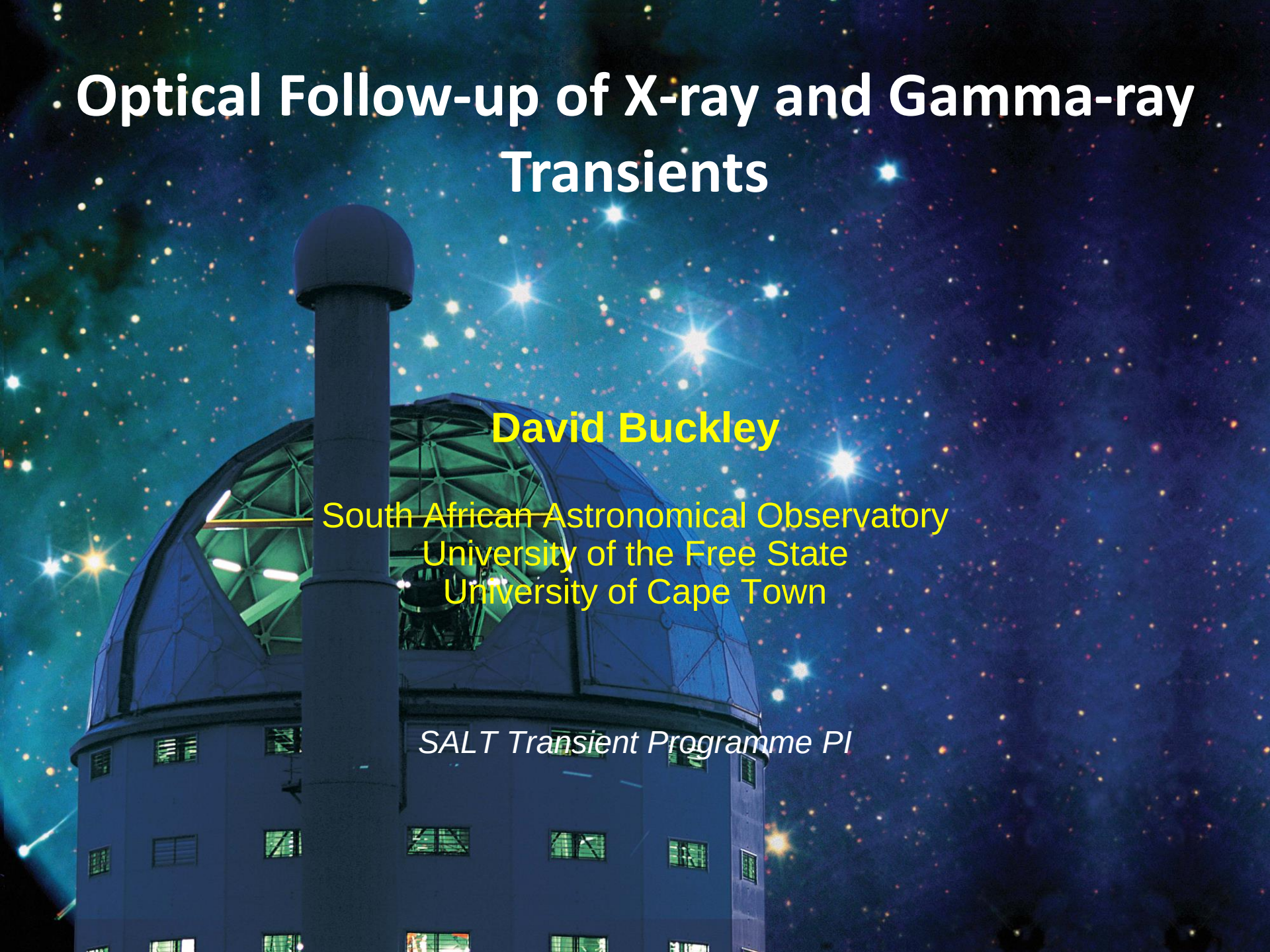
Optical Follow-up of X-ray and Gamma-ray Transients



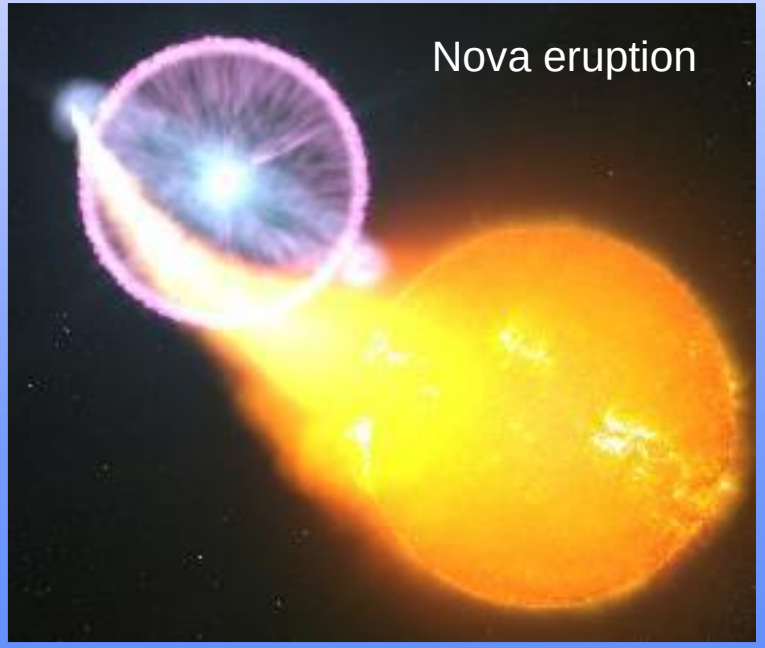
David Buckley

South African Astronomical Observatory
University of the Free State
University of Cape Town

SALT Transient Programme PI

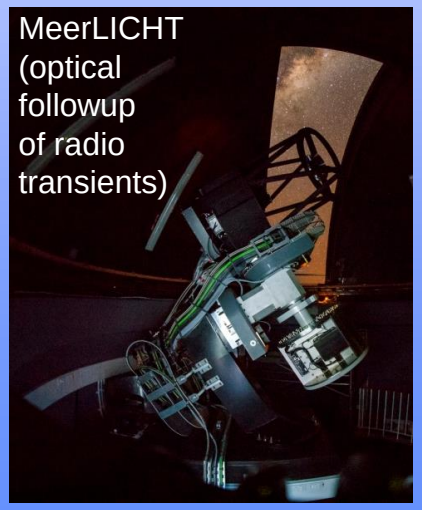
The Transient Universe

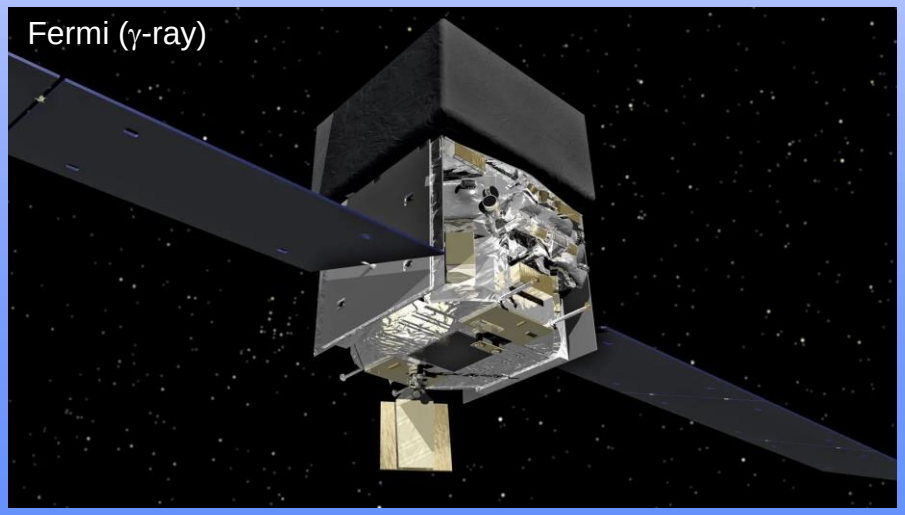
- Time domain and transient astronomy is a growing frontier of discovery space
  - "things that go bump in the night"
- Allows studies of phenomena over timescales of milliseconds to decades
- Observations of transient behaviour for a wide range of objects and timescales, including high energy events (X-rays/γ-rays)
- From Galactic to extragalactic objects
- Most HE transients associated with accretion and resulting outflows

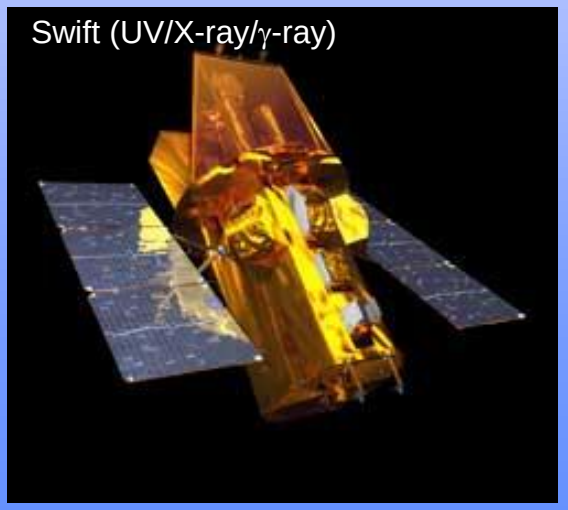


The Transient Universe across the E-M spectrum

- Increasing number of facilities and surveys leading to discoveries of transients of all classes (including new optical facilities at SAAO)
- Some dedicated to specific classes of objects (e.g. supernovae, GRBs)
- Others finding many different classes of transients as a by-product of wide-field surveys (e.g. Gaia, OGLE, PanSTARRS, ZTF, TESS)
- Both ground-based and space-based facilities are sources of alerts
- X-ray/γ-ray satellite for the latter (e.g. Swift, Fermi, MAXI)
- A SALT large science programme on transients began in 2016
- Experience gained helping to pave the way for the next big transient discovery machine: *the Rubin Observatory Legacy Survey of Space and Time(LSST)*
- Need for machine learning tools based on current experiences

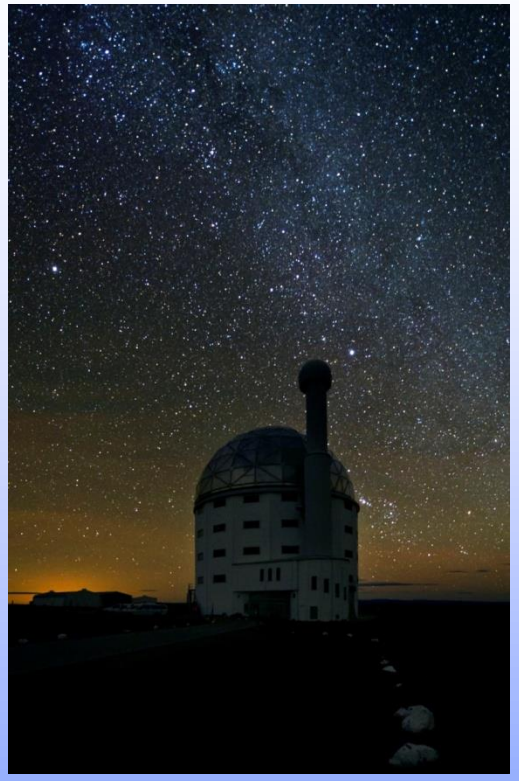


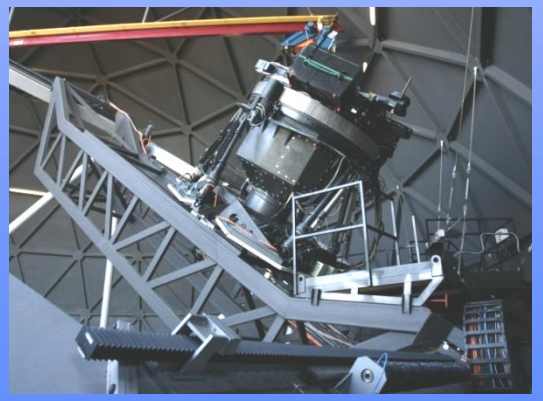


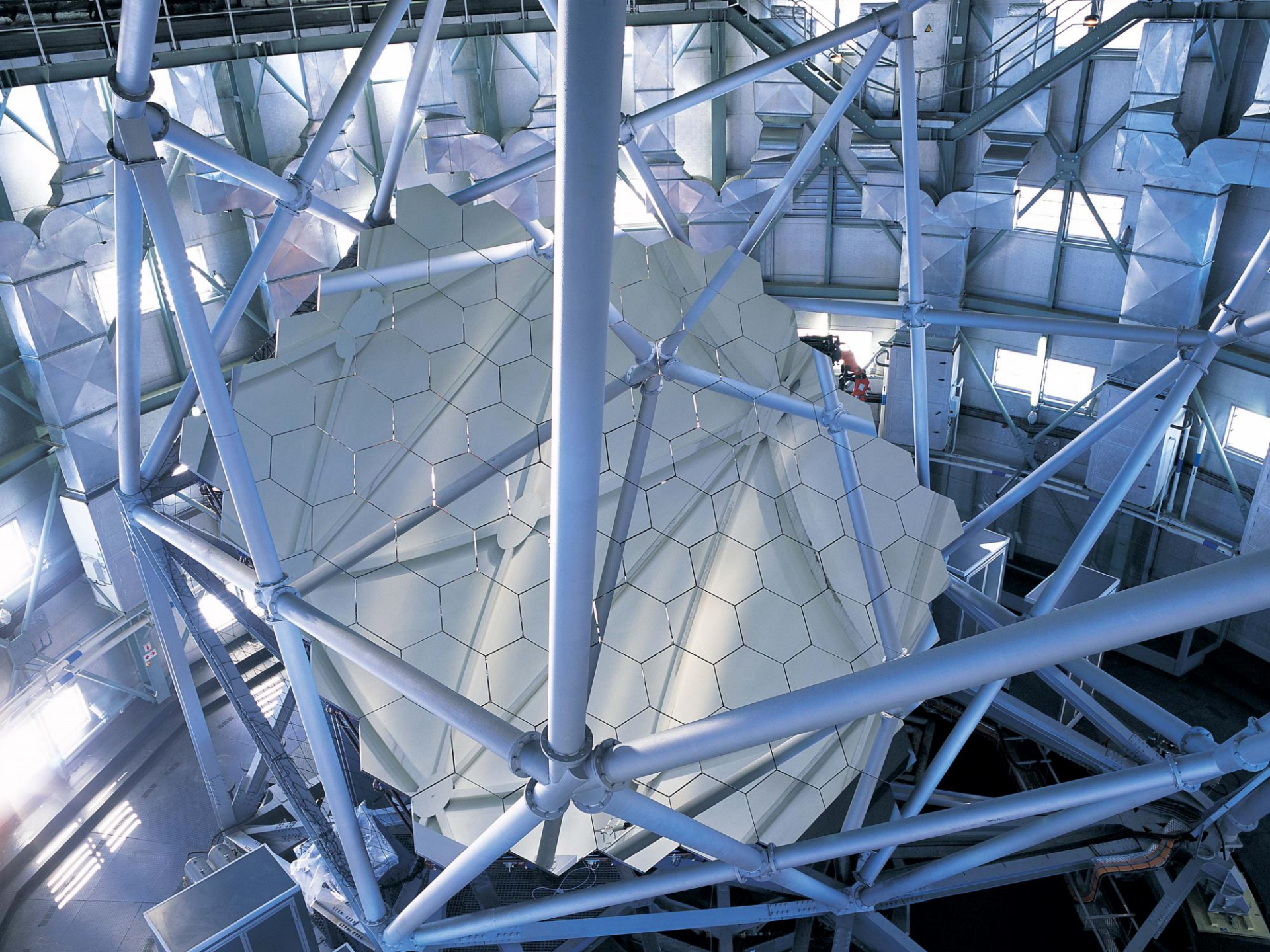


The SALT Transient Programme

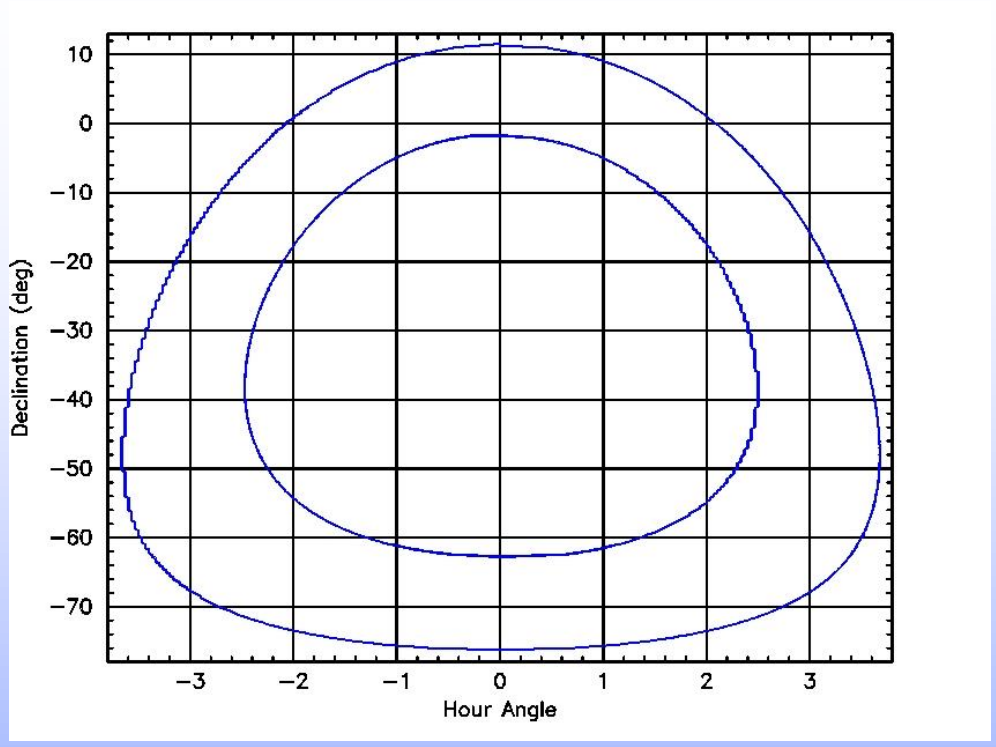
- **SALT Large Science Program on transients**
  - Ramping up since 2016
  - Grown to a large allocation ~400 ksec (111 h) / semester (~15% of time) in 2022
  - High fraction in highest priority class (for ToO)
  - allows for rapid response to alerts
  - monitor objects on different cadences
  - Continuous time resolved observations (0.1 s – few hours)
  - Basic pipeline reduced data available in < 12 h (raw data immediately)
  - Over 60 refereed papers to date, many involving multi-γ facilities
- **Multi-institutional/multi-partner program**
  - 5 South African institutions (SAAO, UCT, UFS, NWU, UJ)
  - 4 other SALT partners (Poland, India (IUCAA), UK, U. Wisconsin) plus other international collaborations
  - 36 co-investigators (incl. 12 graduate students)







Observing Transients With SALT

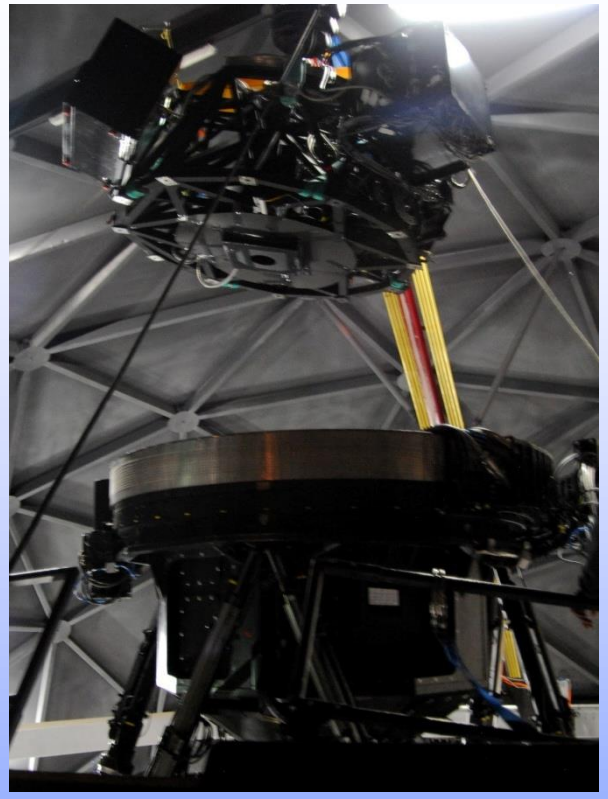


SALT Viewing Annulus

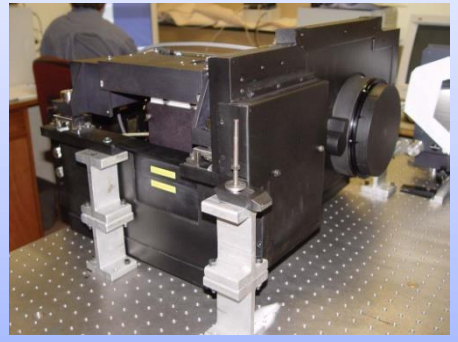
- 100% queue scheduled service observing
- Variety of instruments/modes
- Rapid instrument changes and mode configurations
- Scheduling allows for synoptic monitoring at difference cadences
- Targets of Opportunity can be done at short notice
- Ideal for followup of transients

Observing Transients With SALT

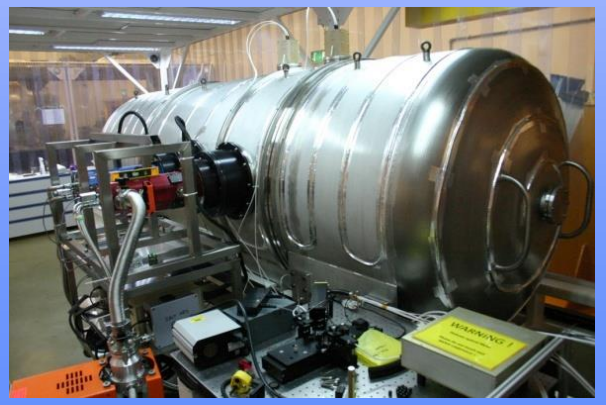
Currently available instruments:



- **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 (15 Hz)
  - Deep multi-filter imaging (griz, UBVRI, Hα)

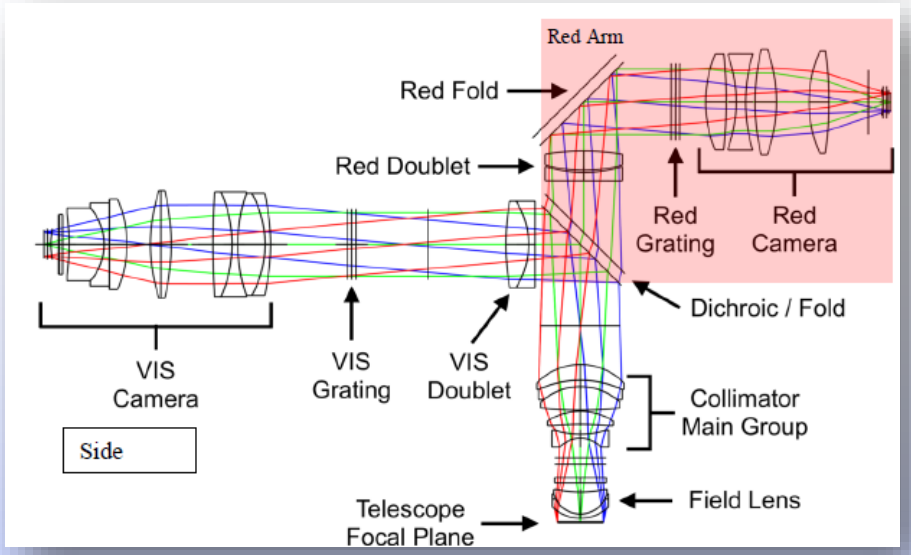


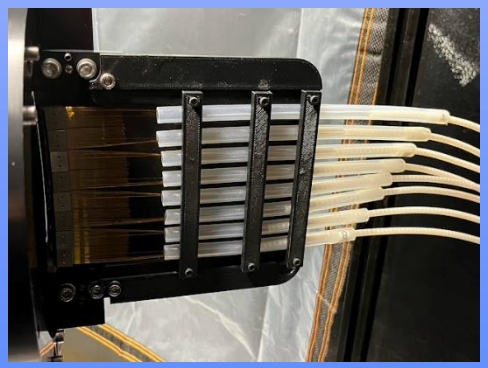
- **High Resolution Spectrograph (HRS)**
  - High resolution (16,000, 34,000, 60,000) 3800 – 8900Å
  - Fibre-fed
  - Precision radial velocity capability (vacuum, laser freq comb soon)

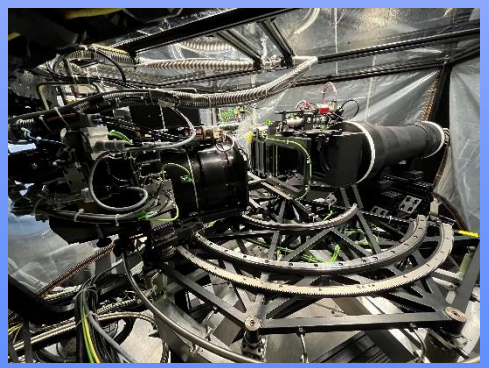
Observing Transients With SALT

Future instruments:

- **RSS Red Arm (2024)**
  - medium resolution (~2000 seeing limited)
  - 6300 – 10000Å at high efficiency (56%)
  - turns RSS into dual-beam instrument
  - optimized for blue and red
  - versatile (different gratings/resolutions)
  - fast modes (~10 Hz)
- **Near-Infrared Integral Field Unit (IFU) Spectrograph (2023)**
  - covering 8000-17,000Å (z,Y,J,H)
  - medium resolution (~2000-5200)
  - Fed by 25 arcsec IFUs (212 fibres)
  - Inside cold room (-40°C)



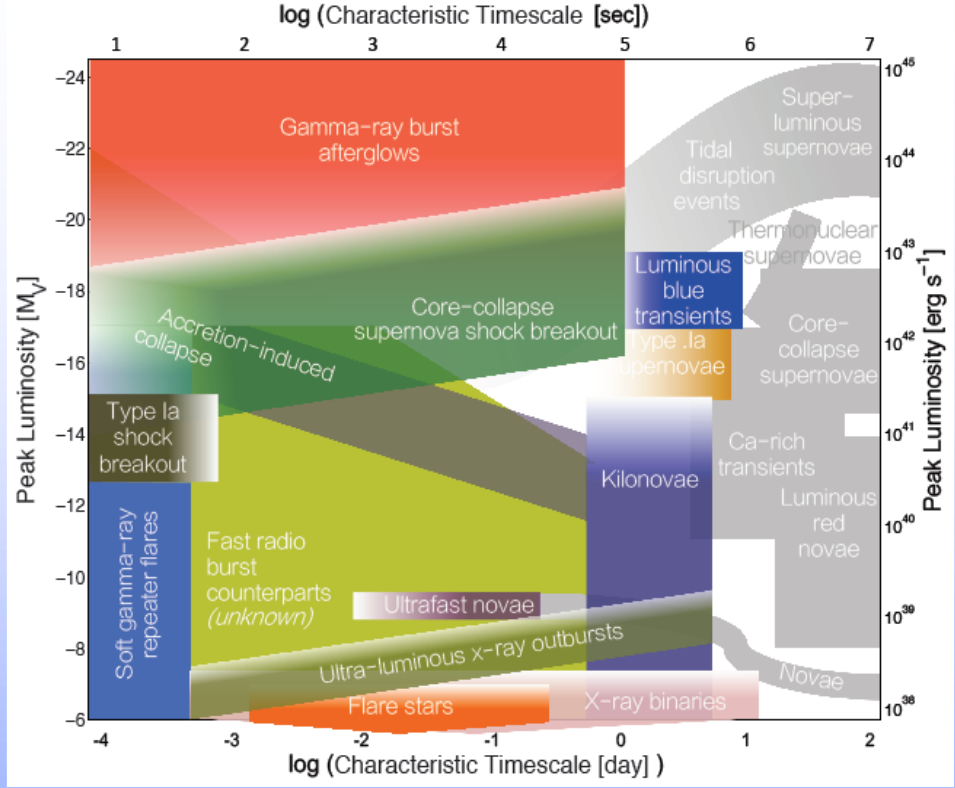


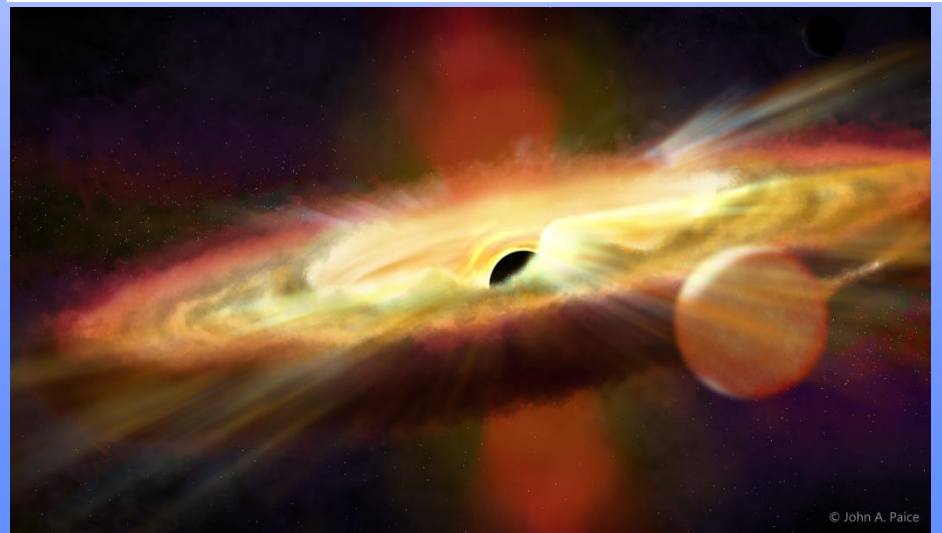


SALT Transient Program

- **Covering wide range in luminosity (& therefore distance)**
- **Variability on a wide range of timescales**
  - Sub-sec domain is relatively unexplored
- Covering many object classes
  - X-ray transients (LMXs; HMXBs)
  - Cataclysmic Variables
  - Novae
  - Intermediate luminosity transients
  - Tidal Disruption Events (TDEs)
    - » From Gaia, OGLE, eROSITA
  - Black Hole microlensing events
  - Flaring Blazars
  - Unusual supernovae (e.g. Super Luminous Supernovae)
  - Gamma-Ray Bursts (GRBs)
  - Multi-messenger (Gravitational Wave & Neutrino) events
  - Radio transients with MeerKAT (ThunderKAT programme)

(red font: relevant to X-ray & /γ-ray sources)

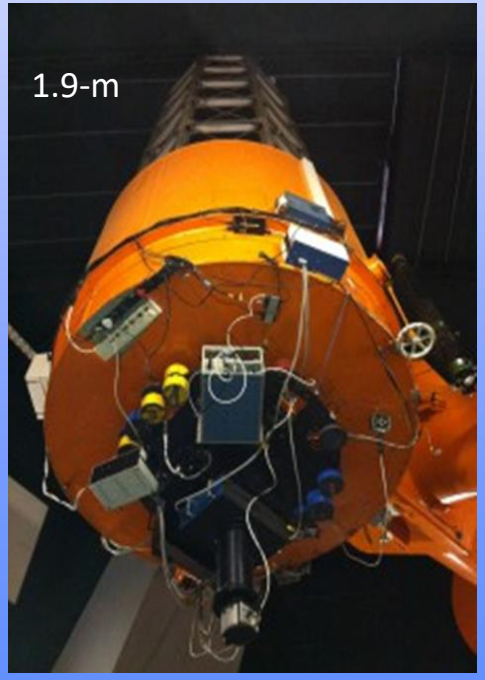


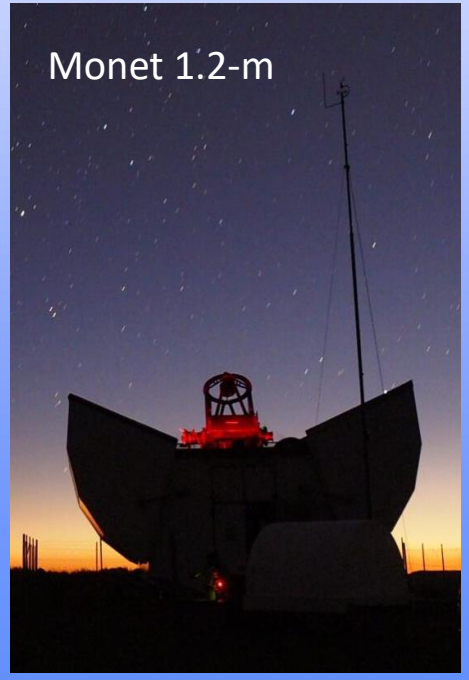


Supporting Optical Observations in South Arica: current & future

- Majority of facilities at the SAAO site in Sutherland
- ~20 telescopes with 0.40 – 1.9-m apertures, in optical and NIR
- Some dedicated to transients (ATLAS, MASTER, MeerLICHT)

- Mostly supporting time series optical photometry, spectroscopy and photo-polarimetry

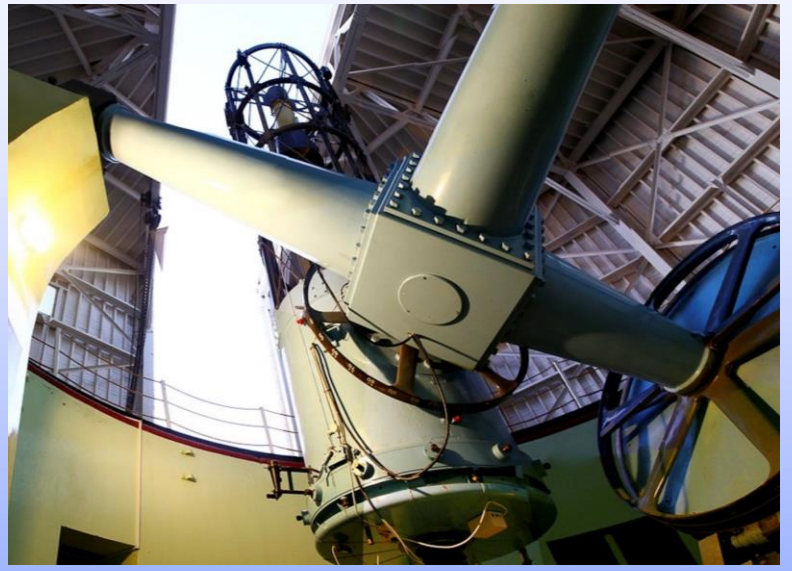




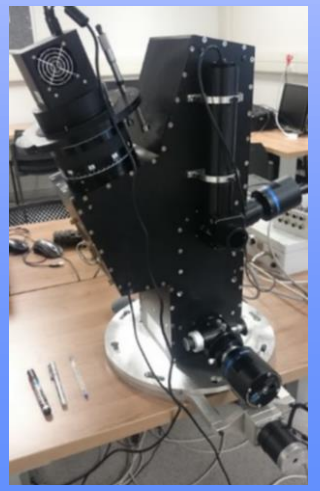
Supporting Optical Observations in South Arica: current & future

Boyden Observatory (University of the Free State)

- Rapid followup telescopes (Watcher, Boötes)
- Refurbishment of Boyden 1.25-m telescope and new spectrograph (~2023)



New spectrograph & spectropolarimeter



- Potential for new robotic facilities in future at various South African universities

The Future: SAAO Intelligent Observatory

- Network telescopes on the Sutherland site to allow automated follow-up from multi-wavelength alert brokers
- Science driver: follow-up on Rubin LSST transient & variable sources and transient alerts from other facilities (including space-based)
- Project started in 2020 with 3 telescopes and utilizing SW system developed at LCO
- Eventually extend to some of the other hosted facilities
- Telescopes now routinely remotely operated and one in autonomous mode
- Eventually part of global networks using AEON protocols

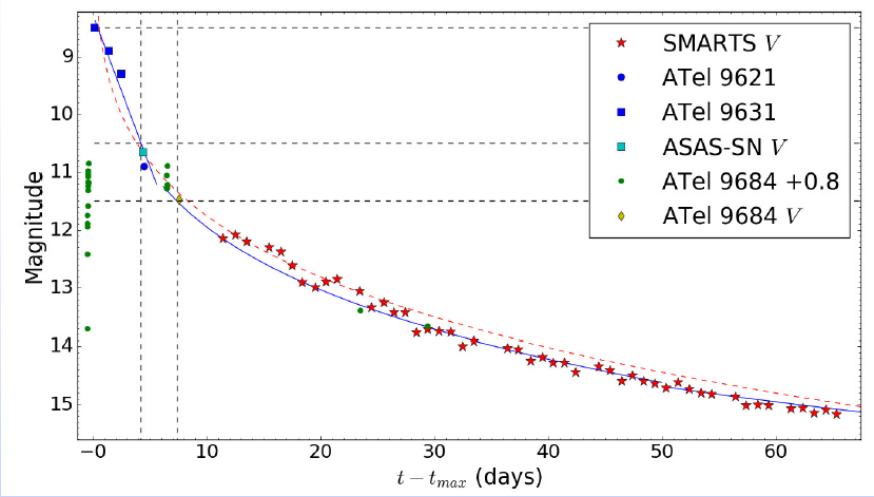
Examples of Science Results from SALT X-ray/γ-ray transient programme

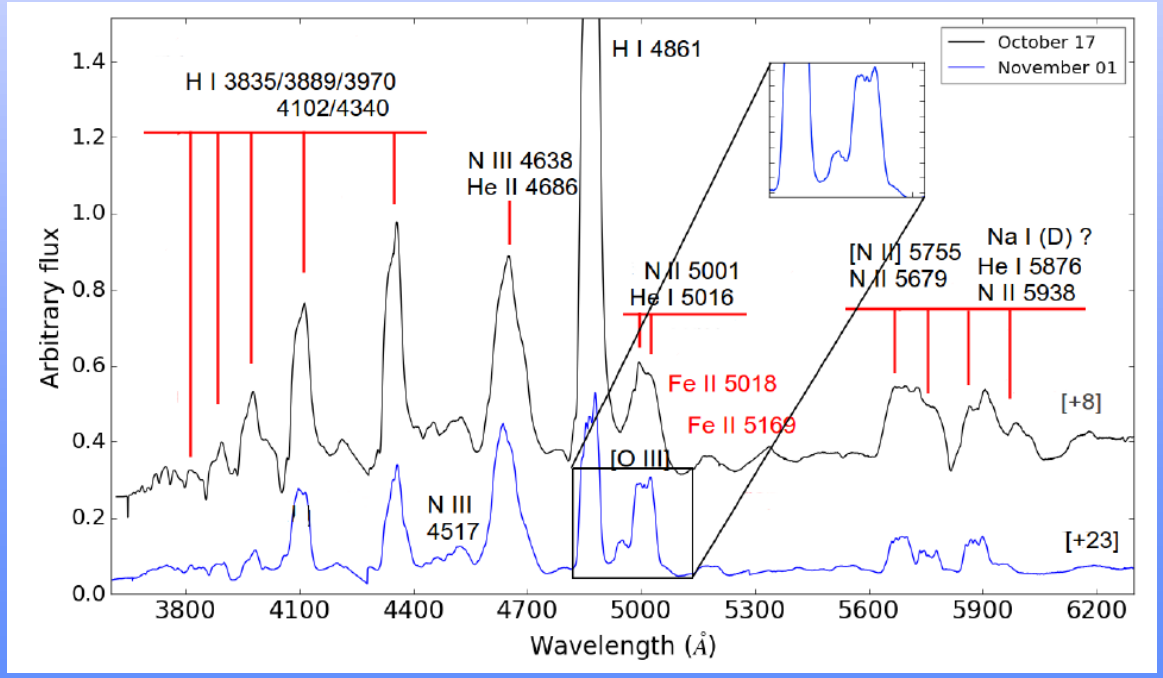
- **Novae**
- **Cataclysmic Variables (& related objects)**
  - super-soft sources
  - magnetic systems
  - white dwarf “pulsars”
- **Low Mass X-ray Binaries (LMXBs)**
  - Neutron star & black holes systems
  - Transitional millisec pulsars
- **High Mass X-ray Binaries (HMXBs)**
  - Be X-ray Binaries
- **Blazars**
  - Followup of gamma-ray flaring blazars
- **GRBs**
  - Bright or long
- **Results of followup on *eROSITA* X-ray survey**
  - Compact binary White Dwarfs
  - Quasi-Periodic Eruptions in non-active galaxies

Novae

Program instigated by Elias Aydi (PhD student at the time, now Hubble Fellow at MSU)

- 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 > $1.2M_\odot$

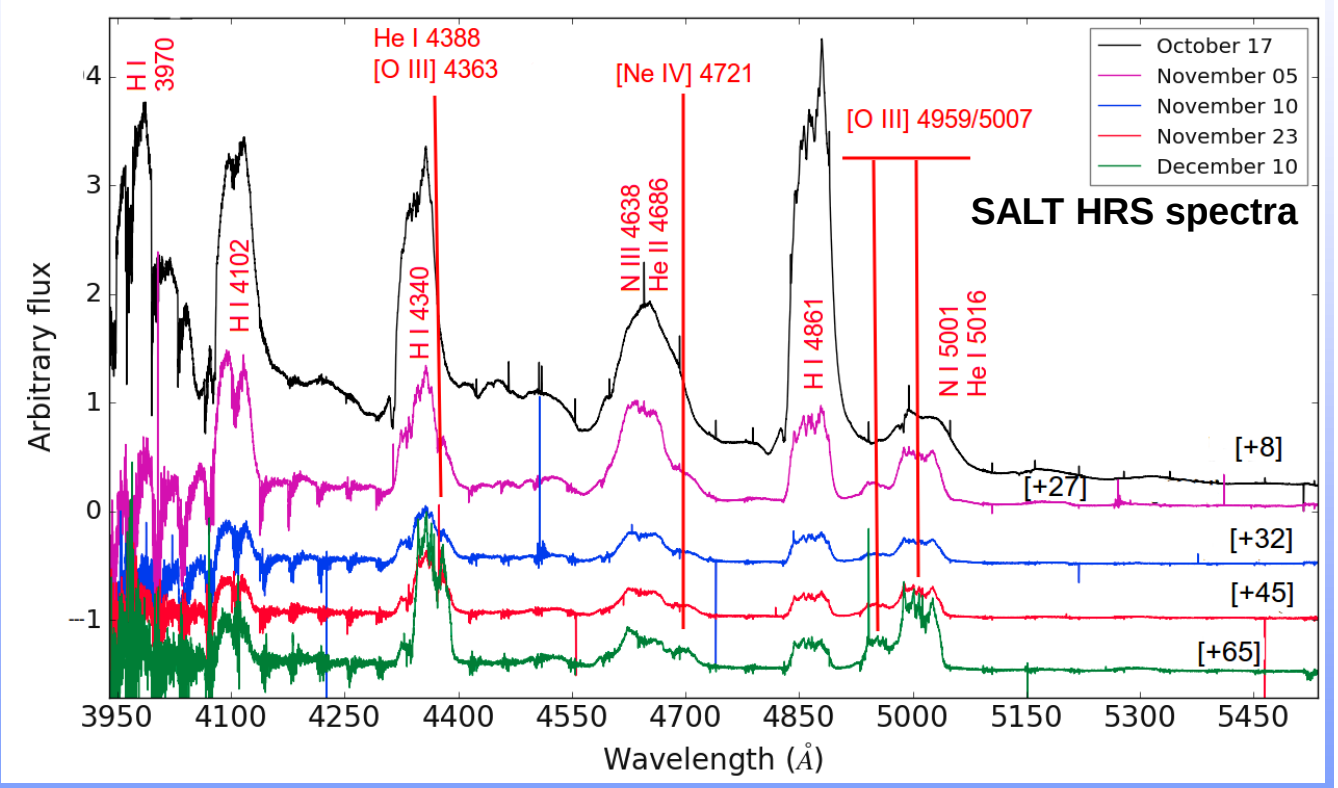


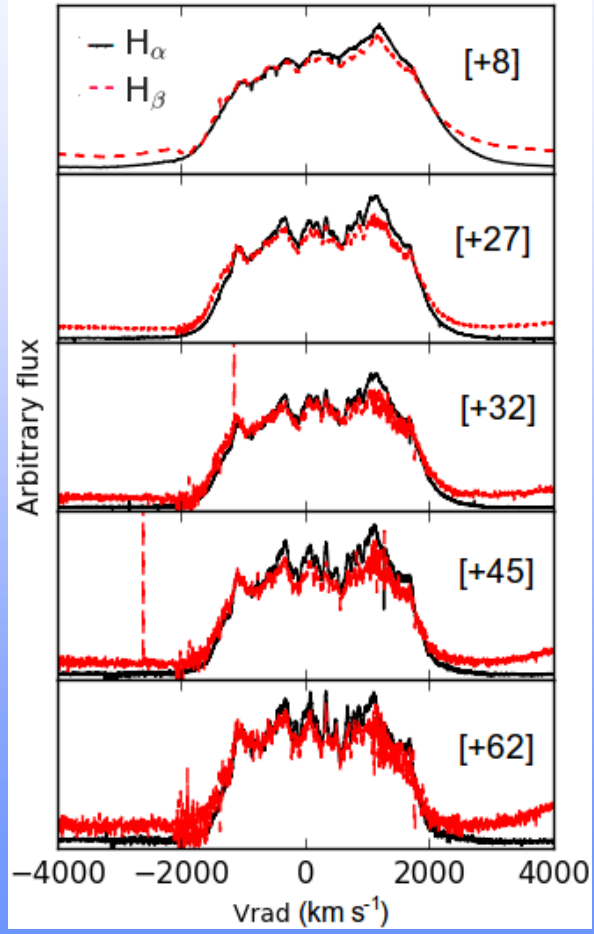


(Aydi, Page, Kuin et al., 2018, MNRAS, 474, 2679)

Nova SMC N 2016-10a

- Observed evolution from initial outburst through nebular phase to supersoft phase



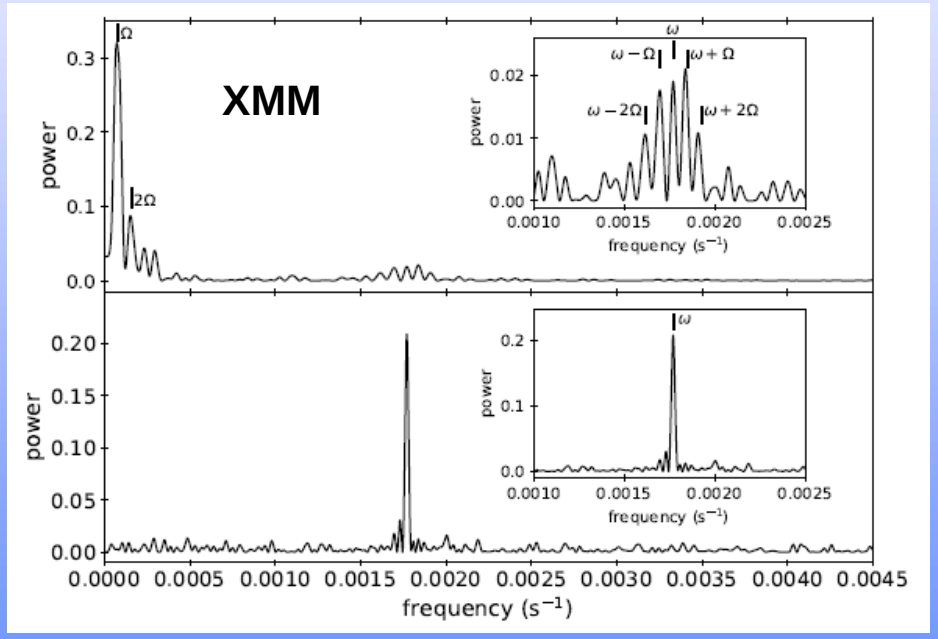


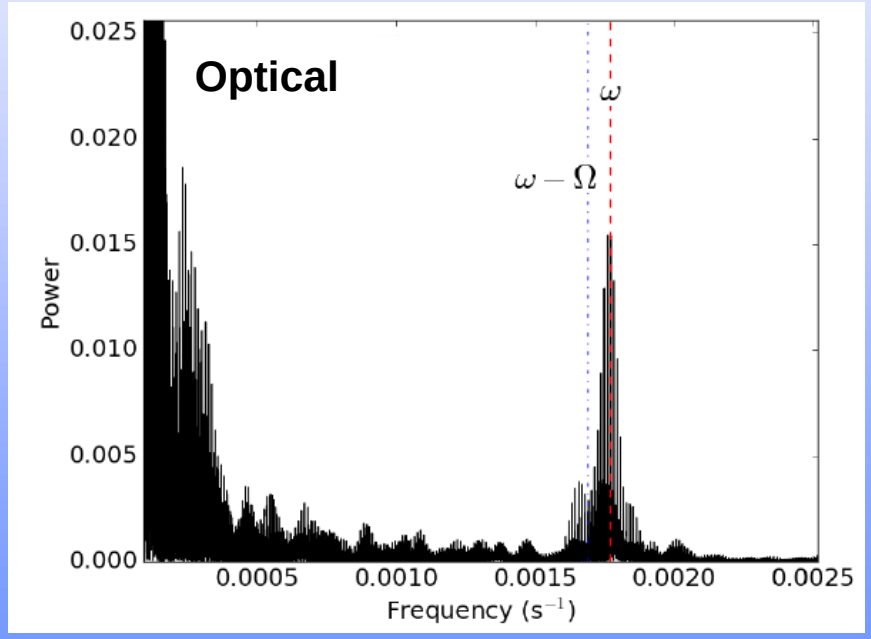
(Aydi, Page, Kuin et al., 2018, MNRAS, 474, 2679)

Nova V407 Lup (ASASSN-16kt)

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

(Aydi, Orio, Beardmore et al. 2018, MNRAS, 480, 572)



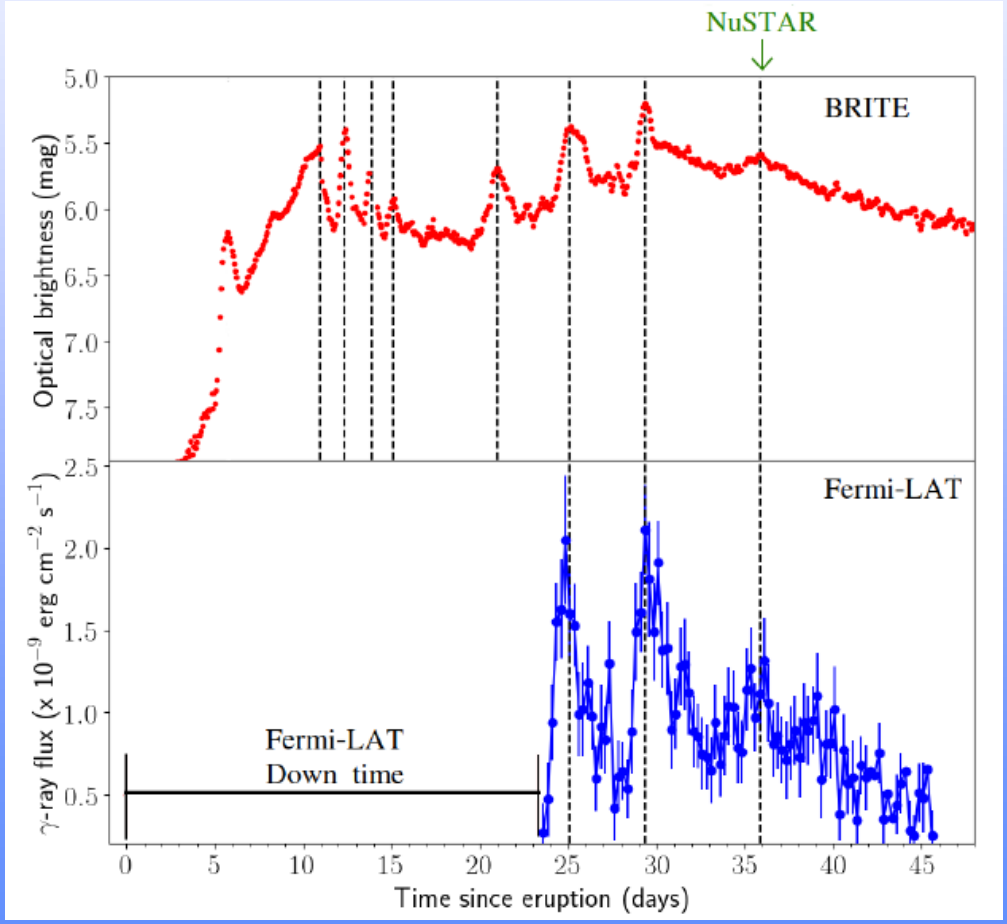


Gamma ray emission from Novae

V906 Car (ASASSN-18fv):

- Unprecedented continuous optical monitoring with BRITE satellites (6 nanosats)
- Complex outbursts different from the normal nova paradigm
- Repeated γ-ray flares from shocks in ejecta

(Aydi, Sokolovsky, Chomiuck et al., 2020, Nat Ast, 4, 766)

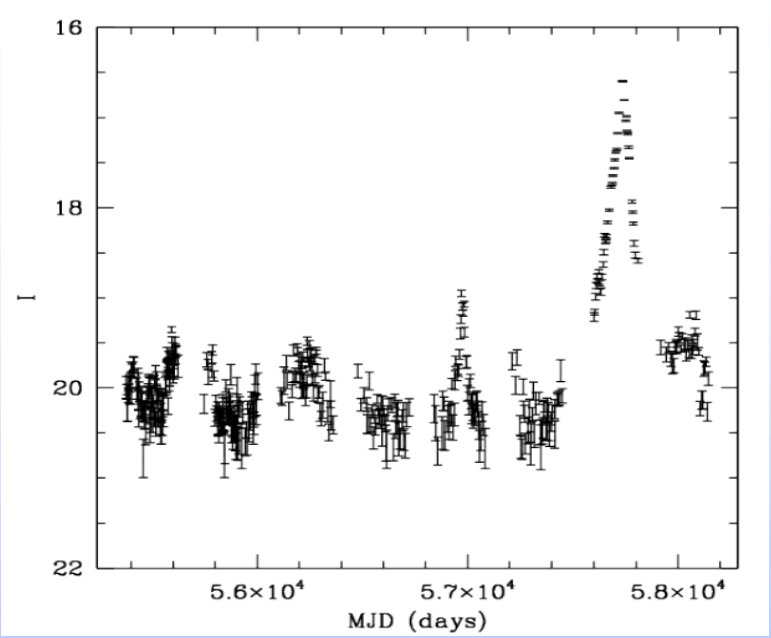


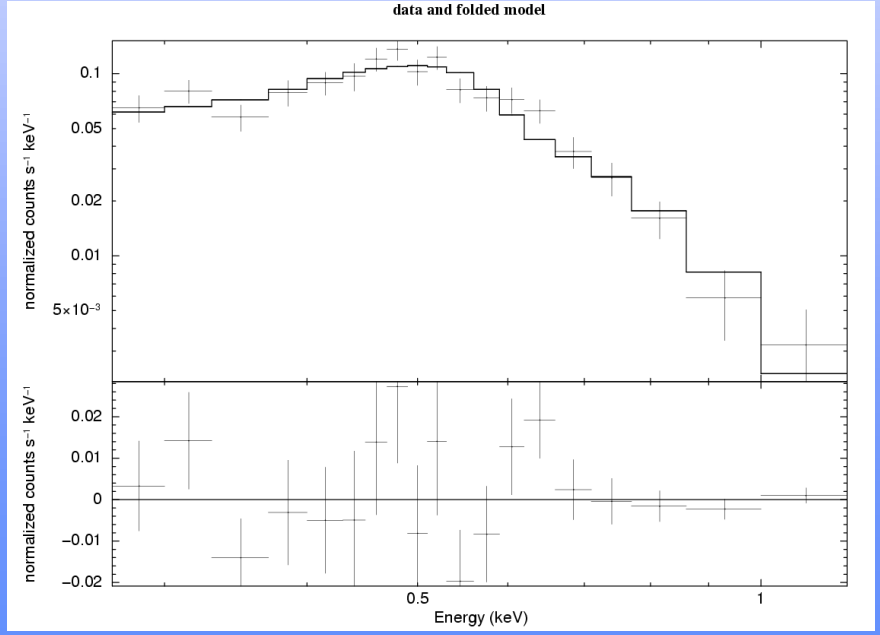
Super Soft Source discovered in the SMC: ASASSN-16oh

- Discovery of a new Super Soft Source in the SMC in Dec 2016
- Followup SALT RSS spectroscopy
  - Strong HeII 4686
  - Small R.V. variations
  - Consistent with 5.6 d 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
  - Outburst from hot (~900,000 K) spreading layer on a on white dwarf
  - *Not* a thermonuclear powered event, as in most SSSs

(Maccarone, Nelson, Brown et al., 2019, Nat Ast, 3, 173)





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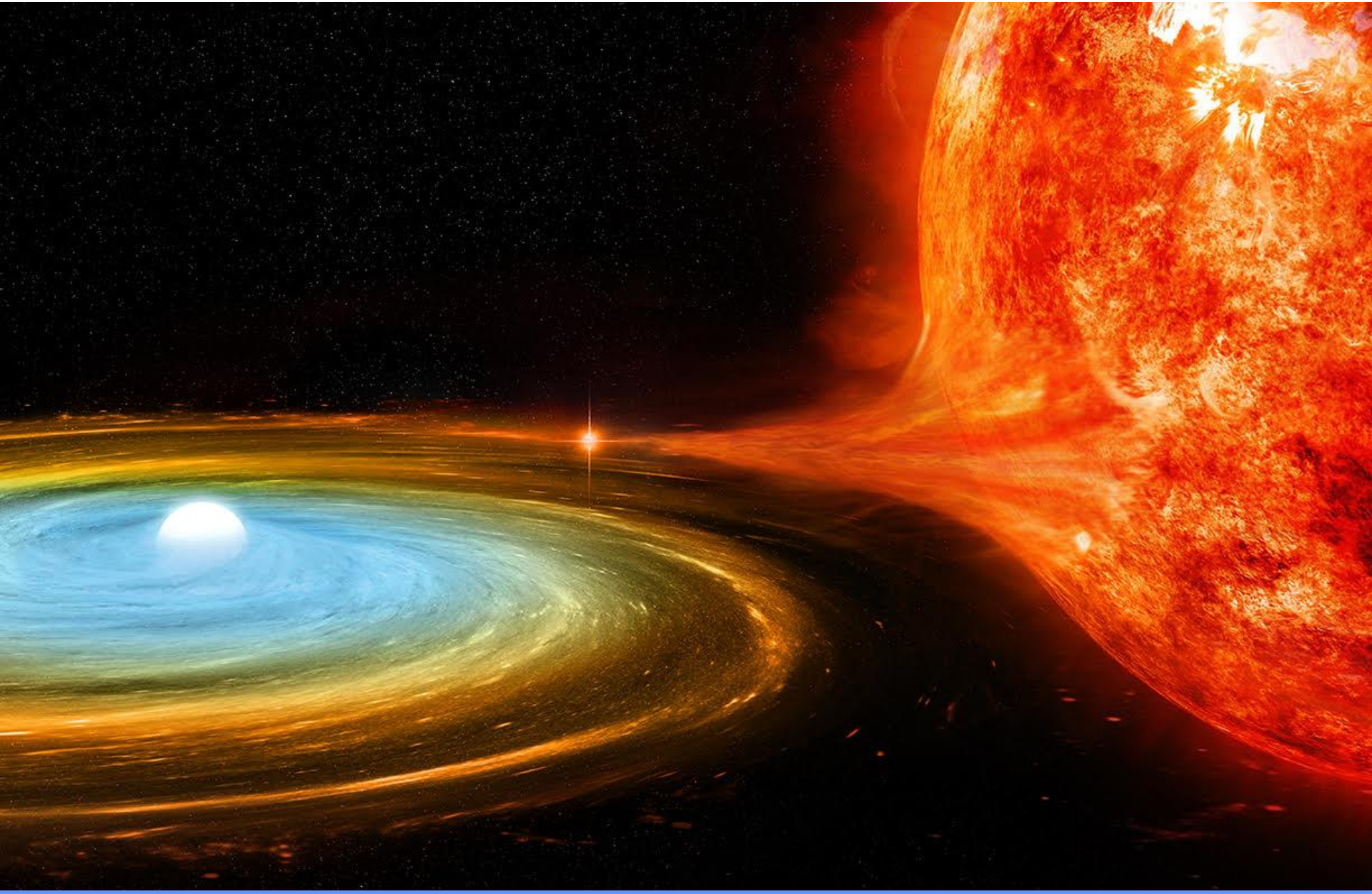
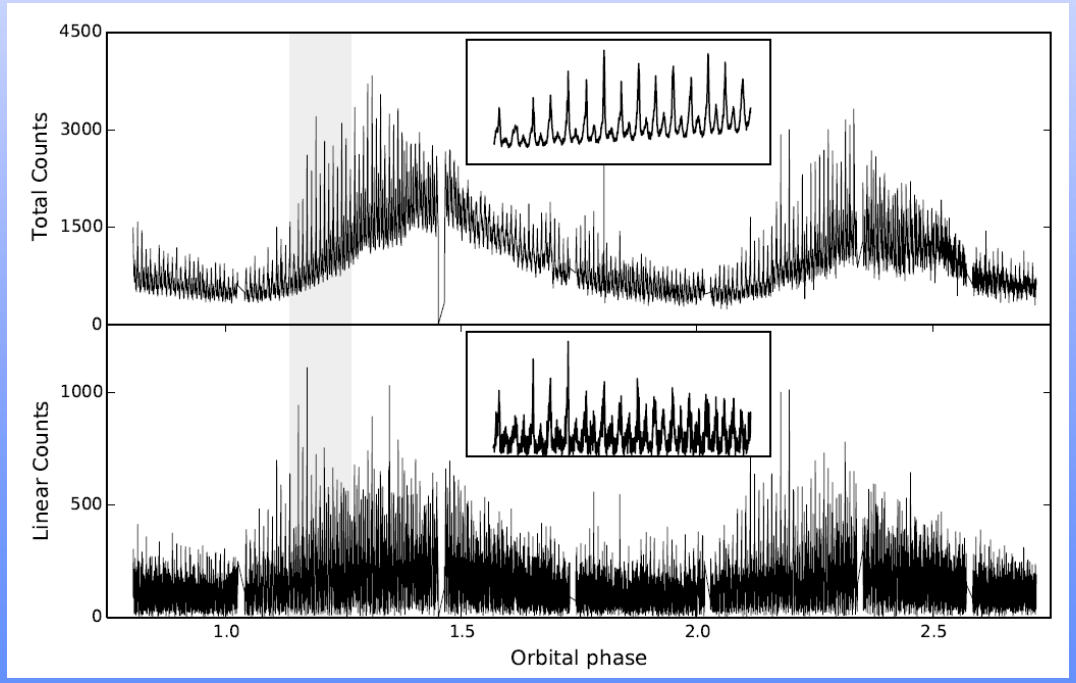
ASASSN-16oh

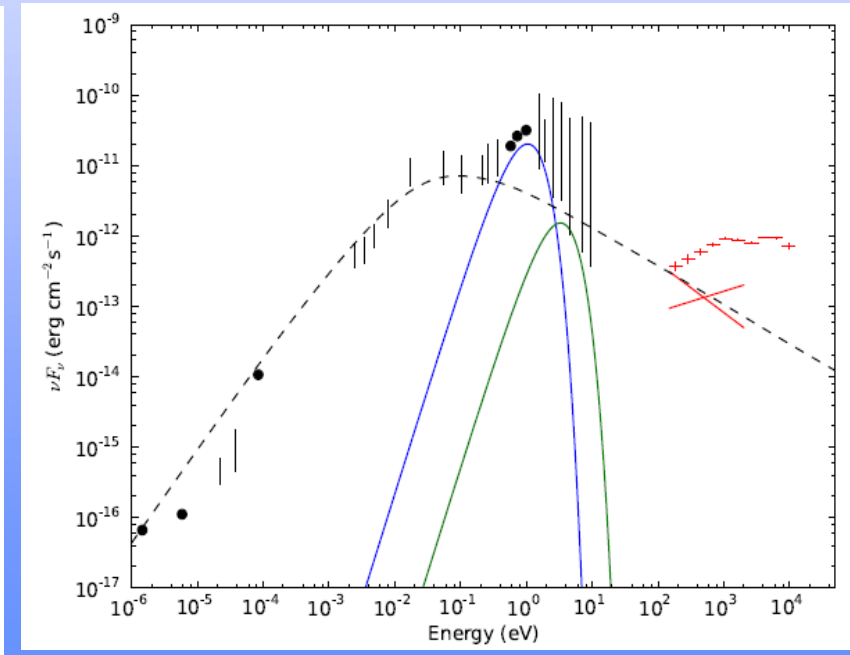


Credit: NASA/CXC/M.Weiss

White Dwarf Pulsars

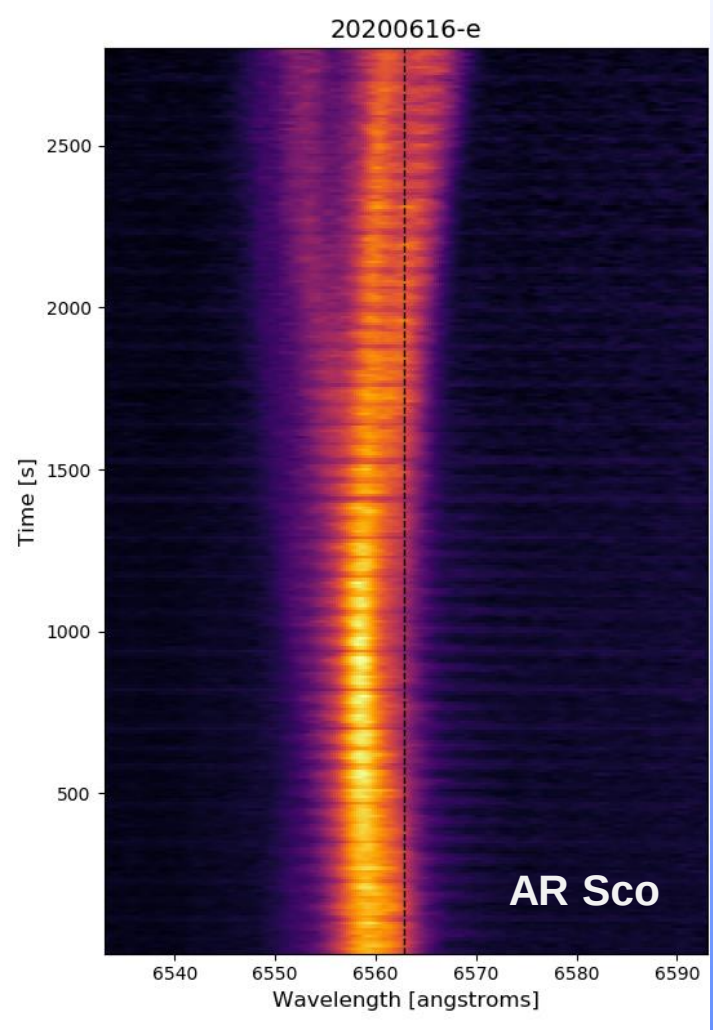
- AR Sco first example (Marsh *et al.* 2016; Buckley et al. 2017)
- Coherent pulsations across the E-M spectrum at 117.12 s spin and 118.2 s beat period with a 3.6 h orbital period
- Strongly polarized (40%) and pulsed: magnetic WD dipole
- System is a detached binary consisting of a rapidly spinning-down highly magnetic (>200 MG) White Dwarf + M5 companion
- SED is non-thermal and powered by spin-down of WD
- New example recently discovered with similar behavior (525 s spin; 4 h orbit)

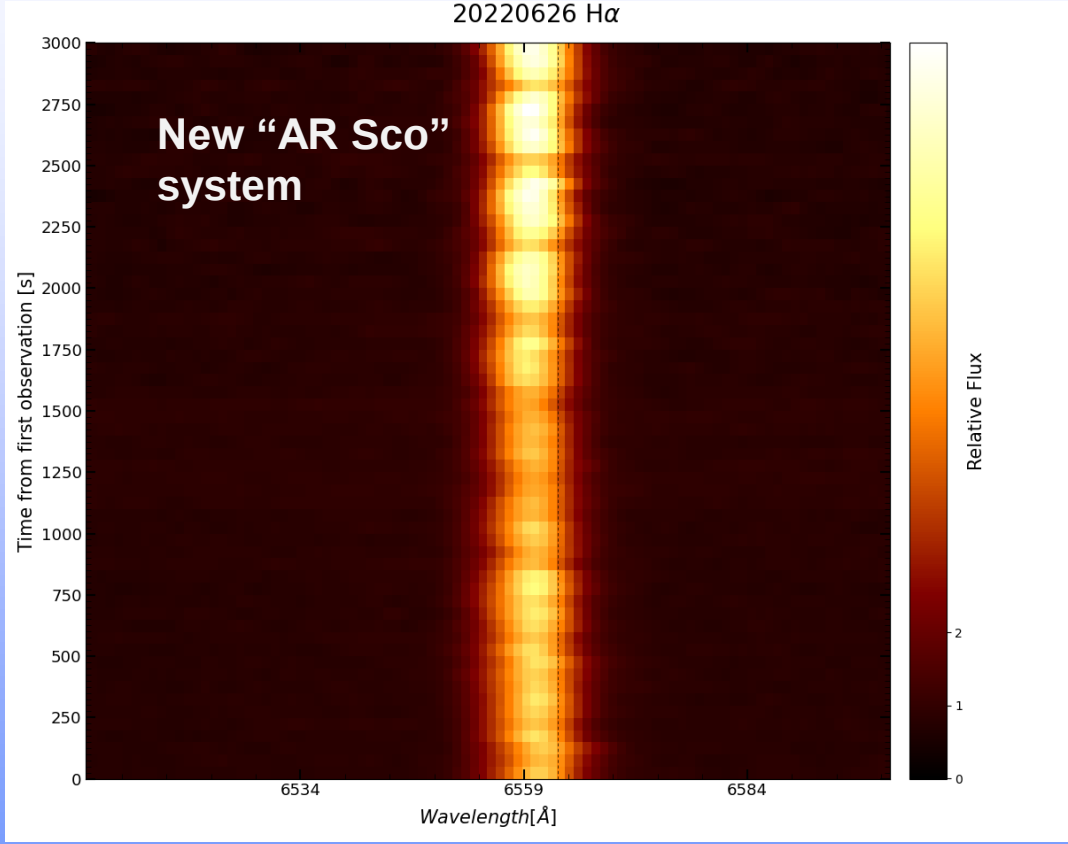




Emission Line Pulsations

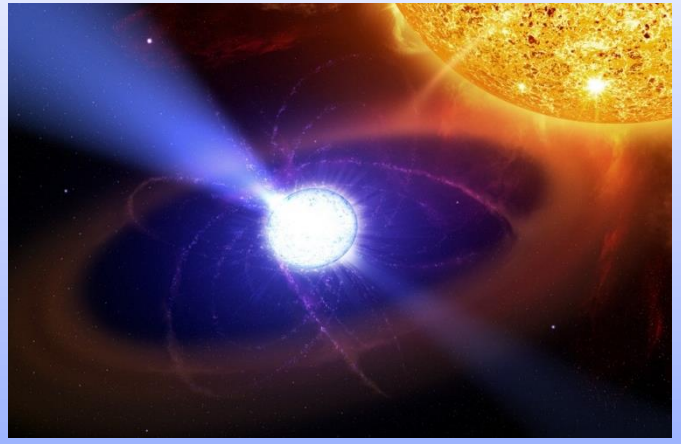
- SALT high speed spectroscopy (10 s and 30 s time res. respectively)
- Both systems show spin pulsations in narrow emission lines from companion

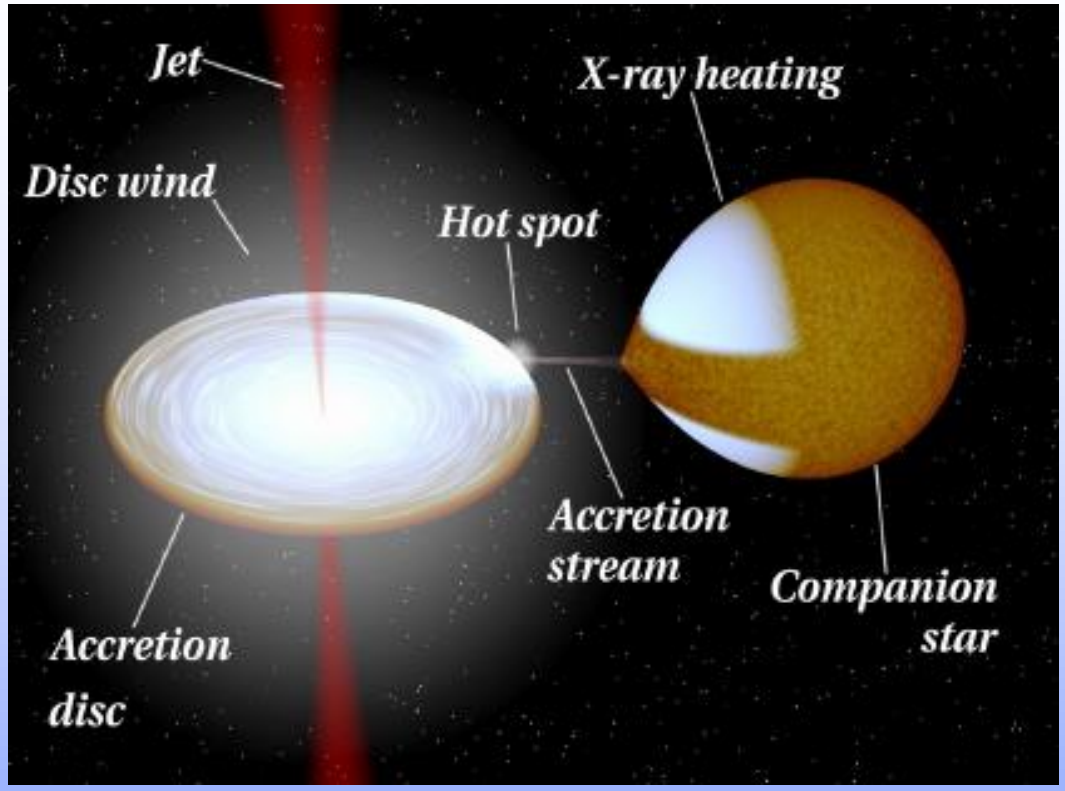




X-ray Binary Transients

- High Mass X-ray Binaries
- Low Mass X-ray Binaries
- Transitional millisec pulsars (also first observations with MeerKAT)

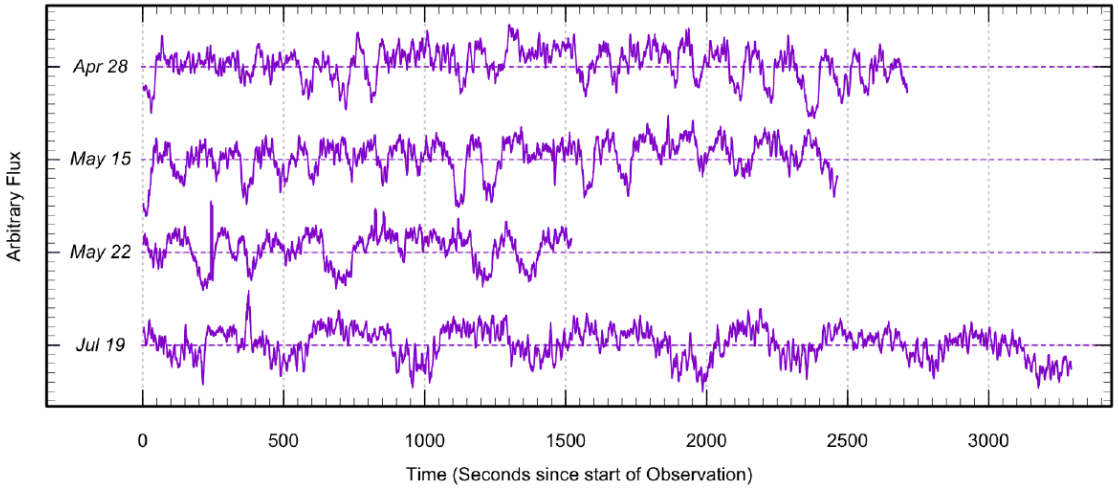


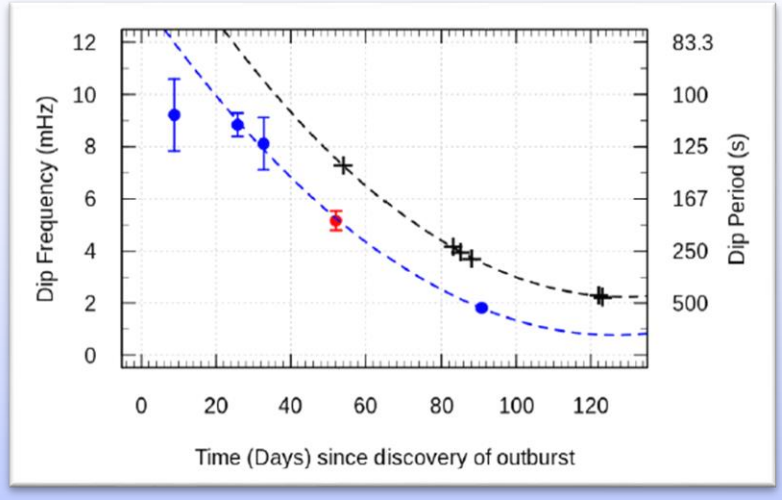


- Involves accretion onto either a neutron star or a black hole.
- Mass donor is usually “normal” M-S star (rare ones a sub-solar)
- Orbital periods of hours – days (LMXBs) or weeks – years (HMXBs)
- Most go through outburst states
- Jets seen in some systems at certain transition times (Hard -> Soft)

Example of an LMXB: Swift J1357-0933

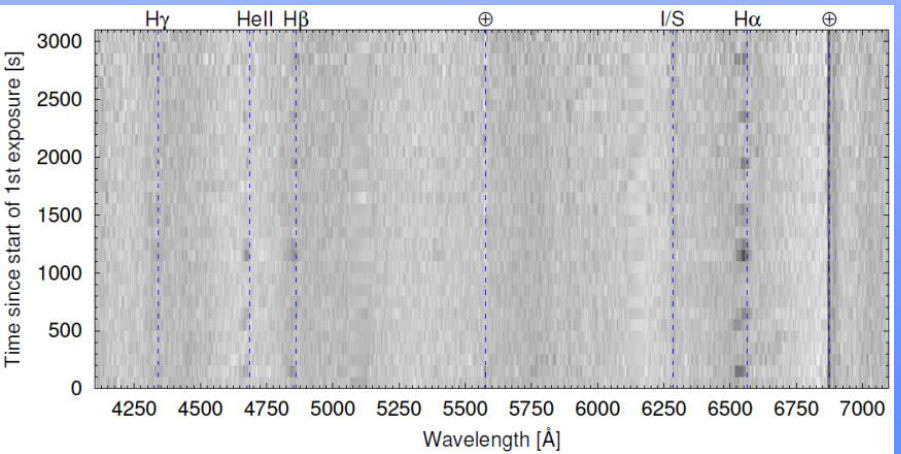
- A black hole X-ray transient (discovered in 2011; M > 9.3 $M_{\odot}$)
- SALT observations during recent o/b in 2017 & 2019 (0.15 s sampling)

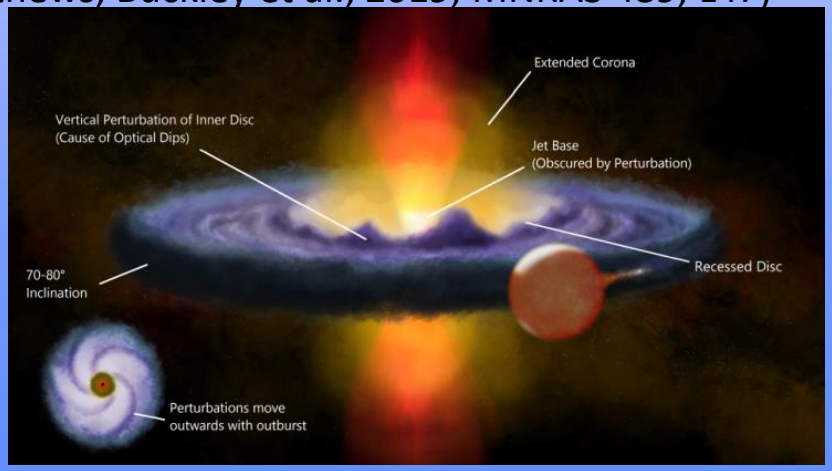




SALT high-speed (0.15 s) photometry *(Paice, Gandhi, Charles et al., 2019, MNRAS, 488, 512)*

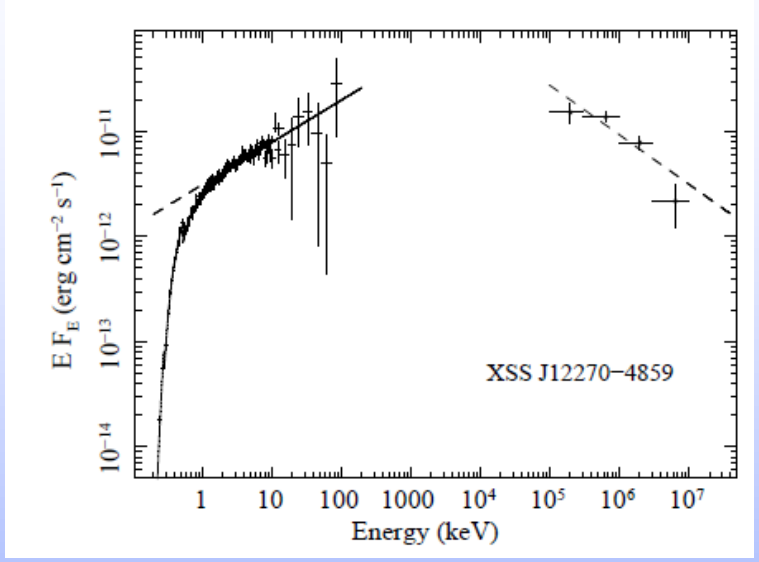
- Time resolved (30 s) spectroscopy during 2017 & 20 revealed transient absorption lines (Balmer & HeII) on same timescale as photometric dips, attributed to clumps in disk/torus
- Evidence of hot dense accretion disk wind (Charles, Matthews, Buckley et al., 2019, MNRAS 489, L47)





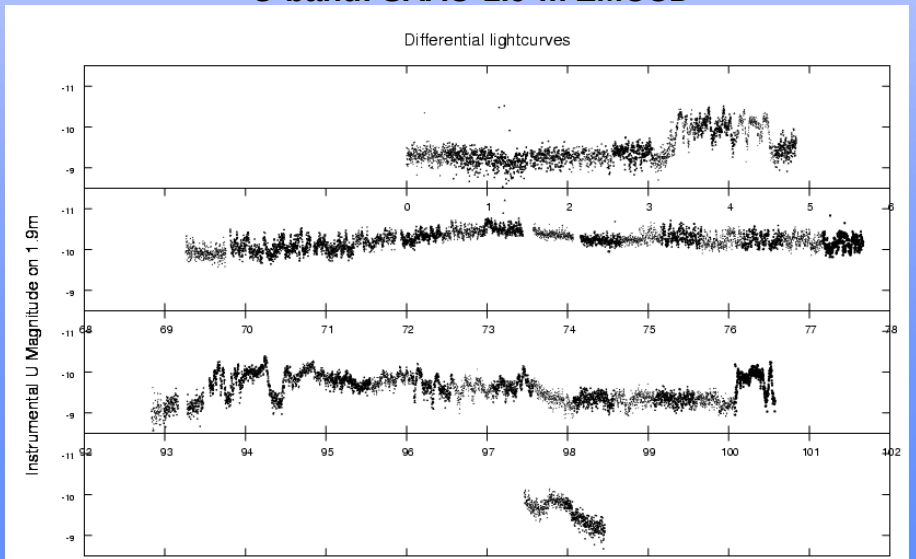
The transitional millisec pulsar XSS J12270-4859

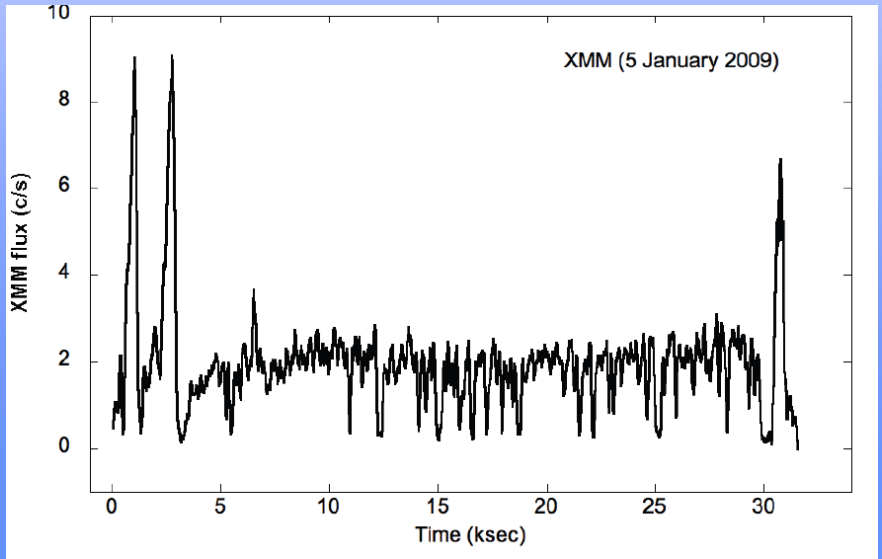
Detected by RXTE & INTEGRAL and coincident with unusual FERMI VHE (0.1-300 GeV) source 2FGL J1227.7-4853



- first seen by RXTE and suggested to an IP, but not confirmed from Suzaku or XMM and no Fe line (as in accreting WDs)
- seen in 1FGL & 2FGL catalogues (24 σ)
- X-ray flares & dips (e.g. EXO0748-676), but not phase dependent and no spectral changes
- weakly abs power law with no cut-off up to 100 keV. Power law slope 1.7 (X-rays) to 2.3 (VHE)
- first considered as microquasar, but these are more X-ray variable and don't exhibit VHE
- detection of 1.69 ms radio pulsations in quiescence (2012) confirms it is an accreting millisec pulsar and a redback LMXB
-

U-band: SAAO 1.9-m EMCCD

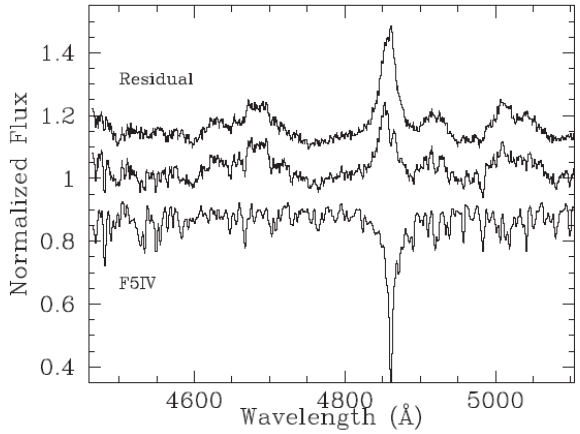


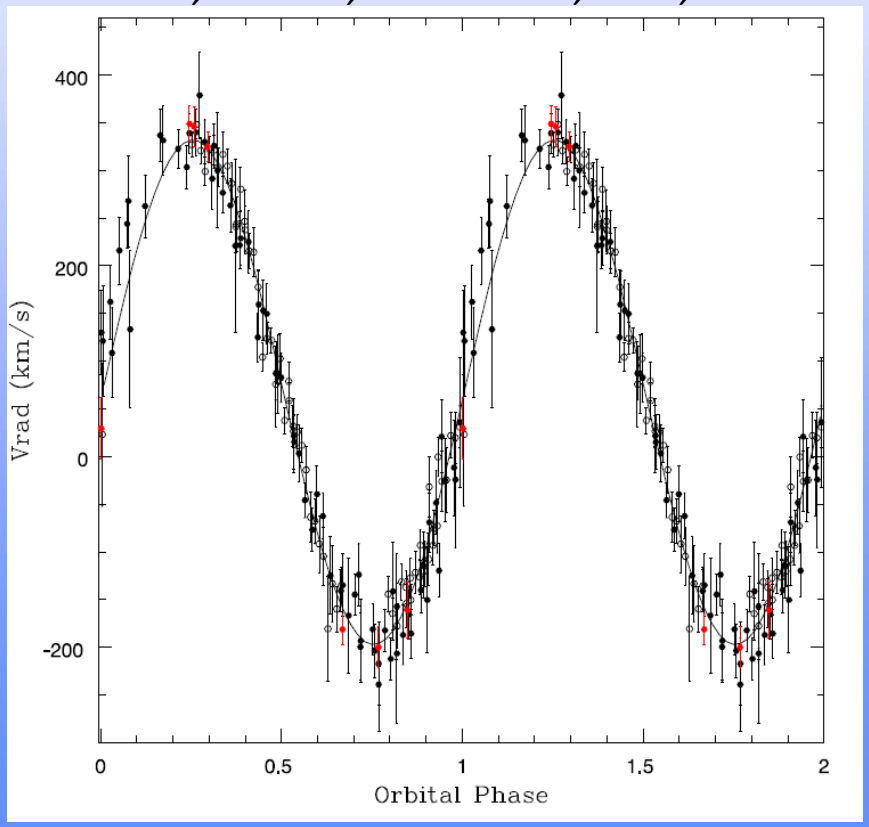


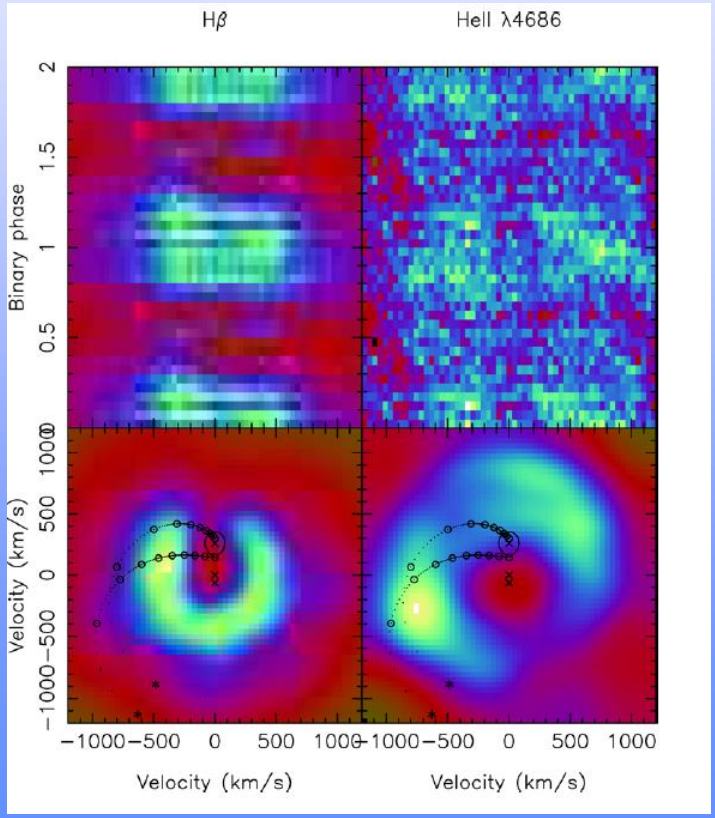
XSS J12270-4859

- 2012 observing campaign (SAAO/SALT, ESO)
  - Spectroscopy & photometry
- Radial velocity curve => 5.9 h orbital period
- Doppler tomography revealed accretion disc
- Spectral type changers from G - > F due to irradiation
- Companion is under massive for its size (0.06 – 0.12 $M_{\odot}$)

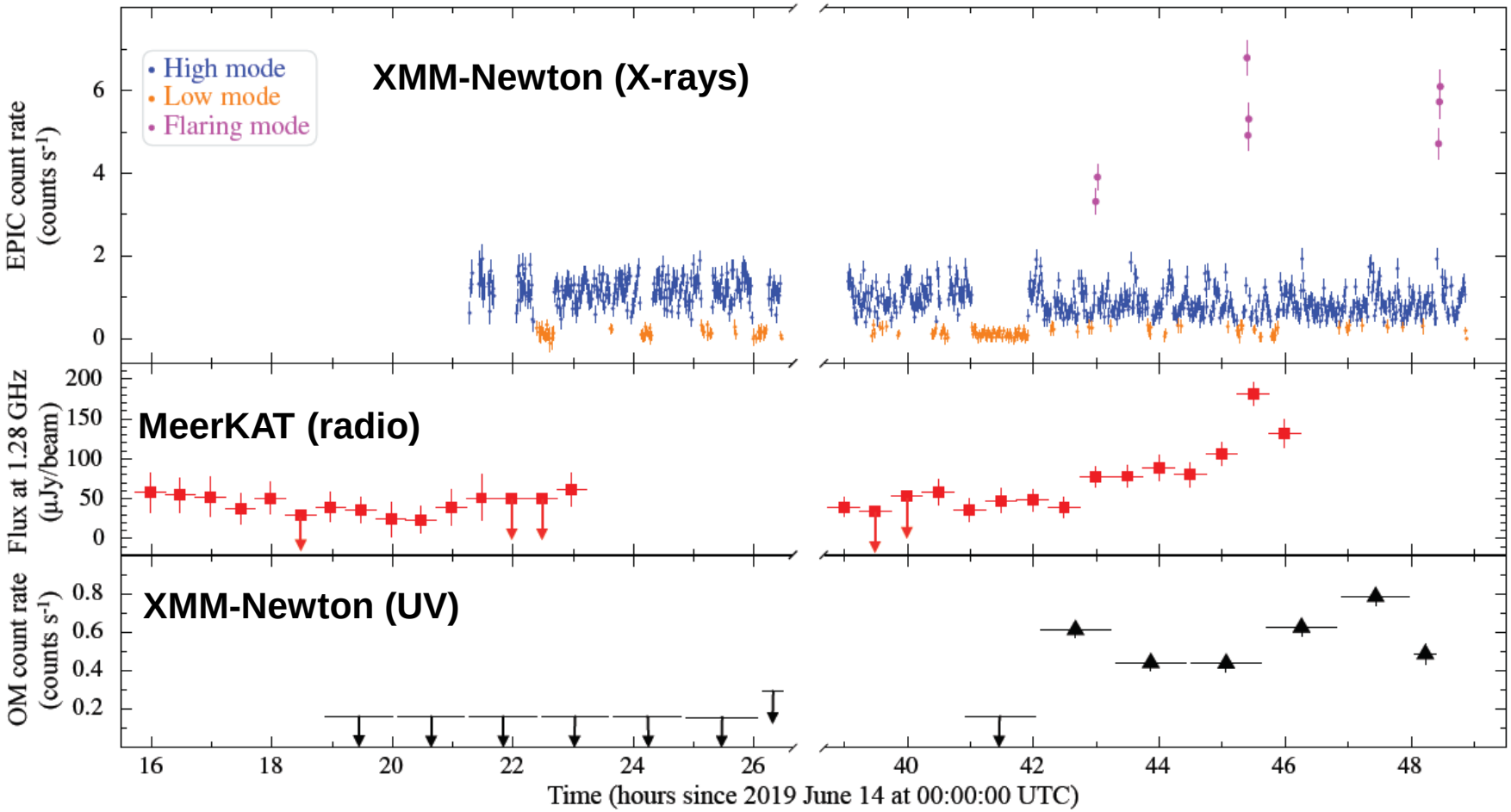
(de Martino, Casares, Mason et a., 2014, MNRAS 444, 3004)







Observations of a new tMSP candidate CXOU J1109-6502

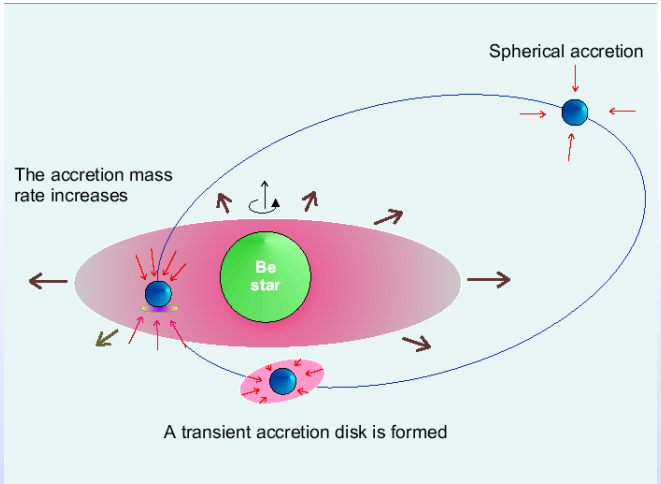


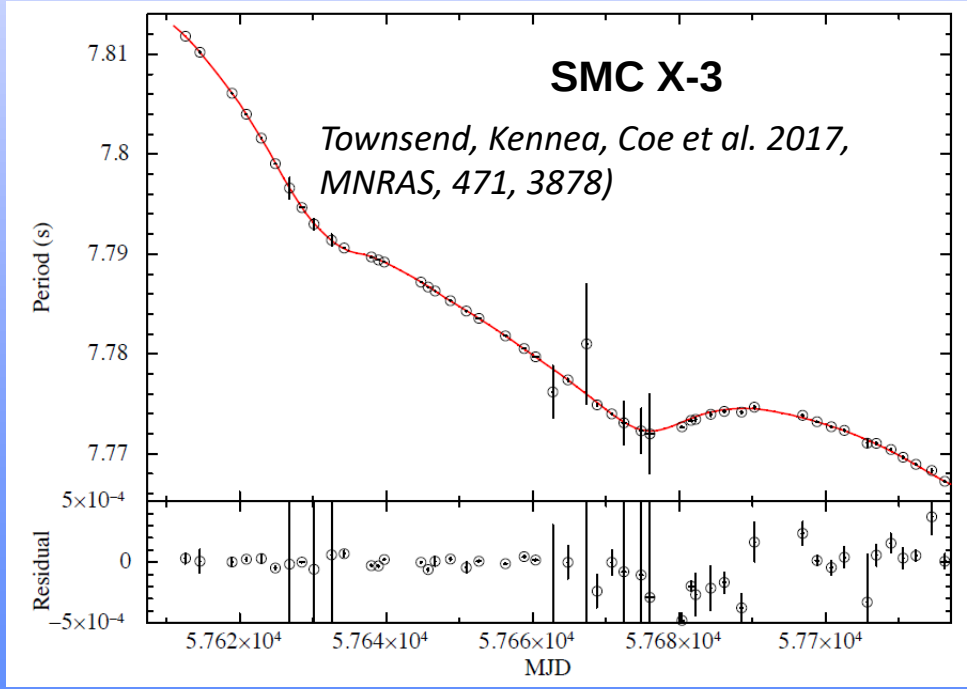
(Coti Zelati, Hugo, Torres et al., 2021, A&A, 655, A71)

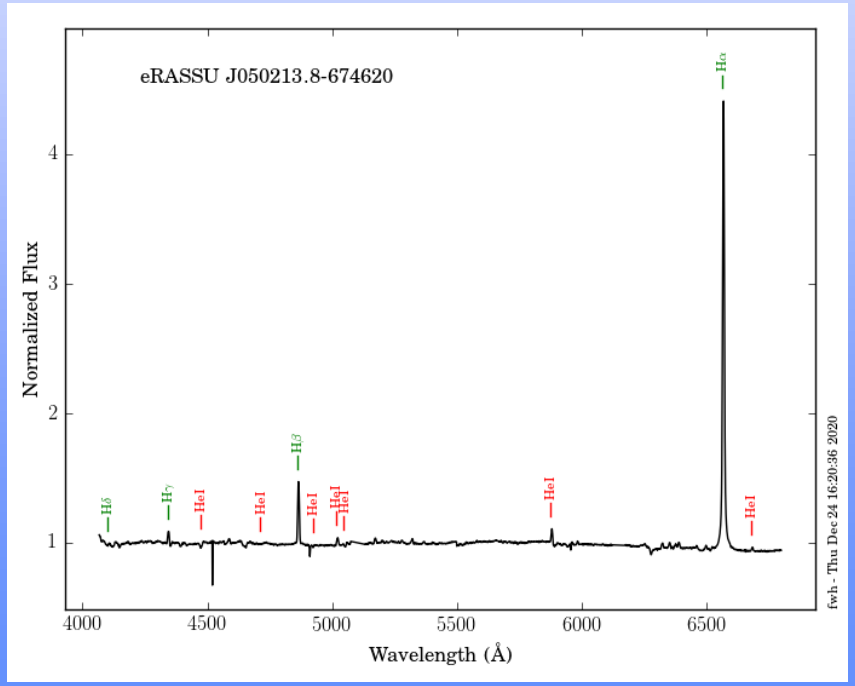
- **Supporting time resolved spectroscopy undertaken with SALT**

High Mass X-ray Binaries: Be XRBs

- Be/Neutron star binaries with elliptical orbits
- Outburst due to periastron passage through Be's disk or changes in Be disk
- Be/X-ray binary outburst (e.g. 2016 super-Eddington outburst of SMC-X3)
- Discoveries of new systems in Magellanic Clouds from X-rays (Swift, eROSITA)
- One new Be-WD SSS
- SALT spectroscopy for monitoring disk emission lines





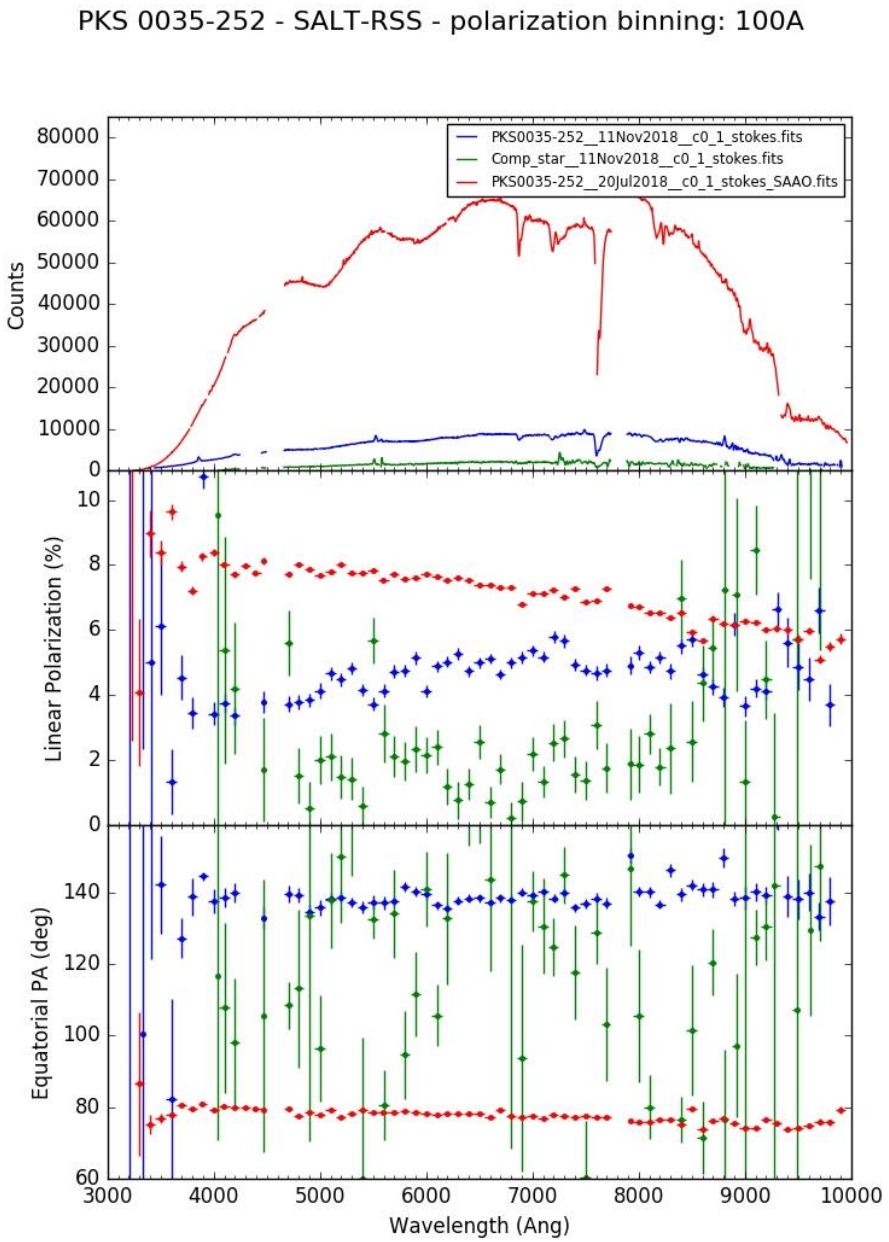


SALT Spectropolarimetry of Flaring Blazars

Program led by UFS, UJ and NWU (van Soelen, Britto, Razzaque & Boettcher) + students (Joleen Barnard, Justin Cooper, Hester Schutte)

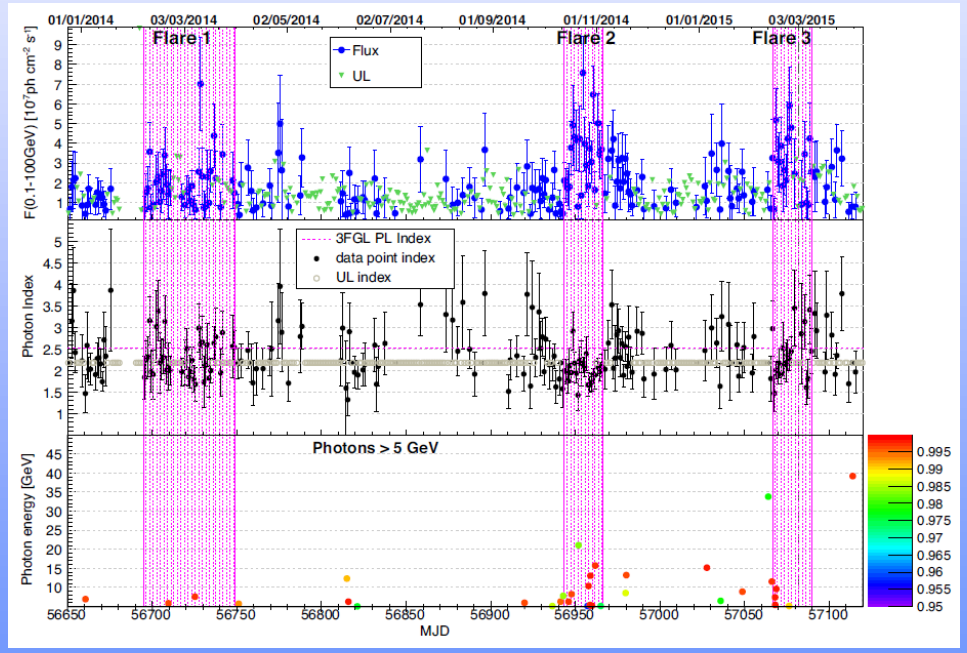
- Alerts from X-ray satellites (e.g. Fermi LAT, Swift BAT)
- Utilizing SALT spectropolarimetric modes
- Observations taken at different epochs and covering flares and quiescent phases
- Investigate the jet geometries through position angle variations during flares

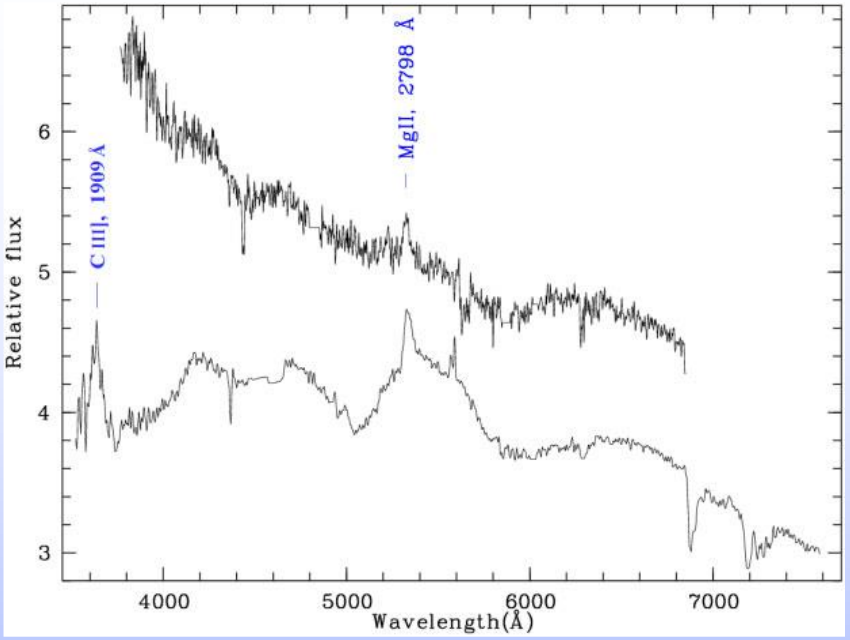
(Example: PKS 0035-252)

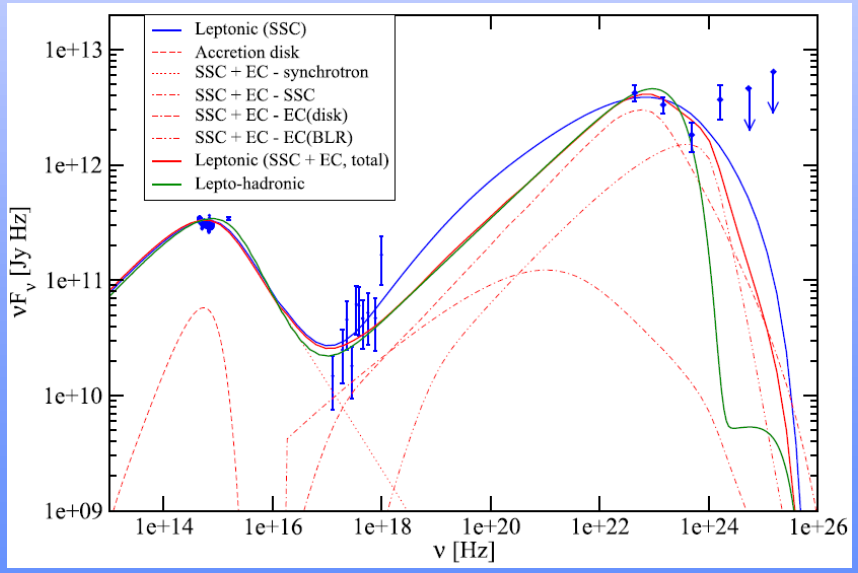


SALT Observations of the FSRQ NVSS J141922-083830

- Optical transient discovered in 2015 from MASTER network (3 mag optical flares)
- Polarization detected at ~14% level
- SALT spectra determined z = 0.903
- Fermi data shows 4 flaring episodes over ~5 y
- SED supports FSRQ classification and one-zone leptonic model

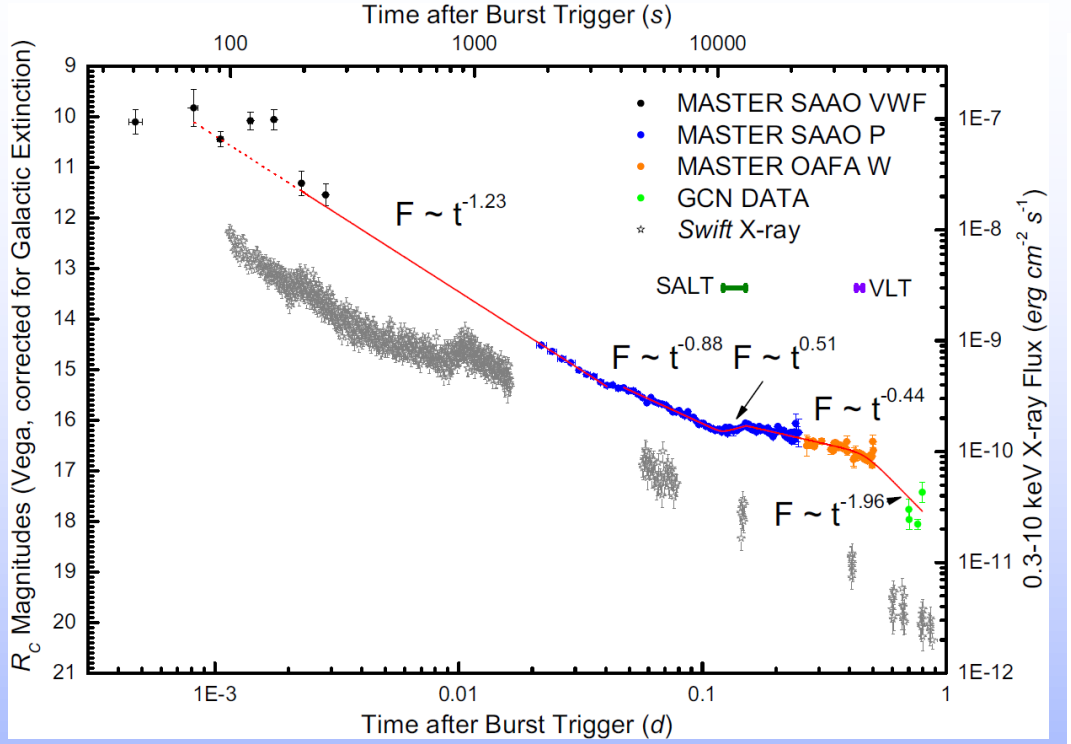


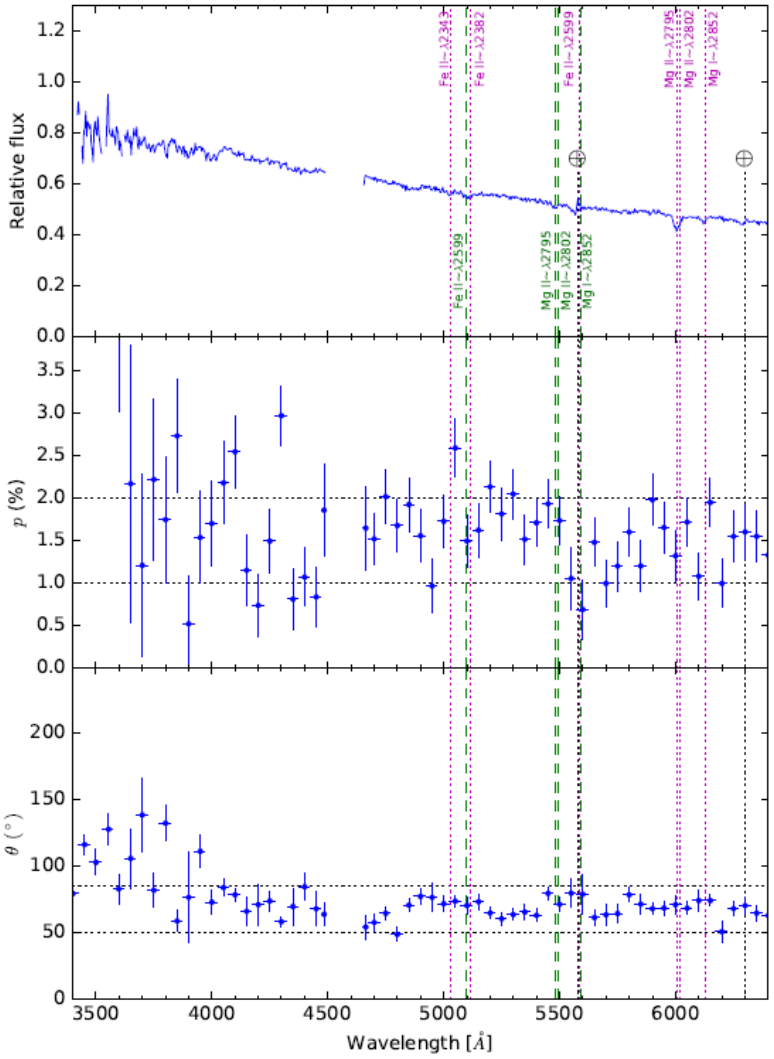




(Buckley, Britto, Chandra et al., 2022, MNRAS in press)

GRBs: Long GRB191221B





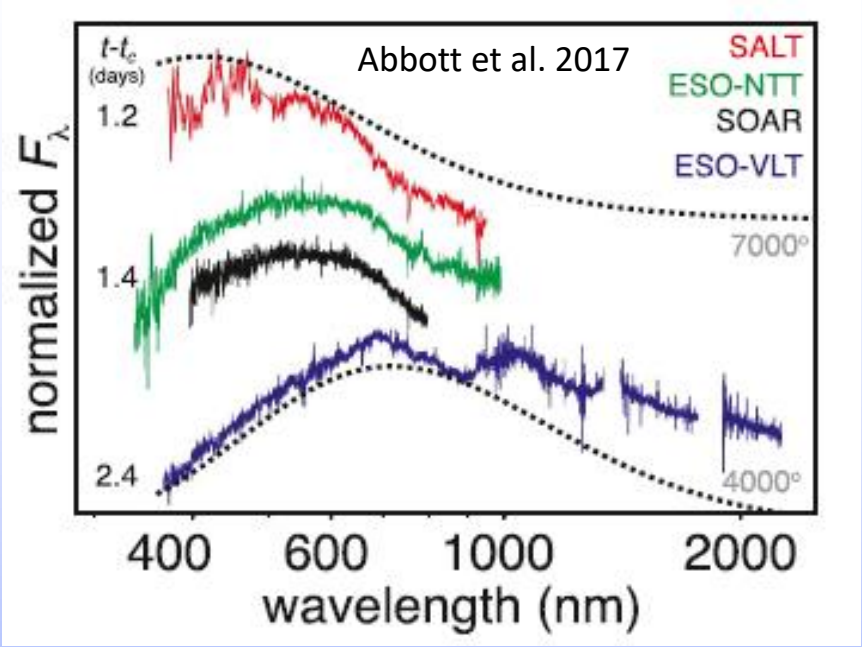
- A long, bright GRB which reached V = 10
- MASTER coverage from ~80 s
- SALT & VLT spectropolarimetry
- 1 – 1.5% polarized
- Consistent with forward shock
- Refreshed shock explains plateau

(Buckley, Bagnulo, Britto et al., 2021, MNRAS 506, 4621)

GW170817: South African follow-up

- SALT observation on 18 & 19 Aug (1.2 & 2.2 d after GW event

- observations done with 3 other telescopes at SAAO:
  - Optical photometry (MASTER-SAAO and SAAO 1-m & KMTNet)
  - Infrared photometry (Japanese IRSF telescope, followed decline over ~2 weeks)
  - SALT & SAAO results have appeared in 9 refereed papers (including *Nature* and *Science*)



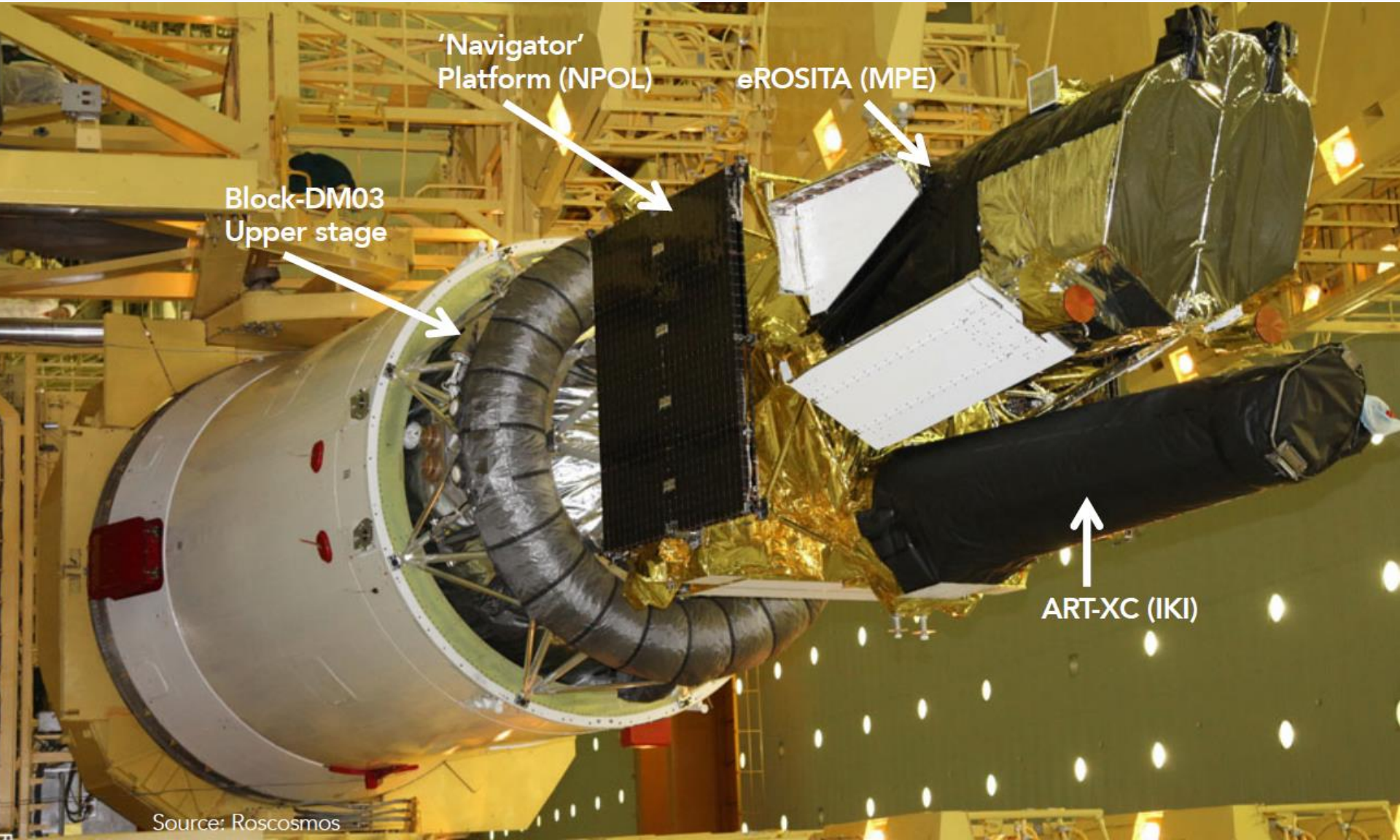
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 474, L71–L75 (2018) doi:10.1093/mnrasl/slx196
Advance Access publication 2017 December 4

A comparison between SALT/SAAO observations and kilonova models for AT 2017gfo: the first electromagnetic counterpart of a gravitational wave transient – GW170817

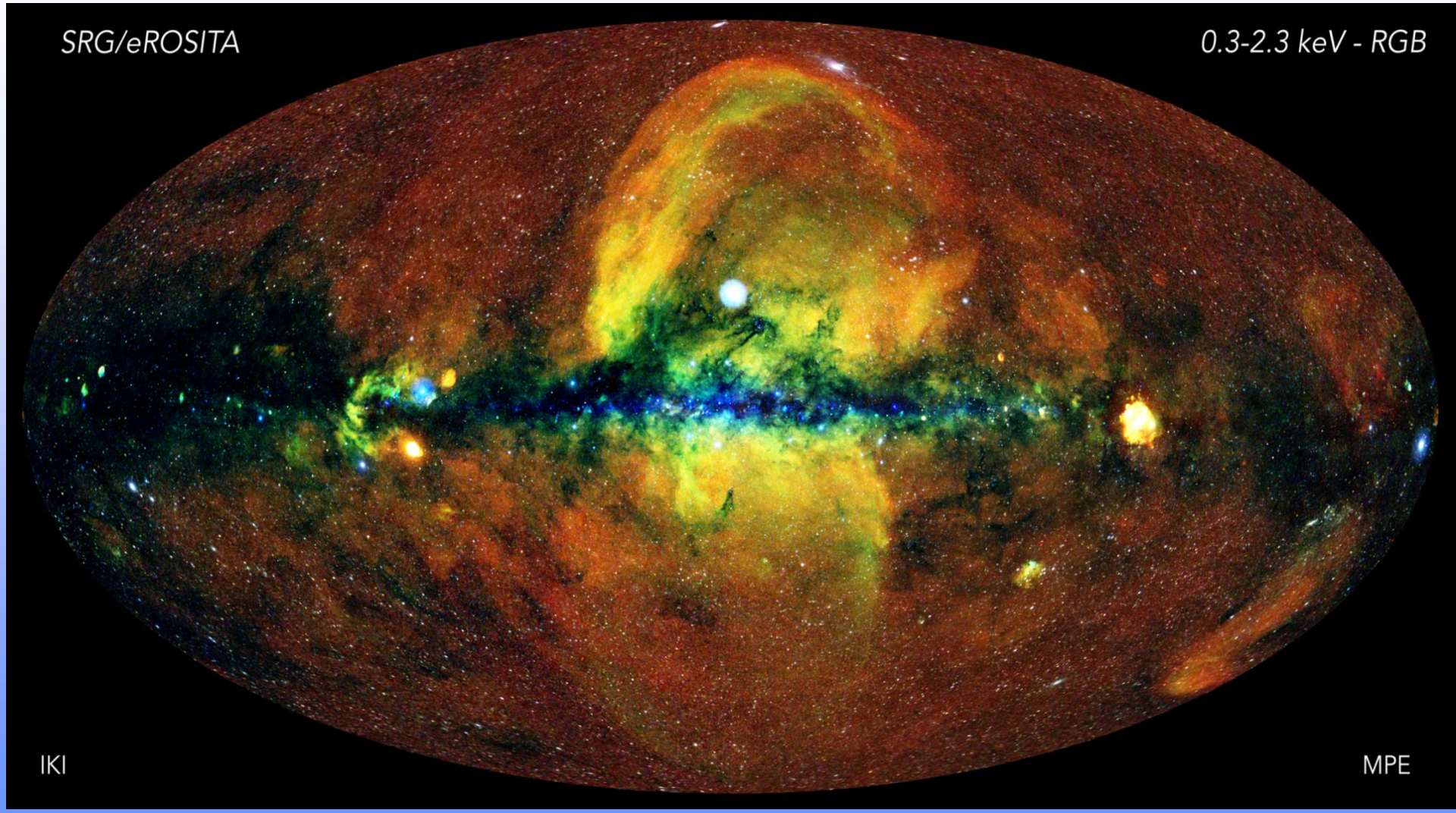
David A. H. Buckley,[1,2★] Igor Andreoni,[3,4,5] Sudhanshu Barway,[1] Jeff Cooke,[3,4,6] Steven M. Crawford,[1,2] Evgeny Gorbovskoy,[7] Mariusz Gromadzki,[8] Vladimir Lipunov,[9,7] Jirong Mao,[10,11,12] Stephen B. Potter,[1] Magaretha L. Pretorius,[13,1] Tyler A. Pritchard,[3] Encarni Romero-Colmenero,[1,2] Michael M. Shara,[14,15] Petri Väisänen[1,2] and Ted B. Williams[1]

Followup of eROSITA-DE X-ray transients

Spectrum Röntgen Gamma satellite



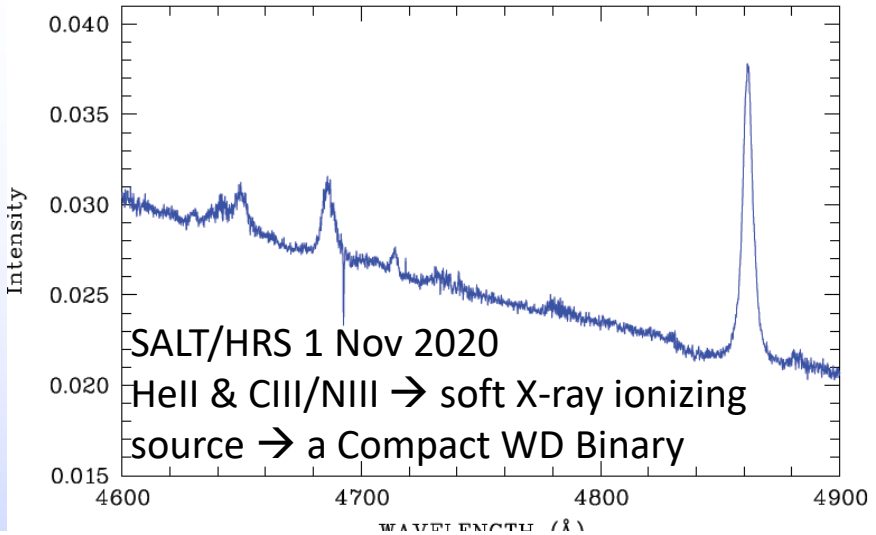
Followup of eROSITA-DE X-ray transients

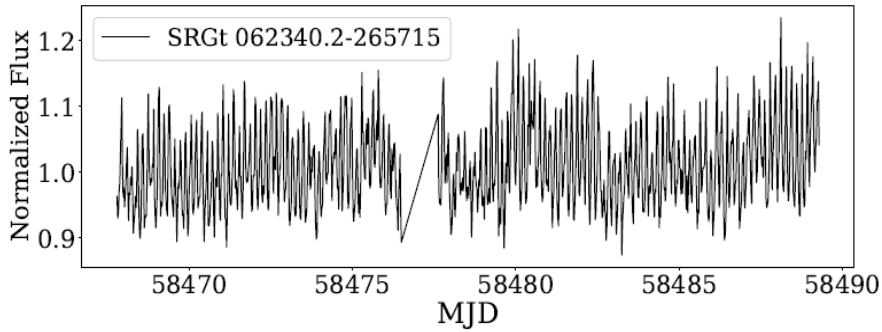


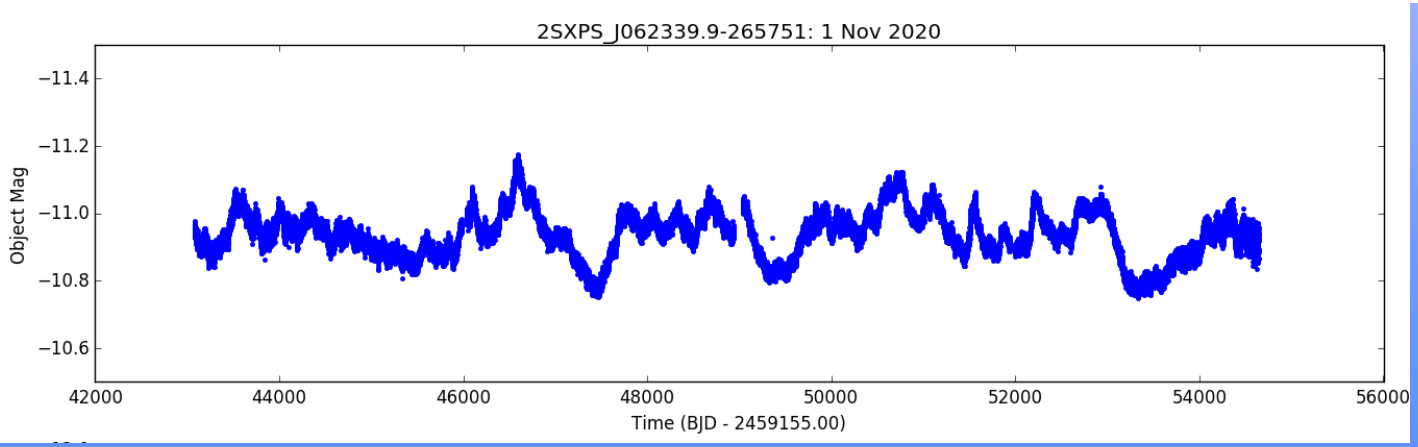
eROSITA accreting Compact White Dwarf Binaries

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 & PARTC-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





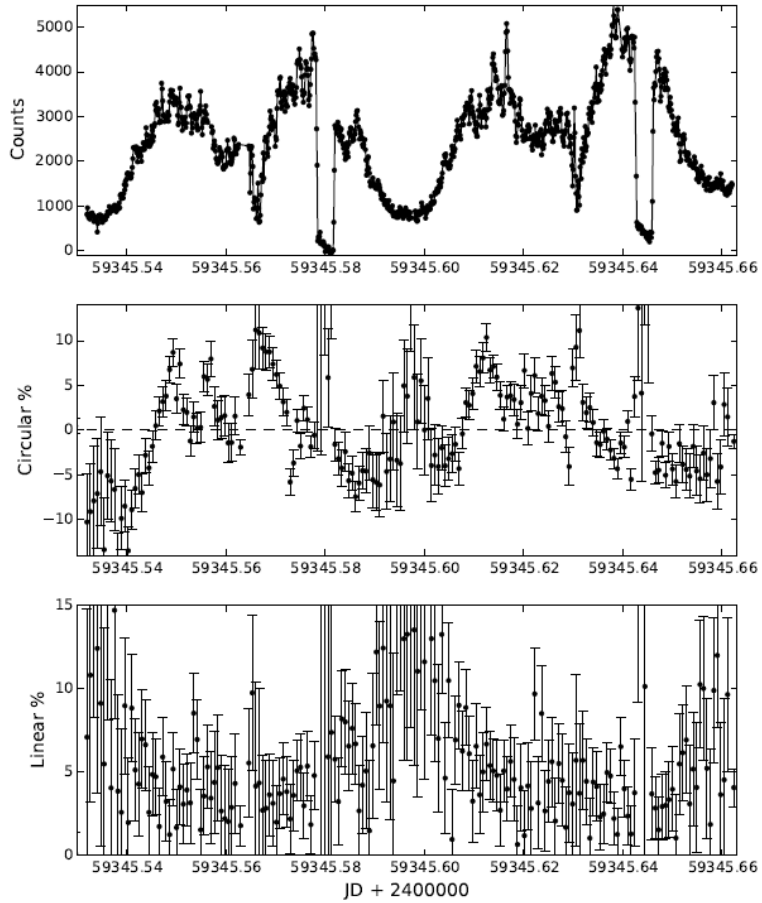


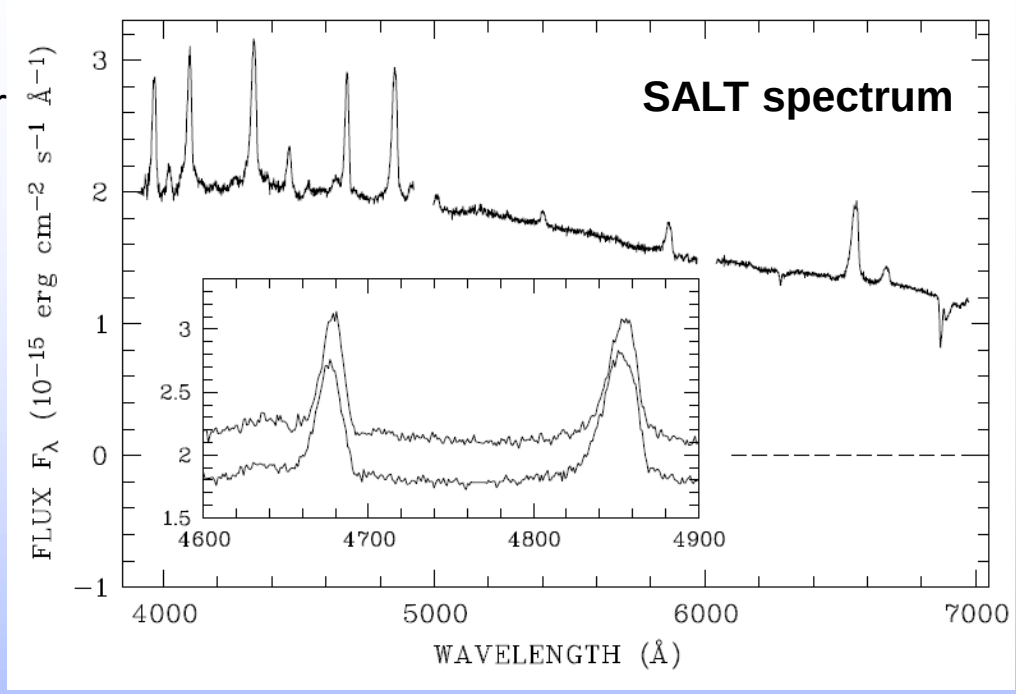
(Schwope, Buckley, Kawka et al. 2022, A&A 661, 43S)

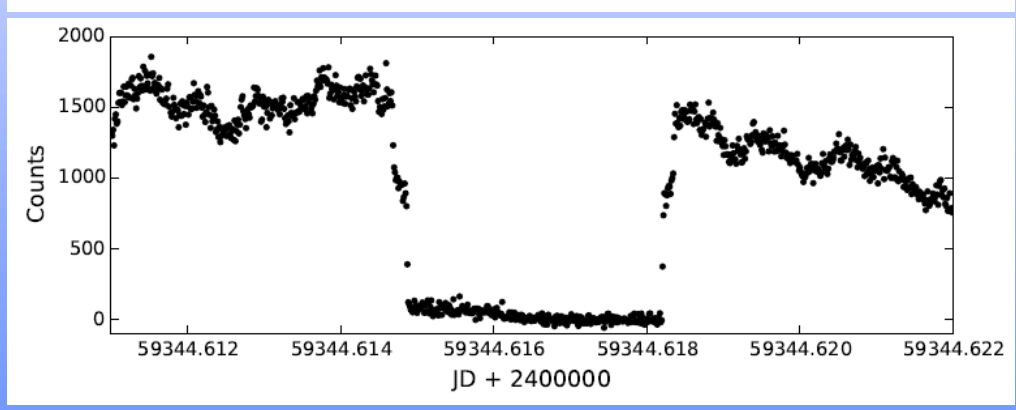
eROSITA accreting Compact White Dwarf Binaries

Second example studied:

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





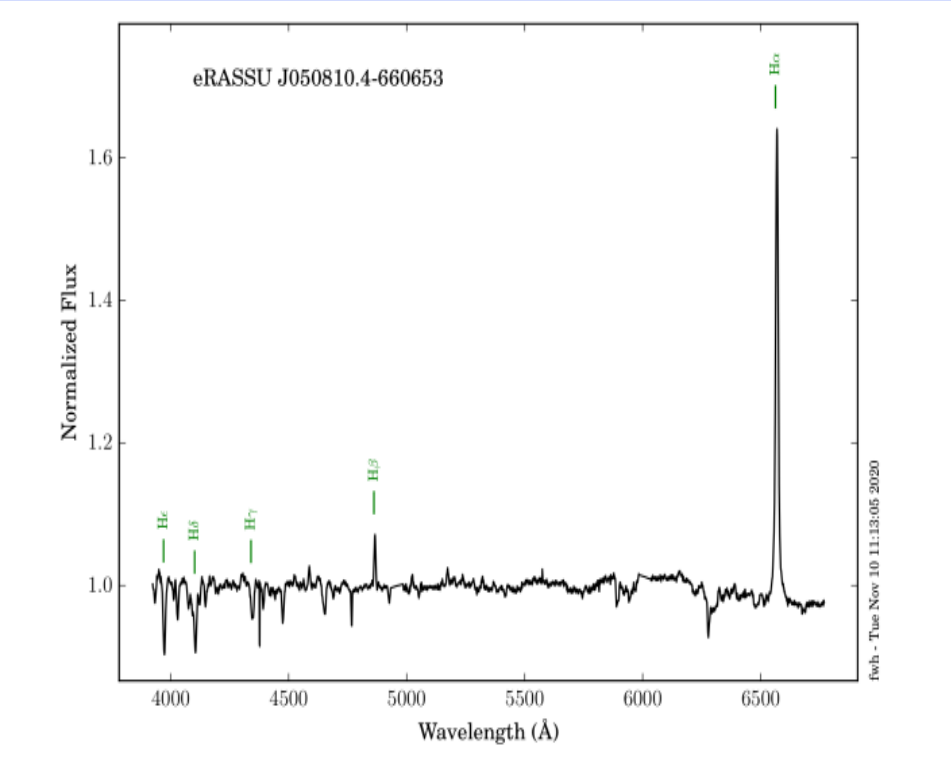


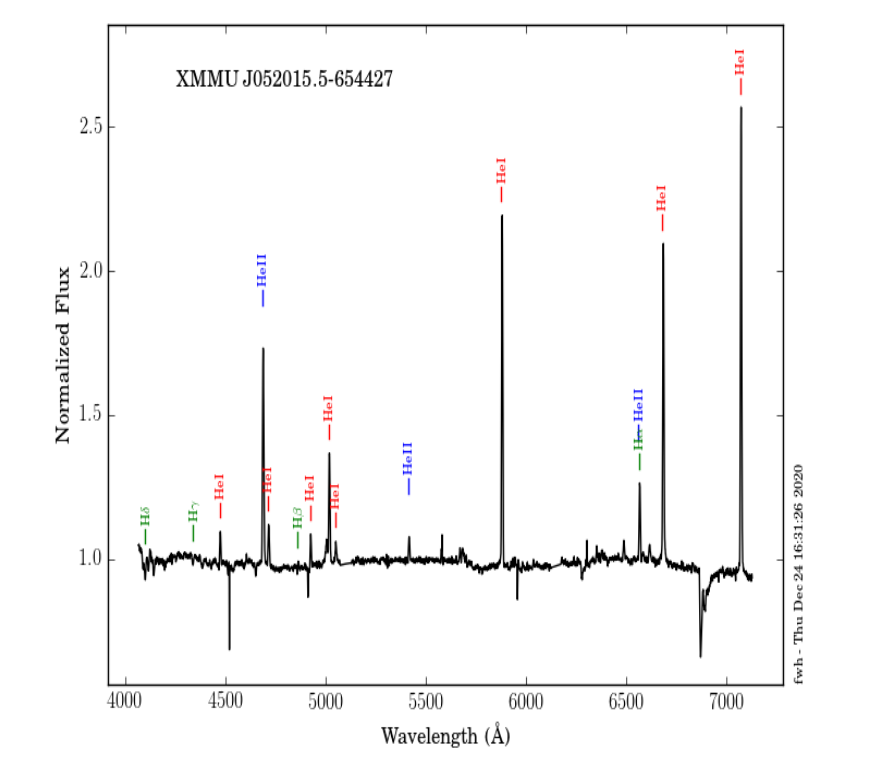
(*Schwope, Buckley, Malyali et al. 2022, A&A, 661, 42S)*

eROSITA HMXB discoveries in the Magellanic Clouds

- SALT observations of transient HMXBs in the MCs, mostly Be X-ray binaries, many harbouring new X-ray pulsars.
- A number of new discoveries have been made in the LMC, which has a relatively low population compared to the SMC
- Optical characterization and Be disk changes from SALT observations
- One new SSS with He spectrum (He donor with H stripped envelope

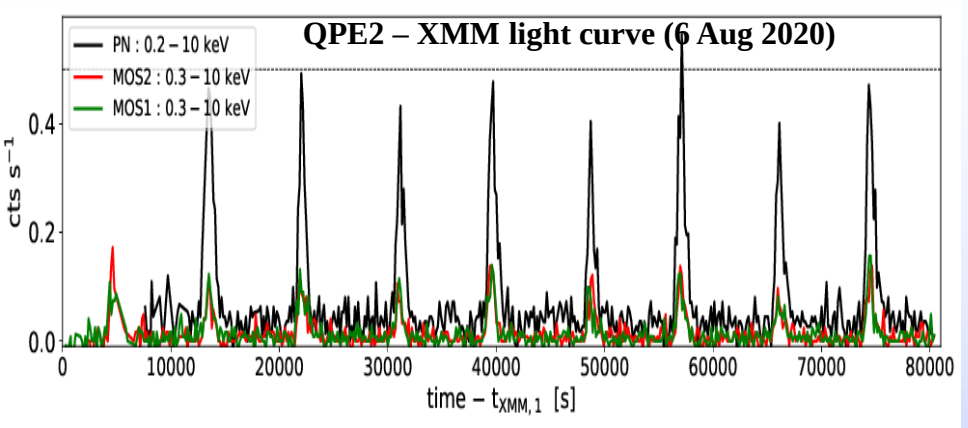
(*Greiner et al., submitted*)

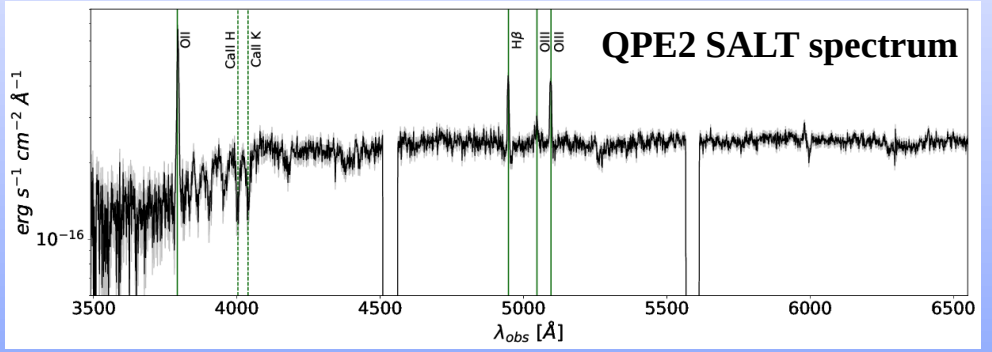




Major eROSITA Discovery: Quasi-Periodic Eruptions In “”Normal” Galaxies

- QPEs are dramatic quasi-periodic soft X-ray bursts, first seen in AGN (e.g. Miniutti+2019), that occur on few hour timescale
- 2 previously known showed AGN-like lines indicative of supermassive black hole
- 2 new eROSITA QPEs seen in non-active galaxies from SALT spectra(Accordia+2021; Nature)
- Followup shows regular X-ray eruptions (every ~18.5 & 2.4 h)
- Periods, amplitudes and profiles inconsistent with current models that invoke radiation-pressure driven accretion disk instabilities
- Proposed explanation involves orbiting compact objects
- Maybe viable candidates for the EM counterparts of extreme mass ratio inspirals





(Arcodia, Merloni, Nandra et al., 2021, Nature 592, 704)

The End