Cosmology from Pan-STARRS
Wide-Field Optical/NIR Surveys

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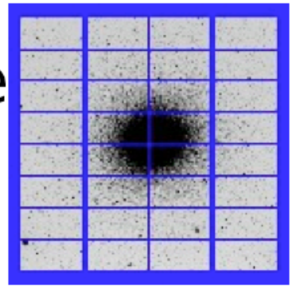
Pan-STARRS, Institute for Astronomy, U. Hawaii

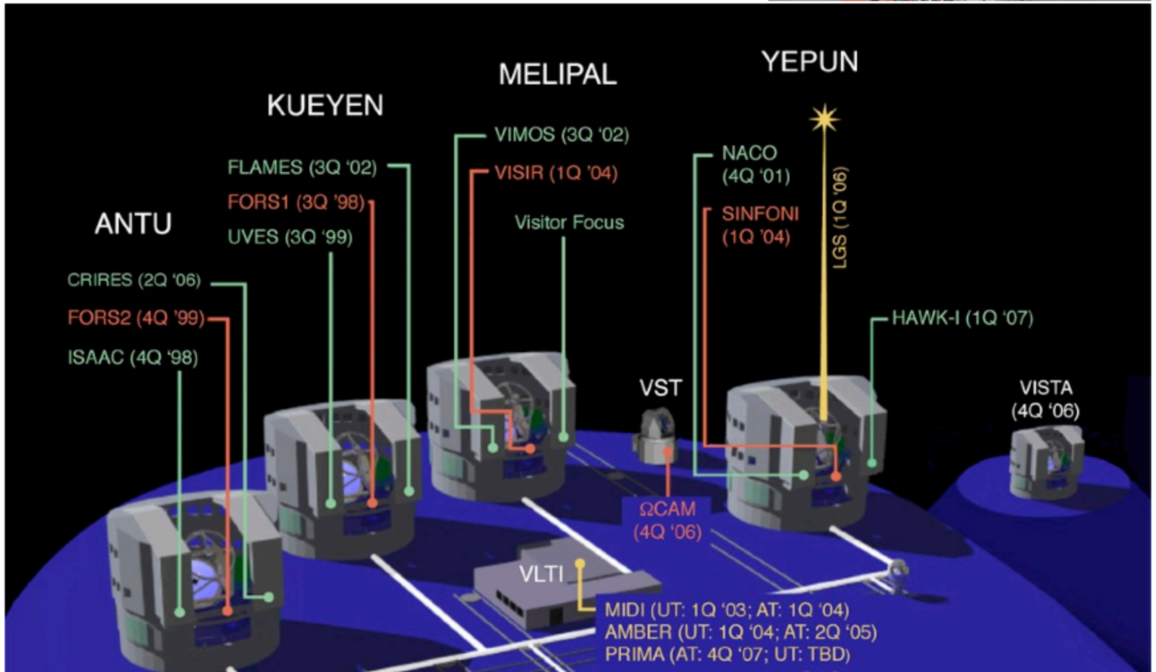
Modern Cosmology, Early Universe, CMB and LSS

Benasque, August 6th, 2010

KIDS: Kilo-Degree Survey

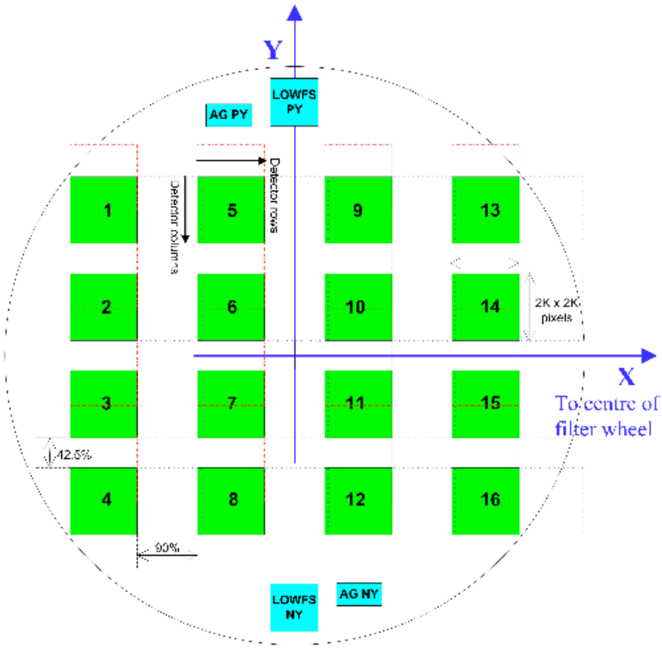
- 1500 deg^2
- 400 nights on VST 2.5m telescope
- OmegaCam: 1 deg^2 CCD camera
- PI: K. Kuijken (Leiden)
- Filter set: ugri+
- 2009-2014?





VISTA Telescope

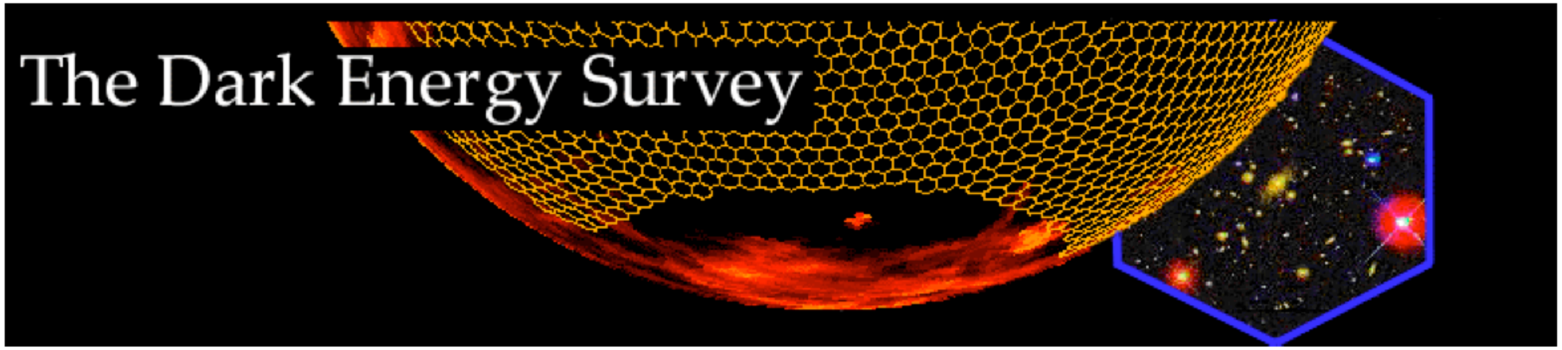
- 4m infrared-dedicated scope
- 0.6 deg^2 sparse camera
- Filter set: zyJHK
- Commissioning now
- VIKING: IR component of KIDS



DES: Dark Energy Survey

darkenergysurvey.org

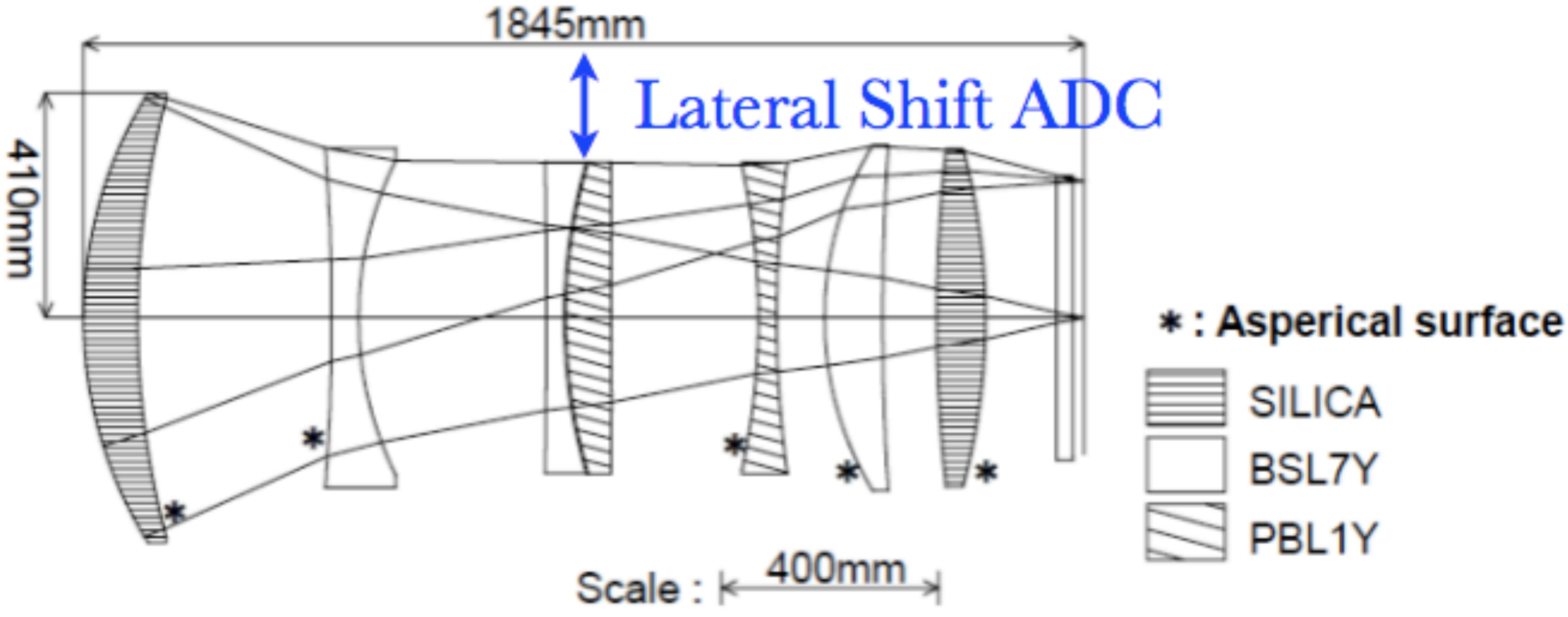
- 4-m CTIO telescope
- 3 deg^2 camera
- 5000 deg^2 survey
- Filter set: griz
- 2011-2014?
- Lead Institution: Fermilab



HyperSuprimeCam

- upgrade Subaru 8-m telescope with 1.8 deg^2 camera
- commissioning late 2011
- survey(s) undergoing definition now

Wide Field Corrector

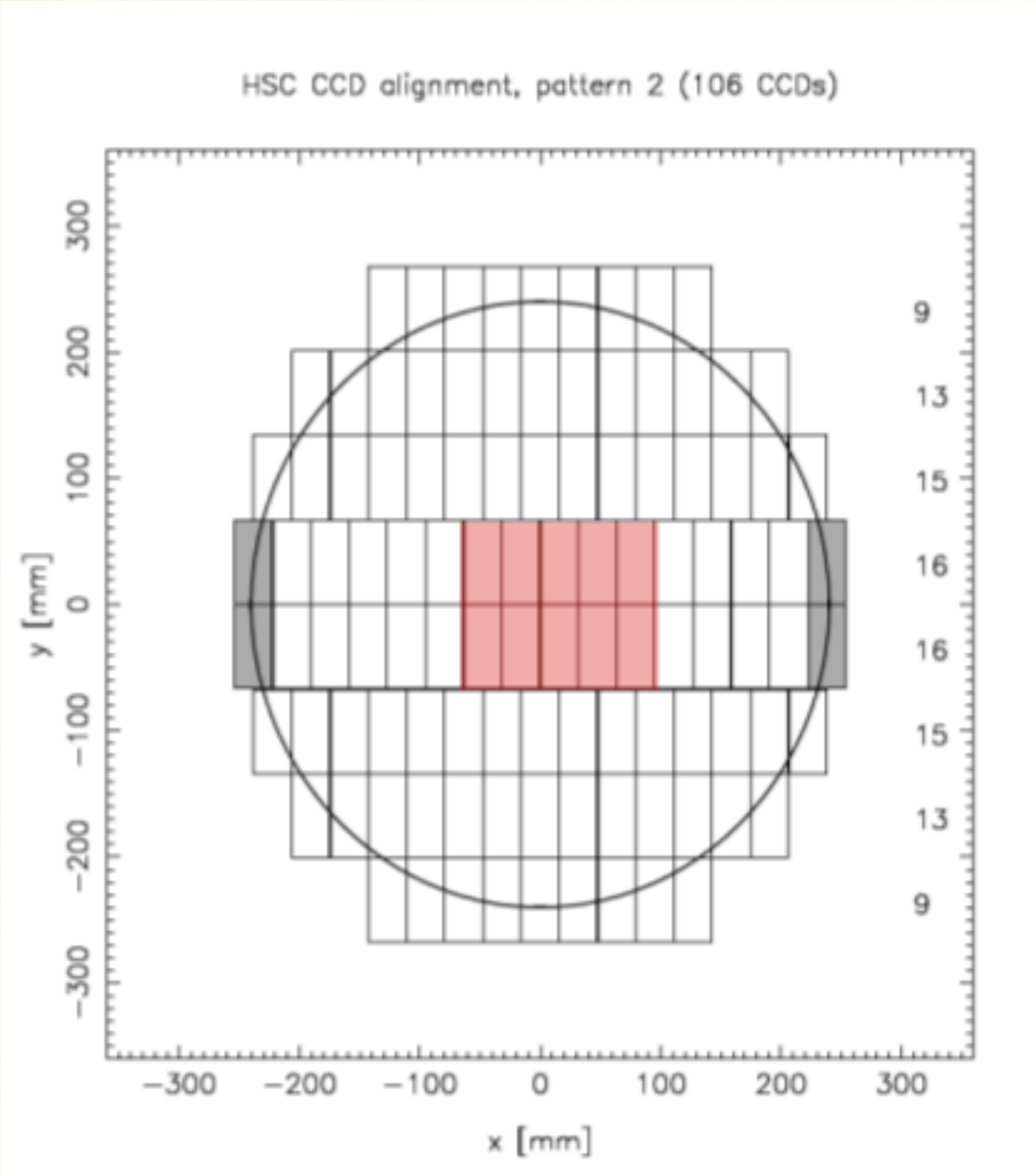


General Lens Data

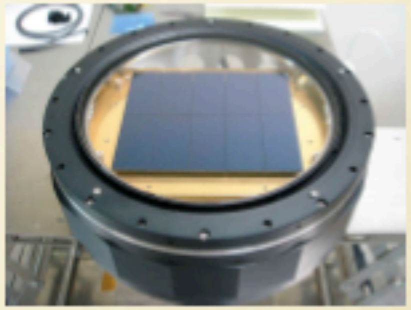
Focal length	18416[mm]
image scale	0.0893[mm/arcsec]
image size	ϕ498[mm]

0.17 arcsec/pix
(15 um pix)

HSC: Focal Plane



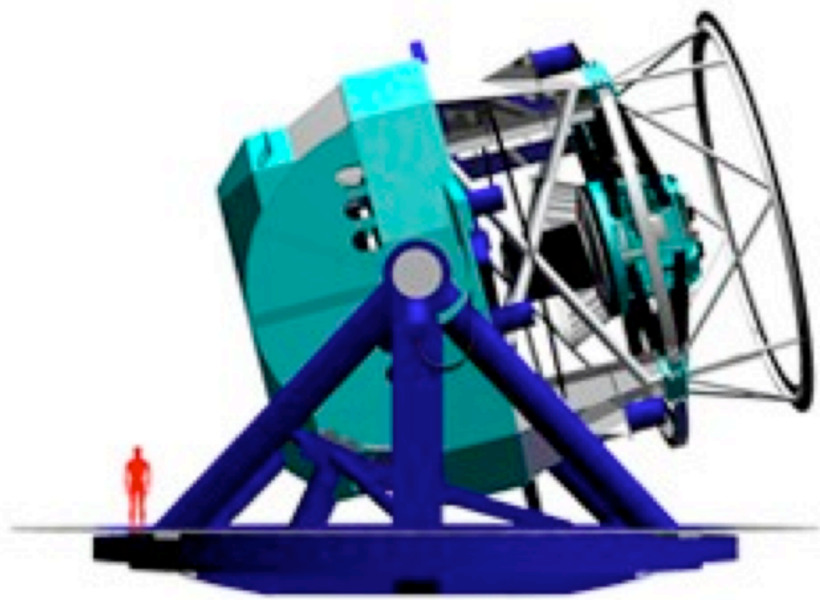
106 2k4kFDCCD

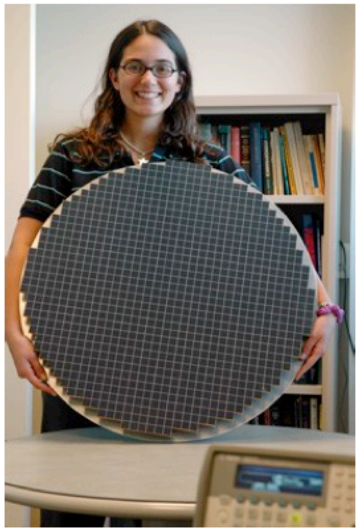


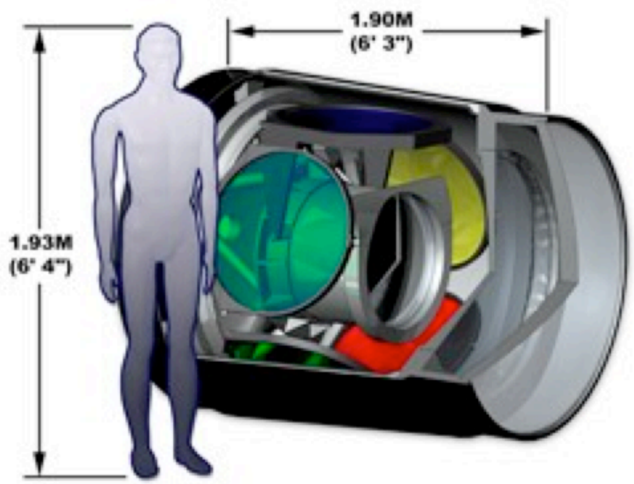
LSST

Large Synoptic Survey Telescope, lsst.org

- 8.4-m telescope
- 10 deg^2 camera
- ~20000 deg^2 survey
- Filter set: ugrizy
- 2015-2024

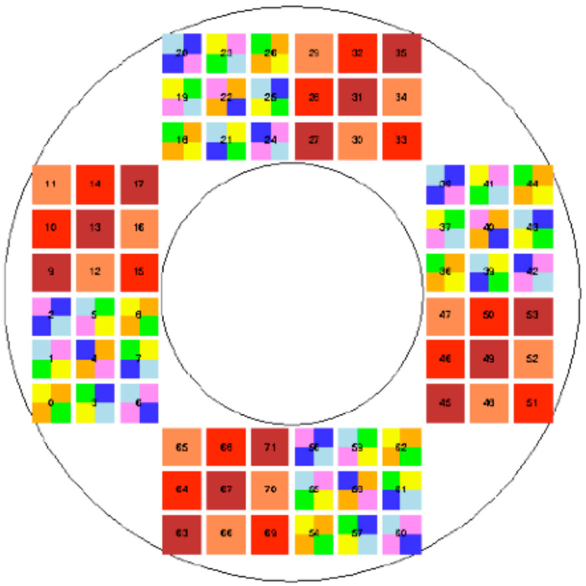




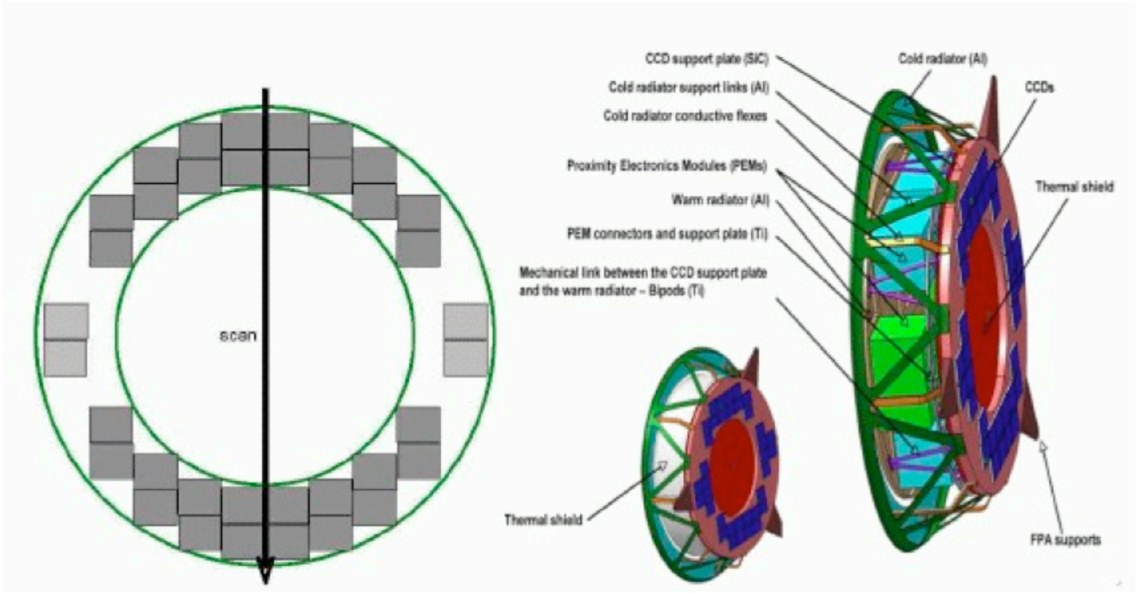


Joint Dark Energy Mission

- many competing concepts
- mission still being defined
- merged with European mission?

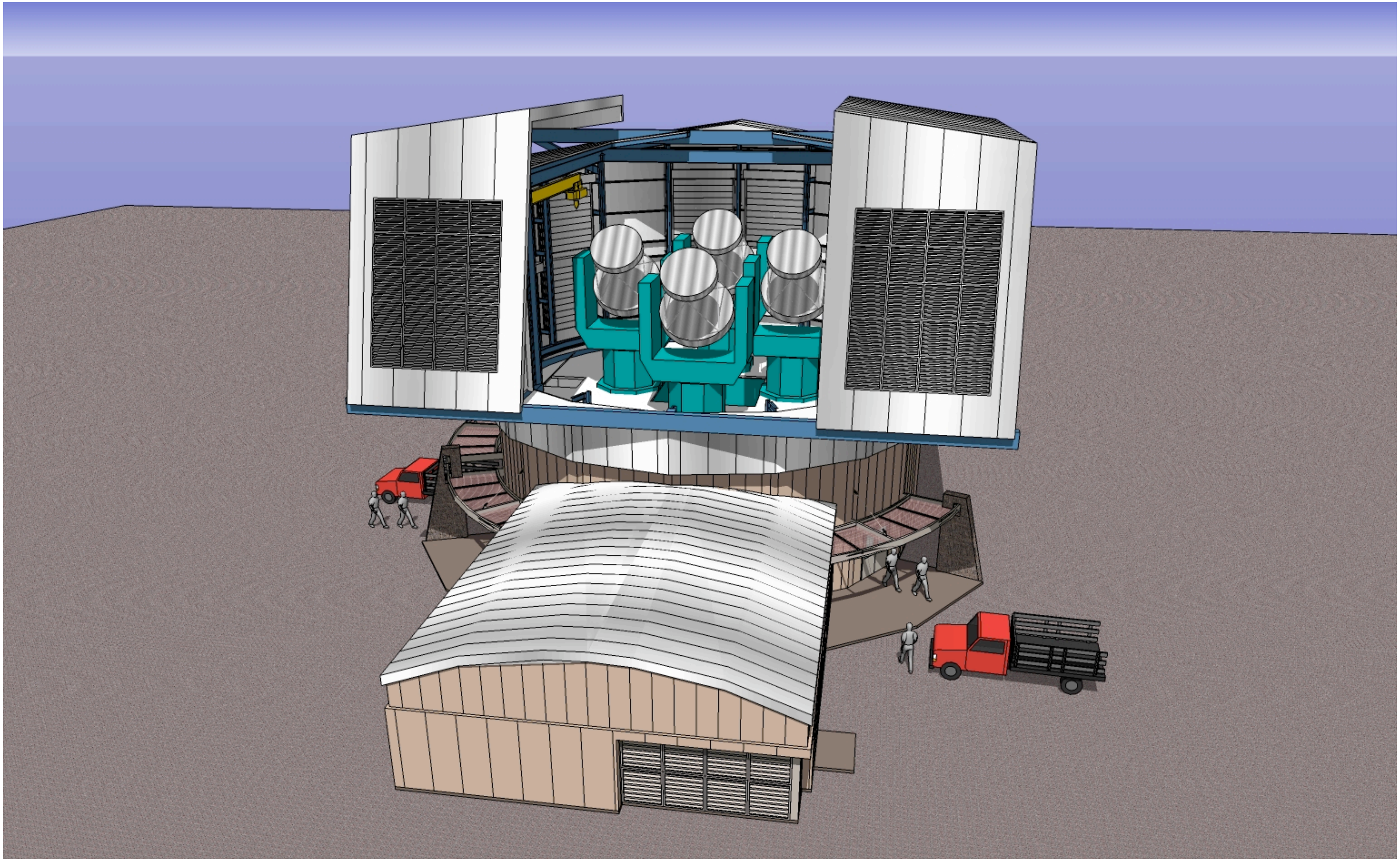


SNAP focal plane

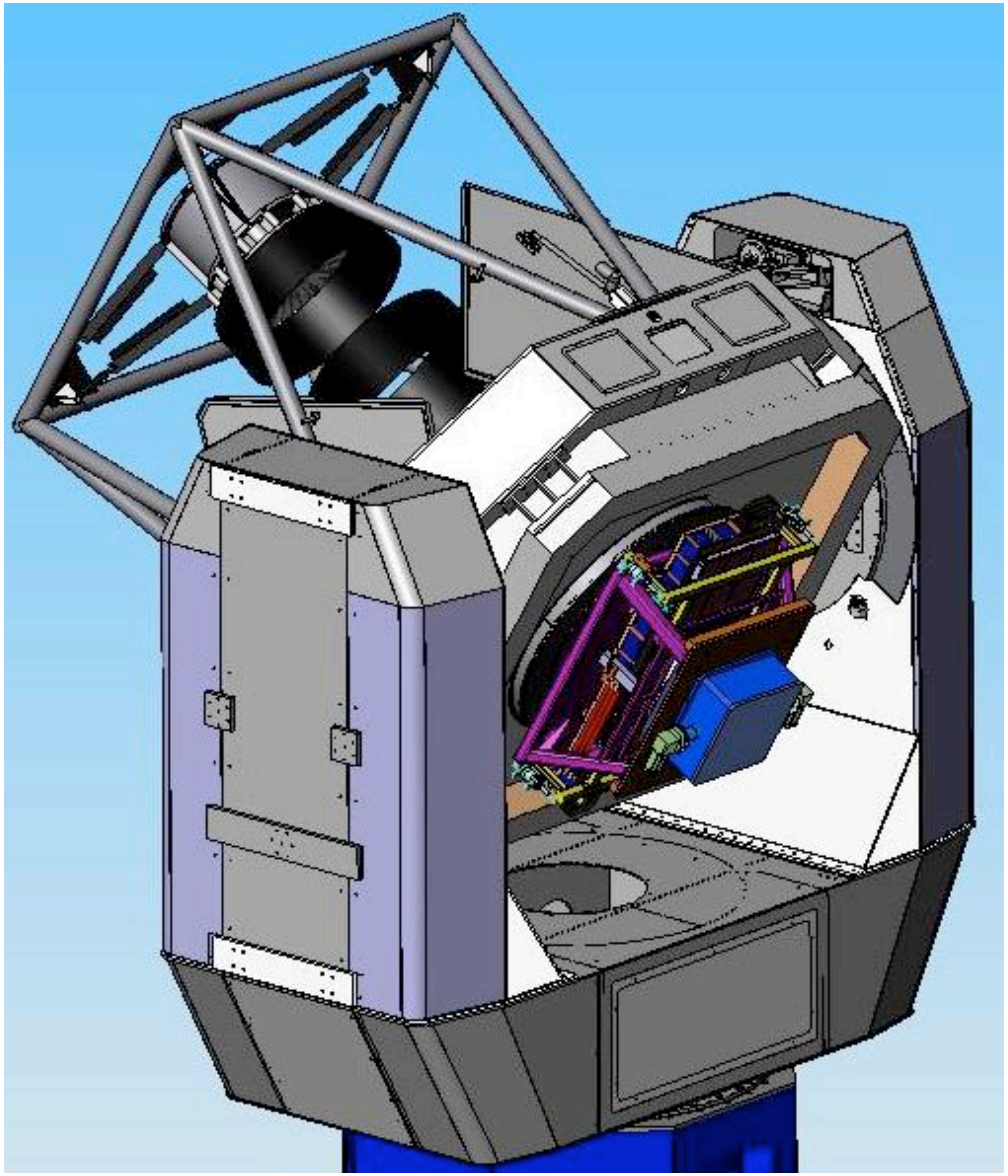


DUNE

Pan-STARRS PS4 Observatory



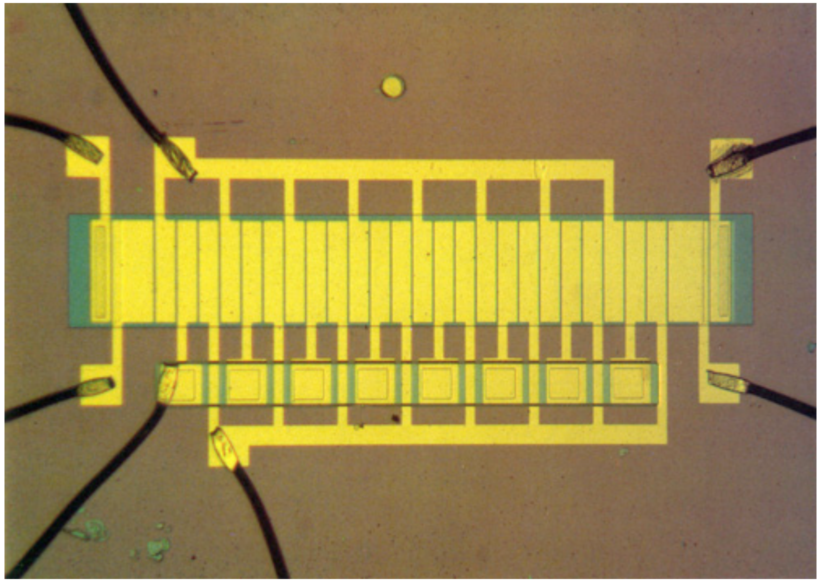
Pan-STARRS1 (Haleakala, Maui)

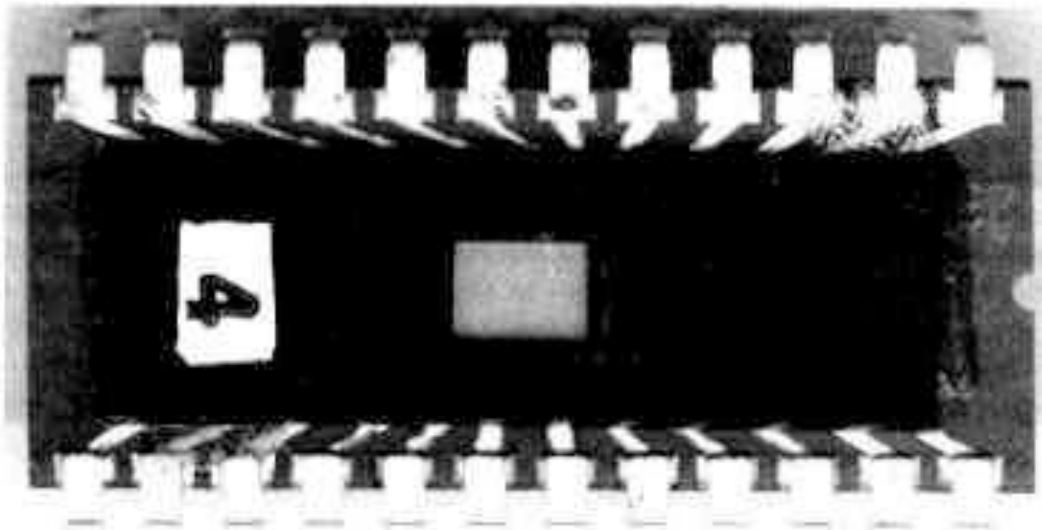


Invention of “charge-coupled device” (CCD) Imager

Boyle + Smith at Bell Labs

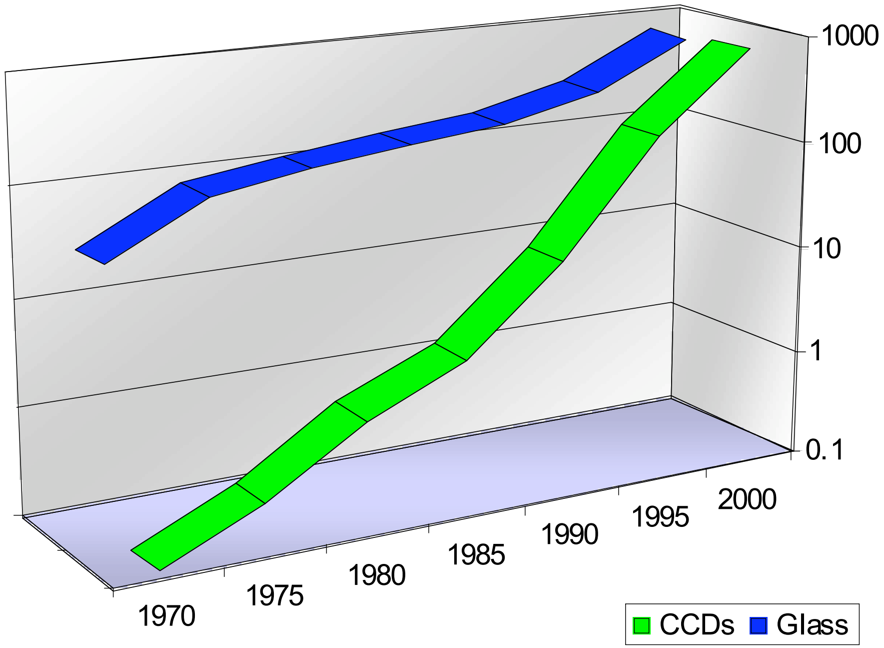
First 8 bit CCD



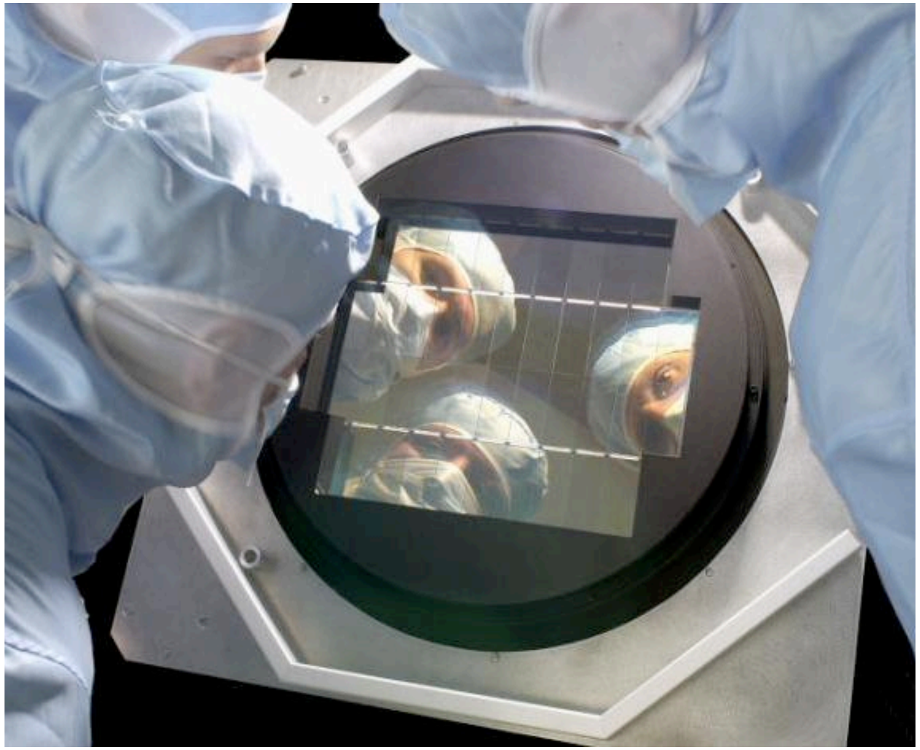


Trends in Astronomy Technology

- Future dominated by detector improvements

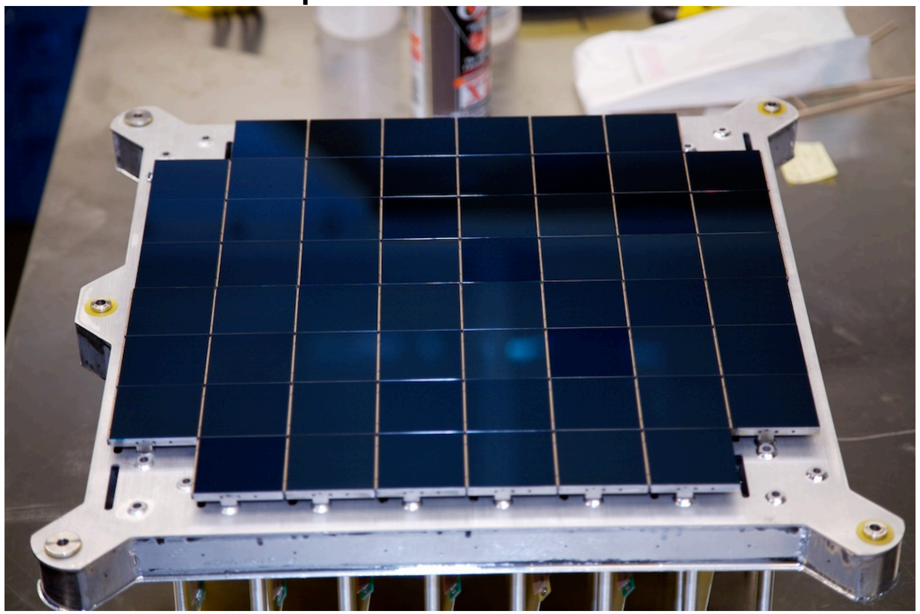


Total area of 3m+ telescopes in the world in m^{2}*, total number of CCD pixels in Megapix, as a function of time. Growth over 25 years is a factor of 30 in glass, 3000 in pixels.*

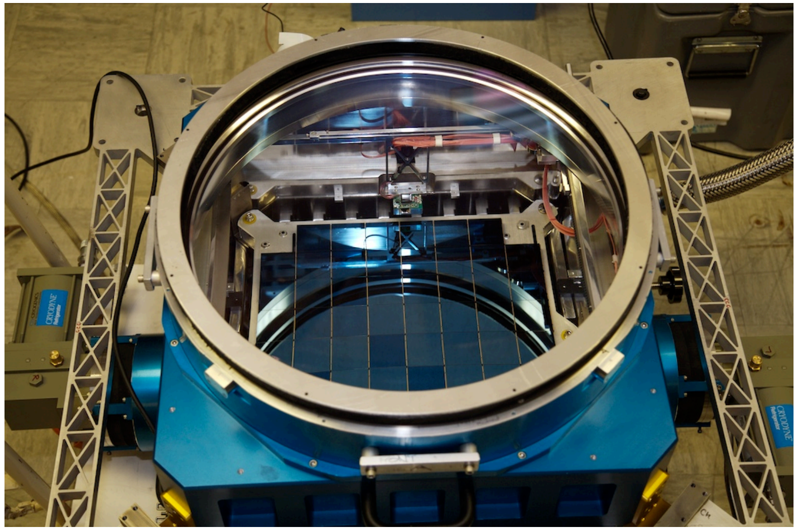


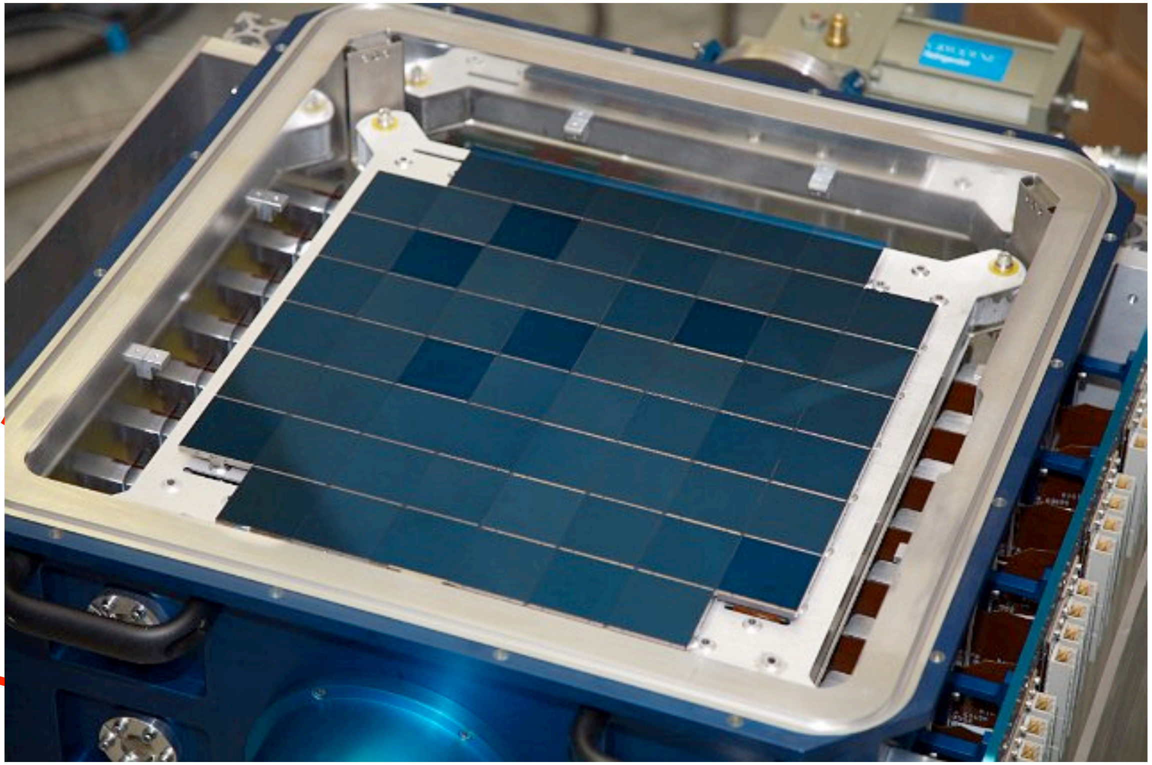
300 Mpix 'megacam' at CFHT

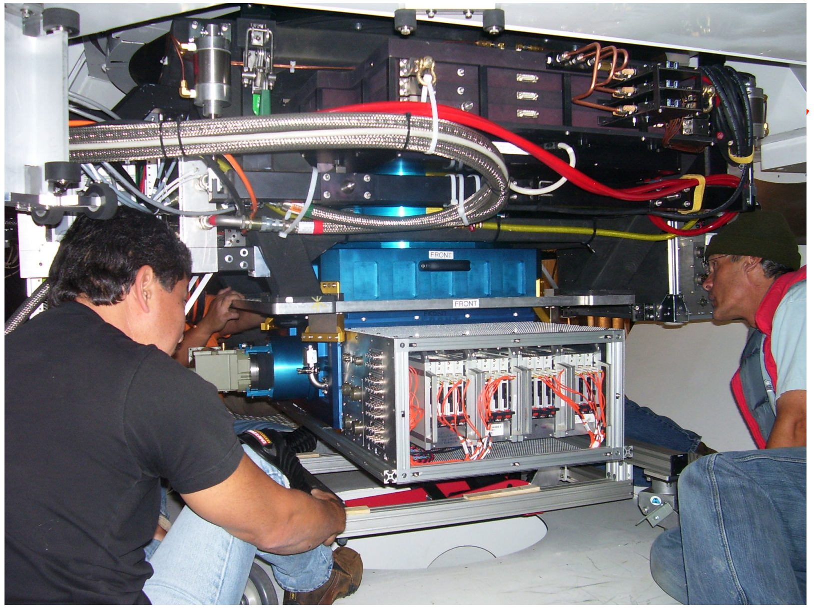
1.4 Billion pixel GPC1 at PS1

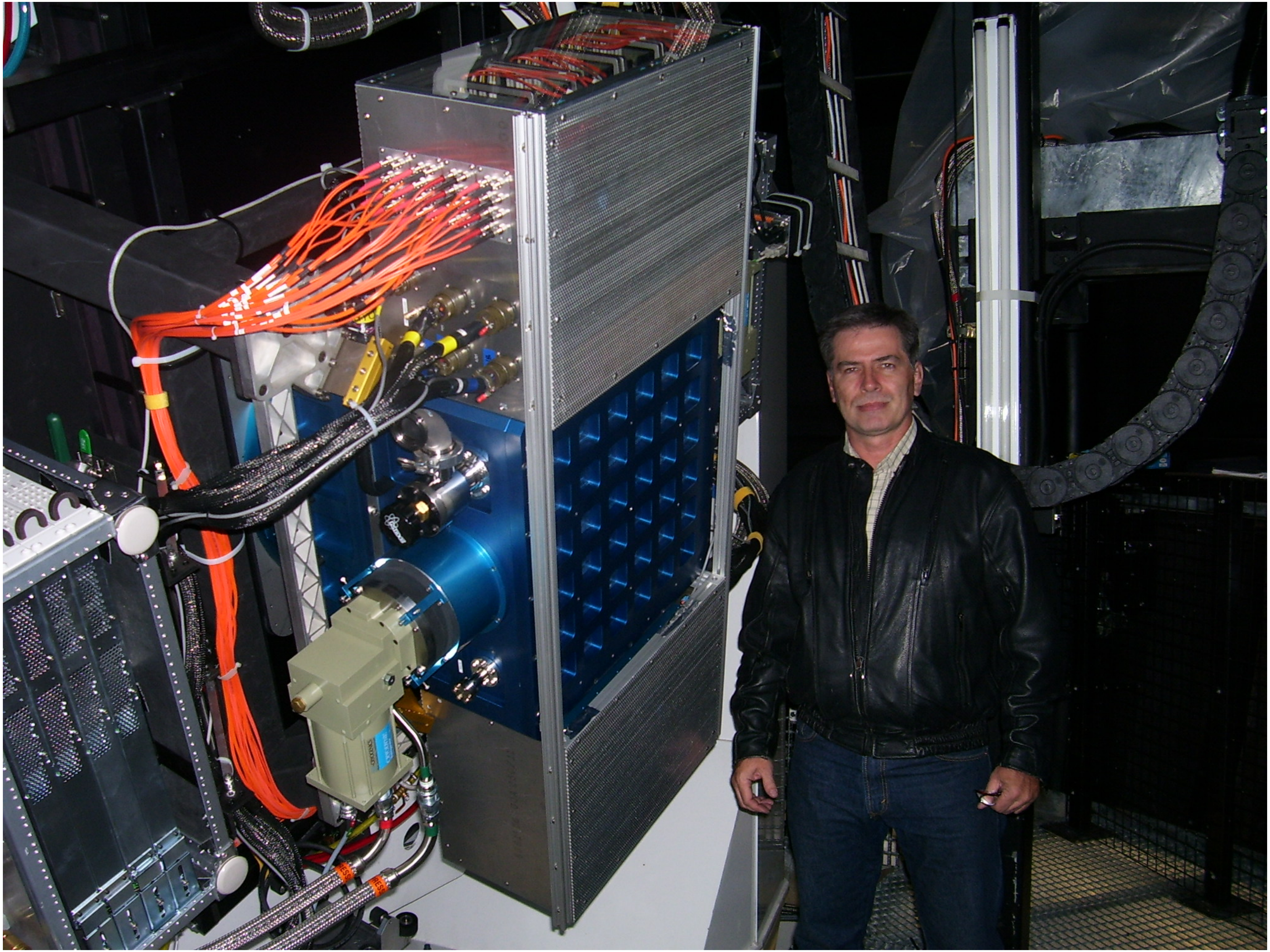


GPC1

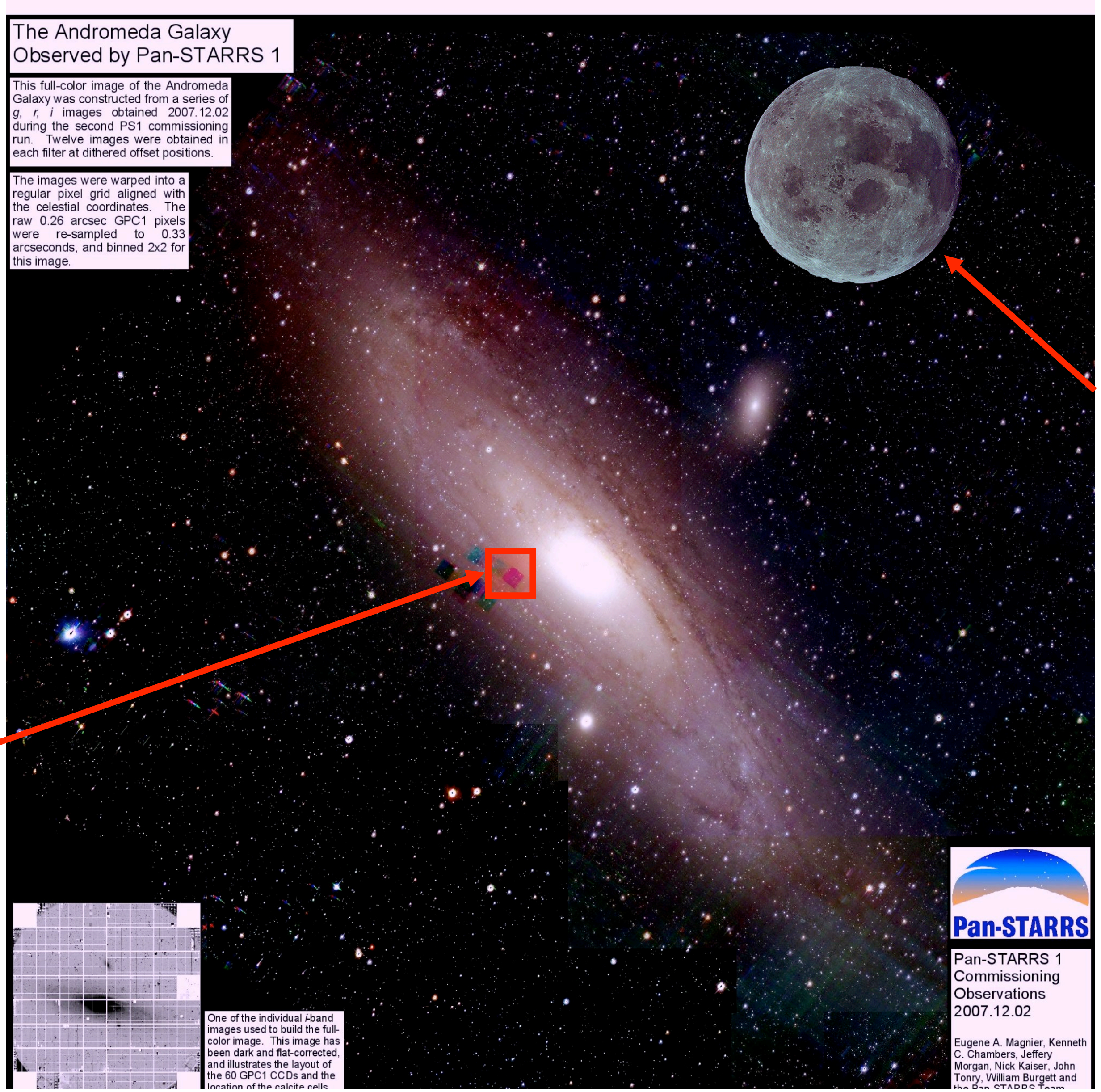








PS1 Commissioning Image – M31 inside GPC FOV

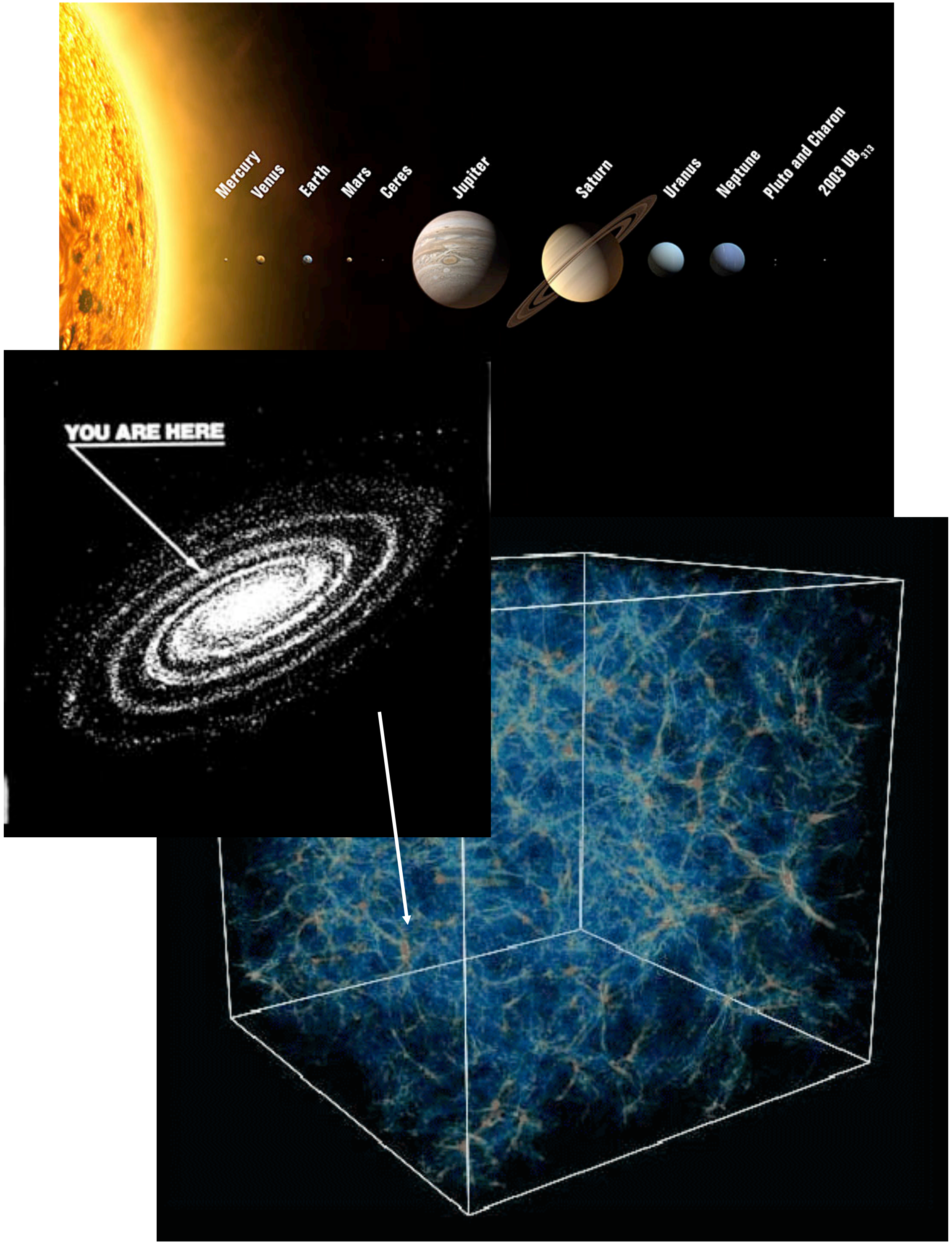


0.5º diameter of Moon only small fraction of GPC FoV

FoV of standard world class research telescope

Orientation

- Solar System (Sun, Mercury, Venus, Earth, Mars, Jupiter…)
  - Our Sun is one star of a 100 billion in the Milky Way Galaxy
- Our Solar System is located In the Orion arm of the Milky Way Galaxy
- The Milky Way Galaxy is in the suburbs of the Virgo Supercluster of Galaxies
- The Virgo Supercluster is one of about a million superclusters that extend as far as we can see…
- So, how did we get here?

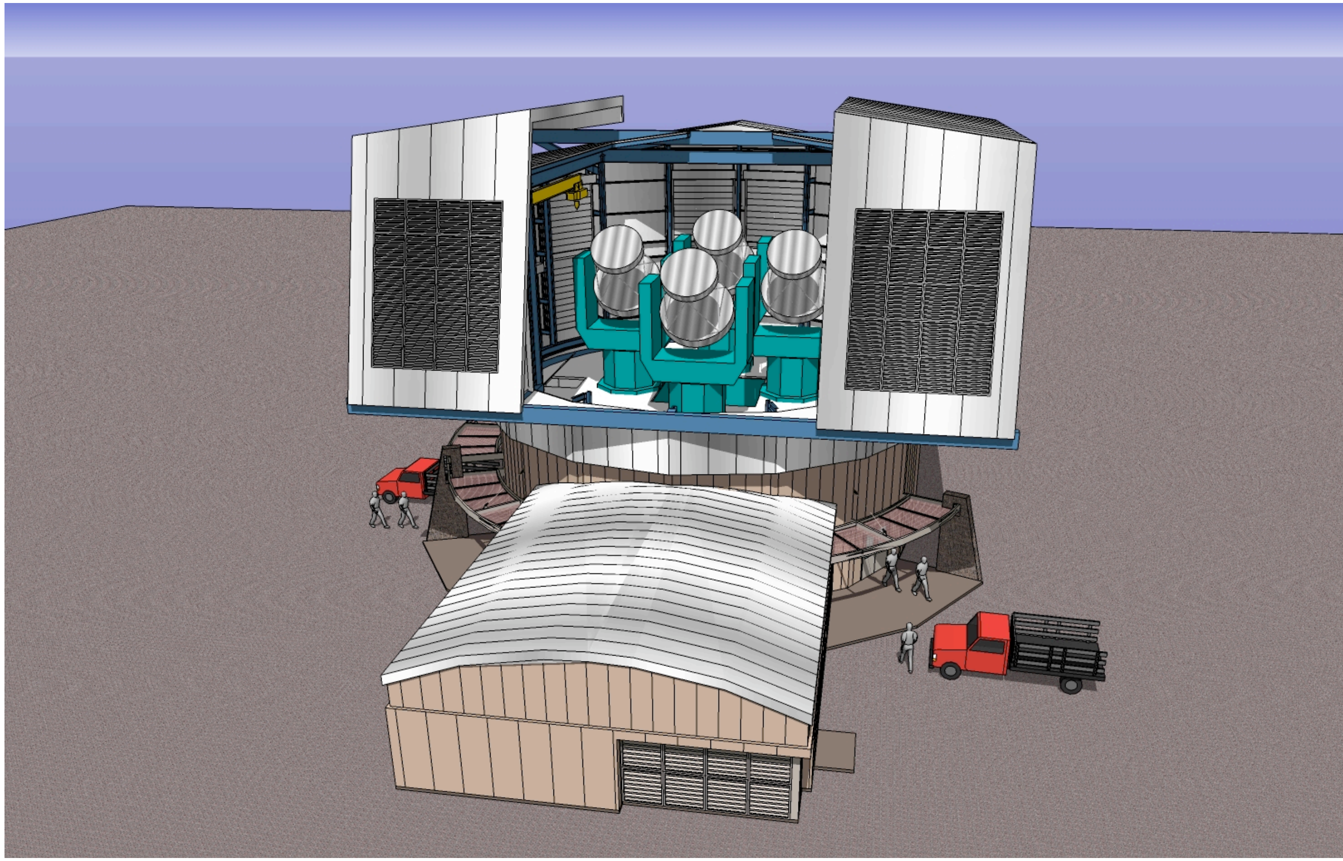


Pan-STARRS overview

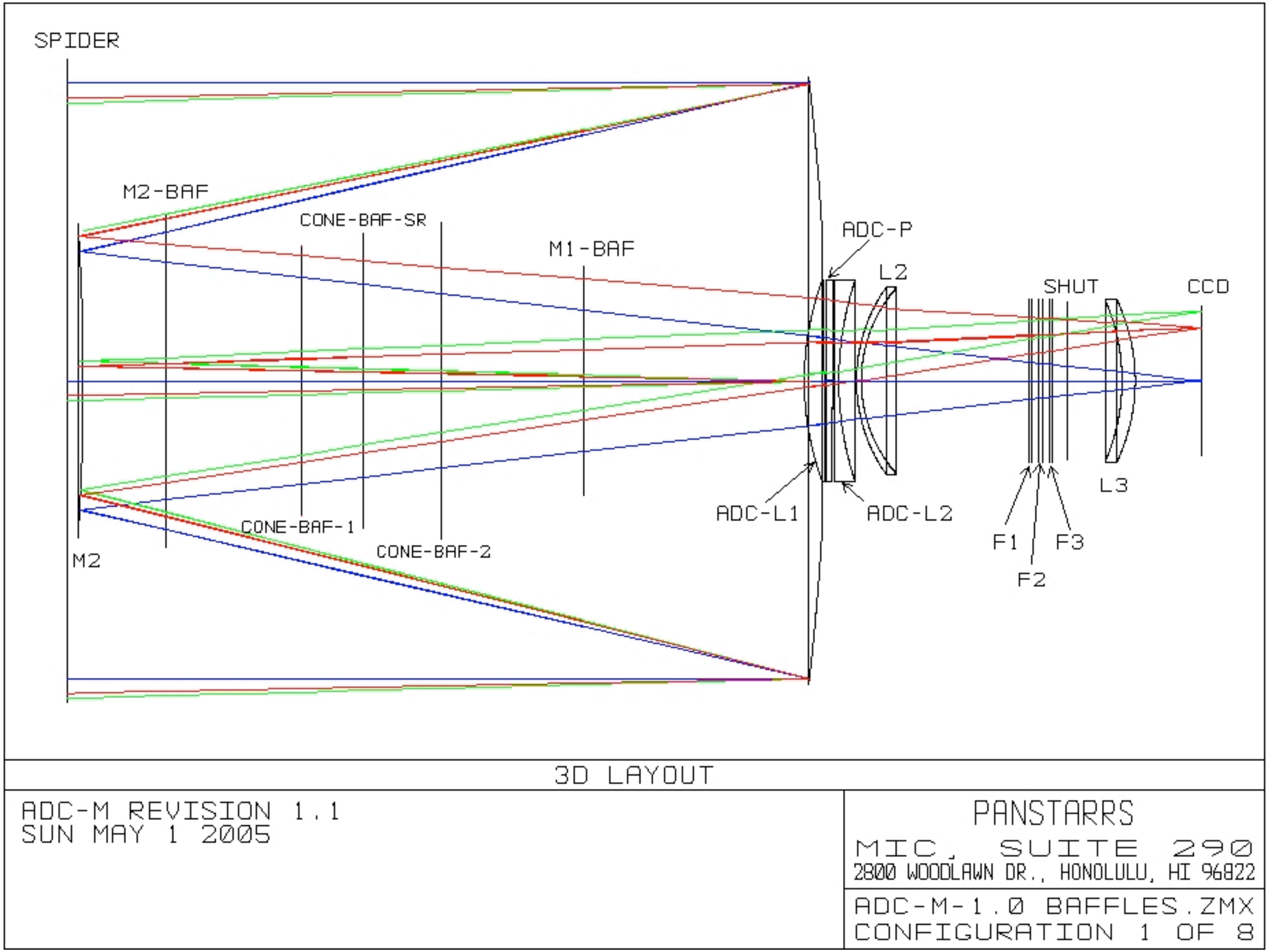
- Pan-STARRS observatory specifications
  - –Four 1.8m R-C + corrector
  - –7 square degree FOV - 1.4Gpixel cameras
  - –Sited in Hawaii
  - –A Ω = 50
  - –R ~ 24 in 30 s integration (meets NAS decadal review “LSST” spec)
    - –-> 7000 square deg/night
  - –All sky + deep field surveys in g,r,I,z,y and w filters

- Time domain astronomy
  - Transient objects
  - Moving objects
  - Variable objects

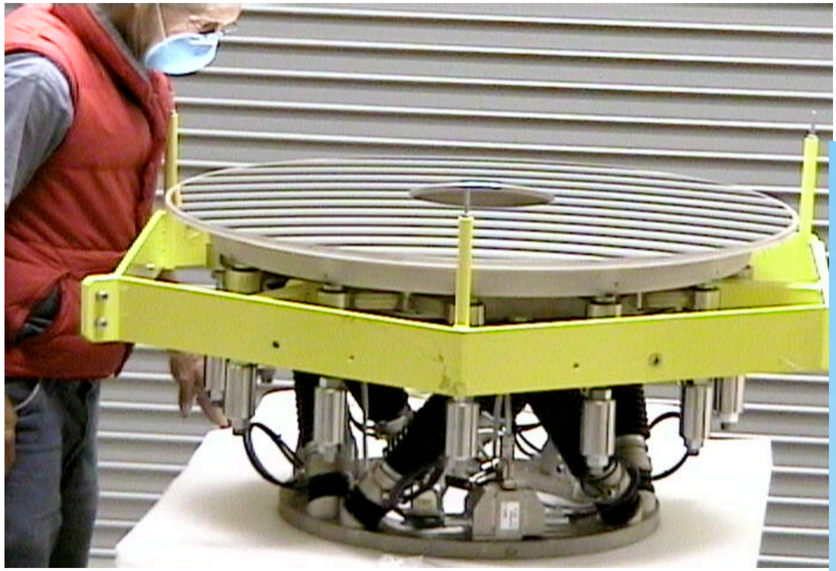
- Static sky science
  - Enabled by stacking repeated scans to form a collection of ultra-deep static sky images

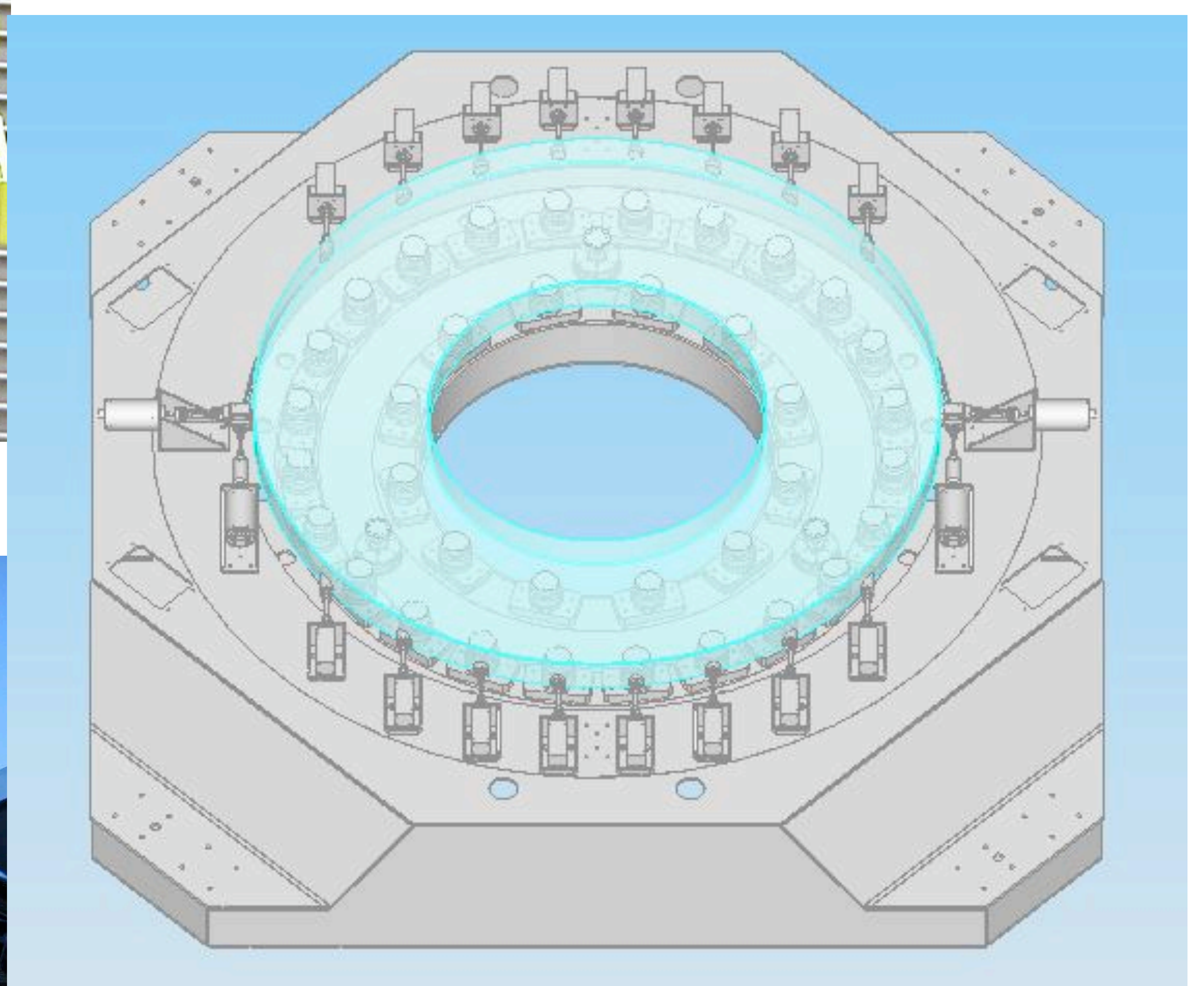


PS-1 Optical Design - RC + 3-element wide-field corrector

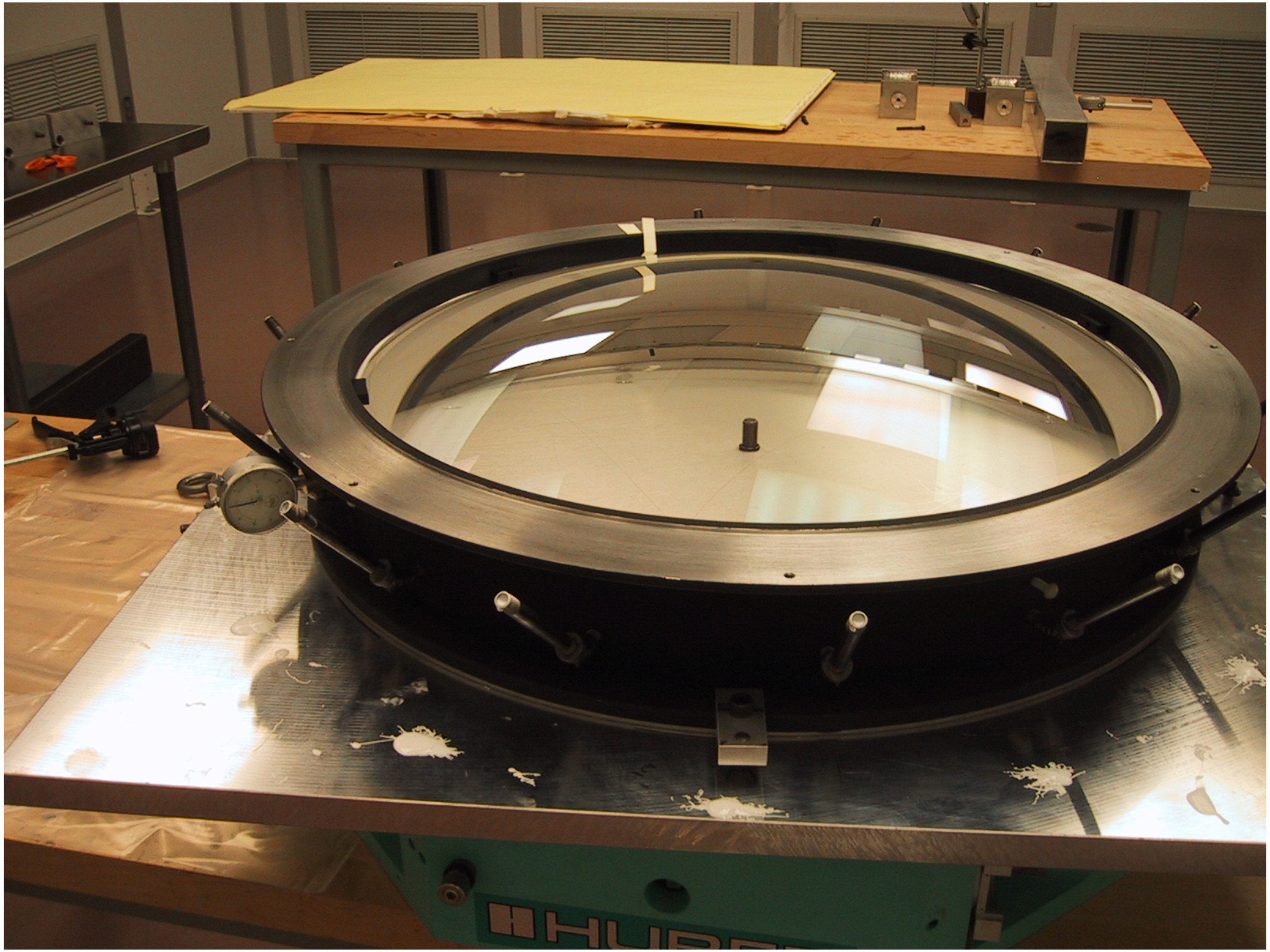


Mirror Support Systems

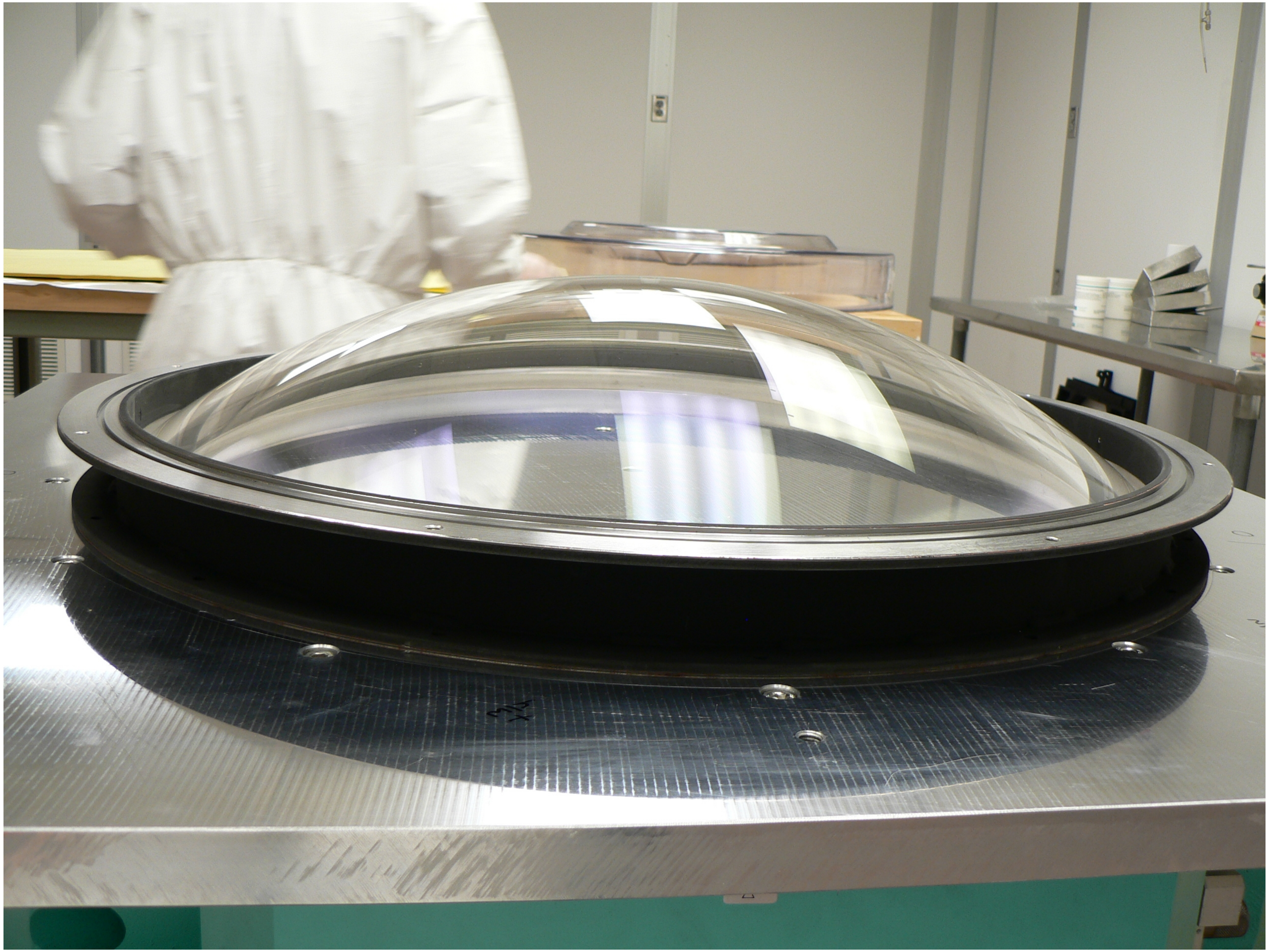




L1 Potted in Its Cell at UW

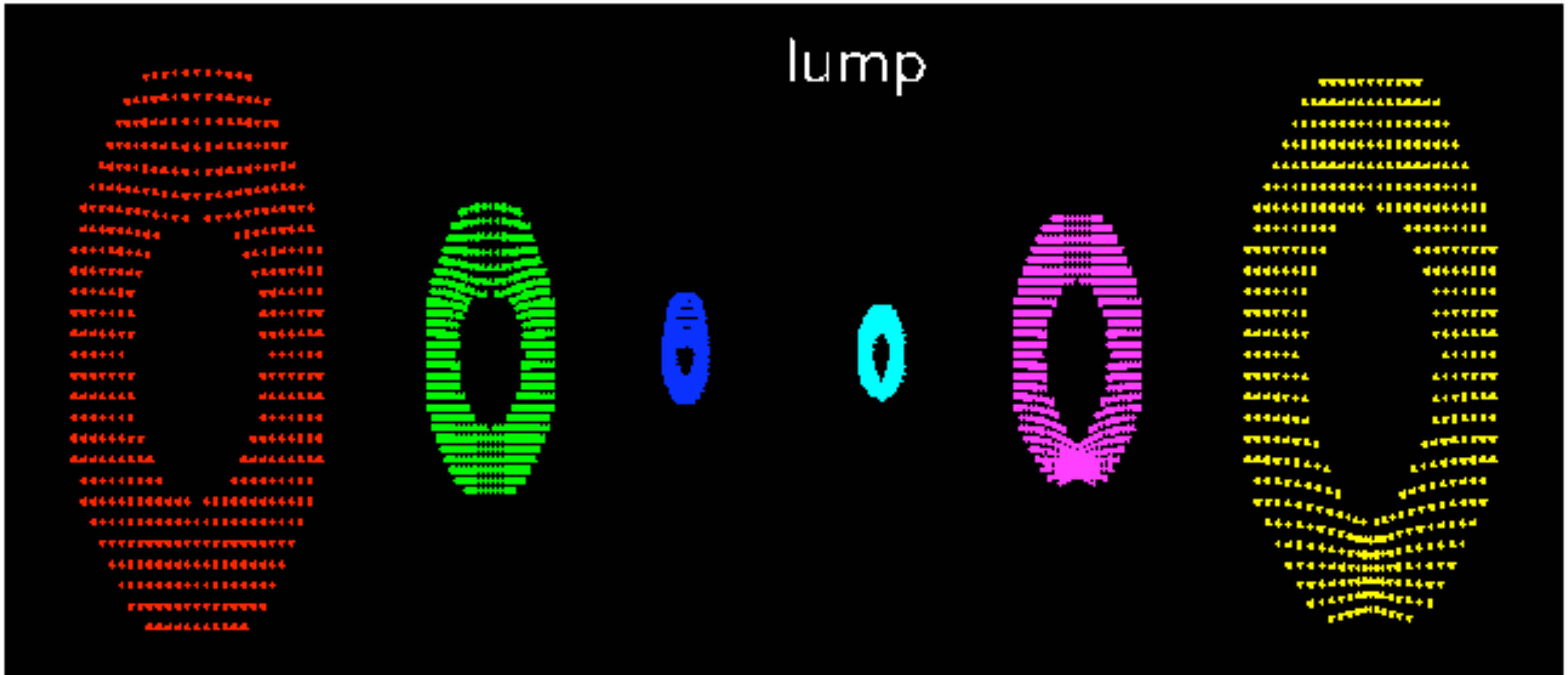


L2 Fit Test at UW

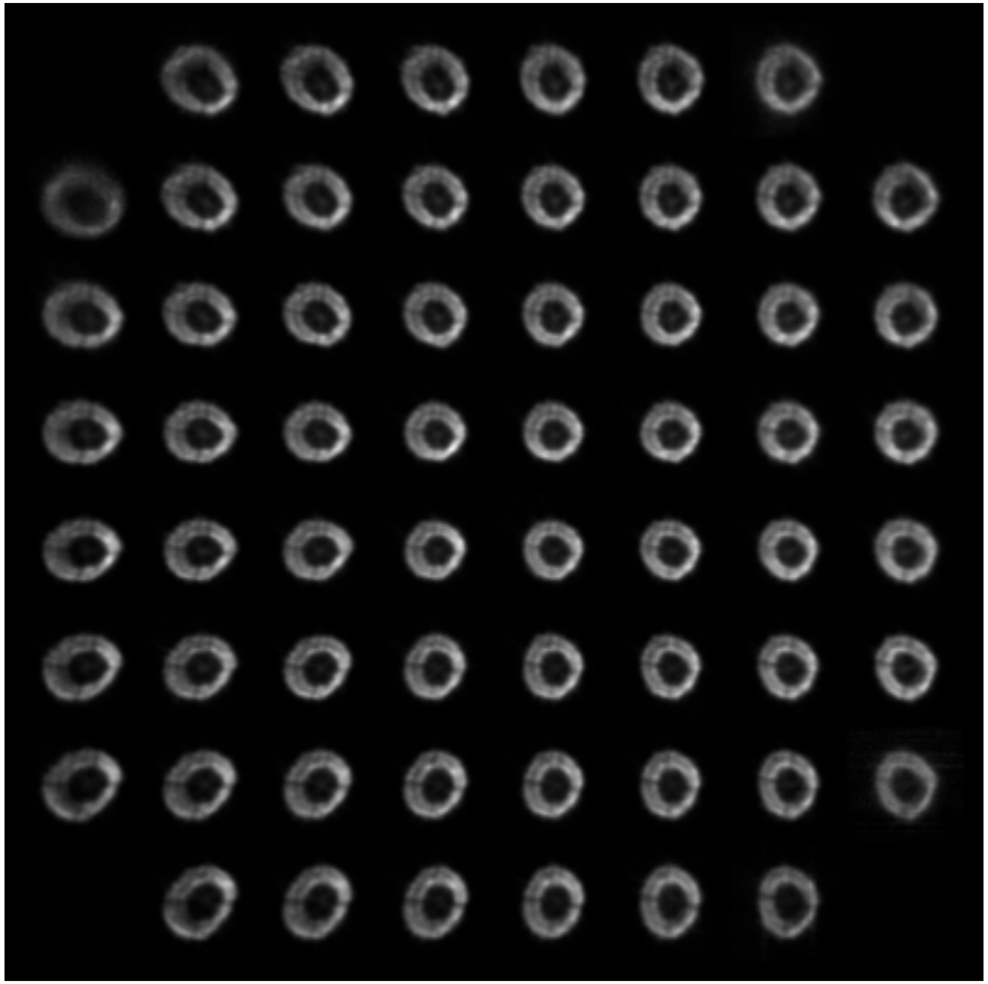


Wavefront-Error Diagnostics

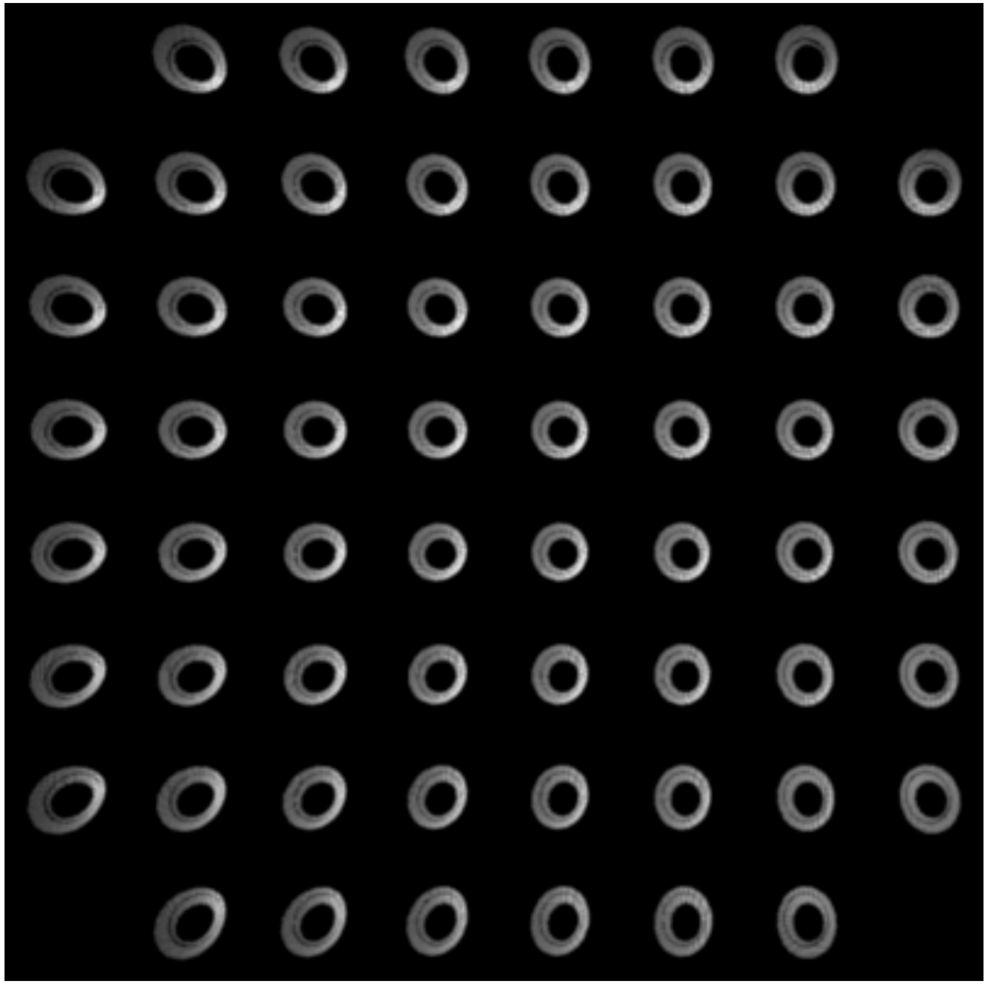
- Many techniques:
  - Shack-Hartmann screens; Hartmann mask; Knife-edge test; Beam-shearing interferometry; Ghost image analysis; Direct metrology; Direct (in-focus) imaging; <u>Out-of focus images</u> (a.k.a “curvatures sensing” or “donut analysis”).
- Advantages of donut analysis



Donut Modeling => Telescope Configuration



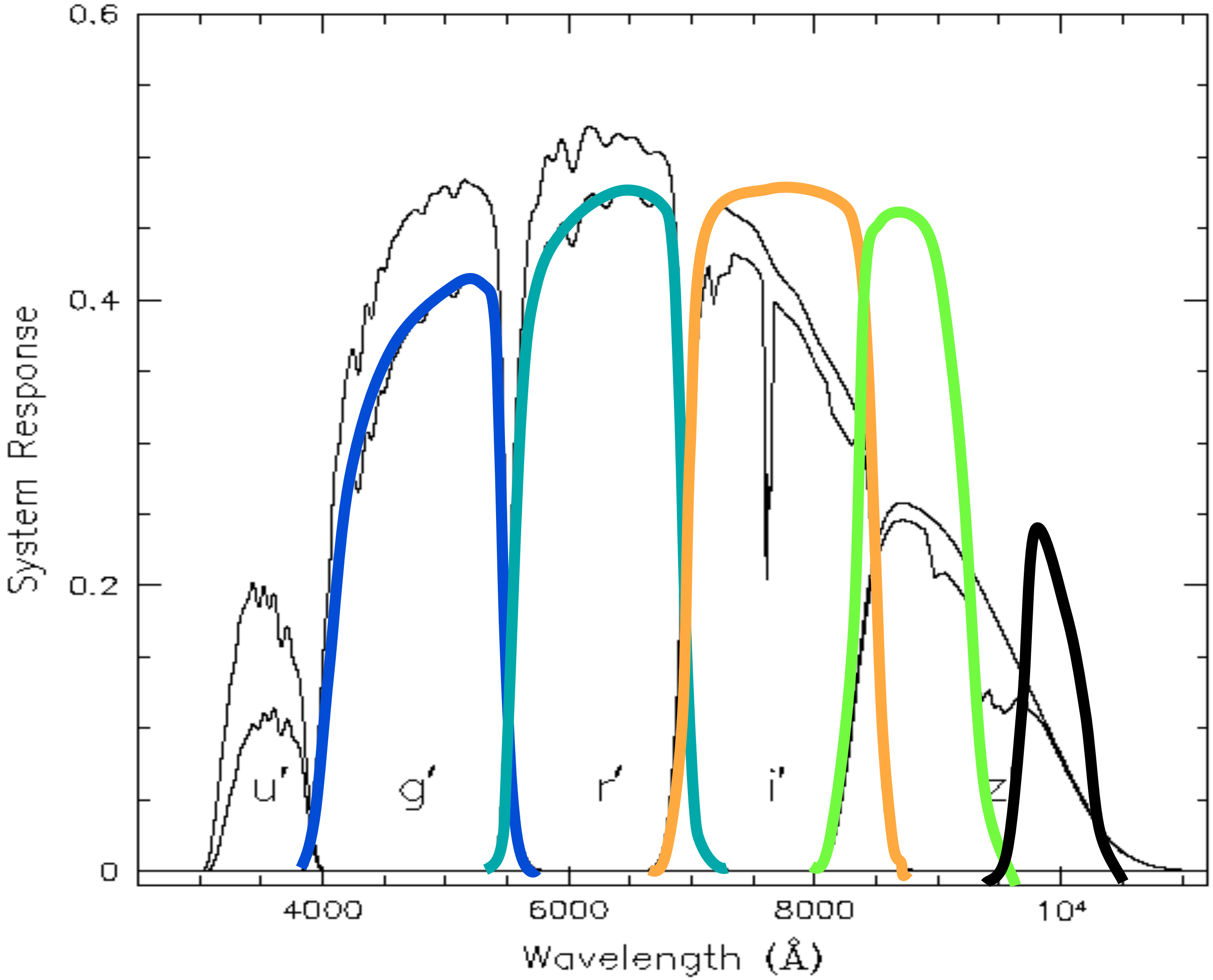
Data



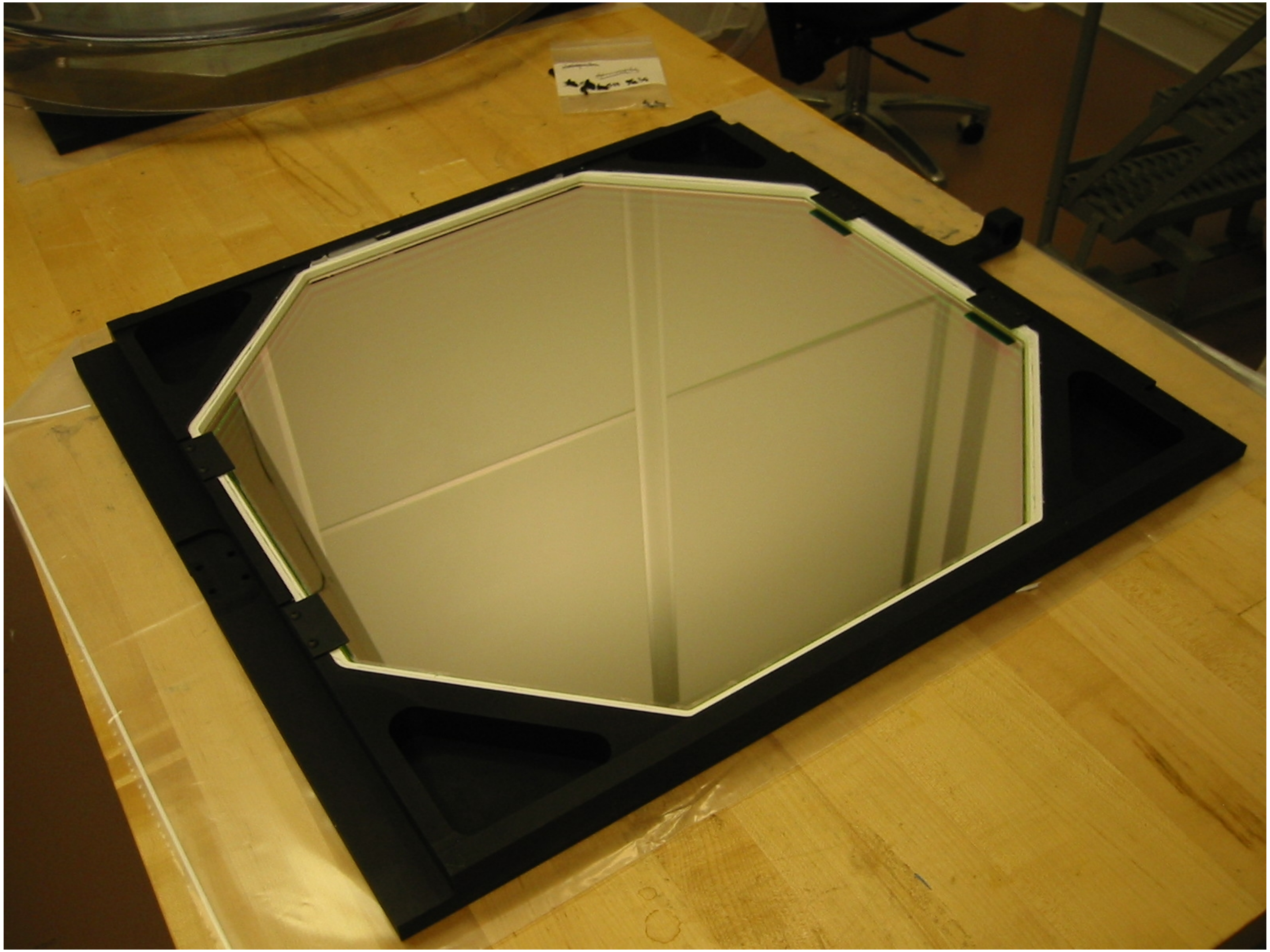
Model

SDSS and Pan-STARRS Bandpasses

Filters closely matched to SDSS - no U-band, but added Y-band at 1 micron with exceptional quantum efficiency

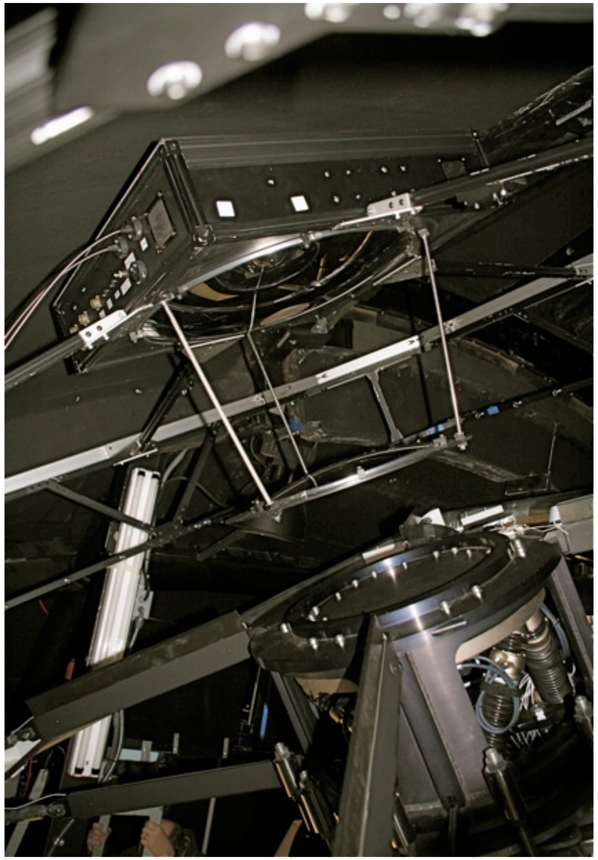


Filter Potted in Frame at UW

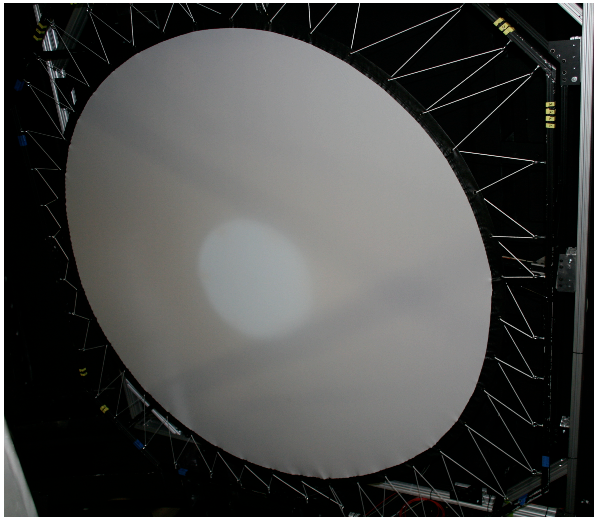


Calibration System Installation at PS1

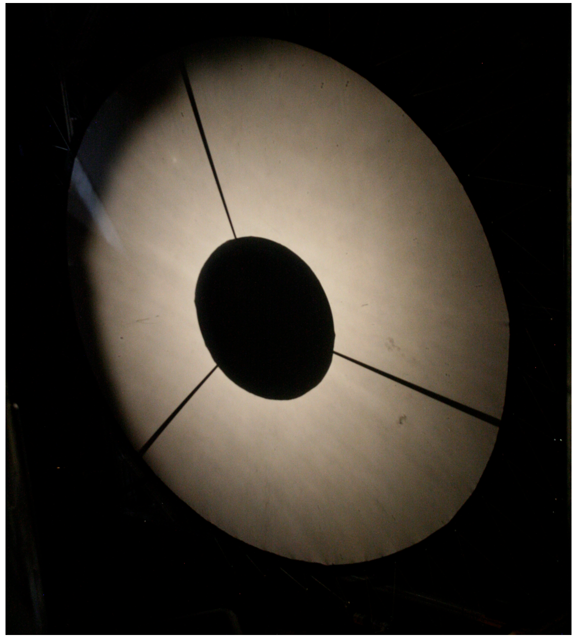
- System operational with white light source and temporary laser source
  - Being used for dome flats
- New laser expected to be installed in June



Frame Assembly



Screen on Frame



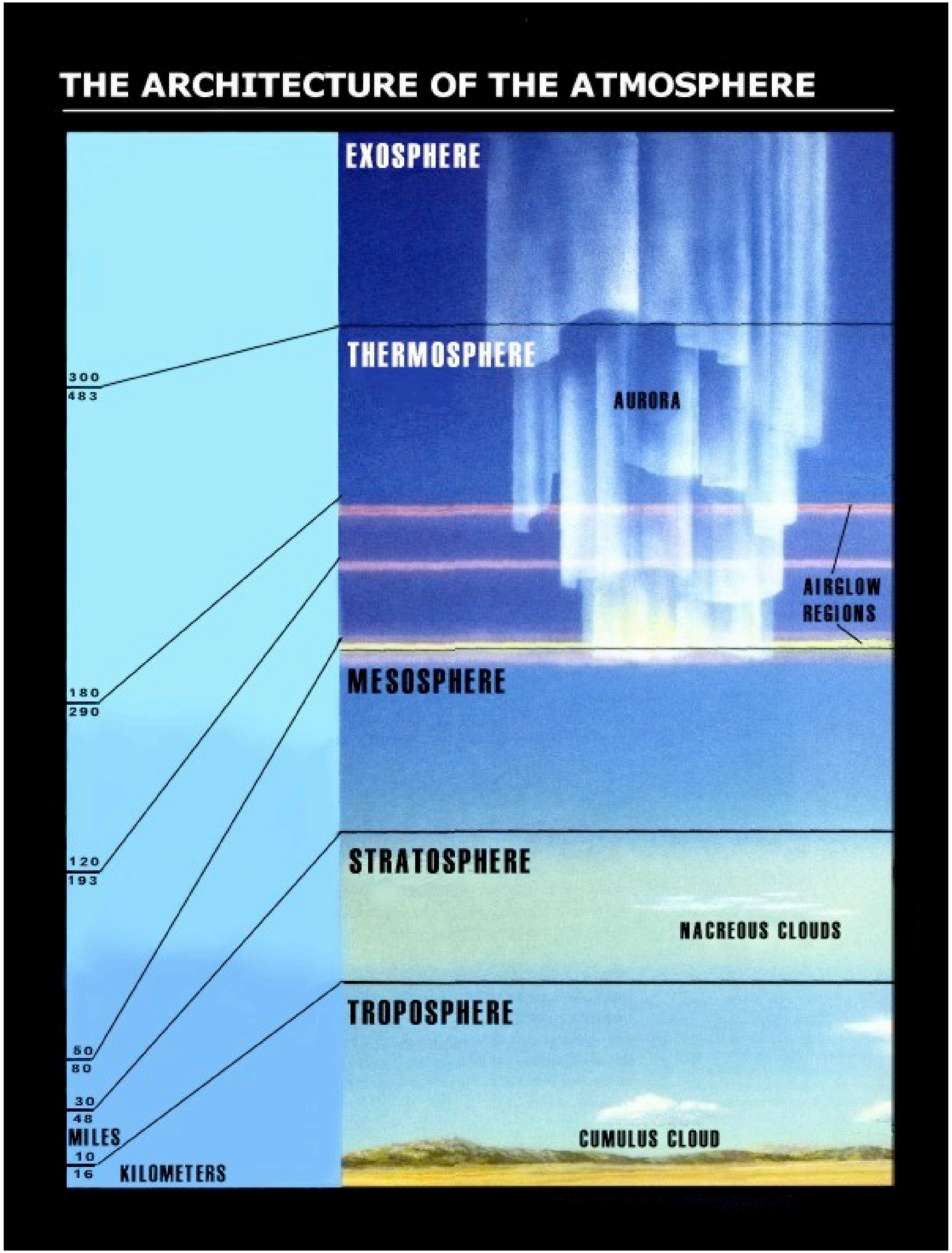
White Light Source Illuminating Screen

spectroscopic sky probe

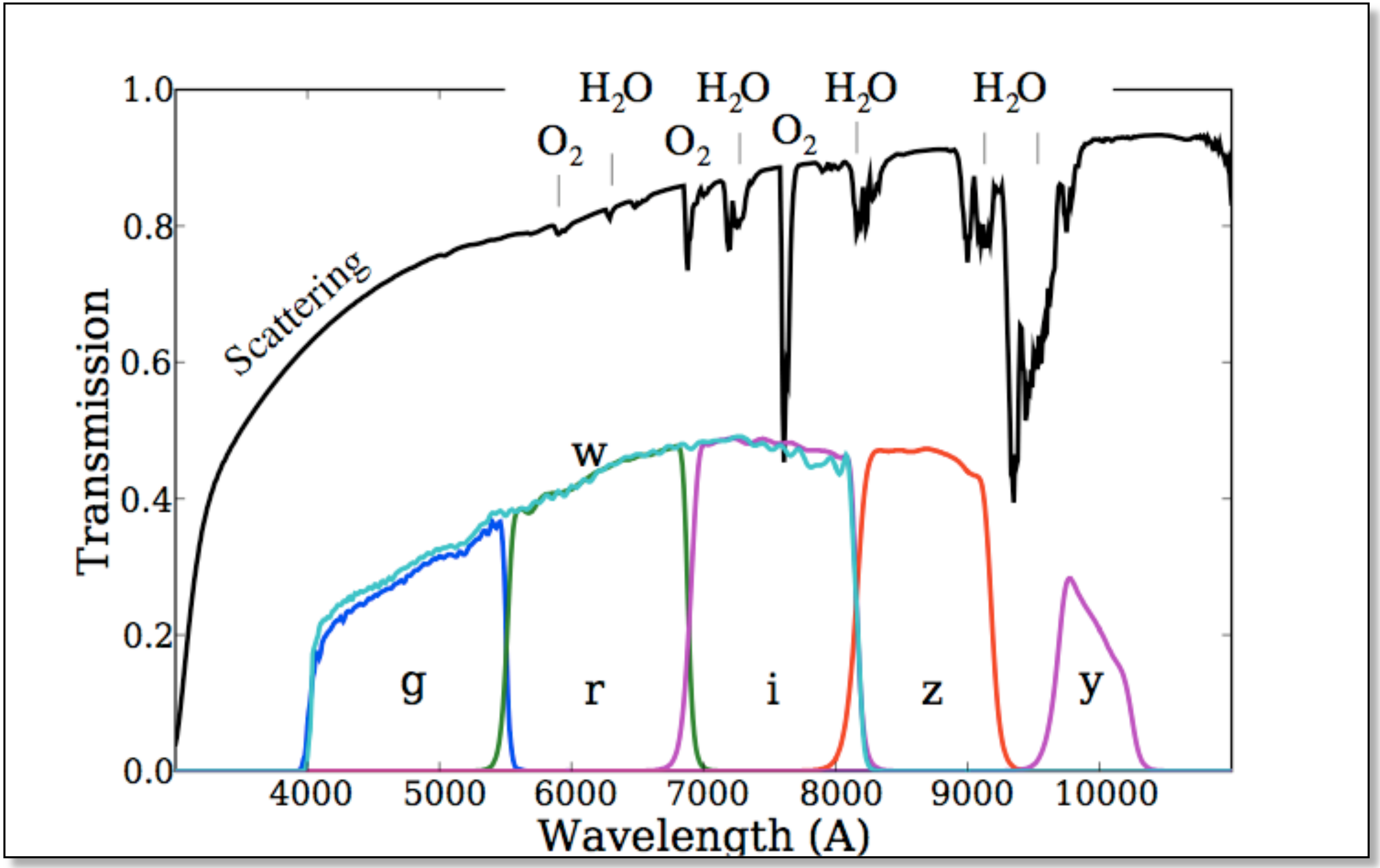
- 3 fiber fed spectrographs
- measure sky emission and stellar continuum
- 16" telescope
- ~30 sec exposures
- targets: F and earlier type stars 9th magnitude
- all-sky bright star spectra catalog

- Measure low-res sky spectra (sky & stars)
- Generate high-res model (MODTRAN)
- Synthesize "fringe frame"

- Not currently implemented

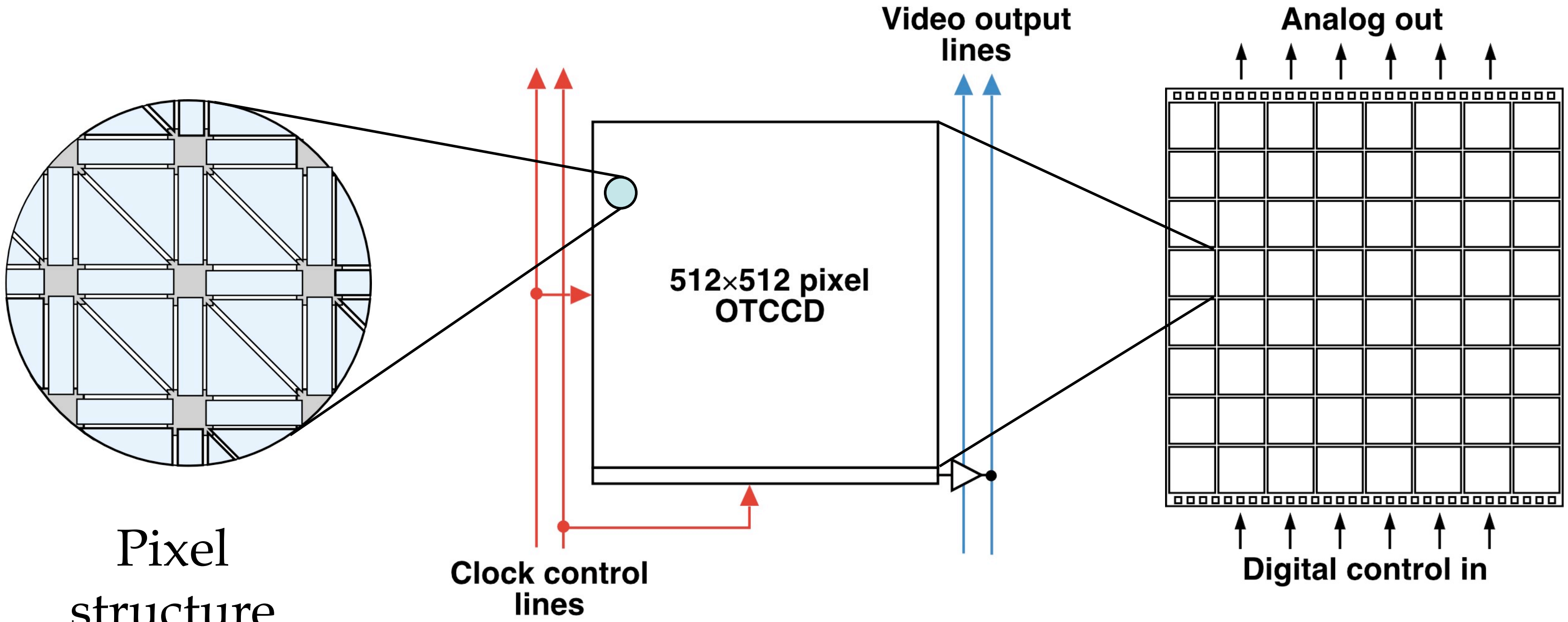


Spectroscopic sky probe can provide accurate calibration of absorption of atmposphere and subtraction of air-glow



Orthogonal Transfer Array

- A new paradigm in large imagers.
- Partition a conventional large-area CCD imager into an array of independently addressable CCDs (cells).
- Massively parallel design allows rapid read-out -> rapid sky coverage



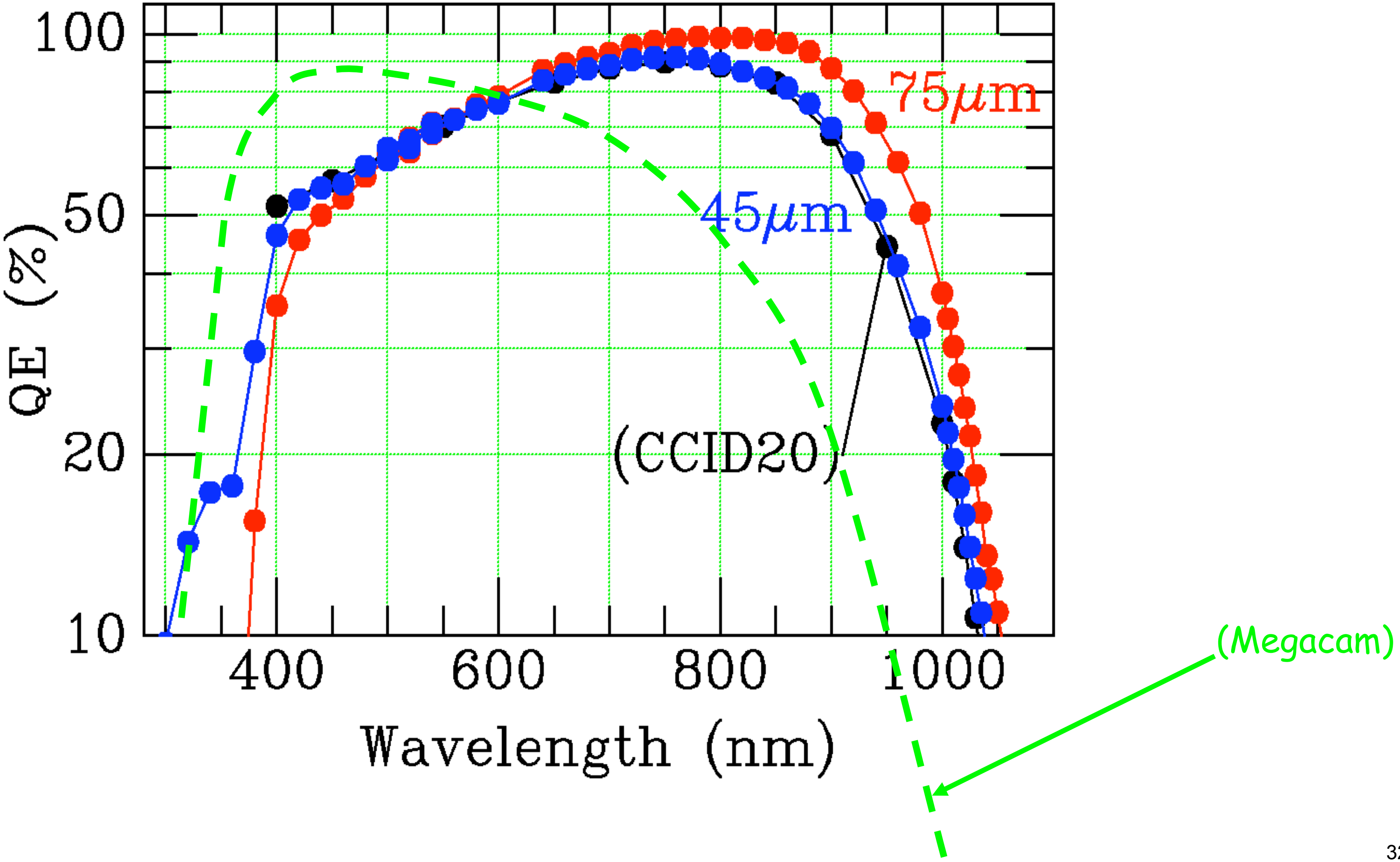
Pixel structure

Independently Addressable Cell

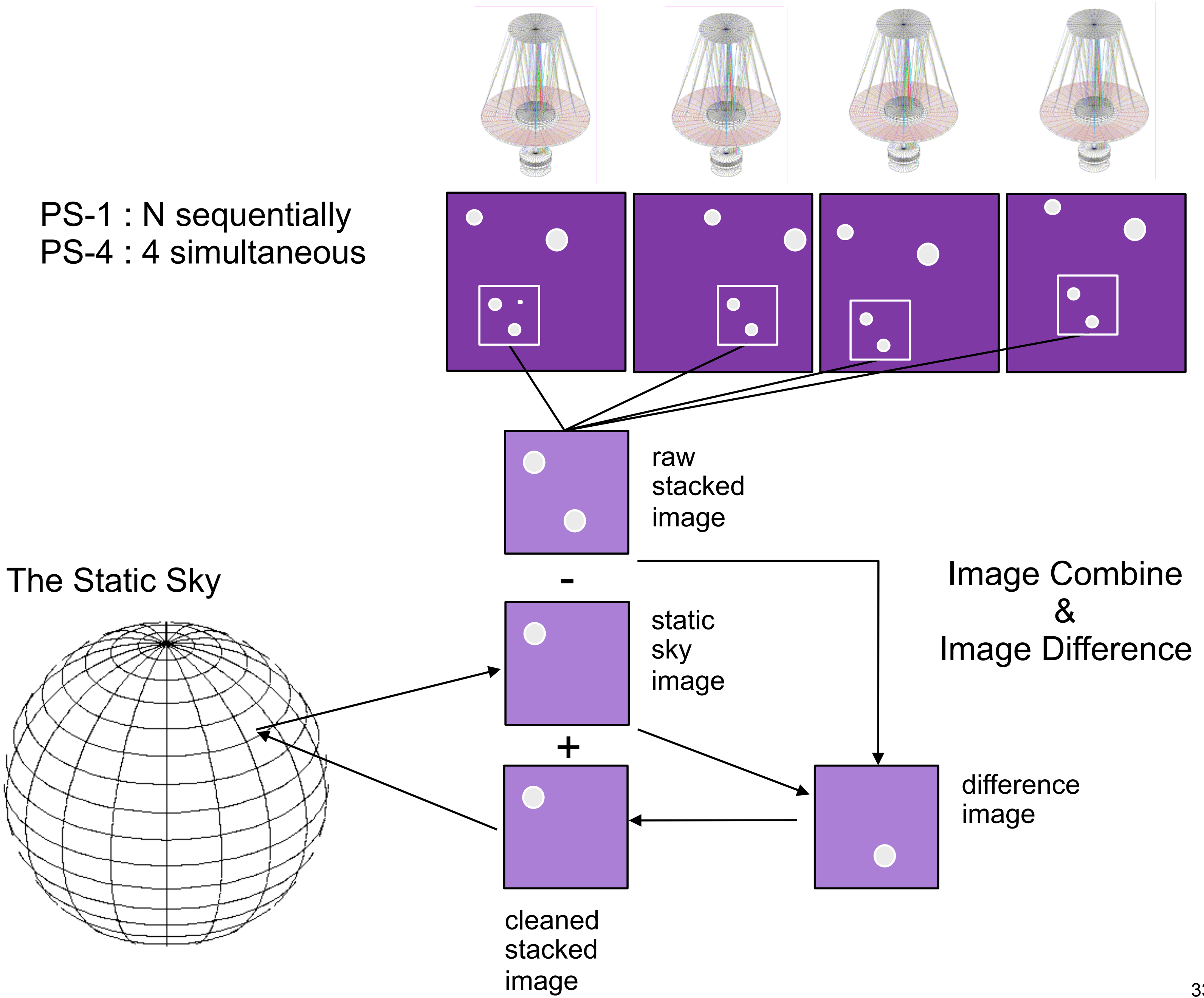
OTA: 8x8 Array of Cells

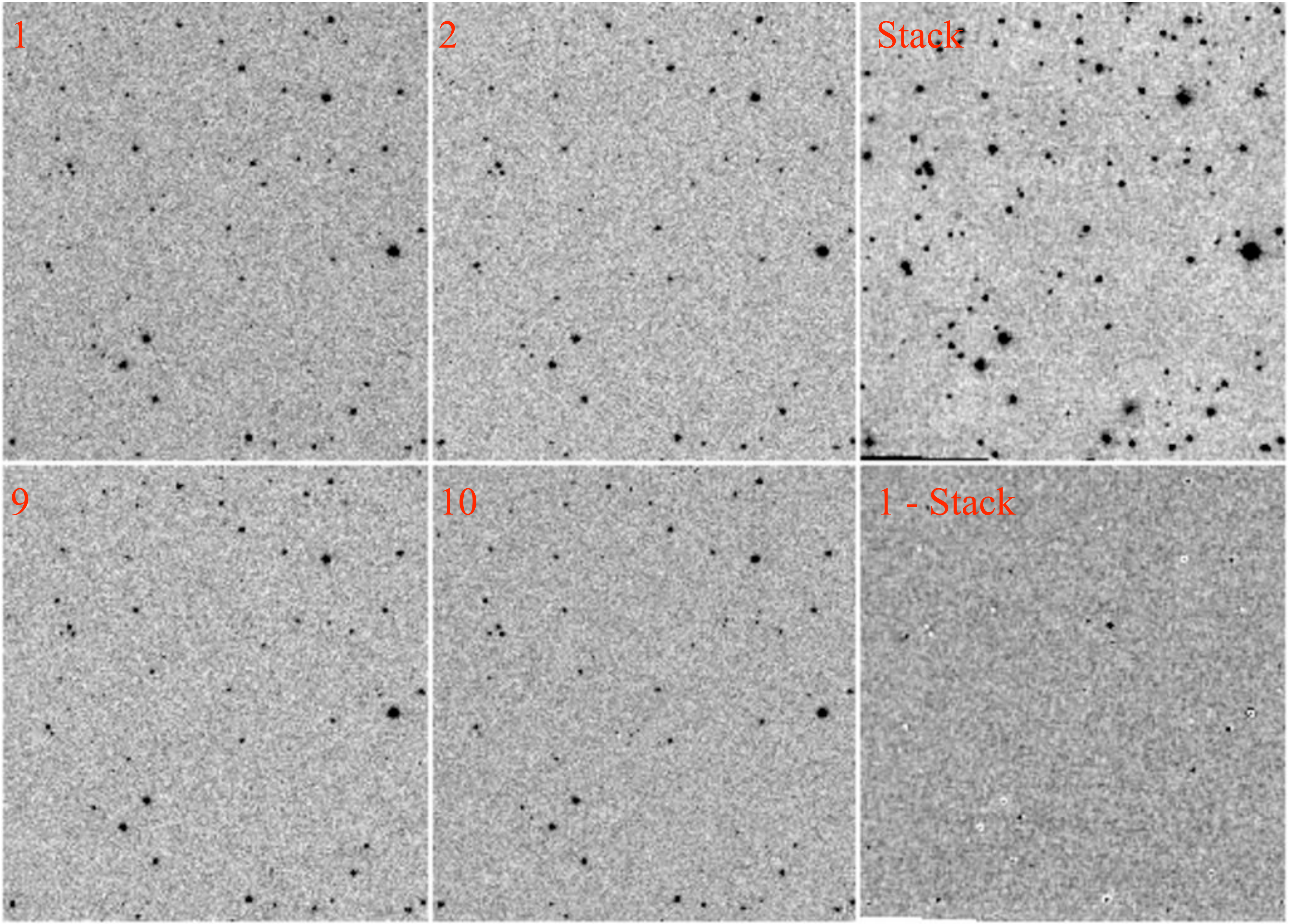
OTA Quantum Efficiency

- OTAs demonstrate expected QE (-65ºC)
  - 70um thick devices have exceptional QE at 1um

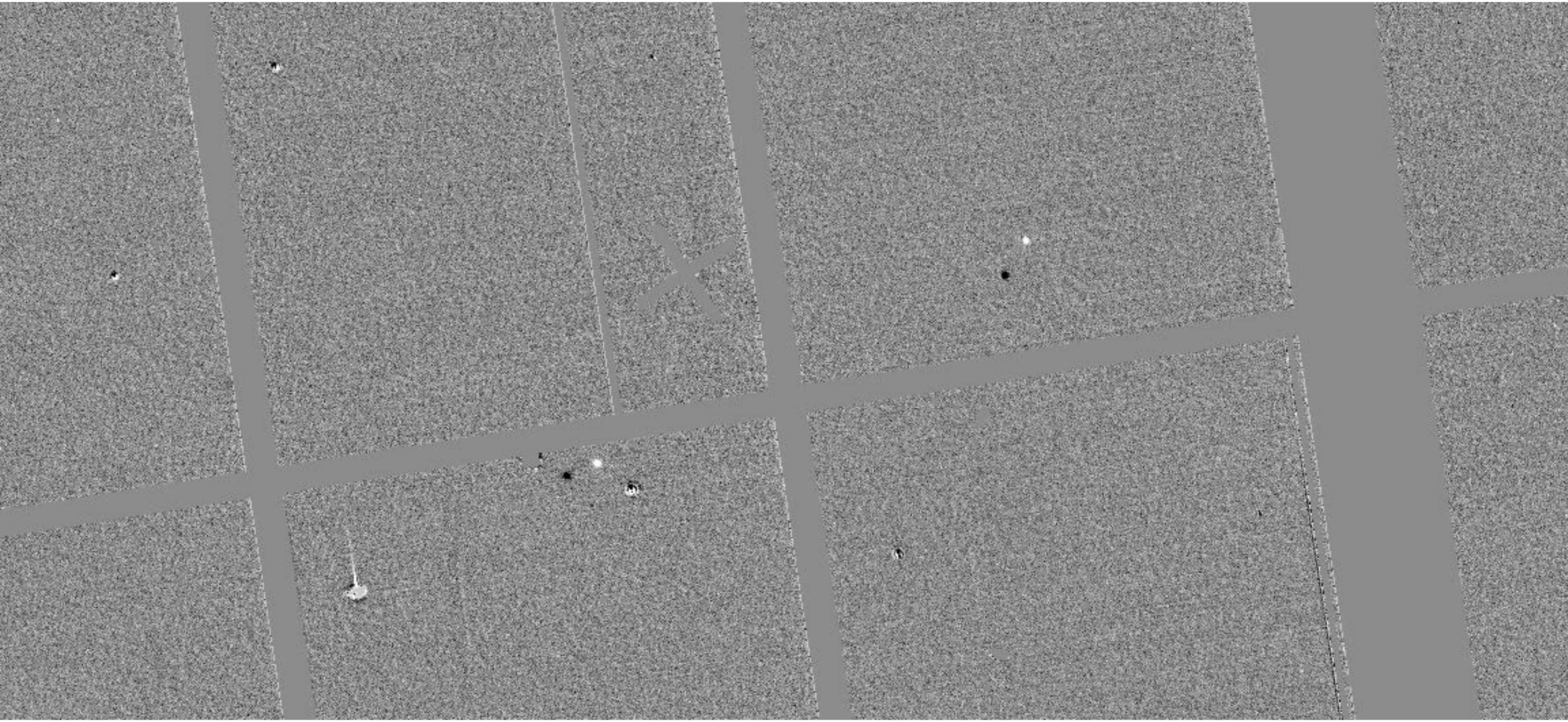


IPP: Real-Time Image Analysis

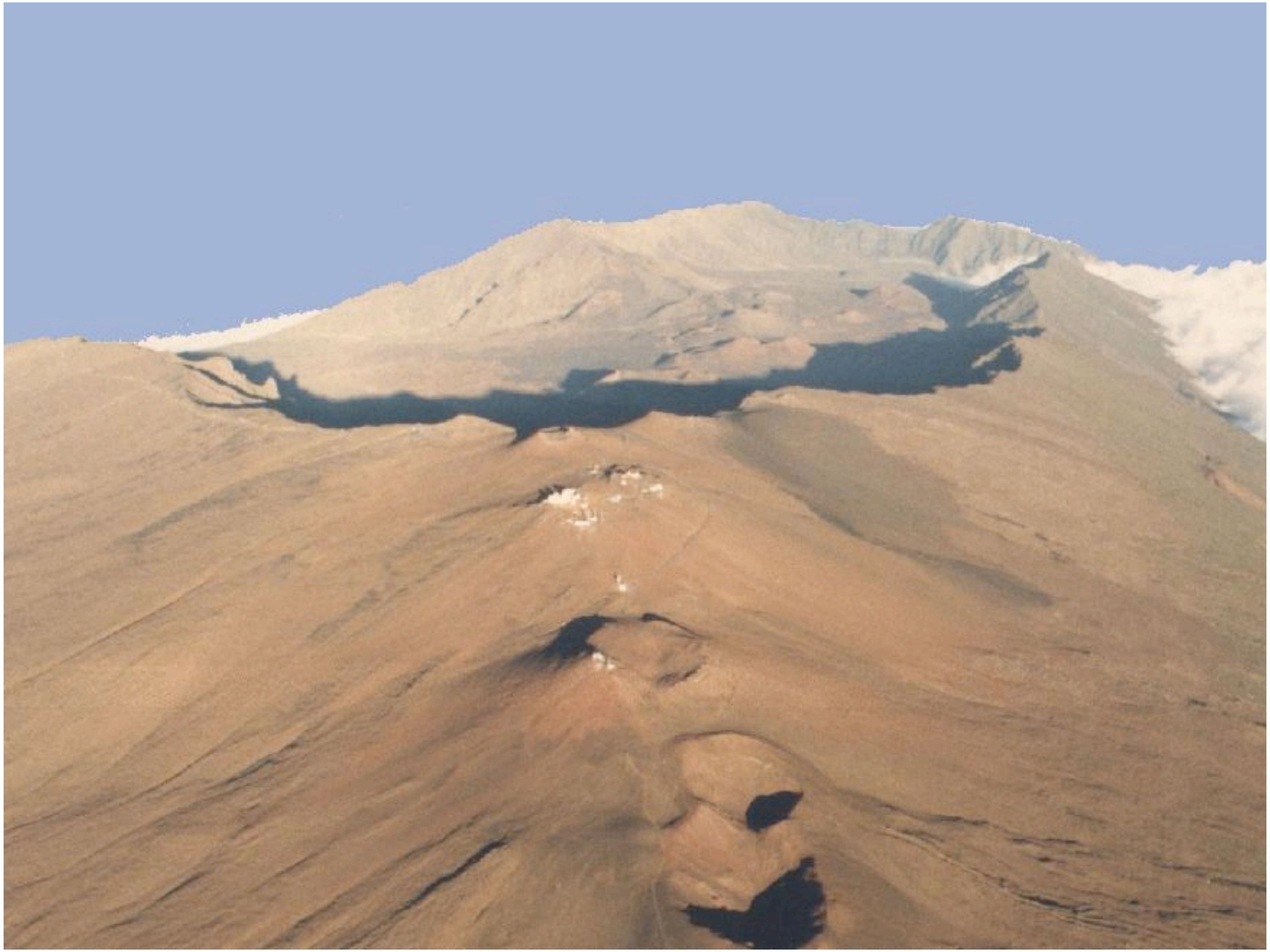




1
2
Stack
9
10
1 - Stack



Haleakala Observatories, Maui, HI



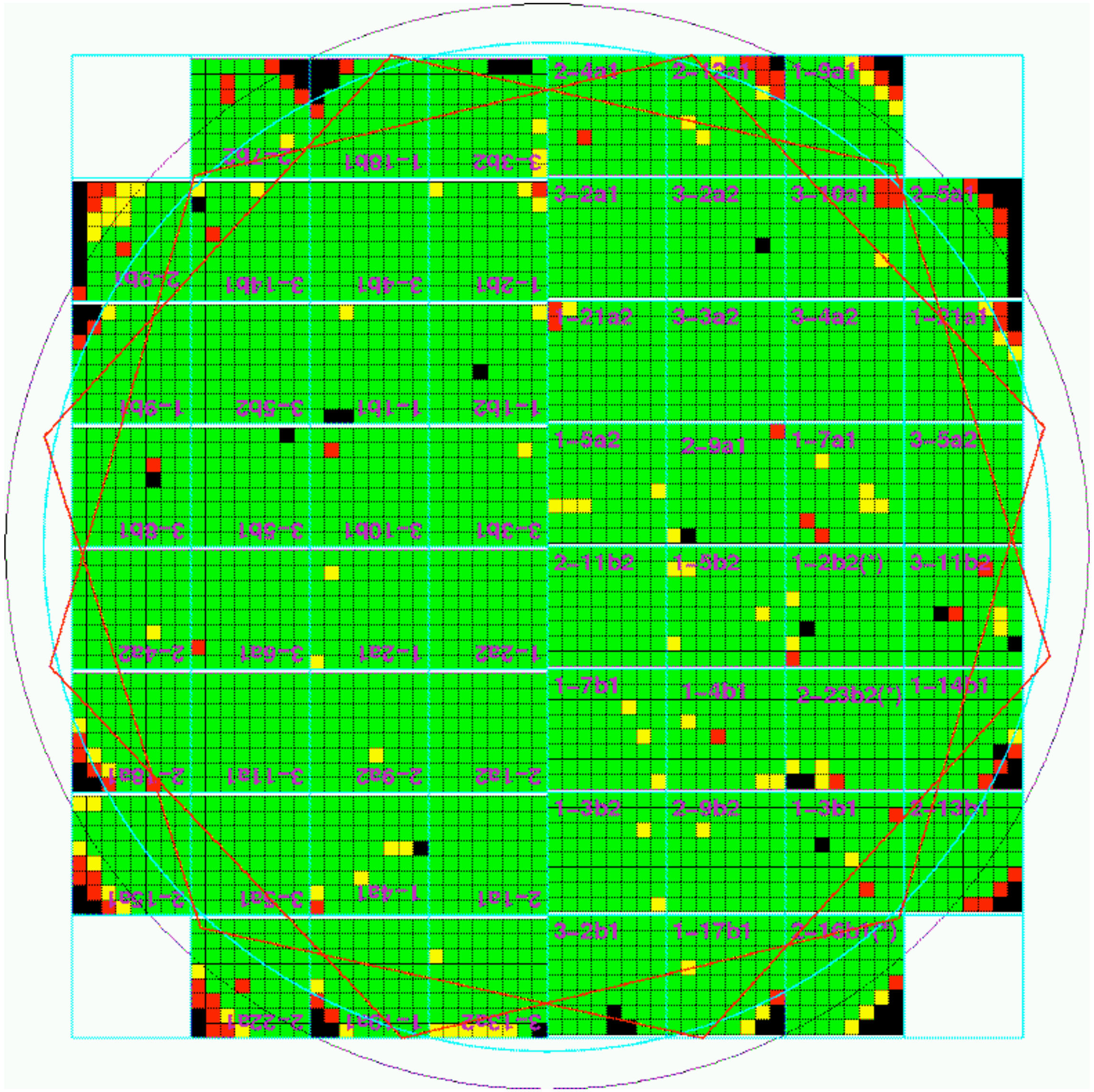
PS1 Surveys

Table 2: *The PS1 Mission Concept Surveys and time distribution.*

PS1 Surveys	Filters	Percent time
3 π Steradian Survey	g, r, i, z, y	56
Calibration Fields	g, r, i, z, y	2
Medium Deep Survey	g, r, i, z, y	25
Solar System "Sweet Spot" Survey	r	5
Stellar Transit Survey -"PanPlanets"	i	4
Microlensing in M31 "Pandromeda" Survey	g, r, i, z, y	2
Principal Investigator Discretionary Time		6

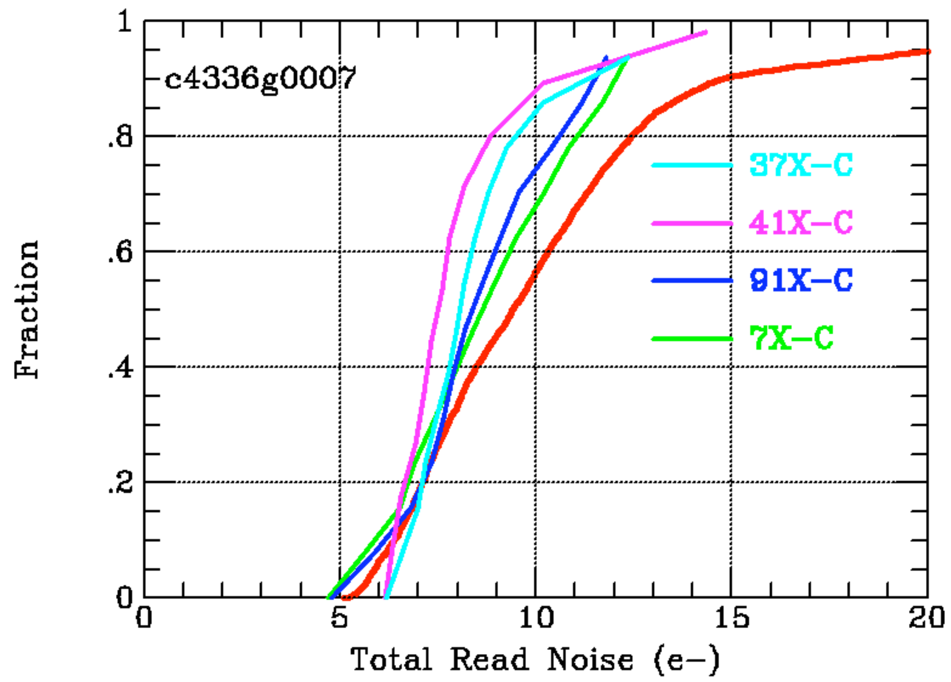
GPC1 Cell Status (post-refurb)

- Cell colors
  - Black = useless
  - Red = probably useless
  - Yellow = probably useful
  - Green = OK
- Cyan circle = 3º
  - 1.7% loss
- Black circle = 3.3º
  - 3.4% loss
- Red = hexagonal sky tesselations



Read Noise Distribution (Nov 2007)

N.B. This is total noise including 1W/m² RFI. Expect to achieve about 6e- with CCID58, 4e- with CCID64



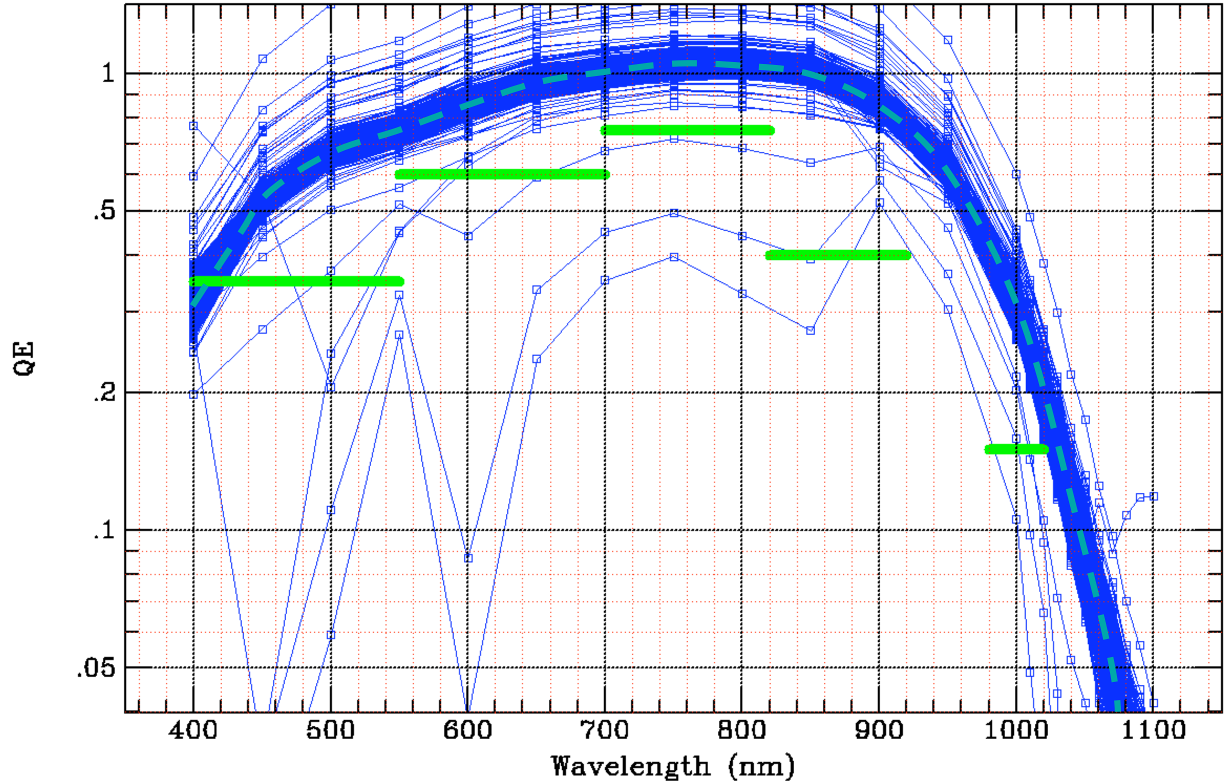
Filter	m1 (mag)	sky (mag/")	sky (e/pix/s)	3pi exp (sec)	3pi sky (e/pix)	MD exp (sec)	MD sky (e/pix)
g	24.90	21.90	1.1	60	63	240	253
r	25.15	20.86	3.5	38	132	240	831
I	25.00	20.15	5.8	30	174	240	1391
z	24.63	19.26	9.4	30	281	240	2246
y	23.03	17.98	7.0	30	209	240	1673

4336 = 07-08-24

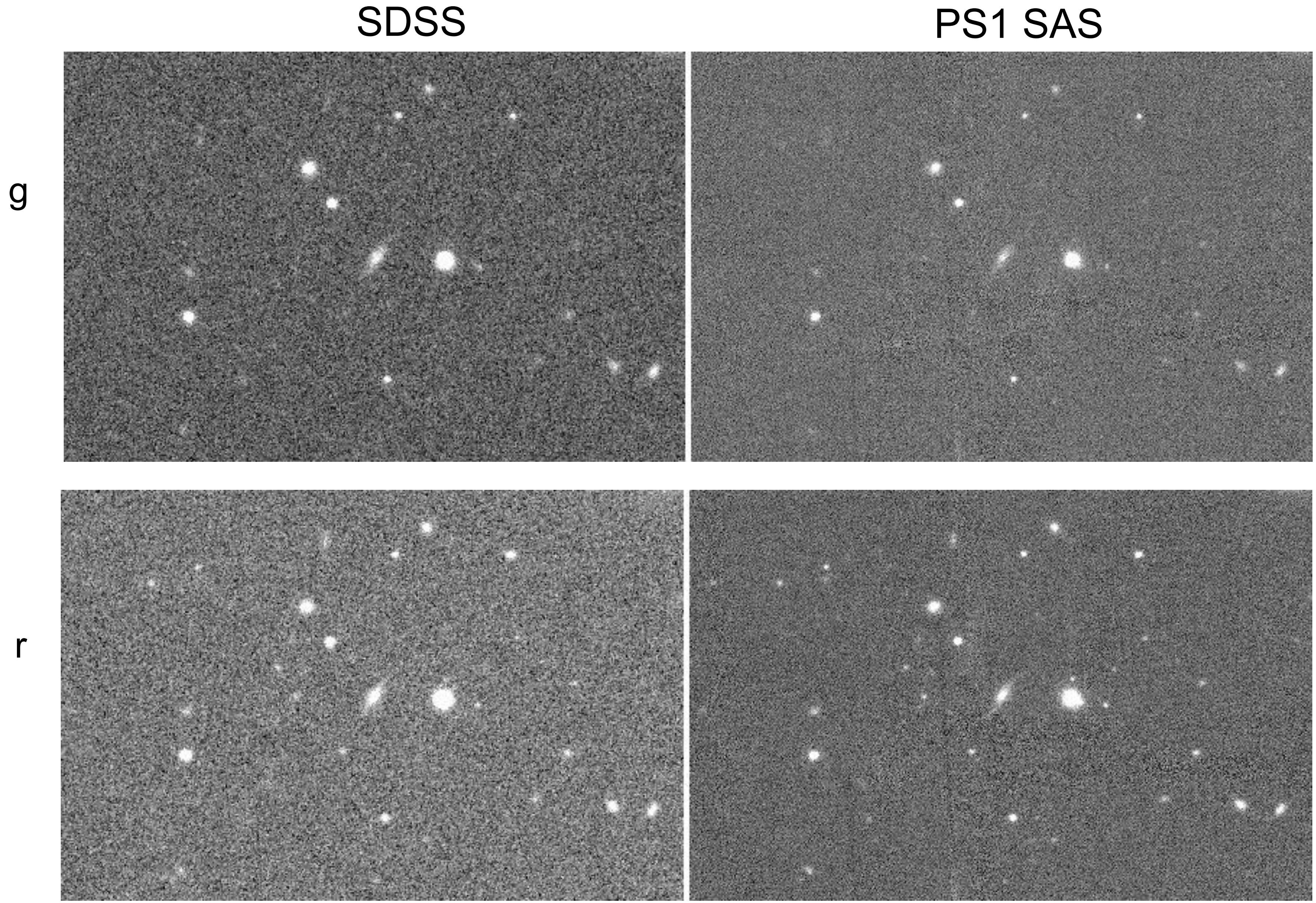
Detectors and Controller: QE

- **3.3.3.10**: QE > 35% 402-552nm
- **3.3.3.11**: QE > 60% 552-691nm
- **3.3.3.12**: QE > 75% 691-818nm
- **3.3.3.13**: QE > 40% 818-922nm
- **3.3.3.14**: QE > 15% at 1μm

3840 QE curves,
QE(750nm) =
1.017 +/- 0.028



PS1 Demo Month – SAS "3 year" Results

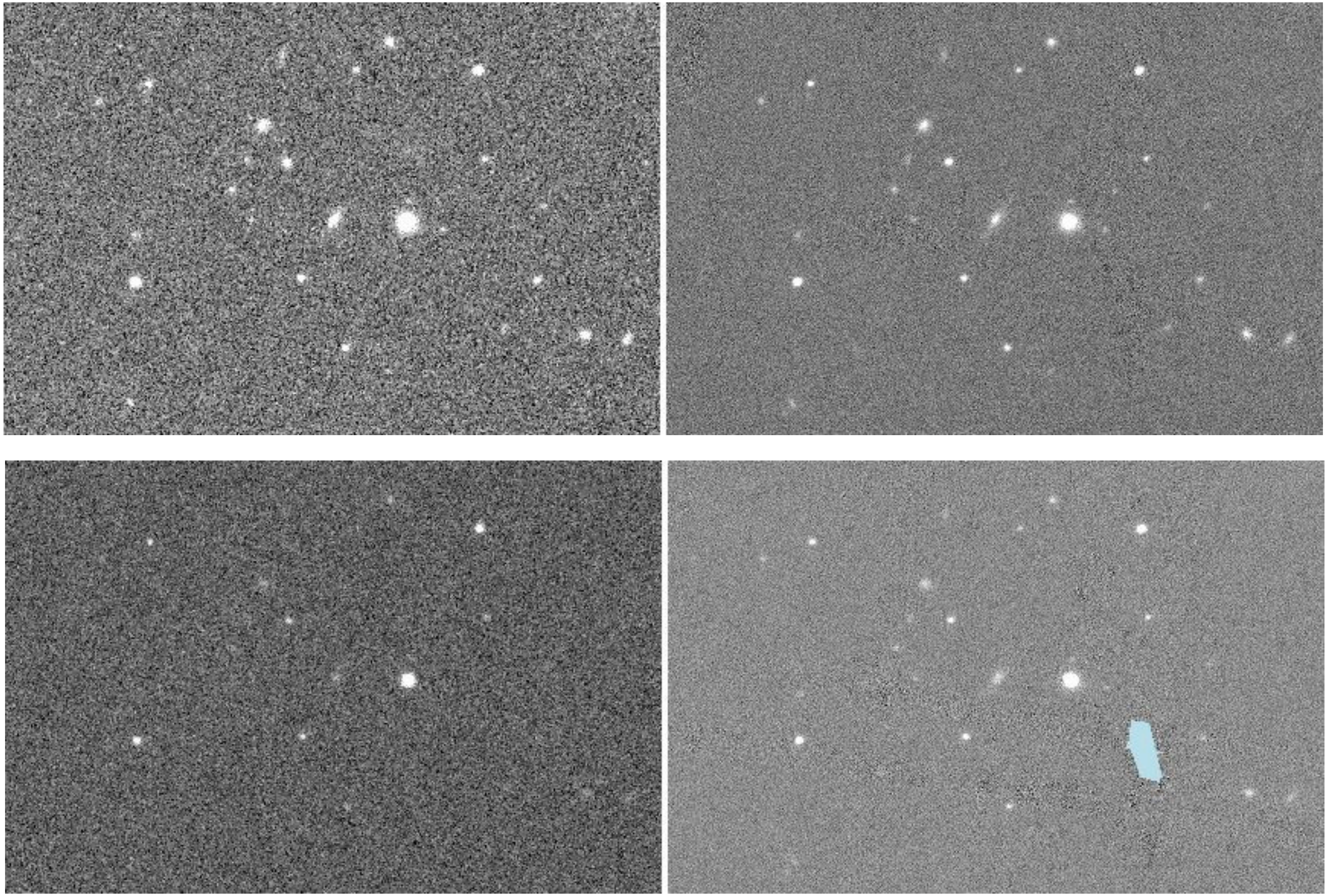


PS1 Demo Month – SAS "3 year" Results

SDSS | PS1 SAS

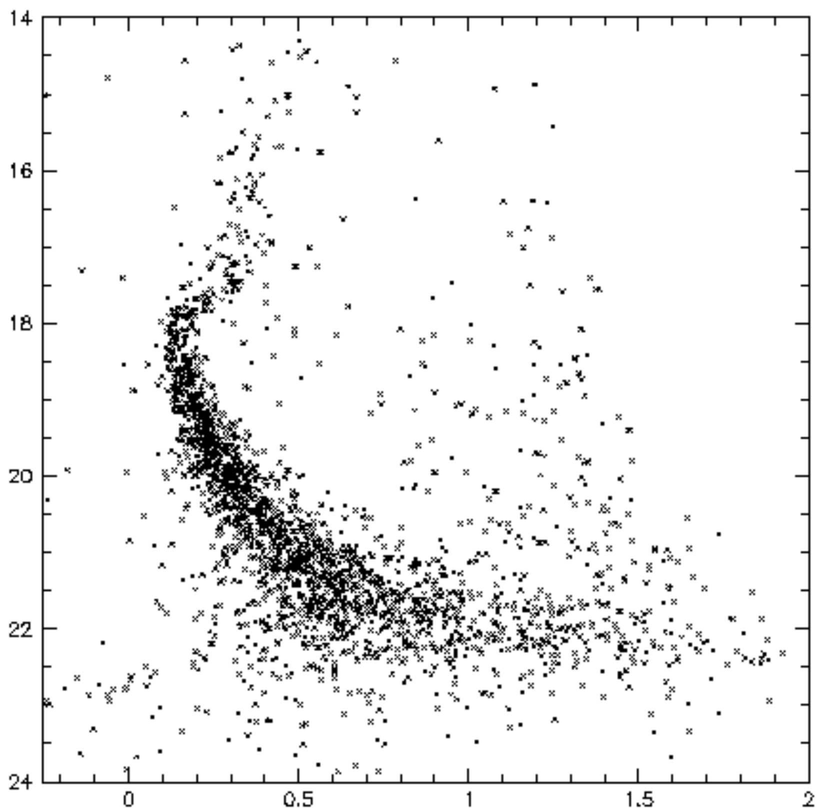
i

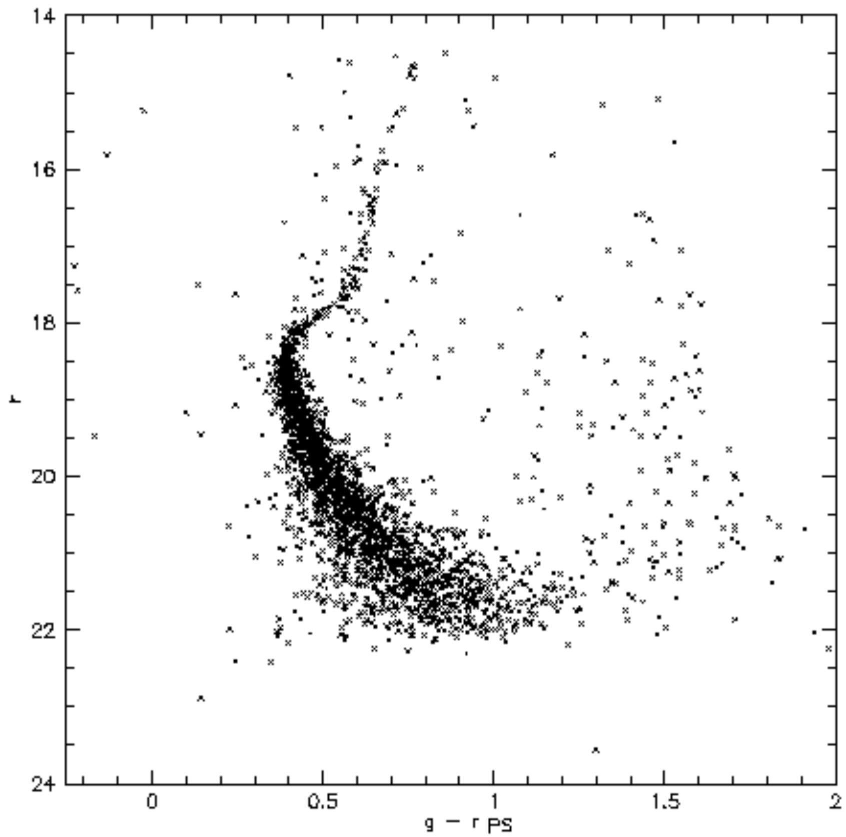
z



Comparison of SDSS photometry with PSPhot

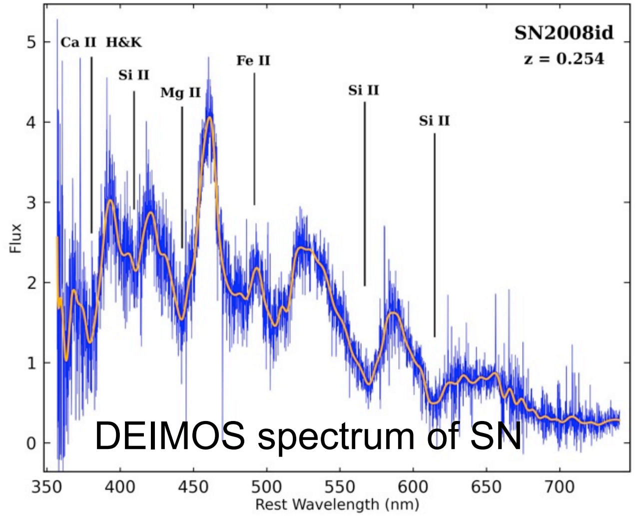
- R. Lupton (SDSS) has used PSPhot to perform photometry in the galactic plane.
- Color-magnitude diagram from M13 are shown (r vs g-r).
- left: SDSS Photo, right: PSPhot

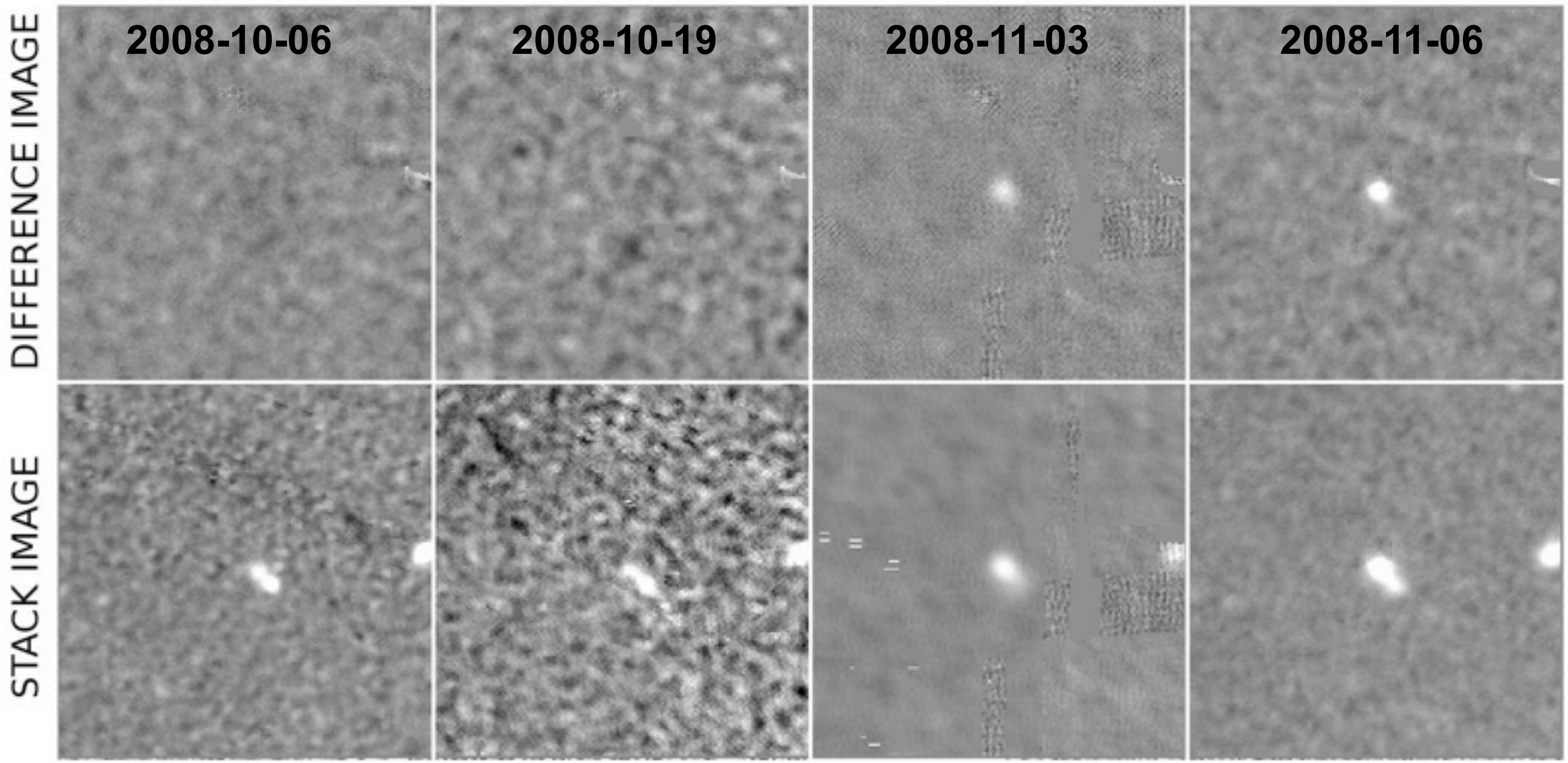




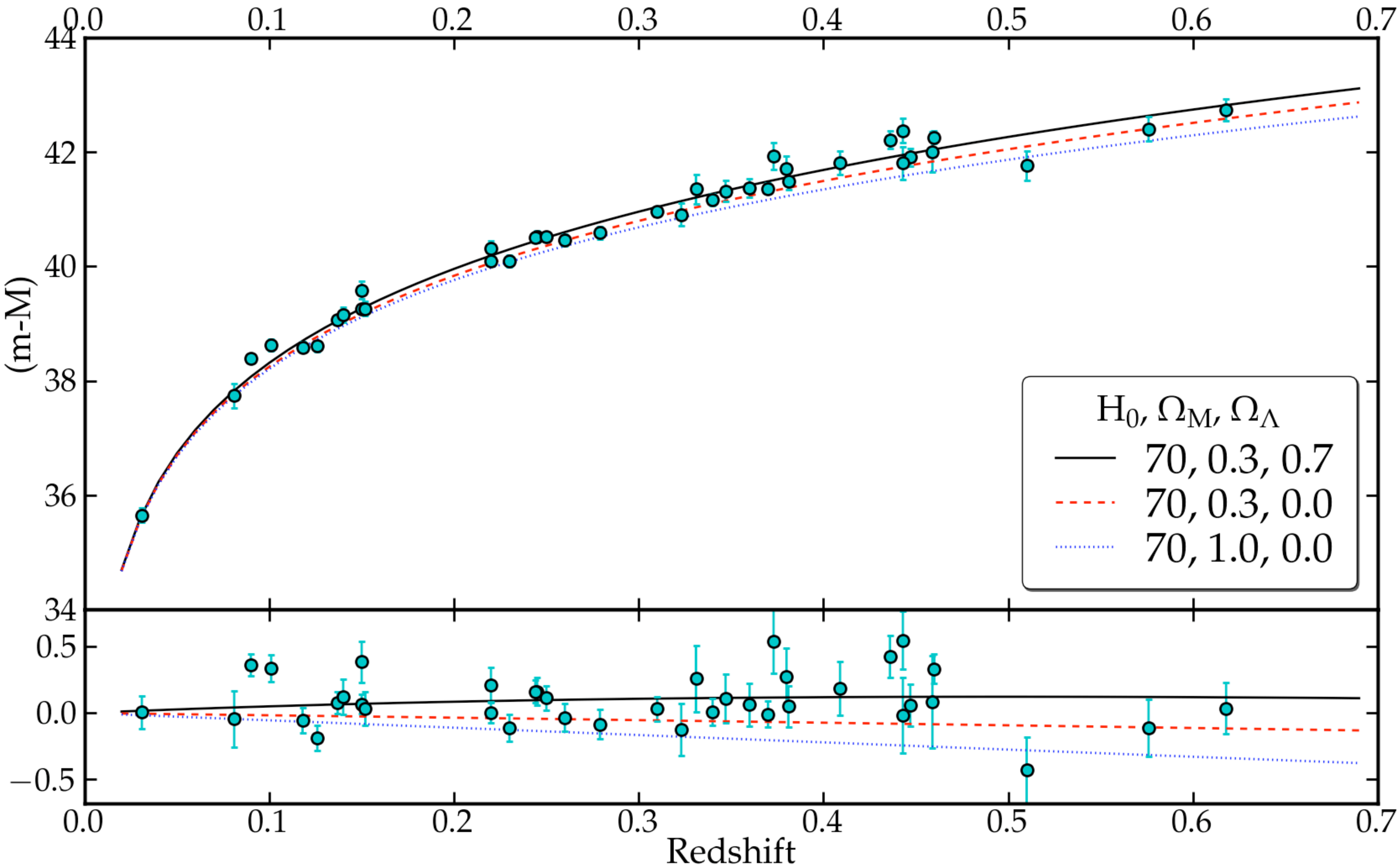
PS1 Discovers Its First Confirmed Type Ia SN: SN2008id (from Run 2)

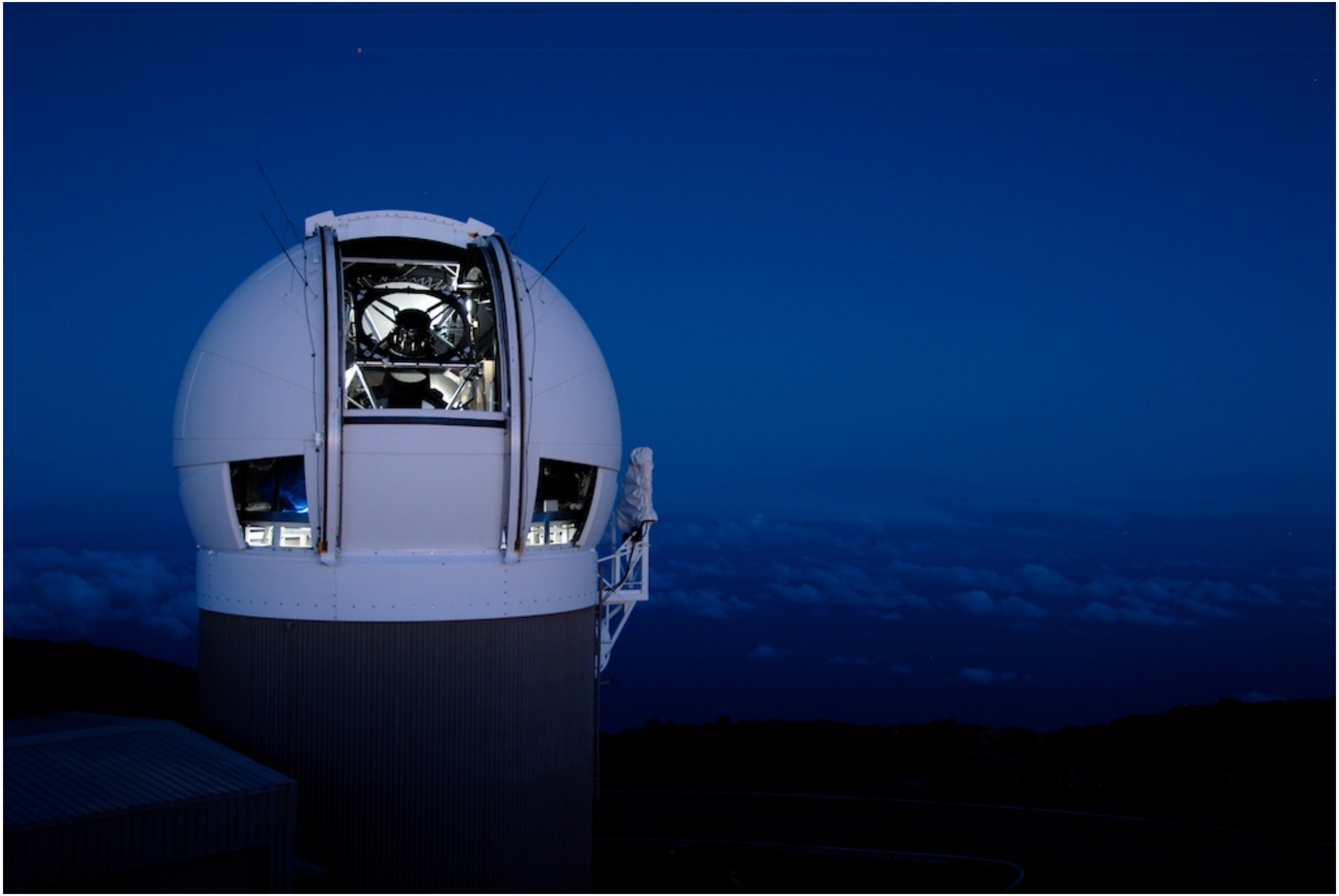
Note: Several more found in Run 3 (Summer 2009)

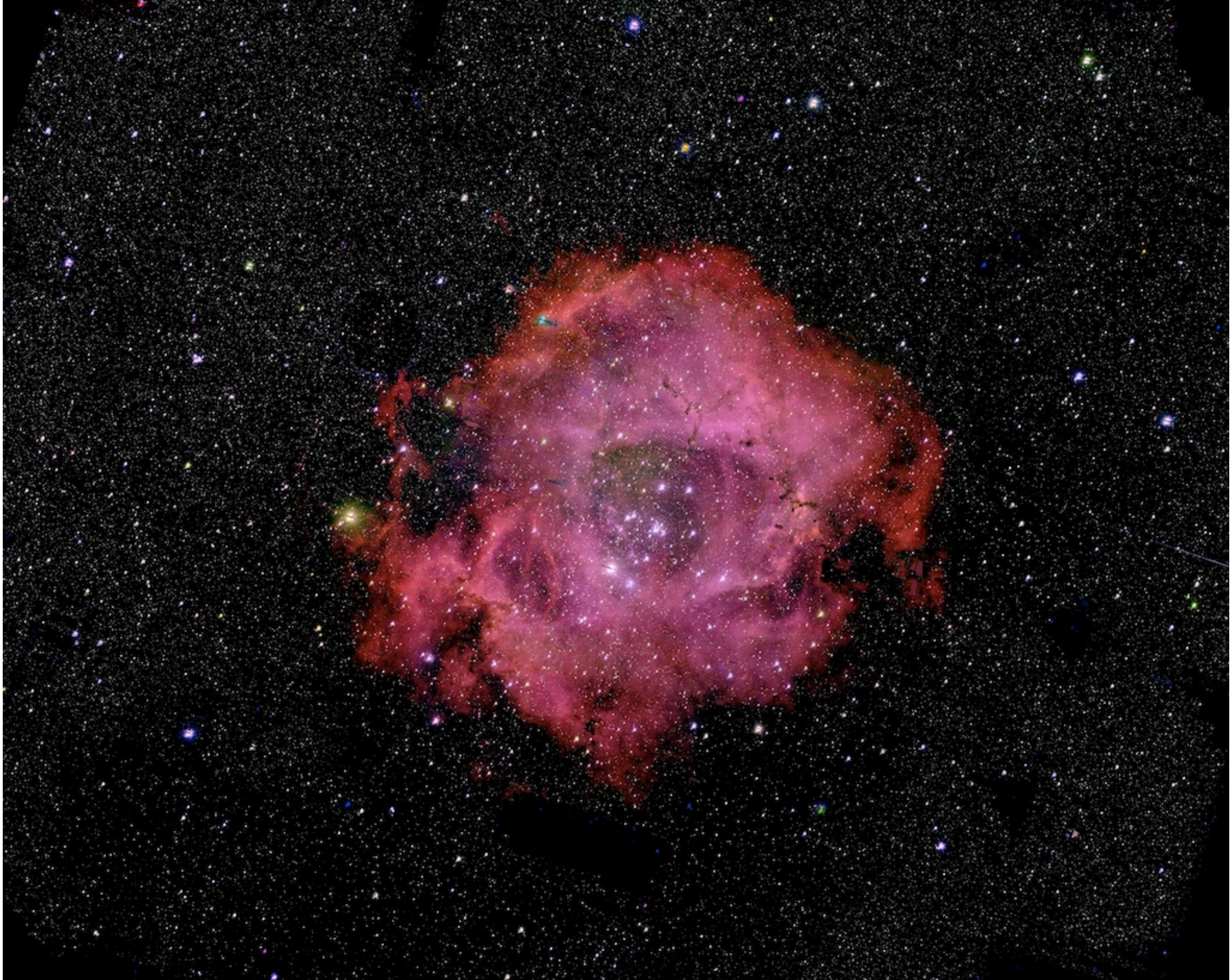




PS1 SN1a Hubble Diagram

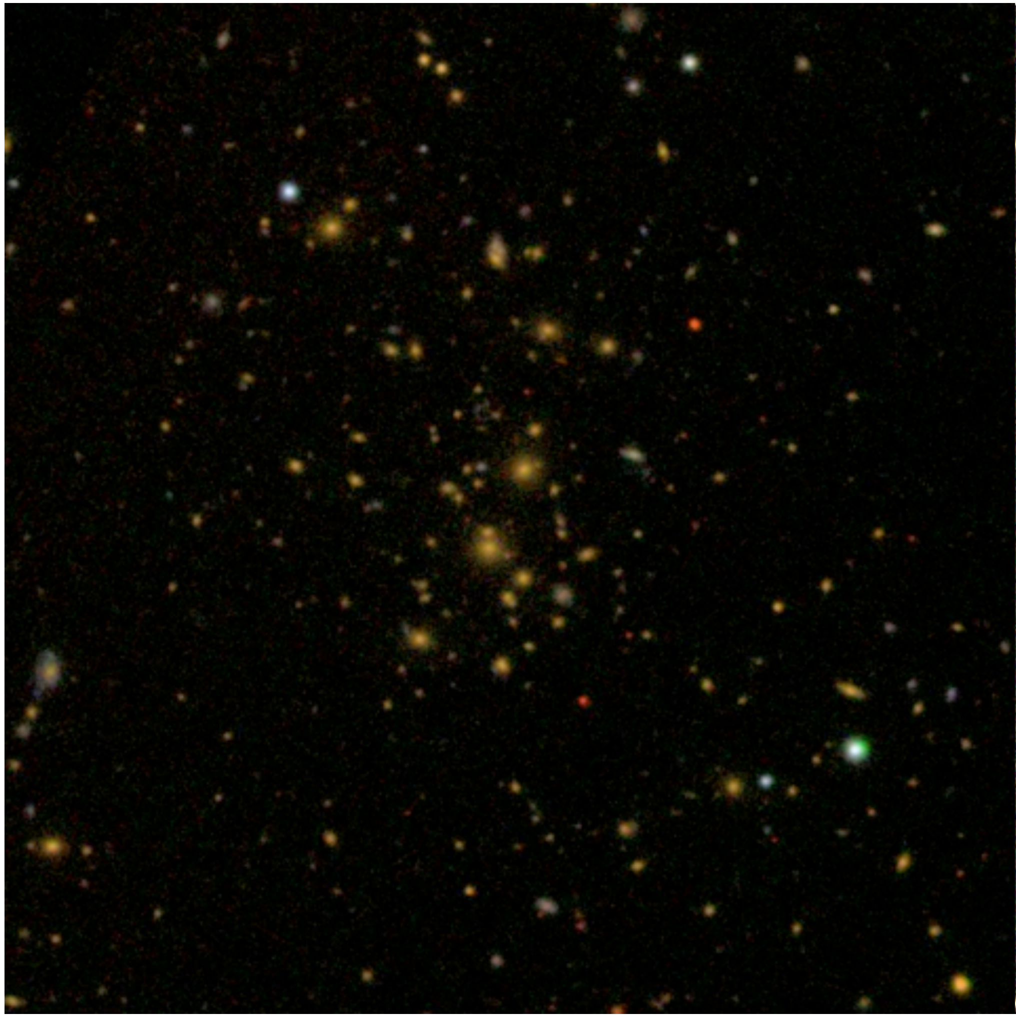




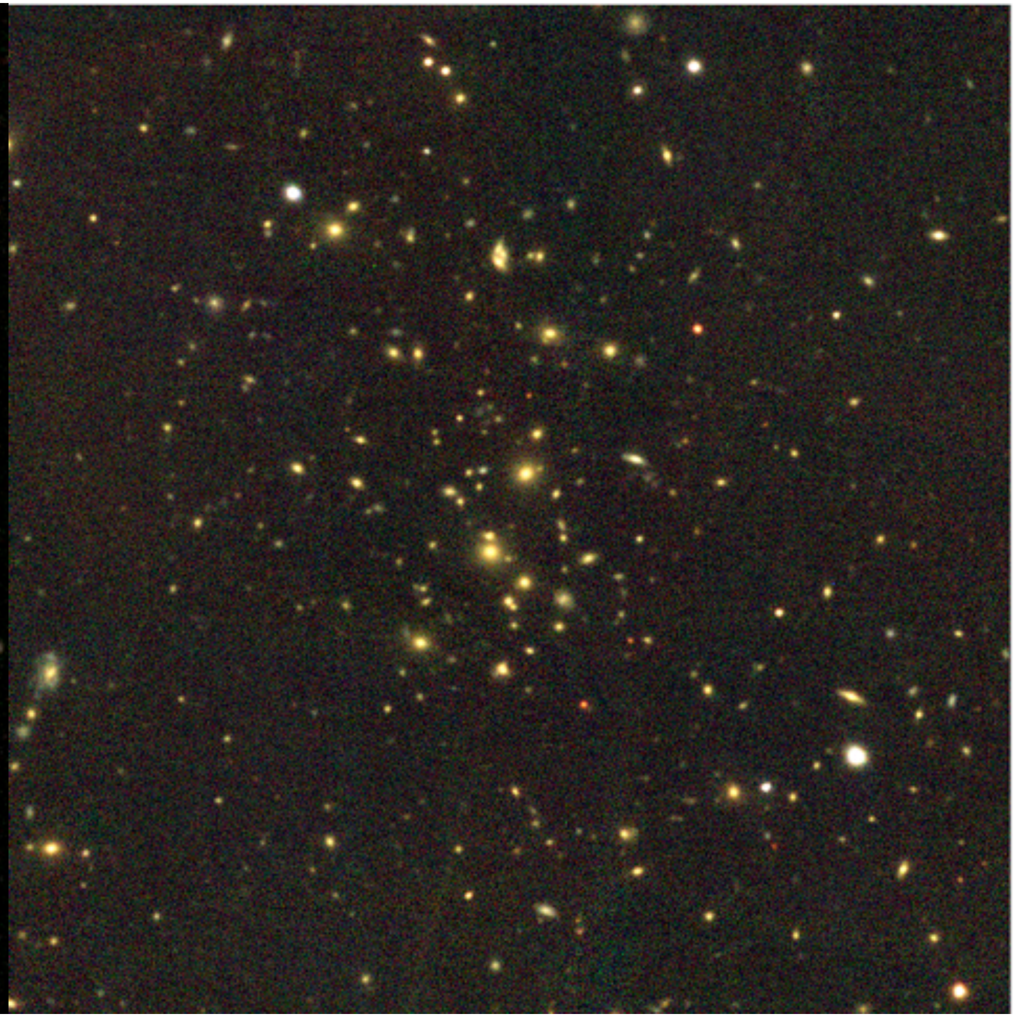


A800

SDSS

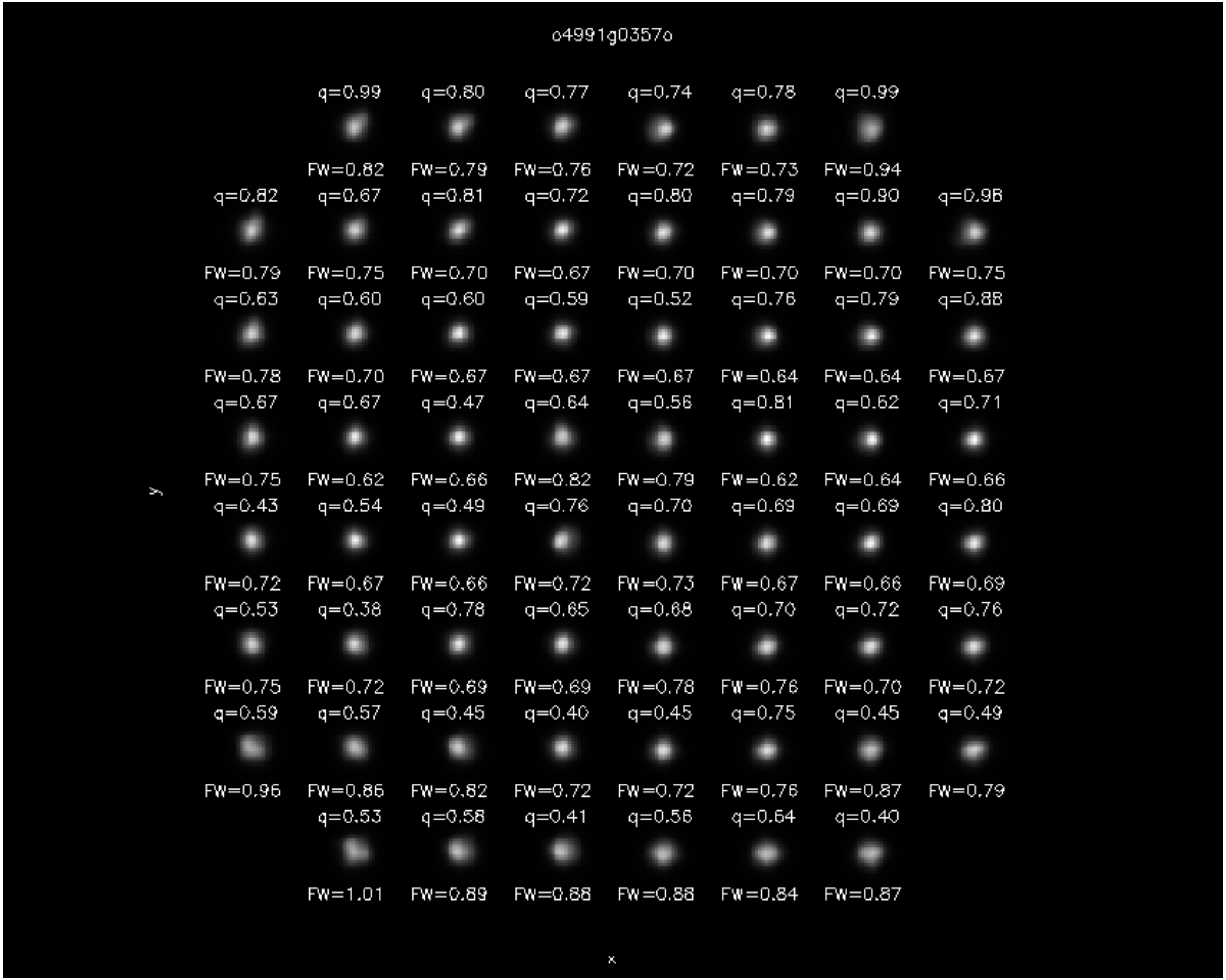


PS1 SAS



On-Sky Performance of PS1 and WL Requirements

- IQ somewhat below spec for FWHM, but PSF anisotropy is very small + smoothly varying across the full FOV by virtue of
    - Design of primary + secondary support structures.
    - System for diagnosing aberrations via curvature sensing
    - Adjustment of tilts + piston of CCDs from measured focal-detector surface deviations + metrology in the lab
- Low level of discontinuities in PSF shape across chip boundaries is a major advantage over other facilities
- Combination of massive numbers of short exposures will help beat down major systematics
- OTCCD removes effects of tracking/guiding errors and wind-driven telescope motions
    - Latter is a big concern for designs with large secondary mirrors
    - OT requires tracking of the convolution kernel for flat fielding.
    - Not currently in use.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q=0.63 q=0.60 q=0.60 q=0.59 q=0.52 q=0.76 q=0.79 q=0.88
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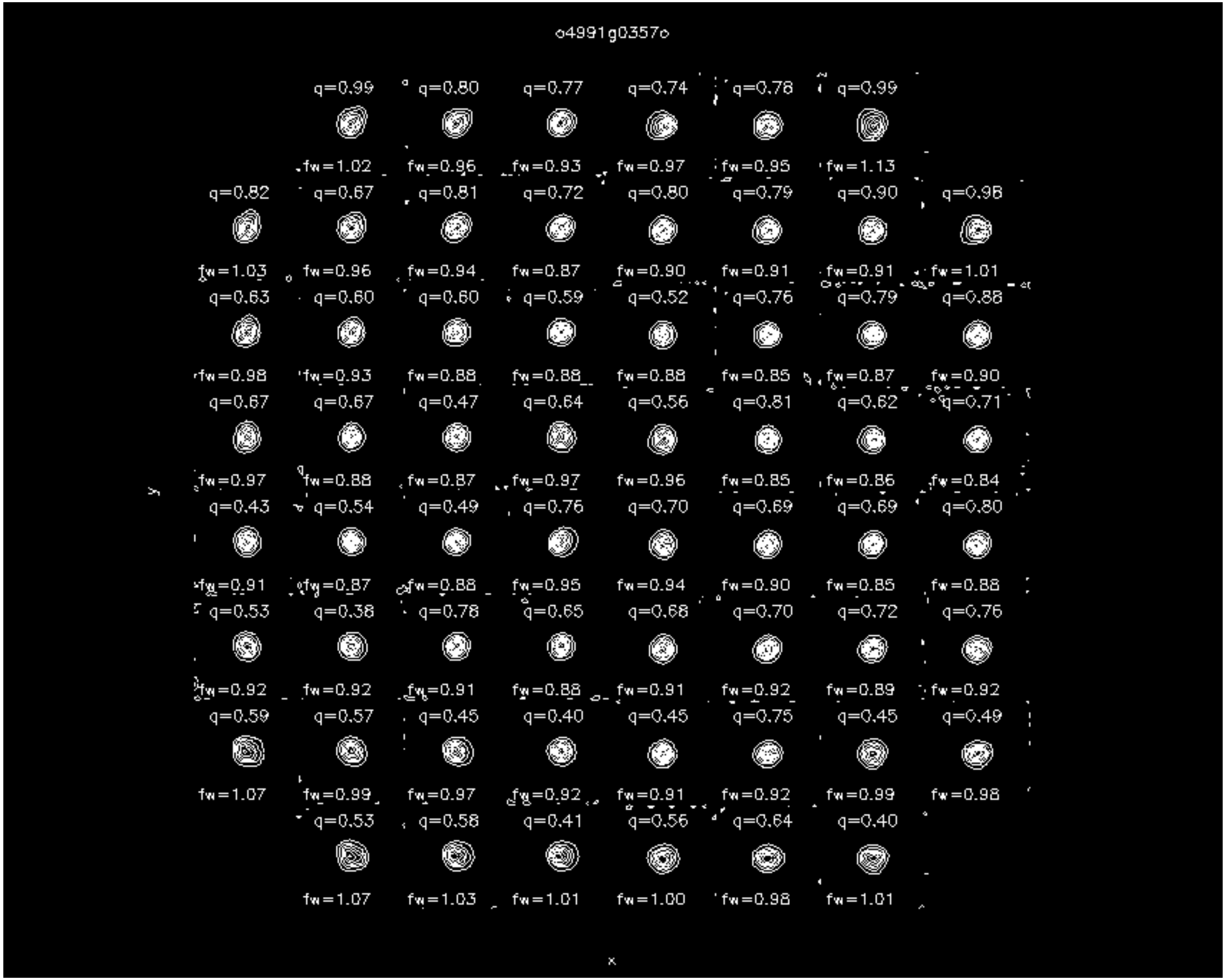
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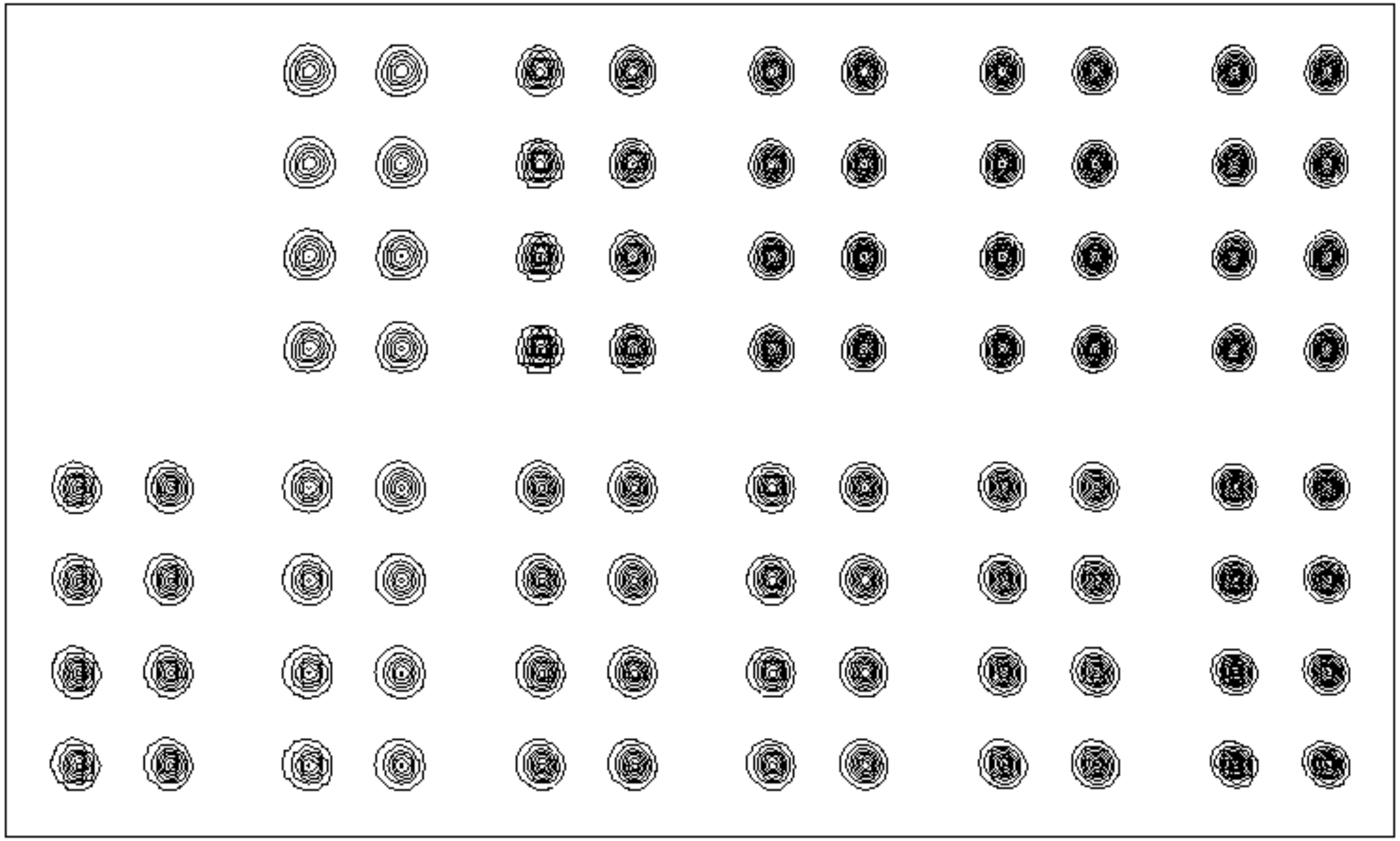
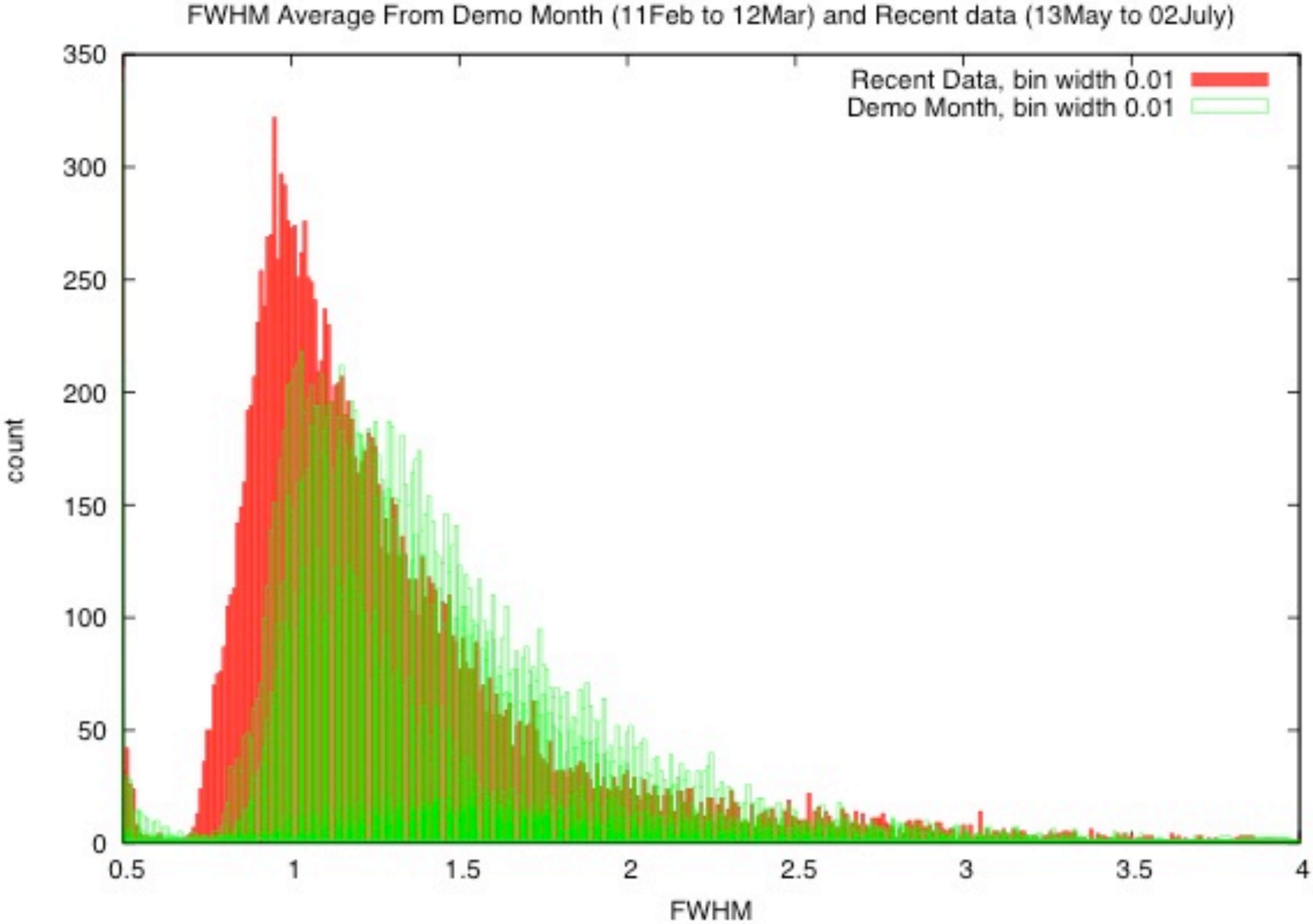
y

12K PSF




FWHM Average From Demo Month (11Feb to 12Mar) and Recent data (13May to 02July)
Recent Data, bin width 0.01
Demo Month, bin width 0.01
count
FWHM
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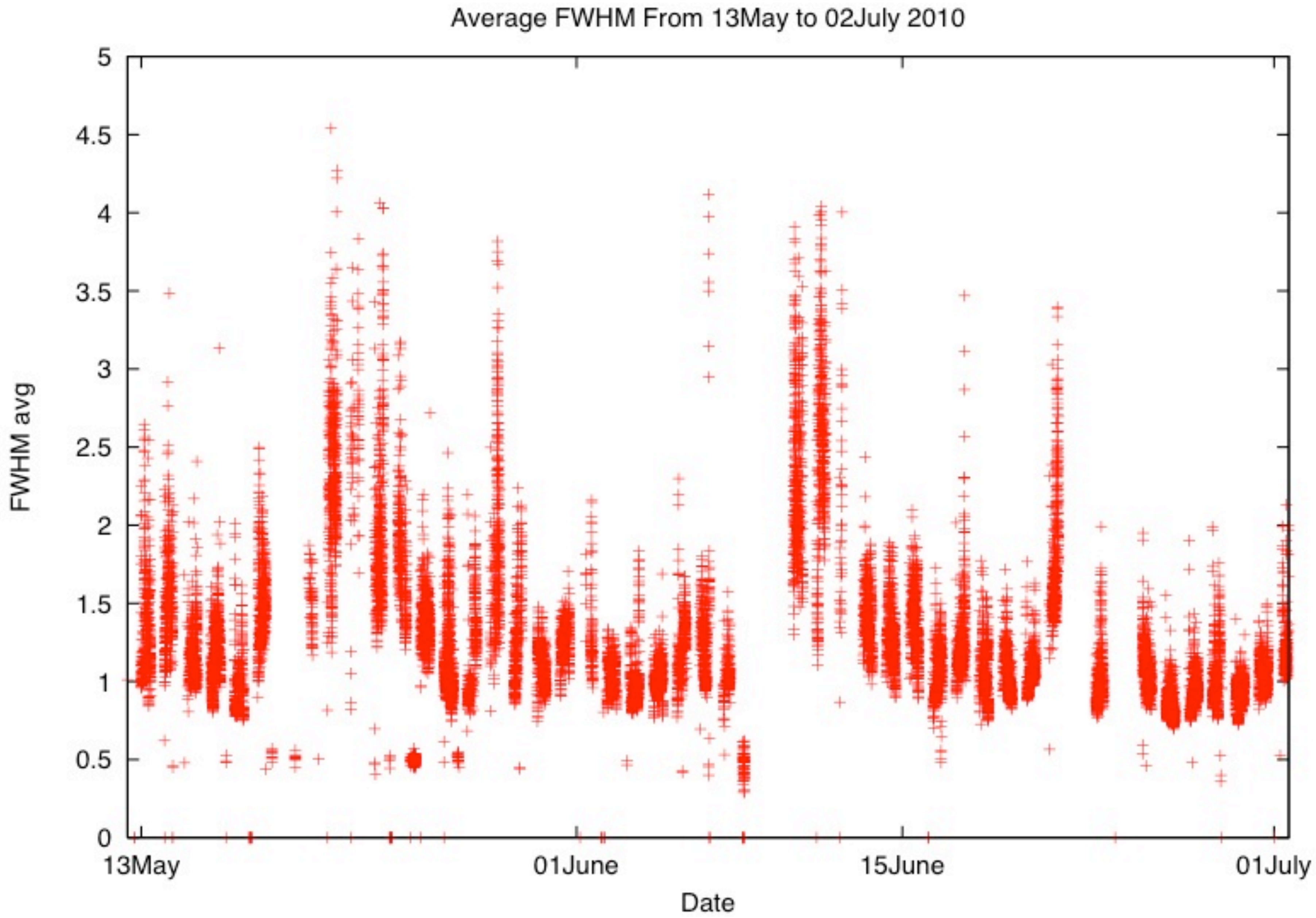
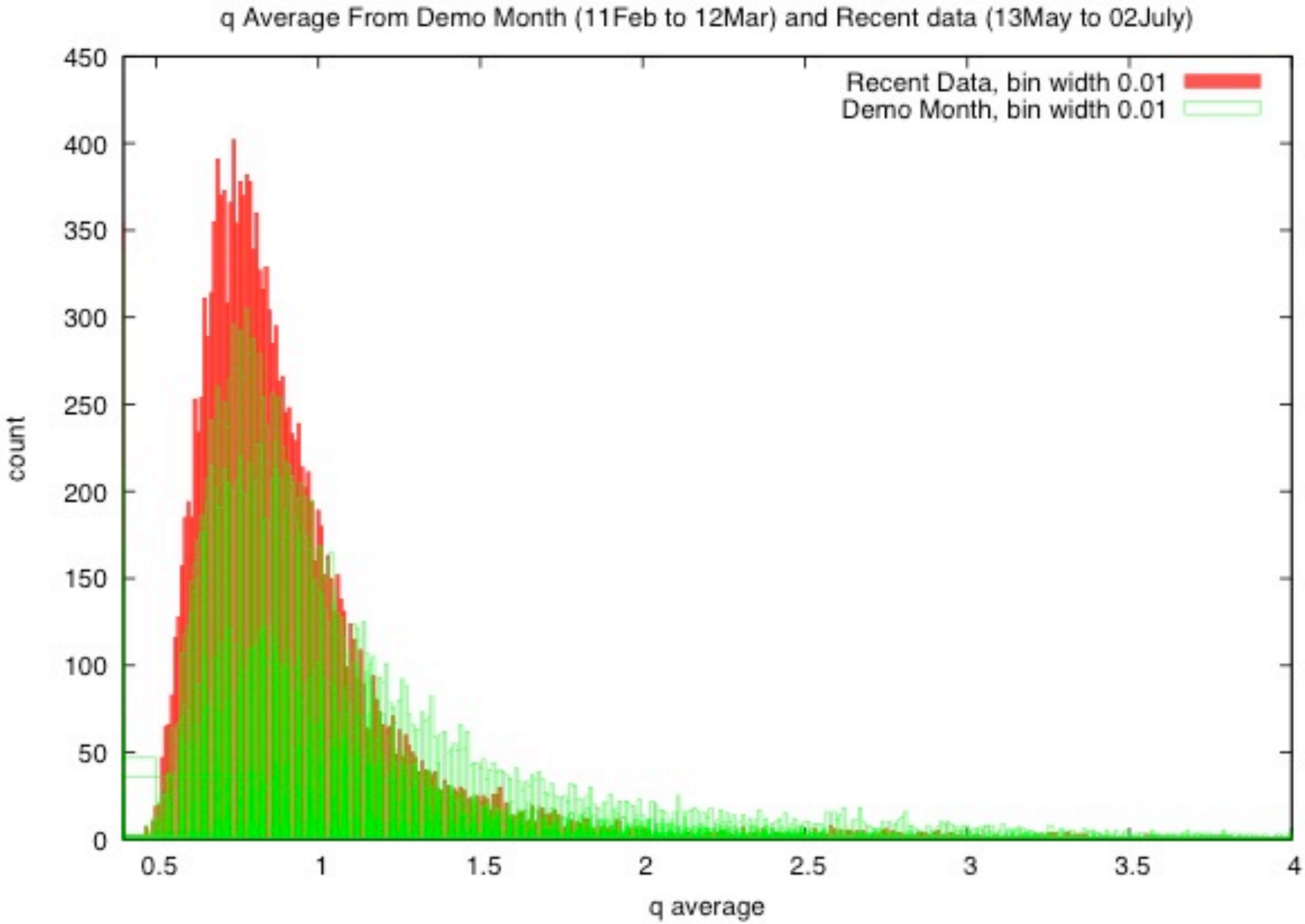
300
250
200
150
100
50
0
0.5
1
1.5
2
2.5
3
3.5
4


Average FWHM From 13May to 02July 2010
FWHM avg
Date
13May
01June
15June
01July
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5



q Average From Demo Month (11Feb to 12Mar) and Recent data (13May to 02July)
Recent Data, bin width 0.01
Demo Month, bin width 0.01
count
q average
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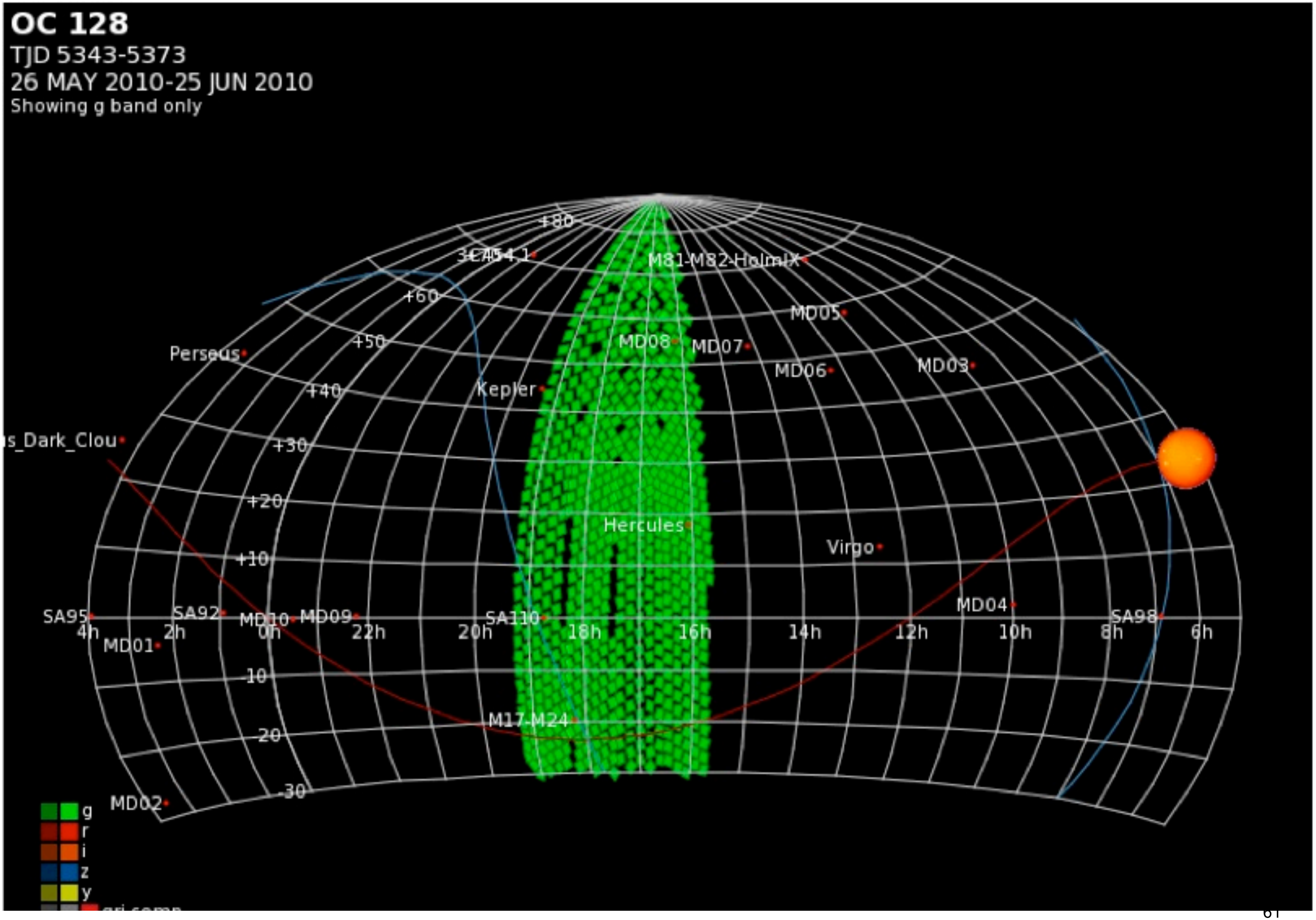
50
100
150
200
250
300
350
400
450
0.5
1
1.5
2
2.5
3
3.5
4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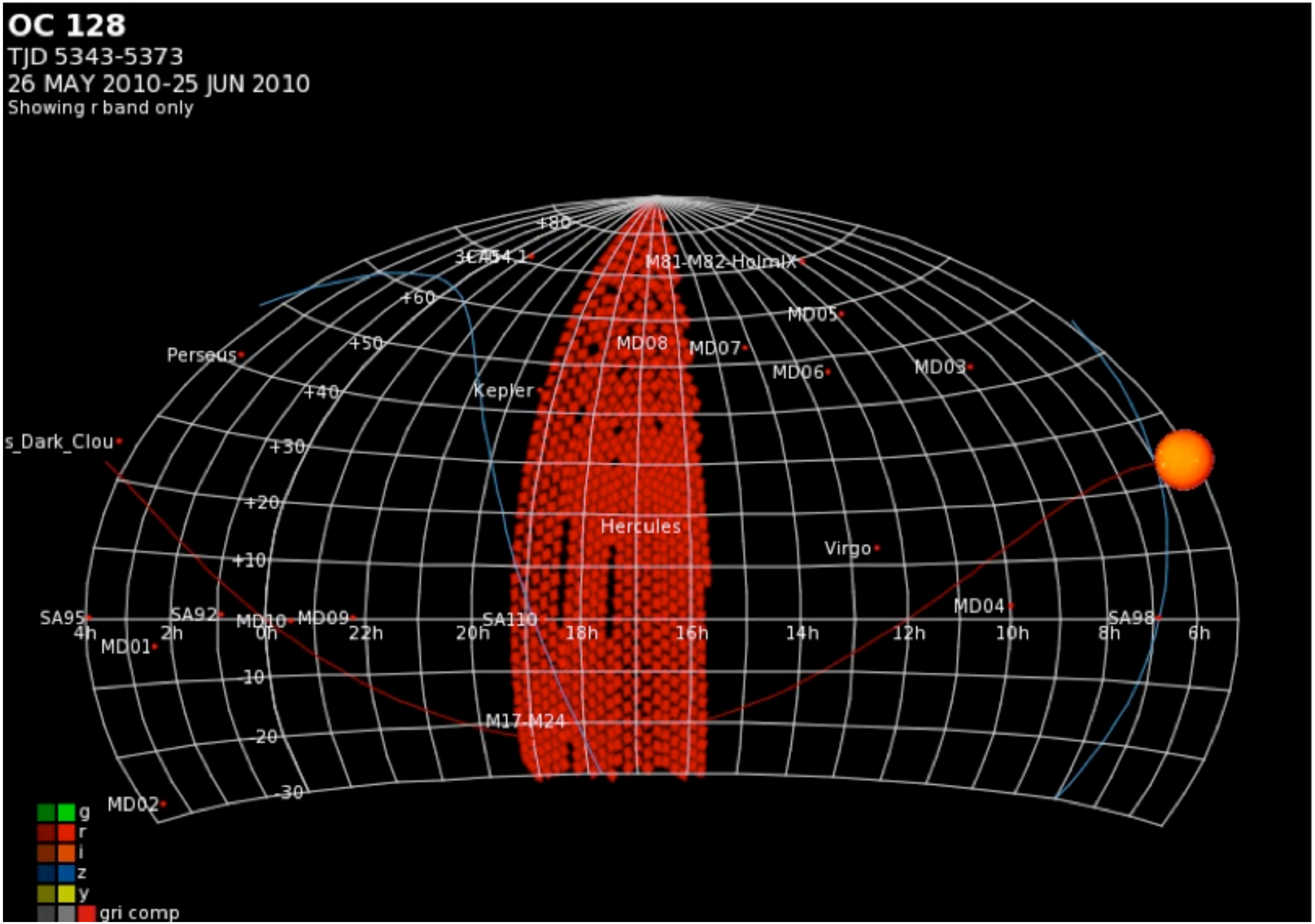
TJD 5343-5373
26 MAY 2010-25 JUN 2010
Showing g band only
+80
3C454.1
M81-M82-HolmIX
+60
MD05
+50
MD08
MD07
Perseus
MD06
MD03
+40
Kepler
+30
+20
Hercules
Virgo
+10
SA95
SA92
MD10
MD09
SA110
MD04
SA98
4h
2h
0h
22h
20h
18h
16h
14h
12h
10h
8h
6h
MD01
-10
M17-M24
-20
-30
MD02
g
r
i
z
y



OC 128
TJD 5343-5373
26 MAY 2010-25 JUN 2010
Showing r band only
+80
3C454.1
M81-M82-HolmIX
+60
MD05
+50
MD08
MD07
Perseus
MD06
MD03
+40
Kepler
s_Dark_Clou
+30
+20
Hercules
Virgo
+10
MD04
SA95
SA92
MD10
MD09
SA110
SA98
4h
2h
0h
22h
20h
18h
16h
14h
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g
r
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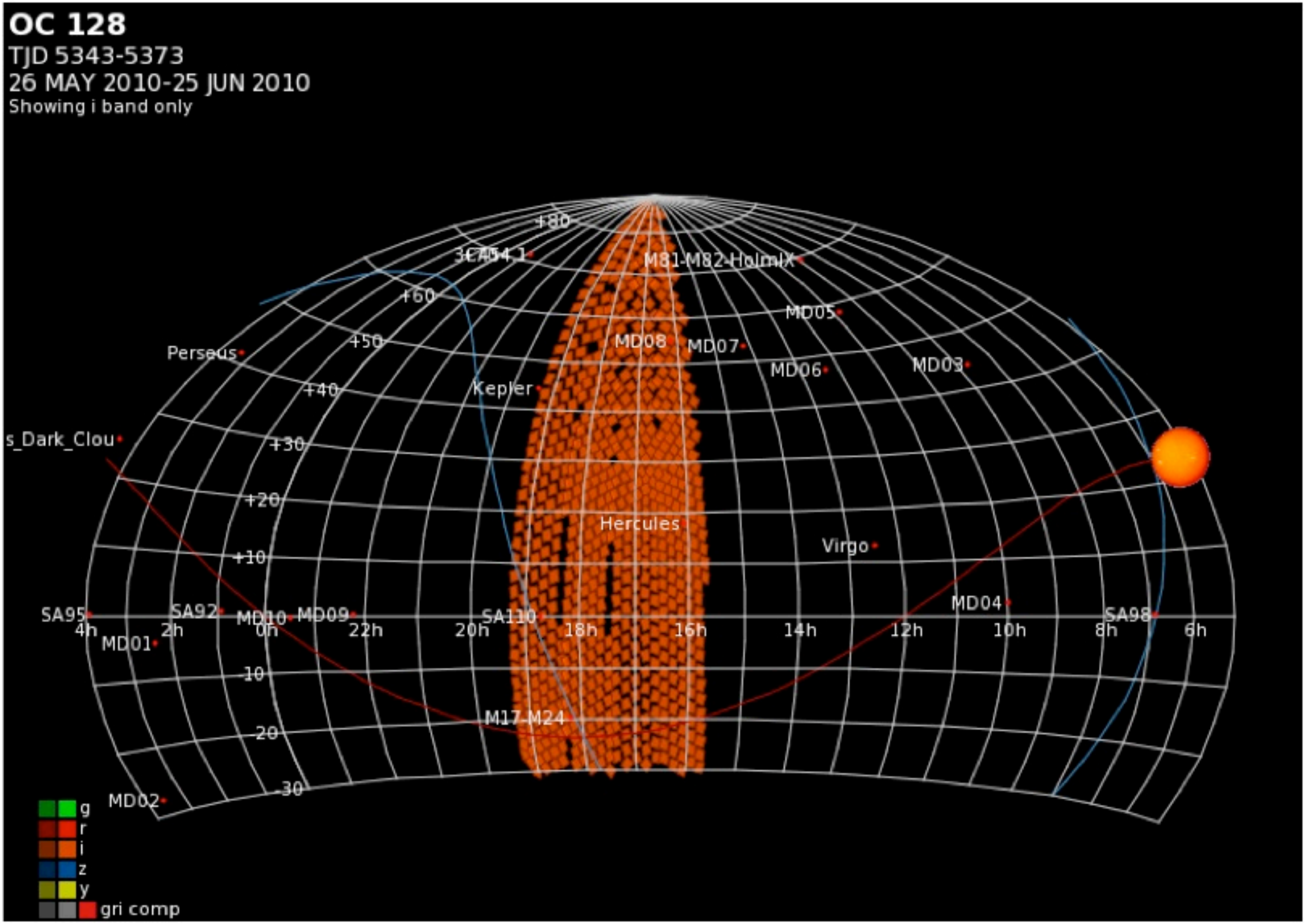
OC 128
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M81-M82-HolmIX
+60
MD05
Perseus
+50
MD08
MD07
MD06
MD03
+40
Kepler
s_Dark_Clou
+30
+20
Hercules
Virgo
+10
SA95
SA92
MD10
MD09
SA110
MD04
SA98
4h
2h
0h
22h
20h
18h
16h
14h
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MD02
g
r
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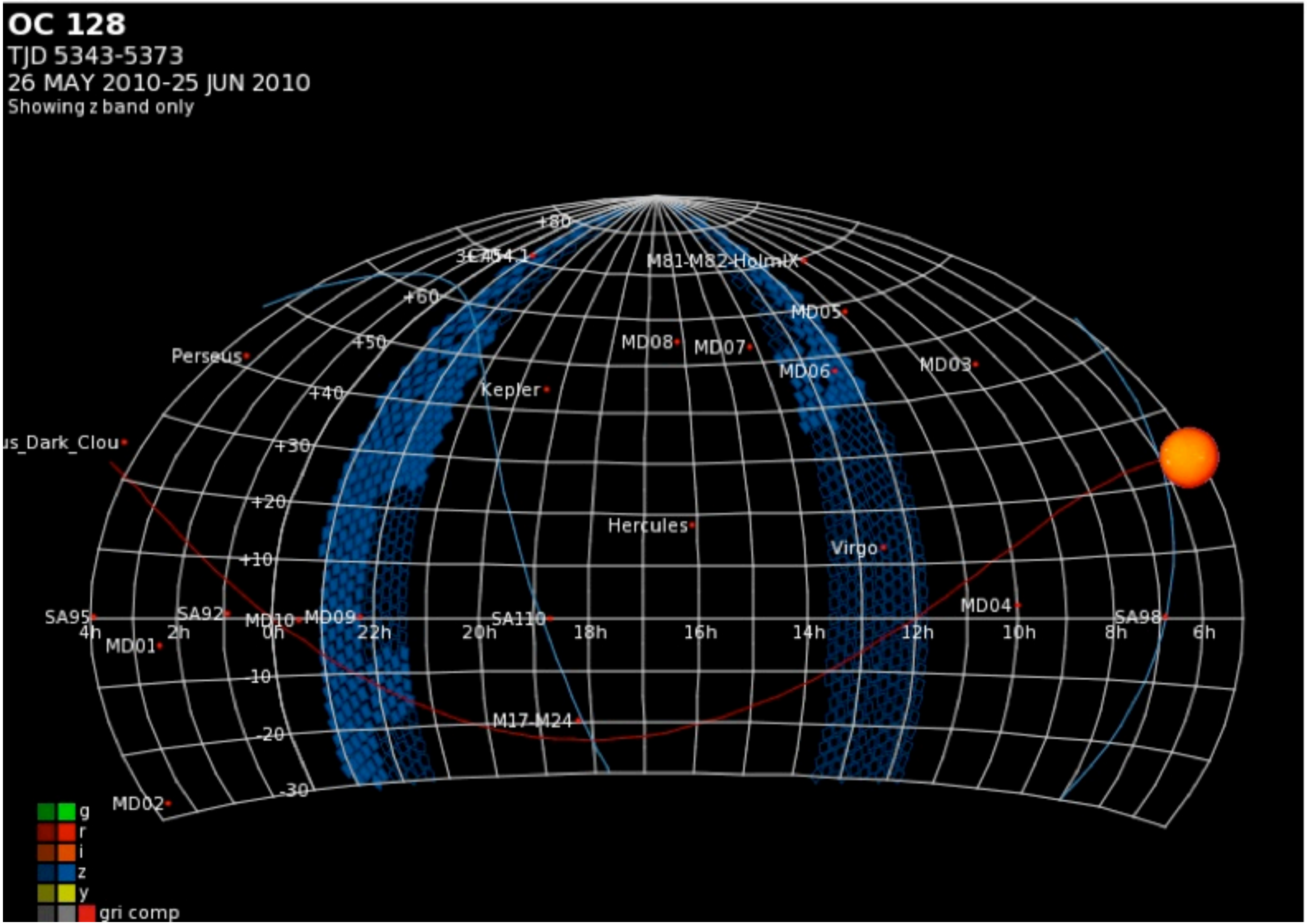
gri comp



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Showing z band only
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+60
+50
+40
+30
+20
+10
-10
-20
-30
3C454.1
M81-M82-HolmIX
MD05
MD08
MD07
MD06
MD03
Perseus
Kepler
us_Dark_Clou
Hercules
Virgo
SA95
SA92
MD10
MD09
SA110
MD04
SA98
4h
2h
0h
22h
20h
18h
16h
14h
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10h
8h
6h
MD01
M17-M24
MD02
g
r
i
z
y
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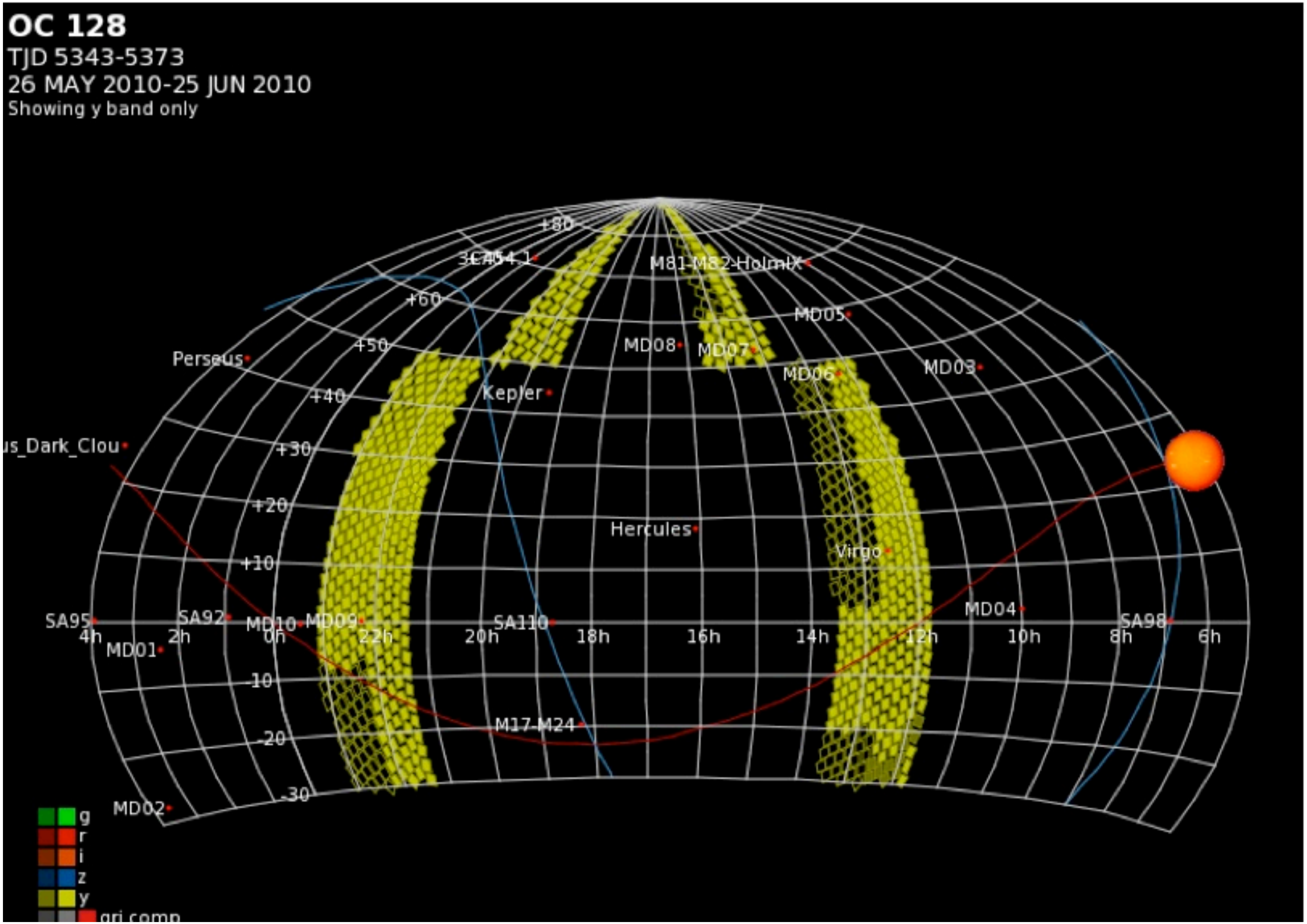

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26 MAY 2010-25 JUN 2010
Showing y band only
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+60
+50
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+30
+20
+10
-10
-20
-30
M81-M82-HolmIX
MD05
MD08
MD07
MD06
MD03
Perseus
Kepler
Hercules
Virgo
MD04
SA95
SA92
MD10
MD09
SA110
SA98
MD01
M17-M24
MD02
4h
2h
0h
22h
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10h
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6h
g
r
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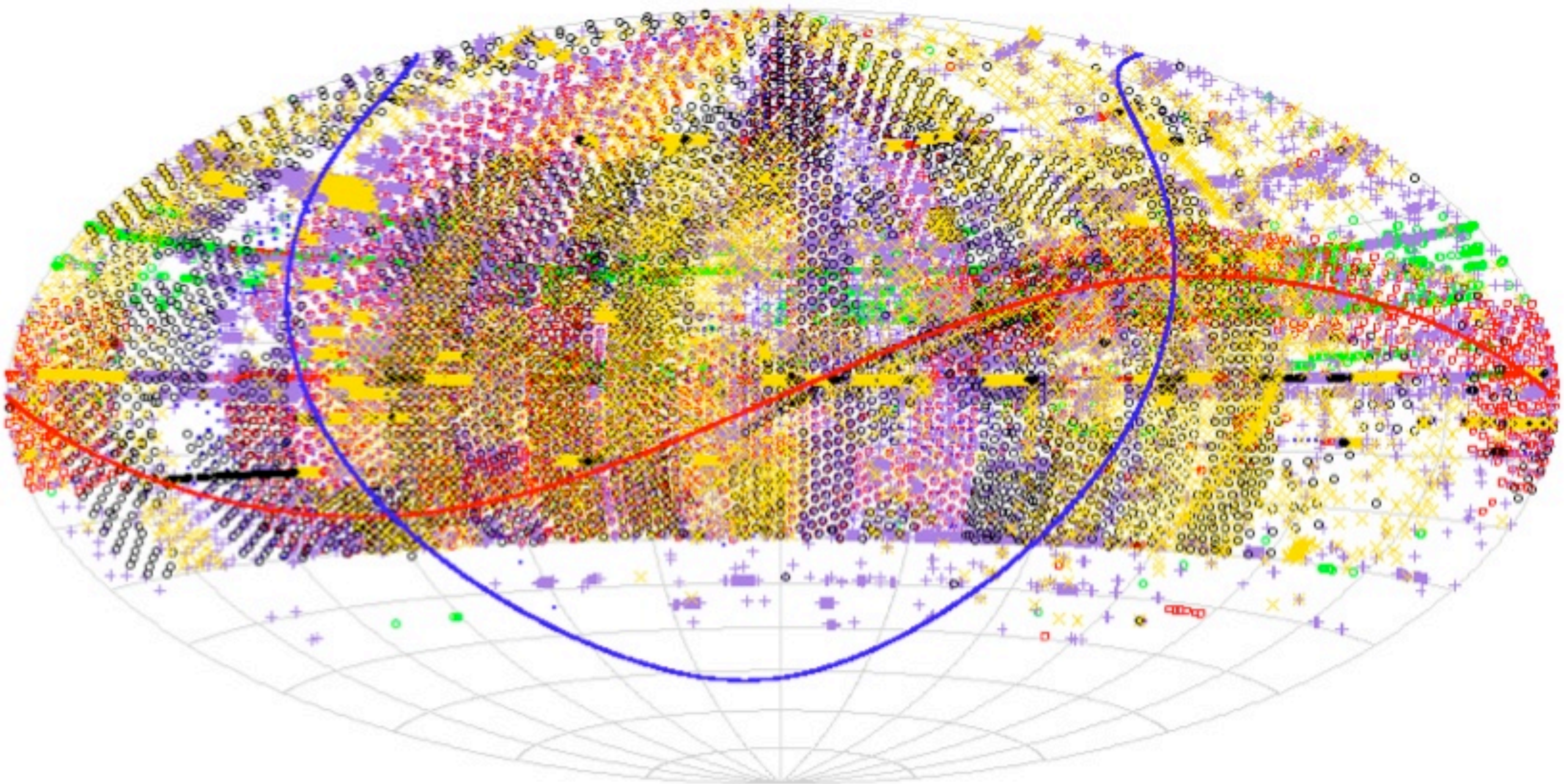
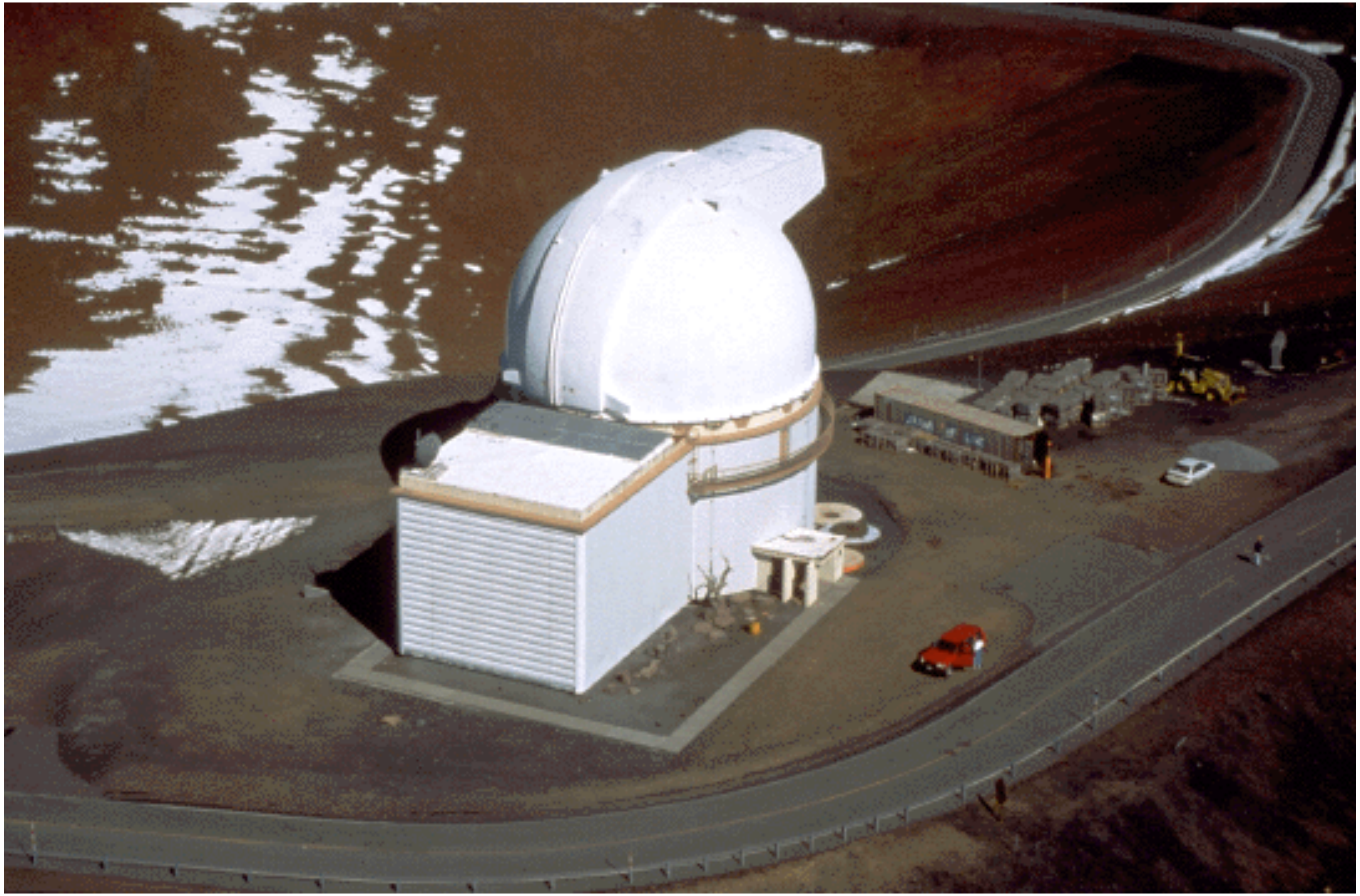
gri comp

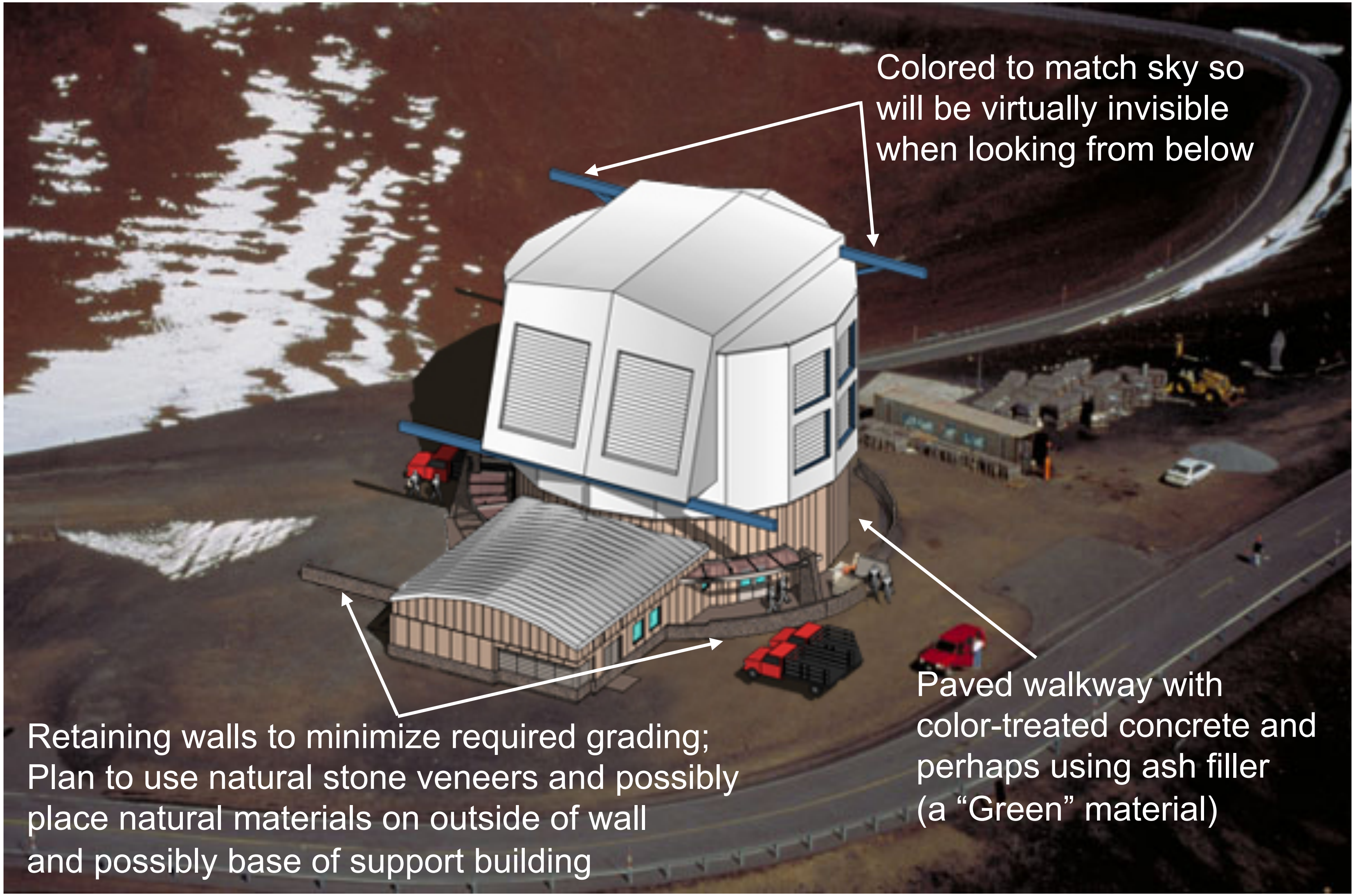
PS1 Sky Coverage



UH 2.2m Site: Preferred Site for PS4

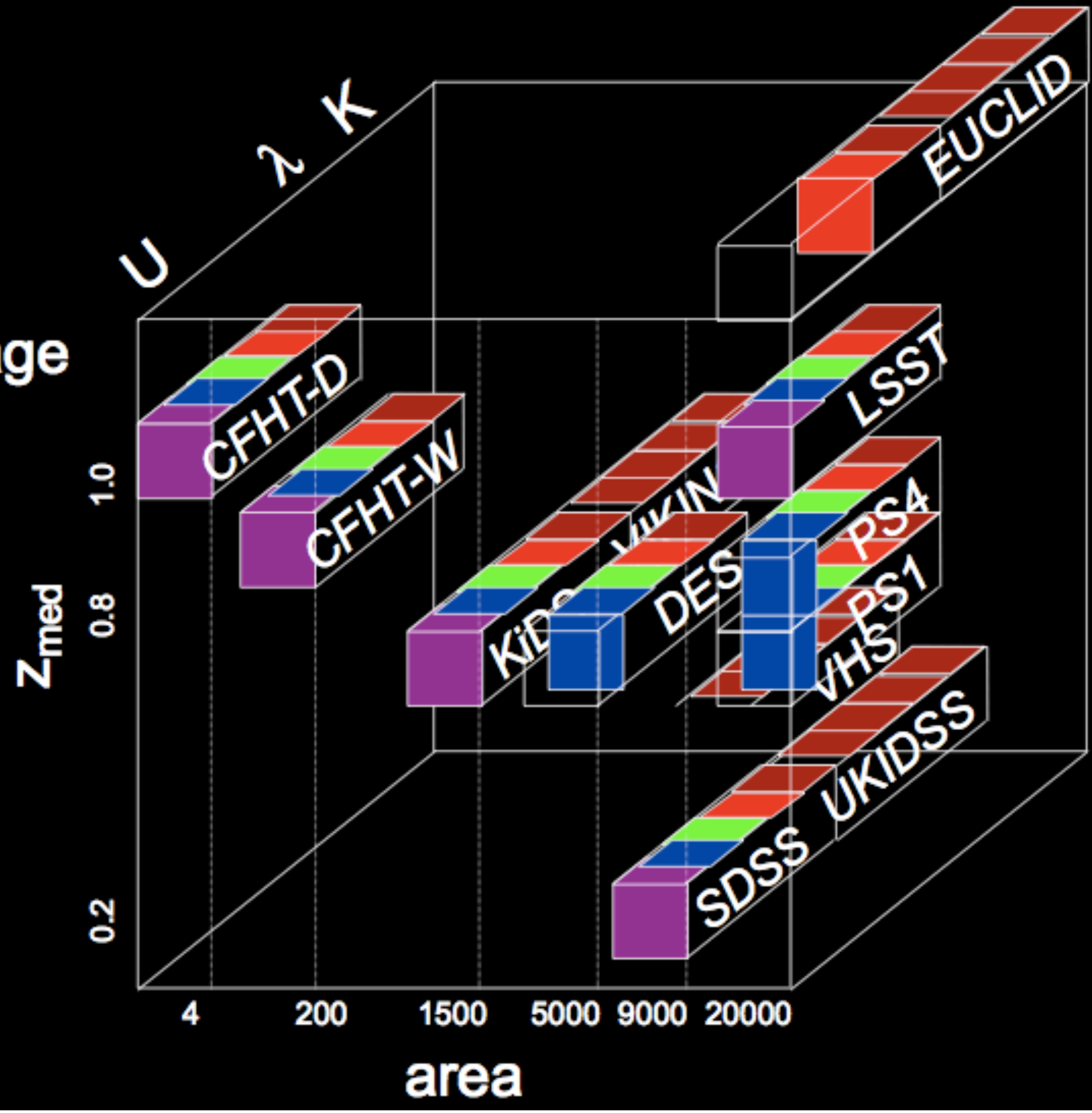


UH 2.2m Site Footprint with Proposed PS4 Building



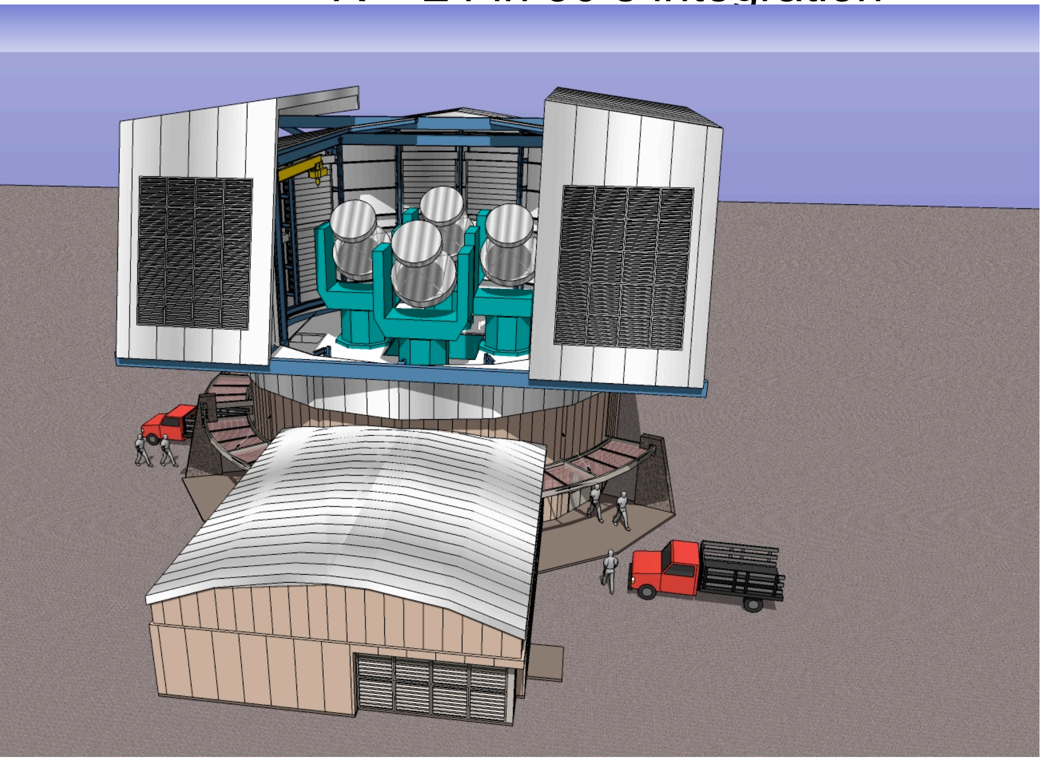
Survey parameters

- Area covered
- Median redshift
- Image quality
- Wavelength coverage



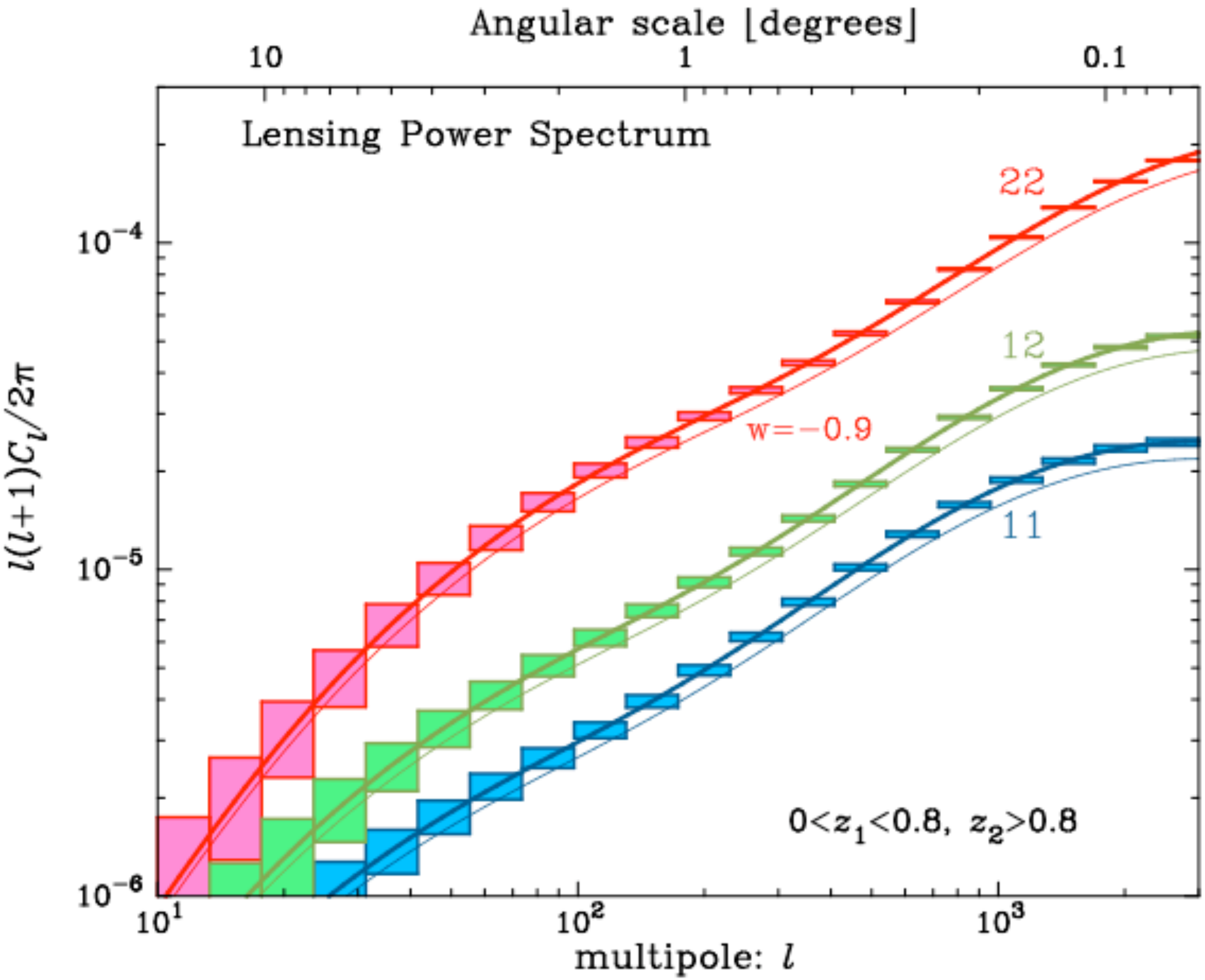
Pan-STARRS in a Nutshell

- Telescopes
  - Four 1.8m R-C + corrector
  - 7 square degree FOV
  - Sited in Hawaii
  - A Ω = 50
  - R ~ 24 in 30 s integration

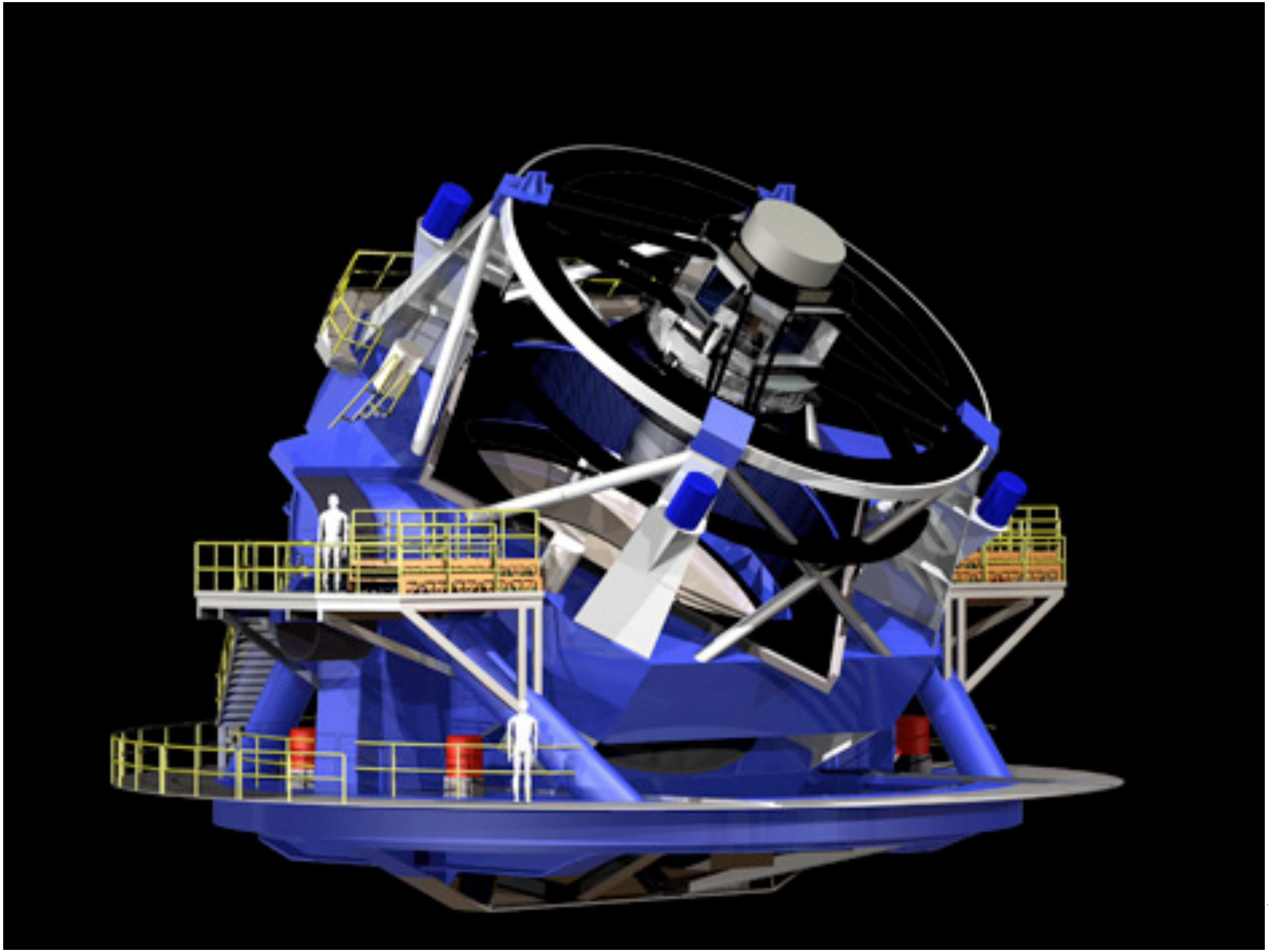


- Detector and controllers
  - 1.44×10^9 0.26” pixels per camera
  - Image motion compensation
  - 512 channel controller
  - few second readout
  - $6e^-$ read-noise
- Operation mode:
  - Broad band optical imaging
  - Four telescopes view the same field to detect transient or moving objects and build up a deep image of the sky
- Data-Processing System
  - Multicolor summed images
  - Difference images for detection of moving and variable objects
  - Catalogs of static, moving, transient objects
- Survey Capability (for Dark Energy):
  - All-sky (3 pi steradian) to r~26 for WL, BAOs and cluster abundance
  - Medium & ultra deep surveys for SN1a

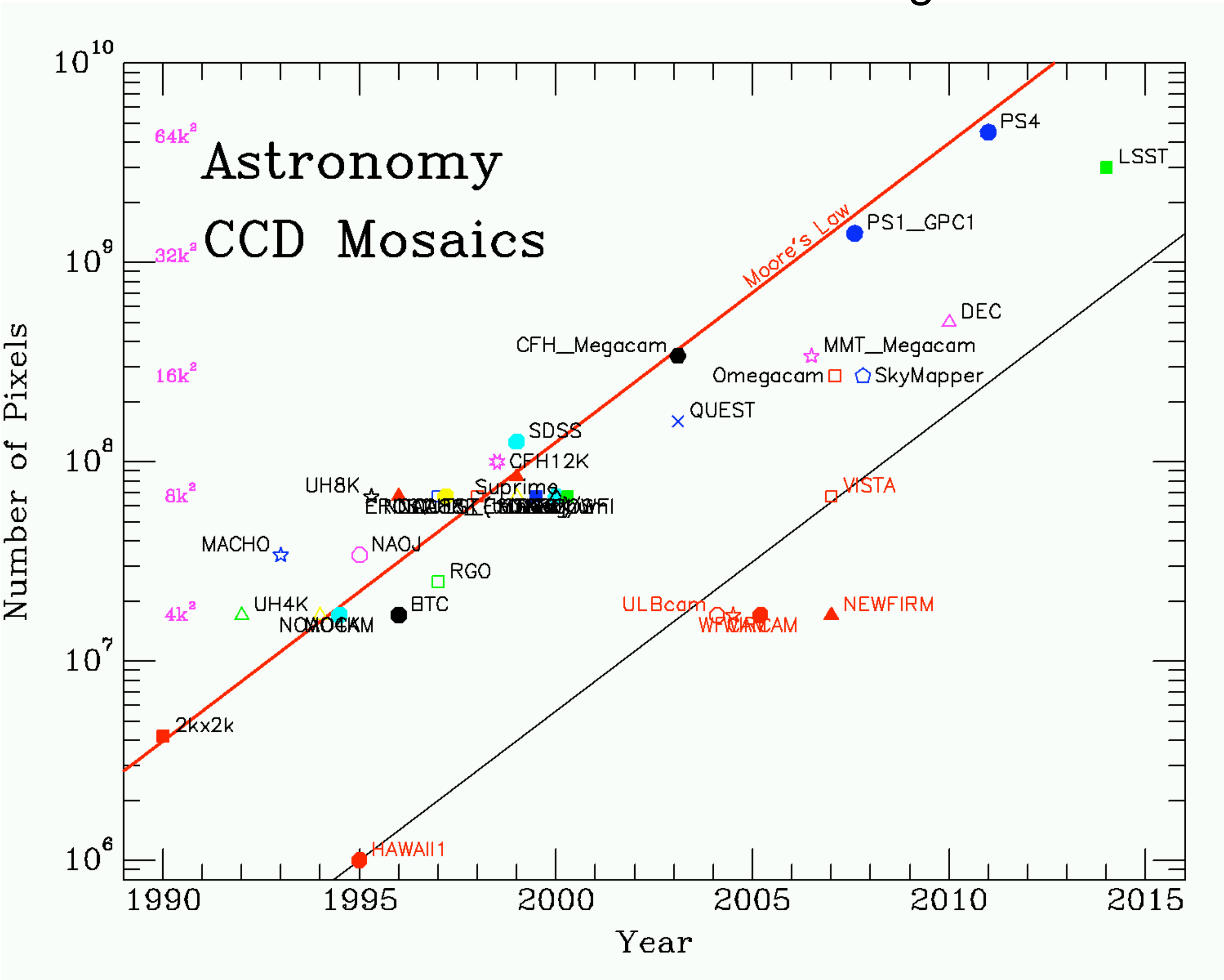
Hoekstra+Jain '08 forecast for "ambitious Stage III survey"



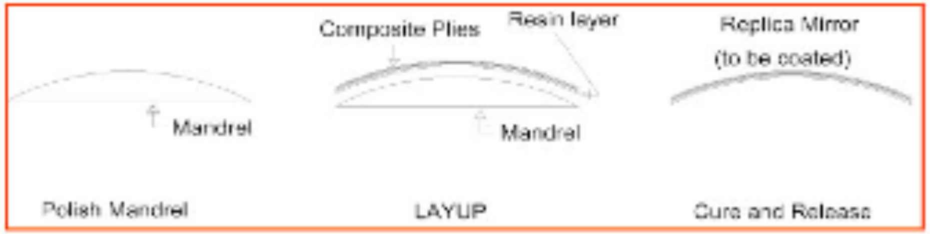
LSST



Growth of Astronomical Imagers



Breaking the telescope cost constraint (CMA Ultra 1m)



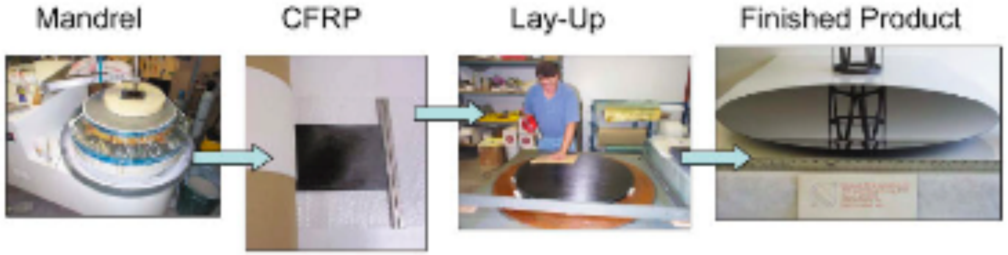


Figure 3. LEFT to RIGHT, image shows the mandrel being polished to optical tolerances, Unidirectional prepreg off the roll, Lay-up of prepreg over the mandrel, Finished CFRP mirror after release from the mandrel.

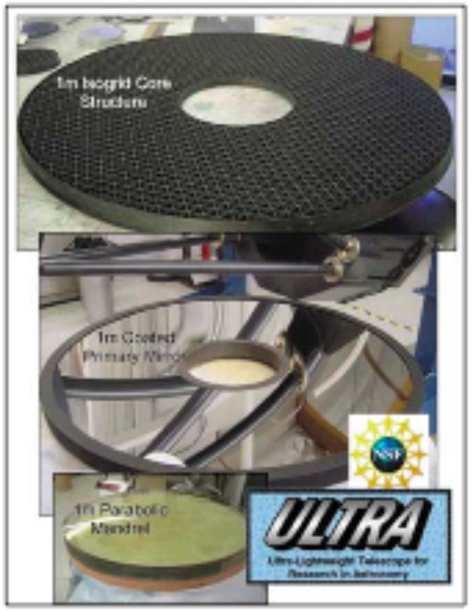


Figure 8. LEFT, Primary mirror, RIGHT, secondary mirror for ULTRA

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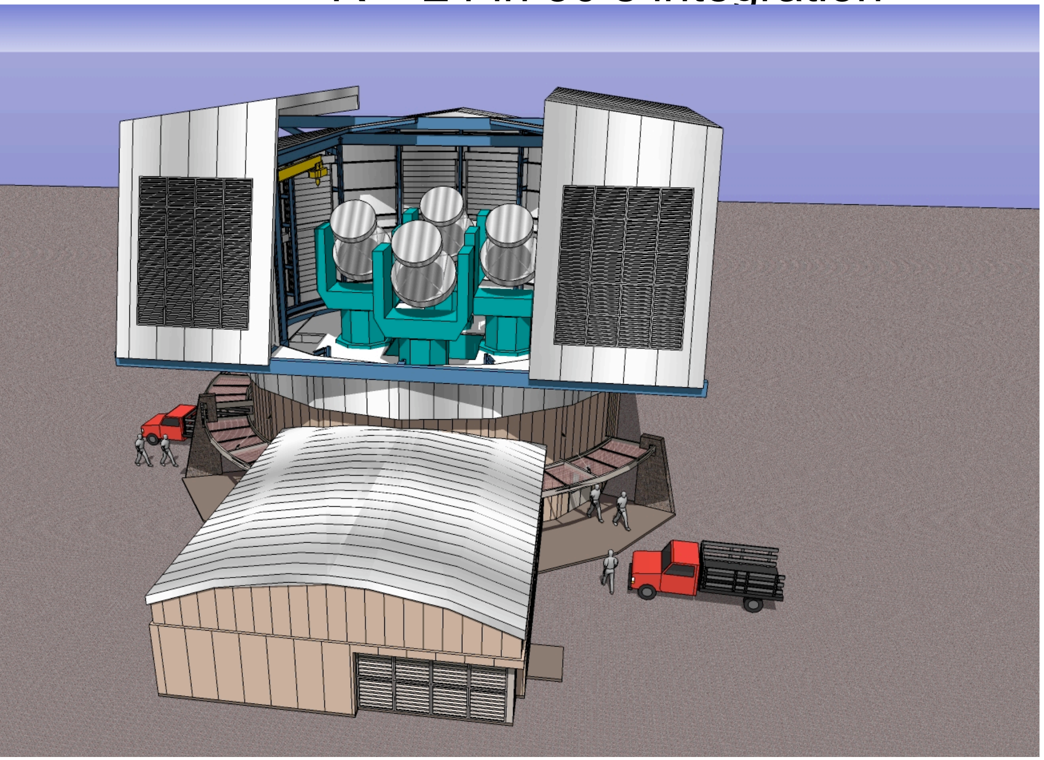

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