The Southern African Large Telescope: SALT

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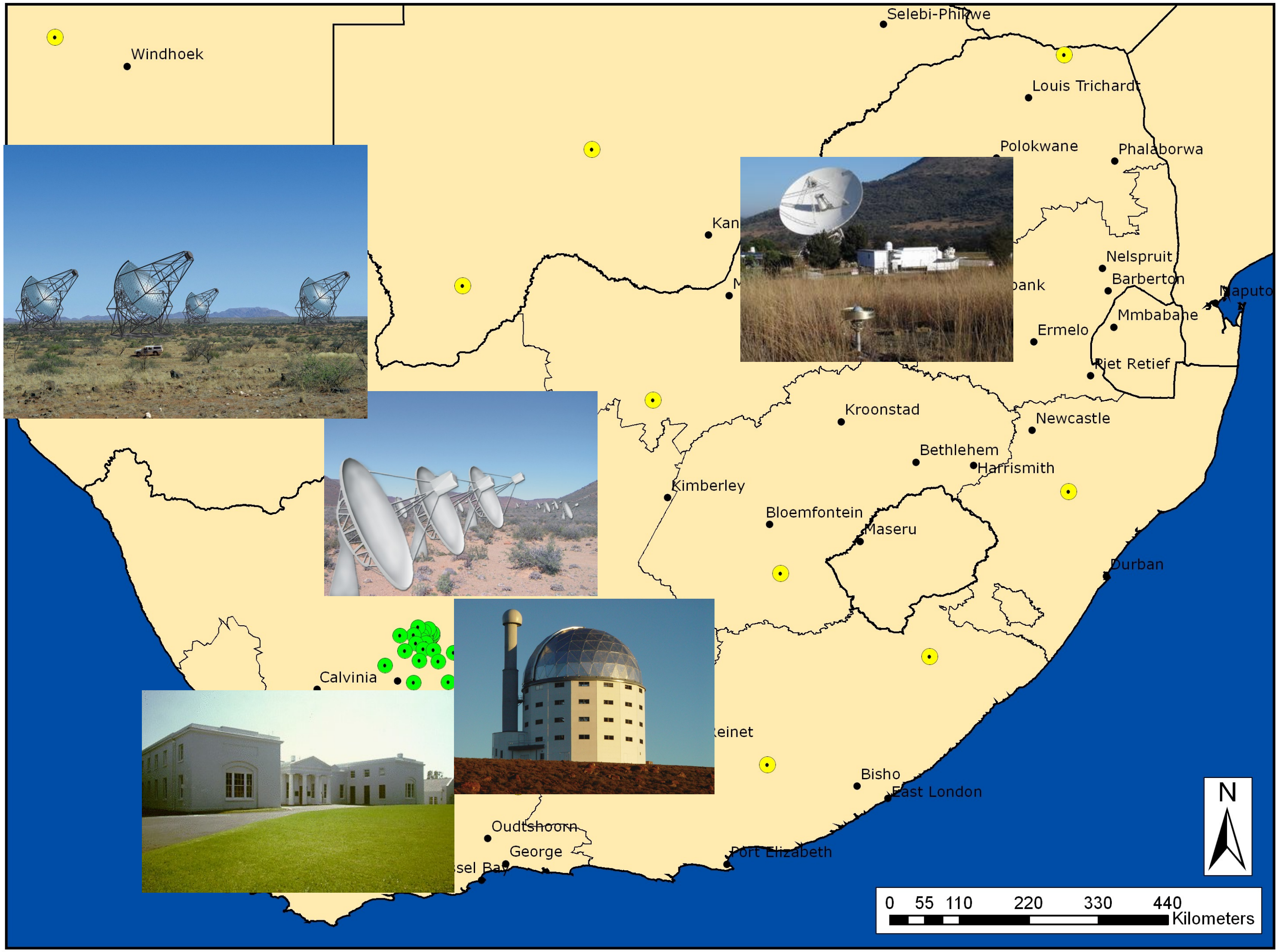
Astronomy in South Africa

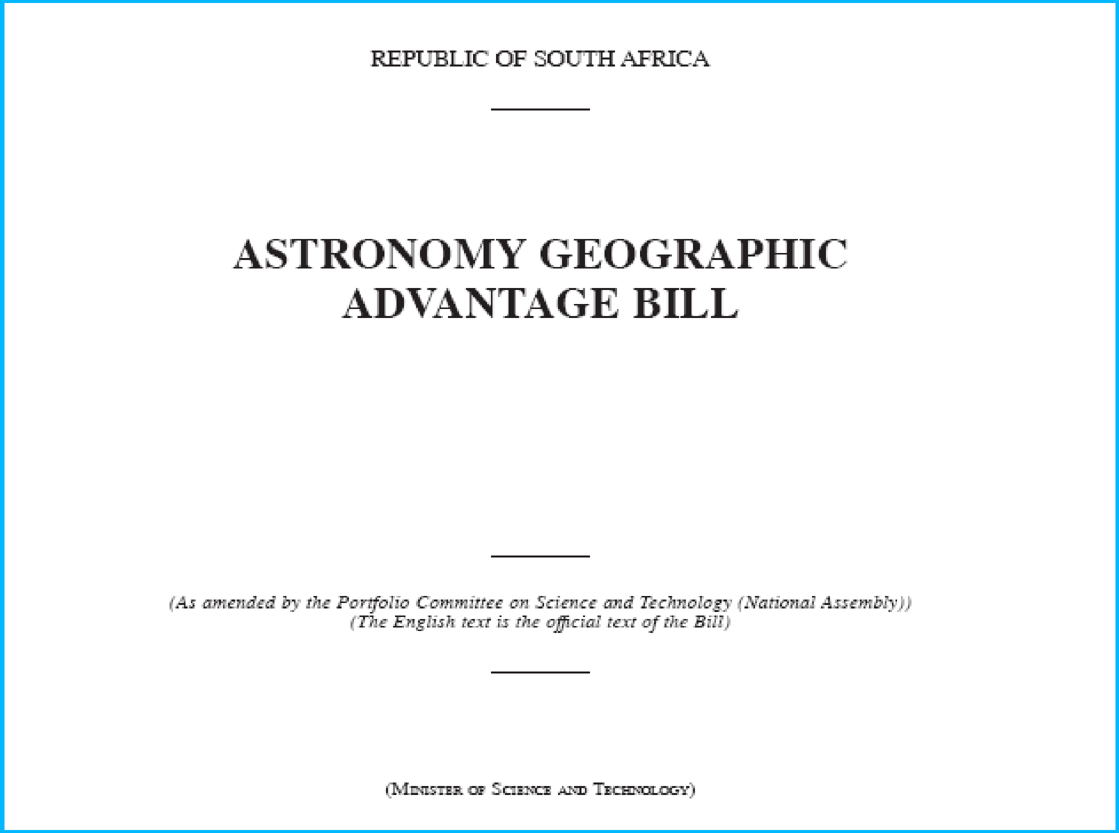


SALT: inaugurated on Nov 10, 2005 !

Our Geographic Advantage:

- SA and Chile are the only regions in Southern Hemisphere where very large-telescope astronomy is possible
- Hence important globally --> international interest in SA
- With major advantages for SA:
  - Can participate in global scale science projects as partner in which SA provides location
  - International partners provide technical/financial resources
  - SA exploits these as opportunity to grow S&T
  - e.g. SALT:
    - 2/3 funded externally
    - 2/3 SALT built internally
  - Aiming to repeat with SKA bid! Once again in the Karoo!
- Therefore need to protect this environment against:
  - Light pollution (residential, industrial)
  - Dust pollution (traffic, industry)
  - Radio interference (all forms)

Legislation: Astronomy Geographic Advantage Act



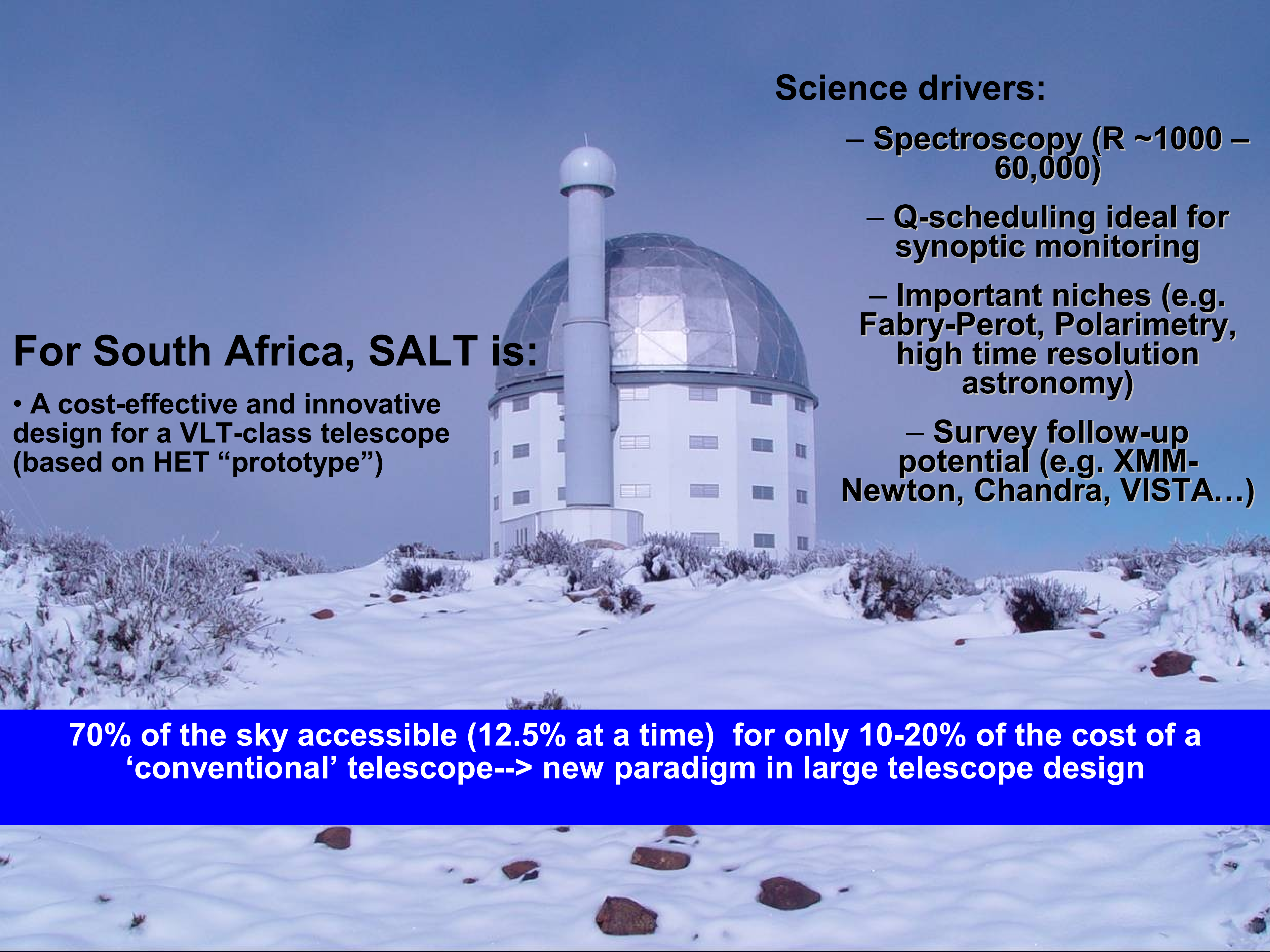
REPUBLIC OF SOUTH AFRICA

ASTRONOMY GEOGRAPHIC ADVANTAGE BILL

(As amended by the Portfolio Committee on Science and Technology (National Assembly))
(The English text is the official text of the Bill)

(MINISTER OF SCIENCE AND TECHNOLOGY)

Passed: November 2007,
now in process of defining regulations



For South Africa, SALT is:

- A cost-effective and innovative design for a VLT-class telescope (based on HET “prototype”)

Science drivers:

- Spectroscopy (R ~1000 – 60,000)
- Q-scheduling ideal for synoptic monitoring
- Important niches (e.g. Fabry-Perot, Polarimetry, high time resolution astronomy)
- Survey follow-up potential (e.g. XMM-Newton, Chandra, VISTA…)

70% of the sky accessible (12.5% at a time) for only 10-20% of the cost of a ‘conventional’ telescope--> new paradigm in large telescope design

Who owns SALT: the shareholders

Total Cost is ~$45M

~$22M: telescope construction

~$9M: 3 first-gen instruments

~$14M: 10 years operations

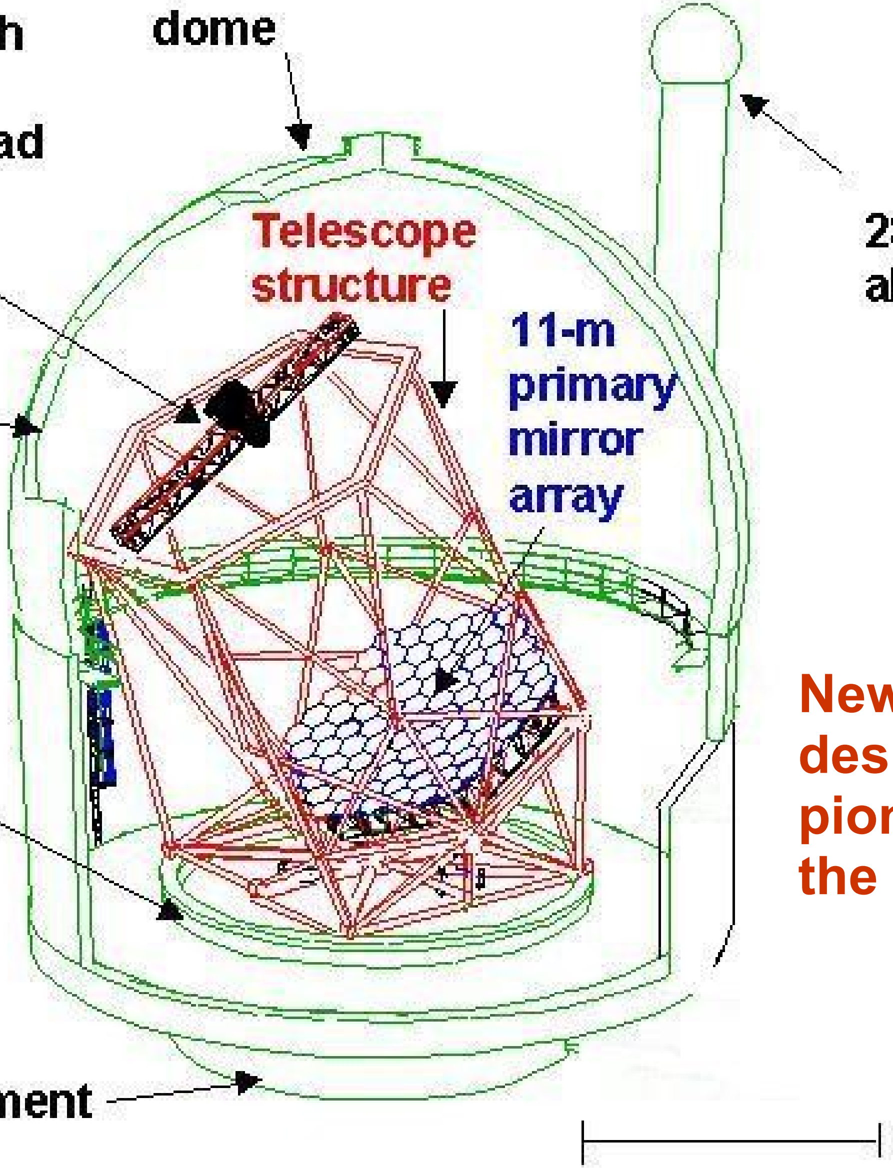
National Research Foundation	34.4%
University of Wisconsin	15.5%
CAMK (Poland)	11.0%
Rutgers University	10.8%
Dartmouth College	9.4%
Goettingen University	4.9%
University of Canterbury (NZ)	4.1%
UK SALT Consortium	3.9%
University of North Carolina	3.1%
Carnegie - Mellon University	3.1%

(Original shareholding 2000)

(HET garners fixed allocation for 10 years)

+American Museum of Natural History (NY), India (IUCAA) which were admitted in 2007

Southern African Large Telescope



26-m diameter dome

Tracker beam with fibre feed and instrument payload

Telescope structure

11-m primary mirror array

28-m mirror segment alignment tower

Dome opening

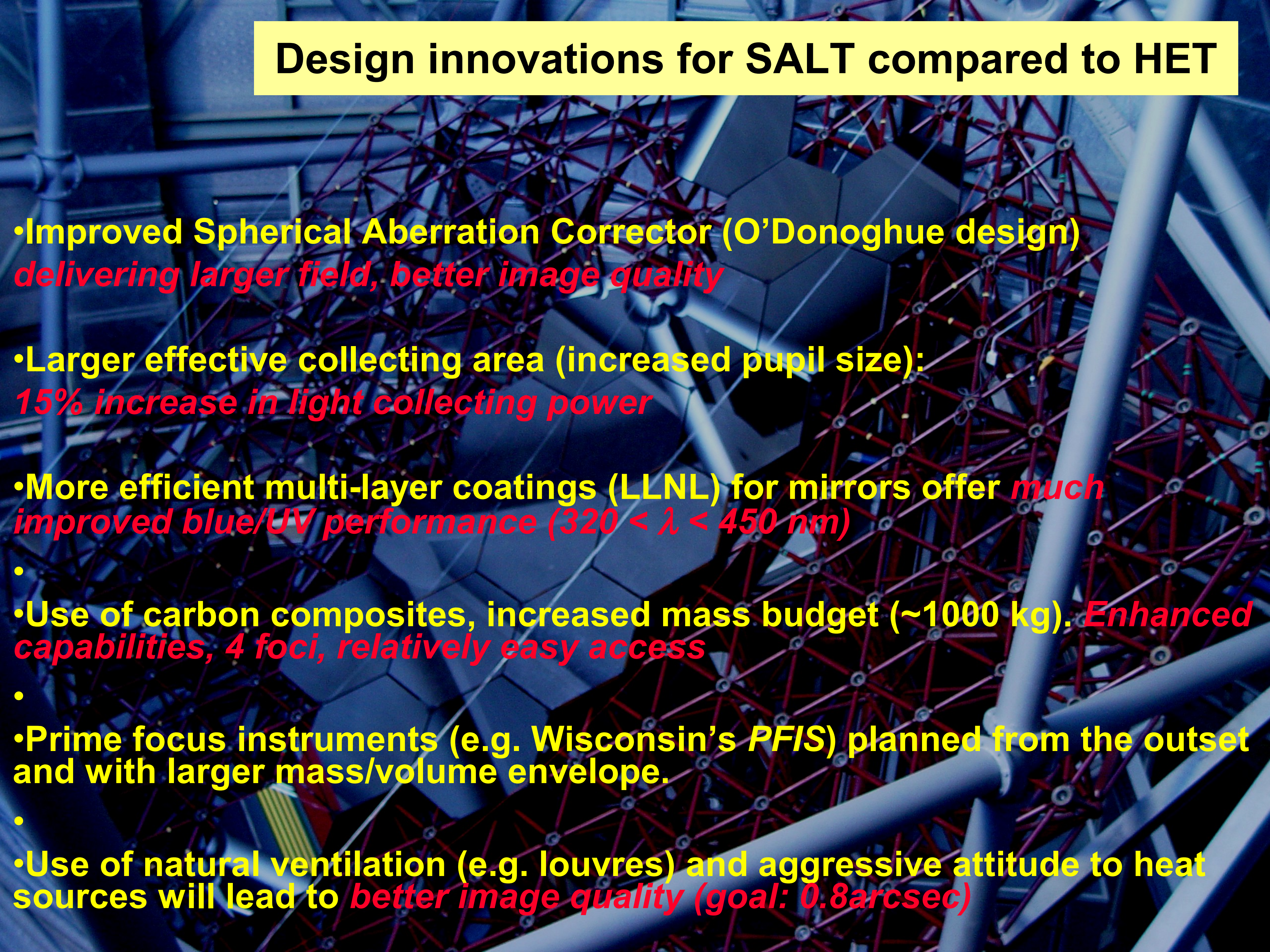
Telescope azimuth rotation bearing

Fibre-coupled instrument basement room

10-m

New paradigm in design has been pioneered by the HET in Texas.

Design innovations for SALT compared to HET



- Improved Spherical Aberration Corrector (O'Donoghue design) *delivering larger field, better image quality*

- Larger effective collecting area (increased pupil size): *15% increase in light collecting power*

- More efficient multi-layer coatings (LLNL) for mirrors offer *much improved blue/UV performance (320 < λ < 450 nm)*

•

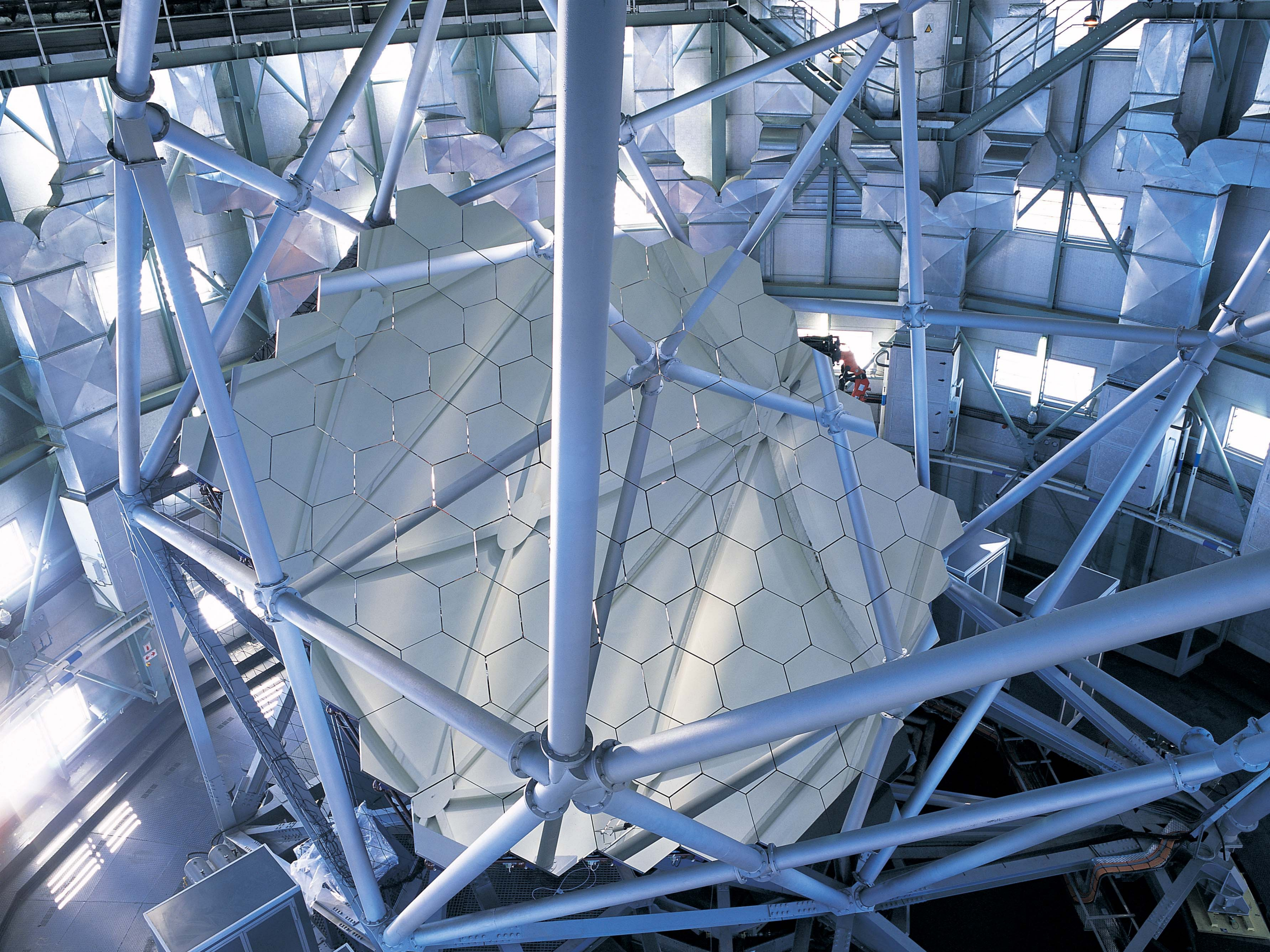
- Use of carbon composites, increased mass budget (~1000 kg). *Enhanced capabilities, 4 foci, relatively easy access*

•

- Prime focus instruments (e.g. Wisconsin's *PFIS*) planned from the outset and with larger mass/volume envelope.

•

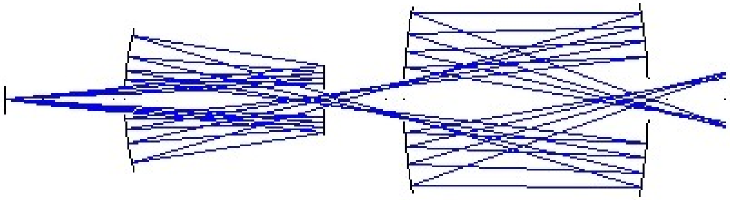
- Use of natural ventilation (e.g. louvres) and aggressive attitude to heat sources will lead to *better image quality (goal: 0.8arcsec)*



Major difference between SALT and HET: the SAC

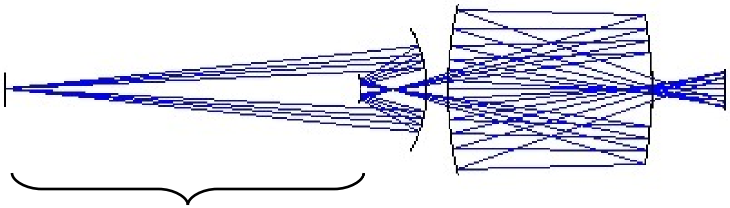
Spherical aberration corrector comparisons

HET SAC

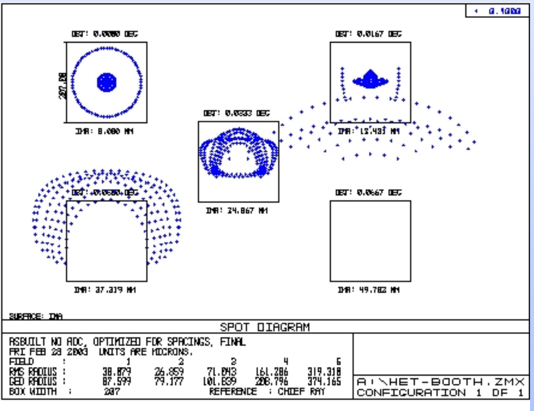


Focal Plane

SALT SAC

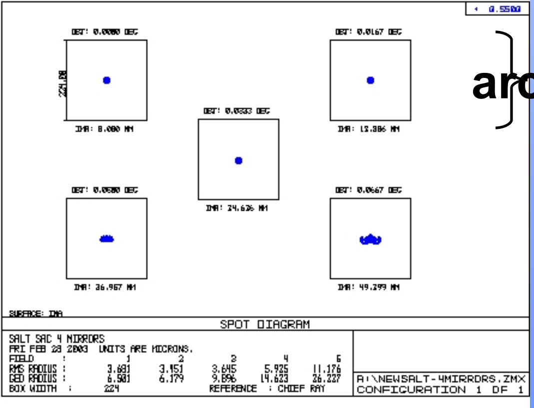


Large back focal distance



```
SPOT DIAGRAM
ASBUILT NO ADC, OPTIMIZED FOR SPACINGS, FINAL
FRI FEB 28 2003  UNITS ARE MICRONS.
FIELD       :        1        2        3        4        5
RMS RADIUS  :   38.879   26.859   71.843  161.286  319.318
GEO RADIUS  :   87.599   79.177  101.839  208.796  374.165
BOX WIDTH   :      207              REFERENCE  : CHIEF RAY
A:\HET-BOOTH.ZMX
CONFIGURATION 1 OF 1
```

Spot diagrams



```
SPOT DIAGRAM
SALT SAC 4 MIRRORS
FRI FEB 28 2003  UNITS ARE MICRONS.
FIELD       :        1        2        3        4        5
RMS RADIUS  :    3.681    3.451    3.645    5.925   11.176
GEO RADIUS  :    6.581    6.179    9.896   14.623   26.227
BOX WIDTH   :      224              REFERENCE  : CHIEF RAY
A:\NEWSALT-4MIRRORS.ZMX
CONFIGURATION 1 OF 1
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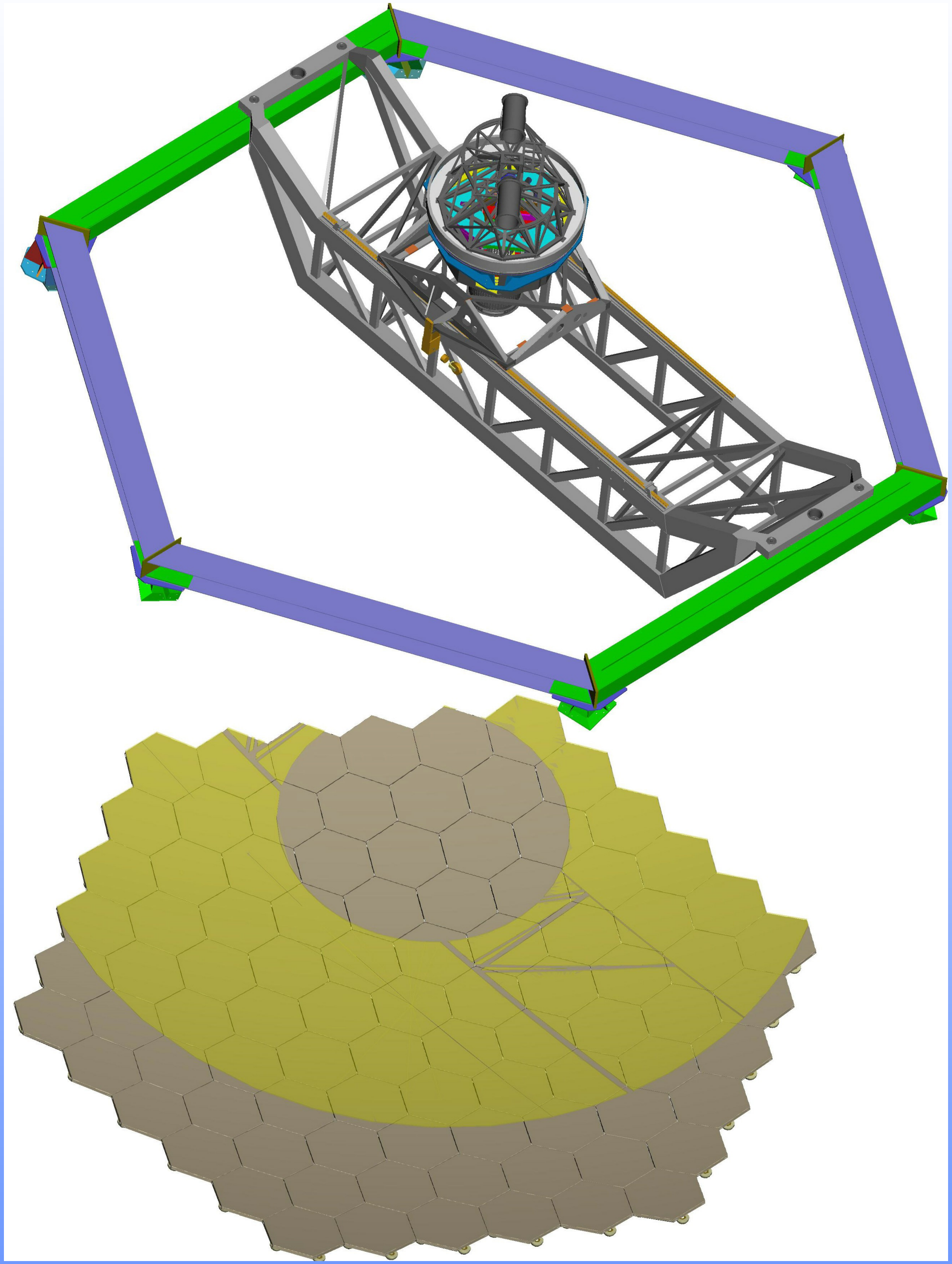
One arcsec boxe

SALT/HET Tracking Principle



Tracker off-centre
and pupil partially on primary mirror array.
At worst extreme, still a ~7 m telescope.

With tracker and 11-m pupil centred on primary mirror array, use full diameter of telescope (HET only 9.1m pupil)

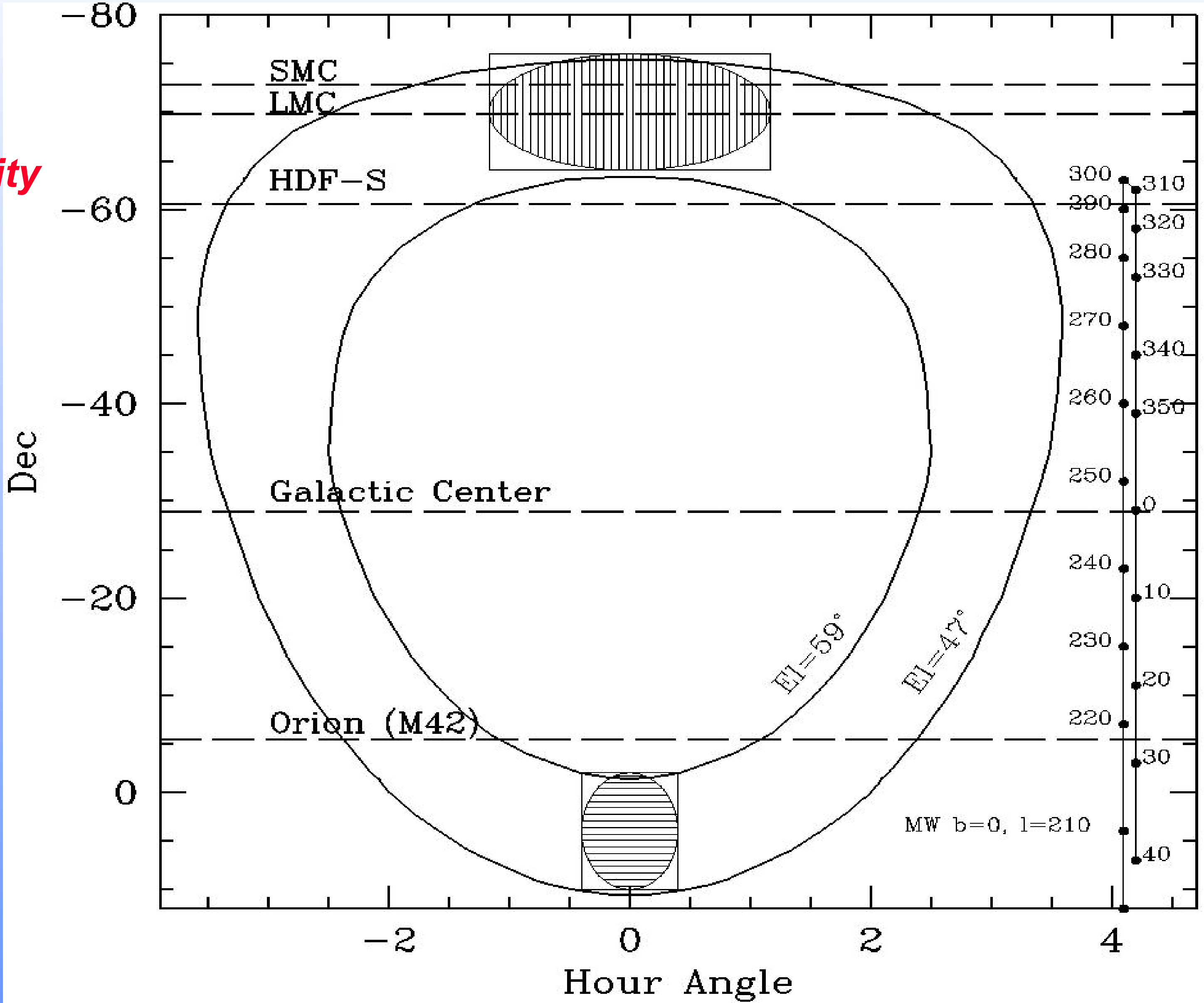
Pupil is always underfilled (→ baffled at exit pupil)

Annulus of visibility for SALT:

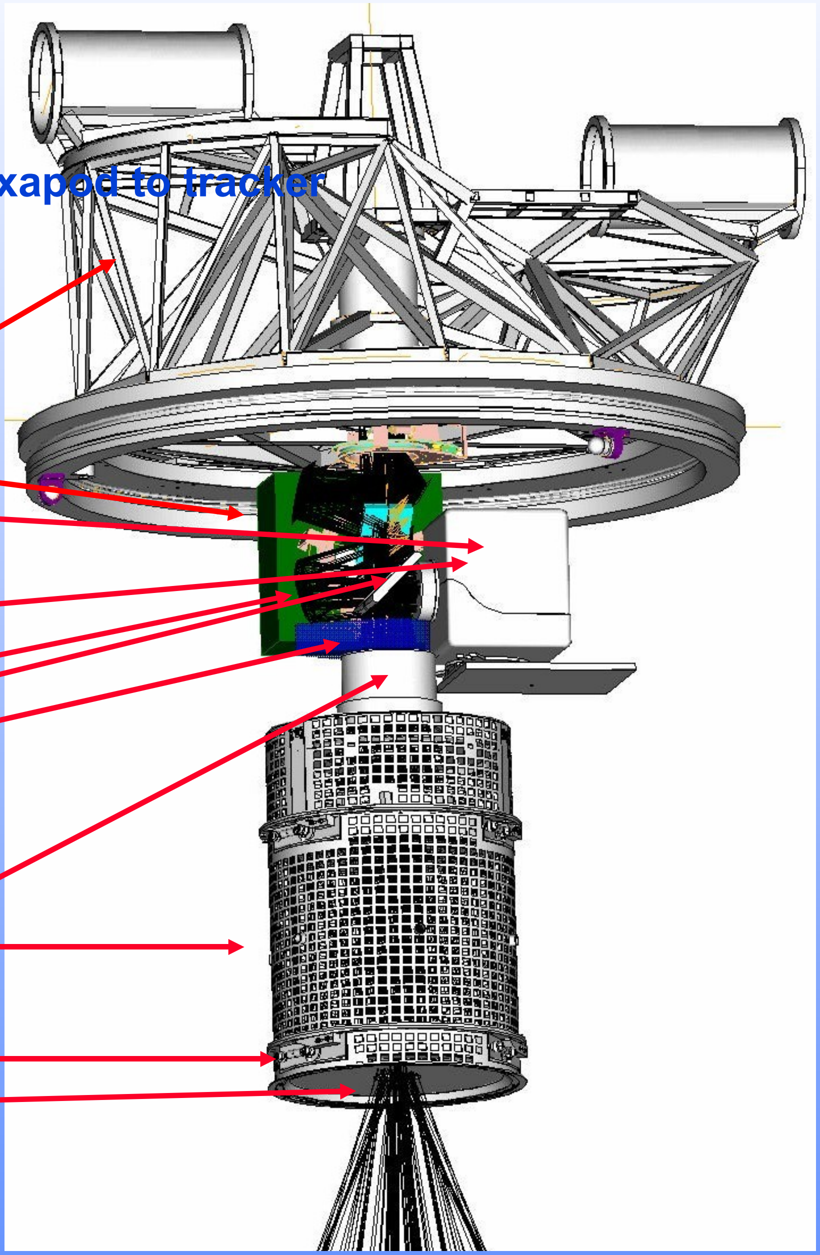
12.5% of visible sky

Shaded regions continuously visible

Rotate in azimuth, to access different parts of sky



SALT Prime Focus Payload



Prime Focus Payload (~1000 kg) mounts via hexapod to tracker and comprises of:

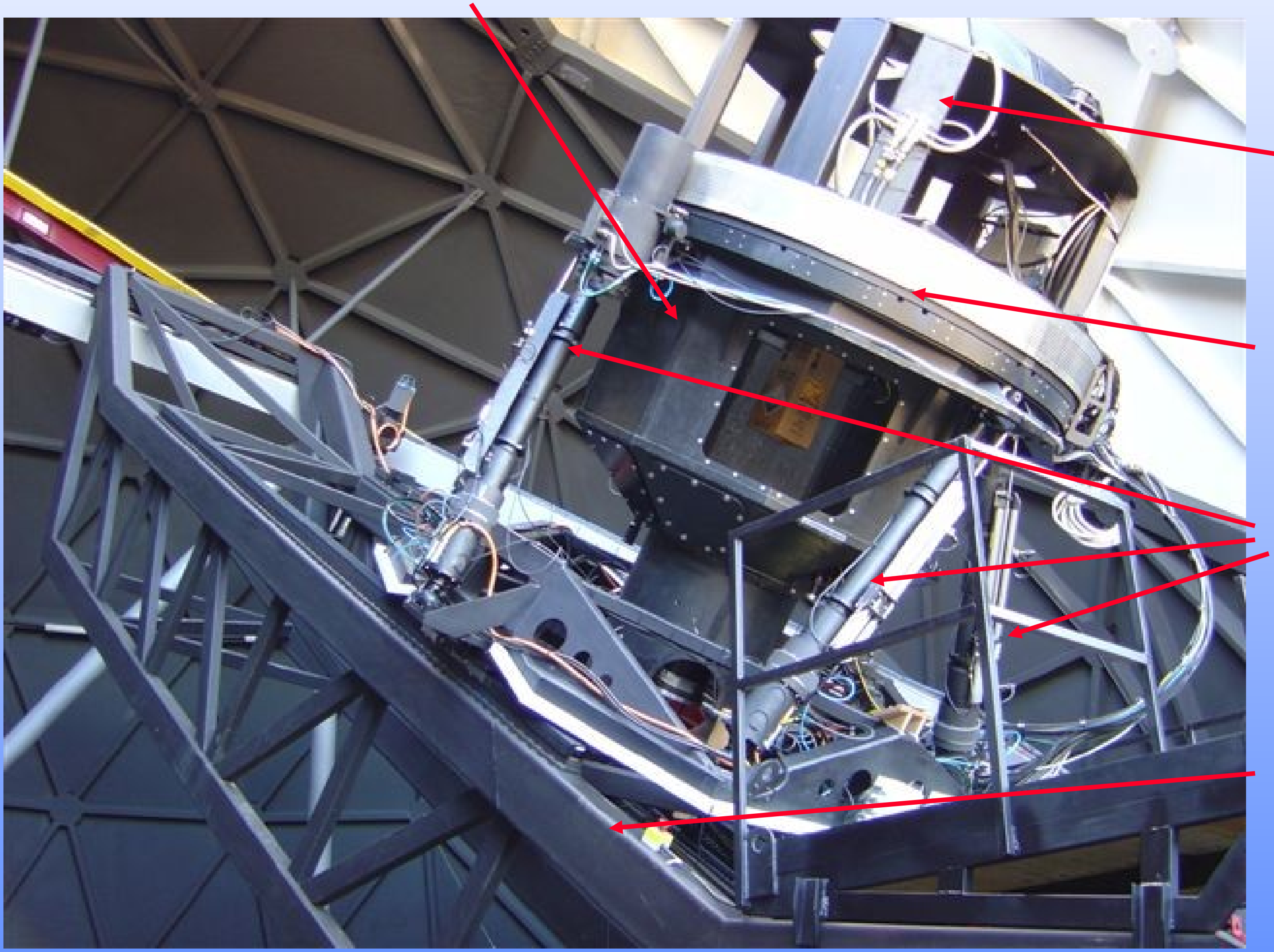
Science instruments:

- **Prime Focus Imaging Spectrograph (PFIS)**
- **Fibre Instrument Feed (FIF)**
- **SALTICAM (optical imager)**

Facility instruments:

- **Acquisition camera (SALTICAM)**
- **Guidance & focus system**
- **PFIS slit-viewing optics**
- **Fold mirrors (to 3 focii)**
- **Moving pupil baffle**
- **Atmospheric Dispersion Compensator (ADC)**
- **SAC structure**
- **Payload alignment system (autocollimator and interferometer)**
- **Calibration system (flats, arcs)**

Instruments are all mounted on Payload

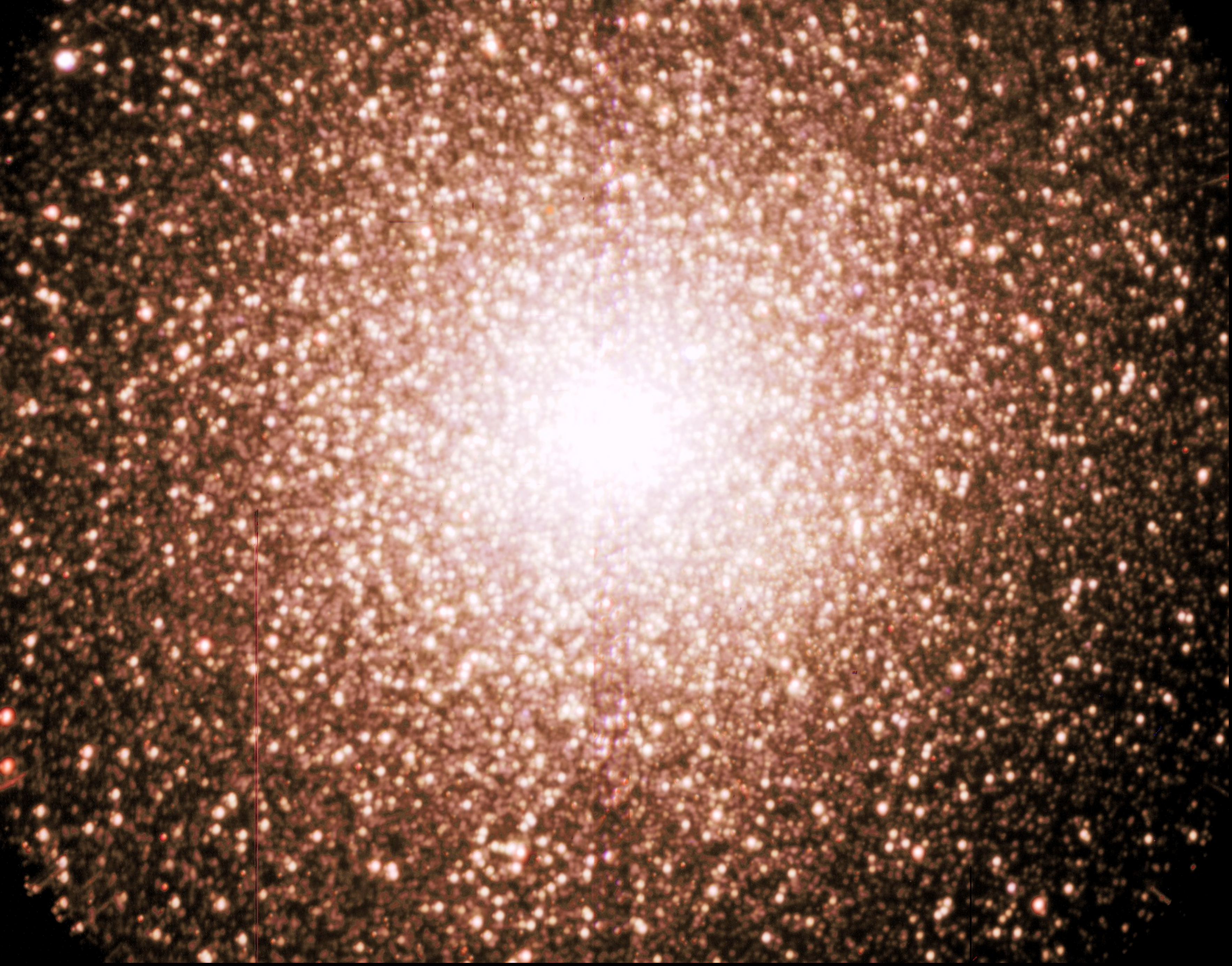


RSS location

Instrument rotator ring

Hexapod legs

Tracker beam



47 Tuc

U-120s
V-20s
I-20s

Commissioning

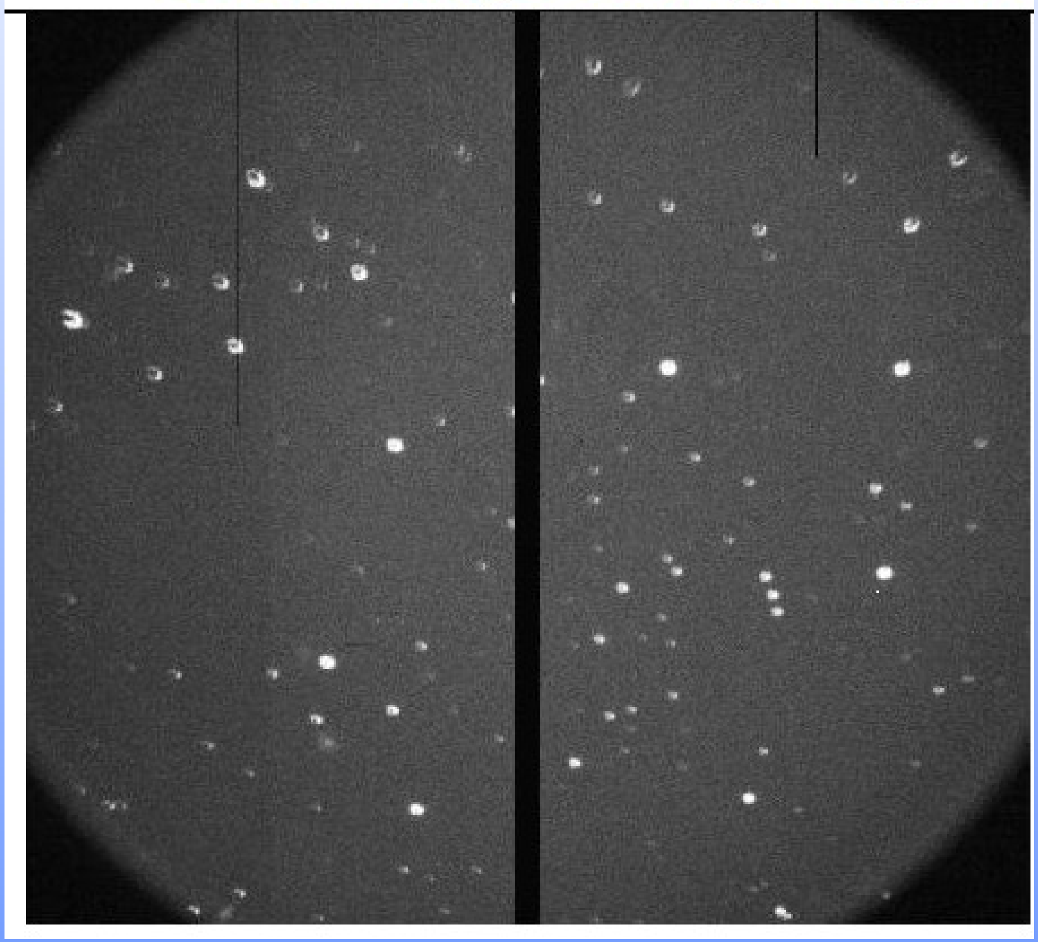
- Has taken longer than initially estimated (original completion date was 17 Dec 04!)
  - A success-based schedule which was not realistic (and was originally linked to it being a copy of HET)
  - Average time for large telescope projects ~2-3 years from first light
- Underestimate of time to complete complex systems
  - Including the Prime Focus Payload
  - Instruments (both took ~1 year longer)
- Commissioning at Prime Focus is difficult!
  - Like working on a satellite payload (space, cabling, heat, mass)

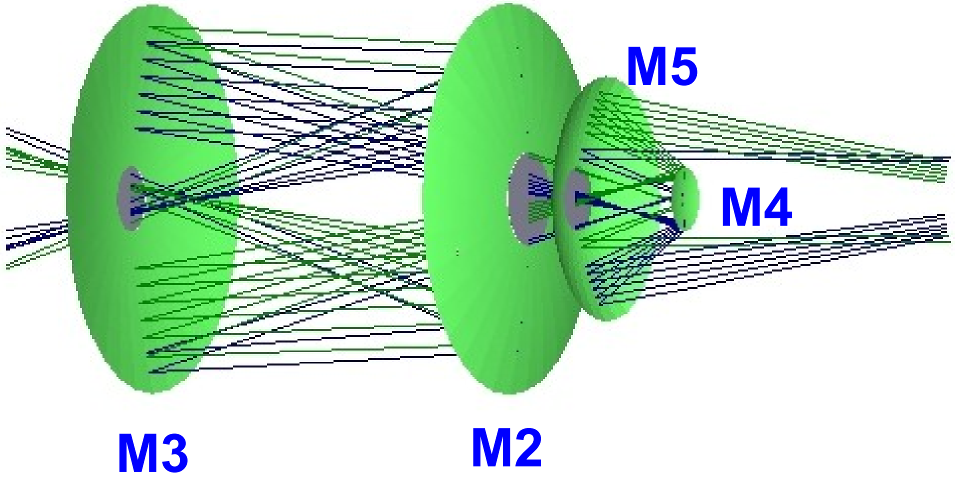
Outstanding issues:

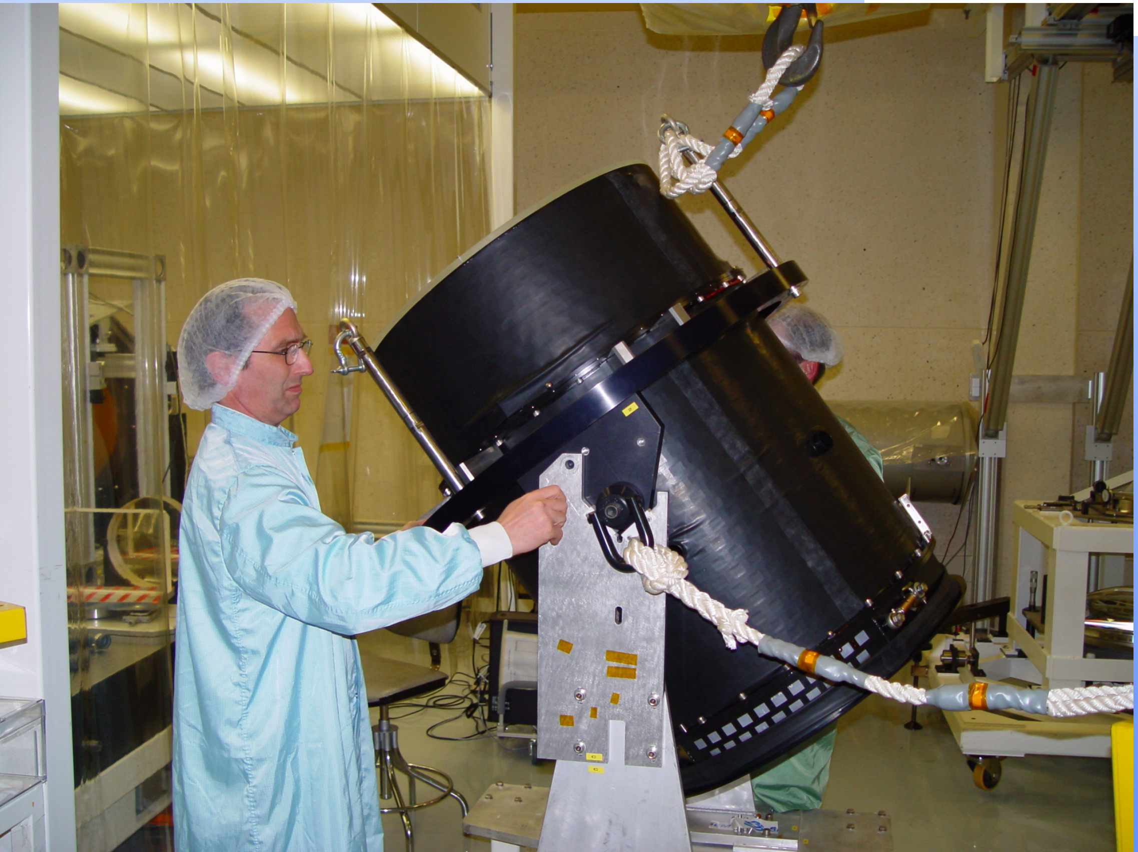
- Image Quality
- RSS throughput (especially in blue)
- SAMS (edge sensor alignment system)
- Mirror cleaning system
- Auto-collimator system (scattered light)
- Already getting some science!

Image Quality

- **Focus gradient**
- **Rho dependency**
- **Field dependency of aberrations**
- **Diagnosing cause has been a long (~2 yr) process**
- **Some recent progress (SAC *is* the cause)**
- **Currently working hard on implementing a solution**




M5
M4
M3
M2

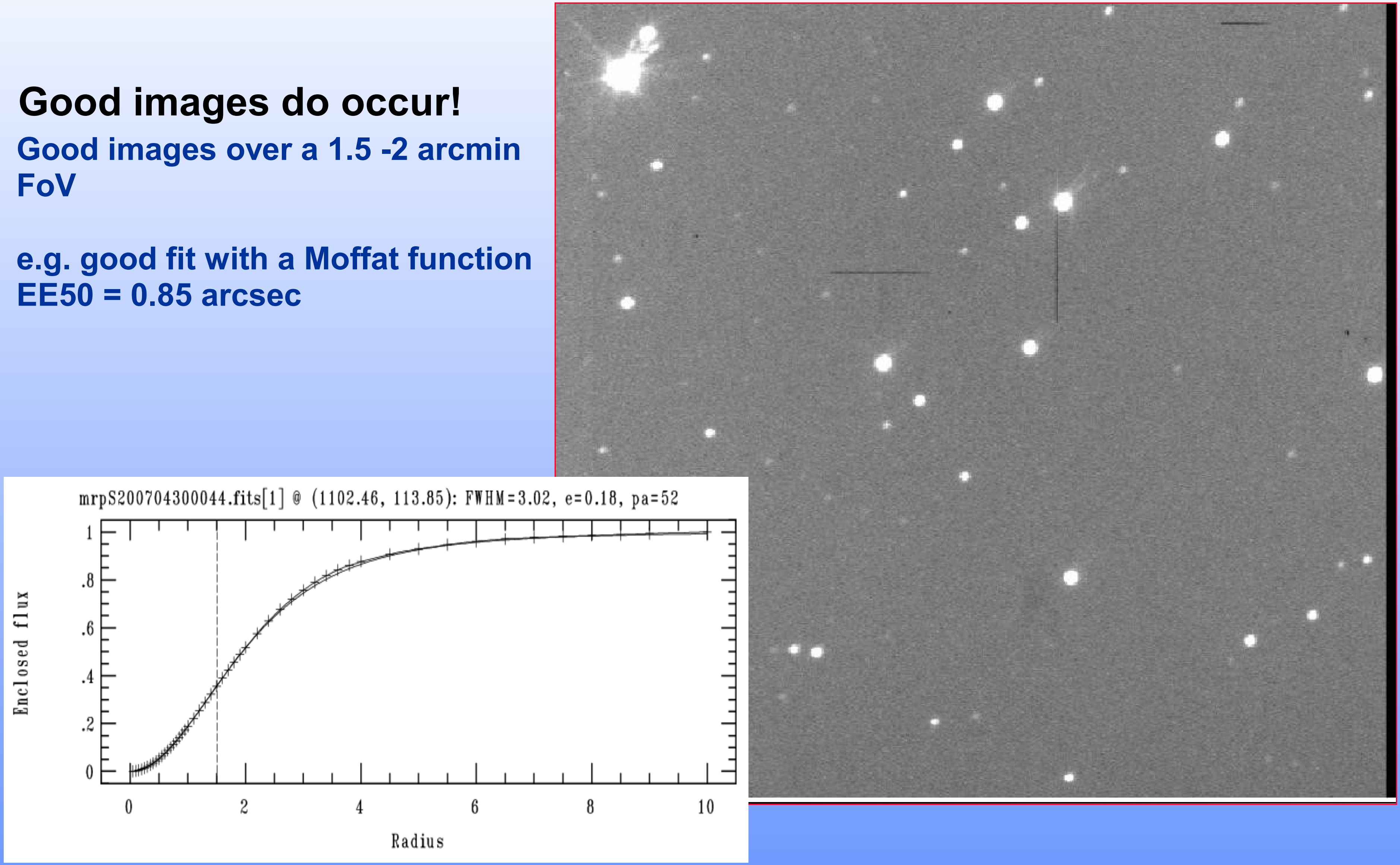


Good images do occur!

Good images do occur!

Good images over a 1.5 -2 arcmin FoV

e.g. good fit with a Moffat function EE50 = 0.85 arcsec



SALT First-Generation Science Instruments

All operate in ‘visible’ (320-900 nm) Science aims:

- **High time resolution astronomy (photometry, spectroscopy, polarimetry)**
- **Efficient multi-object spectroscopy, incl. Imaging and Fabry-Perot.**
- **Good near-UV (to 320nm) sensitivity**
- **Polarimetry (time resolved, all-Stokes)**
- **High precision high resolution (R = $\lambda/\Delta\lambda$ up to 80,000)**

– ***SALTICAM*** **(optical imaging camera) high-speed (~50 ms)**

»

– ***RSS/PFIS*** **(Robert Stobie Spectrograph/Prime Focus Imaging Spectrograph) is capable of high-speed low/med R spectroscopy, spectropolarimetry (all-Stokes) + Fabry-Perot imaging spectroscopy.**

  »Installed on SALT on 11 Oct 2005

  »Currently in commissioning

– ***HRS*** **(High Resolution Spectrograph) RV precision ~few m/s, ideal for exoplanets**

  » Re-design path (dual beam white pupil R4 echelle). CDR April 2004. Contracted with Durham University in 2007. Delivery early 2010.

– ***FIF*** **(Fibre Instrument Feed) for HRS. Currently in construction.**

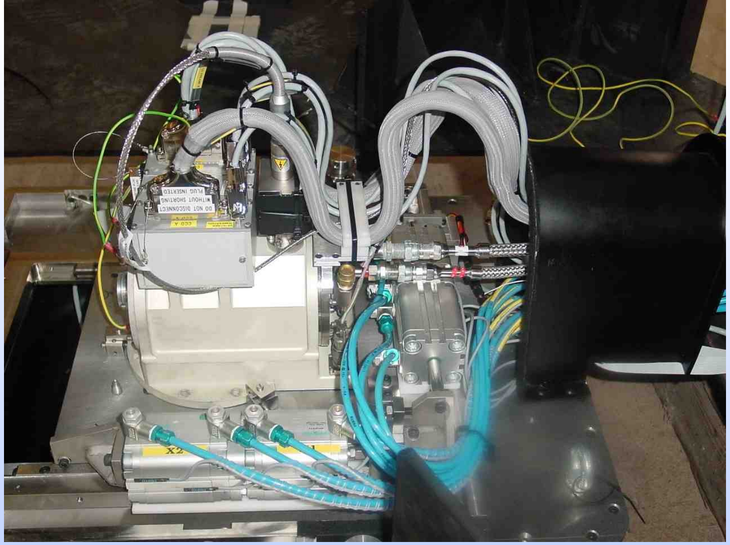
SALT INSTRUMENTS

1. SALTICAM (funded by Univ. of Goettingen)

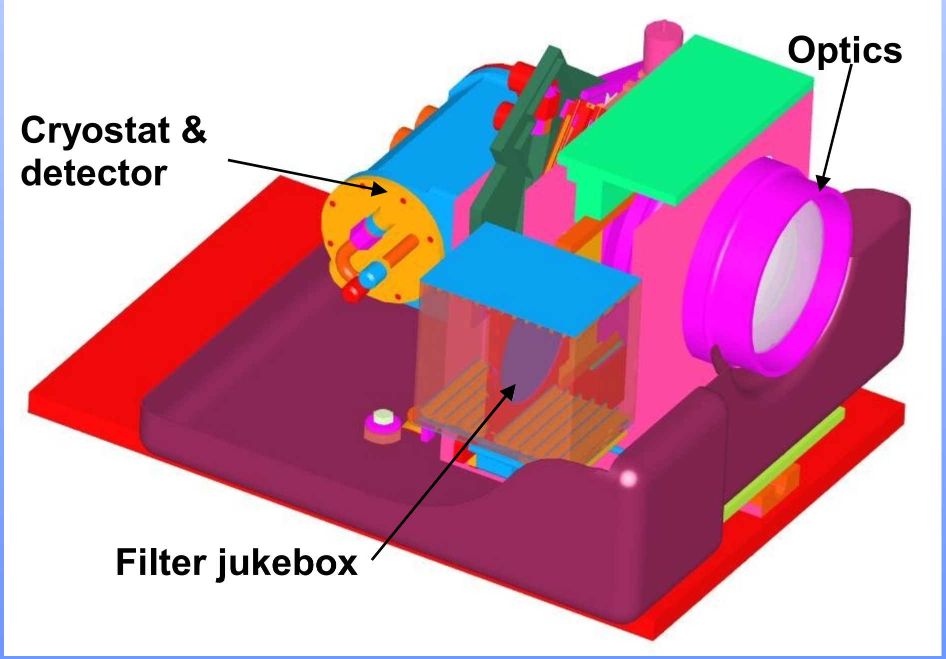
PI: Darragh O'Donoghue (SAAO)
An efficient CCD imager
(8 arcmin FOV).

.

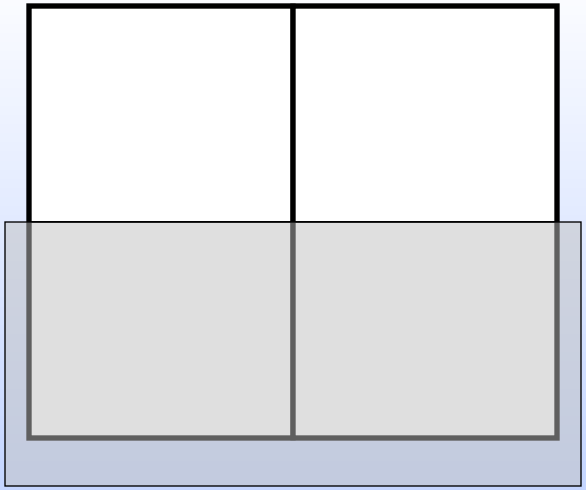
SALTICAM will enable unique science, particularly UV and fast photometry (~70-50 ms).



SALTICAM



SALTICAM: how do you make a CCD operate in "fast" mode?



Answer: use moveable frame-transfer mask

Full Frame Readout Mode (using shutter)

8 arcmin FoV:	**12.3 sec (@3.3e read noise)**
	4.6 sec (@5e)

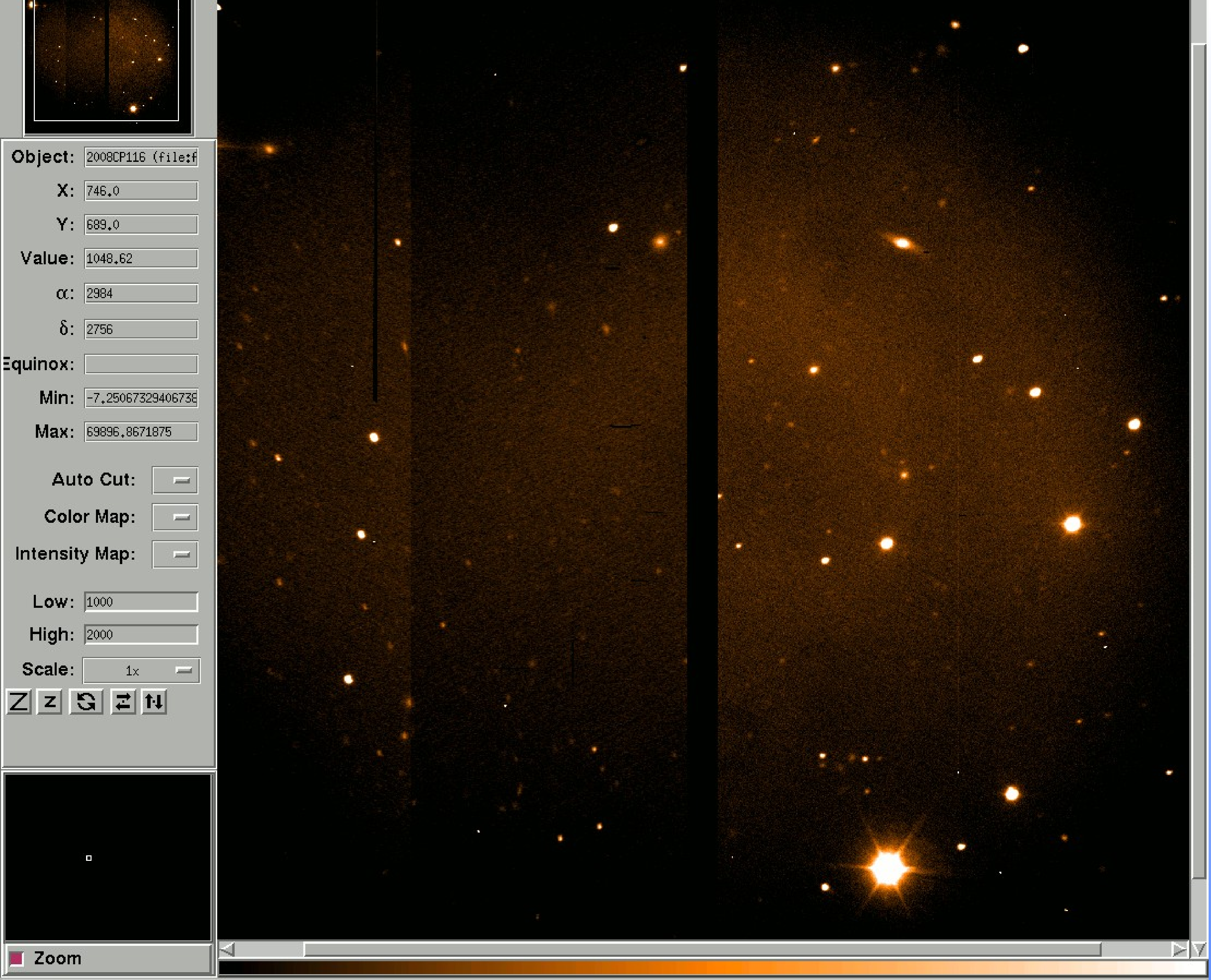
Frame Transfer Mode

Half of 8 arcmin circular FoV	**6.3 sec (@3.3e)**
	2.4 sec (@5e)

Fastest windowed photometry

Slot mode	**0.089 sec (@5 e)**
Slot + windowed mode	**0.058 sec**

(e.g. First Science paper)



Object: 2008CP116 (file:f

X: 746.0

Y: 689.0

Value: 1048.62

α: 2984

δ: 2756

Equinox:

Min: -7.2506732940673

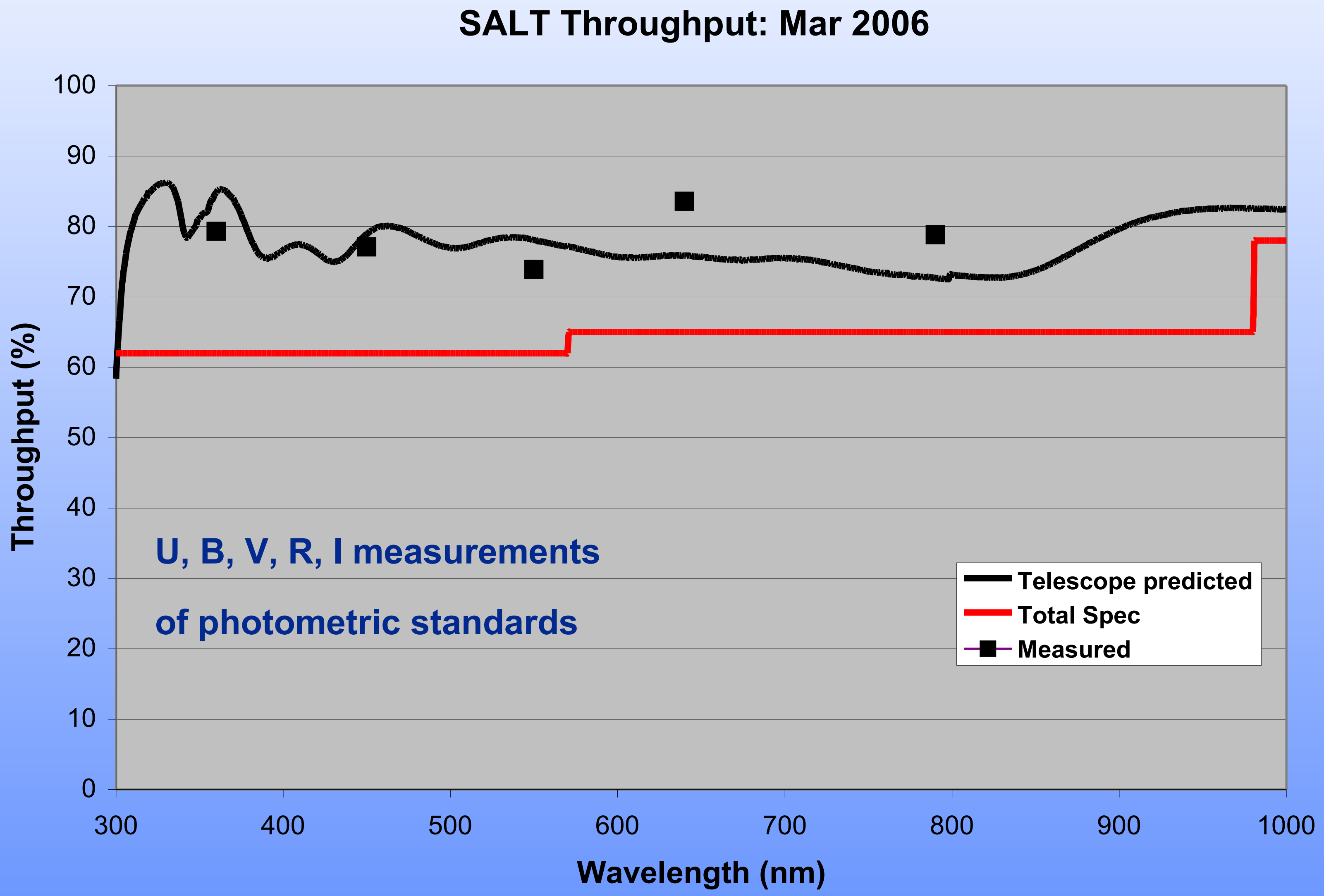
Max: 69896.8671875

Low: 1000

High: 2000

Scale: 1x

Measured SALT performance


SALT Throughput: Mar 2006

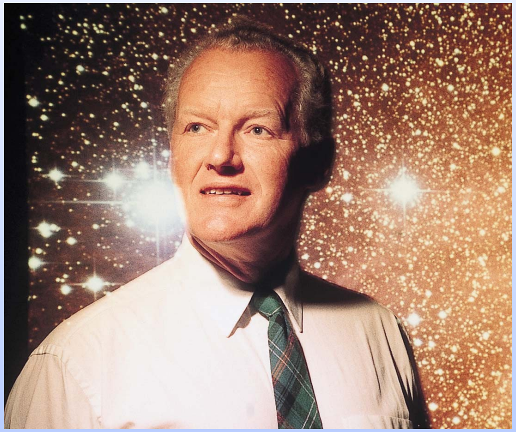
U, B, V, R, I measurements

of photometric standards

The Robert Stobie Spectrograph (RSS)
(built at Wisconsin, Rutgers & SAAO)

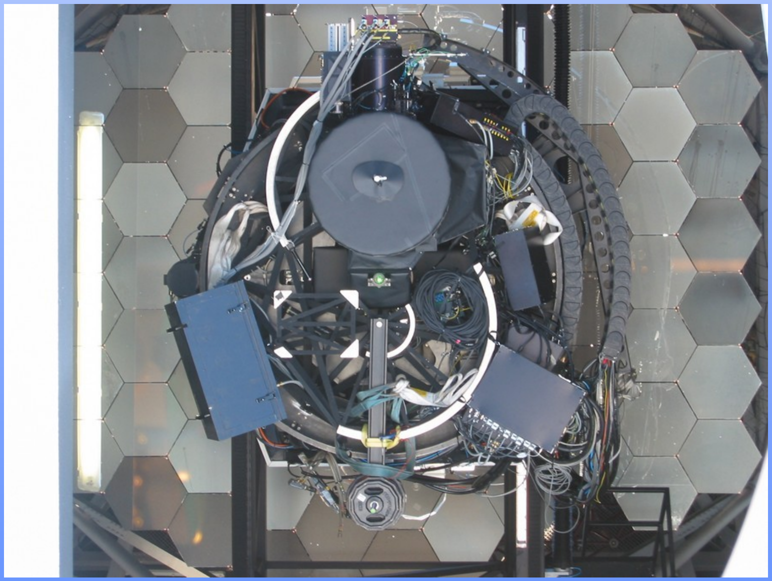
An efficient and versatile Imaging Spectrograph

- capable of UV spectroscopy
- high time resolution ablility
- polarimetry capability
- Fabry Perot imaging (many narrow filters)
- multiple object spectroscopy
    - Can observe ~100 objects at once

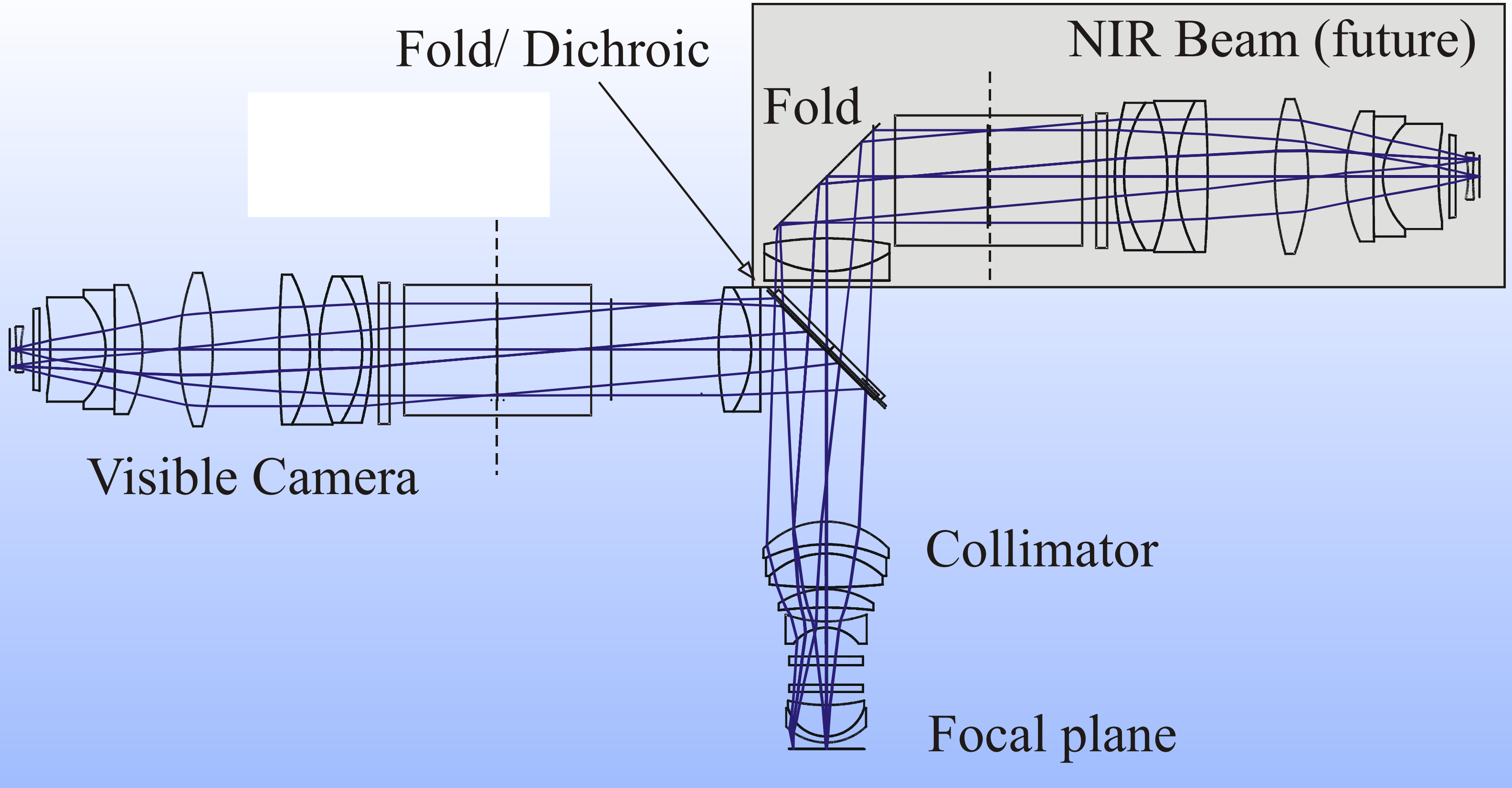


Named in memory of Bob Stobie, previous SAAO Director.

RSS in lab at Wisconsin (Feb 2005)

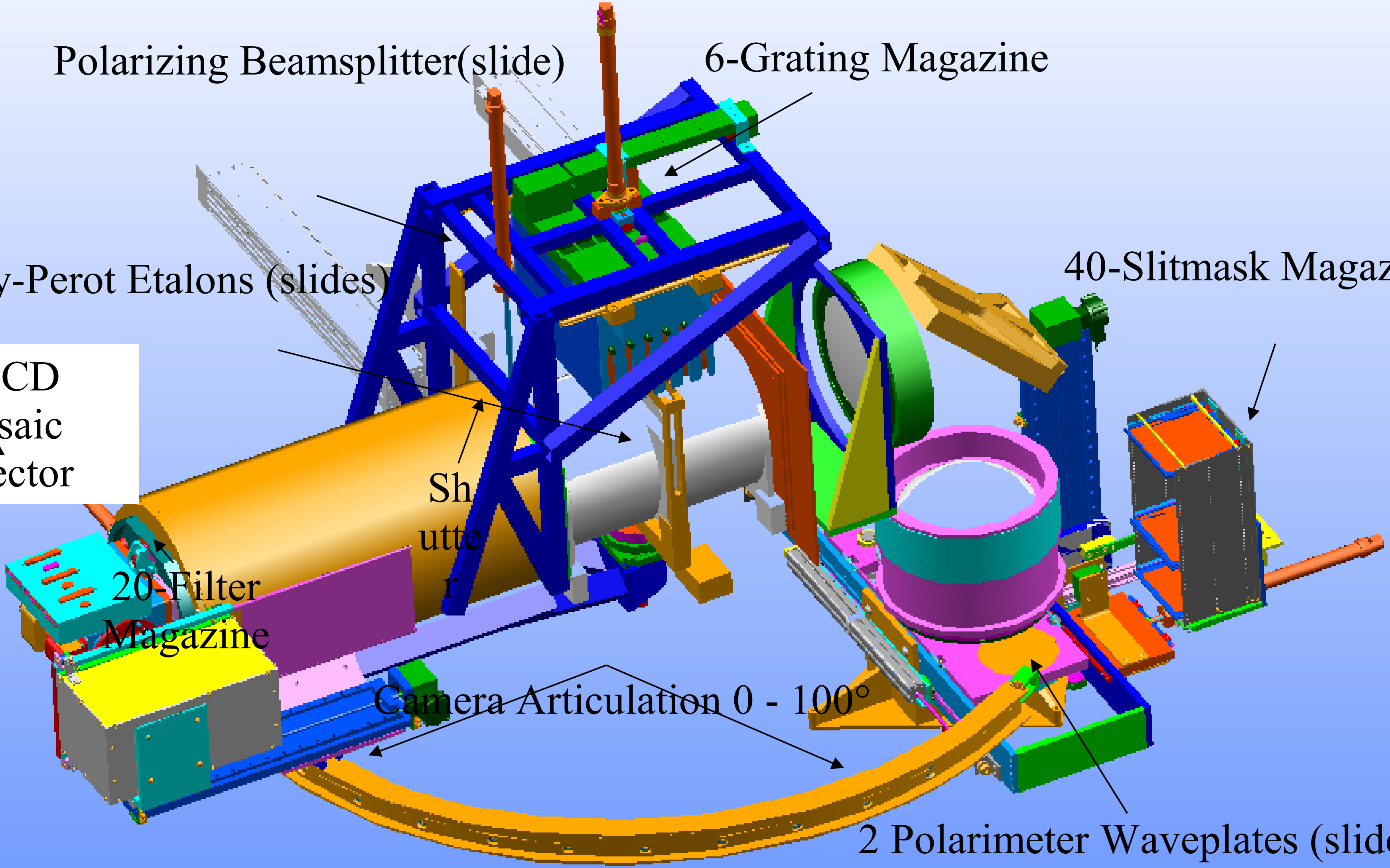


RSS installed on SALT (Oct 2005)



- **RSS: emphasize unique observing modes**
  - **UV spectroscopy to 3200 Ǻ (rare on large telescopes)**
  - **high-throughput VPH gratings 3200 - 9000 Ǻ; Fabry-Perot 4300 - 9000 Ǻ (Visible Beam); later - 1.7 µm (NIR)**
  - **polarimetry (circular and linear) (very rare)**
  - **high-speed detector mode (very rare)**

Mechanisms



Polarizing Beamsplitter(slide)

6-Grating Magazine

2 Fabry-Perot Etalons (slides)

40-Slitmask Magazi

3 CCD Mosaic Detector

Shutter

20-Filter Magazine

Camera Articulation 0 - 100°

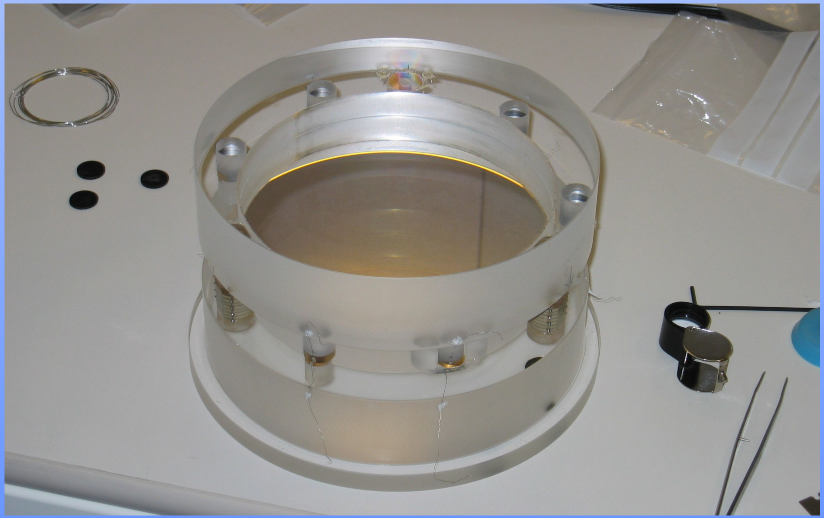
2 Polarimeter Waveplates (slides

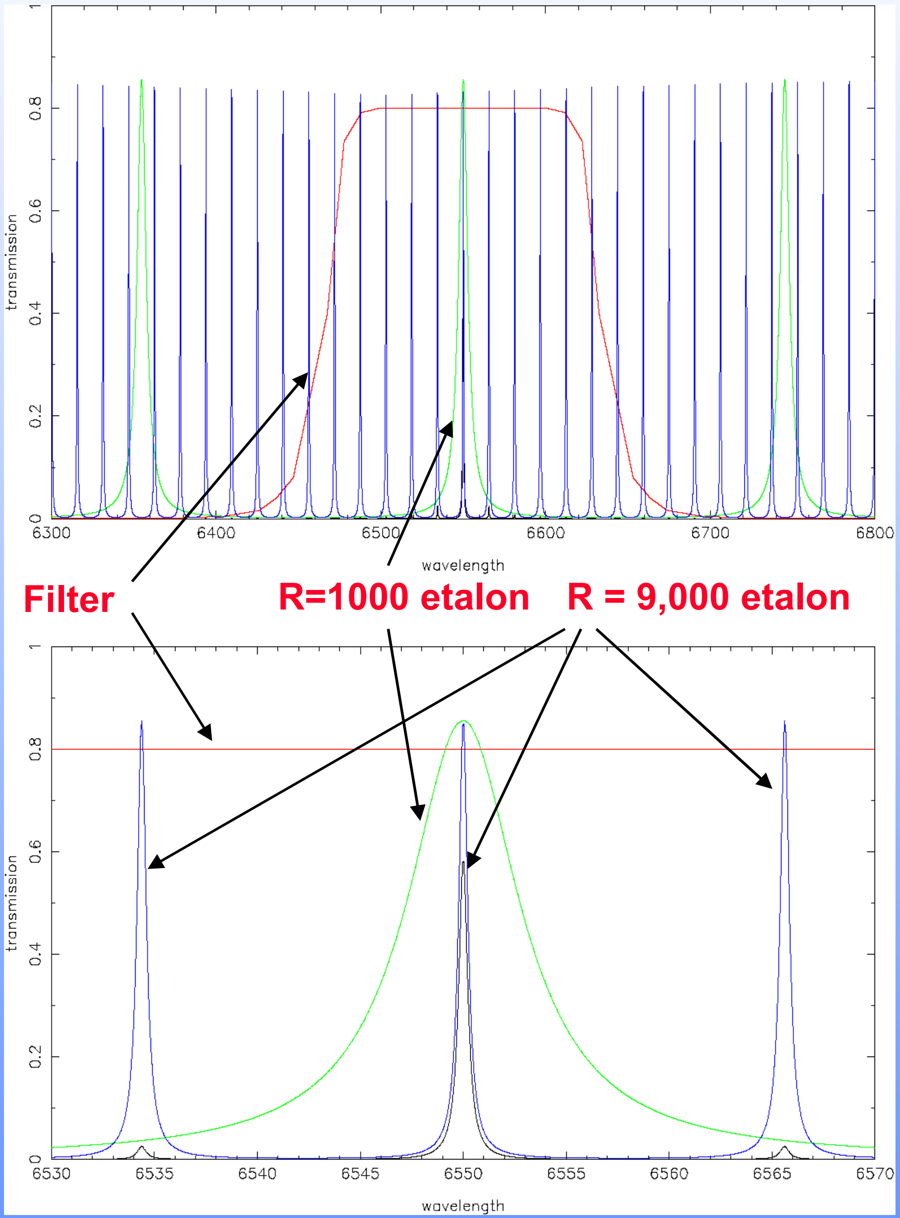
RSS: Fabry-Perot mode

3 resolution modes:

- **low (R = 320-770) 'tuneable filter' (full field)**
- **medium (R = 1250 – 1650) bullseye 3.8' – 3.3'**
- **high (R ~ 9,000) bullseye ~1'**

Using 150mm diameter *Queensgate* etalons Finesse ~30, implying 75-80% throughput Using ~30 R = 50 interference filters (latter can also be used on their own for narrow band imagery).

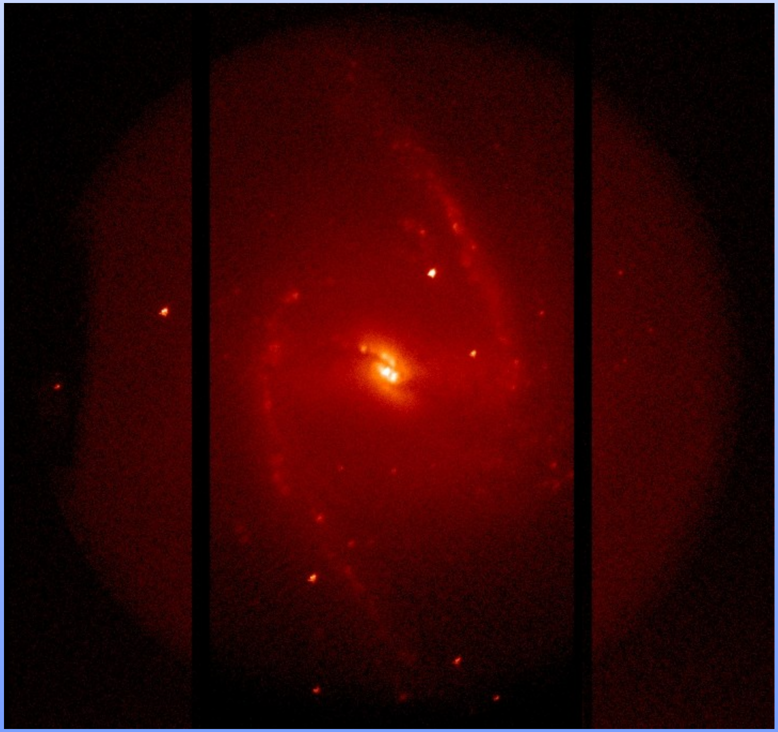




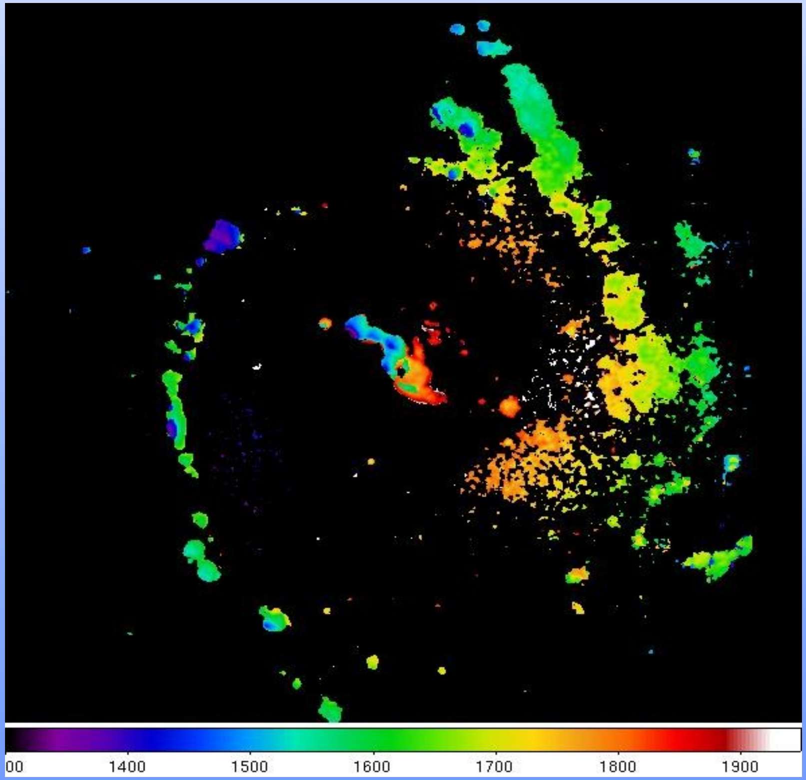
NGC 1365 (nearby, barred spiral)

SALTICAM
b,g,r (60s each)

8.5Å image centered on Hα

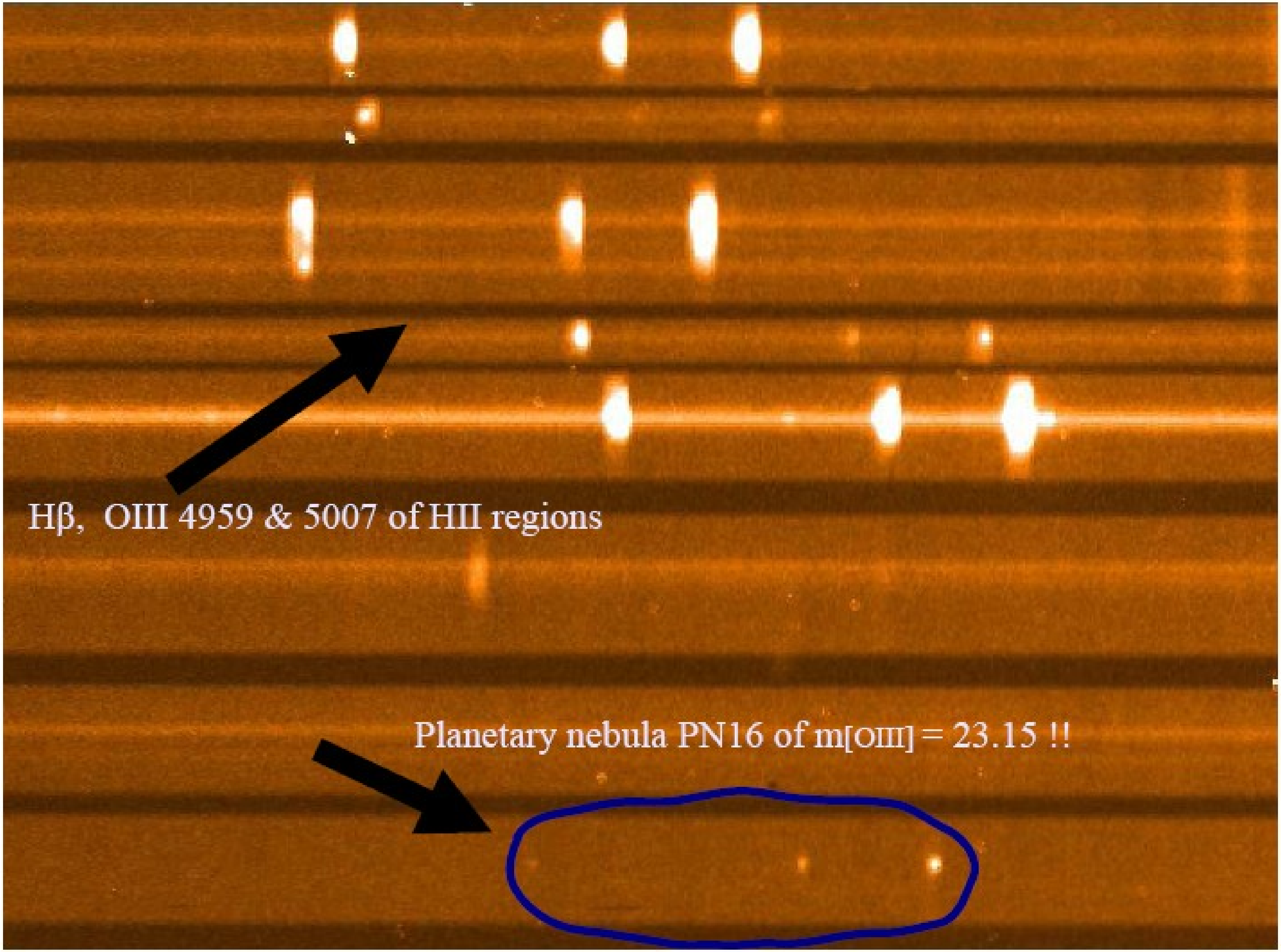


vel map from 18x1min + 8x2min exposures



N.B. For serious velocity mapping, would use 4x higher resolution.
This was first ever SALT FP observations, map was produced within 24 hrs of taking data.

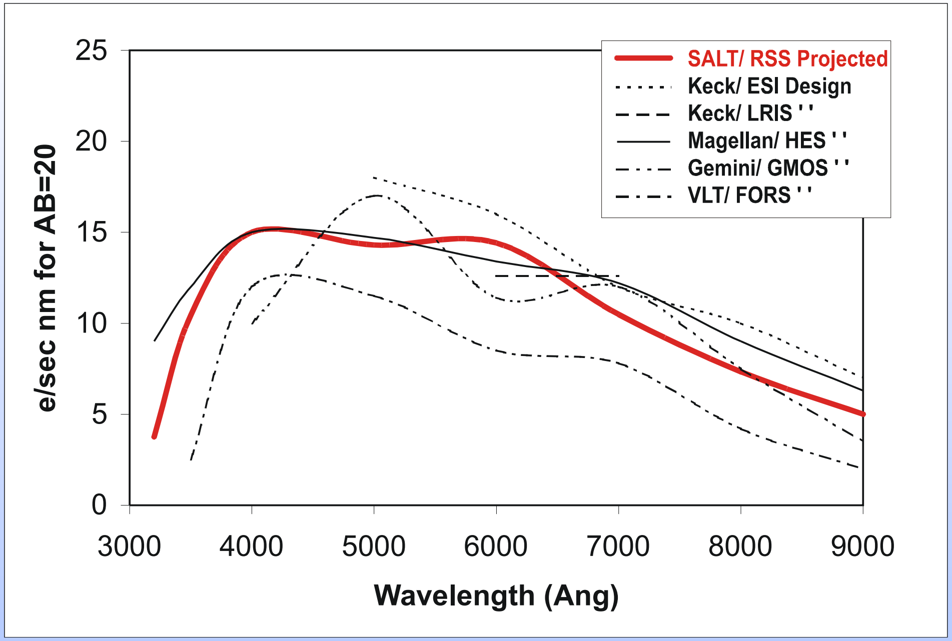
first tests of the MOS mode:


Hβ, OIII 4959 & 5007 of HII regions

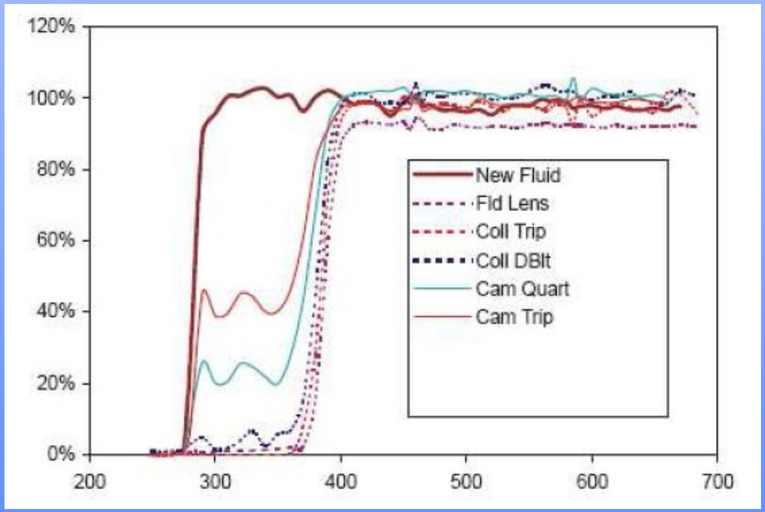
Planetary nebula PN16 of m[OIII] = 23.15 !!

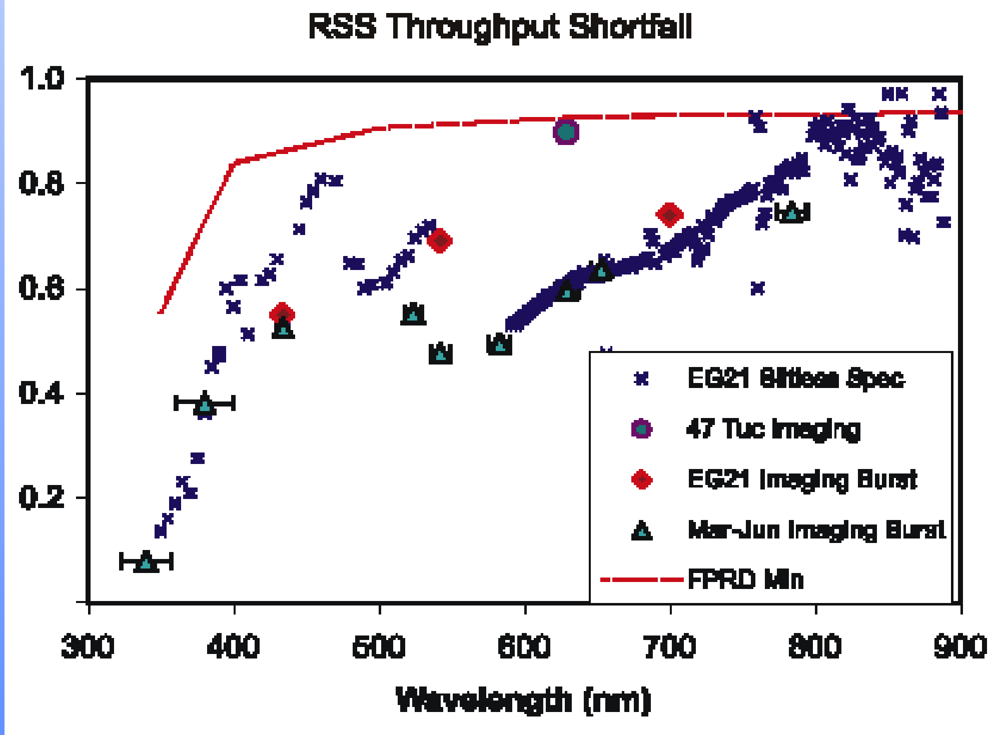
MOS spectra of PNe & HII regions in the dwarf irregular galaxy NGC6822

RSS Throughput



- On telescope Nov 2005 - Oct 2006
  - Long-slit mode, start polarimetry comm.
  - F-P tests, MOS tests
  - on-sky throughput tests
  - Significant underperformance, particularly in the blue (<400 nm)
- Off telescope Nov 2006 - present
  - improving UV throughput, ghosts
  - Measured throughput to be 75 - 100% of design, sensitivity comparable or better than design throughput of other large telescope spectrographs
- Back on telescope for further commissioning Aug-Sep 2008





Future developments:

RSS Near IR arm: instrument parameters:

- Telescope f/# f/4.18, aperture 10 m
- Collimator focal length 622.7 mm
- Camera focal length 302 mm
- Final f/# 2.025
- Final plate-scale 108 μ/arcsec (6.0 pixels/arcsec for HAWAII-2RG)
- Detector HAWAII-2RG (pixels 2048 X 2048 x 18 μ)
- Field of view 8.0 arcmin diagonal
- Nominal spectral range 0.85 - 1.7 μ (dependent on R.P. and optics T)
- Maximum R.P. 11,783 with 0.75 arcsec slit at 110 degree grating angle (spectrometer limit, independent of grating choice)
- Limiting magnitudes: J=20.3; H=20.6

Fibre-fed spectrograph: SALTHRS

SALT will utilize fibre-fed high-resolution spectroscopy of point sources (<2 arcsec) plus background (fibre pairs)

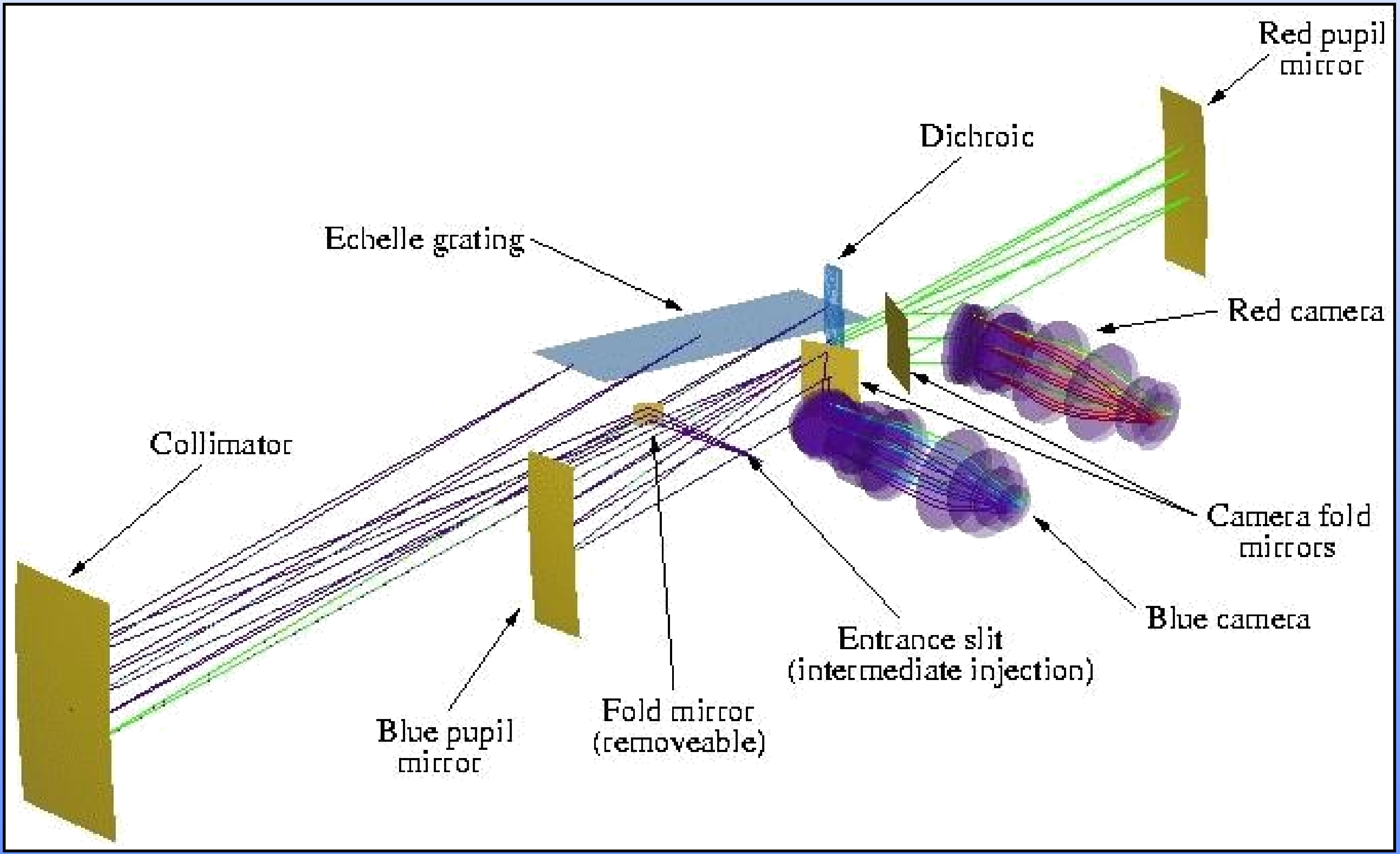
SALT HRS Design
(Completed in Apr 2005 by University of Canterbury, NZ)

- Design is dual beam white-pupil R4 duplex echelle, with VPHG, giving R = 16,000 to 65,000 (depending on image slicer).
- Single object spectroscopy with single fibre sky subtraction (single fibre) and nod/ shuffle.
- Precision radial velocities (to few m/s using Iodine cell, simultaneous Th-Ar, or EDI)
- Housed in a vacuum tank (remove large r.v. error due to P,T variations), as HARPS.
- Using image slicers for high R.

Fibre mode	Resolving Power ($\lambda/\delta\lambda$)	Transmission (SPC + SLT + TEL)	
		480nm	650nm
Low	16,000	13.4%	17.4%
Medium	~37,000	9.4%	12.1%
High	~65,000	6.0%	7.7%

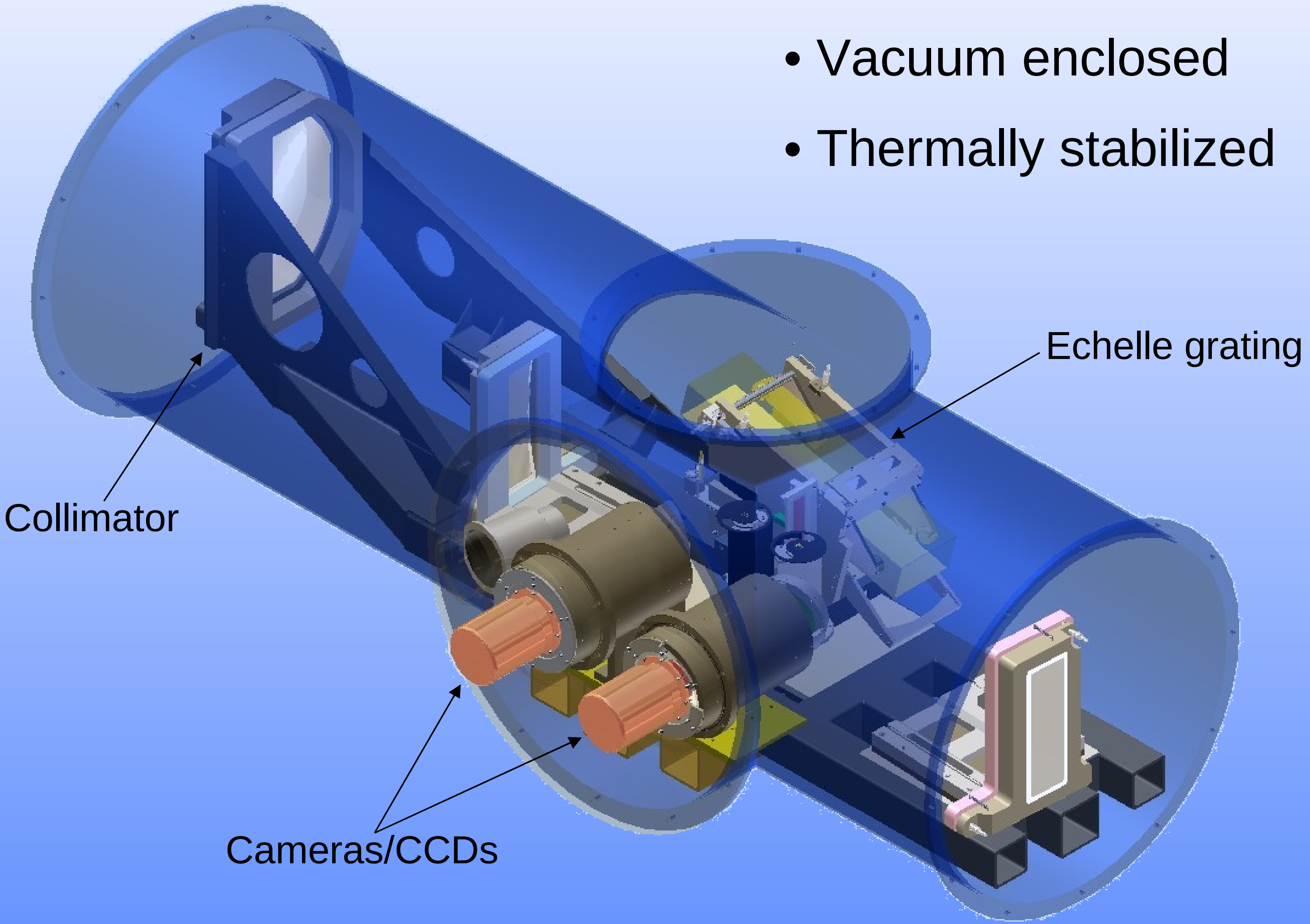
SALT high resolution spectrograph

- R4 echelle grating
- Dual-beam (blue & red), white pupil
- VPH grating cross-dispersion



SALT High Resolution Spectrograph

- Vacuum enclosed
- Thermally stabilized



SCIENCE WITH SALT:

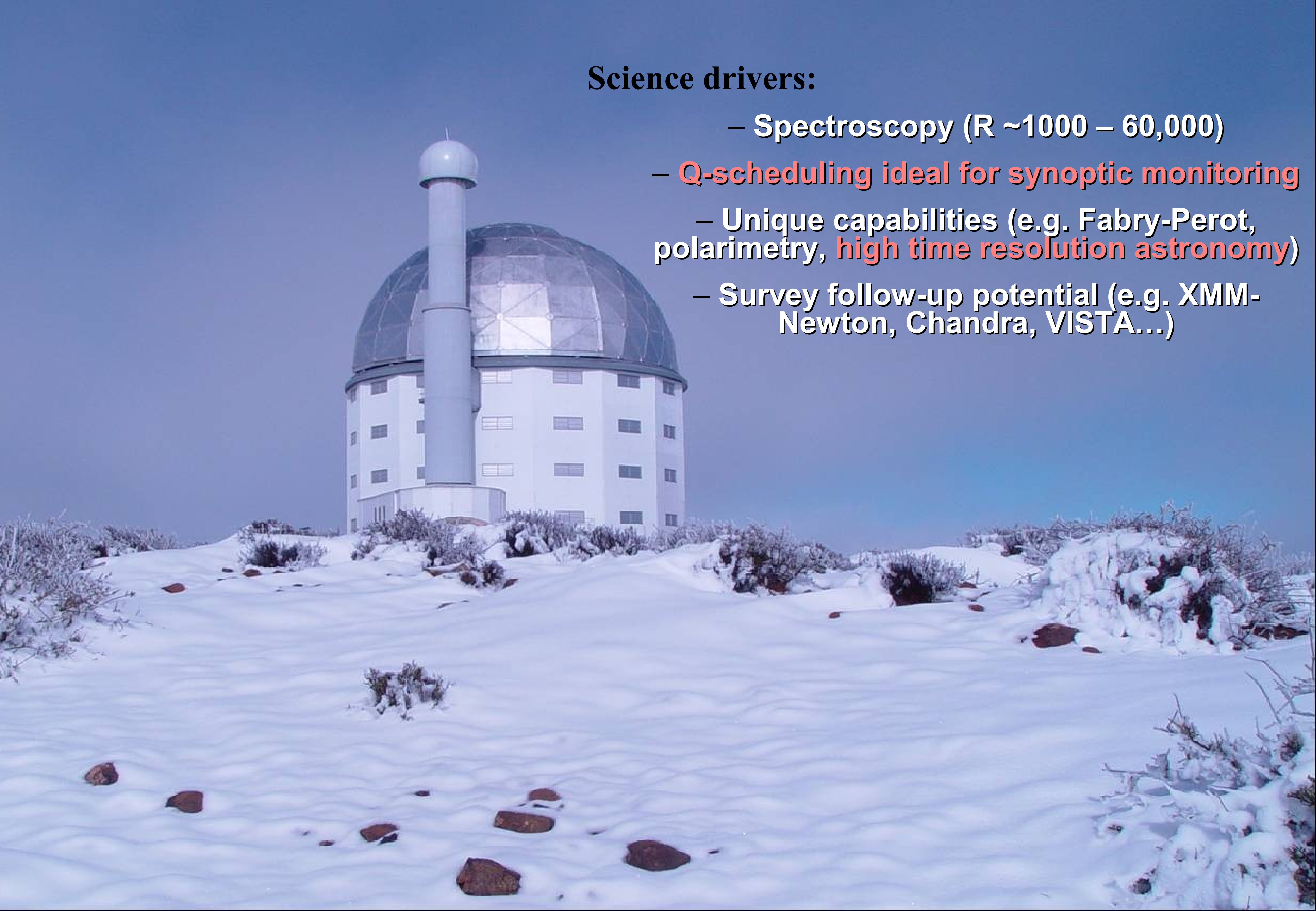
Time Domain Astrophysics

Exploiting SALT’s Strengths

Phil Charles
SAAO/University of Southampton

Outline: **Time Domain Astrophysics**

- accretion/variability timescales introduction/background
- interacting binaries with WD, NS, BH compact objects on short *and* long timescales:
  - WDs: CVs, IPs, UCBs (i.e. DDs), SSS
  - NSs, BHs:
    - mass measurements in quiescent and active XRBs
    - variability in quiescent transients
    - AXPs, milllisecond XR pulsars
  - SS433 as a galactic ULX and related objects
  - accretion disc properties: warped, precessing, irradiated?
- ToOs: e.g. GRB follow-up
- SALT early science results with fast photometry
- prospects for synoptic monitoring

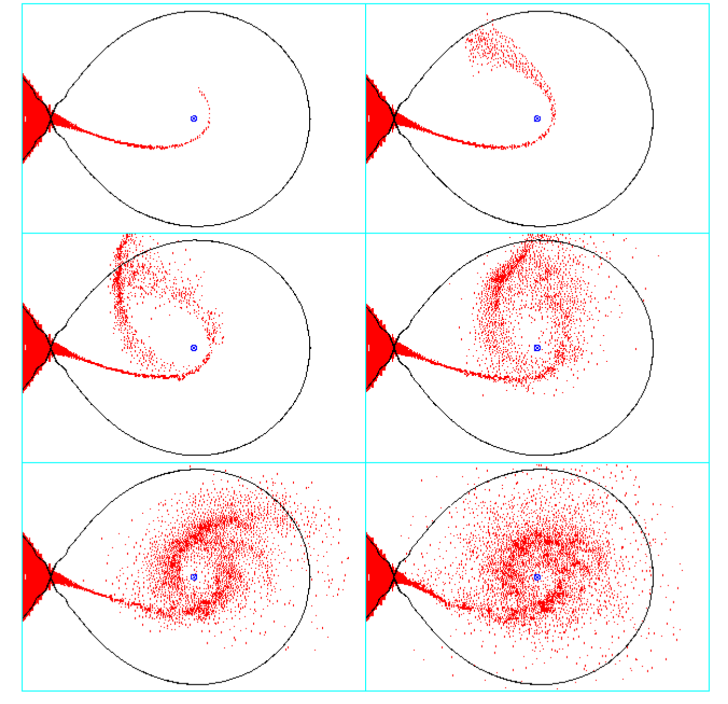


Science drivers:

- Spectroscopy (R ~1000 – 60,000)
- Q-scheduling ideal for synoptic monitoring
- Unique capabilities (e.g. Fabry-Perot, polarimetry, high time resolution astronomy)
- Survey follow-up potential (e.g. XMM-Newton, Chandra, VISTA…)

Accretion and variability

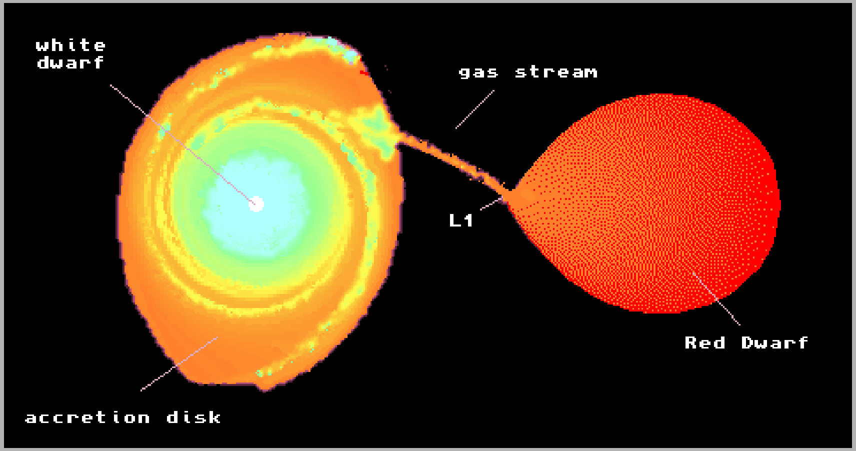
- Rapid variability: tell tale sign of accretion (onto compact stellar remnant, or in AGN)
- Dynamical motions in the accretion flow, P_{spin} (of compact object), oscillation modes → wide range of variability spanning many decades in time domain
- Variability studies offer unique perspectives on physics of accretion discs; processes occurring near compact object and properties of the compact object itself
- Results applicable to discs of all scales, from proto-stars to QSOs
- i.e. translate *time* resolution → *spatial* resolution



Variability in Interacting Binaries

- Accretion onto WD in CVs: classic test bed for accretion via Roche lobe overflow (many optically bright targets)

- P_{orb} : minutes – hours
- P_{spin} : tens of seconds
- Mass accretion events/ outbursts : months
- Magnetic cycles : years – decades



- WD/inner disc dominate soft X-ray, UV (SALT strength)
- Outer disc emission mostly in optical
- Mass donor reveals itself in the red/IR

- For X-ray binaries (NS/BH) → keV/MeV emission +
- variability as fast as milliseconds

Time resolution

- Indirect imaging: time resolution is translated into spatial resolution (e.g. doppler tomography)

- 70s : very active phase of fast broadband photometry produced a vast range of unexplained phenomena

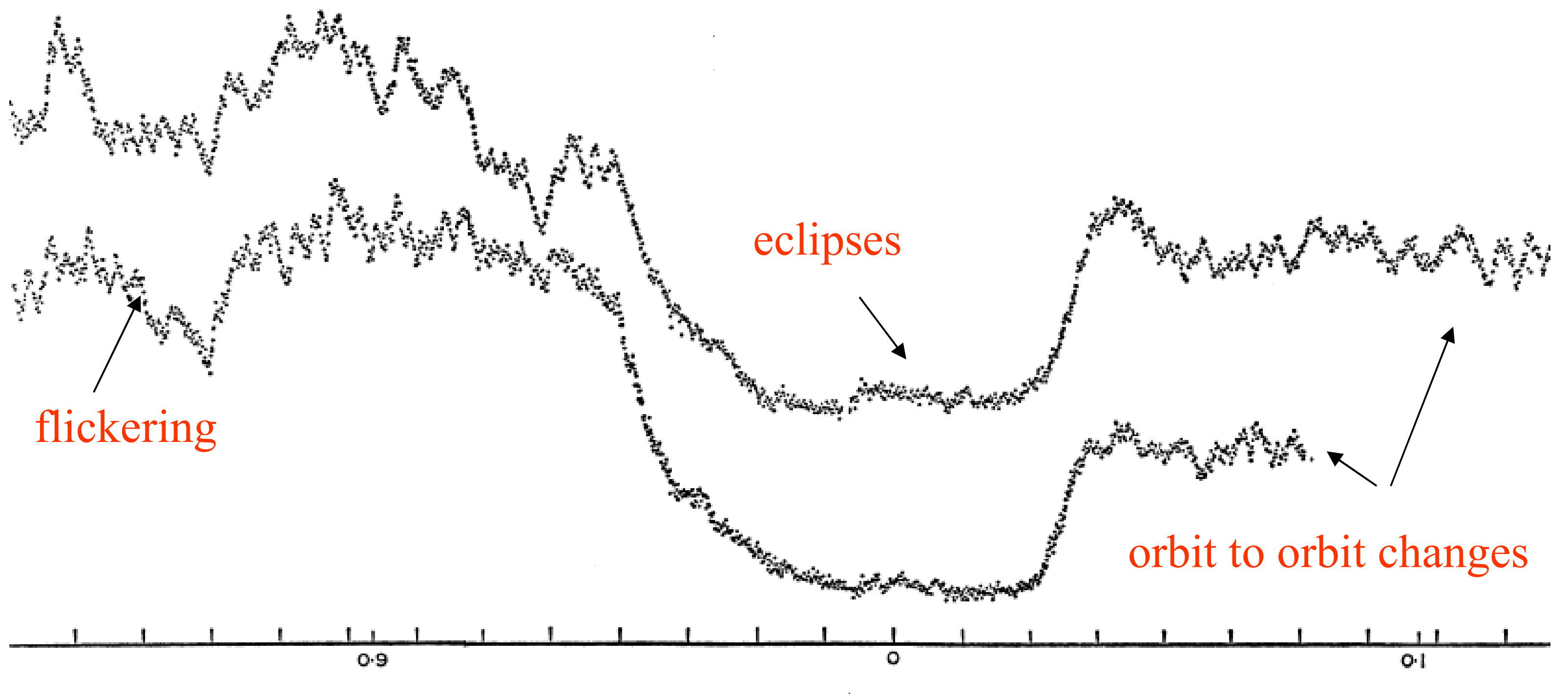
- 80s/90s: dominance of (optical) CCDs → step **back** in terms of achievable time resolution

- Now: fast timing domain again open from UV (HST) to X-ray (RXTE)

- Optical astronomy seriously lagging behind in terms of time resolution!

- Need combination of large telescope **and** fast detectors (where gain is greater than for faint object, background-limited work) → SALT!

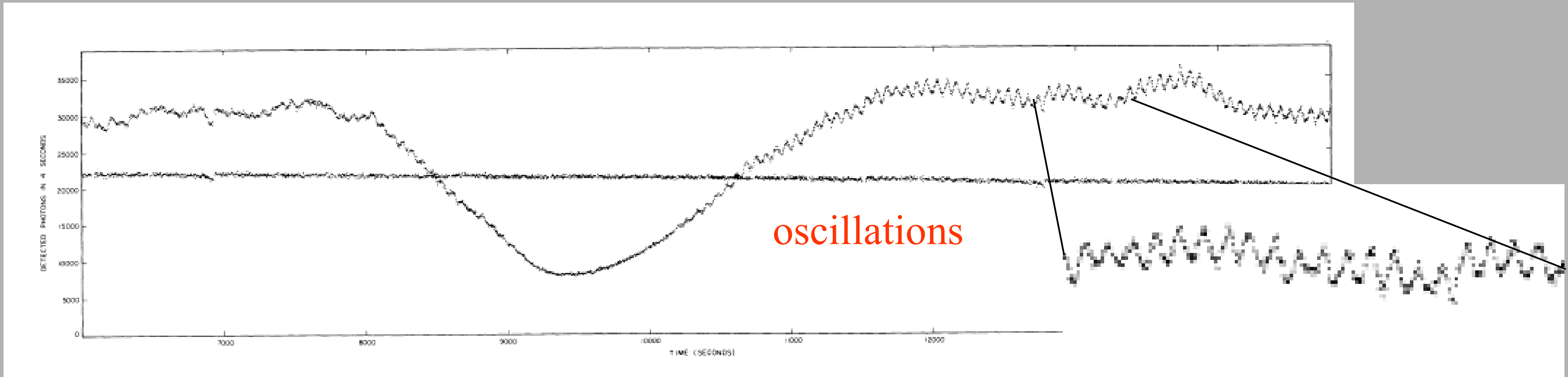
Variability in CVs



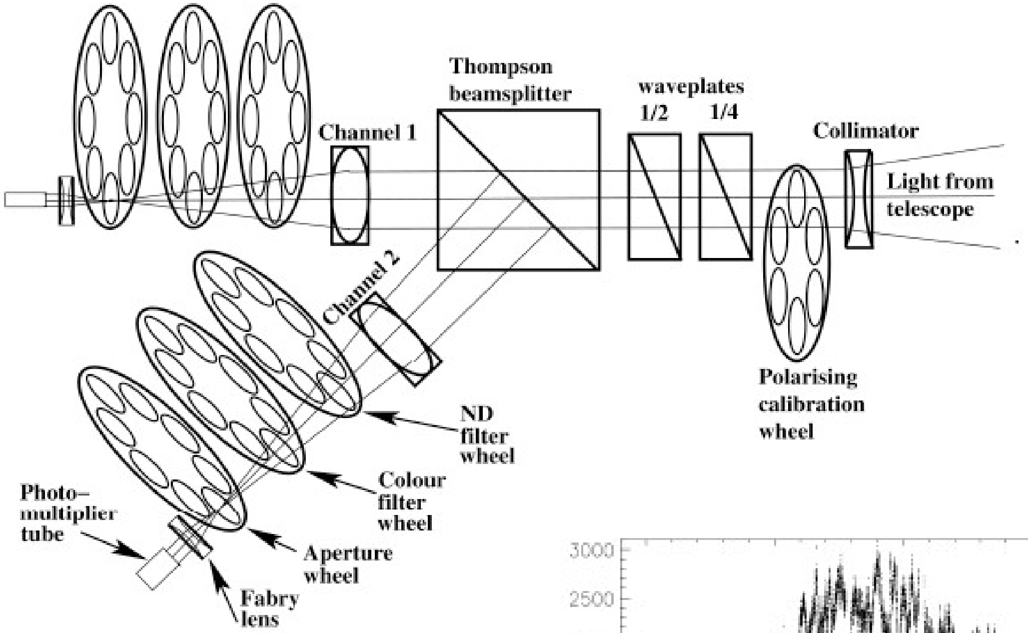
eclipses

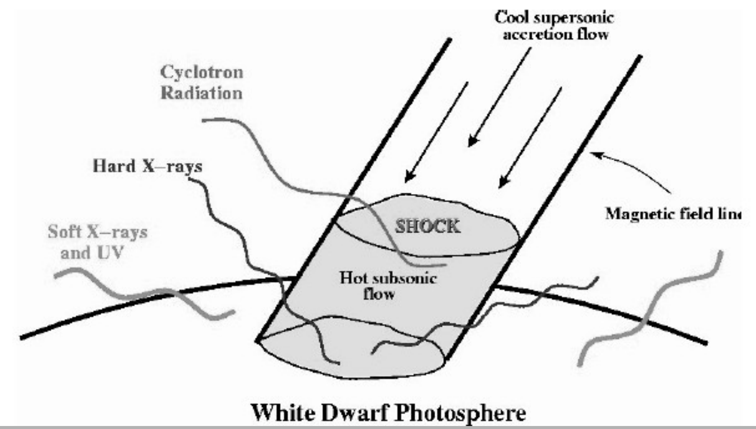
flickering

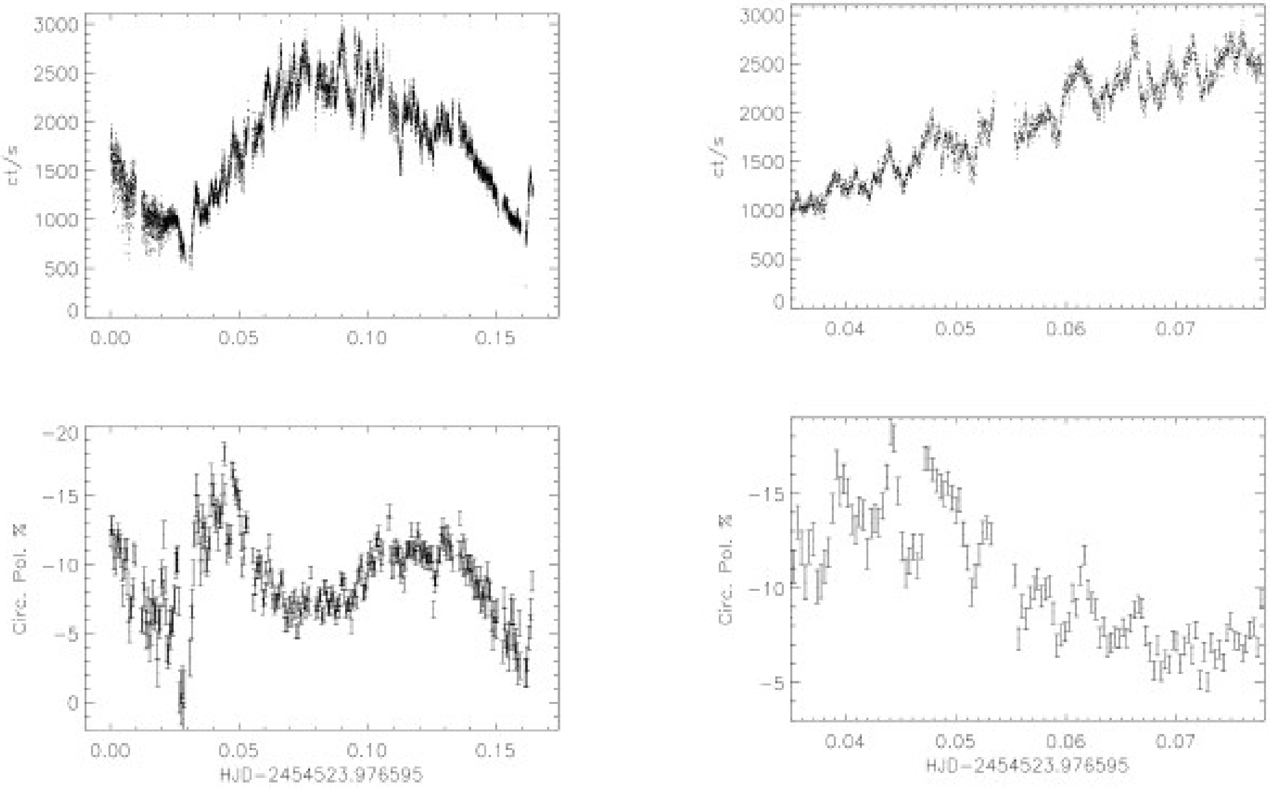
orbit to orbit changes



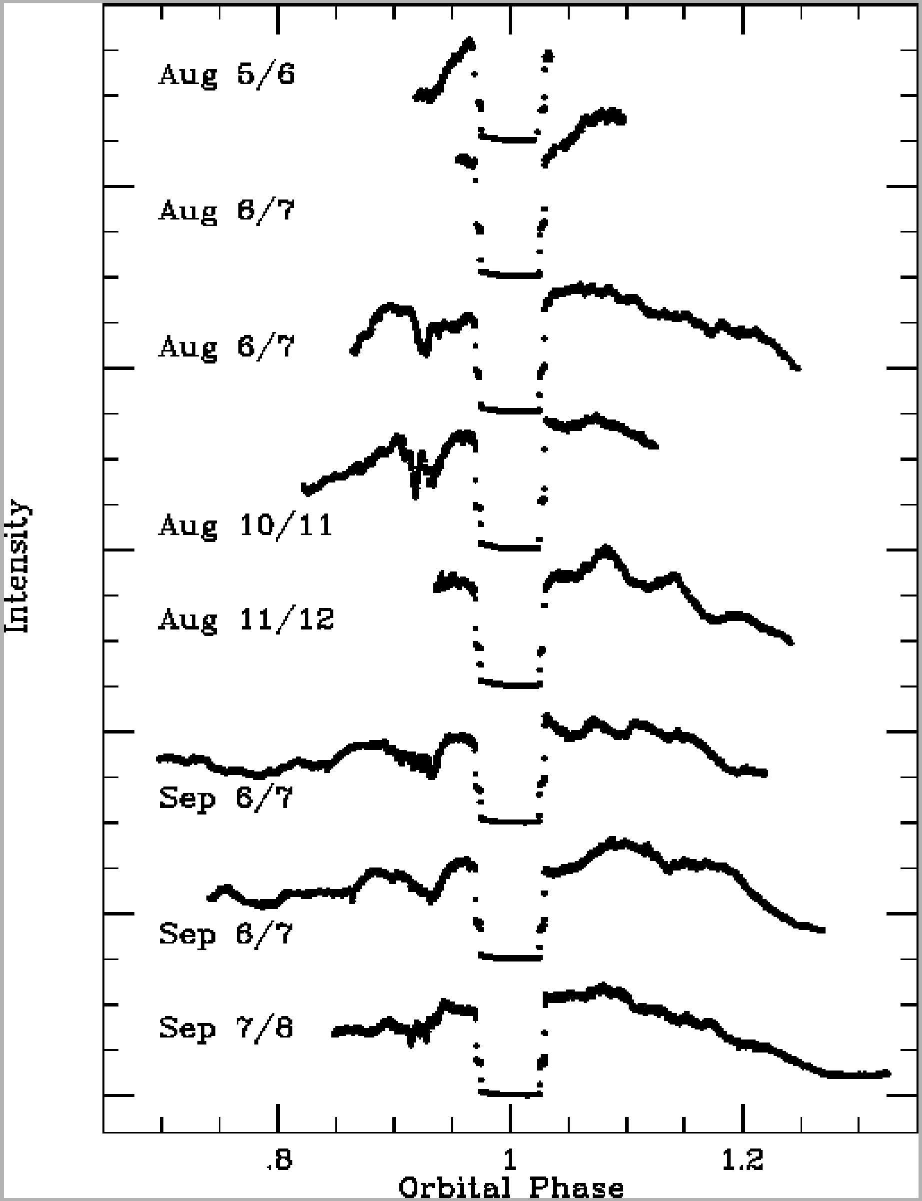
oscillations

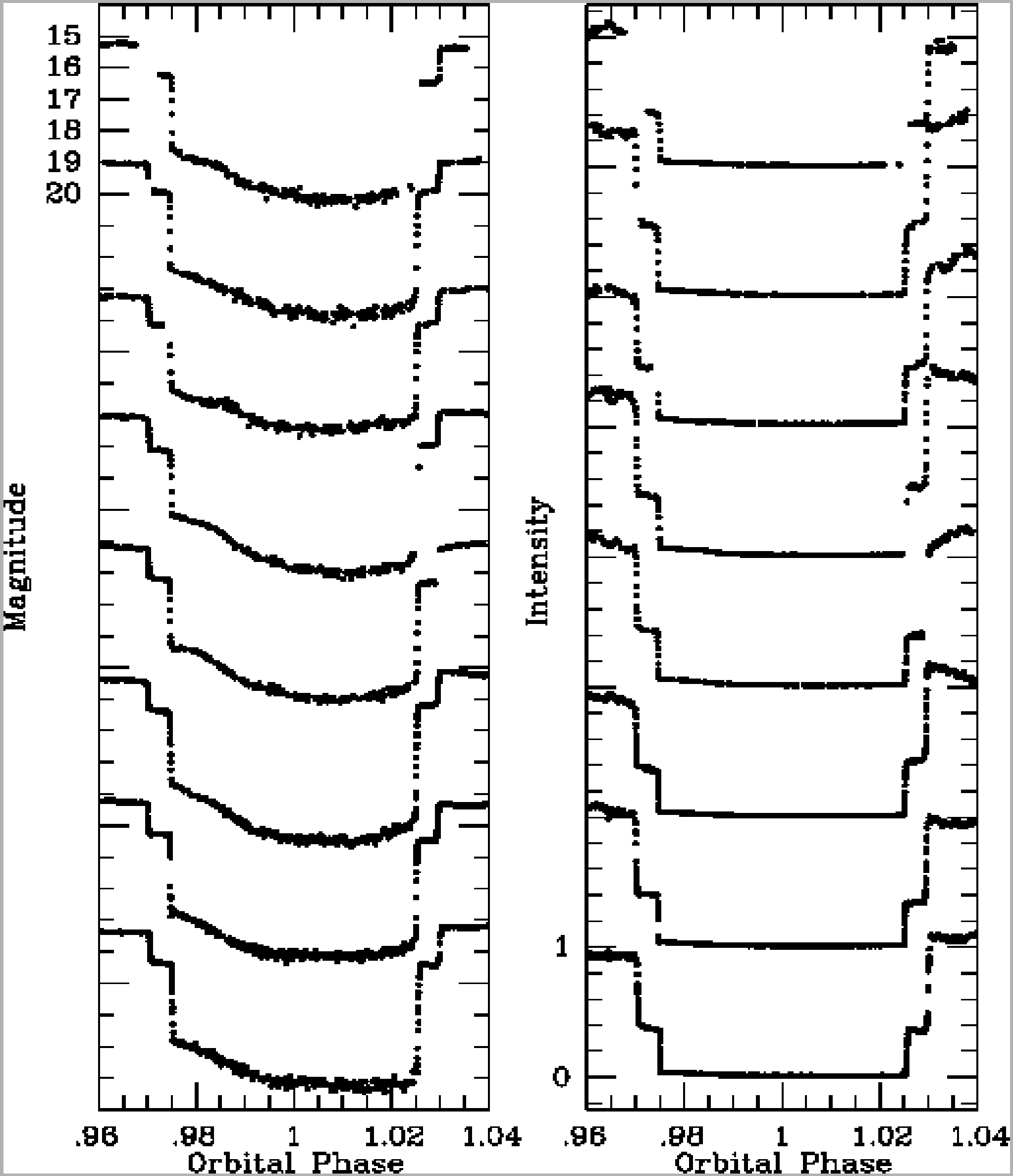

Thompson beamsplitter
waveplates
1/2
1/4
Channel 1
Collimator
Light from telescope
Channel 2
Polarising calibration wheel
ND filter wheel
Colour filter wheel
Photo–multiplier tube
Aperture wheel
Fabry lens

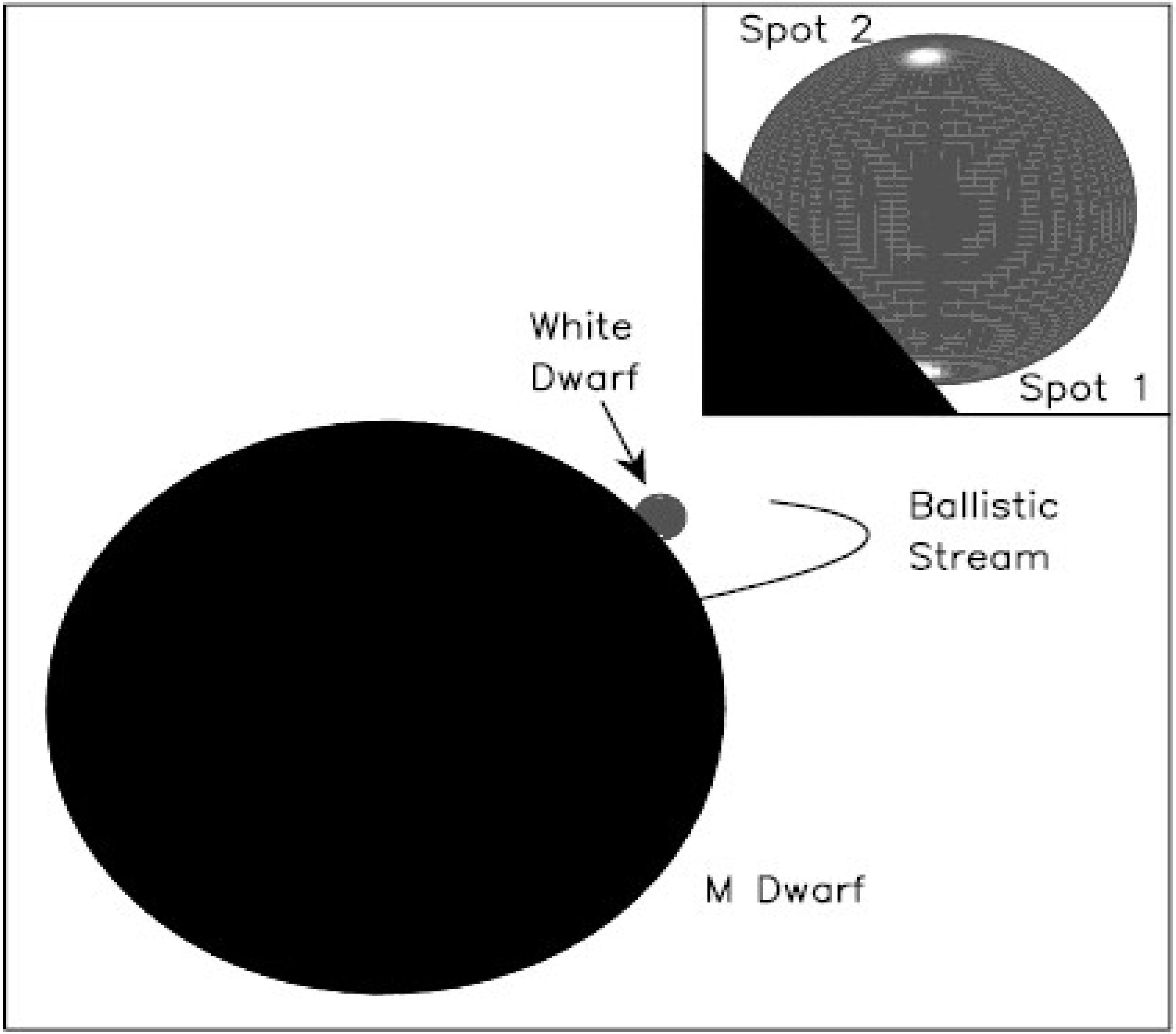

Cool supersonic accretion flow
Cyclotron Radiation
Hard X–rays
Soft X–rays and UV
SHOCK
Hot subsonic flow
Magnetic field line
White Dwarf Photosphere


ct/s
0
500
1000
1500
2000
2500
3000
0.00
0.05
0.10
0.15
0.04
0.05
0.06
0.07
Circ. Pol. %
0
−5
−10
−15
−20
HJD−2454523.976595

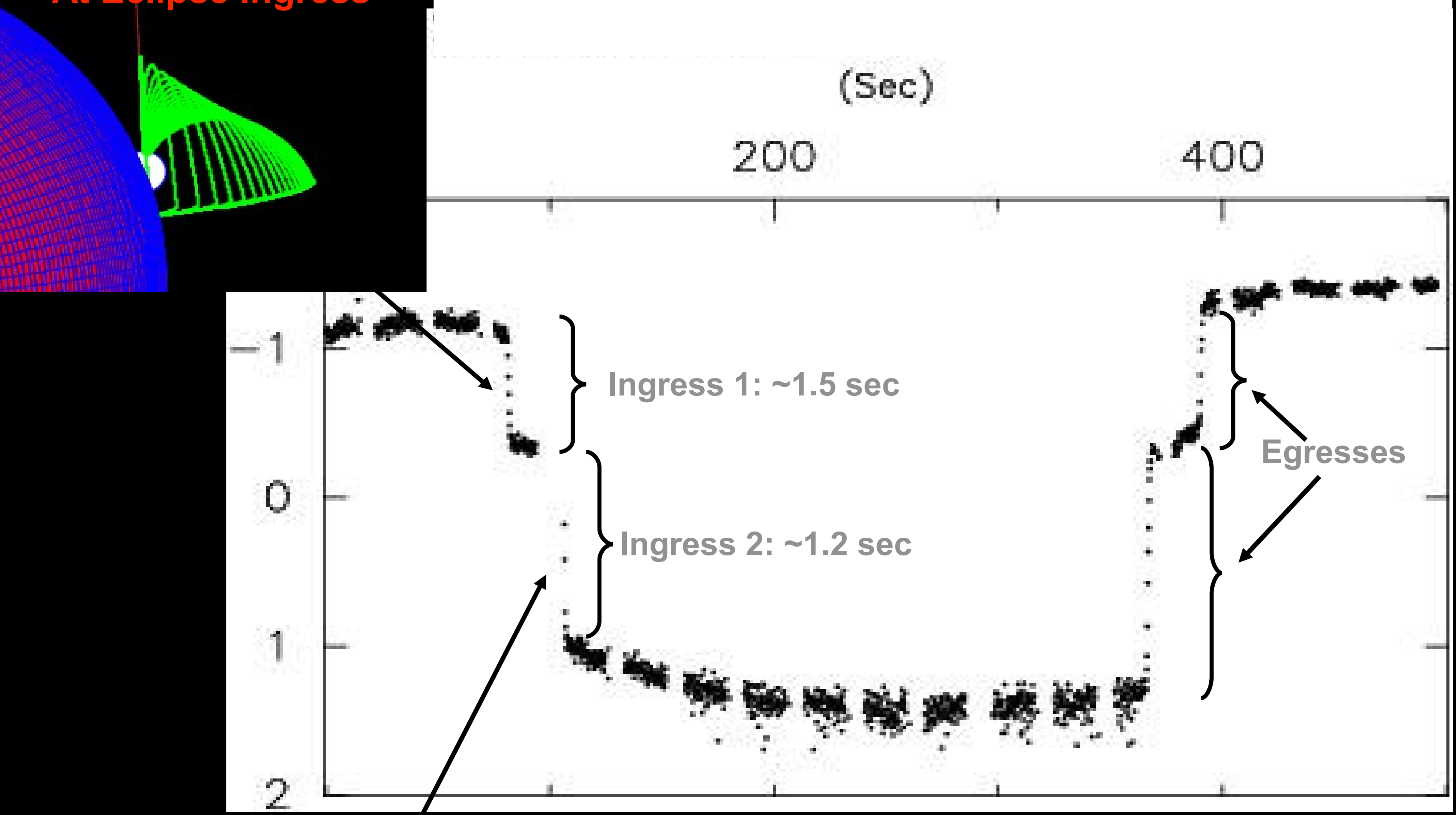
SALTICAM light curves of SDSS J015543.30+002807.2






Spot 2
Spot 1
White Dwarf
Ballistic Stream
M Dwarf

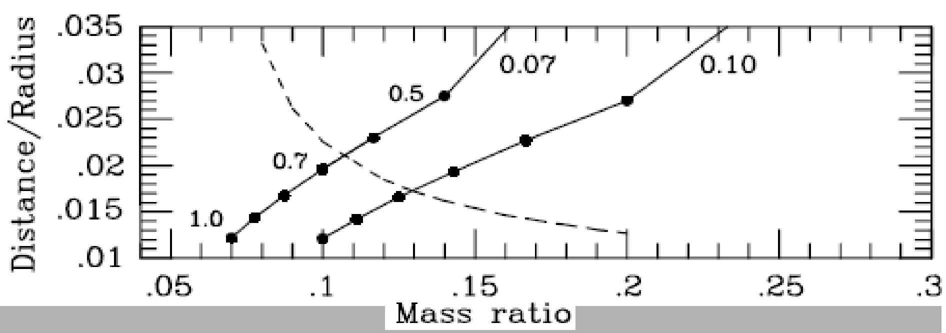
View From Earth
At Eclipse Ingress



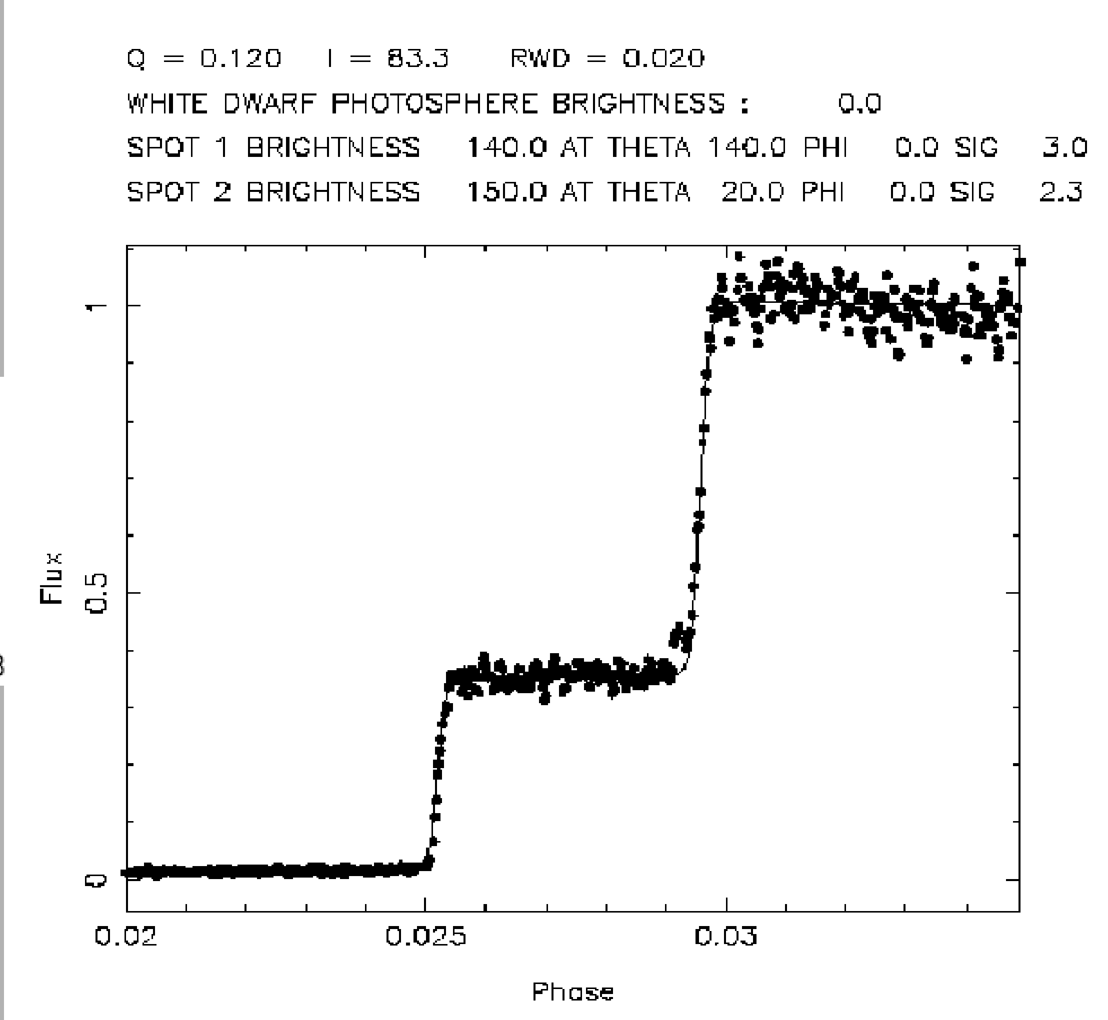
Each point 0.2 sec exposure

Model fit

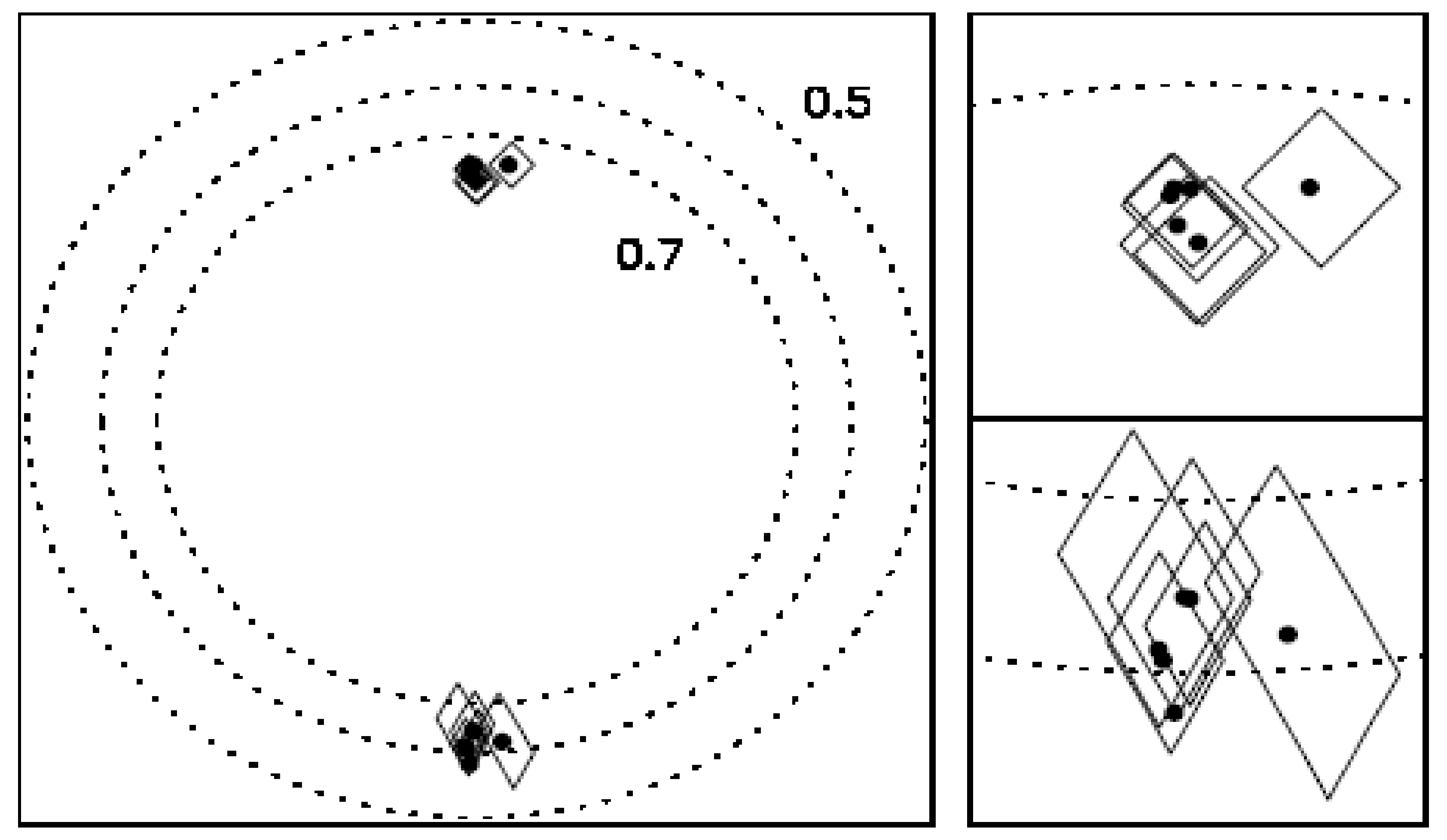
P-M relation (Smith & Dhillon 98) →
$M_2 = 0.07M_O$



→take $M_1 = 0.6M_O$, fit *i* and
spot parameters

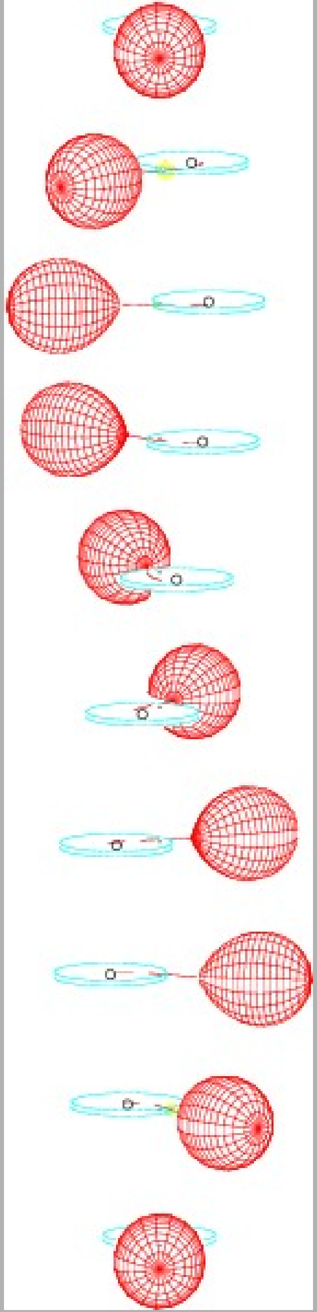


Location of spots on white dwarf



- constrains mass of WD!
- but need low state observations to determine extent of WD photosphere

Astro-tomography (Horne & Marsh)

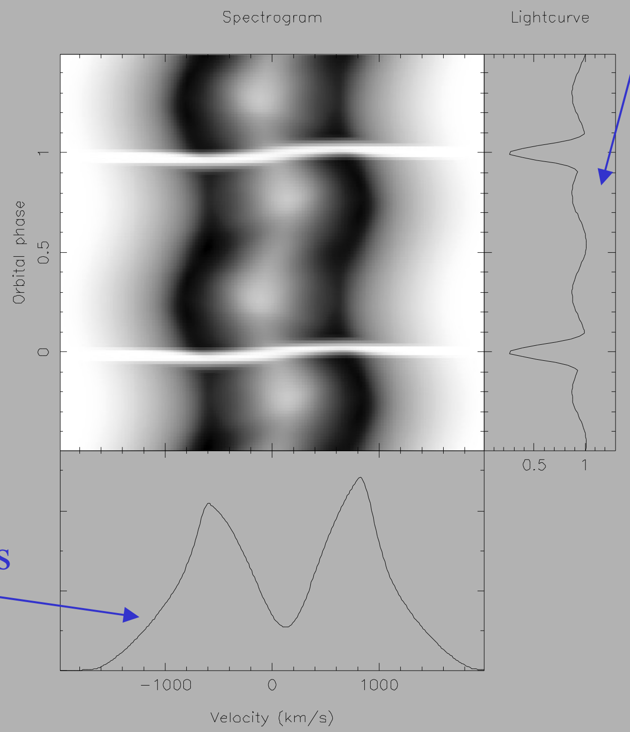


- Angular extent of typical CV (binary separation ~ few R,
  d ~ 100 pc) is ~ micro-arc second

- Indirect image reconstructions exploit the changing view that is provided across the binary orbit

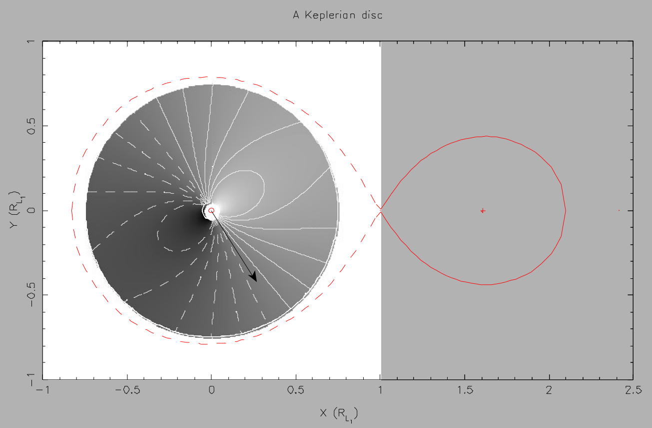
- **Eclipse mapping:** eclipses by the Roche lobe of the companion
- **Doppler tomography:** Doppler motions of up to 10^3 -10^4 km/s
- **Echo mapping:** light travel time delays (seconds), for flares etc

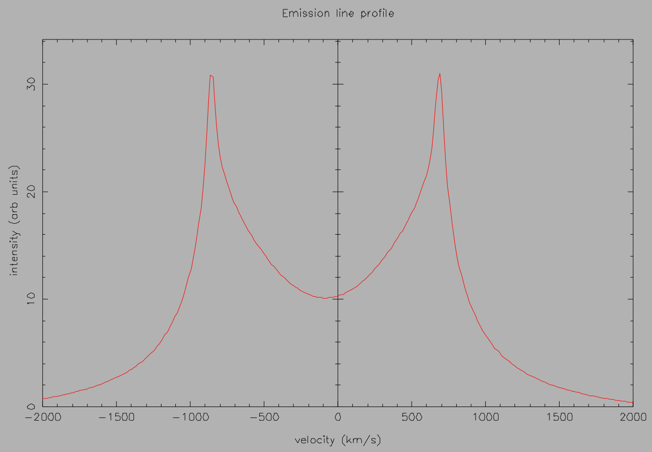
lightcurves



line profiles

Doppler Tomography (from Steeghs, Marsh 03 reviews)

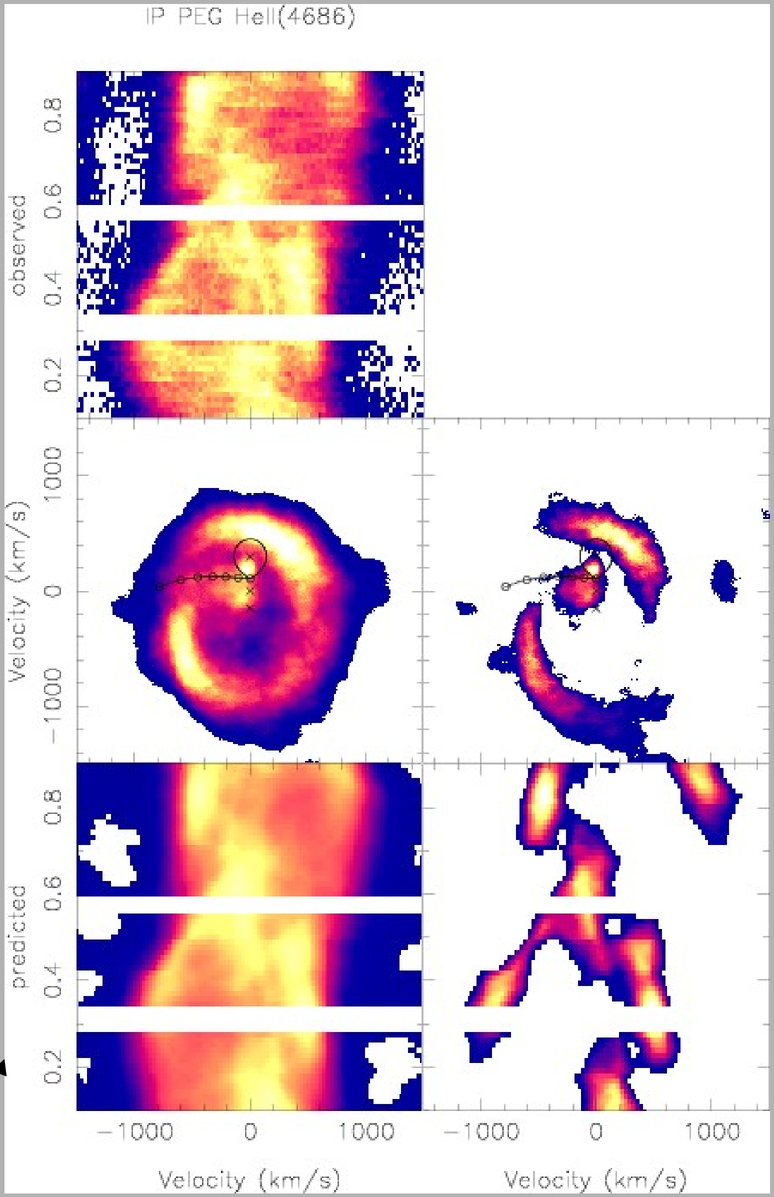




Broad emission lines from the supersonic disc flow

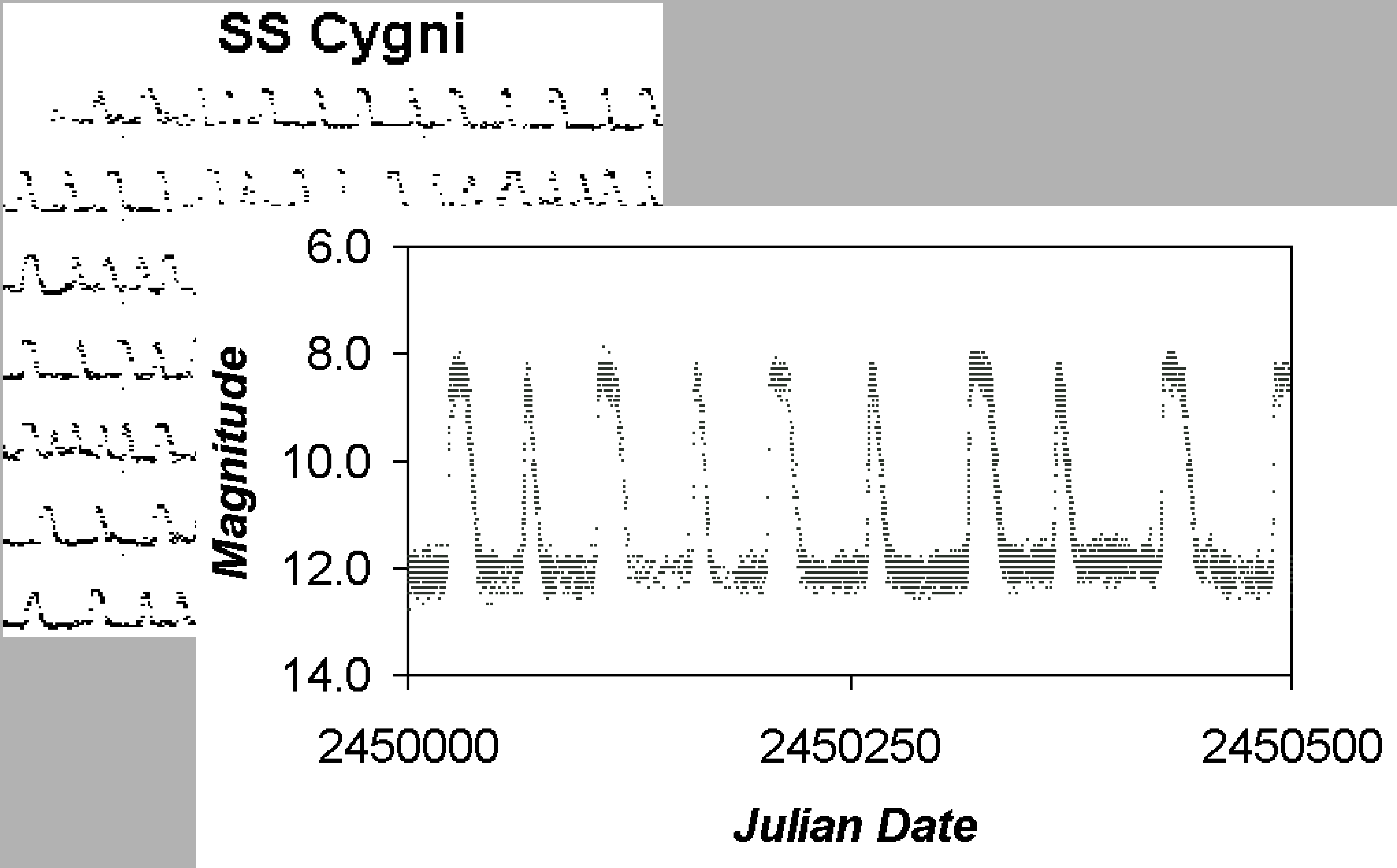
N.B. required Service/TOO facilities at ING!

→ much easier with SALT

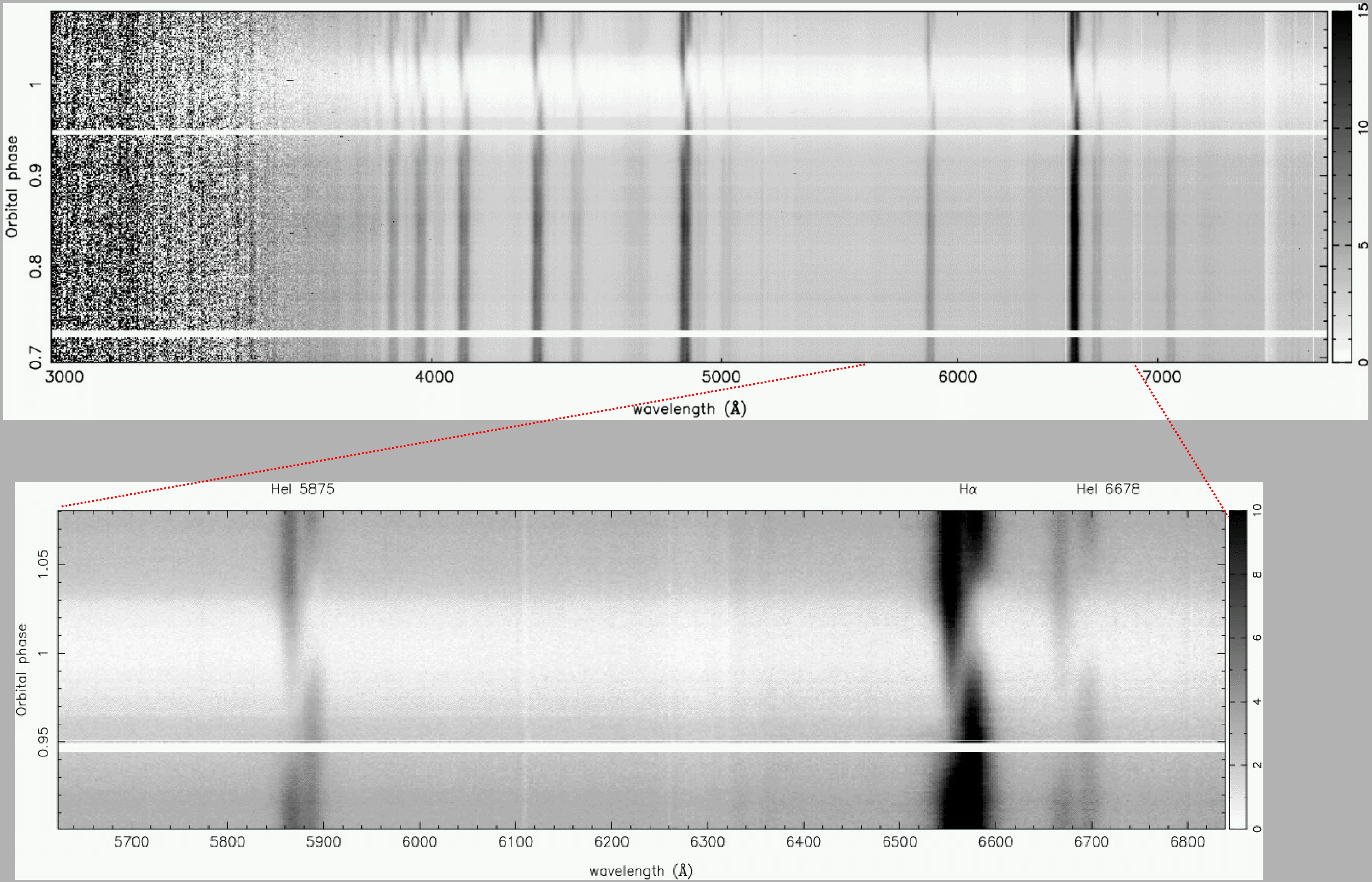


Spiral waves in the accretion disc of IP Pegasi

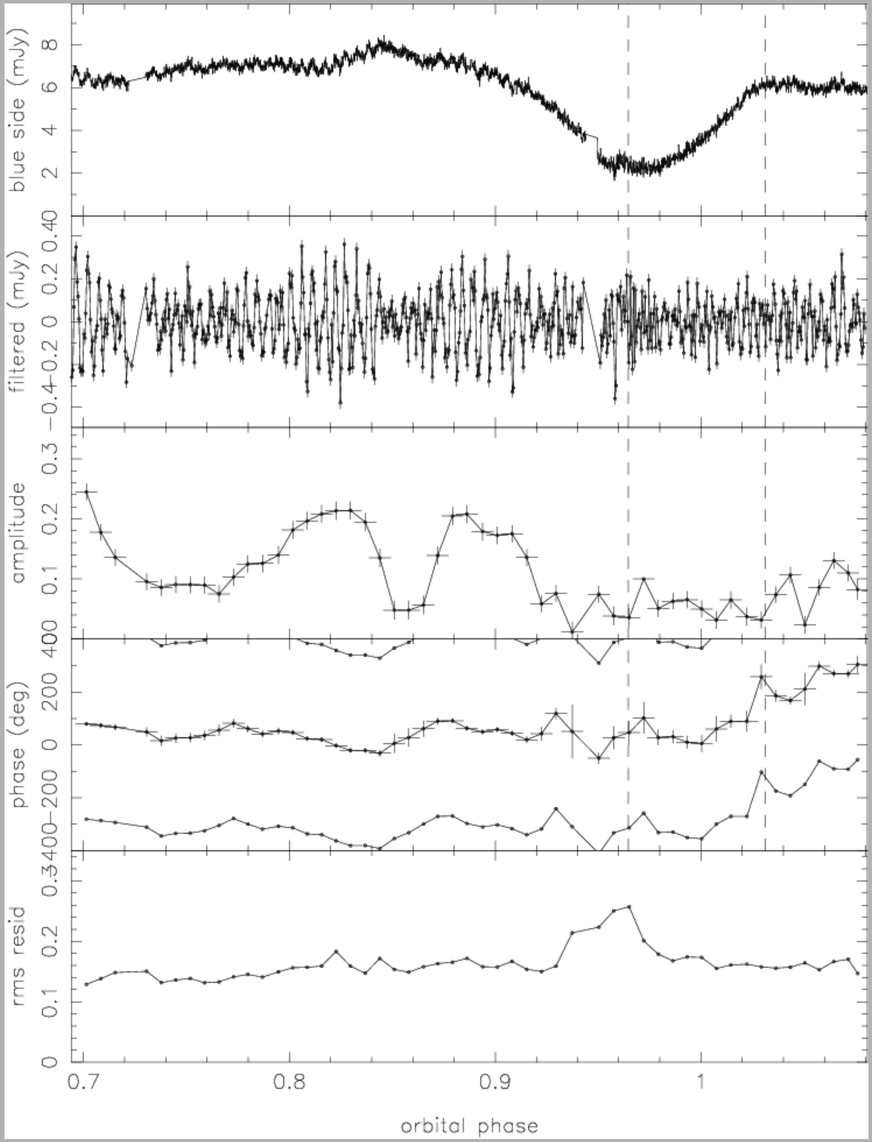
Main problem is irregular (=unpredictable) outbursts!

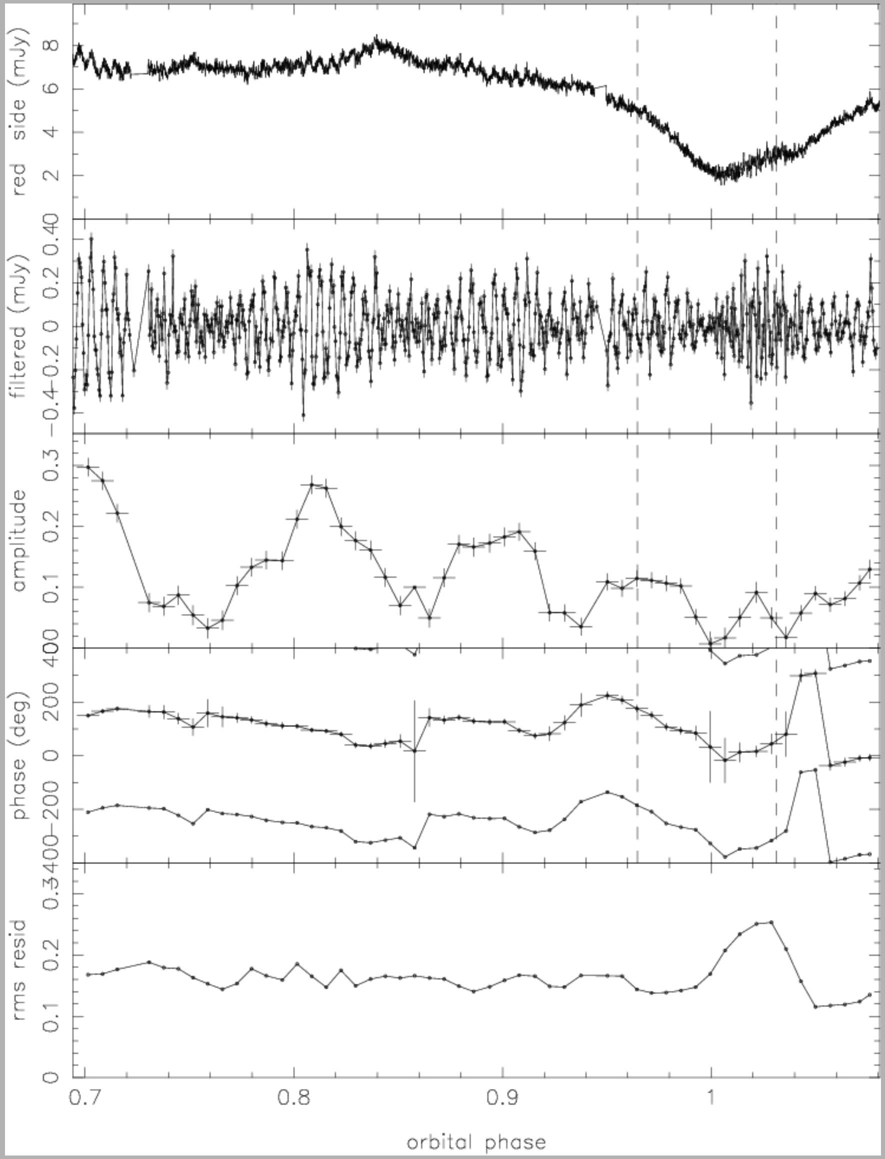


Drift mode observations of V2051 Oph (Steeghs)



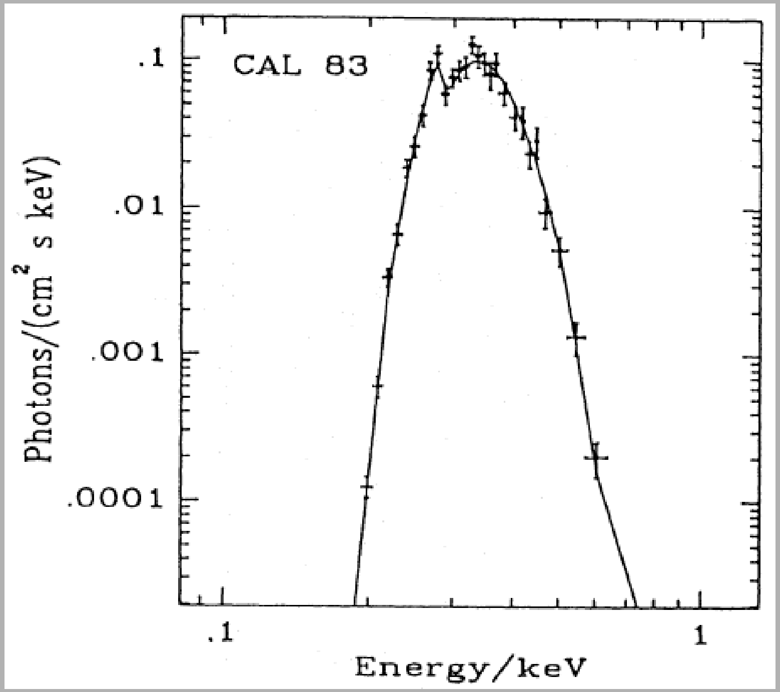
Drift mode observations of V2051 Oph (Steeghs)

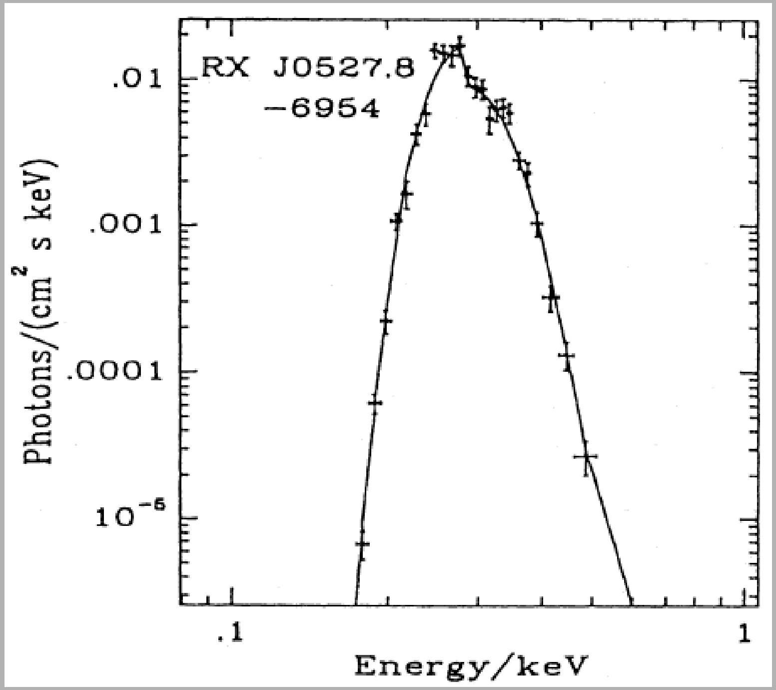




SSS key facts:

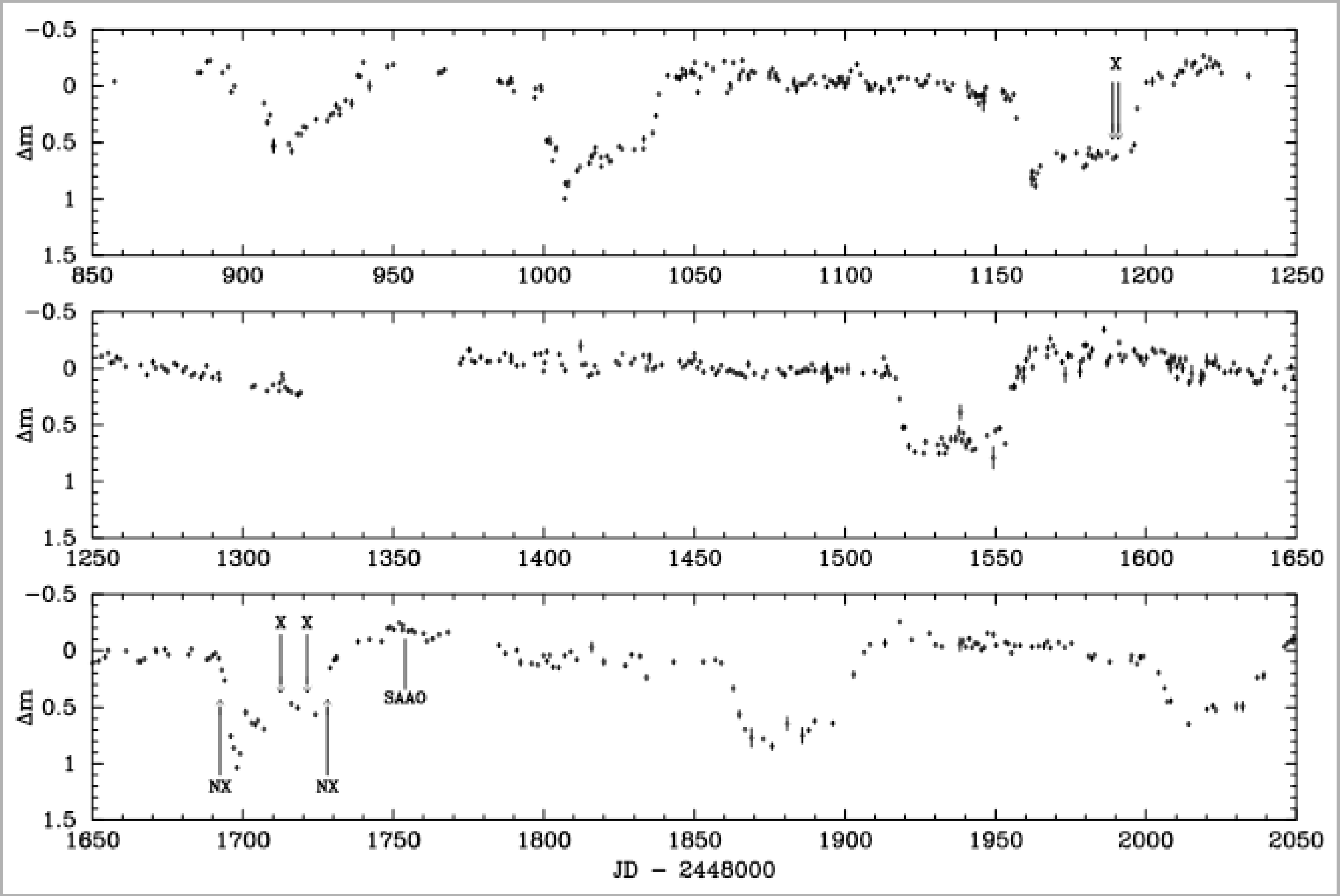
- discovered by Einstein Obs (Long et al 81) as *ultra-softs* (N.B. poor res. of IPC)
- established by ROSAT as SSS with PSPC All-Sky Survey (Trumper 92)
  - $L_X \sim 10^{37}$ - 10^{38} erg s^{-1}
  - < 0.5 keV (T ~ 10^5 – 10^6K)
  - e.g. prototypical sources CAL83, CAL87 in LMC
- potentially important as massive WD / SN Ia progenitors





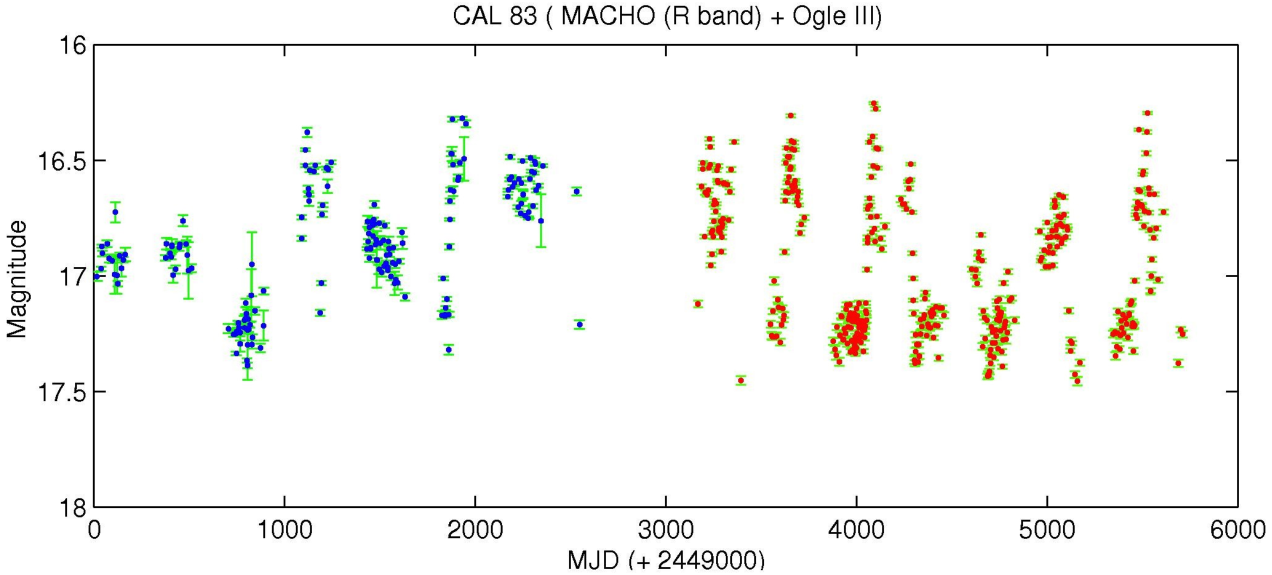
Greiner et al. 1991

RX J0513.9-6951 4-yr light curve from MACHO project



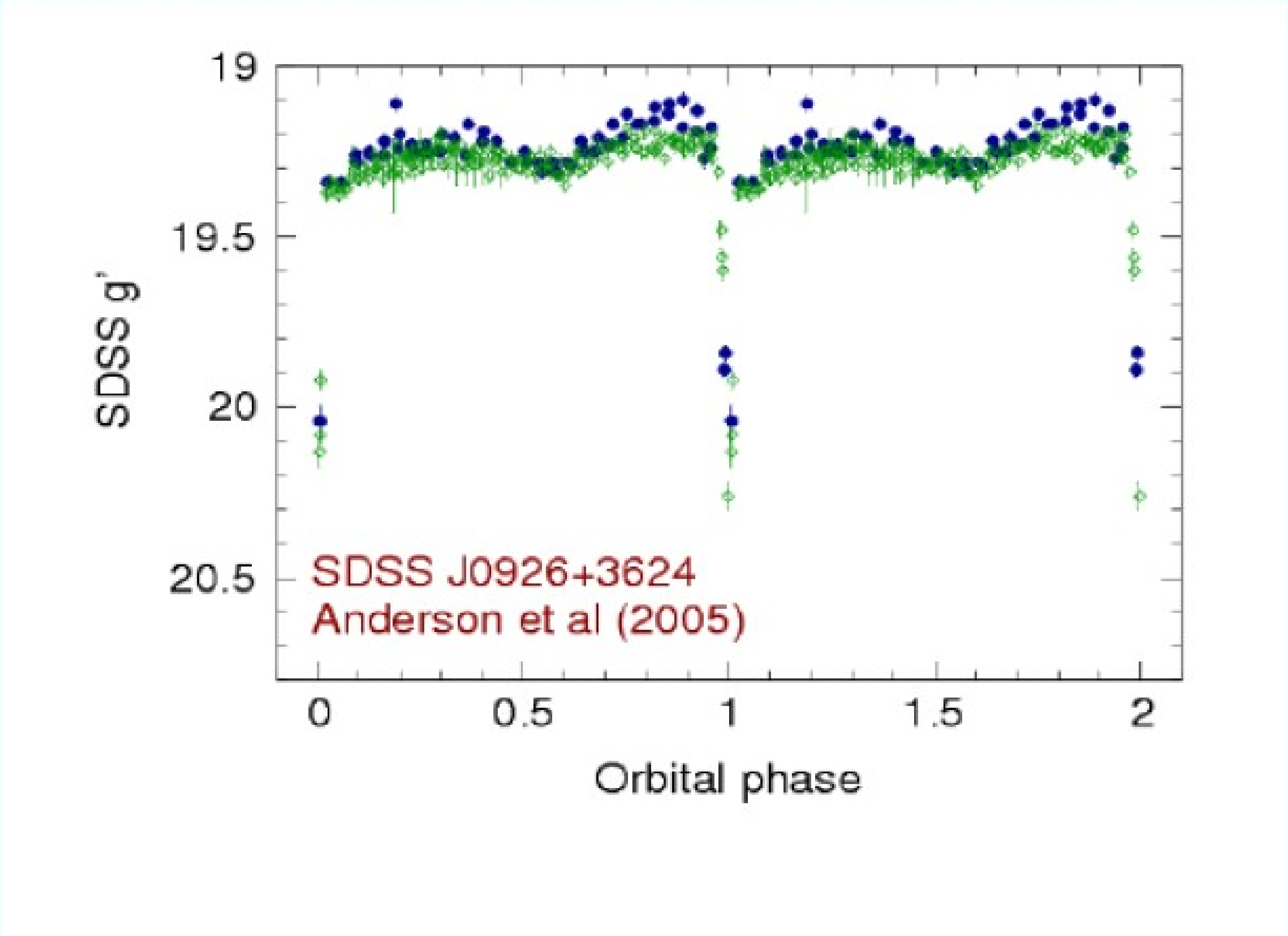
Southwell et al 96

N.B. X-rays *only* detected during optical low states

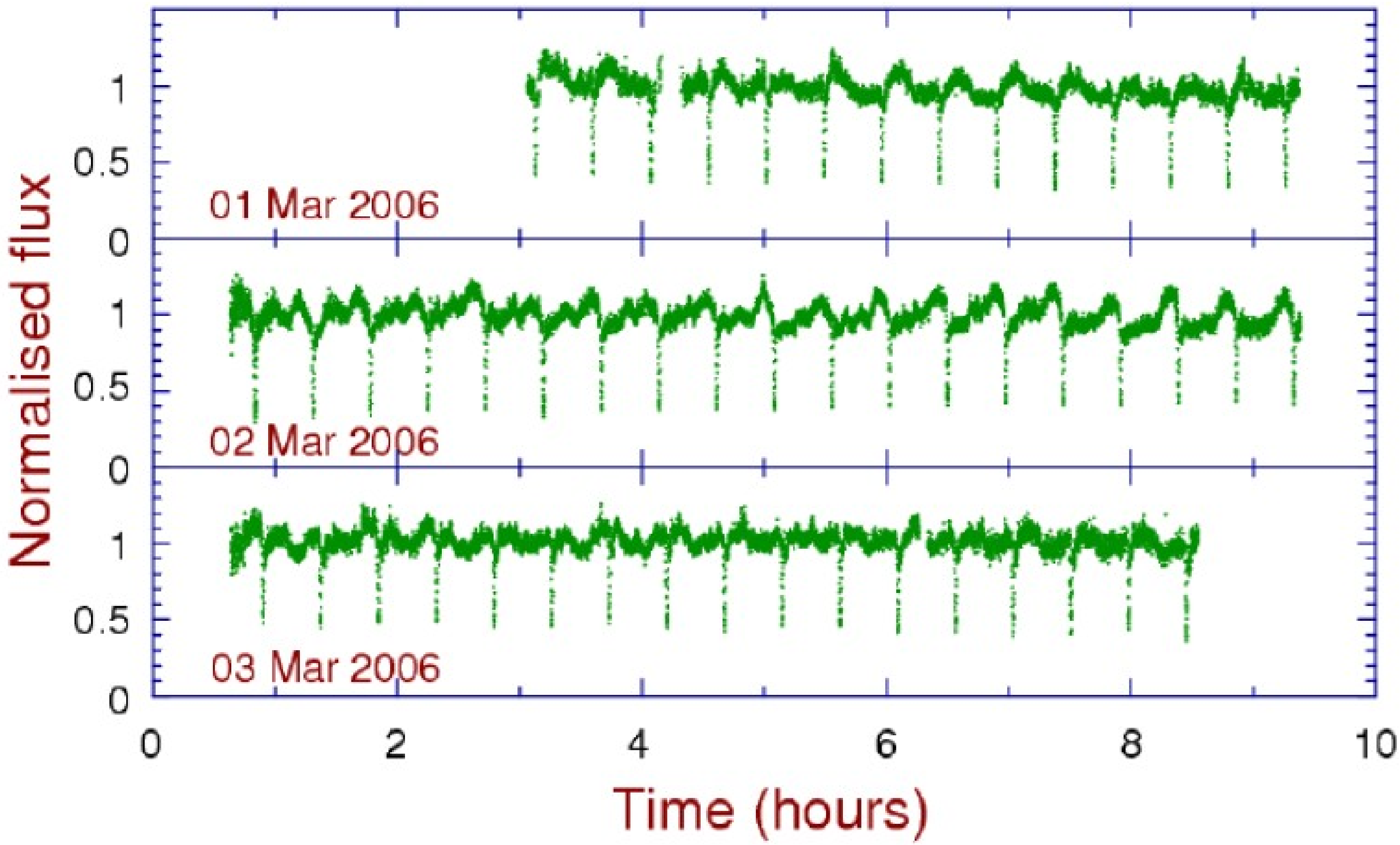


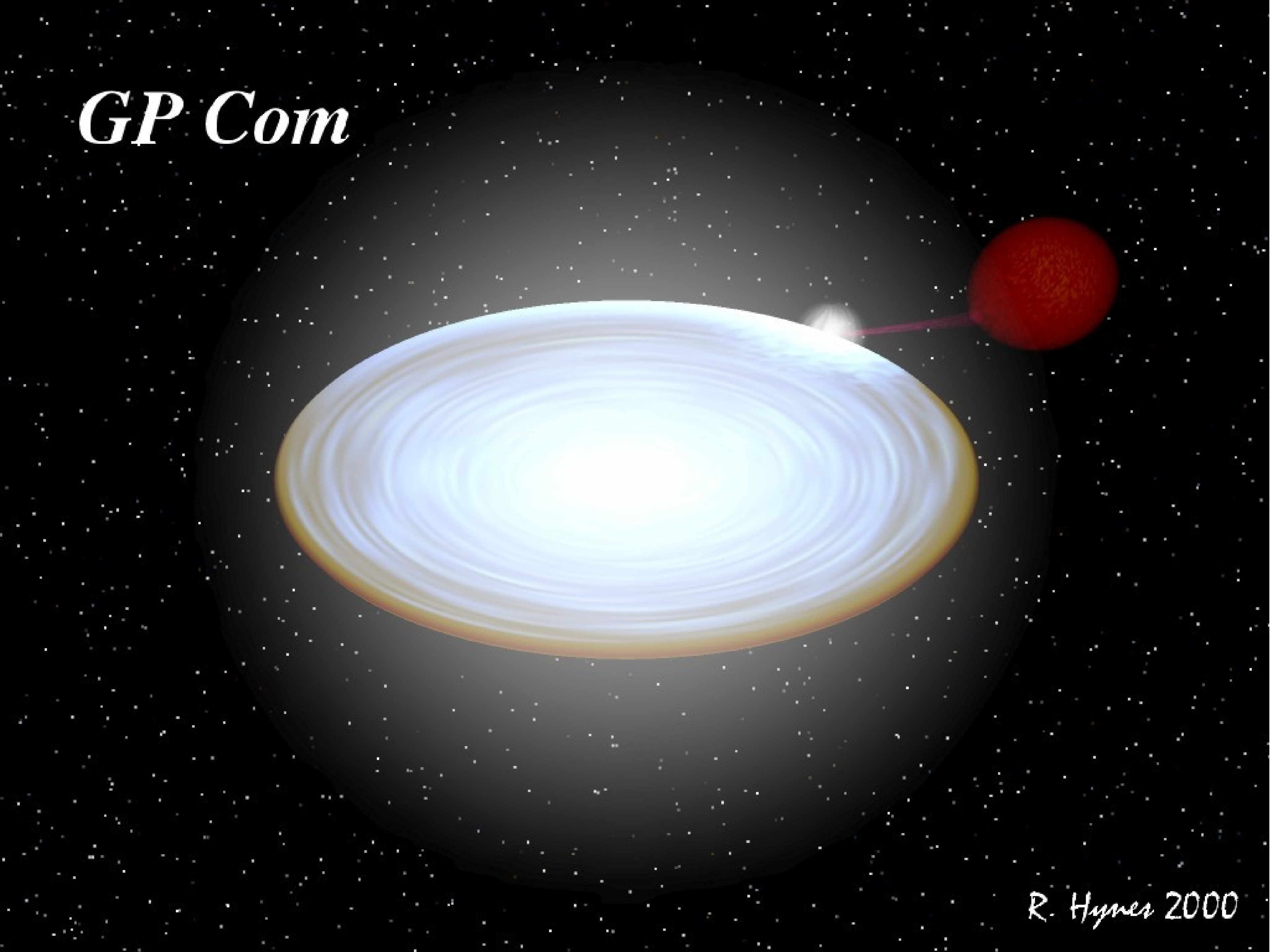
Andry Rajoelimanana (SAAO/UCT)

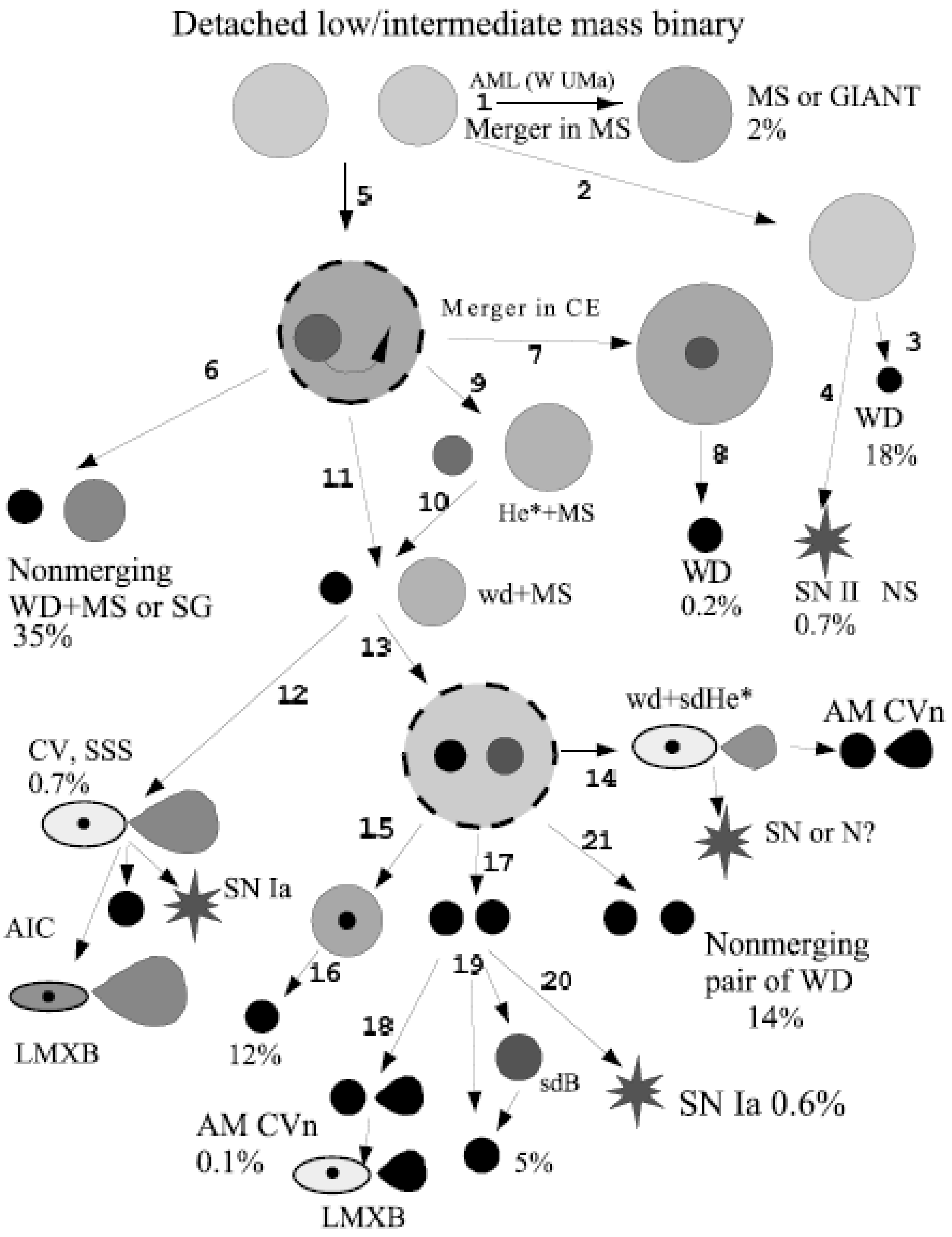
- eclipsing AM CVn star: SDSS J0926+3624
- P=28 mins
- eclipsed for only 1 minute!



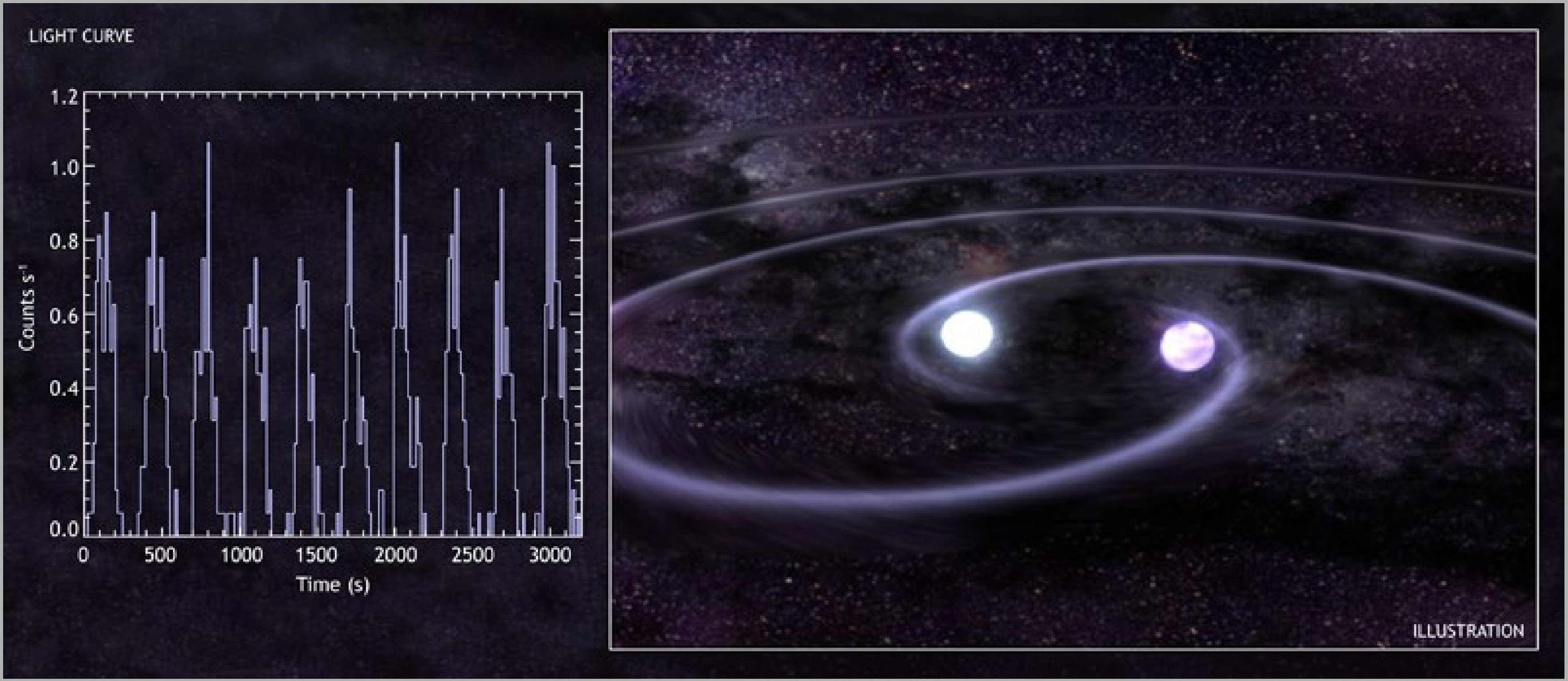
SDSS0926+3624 with 4.2m WHT & ULTRACAM



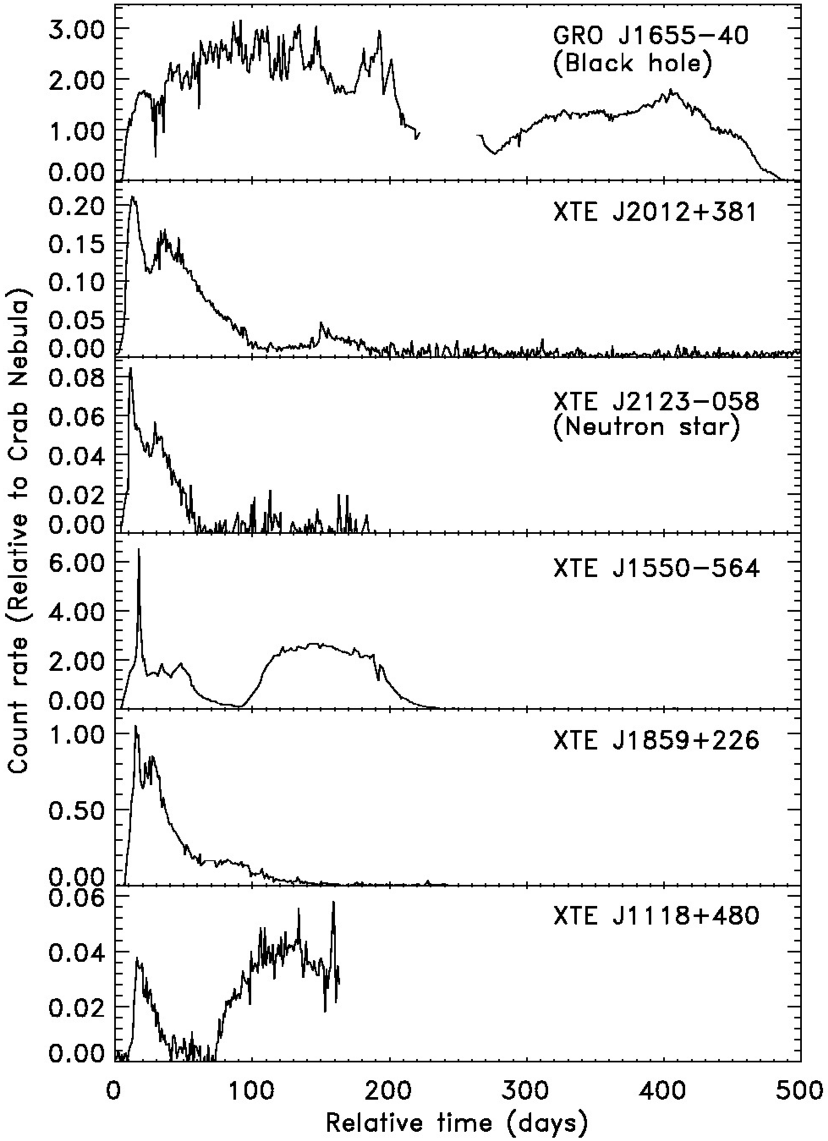

GP Com
R. Hynes 2000


Detached low/intermediate mass binary
AML (W UMa)
1
Merger in MS
MS or GIANT
2%
2
5
Merger in CE
7
3
6
9
4
WD
18%
8
11
10
He*+MS
Nonmerging
WD+MS or SG
35%
wd+MS
WD
0.2%
SN II
NS
0.7%
13
12
wd+sdHe*
AM CVn
CV, SSS
0.7%
14
SN or N?
15
17
21
SN Ia
AIC
16
19
20
Nonmerging
pair of WD
14%
LMXB
12%
18
sdB
SN Ia 0.6%
AM CVn
0.1%
5%
LMXB

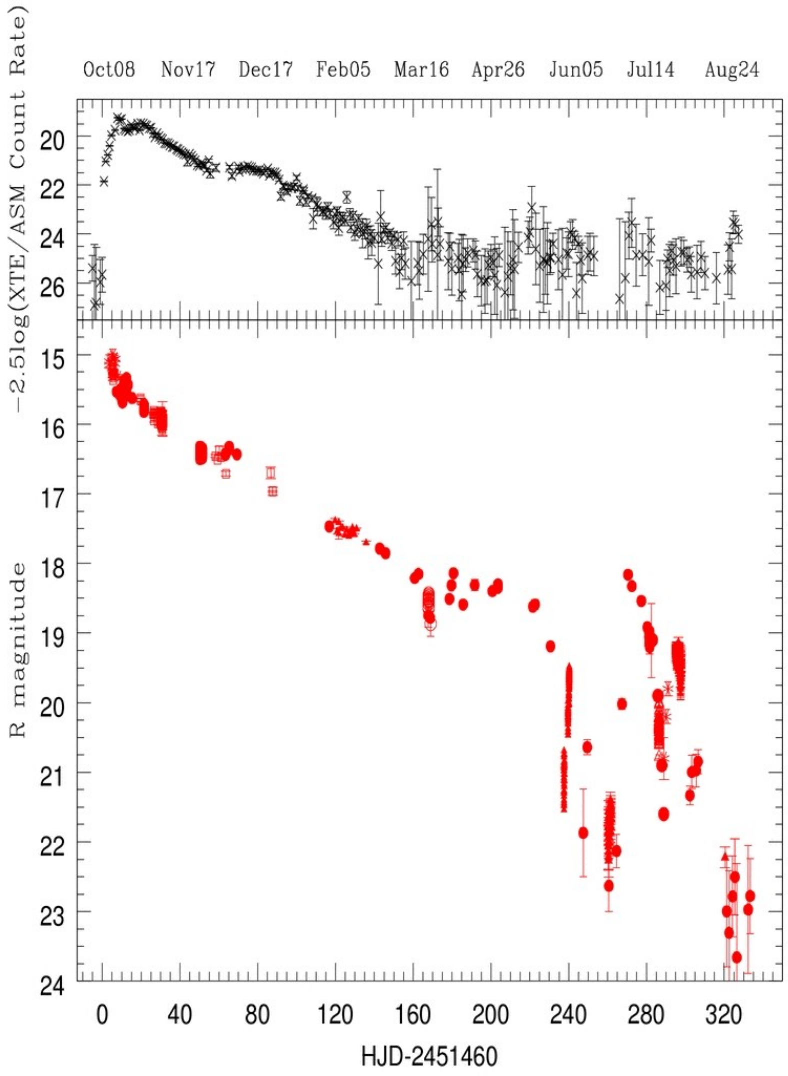
RX J0806.3+1527



LIGO
Louisiana


GRO J1655−40
(Black hole)
XTE J2012+381
XTE J2123−058
(Neutron star)
XTE J1550−564
XTE J1859+226
XTE J1118+480
Count rate (Relative to Crab Nebula)
Relative time (days)
0
100
200
300
400
500
3.00
2.00
1.00
0.00
0.20
0.15
0.10
0.05
0.08
0.06
0.04
0.02
6.00
4.00
0.50

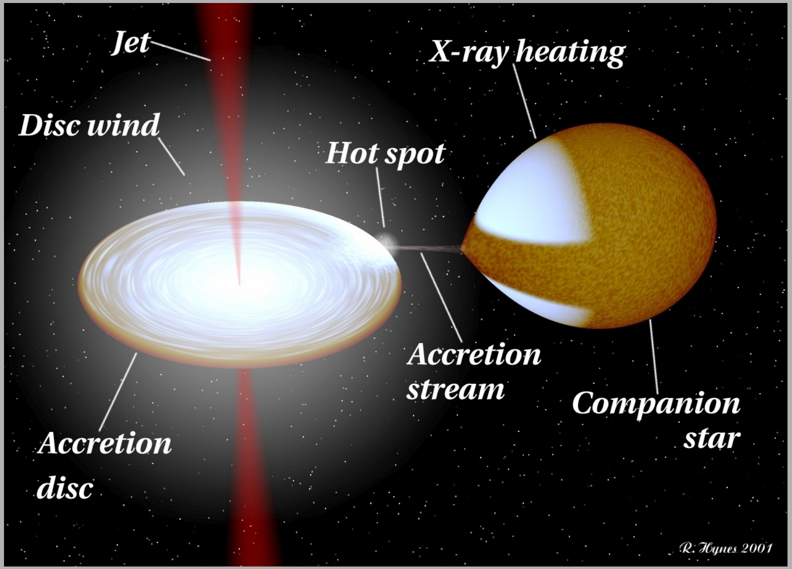
J1859+226

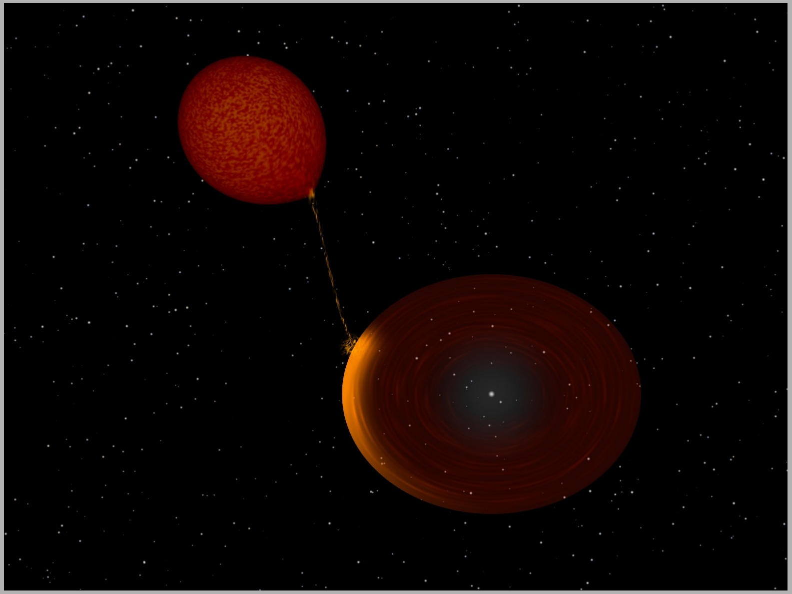

Oct08
Nov17
Dec17
Feb05
Mar16
Apr26
Jun05
Jul14
Aug24
−2.5log(XTE/ASM Count Rate)
20
22
24
26
R magnitude
15
16
17
18
19
20
21
22
23
24
0
40
80
120
160
200
240
280
320
HJD-2451460

Black Hole X-ray Transients

- Black-hole X-ray transients are LMXBs
- Very bright X-ray sources during rare outbursts, usually decades apart (find by ASTROSAT/SSM)
- Optically brighten by up to 8m (irradiation of companion and disc allows echo mapping)
- Can produce relativistic jets (micro-quasars) (study with GMRT)

- In quiescence very faint
- Companion star dominates
- RV + light curve (with SALT/RSS) → masses





The Mass Function

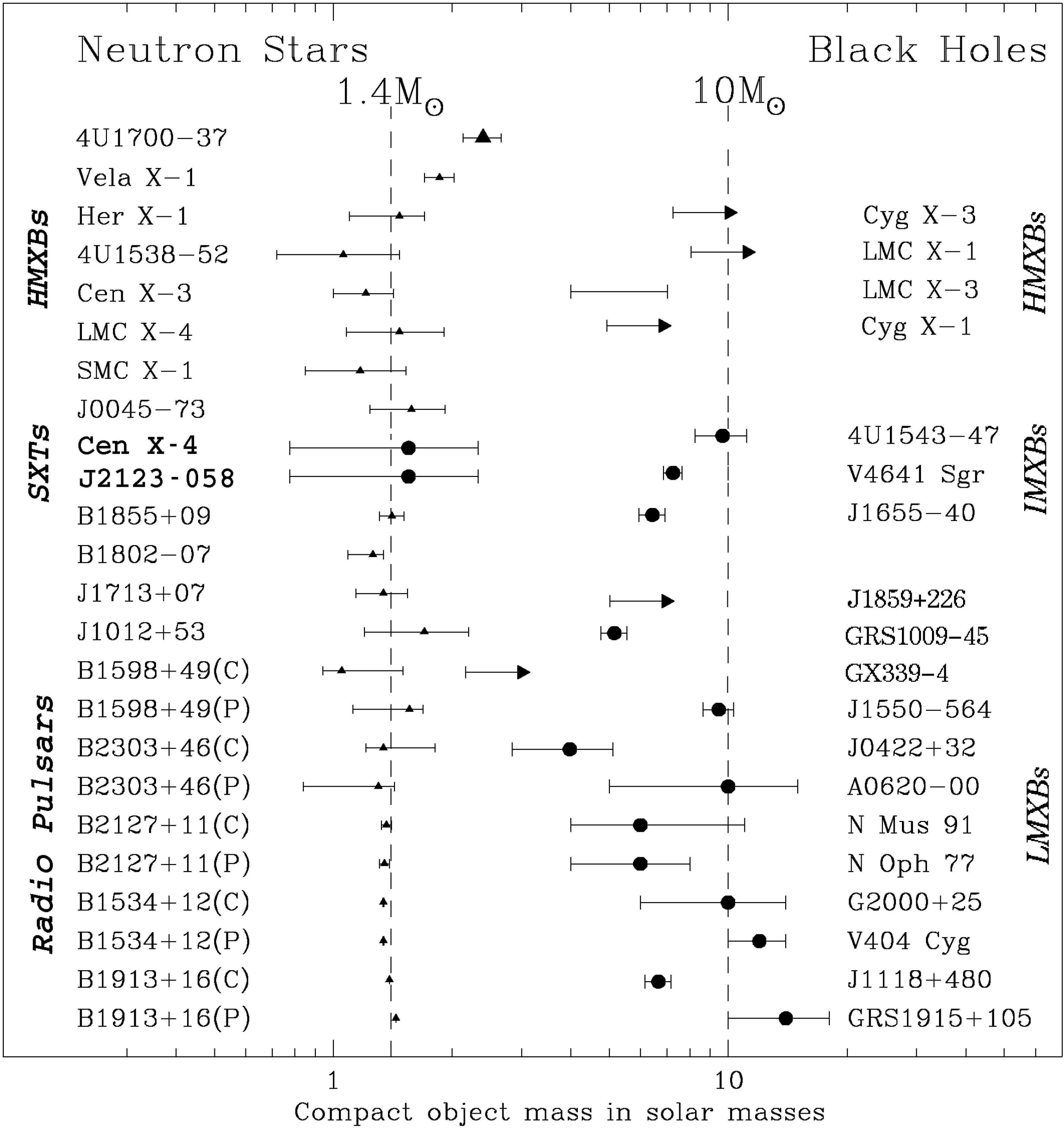
$$f(M) = \frac{P_{\mathrm{orb}} K^3}{2\pi G} = \frac{M_X^3 \sin^3 i}{(M_X + M_C)^2} = \frac{M_X \sin^3 i}{(1+q)^2}$$

$$q = M_C / M_X$$

$$f(\mathrm{M}) < \mathrm{M_X}$$

If $f(\mathrm{M}) > 3\ \mathbf{M}_{\odot}$ → Black Hole independently of *i*, *q*

Mass distribution



19 realistic masses of BHs:
5-14 M

Typical errors 30%

Goals:

- improve statistics
- reduce errors to 10%

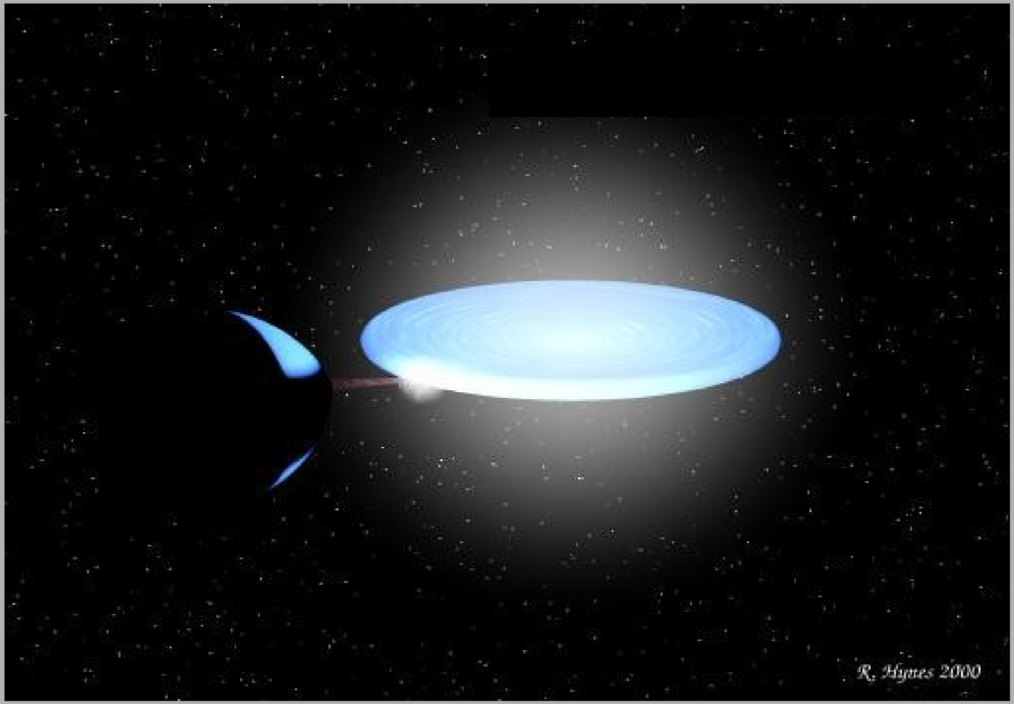
Do BH masses cluster at a particular value?

What are the edges of the BH distribution?

Is there a continuum distribution between NS & BHs?

What can we determine in “active” X-ray binaries?

Optical emission driven by reprocessing of $L_x \approx 10^{38}$ erg/s in gas around compact object i.e. accretion disc



R. Hynes 2000

➔ **Cool, late-type companion star is undetectable**

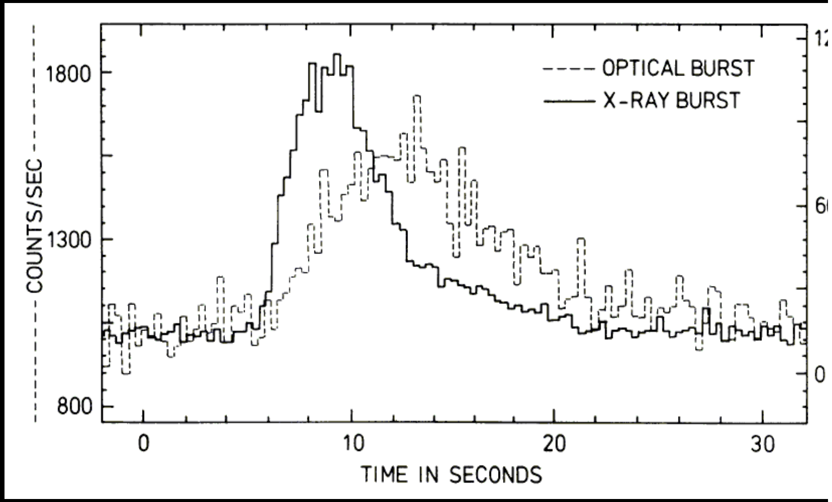
Irradiation does occur e.g. delayed X-ray/optical Type I bursts

- Optical counterparts with time lags consistent with light travel times within the binary

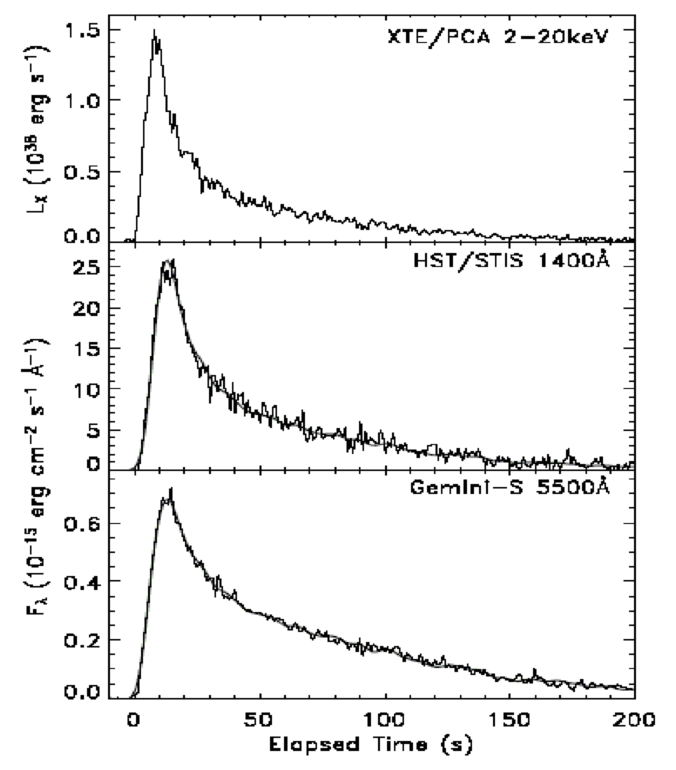
Truemper et al. 1985 SSRv 40 255

Hynes et al. 2004 RevMexAA 20 12

4U1636-53



Lag ~ 3 s



X0748-676

Lag = 4 s

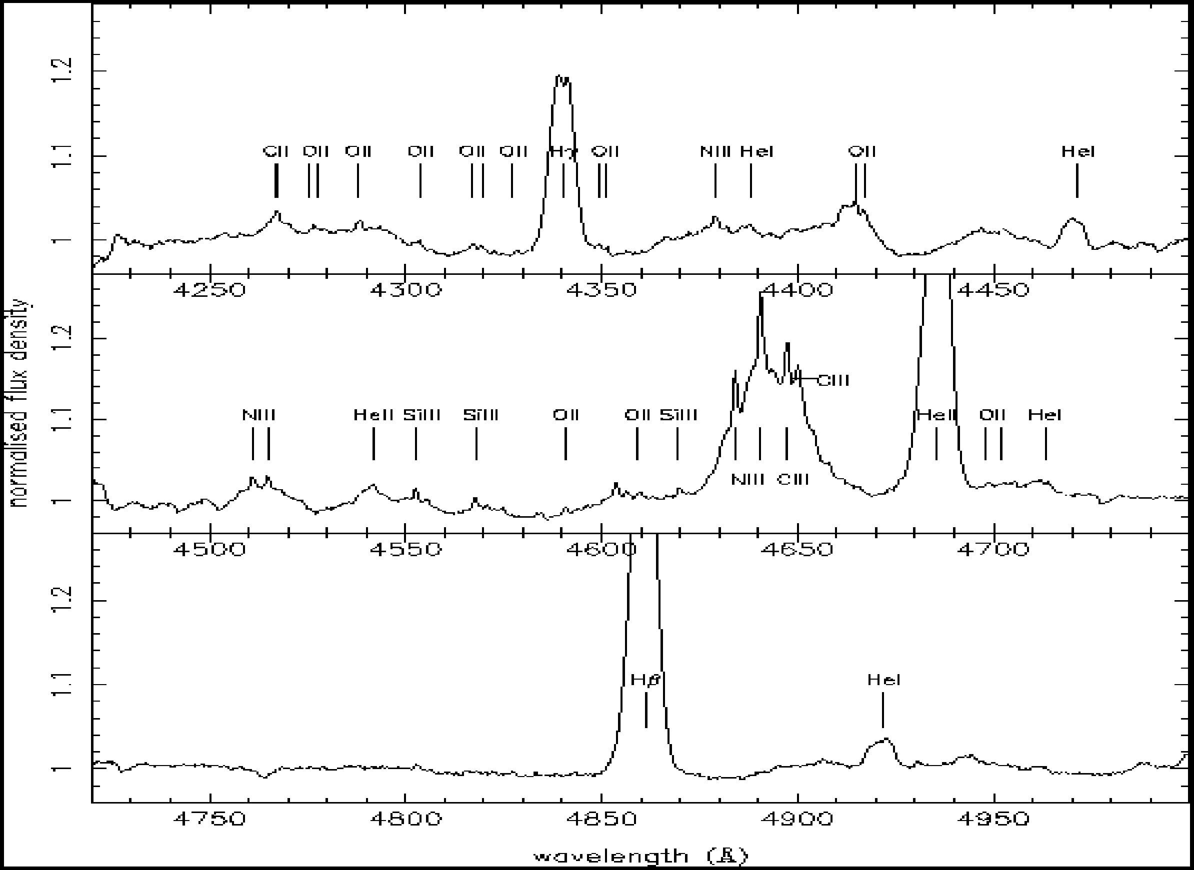
T_{disc}=11500 K (steady)

T_{disc}=26000 K (burst-peak)

SCO X-1

- Steeghs & Casares 2002 ApJ 568 273

Discovery of narrow (FWHM ≈ 50 km/s) high excitation emission lines from the irradiated companion in Sco X-1.



Most intense in Bowen blend:

- NIII 4634, 4641-2
- CIII 4647, 4650-1

Powered by fluorescence resonance triggered by cascade recombination of HeII Ly α photons

Narrowness rules out origin in the disc or accretion flow

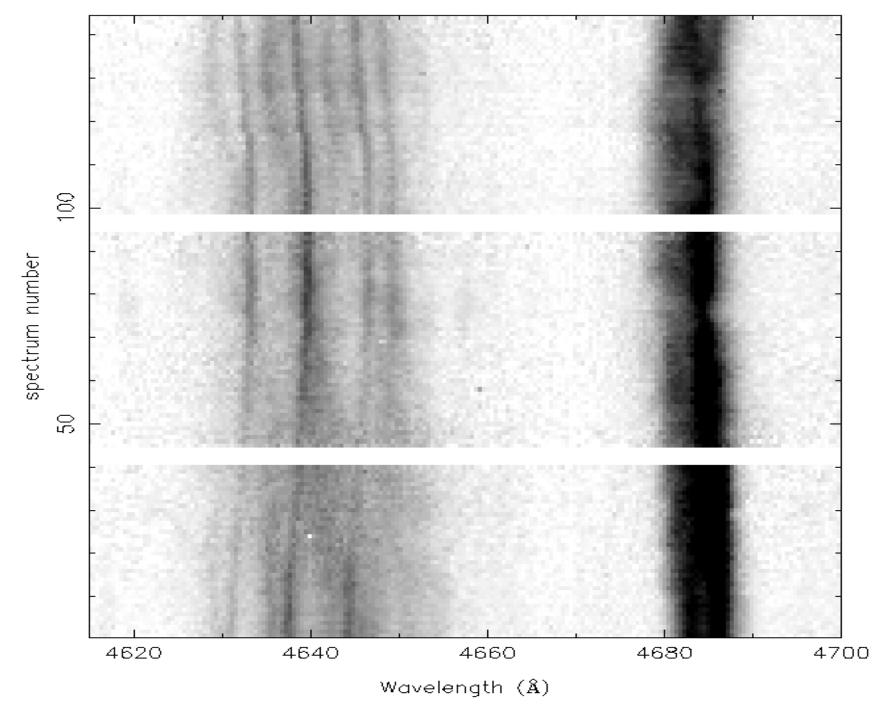
SCO X-1

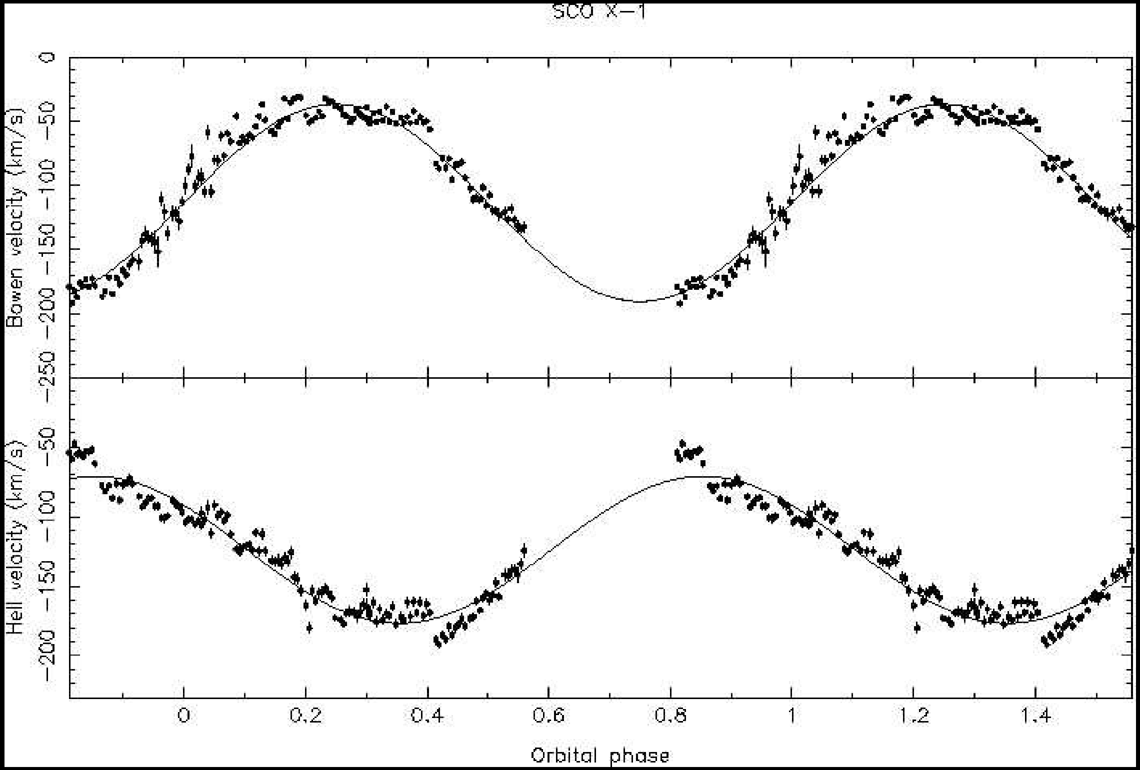
- Steeghs & Casares 2002 ApJ 568 273

  Doppler shift traces the motion of the donor star

  Multigaussian fit to NIII & CIII → measure the orbit

NIII/CIII





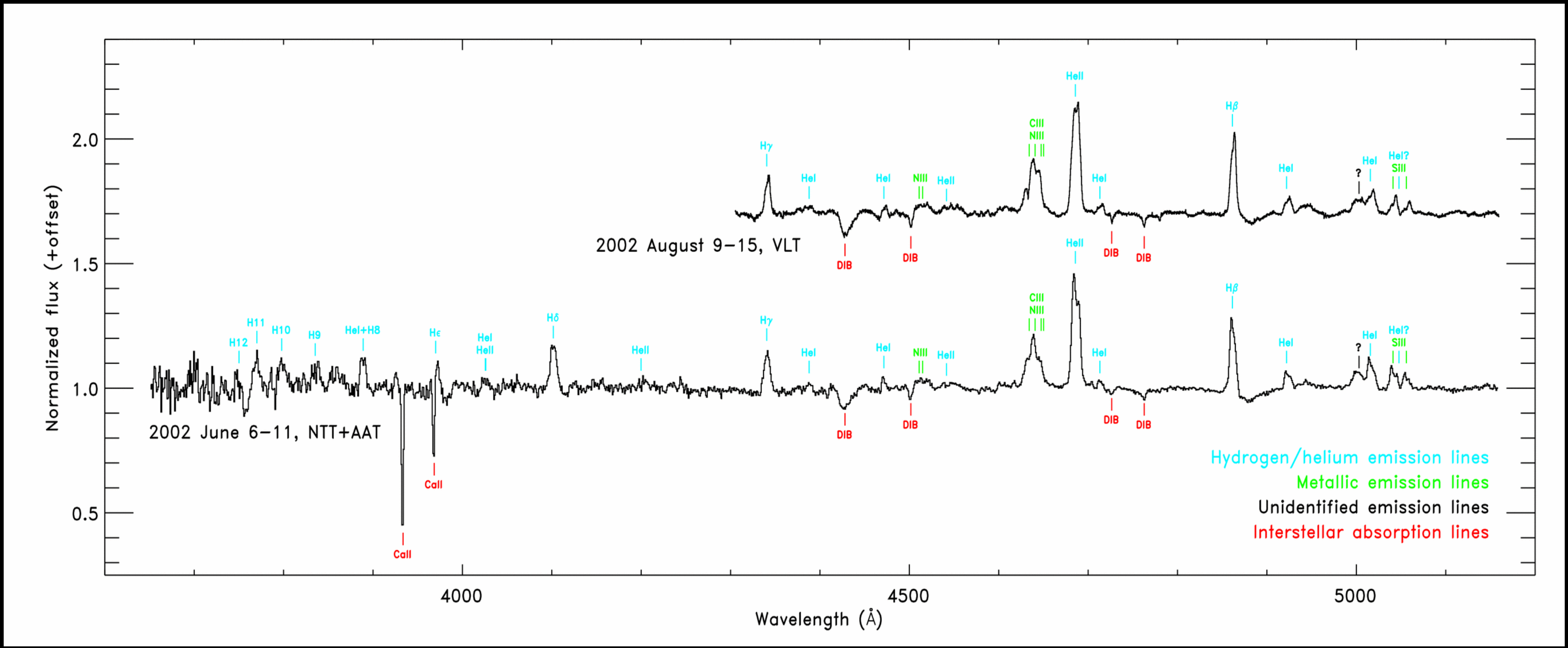
→ **New window to measure *f(M)* in ~ 20 galactic LMXBs**

GX 339-4

Hynes et al. 2003 ApJ 583 L95

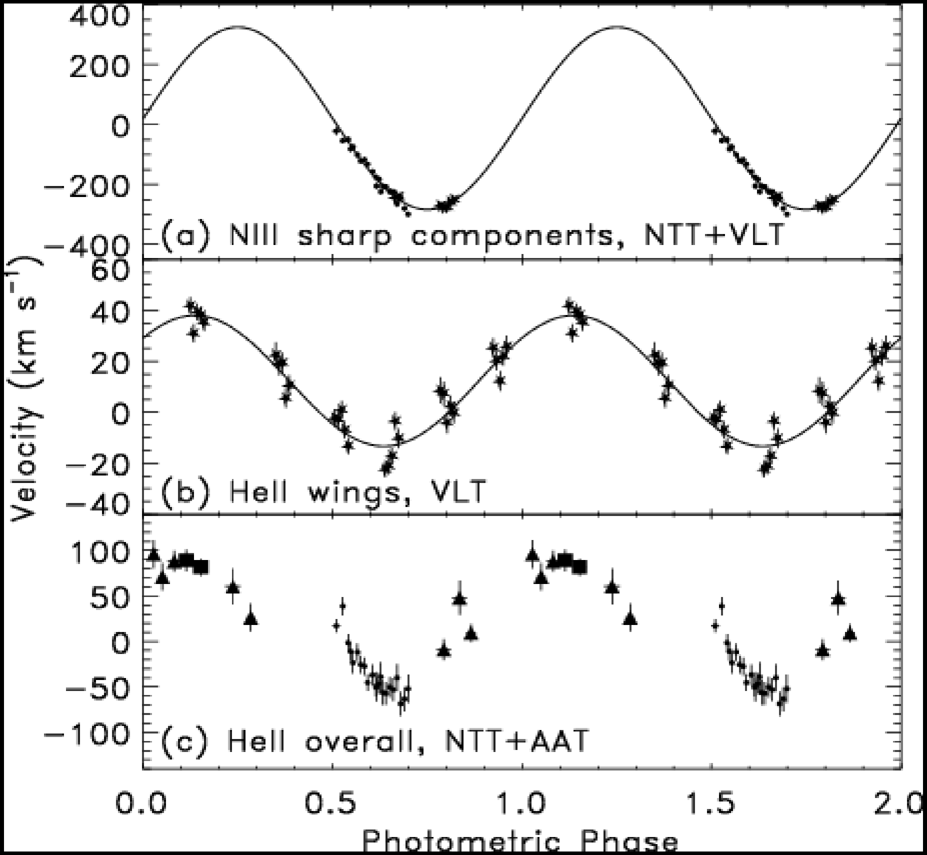
Classic Black Hole candidate based on X-ray properties

Outburst in 2002 (i.e. ToO!) → AAT+NTT+VLT campaign



GX 339-4

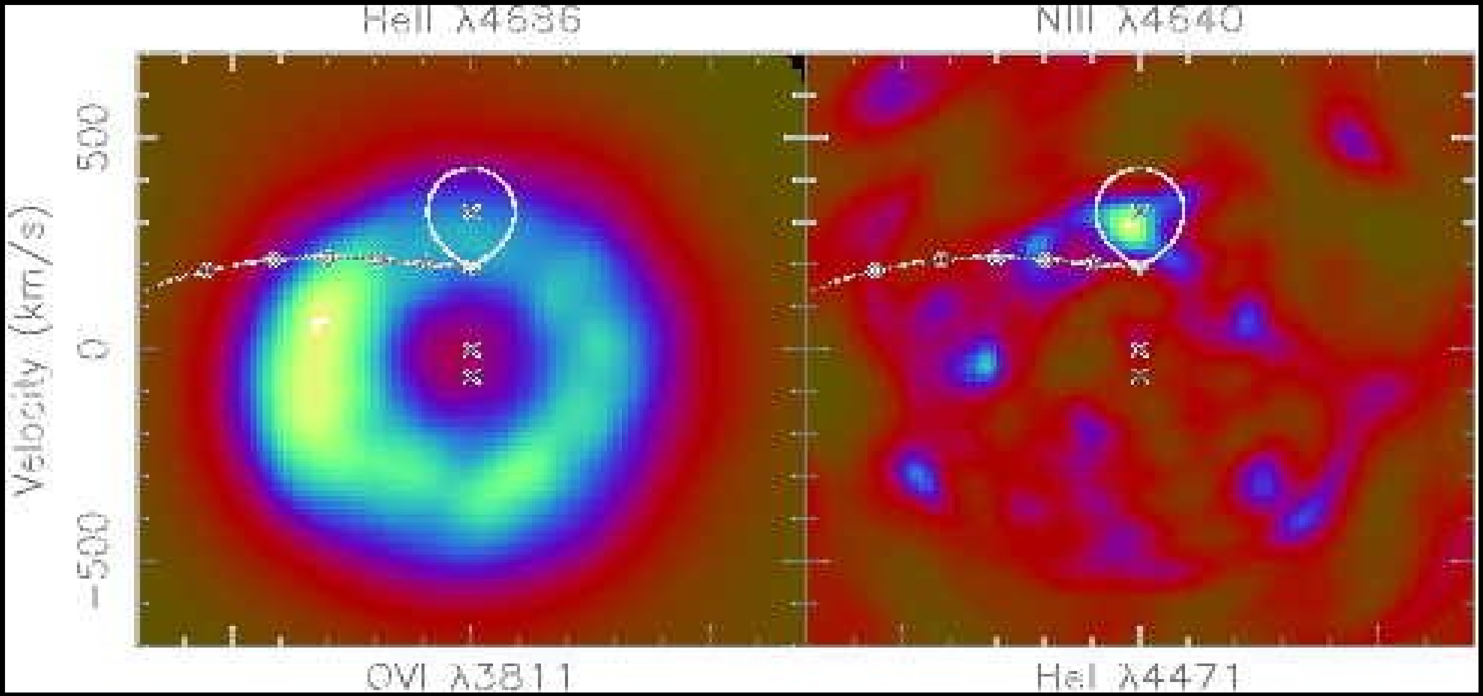
Multigausian fit to NIII, fixing P=1.76 d (from HeII radial velocities)



$K_{em}=317 \pm 10$ km/s $\leq K_2$ $\longrightarrow$ $f(M) \geq 5.8 \pm 0.5\ M_{\odot}$ Black Hole!!

X1822-371

Doppler Tomography → $K_{em} = 300 \pm 8$ km/s ≤ K

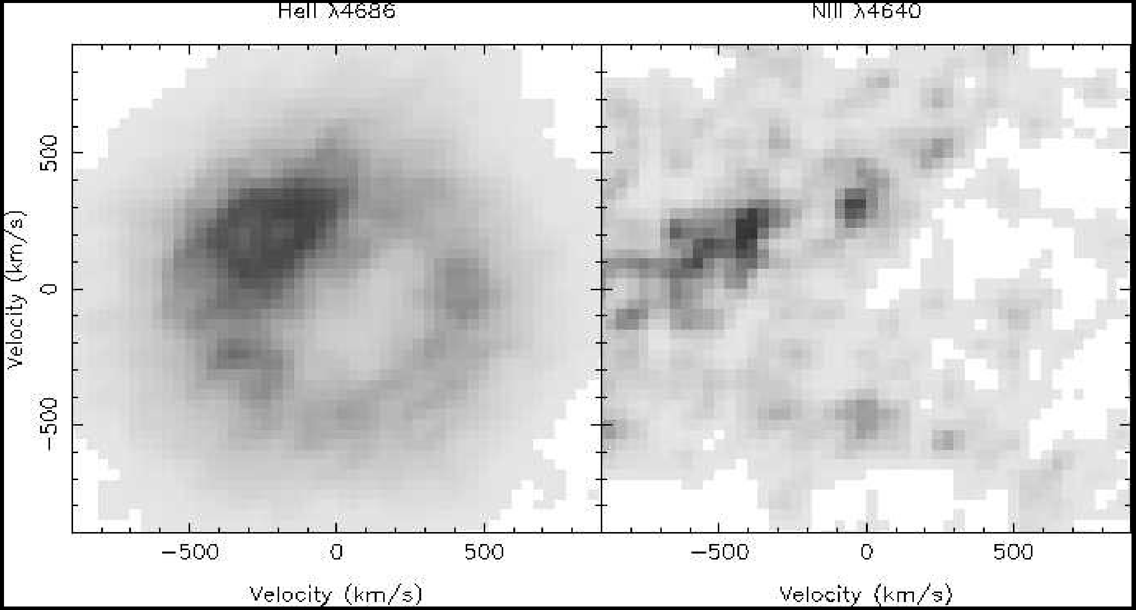


→ **$M_1 \geq 1.14(6)\ M_\odot$** **$M_2 \geq 0.36(2)\ M_\odot$**

K-correction: $K_{em}/K = 1 - f\, q^{1/3}\, (1+q)^{2/3}$ with $f \leq 1$

ToO observations of XTE J1814-338

Millisecond Transient pulsar with P_{spin}= 3ms and P_{orb}=4.2 hr (Markwardt et al. 2003), discovered on June 6 2003.



VLT 23 June 2003

- 20x12m spectra = 1 cycle

K_{em} =345 ± 19 km/s ≤ K_2

$i \geq 42_o$ (M_X<3.1 $M_\odot$)

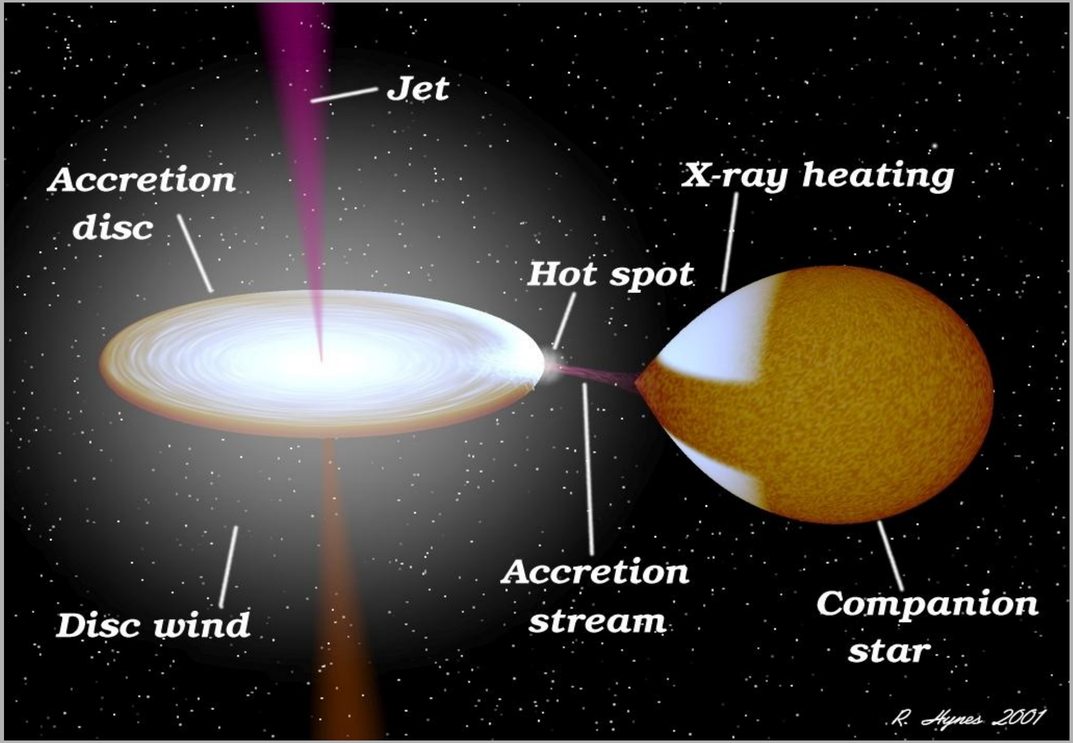
$i \leq 71_o$ (no X-ray eclipses)

M_X = 0.8-2.4 $M_\odot$

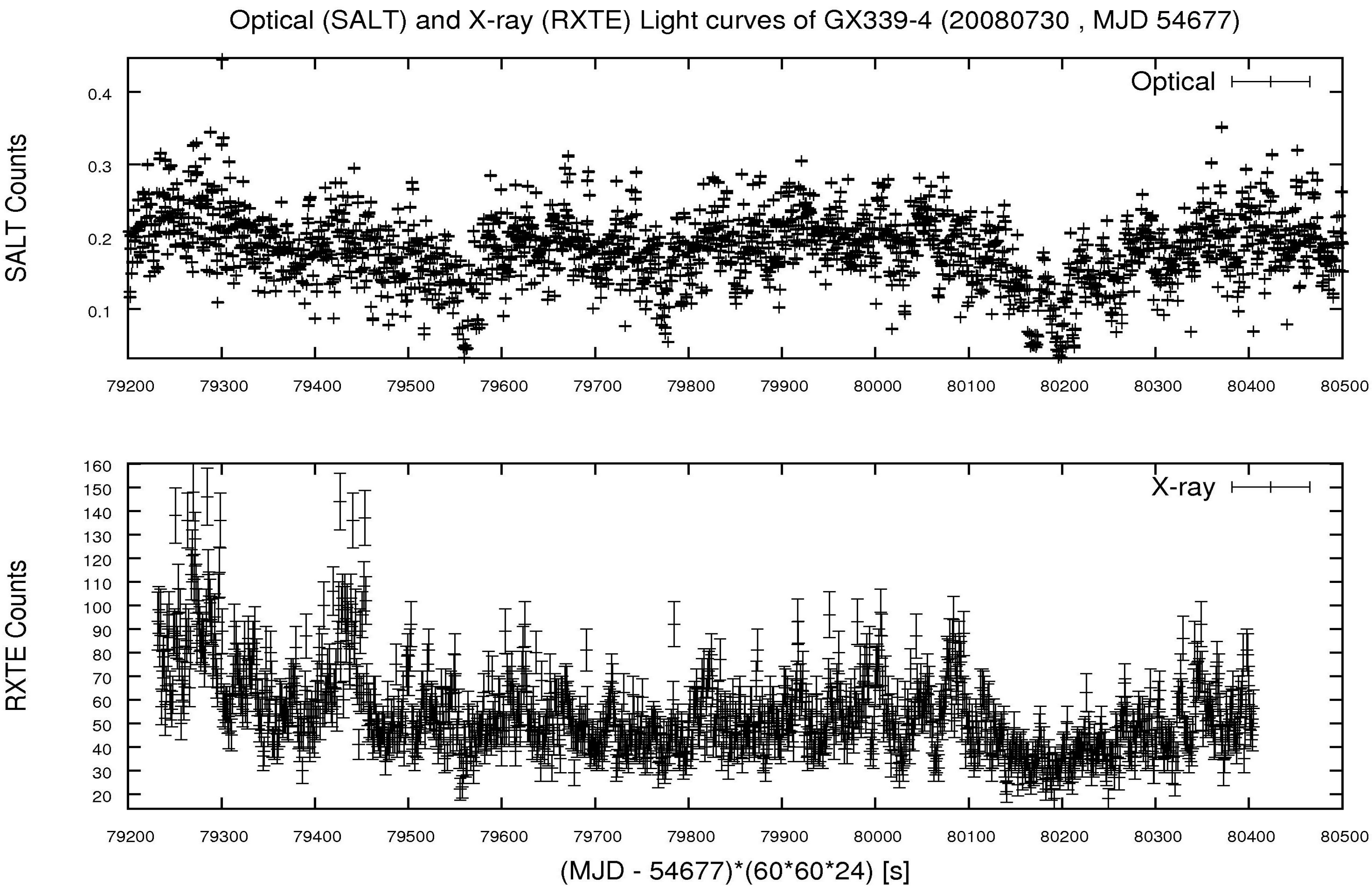
M_2 = 0.12-0.52 $M_\odot$

X-ray Periodicities in XRB

- Typical X-ray Periodicities < 10 days:
  - P_{spin} ~1ms – 1ks
  - P_{QPO} ~1ms – 1ks
  - $P_{flicker}$ ~ 1s – 1hr
  - P_{orb} ~1hr – 10 days

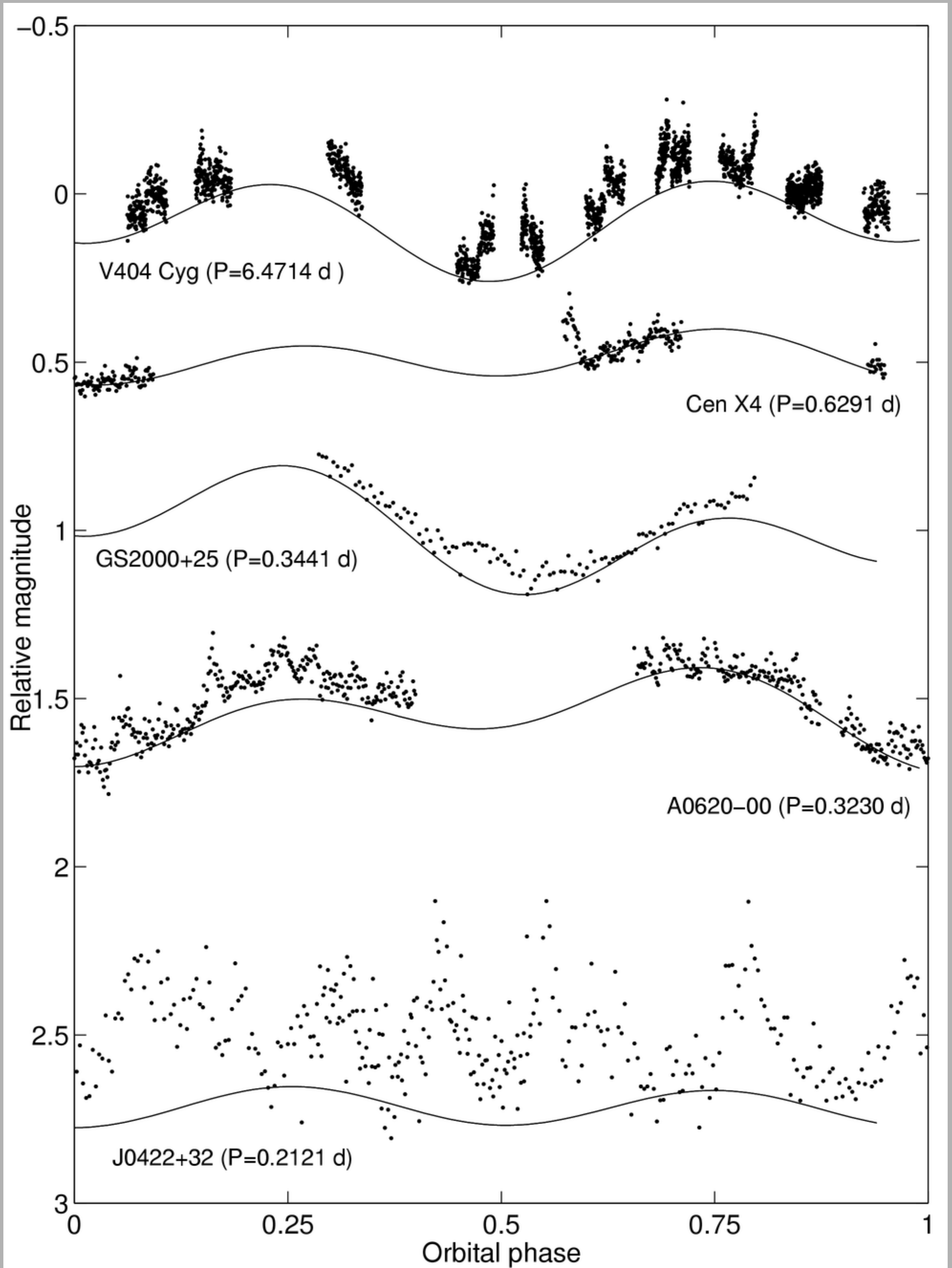


- Long-term (*non*-orbital) periodicities (mostly in X-rays) have been discovered from ~ 20 XRBs

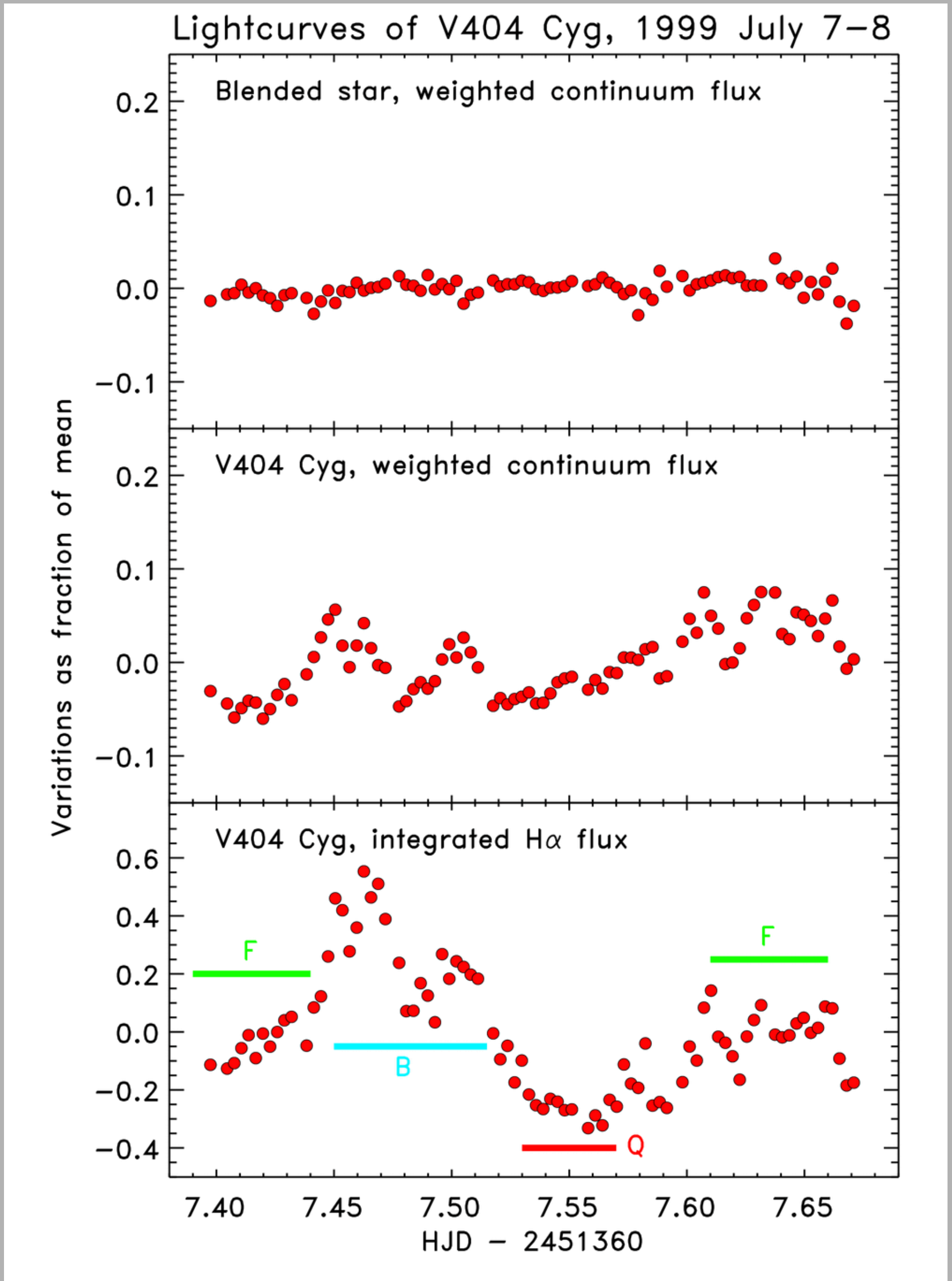


Marissa Kotze (SAAO/UCT)

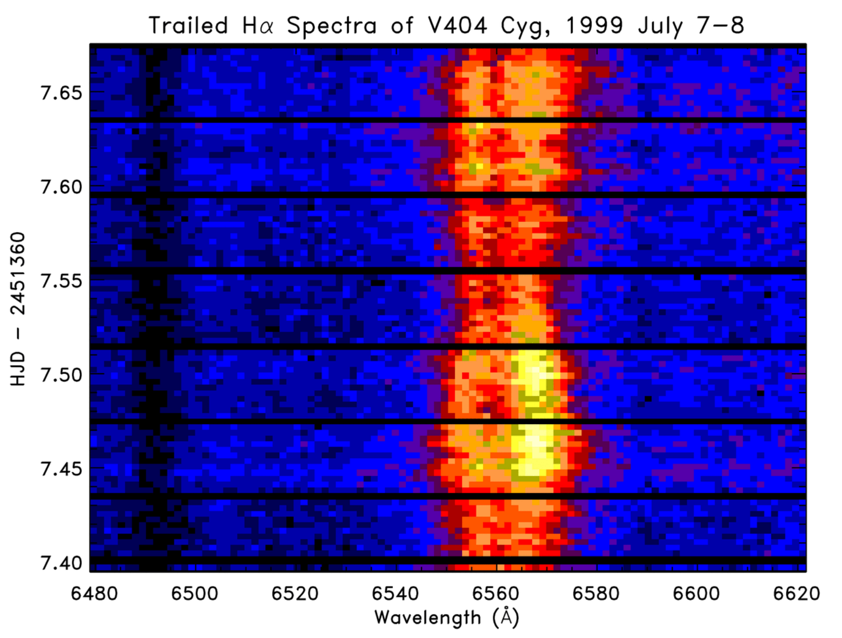
5 Quiescent Transient Optical Lightcurves

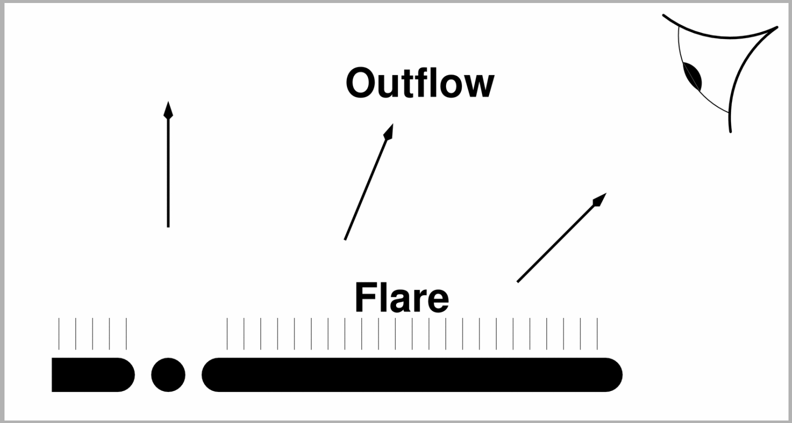


WHT/ISIS fast spectroscopy of V404 Cyg



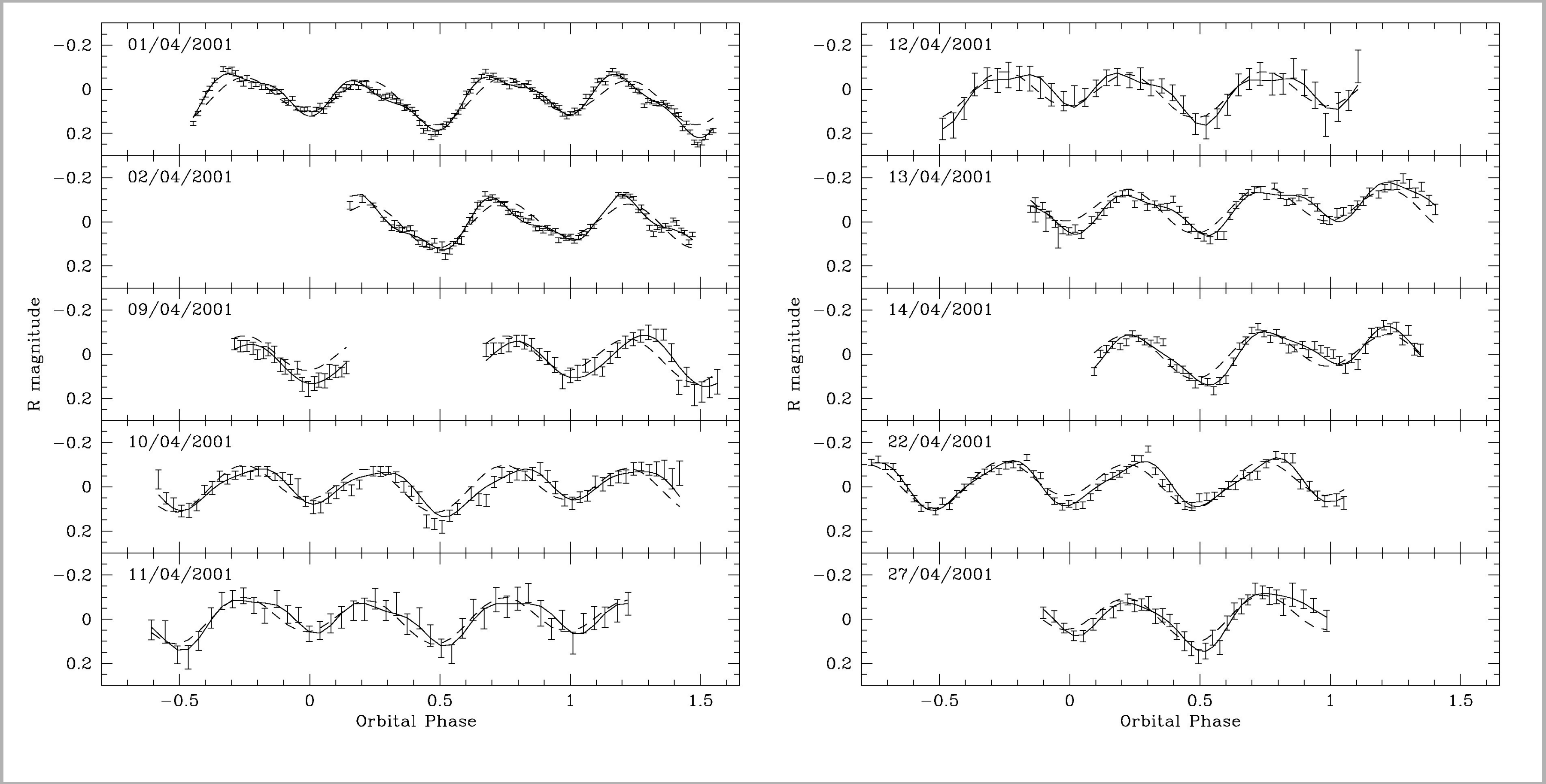
Trailed spectrogram showing flares





N.B. red asymmetry is not phase dependent
-could be absorption of blue wing by disc
-key point is likely mass loss as well as accretion

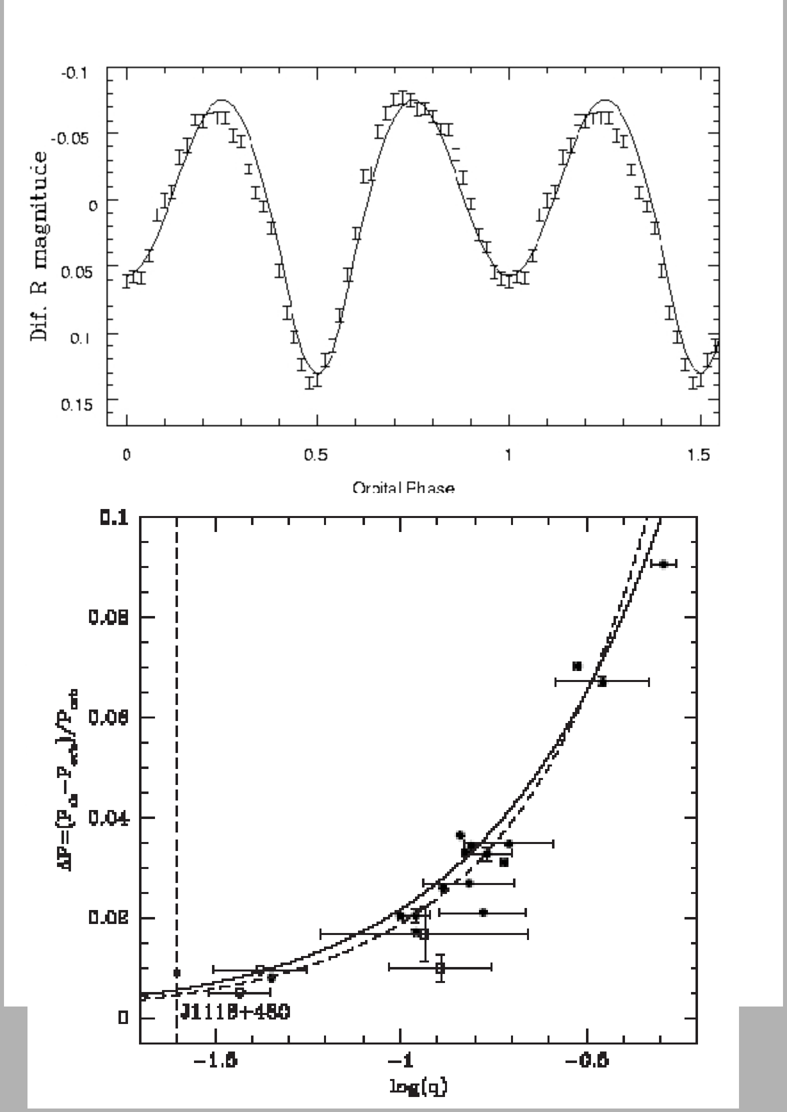
- Precessing disc in decline phase of J1118+480 (Zurita et al 2002)



Zurita et al 2002 MN 333, 791

- Ellipsoidal modulation well defined by many months of observations
- After subtraction, superhump P is present with differential of only 0.3% (wrt Porb)
- i.e. ~52d precession P (Hα→spectroscopic evidence for motion on this P)
- Simulations of precessing disc show that P differential is smaller if *q* is larger

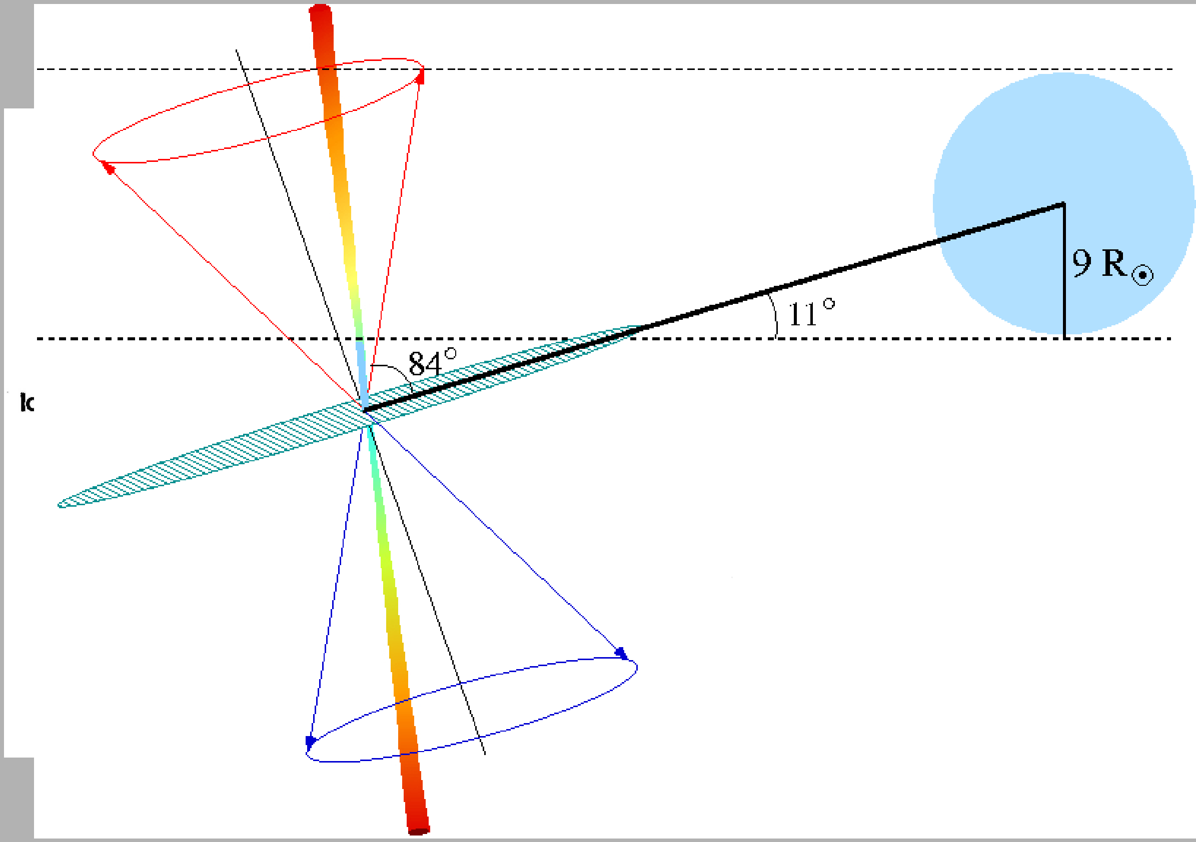
- Hence photometry of SXTs in outburst can yield constraints on *q* → **importance of complementary small telescope monitoring**



J1118+480 mean light curve

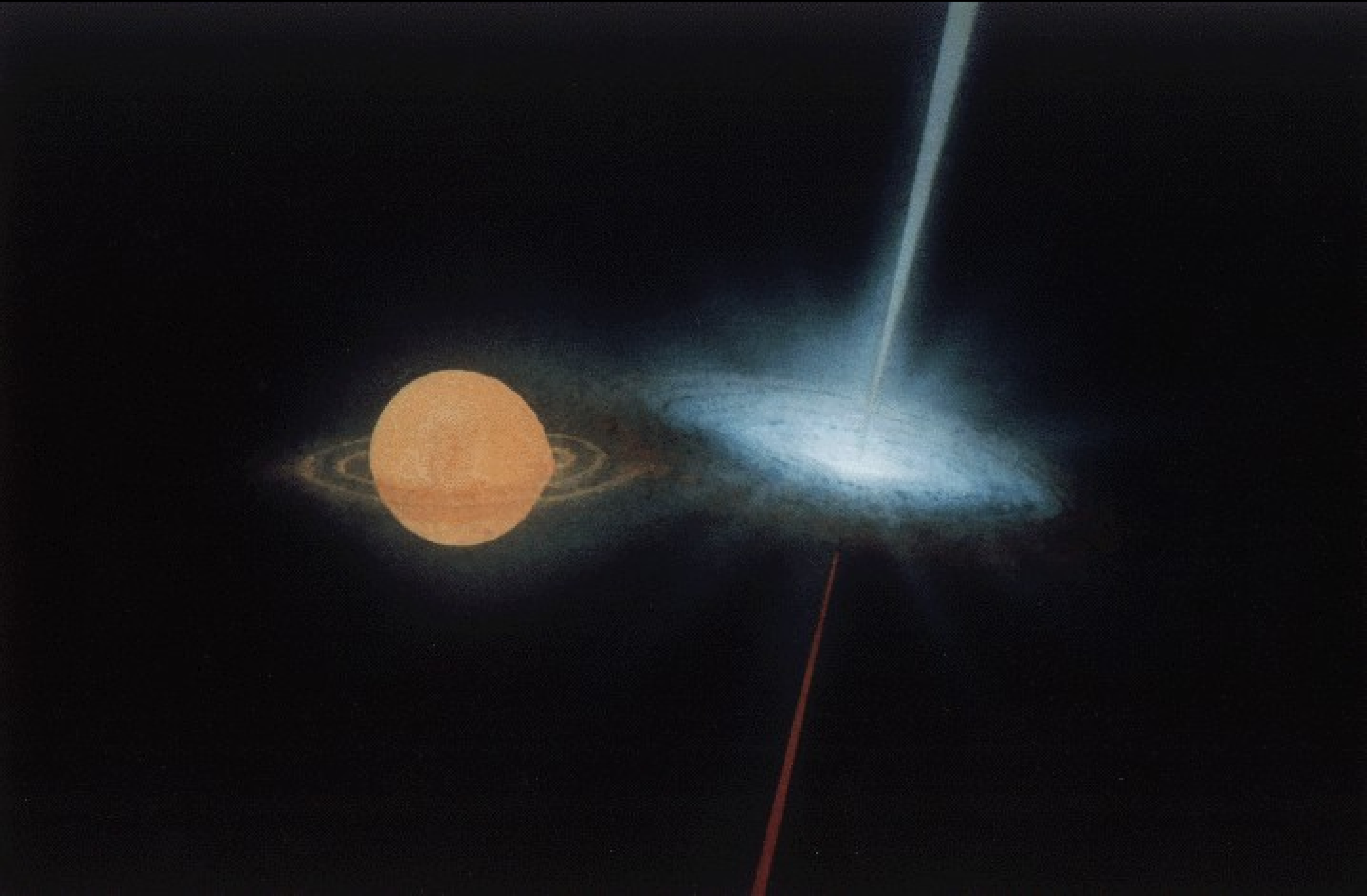
SS433

- SS 433: original relativistic jet source in the Galaxy
- only continuously emitting micro-quasar
- key feature: 162d precession observed for >2 decades
- *moving* emission lines well explained by Kinematic Model (Margon 1984 ARAA)
- weak X-ray source $L_X \sim 10^{36}$ erg/s but jet KE ~ 10^{40} erg/s
  - → link to Ultra-Luminous X-ray sources (ULX)!
  - i.e. if Eddington-limited, require $M_X > 10\ M_\odot$
- 13d P → likely HMXB with ~B donor → v high mass transfer rate ~ $10^{-4}\ M_\odot$/y



System parameters:

- $v = 0.265c$ $d = 5.5$ kpc
- $P_{prec} = 162.5$d $P_{orb} = 13.1$ d
- $i = 79^\circ$ $\theta = 11^\circ$
- $e < 0.05$



Fundamental Property: Precessing jets and discs

- ~20 XRB exhibit X-ray "Superorbital" $P_{long} > 10$ days
  - see e.g. Clarkson et al 03

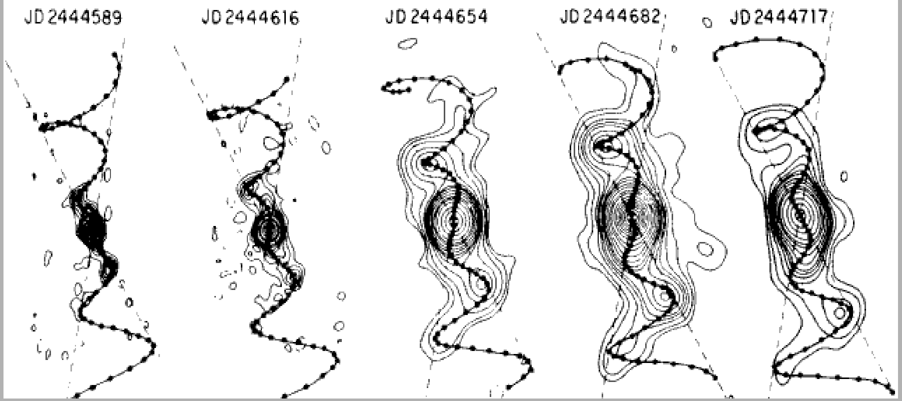
- Some examples:

Seen with X-ray All Sky Monitors, e.g: Ariel 5, BATSE, RXTE

Neutron Star XRB		Black Hole XRB	
Her X-1	35d	**SS433**	160d
LMC X-4	30d	LMC X-3	99d
SMC X-1	50-70d	J1716-389	99d
Cyg X-2	50-80d	4U1957+11	117d
		GX339-4	190-250d

XRBs ideal to study disc properties, because:

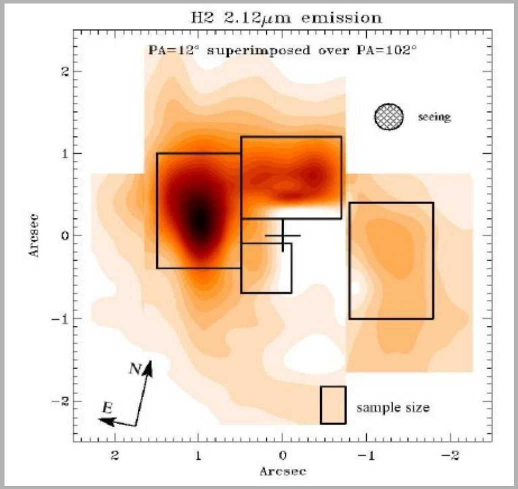
- (Precessing) disks and/or warps are becoming ubiquitous:



4885 MHz VLA maps of SS433

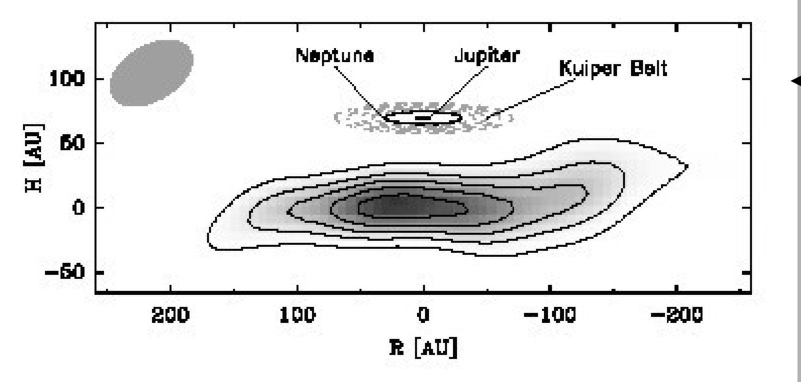
Microquasars

AGN



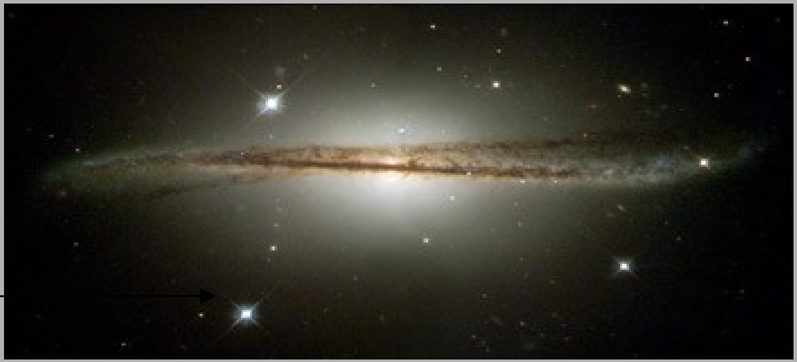
NGC 1068 with VLT/ISAAC

YSO's

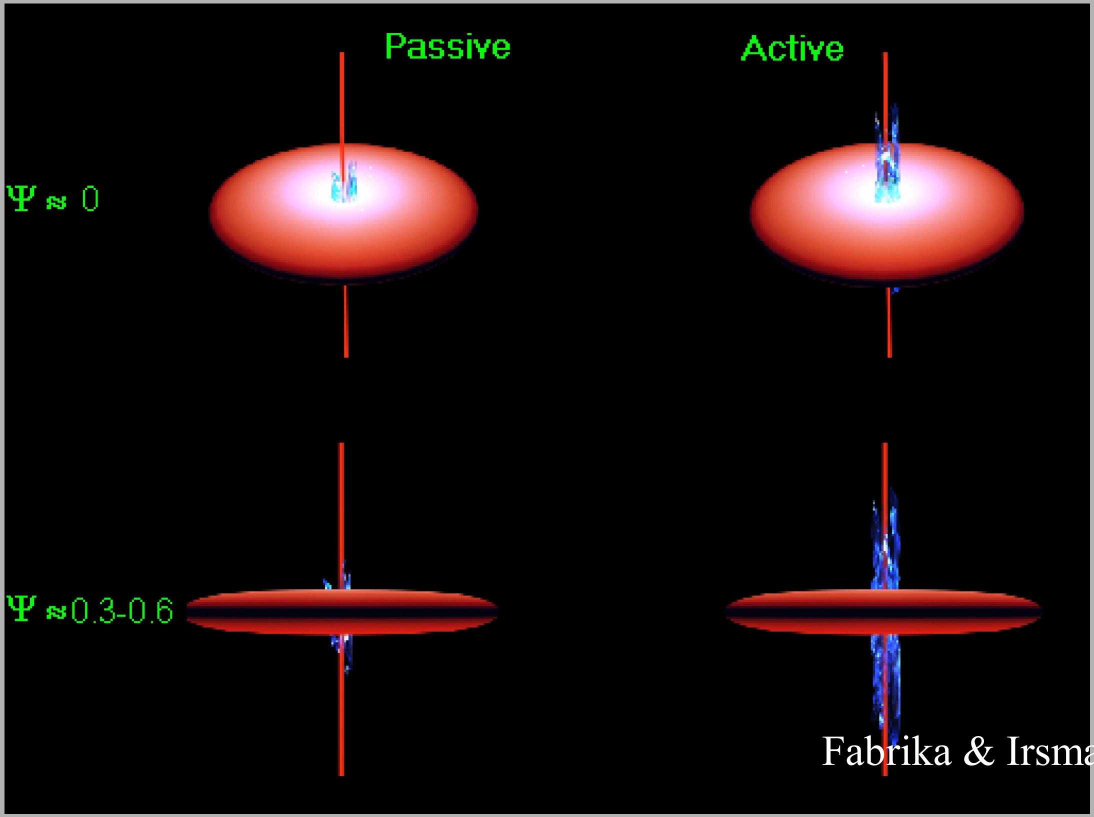


CO (1—0) emission from Bok Globule BC26

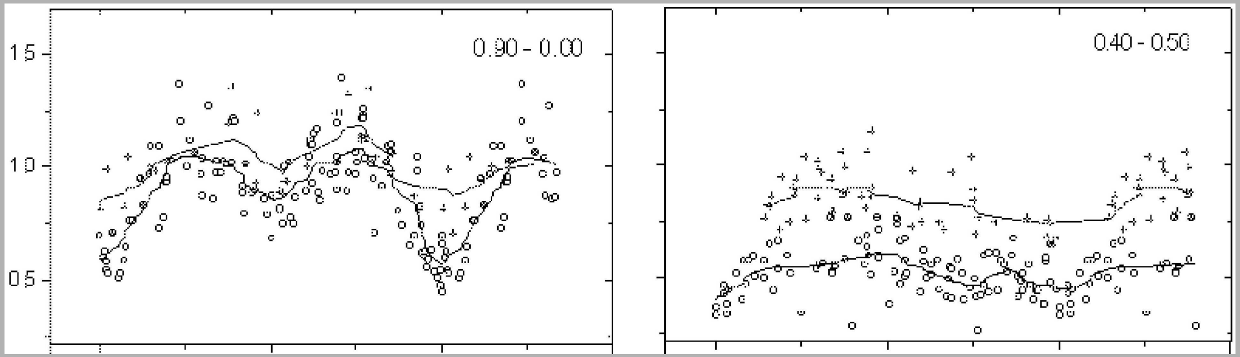
Galactic Disks



Warped Spiral Galaxy ESO 510-G13



Fabrika & Irsmambetova 02

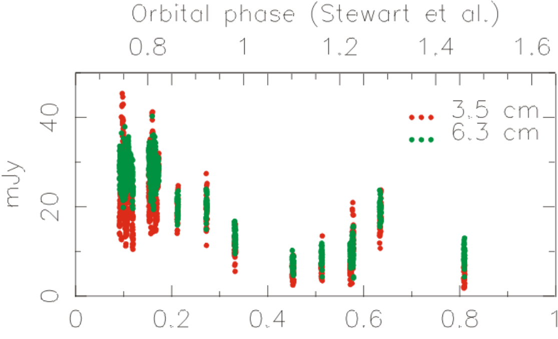


Importance of long-term observations of HMXBs:

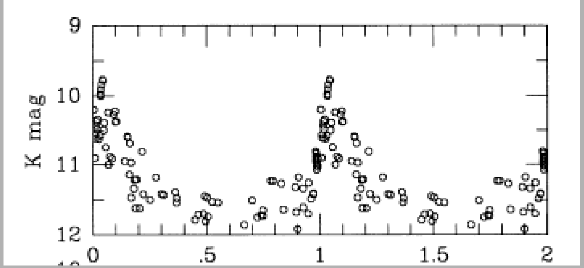
- need more systematic coverage of all orbital and precessional phases with high resolution, high S/N blue spectroscopy (impossible amount of observing time, but ideal for Q-scheduled telescopes like SALT!)
- probable ULX if seen close to jet axis (i.e. non-isotropic)
- other candidates for galactic ULXs, including (at least) two neutron stars (A0538-66; Cir X-1)!
- other BH HMXB candidates: J1716-389, INTEGRAL high N_X sources

Cir X-1: An (Old/Young), (High/Low-mass) X-ray Binary

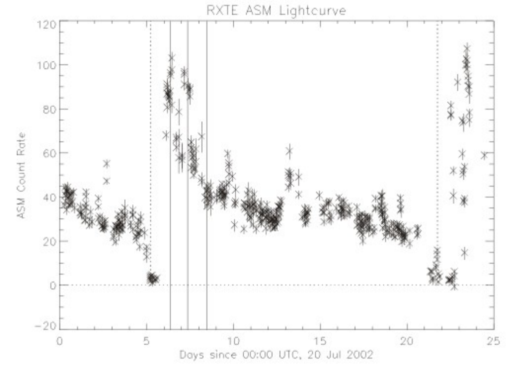
16.6 d Orbital Cycle



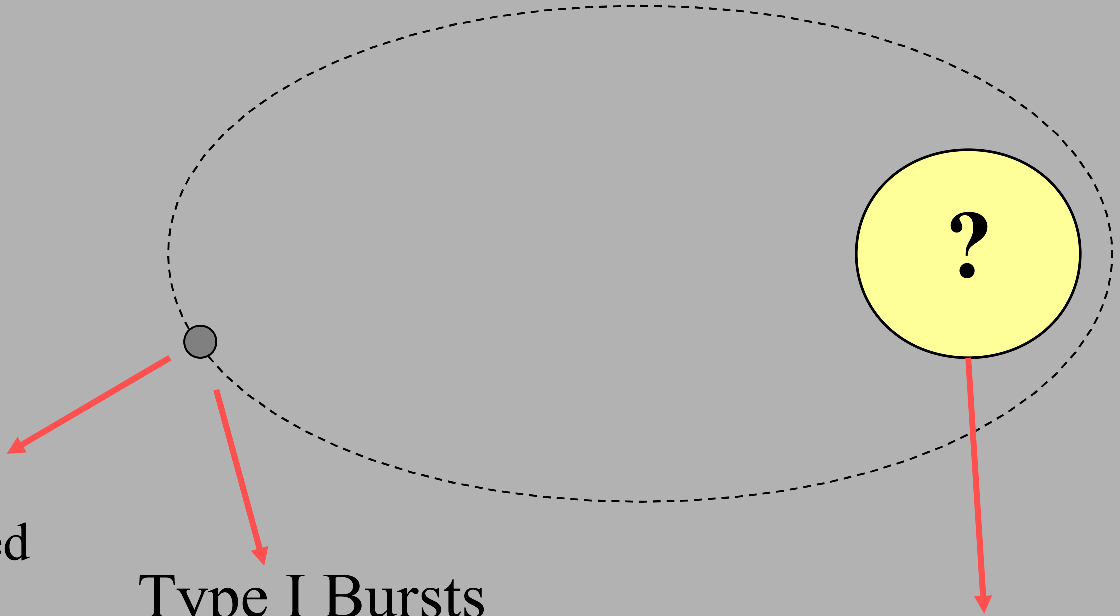
Radio



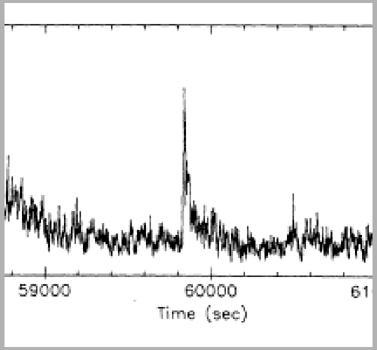
Infrared



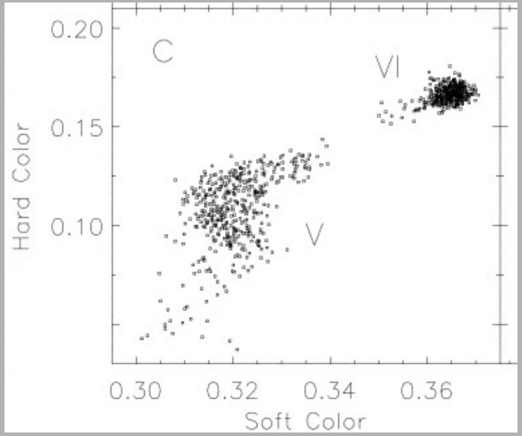
X-ray



Type I Bursts

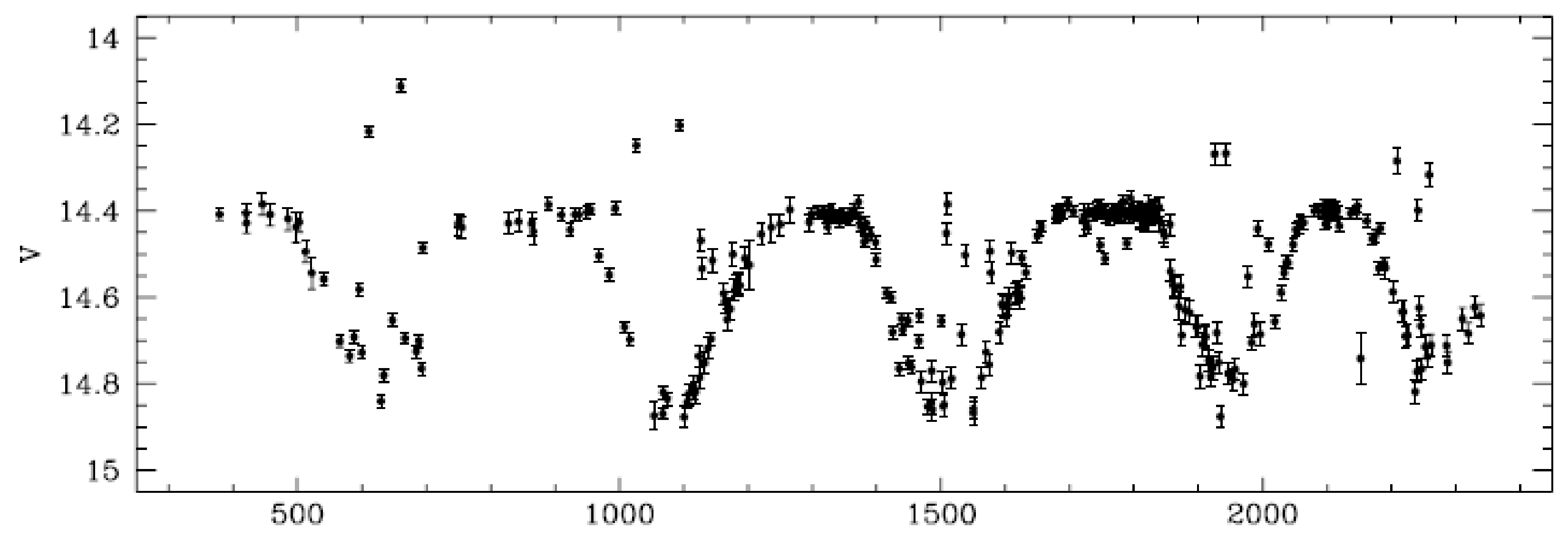


HB QPO's Present

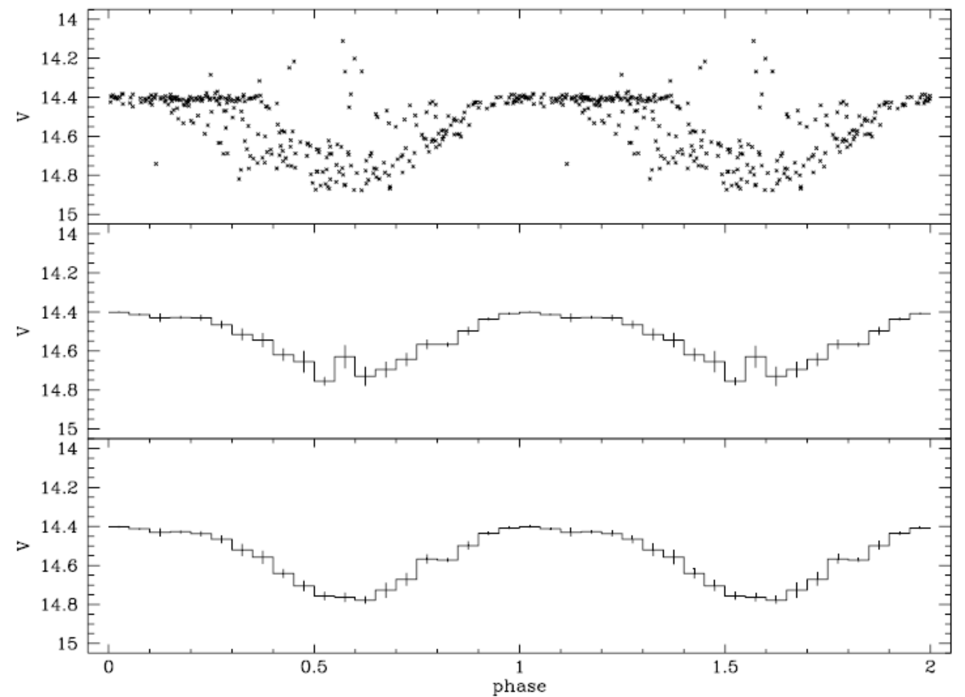


(Tennant et al 1986, Glass 1994, Fender et al 1998, Shirey et al 1998)

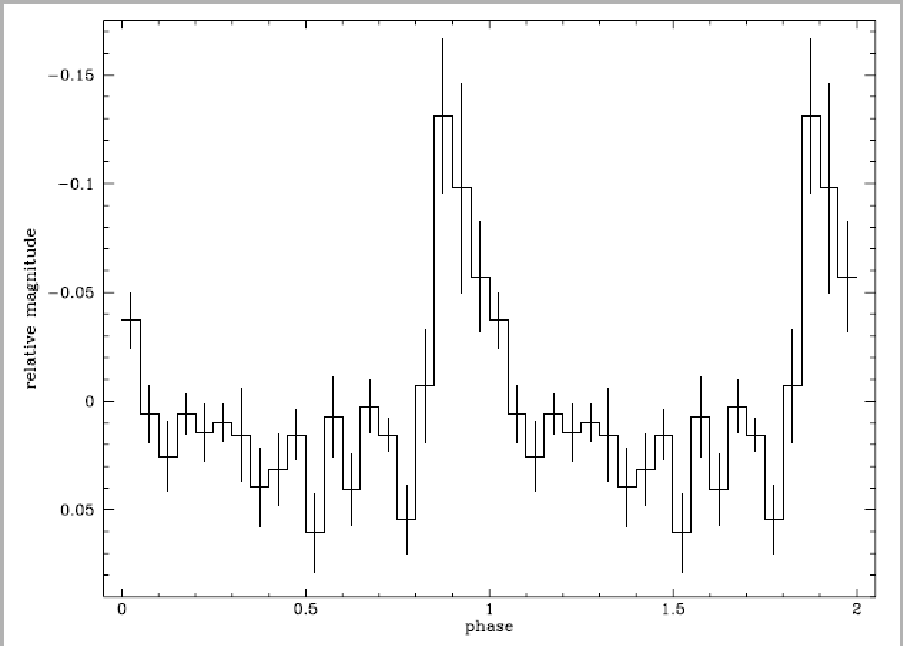
MACHO light-curve of A0538-66 (McGowan et al)



contains a 421d cycle:



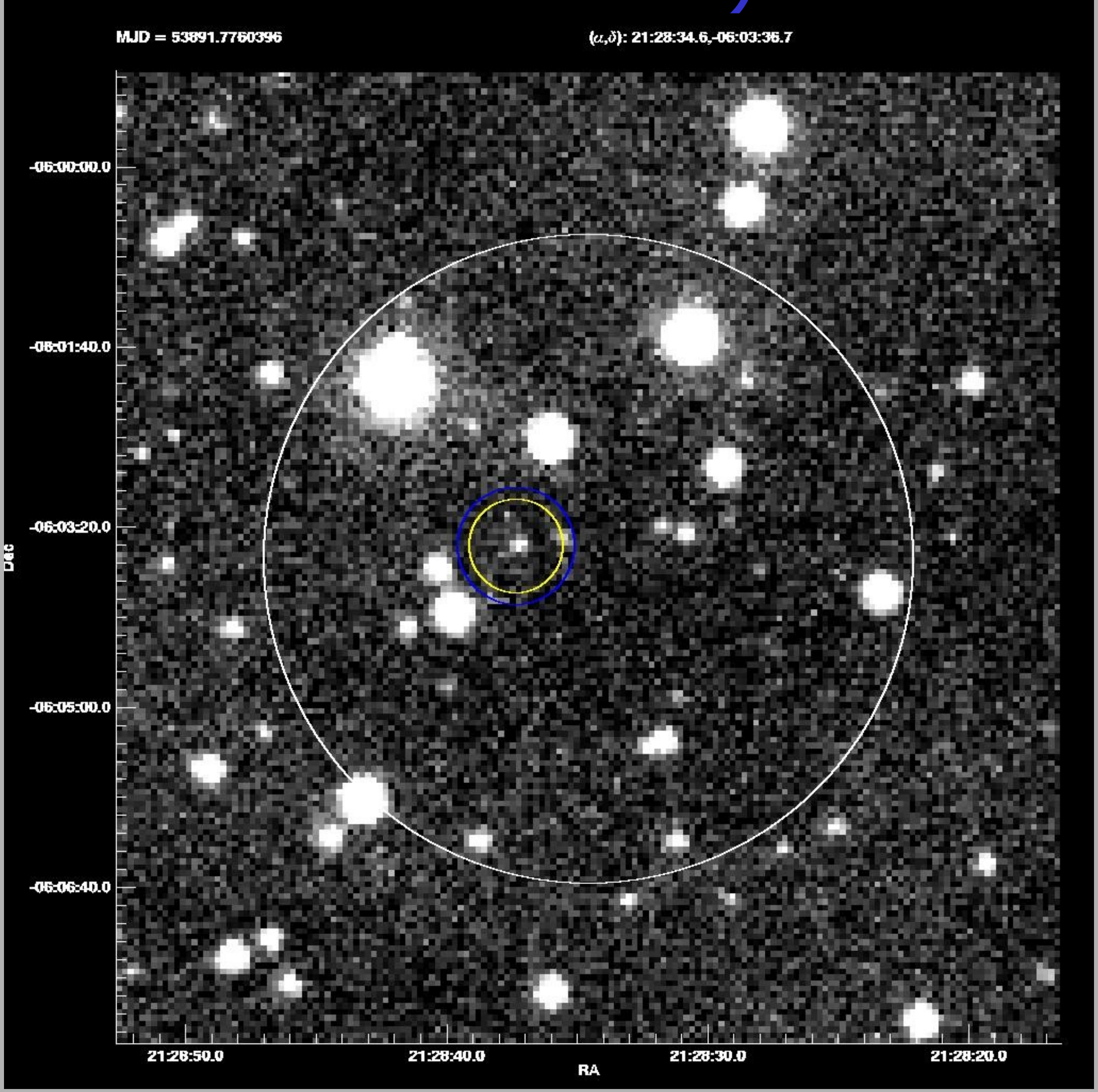
and the 16.6d orbital cycle:



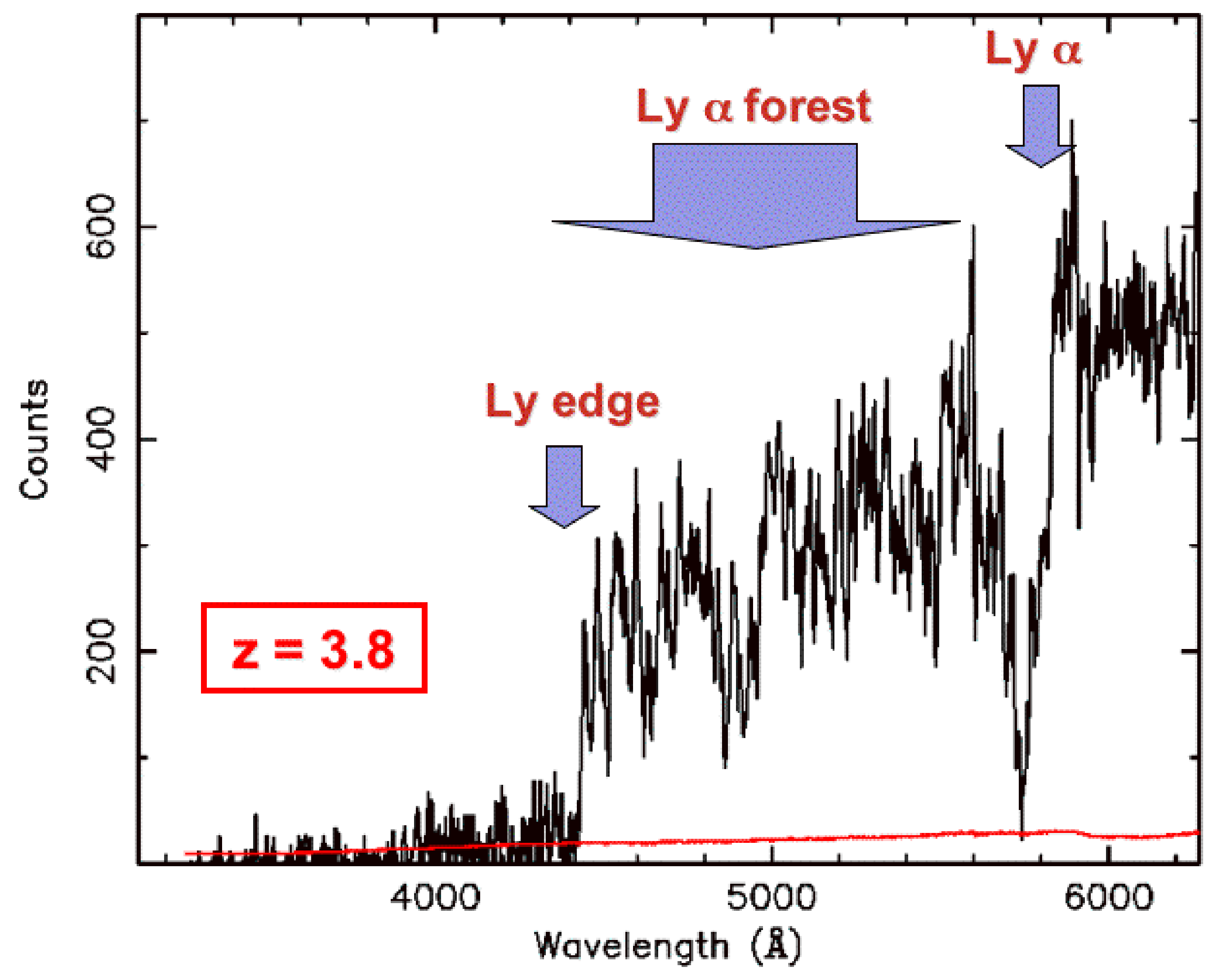
GRB 060605 (SA & U. North Carolina)

SALT Observations ~8 hours After alert

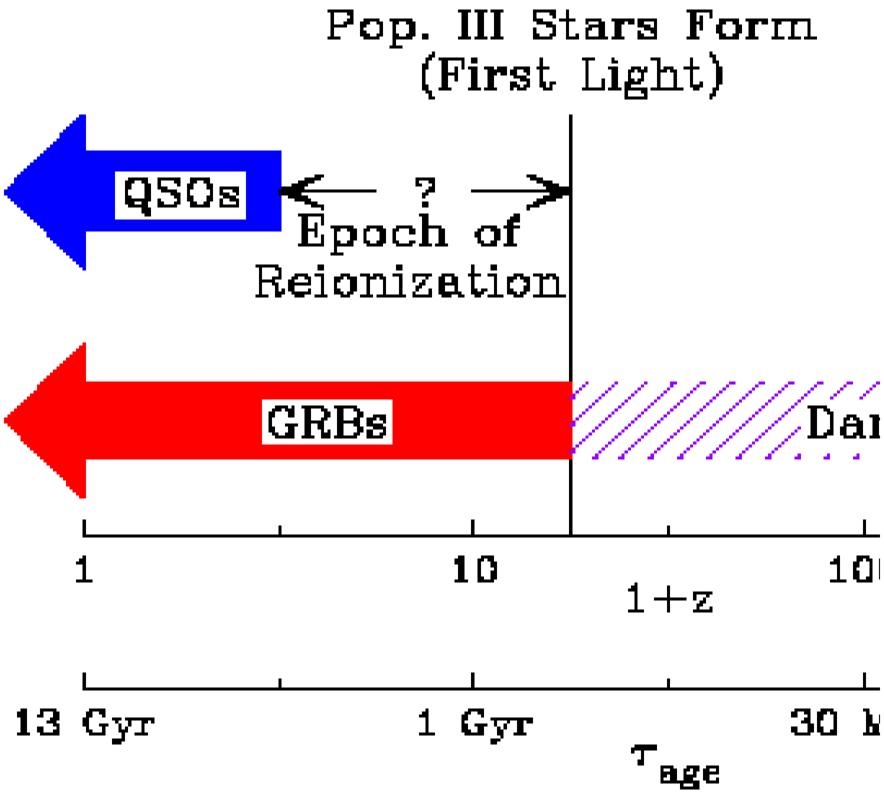
- **MSSSO obs. at V ~ 15**
- **SAAO obs. at V ~ 20**

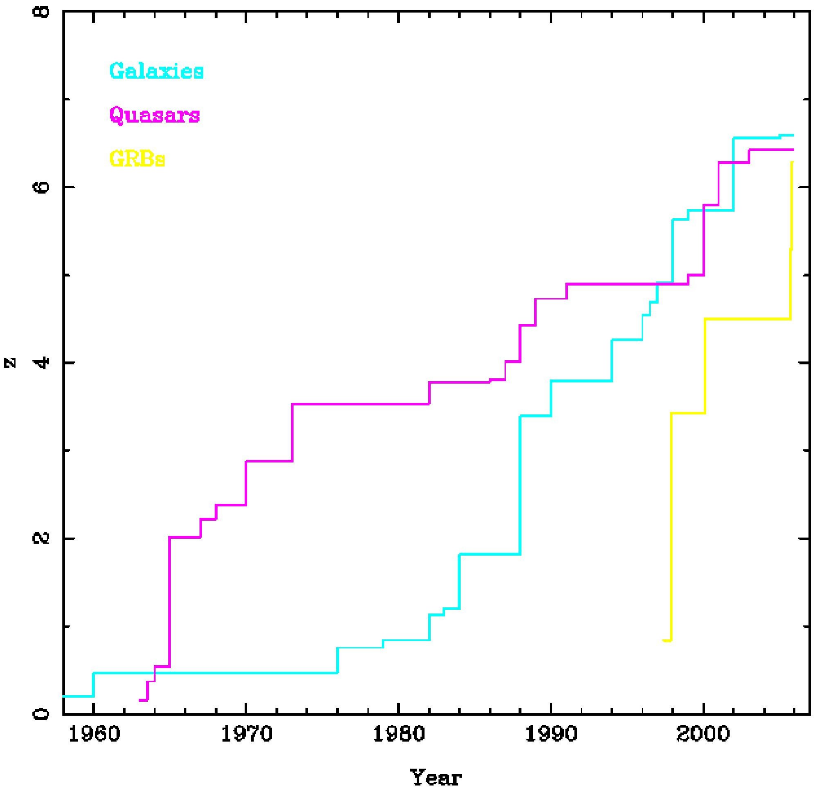


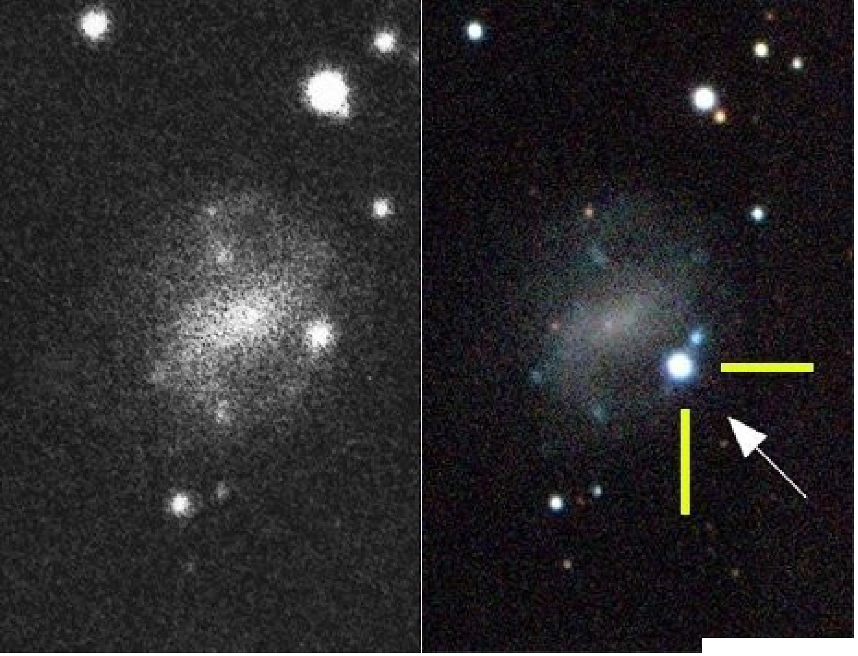
GRB 060605
(SA & U. North Carolina)

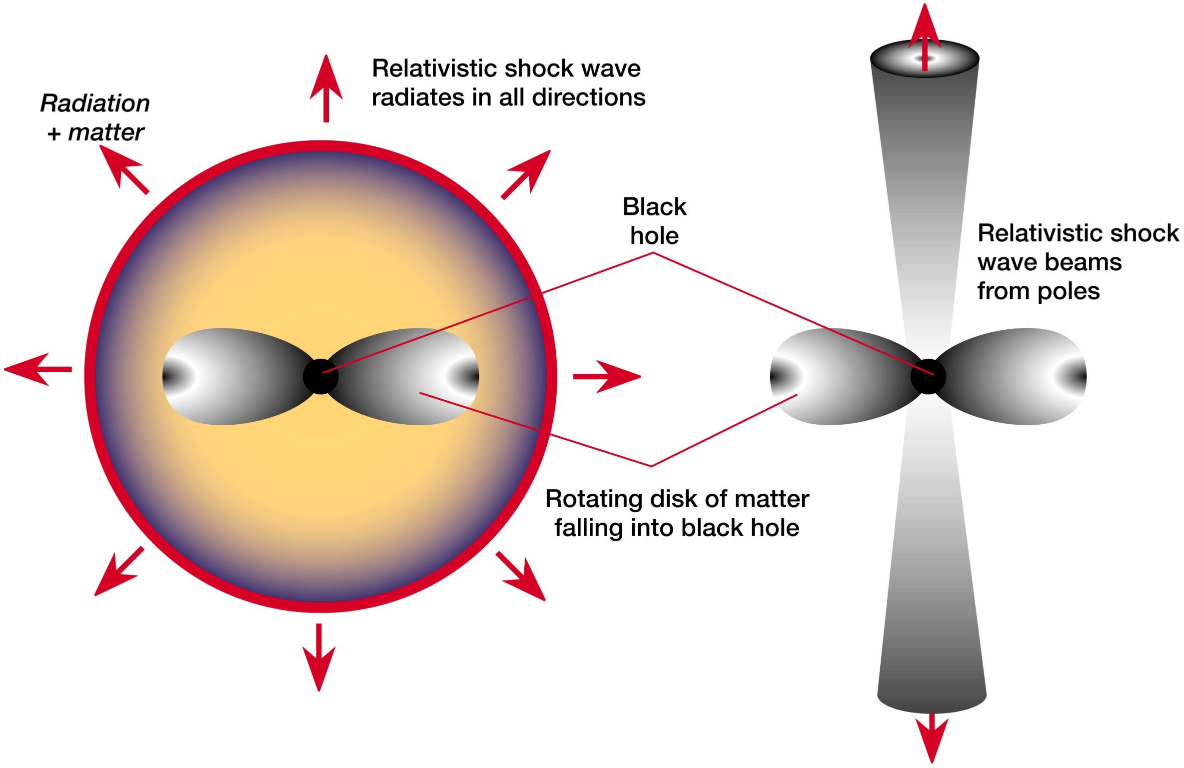


Importance of G

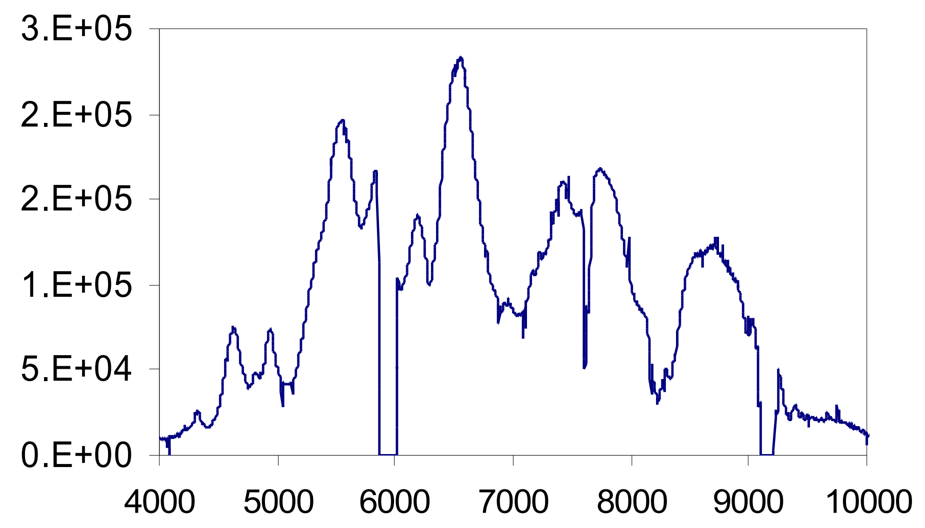


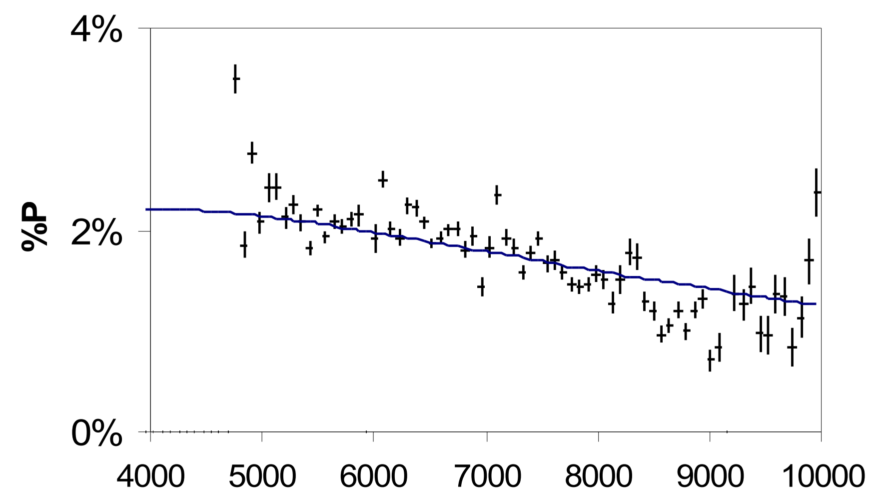





Radiation
+ matter
Relativistic shock wave
radiates in all directions
Black
hole
Relativistic shock
wave beams
from poles
Rotating disk of matter
falling into black hole

On-sky RSS polarimetry commissioning (Oct 2006): Spectropolarimetry of SNe (Nordsieck, Potter)





Spectropolarimetry of SN2006mq

Conclusions and future SALT projects:

- **rapid variability in accreting binaries is a powerful probe of accretion processes close to white dwarfs, neutron stars and black holes**
- **detector developments in the optical (fast read-out, frame-transfer) now allow high speed photometry/spectroscopy to be obtained (only SALT has this as a standard feature!)**
- **after a relatively quiet decade or two, high time resolution observations will bring many new discoveries as SALT operations begin, e.g.**

- **quiescent XRTs for BH/NS masses with minimum assumptions!**
- **fluorescence of secondary in active XRBs (e.g. UCXBs) and future XRTs**
- **monitoring of SS433 on orbital and precessional periods**
- **other galactic ULX candidates, including (at least) two neutron stars (A0538-66; Cir X-1)!**
- **monitoring ULX in optical in nearby galaxies**
- **irradiation-driven warping → superorbital variations in HMXBs → infers properties of accretion disks**

N.B. Large telescopes are not just for observing faint targets, they also allow us to explore new regions of parameter space in relatively bright ‘well-known’ objects – Time Domain Astrophysics is the `new frontier’!