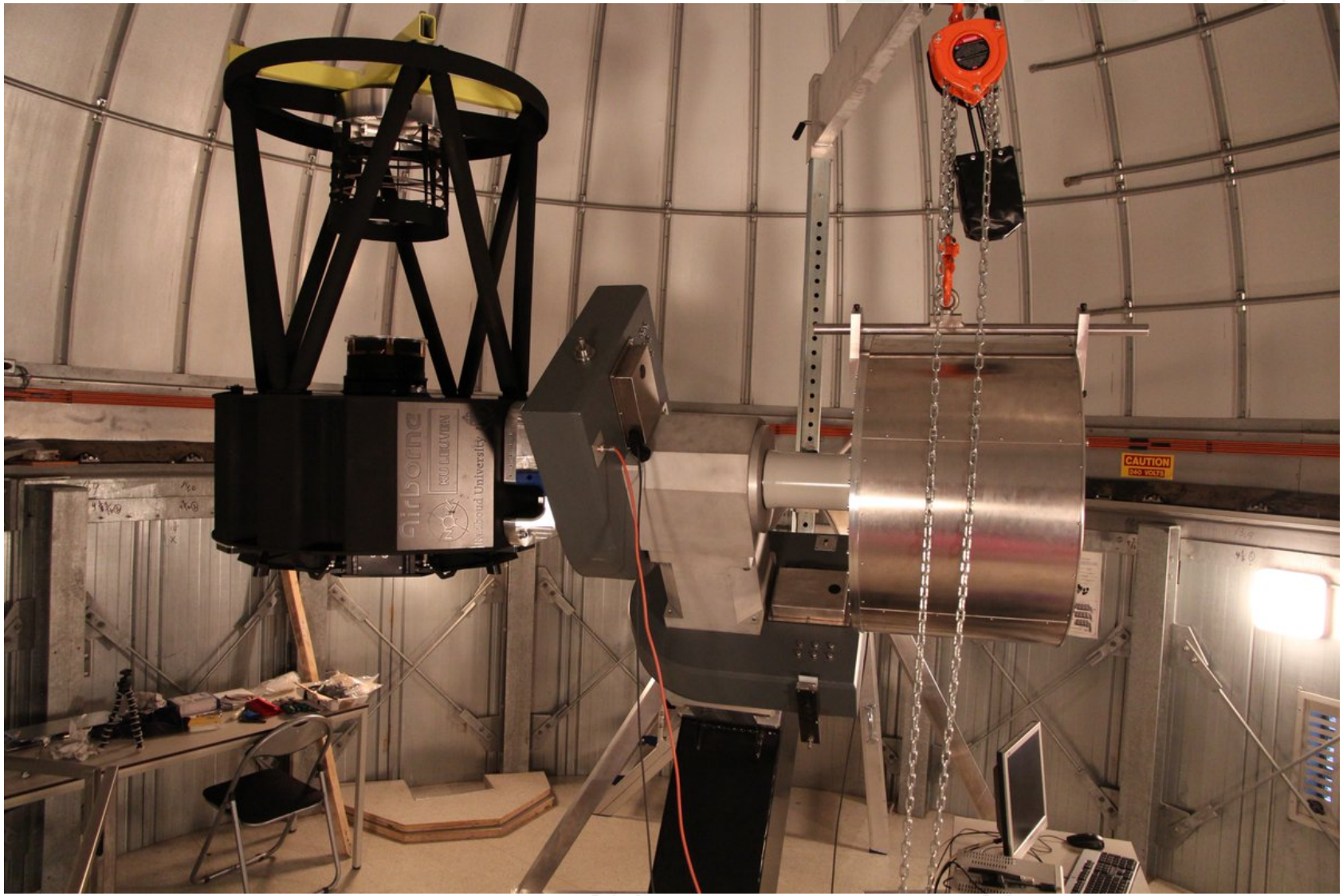
Fast Transients: BlackGEM & MeerLICHT



Paul Groot
Radboud University & NOVA

Radboud University

Talk Outline

- What are BlackGEM and MeerLICHT?
- Scientific motivation
- Current Status
- Survey plans & Timeline
- Future plans

Developments in Astronomy

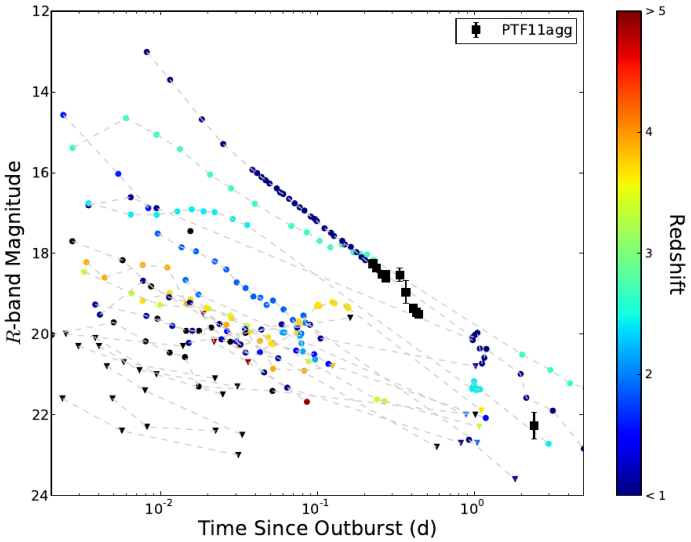
- Better detectors & more/larger telescopes
  → Higher sensitivity and more time on sky
- Opening up of wavelength ranges & multimessenger
  → Move from domains to astrophysics problems
- Faster computers, more storage capacity, better connections
  → Faster data processing

→ 'Photon starved' to 'neuron starved'
→ Domain astronomers (radio/optical/theory) to 'problem solvers'
→ From a still picture to a movie.

A new era

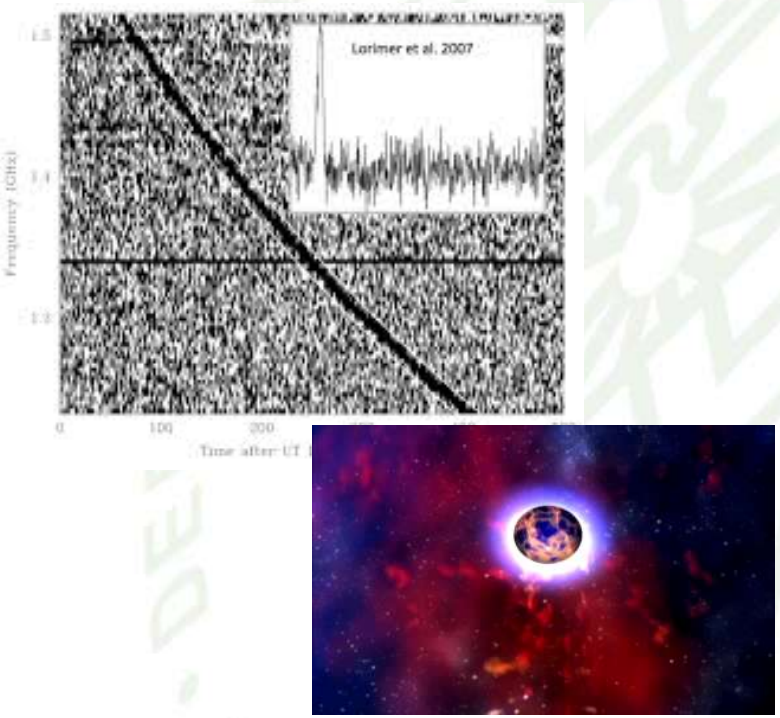
Expanding possibilities allows:

a) Targeted searches for known but unidentified (rare) phenomena
b) Targeted searches for possible/predicted phenomena
c) True exploration of new space (‘fishing expeditions’)



a) GRB Orphan Afterglows

(Cenko et al. 2013; 2015)

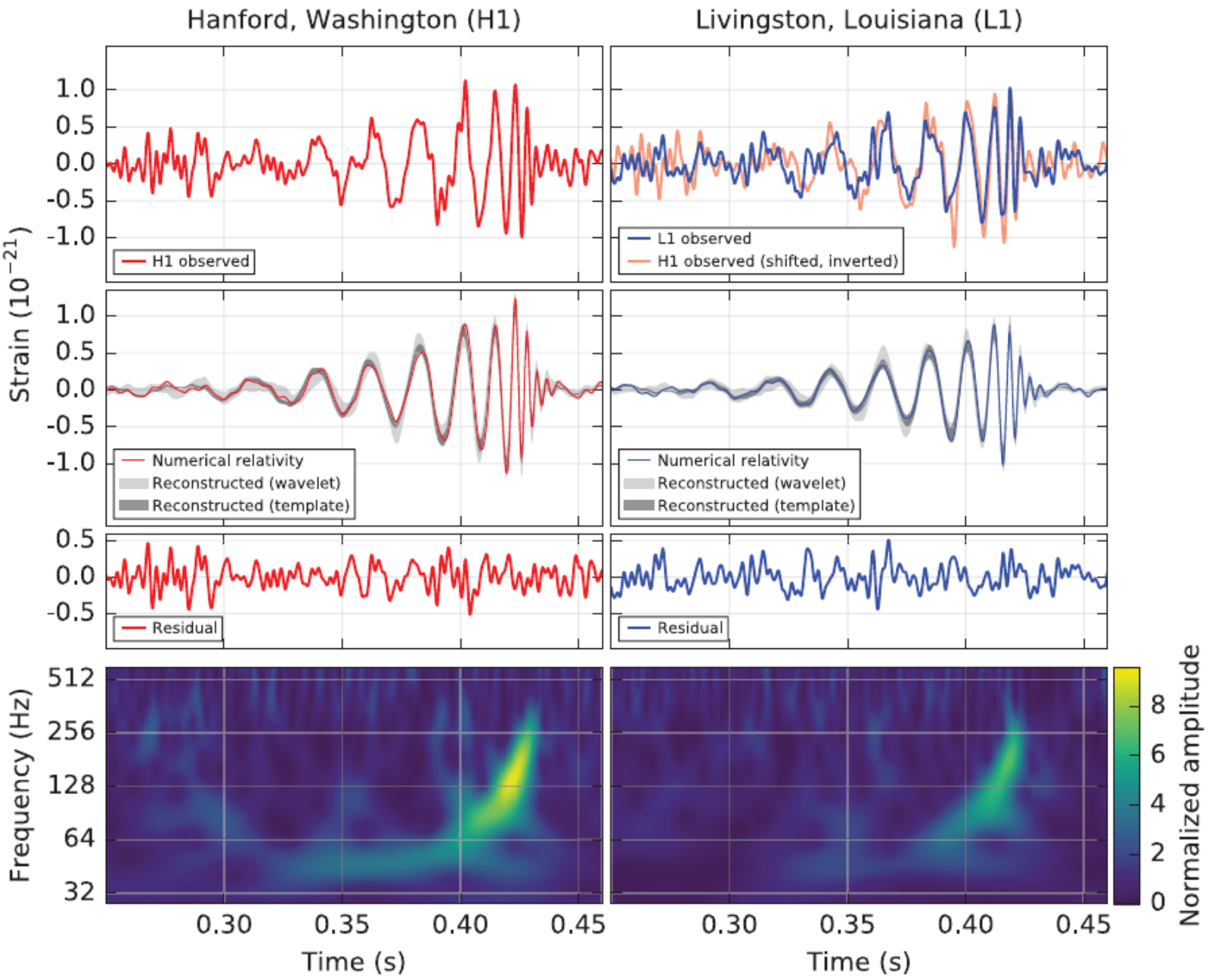


b) Gravitational wave and FRBs counterparts

?

c) The unknown

Gravitational waves detected



GW150914

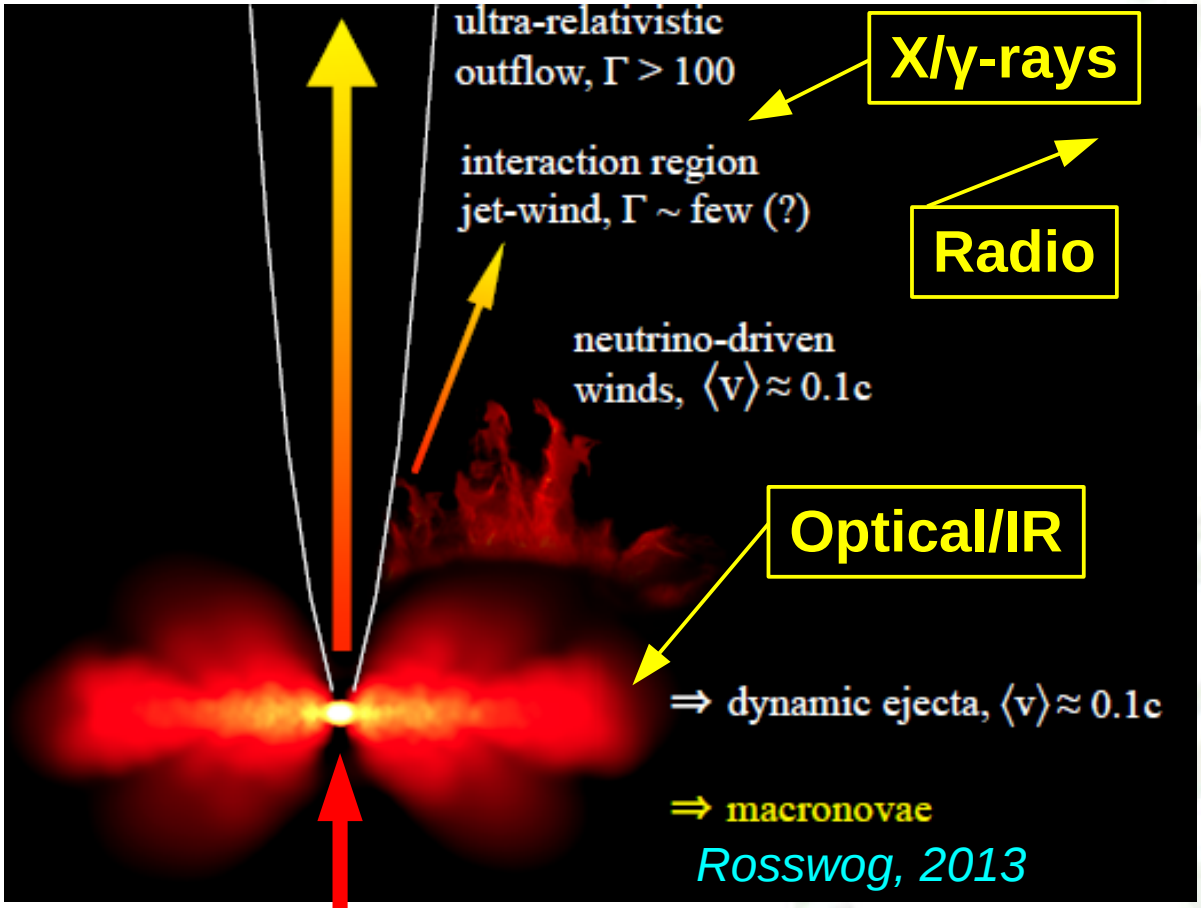
29+36 Solar mass Black holes Merging

62 Solar mass Black hole formed

3 Solar masses of energy radiated in GW

University

Why optical GW follow-up?



Optical has advantages:

- Macronova emission isotropic
  → high rate
- Visible for ~days timescale
  → gives time, but still prompt
- Brightness: $20 < g < 23$, for events at d<200 Mpc

Gravitational wave merger has just happened here: Black Hole born

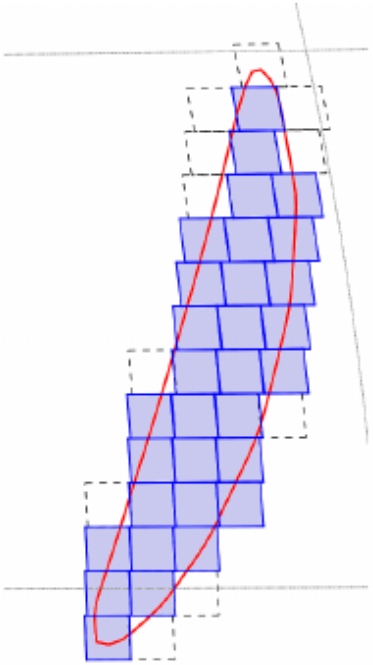
Optical follow-up optimal choice in visibility, rate, affordability, and brightness for GW events. Requires large field-of-view (>10 sqd), robotic, depth and high accuracy

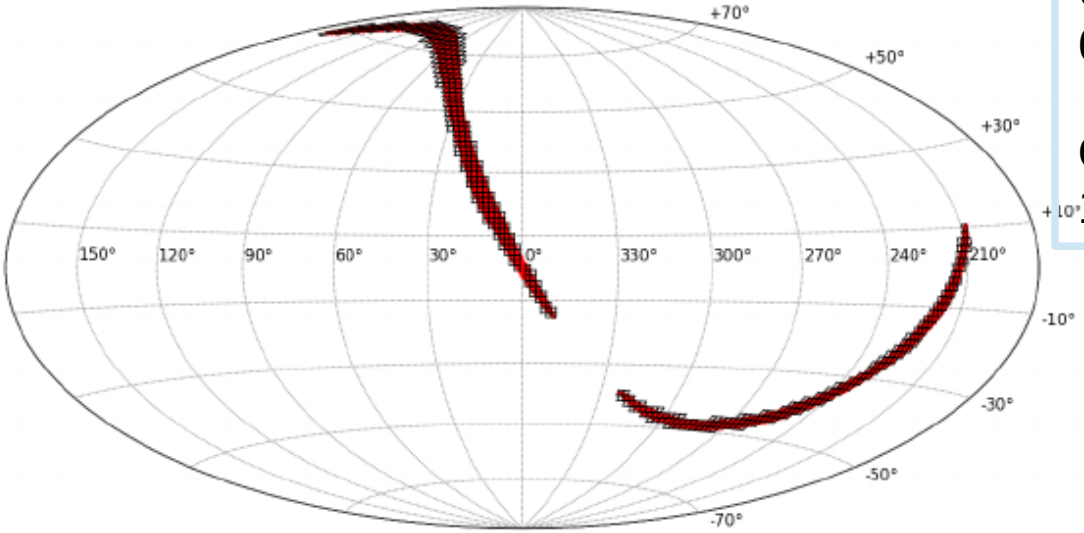
LIGO/Virgo Counterparts

Radboud University is a member of the Virgo Consortium

- Kilonova counterparts to gravitational wave events
- Challenge: faint (~22nd mag), fast (~days), poor localization (>100 sqd.)
- Flexible array to tile the error boxes efficiently

- Each telescope equiped with six filters (u,g,r,i,z + 'q' wide band)





GW150914: 640 sqd.

GW151226: 1440 sqd.

Efficient (ranked) tiling of the error box: *Ghosh et al. 2016*

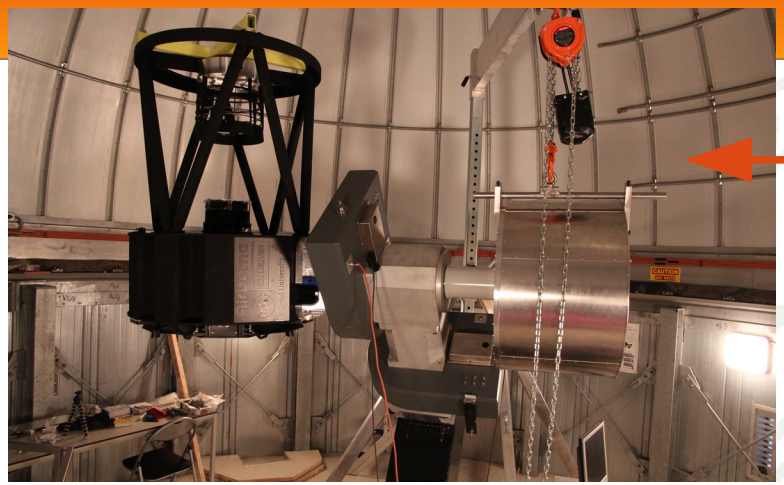
BlackGEM & MeerLICHT

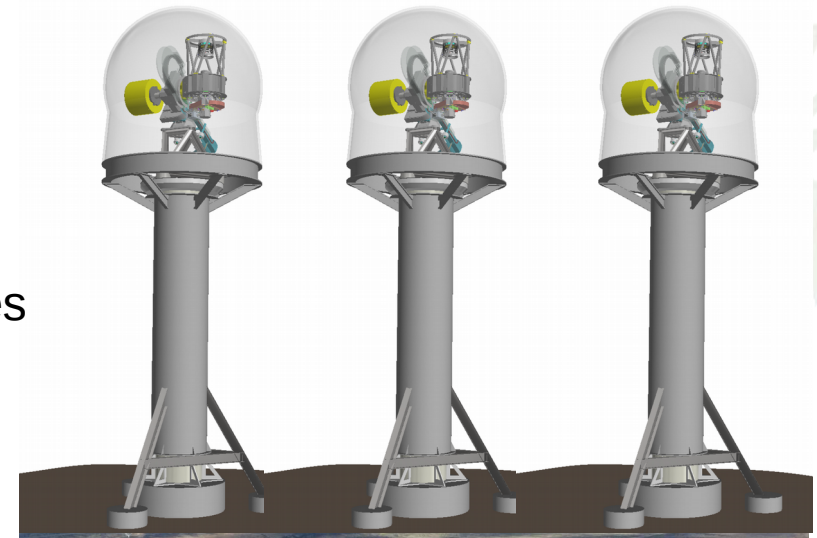
BlackGEM

Phase 1:
- 3 wide field telescopes
- 8 square degrees total
- 65cm diameter each
- g=23 in 5 minutes
- ESO La Silla
- Seeing limited (<1")
- *u,g,q,r,i,z* filter set
  ("PTF South" / "Proto-LSST")

Phase 2:
- Expansion to 15 telescopes
- 40 square degrees
  ("ZTF South")

Science:
- ***GW counterparts***
- Southern Sloan
- Fast Transients & Variables
- Nearby Universe Survey





MeerLICHT

- BlackGEM prototype (technically identical)
- Twinned to MeerKAT radio
- Sutherland, South Africa
- Operational early 2017

Science

Radio – optical activity
- *GW Counterparts*
- X-ray binaries
- Supernovae
- Compact binaries
- Novae
- Flare Stars
- *Fast Radio Bursts*

Radboud University

BlackGEM & MeerLICHT

Typical size of each BlackGEM image: 1.65˚ x 1.65˚

BlackGEM @ ESO La Silla, Chile

BlackGEM telescope

- 65 cm main mirror
- 110 Mpix camera (1 chip)
- 2.7 square degree field-of-view
- 10 second readout

- Carbon-fibre structure
- Fornax 200 mount
- Fully robotic

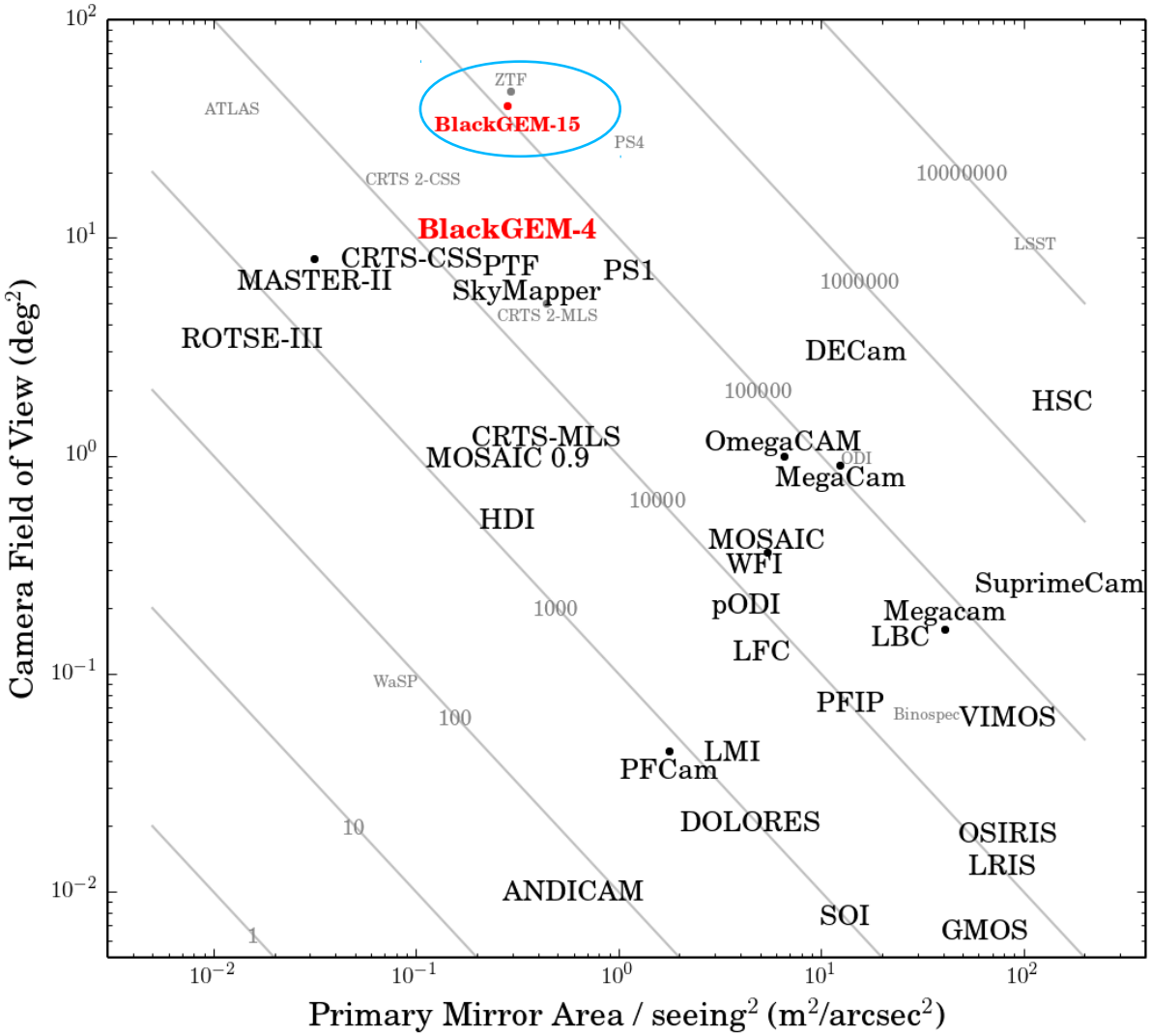
- Status: *Prototype finished*

Phase 1 (2018)
- 3 telescopes (8.1 sqd)

Phase 2 (2019+)
- 15 telescopes (40 sqd)

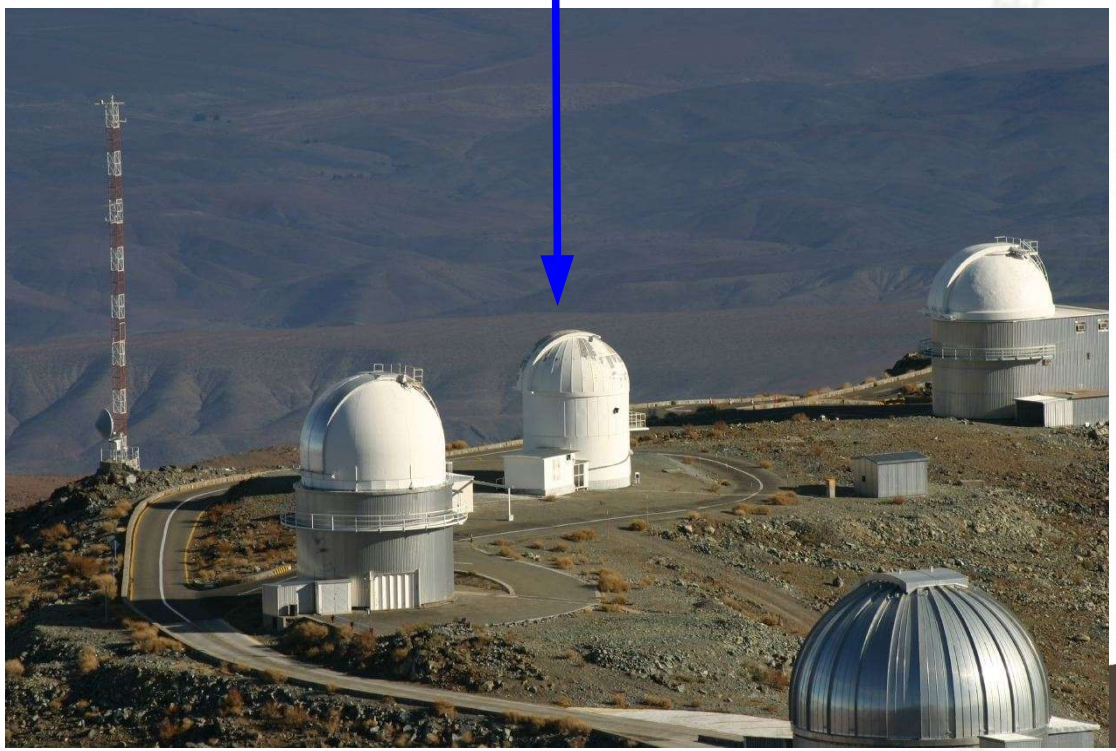
Aperture vs. seeing: by design

- Excellent seeing (σ) and dark site: ESO La Silla, median seeing 0.95”
- Telescope design limited by ***site***, not optics
- Background limited regime: sensitivity scales with diameter/seeing (D/σ):
  i.e. 1.2m on 2” site = 0.6m on 1” site



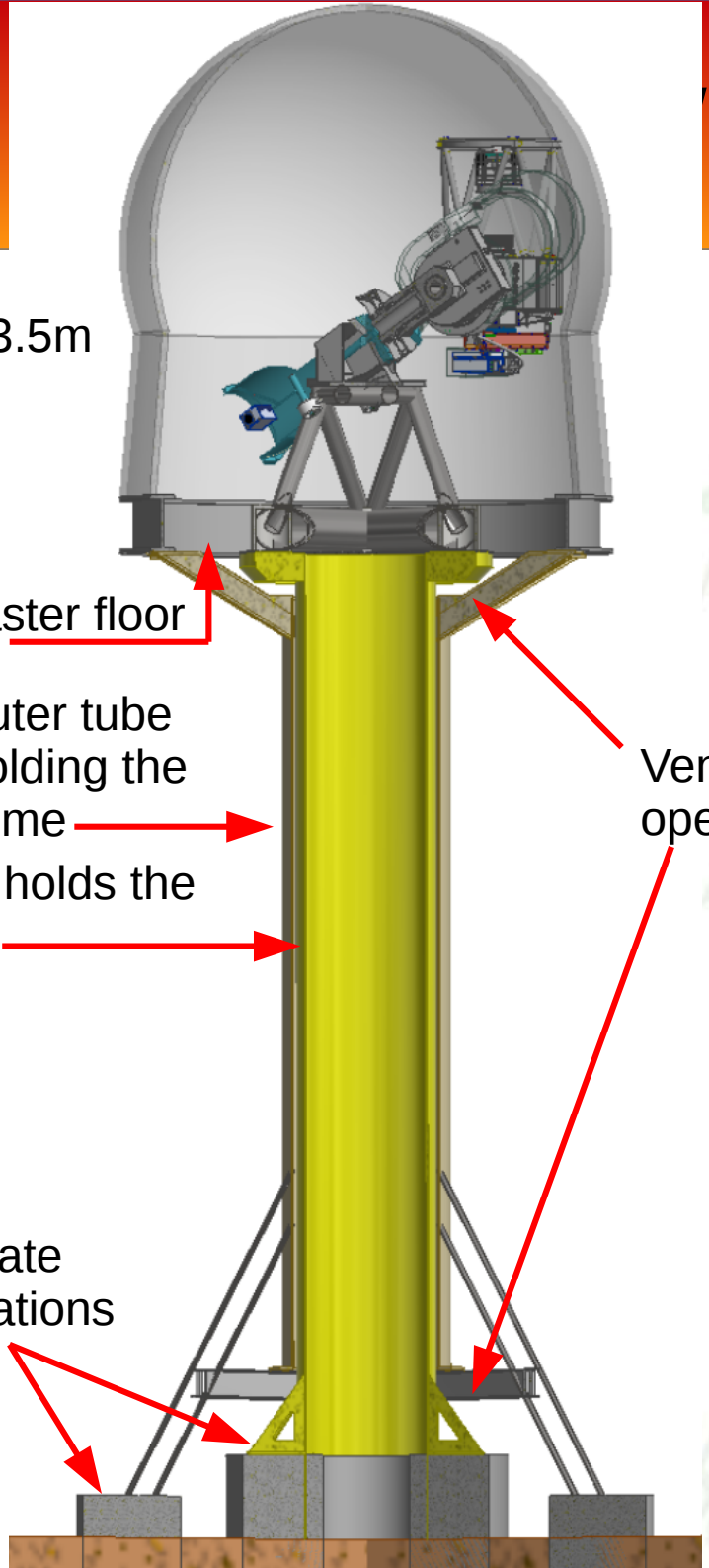
Dome/Building

- One Baader AllSky 3.5m clam-shell dome, one per telescope
- Telescope on ~7m hight cylinder above ground to limit ground seeing
- Design: Radboud U. TechnoCenter, inspired by telescope at Radboud
- Site: Former GPO telescope site on La Silla. GPO building removed by ESO
- Status: In FDR

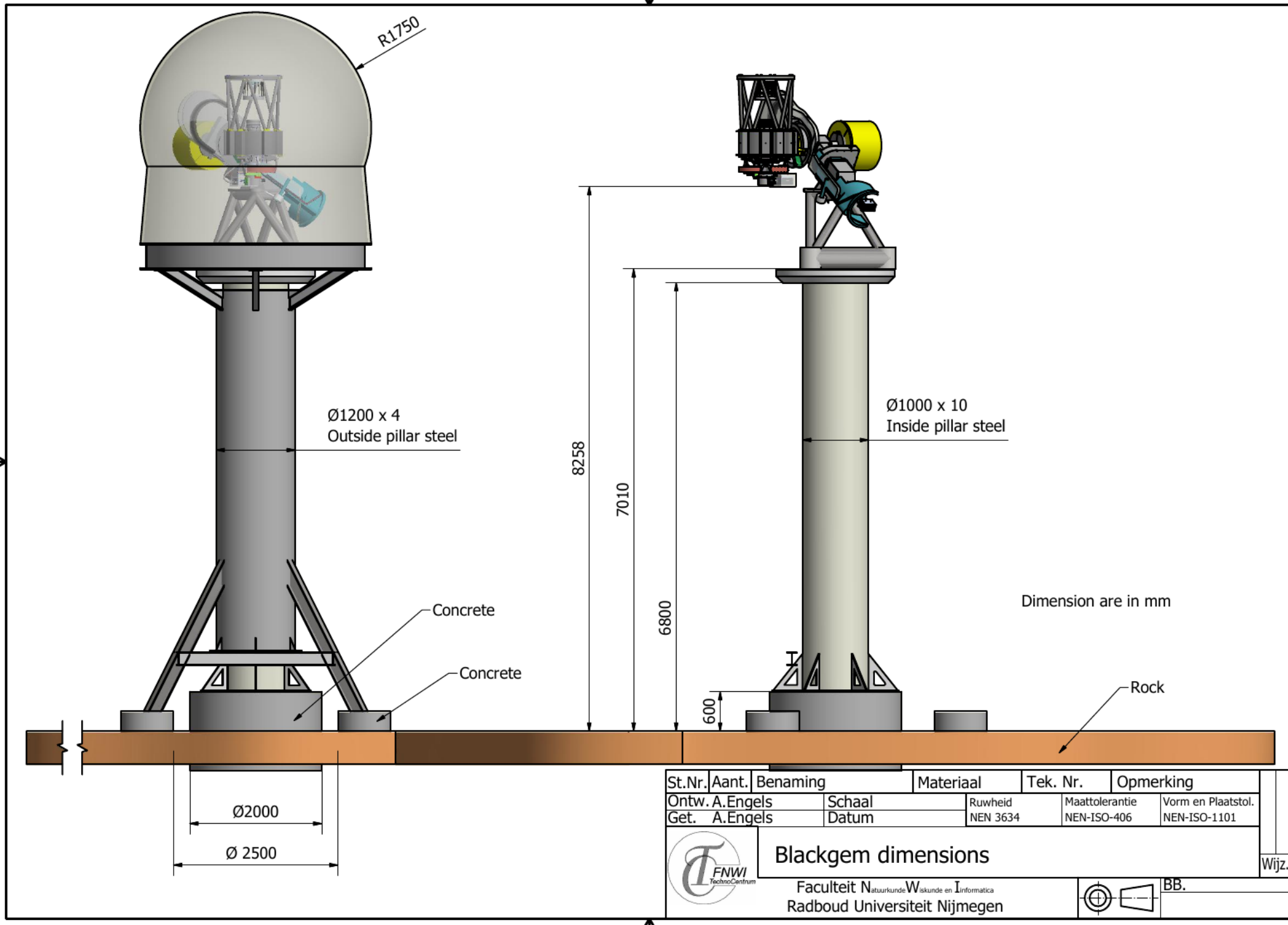


GPO site has room for 15 BlackGEM telescope units

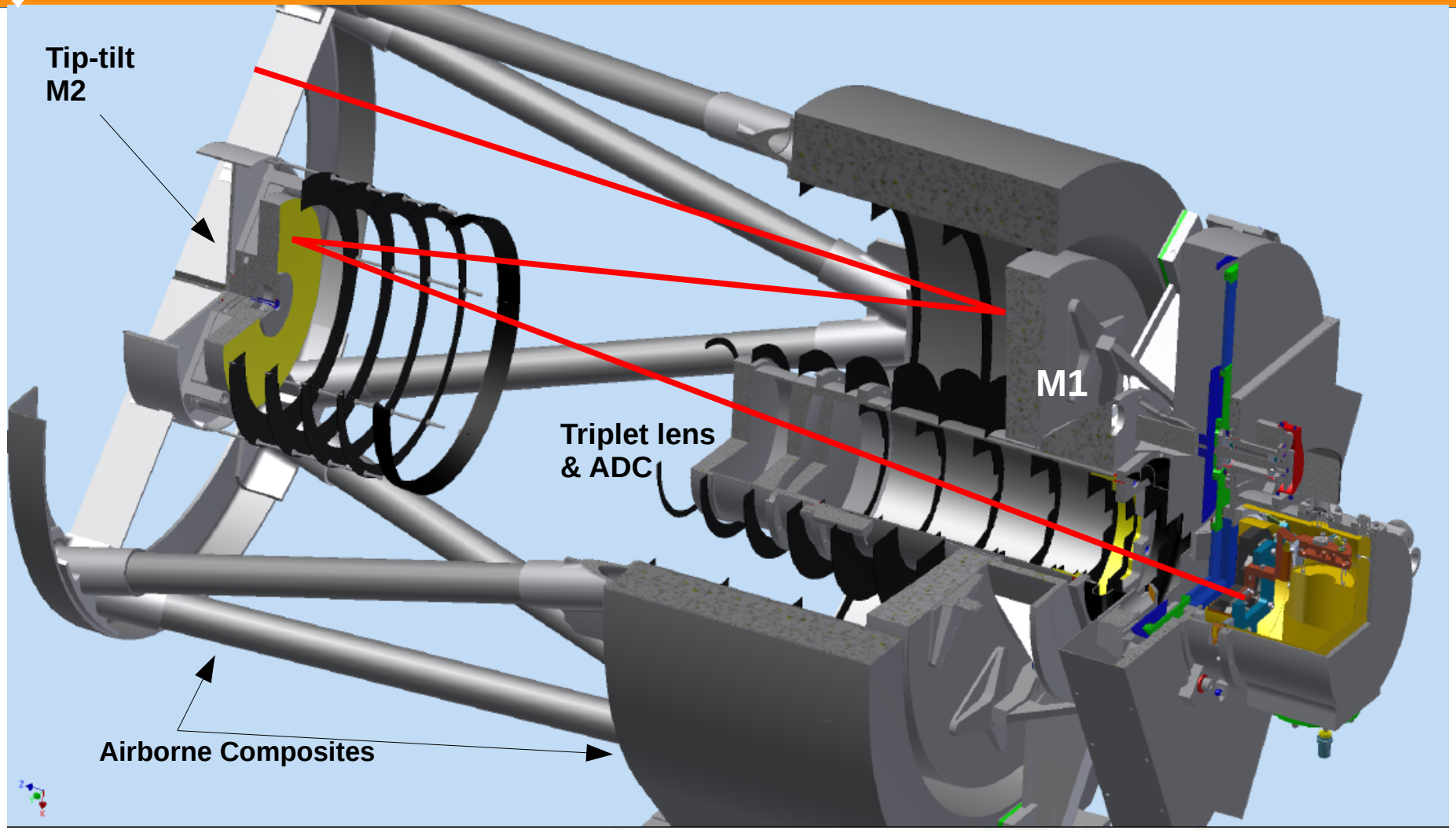
Building


Baader 3.5m dome
Raster floor
Outer tube Holding the dome
Inner tube holds the telescope
Ventilation openings
TiO coating on outside to prevent daytime heating
Separate foundations

Demo/Building



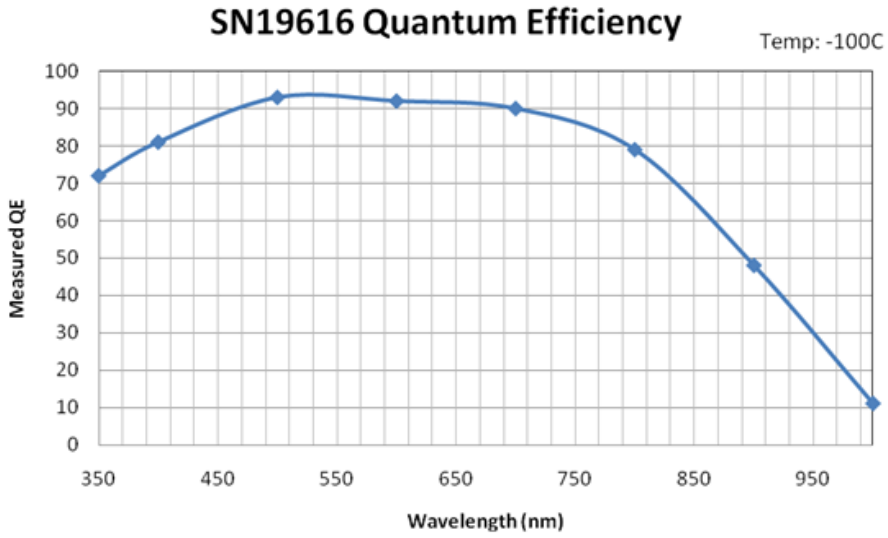
BlackGEM telescope

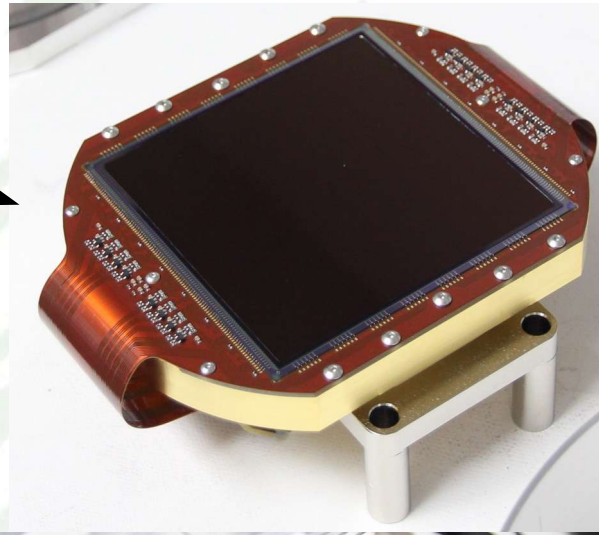


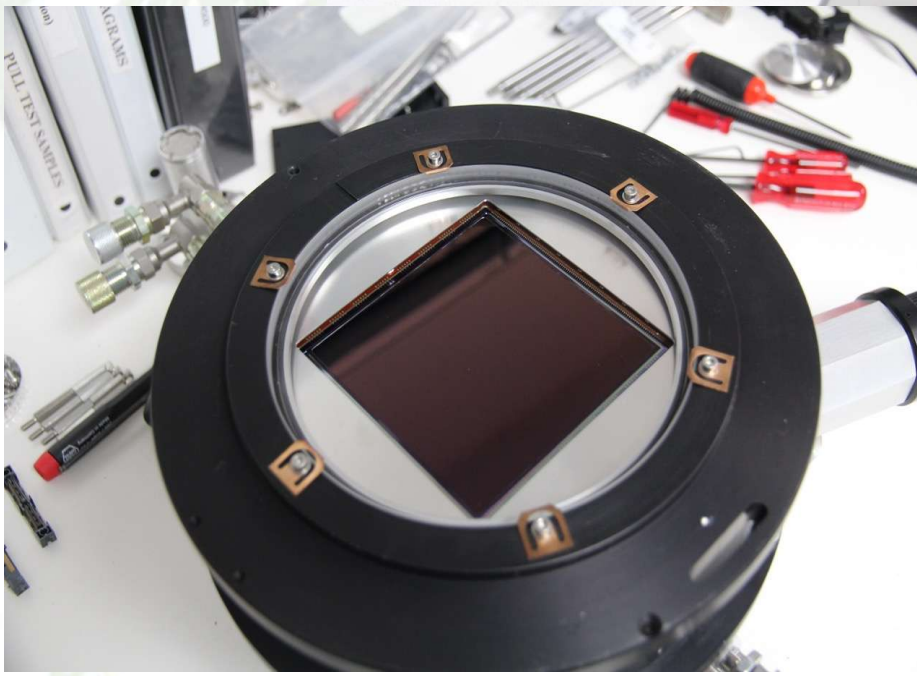
- Wynne-Harper design: flat (<10 micron), achromatic focal plane of 10cm x 10cm
- Third lens in triplet acts as ADC by side-ways movement
- Butterfly shutter + six-filter filter wheel.

CCD & Filters

- STA1600, 10.5k x 10.5k CCD, 9 µ pixel : 110 Mpixel chip
- Scale on sky: 0.562”/pix, total field of view: 2.7 sqd/telescope
- Readout time: 7 seconds (at 1 MHz on 16 ports), RON: 5.5 e-
- Status: ***Final, first delivered and integrated in cryostat***



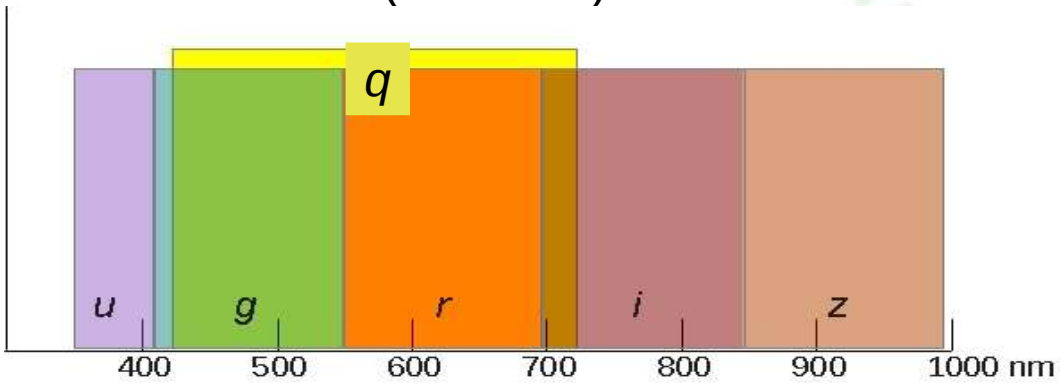




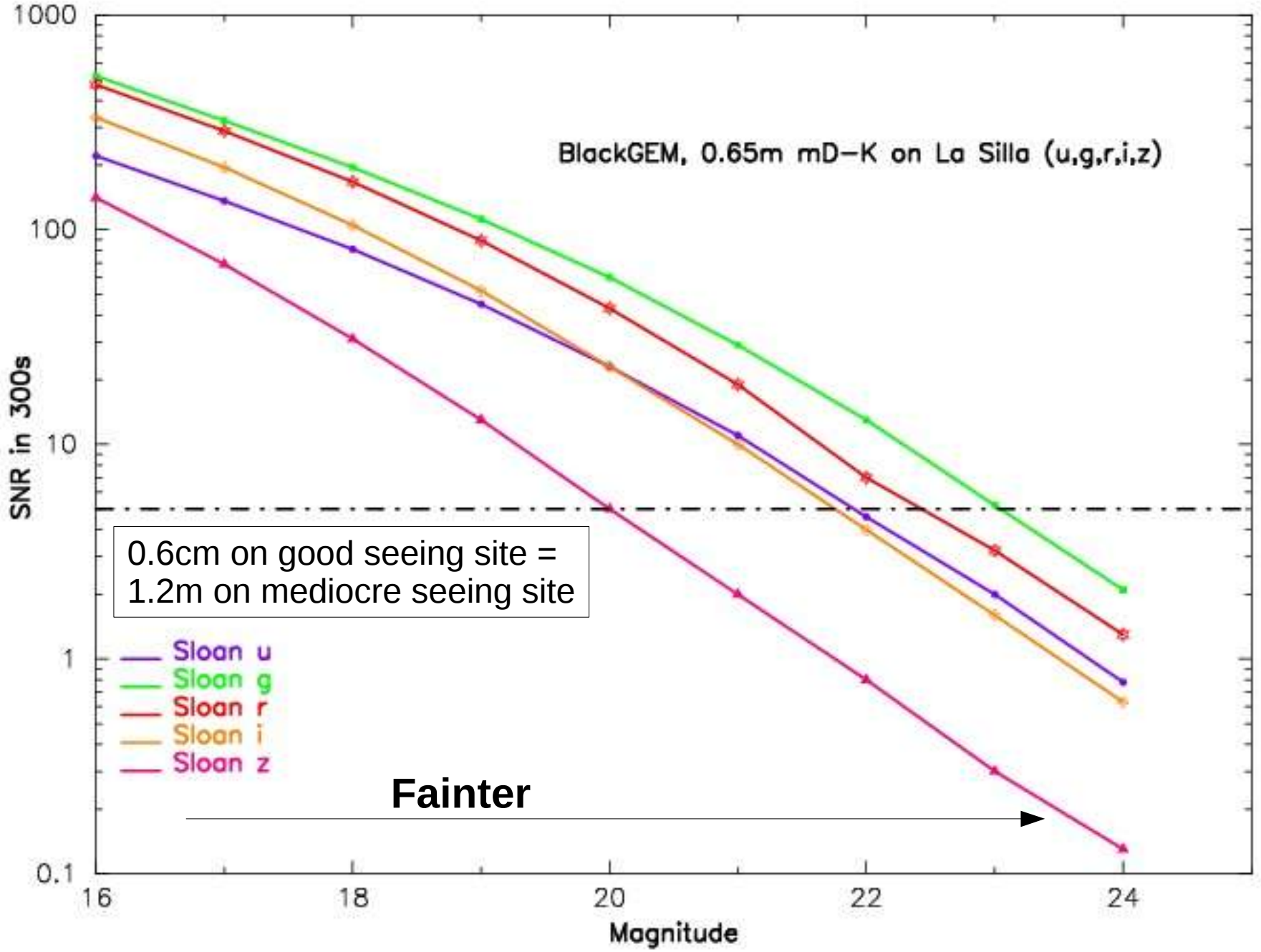
Filters:

Sloan u,g,r,i,z filters plus broad-band q (440-720nm)

Status: delivered (Astrodon)



Performance



Control software and electronics

All autonomous observatory control software and electronics provided by

Sybilla Electronics and ***Cilium Engineering***

Based on the ***Projekt Solaris*** currently running in Australia, South Africa and Argentina

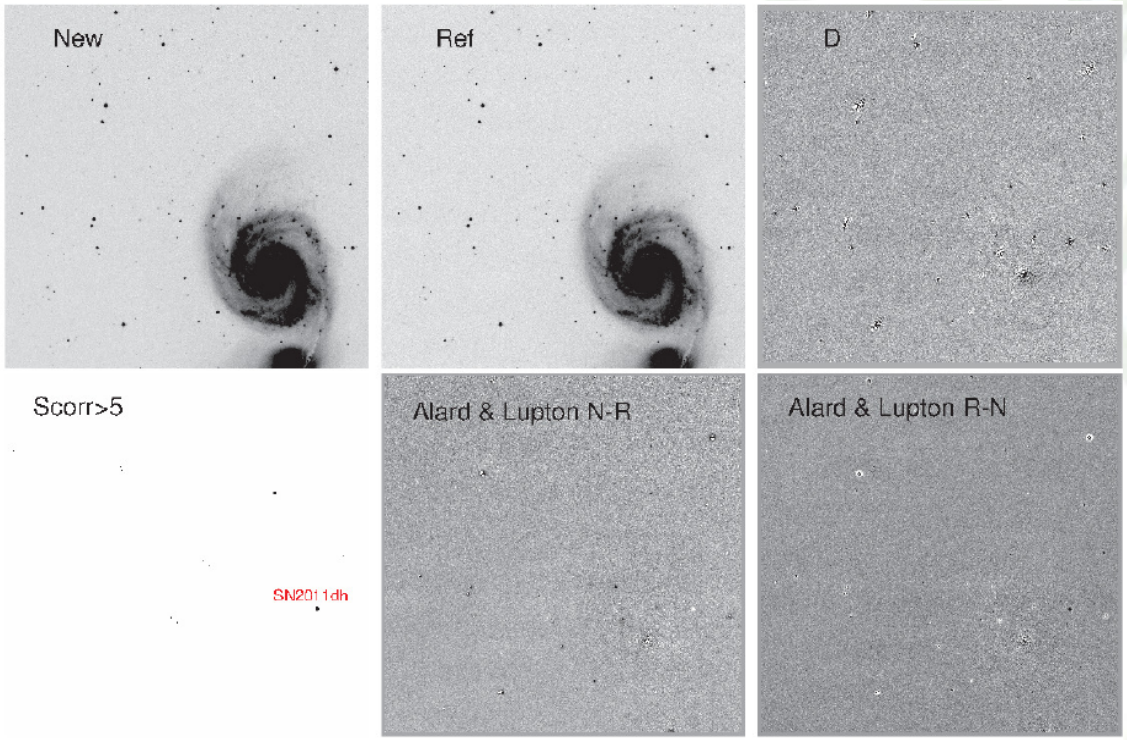
Data Reduction Software

Based on the *subpipe* pipeline developed and used by the ***SkyMapper*** team

Adapted and enhanced by MeerLICHT/BlackGEM team, in particular
Kerry Patterson (UCT), Paul Vreeswijk (Weizmann), Bart Scheers (CWI)

Aim is to have real-time pipeline for transients and variables, using image subtraction and forced photometry.

Database to keep all images, flux measurements and transients.



Example of difference imaging (Zackay et al., 2016)

BlackCloud: A cloud solution

- Aim is to make all BlackGEM data instantly accessible:
  - → A live database of any transient is maintained 'on the fly', live processing of 'previous' image during the night, instant alerts
  - → All images kept on (spinning) disk for re-reductions and target photometry at any time
  - → A live database of all sources, including variability.

- Complete set-up ideal for cloud solution on compute, database and storage of BlackGEM data: the BlackCloud.

- 1 Pb of data storage, 150 Tbyte of live database.

BlackGEM Team & Consortium

Principal Investigator: Paul Groot (Radboud University)
Project Scientist: Gijs Nelemans (Radboud University/Leuven)
Project Manager: Steven Bloemen (Radboud University)

Consortium Partners in Phase 1:

NOVA

Radboud Universiteit

KU Leuven

NOVA = Amsterdam, Leiden, Groningen, Radboud

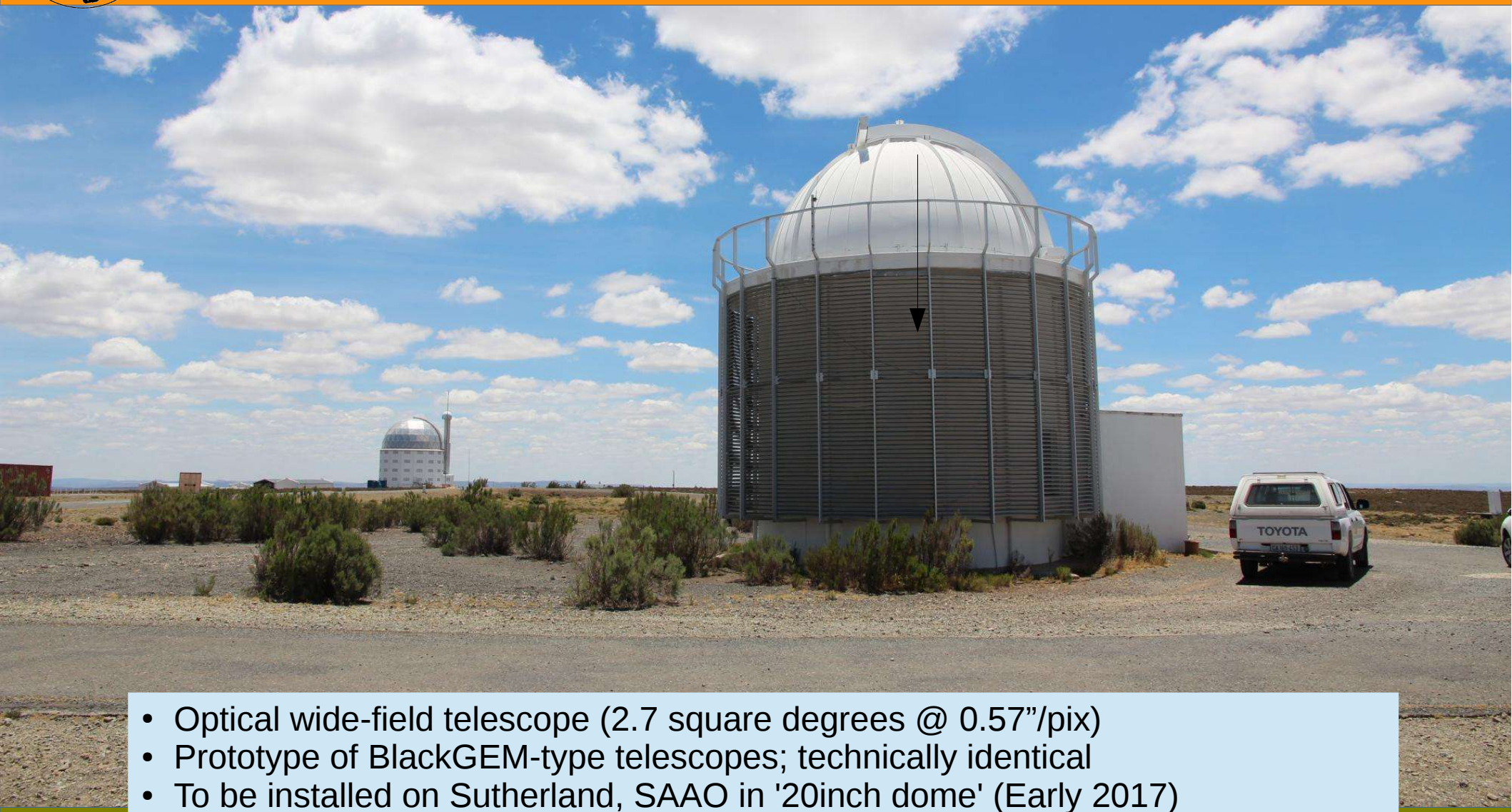
Possibility for new partners (for 5 year operation):

- 100 kEuro to join at PI-level (one faculty member + PDRAs/PhDs)
  (all data, science team, lead science case)
- 750 kEuro to join at Institute level (full institute)
  (all data, science team, lead science case, consortium board)

→ Will go up to 150 k€ and 1 M€ after start operation MeerLICHT

www.blackgem.org ; **@BlackGEM_Array**

MeerLICHT

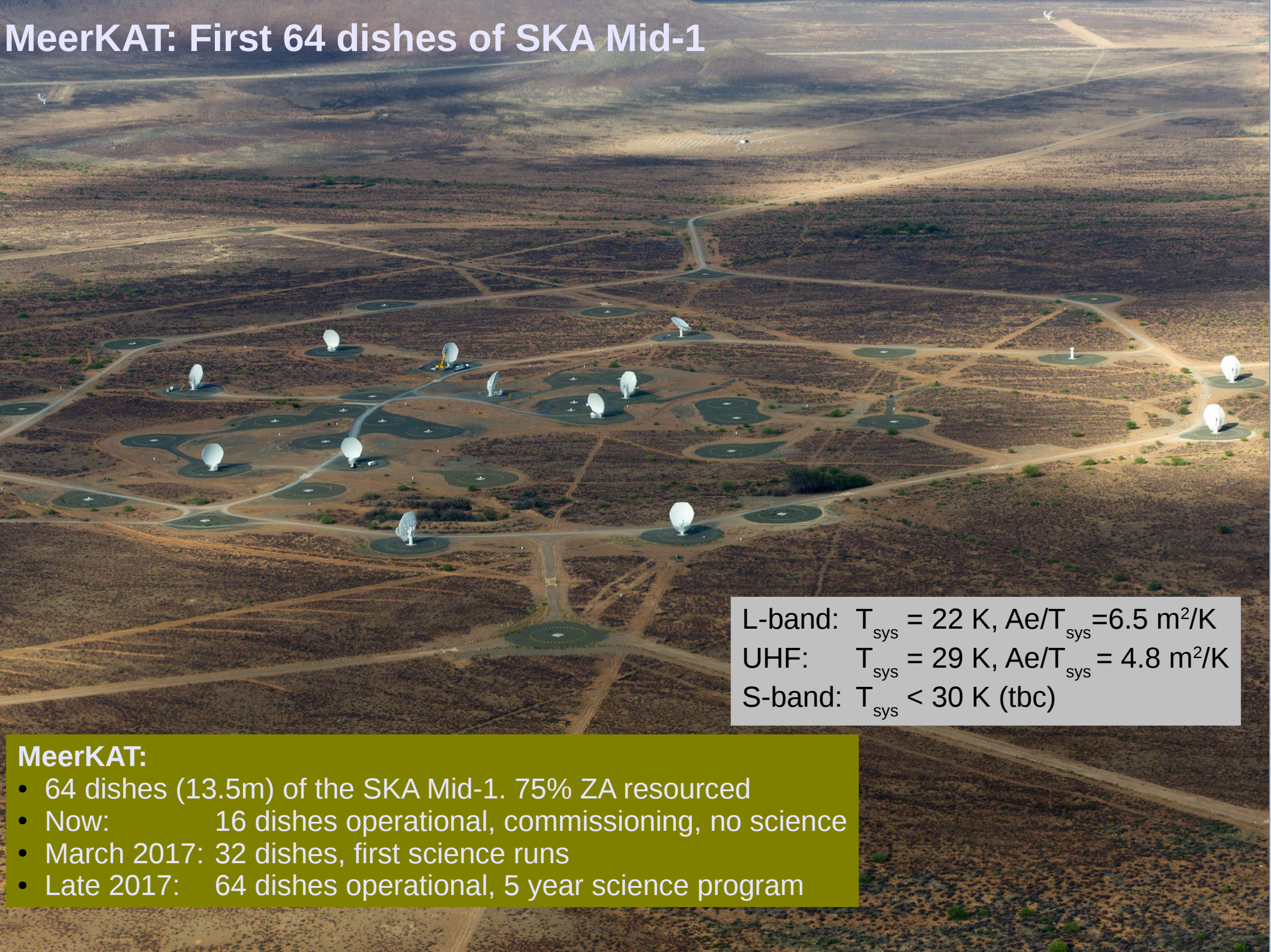


- Optical wide-field telescope (2.7 square degrees @ 0.57”/pix)
- Prototype of BlackGEM-type telescopes; technically identical
- To be installed on Sutherland, SAAO in '20inch dome' (Early 2017)
- 60s cadence, filter sequence: *g,q,r,q,i,q,u,q,z,q,etc.*...

Twinned to MeerKAT radio array: 'always-on' optical-radio synoptic survey

MeerLICHT & MeerKAT

MeerKAT: First 64 dishes of SKA Mid-1



L-band: T_{sys} = 22 K, Ae/T_{sys}=6.5 m^2/K
UHF: T_{sys} = 29 K, Ae/T_{sys} = 4.8 m^2/K
S-band: T_{sys} < 30 K (tbc)

MeerKAT:

- 64 dishes (13.5m) of the SKA Mid-1. 75% ZA resourced
- Now: 16 dishes operational, commissioning, no science
- March 2017: 32 dishes, first science runs
- Late 2017: 64 dishes operational, 5 year science program

MeerLICHT Consortium

PIs:	Paul Groot (Radboud U.), Patrick Woudt (UCT)
Consortium repr.:	Rob Fender (Oxford), Ben Stappers (Manchester), Rudy Wijnands (UvA)
Project Scientist:	Elmar Körding (Radboud)
Project Managers:	Steven Bloemen (Radboud), Vanessa McBride (UCT)
Instrument Scientist:	Retha Pretorius (Oxford)

University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

Radboud University

NWO

NRF National Research Foundation

UNIVERSITY OF OXFORD

ANTON PANNEKOEK INSTITUTE
UNIVERSITEIT VAN AMSTERDAM

MANCHESTER 1824
The University of Manchester

www.meerlicht.org ; @MeerLICHT_ZA

Aim and Schedules

BG-SASS: (8 sqd, 2018) **Southern All Sky Survey**

First 9 months, full time

Full Southern Sky in u,g,q,r,i,z down to ~22nd mag

BG-FSS: (8 sqd, 2018+) **Fast Synoptic Survey**

50% of time, bright time

Rates : $N_{candidates}(l,b,\tau,mag,colour)$ $(degr^{-2}\,hr^{-1}\,mag^{-1})$

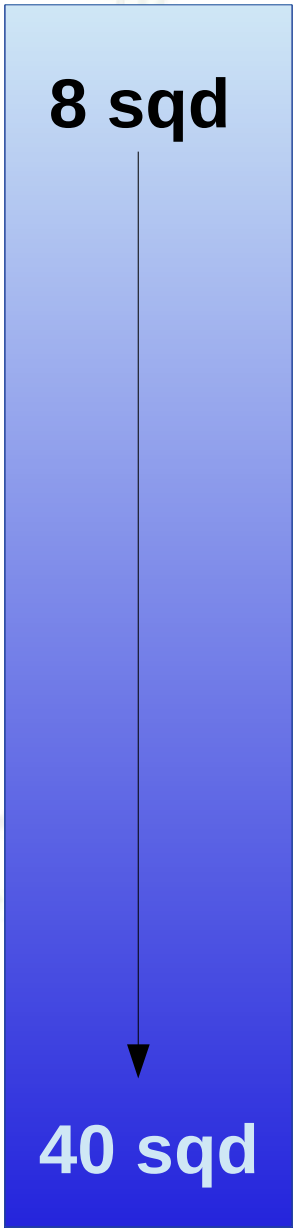
- Number of fiducial fields: ~200 square degrees
- Cadence: once every minute, in 2 bands (*q,r*)
- Time per sqd: 7-14 nights (3800-7200 exposures/object)

BG-TSM: (8-40 sqd, 2018+) **Trigger Mode**

→ ***15 telescopes***

GW events + FSS

- Follow-up on Virgo/LIGO detections
- Cover the error boxes in a tiling pattern (Fly's Eye Mode)
- Follow late-term afterglows (Zoom Mode)
- Continuation of BG-FSS in 'no-trigger' time



BlackGEM Surveys

To properly facilitate GW searches, BlackGEM performs additional programs:

- **BlackGEM Southern All Sky Survey**: ***'Southern Sloan'***
  → 30 000 sqd down to 22nd mag in u,g,q,r,i,z at 1” median seeing
  →Reference frame for GW searches, but stand-alone science:
  (galactic streams/structure, dwarf galaxies, stellar populations, 'gems', quasars, weak lensing, high-z galaxies, etc.)

- **BlackGEM q-band Scan:** ***‘What was there yesterday?’***
  → Visible 10 000 square degrees in q-band every 14 days
  → Itself a fantastic resource for finding SN, TDE, Novae, etc.

- **BlackGEM Fast Synoptic Survey**: ***'Kepler on steroids' : what else goes bang?***
  → High cadence (1 min), multi-colour (simultaneous), wide-field
  → Deep drilling fields: thousands of exposures over weeks time-scale

- **BlackGEM Twilight Program:** ***‘Local Universe transients’***
  → Every twilight (30 minutes) scan Local Universe galaxies in 2 bands for new transients (incl. SMC/LMC, Fornax Cluster, Cen A/M83 group, etc.). Fifteen fields per twilight.

- **BlackGEM Trigger Mode**: ***'Transients Galore'***
  → GW error box coverage in multiple colours
  → 100s of sqd in multiple times over ~week time scale down to *g*=23

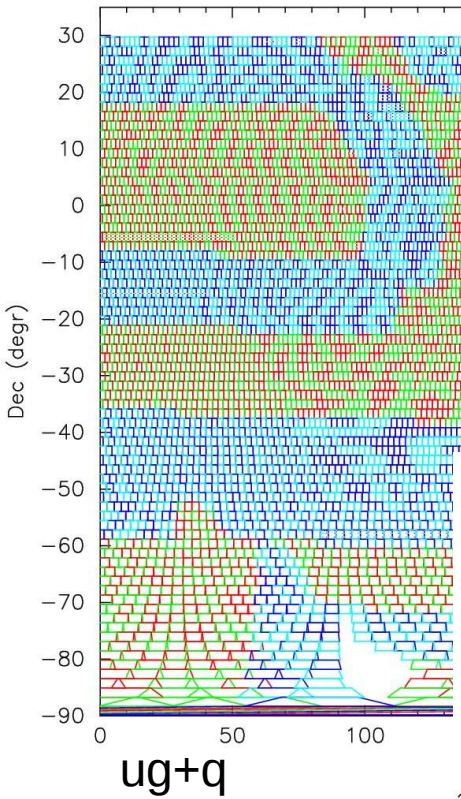
BG-SASS & BG-FSS Planning

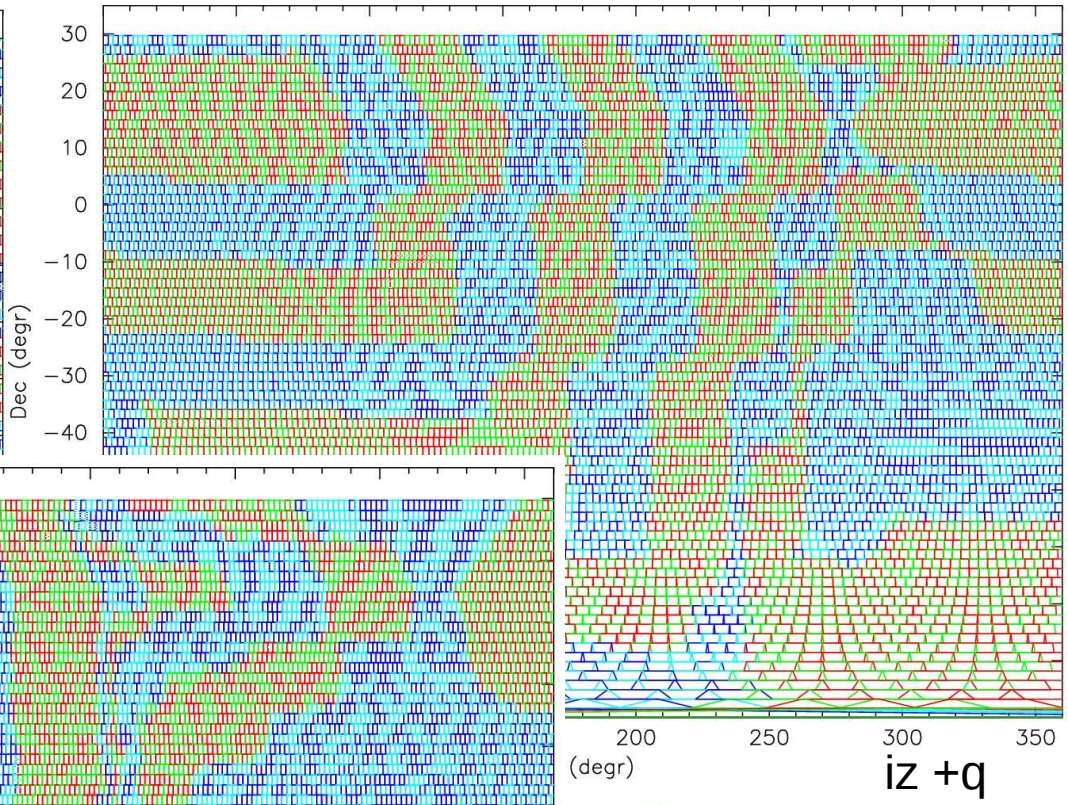
BlackGEM Southern All Sky Survey and Fast Synoptic Survey Planning
Start of operations + 15 months

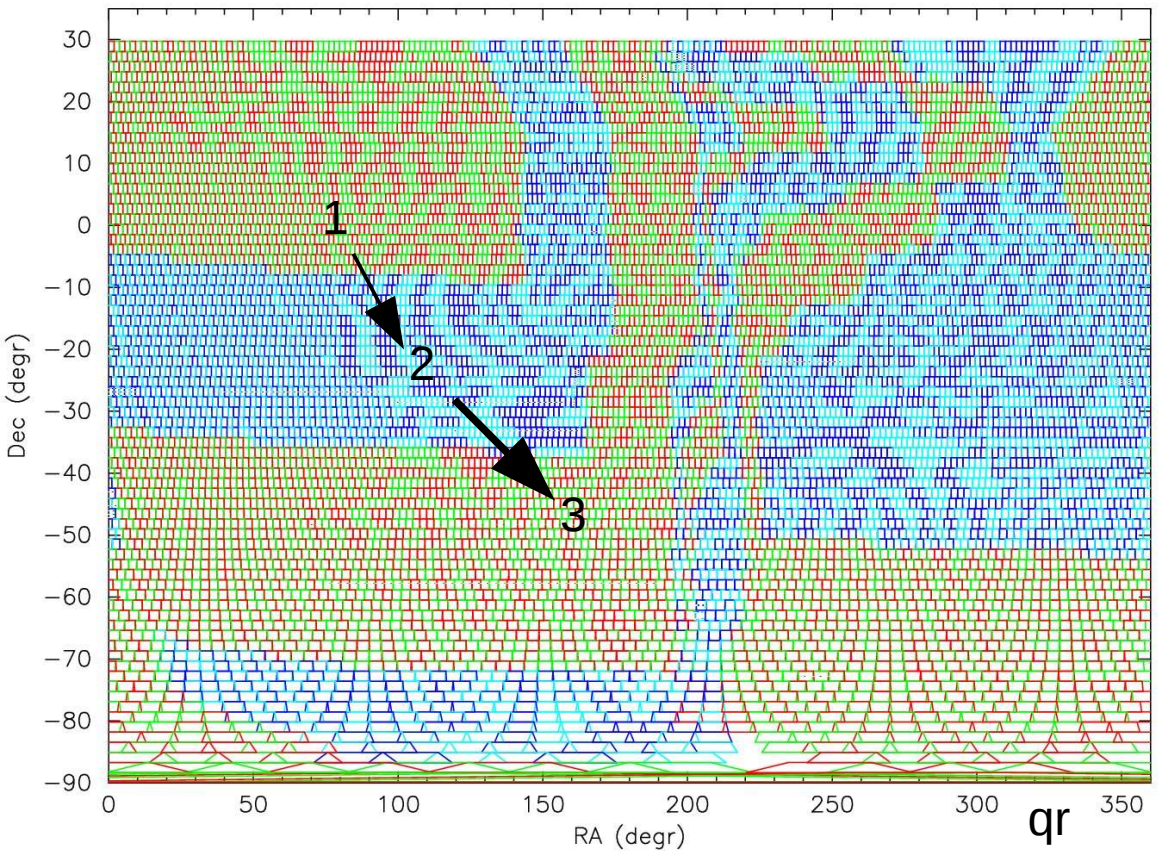
●	○	●	○	●	○
qr 18 nights	iz 11 nights	qr 18 nights	iz 11 nights	qr 18 nights	iz 11 nights
qr 3n	ug 15 nights	iz 11 nights	qr 3n	ug 15 nights	iz 11 nights	qr 3n	ug 12 nights	qr 3n	iz 11 nights
qr 3n	ug 12 nights	qr 3n	iz 11 nights	qr 18 nights	iz 5nights	qr 3n	qscan 6n	ug 15 nights	q scan	iz 5nights	qr 3n
ug 18 nights	iz 11 nights	q scan	ug 6nights	FSS 9n	iz 11 nights	q scan	ug 6nights	FSS 9n	q scan	FSS 7n	iz 1
q scan	ug 6nights	FSS 9n	q scan	FSS 8n	q scan	ug 6nights	FSS 9n	q scan	FSS 8n	q scan	ug 6nights	FSS 9n	q scan	FSS 8n

qr: 18n, 18n, 18n, 3n, 3n, 6n, 6n, 18n, 6n
iz+q:7x11, 5n, 5n, 11n, 11n, 1n
ug+q: 15n,15n,12n,12,0n,12n,18n, 5x6n

BlackGEM Southern All Sky Survey







Month by month coverage *(green/red and blue/blue are subsequent months)* using planning of previous slide

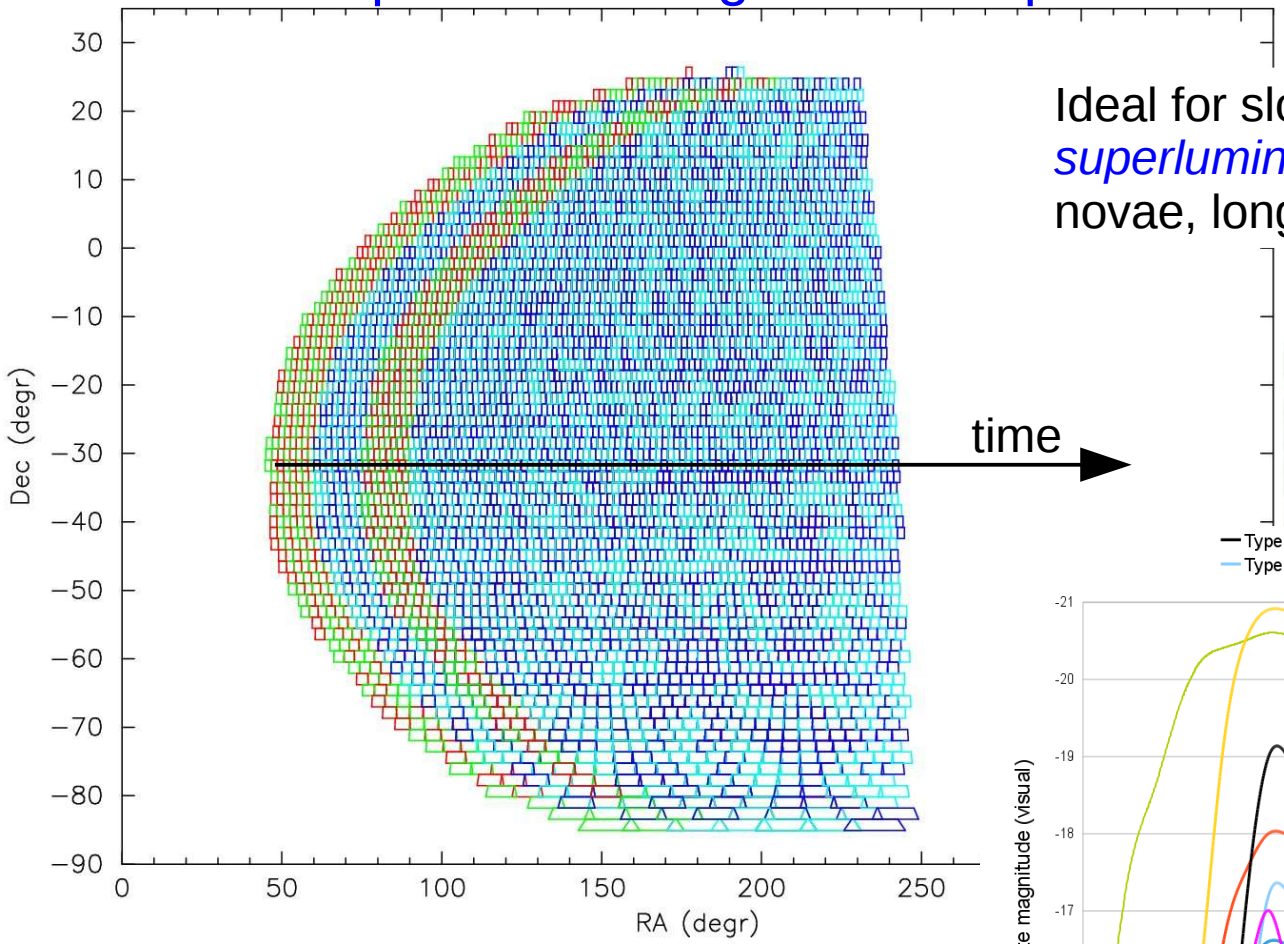
Two bands,
5x 60s each.

Alternating:
q,r,q,r,q,r,q,r,q,r
= 700 sec total,

good for asteroid detection/removal

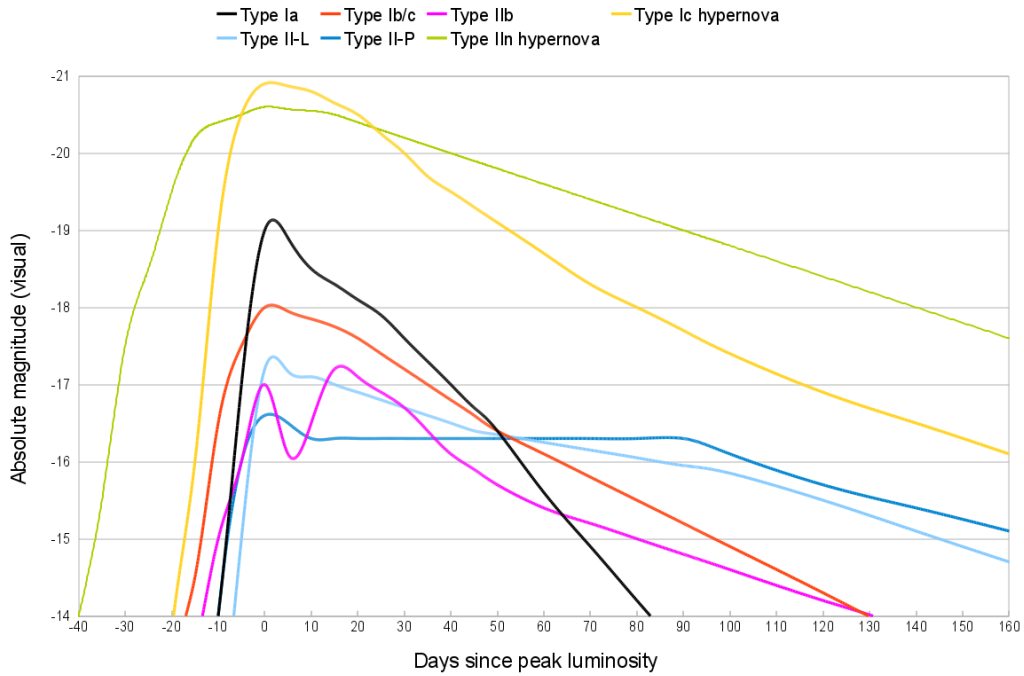
BlackGEM Bi-Weekly q-scan

Every two weeks 3 nights will be used to scan the available sky:
10000 sqd. in 60s integrations in q-band



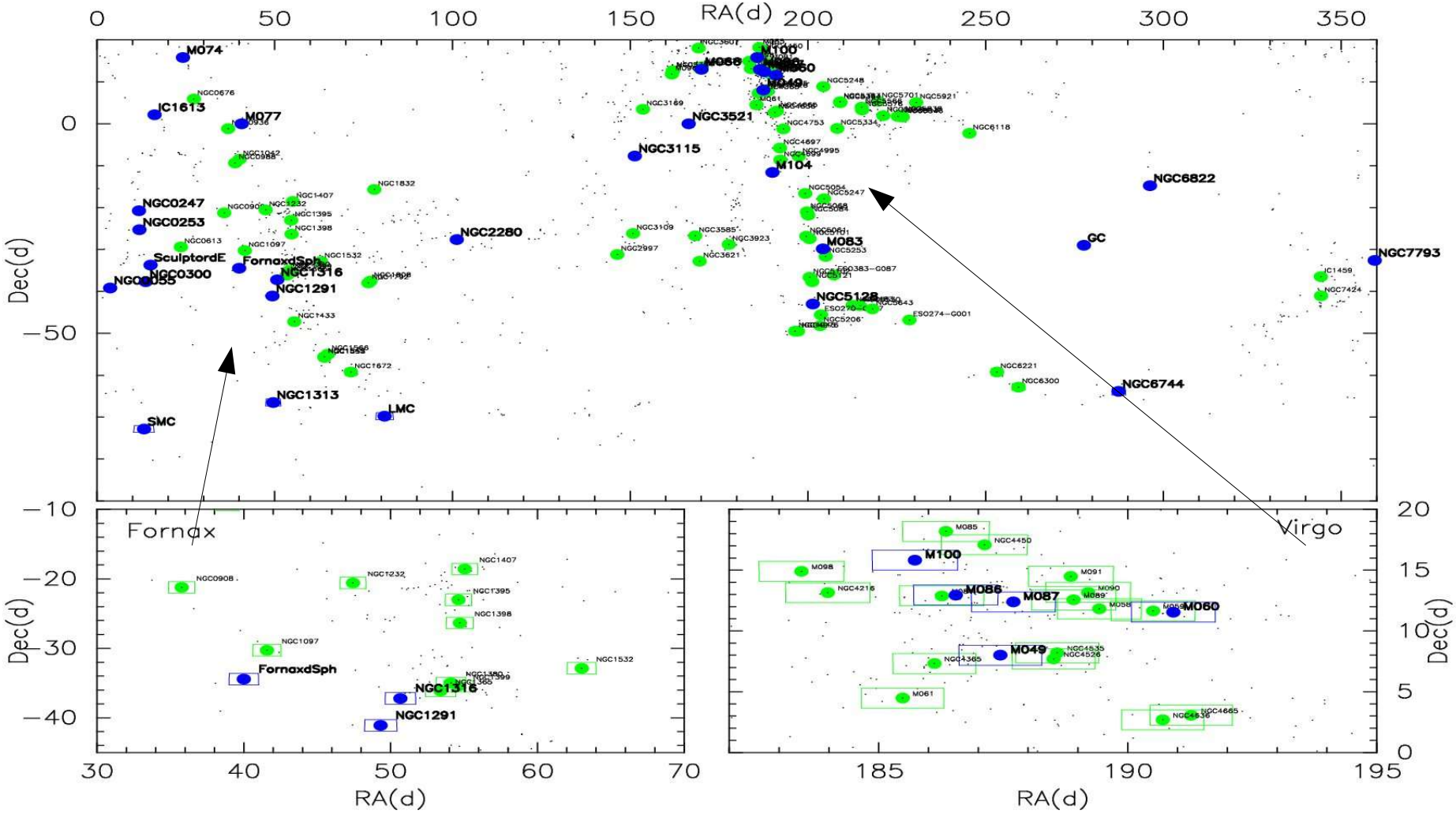
time

Ideal for slower transients/variables: *superluminous supernovae;* TDEs, novae, long-period variables, etc



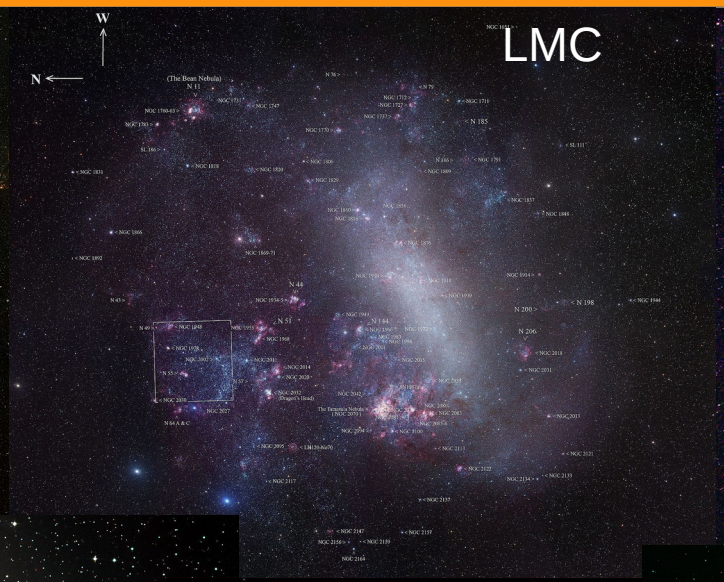
BlackGEM Twilight Survey

- Every twilight a 30-min window @ end/start twilight calibs and start/stop main data-taking
- In this window: 15x3 fields (2.7 sqd each) in two bands: *u* and *r*
- N*earby Universe galaxies* with high integrated brightness profiles (incl. Gal.Cen. and Ω Cen)



Points: d< 30 Mpc & B<14 mag; green: 120 brightest, blue 30 brightest

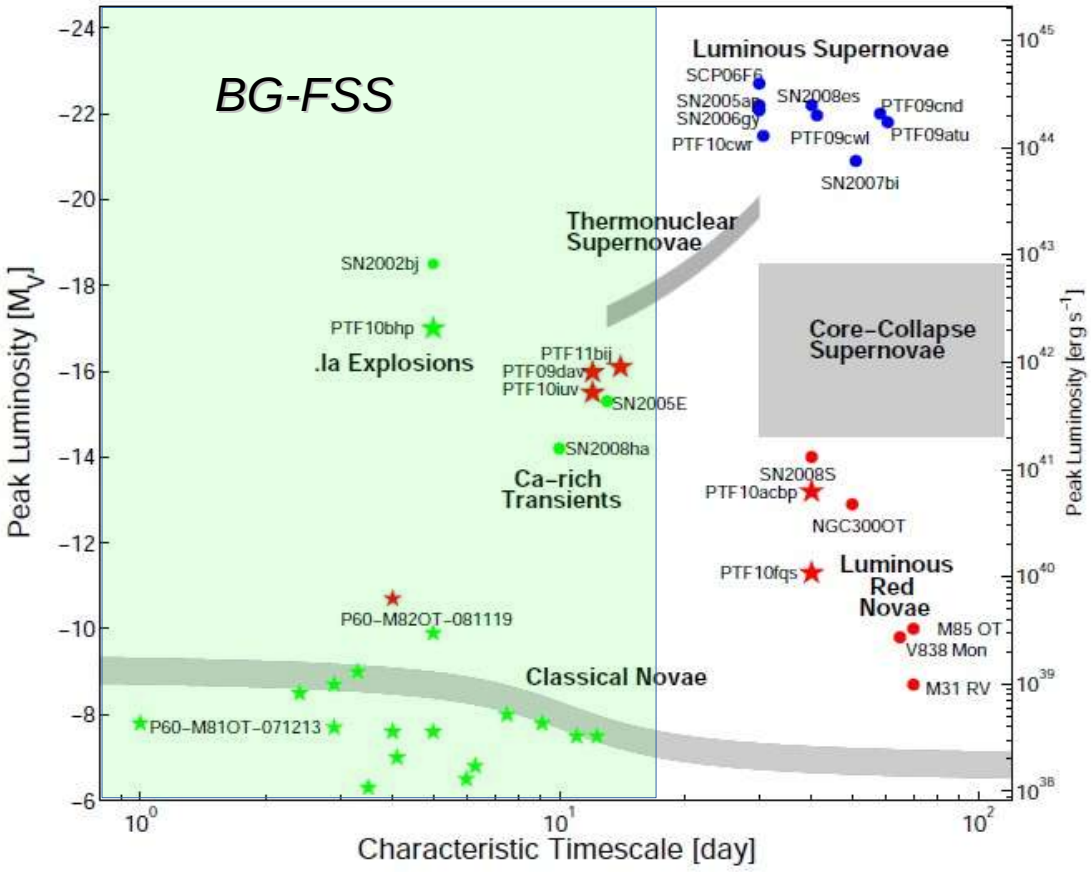
BlackGEM Twilight Survey



BlackGEM Fast Synoptic Survey

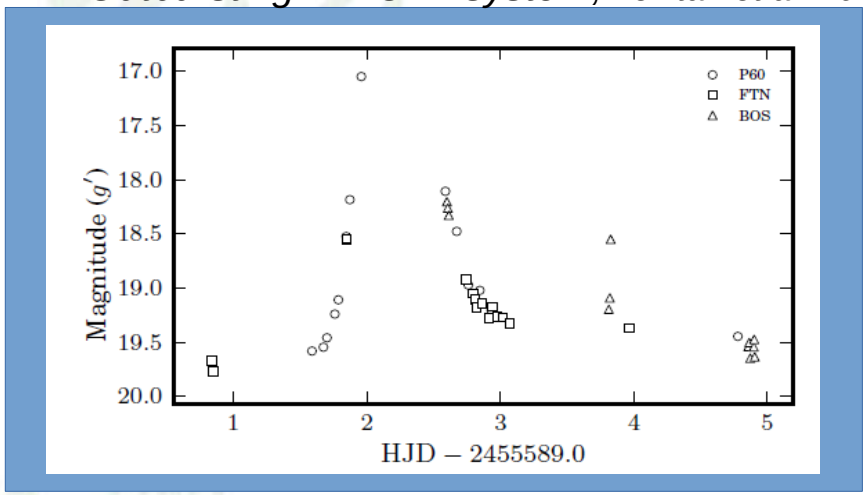
High Cadence survey to characterize fast transient phase space:
"What goes 'bang'- 'bang' in the night?"

→ 60s integrations, 2 bands (qr alternating), continuous for 2 weeks
i.e. 2800 q-band & 2800 r-band observations, 140s effective cadence

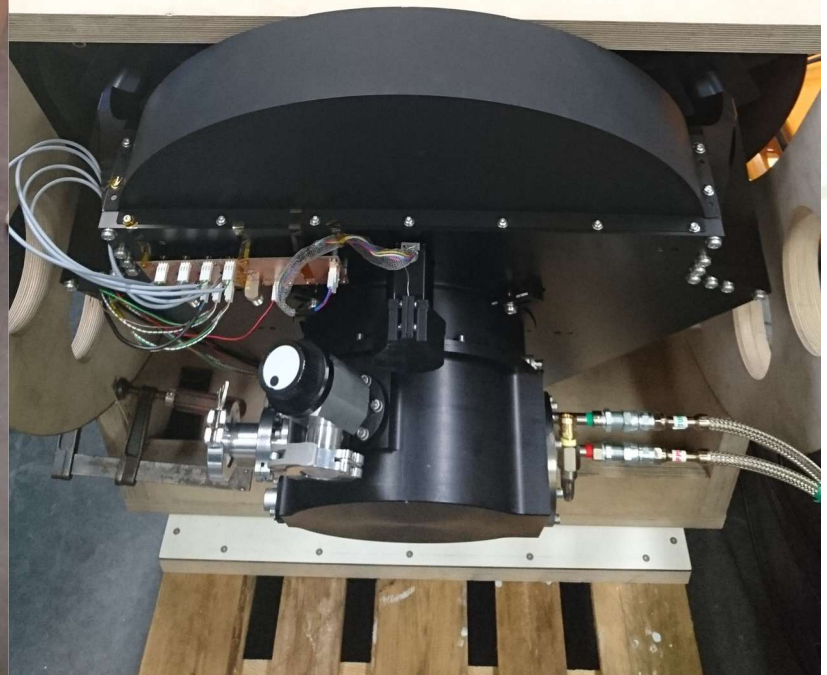


- Fast transients
- Short-period variables
- Fast-moving objects

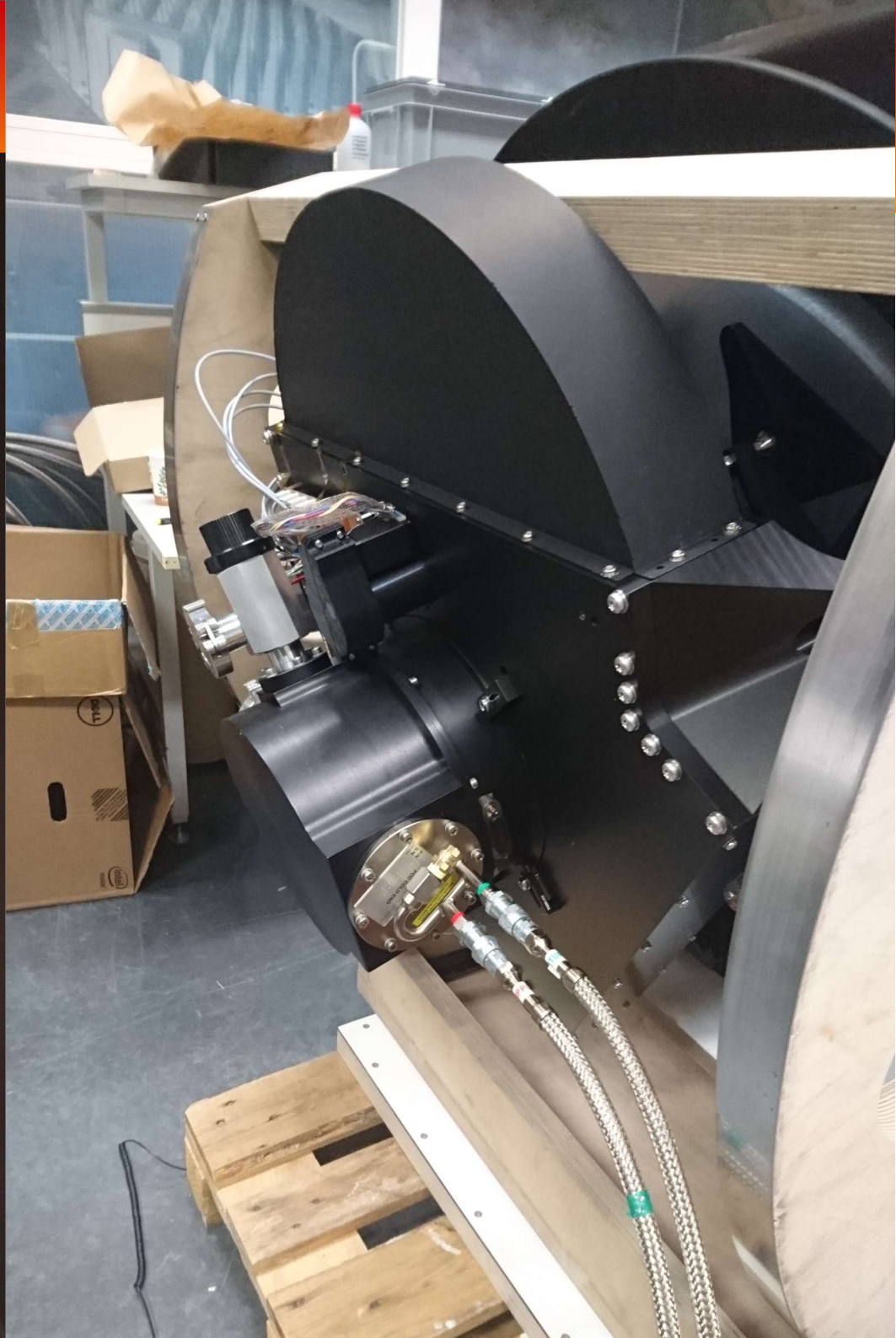
Outbursting AM CVn system; Levitan et al. 2012



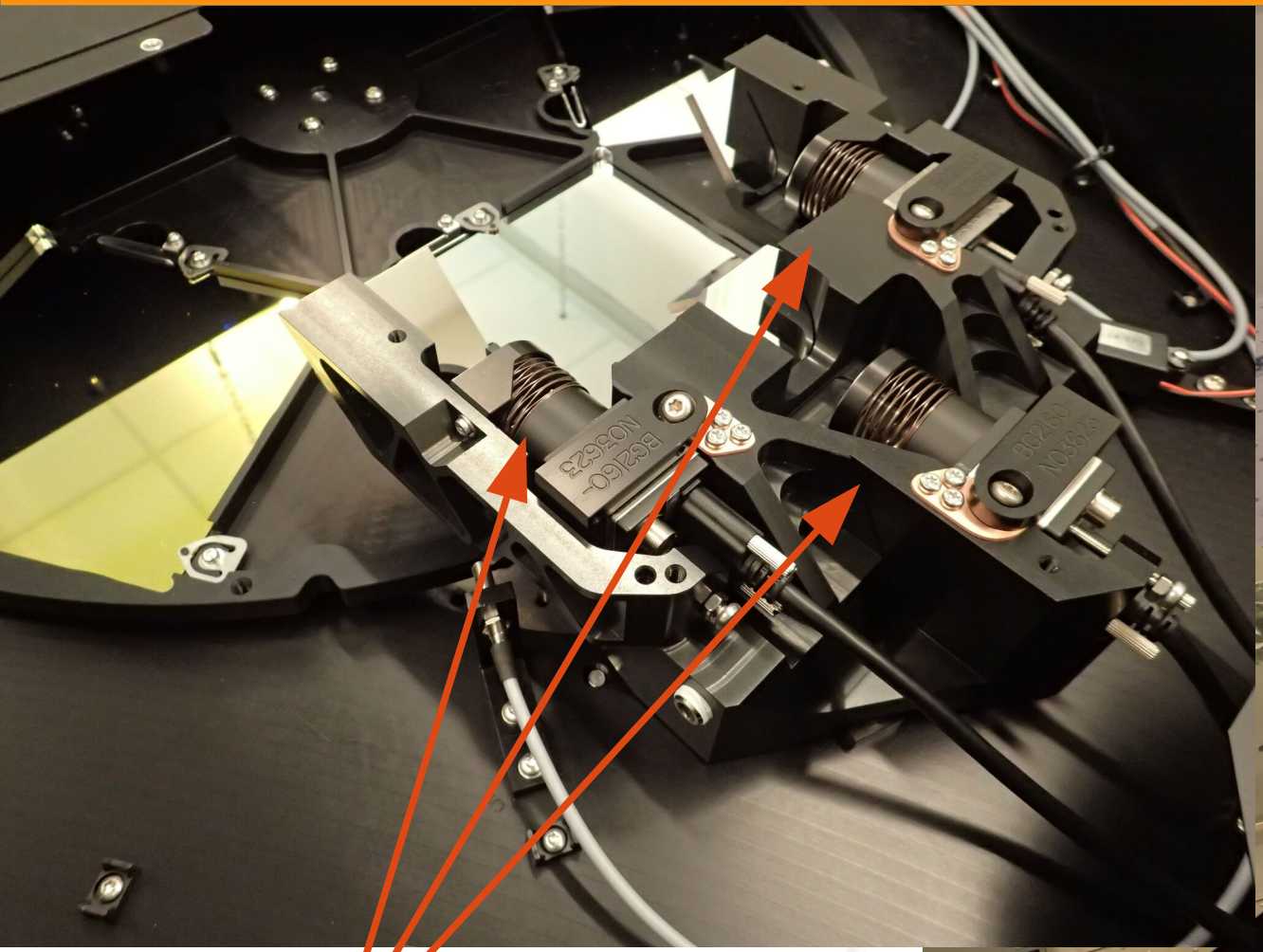
MeerLICHT



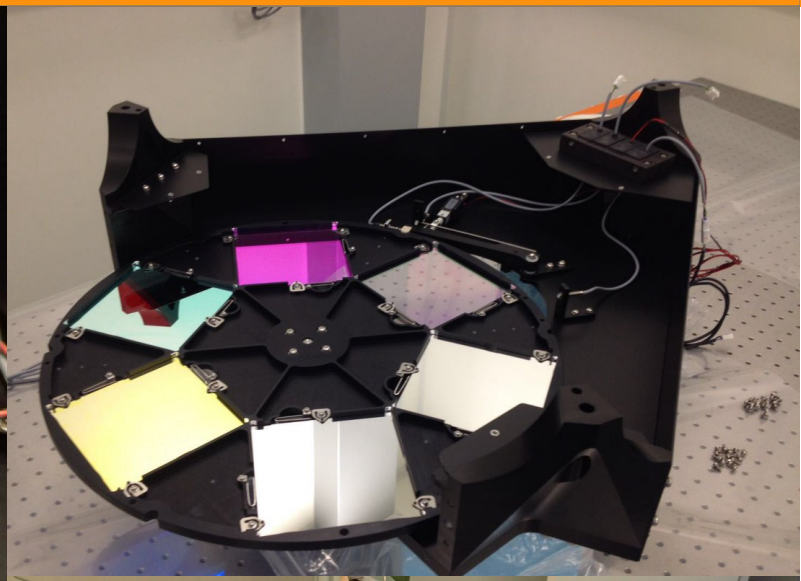
Sept. 2016



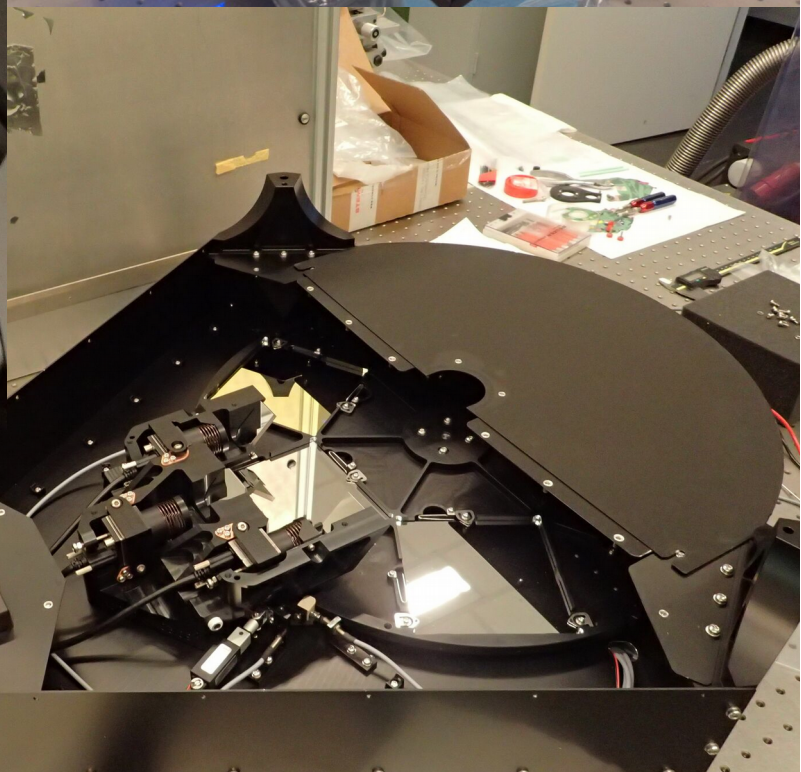
Guide cameras & Filters



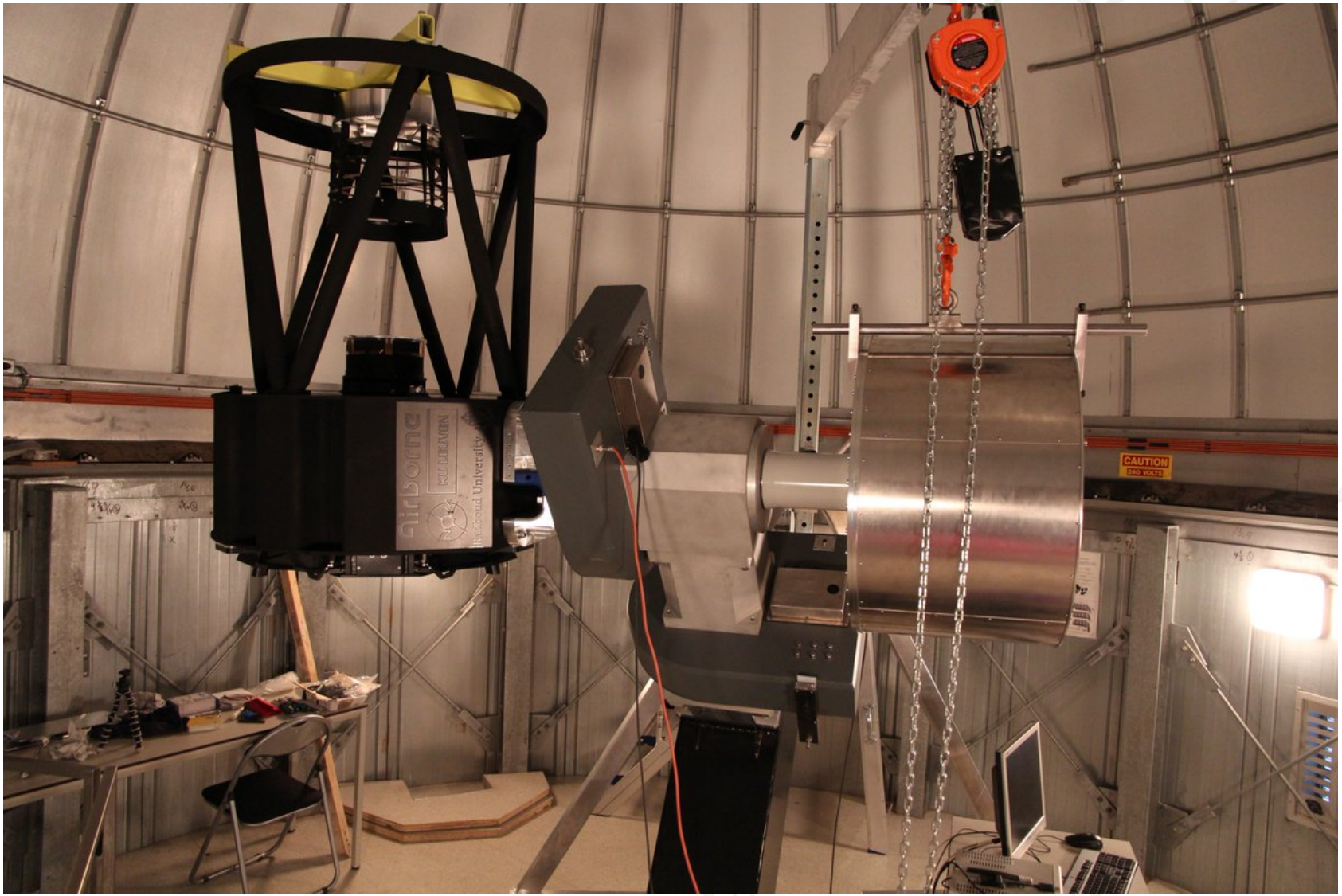
3 Guide cameras



Filter wheel



Equatorial Mount

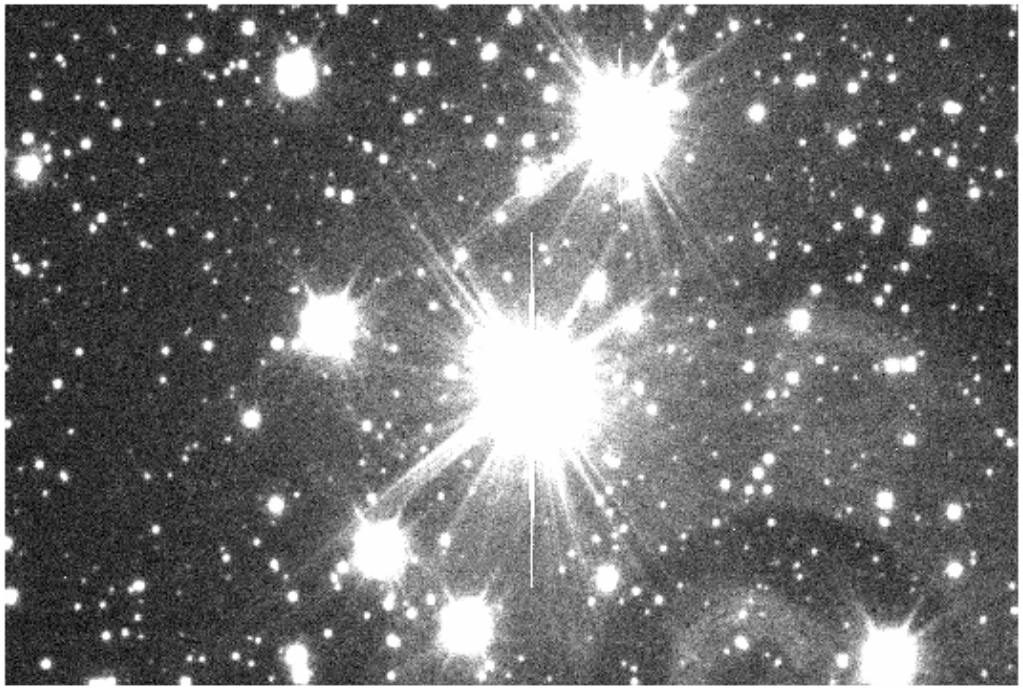


Fornax 200 mount

Co-designed with BG team

Made by Fornax (Hu)

Synoptic Surveys with Alt-Az tel.

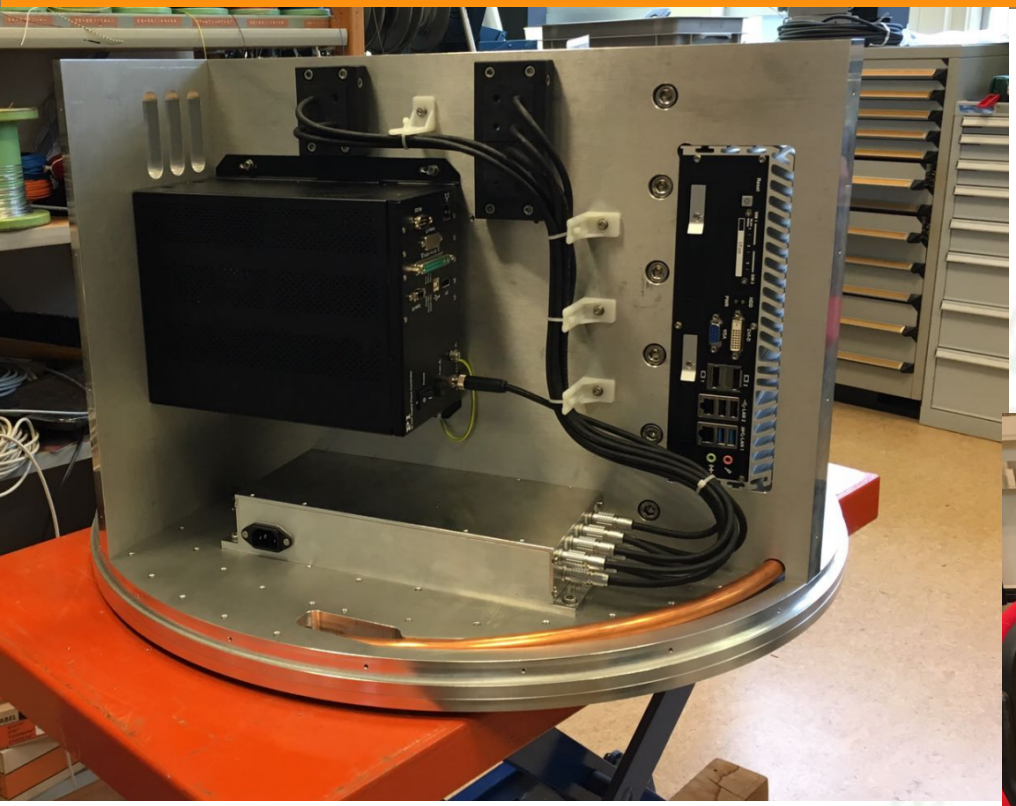


ΩWhite on the VST: *Macfarlane et al. 2015, 2016; Toma et al. 2017*

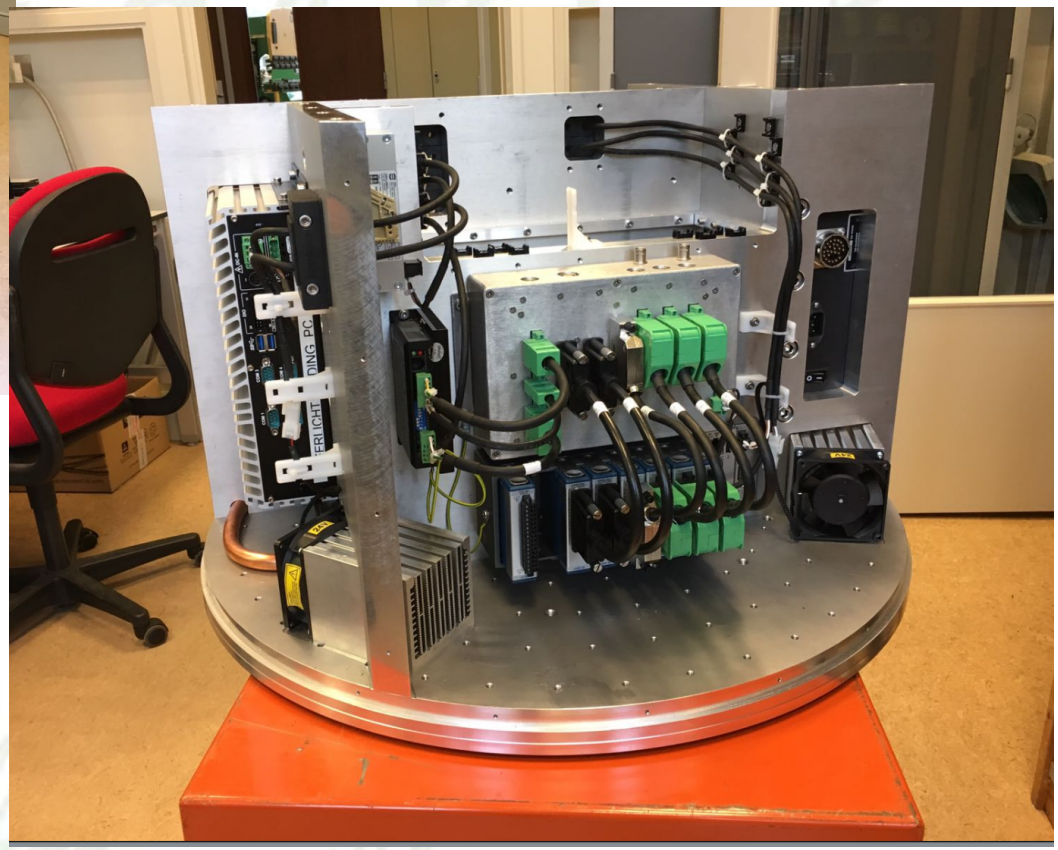
Rotating diffraction spikes biggest source of false positives in 'variables' !!

A problem LSST will have to solve in software

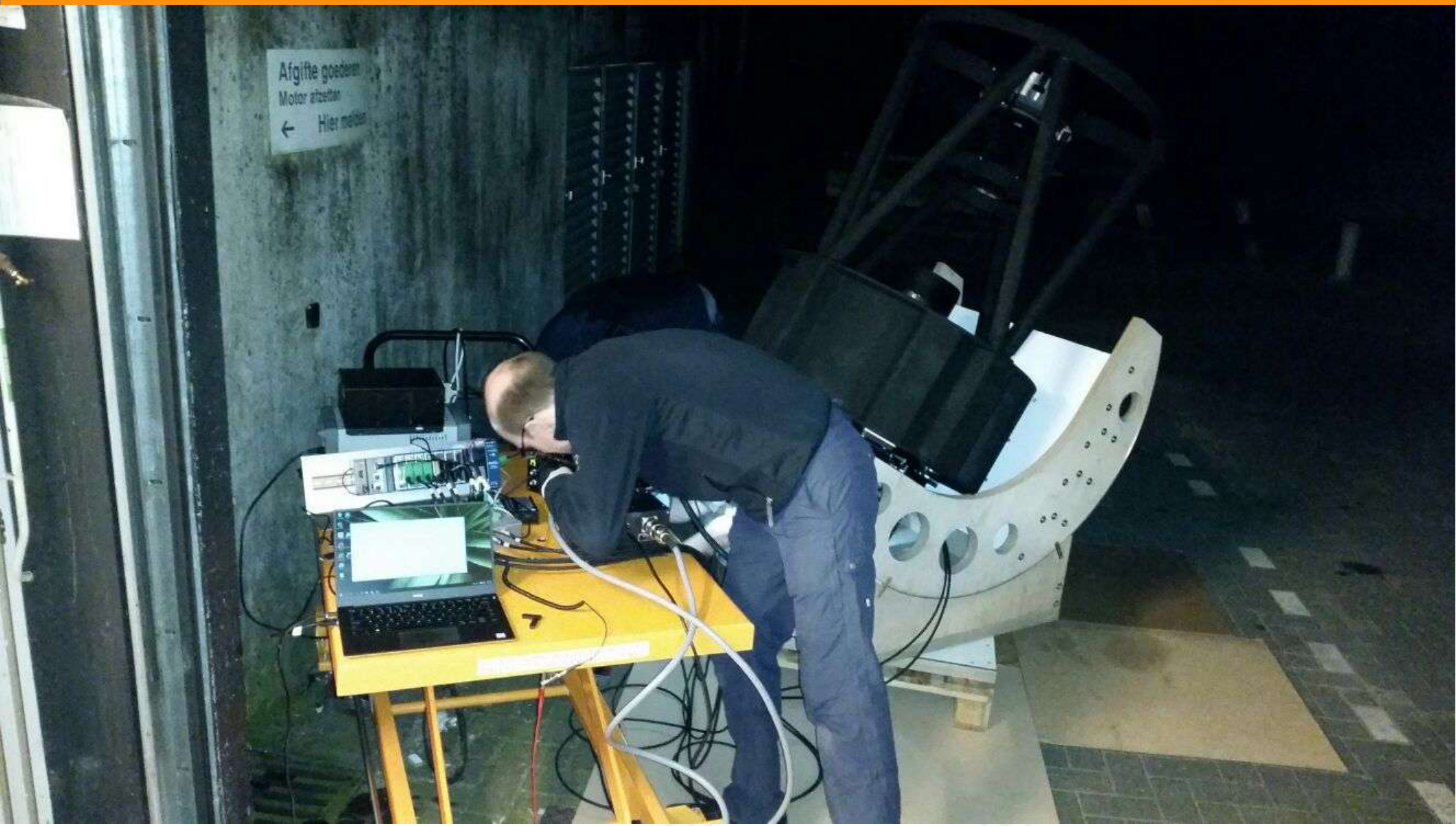
Counterweight / Electronics



All electronics in closed-box counter-weight.
Water-cooled to prevent turbulence.

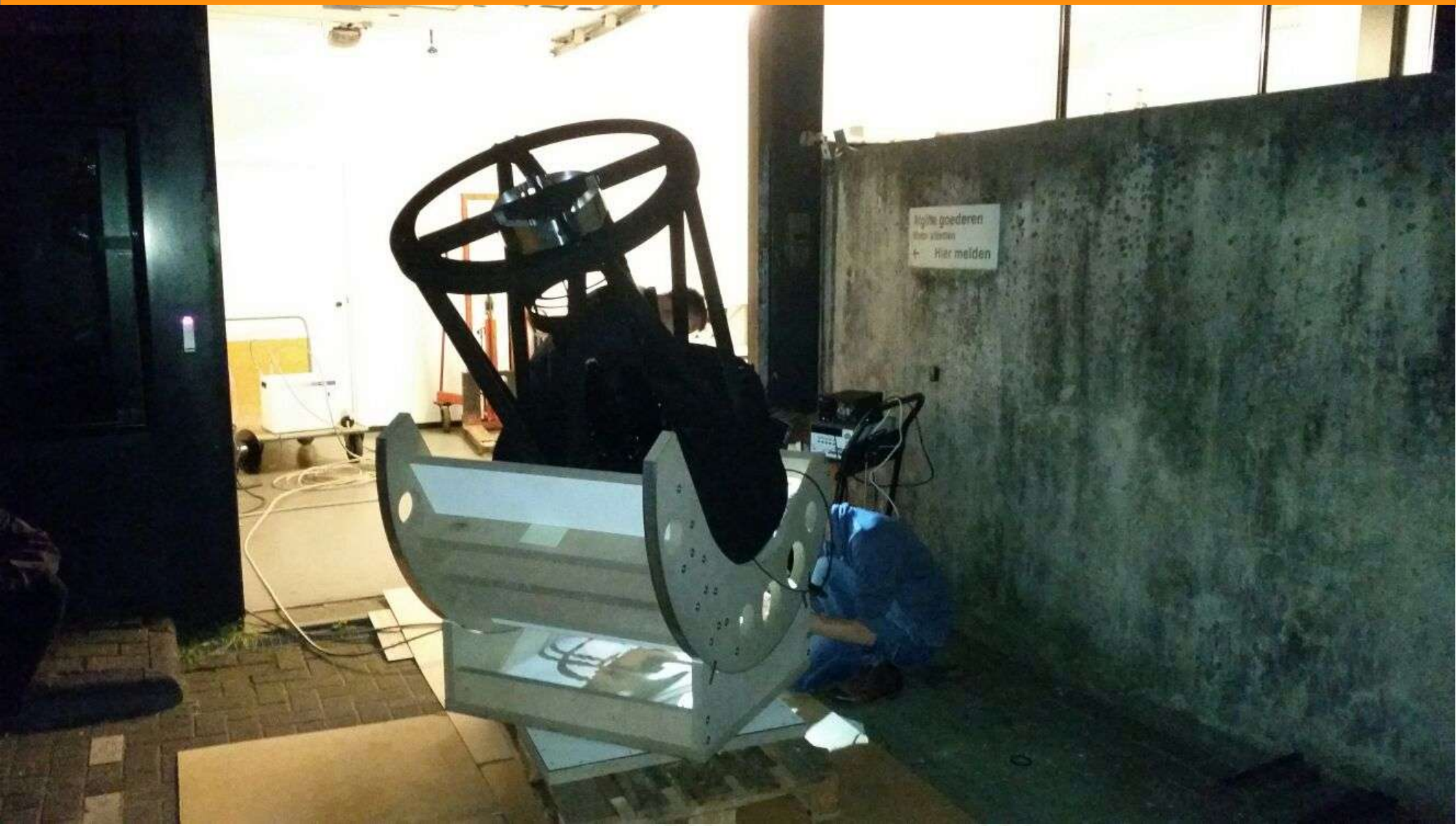


MeerLICHT



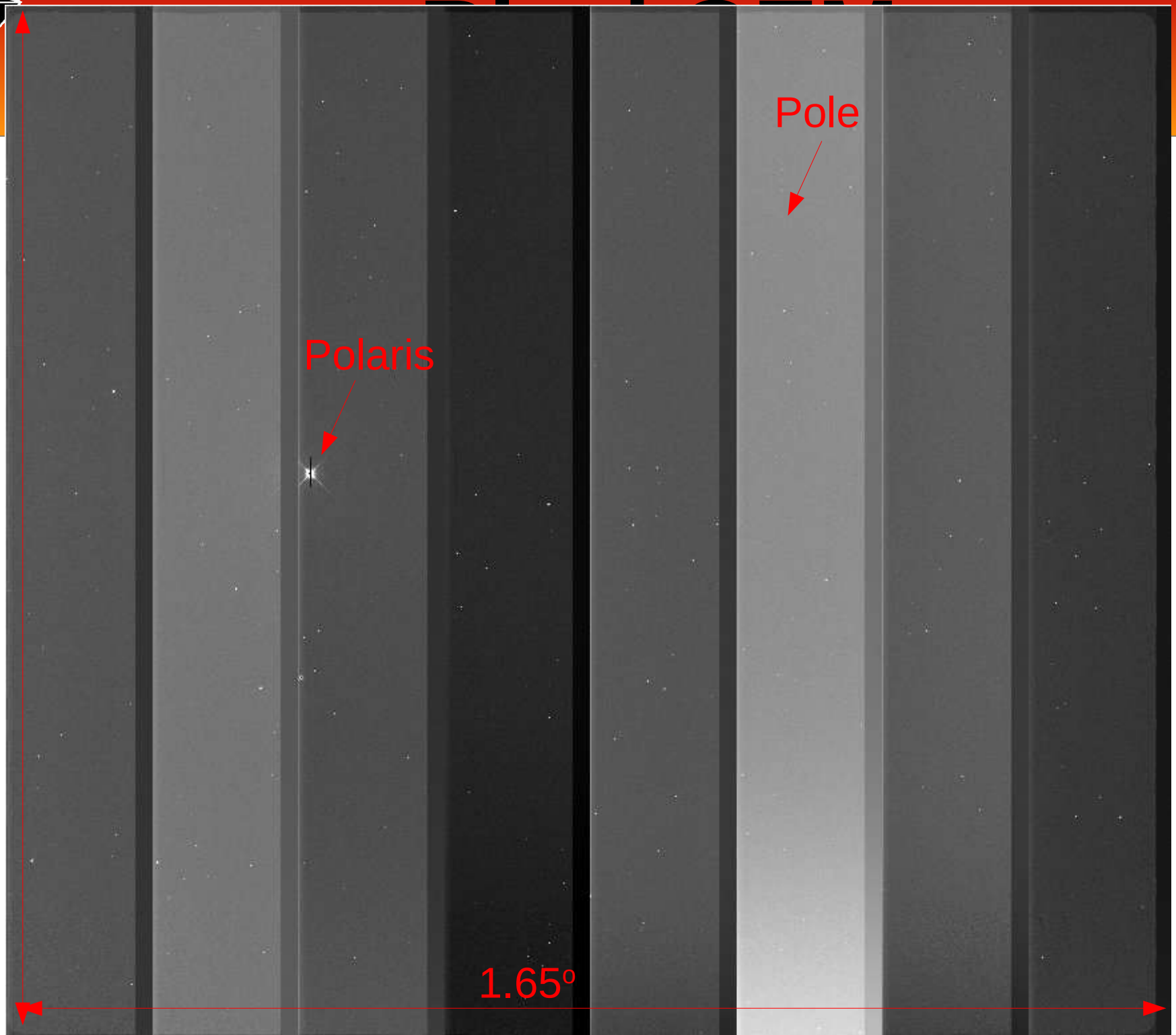
22/9/2016, at the NOVA / ASTRON Parking Lot in Dwingeloo

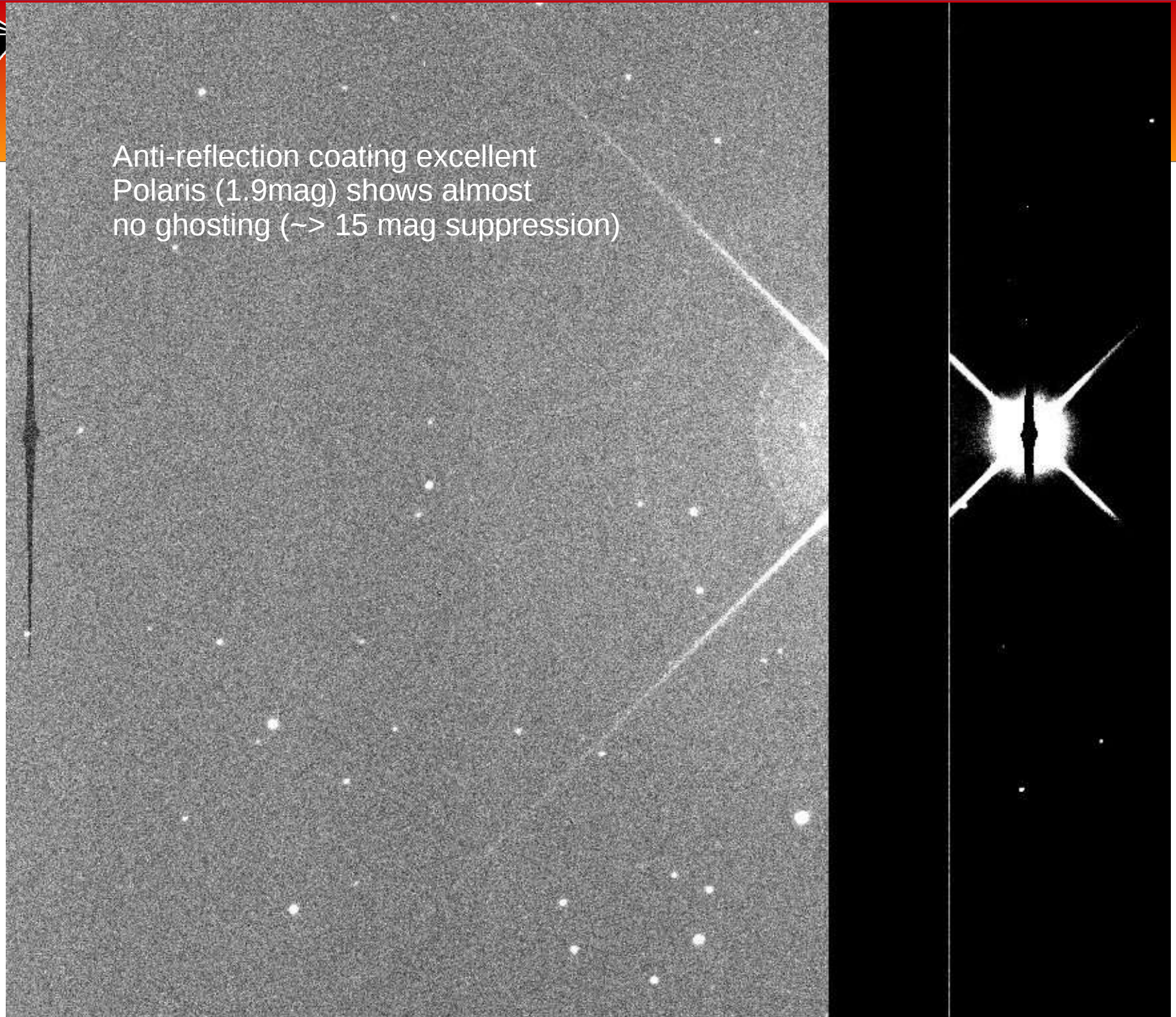
MeerLICHT



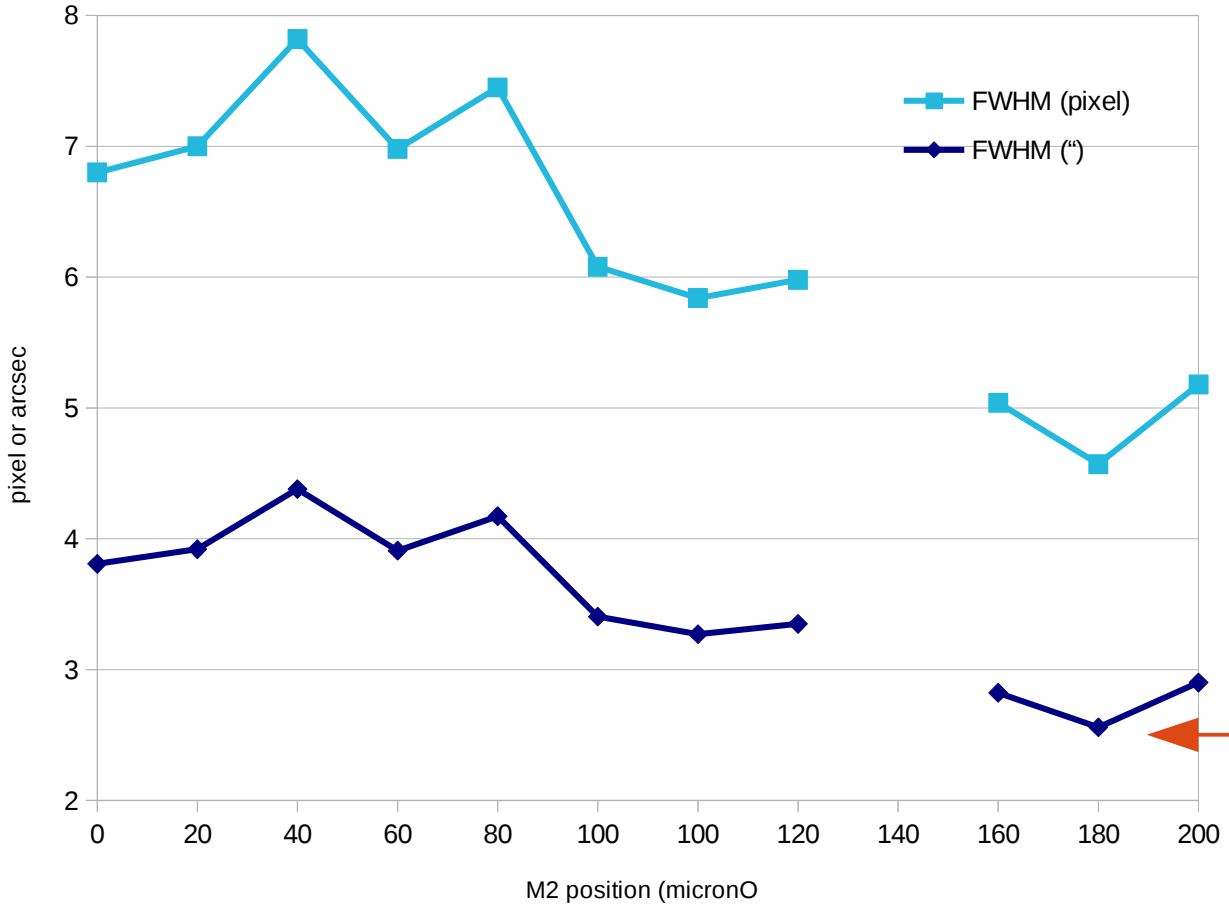
22/9/2016, at the ASTRON Parking Lot

1st Light, full CCD


Pole
Polaris
1.65°
1.65°


Anti-reflection coating excellent
Polaris (1.9mag) shows almost
no ghosting (~> 15 mag suppression)

Active focus control

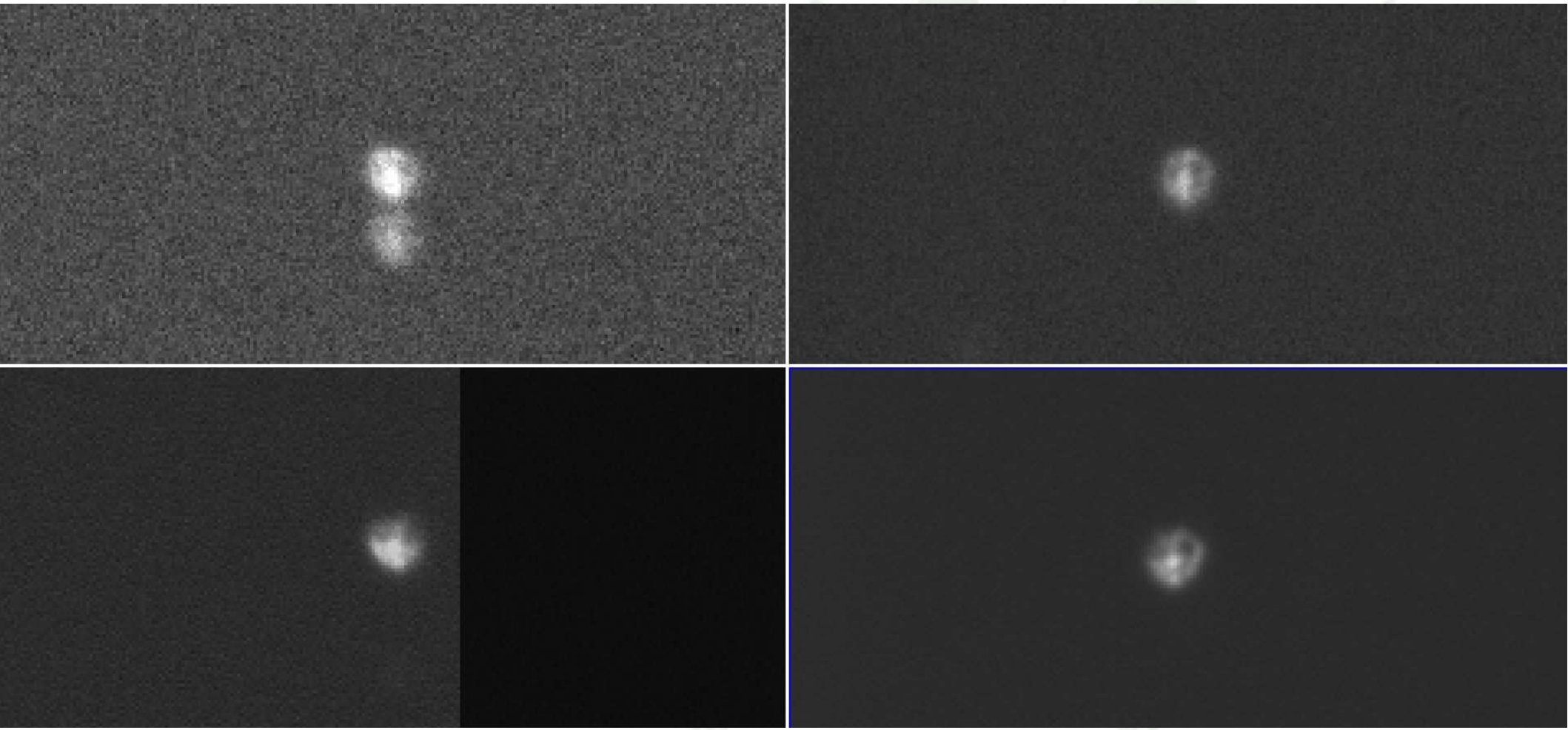


Using active M2 focus control over range 0 – 200 micron

2.5” !!!

MeerLICHT 1st light

Image quality at 0 micron focus, in four corners of CCD
(1.15 degrees away from center each)



ZEMAX simulation shows this is due to 0.02 degree tilt of M1.

First light CCD: 22/9/2016

File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help

File ML_12000x10600_73.fits
Object
Value 4765
WCS
Physical X 6406.000 Y 8598.000
Image X 6406.000 Y 8598.000
Frame 12 x 1.000 0.000 °

Taken from backlot of NOVA-OIR building in 2.5” seeing

file edit view frame bin zoom scale color region wcs help
- + to fit zoom 1/8 zoom 1/4 zoom 1/2 zoom 1 zoom 2 zoom 4 zoom 8

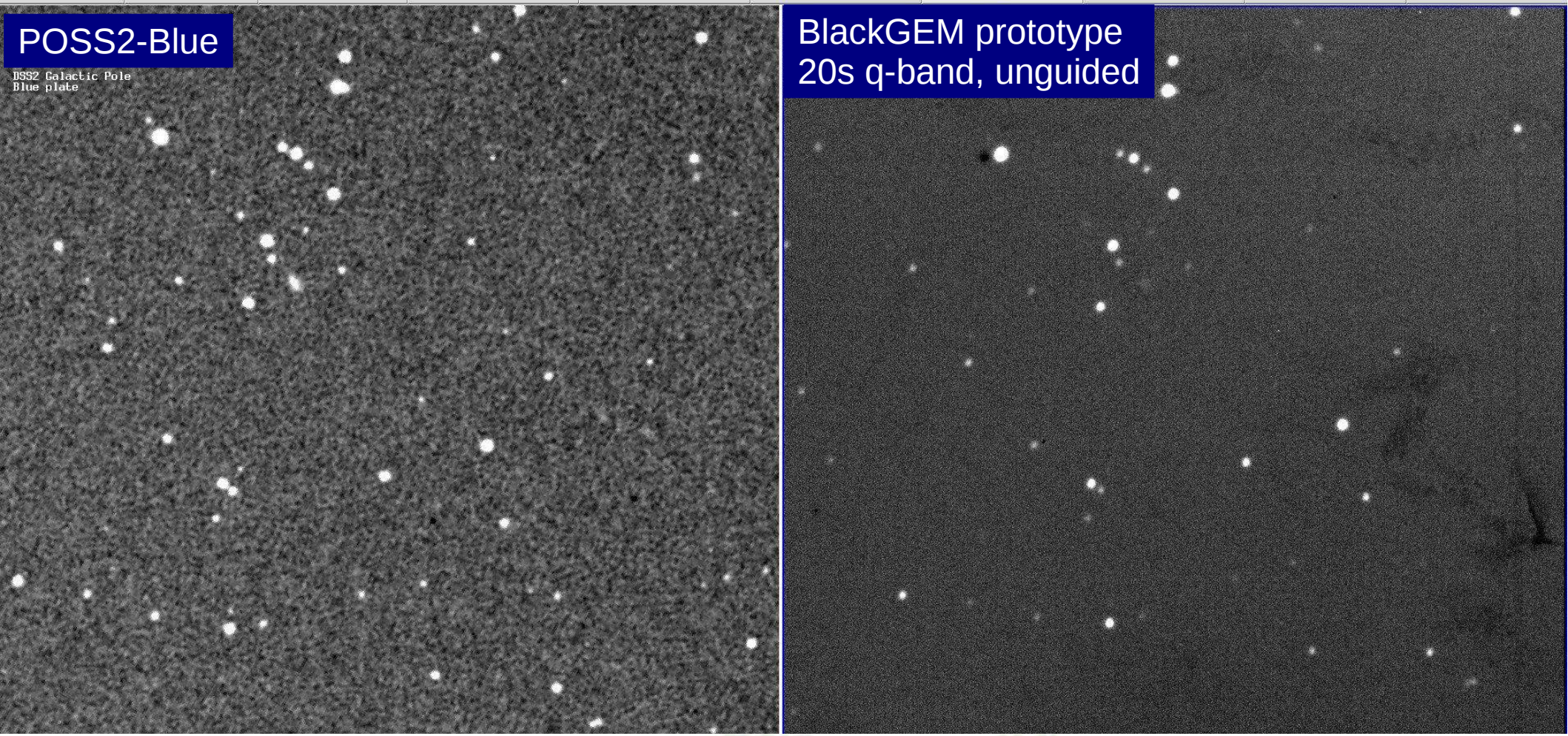
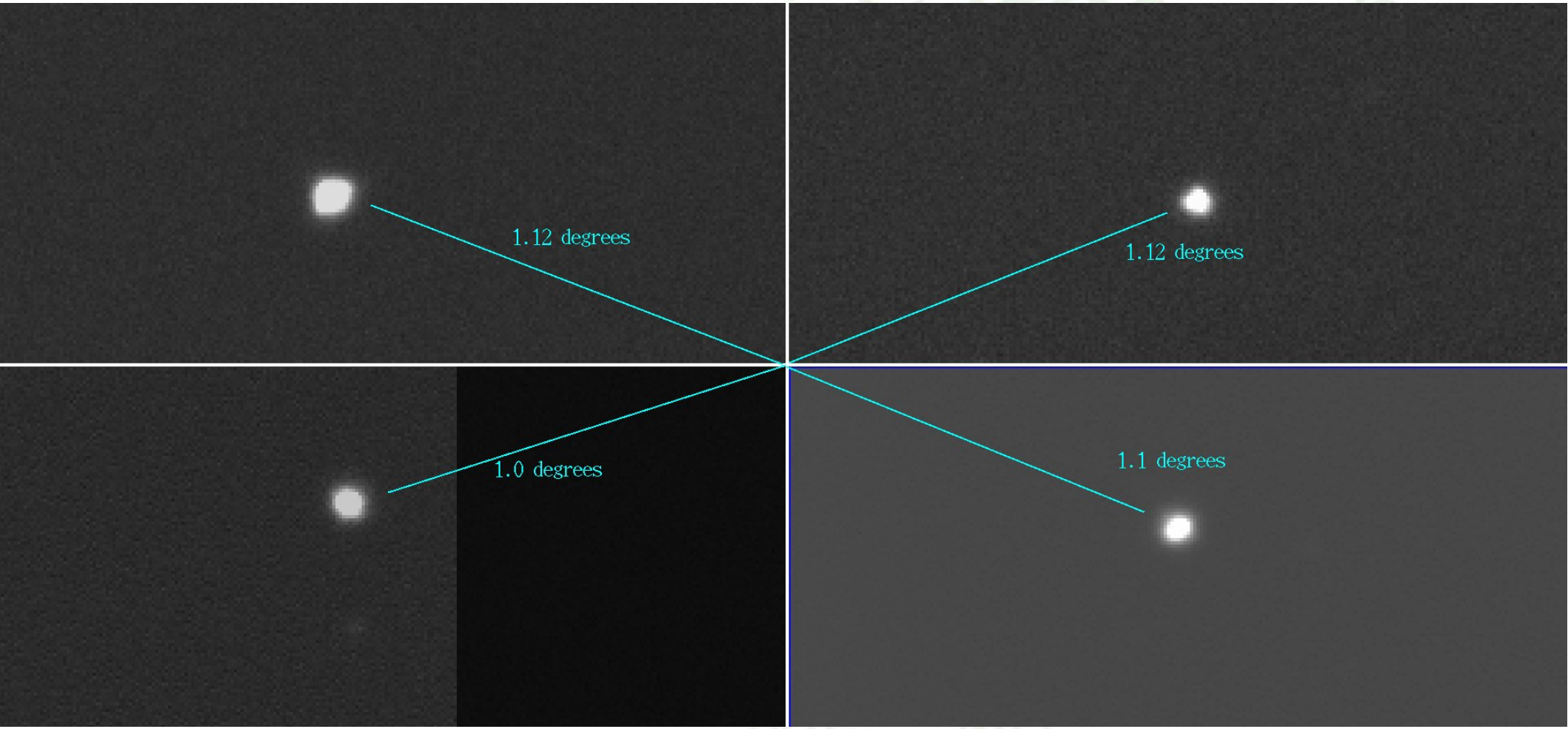


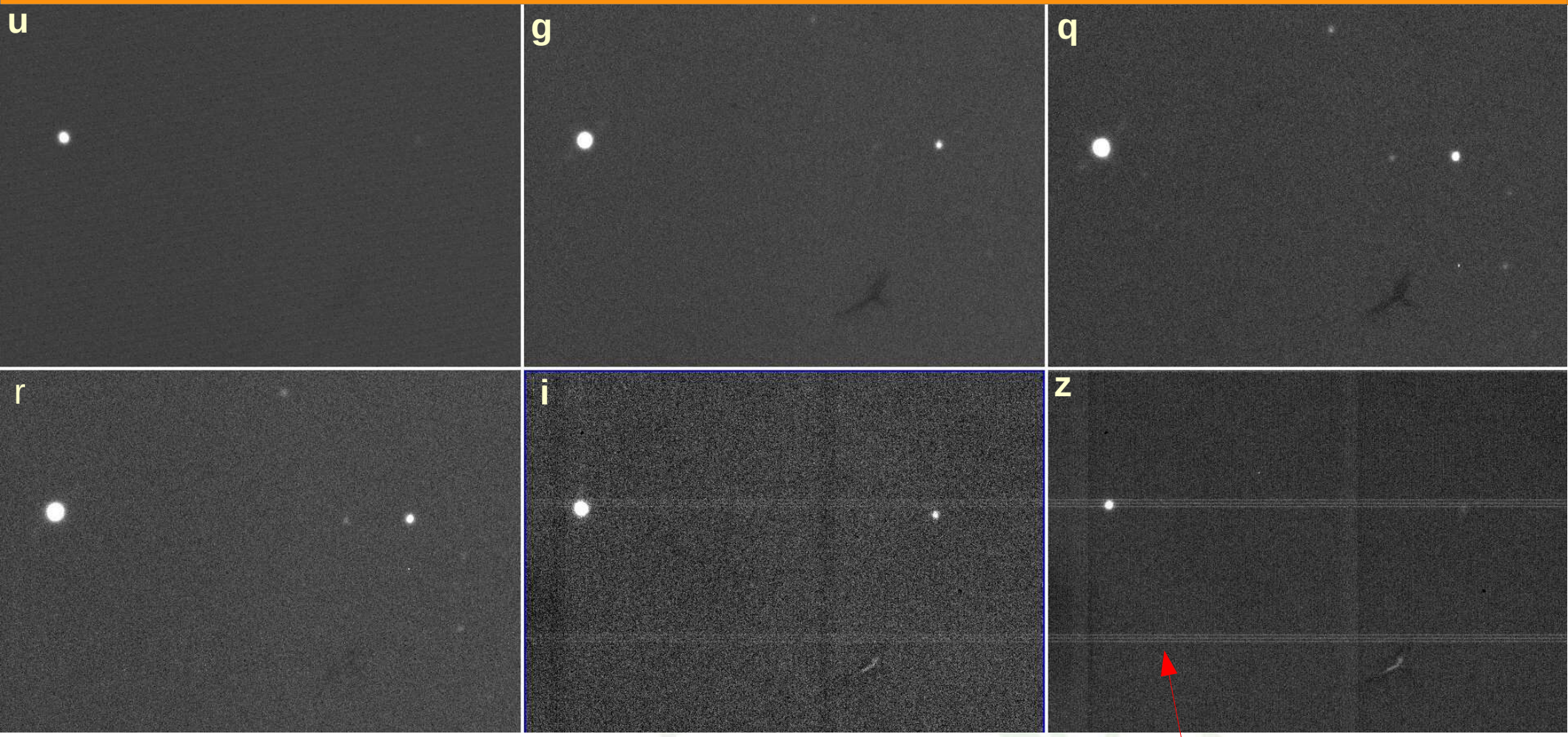
Image quality and depth approaching POSS2 plates in 20 seconds

Best focus

Image quality at 180 micron focus, in four corners of CCD
(1.15 degrees away from center each)



Filters



All exposures 5 seconds, unguided, on Pole

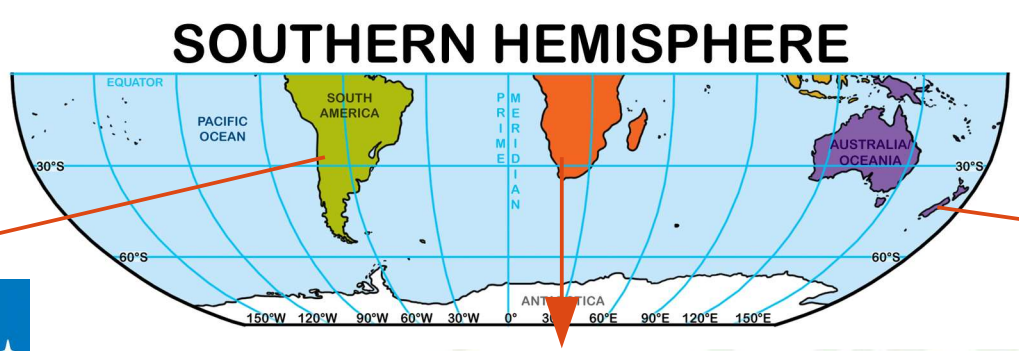
Reflection on backing Structure CCD

Schedule

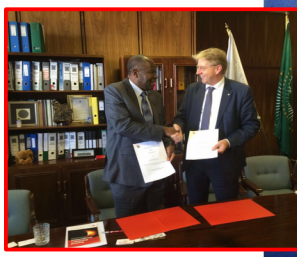
- Testing @Radboud: February
- Shipment MeerLICHT → ZA, early March (plane)
- Commissioning MeerLICHT @SAAO, mid-March – May
- Start operations MeerLICHT: June/July 2017
- Final Design Review BlackGEM: Late February
- Ordering long-lead items/assembly BlackGEM: March 2017 – March 2018
- Shipment BlackGEM → Chile: May 2018
- Commissioning BlackGEM → July/August 2018
- Start operations: September 2018.

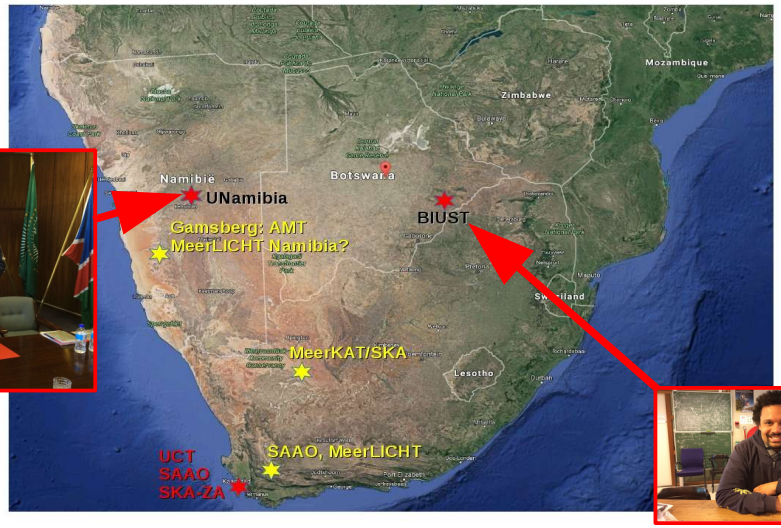
Future plans

- Expansion of BlackGEM to 15 telescopes (requires additional 15 MEuro)
- Chile, NZ and/or Southern Africa
- Development/addition of low-cost spectroscopic telescopes



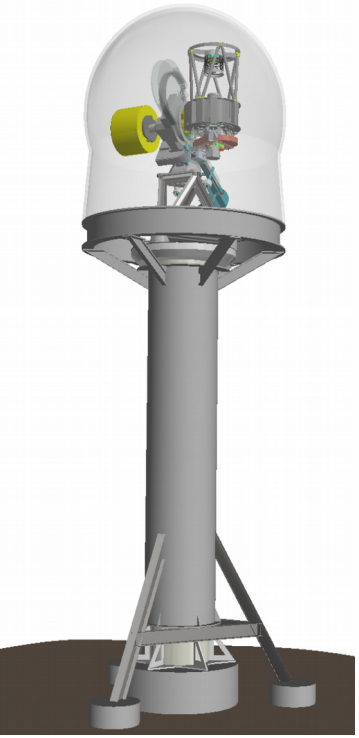
South Africa or Namibia





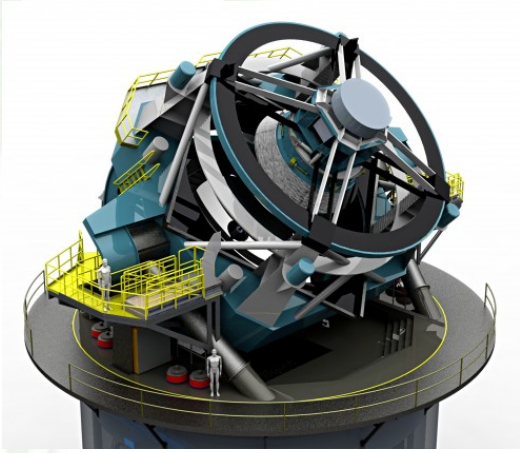
Mt. John
U. of Canterbury
Christchurch

BlackGEM & LSST



BlackGEM & LSST highly complementary

- Different parts of synoptic parameter space (hours – days vs. weeks)
- Different parts of magnitude range (23^{rd} vs. 26^{th})
- Different science case, but....
- Five years earlier (2018 vs. 2023)



- Identical ***type*** of data; same ***field-of-view***
- Highly similar ***quality*** of data
- Same ***location***, same ***sky***

BlackGEM closest project to LSST, until the LSST itself