Optical observations of gamma-ray binaries with SALT:

Orbital parameters for the gamma-ray binaries LMC P3 and 1FGL J1018.6-5856

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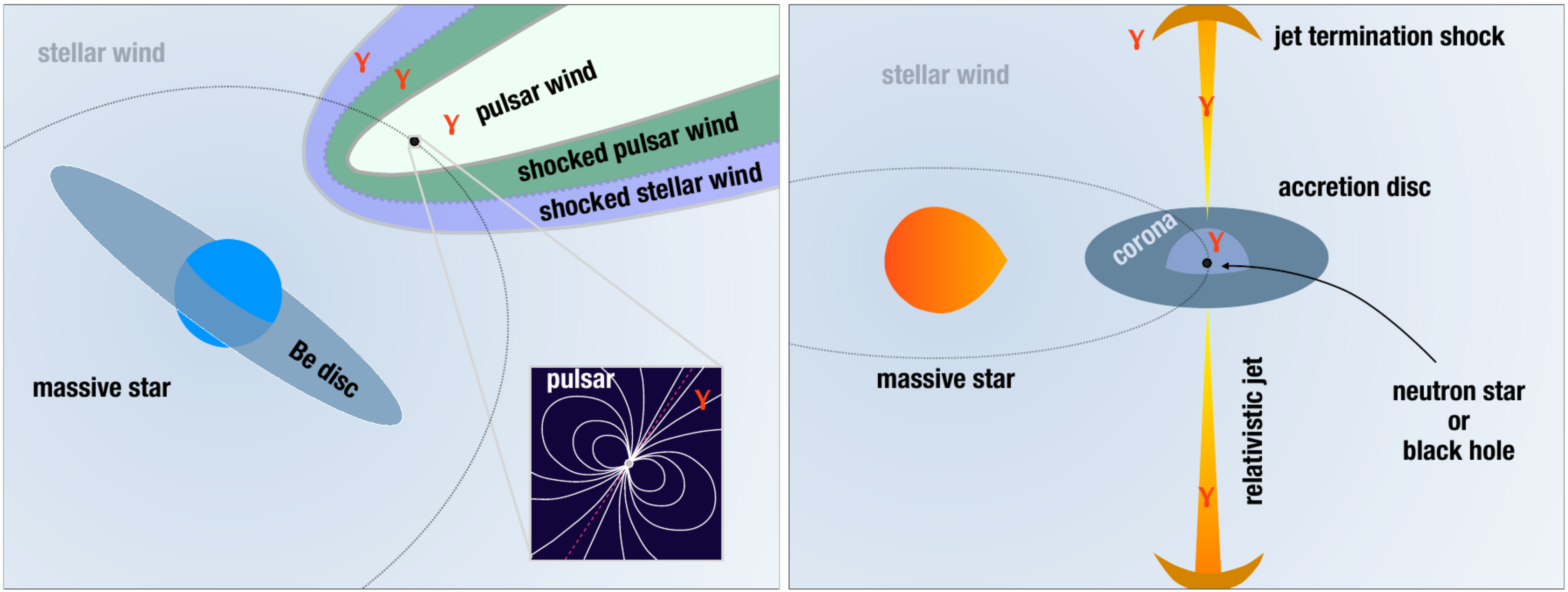
Image credit: H. Szegedi

Gamma-ray binaries



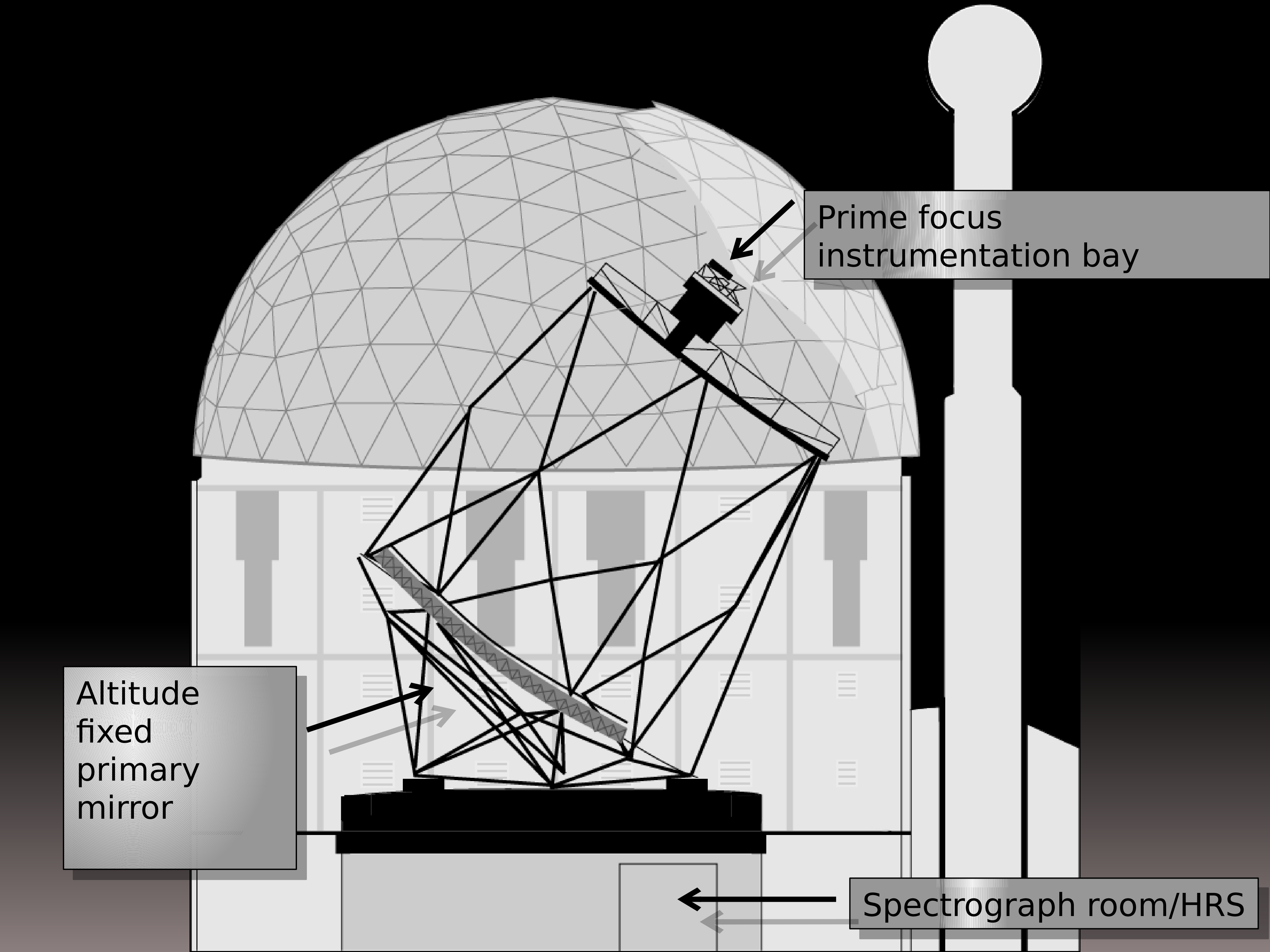
Dubus 2013

Southern African Large Telescope

11-metre optical telescope in the Southern Hemisphere

- An international partnership
  - South Africa/NRF
  - USA (Dartmouth/Wisconsin/Rutgers)
  - Germany
  - Poland (Nicolaus Copernicus Astronomical Centre)
  - India
  - UK
  - New Zealand

- **Routine science operations since late 2011**
  - RSS – longslit, MOS, spectropolarimetry, Fabry-Petor modes
  - HRS – fibre feed high stability spectrograph
  - BVIT – High speed photometry (visitor instrument)
  - SALTICAM - photometry


Prime focus
instrumentation bay
Altitude
fixed
primary
mirror
Spectrograph room/HRS

High Resolution Spectrograph

- Dual-beam fibre fed, Échelle spectrograph
- Blue and red arms operating between 370-550 nm & 550-890 nm respectively
- There are three modes
    - Low Resolution, R ~14,000
    - Medium Resolution, R~40,000 and
    - High Resolution, R~65,000
    - High Stability, R~65,000
- Wavelength calibration was performed using the pipeline discussed in Kniazev, Gvaramadze & Berdnikov (2016).

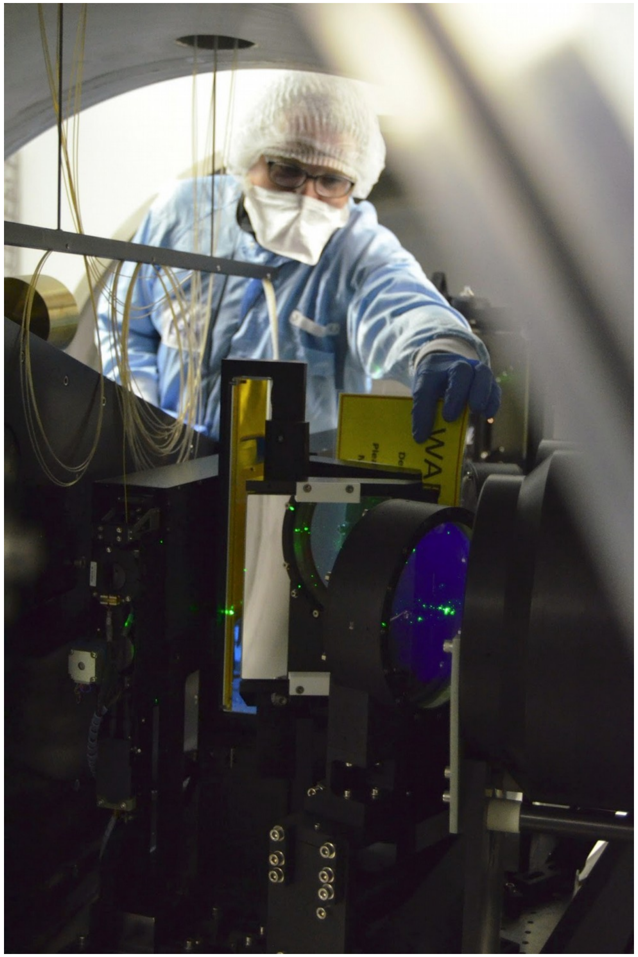


Image credit: Lisa Crause

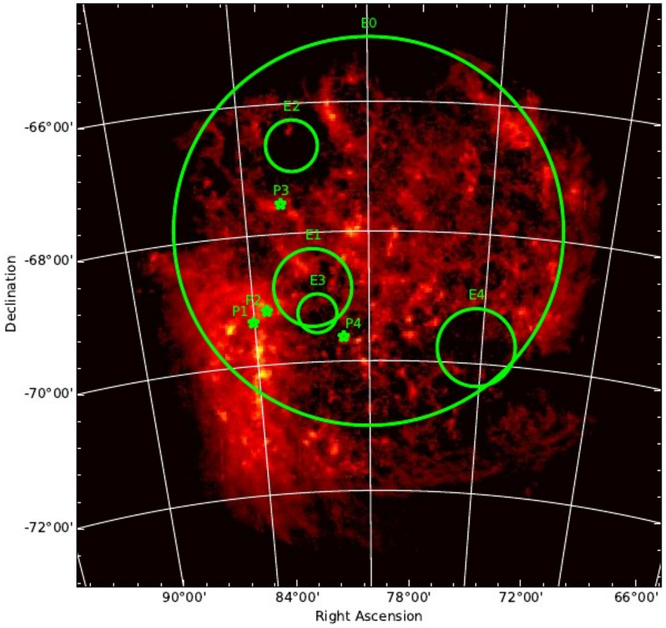
LMC P3

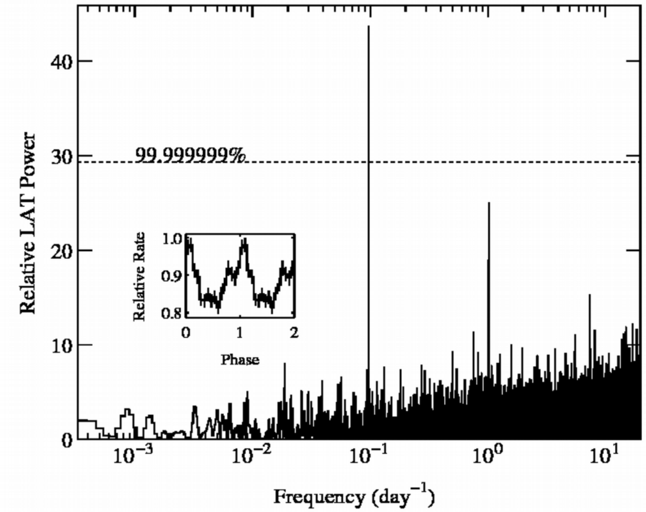
- Gamma-ray emission was identified as as part of the Fermi-LAT deep observations of the LMC (Fermi-LAT Collaboration 2016)
  - Detected as a point-like sources with no known counterpart

- That sources was identified through a search for periodic emission in the Fermi-LAT data which subsequently found a 10.301 ± 0.002 days period (Corbet et al. 2016)

- The source was co-incident with the X-ray source CAL 60/CXOU J053600.0-673507 which has previously been identified as a potential binary system (Crampton et al., 1985; Seward et al., 2012)

- The optical star is identified as a 05 III(f) type star, the earliest of all the gamma-ray binaries.

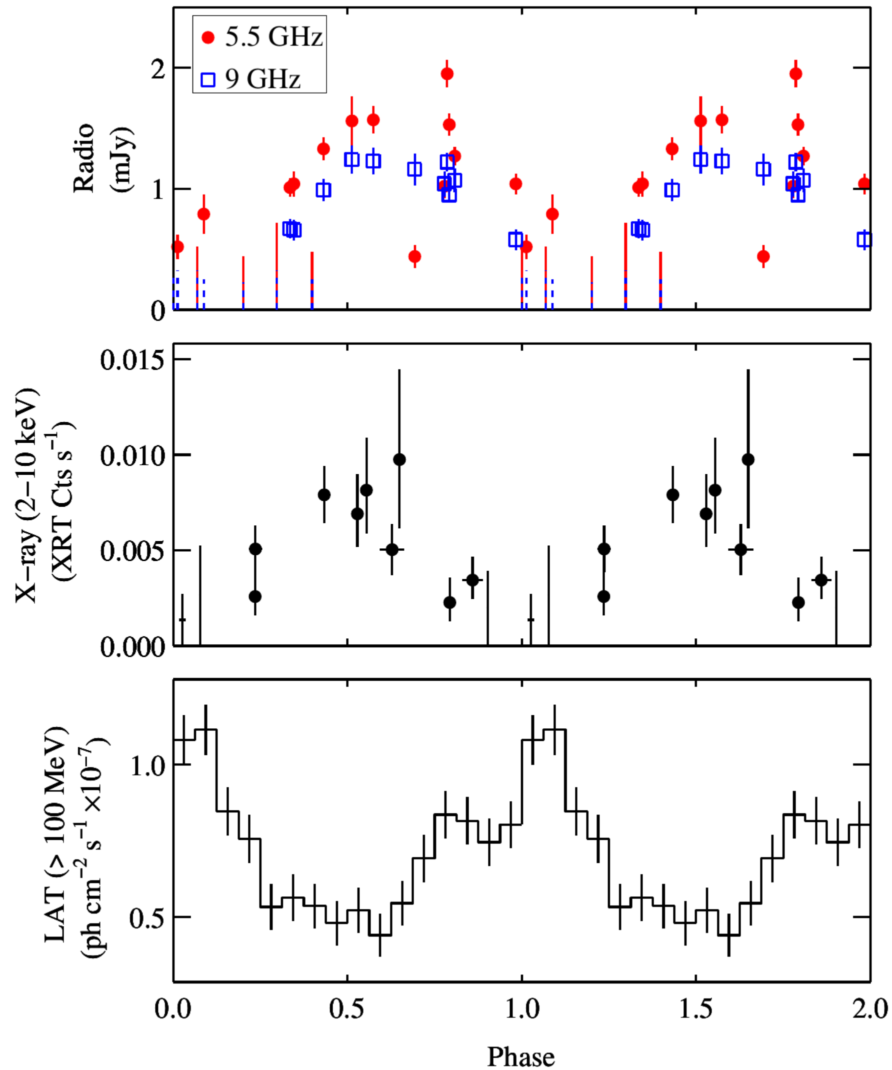




- Corbet et al. 2016

Discovery of LMC P3

- Corbet et al. 2017
  - Radio observations were undertaken with ATCA
  - X-ray observations with Swift
  - Gamma-ray observations with Fermi-LAT
  - Phase 0.0 is taken at the peak of the gamma-ray emission (MJD 57410.25)
  - Folded on the 10.301 period the radio and X-ray observations show a periodicity.
  - However, the X-ray and Radio are out of phase with the gamma-ray observations.
  - This out off phase is seen for other gamma-ray binaries, i.e. LS 5039



Corbet et al. 2017

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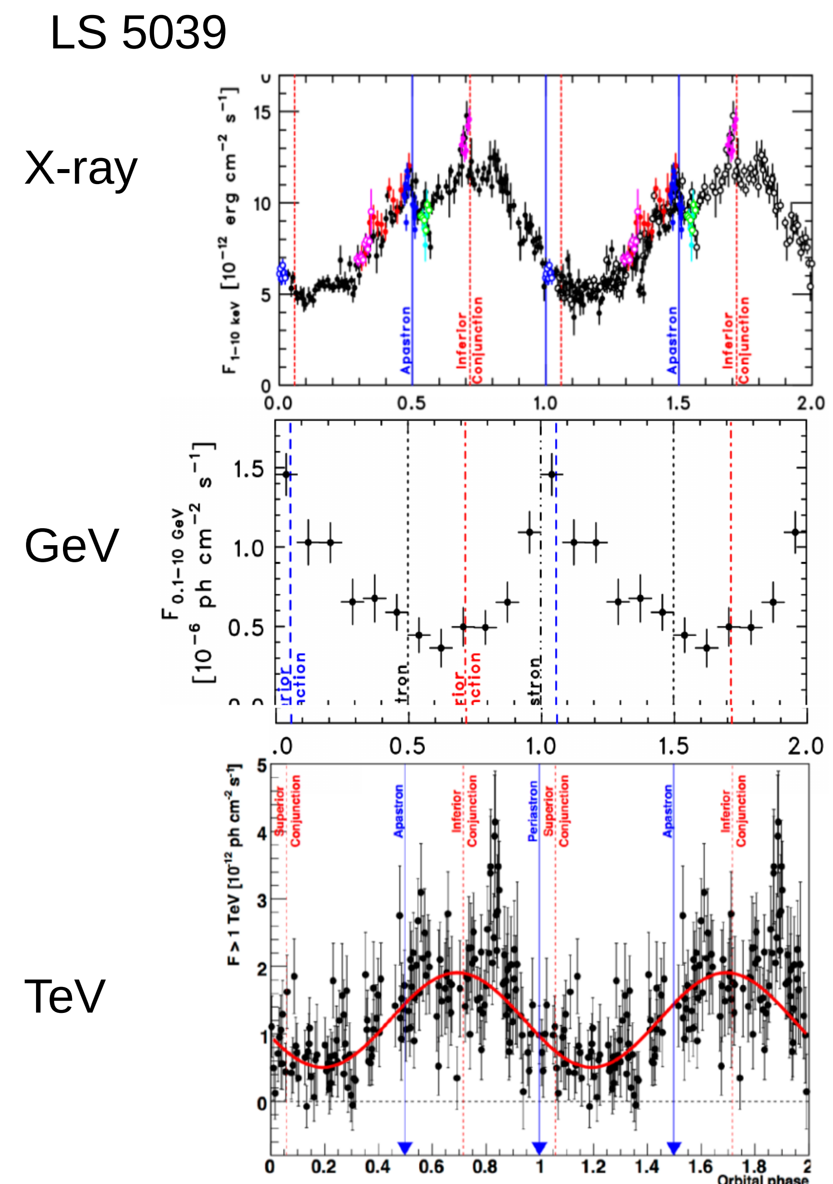
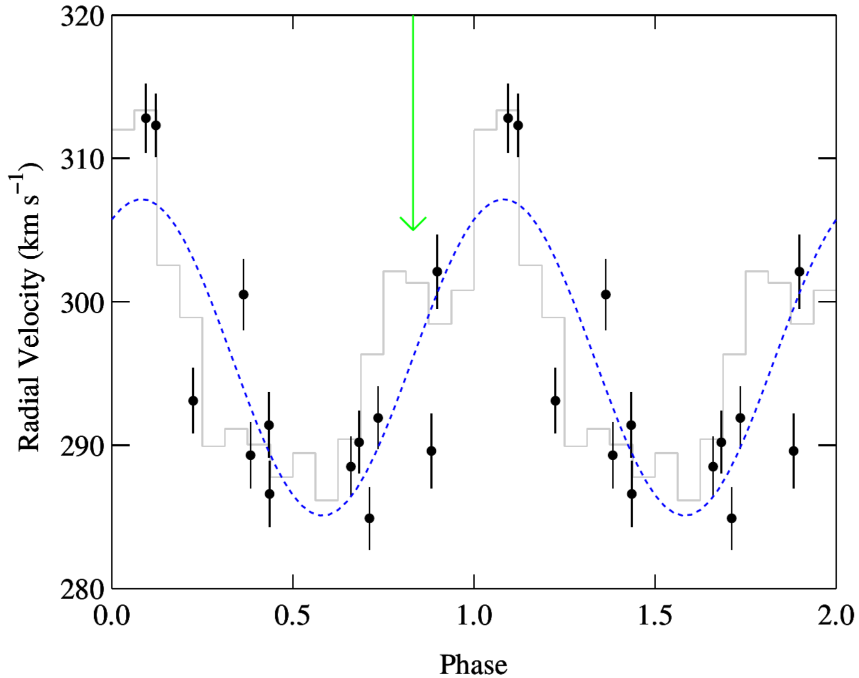


Kishishita et al. 2009, Fermi/LAT collaoboration et al. 2009, H.E.S.S. Collaboration et al 2005

Discovery of LMC P3

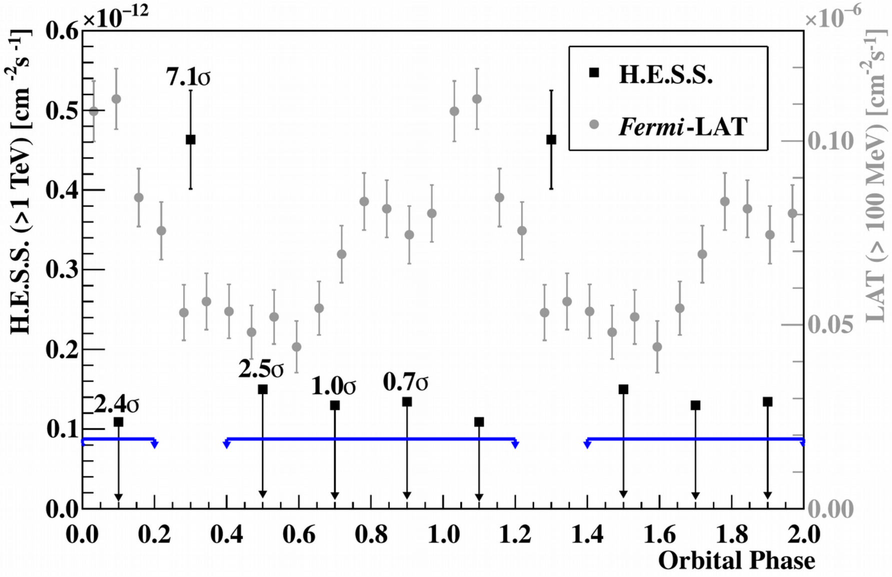
- Corbet et al (2017)
  - Confirmation of the binary nature came from the radial velocity measurements of the optical star.
  - SOAR and SAAO observations folded on 10.301 days.
- This made it at the first gamma-ray binary discovered outside of the Milky Way.
- It is the most luminous of all gamma-ray binaries.

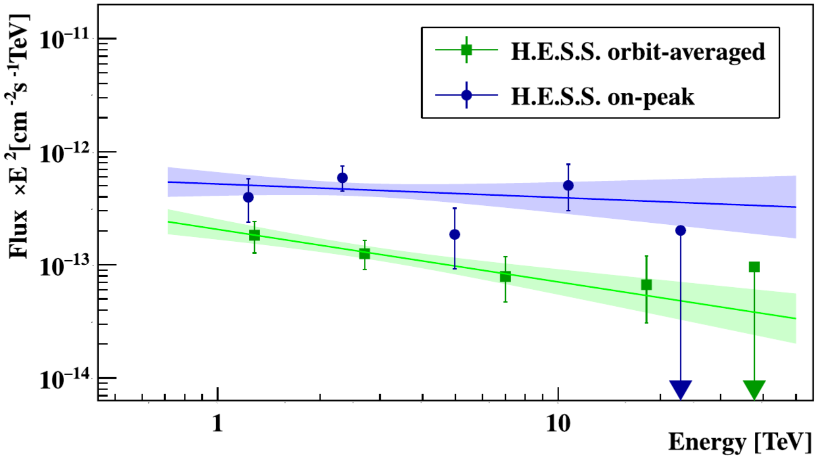


Corbet et al. 2017

H.E.S.S. Observations

- H.E.S.S. observations of the LMC included an effective 100 h observation of LMC P3.
- LMC P3 was detected the source with a 6.4σ significance.
- No significant periodicity could be detected directly with the H.E.S.S. data.
- Folded on 10.301 days the VHE light curve shows a significant detection in only one phase bin.
    - This is off phase with the Fermi-LAT results.

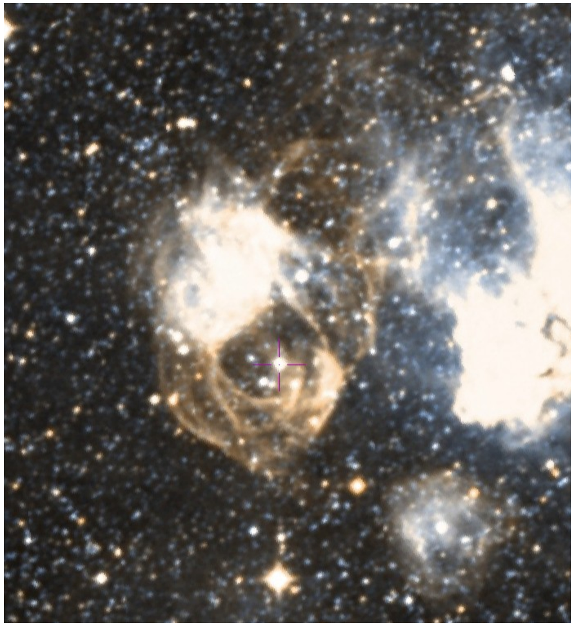


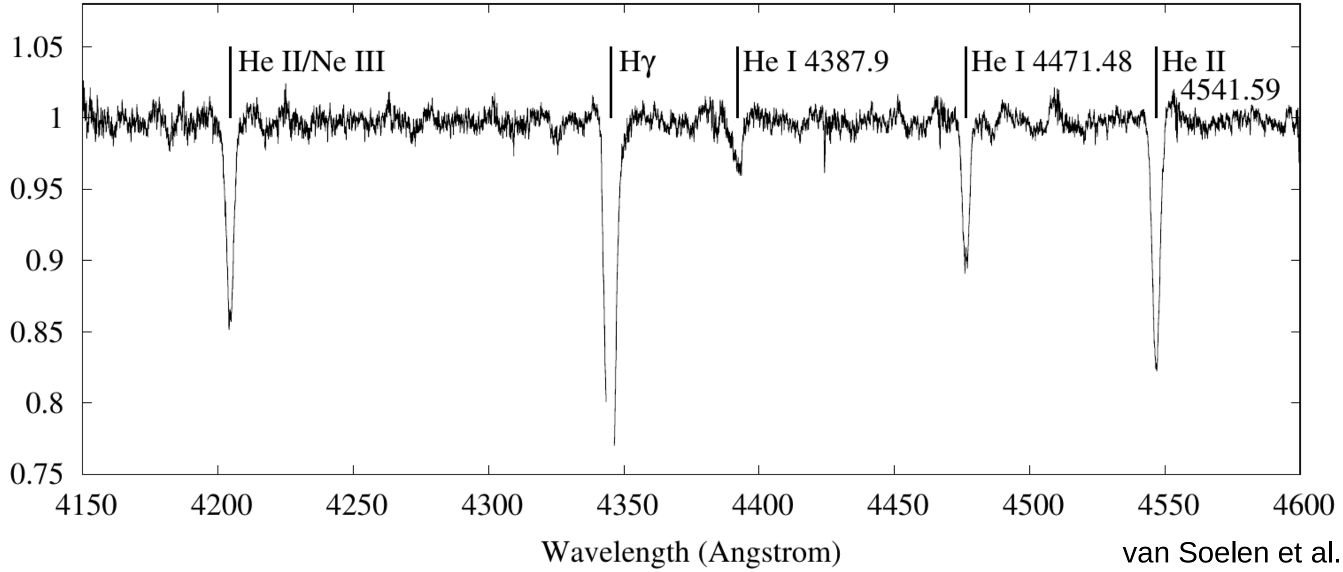


H.E.S.S. Collaboration et al. 2018.

SALT HRS observations

- The system was observed 24 times with the HRS/SALT between 2016 September 14 and 2017 February 06
- Because the target lies within a nebula, and in the LMC, the background in the sky fibre was significantly different from the sky in the target fibre (16’’ separation).
- Restricted performing cross-correlation (rvsao) using the blue part of the spectrum where the sky line contamination was not significant.

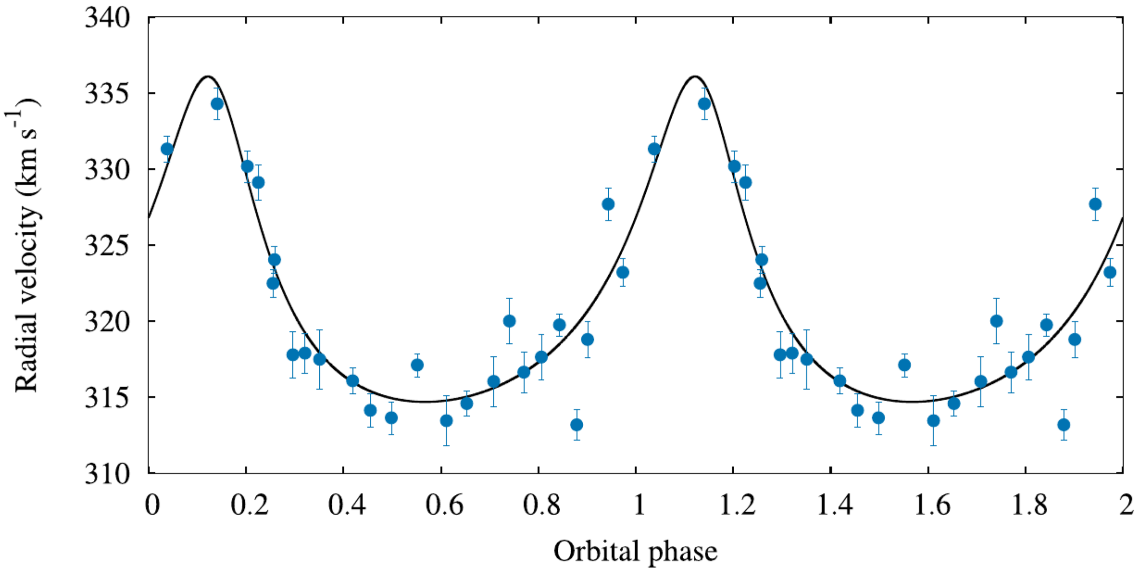




van Soelen et al. 2019

Results

- A free fit to the binary gives a period of 10.314±0.044 days
- But a Lomb-Scargle search for periodicity does not find any significant period
- Adopted a 10.301 day period



Parameters	Free	Fixed (adopted)
Time of periastron (HJD)	2457411.77 ± 1.34	2457412.13 ± 0.29
Orbital period (d)	10.314 ± 0.044	10.301 ± 0.000
Systemic velocity relative to template (km s^{-1})	0.73 ± 0.59	0.68 ± 0.55
Systemic velocity (km s^{-1})	321.23 ± 0.88	321.18 ± 0.85
K (velocity semi-amplitude)	10.69 ± 1.24	10.69 ± 1.23
Eccentricity	0.39 ± 0.08	0.40 ± 0.07
Longitude of periastron (deg)	12.9 ± 12.8	11.3 ± 12.0
Mass function ($M_\odot$)	0.0010 ± 0.0004	0.0010 ± 0.0004

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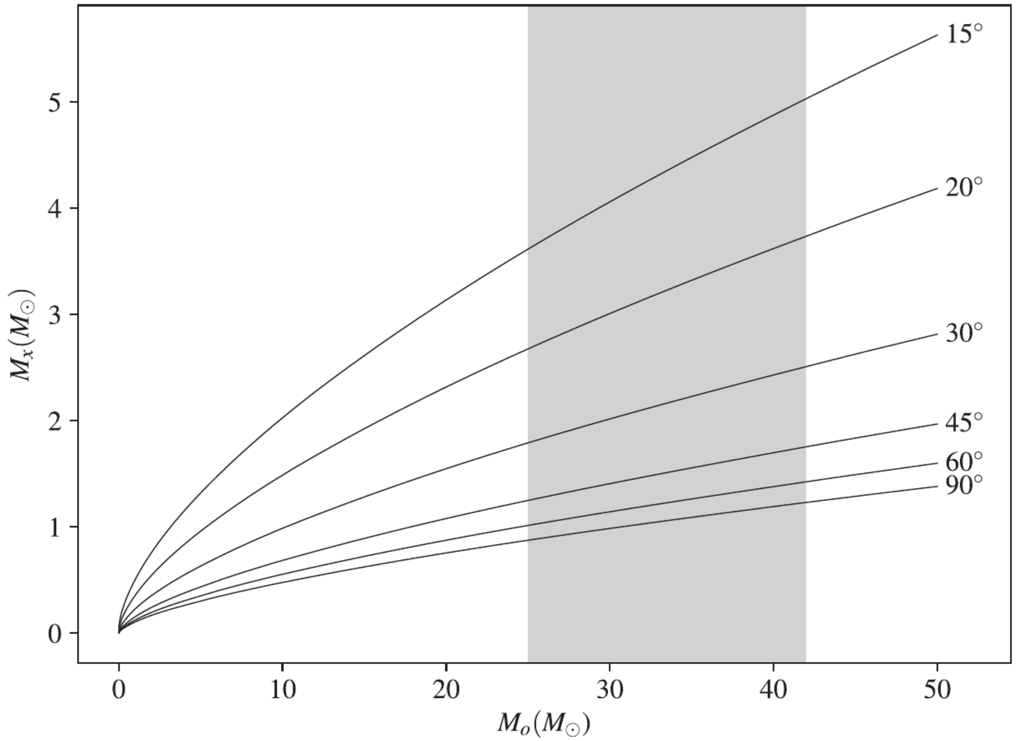
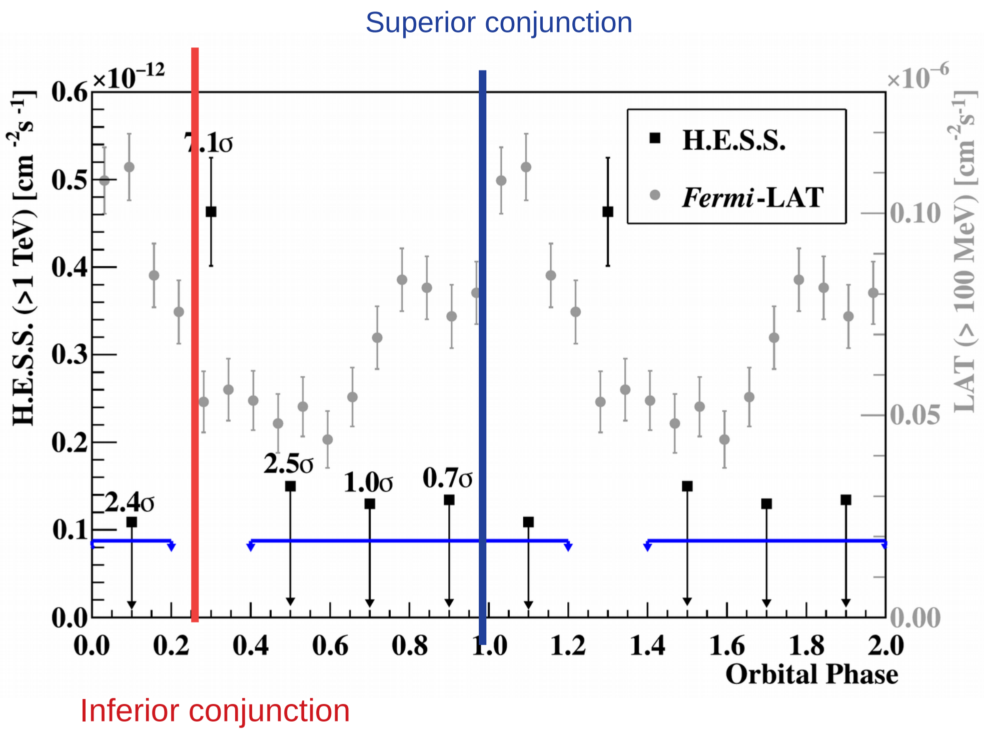
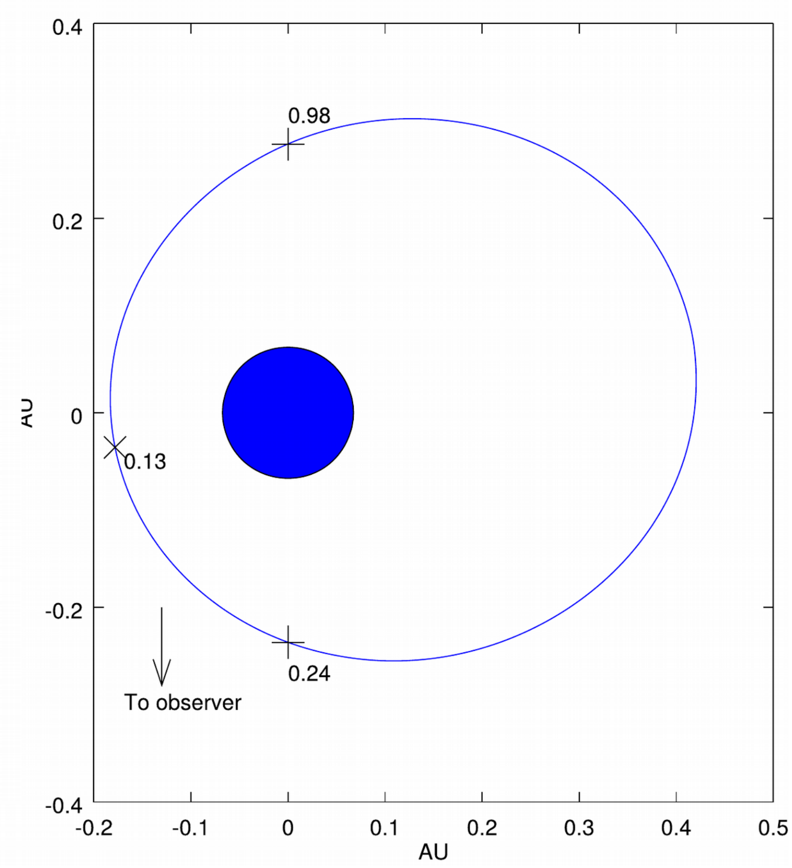


Except for low inclinations, the mass function favours a neutron star companion.

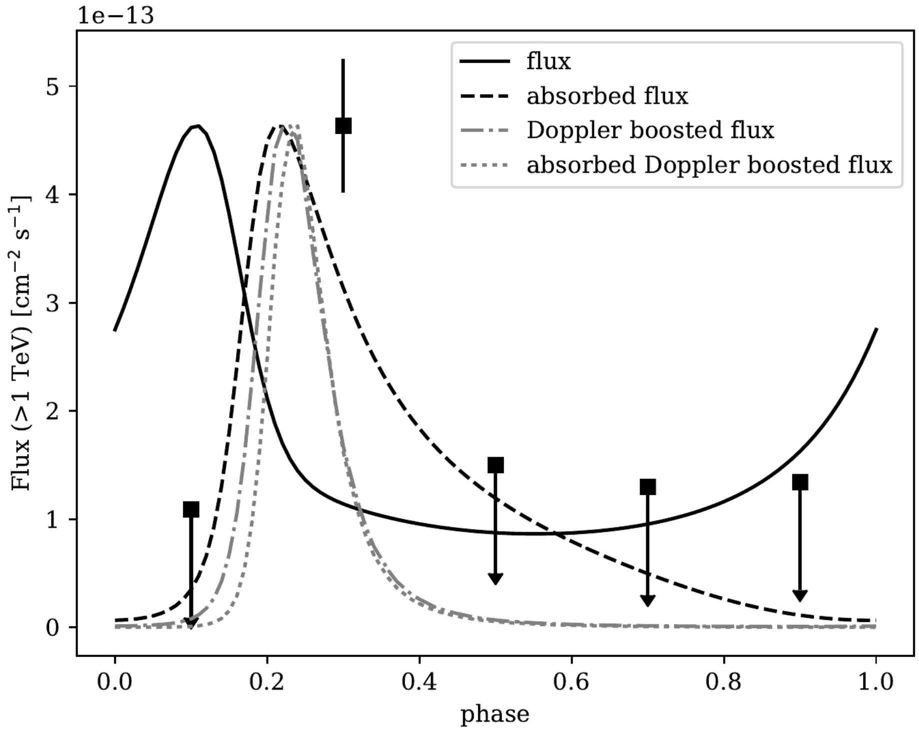




The binary orientation of the LMC P3. This is calculated assuming a M_{star} = 33.5 M_{sun} and radius of R_{star} = 14.5 R_{sun} and M_p = 1.4 M_{sun}.

Point source approximation modelling

- Approximate model looking at the gamma-ray emission and the gamma-gamma absorption for LMC P3.
  - Point-source IC and gamma-gamma approximation (e.g Khangulyan et al., 2014; Zabalza, 2015; Dubus 2006)
  - A constant electron spectrum (p=2) is assumed.
- The gamma-gamma absorption shifts the data peak to around 0.23.
- A similar shift is also possible with a Doppler boosting of the emission.



Orbital parameters, with an inclination of 45 degrees.
Assumes the optical star is point-like, using the analytical approximation of Khangulyan et al., (2014) as implemented in Zabalza (2015) a constant electron spectrum (p=2) is assumed.

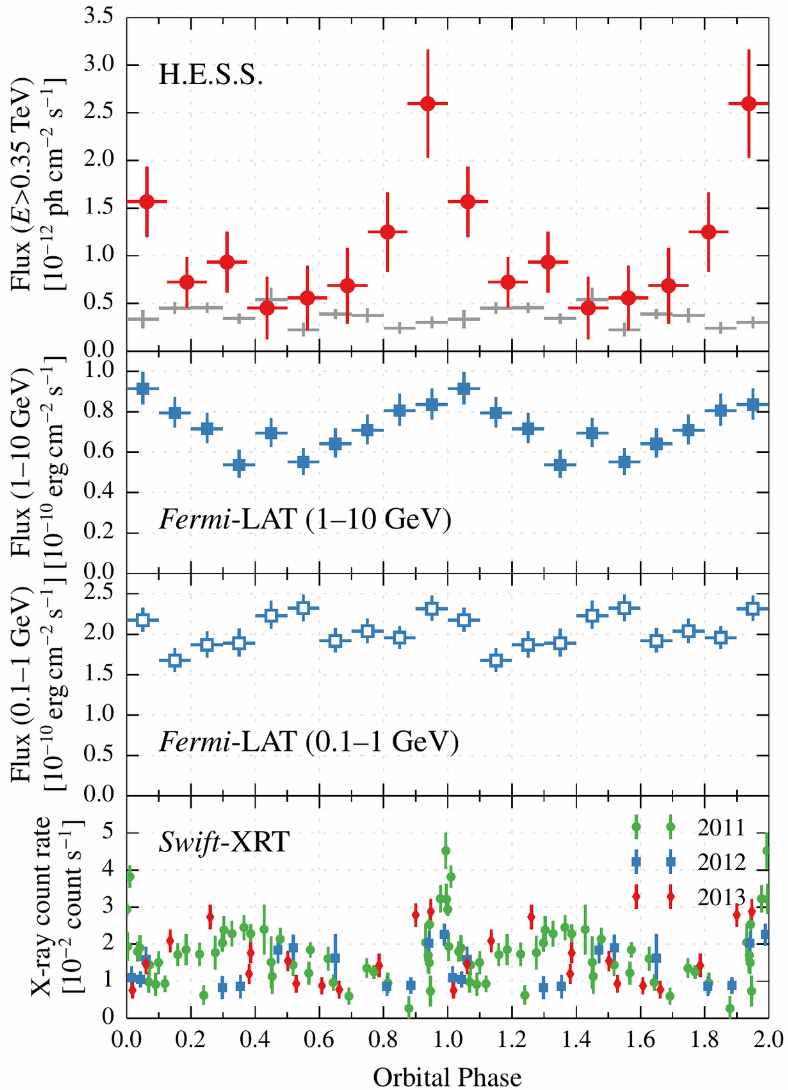
A Γ=2 bulk flow

A point source gamma-gamma absorption

Flux normalized to maximum of HESS data.

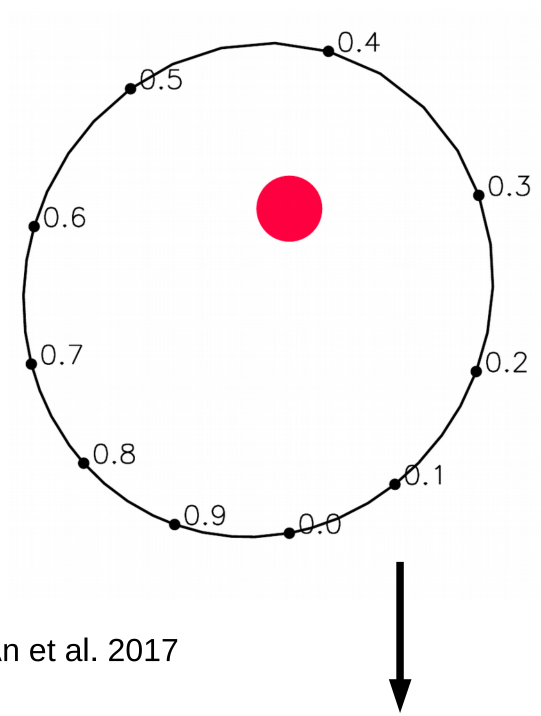
1FGL J1018.6-5856

- Discovered by Fermi-LAT Collaboration (2012) as a variable gamma-ray sources with a period of 16.58 ± 0.04 days co-incident with a O6V((f)) type companion.
- The GeV and TeV emission shows a similar peak
- There is a peak in the X-ray light curve at a similar phase, though a maximum around phase 0.3 as well.
- An et al. 2015 found a 16.544± 0.008 day orbital period from Swift observations

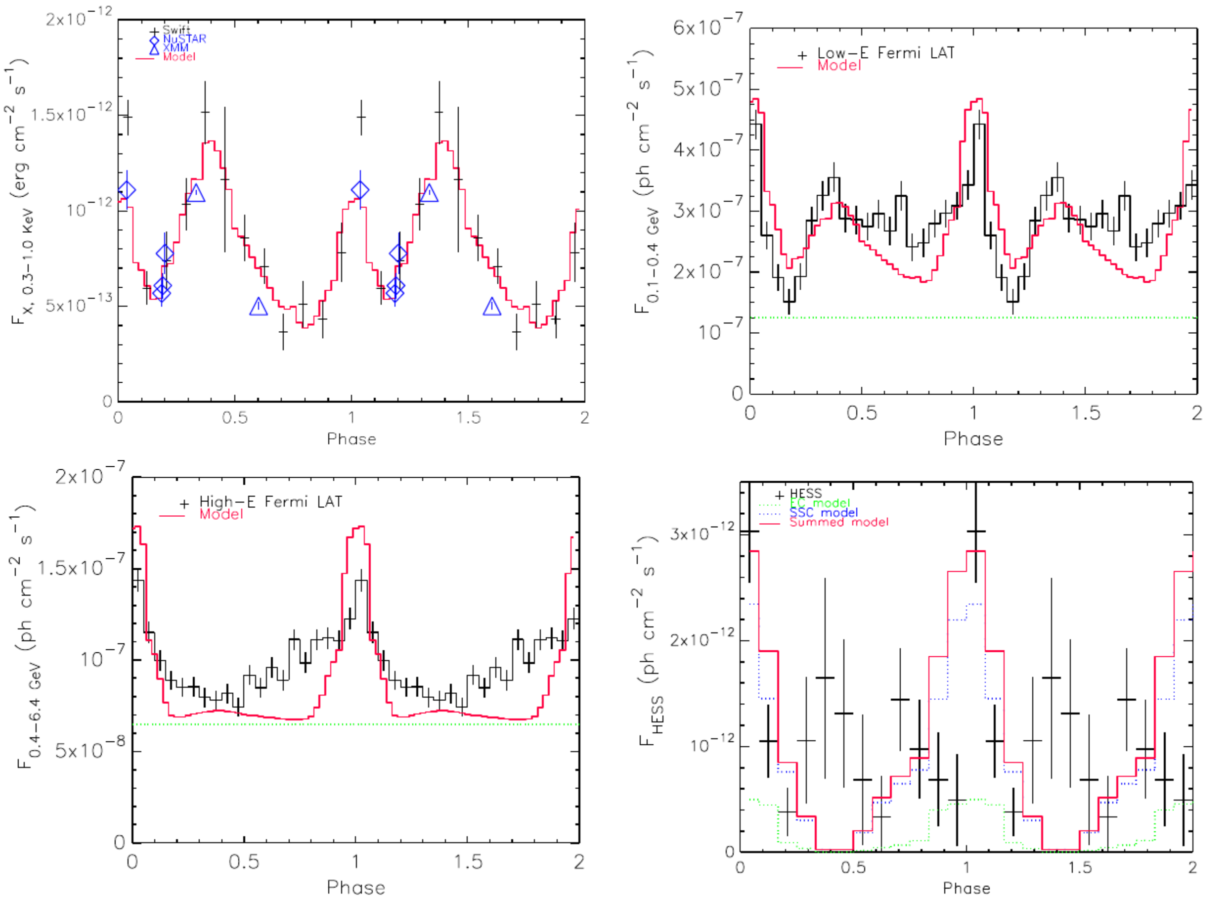


Multi-wavelength liight curves folded on 16.58 d (Abramowski et al. 2015)

1FGL J1018.6-5856



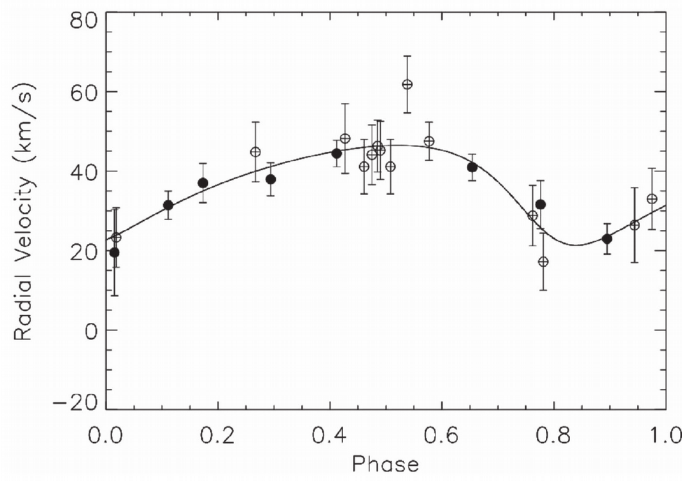
An et al. 2017



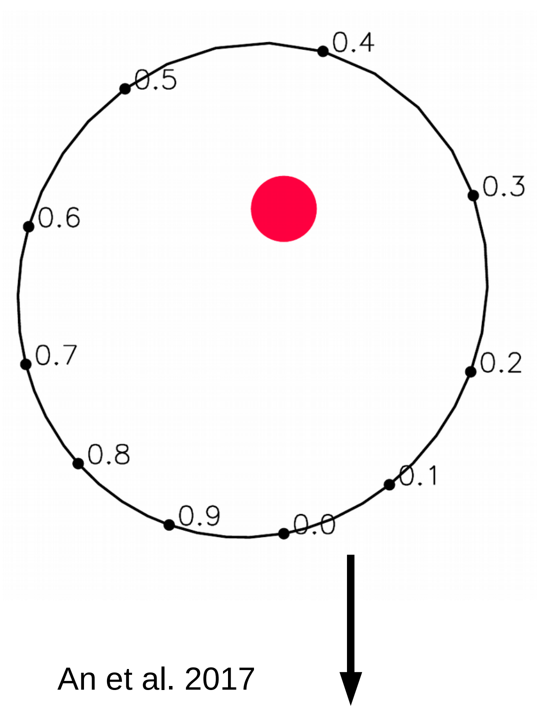
- In An et al. 2017, through modelling the source, it was proposed that the source was eccentric with periastron at phase 0.39 and inferior conjunction at phase 0

1FGL J1018.6-5856

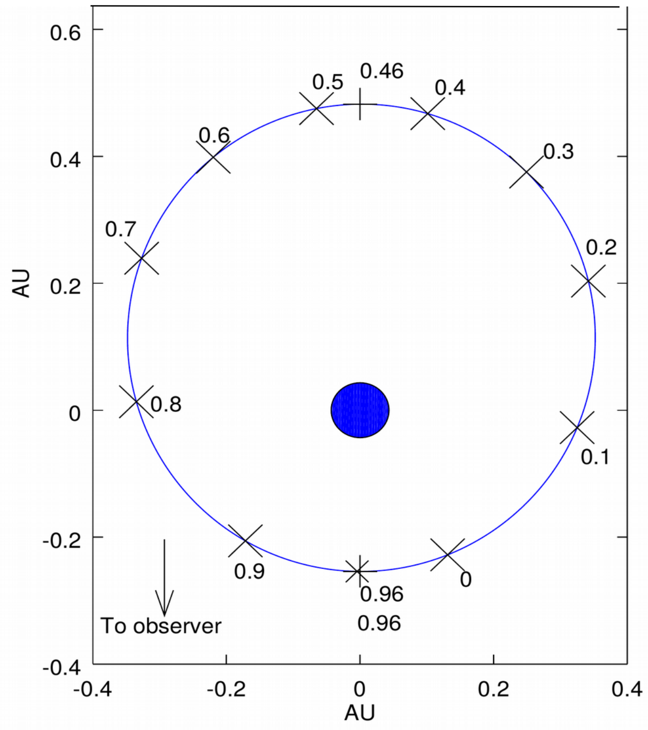
- However Monageng et al 2017 combined new SALT/HRS data with Goodman High-Throughput Spectrograph onboard the SOAR from Strader et al. (2015) and found a very different orbital solution to what was proposed by the modelling
- The eccentricity found (*e*=0.31 ± 0.16) was similar to the model (*e*=0.35) but the orientation was different.



Combined radial velocities (Monageng et al. 2017). NB: the choice of phase 0 is different to the gamma-ray observations/modelling



An et al. 2017



Binary orientation using Monageng+ parameters but the same T_0 time as Fermi-LAT observations

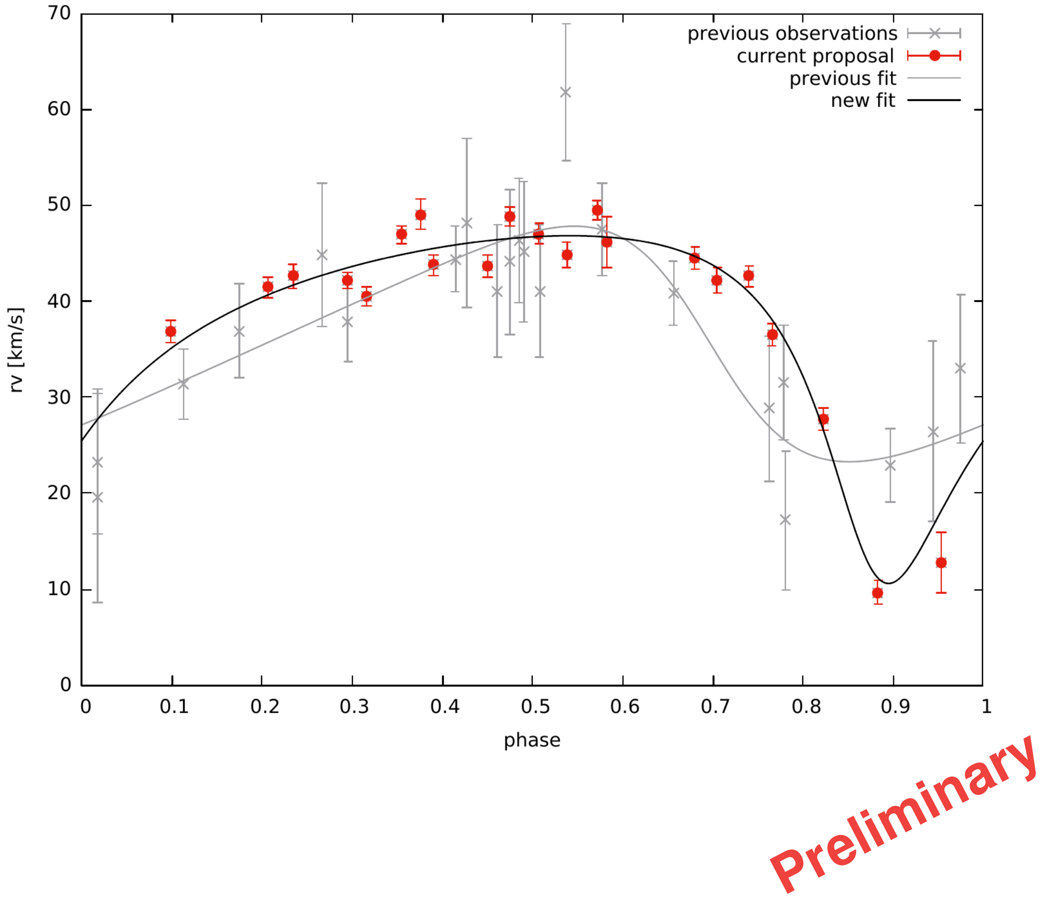
Preliminary new radial velocity results

- Because of the discrepancy and the larger uncertainty in longitude of periastron we are undertaking further SALT/HRS observations

- We have a **very** preliminary result from the observations using the radial velocity fit to H-beta line

- The curve shows a larger amplitude and shifts the position of periastron.

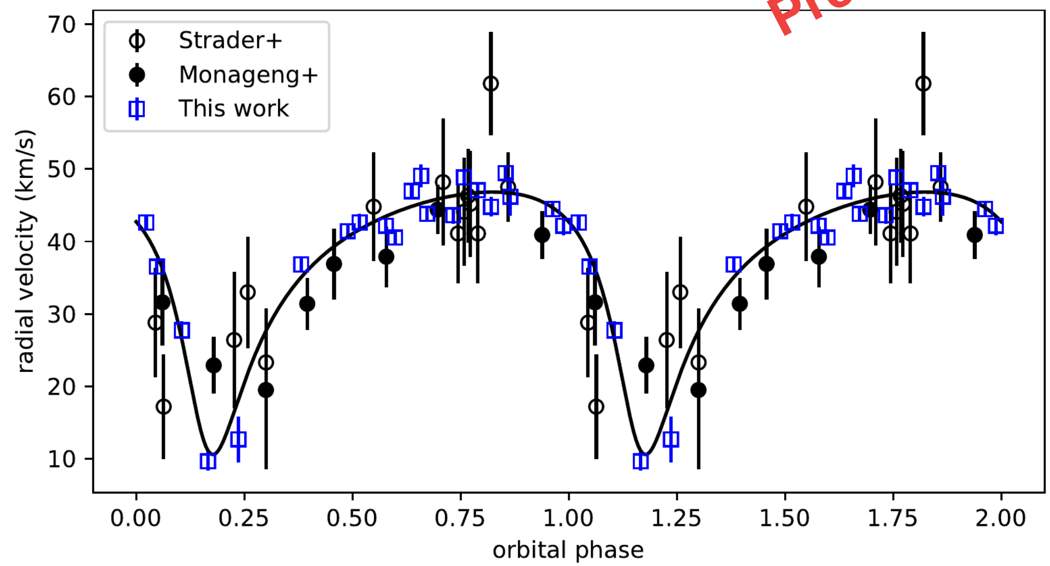
- The errors are only the statistical error based on the line fit.

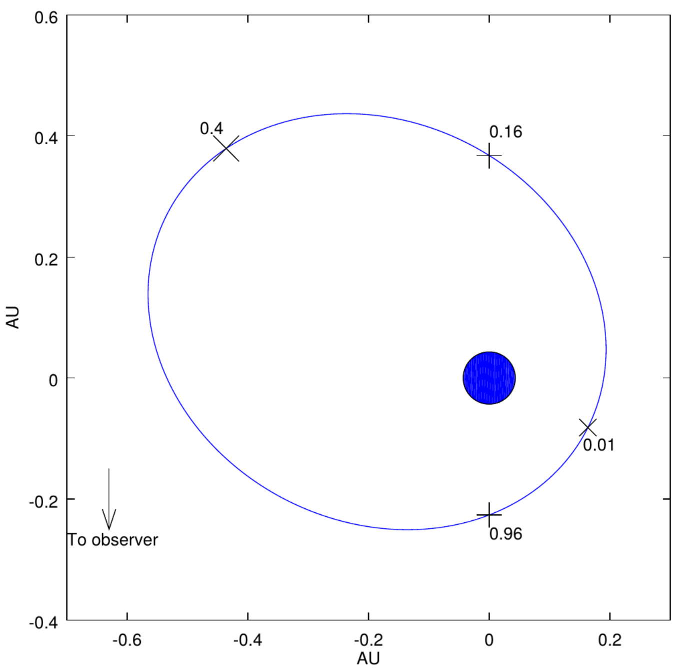


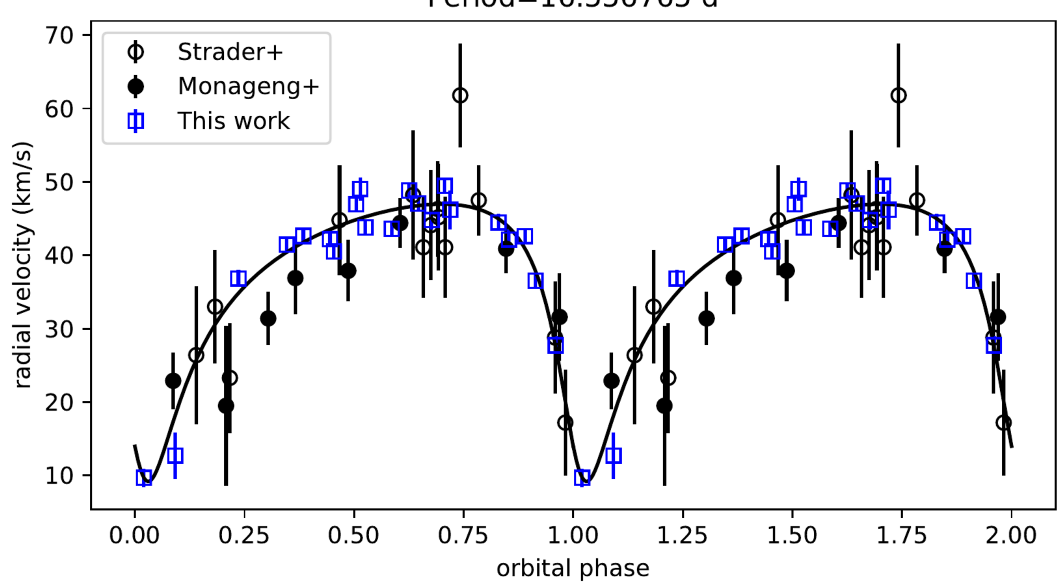
Preliminary new radial velocity results

Preliminary

- The combined fits give a different binary orientation and give an eccentricity of closer to *e*~0.5
- The radial velocity curve is also better fit by a slightly different period.
- However, this is **very preliminary** and we need to get more observations around periastron to determine if this correct and properly cross-check before we draw firm conclusions.







Conclusions

- LMC P3
  - Using SALT/HRS observations we have the best orbital solution for LMC P3, the first gamma-ray binary detected outside of the Galaxy.
  - A neutron star mass is favored for most inclinations (>30 deg).
  - The spectral model fitting gives a temperature of 36351 ± 53 K
  - The orientation places inferior conjunction at 0.24 and superior conjunction at 0.98
  - A simple toy model shows that this orientation can explain the H.E.S.S. observations either via a gamma-gamma absorption or possibly through additional Doppler boosting.

- 1FGL J1018.6-5856
  - New observations are under way but the very preliminary results are hinting towards a different orientation.
  - This may mean we must re-look at the interpretation of the multi-wavelength results
  - More observations are being requested to complete this.

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Thank you

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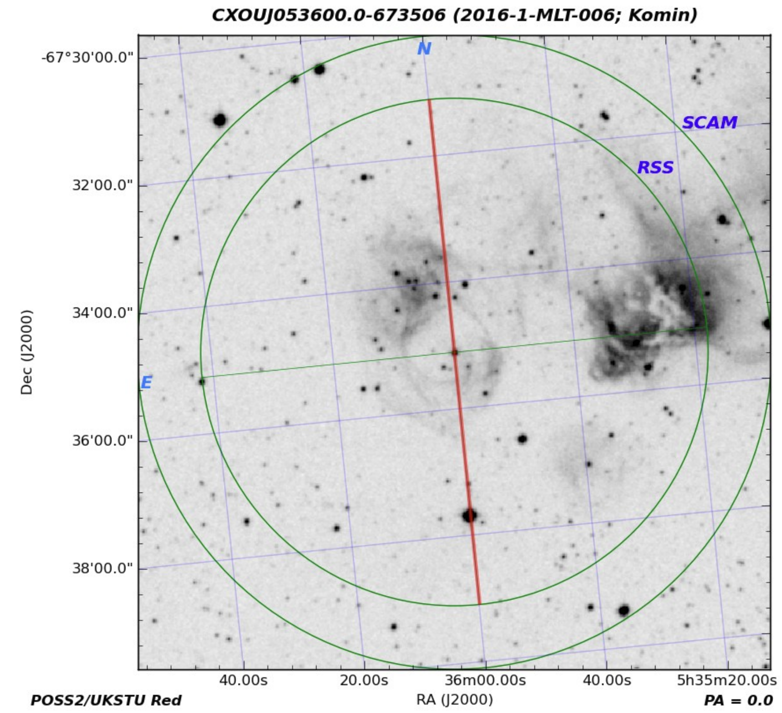
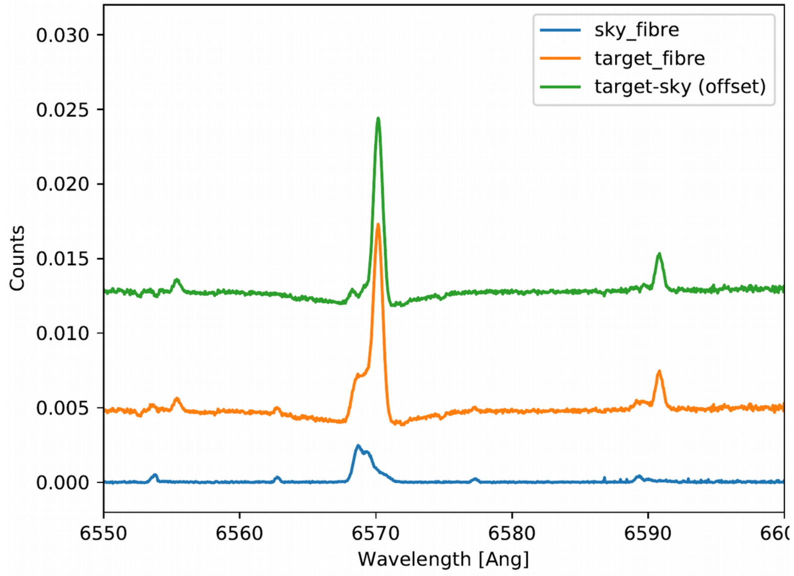
Backup slides

SALT HRS observations

- The system was observed 24 times with the HRS/SALT between 2016 September 14 and 2017 February 06
  - Low Resolution Mode (R = 14 000).
  - 2 x 1 220 s exposures (except for two nights which 2×1 640 s).
  - Orders were extracted and wavelength calibrated using the HRS pipeline Kniazev, Gvaramadze & Berdnikov (2016).
  - Individual orders were normalized and merged into a single one dimension spectrum using the standard IRAF /PYRAF packages.
  - Heliocentric correction was performed for each individual exposure using RVCORRECT / DOPCOR and nightly observations were averaged together.
- Because the target lies within a nebula, and in the LMC, the sky fibre was significantly different from the sky as measured at the target (16’’ separation).
- For this reason we were restricted to using the blue part of the spectrum where the sky line contamination was not significant.





Spectral model fit

- The velocity of the template and stellar properties were determined using ULySS (Koleva et al. 2009) with the medium spectral-resolution MILES library.
- A fit over the the 4160–5000 Å wavelength range gives a radial velocity of cz = 320.7±0.7 km s^{-1}
- A best fit to the atmospheric properties of the star gives
  - Teff = 36351 ± 53 K,
  - log g = 3.4 ± 0.1 [log(cm s^{-2})],
  - [Fe/H] = 0.25 ± 0.01
- This is compatible with an O III type star, though the values are lower than those of an O5 III star in, for example, Martins et al. (2005). However, the exclusion of parts of the Balmer lines prevents us from undertaking more detailed stellar atmospheric modelling.