Compact Binaries

Observing Compact Binaries with SALT and SAAO Telescopes

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Potential Observational Information

Photometry:

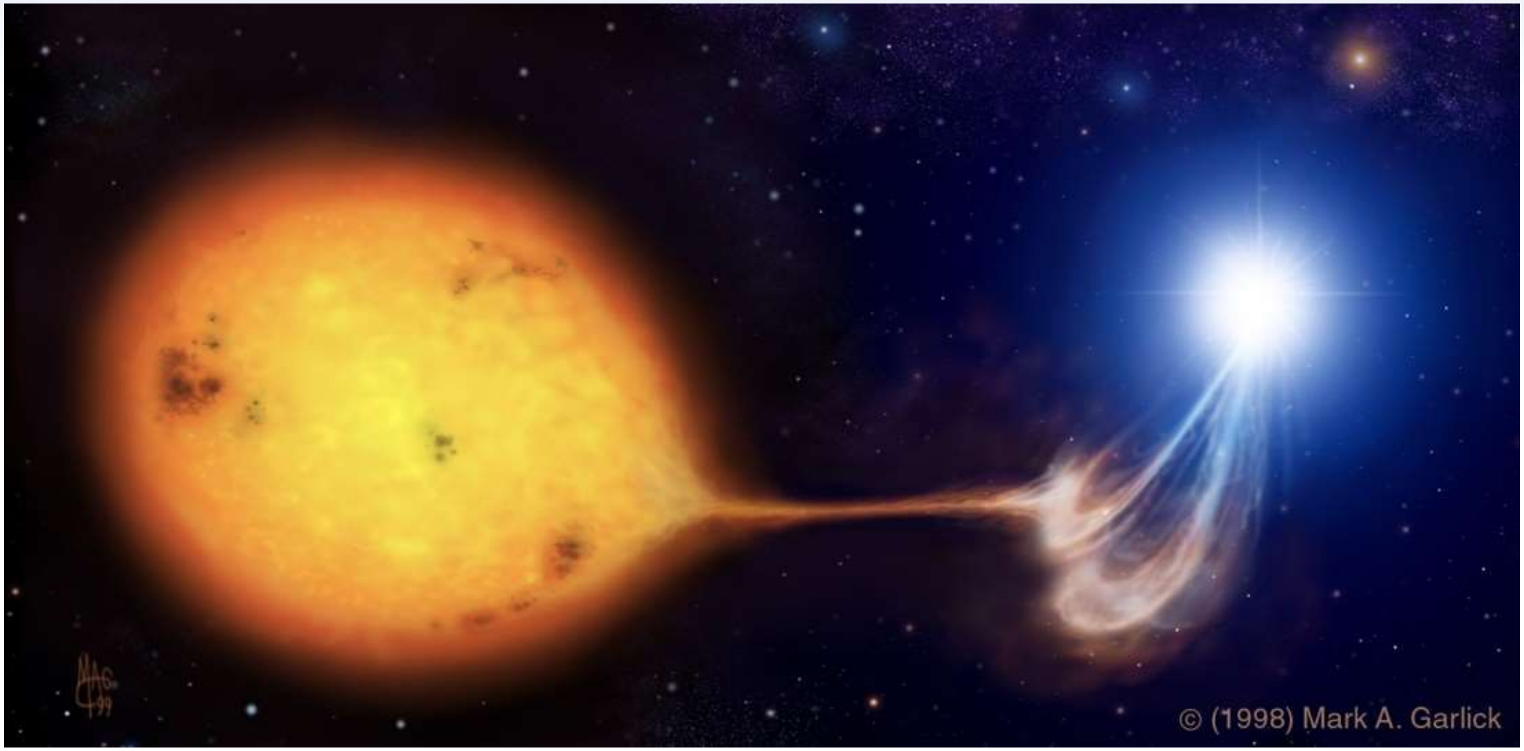
- Light curves
  - Periodic (e.g. orbital, spin)
    - Eclipses (of compact object and/or accretion regions)
    - Dips or modulations (e.g. accretion spots, heated regions)
    - Variations of companion star (shape, irradiation)
  - Quasi-periodic (e.g. QPOs from accretion columns)
  - Aperiodic (flickering)
- Colour information
  - Spectral energy distributions
  - Detection of different components (i.e. accreting object, companion donor)

Spectroscopy:

- Continuum and spectral lines (temperature, ionization state, abundance, gravity…)
- Radial velocities
  - component stars
  - Accretion processes (disks, streams)
  - Tomography to map the above
- Spectropolarimetry
  - Magnetic fields

Interactions in close binaries

- Distortion of the star(s) from spherical shape: ellipsoidal modulation

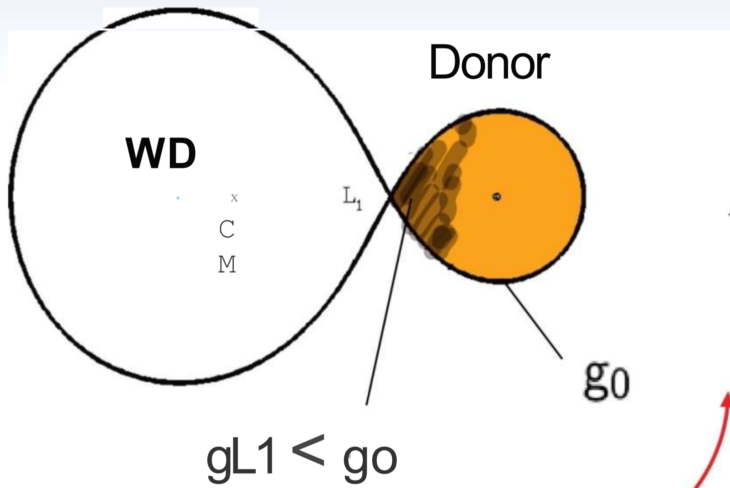


Gravity darkening

bright cp=0.25

fainter--------

cp=0.5

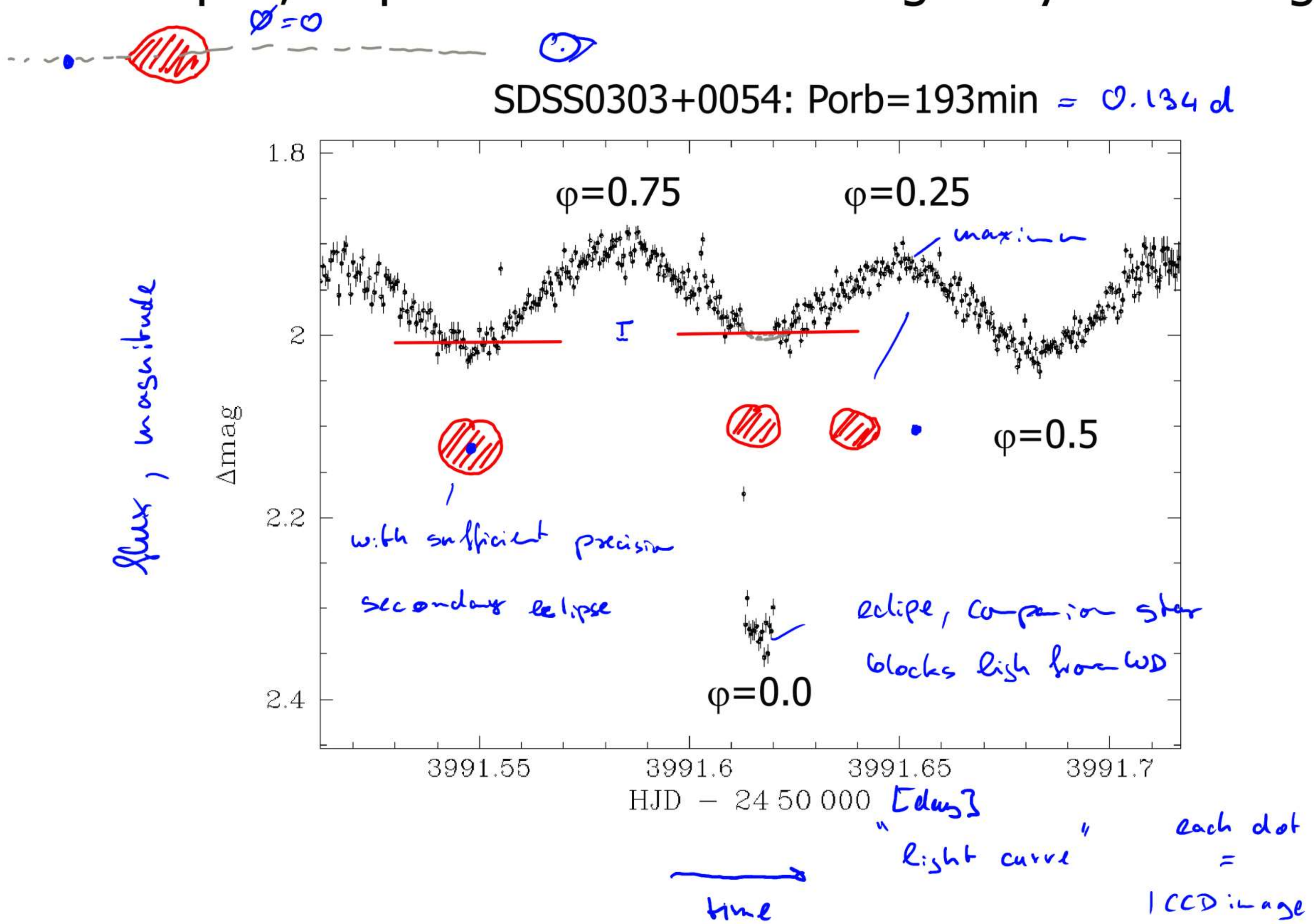


faint

cp=0.0

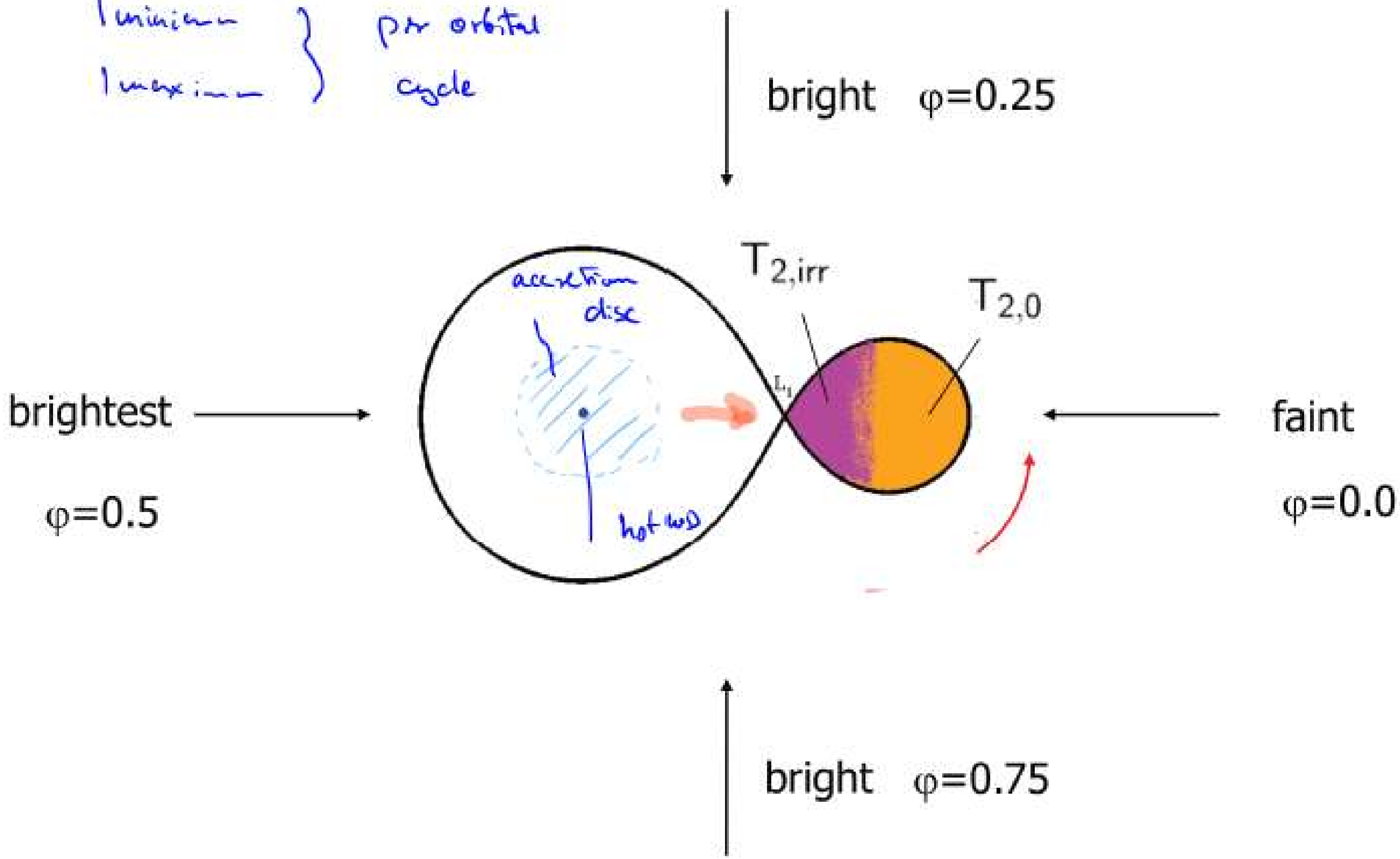
bright cp=0.75

Eclipse, ellipsoidal modulation & gravity darkening

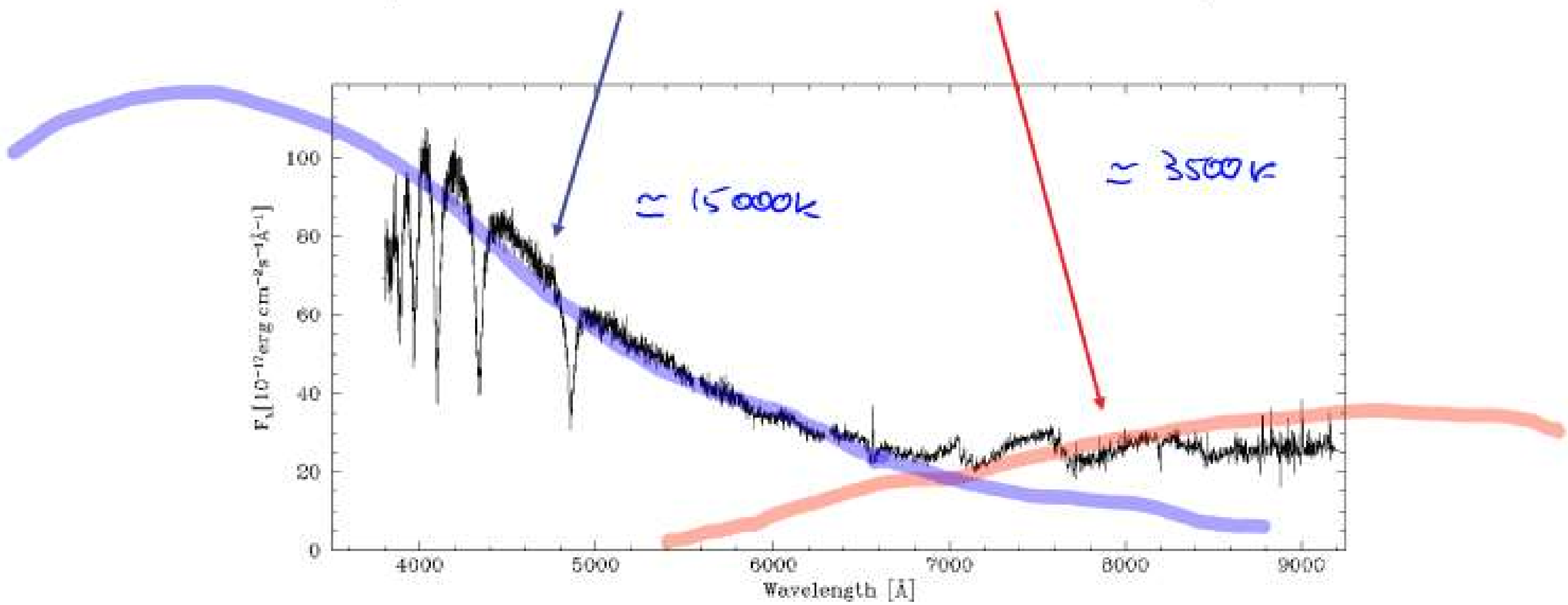


Reflection effect

1 minimum } per orbital cycle
1 maximum }



Example: hot WD + low-mass companion



$R_{WD} \ll R_2$

$T_{WD} \gg T_2$

$L \propto R^2 T_{eff}^4 \Rightarrow T$ "wins"

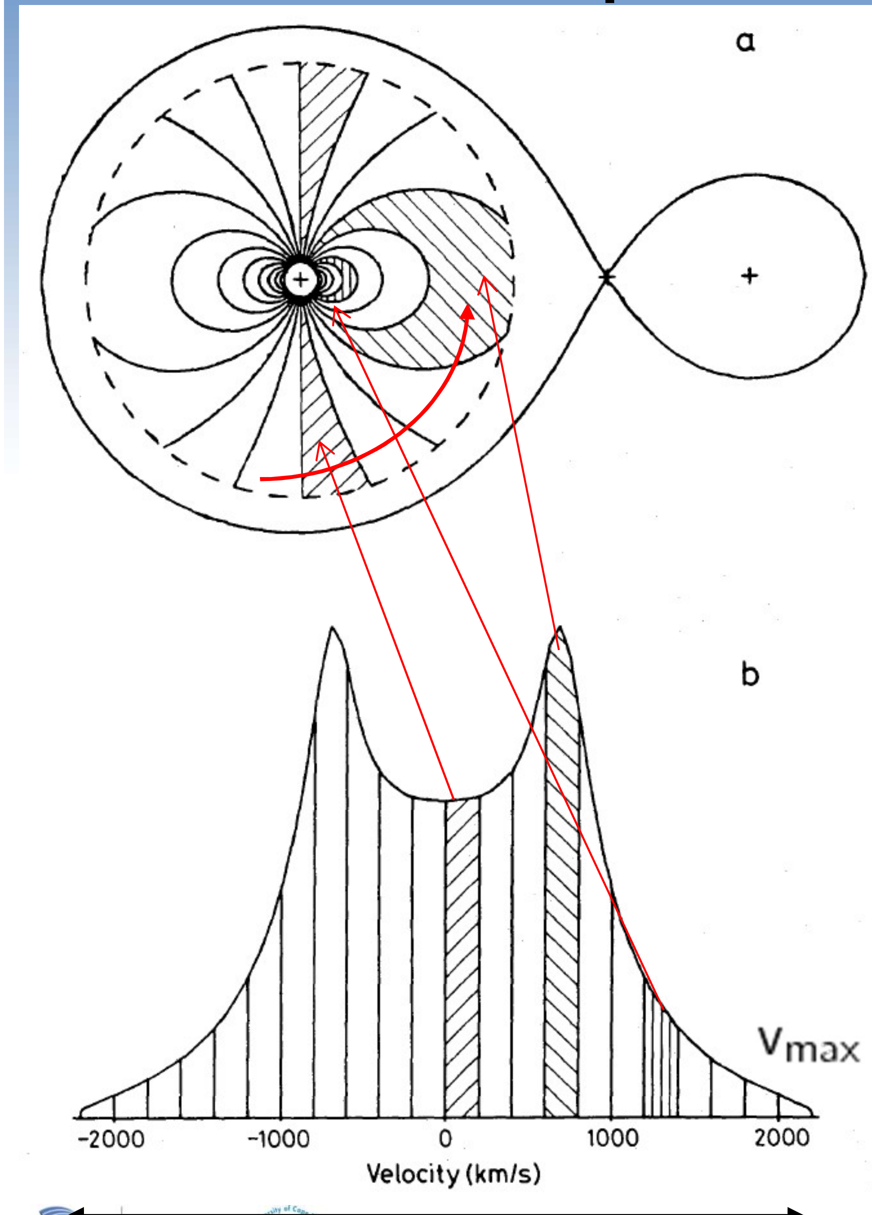
approx. to scale

Doppler Tomography

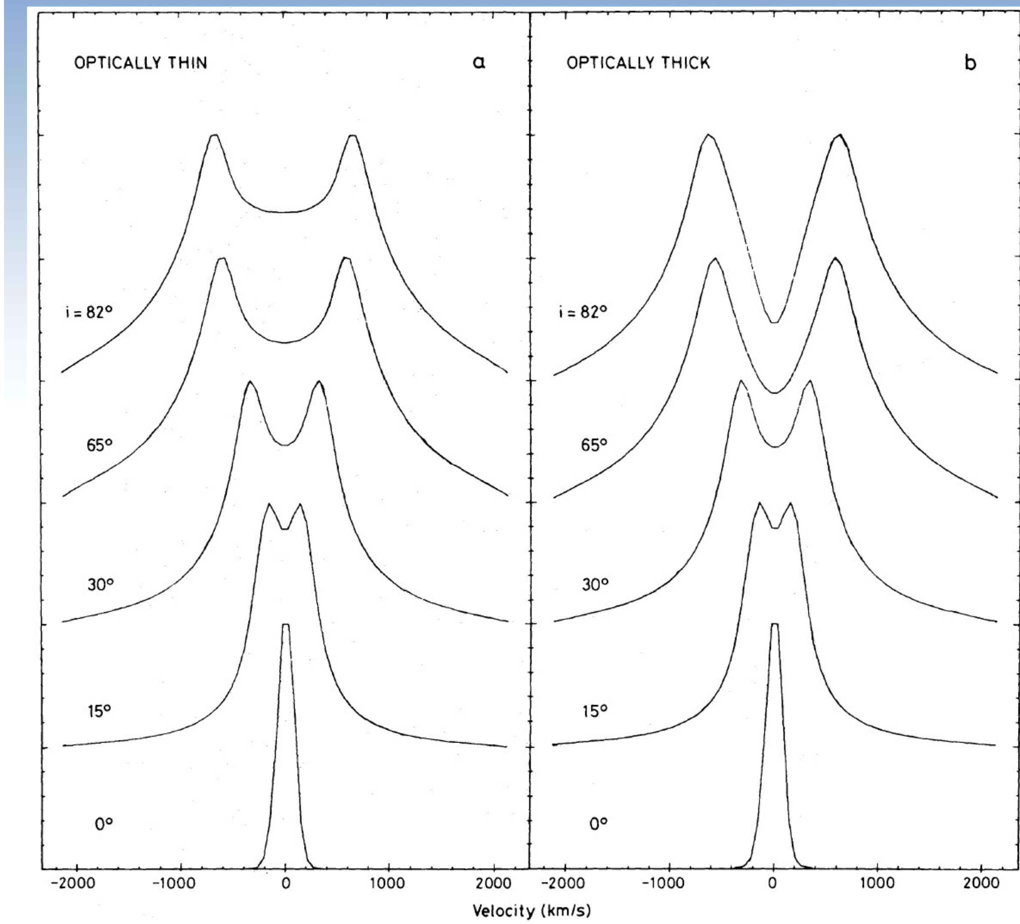
- Takes radial velocity information and maps the emission to a Doppler “map”
- Used on any system with a periodic changing emission line position
  - Orbital
  - Spin

- Used for disk accreting CVs to probe accretion disk
- Used on magnetic CVs to probe interaction of stream with the magnetic field
- Psuedo free-fall velocities of stream are “stopped” by magnetic field and redirected along field lines

Line profiles from accretion discs

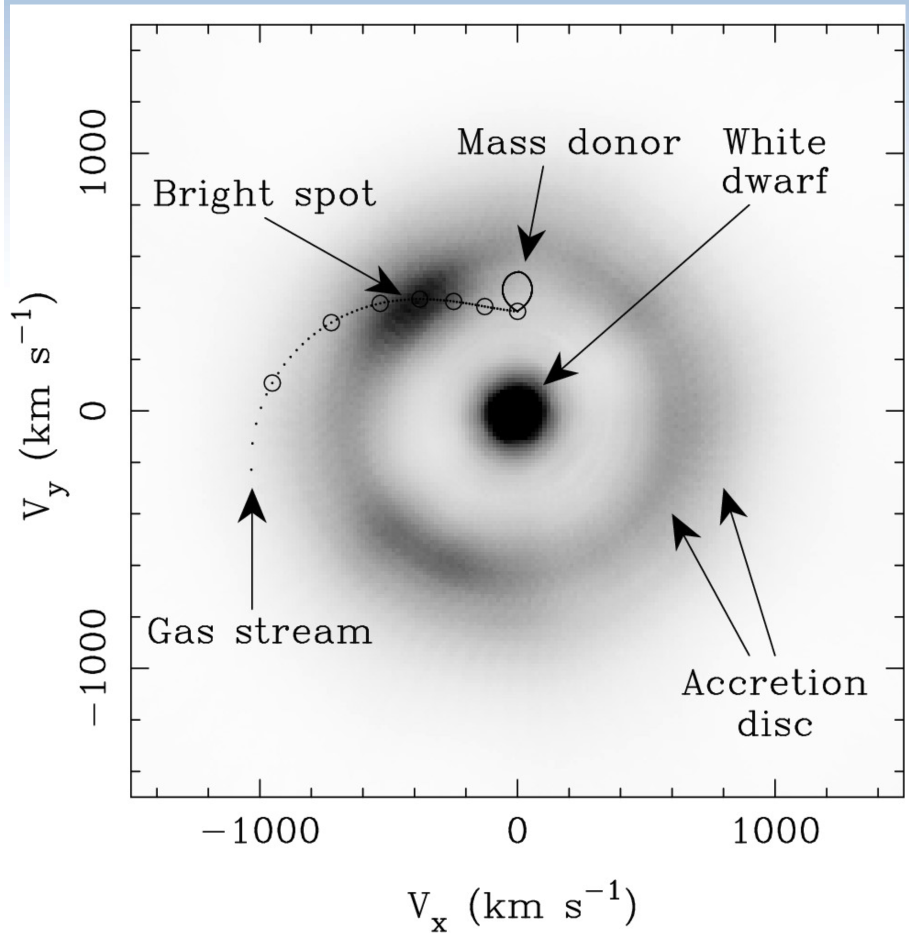


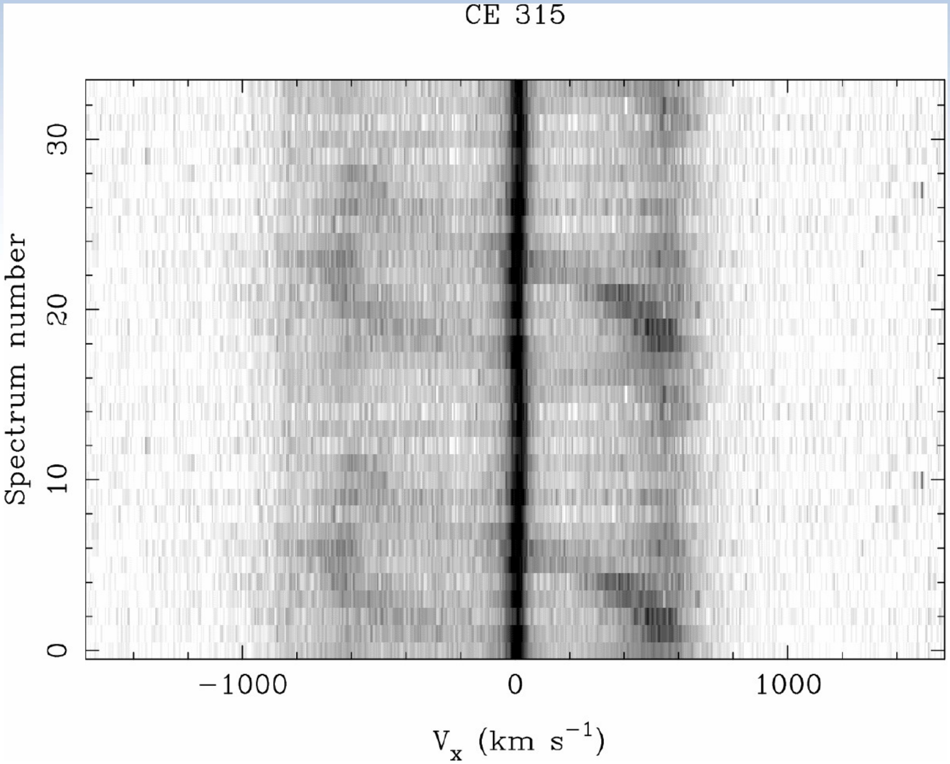
FWZI



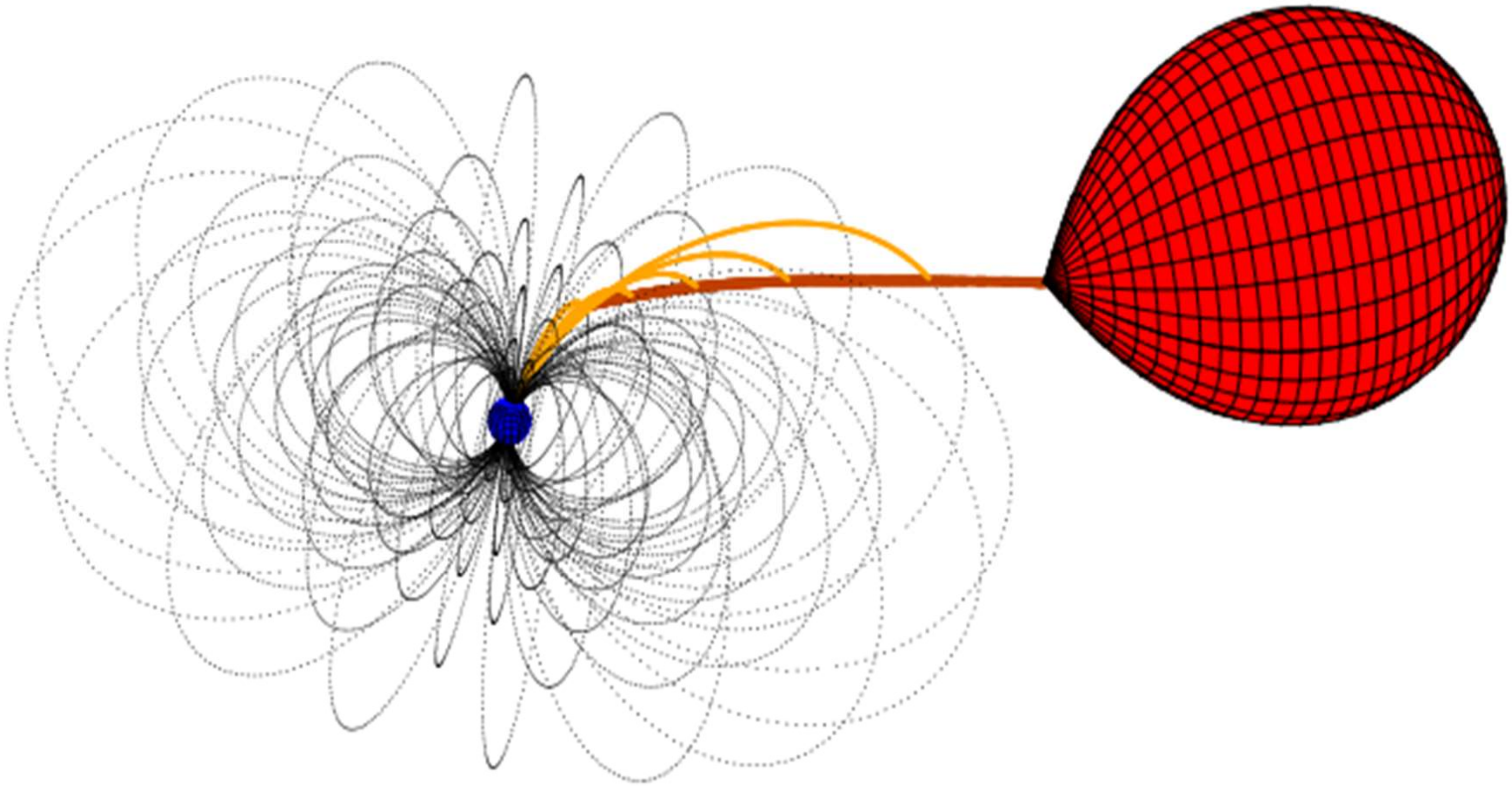
$$\sin i \, v_{max} = \sqrt{\frac{GM_*}{R_*}}$$

The components of a binary star in velocity space



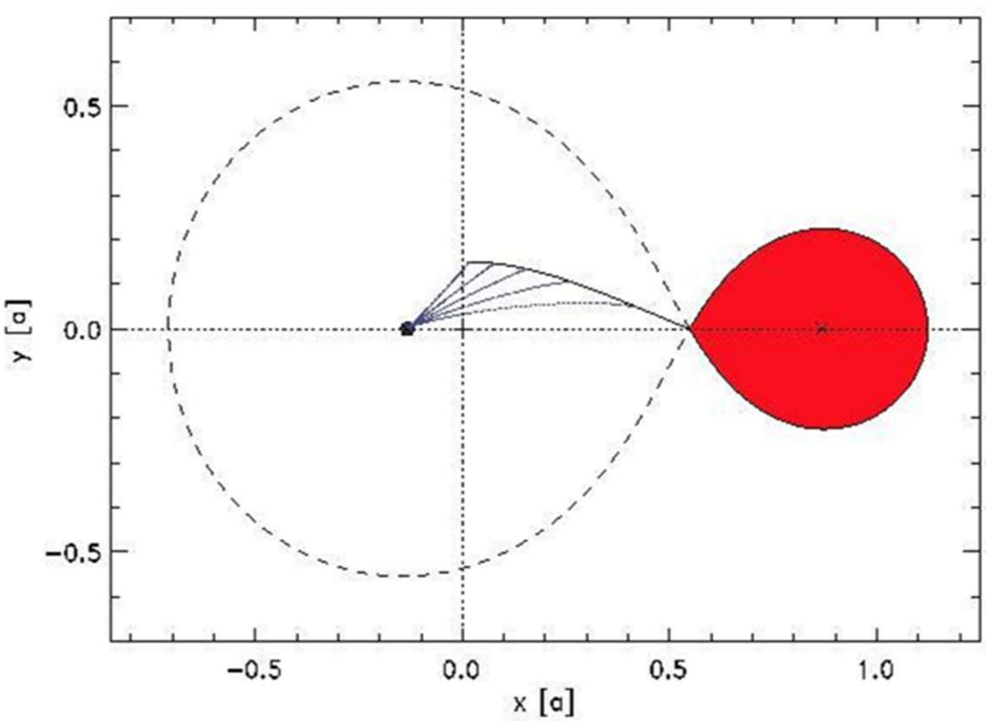


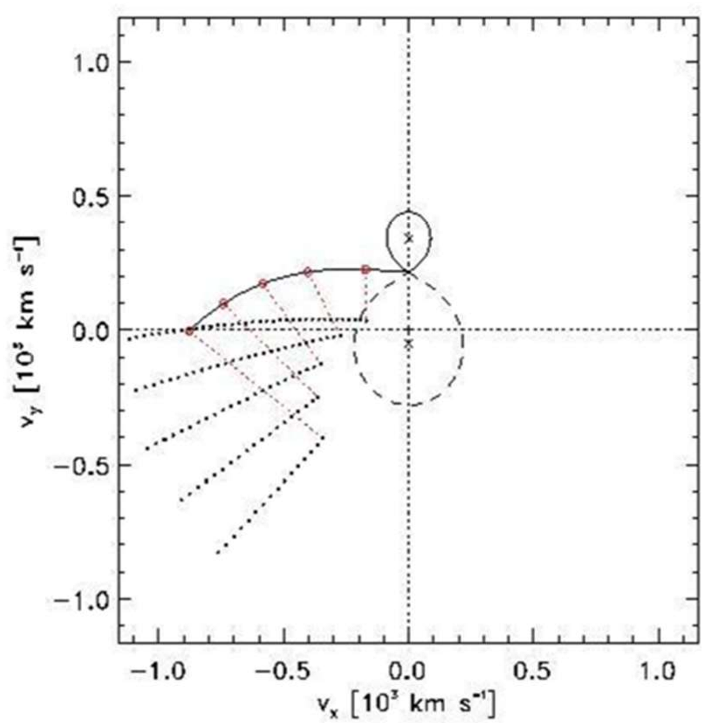
Magnetic cataclysmic variables - polars



Doppler tomography of polars

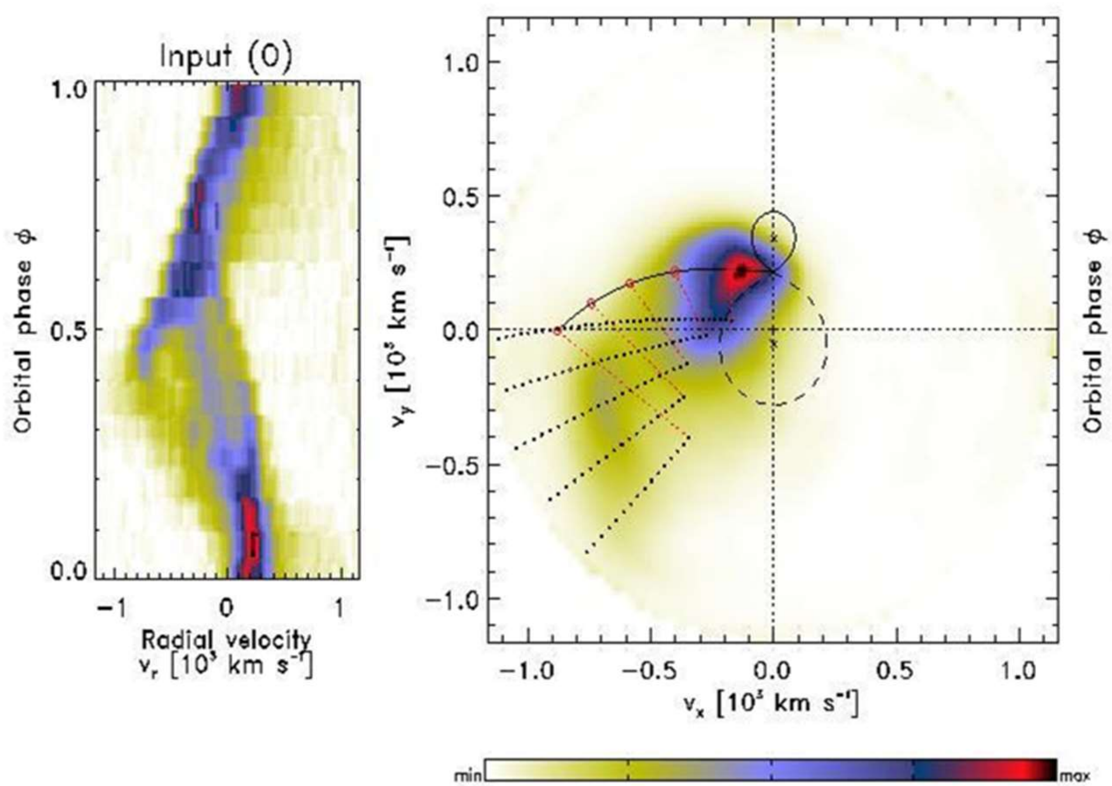
- From the spatial model determine the corresponding model velocity profile taking into account the inclination of the system





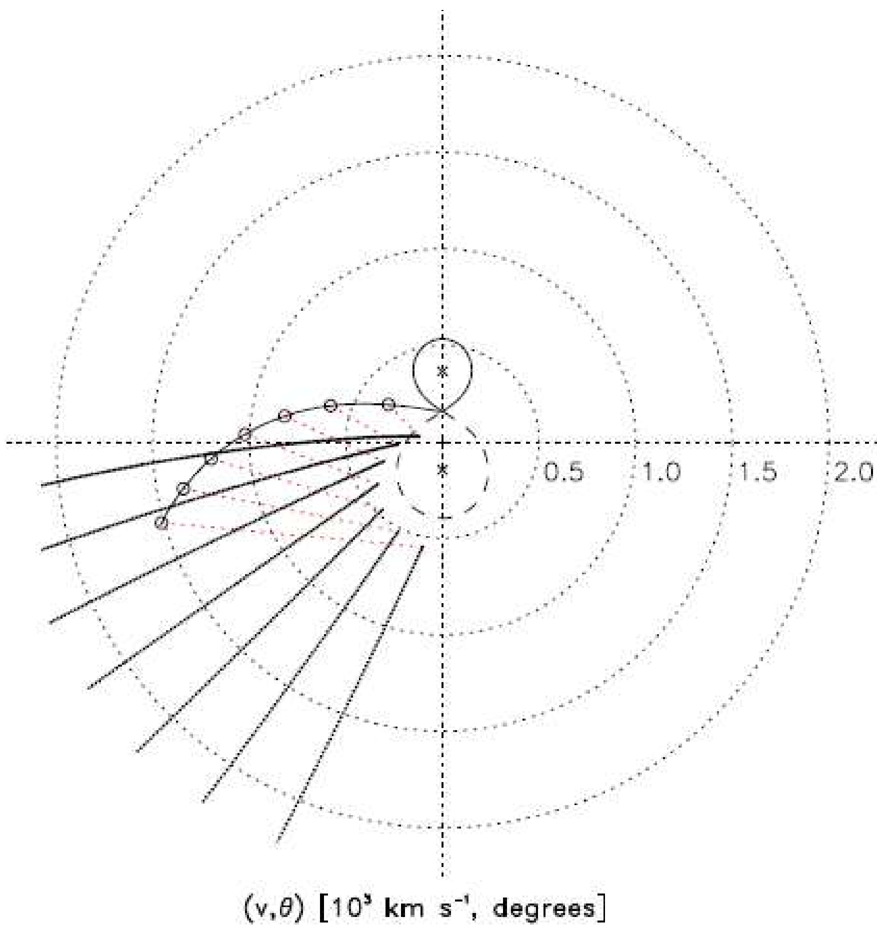
Doppler tomography of polars

- Compare the model velocity profile on the Doppler tomogram to aid the interpretation of the emission distribution
- CTCV J1928-5001

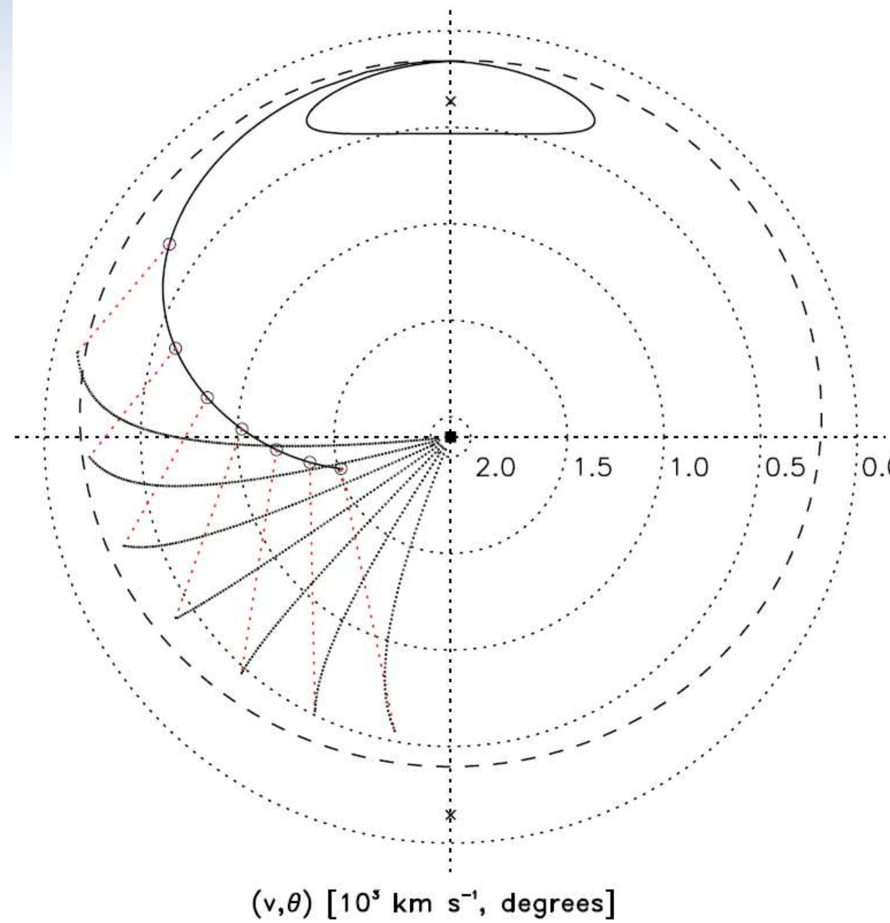


Tomograms

Standard velocity space



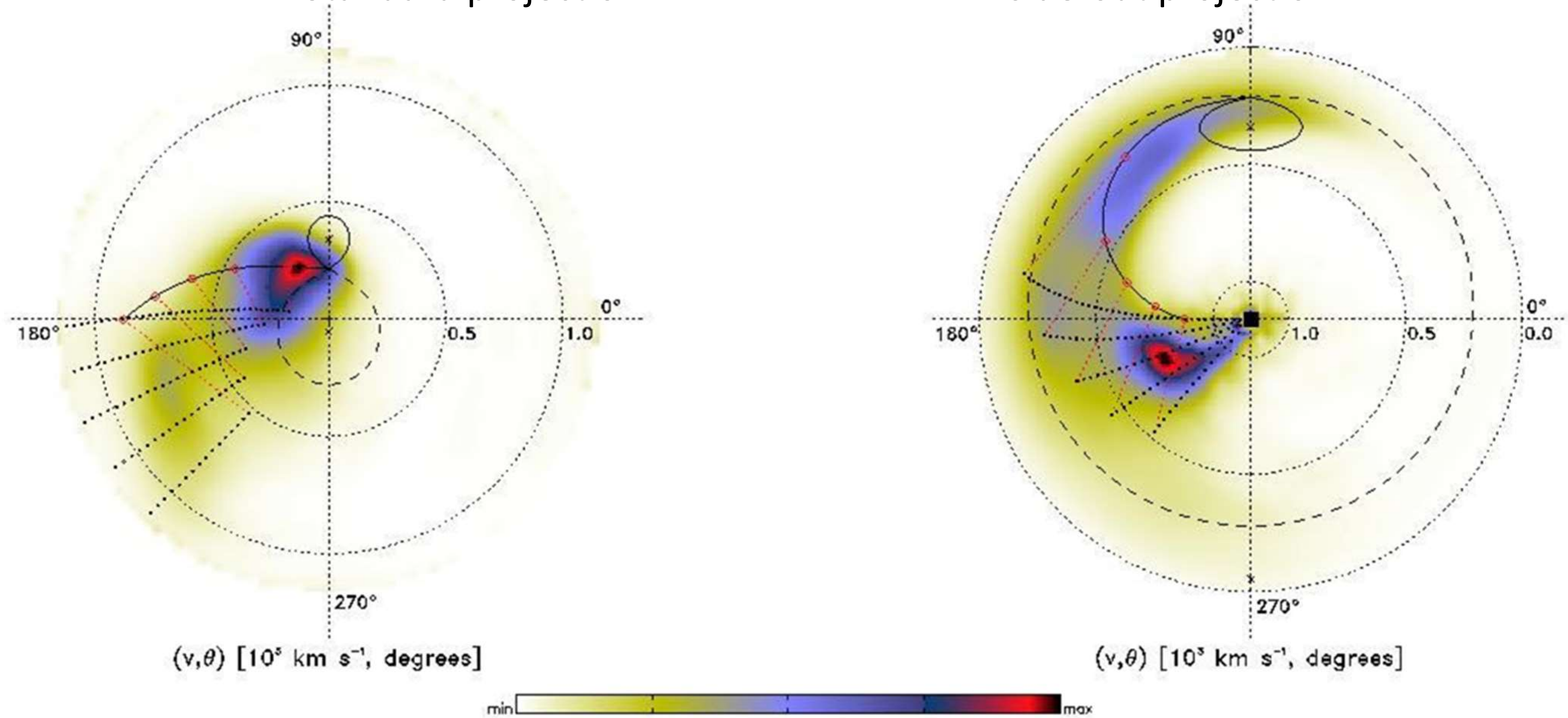
Inside-out velocity space



Doppler tomography of polars

- Doppler tomograms
- CTCV J1928-5001

Standard projection | Inside-out projection



What is SALT?

One of the "Big Five": Segmented Mirror Telescopes

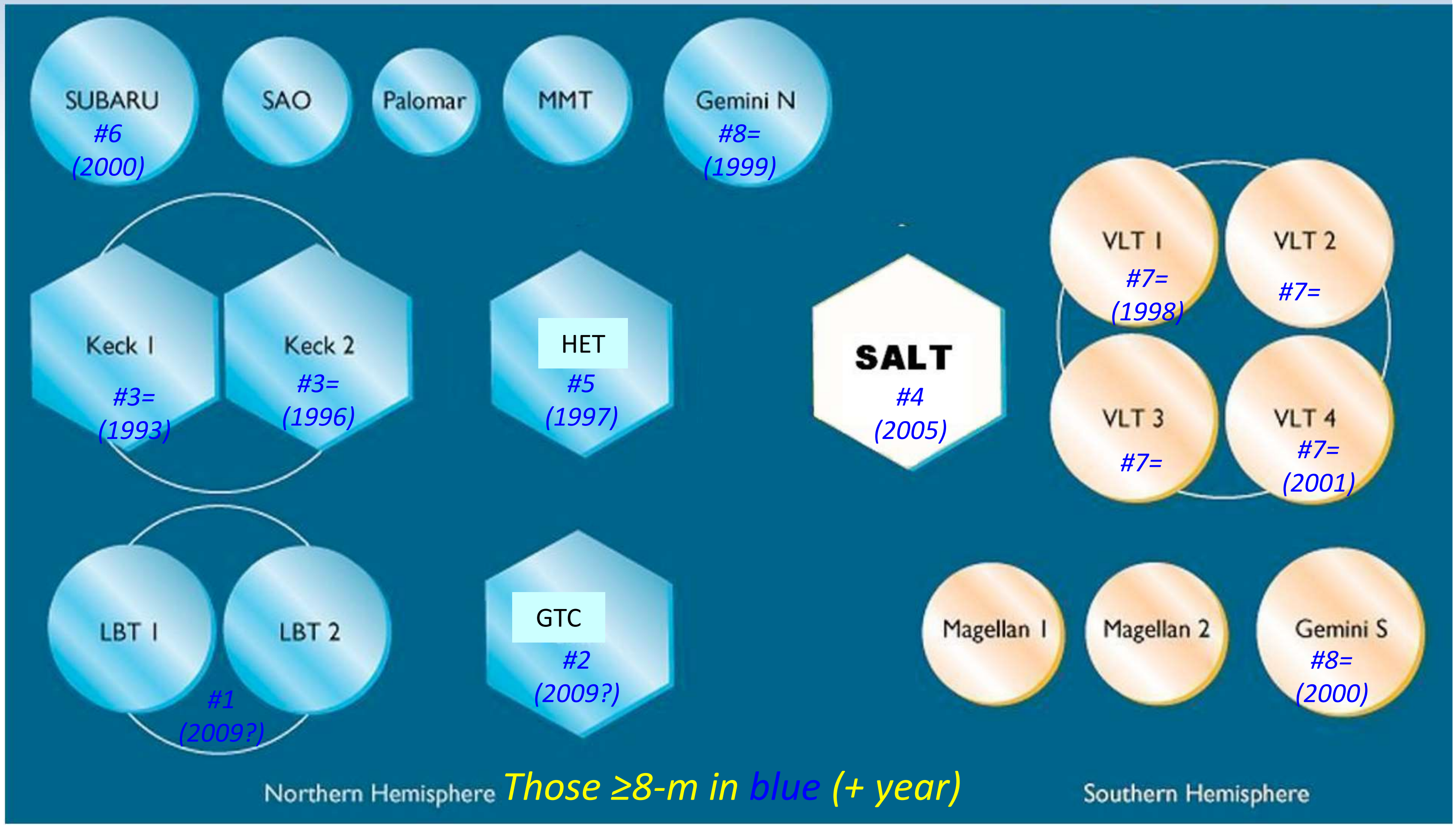
- Keck I (1993) & Keck II (1996): Hawaii, USA
- HET (1999): Texas, USA
- SALT (2005): South Africa
- GRANTECAN (GTC, 2009): Canary Islands, Spain

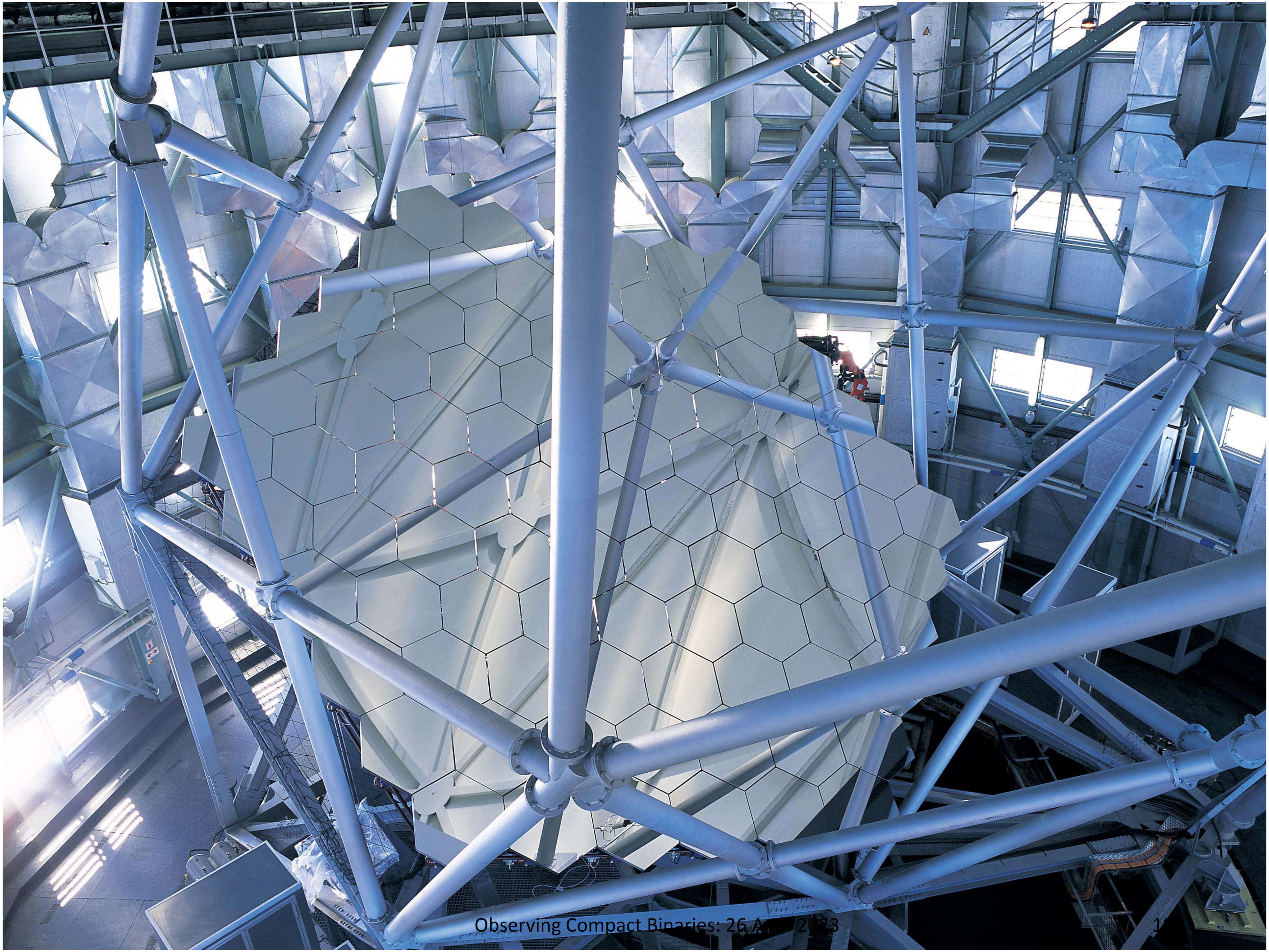
These telescopes have the largest light grasp

Ranking of the Telescopes in the World (as *single* telescopes)

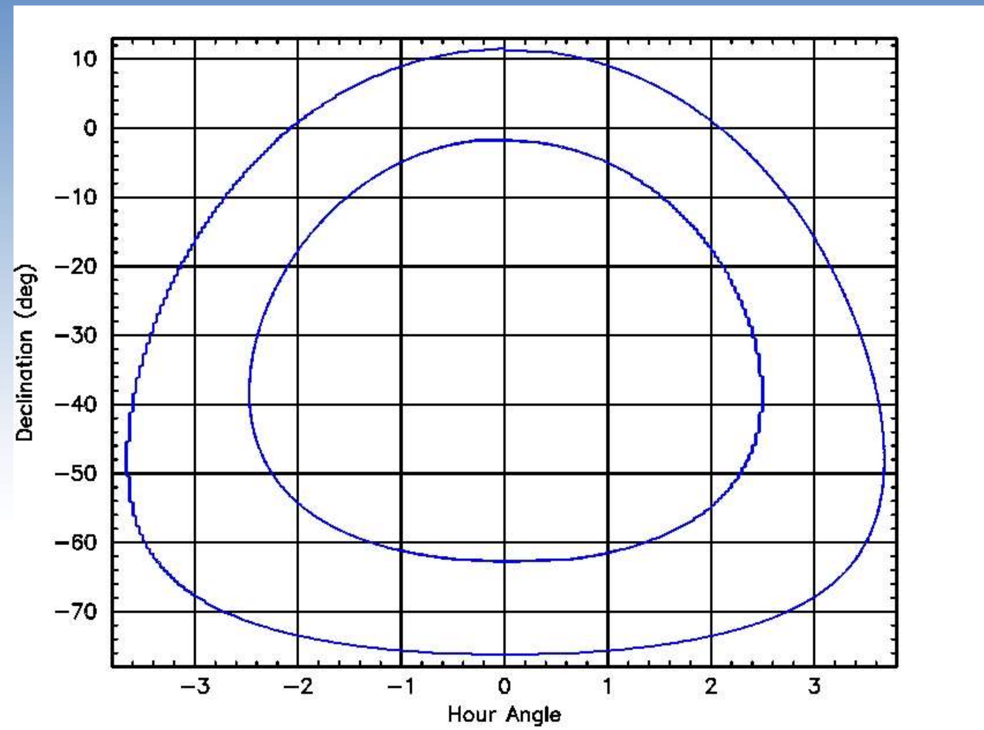
<u>*Rankings:*</u>

1. LBT 2 x 8.4
2. GTC 10.4
3. Keck 9.8
4. SALT 7 - 9.2
5. HET 7 - 9.0
6. Subaru 8.3
7. VLT 4 x 8.2
8. Gemini 2 x 8.1





Observing CBs With SALT



SALT Viewing Annulus

- 100% queue scheduled service observing
- Variety of instruments/modes
- Rapid instrument changes and mode configurations
- Scheduling allows for synoptic monitoring at difference cadences
- Targets of Opportunity can be done at short notice
- Ideal for followup of transients

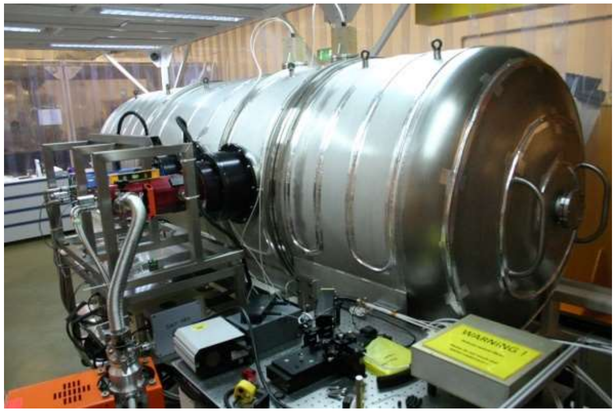
Observing CBs With SALT

Available Instrumentation:

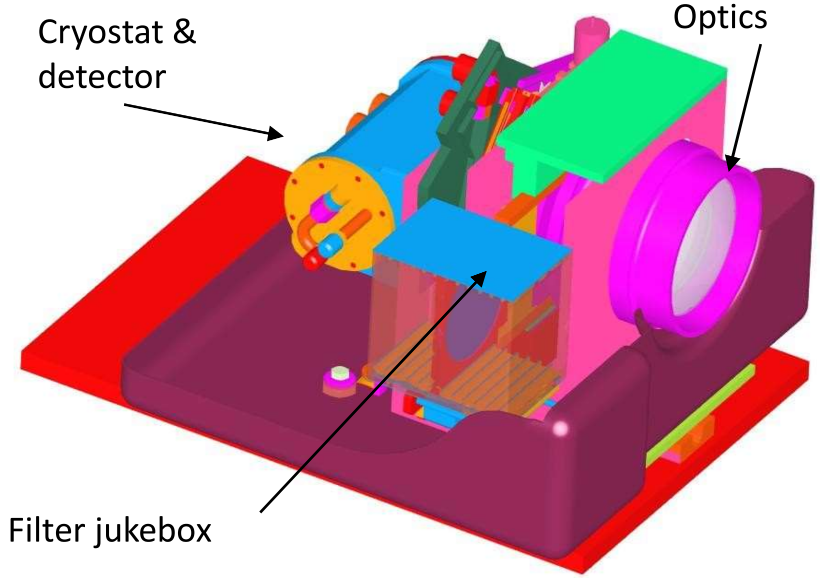
- **Robert Stobie Spectrograph (RSS)**
  - Low-medium resolution (300 – 6000)
  - 3200 – 9000Å
  - Fast spectroscopy (10 Hz)
  - Fast imaging (10 Hz)
  - Spectropolarimetry
  - Imaging polarimetry
  - Fabry-Perot imaging

- **SALTICAM**
  - Fast imaging (10Hz)
  - Deep multi-filter imaging (griz, UBVRI, Hα)

- **SALTICAM High Resolution Spectrograph (HRS)**
  - High resolution (16,000, 34,000, 60,000)
  - 3800 – 8900Å



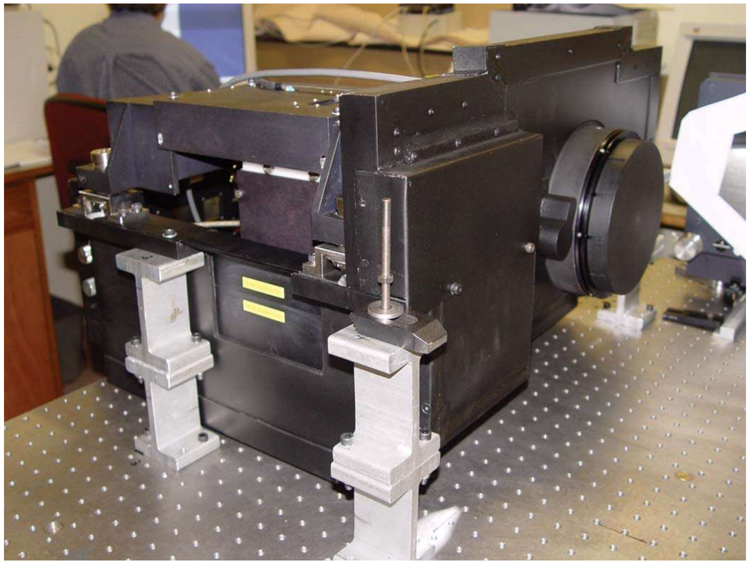
SALTICAM (built at SAAO)



Serves as acquisition camera, commissioning instrument and science imager

An efficient "video" camera (~10 Hz) over entire science FoV (8 arcmin).

Efficient in the UV/blue (capable down to atmospheric cutoff at 320nm)



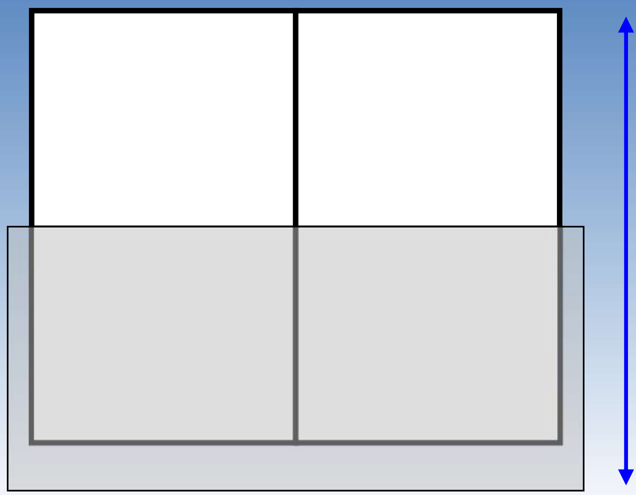
Capable of broad and intermediate-band imaging and high time-resolution (to ~70 ms) photometry.

CCD time resolution capabilities:

SALTICAM:

Moveable frame-transfer mask (mask half of array or use slot mode for fast readout).

Will invariably use 2 x 2 binning (1 binned pixel = 0.24 arcsec)



Full Frame Readout Mode (using shutter)

8 arcmin FoV: 13.8 sec (@2.3e read noise)

5.5 sec (@4e)

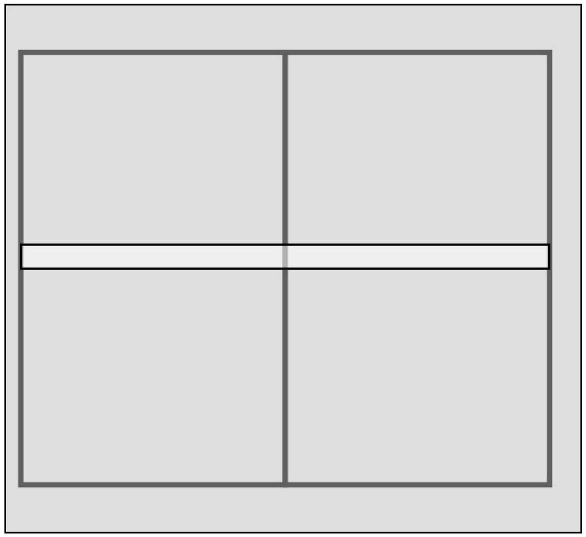
Frame Transfer Mode

Half of 8 arcmin circular FoV 6.3 sec (@2.3e)

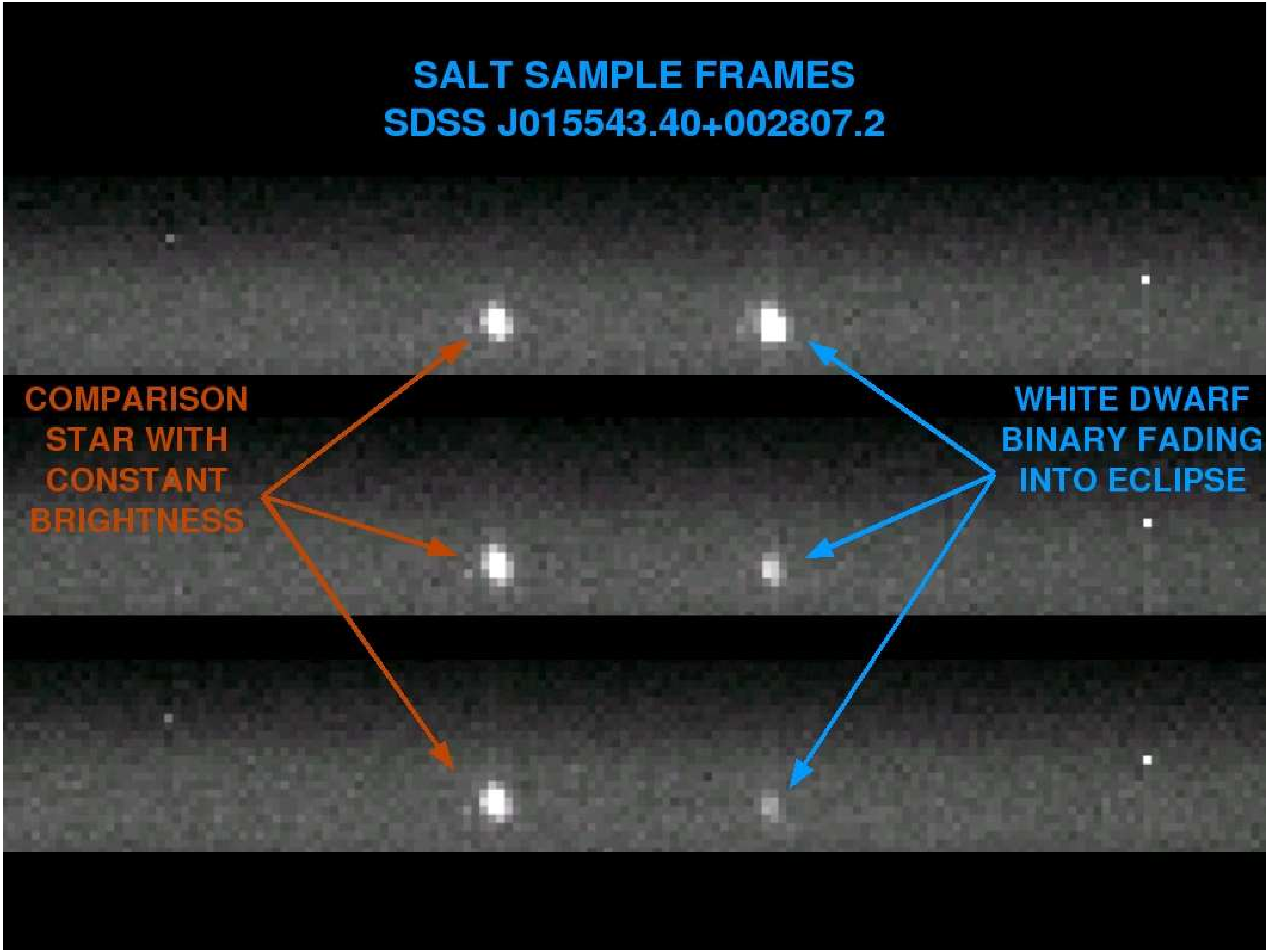
2.4 sec (@4e)

Fastest windowed photometry

Slot mode 0.076 sec (@4 e)



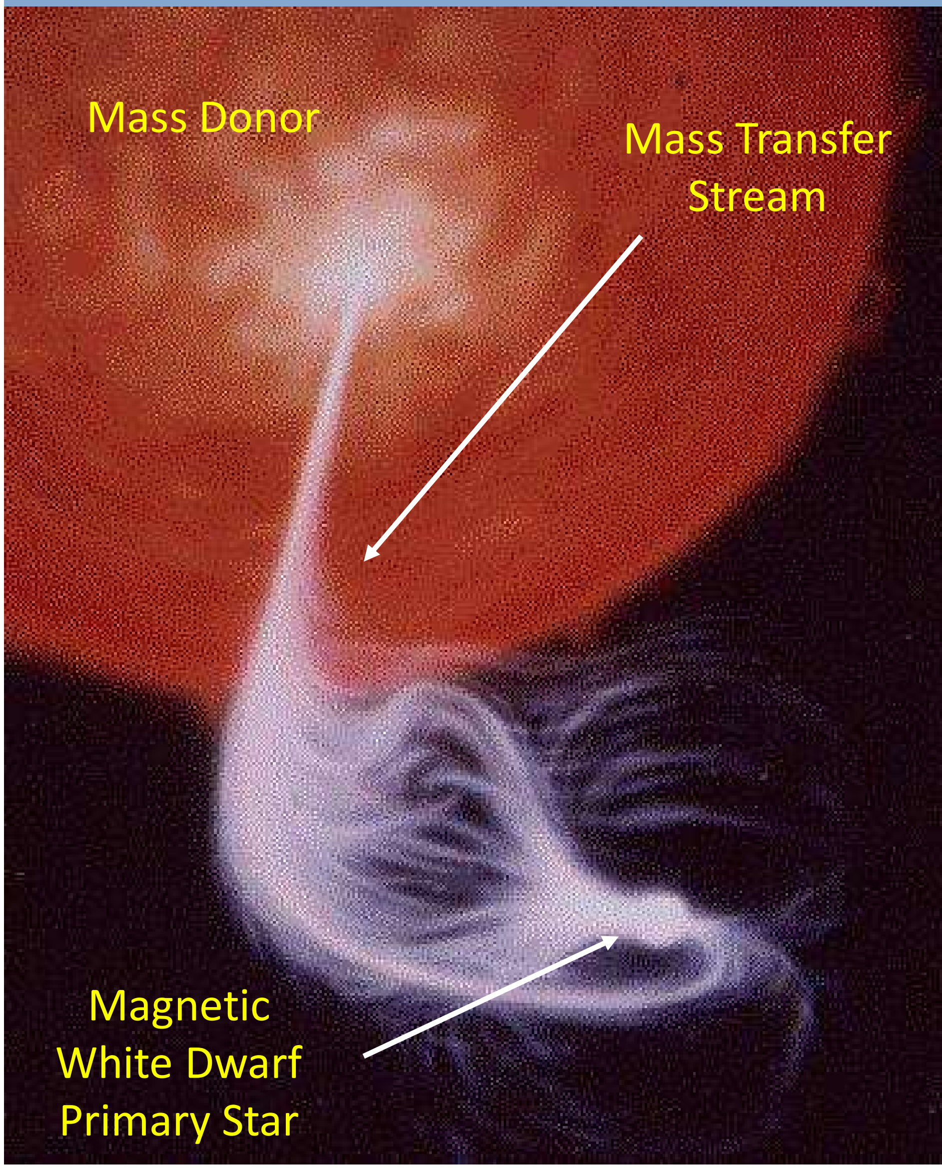
Unvignetted slot size is 64 pixels (~ 11 arcsec)


SALT SAMPLE FRAMES
SDSS J015543.40+002807.2
COMPARISON STAR WITH CONSTANT BRIGHTNESS
WHITE DWARF BINARY FADING INTO ECLIPSE

Compact Binaries

First SALT Science:

high-speed SALTICAM photometry of magnetic cataclysmic variables



- Strongly magnetic white dwarf ($10^1 – 10^2$ G) channels accretion directly to magnetic poles of white dwarf
- Multi-λ emission sites (X-rays, EUV, UV, optical, IR, radio), sites & mechanisms (thermal & non-thermal)
- Often discovered by virtue of X-ray emission from cooling shock

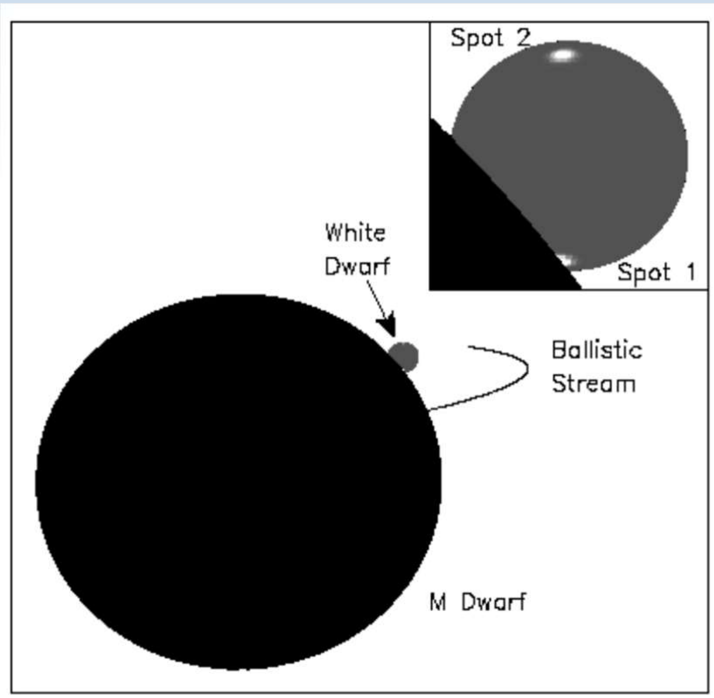
Mon. Not. R. Astron. Soc. **372,** 151–162 (2006) doi:10.1111/j.1365-2966.2006.10834.x

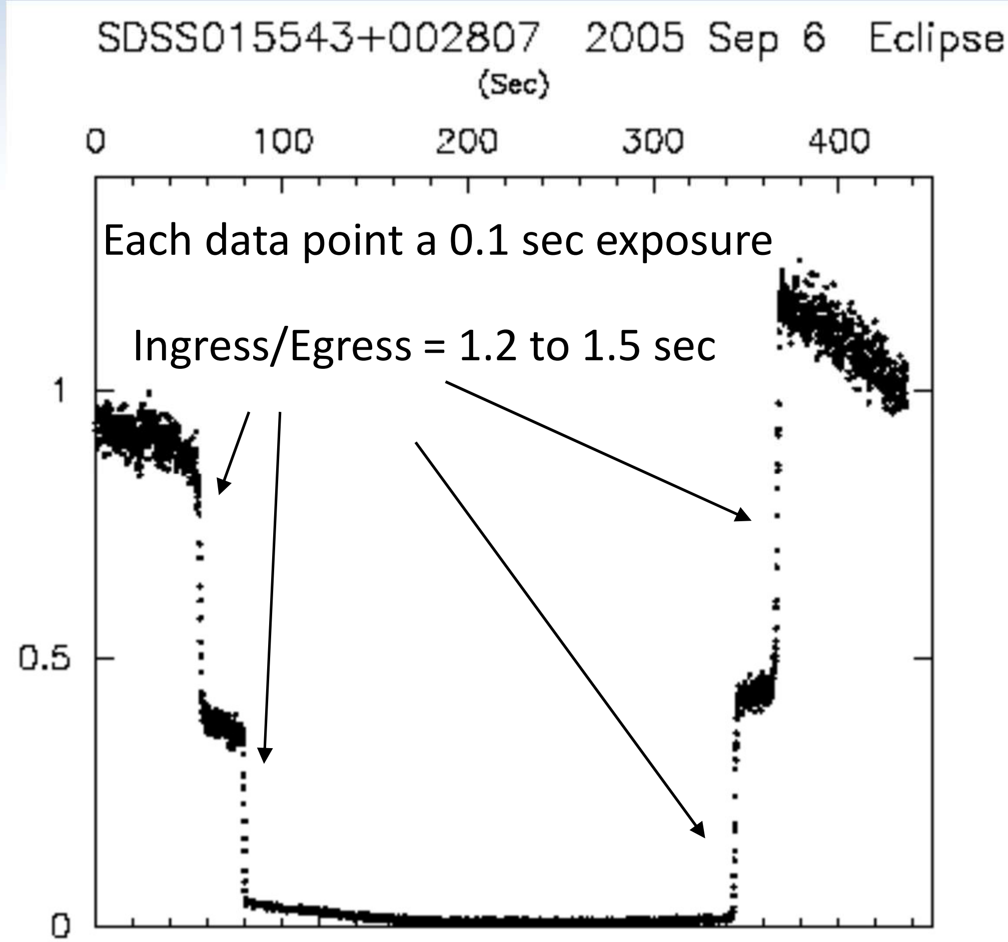
First science with the Southern African Large Telescope: peering at the accreting polar caps of the eclipsing polar SDSS J015543.40+002807.2

D. O'Donoghue,[1★] D. A. H. Buckley,[1,2] L. A. Balona,[1] D. Bester,[2] L. Botha,[1] J. Brink,[1,2] D. B. Carter,[1] P. A. Charles,[1] A. Christians,[1] F. Ebrahim,[1,2] R. Emmerich,[1,2] W. Esterhuyse,[2] G. P. Evans,[1] C. Fourie,[1] P. Fourie,[1] H. Gajjar,[1,2] M. Gordon,[1] C. Gumede,[2] M. de Kock,[2] A. Koeslag,[2] W. P. Koorts,[1] H. Kriel,[1] F. Marang,[1] J. G. Meiring,[2] J. W. Menzies,[1] P. Menzies,[1] D. Metcalfe,[1] B. Meyer,[1] L. Nel,[2] J. O'Connor,[1] F. Osman,[1] C. du Plessis,[1] H. Rall,[1] A. Riddick,[1] E. Romero-Colmenero,[1] S. B. Potter,[1] C. Sass,[1] H. Schalekamp,[2] N. Sessions,[2] S. Siyengo,[1] V. Sopela,[1] H. Steyn,[1] J. Stoffels,[1] J. Scholtz,[1] G. Swart,[2] A. Swat,[2] J. Swiegers,[2] T. Tiheli,[1] P. Vaisanen,[1] W. Whittaker[2] and F. van Wyk[1]

SALT Science

An example: a light curve of the eclipsing magnetic CV (Polar) SDSS 015532+002807 (aka FL Cet) taken with SALTICAM in slotmode

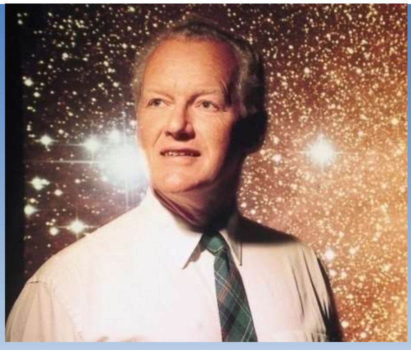




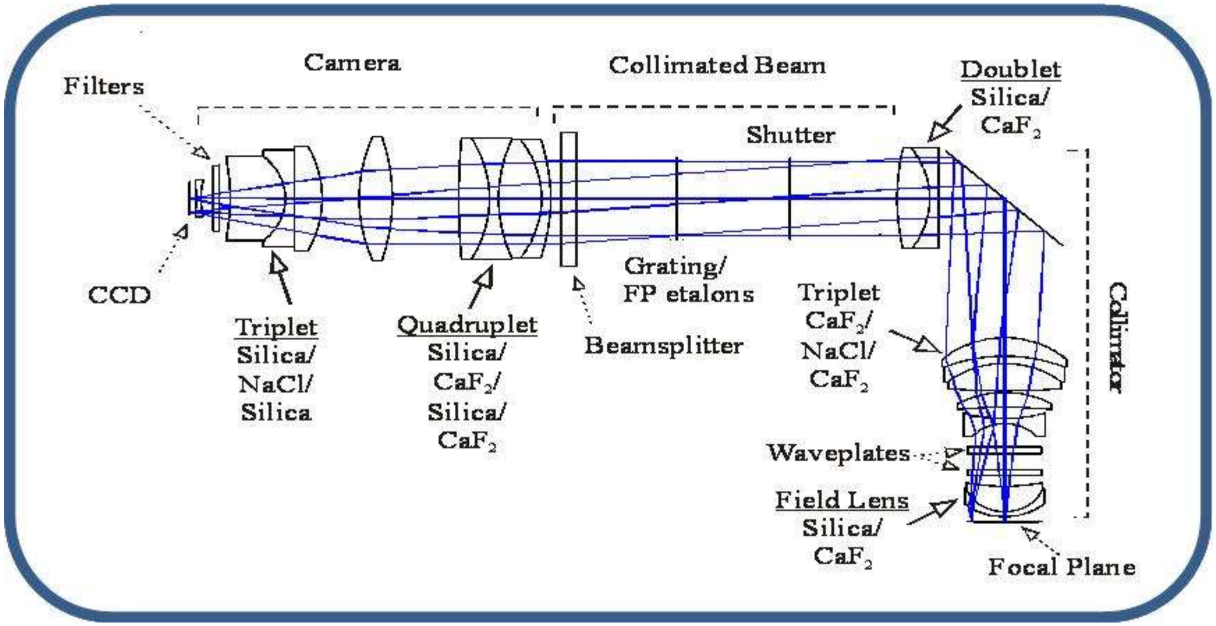
The Robert Stobie Spectrograph (RSS)

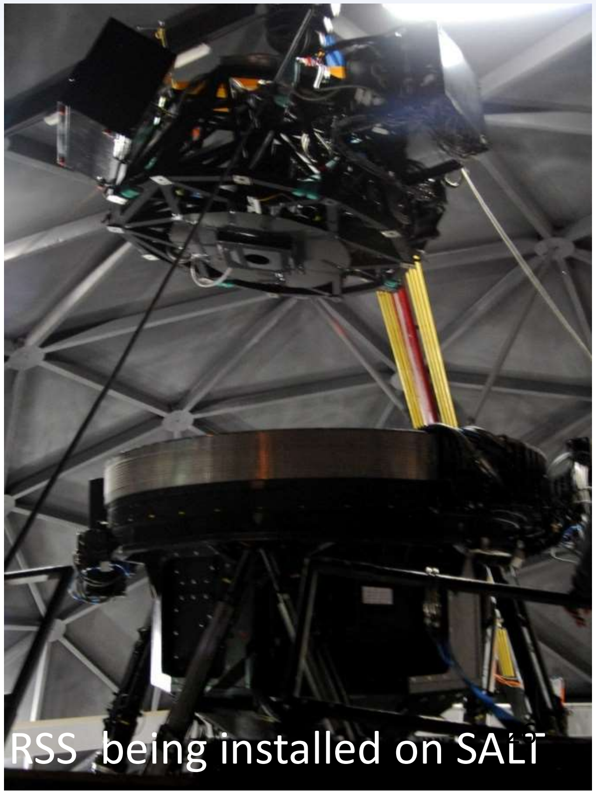
An efficient and versatile Imaging Spectrograph

- capable of UV-Vis spectroscopy from 310 – 900nm using VPHGs *(red extension to 1.7μm, using a dichroic, is under construction)*
- high time resolution ablility (~0.1 s)
- specto- and imaging polarimetric capability
- Fabry Perot imaging (incl. with pol.)
- multiple object spectroscopy
  - Can observe ~50 objects at once

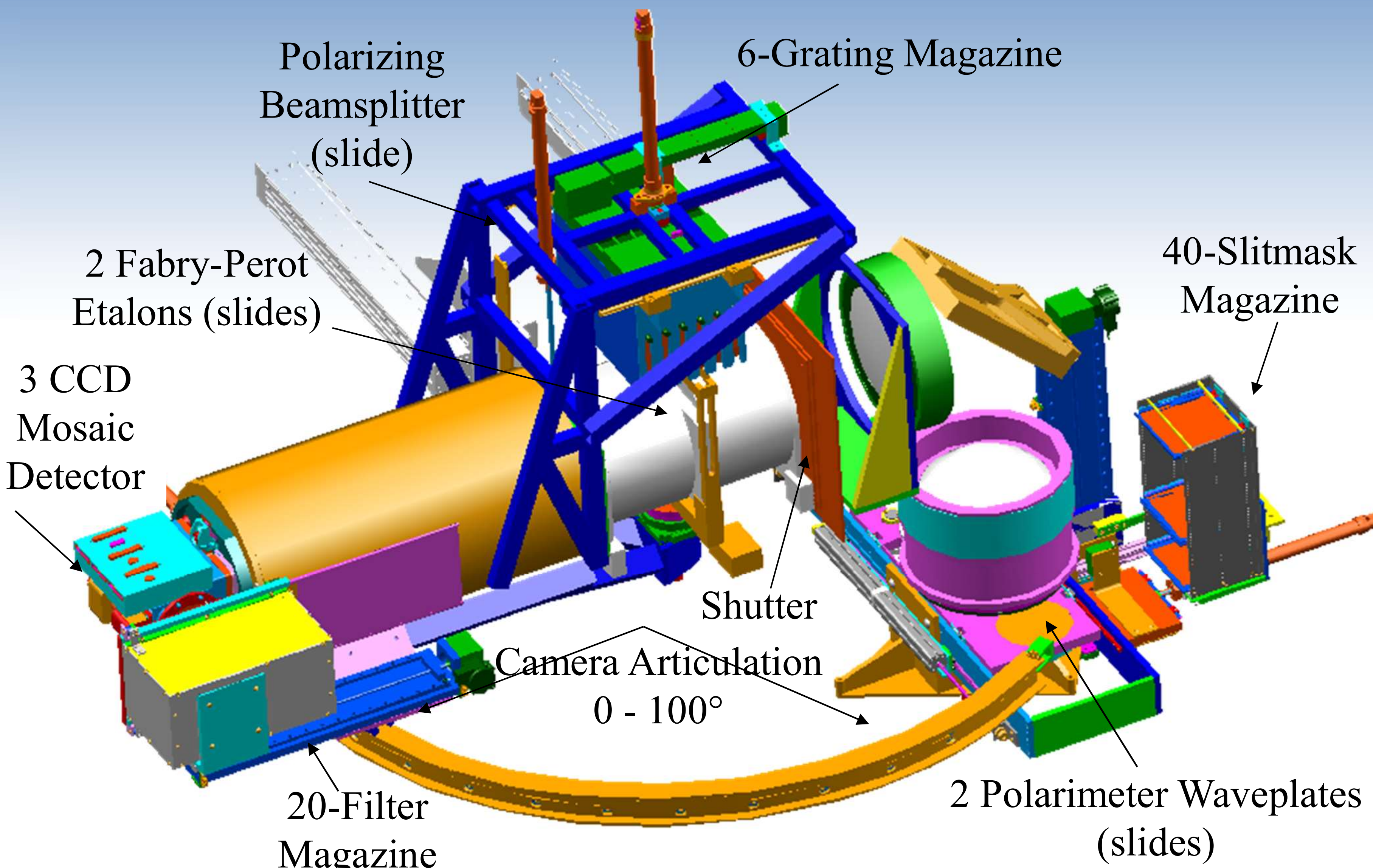


Named in memory of Bob Stobie, previous SAAO Director & one the instigators of SALT.

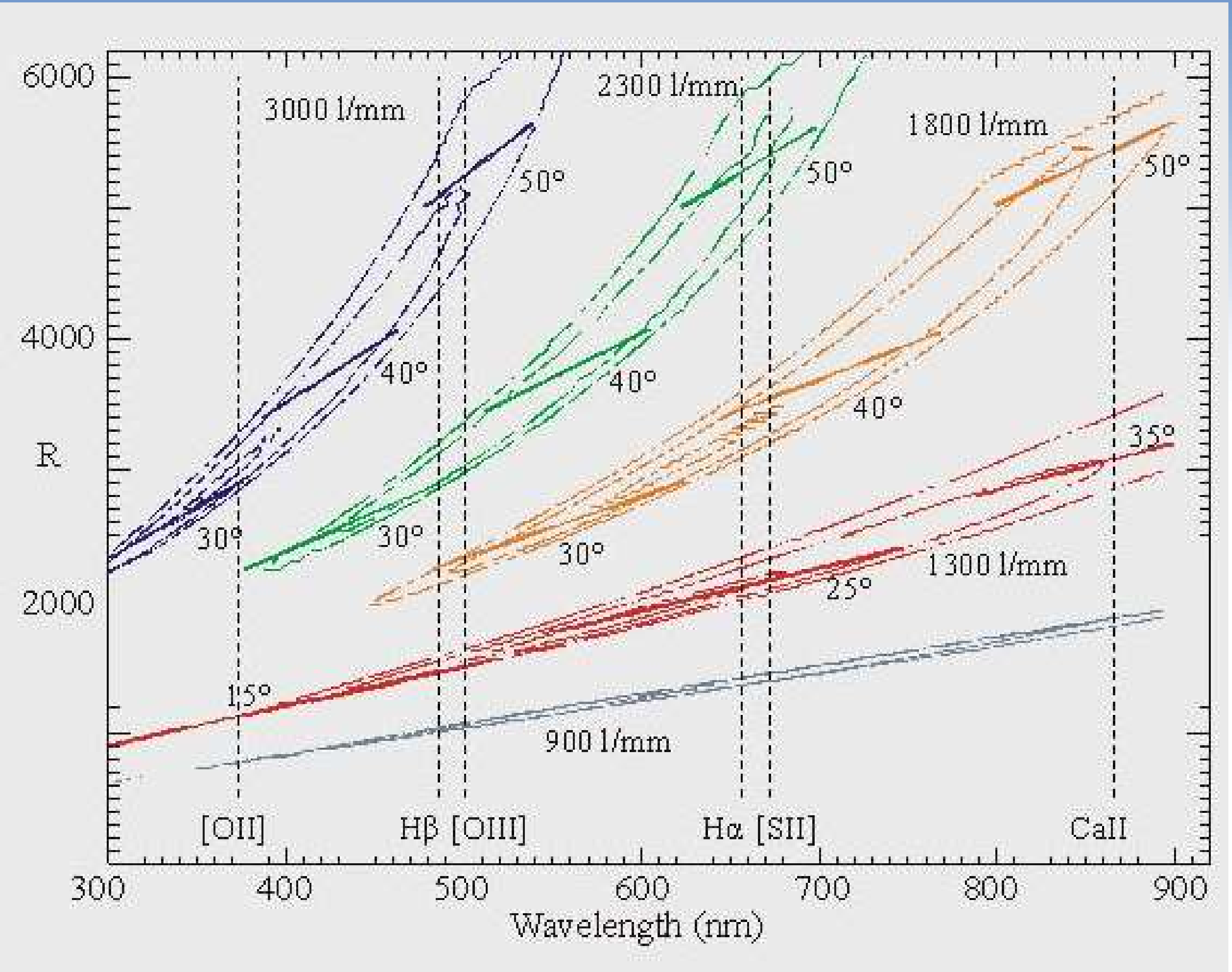




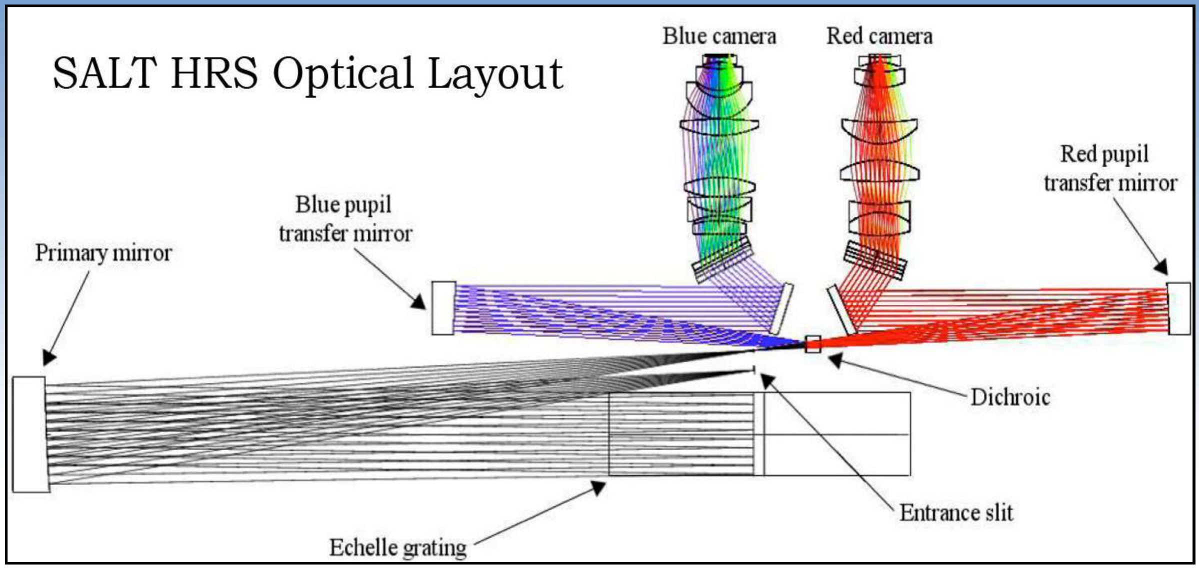
RSS Mechanisms

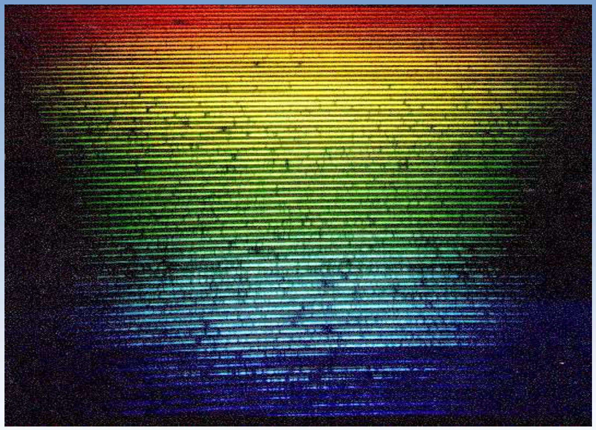


RSS complement of diffraction gratings



SALT High Resolution Spectrograph (HRS):

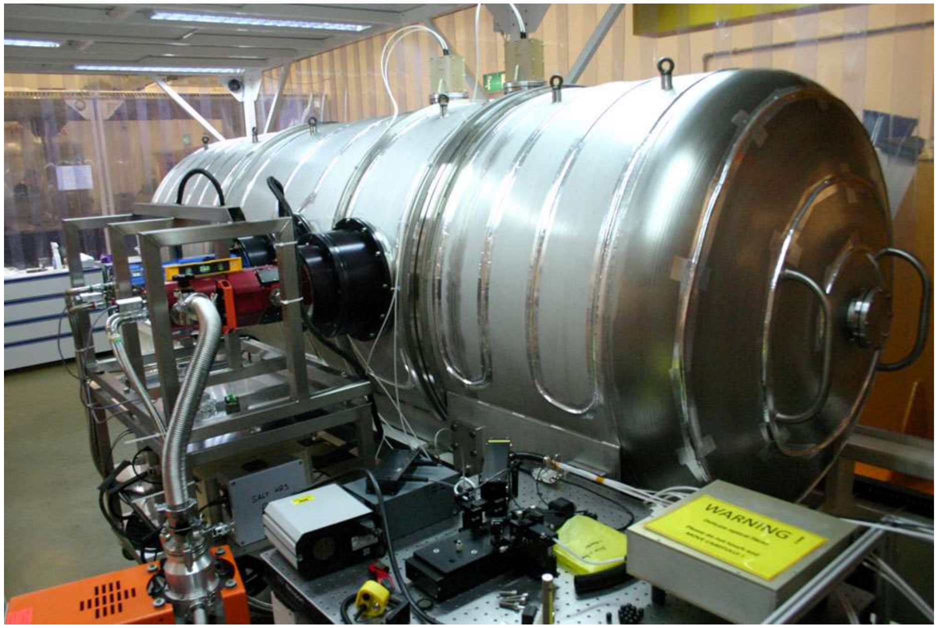




Fibre-fed with dual fibres for star/sky

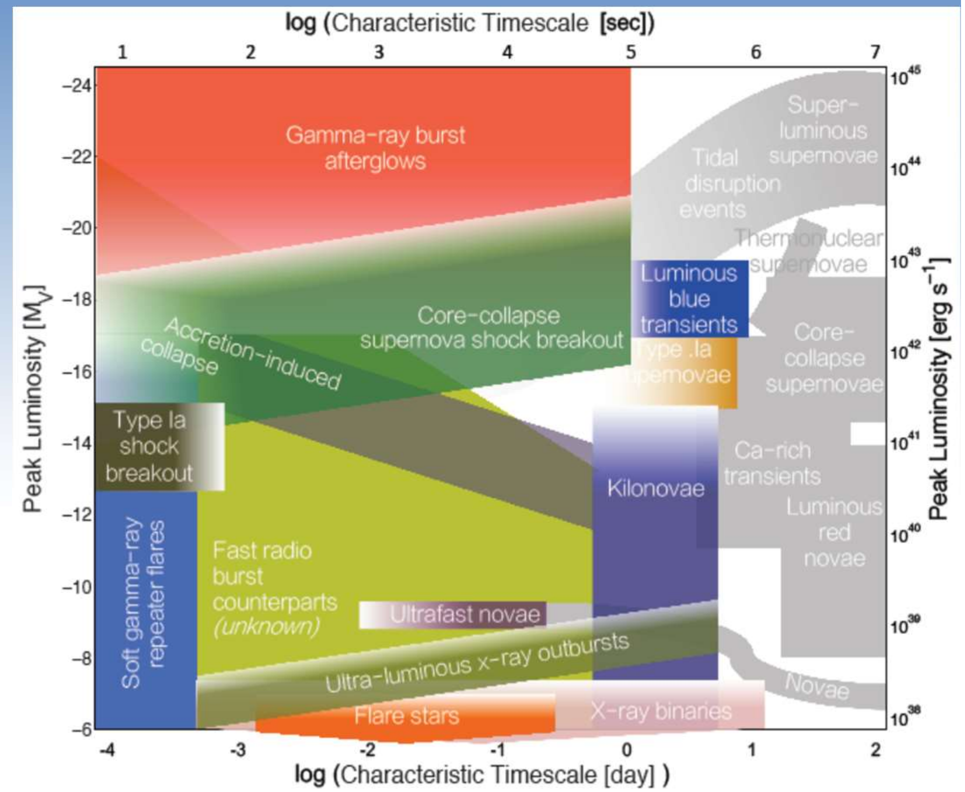
Three resolution modes R ~ 16,000 – 70,000
λ ~ 380 – 890 nm

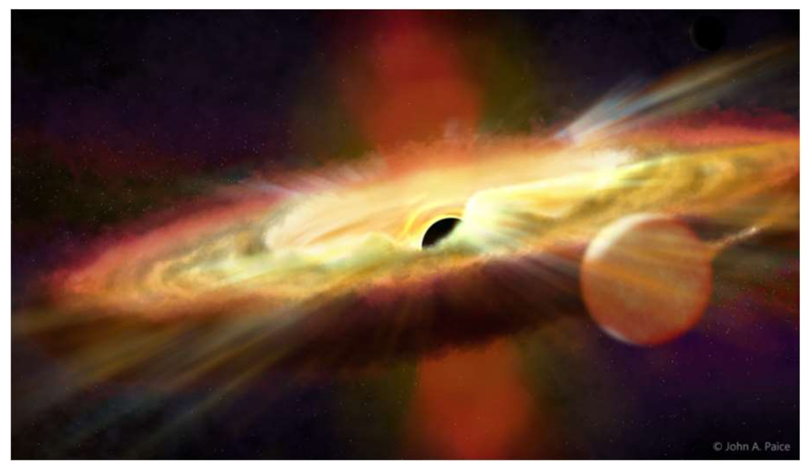
Designed for very ***high stability***
- Housed in vacuum tank
- Temperature stabilized
- Minimize refractive index of air effects
- Minimize dimension changes
- Precision radial velocities (m/s)



The SALT Transient Program

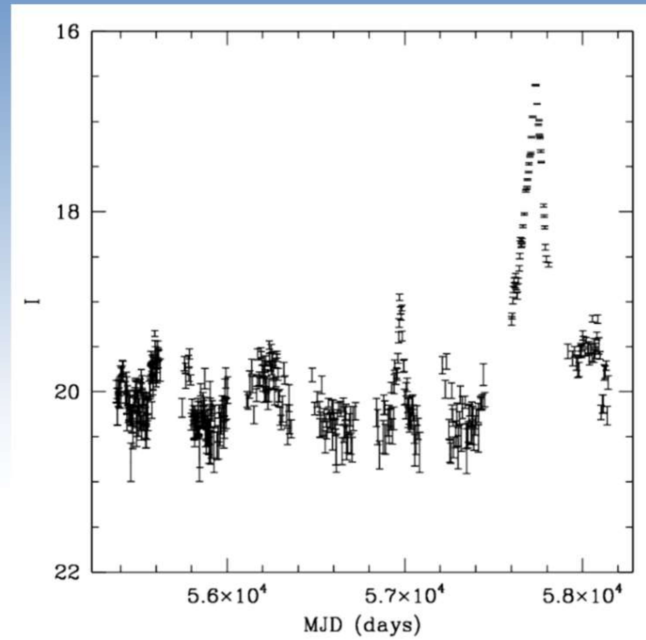
- Covering wide range in luminosity (& distance)
- Variability on wide range of timescales
  - Sub-seconds domain a new frontier
- Covering many object classes, including Compact Binaries:
  - X-ray transients
  - X-ray binaries (LMXBs, HMXBs)
  - Cataclysmic Variables
  - Novae, Recurrent Novae
  - Intermediate luminosity transients
  - Multi-messenger (Gravitational Wave & Neutrino) events
  - Radio transients with MeerKAT (ThunderKAT programme)

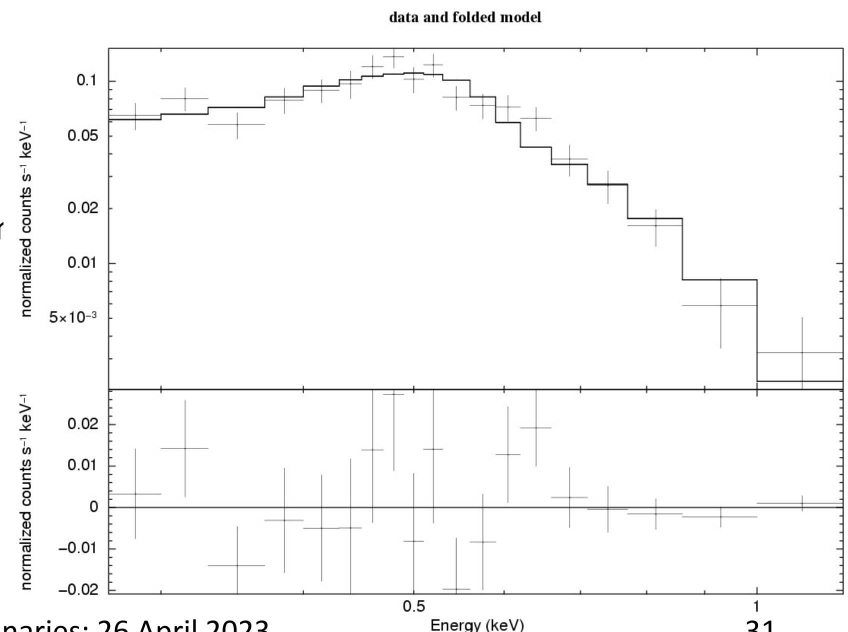




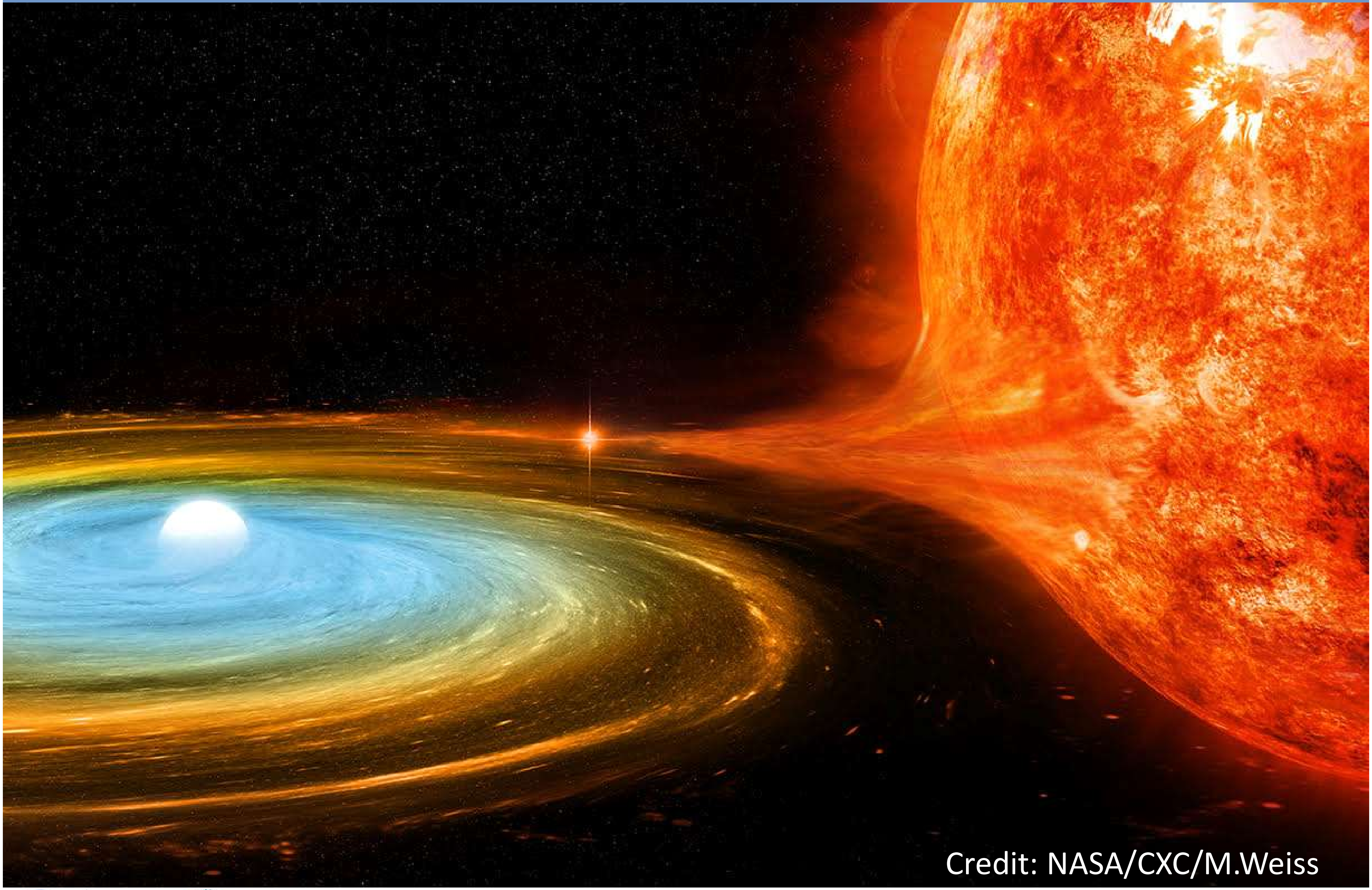
New Super Soft Source: ASASSN-16oh

- Discovery of a new Super Soft Source in the SMC in Dec 2016
- Followup SALT RSS spectroscopy
  - Strong narrow HeII 4686
  - Small R.V. variations consistent with ~3d period
- Followup LCO photometry (DDT)
  ~34 hours over X-mas period 2016
- OGLE photometry
  - Symmetrical and long-lived (~200 d) outburst
  - Evidence of previous lower amplitude ones
- Swift/ASTROSAT observations
  - Very soft X-ray spectrum
- Paper published in *Nature Astronomy* (Maccarone et al, 2019, Nat Ast, 3,)
  - Outburst from hot (~900,000 K) spreading layer on a or dwarf
  - *Not* a thermonuclear ignition event





ASASSN-16oh: SSS

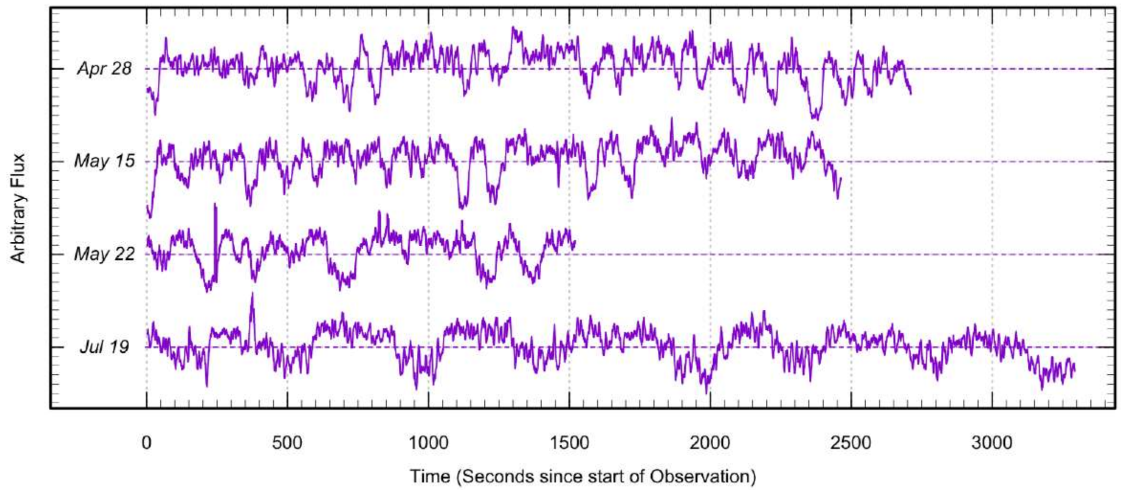


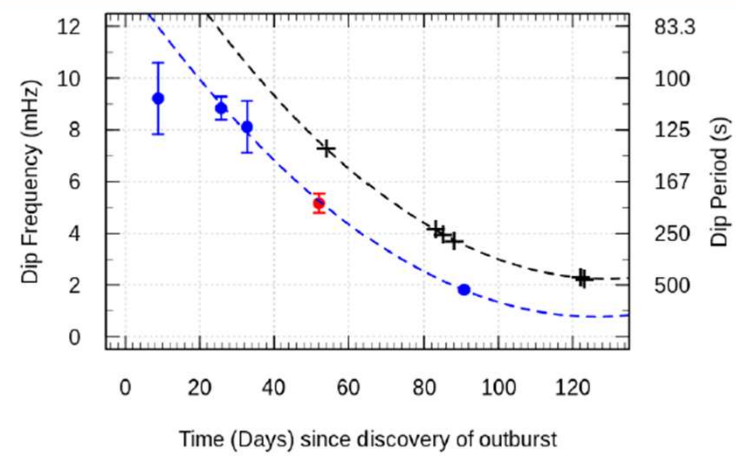
Credit: NASA/CXC/M.Weiss

Compact Binaries

Example of an LMXB: Swift J1357-0933

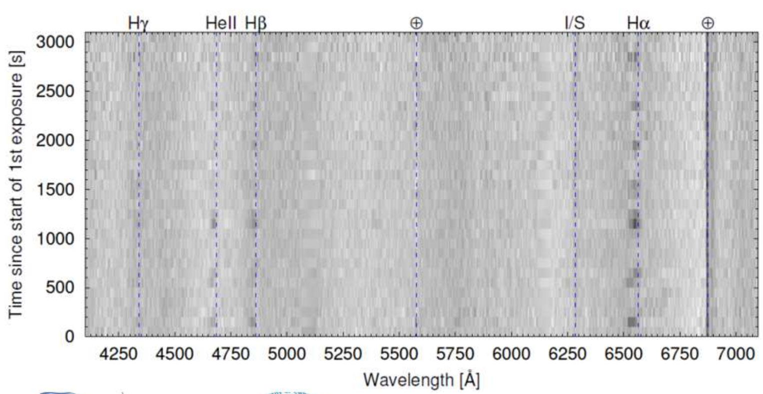
- A black hole X-ray transient (discovered in 2011; M > 9.3 $M_{\odot}$)
- SALT observations during recent o/b in 2017 & 2019 (0.15 s sampling)

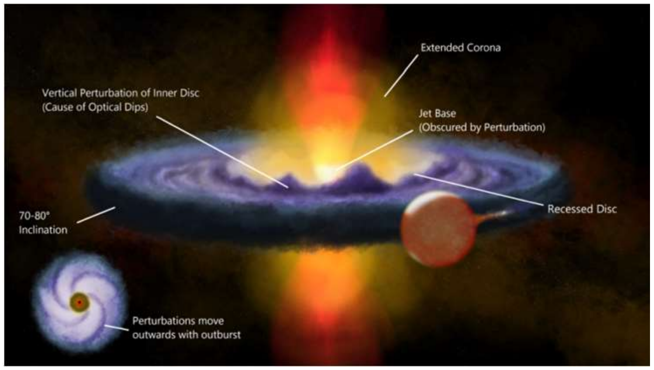




SALT high-speed (0.15 s) photometry of Swift_J1357.2-0933 (Paice et al. 2019)

- Time resolved (30 s) spectroscopy during 2017 & 20 revealed transient absorption lines (Balmer & HeII) on same timescale as photometric dips
- Evidence of hot dense accretion disk wind (Charles et al. 2019)

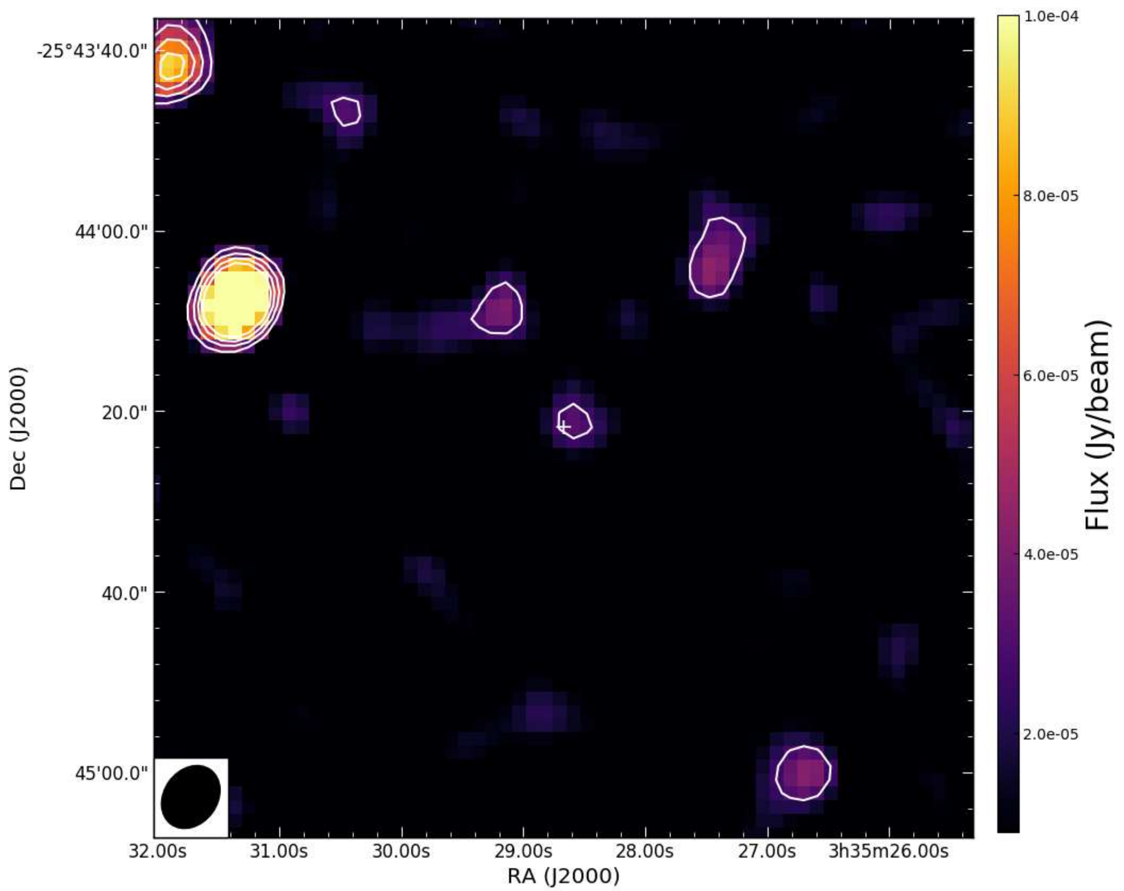


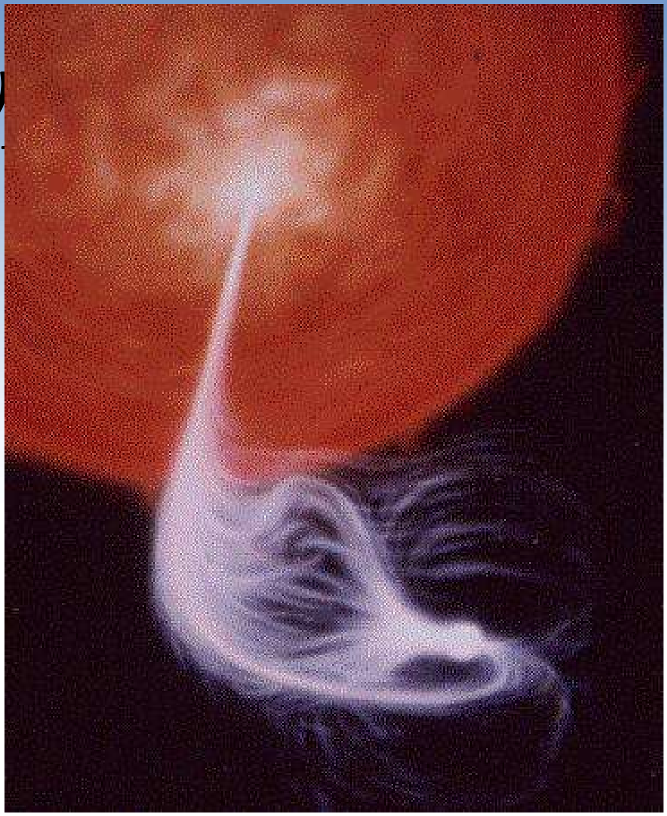


Magnetic Cataclysmic Variables

Observation of UZ For, an eclipsing magnetic CV (polar)

- First simultaneous MeerKAT/ optical (SALT/SAAO 1.9-m/MeerLICHT observations
- PhD research of Zwidofhelangani Khangale (UCT/SAAO)



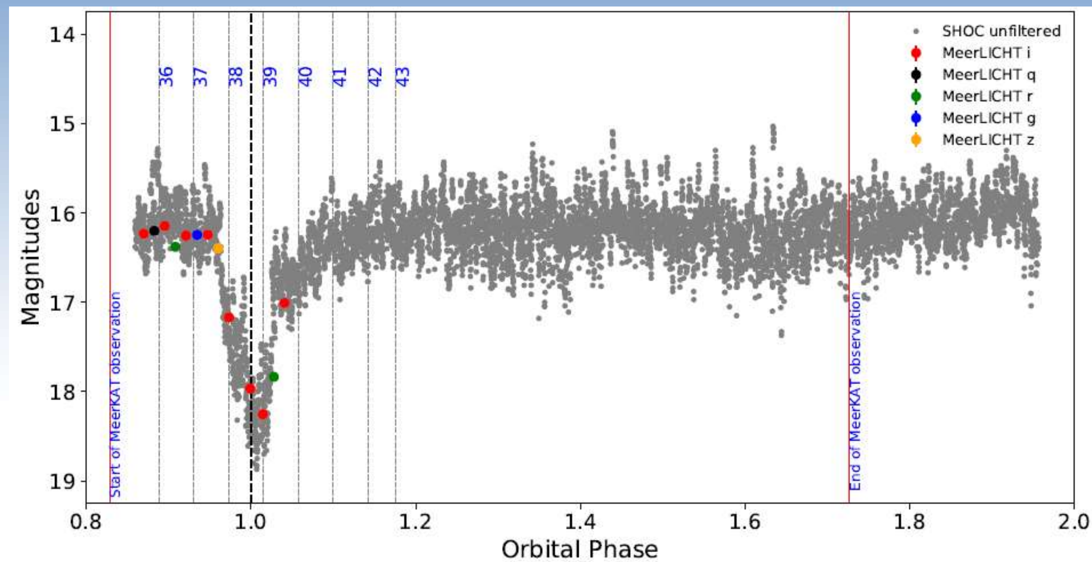


Magnetic Cataclysmic Variables

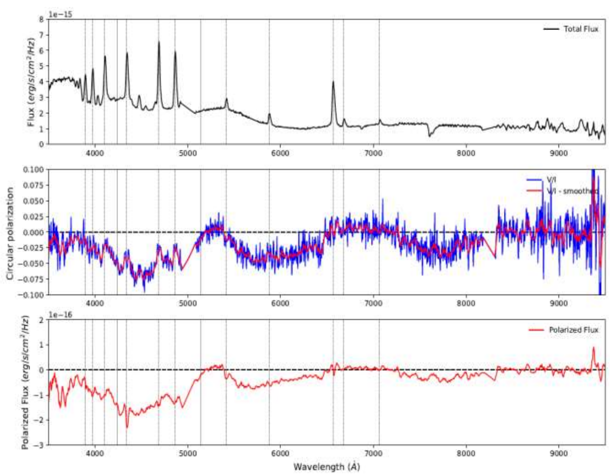
Compact Binaries

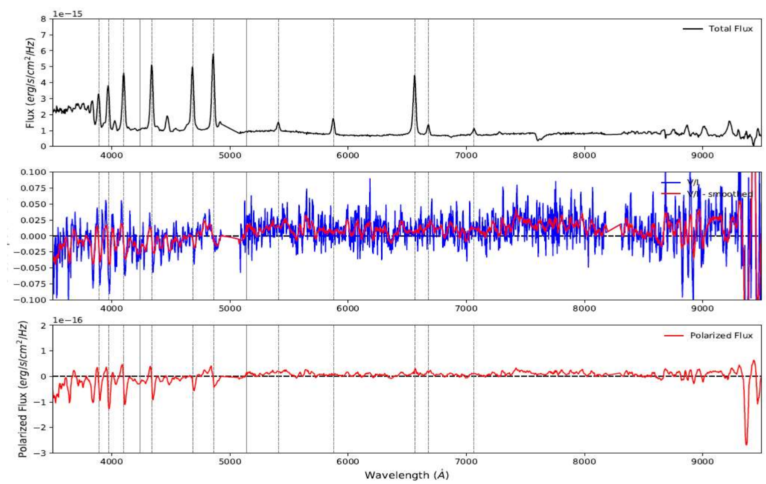
UZ For

- Simultaneous light curve from SAAO 1.9-m + SHOC and MeerLICHT:



- Simultaneous circular spectropolarimetry from SALT:

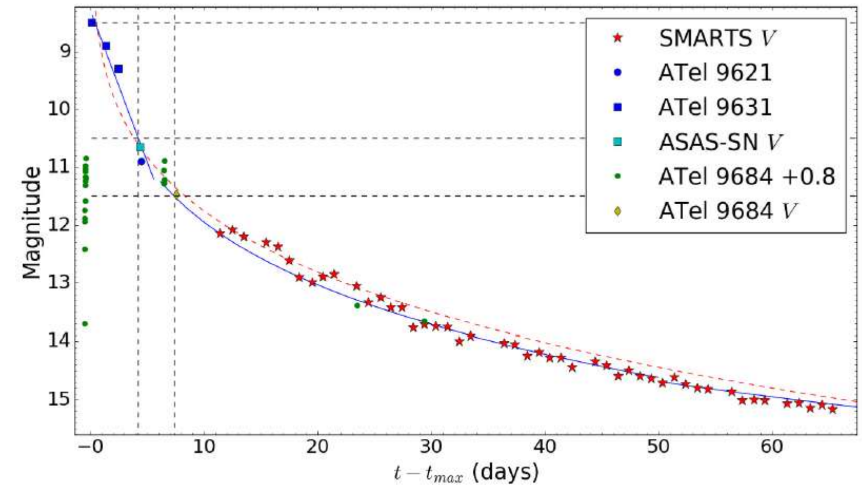


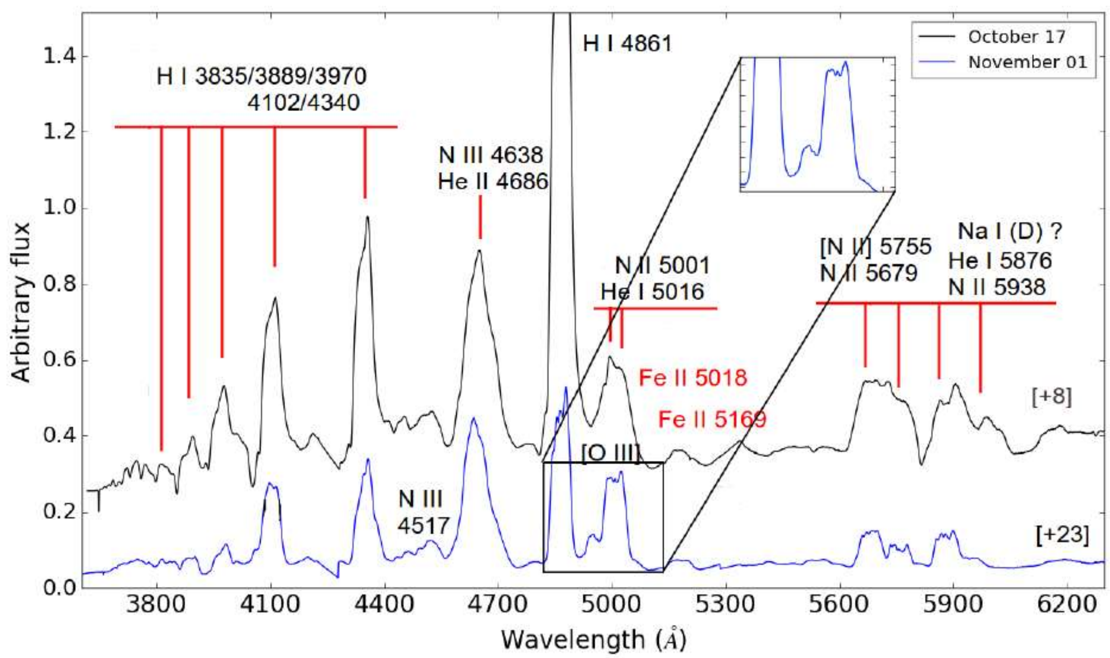


Novae

Program instigated by Elias Aydi (PhD student at the time)

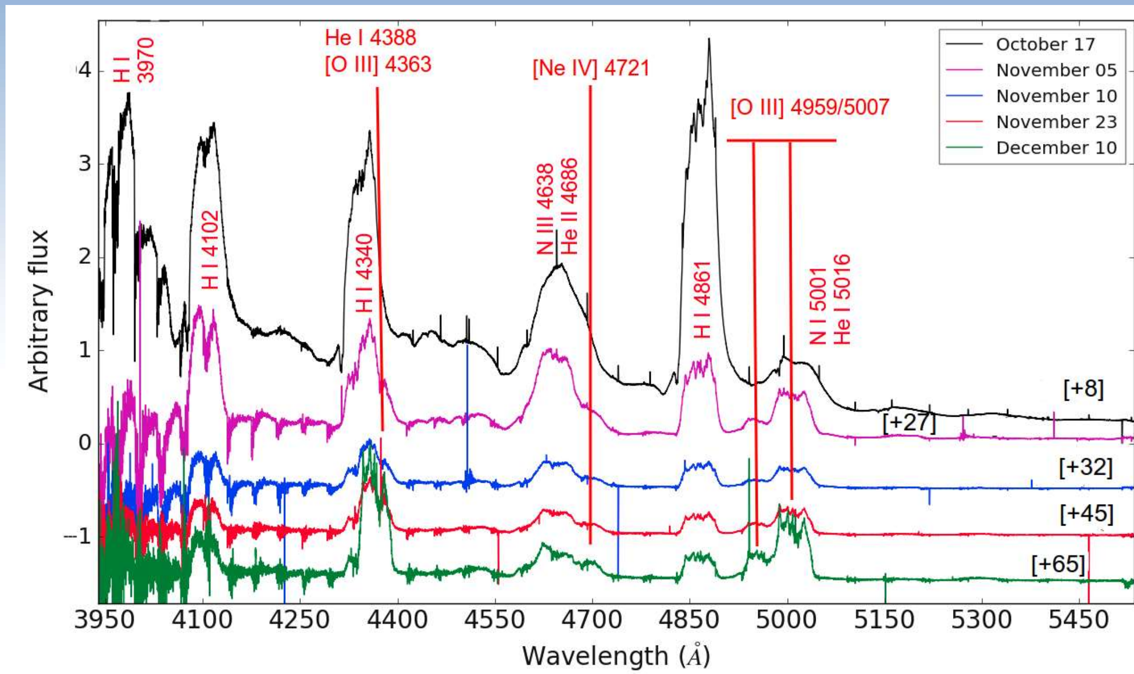
- Discovery of nova SMCN 2016-10a (in SMC) by MASTER (V = 9)
- Follow-up by SALT (opt) Swift (UV/X-ray), SMARTS (opt/NIR), Chandra (X-ray)
- *M_V (max) = -10.5* (most luminous)
- Fast He/N nova; WD mass > 1.2$M_\odot$



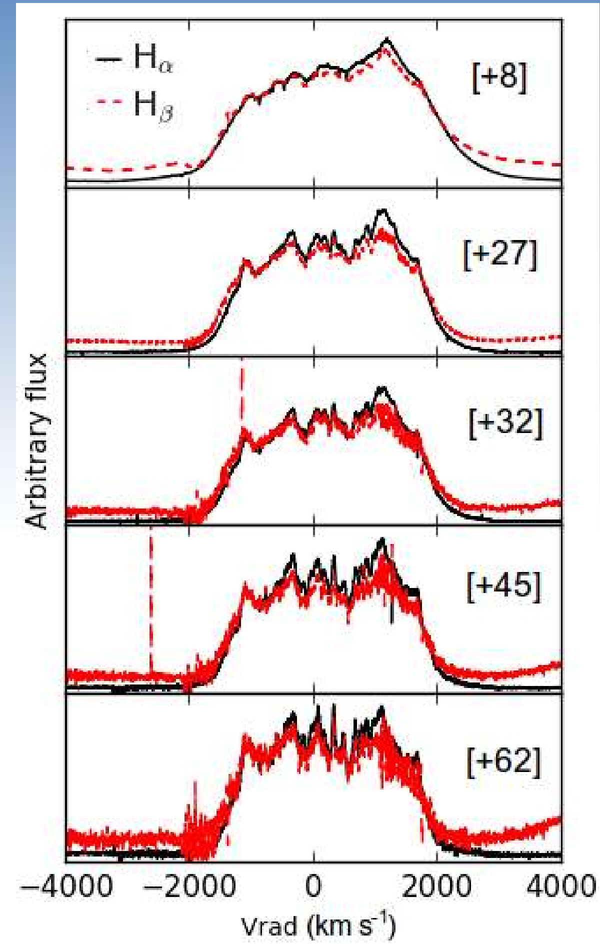


Nova SMC N 2016-10a

- Evolved through nebular phase to supersoft phase



SALT HRS spectra



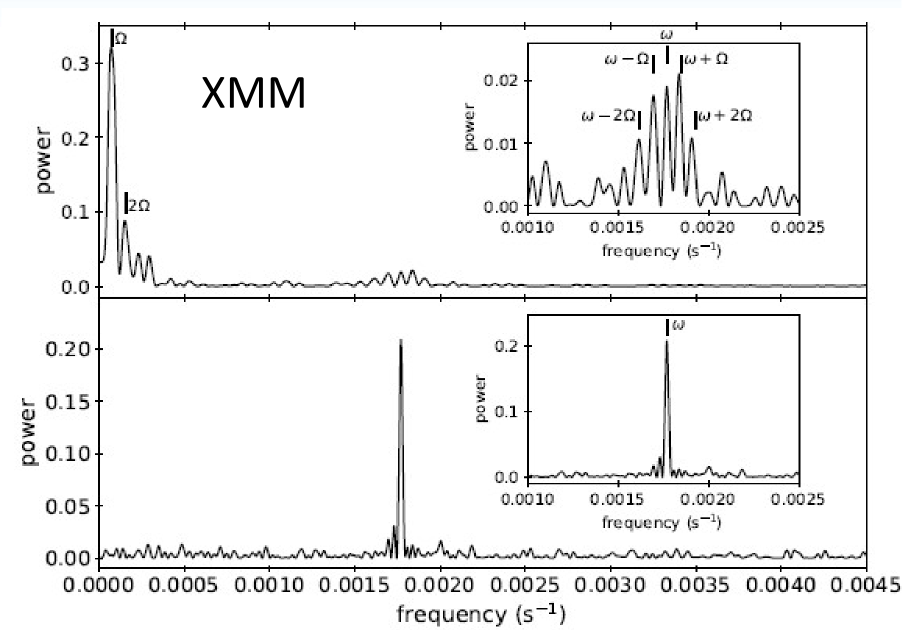
2018:

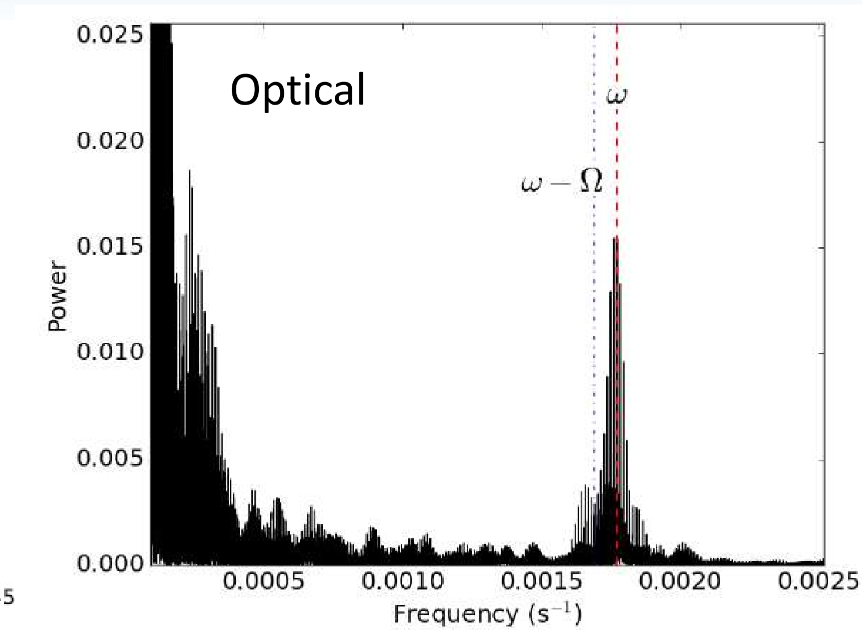
Multiwavelength observations of nova SMCN 2016-10a — Probably the brightest nova in the SMC

E. Aydi[1,2⋆], K. L. Page[3], N. P. M. Kuin[4], M. J. Darnley[5], F. M. Walter[6], P. Mróz[7], D. Buckley[1], S. Mohamed[1,2], P. Whitelock[1,2], P. Woudt[2], S. C. Williams[8,5], M. Orio[9,10], R. E. Williams[11], A. P. Beardmore[3], J. P. Osborne[3], A. Kniazev[1,12,13] V. A. R. M. Ribeiro[14,15,16], A. Udalski[7], J. Strader[17] and L. Chomiuk[17]

Nova V407 Lup (ASASSN-16kt)

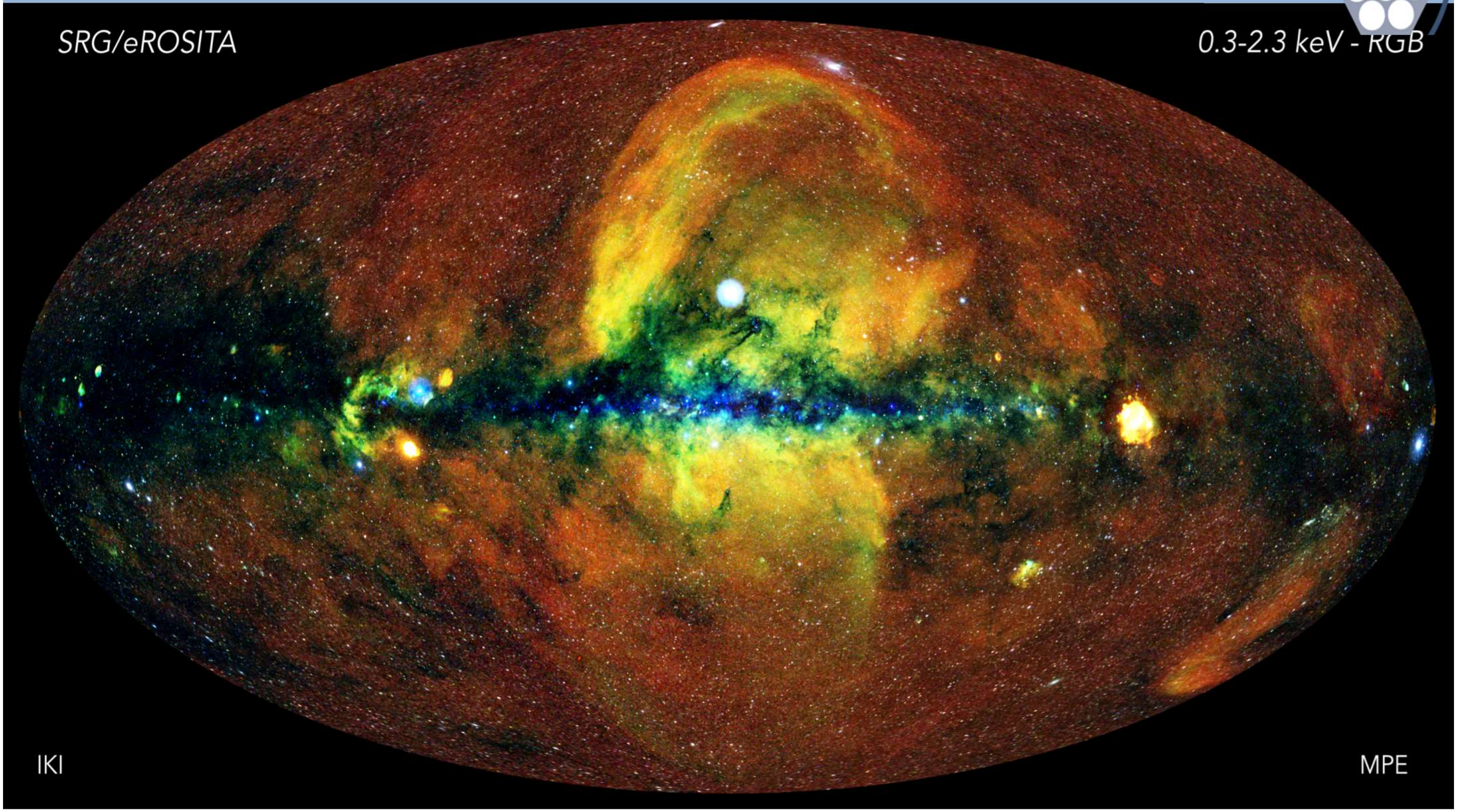
- Another fast nova (Aydi et al. 2018)
- Evidence that the remnant is an intermediate polar (magnetic WD)
  - 3.57 h orbital period and 565 s spin period
  - Spin modulation of hot-spot?





Recent SALT Transient Initiative

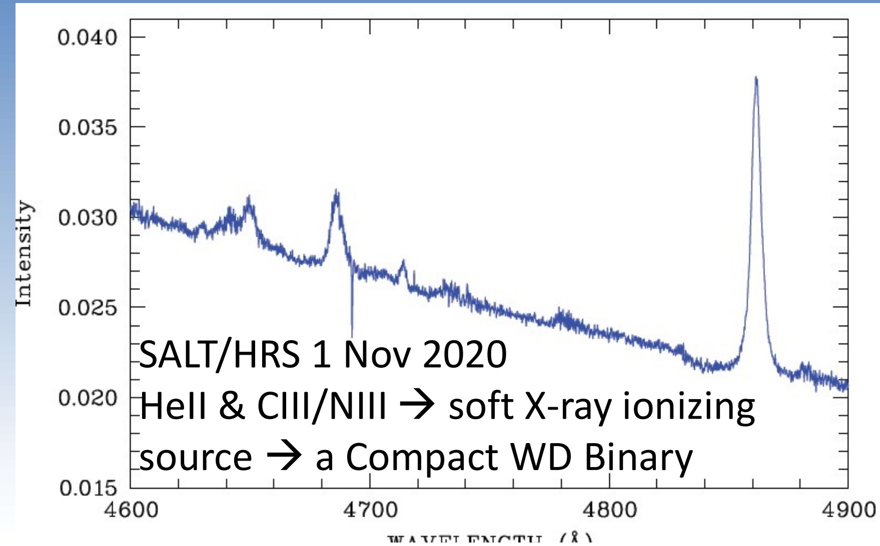
Following eROSITA-DE X-ray transients

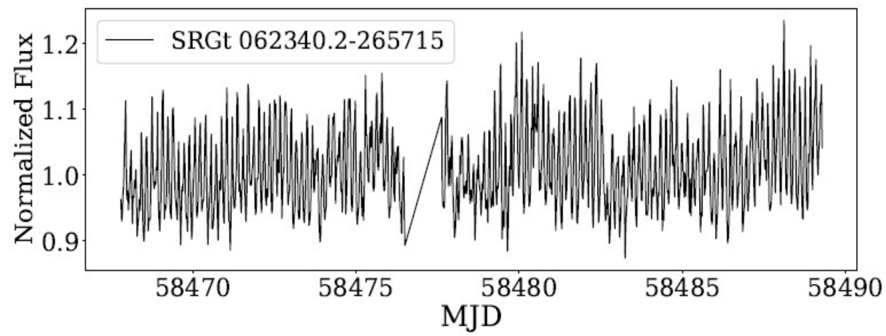


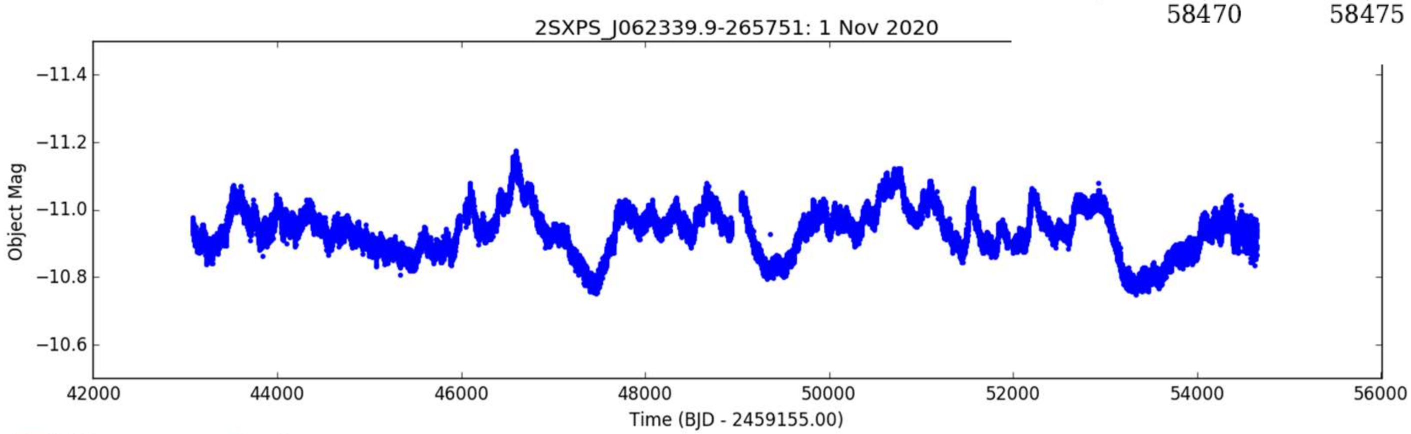
eROSITA accreting Compact White Dwarf Binaries

First example studied:

- SRGt J062339.9-265751: factor 50 variability between eRASS:1 and :2 Factor 10 variability in eRASS:2
- Detected with both instruments on SRG (eROSITA & ATC-XC)
- Bright, thermal X-ray spectrum
- Among the brightest objects of its kind (g ~12.5)
- 3.9 h period seen in TESS
- Looks like a mCV from SALT spectrum and SAAO high speed photometry



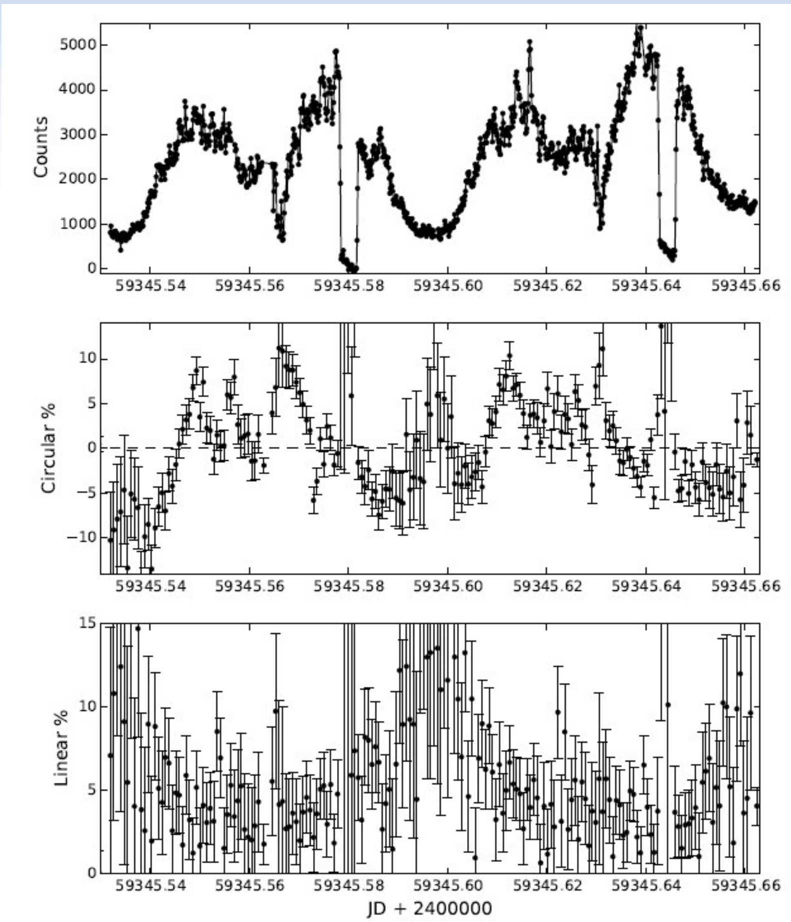


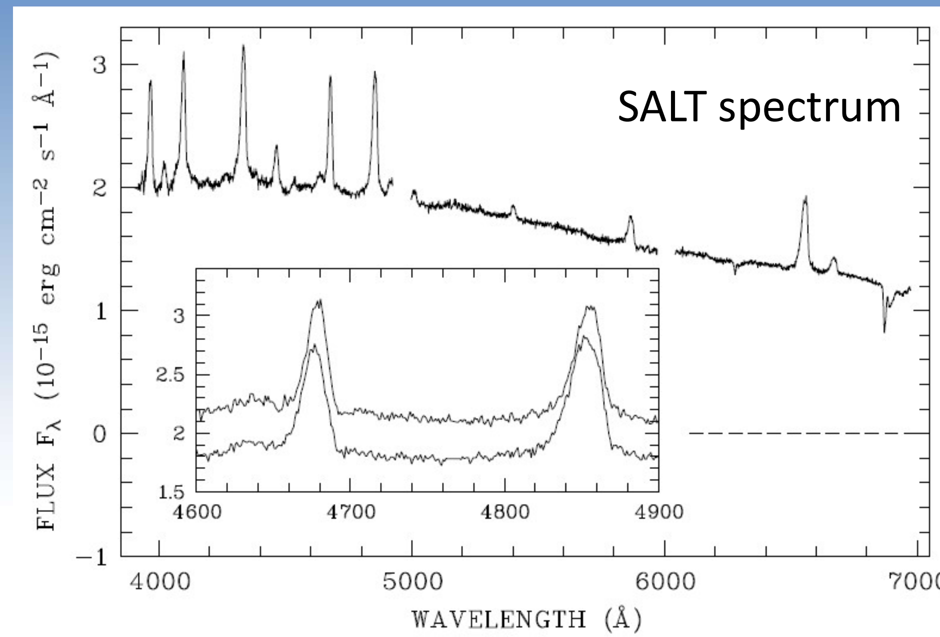


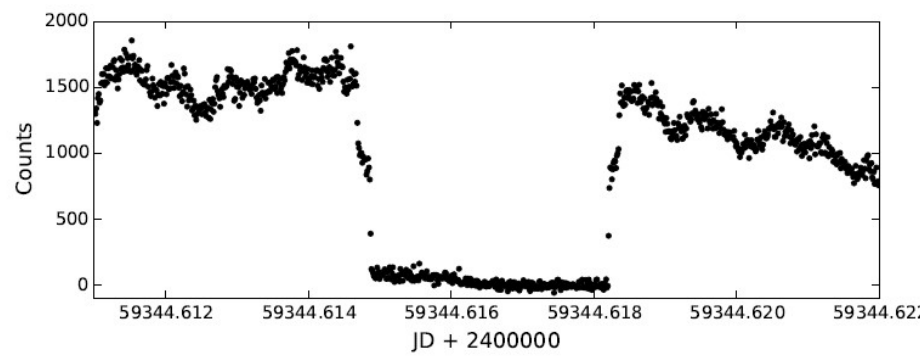
eROSITA accreting Compact White Dwarf Binaries

Second example studied:

- eRASSt J192932.9-560346 is a new polar (magnetic CV).
- Eclipsing system with 1.54 h period
- Two-pole system

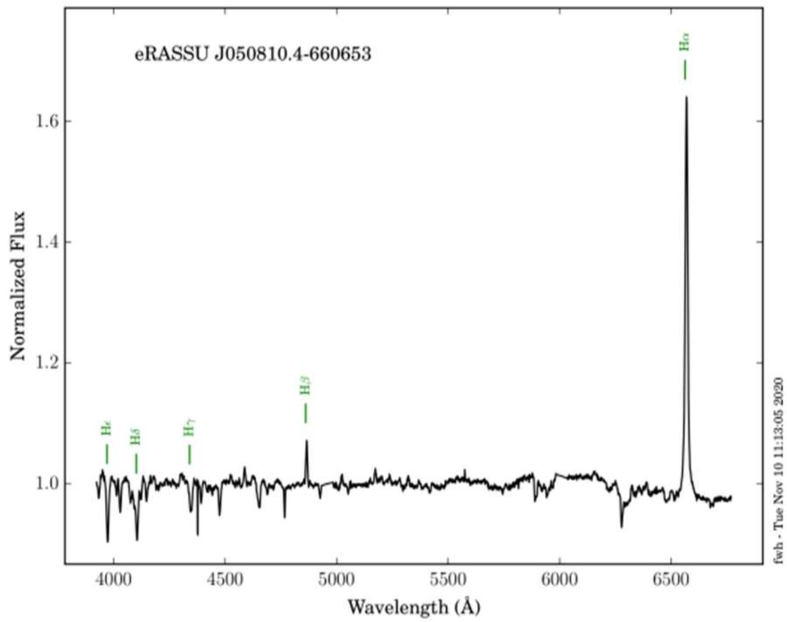


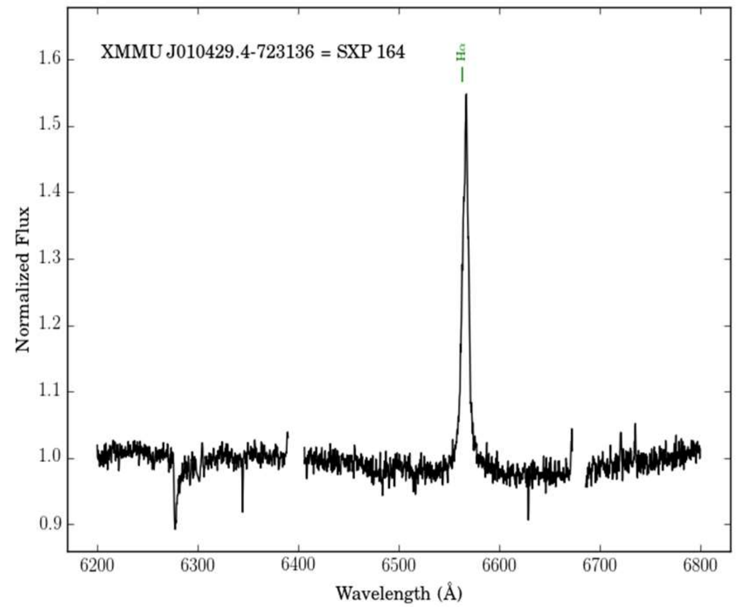




eROSITA discoveries of High Mass X-ray Binaries in the Magellanic Cloud

- SALT observations of transient HMXBs in the MCs, mostly Be X-ray binaries, many harbouring X-ray pulsars.
- A number of new discoveries have been made in the LMC, which has a relatively low population compared to the SMC





An example: the White Dwarf "Pulsar" AR Sco

Discovery as pulsing WD: June 2016

LETTER

doi:10.1038/nature18620

A radio-pulsing white dwarf binary star

T. R. Marsh[1], B. T. Gänsicke[1], S. Hümmerich[2,3], F.-J. Hambsch[2,3,4], K. Bernhard[2,3], C. Lloyd[5], E. Breedt[1], E. R. Stanway[1], D. T. Steeghs[1], S. G. Parsons[6], O. Toloza[1], M. R. Schreiber[6], P. G. Jonker[7,8], J. van Roestel[8], T. Kupfer[9], A. F. Pala[1], V. S. Dhillon[10,11,12], L. K. Hardy[10], S. P. Littlefair[10], A. Aungwerojwit[13], S. Arjyotha[14]‡, D. Koester[15], J. J. Bochinski[16], C. A. Haswell[16], P. Frank[2] & P. J. Wheatley[1]

First followup: Jan 2017

nature astronomy

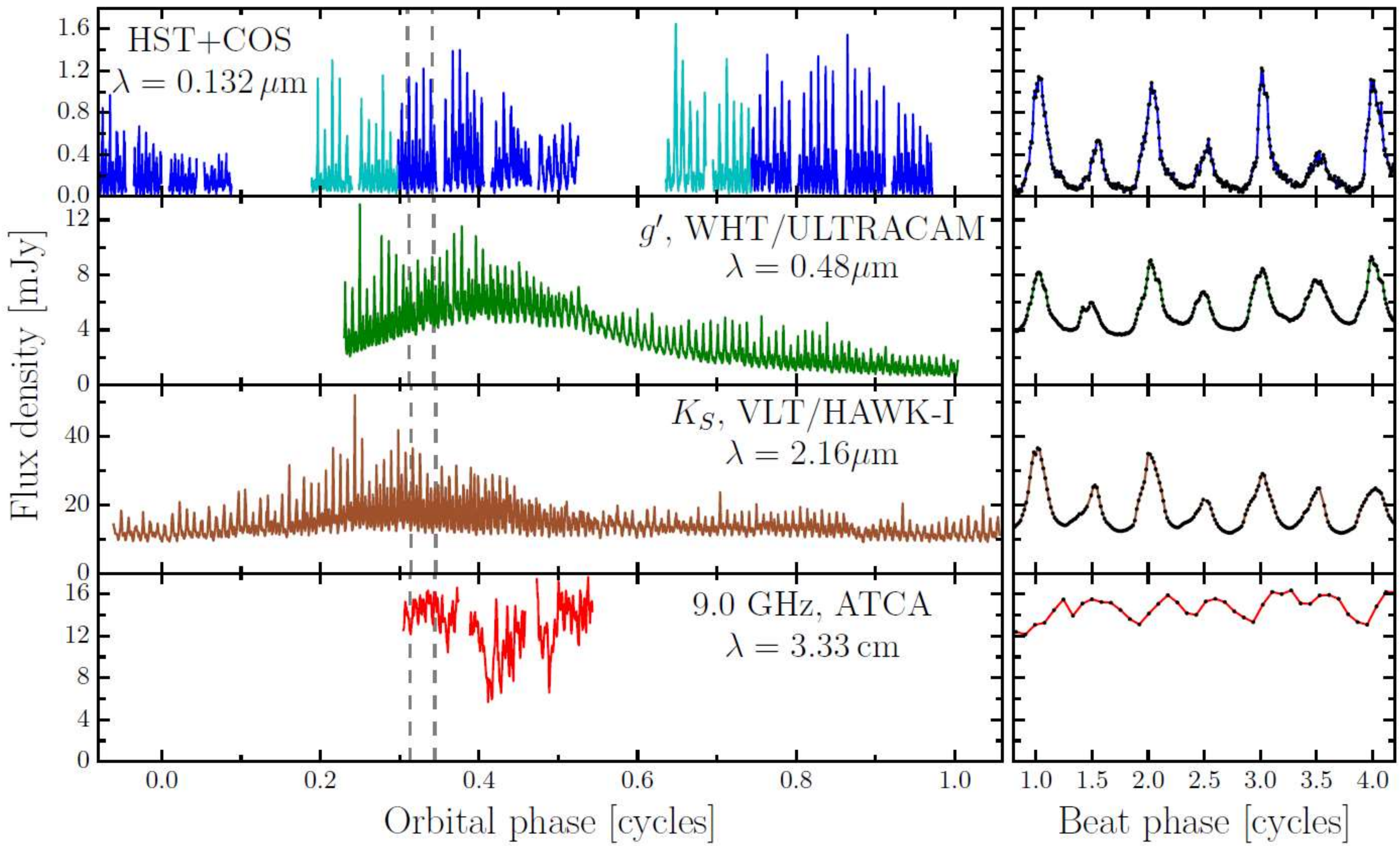
ARTICLES

PUBLISHED: 23 JANUARY 2017 | VOLUME: 1 | ARTICLE NUMBER: 0029

Polarimetric evidence of a white dwarf pulsar in the binary system AR Scorpii

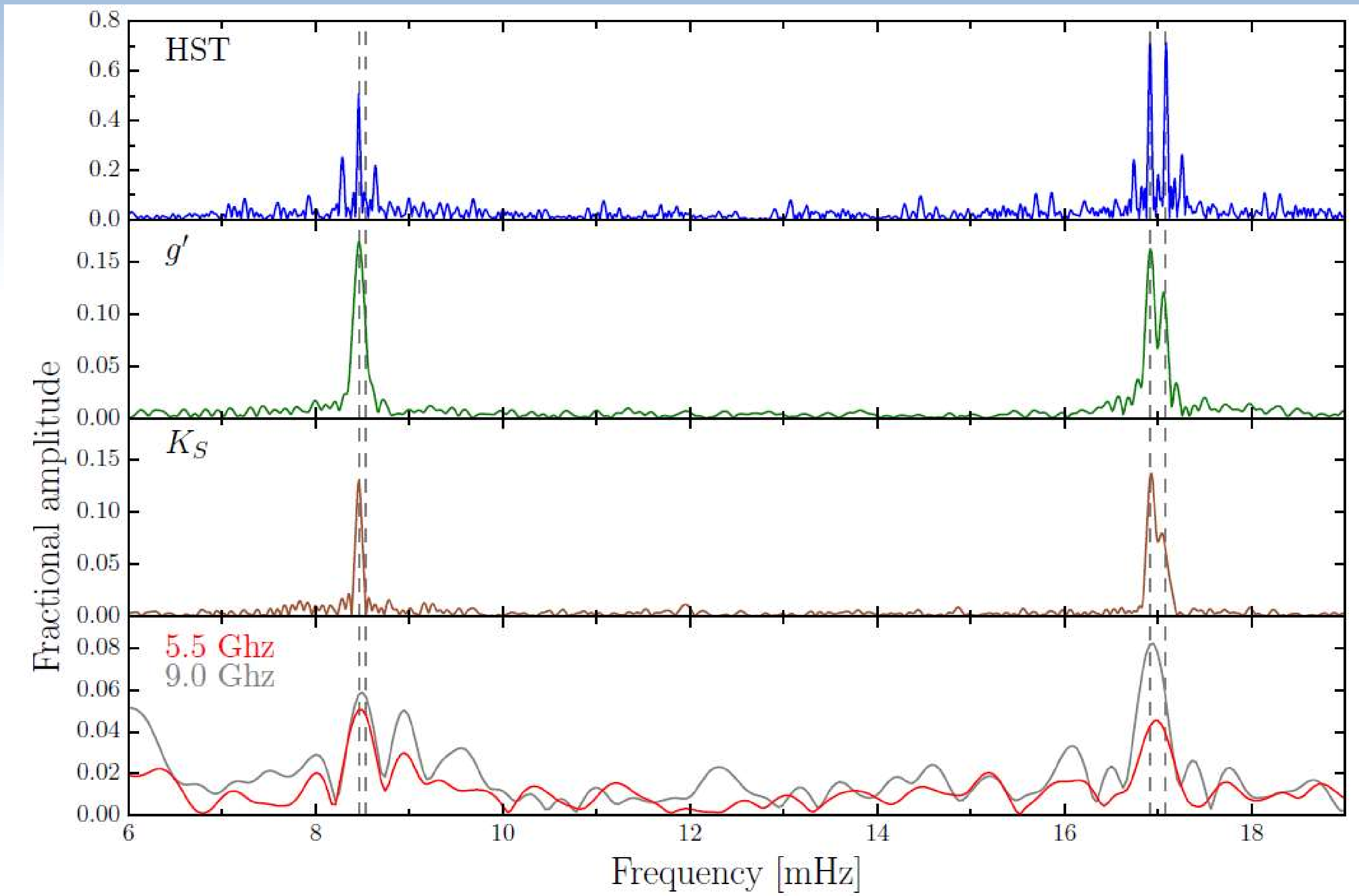
D. A. H. Buckley[1]*, P. J. Meintjes[2], S. B. Potter[1], T. R. Marsh[3] and B. T. Gänsicke[3]

The Short Period Pulsations



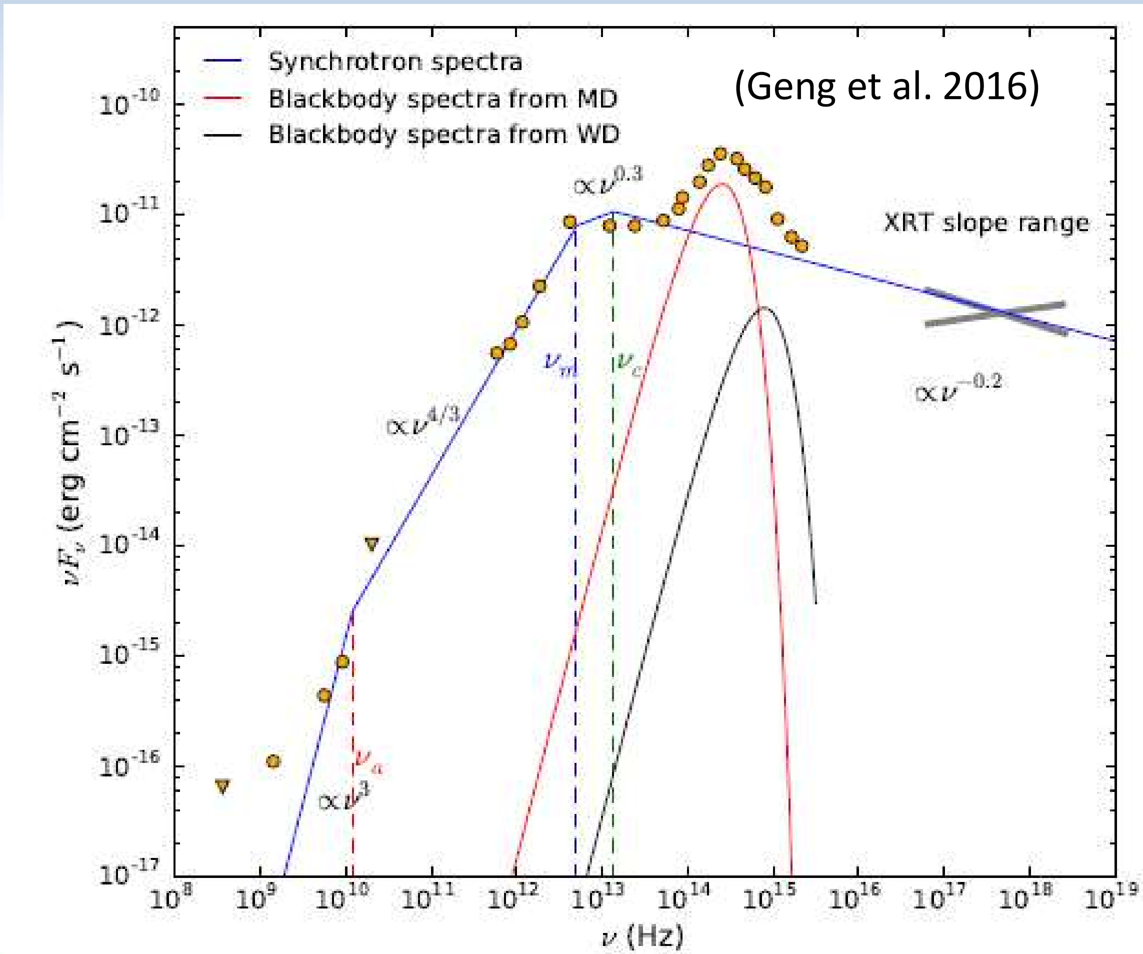
Power Spectra

- Coherent pulsations detected at two periods (117.12 s spin; 118.20 s) and their harmonics



Spectral Energy Distribution

- Two main synchrotron components
  - <10^{13} Hz (radio-IR)) from pumped coronal loops
  - > 10^{13} Hz (IR-optical-UV-X-ray) from particle acceleration from high induced *E*-field or within the WD magnetosphere.



What powers AR Sco ?

- The *observed* pulsed luminosity of the system $L_{pulse} = 0.6 - 3.6 \times 10^{32}$ *erg s*$^{-1}$

- Could accretion be responsible? No!
  - No flickering in the light curves
  - No broad or complex emission lines from an accretion disk or stream
  - Low $L_X \sim 5 \times 10^{30}$ *erg s*$^{-1}$ (~10^{-2} that of a typical magnetic CV)
  - No mass transfer => *detached* binary (companion not filling Roche lobe)

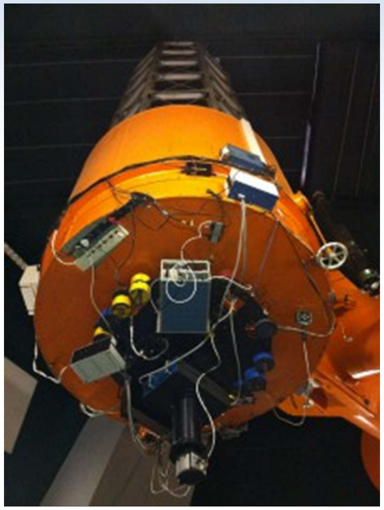
- Most likely explanation is *spin-down power from a radiating dipole in the form of a magnetic WD.*

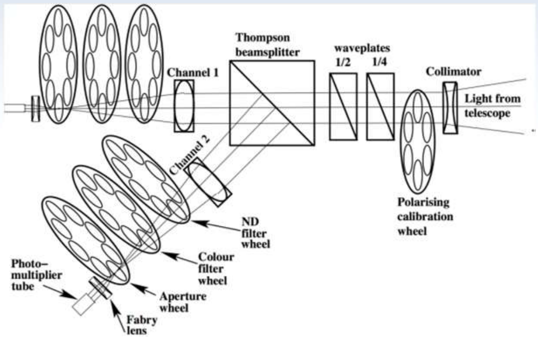
- The spin-down power is given as: $L_{\dot{\nu}_s} = -4\pi^2 I \nu_s \dot{\nu}_s$
  - For a neutron star: $L_{\dot{\nu}}(\mathrm{NS}) = 1.1 \times 10^{28}$ *erg s*$^{-1}$ *(~4 orders of mag too low)*
  - For a white dwarf: $L_{\dot{\nu}}(\mathrm{WD}) = 1.5 \times 10^{33}$ *erg s*$^{-1}$ *(consistent with observations)*

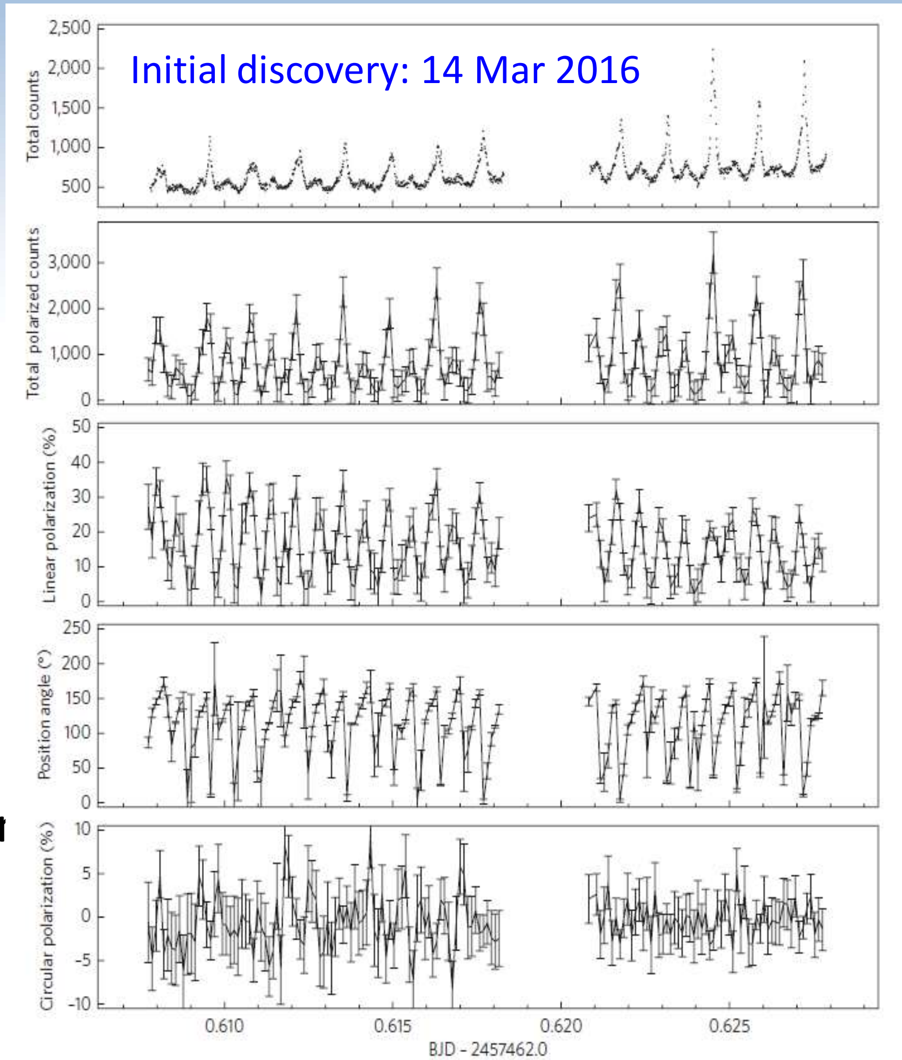
- Conclusion is that AR Sco is a *detached* WD/M-dwarf binary with 3.6-h orbital period powered by WD magnetic dipole spin-down.

Polarimetric Observations

- All-Stokes (linear + circular) polarimetry first conducted with SAAO 1.9-m + HIPPO (2-channel; photon counting photopolarimeter) in March 2016





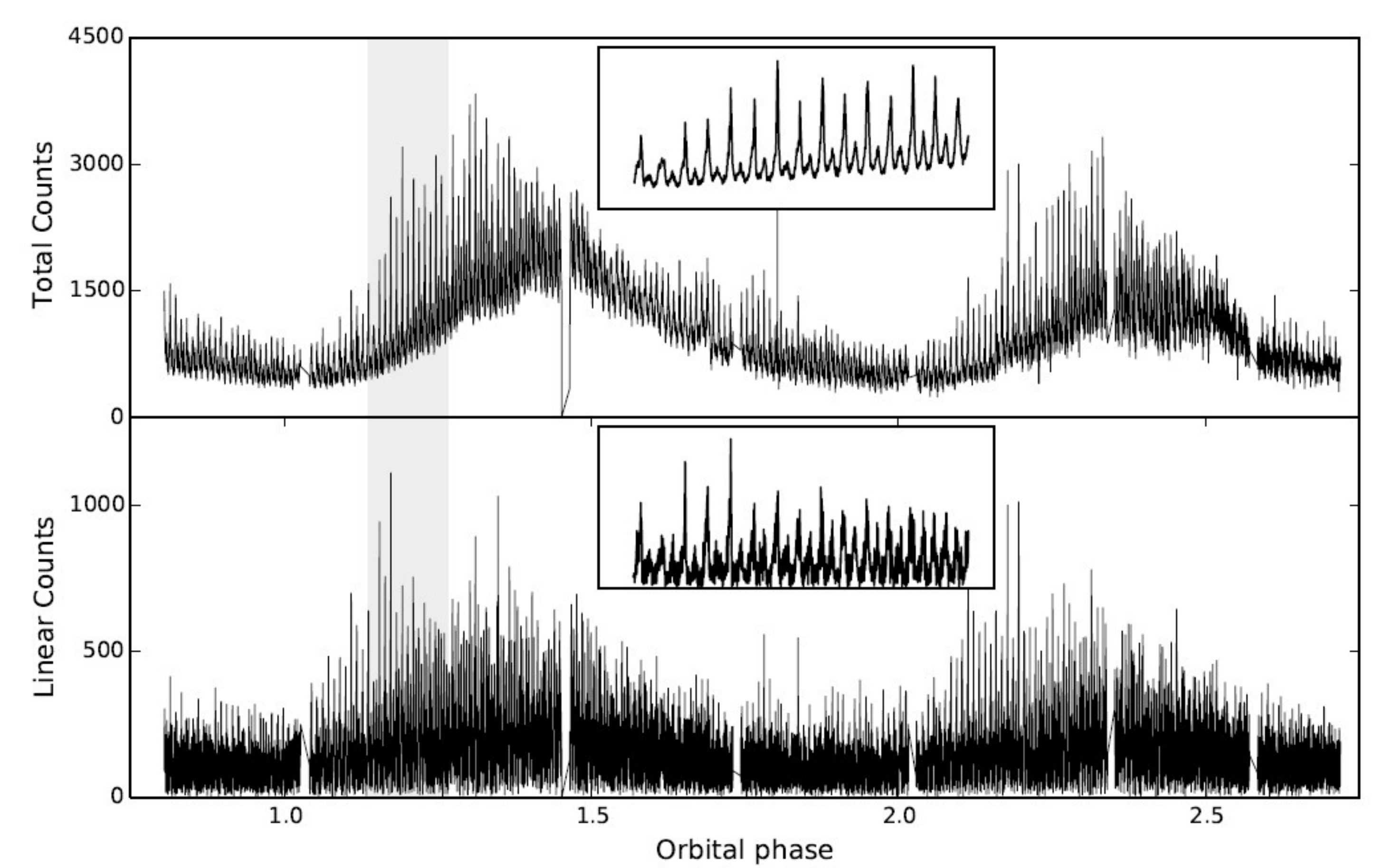


- Discovered strongly pulsed linear polarization modulated at the 117 s spin and 118 s beat period) *and* their harmonics

(Buckley et al. 2017, Nat Ast 1, 0029)

Polarimetry

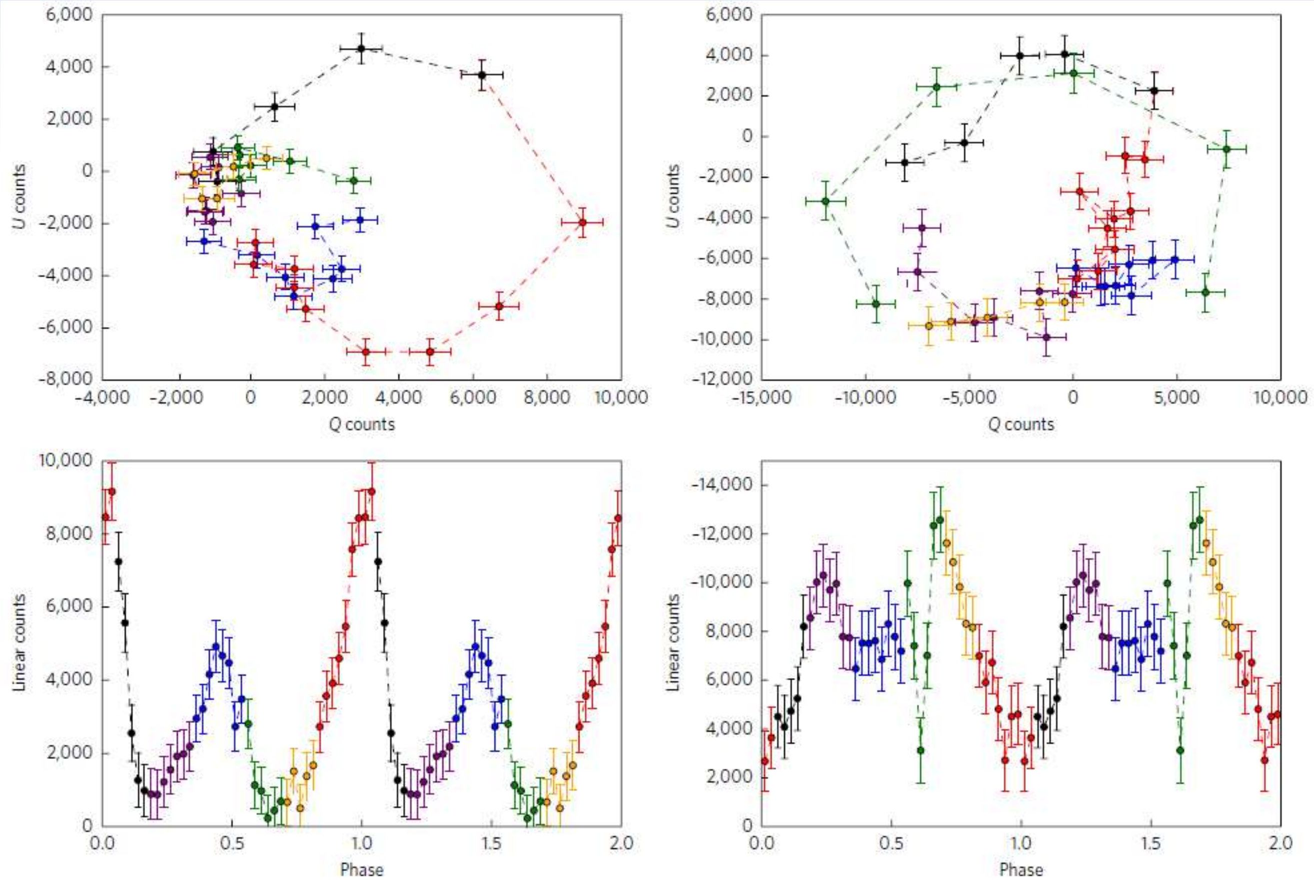
- Large photometry/polarimetry campaigns were conducted in 2016 & 2017 at SAAO
- Observations covers *many* orbital cycles with >65 h of data over ~2 weeks (*Potter & Buckley 2018, MNRAS, 481, 2384*)
- Data used for time-series investigation and determining a geometric model for the polarized emission



Interpreting the spin modulation

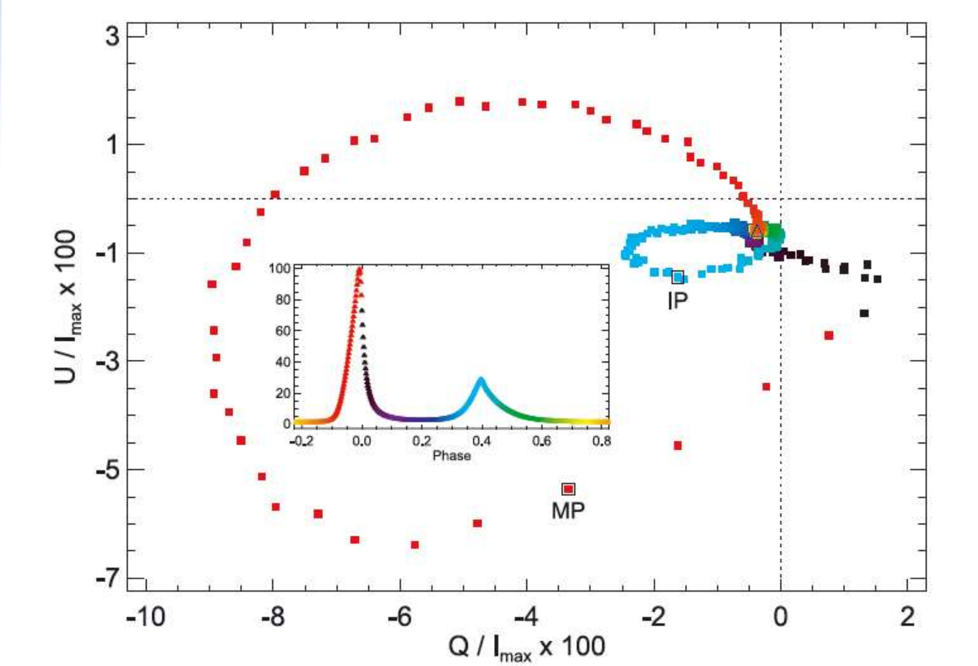
- Looks very like what is expected from a rotating dipole
- In the Stokes *Q, U* plane, polarization changes execute counter-clockwise loops

14 Mar 2016 15 Mar 2016

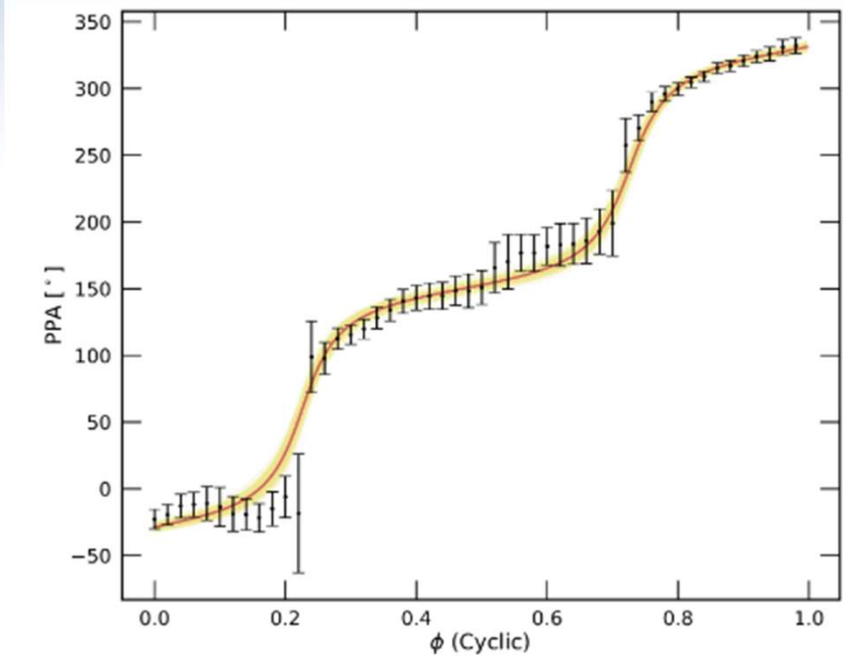


Interpreting the spin modulation

- Interpretation in term of RVM (rotating vector model) for neutron star pulsars (e.g. Crab pulsar)

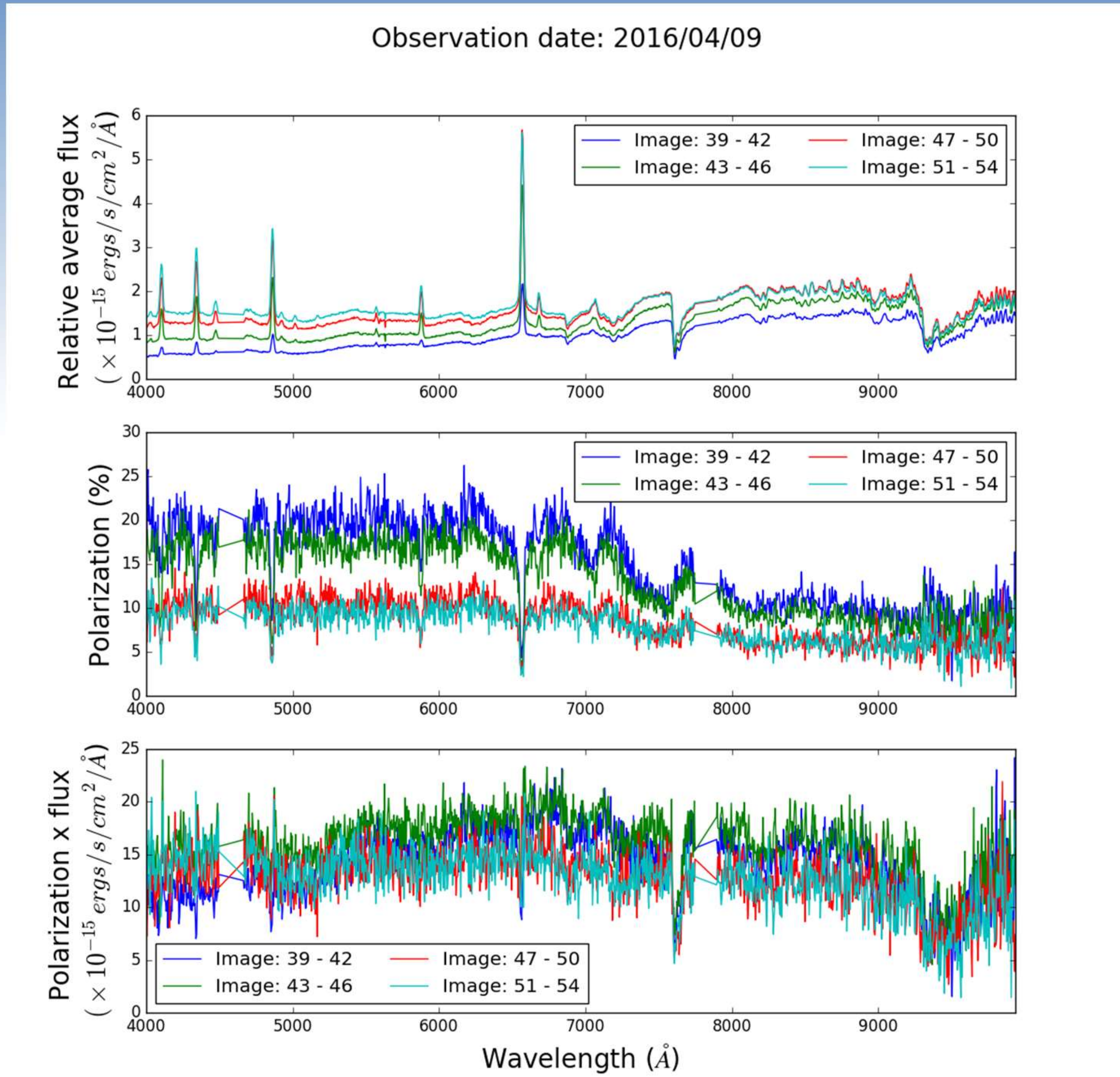


(Słowikowski *et al.* 2009)



(du Plessis *et al.* 2019)

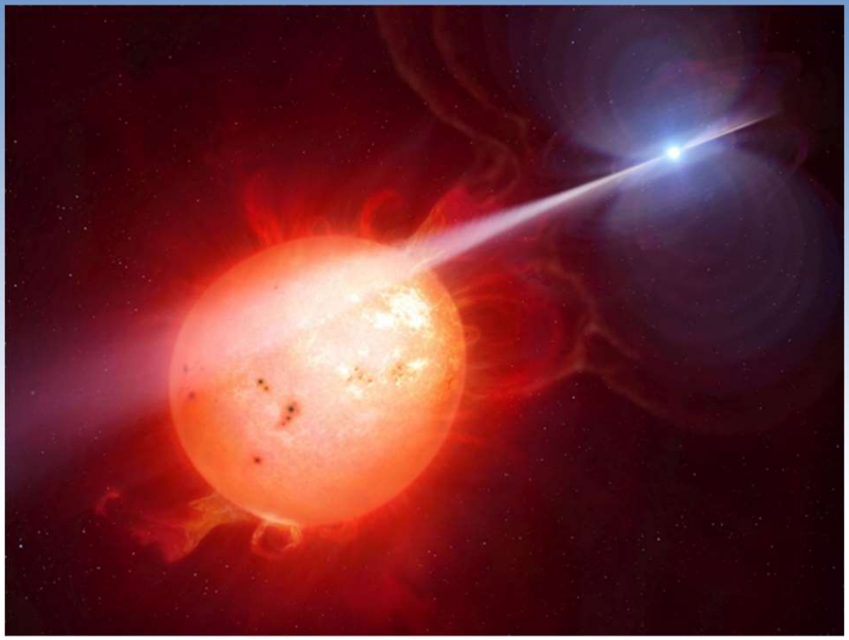
SALT Spectropolarimetry



NRF National Research Foundation | SAAO South African Astronomical Observatory

VRYSTAAT YUNIVESITHI YA FREISTATA UV

June 2020 AR Sco campaign

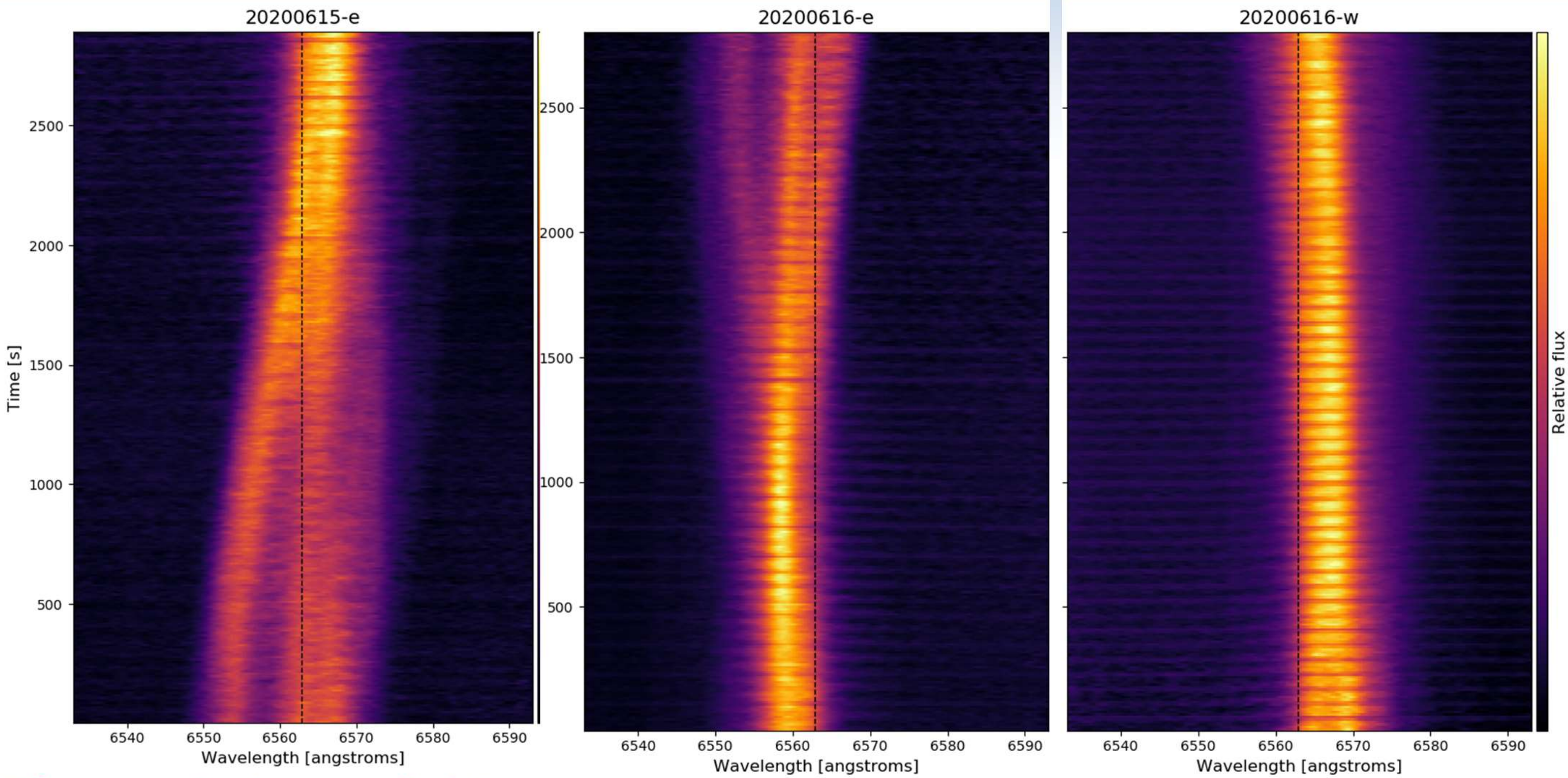


- **SALT spectroscopy 14 – 16 June**

- **Supported with simultaneous observations:**
  - **optical high-speed photometry (SAAO 1-m + SHOC)**
  - **NICER X-ray observations**
  - **MeerKAT radio obsrvations**

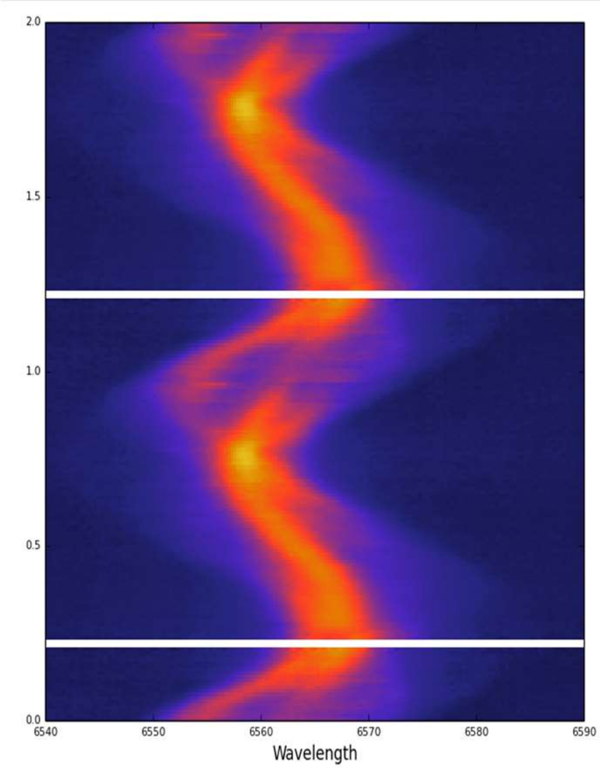
SALT Time Resolved Spectroscopy

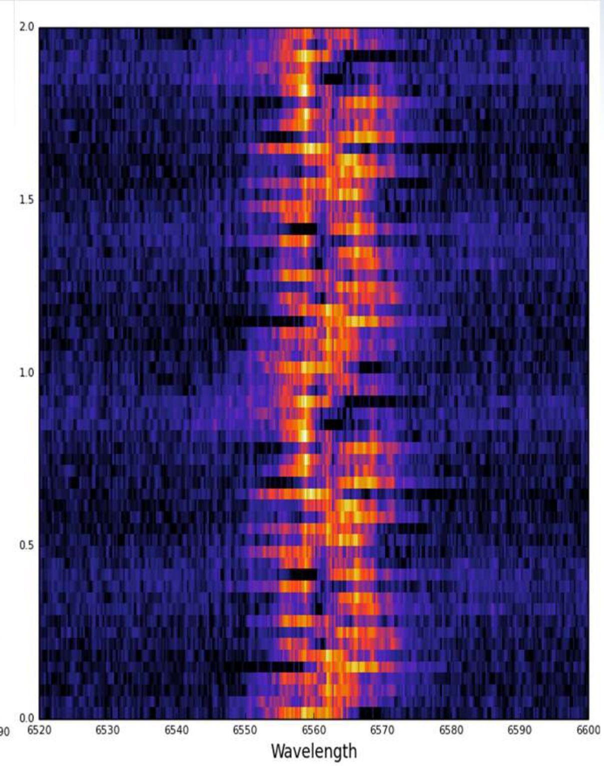
- Obtained 6 SALT tracks which combined to cover the whole 3.5 h orbit
- 10 s exp & no dead-time in FT mode (cf. 15 s & 40 s deadtime on *Keck/LRIS*)
- Data are superb quality showing pulsations at the ~1 min harmonic of the spin period, in lines and continuum

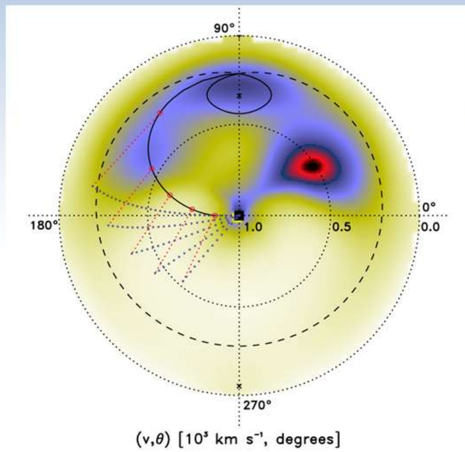


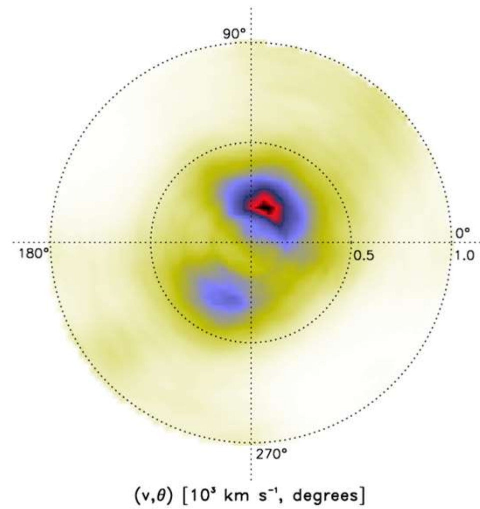
Tomography

- Trailed spectra (gap at ϕ ~0.2 is filled by ~1 h of *Keck* observation)
- In-side out tomography show emission on trailing side of secondary
- Spin tomography shows two poles



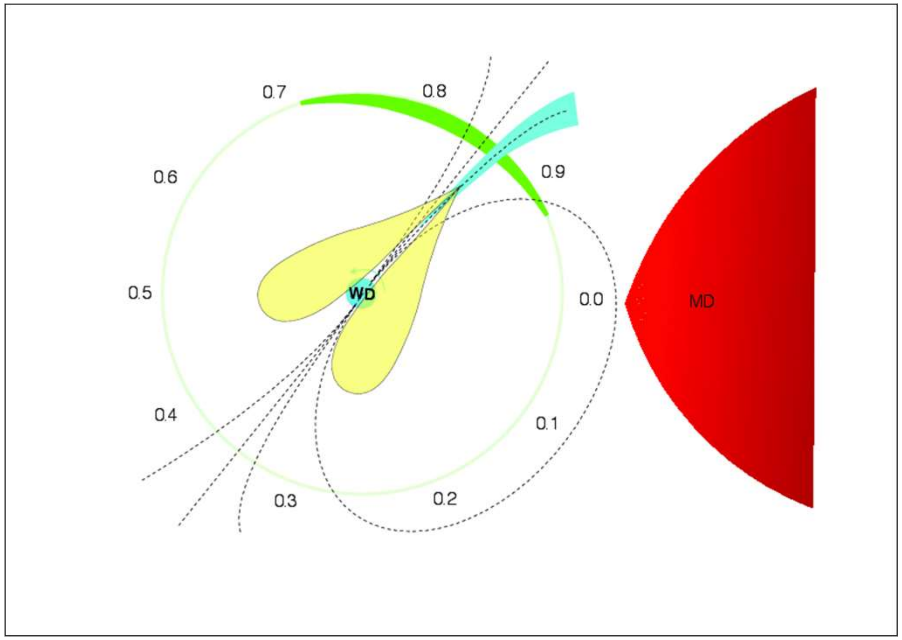


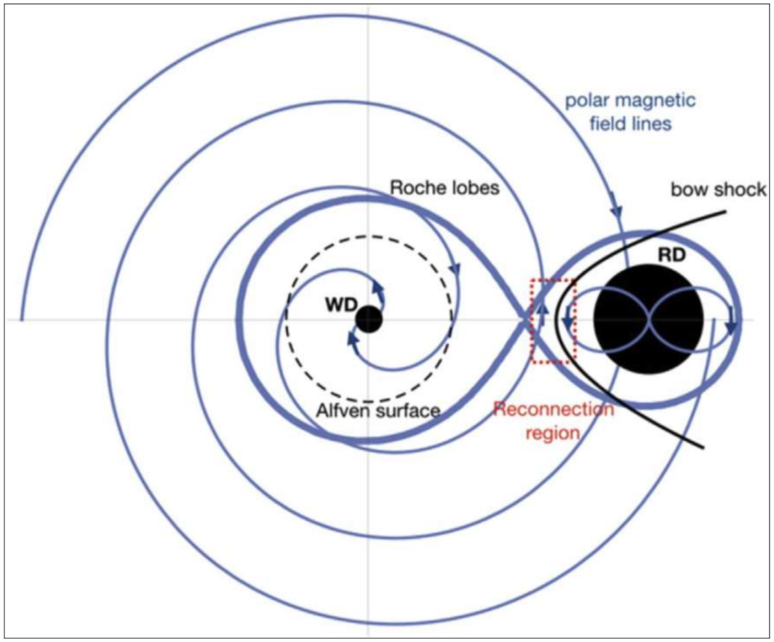




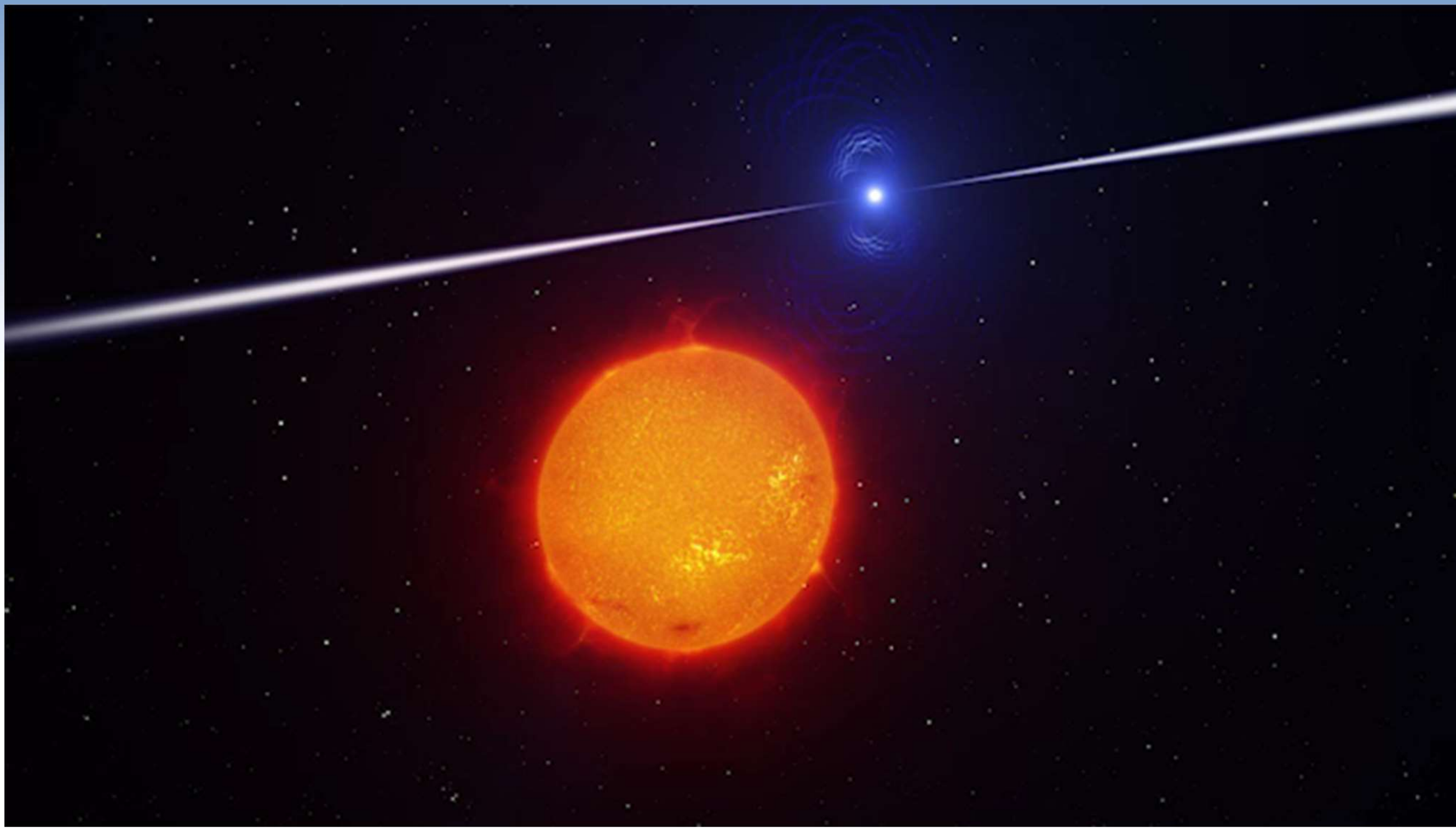
Summary of Properties

- AR Sco is a unique system with pulsar-like characteristics
  - Dominated by synchrotron emission powered by spin-down of a strongly magnetic WD
  - Magnetospheric interactions between WD and M-dwarf companion
  - Strong spin-modulated polarization
- Very successful multi-wavelength campaign conducted in 2020
- Superb data quality will allow detailed investigation on relative phasing of the light curves and locations of the different emission sites
- Test and develop AR Sco models





AR Sco



The End