Basic requirements to the instrument for diagnostics of chromospheric magnetic fields with SOLAR-C

Y. Katsukawa (NAOJ)

SOLAR-C subWG for chromosphere/corona magnetic field measurments

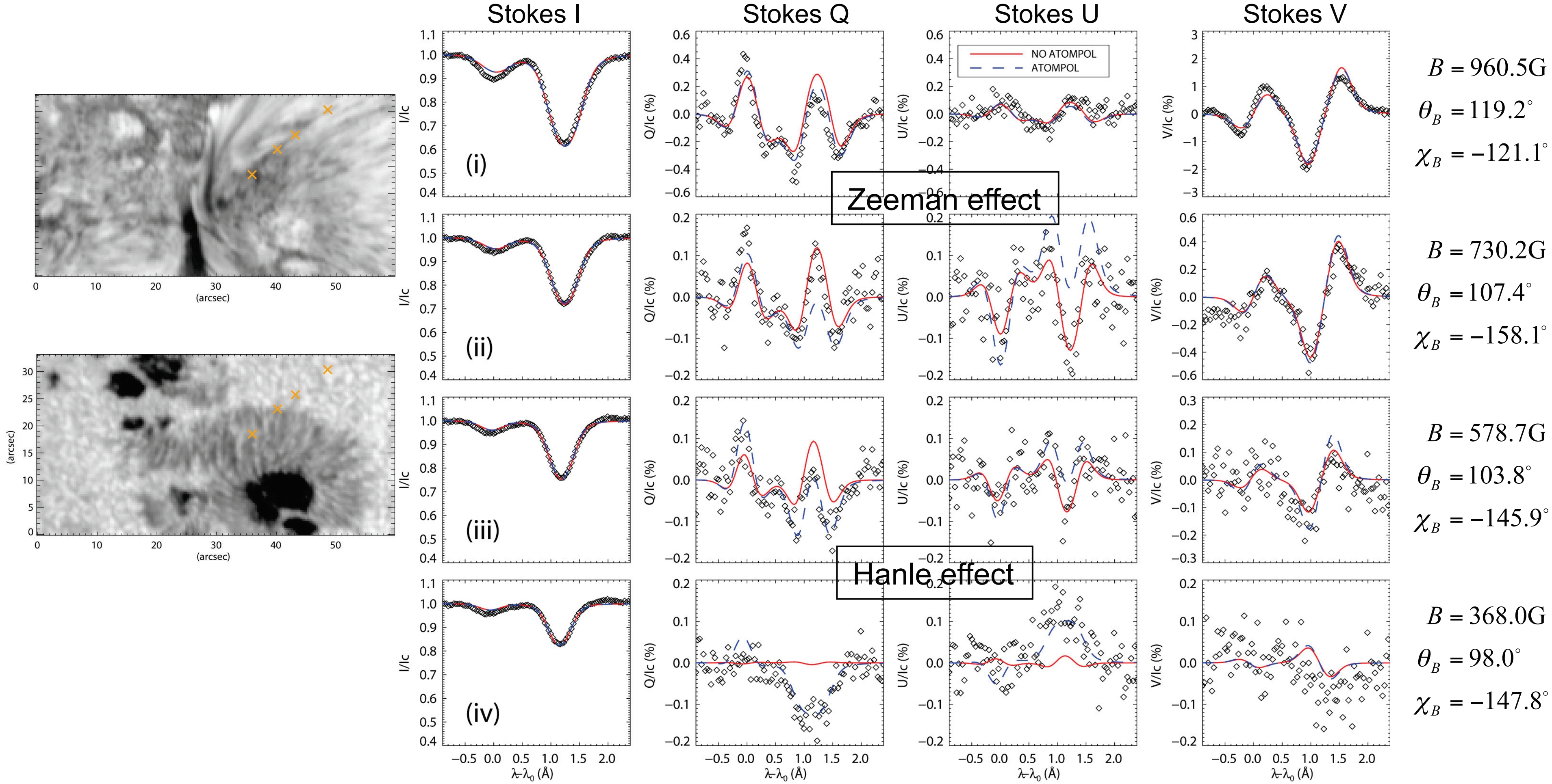
Key concepts of the optical telescope

- The 1.5mΦ optical telescope is the main one in SOLAR-C Plan-B.
  - High throughput with higher resolution. One order of magnitude improvement in the spectro-polarimetric sensitivity.
  - The improvement allows us to diagnose chromospheric magnetic fields, which have been difficult in existing instruments.

1. Utilizing the Hanle effect in addition to the Zeeman effect
   - The transverse Zeeman effect is not sensitive to magnetic fields weaker than several hundreds gauss.
   - The Hanle effect can make significant polarization signals with magnetic fields weaker than 100 gauss.

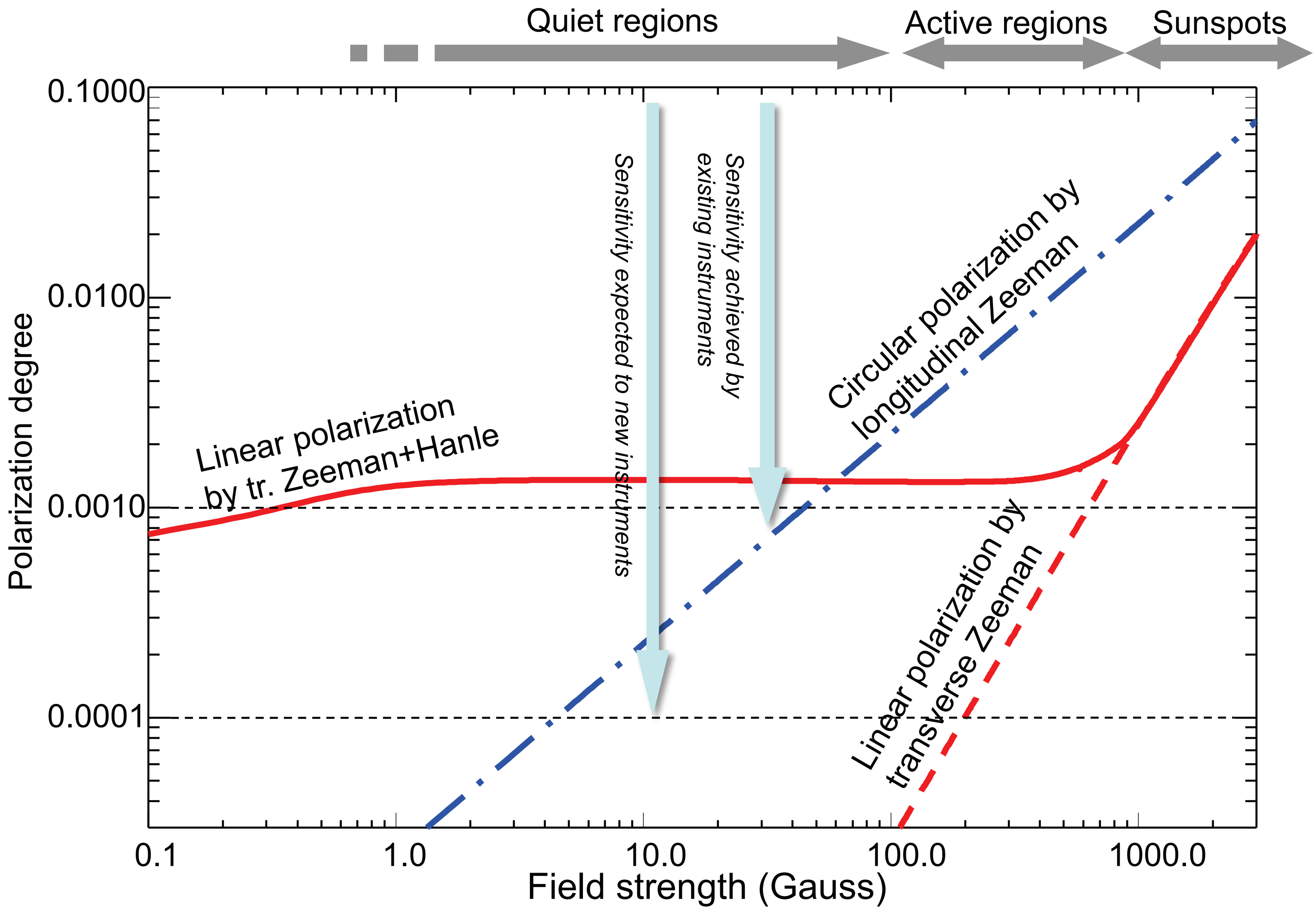
2. High polarization sensitivity of $S/N \sim 10^4$
   - In order to observe polarization signals by the joint action of the Zeeman and Hanle effect in chromospheres, higher polarization sensitivity is required.
   - We can observe magnetic fields of >10 gauss if we can reach the polarization sensitivity of $S/N \sim 10^4$.

Hanle effect in He I 10830 Å

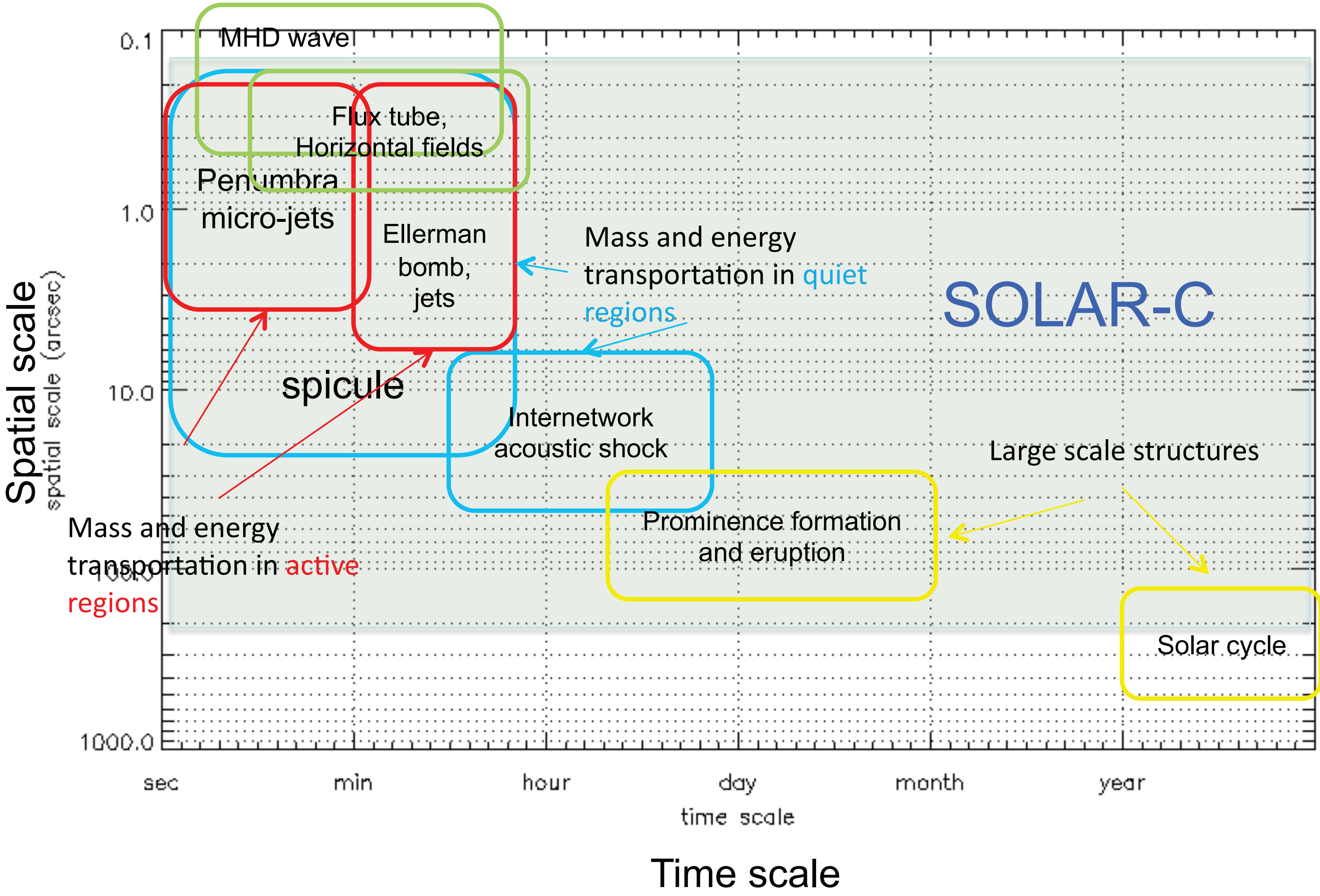


When B>several hundreds gauss, the Zeeman effect is dominating polarization signals. The Hanle effect becomes significant in the weak field regime. Amplitudes of the polarized spectral profiles are ~0.1%.

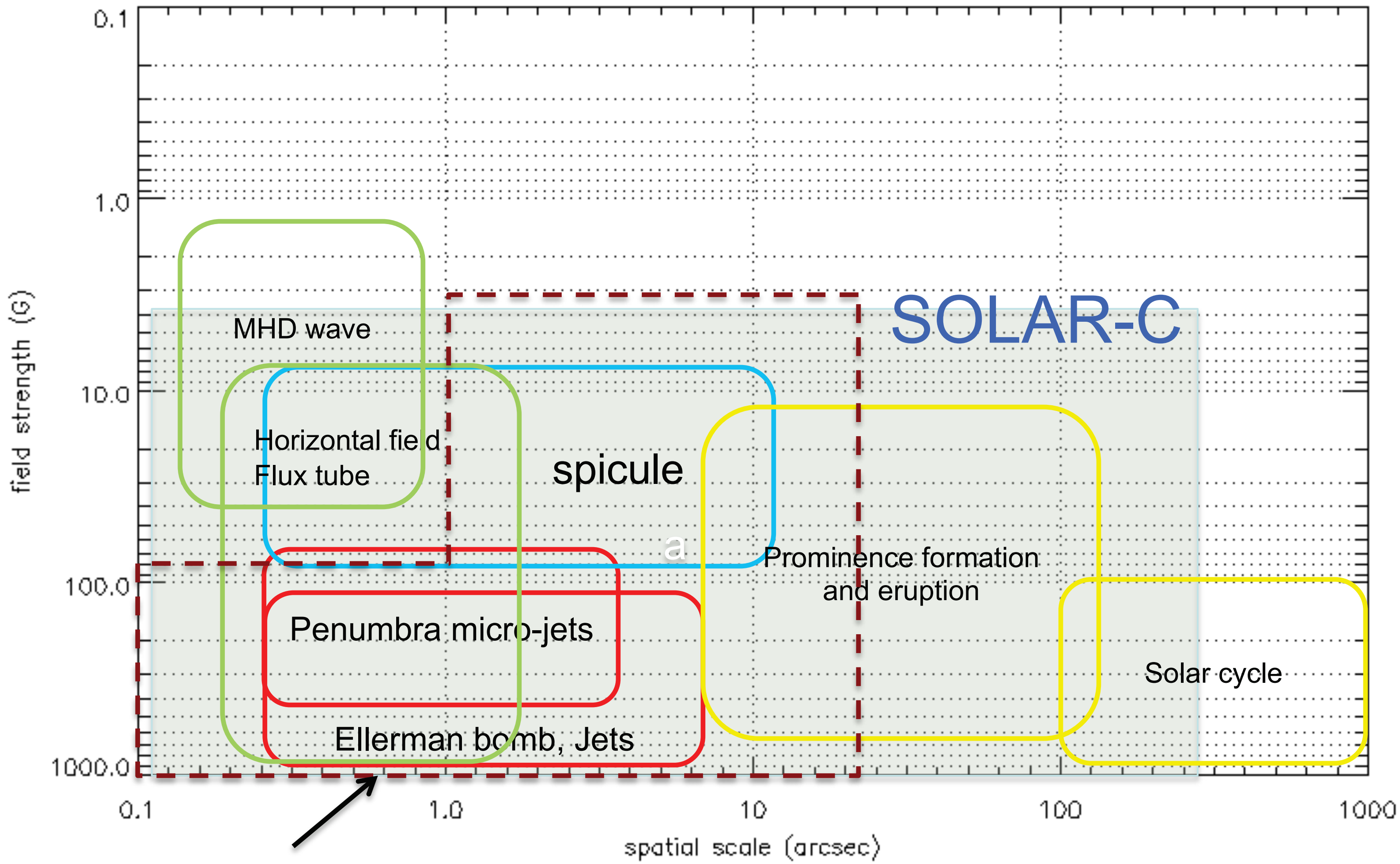
Polarization signals in He I 10830Å



Science targets with the diagnostics of chromospheric magnetic fields



Science targets with the diagnostics of chromospheric magnetic fields



Ground-based telescopes will do a good job in the area.

Choices of chromospheric lines

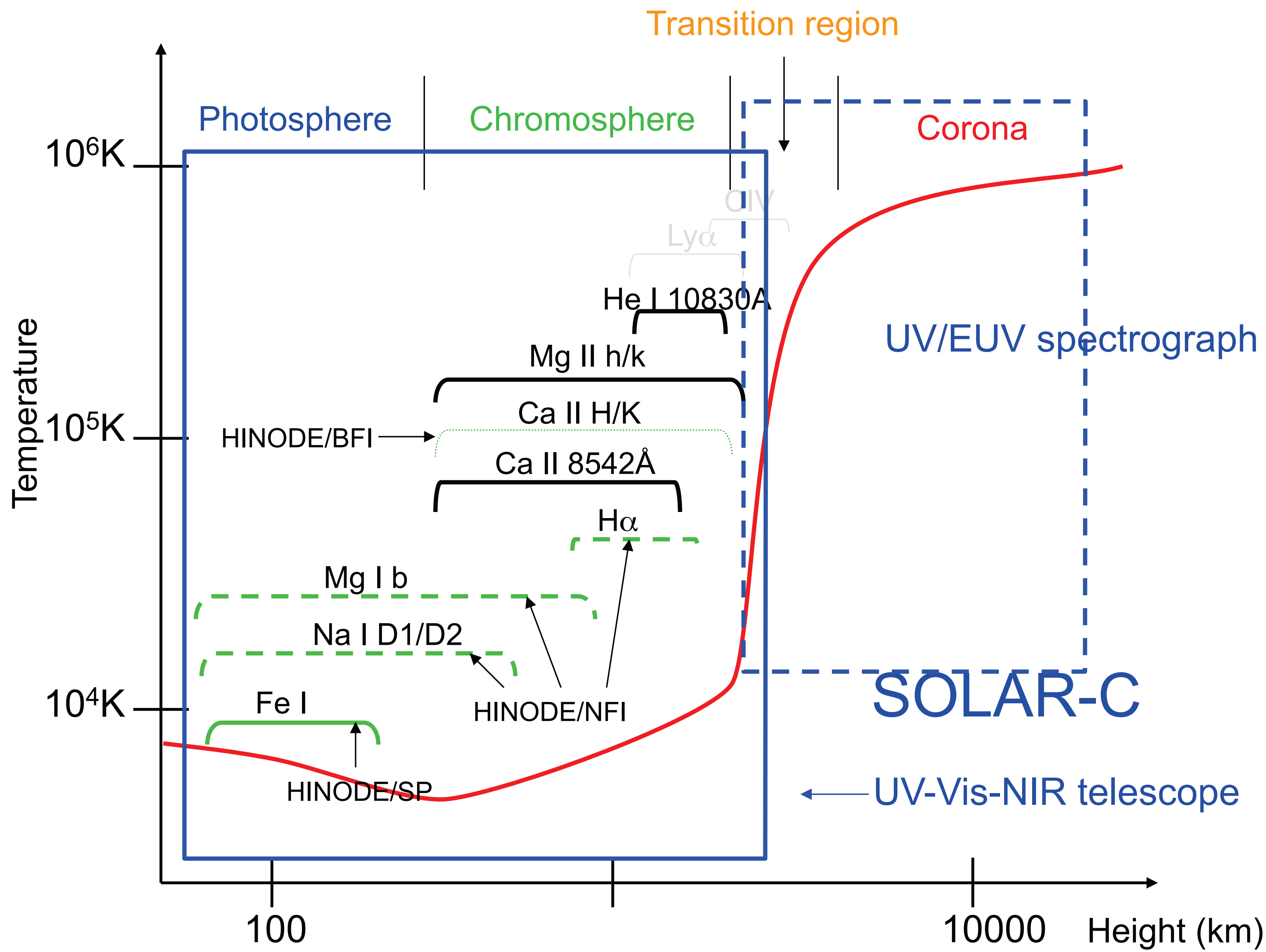
- The subWG discussed priority of chromospheric lines for SOLAR-C in terms of:

  (1) Good sensitivity to the upper chromosphere

  (2) Good sensitivity to physical quantities (magnetic fields, velocities, and temperatures)

- Diagnostics of mag. fields
  1. He I 10830Å
  2. Ca II 8542Å
  3. Hα 6563Å

- Diagnostics of dynamics (T, v)
  1. Mg II k 2796Å
  2. Ca II 8542Å
  3. Hα 6563Å

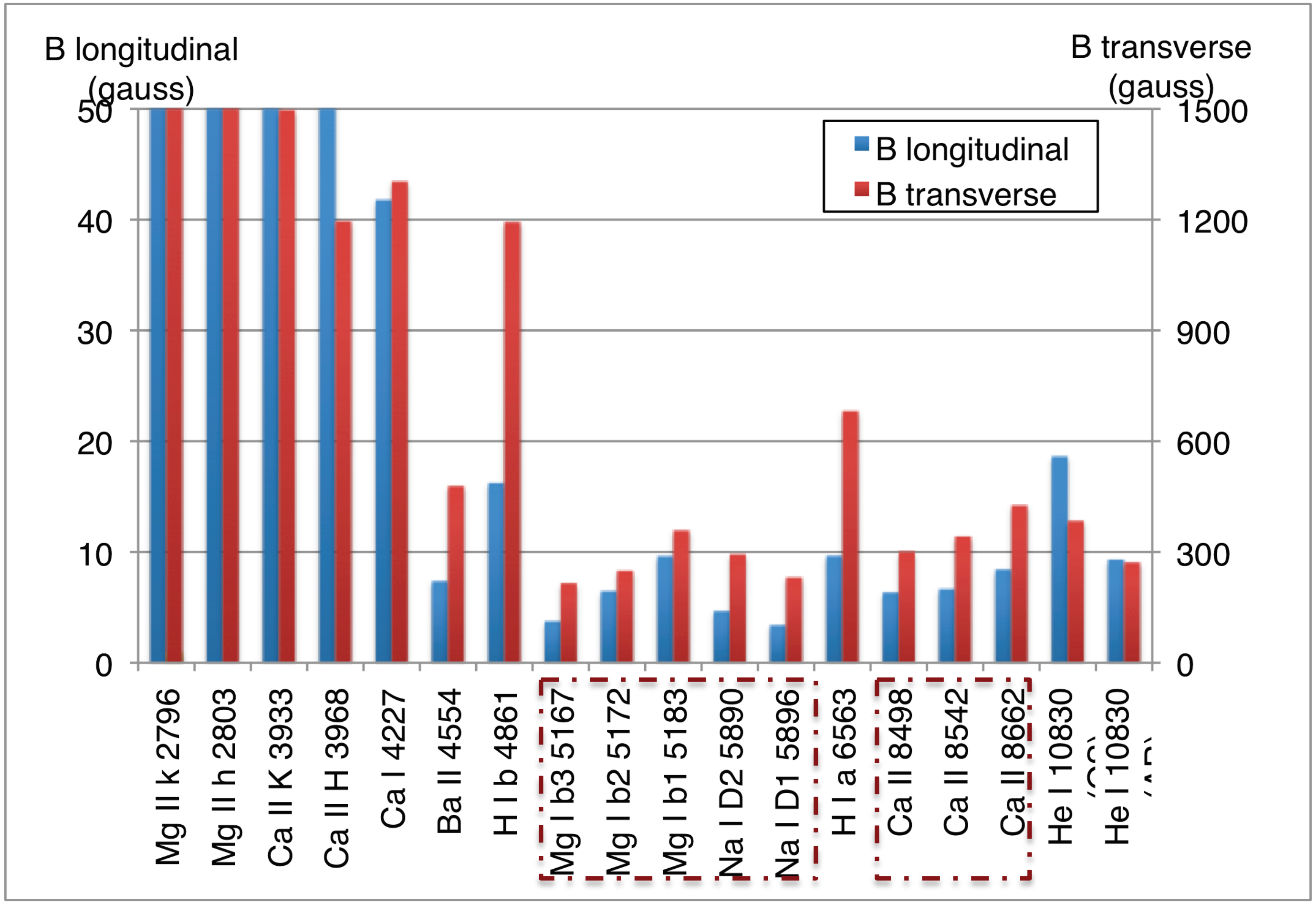


Transition region
Photosphere
Chromosphere
Corona
10^6K
10^5K
10^4K
Temperature
CIV
Lyα
He I 10830A
Mg II h/k
Ca II H/K
HINODE/BFI
Ca II 8542Å
Hα
UV/EUV spectrograph
Mg I b
Na I D1/D2
Fe I
HINODE/NFI
SOLAR-C
HINODE/SP
UV-Vis-NIR telescope
100
10000
Height (km)

Candidates of chromospheric lines

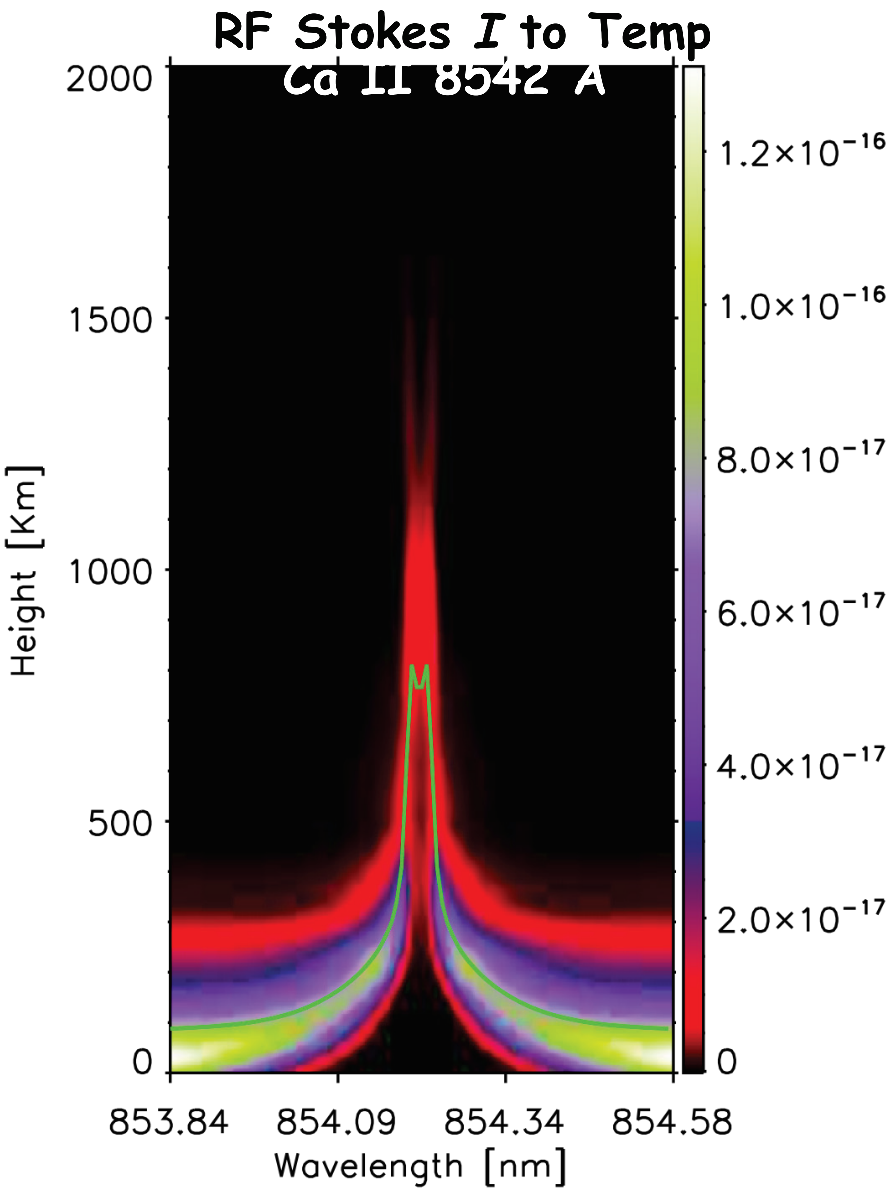
Line	1.2λ/D [arcsec]	Photon [/Δλ/0.1"/sec]		Response height [km]	Zeeman effect			Hanle effect
		Cont.	Center		geff	Bl [G]	Bt [G]	
Mg II k 2796 Å	0.046	$2.9x10^4$	$2.9x10^5$	~1300	1.17	$8.5x10^1$	$2.1x10^3$	x
Mg II h 2803 Å	0.046	$3.1x10^4$	$2.5x10^5$	~1200	1.33	$7.3x10^1$	$1.8x10^3$	-
Ca II K 3933 Å	0.065	$6.1x10^5$	$3.2x10^5$	~940	1.17	$6.2x10^1$	$1.5x10^3$	x
Ca II H 3968 Å	0.065	$7.1x10^5$	$3.3x10^5$	~980	1.33	$5.1x10^1$	$1.2x10^3$	-
H I β 4861 Å	0.080	$1.2x10^7$	$1.9x10^6$	1000-2000	1.00	$1.6x10^1$	$1.2x10^3$	x
Mg I b3 5167 Å	0.085	$1.4x10^7$	$1.5x10^6$	300-600	2.00	$3.7x10^0$	$2.2x10^2$	x
Mg I b2 5172 Å	0.085	$1.4x10^7$	$1.1x10^6$	300-600	1.75	$6.5x10^0$	$2.5x10^2$	x
Mg I b1 5183 Å	0.086	$1.4x10^7$	$1.0x10^6$	200-600	1.25	$9.6x10^0$	$3.6x10^2$	x
Na I D2 5890 Å	0.097	$1.6x10^7$	$7.9x10^5$	~370	1.17	$4.7x10^0$	$2.9x10^2$	x
Na I D1 5896 Å	0.097	$1.6x10^7$	$9.2x10^5$	~350	1.33	$3.4x10^0$	$2.3x10^2$	-
H I α 6563 Å	0.108	$1.6x10^7$	$3.0x10^6$	1000-2000	1.00	$9.7x10^0$	$6.8x10^2$	x
Ca II 8498 Å	0.140	$1.3x10^7$	$3.8x10^6$	~680	1.07	$6.3x10^0$	$3.0x10^2$	x
Ca II 8542 Å	0.141	$1.1x10^7$	$2.4x10^6$	~780	1.10	$6.7x10^0$	$3.4x10^2$	x
Ca II 8662 Å	0.143	$1.2x10^7$	$2.4x10^6$	~710	0.83	$8.4x10^0$	$4.3x10^2$	-
He I 10830 Å (QS)	0.179	$1.9x10^7$	$1.8x10^7$	~2000	1.42	$1.9x10^0$	$3.8x10^2$	x
He I 10830 Å (AR)	0.179	$1.9x10^7$	$1.6x10^7$	~2000	1.42	$9.3x10^0$	$2.7x10^2$	x

Sensitivities to the Zeeman effect



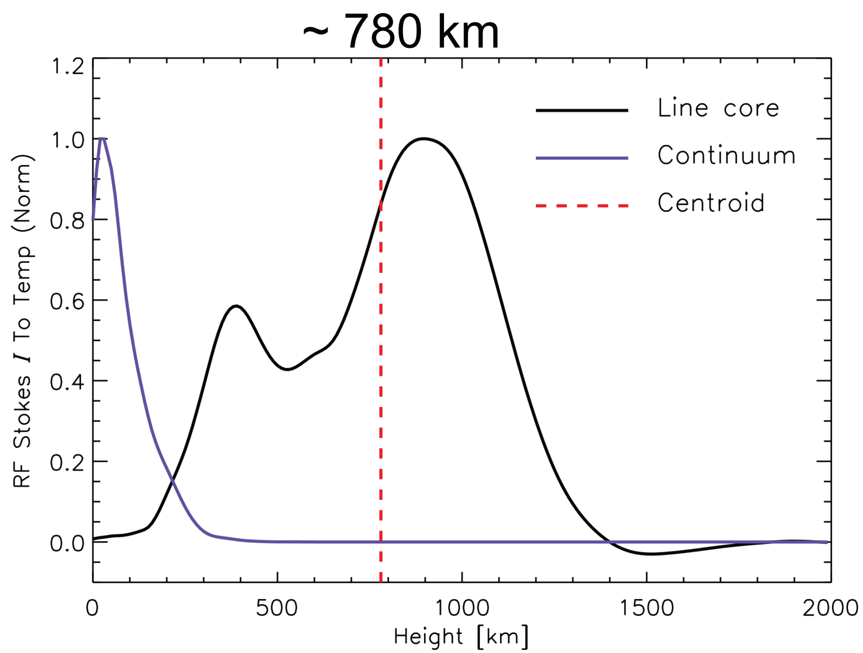
- Sampling
  - Spatial sampling: 0.1"/pix
  - Temporal sampling: 1sec
  - Wavelength sampling: $\lambda/\Delta\lambda=2\times10^5$

Formation “height” of spectrum lines



(by courtesy of H. Uitenbroek)
- Response Functions can be used to investigate the sensitivity of spectral lines to model parameters.
- RFs depend on the atmospheric height and wavelength (2D-functions).

- Centroid of RFs at different wavelengths provide information on the average sensitivity of spectral lines: “Formation Heights”

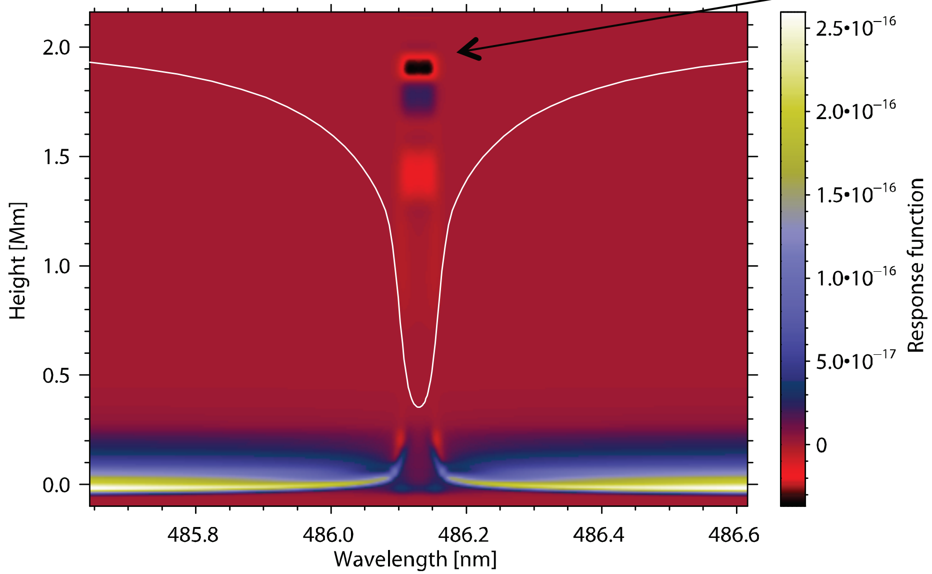


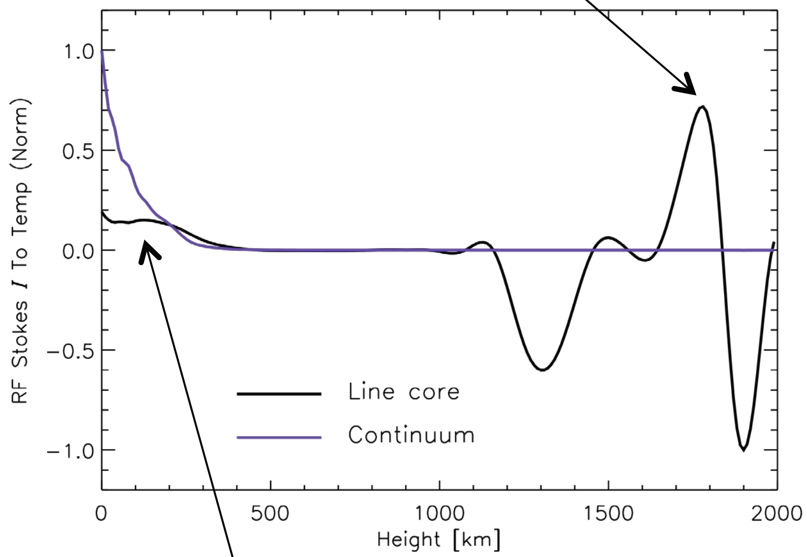
Complex formation: Hα 6563 Å

- Determining a "formation height" in some spectral lines is rather difficult. Instead, one has to talk about "average" formation.

Complex response to T

RF Stokes *I* to Temp

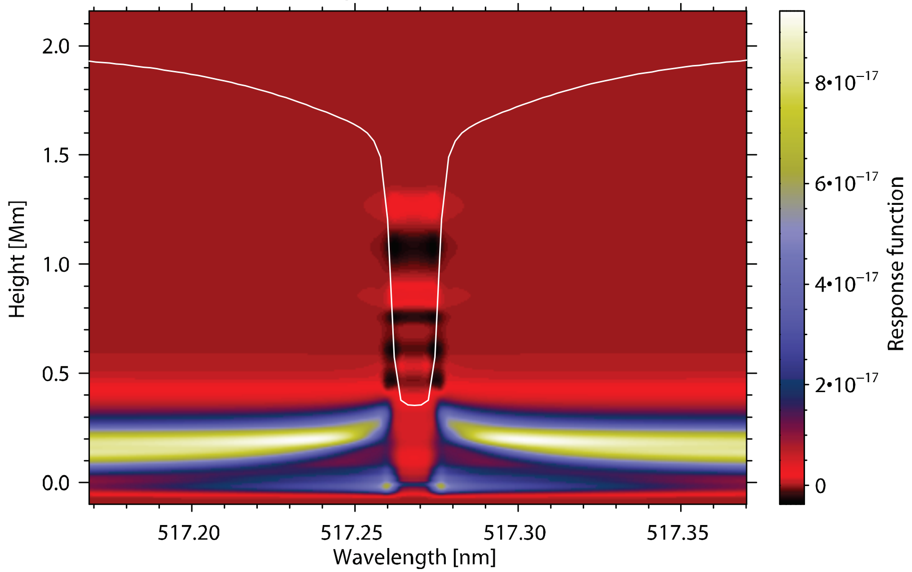




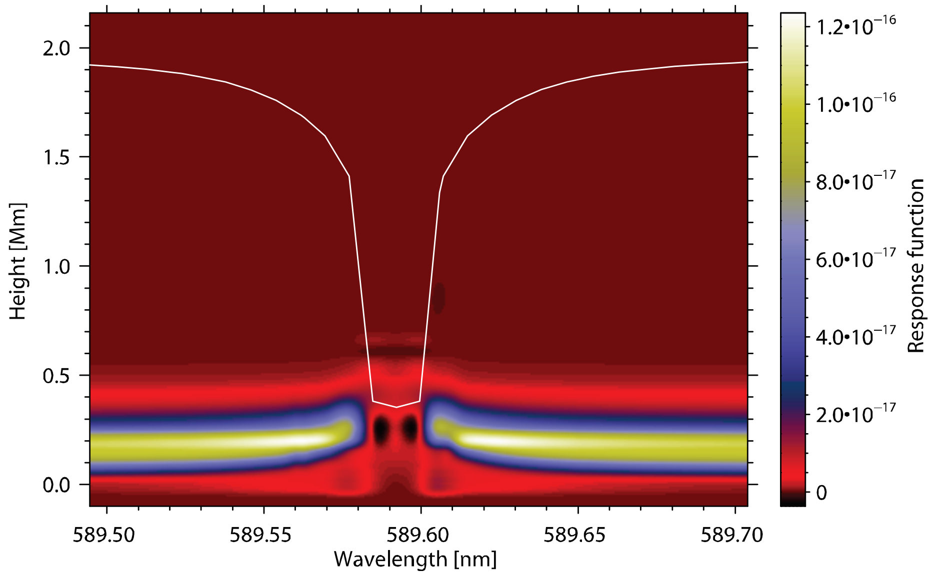
Photospheric contribution

Other chromospheric lines

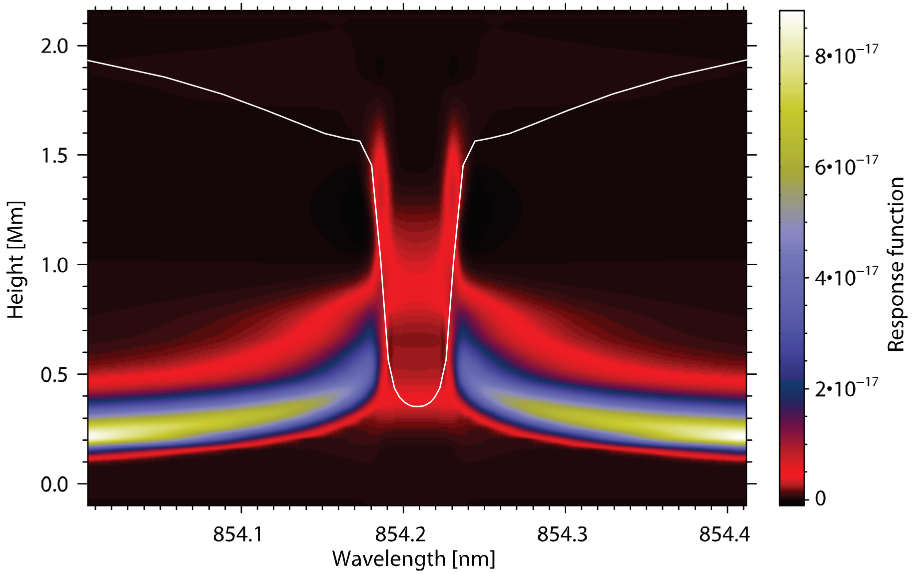
Mg I b2 5173



Na I D 5896



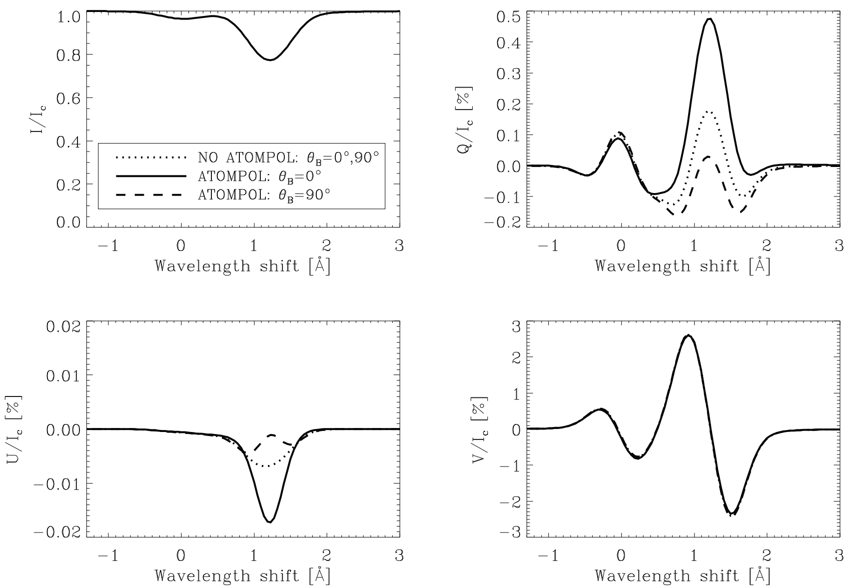
Ca II 8542



- Mg I b, Na I D are lines to provide good diagnostics of the low chromosphere.
- Ca II IRT can reach relatively high in the chromosphere.

He I 10830Å

Stokes profiles in EFR



Population of He I triplet (FAL1993)

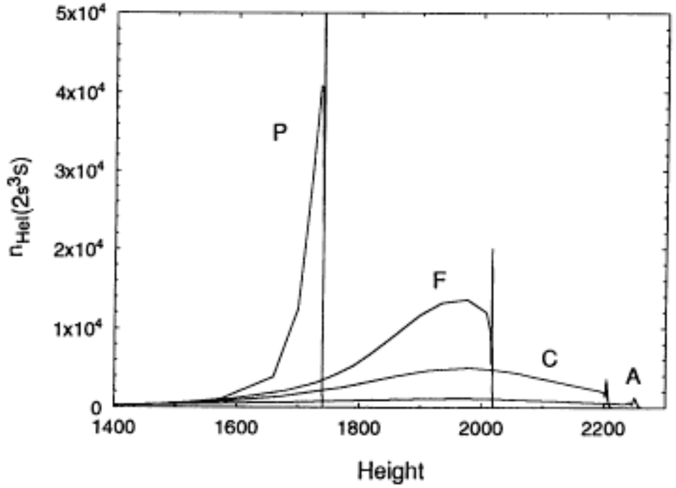


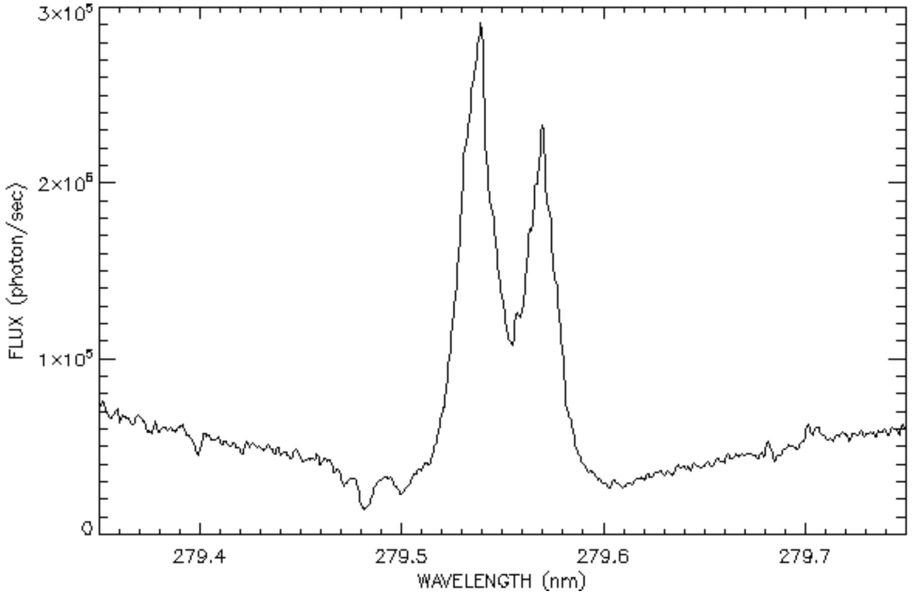
FIG. 28.—Number density (cm^{-3}) of the 2s ^3S level of He I vs. height (km) calculated for models A, C, F, and P.

(by courtesy of R. Centeno and J. Trujillo Bueno)

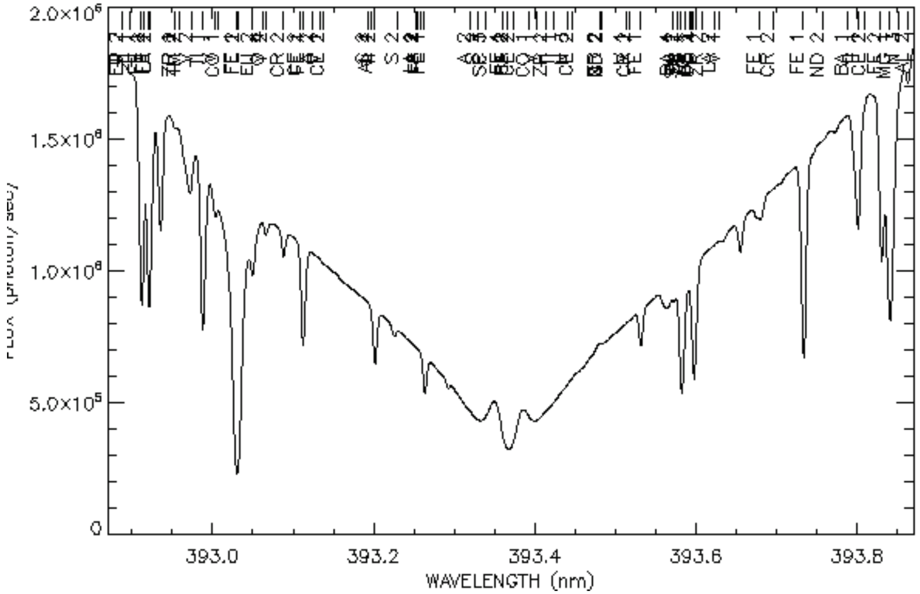
- High sensitivities to magnetic fields through the Hanle and Zeeman effect.
- Easy to interpret because it forms at a thin layer at upper chromospheric layers（by UV irradiation) without affected photospheric and low chromospheric atmospheric condition.
- The diagnostics methodology with the line is being matured.

Mg II k/h to reach higher chromosphere

Mg II k 2796 Å

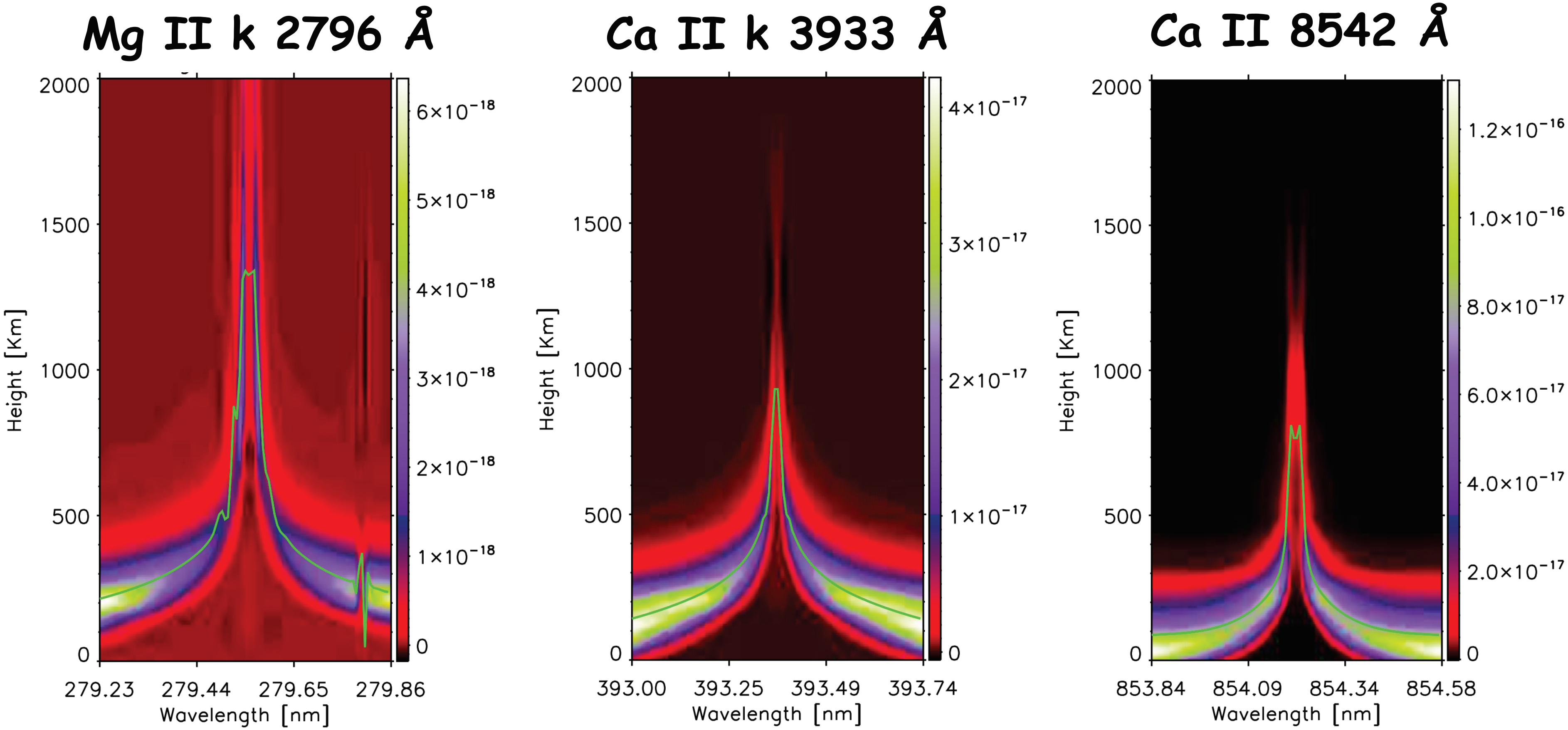


Ca II k 3933 Å

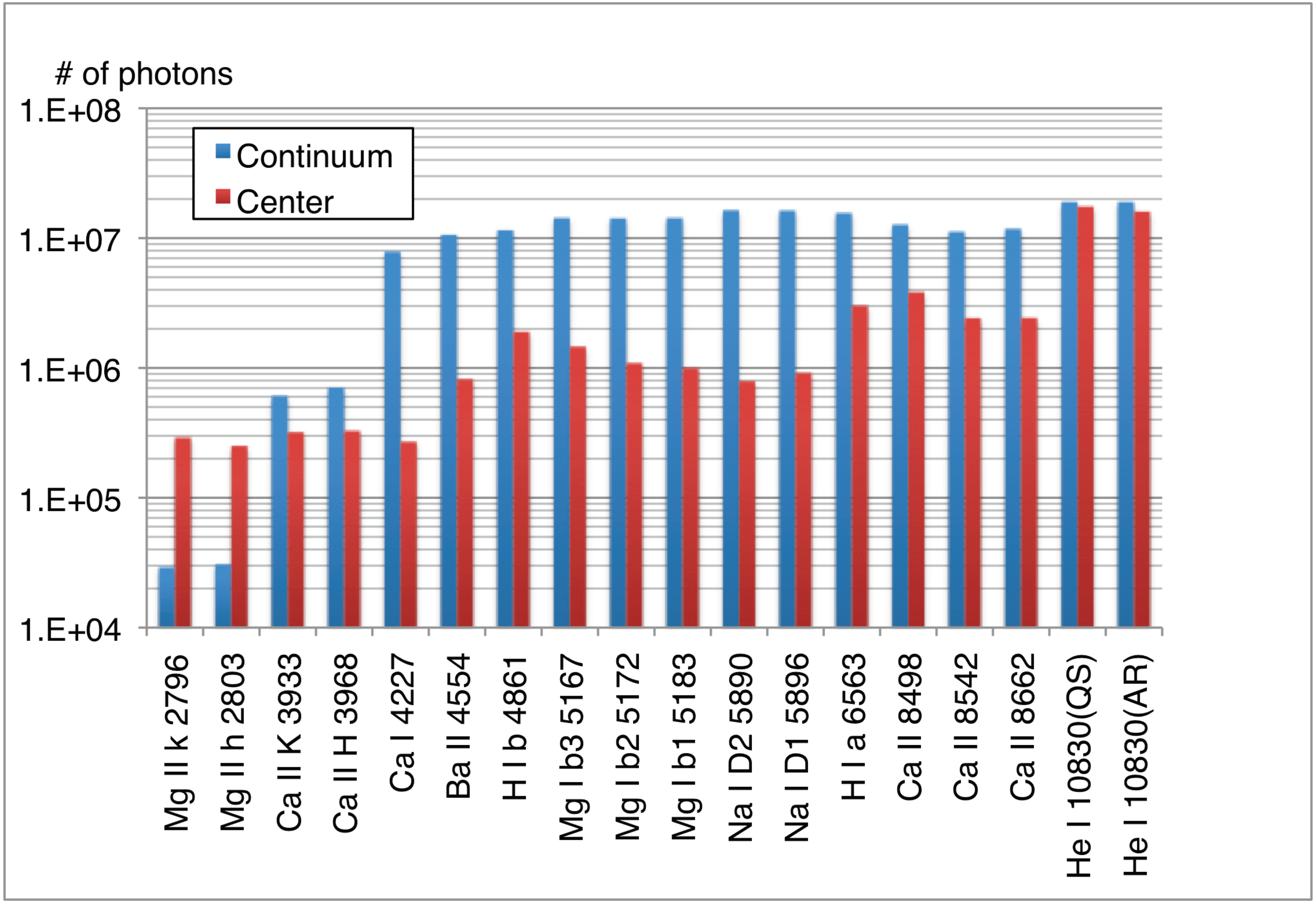


- Higher opacity in Mg II k/h than Ca II H/K, which allow us to reach high in the chromosphere.
- Lower continuum intensities, which allows us high contrast imaging of the chromosphere without affected by photospheric contamination.
- Ground-based observations cannot access the line.

Mg II k/h to reach higher chromosphere



- Higher opacity in Mg II k/h than Ca II H/K, which allow us to reach the higher chromosphere.



- Sampling
  - Spatial sampling: 0.1"/pix
  - Temporal sampling: 1sec
  - Wavelength sampling: $\lambda/\Delta\lambda=2\times10^5$

High throughput to be achieved with the 1.5m φ telescope

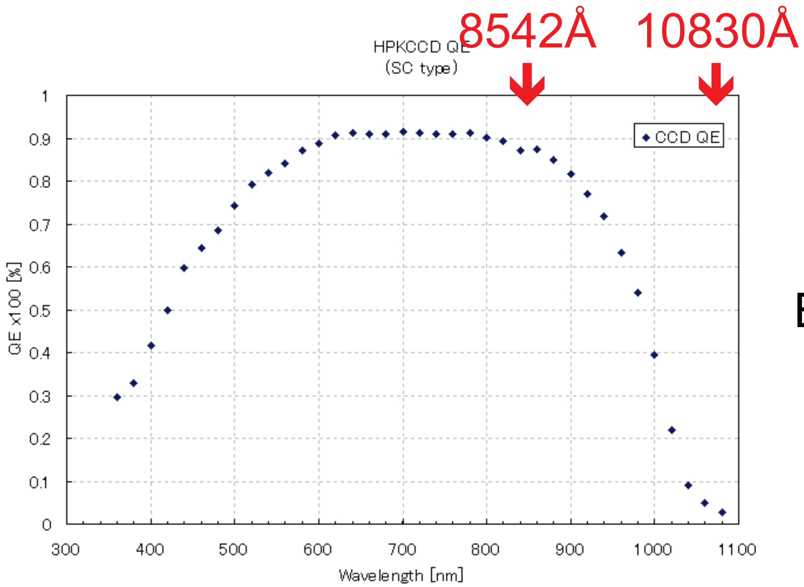
- S/N~10^4 for high precision spectro-polarimetry
  - Ca II 8542Å: 0.18"/pix, ~10sec integration
  - He I 10830Å: 0.18"/pix, 3-10sec integration

- S/N~10^2 for high-speed spectroscopy
  - Mg II k 2796Å: 0.06"/pix, <0.5sec integration
  - Ca II 8542Å: 0.06"/pix, <0.1sec integration

NIR detector for SOLAR-C

- For observing He I 10830Å in SOLAR-C, a NIR detector is essential to achieve high throughput for chromospheric diagnostics.

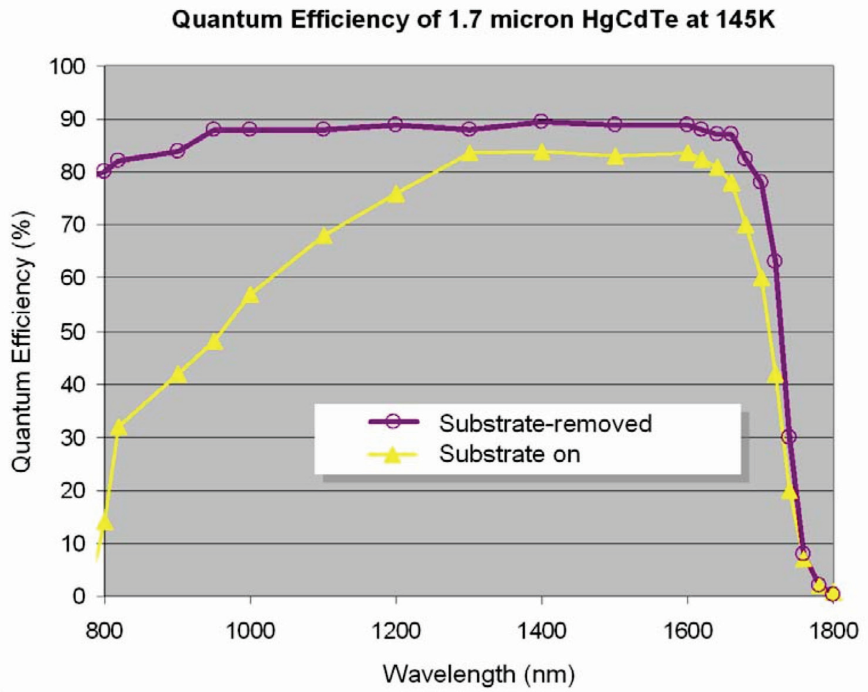
- The QE of Si CCD is less than 10% at 1.08μm, which is almost one order of magnitude smaller than the efficiency of NIR detectors. The merit of the large throughput with the 1.5mϕ aperture in SOLAR-C is significantly reduced if we use the CCD.

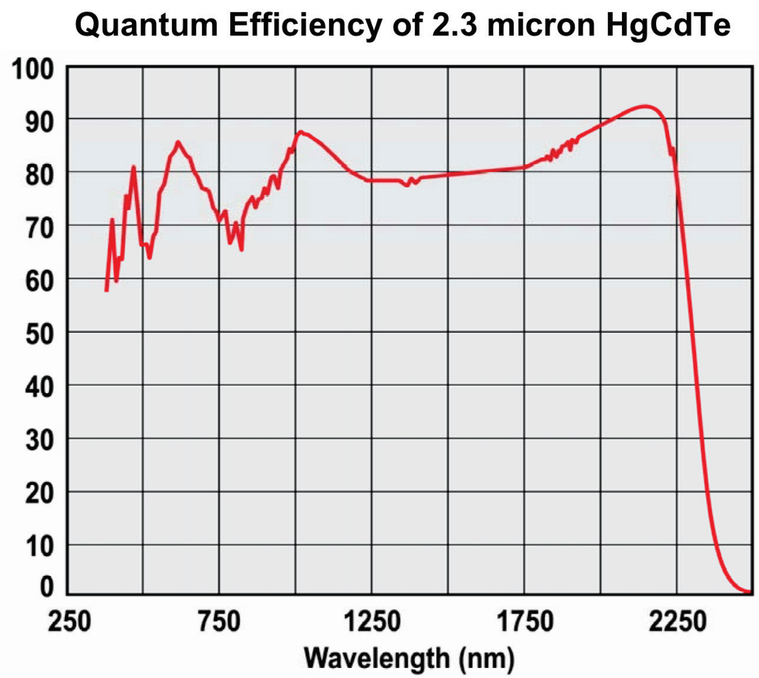


Example of QE of CCD

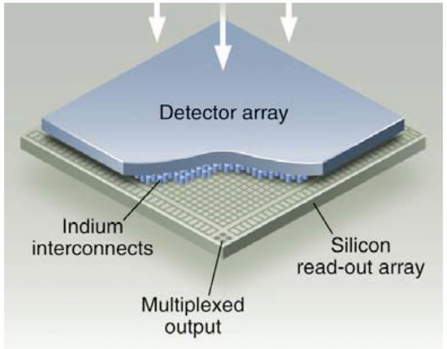
- One of the technical issue is that a NIR detector has to be cooled down to achieve low dark currents. In ground-based observation, LN_2 is used to cool a detector down below 100K. But a coolant cannot be used in a space mission. It is difficult to use a cryocooler because it causes significant disturbances and degrades image quality.

Quantum Efficiency of substrate-removed HgCdTe



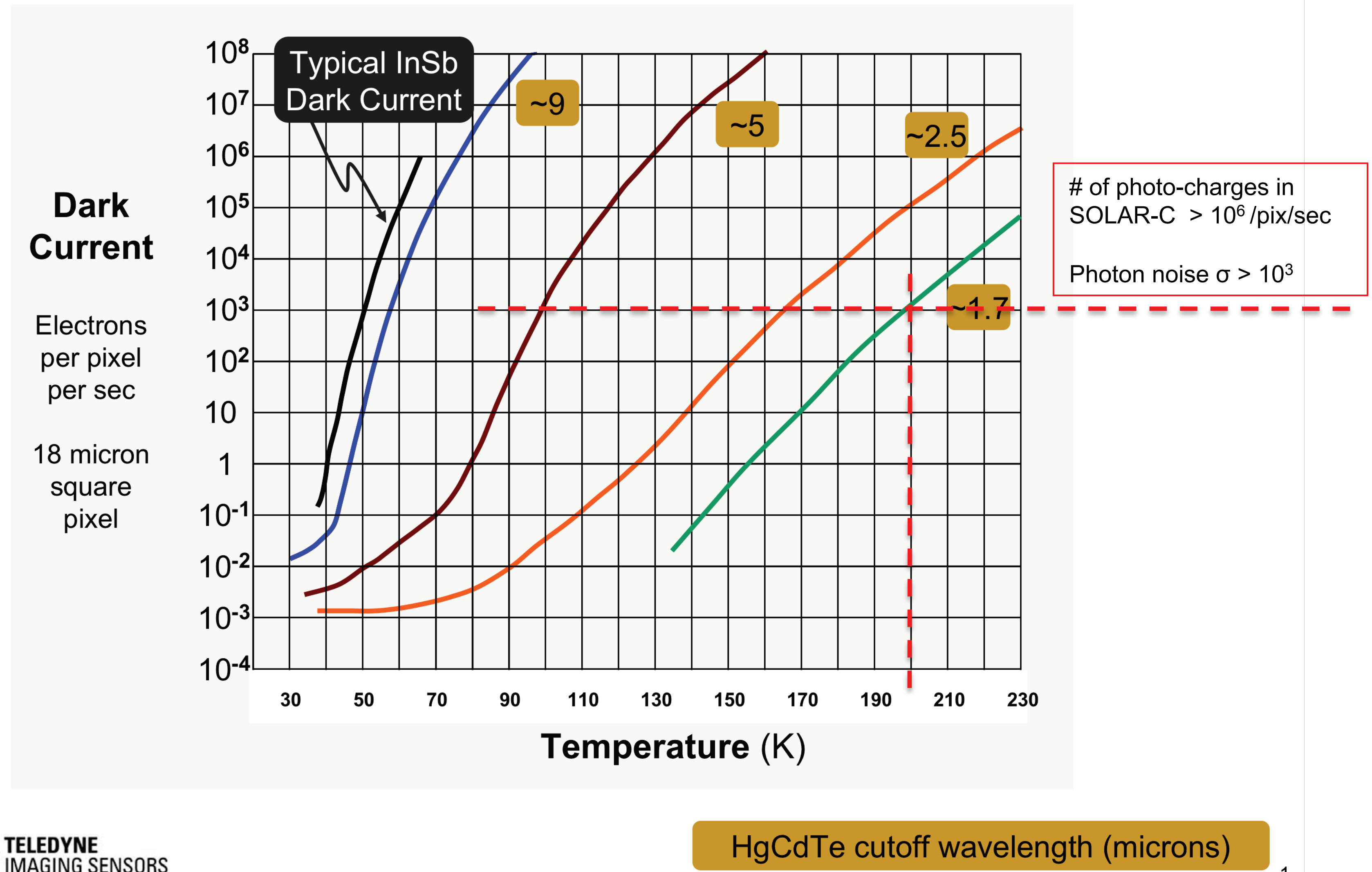


- Overall improved QE
  - Response to visible and UV
    - Less susceptible to cosmic rays
      - Eliminates fringing in substrate material



TELEDYNE IMAGING SENSORS
A Teledyne Technologies Company

Dark Current of MBE HgCdTe



TELEDYNE IMAGING SENSORS
A Teledyne Technologies Company

Requirements to the instruments

- Spatial resolution
  - ~0.2" for magnetic field diagnostics with high S/N (photon noise limited).
  - Diffraction limited resolution (0.05" with 1.5mφ) for intensity and velocity diagnostics with lower S/N.
- FOV
  - 200"x200" to cover medium size active region.
- Spectral resolution
  - $\lambda/\Delta\lambda>100{,}000$ to resolve thermal widths of chromospheric lines.
- Polarimetric sensitivity
  - Photometric sensitivity of $(1\text{-}3)\times10^{-4}$, instrument polarization calibrated with the order of 10^{-3}.
- Two dimensional spectroscopic capability
  - A single slit spectrograph is not adequate to investigate rapid evolution of chromospheric dynamics.

Effective area