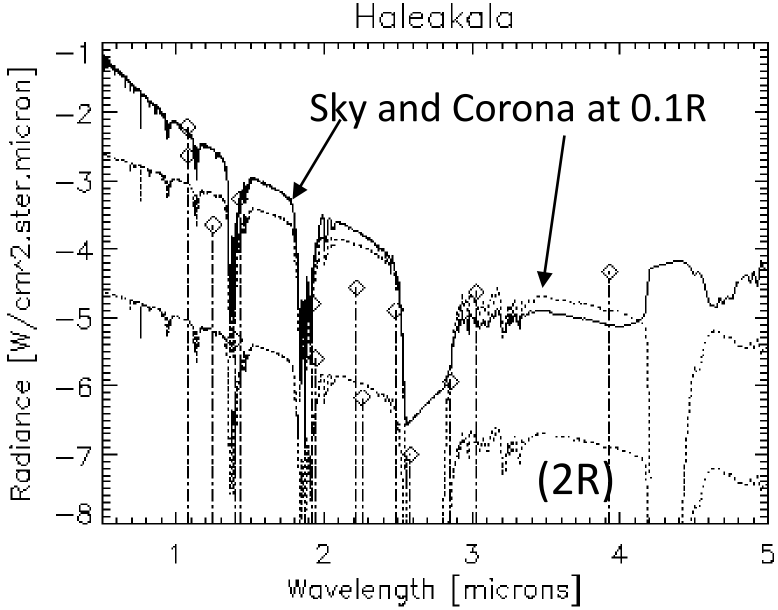
Scattering polarization magnetometry

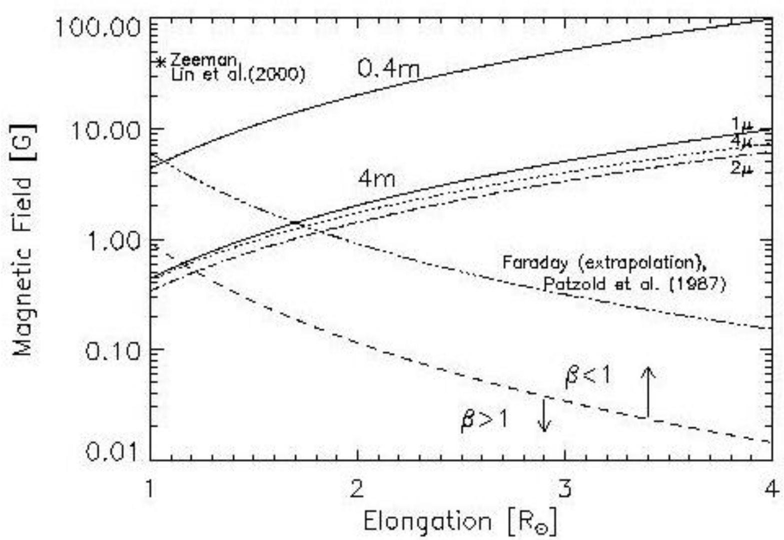
Jeff Kuhn and Gabriel Dima

Coronal IR Wavelengths and benchmark coronal magnetic sensitivity

Wavelength (μm)	Line
0.53	FeXIV
0.637	FeX
0.789	FeXI
1.075	FeXIII
1.083	HeI
1.25	S IX
1.43	Si X
2.218	FeIX
2.326	CO
2.58	SiX
3.028	MgV III
3.93	Si IX
4.651	CO

Temperature sensitivity from 3000K to 3MK

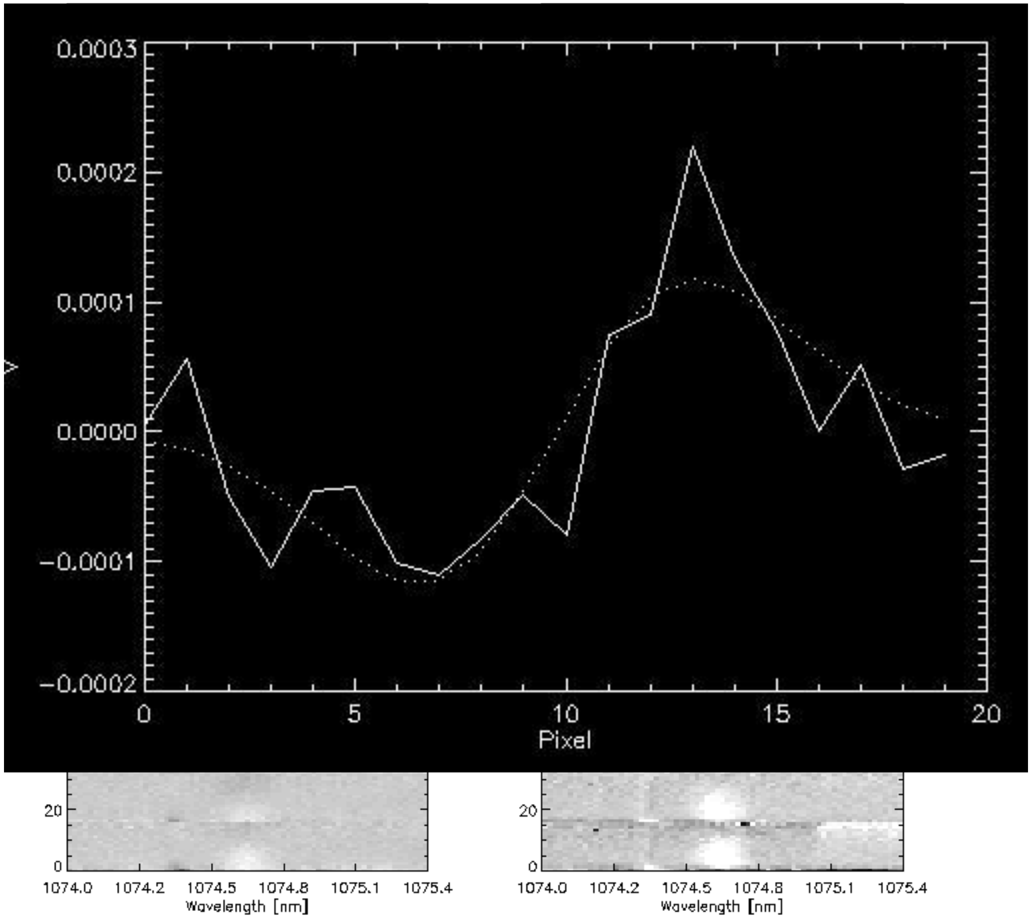




Stokes V: FeXIII IR Coronal Polarimetry

I

Q



B=4.6G

U

V

Measuring Coronal Fields with Zeeman affect and with instrument crosstalk

- Unlike photospheric Zeeman observations, in the corona there is a strong linear polarization signal, and only a weak intrinsic Stokes V signal. Even small U-V cross-talk dominates measured Stokes V
- In weak-field approximation, $V = Bk \cdot dI/d\lambda$, the observed circular polarization can be written as
  - $V'(\lambda) = \alpha \cdot I(\lambda) + Bk \cdot dI(\lambda)/d\lambda = \alpha \cdot I(\lambda + Bk/\alpha)$,
- Thus, *B* can be directly measured by comparison with the shift of *V* with respect to *I* in the spectral direction.

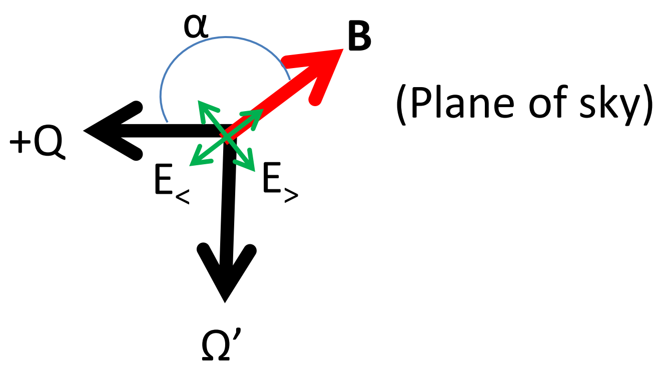
Coronal Hanle Magnetometry

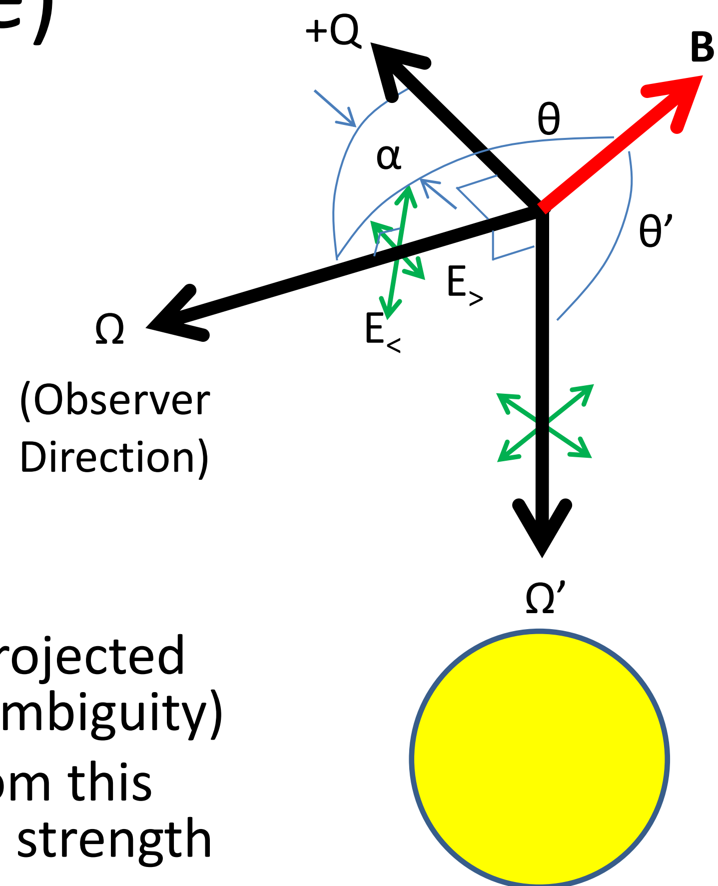
- Requires simultaneous observations of the Hanle linear polarization from two coronal emission lines formed with similar magnetic fields, or from same region
- Requires a forbidden line + permitted line Hanle measurement
- Requires measuring orientation and degree of polarization from both lines
- Recovers direction and strength of local coronal magnetic field

Limiting CHM issues

- Collisional depolarization of the forbidden line may not be known
- The foreground/background line-of-sight contribution to the observables may not be known
- The permitted and forbidden lines may not sample the same local magnetic field

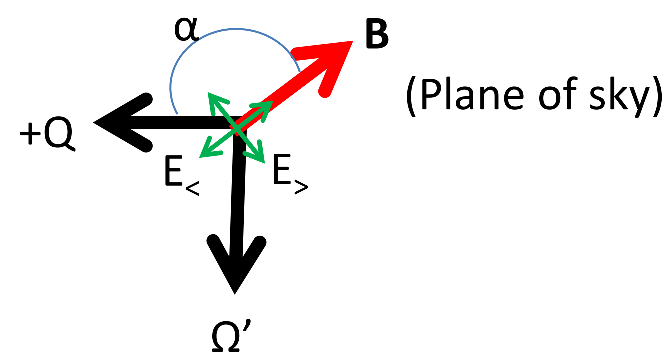
CHM concept sketch (permitted source)





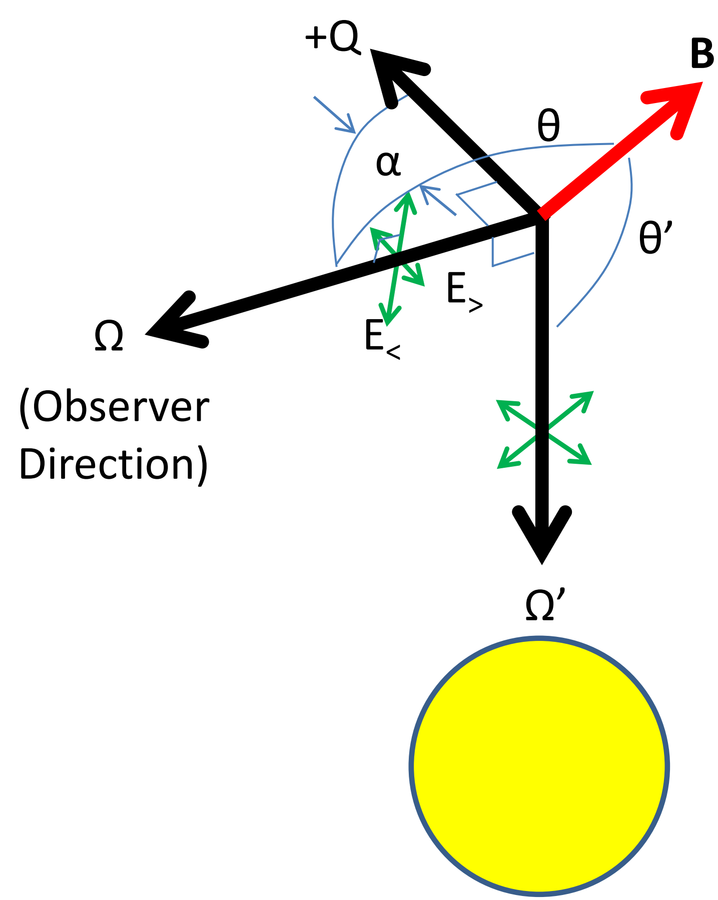
- Forbidden line gives B field direction projected on the sky (modulo 90 deg Van Vleck ambiguity)
- Permitted line polarization deviates from this angle by amount that depends on field strength
- Degree of polarization of both lines encodes the angle B makes out of the plane of the sky
- Saturated Hanle polarization tends to +Q orientation

Forbidden CEL: Classical strong field (saturated) Hanle regime



$$p = \frac{(1-\mu^2)(1-3\mu'^2)}{3-\mu^2-\mu'^2+3\mu^2\mu'^2},$$

$$\mu = \cos\theta, \quad \mu' = \cos\theta'$$



$\mu'^2 < 1/3$:

$$\sin\theta\sin\alpha = \pm\cos\theta' \rightarrow \mu' = \pm\sqrt{1-\mu^2}\sin\alpha$$

$$p(\alpha,\mu) = \frac{1-3\sin^2\alpha-\mu^2+6\mu^2\sin^2\alpha-3\mu^4\sin^2\alpha}{3-\sin^2\alpha-\mu^2+4\mu^2\sin^2\alpha-3\mu^4\sin^2\alpha}$$

$$0 < p < 1/3$$

$\mu'^2 > 1/3$:

$$\sin\theta\cos\alpha = \pm\cos\theta' \rightarrow \mu' = \pm\sqrt{1-\mu^2}\cos\alpha$$

$$p(\alpha,\mu) = \frac{1-3\cos^2\alpha-\mu^2+6\mu^2\cos^2\alpha-3\mu^4\cos^2\alpha}{3-\cos^2\alpha-\mu^2+4\mu^2\cos^2\alpha-3\mu^4\cos^2\alpha}$$

$$-1 < p < 0$$

Permitted CEL:Unsaturated Hanle Regime

0=cosθcosθ’ + sinθsinθ’cosχ

$$\tan\alpha_1 = H,\ \tan\alpha_2 = 2H \quad \mathrm{H{=}0.88\ B/}\gamma\ [\mathrm{G}/10^7 s^{-1}]$$

$$C_1 = \cos\alpha_1 \cos(\alpha_1 + \chi) \qquad \mathrm{S}_1 = \cos\alpha_1 \sin(\alpha_1 + \chi)$$

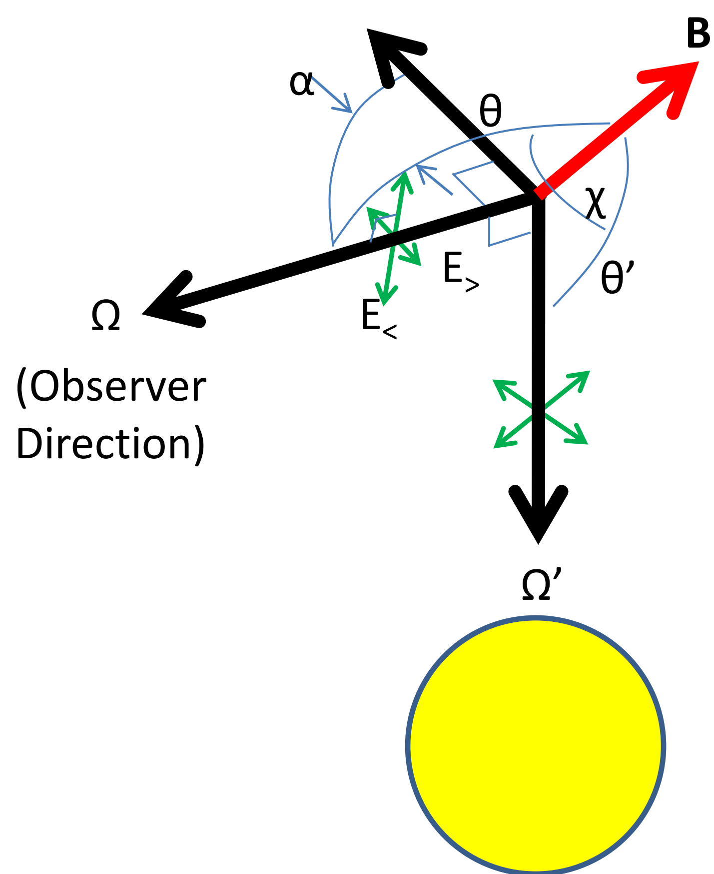
$$C_2 = \cos\alpha_2 \cos(\alpha_2 + 2\chi) \qquad \mathrm{S}_2 = \cos\alpha_2 \sin(\alpha_2 + 2\chi)$$

$$R_{00} = (3/8)(3 - \mu^2 - \mu'^2 + 3\mu^2\mu'^2) + (3/2)C_1\mu\mu'\sqrt{1-\mu^2}\sqrt{1-\mu'^2}$$
$$+(3/8)\mathrm{C}_2(1\text{-}\mu^2)(1-\mu'^2)$$

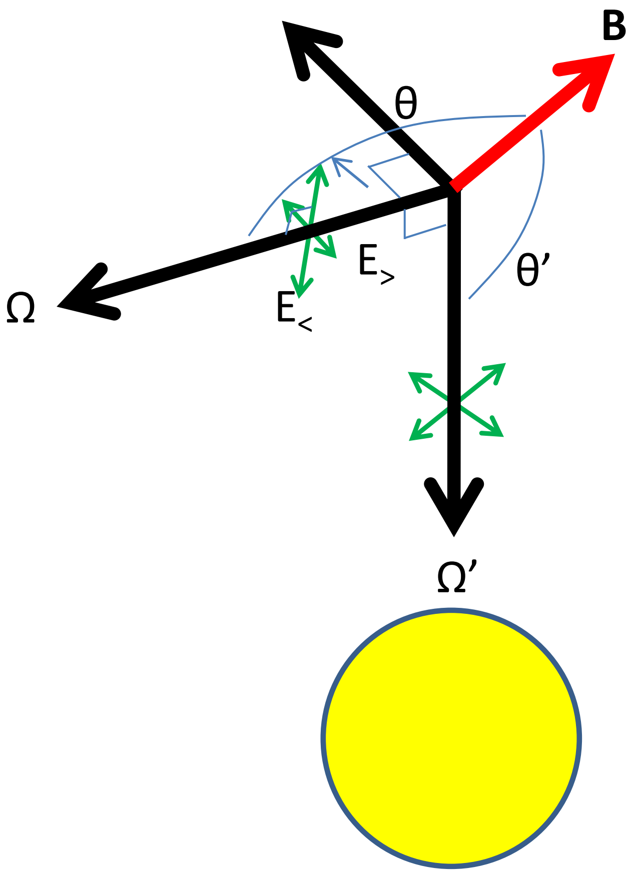
$$R_{10} = (3/8)(1-\mu^2)(1-3\mu'^2) + (3/2)C_1\mu\mu'\sqrt{1-\mu^2}\sqrt{1-\mu'^2}$$
$$-\ (3/8)\mathrm{C}_2(1+\mu^2)(1-\mu'^2)$$

$$R_{20} = (3/2)S_1\mu'\sqrt{1-\mu^2}\sqrt{1-\mu'^2} - (3/4)S_2\mu(1\text{-}\mu'^2)$$

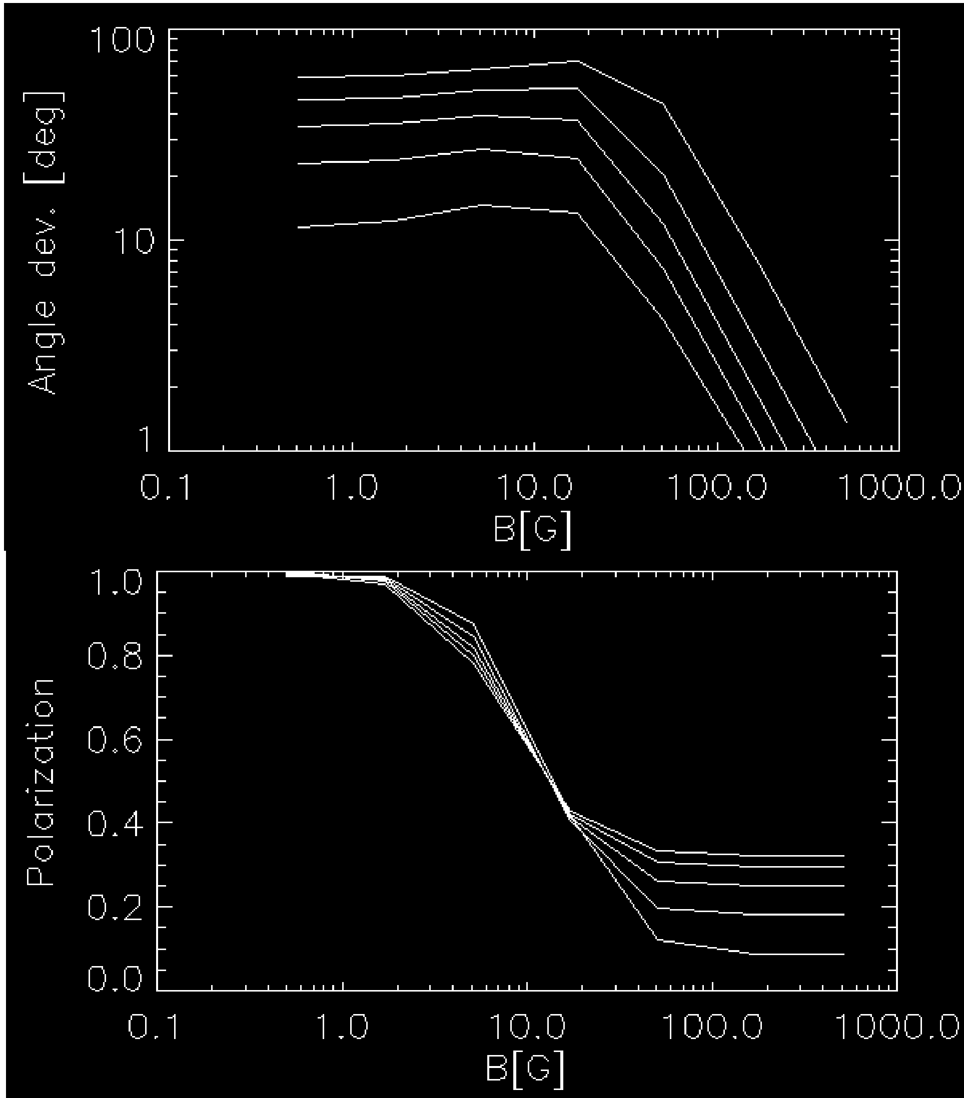
*E.L.Chpt*5



Example: He I 1083
HeI Polarization angle deviation from Si X



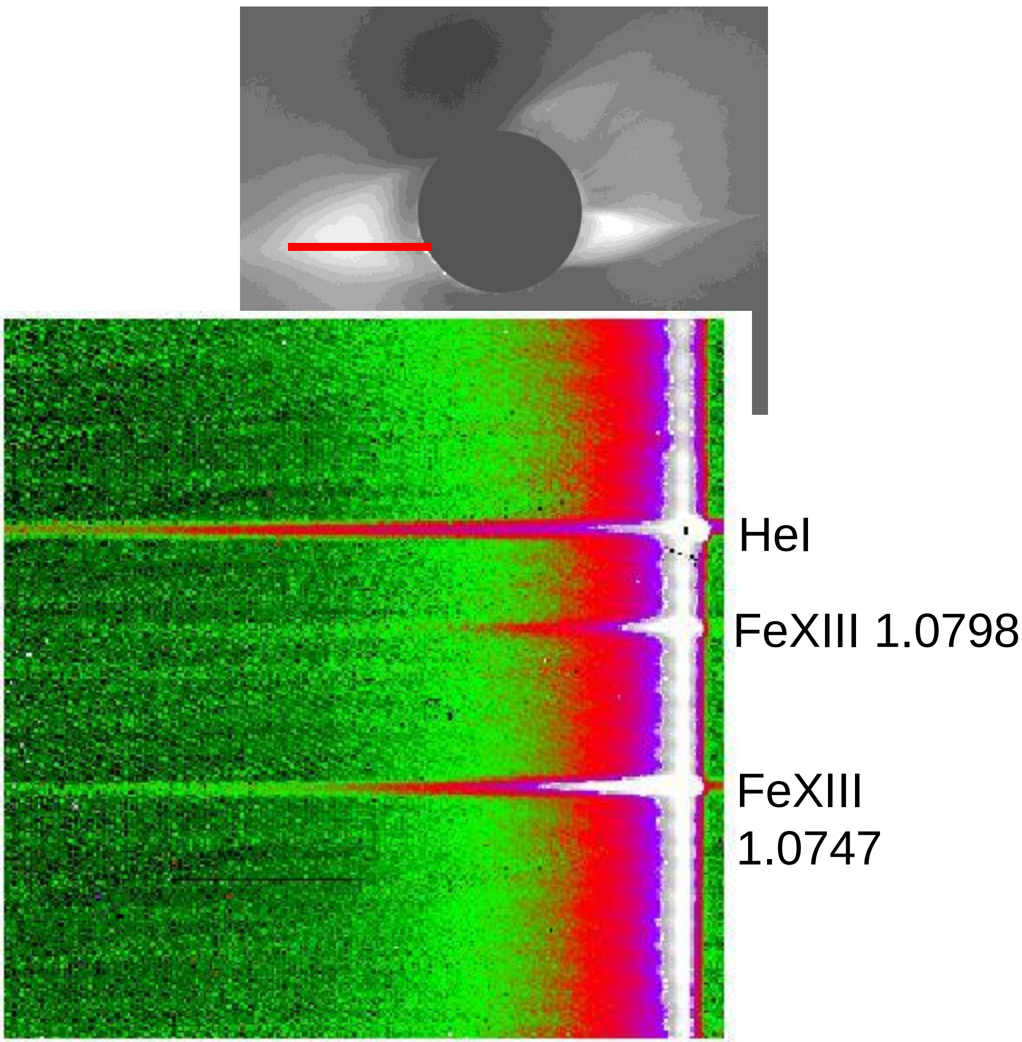
μ=0.1
0.1< μ'<0.6

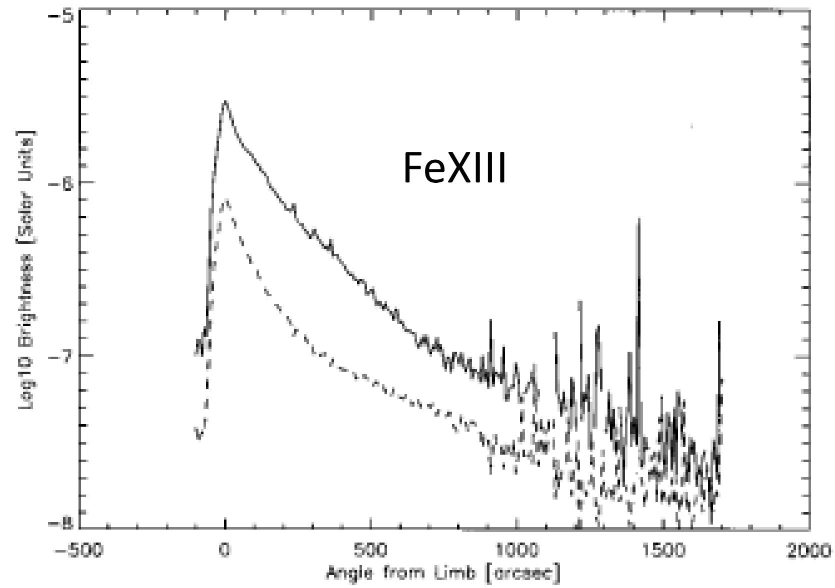


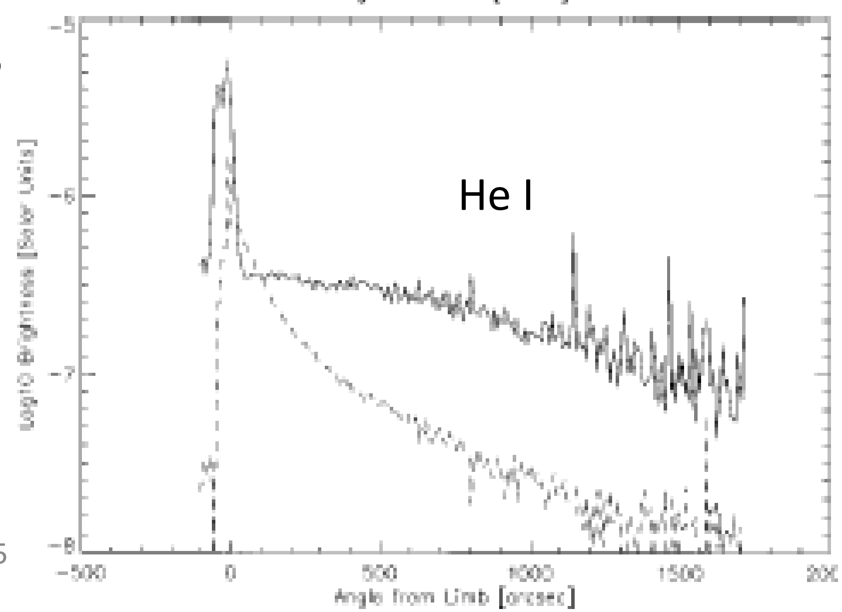
Classical Hanle Notes

- $B > B_{crit}$:
  - polarization angle deviation is small
  - Polarization strength encodes B geometry
- $B < B_{crit}$
  - B orientation and B strength are encoded in polarization degree and angle
  - Polarization angle deviation is large

Coronal Helium

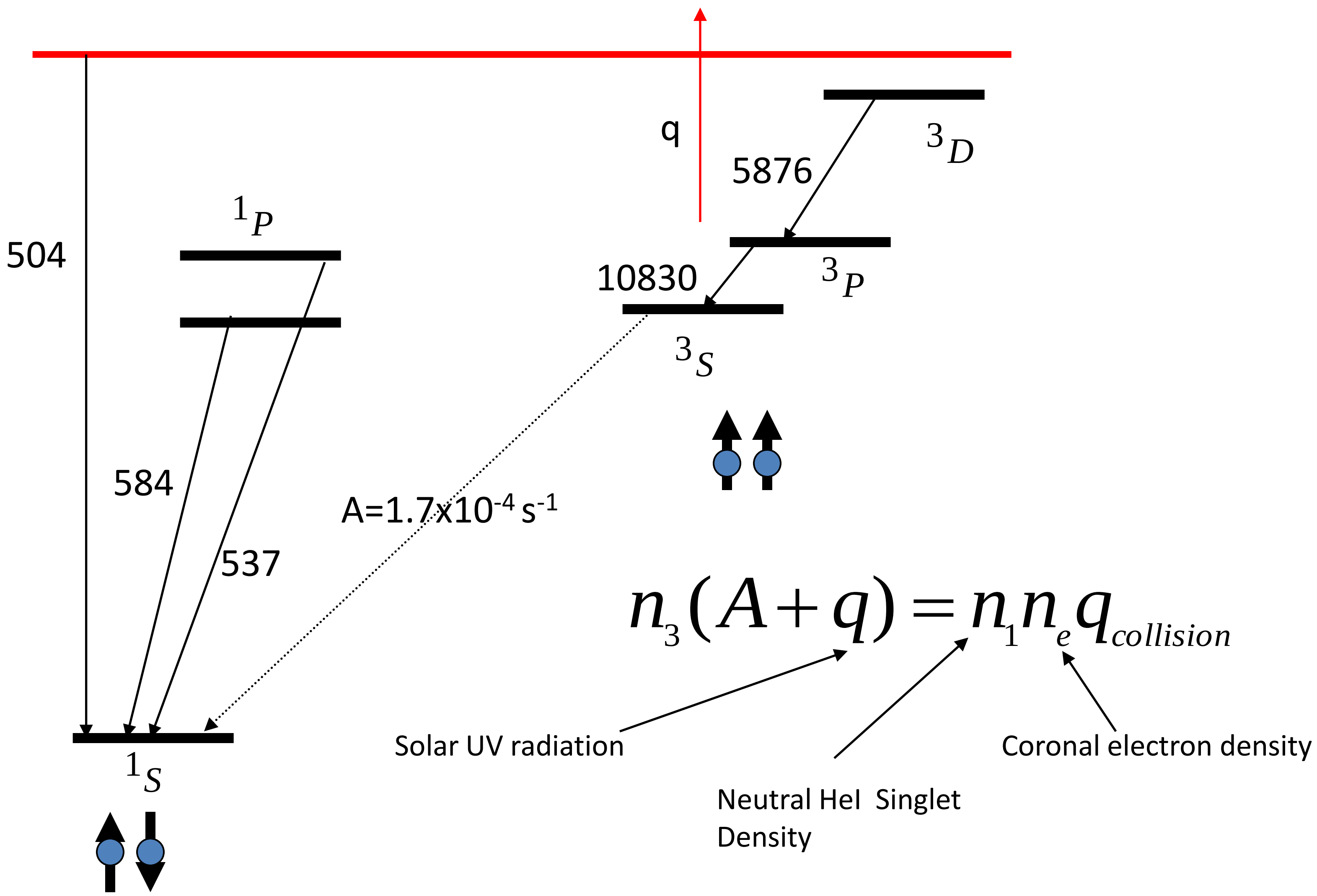






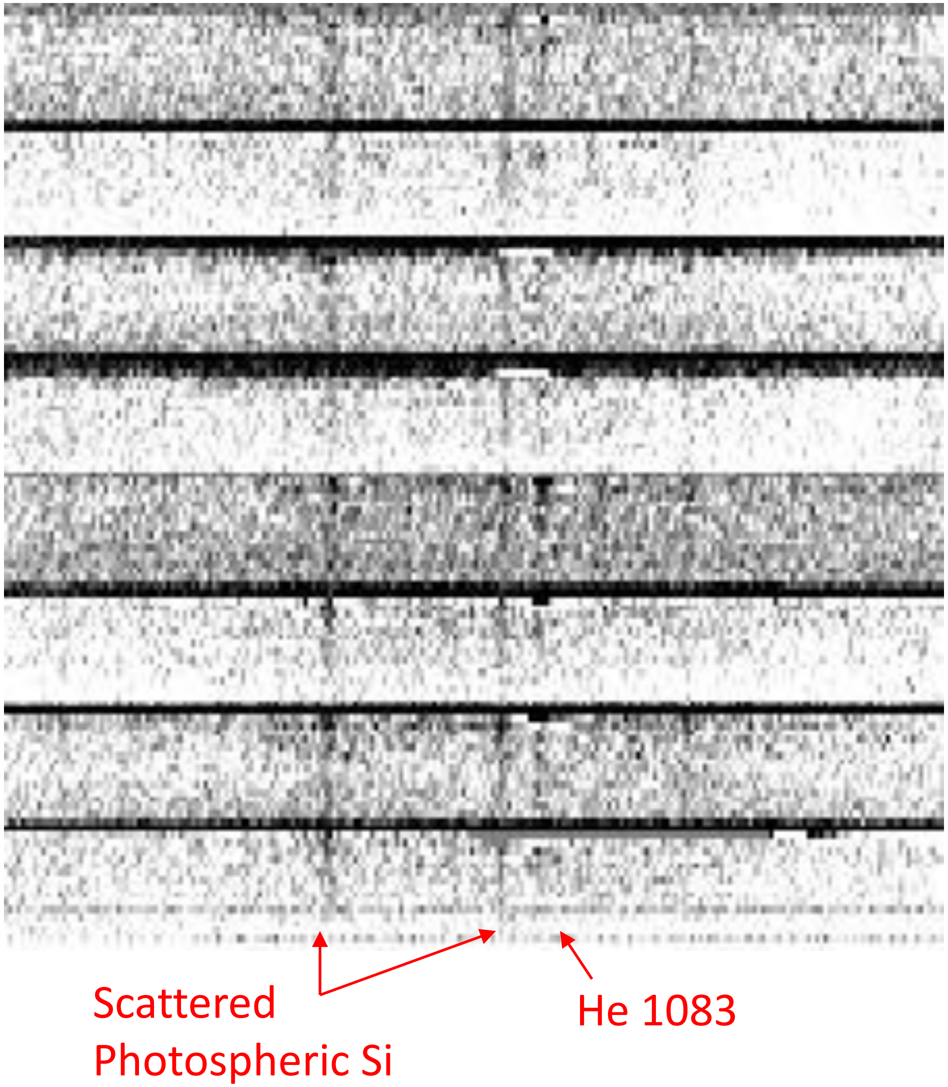
(Kuhn, Penn, and Mann 1996)

Helium



$$n_3(A+q) = n_1 n_e q_{collision}$$

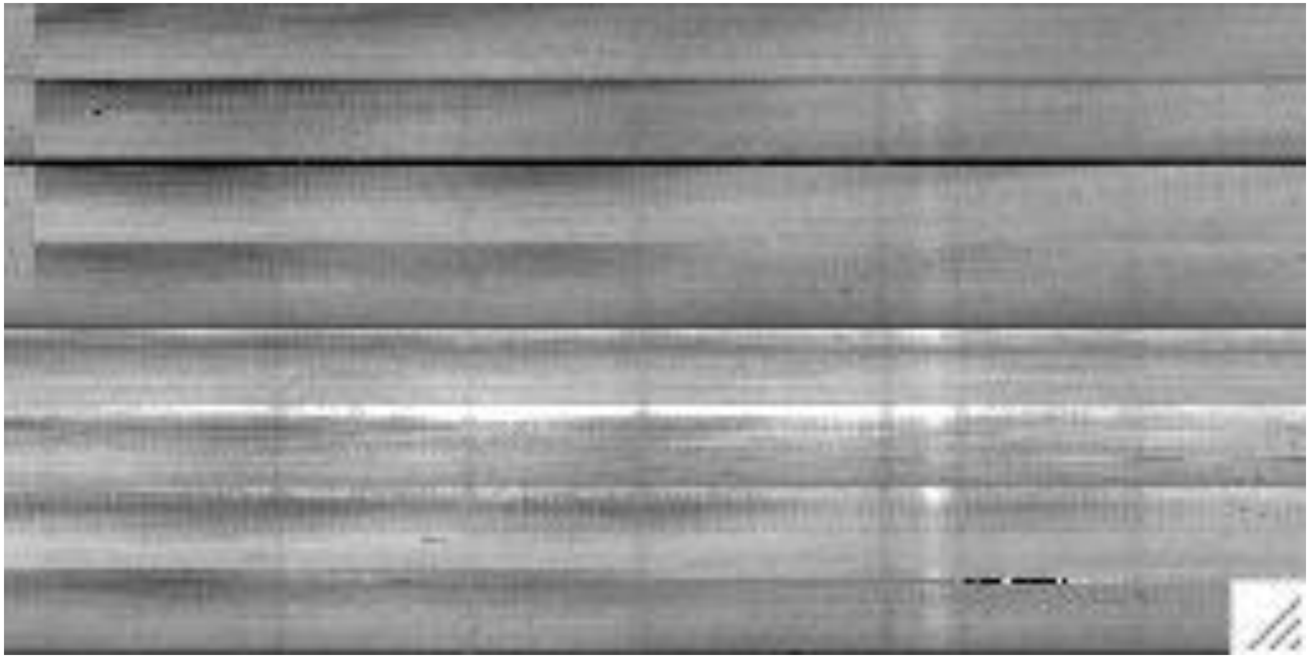
SOLARC imaging spectropolarimeter: limb, Q



Q>0 →perpendicular polarization to limb

Cool He 0.25R from solar limb

- Stokes Q: Near Pole, Feb. 15, 2007



Dusty plasma, Neutral He formation

(Moise, Raymond, Kuhn 2011)

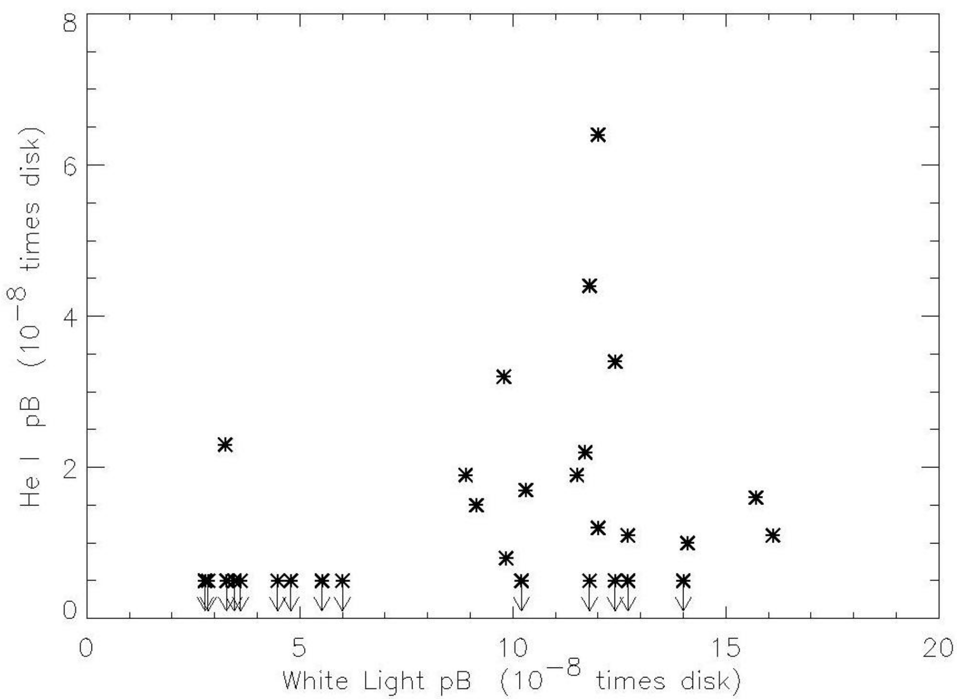
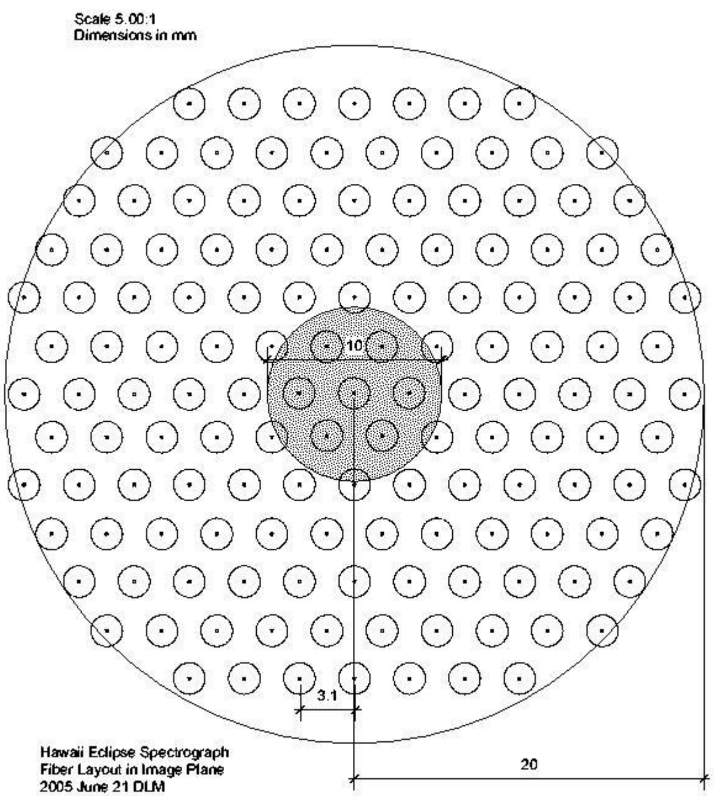
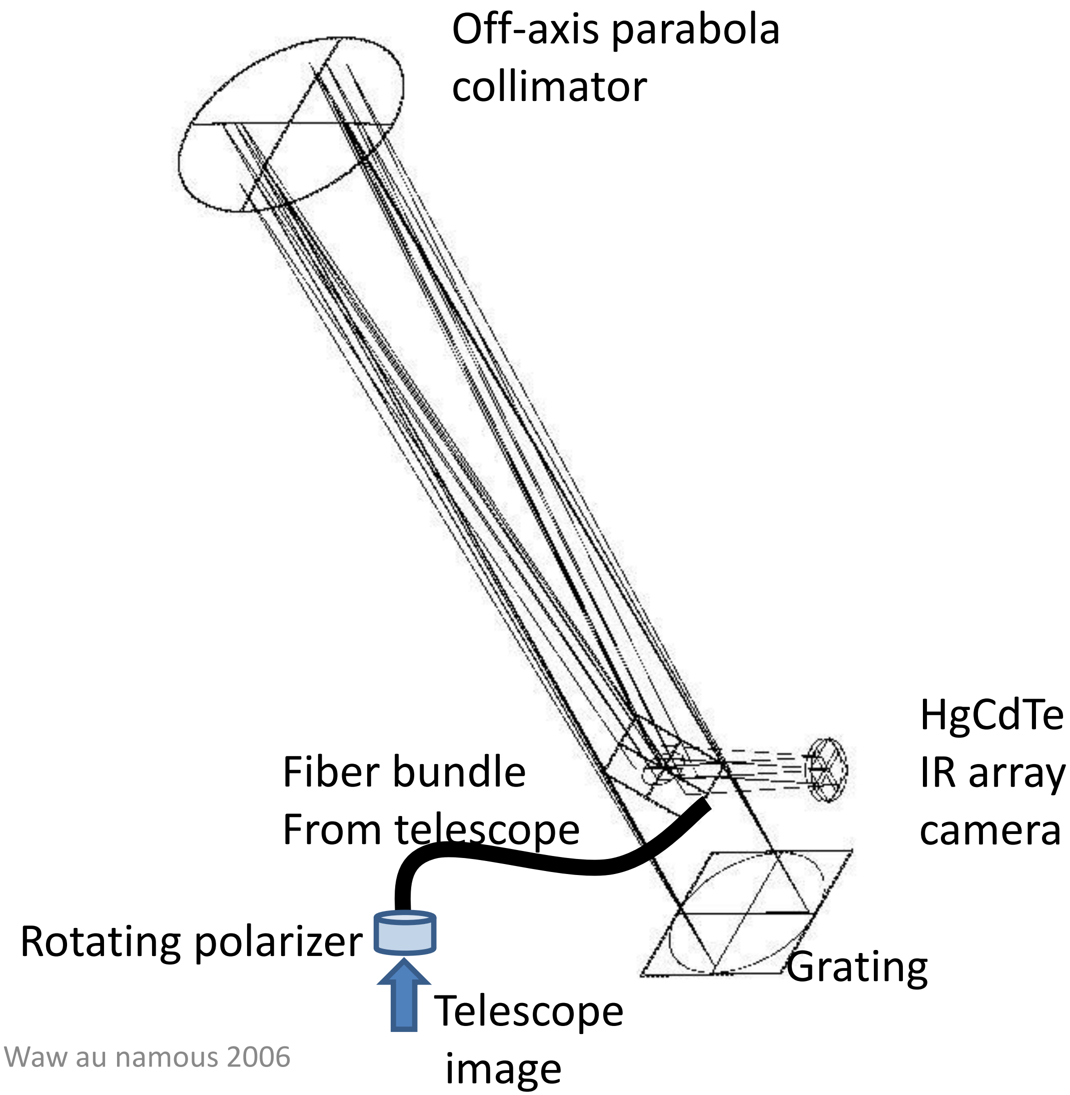


Fig. 3.— The polarized brightness in He I 1083.0nm plotted against the white light polarized brightness from MLSO. Non-detections are plotted as upper limits at 0.5×10^{-8} times the disk intensity.

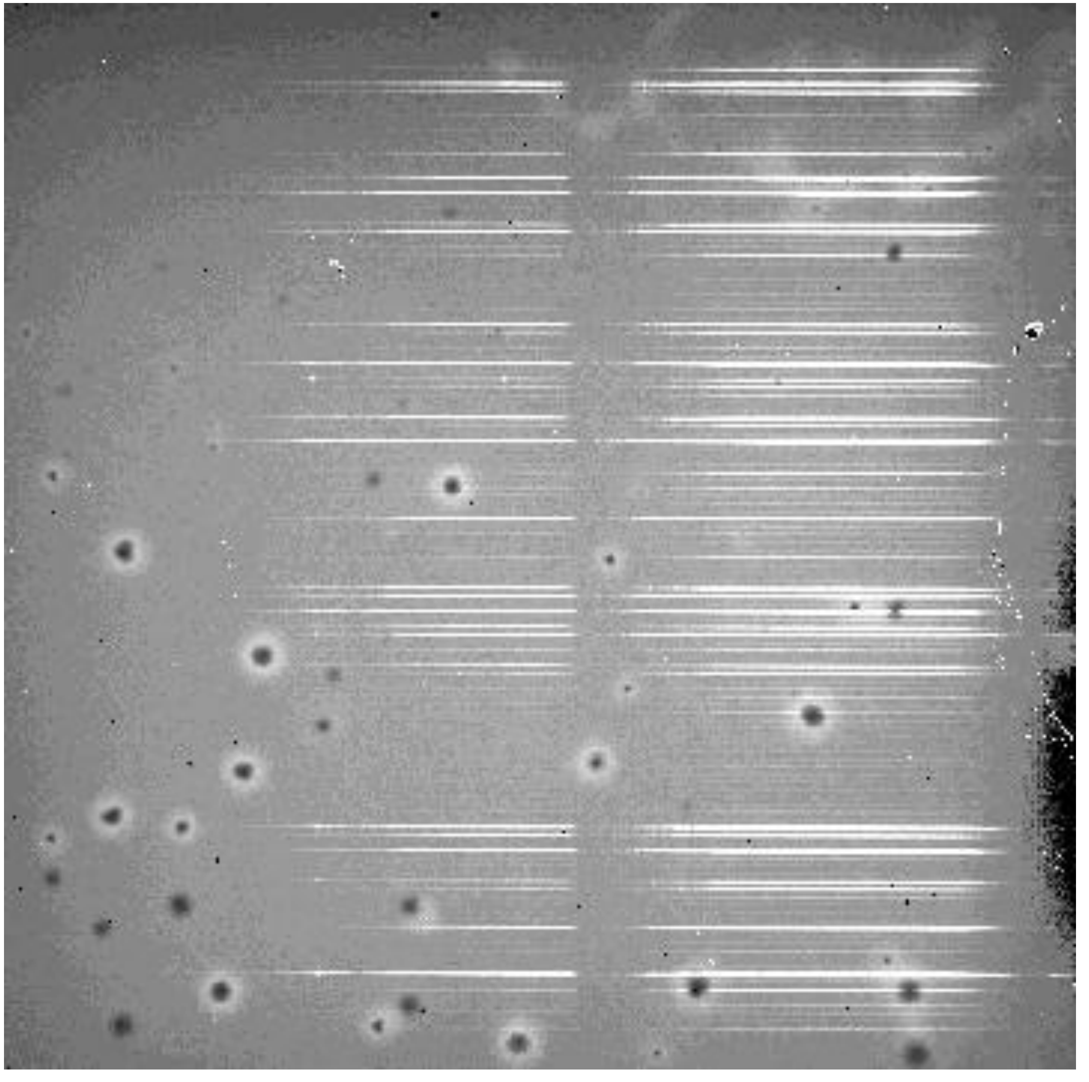
2006 Libya: Eclipse Imaging Spectropolarimeter





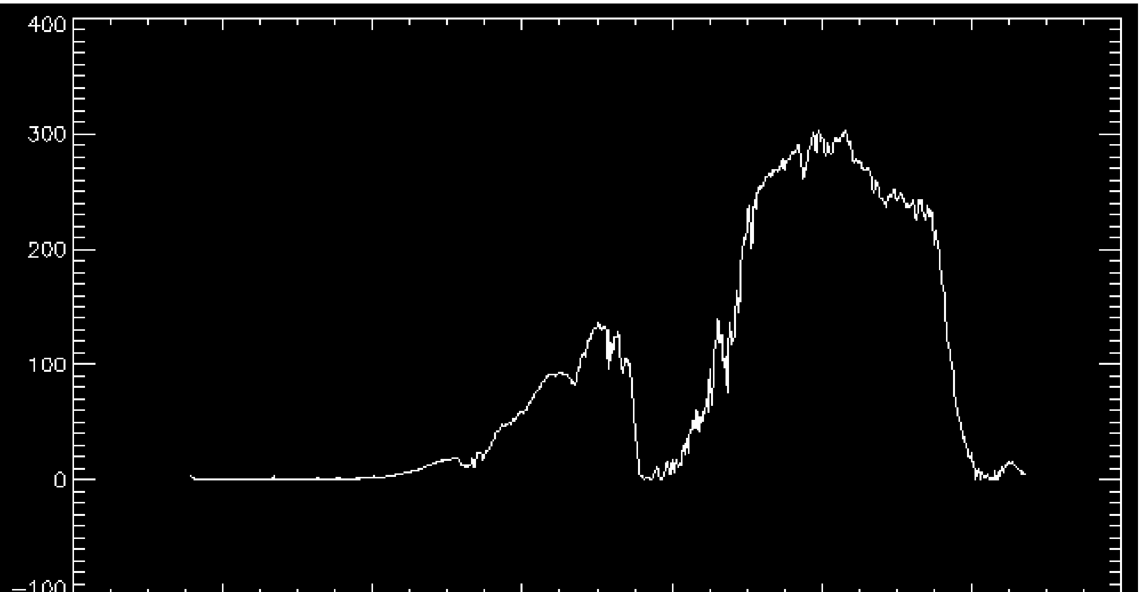
Waw au namous 2006

Raw IR, polarized fiber spectra

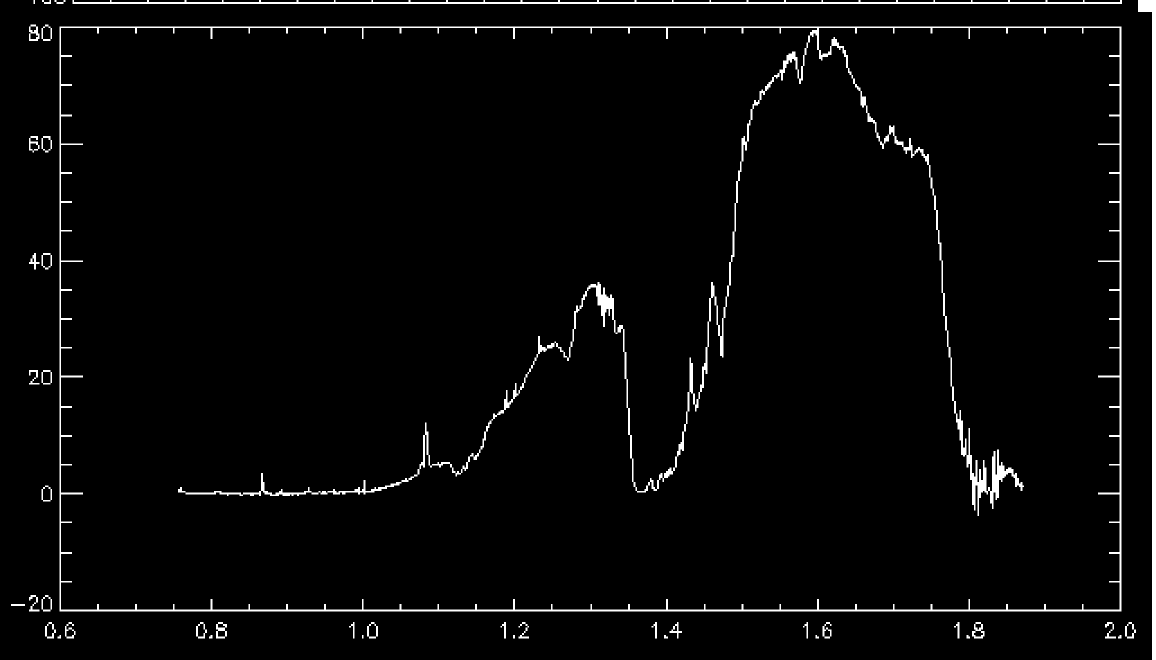


λ →

Summed corona and sky spectra

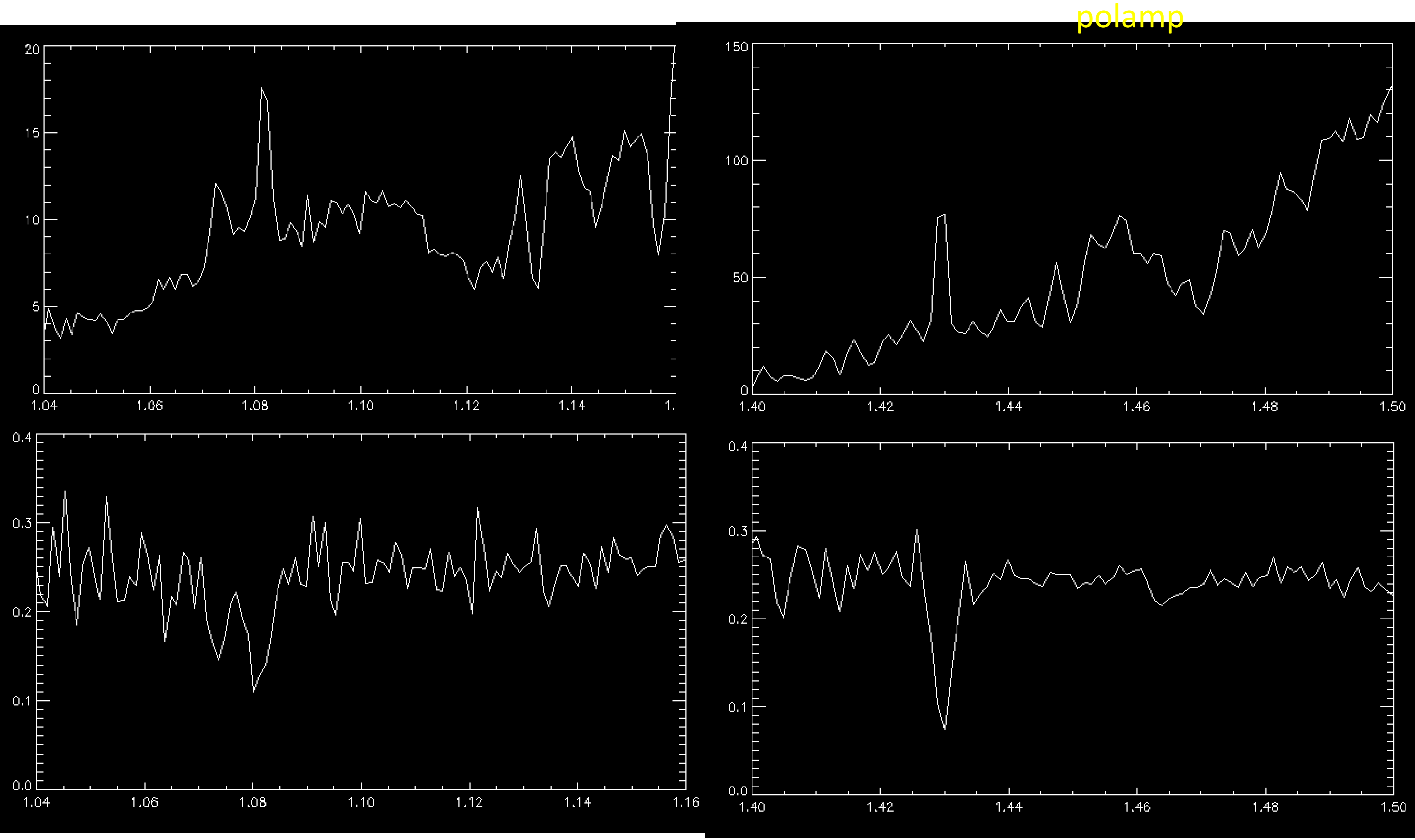


Sky: avespec,spskfix,srefsk,r,1.,2.
IDL> plot,lam,srefsk

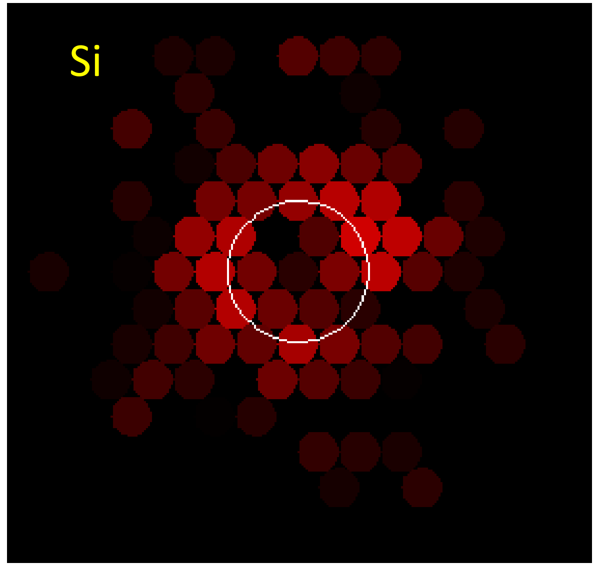


Corona: avespec,spav,sref,r,1.,2.
IDL> plot,lam,sref

Spectra and Hanle depolarization



Si X is strongest coronal line



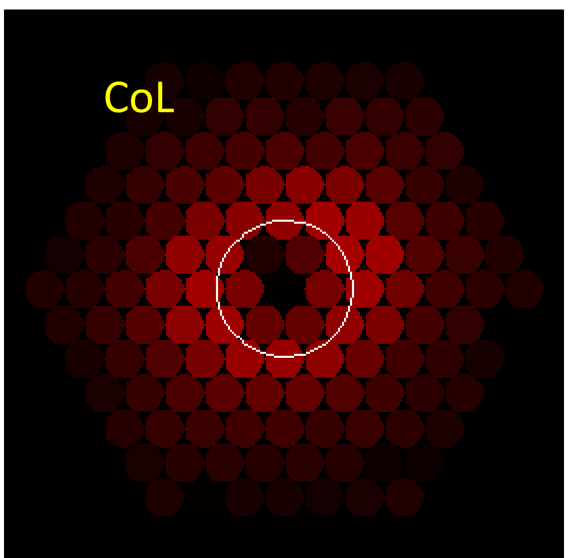
ii = bytscl(alog10(pvec(*,11)),-1,0)

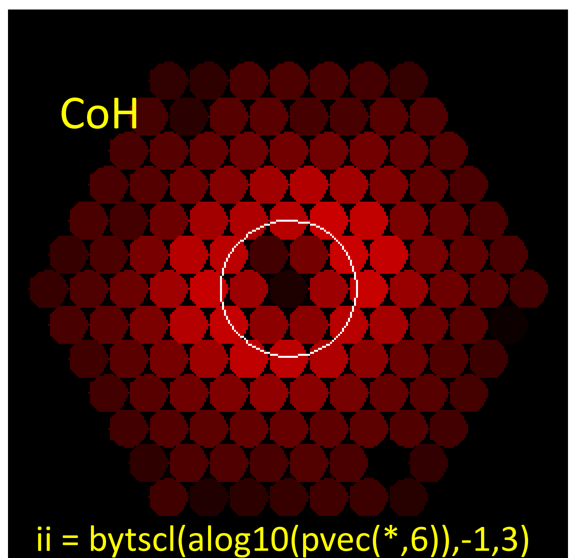
ii = bytscl(alog10(pvec(*,3)),-1,3)

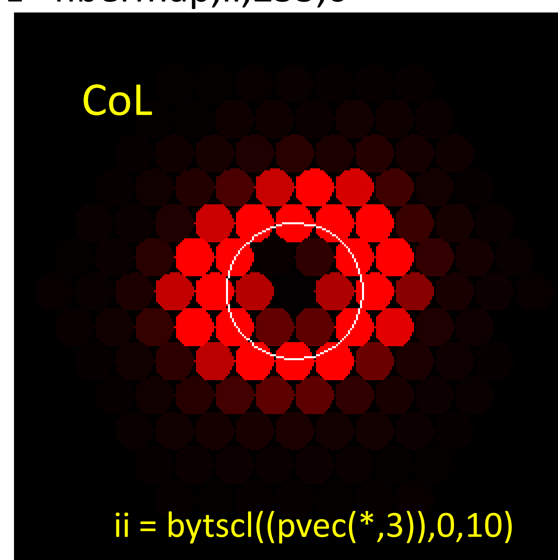
ii = bytscl(alog10(pvec(*,10)),-1,0)

ii = bytscl(alog10(pvec(*,12)),-1,2)

IDL> fibermap,ii,255,0



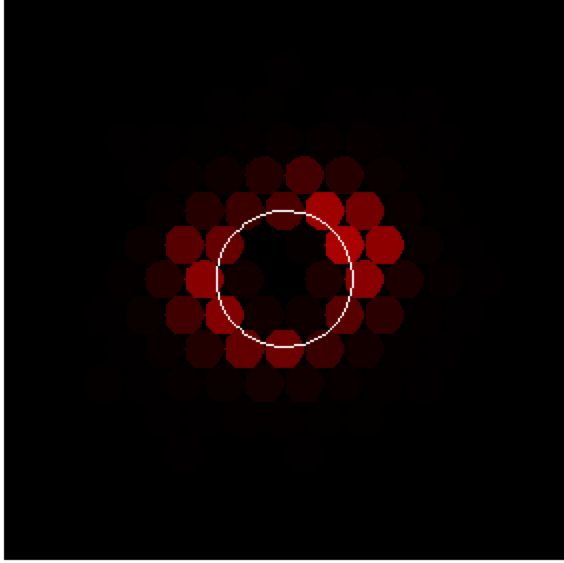




Line intensities, linear scale

Use
```
getline,lam,spsk,spmean,xl,xlc,spline,scont
Ints = reform(scont(*,0,1))
Fibermap,ints,20,0
```

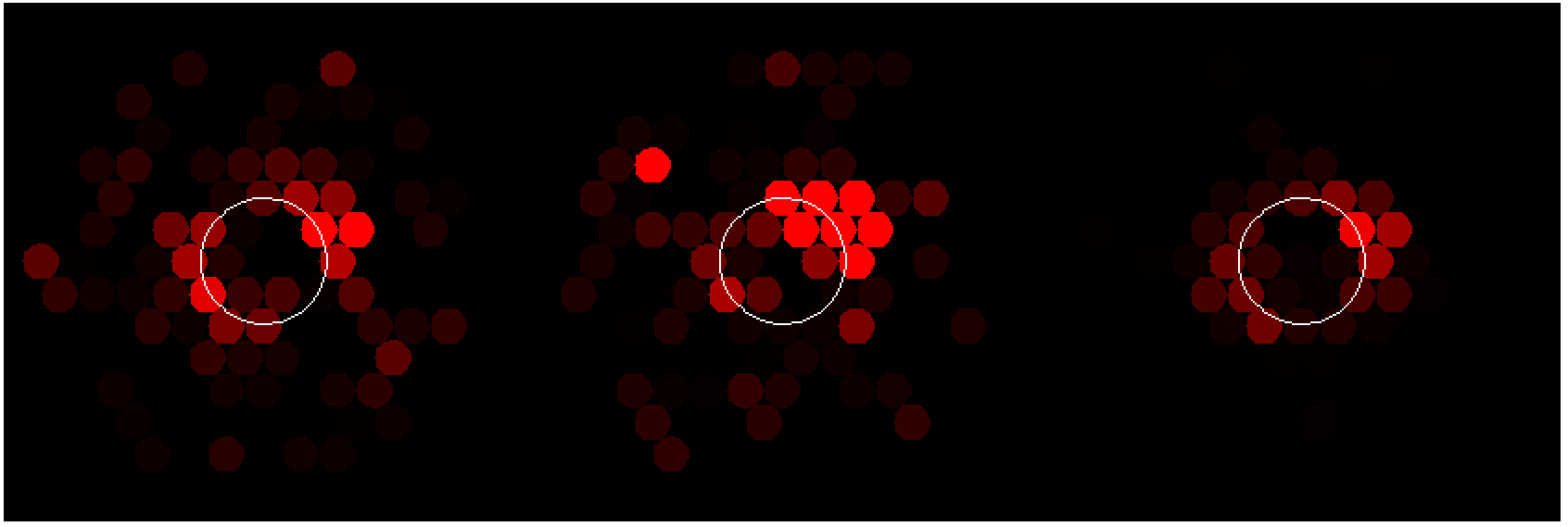
Cont



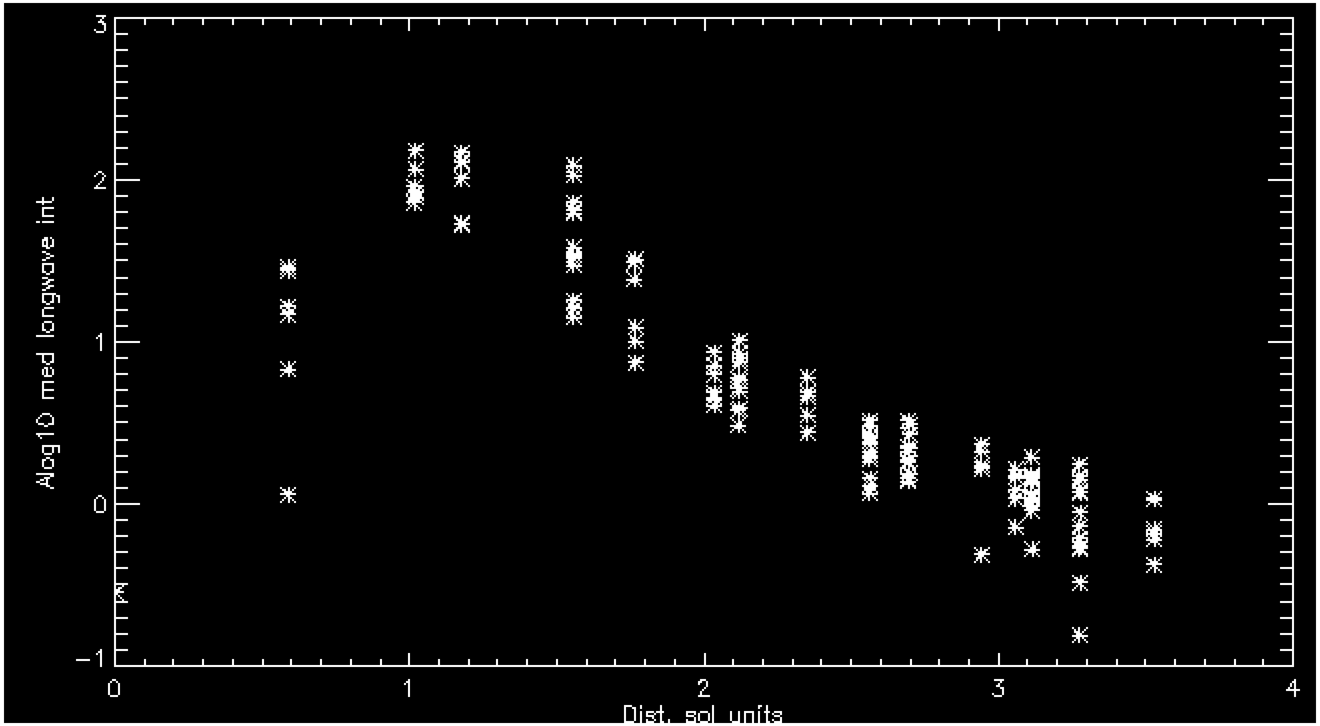
He

Fe

Si

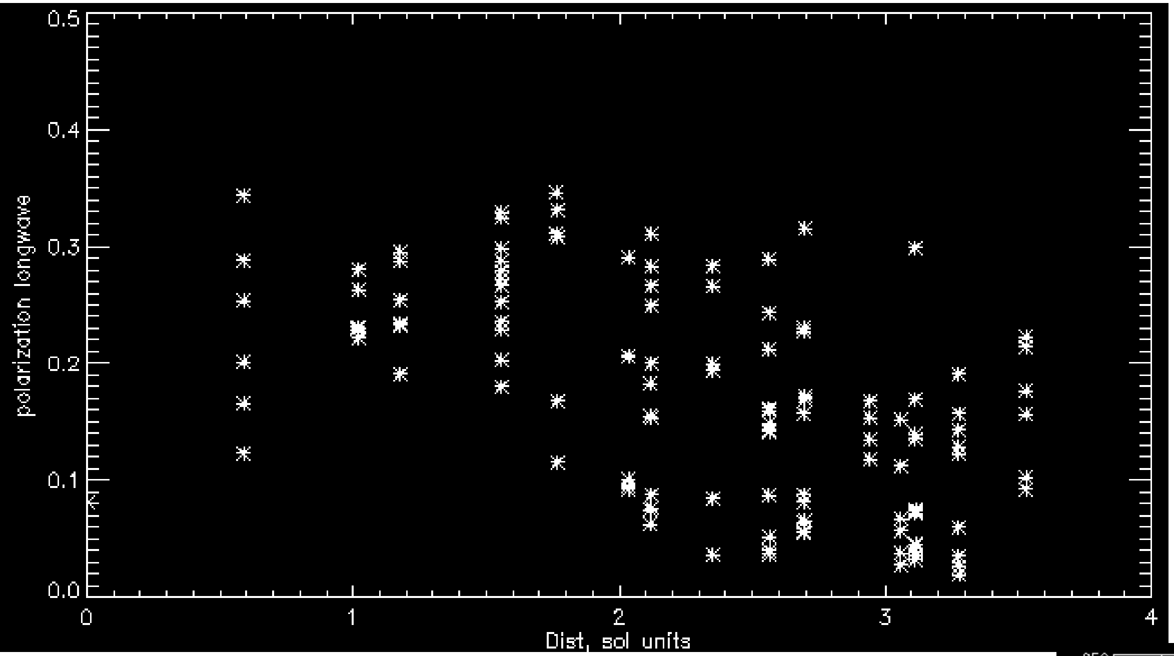


Longwave bright vs. distance



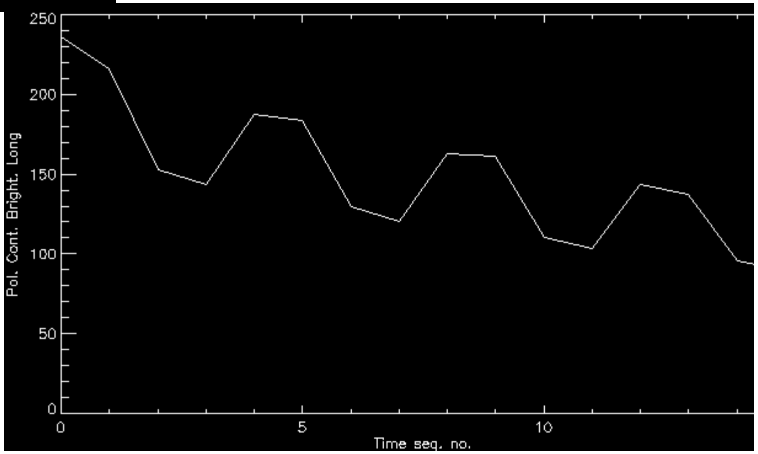
plot,r,alog10(pvec(*,6)),psym=2,xtit='Dist, sol units',ytit='Alog10 med longwave int'

Polarization vs. fiber distance



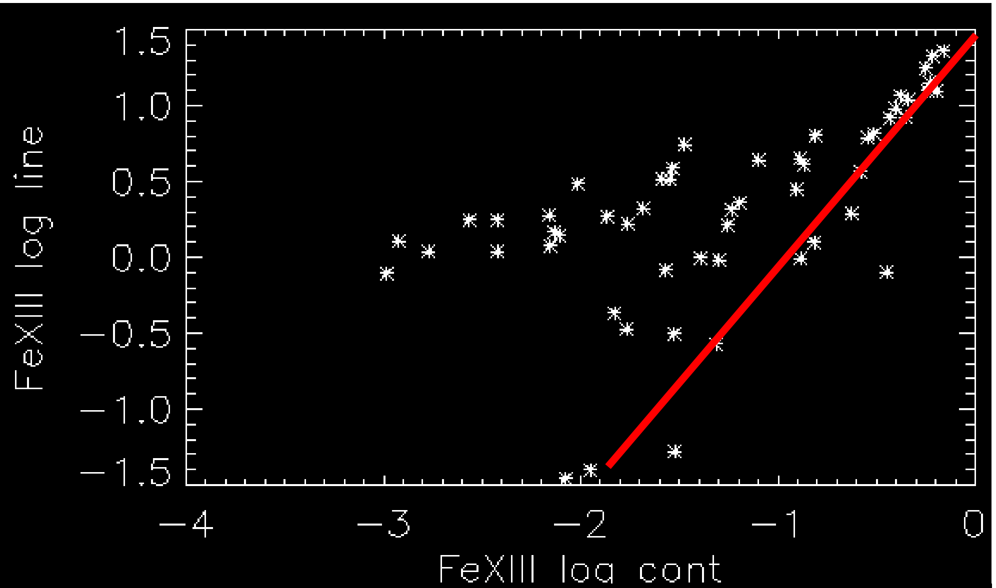
plot,r,(pvec(*,7)),psym=2,
xtit='Dist, sol units',
ytit='polarization longwave',
yr=[0,.5]

```
phs = !pi*findgen(nphs)/2.
one = phs
one(*) = 1./float(nphs)
cphs = cos(phs)/(nphs/2.)
sphs = sin(phs)/(nphs/2.)
   ii = total(vec*one)
   uu = total(vec*cphs)
   qq = total(vec*sphs)
   pvec(ifb,oprm+1) = sqrt(qq*qq+uu*uu)/ii
   pvec(ifb,oprm+2) = atan(uu,qq)/2.
```



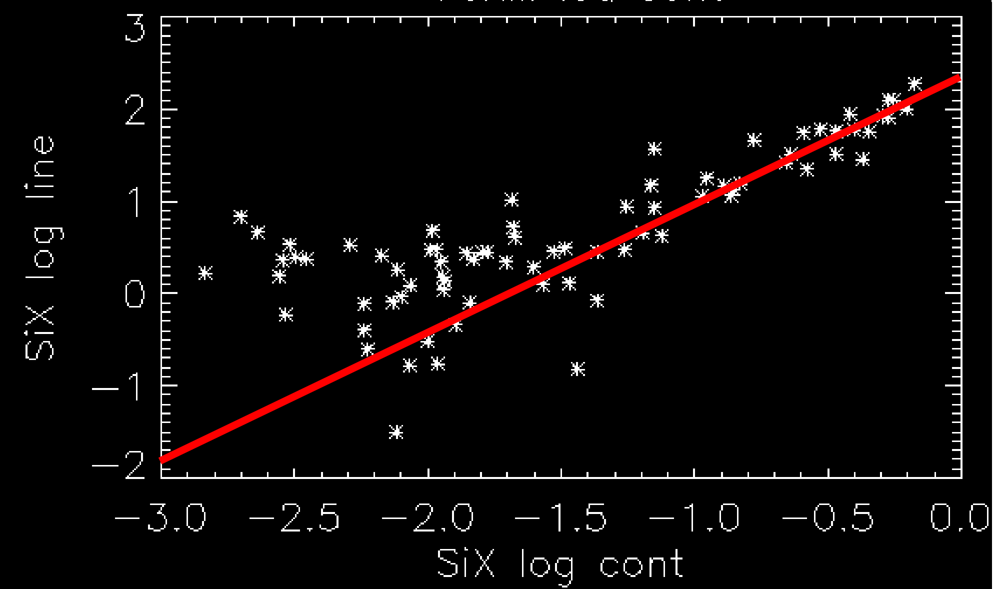
IDL> plot,dvec(7,0:15,2),xtit='Time seq. no.',ytit='Pol. Cont. Bright. Long'

SiX (vs. FeXIII) is a powerful coronal diagnostic



FeXIII useful dynamic range: $10^{0.6}$

Line/continuum exponent: 3/2



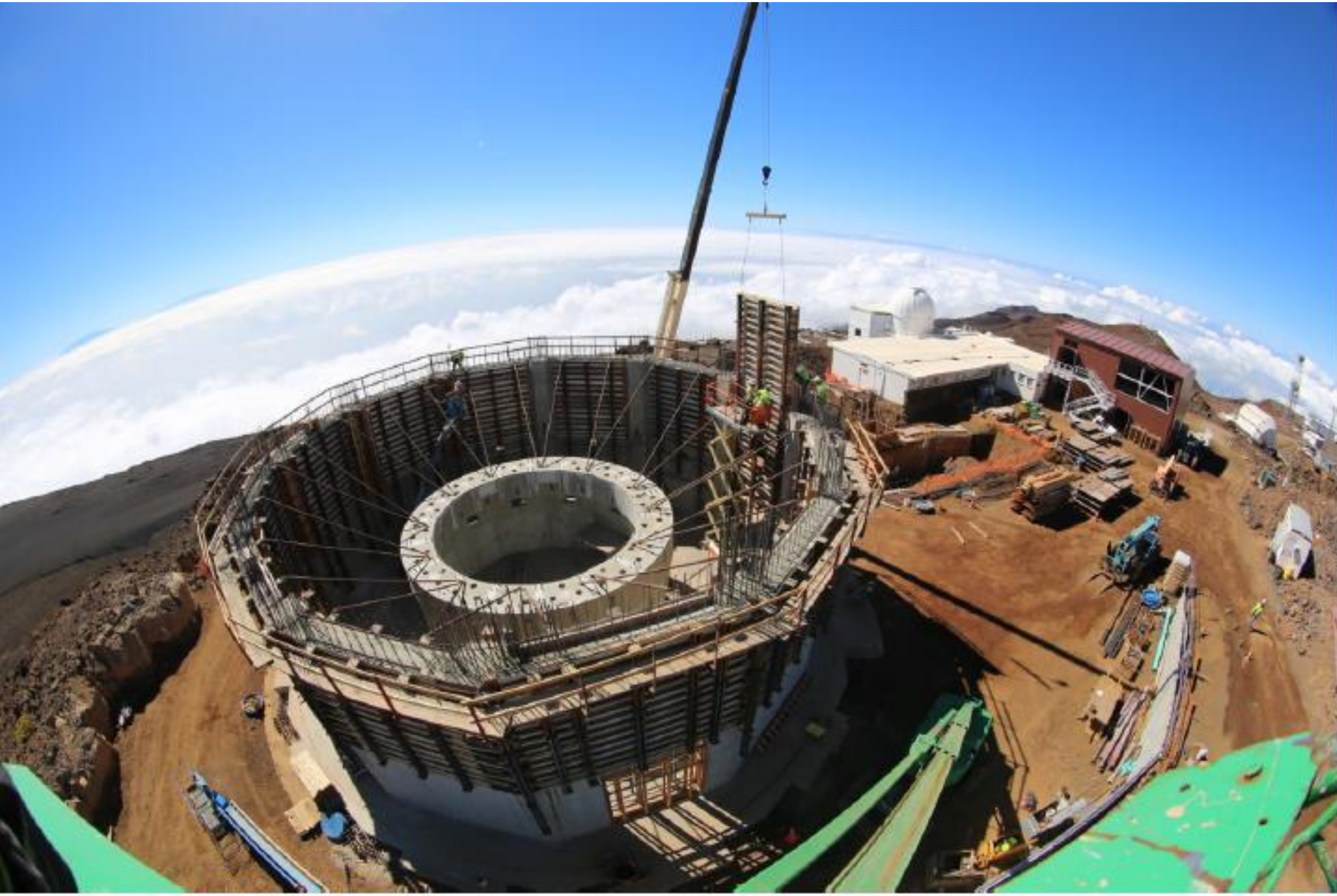
SiX useful dynamic range: $10^{1.6}$

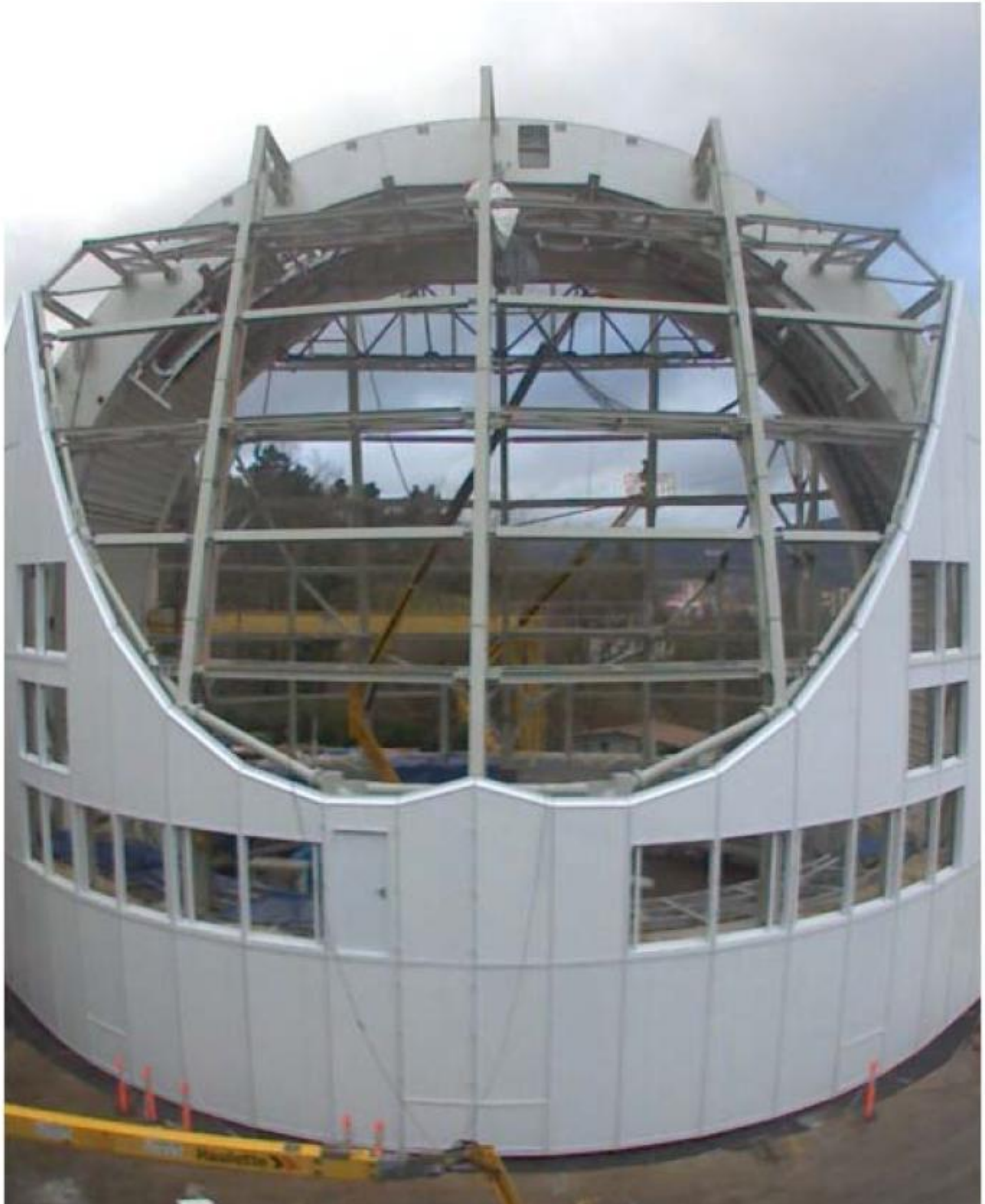
Line/continuum exponent: 4/3

FORWARD goals

- Model IR continuum polarization variability
- Model K-corona IR continuum brightness
- Model SiX and FeXIII polarization amplitude and direction variability
- Demonstrate HeI + SiX CHM

Daniel K. Innouye Solar Telescope (DKIST)

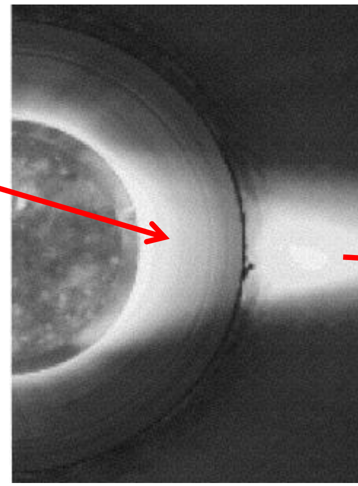




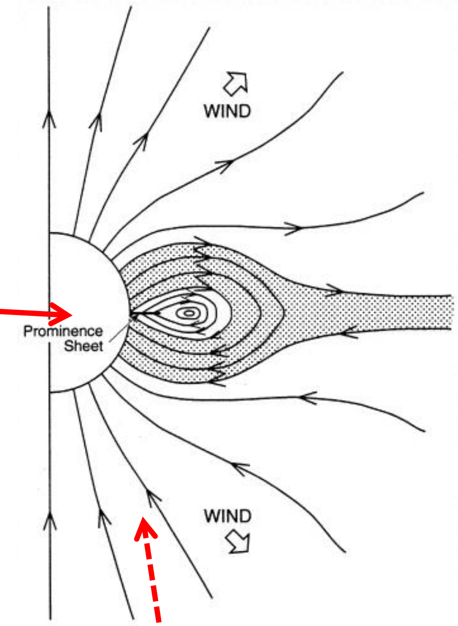
Descriptive and quantitative coronal magnetometry

Can we get from **this** phenomenon

Or this

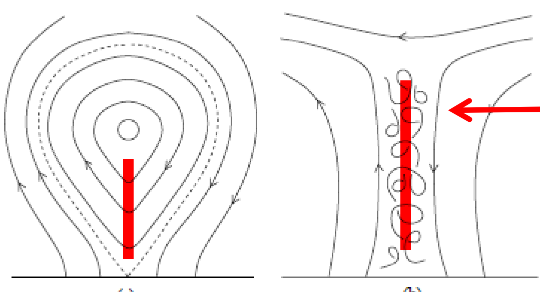


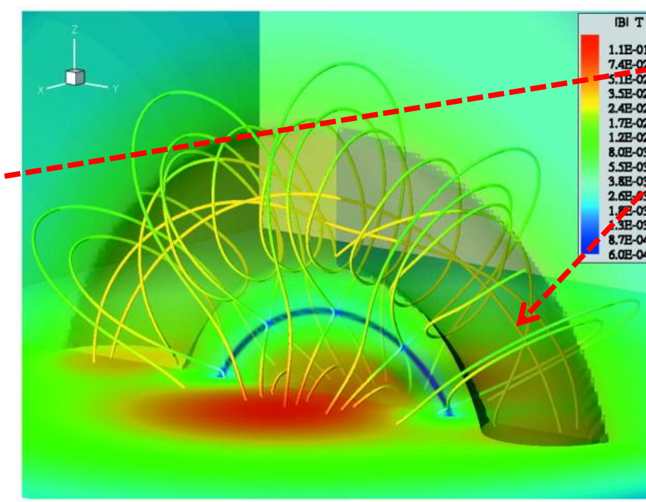
To this understanding



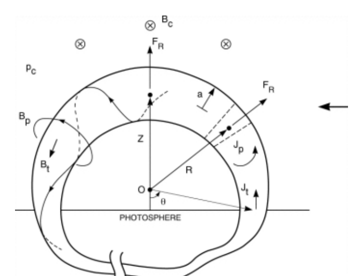
(models from Ballegooijen and Cranmer; Chen et al; Low; Gibson; Roussev et al.)

To these models

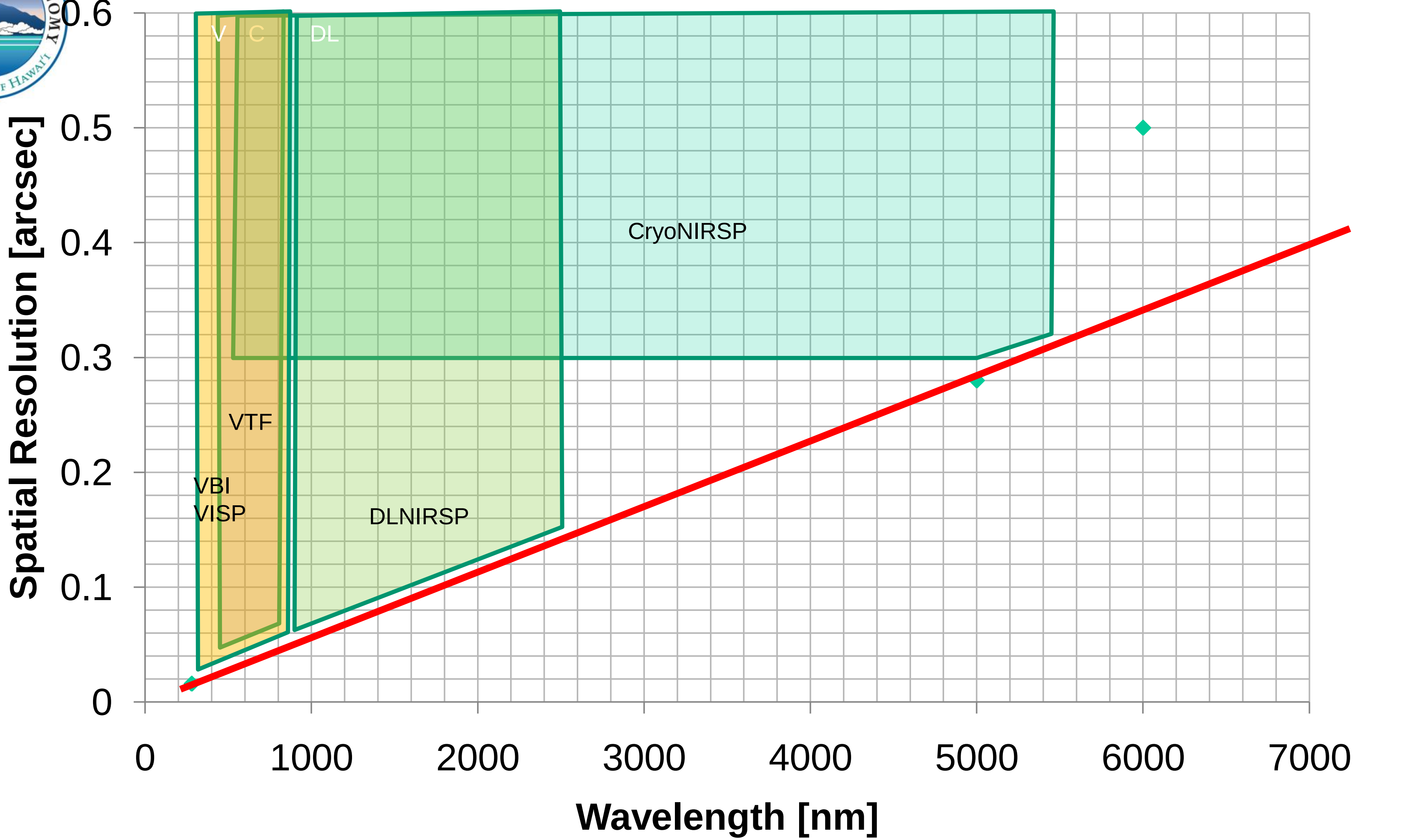




We draw these lines but can't yet measure them.



CryoNIRSP Wavelength and Angular Resolution



CryoNIRSP Wavelengths and benchmark coronal magnetic sensitivity

Wavelength (µm)	Line
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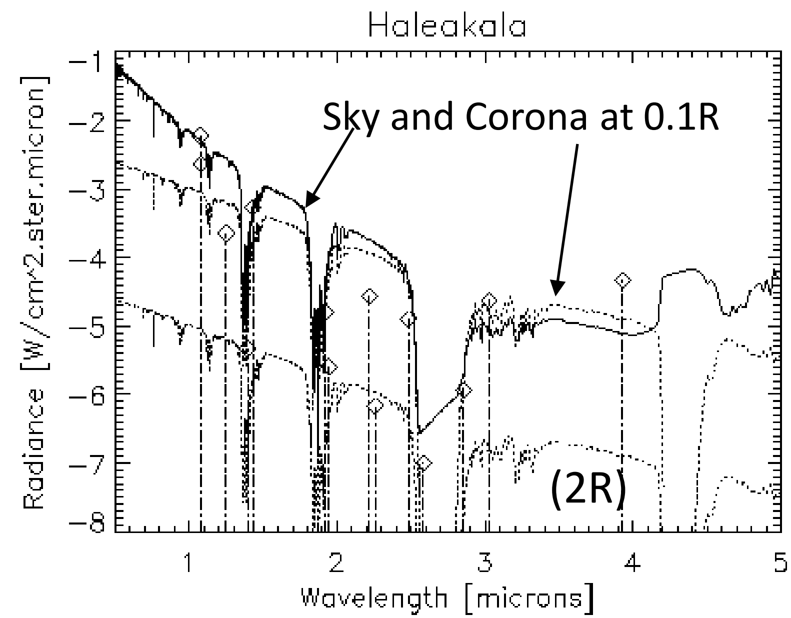
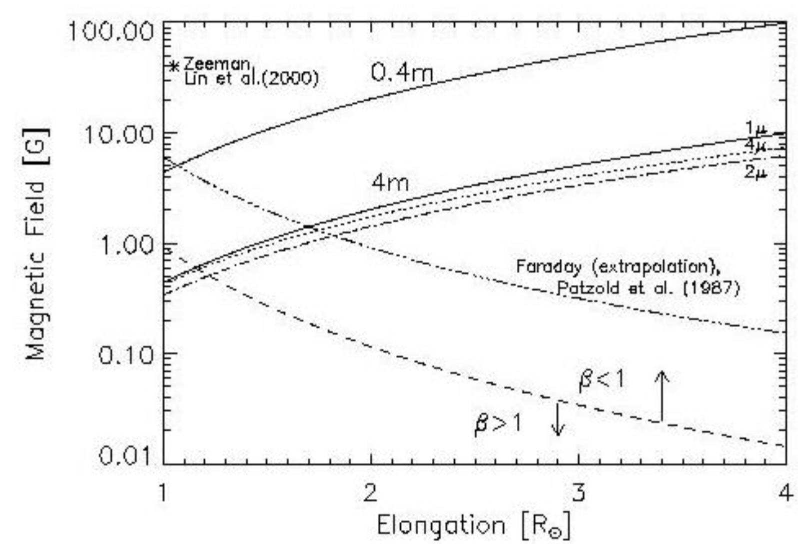




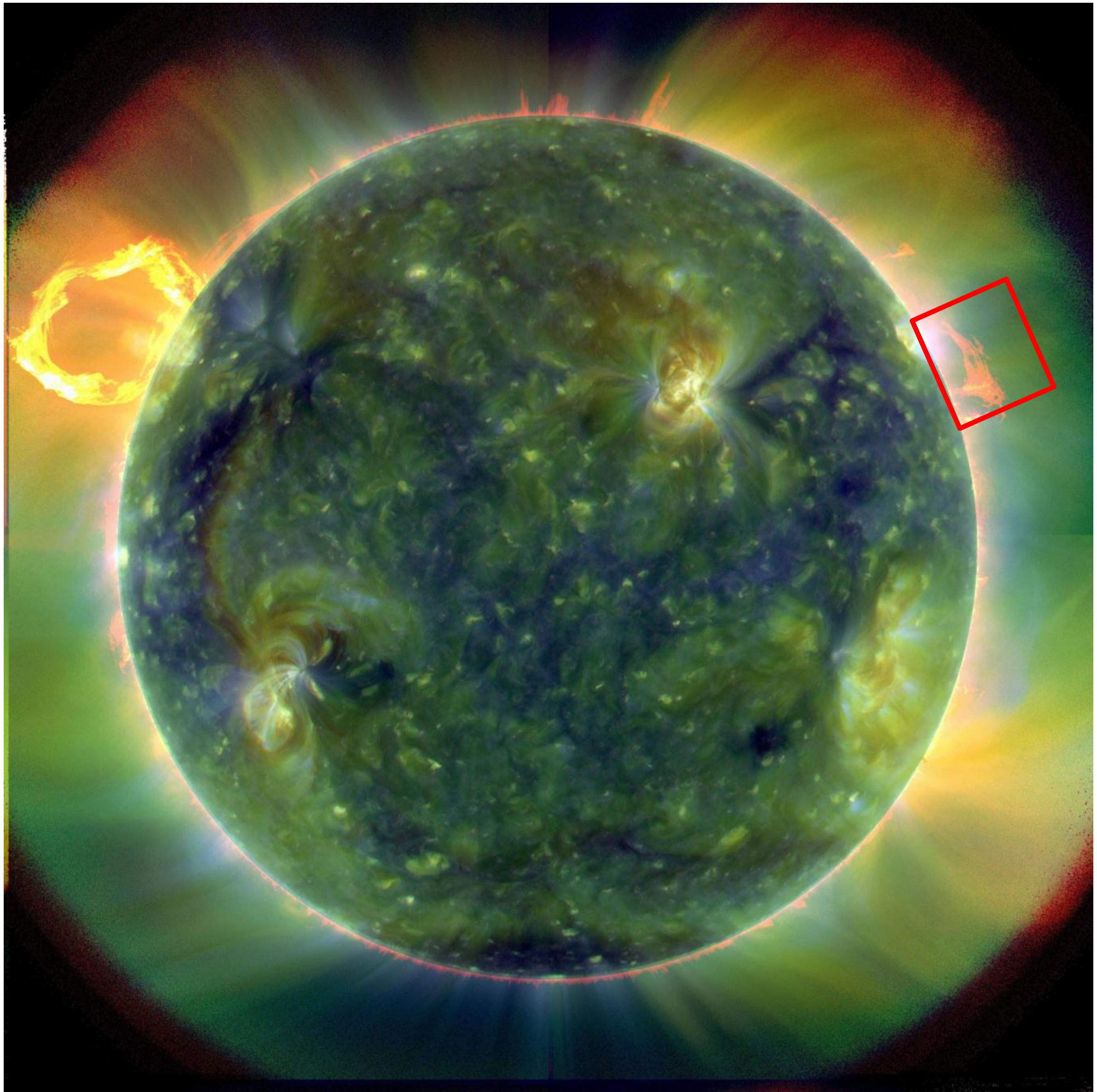
Temperature sensitivity from 3000K to 3MK

DKIST and CryoNIRSP: emergent science frontiers

- The molecular photosphere
  - Ambipolar dynamics in sunspots
- Observing the heliosphere from the ground
  - A dusty plasma, "inner source"
- Our dark energy problem
  - Seeing coronal magnetism
  - Permitted + Forbidden line Hanle Vector coronal magnetometry
- Night-time solar physics
  - Imaging magnetism in other stellar atmospheres and learning from solar magnetism
  - Circumstellar science (imbedded stars…)

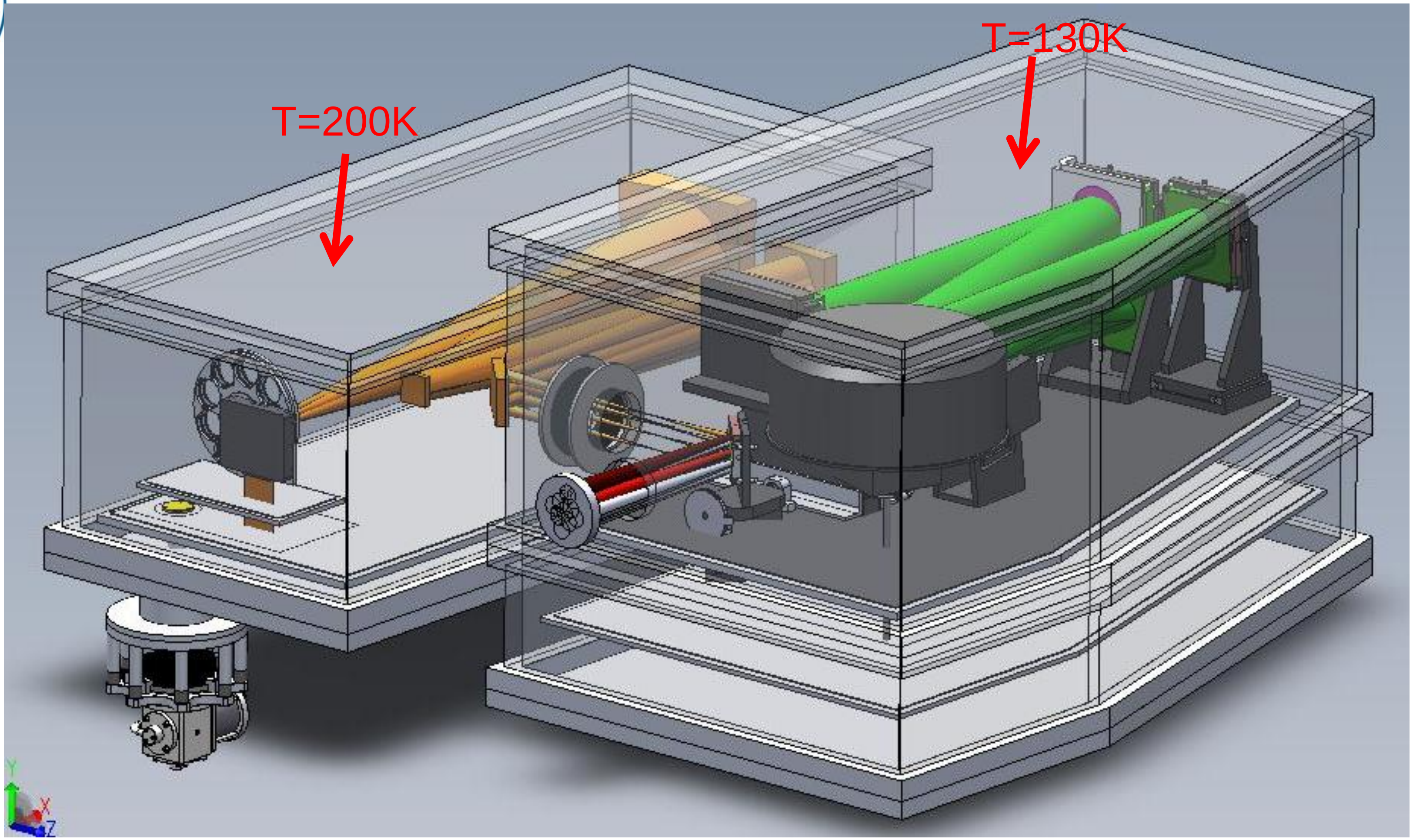
CryoNIRSP FOV

4’ slit
3’ scan
90s



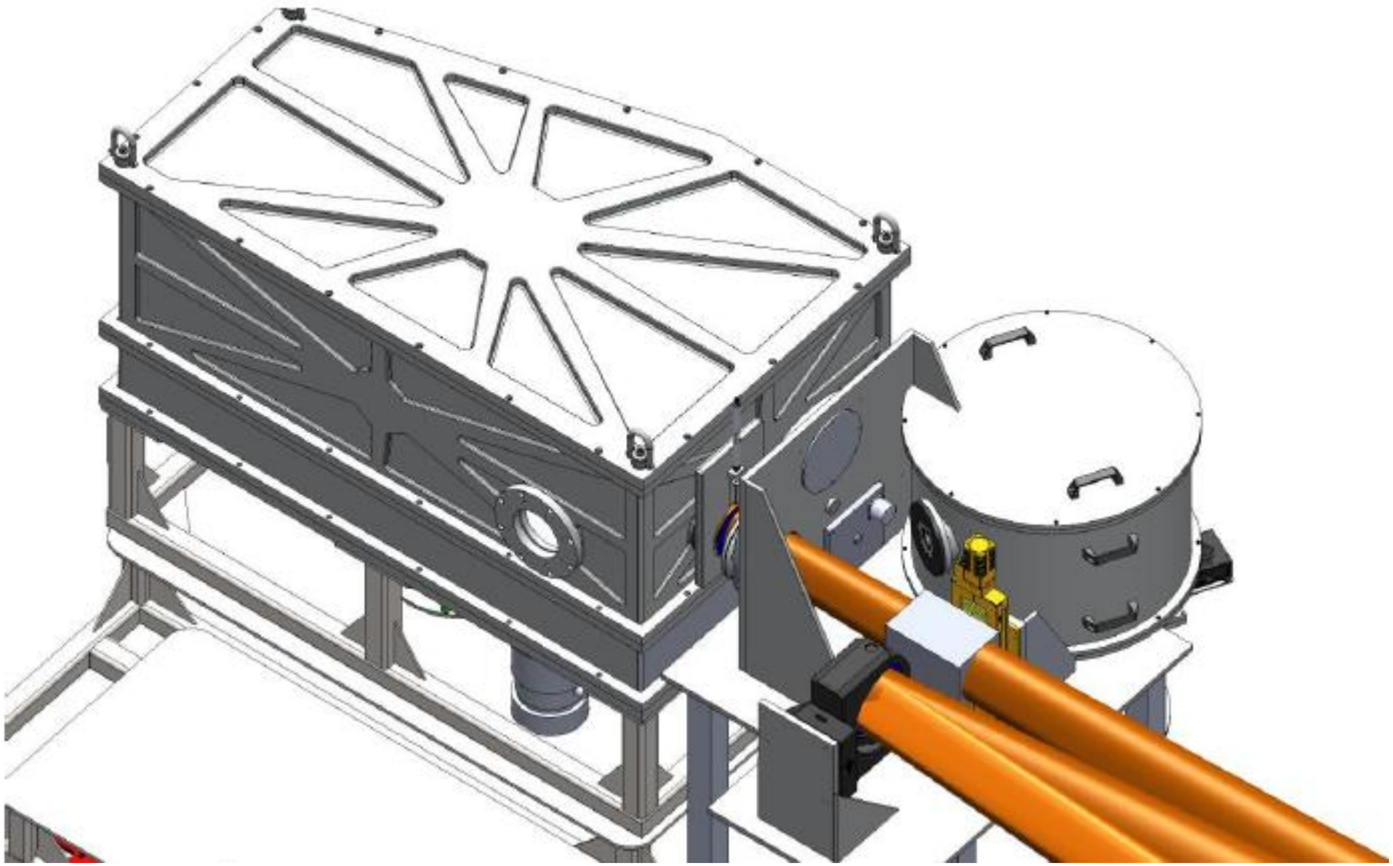
CryoNIRSP

Mass: 2500kg

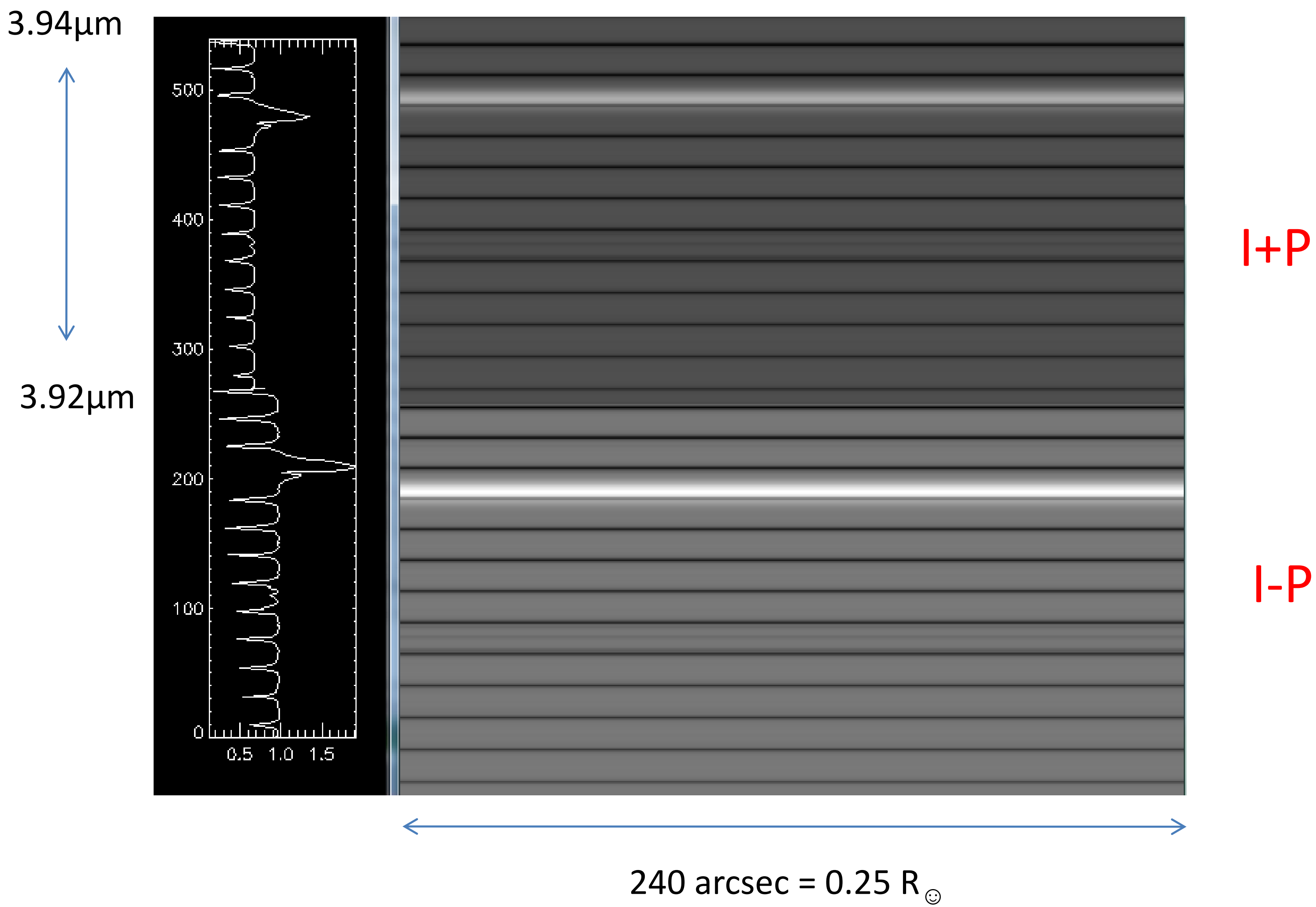


CryoNIRSP

CryoNIRSP: March, 2014



CryoNIRSP Single Slit Data Sample: Si IX 3.93μm



DKIST and CryoNIRSP will measure B>4G at this resolution in about 1hr