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Science & Technology Facilities Council

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LJMU ASTROPHYSICS RESEARCH INSTITUTE

Liverpool Telescope
and
15 years of robotic operations

Iain Steele

Liverpool John Moores University, UK.

Outline

- Liverpool Telescope
- “User view” of the robotic telescope
- Science Examples
- Key elements for robotic operations

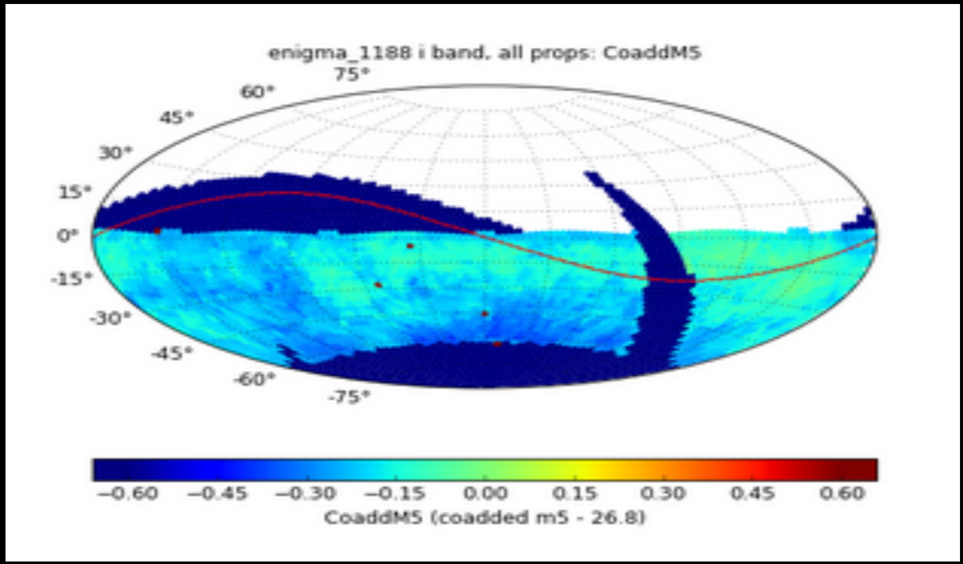
- Discussion and questions

- First light in July 2003, robotic observations began in 2004.
- Clamshell design enclosure; two shutters, three separate portals (3 mins to open).
- Designed for *rapid* follow-up of transient sources such as novae, supernovae and GRBs.
- World’s largest *fully autonomous*, robotic telescope. ***Not* ‘remote control’.**

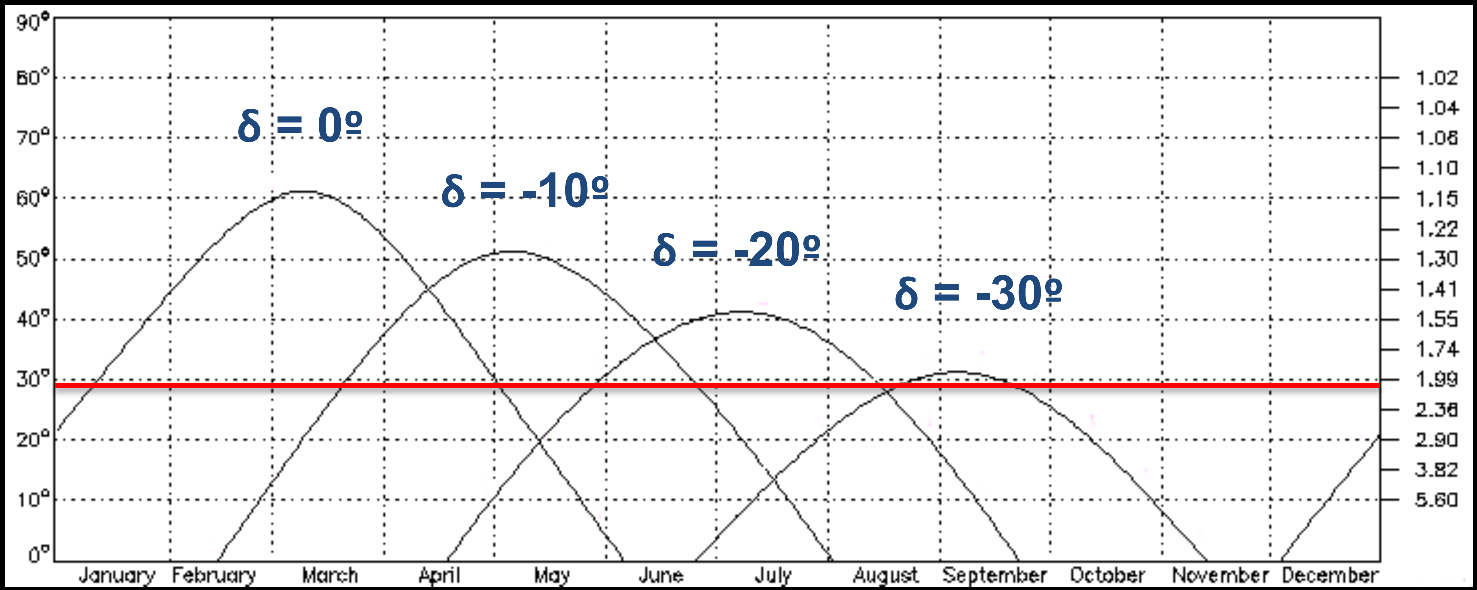
ORM, La Palma (342ºE, 29ºN)

Excellent conditions & simple logistics (4 hour flight!)

Northern Equatorial site still provides excellent access to a large fraction of the LSST field



Altitude



AM

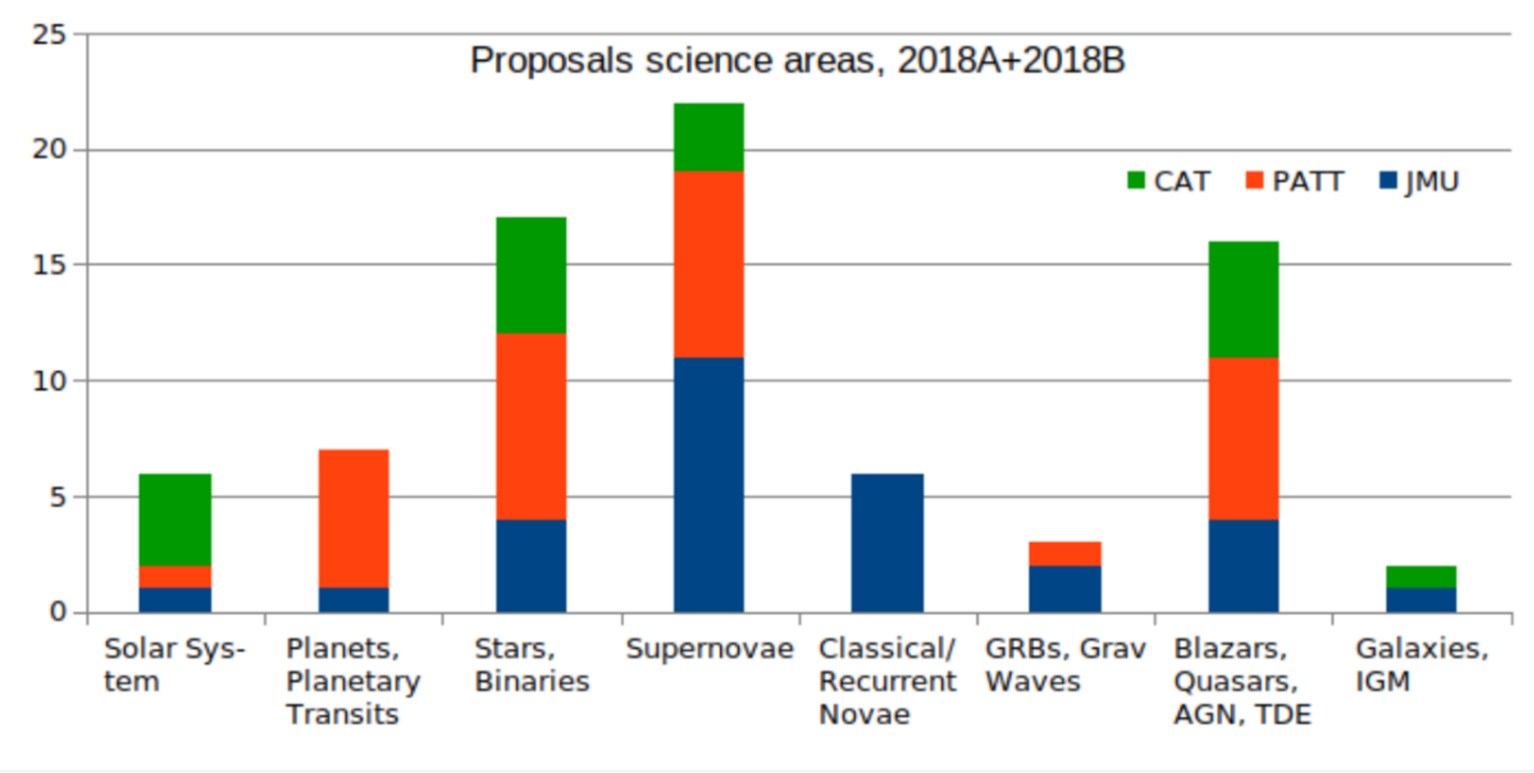
- Ritchey-Chrétien Cassegrain optics (f/3 primary mirror)
- Primary mirror (M_1): 2.0m diameter (0.45m central bore)
- Secondary mirror (M_2): 0.62m diameter (moves axially for focus)
- Altitude/azimuth mount. Altitude range: 25°–88°
- Slew rate 2°/sec on all axes
- Acquisition and Guidance (A&G) box at Cassegrain focus gives one straight-through port and eight science fold ports accessed by deployable science fold mirror at 45°. Instrument Change Time < 30 seconds.

J. Marchant, LT.

International Common User Facility

Currently Each Semester:

- 300 hours for LJMU staff (JMU)
- 300 hours for other UK users (PATT)
- 150 hours for Spanish users (CAT)
- 50 hours international (CCI) time
- Up to 50 hours OPTICON time (EU)
- 150 hours (UK + Spain) for education via the



C. Copperwheat

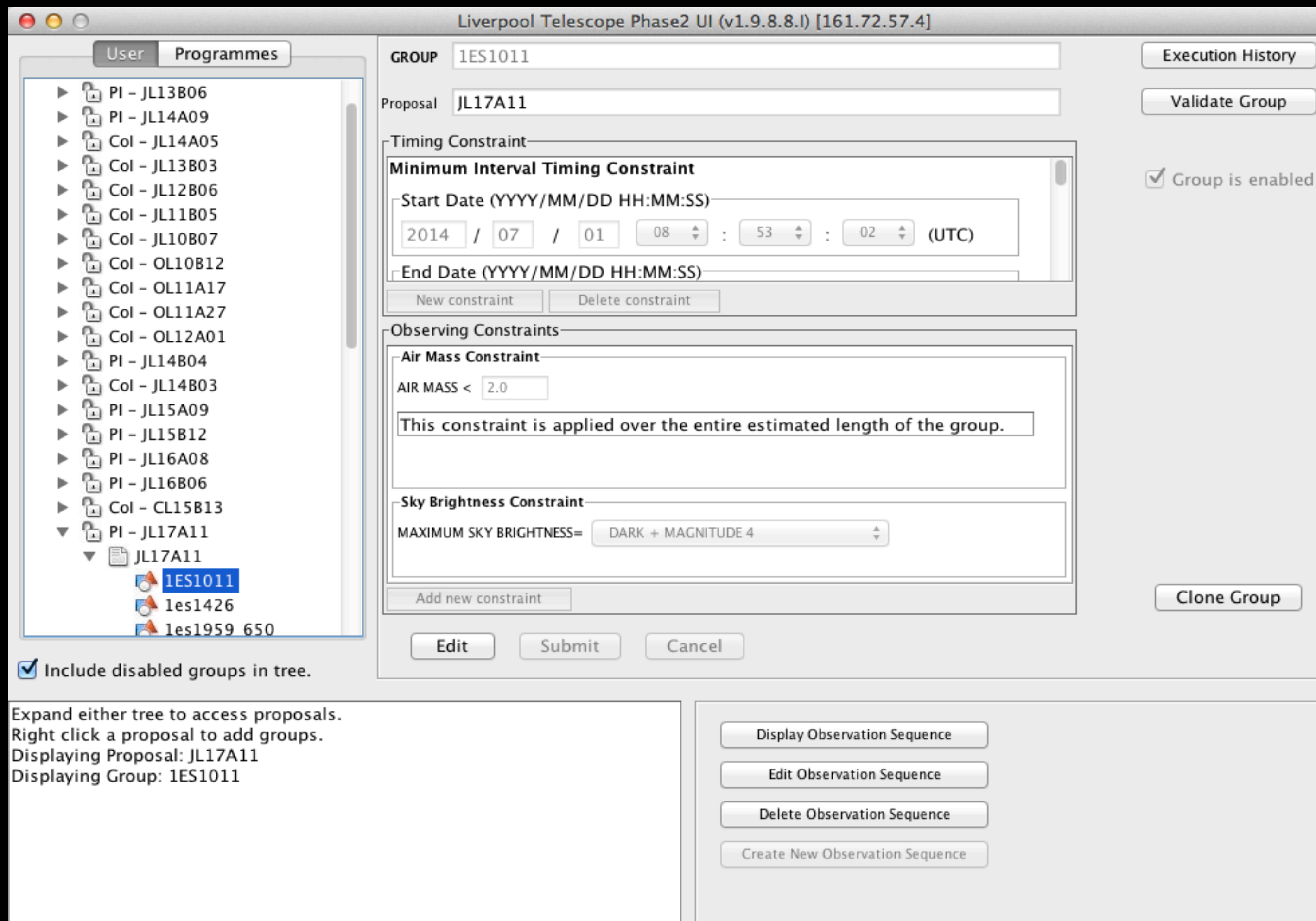
Observing Procedure

Phase 1

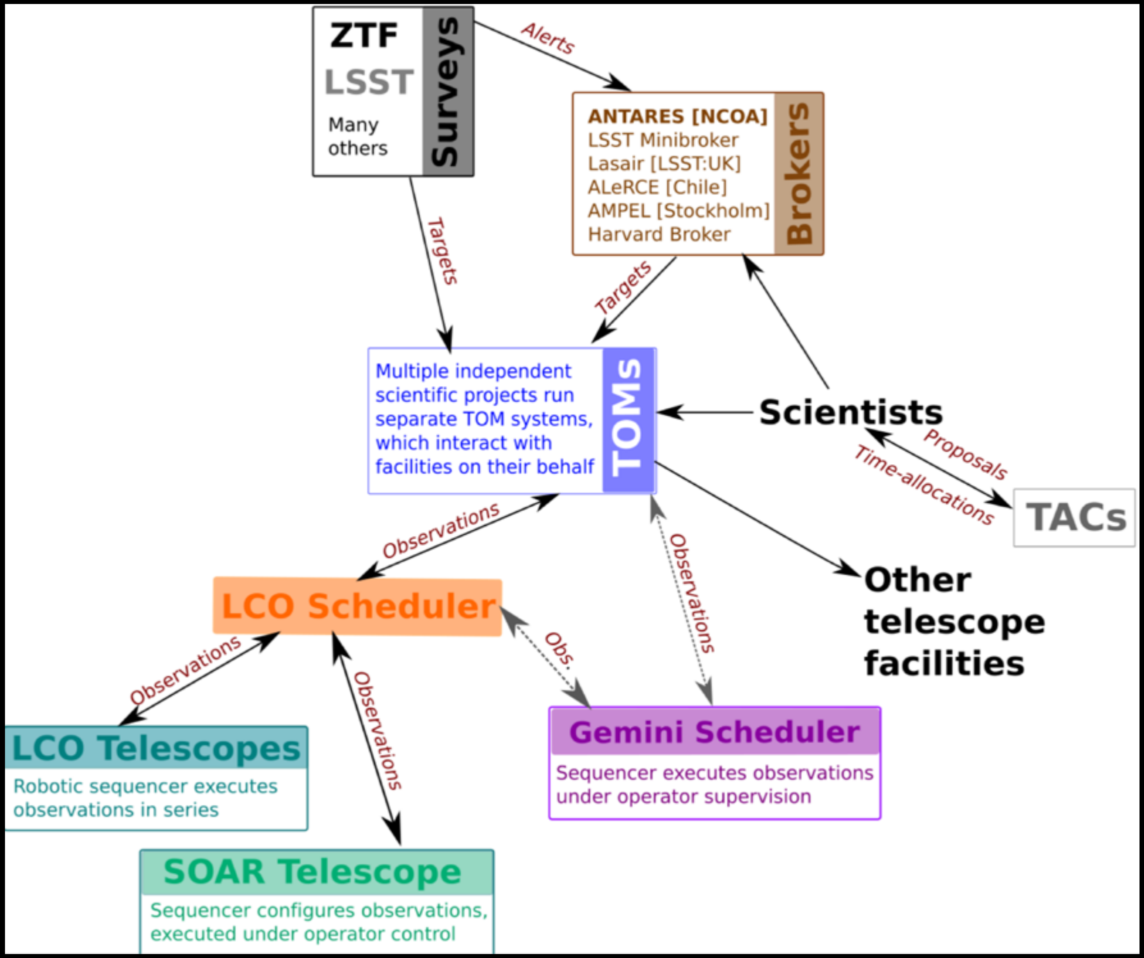
- Users submit a proposal via the relevant call. Two deadlines each year for 8 month long semesters (one month overlap at the start and end of every semester).
- Peer review process.

Phase 2

- Users enter co-ordinates and observational constraints into online Java tool or via remote telescope mark-up language (RTML) for some instruments.
- Wizards available for each instrument
- Intelligent scheduling system identifies priority observation.
- GRB triggers from SWIFT- immediate override of current observation and carry out RINGO3 polarimetric monitoring.



Currently Integrating with TOM Toolkit



Timing constraints

Five types of timing constraint which control when and how often targets are observed:

FLEXIBLE time : observations can be carried out at *any time* during the semester when the observing conditions are appropriate.

MONITOR time : observations are required *regularly* according to user-specified cadence.

INTERVAL time : observations are taken as *often as possible* according to the specified interval.

PHASED time : observations at a *particular phase* of periodic cycle e.g. eclipsing binary.

FIXED time : observations will only be carried out at a *specified time*, or not at all e.g. occultations, or observations which must be simultaneous with a scheduled observation on some other facility (very intrusive to telescope operation so must be a clear need).

Robotic control system

Dispatch Scheduler selects next observation according to algorithm combining:

1. Proposal science priority (A, B or C).
2. Repeat observations have a higher priority than one-off observations.
3. Urgent observations have a higher priority.
4. Ratio of current elevation versus highest possible elevation that night.
5. Matching of actual (seeing/lunar) conditions to those requested.

Calibrations:
Standards observed every ~3 hours, and when no science groups available
Twilight flats: obtained most mornings/evenings.

Scheduler overrides:
Two types:
1. Pre-planned 'fixed' groups
   (e.g. exoplanet transit)
2. Immediate, target-of-opportunity
   (e.g. gamma-ray burst)

http://telescope.livjm.ac.uk/TelInst/Robotic/

Benefits of robotic observing

Operational

- Low operational costs: main cost is staffing. No visiting astronomers staying on La Palma.
- Site visits every ~4-6 months, 2-3 staff for 1 week.
- Safer- unmanned, no visiting astronomers, no-one on site or in Liverpool overnight.
- Engineers break things! Reliability is always better when no-one is on site.
- Continued operation through COVID-19 pandemic when all other telescopes on La Palma closed down.

Science

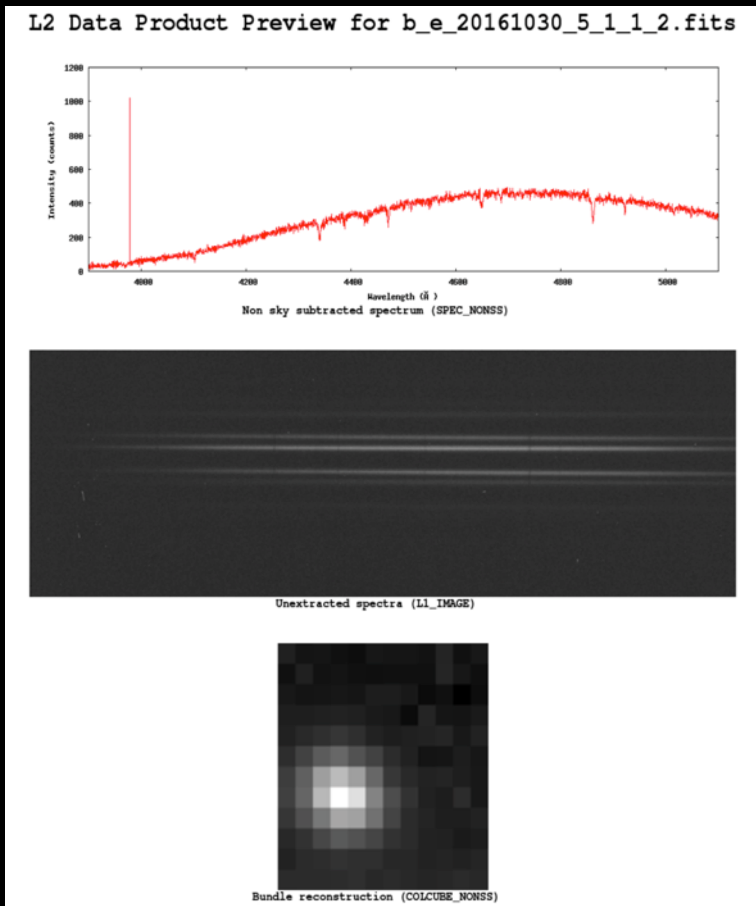
- Rapid response to triggers: GRB science. On target and taking data within ~2 mins of trigger.
- Observing efficiency, little down time- all instruments on telescope all the time
- Standardized observing procedures make data pipelining easier
- Efficient interleaving of science programs, typically 15-20 different programs per night
- Regular and intensive monitoring easily available depending on science requirements

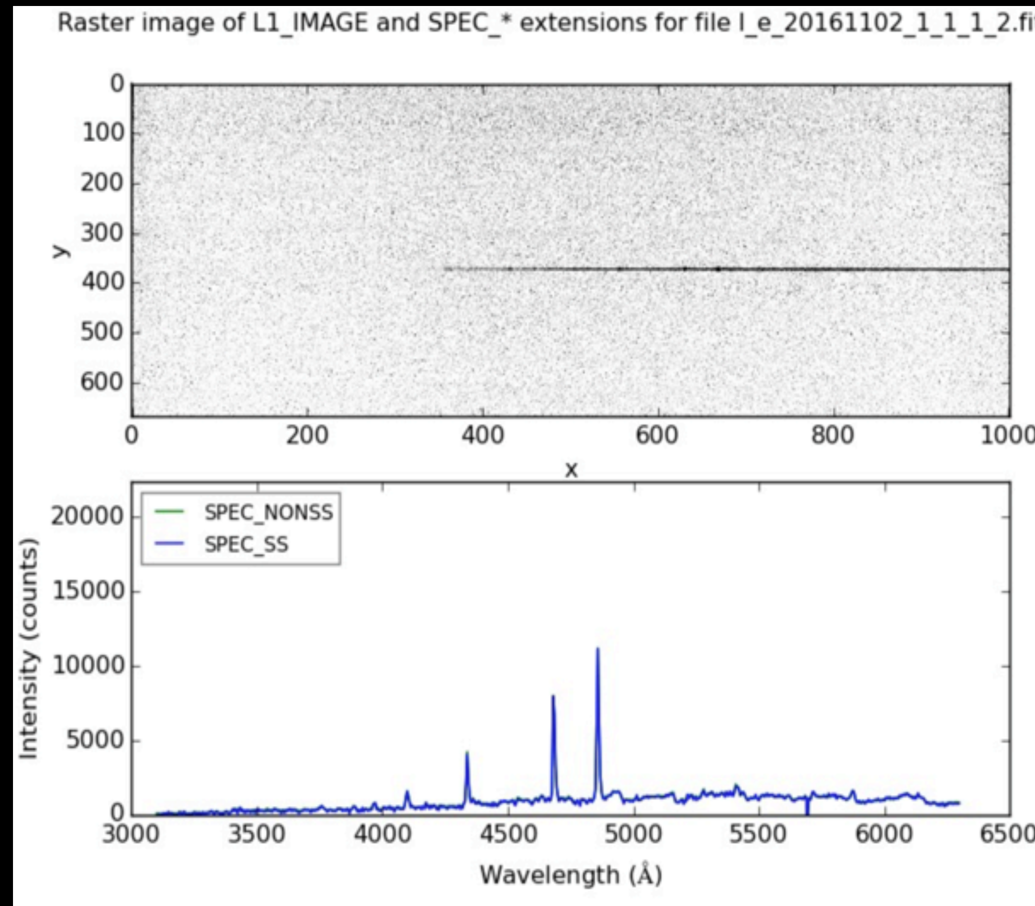
http://telescope.livjm.ac.uk/TelInst/Robotic/

Instrumentation

- IO:O – 10x10 arcmin optical imager (many filters)
- IO:I – 6x6 arcmin near-IR imager (H-band)
- FRODOspec – fibre-fed integral field spectrometer
  R~2500/5500, red+blue simultaneously
- SPRAT – long-slit spectrometer
  R~ 350, 400-800 nm wavelength coverage
- LOTUS – long-slit UV spectrometer
  R~300, 320 – 630 nm wavelength coverage
- RISE – 9 arcmin diam. rapid-readout (0.8 sec) optical imager
  Large (1.0” binned) pixels but PSF still fully sampled
  Fixed (V+R) filter
- MOPTOP– multicolour polarimeter
- Sky-cameras – three wide-field imagers (all-sky, 9º, 1º)
  Photometry down to 6th, 13th, 18th mag

Data Pipelines for all instruments



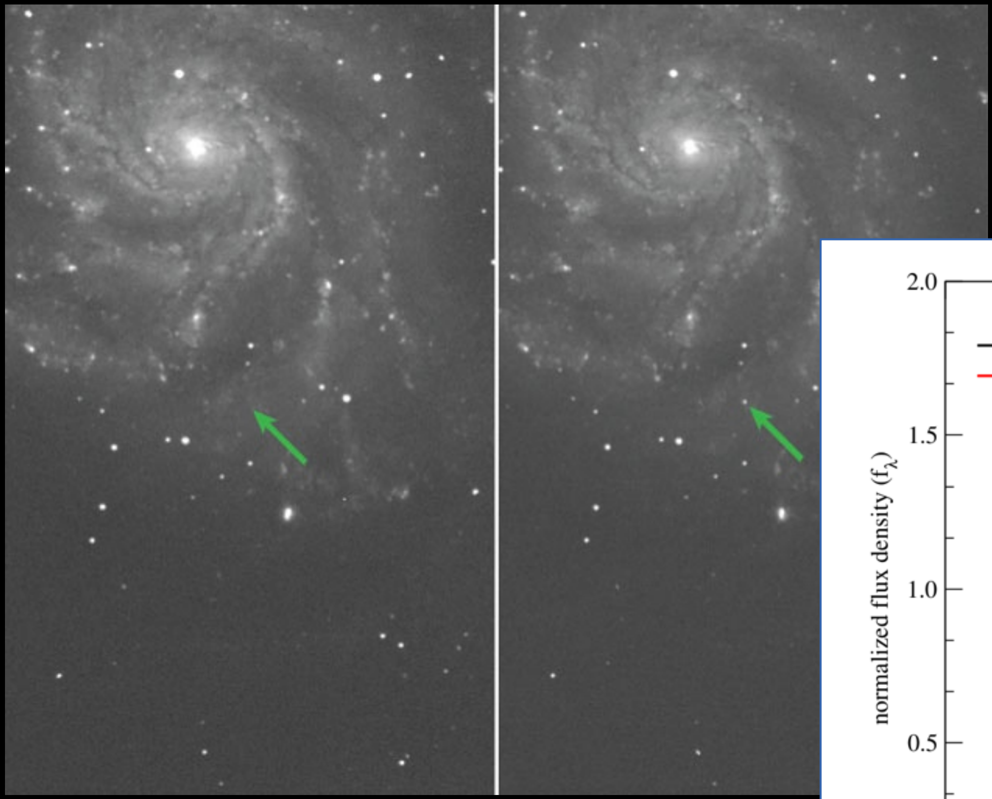


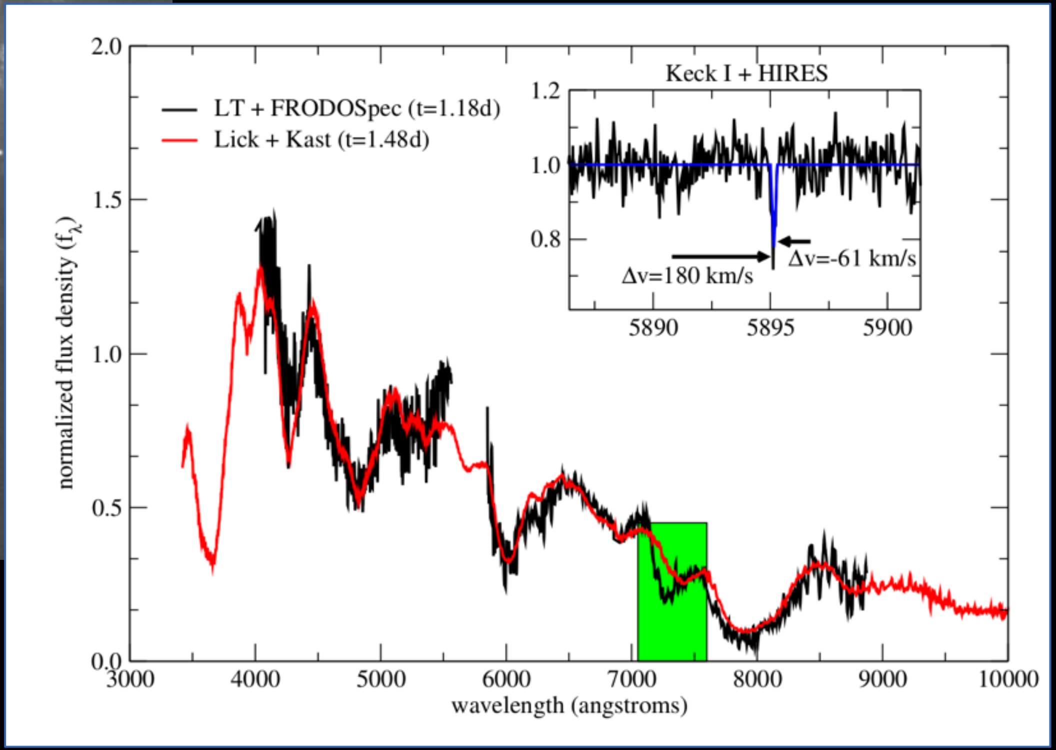
Data to users in < 10 minutes

Proposal	User Name	16/08	15/08	14/08	13/08	12/08	11/08
JL20A01	Matt Darnley	-	-	8	10	-	13
JL20A04	Jon Marchant	-	-	26	-	29	-
JL20A07	Paolo Mazzali	-	-	5	-	6	-
JL20A09	Dan Perley	-	7	-	-	-	5
JL20A13	Chris Copperwheat	-	6	2	2	-	4
JL20A14	Ross McWhirter	-	120	-	-	-	-
JL20A16b	David Bersier	-	12	-	-	-	13
JL20A17	Paolo Mazzali	-	-	-	3	-	-
JL20B09	Paolo Mazzali	-	9	-	9	-	2
JL20B15	Dan Perley	-	-	-	-	-	15
PL20A05	Chris Frohmaier	-	7	-	-	6	4
PL20A07	Amaury Triaud	-	-	59	-	-	100
PL20B08	Nuria Jordana	-	36	24	36	24	36
PL20B23	Ian McHardy	-	-	4	-	-	4
PQ20A02	Boris Gaensicke	-	-	-	-	3	-
CL20A01	Jesus Maiz	-	-	30	146	155	-
CL20A09	Pablo Sanz	-	-	-	-	100	-
CL20A11	Ismael Perez Fournon	-	17	-	-	-	-
CL20A12	Ismael Perez Fournon	-	9	-	-	-	-
CL20B02	Luis Goicoechea	-	-	-	1	-	-
CL20B06	Jose Moreno	-	5	-	-	-	-
CALIB	CALIB	-	12	9	12	22	10
DL12A02	Martin Altmann	-	40	-	-	-	-
FrodoFlat	LTOps	-	8	12	12	12	12
FrodoStand	LTOps	-	12	24	12	15	22
IOOStand	LTOps	-	42	21	28	21	35

Science: Transient follow-up

- Diverse instrument suite and robotic control makes the LT a powerful tool for the follow-up of transient sources



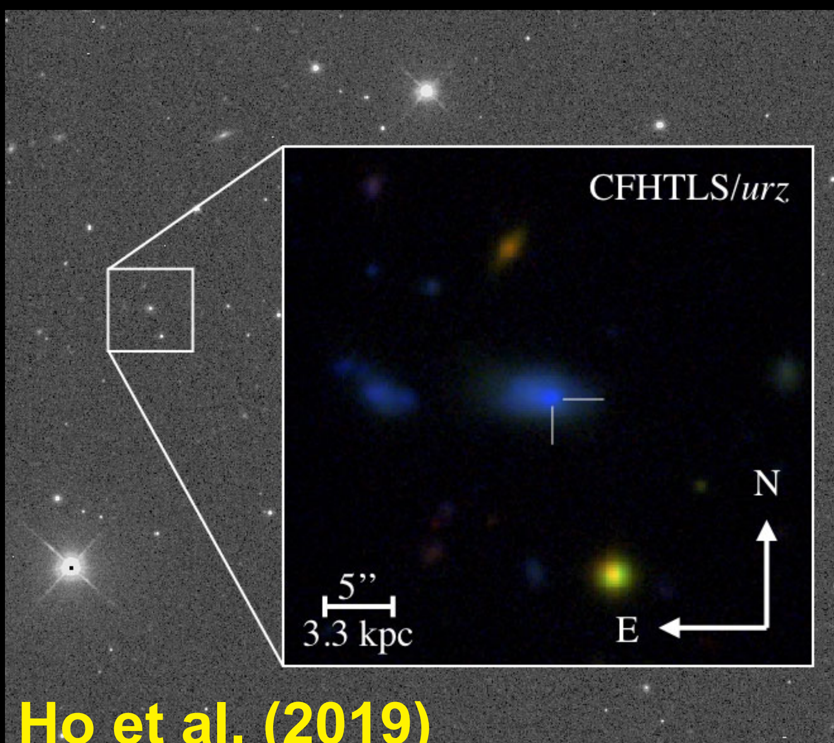


SN 2011fe:
Nugent et al. (Nature, 2011)

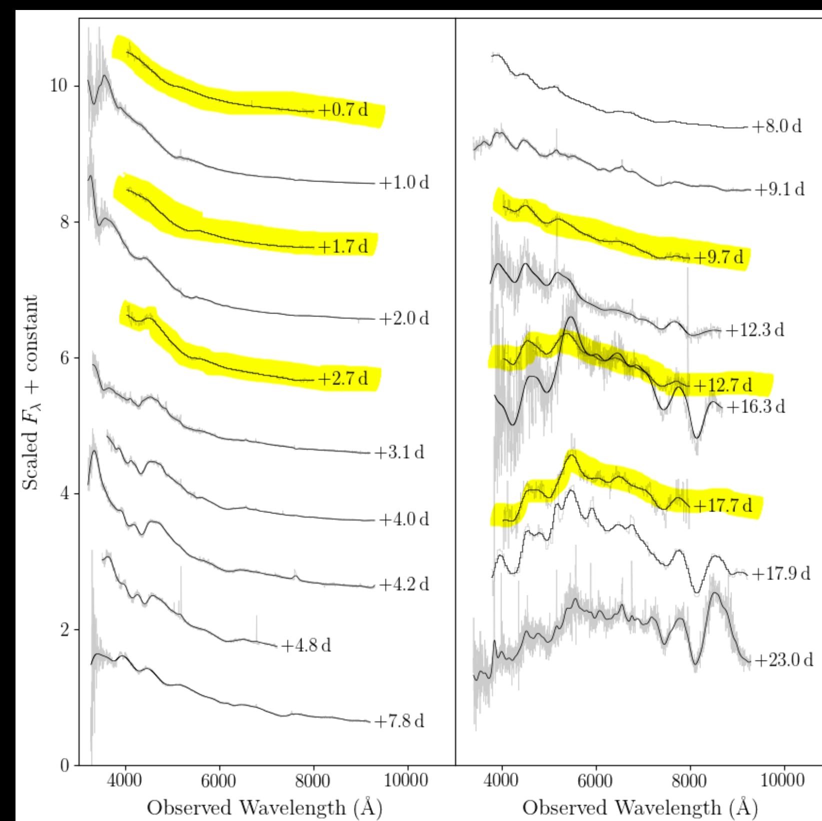
Science: Rapid Supernova follow-up

- SN2019gep discovered by Zwicky Transient Facility
  - Broad lined type Ic SN
- Earliest ever spectrum of a stripped-envelope supernova from LT

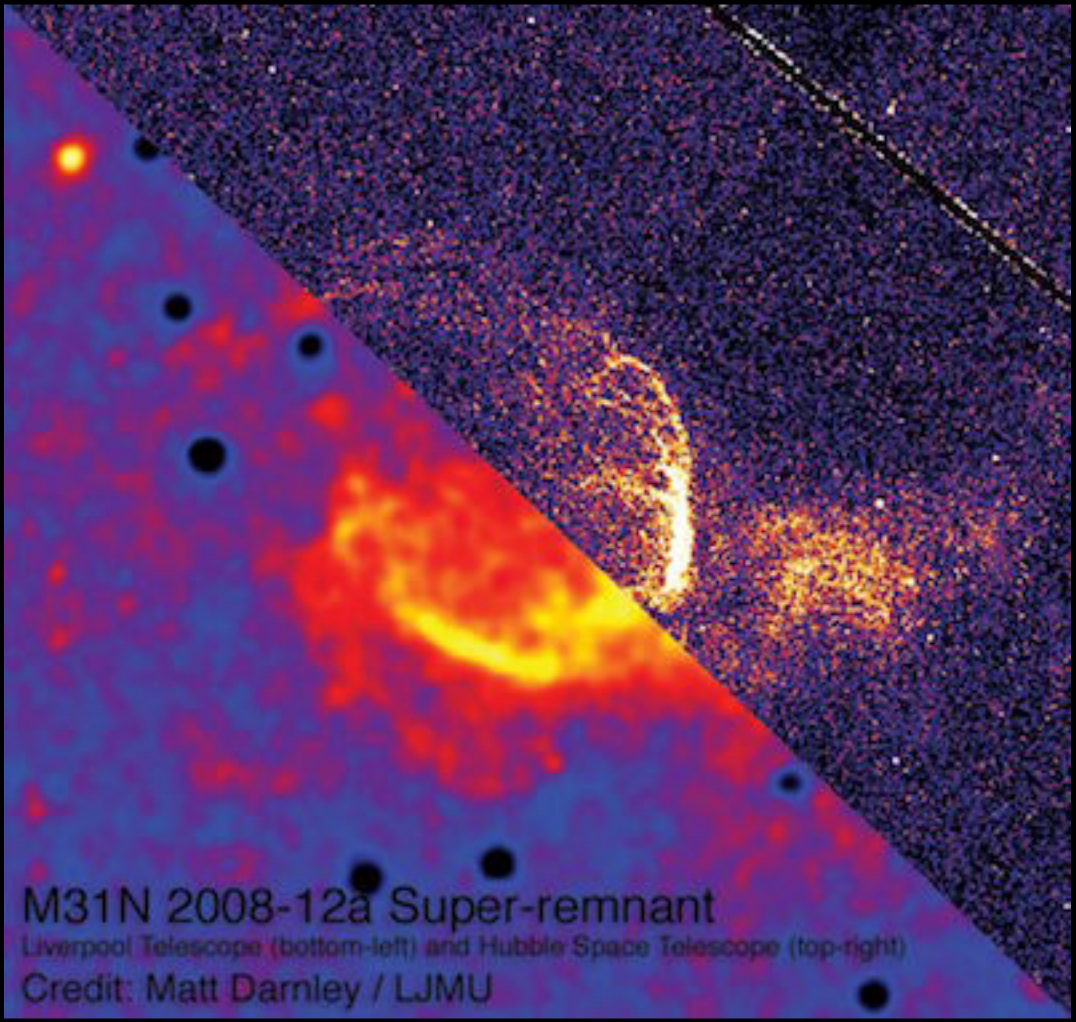
- Monitoring campaign reveals shock breakout in a massive shell of dense circumstellar material



Ho et al. (2019)



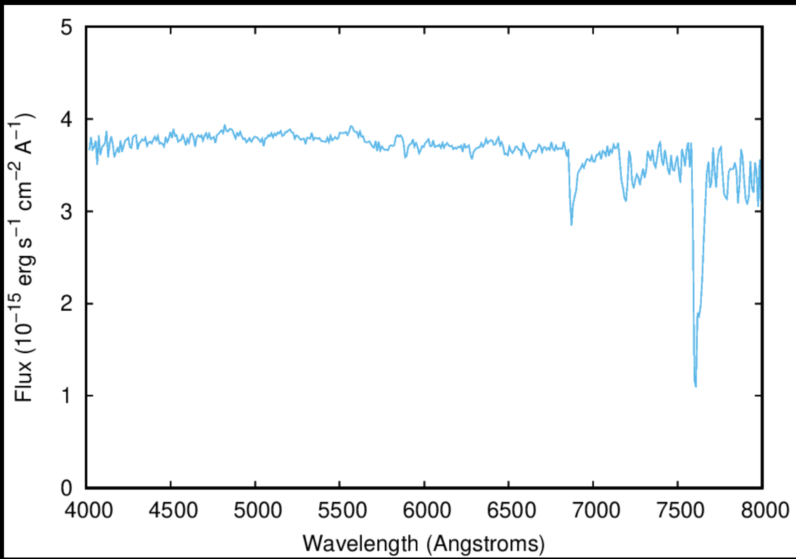
Science: Recurrent Nova super-remnant



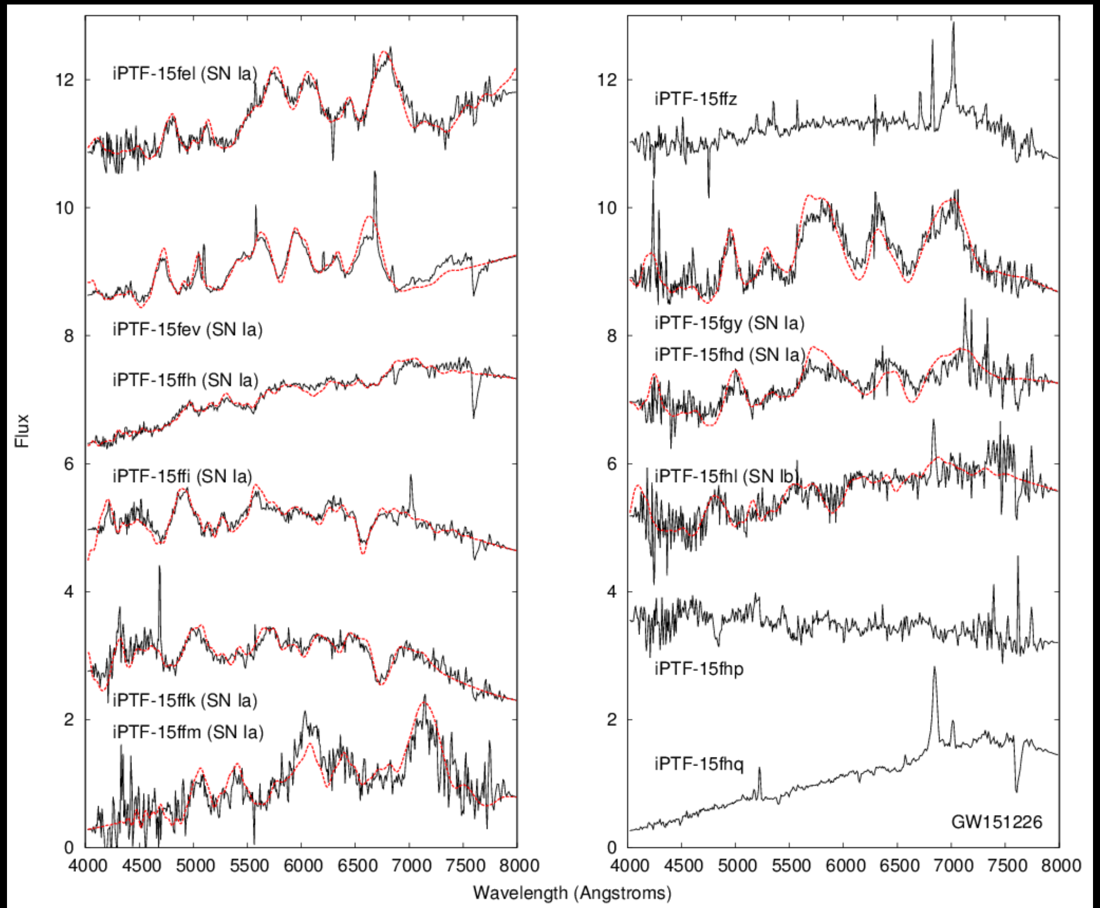
- M31N 2008-12a most rapidly-recurrent Nova (every year)
- Massive 'bubble' caused by pile-up of surrounding ISM material
- Likely SN Ia progenitor: powerful source for the study of supernova origins

Darnley et al. (2019, Nature)

Science: Multimessenger follow-up

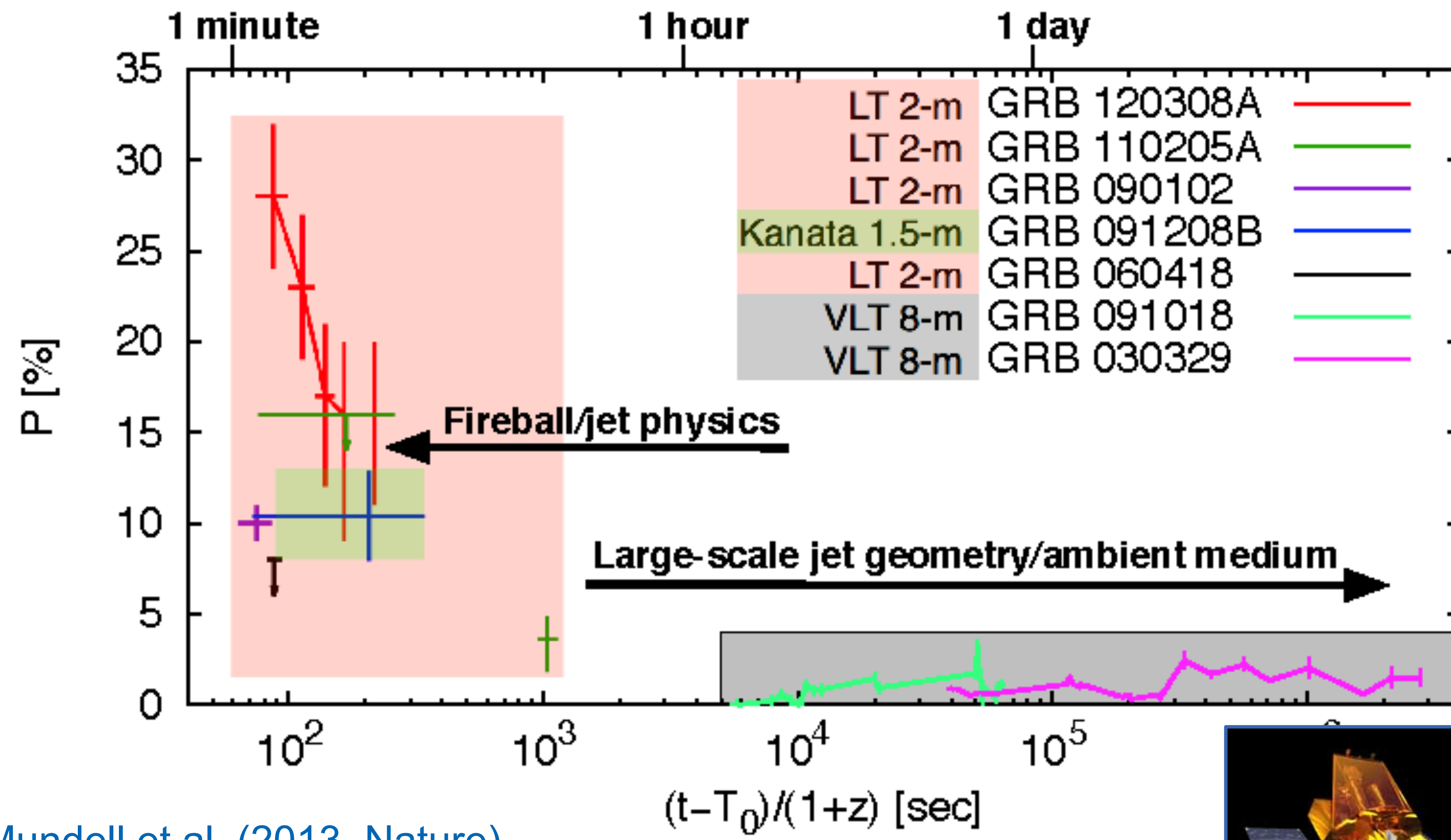


First spectrum following up IceCube-170922A neutrino event (IceCube Collaboration 2018)

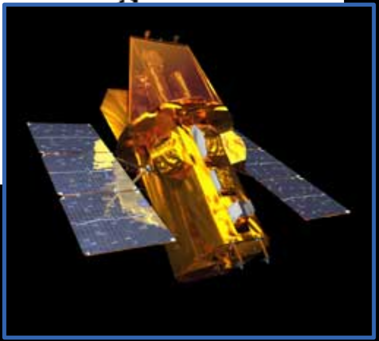


SPRAT spectra of candidate counterparts obtained during GW151226 campaign (Copperwheat et al. 2016)

Science: Polarimetric follow-up of Swift GRBs



Mundell et al. (2013, Nature)



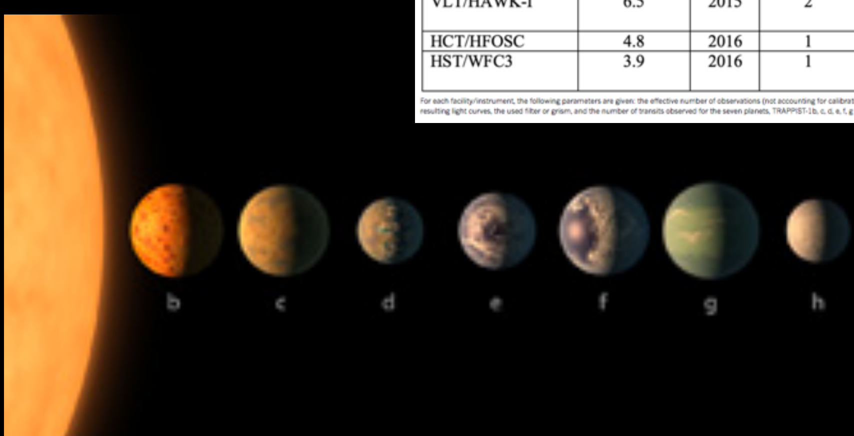
Science: LT observations of TRAPPIST-1

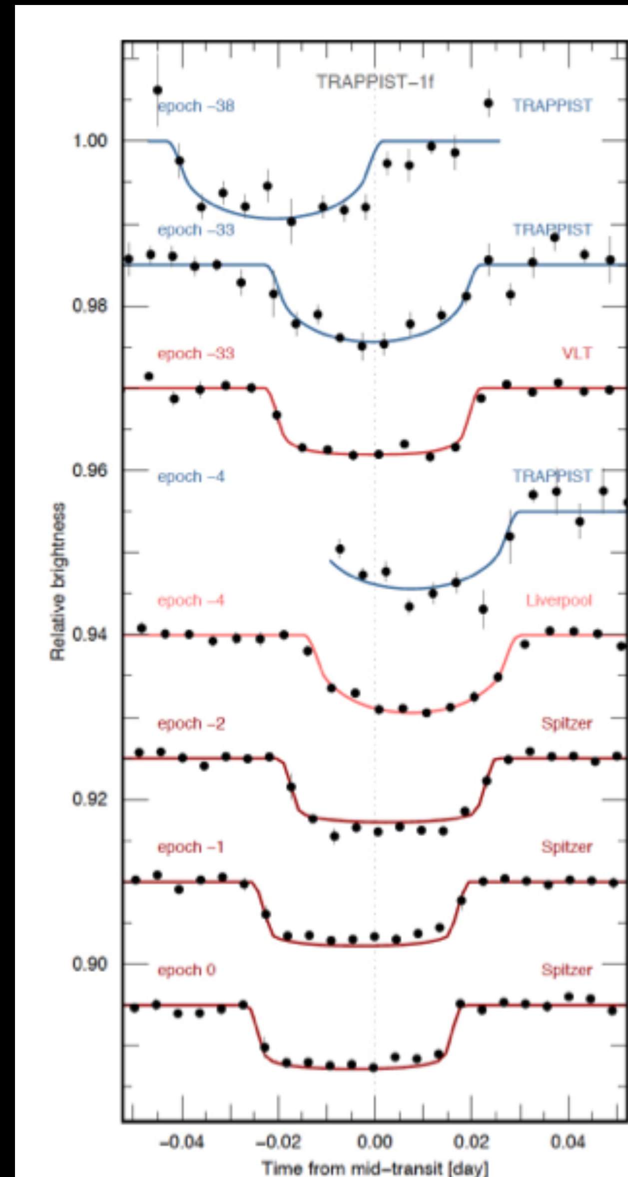
- 3 Earth-sized planets found transiting a 0.08M_{sun} star 12 parsecs away
- 7 planets orbit star within distance of Mercury orbit.
- Transit observations taken using the IO:O imager camera on the Liverpool Telescope (50 hours).
- Monitoring how light from the star changes when the planet passes in front of it.

Extended Data Table 1 | Summary of the observation set used

Facility/instrument	Number of hrs	Year(s)	Number of light curves	Filter/grism	Number of transits
TRAPPIST-South	677.9	2013 2015 2016	214	I+z	b: 13, c: 1, d: 3, e: 5, f: 3, g: 4
Spitzer/IRAC	476.8	2016	30	4.5 µm	b: 16, c: 11, d: 5, e: 2, f: 3, g: 2, h: 1
TRAPPIST-North	206.7	2016	75	I+z	b: 4, c: 3, [illegible]
LT/IO:O	50.3	2016	10	z'	b: 1, c: 1, e: 1, f: 1
[illegible]	[illegible]	[illegible] 2016	[illegible]	[illegible]	[illegible]
WHT/ACAM	25.8	2016	4	I	b: 1, c: 1, d: 1
SAAO-1m/SHOC	10.7	2016	5	z'	None
VLT/HAWK-I	6.5	2015	2	NB2090	b: 1, c: 1, e: 1, f: 1
HCT/HFOSC	4.8	2016	1	I	b: 1
HST/WFC3	3.9	2016	1	G141 (1.1-1.7 µm)	b: 1, c: 1

For each facility/instrument, the following parameters are given: the effective number of observations (not accounting for calibration and overhead times), the year(s) of observation, the number of resulting light curves, the used filter or grism, and the number of transits observed for the seven planets, TRAPPIST-1b, c, d, e, f, g and h.





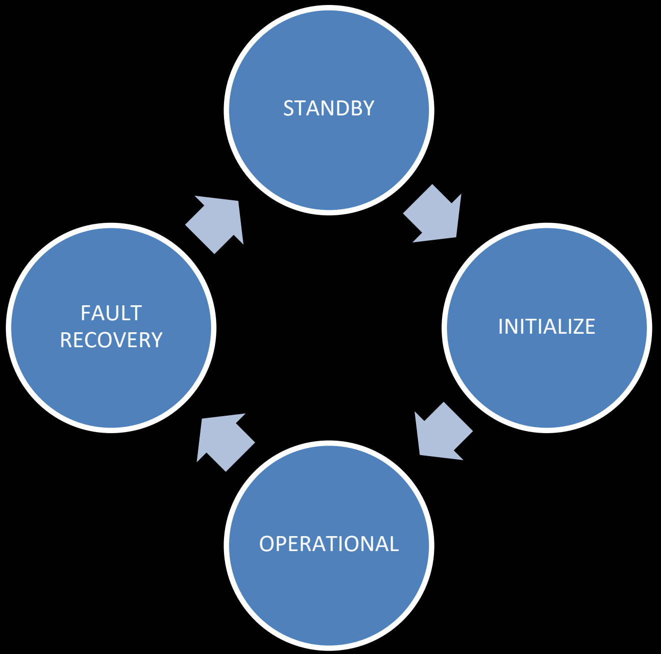
Gillon et al. 2017, Nature, 542, 456.

KEY ELEMENTS FOR ROBOTIC OPERATION

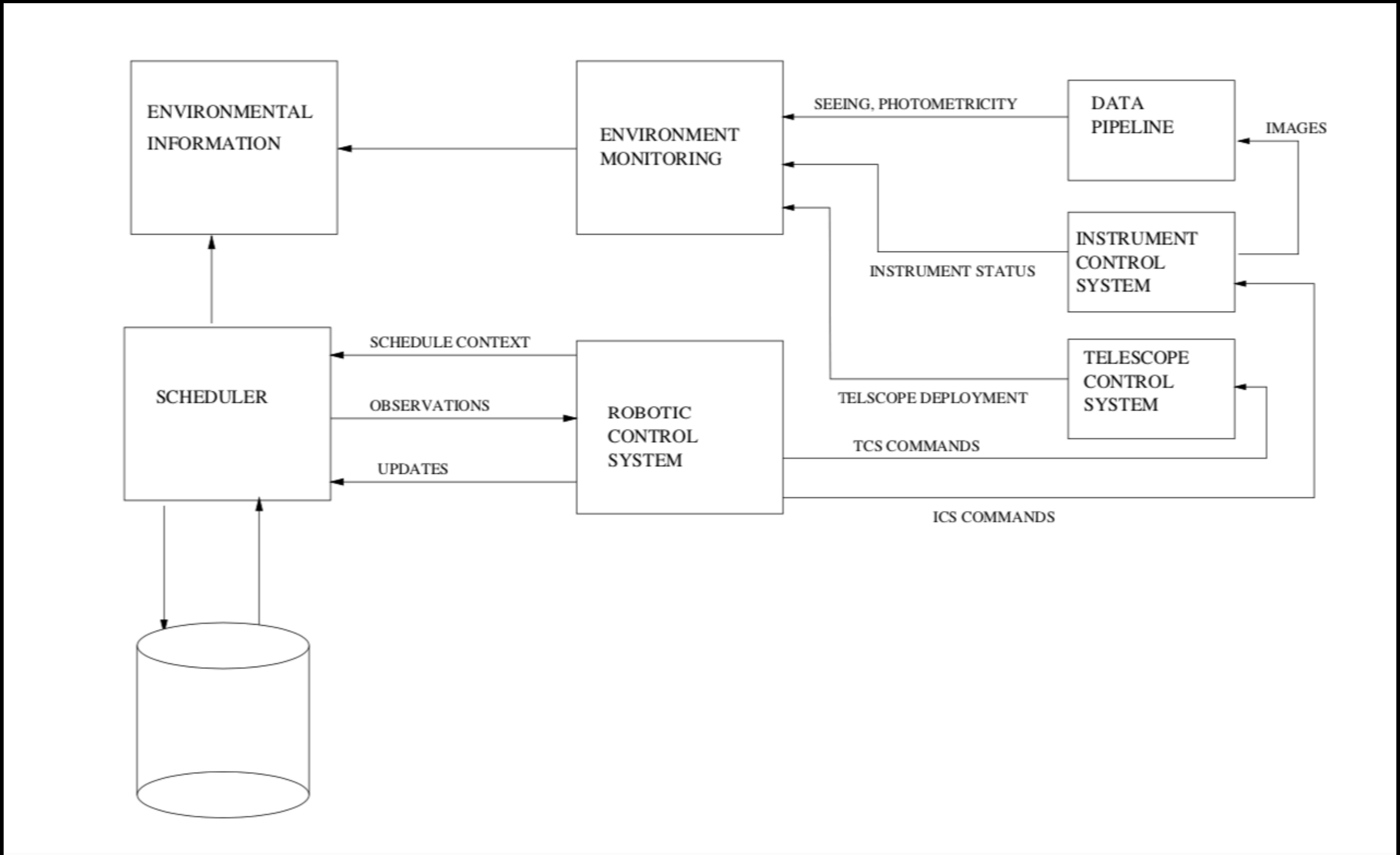
- AUTOMATIC FAULT RECOVERY
  - Devolved Responsibilities to subsystem
  - Robust state model
- ”ROBOTIC CONTROL SYSTEM” – VIRTUAL ASTRONOMER
  - Database for Scheduling Observations (“What next?”)
  - Sequencing Commands (“What commands in what order”)
  - Reactive (“What to do when something unpredictable happens?)
- RELIABLE ENVIRONMENTAL MONITORING
  - Safety Interlock Systems
  - Weather
  - Sky Conditions
- STANDARDIZED SOFTWARE APIs FOR ALL INSTRUMENTS
- DATA PIPELINES THAT CAN ASSESS DATA QUALITY IN REAL TIME
- (ROBUST HARDWARE)

FAULT RECOVERY / RETURN TO A KNOWN STATE

- AFTER ANY FAULT REINITALIZE ALL MECHANISMS!



ROBOTIC CONTROL SYSTEM



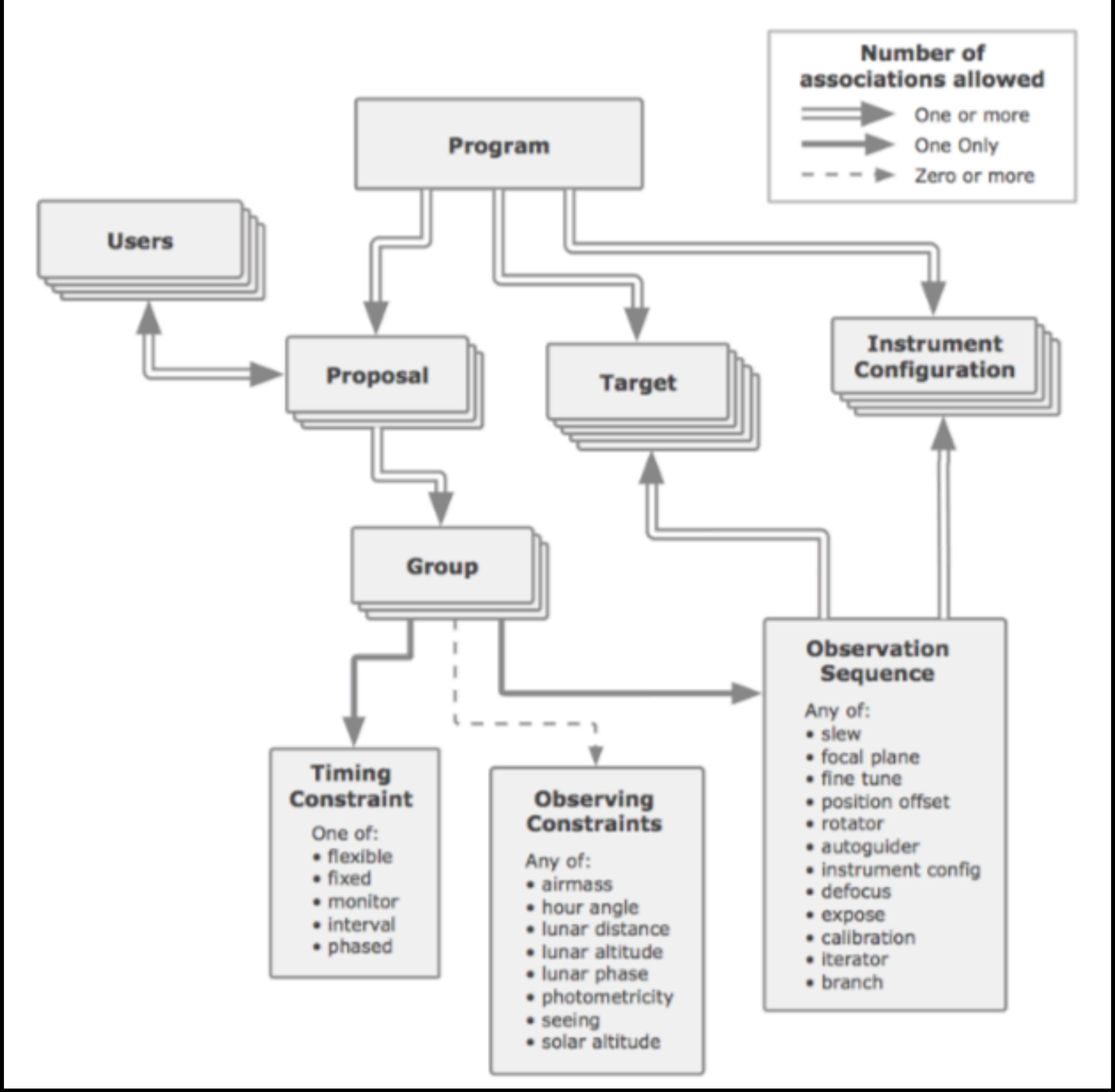
- Fraser & Steele (2002), Proc SPIE 4848

SCHEDULING

- Simple Dispatch Scheduler works well given changeable conditions limit “look ahead” time horizon
- Develop metrics for variables such as
  - Science Priority
  - Airmass
  - Time to set
  - Time left in semester
  - Matching seeing and sky brightness
- Combine multiplicatively and pick what is best to do now.
- Whatever solution you choose users will say you are doing it wrong!
- Fraser (2008), Proc SPIE, 7019

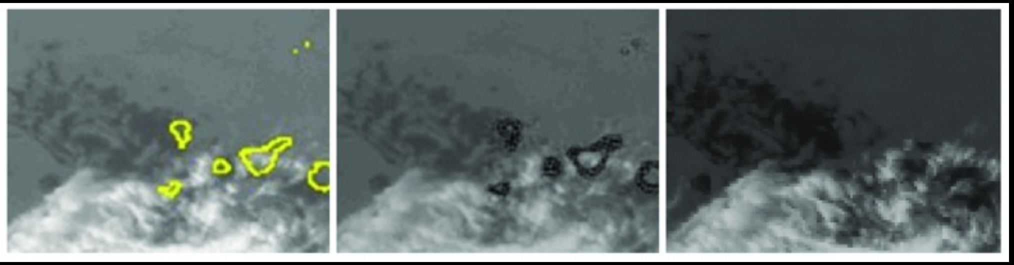
DATABASE

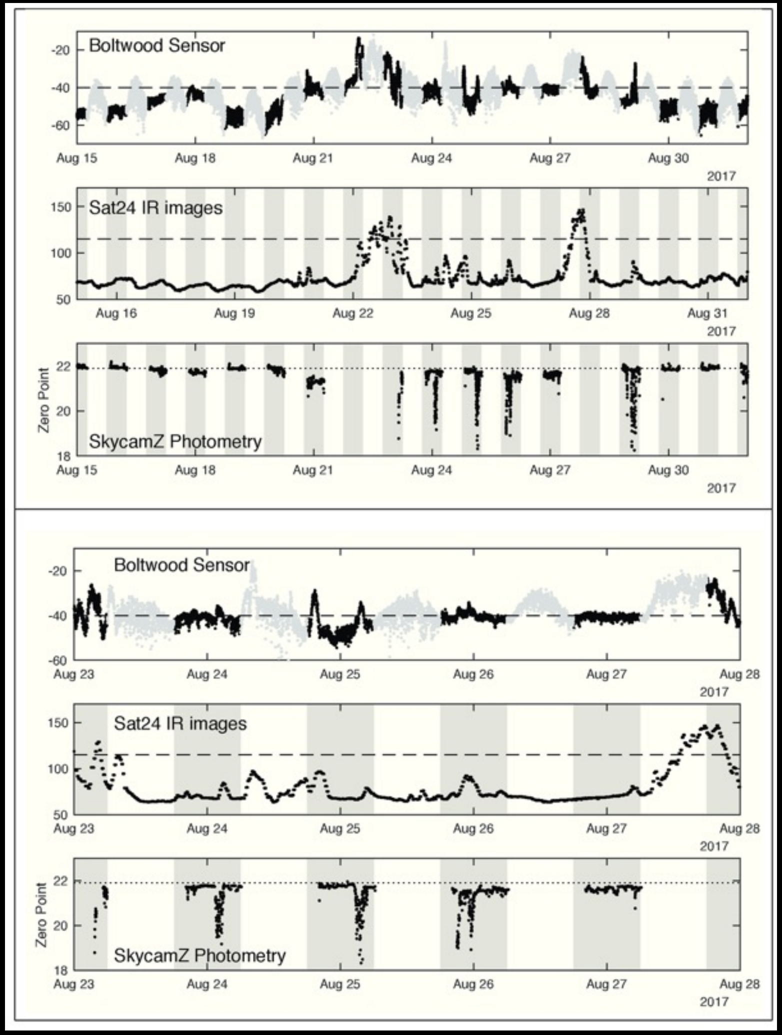
Steele (1997), Proc SPIE, 3112, 222
Steele (1998), Proc SPIE, 351, 232
Fraser (2002), Proc SPIE, 4848, 443
Fraser (2004), Proc SPIE, 5493, 331
Smith (2010), Proc SPIE, 7737, 11



ENVIRONMENTAL MONITORING

- BASIC THINGS LIKE HUMIDITY, TEMPERATURE, RAIN CAN BE MEASURED WITH A WEATHER MAST
- CLOUD COVER
  - 10 MICRON SKY TEMPERATURES (Marchant (2008), Proc SPIE, 7012, 3)
  - SATELLITE DATA (Smith et al, (2018) Proc SPIE, 10704
  - PHOTOMETRIC ZERO POINTS





STANDARDIZED INSTRUMENT API

Super-class	Class	Description
ACQUIRE	ACQUIRE	Command to acquire a target.
CALIBRATE	ARC	Take an arc-lamp calibration.
CALIBRATE	BIAS	Take a bias frame (engineering mode).
CALIBRATE	DARK	Take a dark frame (engineering mode).
CALIBRATE	DAY_CALIBRATE	Perform day-time calibrations (dark and biases, used robotically).
CALIBRATE	LAMPFLAT	Take a flat-field using a lamp.
CALIBRATE	SKYFLAT	Take a flat-field using the sky (engineering mode).
CALIBRATE	TWILIGHT_CALIBRATE	Perform twilight calibrations (sky-flats, used robotically).
EXPOSE	GLANCE	Take an exposure, save to a temporary filename.
EXPOSE	MOVIE	Keep taking exposures of a certain length until told to STOP.
EXPOSE	MULTRUN	Take a certain number of exposures of a certain length.
EXPOSE	RUNAT	Take an exposure, starting a specified time.
EXPOSE	SAVE	Save a temporary exposure to a "real" filename.
INTERRUPT	ABORT	Abort a running exposure.
INTERRUPT	GET_STATUS	Get instrument status information.
INTERRUPT	PAUSE	Pause a running exposure, closing the shutter.
INTERRUPT	REBOOT	Reboot or re-datum the instrument.
INTERRUPT	RESUME	Resume a paused exposure.
INTERRUPT	STOP	Stop a running exposure.
SETUP	CONFIG	Configure the instrument (binning, windows, filters etc).
SETUP	LAMPFOCUS	Focus on a lamp (internal instrument focusing only).
SETUP	SET_LOGGING	Set the detail level of the logs.
SETUP	STARFOCUS	Focus on a star (internal instrument focusing only).
SETUP	TELFOCUS	Focus the telescope.
SETUP	TEST	Perform instrument tests.

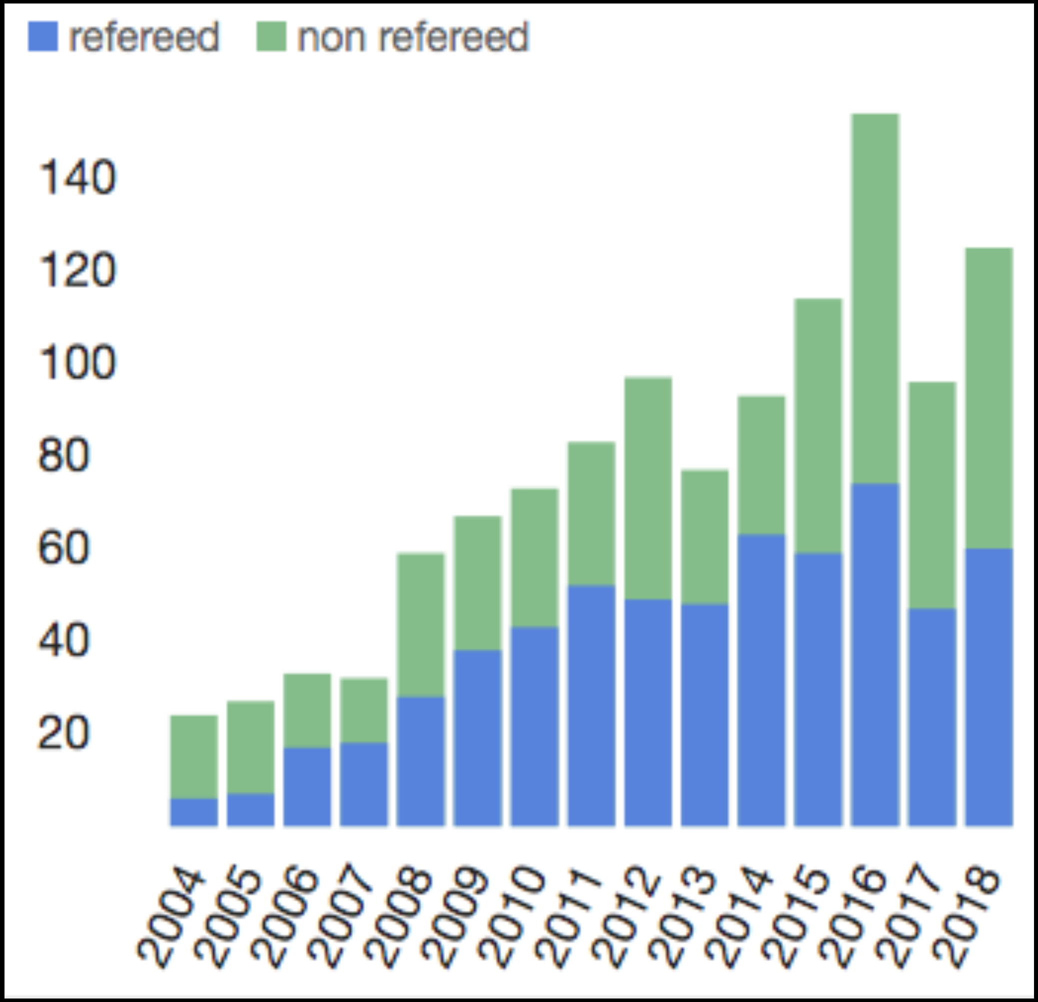
Mottram (2004)

Proc SPIE 5492

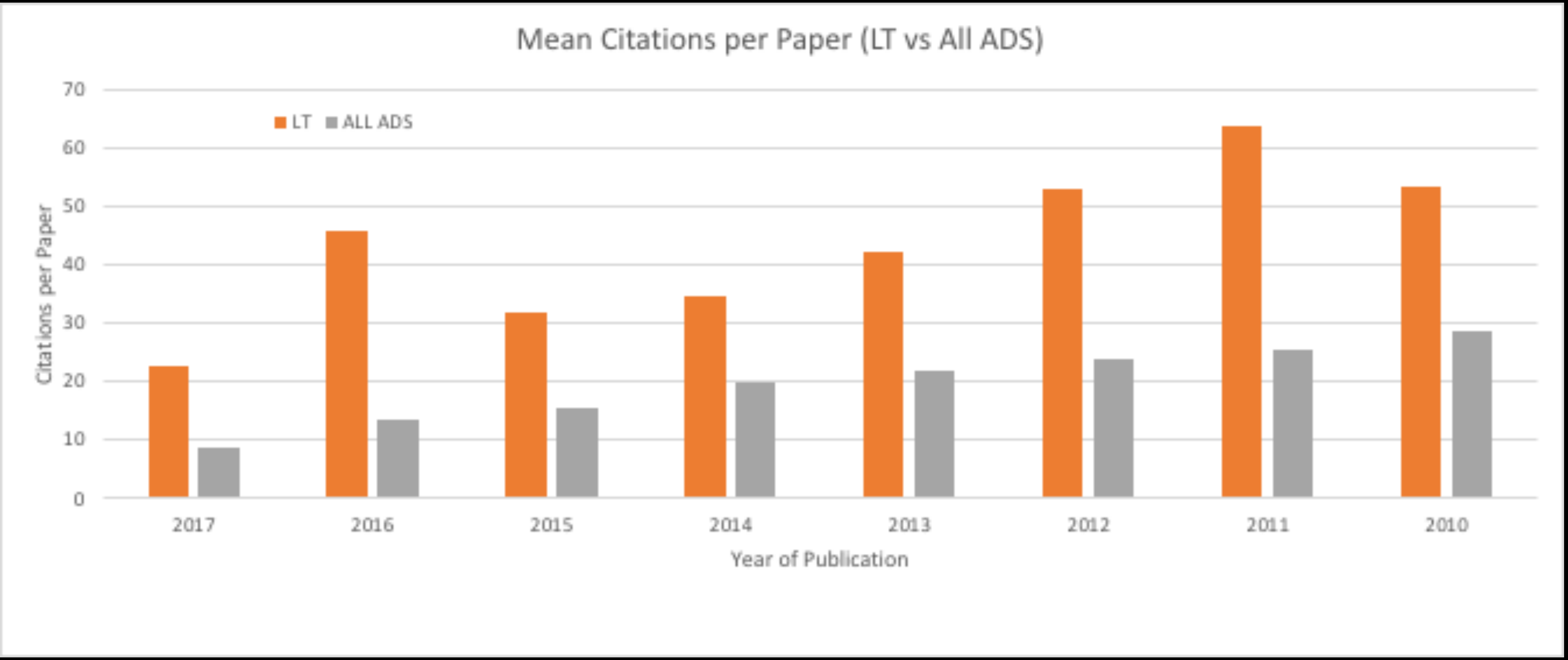
User Support: a warning!

- We operated for first few years in a more conventional "service observing" mode.
- When we moved to full robotic operations, user support requirements did NOT decrease
  - Questions about optimal use
  - Questions about why an observation did/did not work
  - Questions about data products
- An expectation that since the telescope is robotic everything is done for you!
- A lack of sense of user ownership of data can mean publication delays. Ongoing engagement post data taking needed to combat this.

But it is worth it!



High Impact papers…

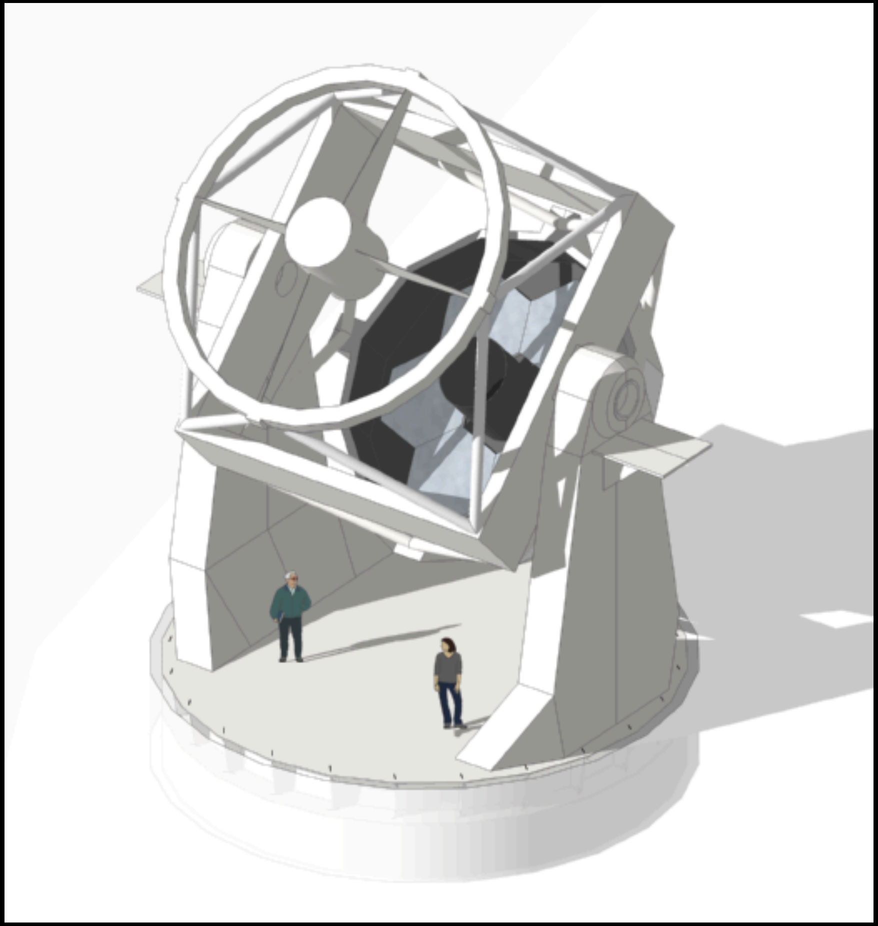


High Impact papers…

Telescope	Mirror Diameter	Number of Publications	Number of Citations	Citations / Publication
Mercator	1.2m	524	7575	14
LT	2.0m	352	13316	38
(FTN + FTS)/2	2.0m	124	3700	30
NOT	2.5m	952	28557	26
INT	2.5m	963	20039	20
WHT	4.2m	988	25949	25
VLT / 4	8m	1707	43970	19
GTC	10m	667	13128	30

A new 4.0m Robotic Telescope

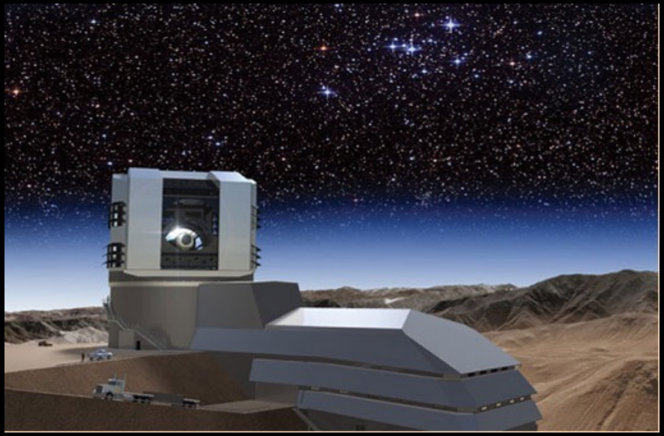
- In design stage. First light 2024.
- 4 metre segmented primary mirror, fully autonomous and robotic. Similar in design to LT.
- Focused on time domain science and follow-up.
- Agile and fast slewing. **Lightweight** and **compact**.
- Euro 25 million project with collaborators from Spain, Thailand, (China?). Looking for new partners.
- Selected as STFC Priority Project
- At least 5 focal stations for instrumentation: cassegrain or nasmyth.



Copperwheat, C. M. et al., 2014, SPIE, 9145, 11

http://www.robotictelescope.org/

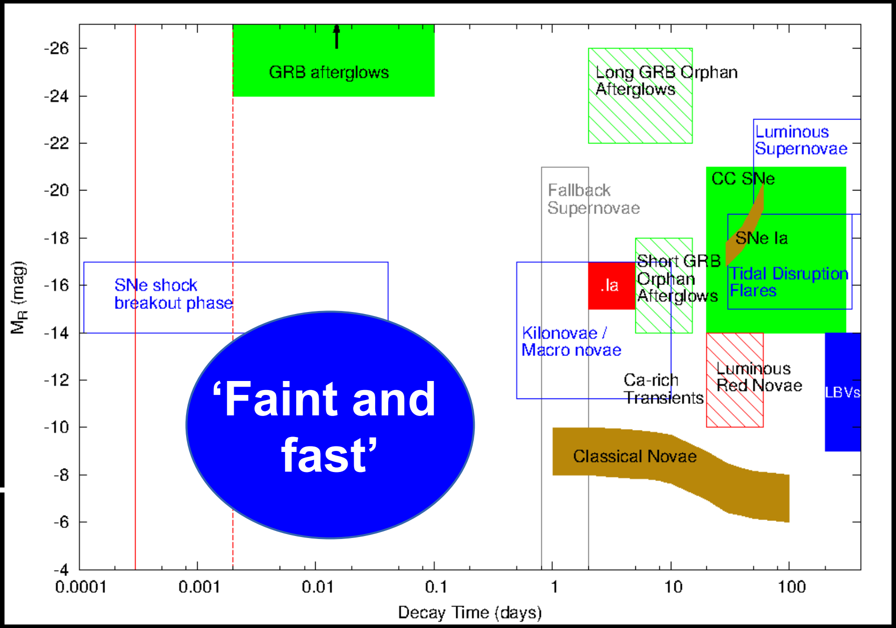
Motivation: transient science



Serious issue in the LSST era:

- vast increase in discovery rate (~1e6 alerts *per night*!)
- Significant risk that the transient science potential of the survey will not be fully realised

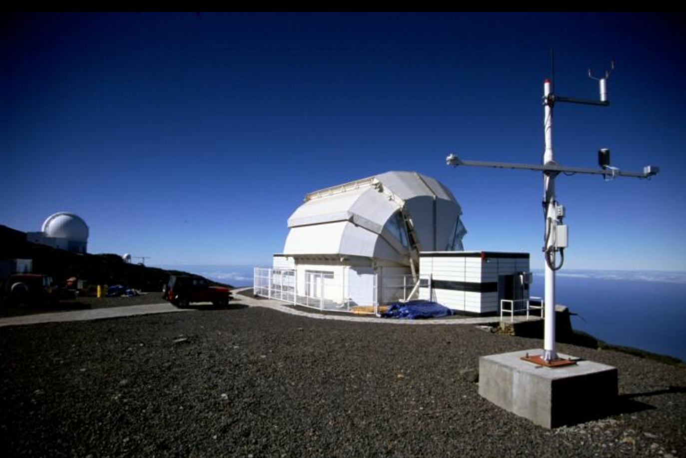
- Initial classifications from LSST photometry and machine learning algorithms
- Spectroscopy required for identification of rare subtypes and new phenomena, and exploitation of the most interesting targets
- **NRT design requirements**: Opt/IR spectroscopy. Low/intermediate resolution. Automatic response to triggers **within 30 seconds**. Small observing overheads. Depths down to R~21-22



(Adapted from LSST science book)

LT: telescope.livjm.ac.uk

NRT: www.robotictelescope.org



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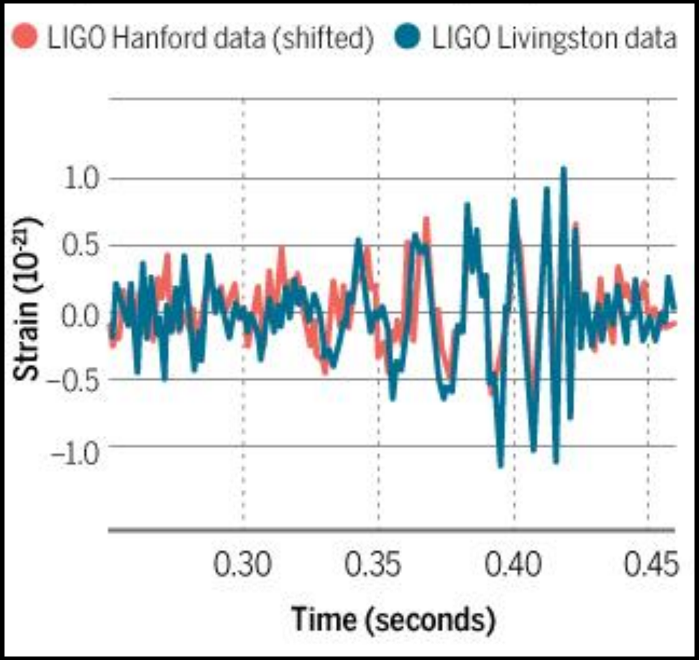
ASTROPHYSICS RESEARCH INSTITUTE

LIVERPOOL JOHN MOORES UNIVERSITY

Motivation: gravitational waves

- A whole new type of astronomy: transient detections via non-electromagnetic means. Huge discovery potential
- Electromagnetic follow-up programme active. EM counterpart detection achieved.



- Full LIGO/Virgo sensitivity in ~2022: expected discovery rate 100s transients per year
- Observational challenges: ~few deg positional uncertainty, fast fading (?)
- **Requirements:** wide FoV search capability. Rapid response. Efficient spectroscopic classification of large numbers of candidates. Infrared.