The CLASP and CLASP2 Missions

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and CLASP and CLASP2 team

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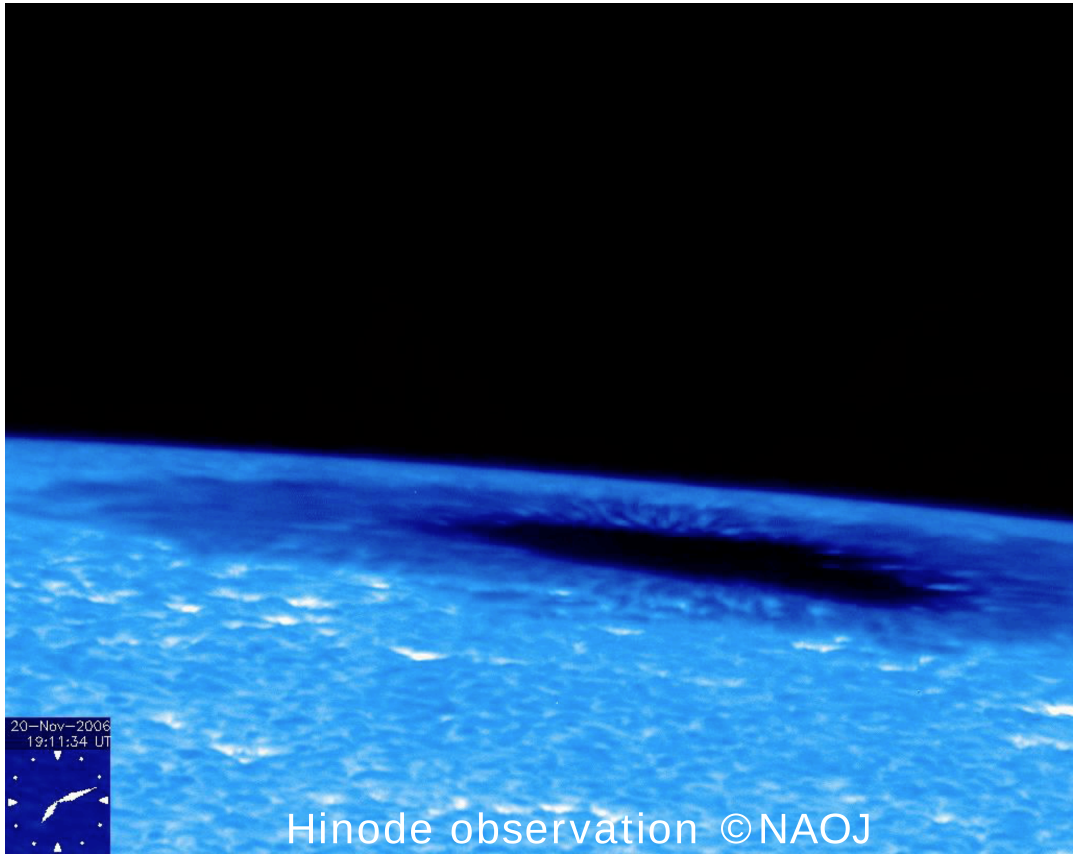
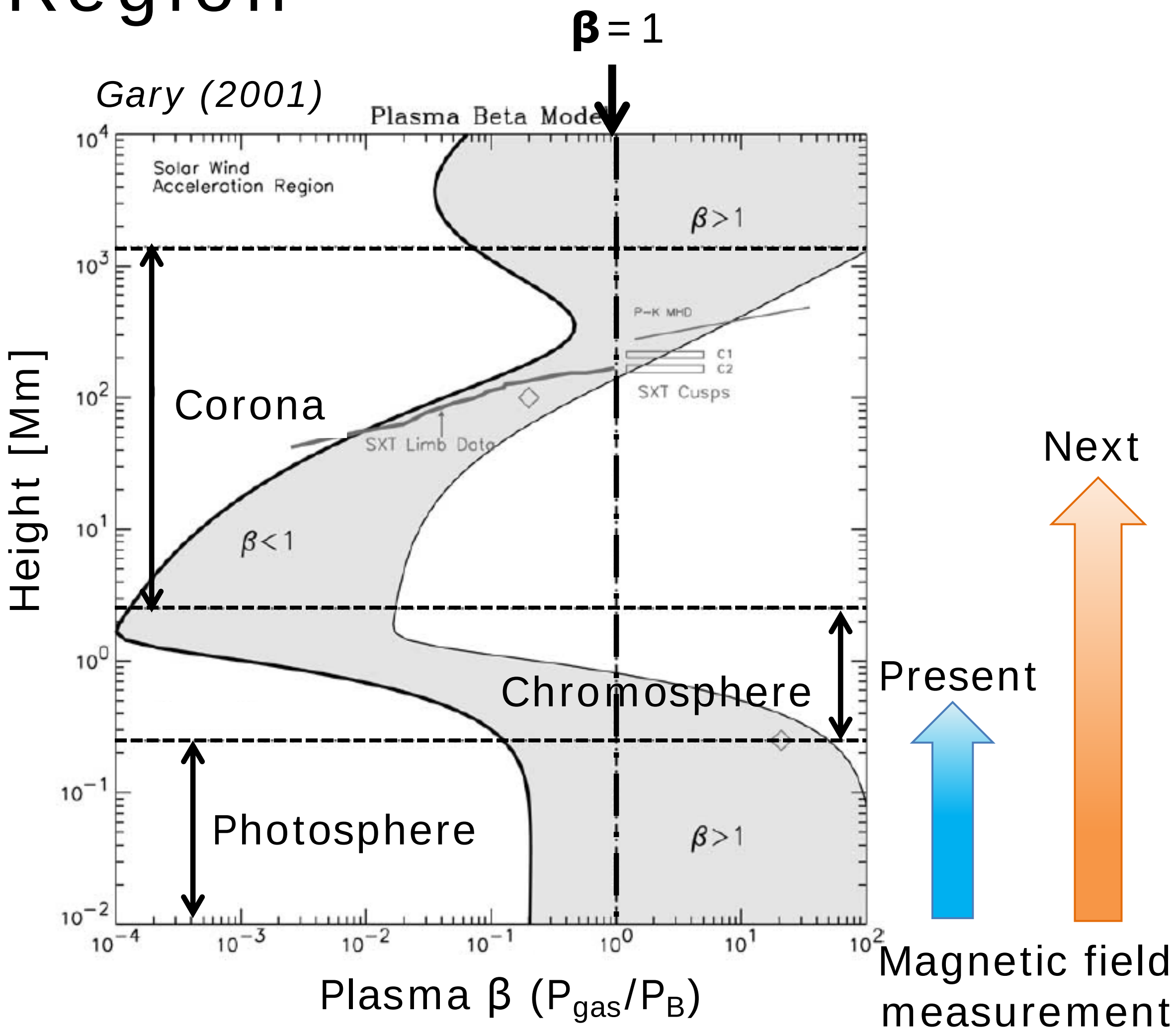
Growing Demand: Magnetic Field Measurement in β<1 Region



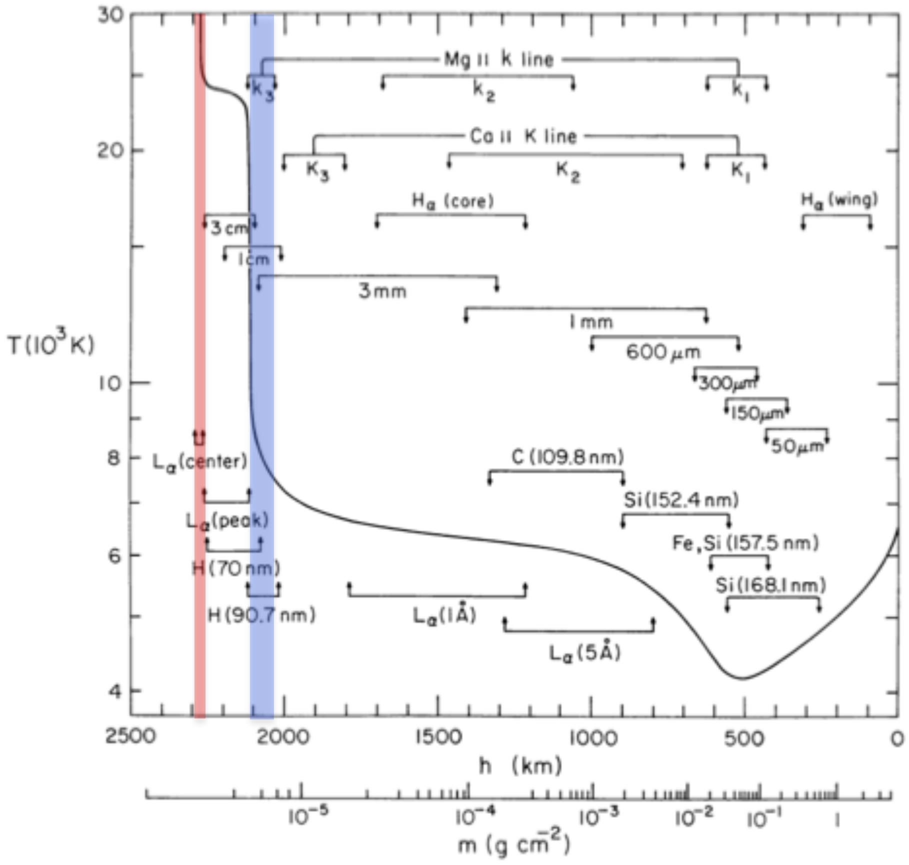
Quiet photosphere (β>1) → Dynamic chromosphere (β<1)

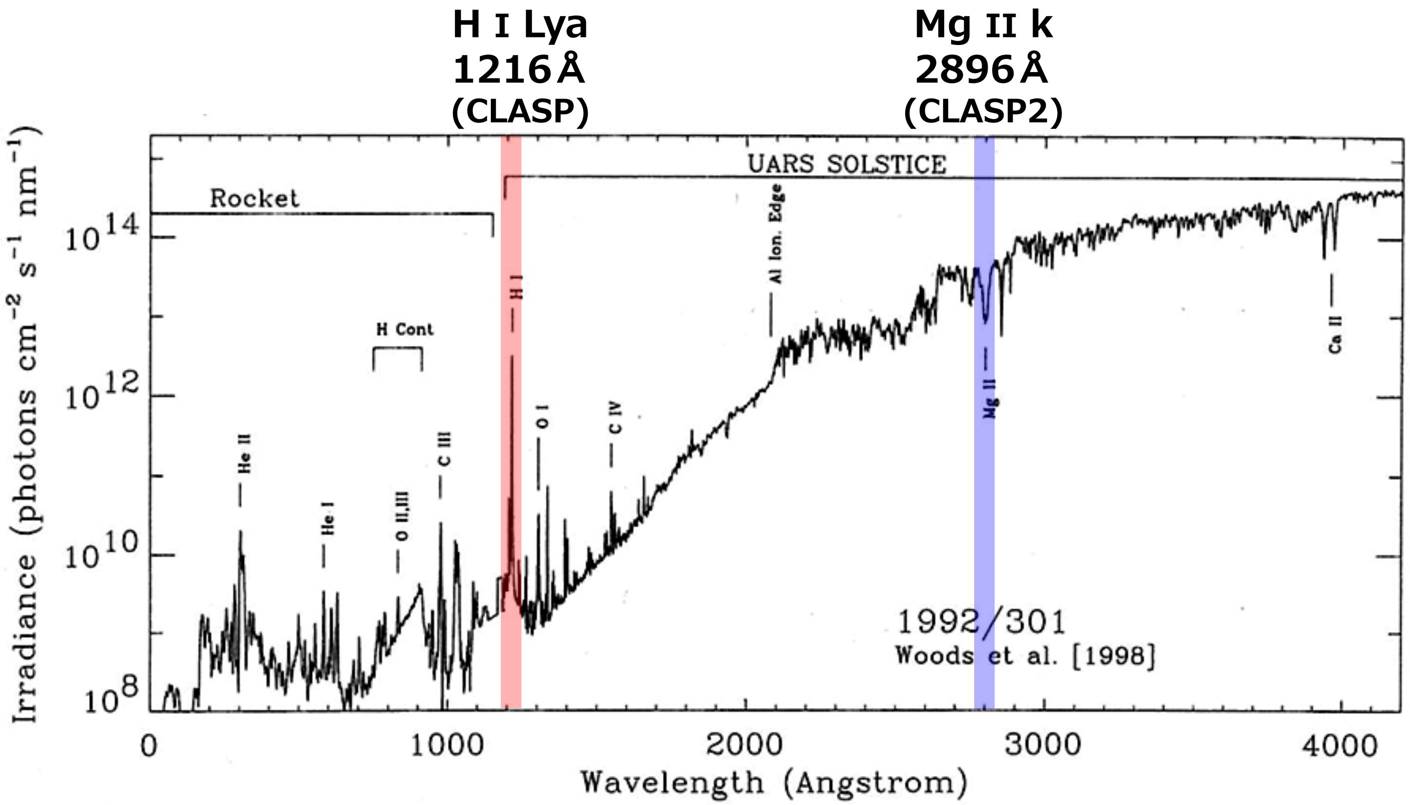


UV Spectral Lines

- Sensitive to physical properties at the layer where the temperature suddenly increases (upper chromosphere and transition region)

Vernazza+(1981)





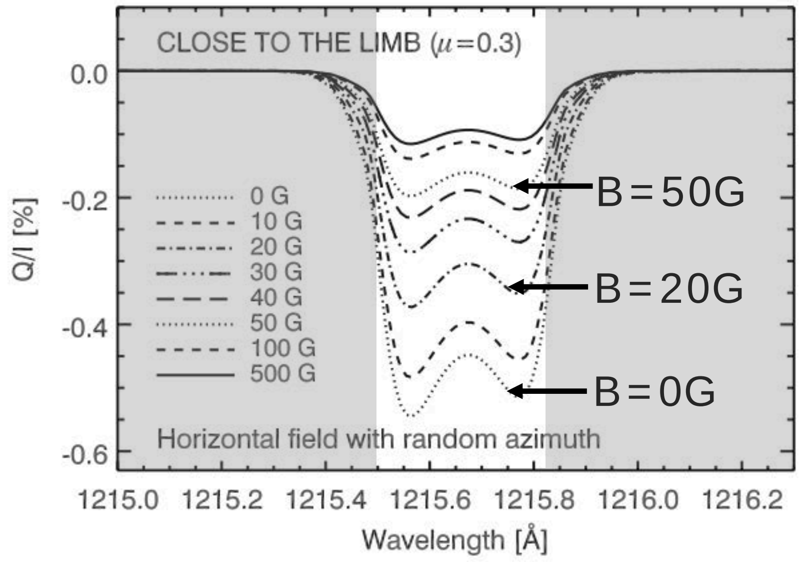
Compelling UV Spectral Lines: H I Lya & Mg II k

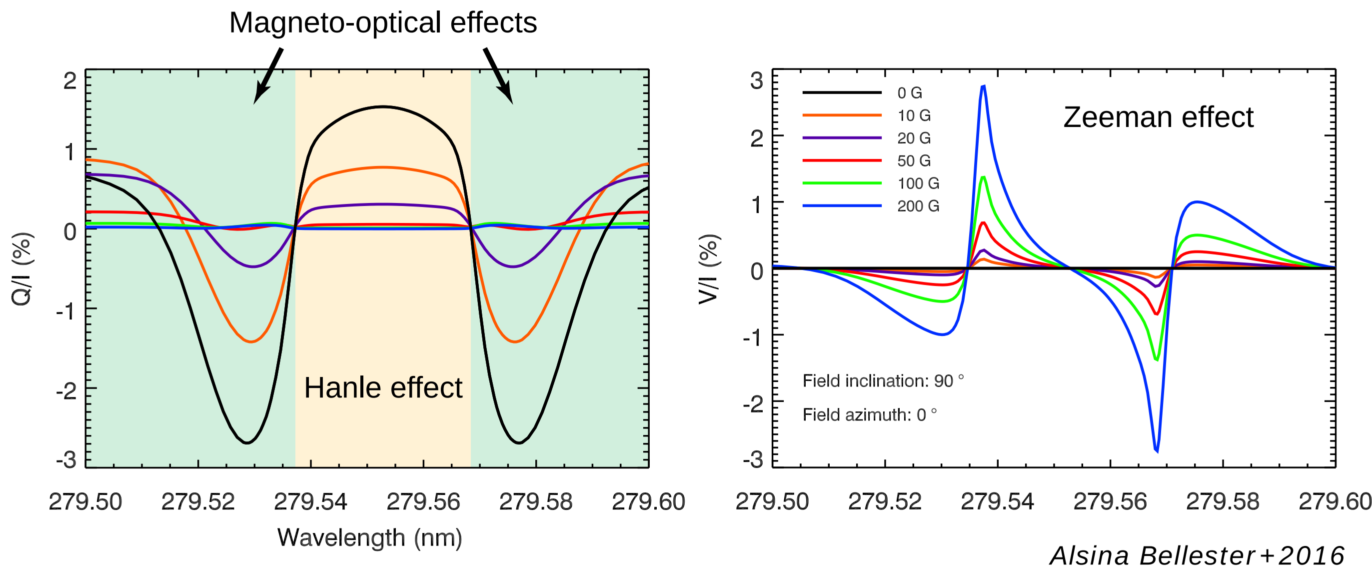
- Measurable scattering pol. (P_{LP}>0.1% at line core)

- H I Lya at 1215.7 A
  - Hanle effect at B>10G & B_H~50G
  - Access the transition region

- Mg II k at 2896 A
  - Hanle effect at B>5 G & B_H~25G
  - Stokes-V induced by Zeeman

Trujillo Bueno+ 2011



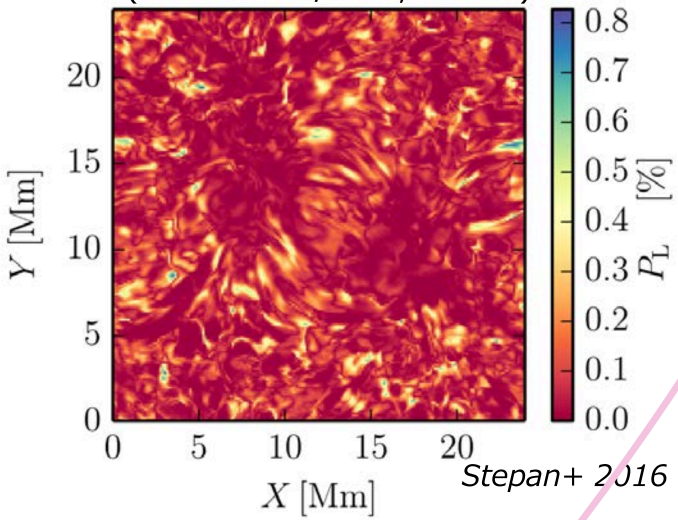


Alsina Bellester+2016

A New Window to Access the Base of Corona

(DKIST coronagraph)

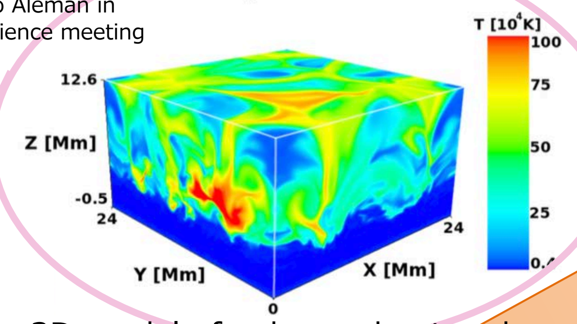
Ca II 8542 Å
(SUNRISE-3/SCIP, DKIST)



Stepan+ 2016

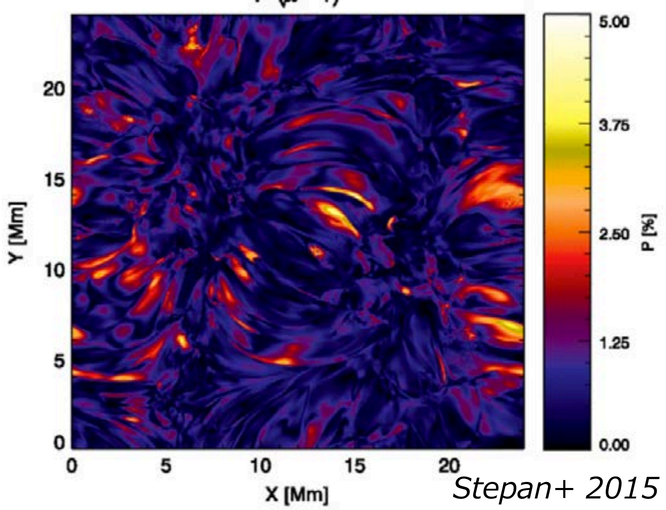
Mid-Chromosphere

Adopted from presentation by del Pino Aleman in CLASP2 science meeting



3D model of enhanced network
(Carlsson+2015)

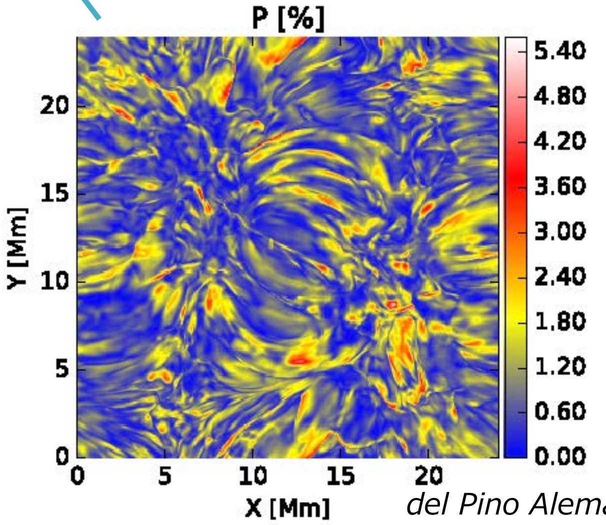
H I Lya 1216 Å (CLASP)



Stepan+ 2015

Transition Region

Mg II k 2896 Å (CLASP2)



del Pino Aleman+

Up-Chromosphere

Ca I 4227 Å
(SUNRISE-3/SUSI
DKIST?)

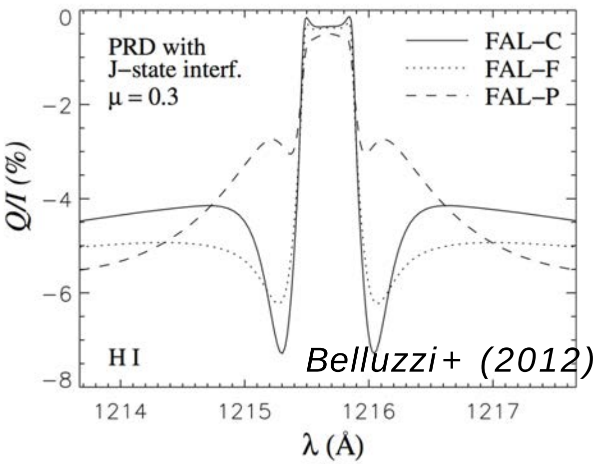
Ca II k 3933 Å
(SUNRISE-3/SUSI)

Challenges in UV Spectro-Polarimetry

NO definitive previous measurements!

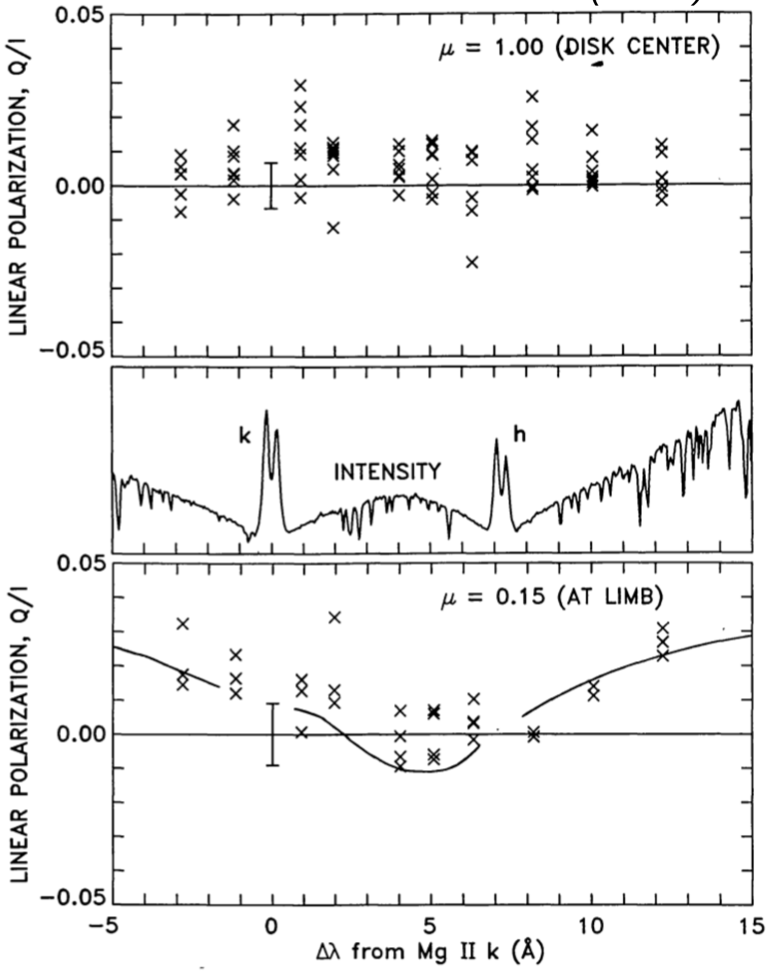
- Observations from space
- High-precision (~0.1%) in UV
  - Limited number of photons
  - No commercial polarimeter
- Interpretation of scattering polarization
  - Stratification of atmosphere
  - Local anisotropy

<u>Final Goal</u>: Use Hanle effect (modification of scattering pol. by magnetic field) to diagnose the magnetic field



Belluzzi+ (2012)

Whenz and Stenflo (1987)



Measurement by UVSP aboard the Solar Maximum Mission satellite

CLASP (2015) & CLASP2 (2019)

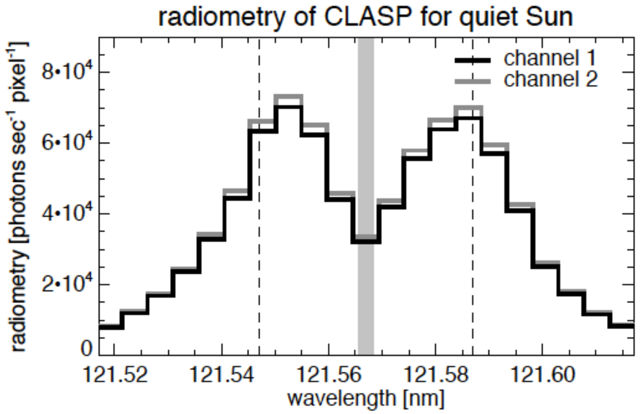
CLASP: **C**hromospheric **L**yman-**A**lpha **S**pectro-**P**olarimeter
CLASP2: **C**hromospheric **LA**yer **S**pectro-**P**olarimeter

- High-precision (<0.1%) spectro-polarimetery in
  - Vacuum UV, H I Lyα, at 121.6 nm with CLASP
  - Near UV, Mg II h & k around 280 nm with CLASP2

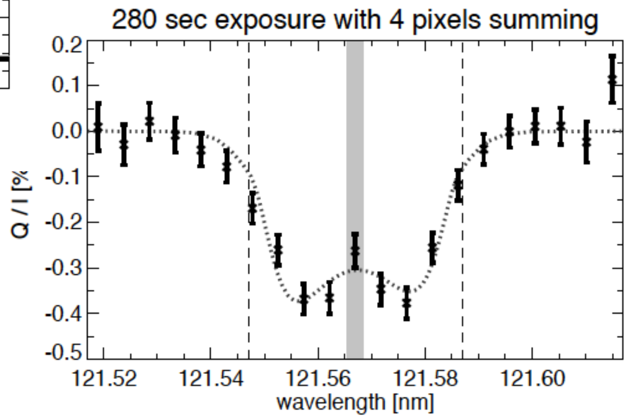
- International NASA sounding rocket programs
  - Launched at White Sands Missile Range, NM, USA
  - Successful recovery of instrument: CLASP → CLASP2

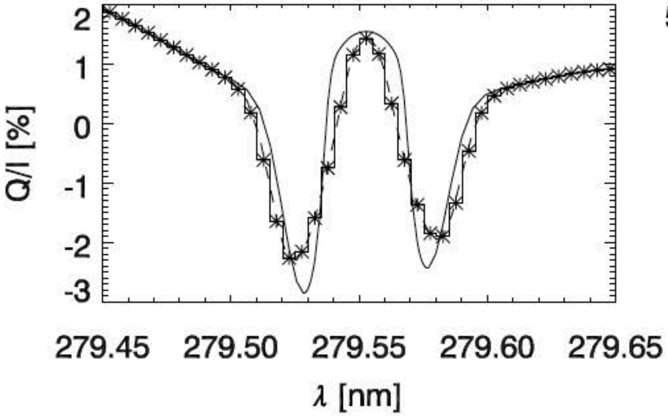
Credit: US Army Photo, White Sands Missile Range

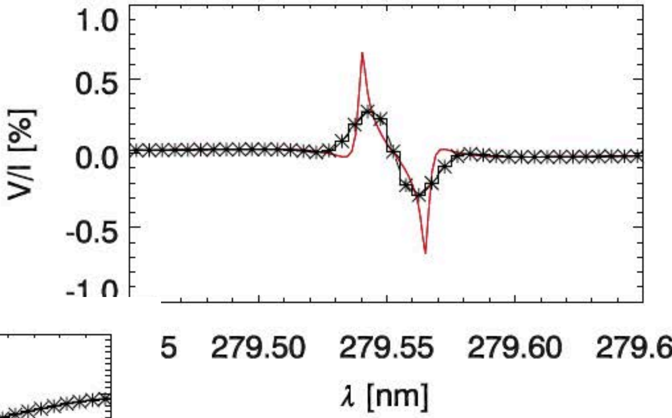
Specifications



CLASP1
wavelength sampling:
0.048 A/pix



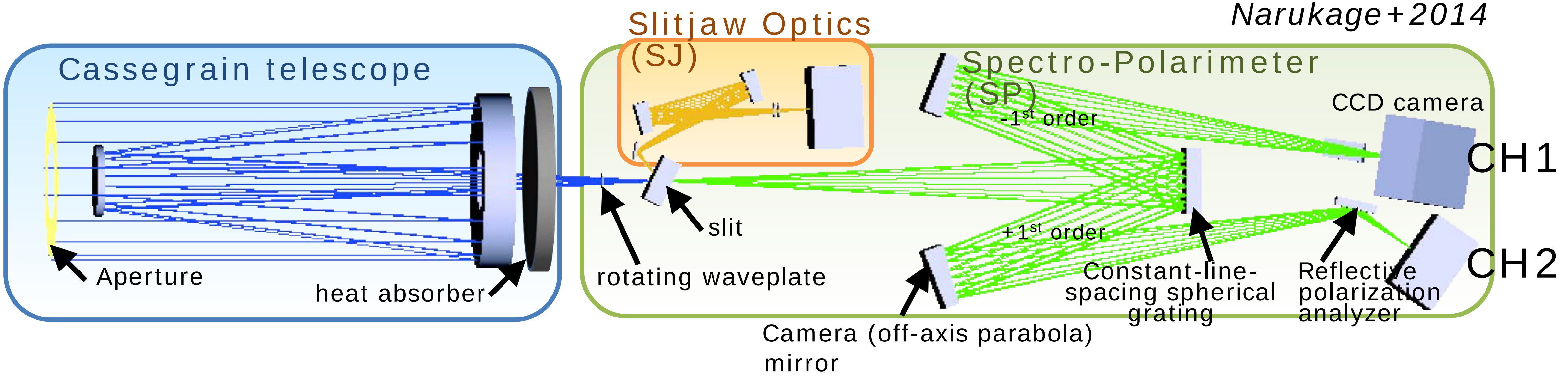




CLASP2
wavelength sampling:
0.05 A/pix

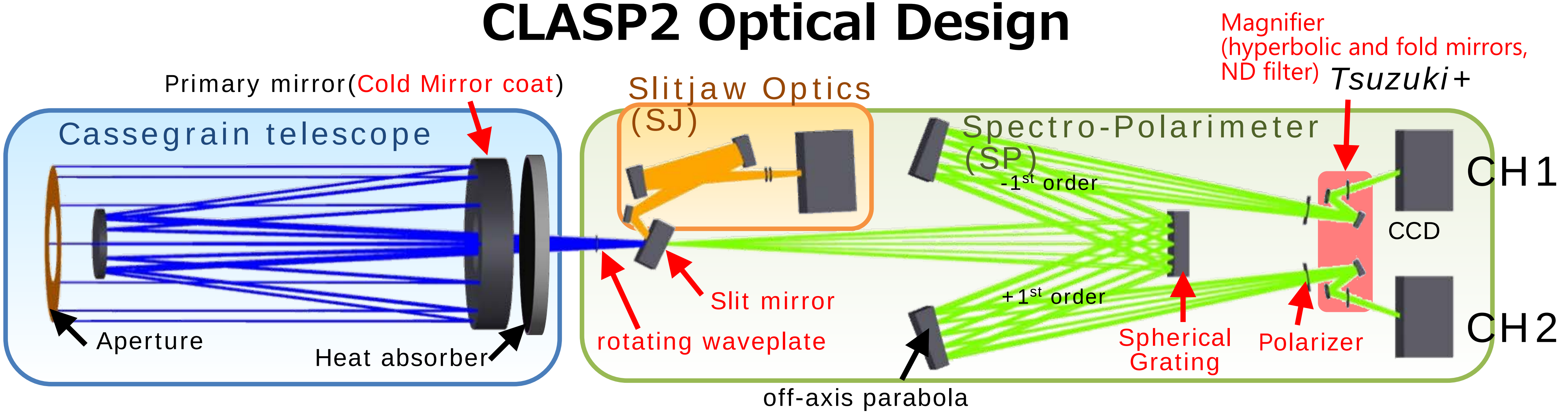
	CLASP	CLASP2
Observables	Stokes-I, Q, U	Stokes-I, Q, U, V
Spectral Lines	Lya (121.6 nm)	Mg II h & k at 280.0 nm
Resolutions	0.1A (wavelength) & 2-3” (spatial)	0.1A (wavelength) & 2” (spatial)
Slit Length	400”	200”
Science Target	Quiet Sun near the limb	Quiet Sun near the limb & Plage
Pol. Precision	0.1% at 3σ	

CLASP Optical Design



- Two symmetric channels: CH1 & CH2
  - Simultaneously measure orthogonal polarization states
- High throughput in VUV
  - Minimize number of optical components
    - Grating working as a beam splitter as well
  - High-reflectivity coating to all optical components *(Narukage+2017)*

CLASP2 Optical Design



- Two symmetric channels: CH1 & CH2
  - Simultaneously measure orthogonal polarization states
- High throughput in VUV
  - Minimize number of optical components
    - Grating working as a beam splitter as well
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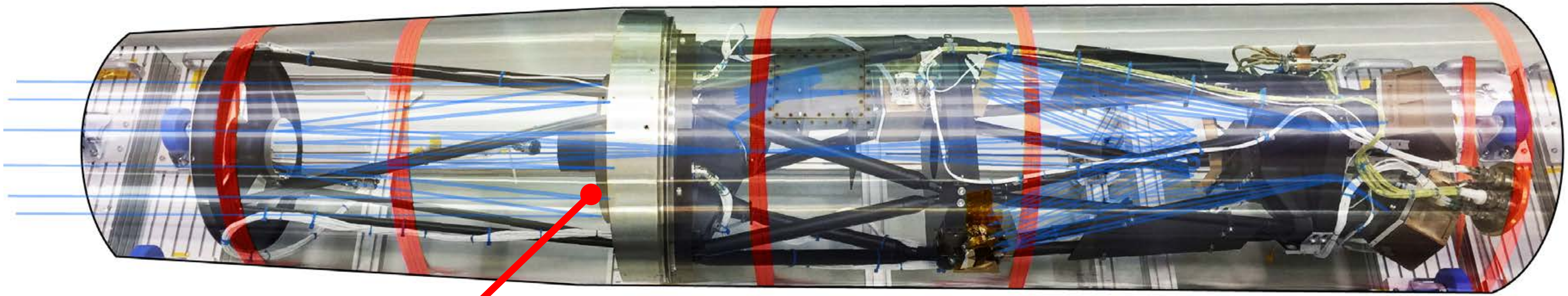
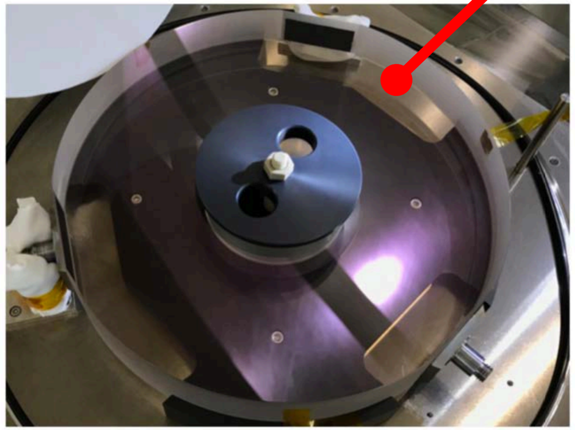
Visible Light Rejection

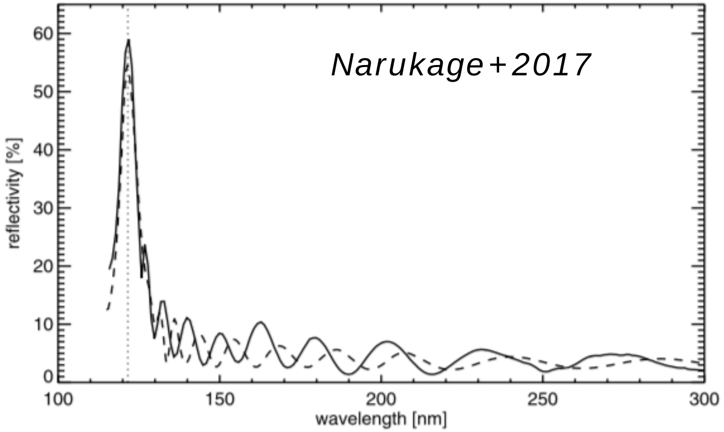


- Cold mirror coatings & heat absorber on the primary mirror
- Black plated to all structures.



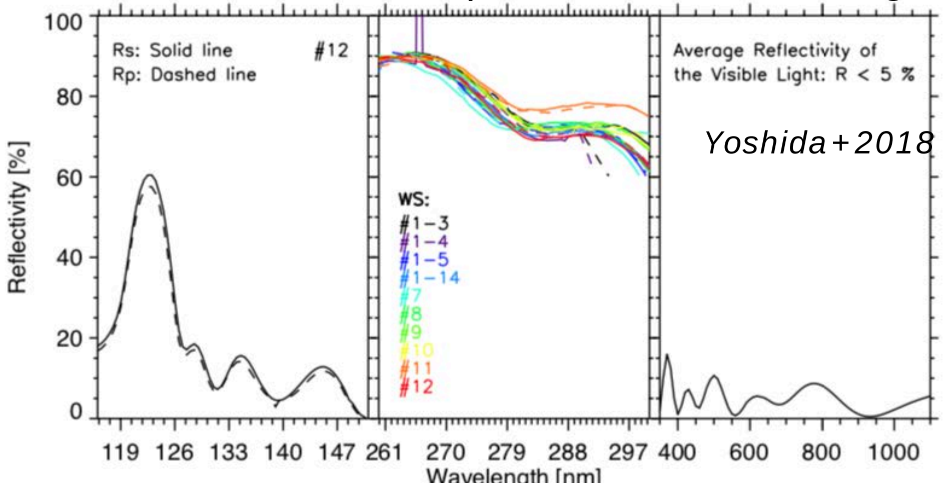
CLASP2 primary mirror

CLASP: Cold mirror coating at 121 nm



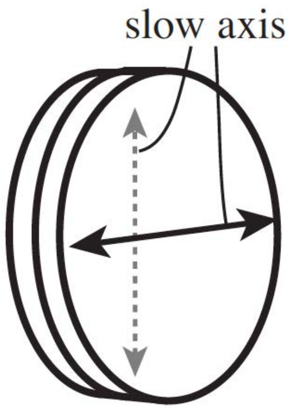
Recoat

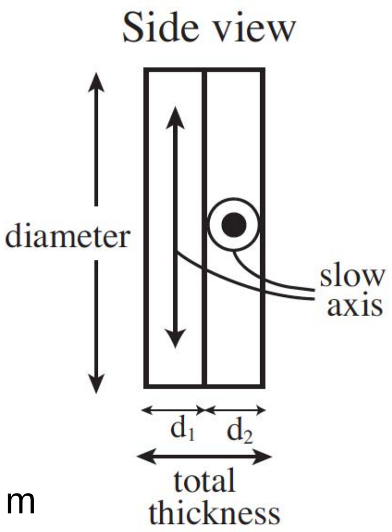
CLASP2: Dual-bandpass (121 nm for SJ & 280 nm for SP) cold mirror coating



High-Precision UV Polarimeter - MgF_2 waveplate -

Optical contact zero-order waveplate



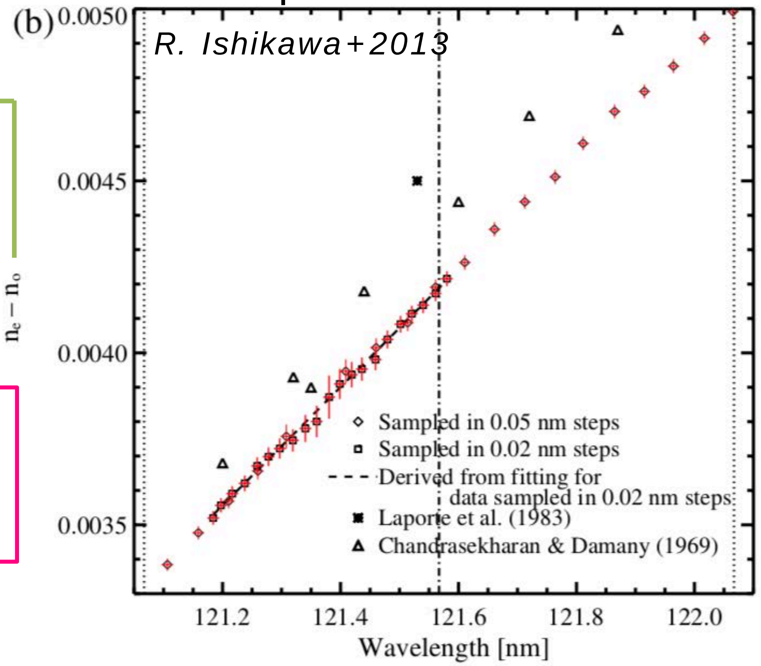


ϕ30 mm
$d_1+d_2=1$ mm

$$\delta = \frac{2\pi\,(n_e - n_o)(d_1 - d_2)}{\lambda}$$

Target retardation (δ)
- CLASP: 180° for Q/U
- CLASP2: 127°(233°) for Q/U/V

MgF_2 Bi-refringence around Lya
updated in decades



- The birefringence was precisely measured around 121.6 nm (2009 - 2013) and 280 nm (in 2016) at the synchrotron facility
  - CLASP half-waveplate was found to have the suitable phase retardation of ~234° around 280 nm. We decided to keep the CLASP waveplate in CLASP2.
  - The measured bi-refringence was also used to fabricate the waveplates for polarization calibration.

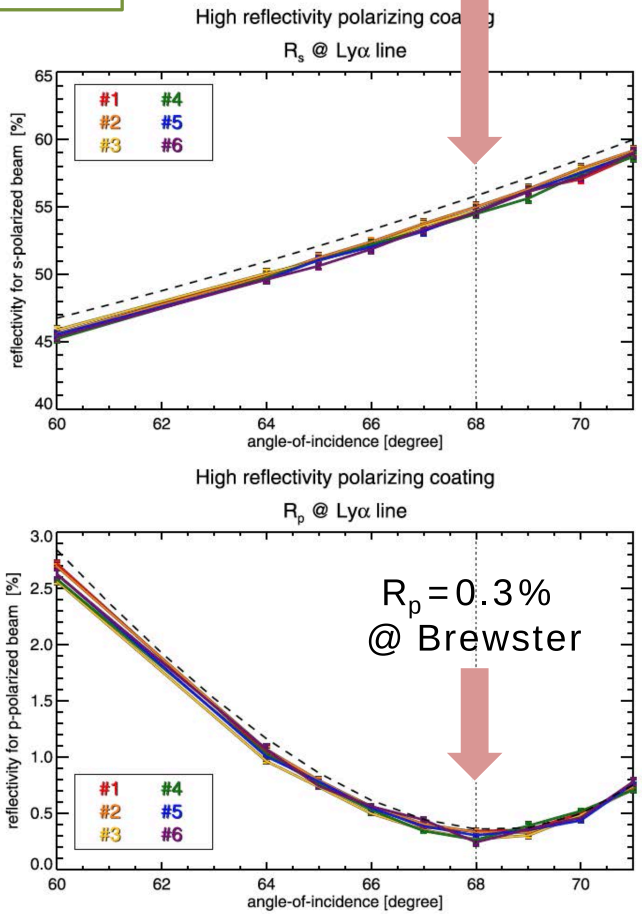
High-Precision UV Polarimeter - polarization analyzer -

High-Reflective Type (CLASP, 122 nm)

Original plan: MgF_2 plate at Brewster, R_s~21%

Two-layer coating on fused silica substrate (72 x 33 mm)

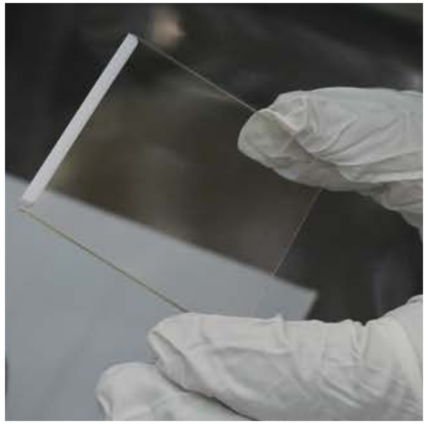
Bridou+ 2011
Narukage+ 2017



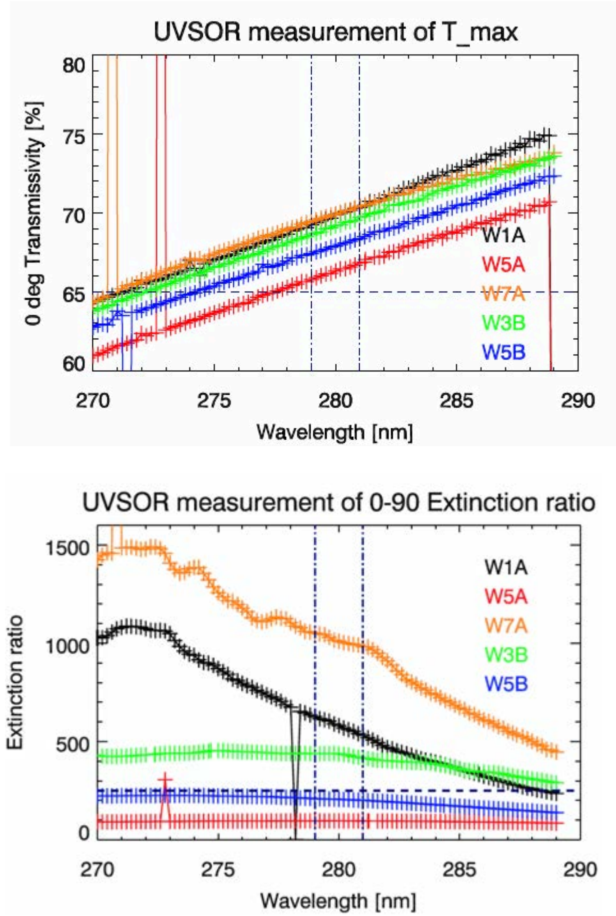
Transmissive Type (CLASP2, 280 nm)

Wire-grid UV polarizer (*Berger+2012, for IRIS SOLC filter*)

Transmissivity: $T_{\parallel}$~70%
Extinction ratio: $T_{\parallel}/T_{\perp}$>500



Substrate: Fused Silica
- 50 x 50 mm, t=1mm

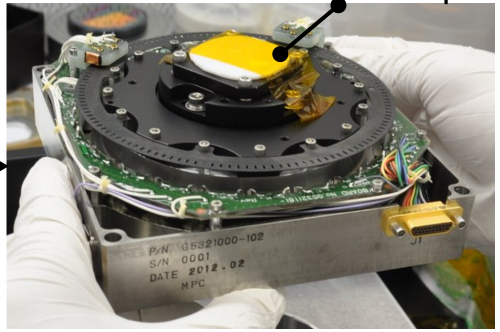


High-Precision UV Polarimeter - Polarization Modulation Unit -

Send exposure trigger every 22.5°

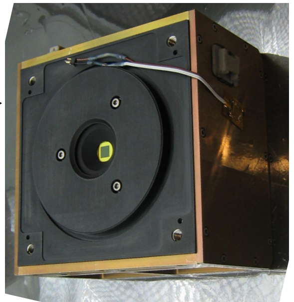
PMU-DRV

continuously rotate
CLASP: 4.8 s/rot
CLASP2: 3.2 s/rot

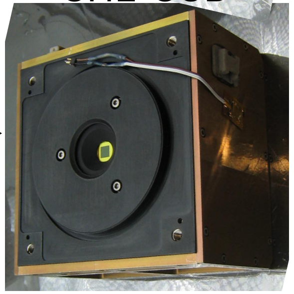


PMU-ROT

CH1 CCD



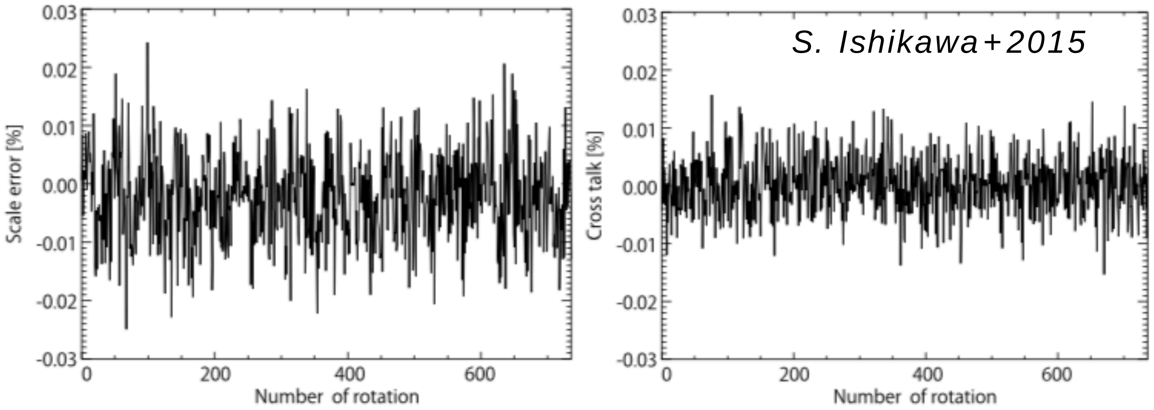
CH2 CCD



- Frame transfer
- Lumogen-E coating
- Low readout noise (6e- rms)

Champey+2014, 2015

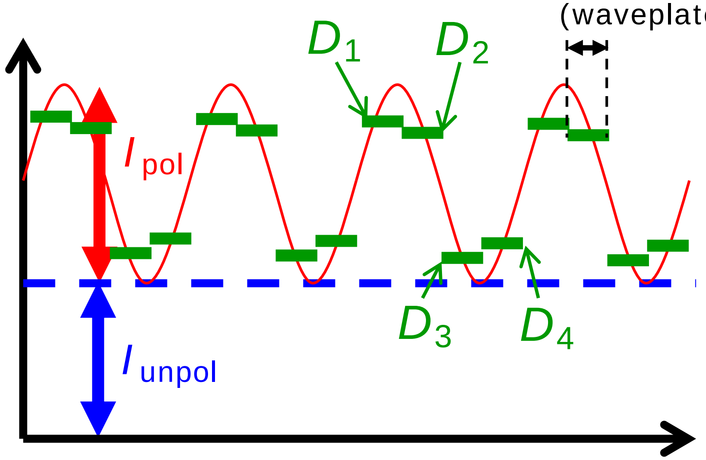
Being a key factor for precise polarimetry in space
Solar-C/SUVIT→CLASP&CLASP2→SUNRISE-3/SCIP&SUSI



Scale error and cross talk due to non-uniformity<0.01%!

Modulation measured by CCD

0.3/0.2 sec in CLASP/CLASP2 (waveplate rotation of 22.5°)



Error Budget Control

- List up and evaluate all possible source of errors and confirm that the polarization precision of ~0.1% can be met at 3σ level.

Error breakdown for spurious polarization	Error (1σ)
Photon noise with nine-pixel summing	0.019 %
Readout noise of CCD camera	0.007 %
Fluctuation of exposure duration	10^{-4} % †
Time variation of source intensity	≲ 0.018 %†
Intensity variation caused by pointing jitter	≲ 0.023 %†
Image shift from waveplate rotation	≈ 0 %†
Off-axis incidence with 200 arcsec	≈ 10^{-4} %
Non-uniformity of coating on primary mirror	10^{-3} %
Error in polarization calibration	0.017 %
Root-sum-square	≲ 0.039 %

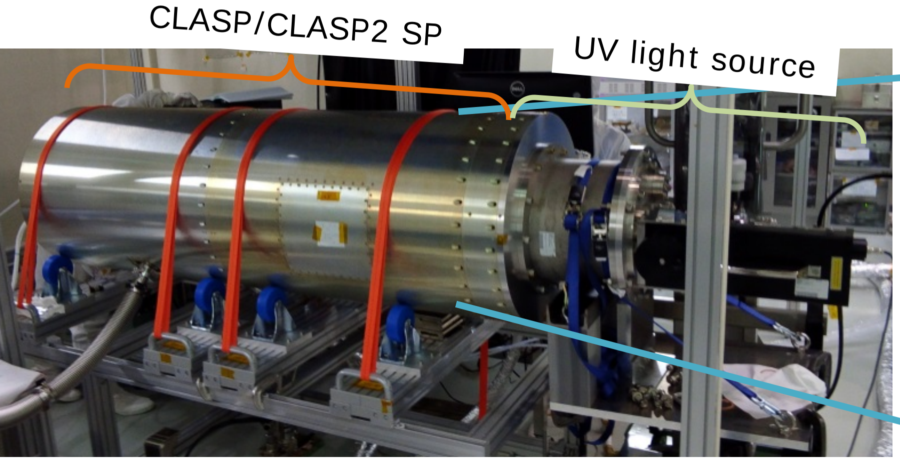
Estimation with single channel demodulation (i.e., worst case) [applies to the four † rows]

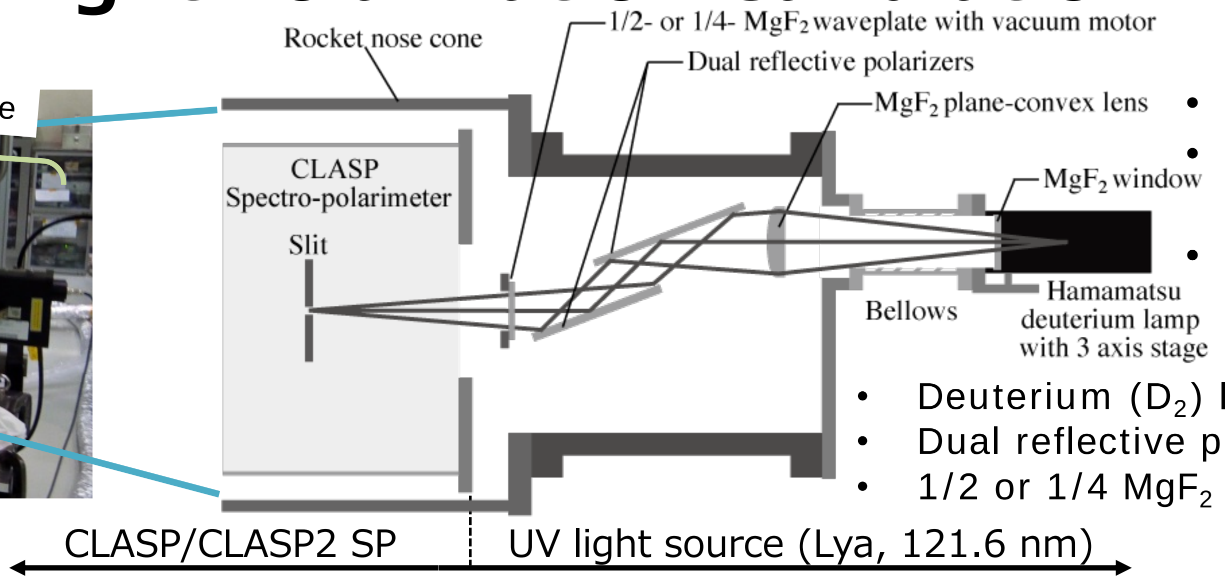
Spurious pol. due to telescope is negligibly small [applies to the off-axis and coating rows]

R. Ishikawa+2014

See *Giono+2016* for results of CLASP pol. calibration

Pre-Flight Polarization Calibration



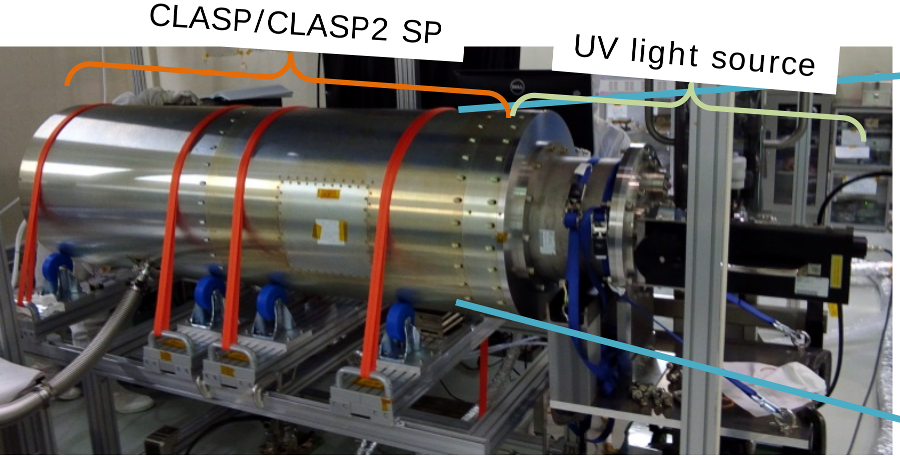


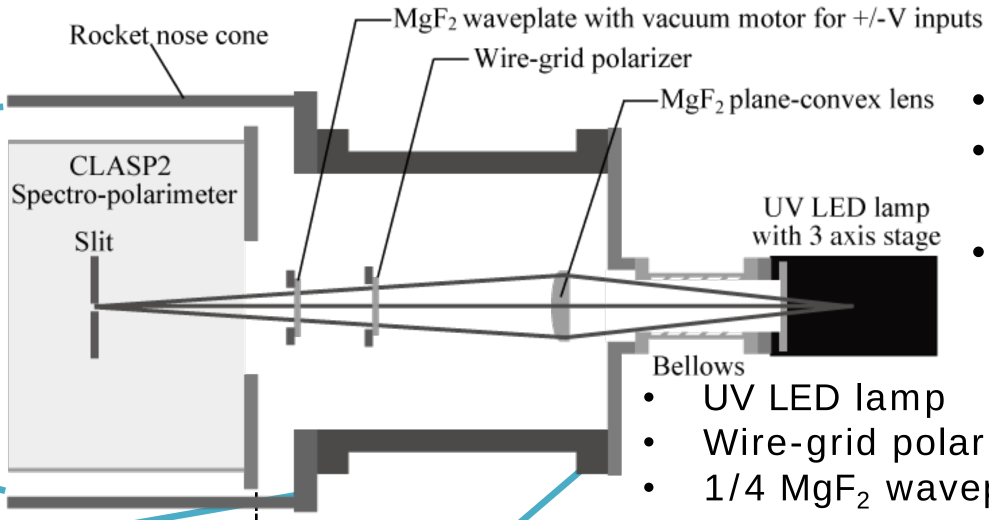
- Same F as telescope
- Linear & circular pol. inputs with p>0.99
- Polarization elements are on vacuum motor

- Deuterium (D_2) lamp
- Dual reflective polarizers
- 1/2 or 1/4 MgF_2 waveplates

See Poster 95 *Song*+ for results of CLASP2 pol. calibration

Pre-Flight Polarization Calibration



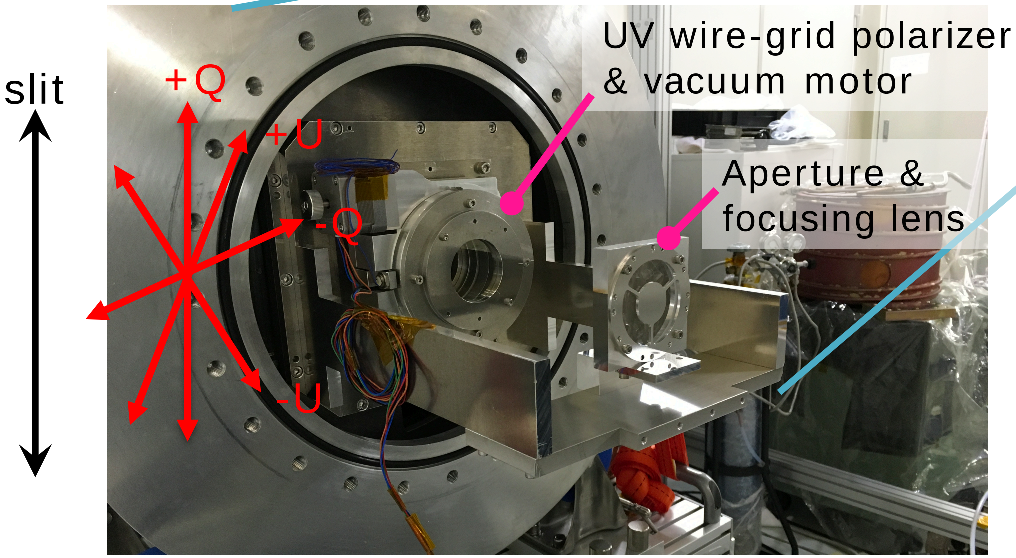


- Same F as telescope
- Linear & circular pol. inputs with p>0.99
- Polarization elements are on vacuum motor

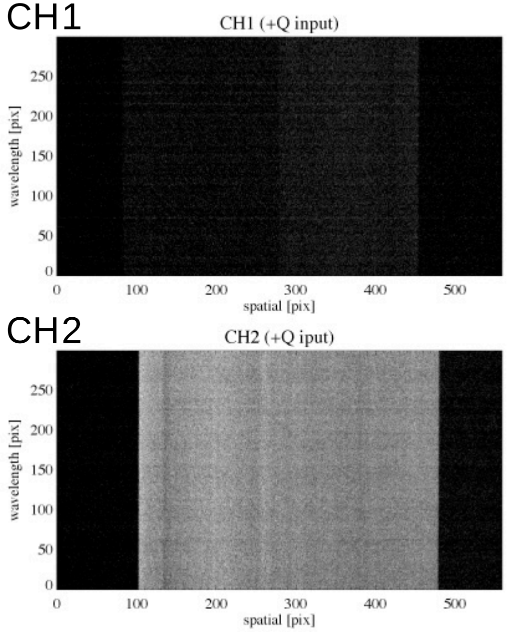
- UV LED lamp
- Wire-grid polarizer with higher ER
- 1/4 MgF_2 waveplate

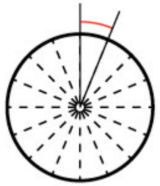
CLASP/CLASP2 SP | UV light source (Mg II h & k, 280 nm)

CLASP2 light source chamber



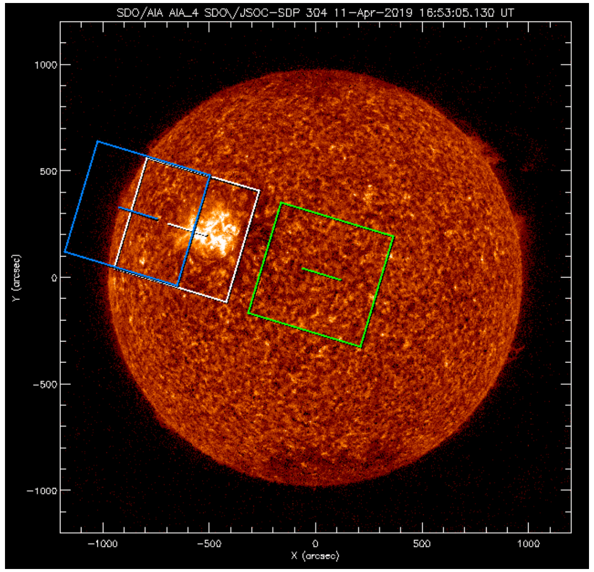
Example of modulation (+Q input)

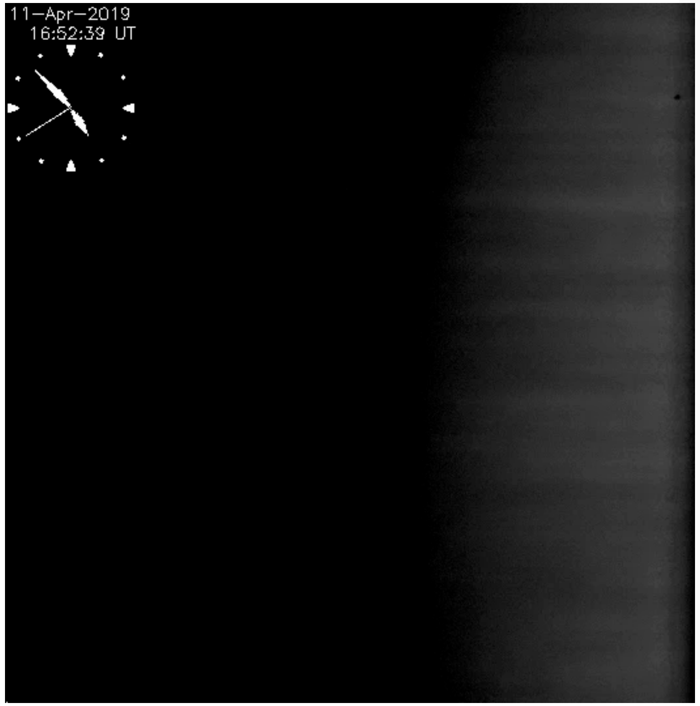




waveplate rot. & exposure (every 22.5°)

Strategies for High-Precision UV Spectro-Polarimetry

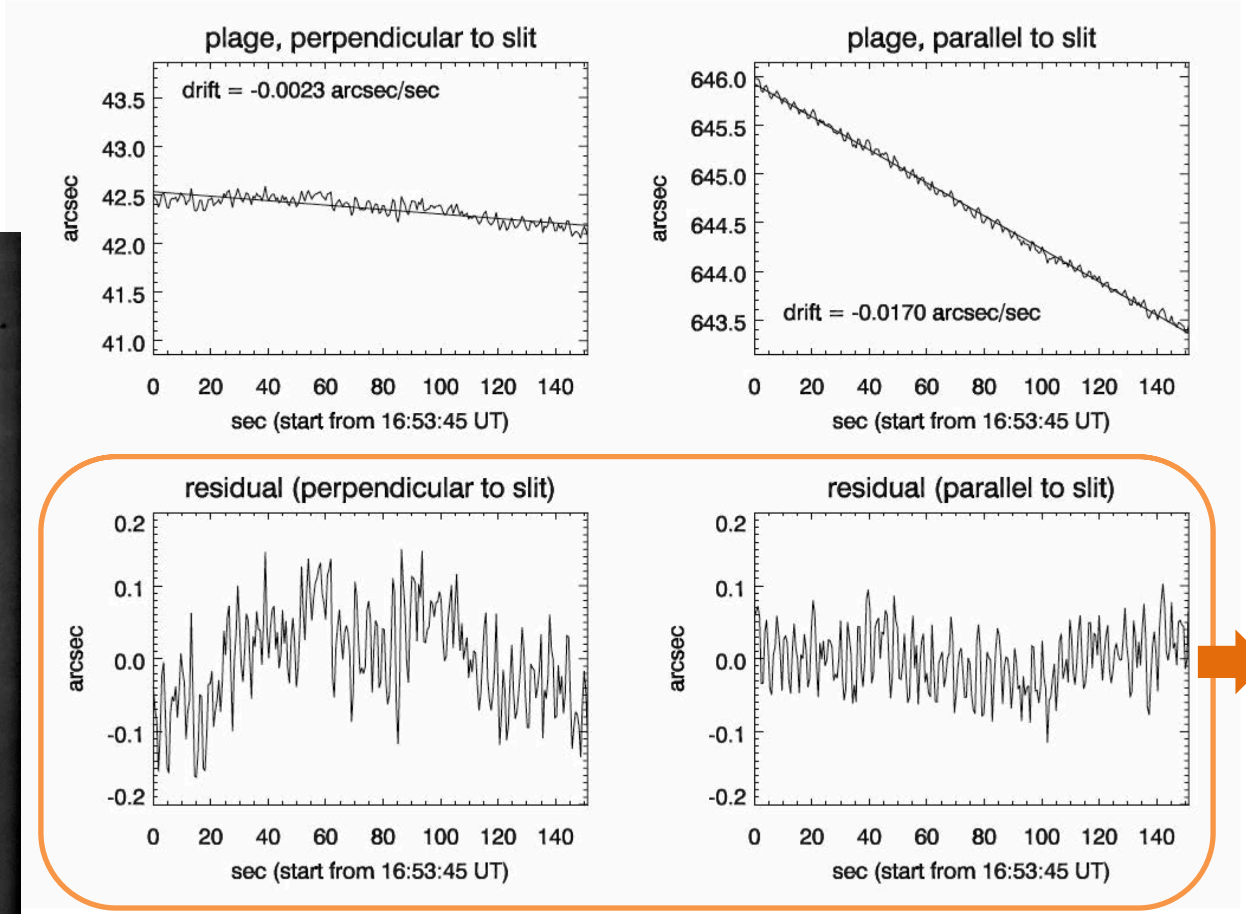




CLASP2/SJ movie

Perfect Flight!
- Stable Pointing -

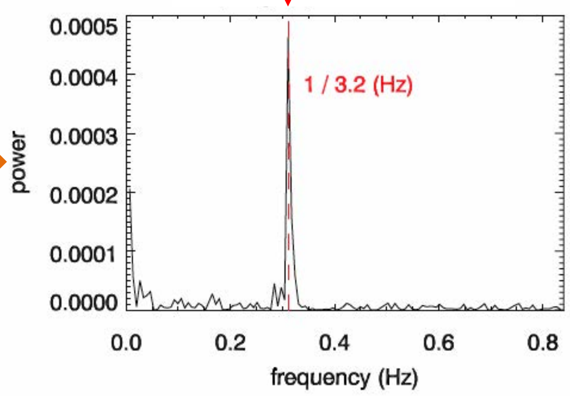
- Drift ~ 1″/min & Jitter << +/-0.1″ (P-V)



April 11, 2019 at 16:51UT

Credit: US Army Photo, White Sands Missile Range

3.2 sec = PMU rotation
Jitter mainly comes from the waveplate wobbling



On-board Polarization Calibration

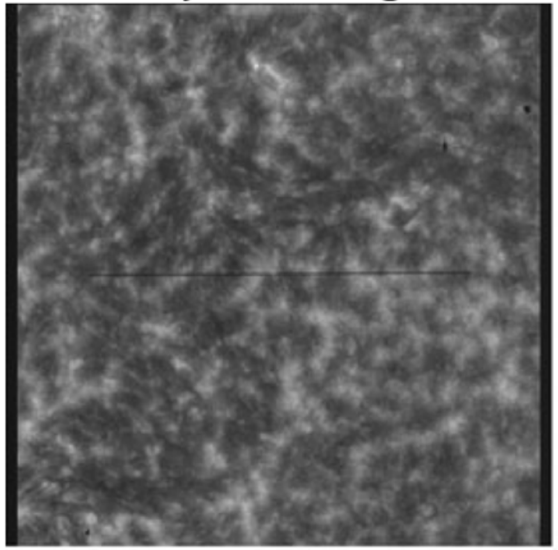
Confirmation of zero-level with the disk center observation

CLASP (Lya obs.)

Measured spurious pol.
< 0.03 ± 0.014 %

Giono+2017

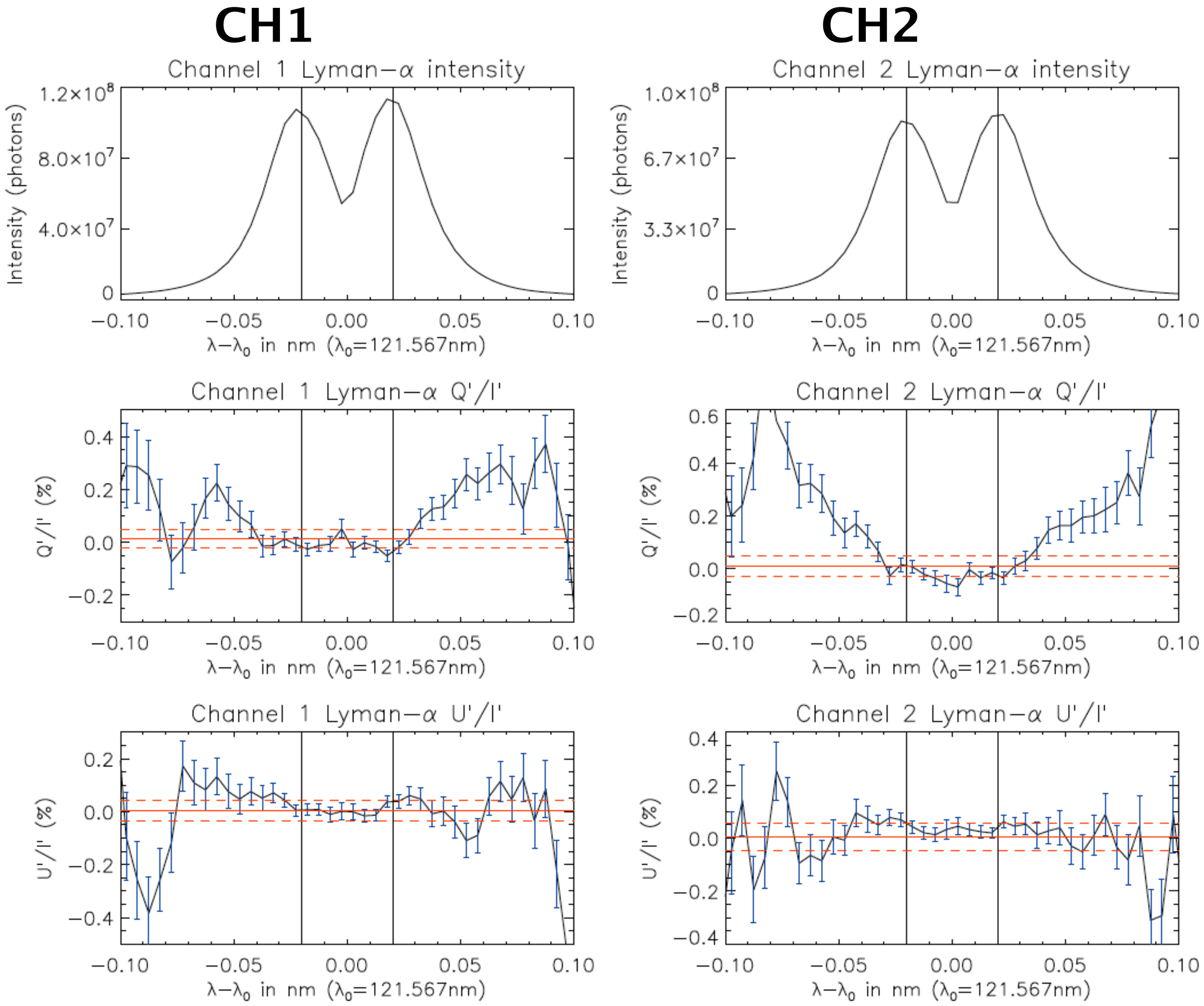
Slit-jaw images



Scattering polarization at the disk center is expected to be zero because of the geometry

spatially (~400”) and temporally (3 PMU rot.) averaged Q/I

spatially (~400”) and temporally (3 PMU rot.) averaged U/I

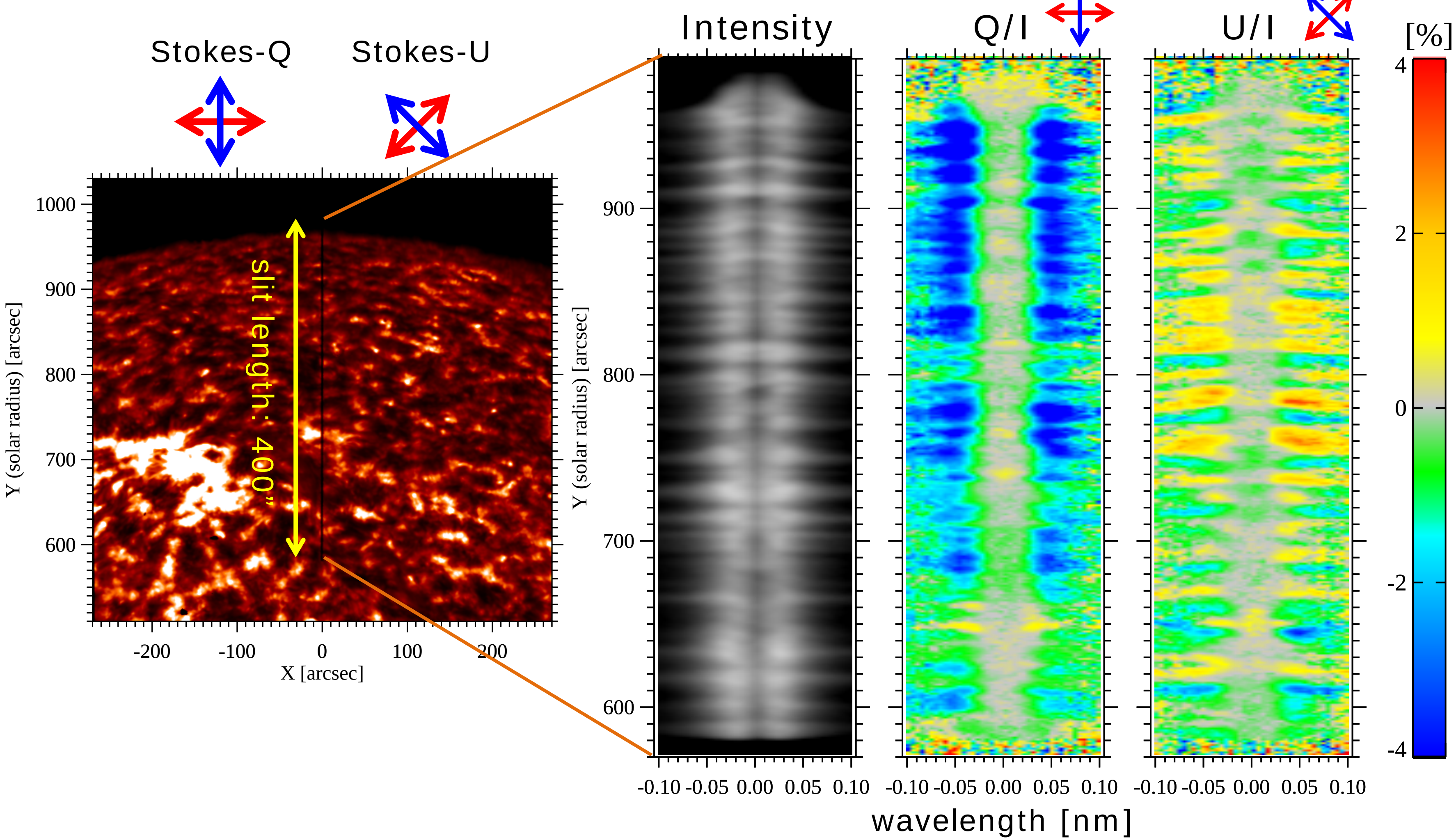


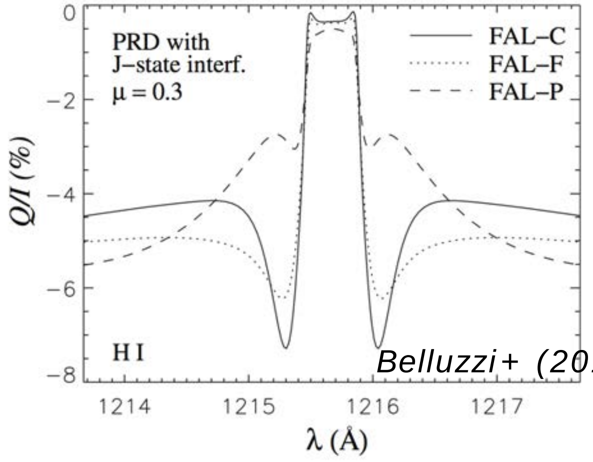
CLASP Science Highlights (Polarimetry)

First Detection of Scattering Pol. in VUV

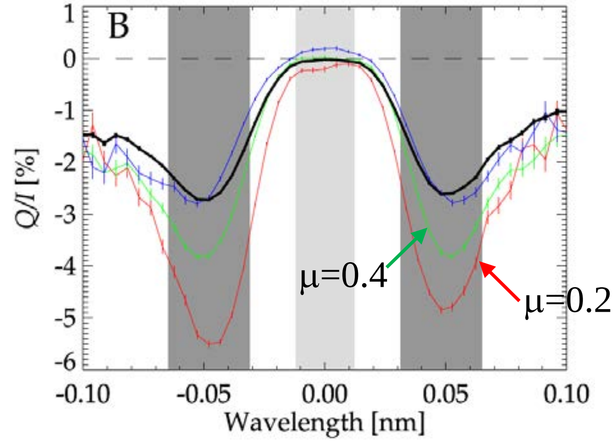
Lya wing (scattering pol. ONLY)

Clear CLV up to 6% in Q/I
Fluctuating at a few% at ~10” both in Q/I and U/I





Belluzzi+ (2012)

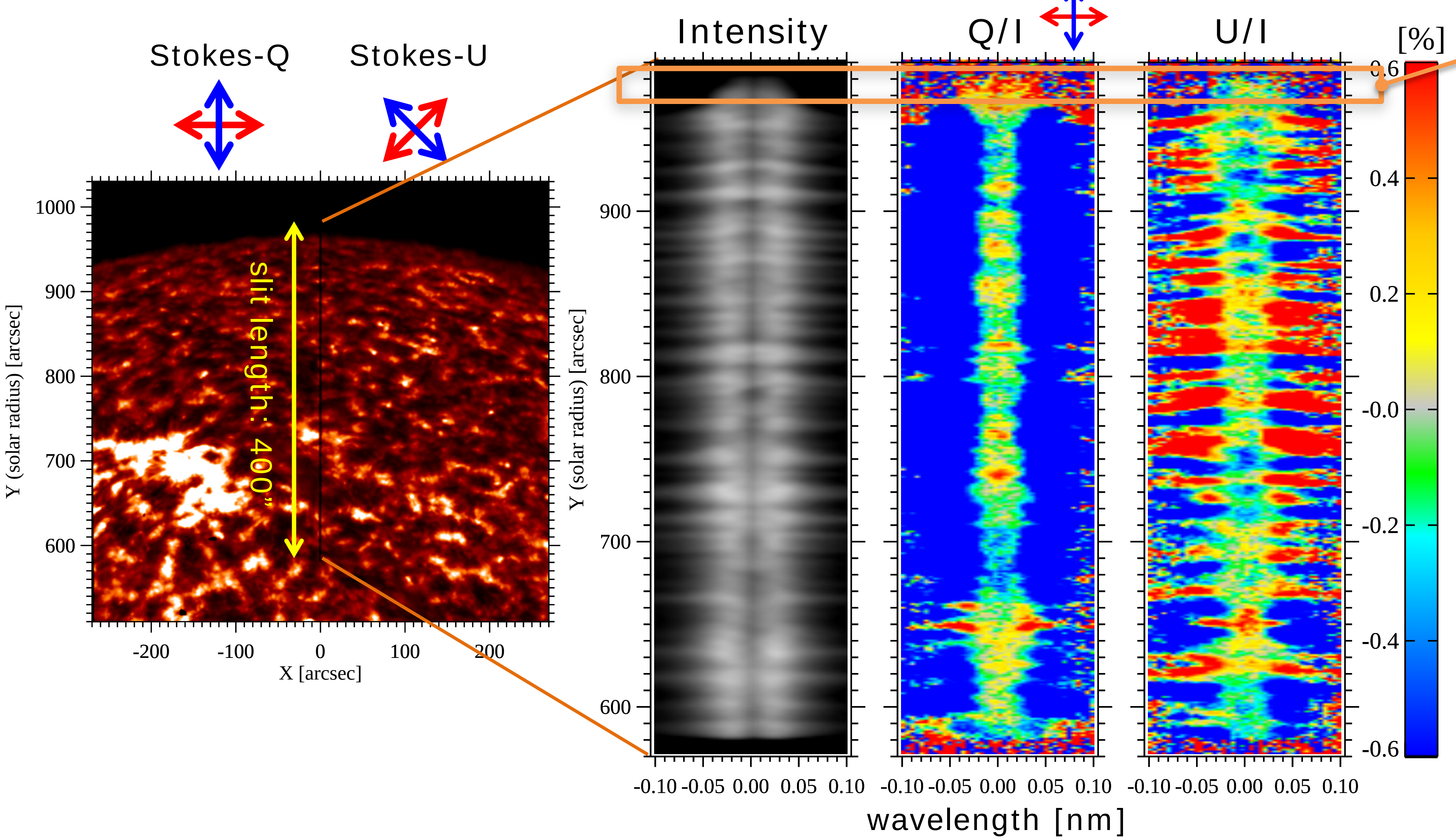


Kano+ (2017)

First Detection of Scattering Pol. in VUV

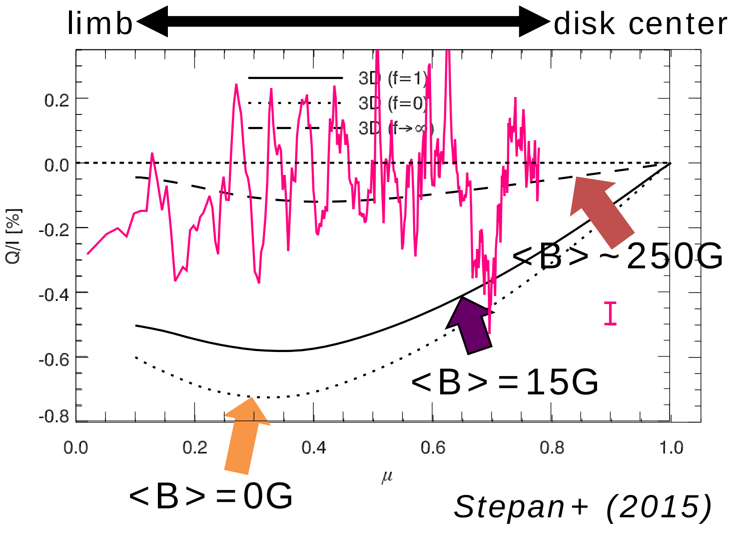
Lya core
(scattering pol. & Hanle)

No Clear CLV in Q/I
Fluctuating at a few of 0.1% both in Q/I and U/I



Scattering pol. in off-limb spicule
→Yoshida's talk tomorrow!

CLV of spatial average of pol.
with 3D MHD model



Stepan+ (2015)

More geometrical complexity
of the transition-region plasma

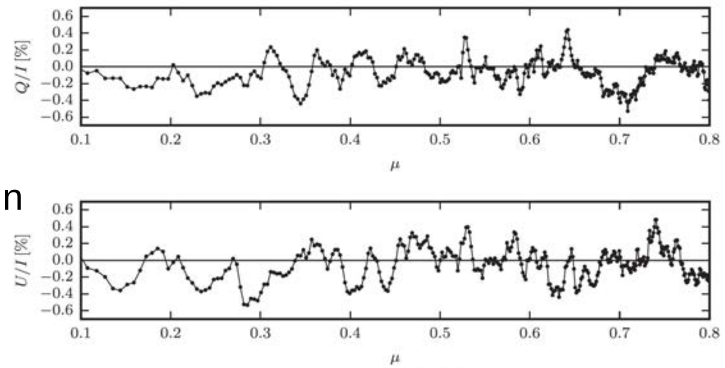
Kano+ (2017)

CLASP Science Highlights (Polarimetry)

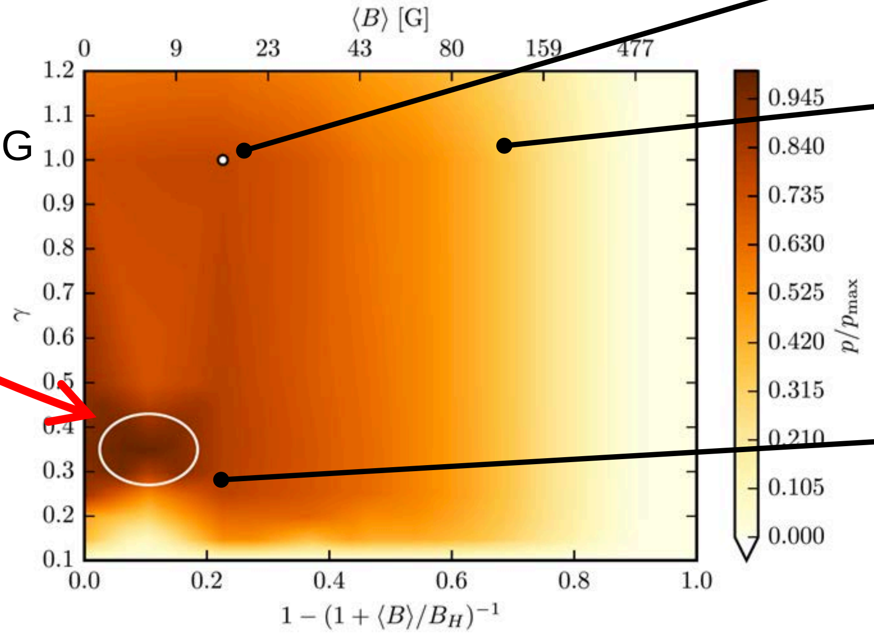
Constraints on Geometrical Complexity and Magnetic Field

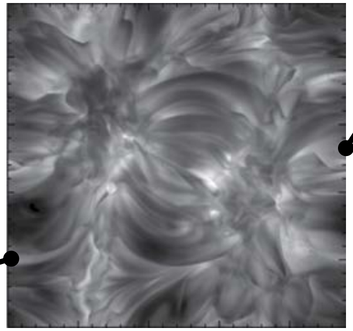
Stepan+2018, Trujillo Bueno+2018

CLASP observation

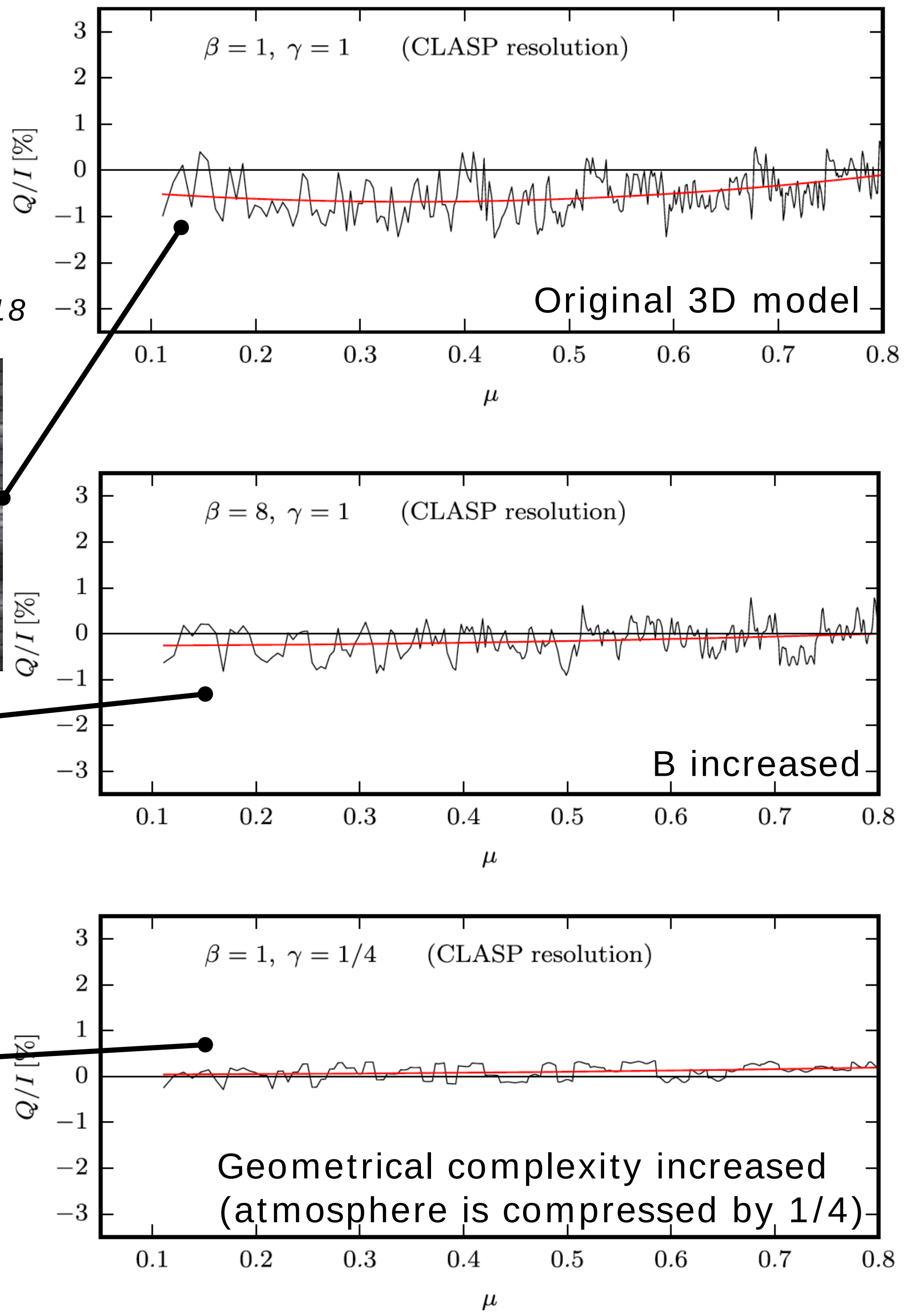


Best Agreement with <B>~7G & γ~1/3



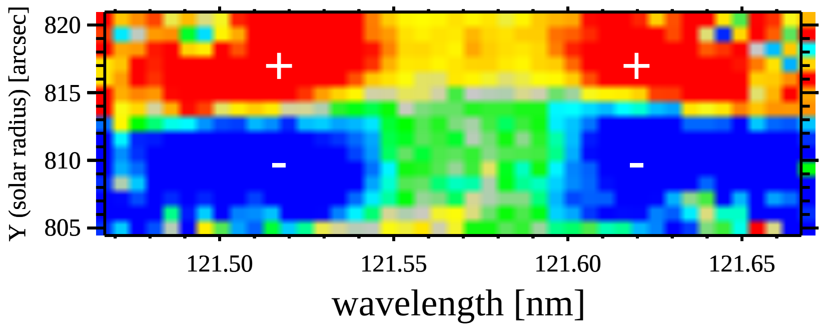


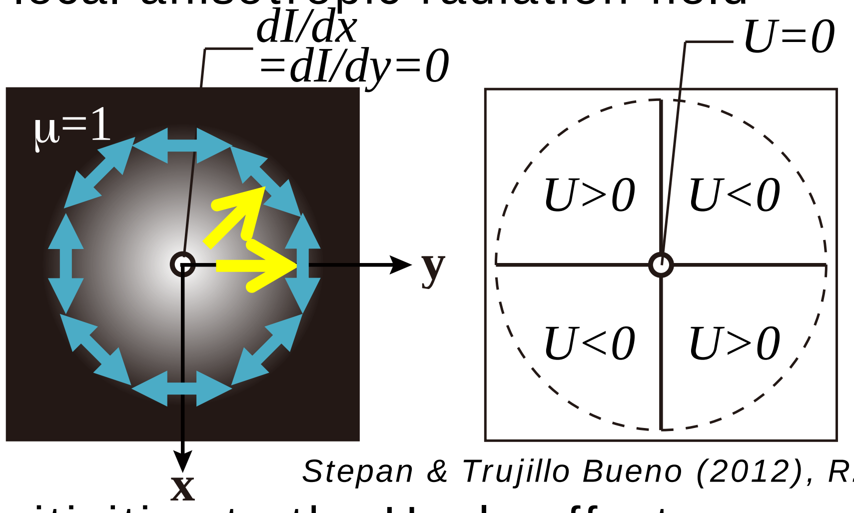
Original 3D model (Carlsson+2016)



How to Disentangle Hanle effect?

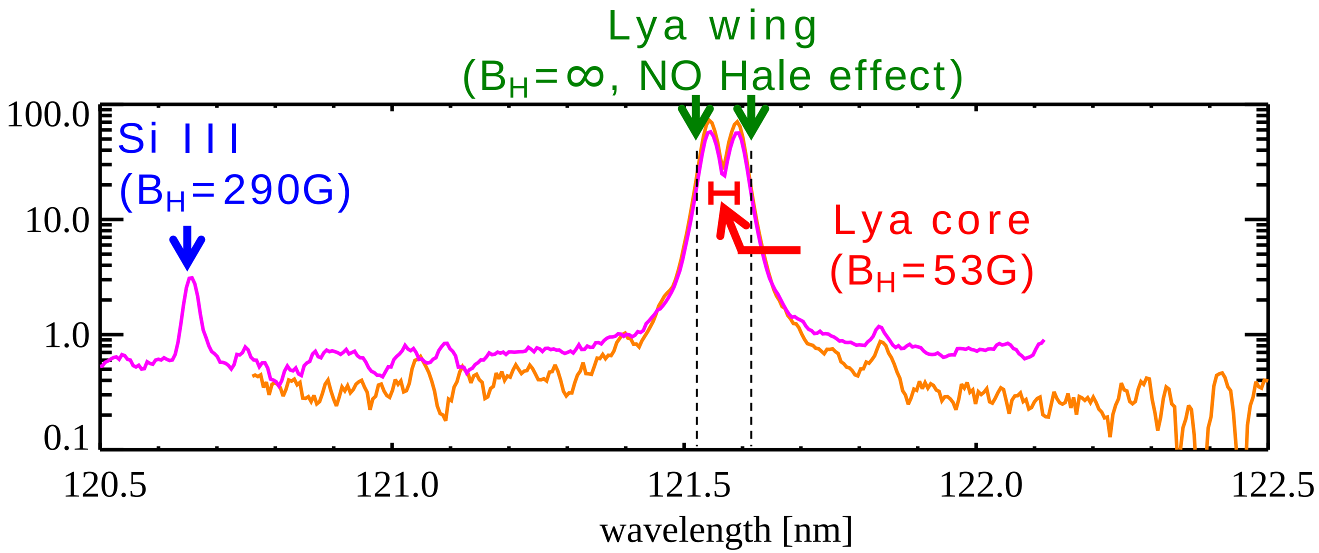
- Focus on Stokes-U, which is only affected by the local anisotropic radiation field
  - + and – distribution is due to the local scattering of a bright structure





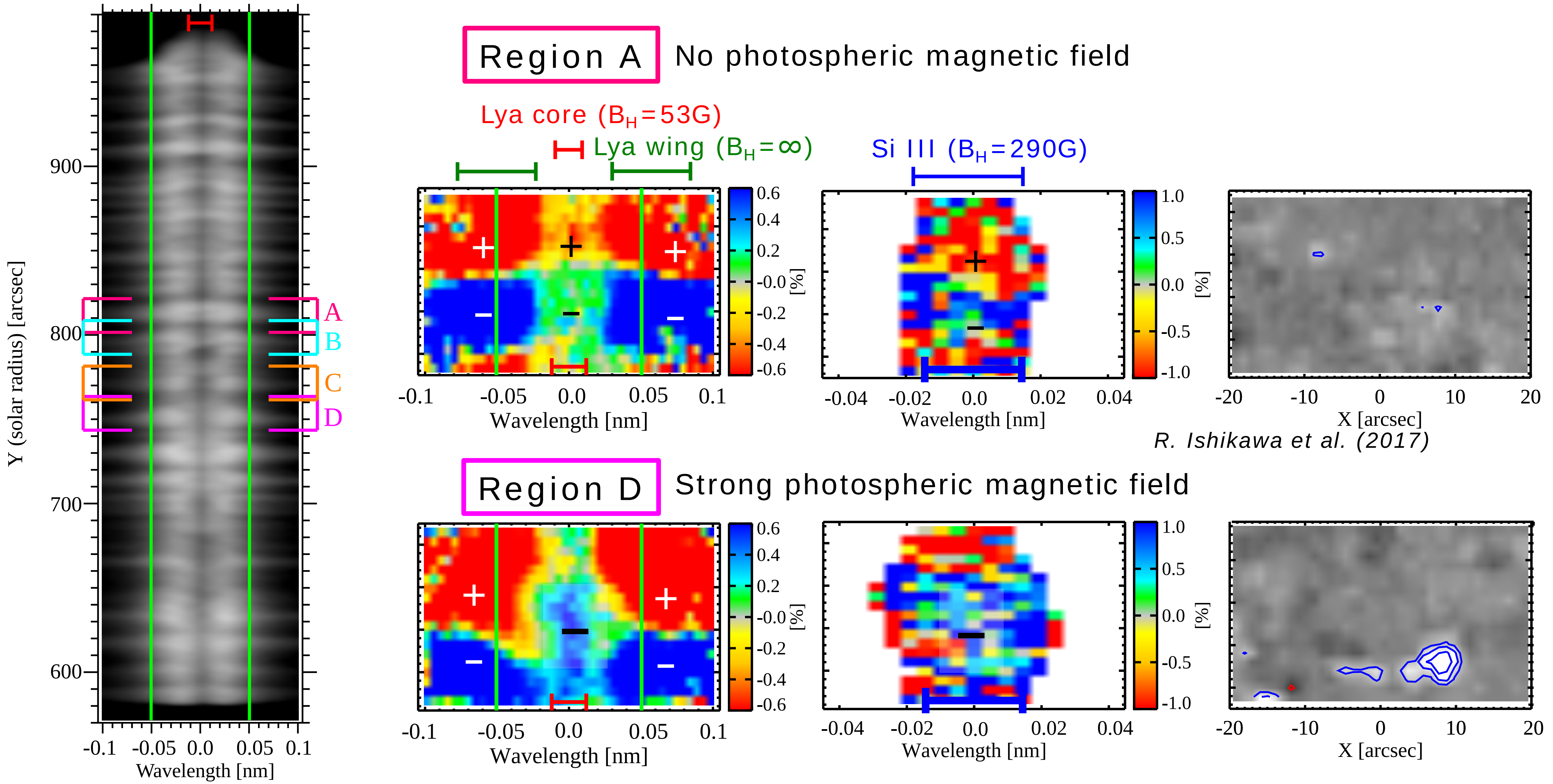
Stepan & Trujillo Bueno (2012), R. Ishikawa+(2017)

- Compare three spectral ranges with different sensitivities to the Hanle effect



CLASP Science Highlights (Polarimetry)

U/I in Magnetized & Non-Magnetized Regions



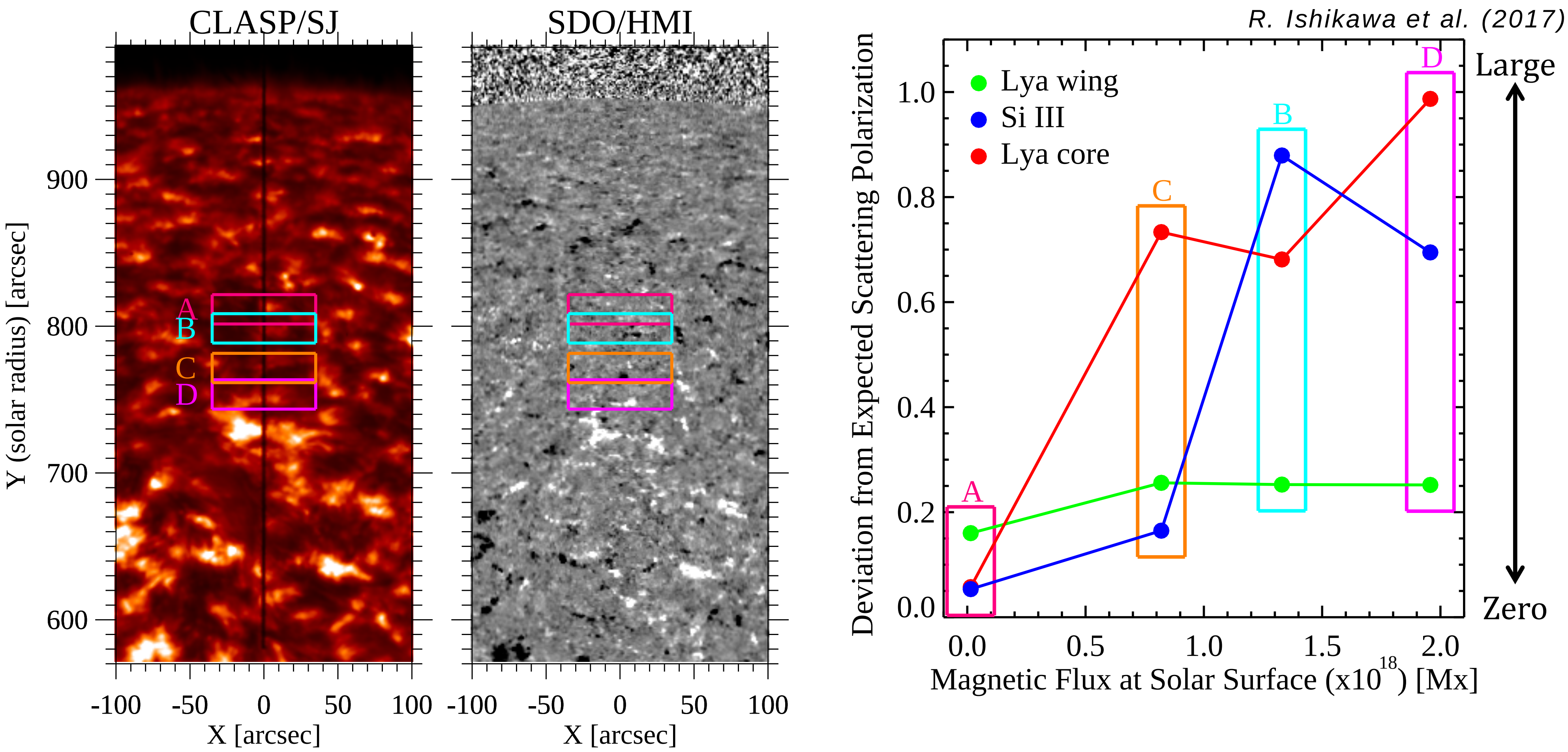
R. Ishikawa et al. (2017)

CLASP Science Highlights (Polarimetry)

Observational Evidence of Hanle Effect

- In Lyα core and Si III, U/I deviates from the positive and negative spatial distribution as photospheric magnetic flux increases

R. Ishikawa et al. (2017)

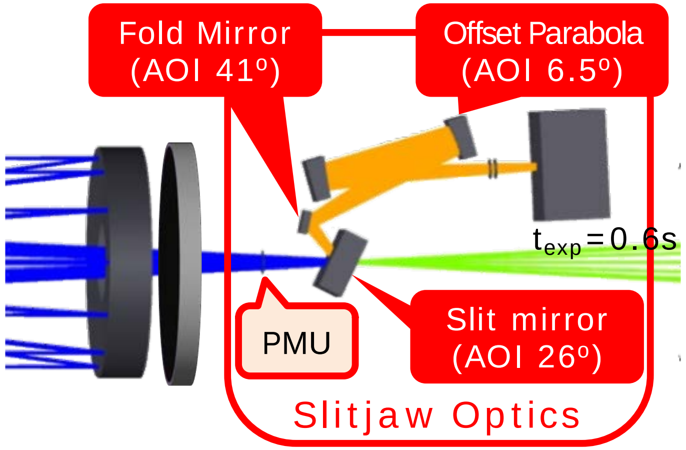


Lya core
B_H=53G

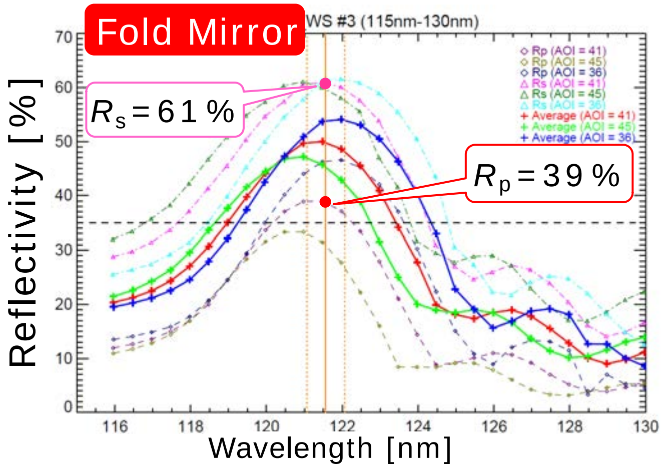
Si III
B_H=290G

Lya wing
$B_H=\infty$

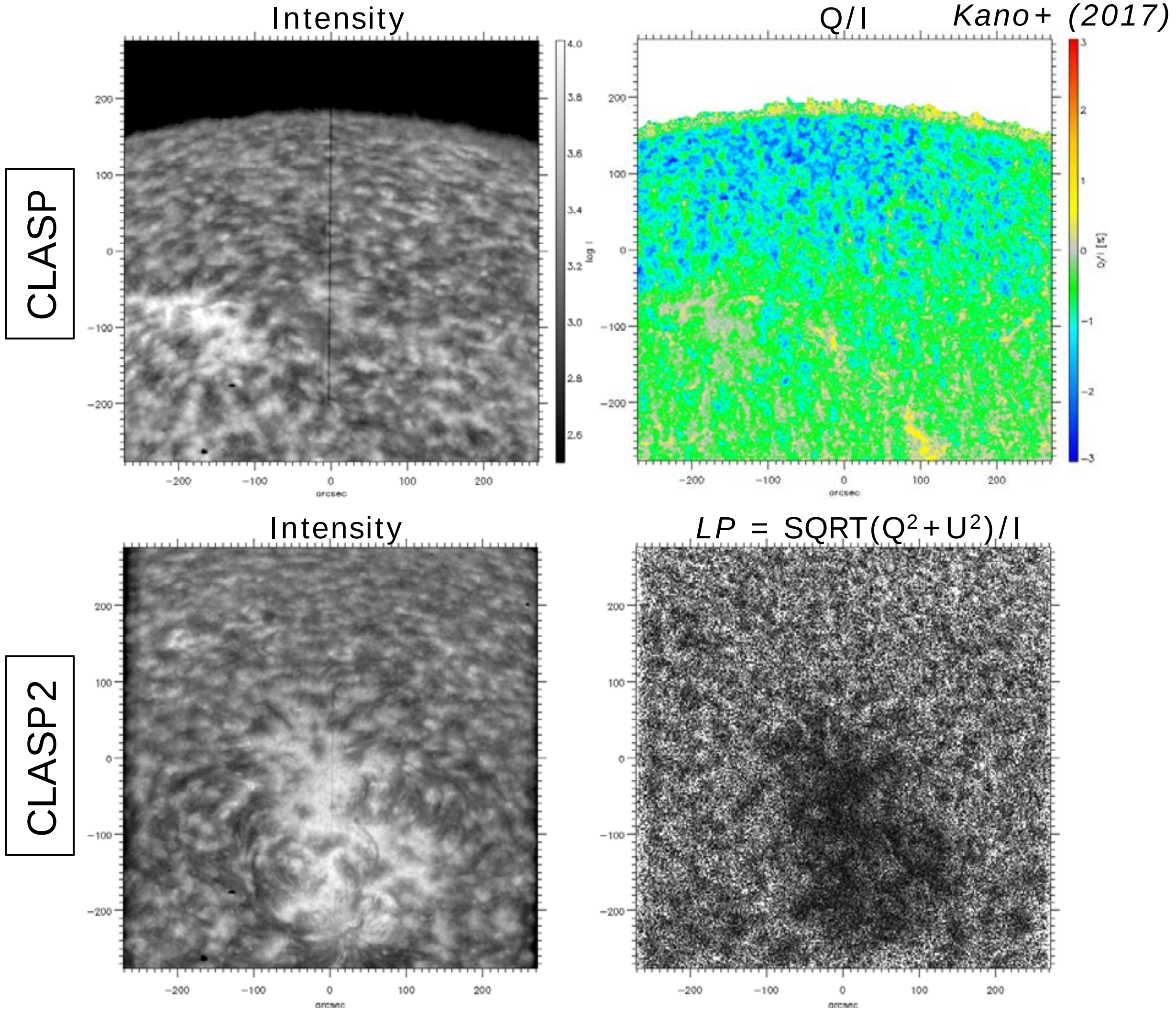
Bi-Product : Lya Imaging Polarimetry



- Total Reflectivity: $R_s = 34\%$ & $R_p = 20\%$
- Polarization Power: $P = \frac{R_s - R_p}{R_s + R_p} = 26\%$

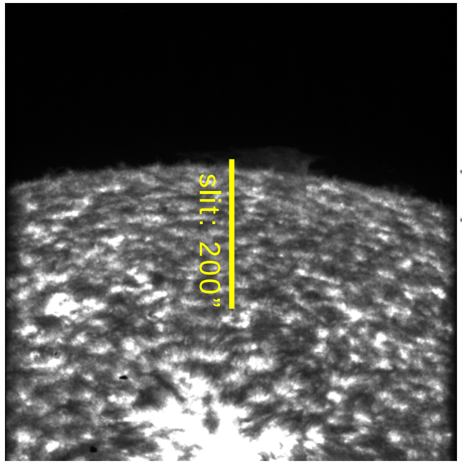


Magnet-Optical effect in Lya wing *(Alsina Ballester+2019)*
can be a diagnostic tool of magnetic field?

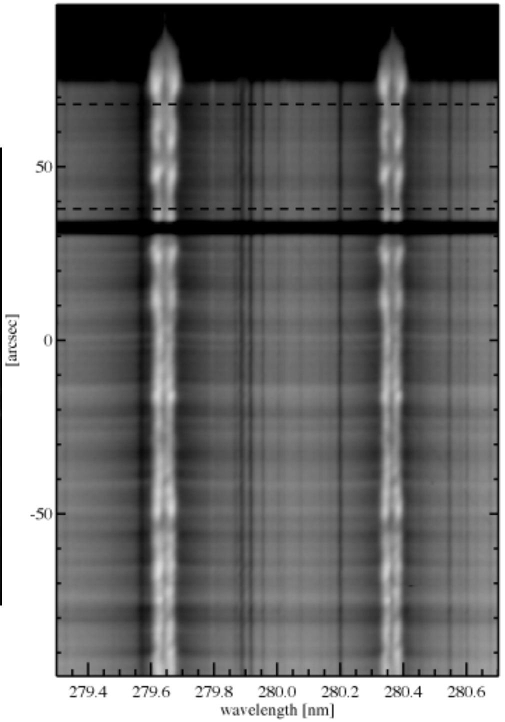


CLASP2 Preliminary Results

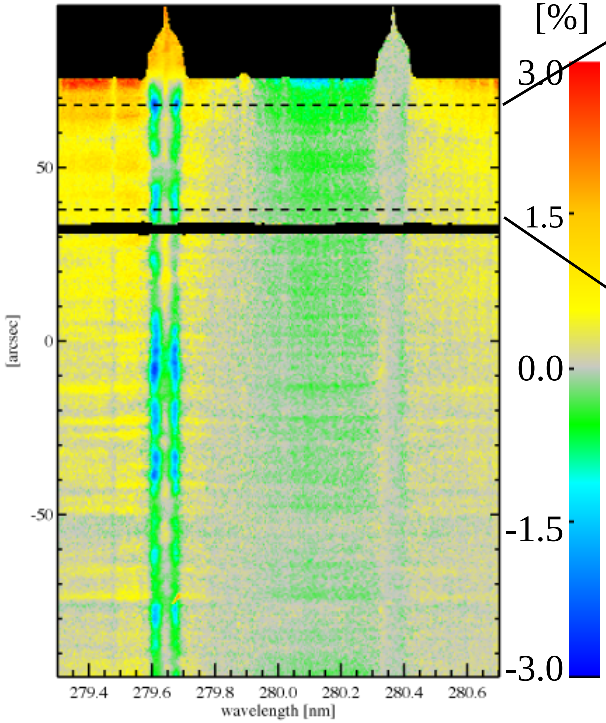
Detection of Scattering Pol. around Mg II h & k



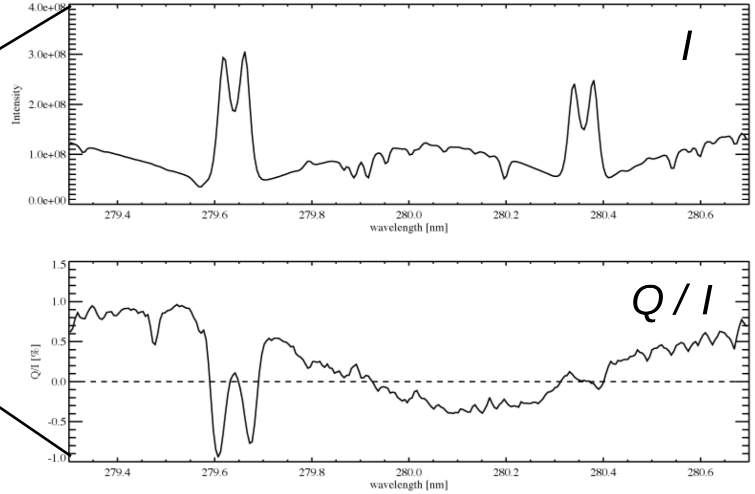
Temporally averaged intensity



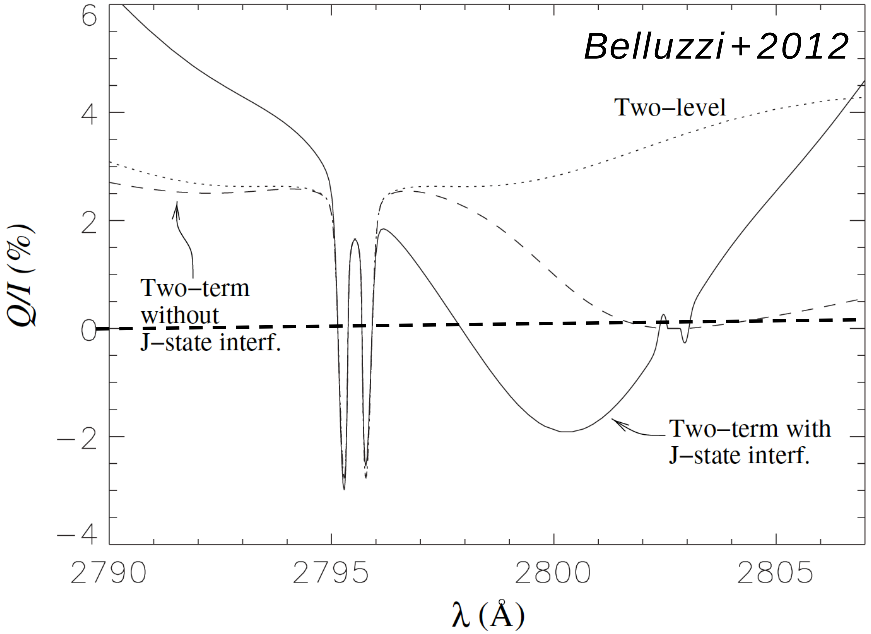
Temporally averaged Q/I



Temporally & spatially averaged



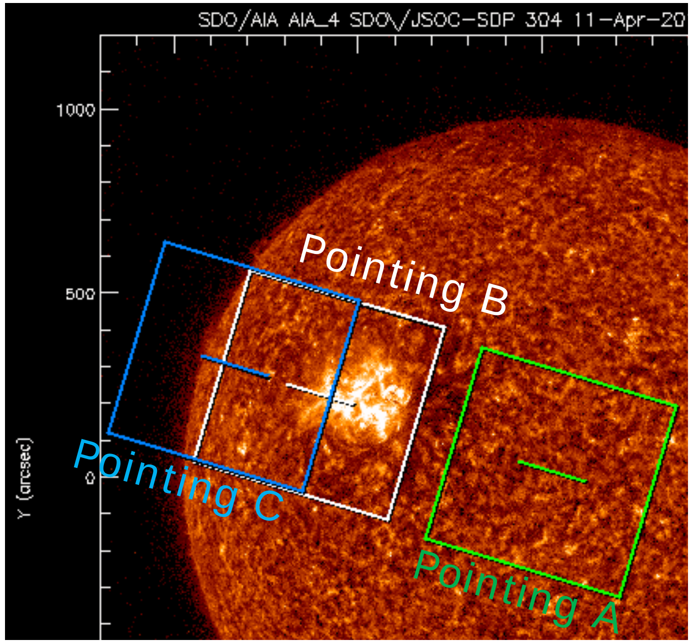
- Wavelength structure of Q/I is consistent with the theoretical prediction *(Belluzzi+2012)*.
  - Mg II k shows the strong scattering polarization while Mg II h shows the exactly zero at the center.

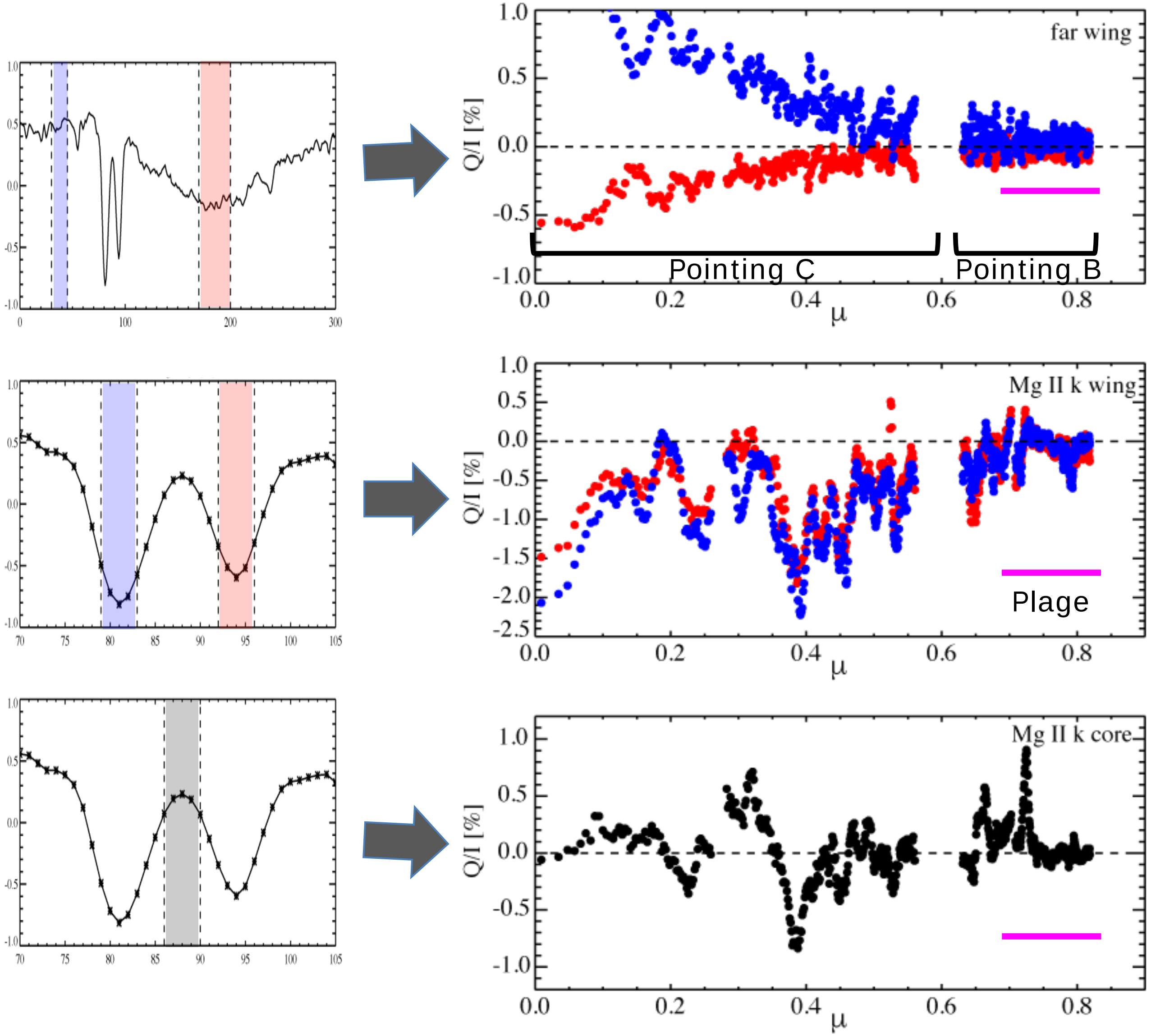


Center-limb-variation of Q/I

- Clear CLV in far wing
- Presence of CLV is not clear in Mg II k wing & core

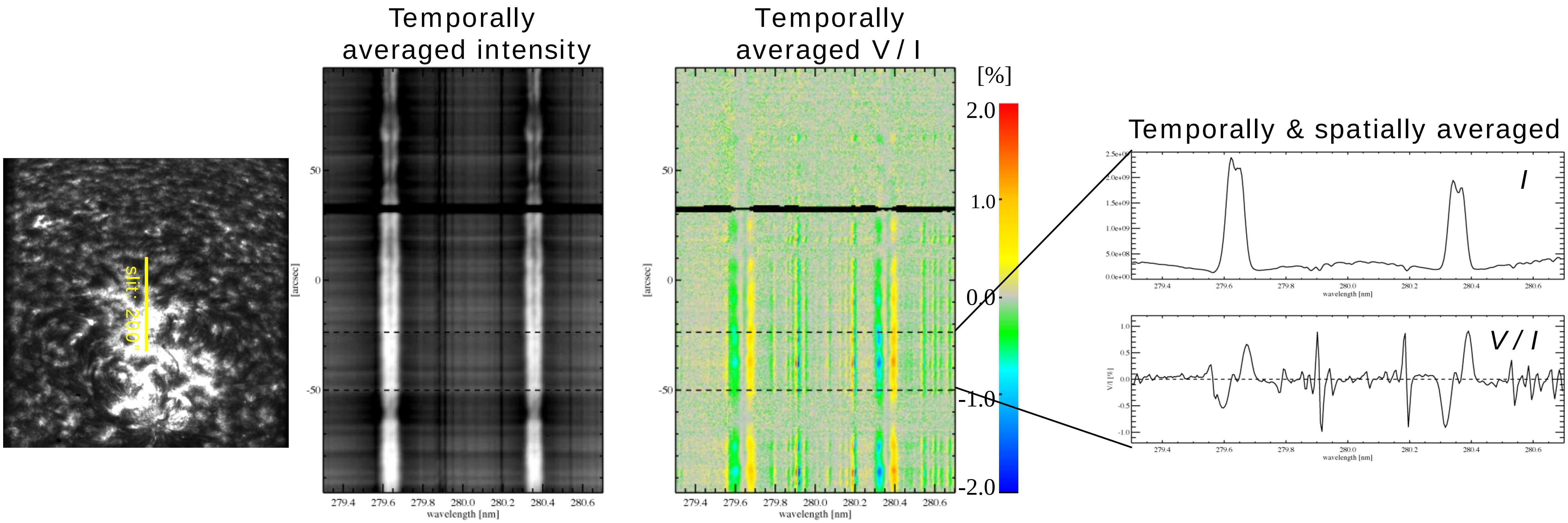
Further investigation & discussion will be in Rachmeler+ in AGU





CLASP2 Preliminary Results

Significant V/I over the Plage



- Would be induced by the longitudinal Zeeman effect
- Many spectral lines (Mg II h & k, Mg II triplet, Mn I, etc.…) show V/I

Conclusions: CLASP & CLASP2

- Demonstrated that high-precision UV spectro-polarimetery is feasible & detected scattering polarization in UV

- As a diagnostic tool of magnetic field
  - Multi-wavelength spectro-polarimetry (Lya & Si III in CLASP) can be powerful tool
  - Improvement of solar atmospheric model is required.

- Remaining issue: clarification of importance of Mg II k line
  - How V/I can facilitate the inferring of the magnetic field?
  - Simultaneous observation of scattering polarization in Mg II k and Lya can provide the useful information?