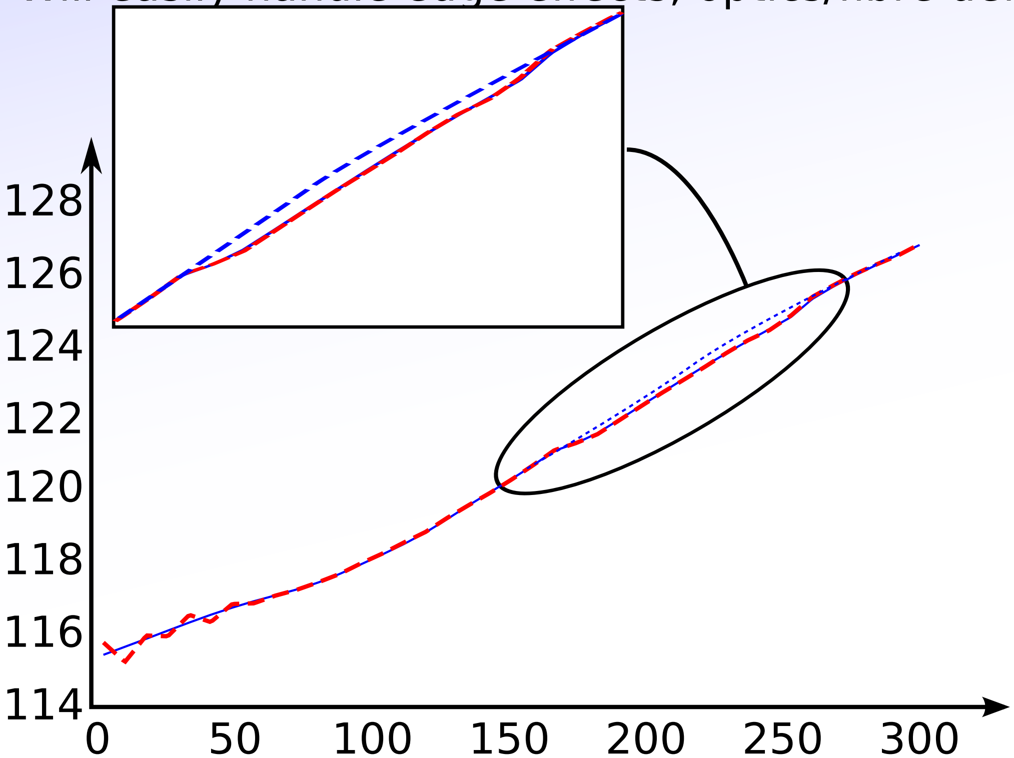

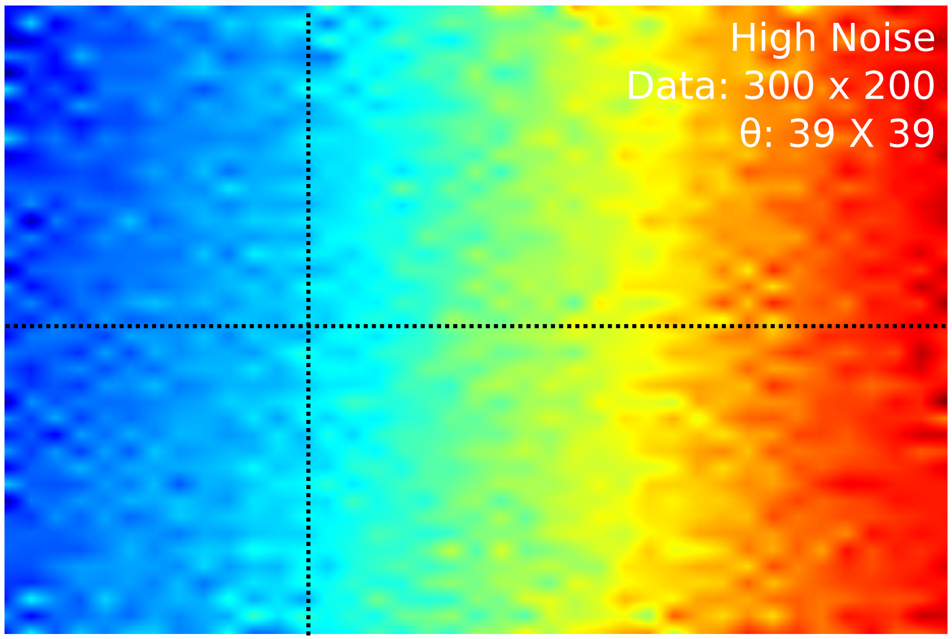

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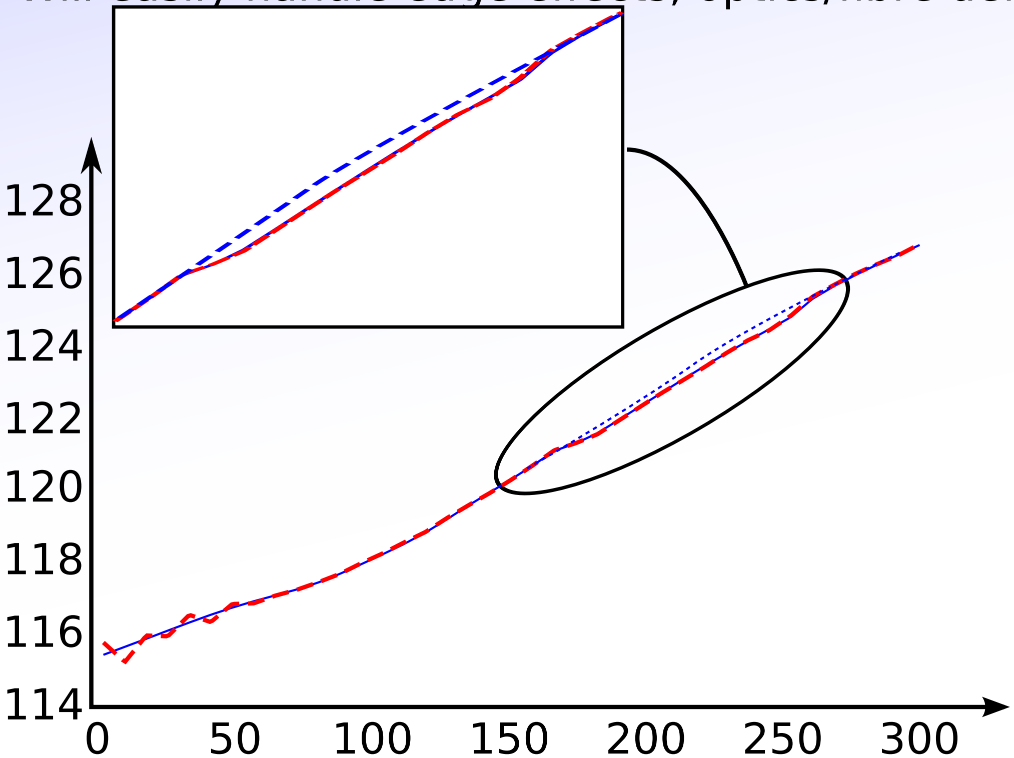

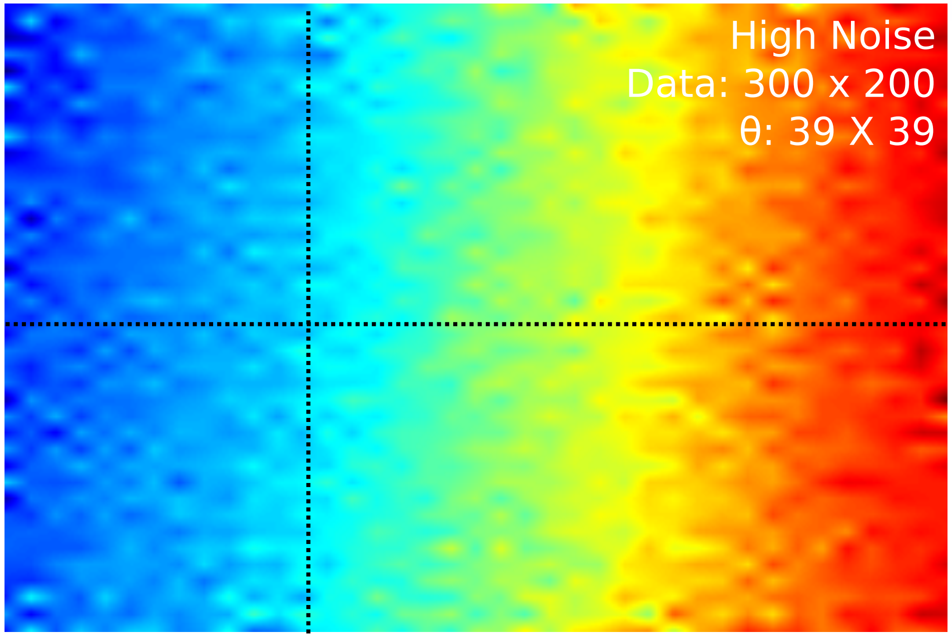

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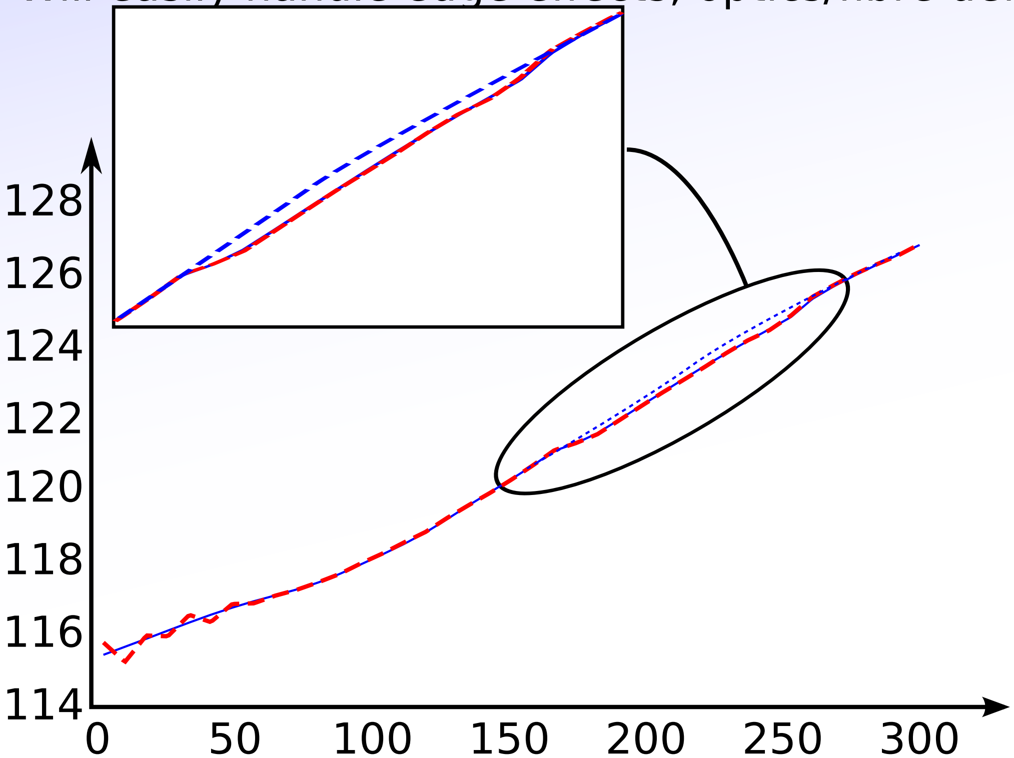

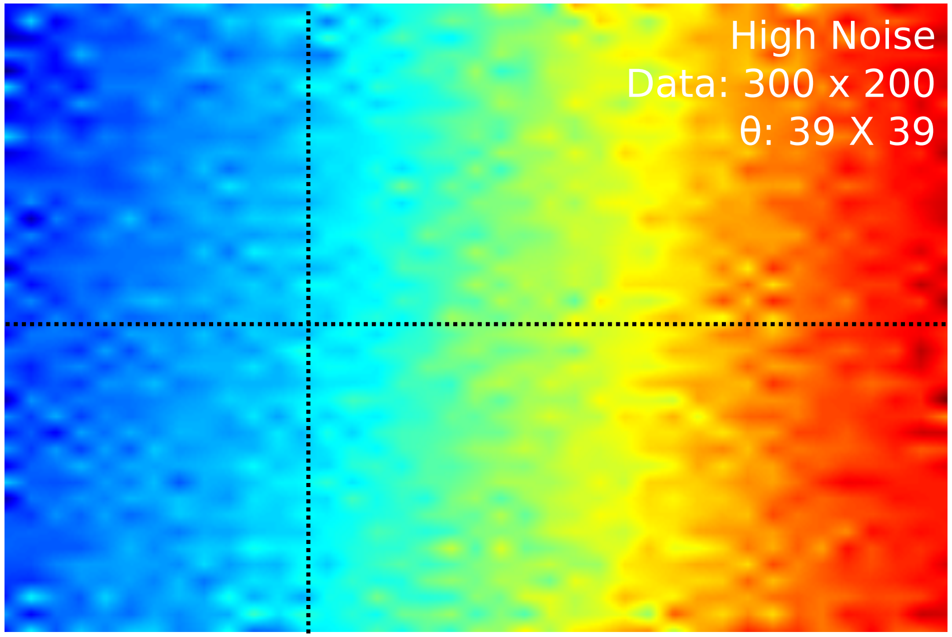

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Needs more development to handle the large images though (we've never had to handle this much data before!)

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The MSE CIS system has many advantages over traditional MSE systems:

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- Complete a systematic study of the accuracy of inferred pitch angle image so we can decide what is best to build.

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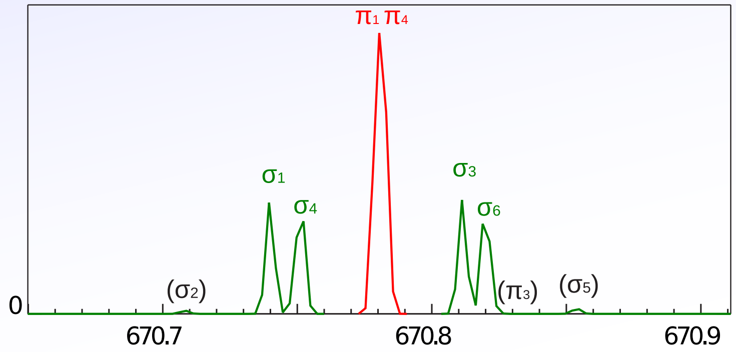

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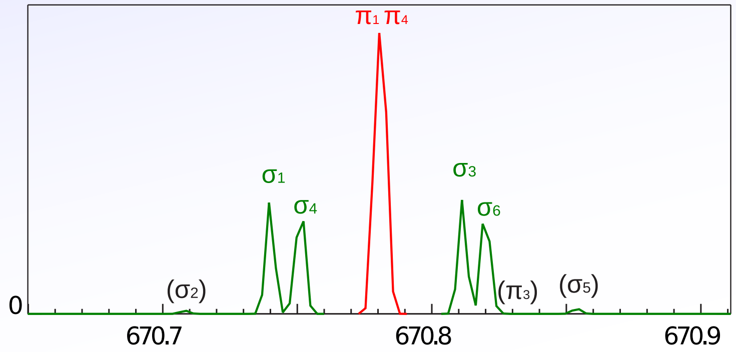

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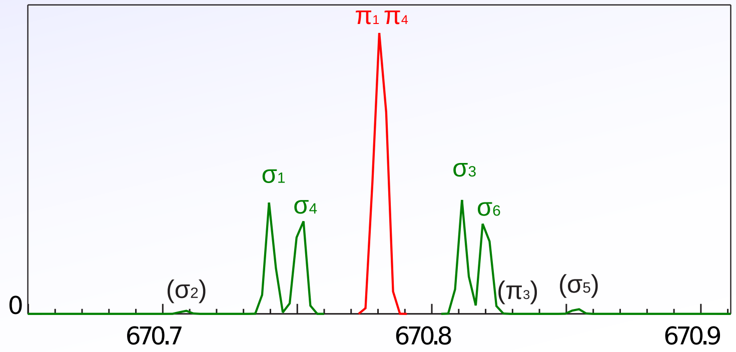

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Modelling work started but the details of Lithium beam (intensity/flux, attenuation model etc) are still needed.

Finally...

We are proposing to design and build a 2D MSE and/or Zeeman coherence imaging system to help improve diagnostic capability at AUG.

This presentation has been of just the modelling work and should give an idea of what these systems are, and what they capable of.

Please tell me if you have any corrections to models and input parameters or if you have any other ideas or concerns. Any input is welcome!

We also want to know what everyone at AUG would want from either system.

Thanks for listening.