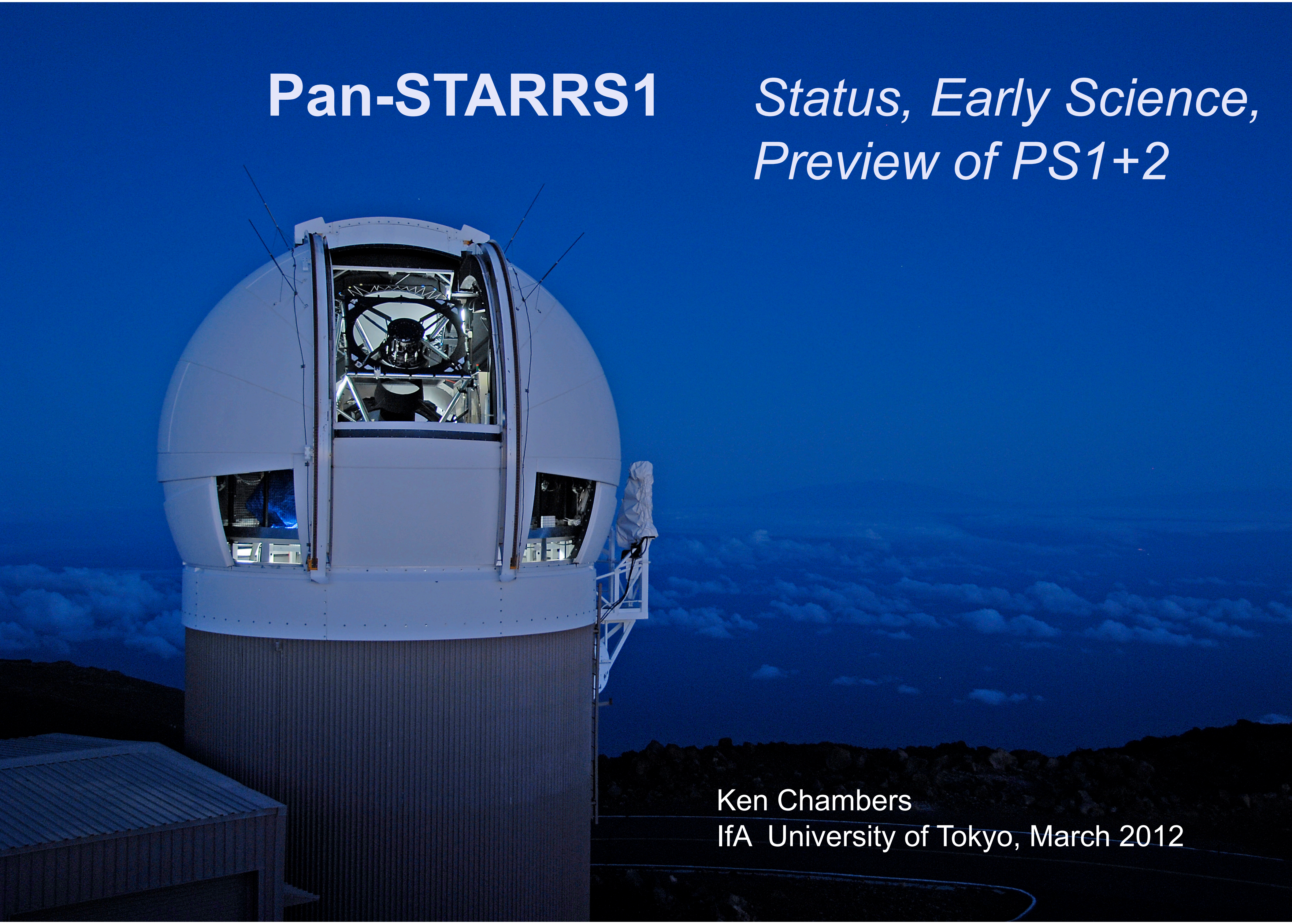
Pan-STARRS1 *Status, Early Science, Preview of PS1+2*



Ken Chambers
IfA University of Tokyo, March 2012

The PS1 System

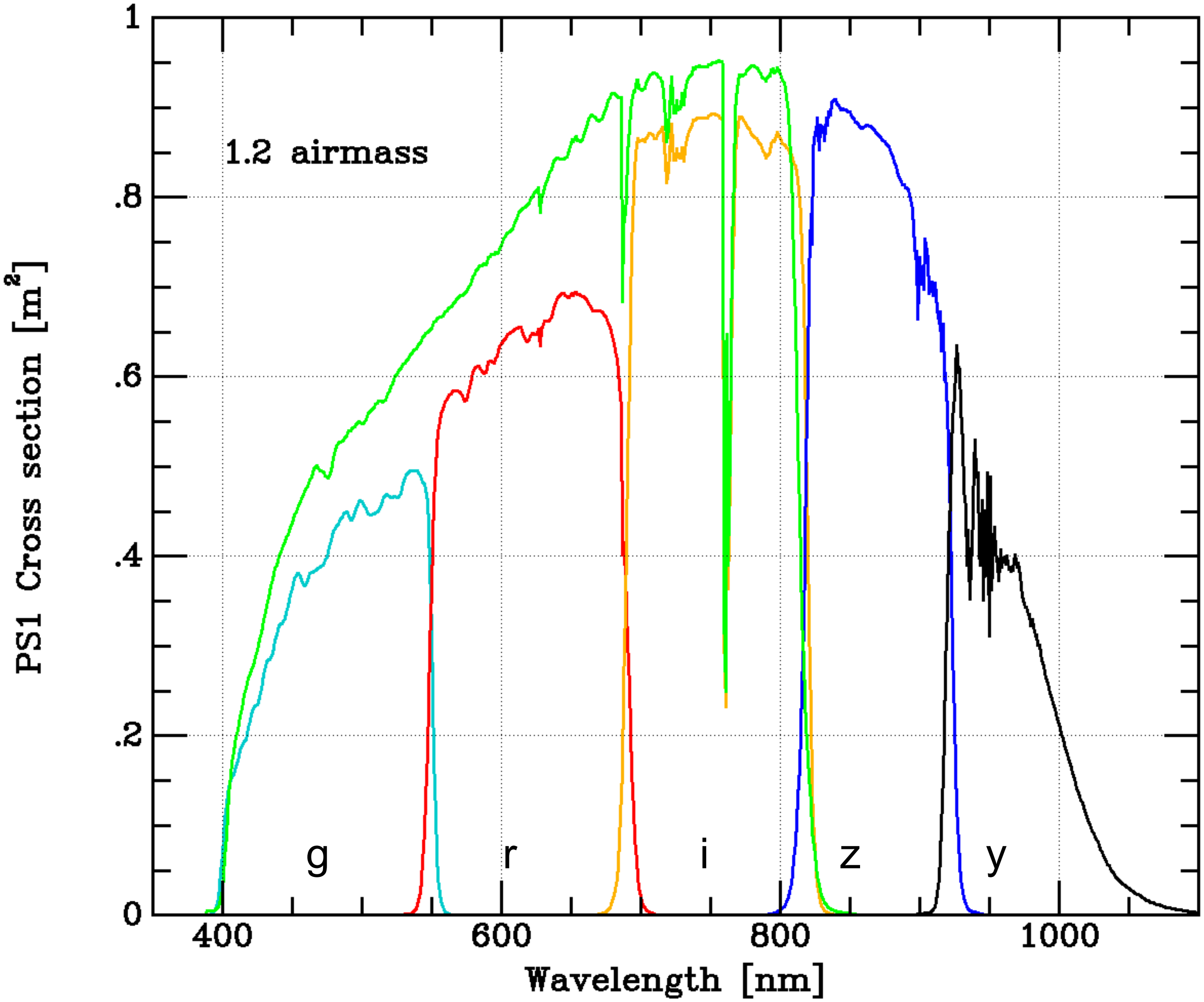
- Pan-STARRS is largest wide field sky survey system in operation, and will be for a decade
  - 1.8 meter telescope at f/4.4 with 3.2 degree diameter FOV
  - 1.4 Gigapixel Camera, 10um pixels, 0.256''/pixel
  - 6 filters: g, r, I, z, y, w

- Image data rate – steady state
  - Raw image data rate: 0.5GByte/sec
  - Reduced image data rate: 3.5 Gbyte/sec

- Catalog data from 3.5 year PS1 Science Mission
  - 36 Billion single epoch detections
  - 20 Billion detections from final stacked images
  - 5 Billion objects (associations of detections)

- Challenge
  - Complete the PS1 Survey – goal of Dec 31, 2013
  - Final re-processing of data, including image differencing and covariance between pixels
  - Serving the data products to the community one year later at the end of 2014

PS1 Effective area per bandpass

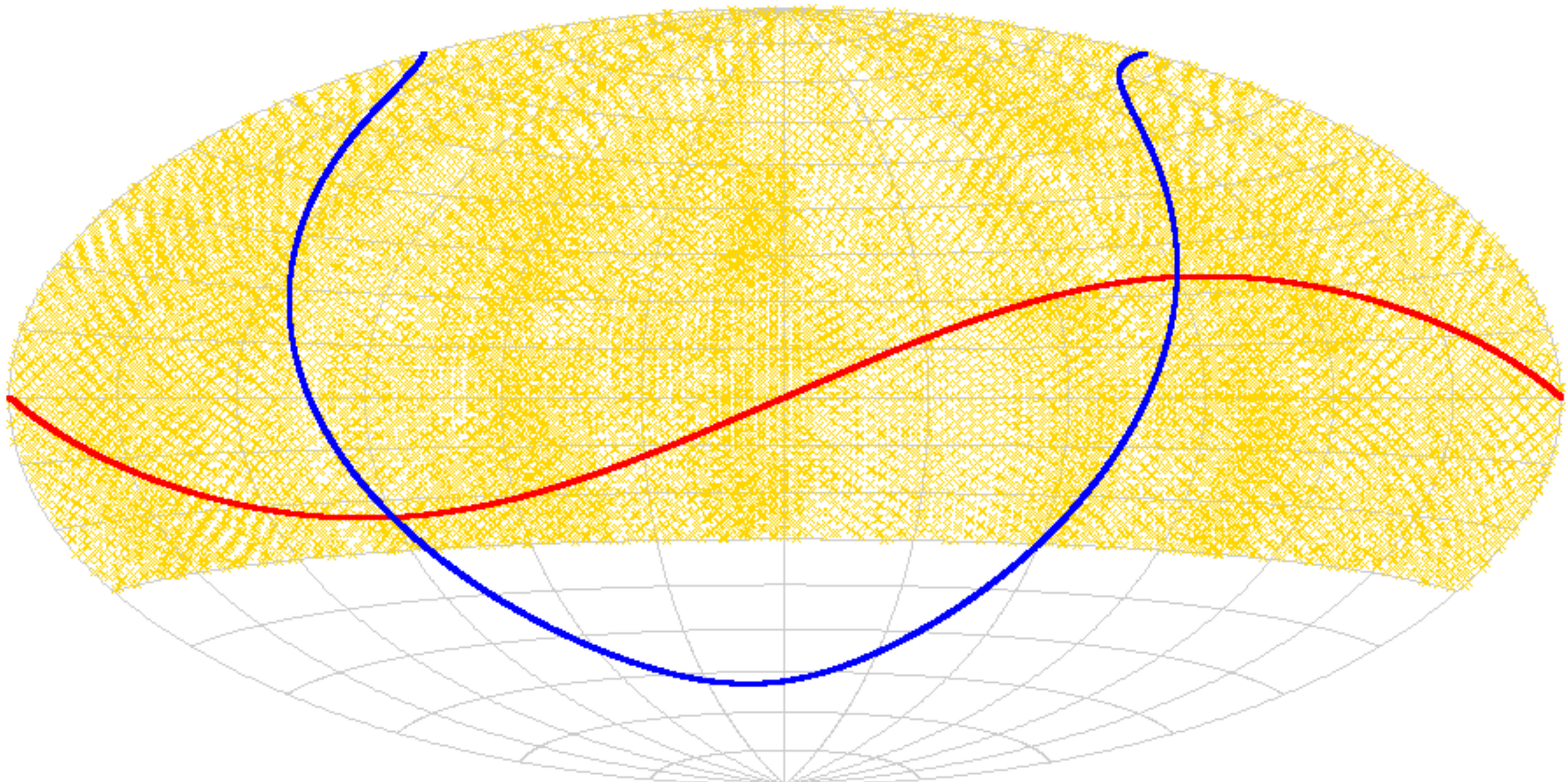


PS1 and Comparison Surveys

Table 1: PS1 Surveys and Comparison Surveys

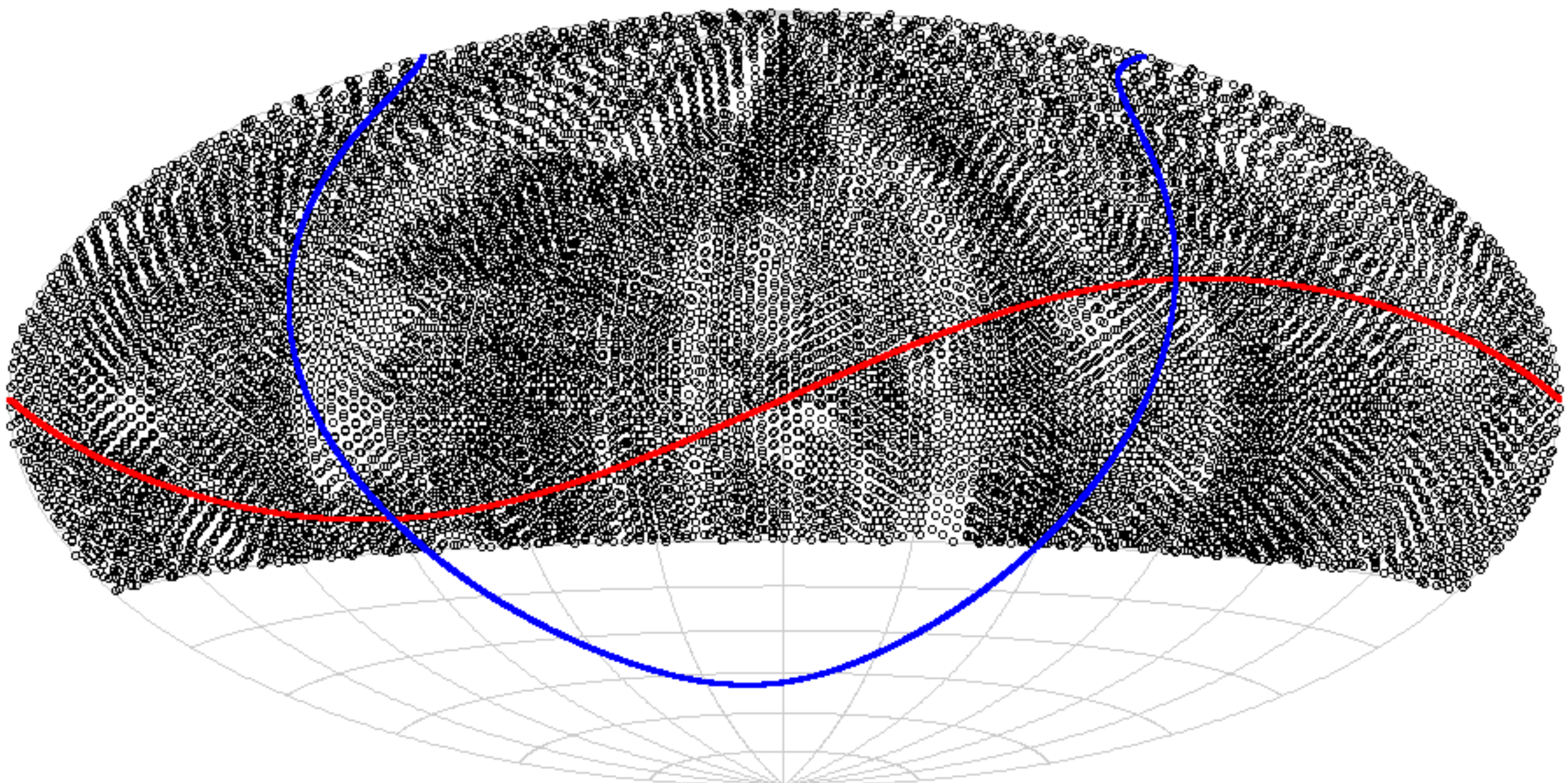
survey	**area sq deg**	**region**	**pixel size arcsec**	**image quality median FWHM**	**filters**	**cadence**	**lim mag per dwell**	**lim mag per sum**
PS1							g,r,i,z,y	g,r,i,z,y
3π	30000	$\delta > -30$	0.256	1.1”	$grizy$	25 min, 1 mth	22.2, 22.0, 21.5, 20.8, 19.8	23.4, 23.2, 22.7, 22.0, 21.1
MD	70	std fields	0.256	1.1”	$grizy$	3 min, 1 day		25.0, 25.0, 25.1, 24.4, 23.5
SS	5000	ecliptic	0.256	1.1”	w	25 min	22.5(w)	...
STS	49	bulge	0.256	1.1”	i	8 min	21.7(i)	...
M31	7	M31	0.256	1.1”	r, i	2hrs	22.2(r), 21.7(i)	...
								u, g,r,i,z
SDSS	8000	galactic cap	0.396	1.3”	$ugriz$	one epoch	...	22.5, 23.2, 22.6, 21.9, 20.8
PTF	...	available	1.100	2.0”	g', R	1 min, 5 days	21.3(g), 20.6(R)	...
DES	5000	s. gal. cap	0.270	0.9”	$grizy$	one epoch	...	24 (predicted in i band)
HSC	2000	...	0.170	0.5”	$grizy$	...	...	26.2

3pi sky coverage to March 1, 2012



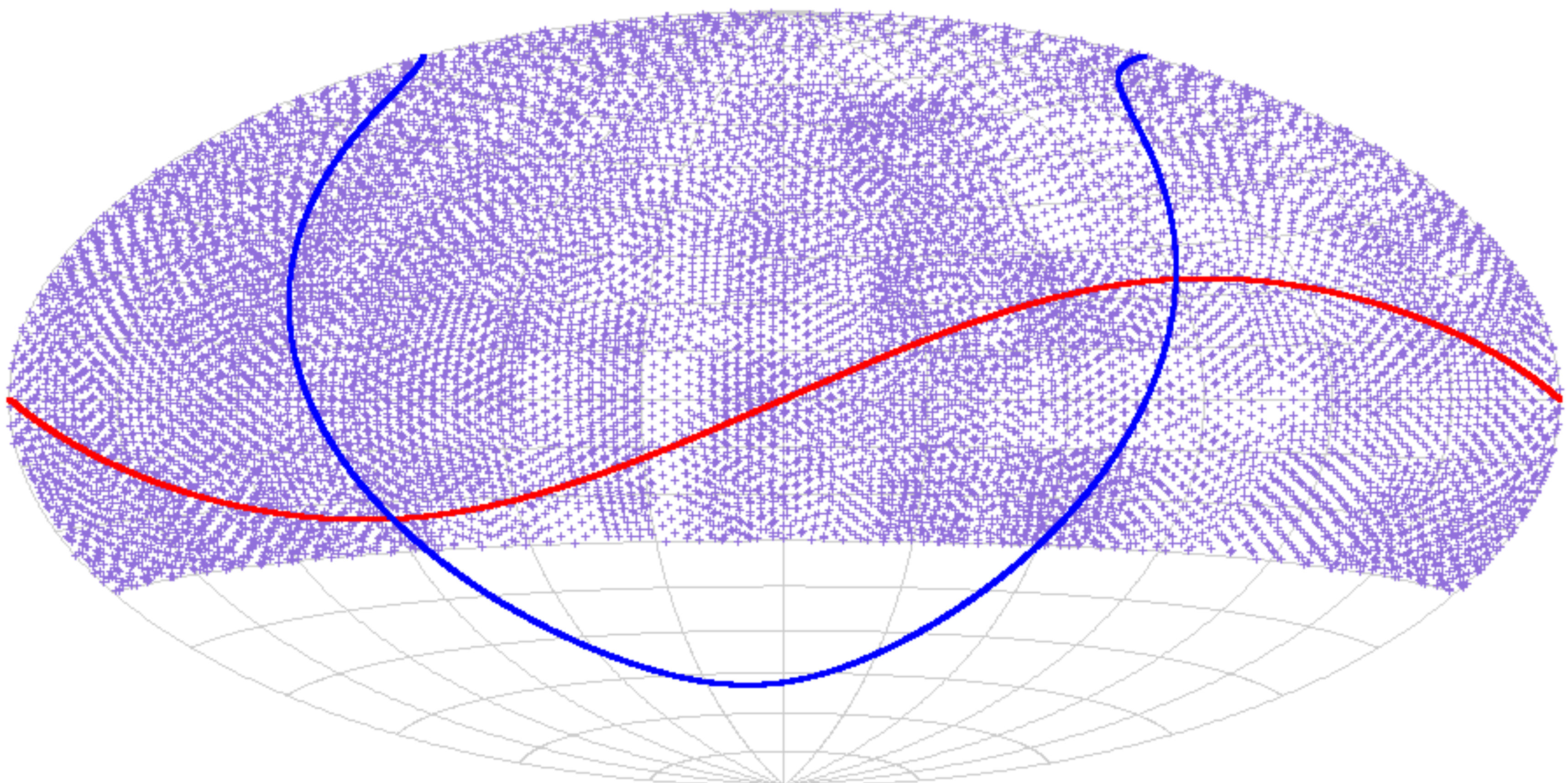
y band

3pi sky coverage to Mar 1, 2012



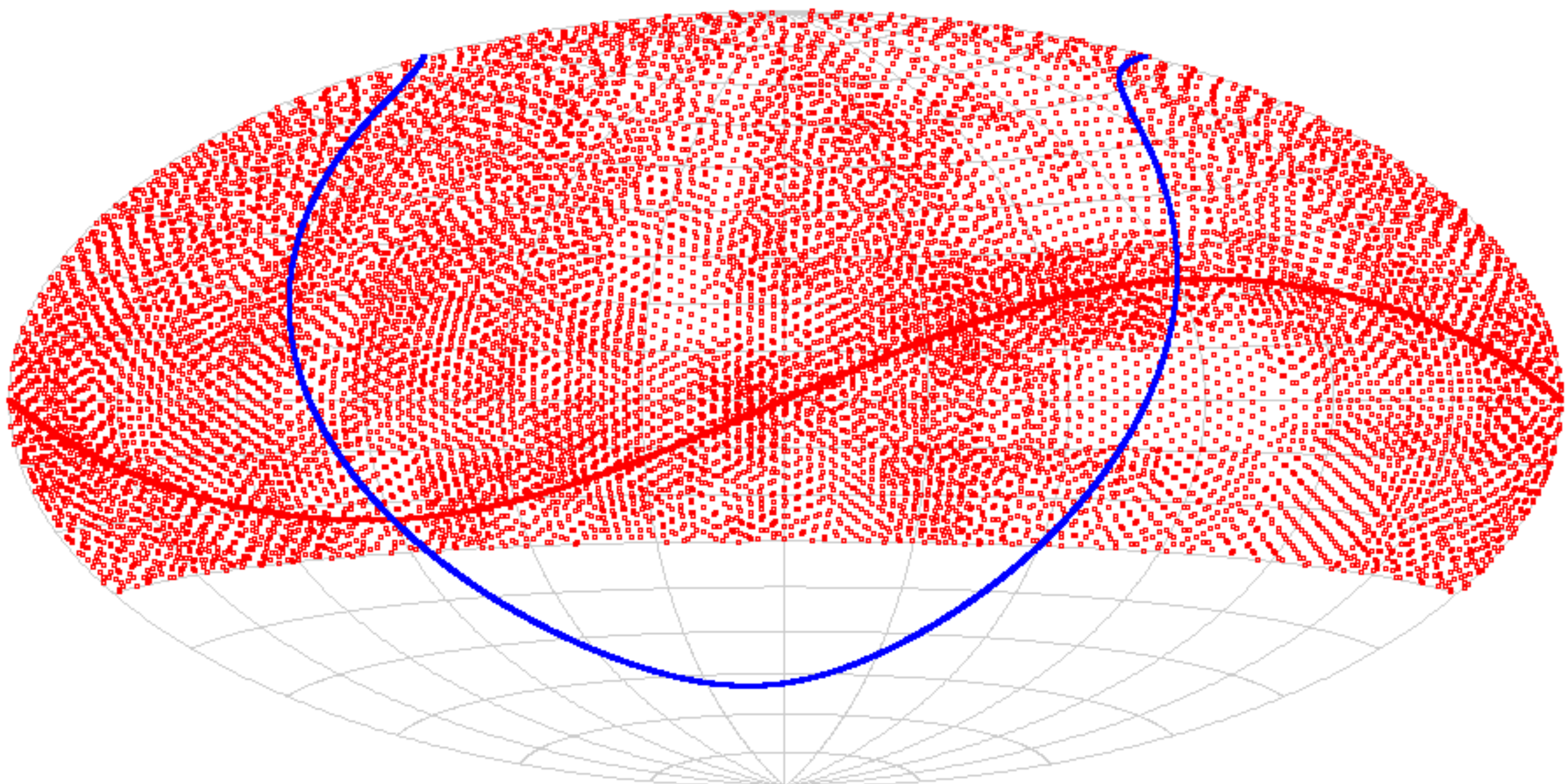
z band

3pi sky coverage to Mar 1, 2012



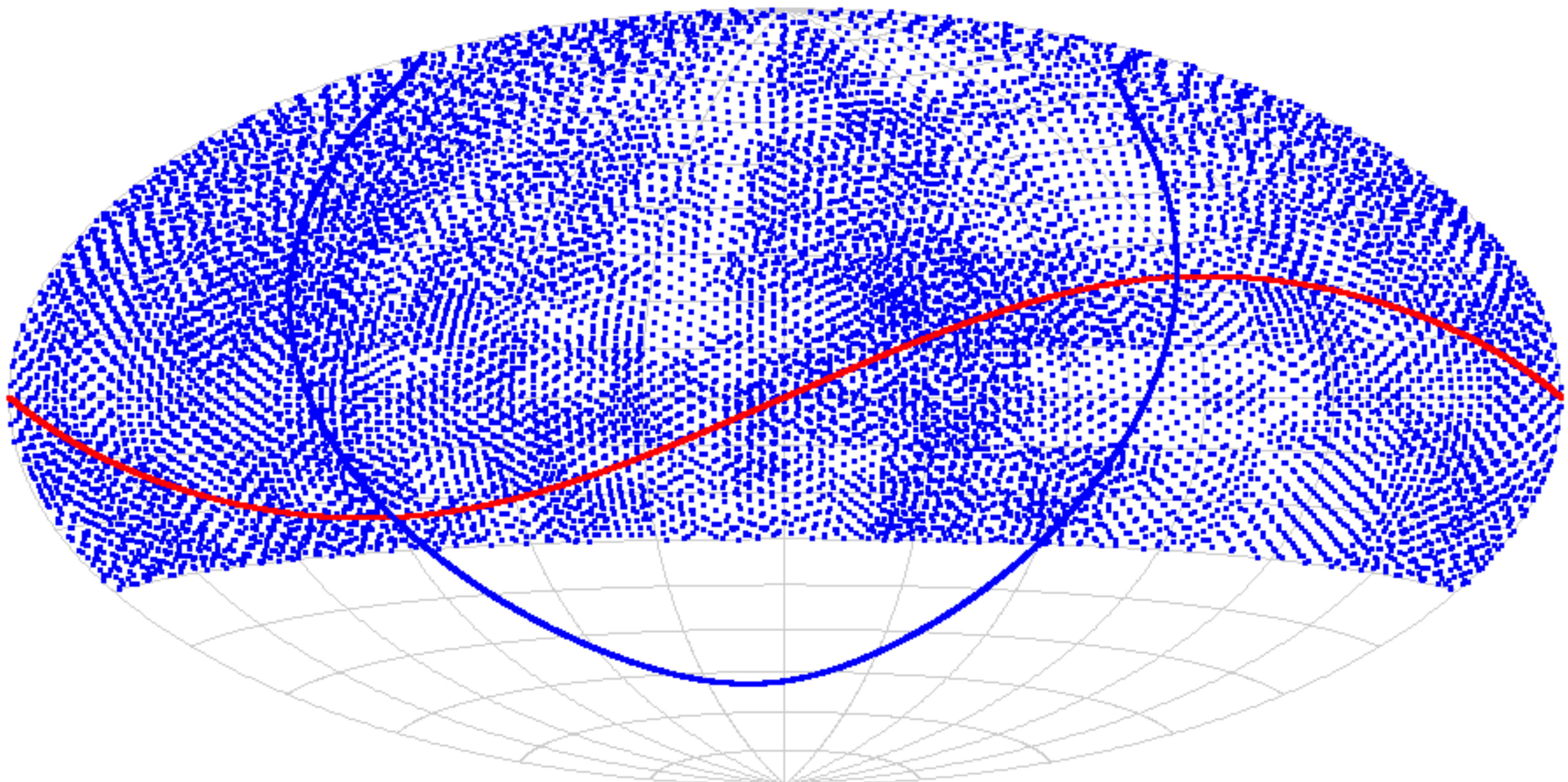
i band

3pi sky coverage to Mar 1, 2012



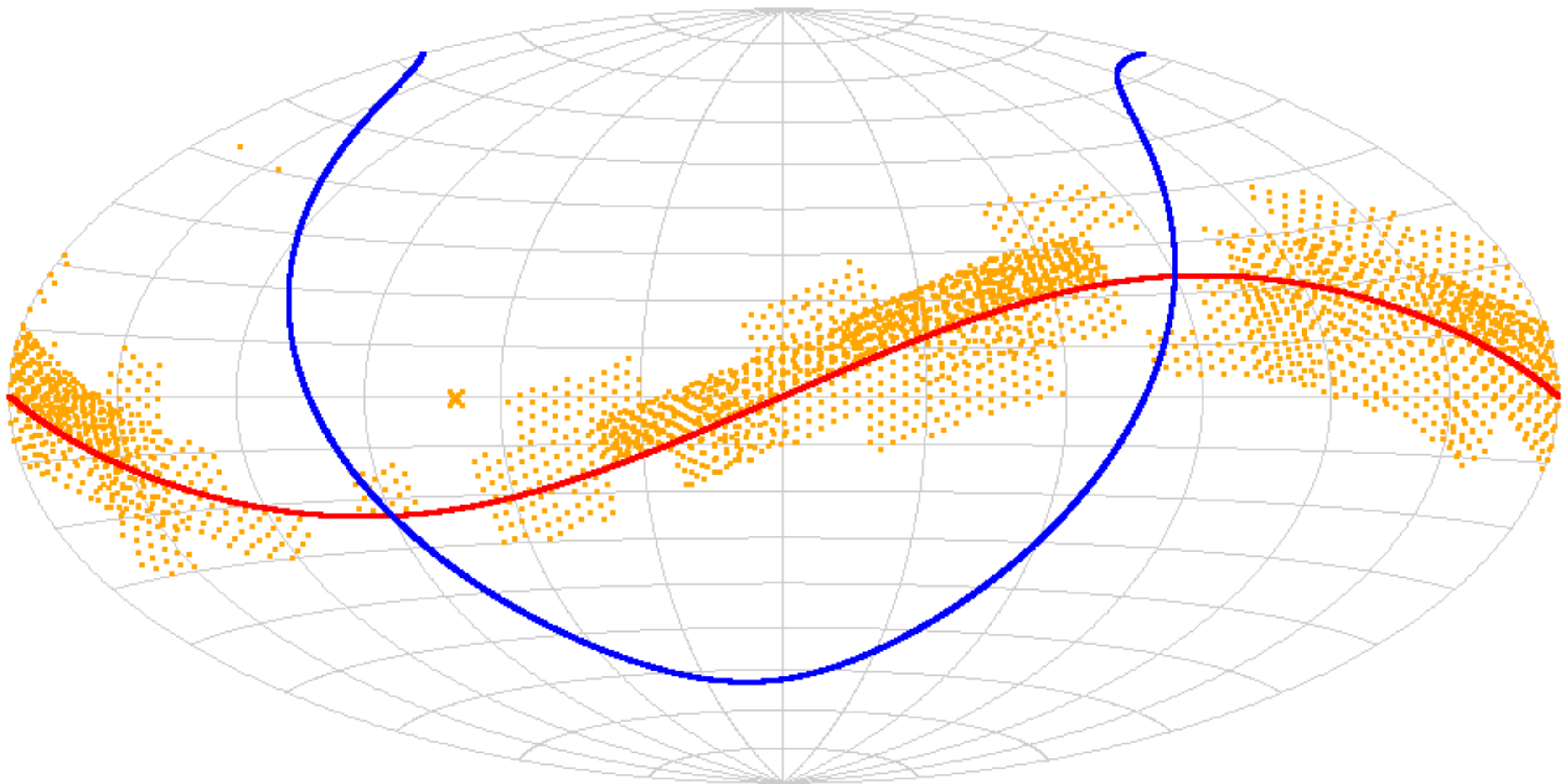
r band

3pi sky coverage to Jan 1, 2012



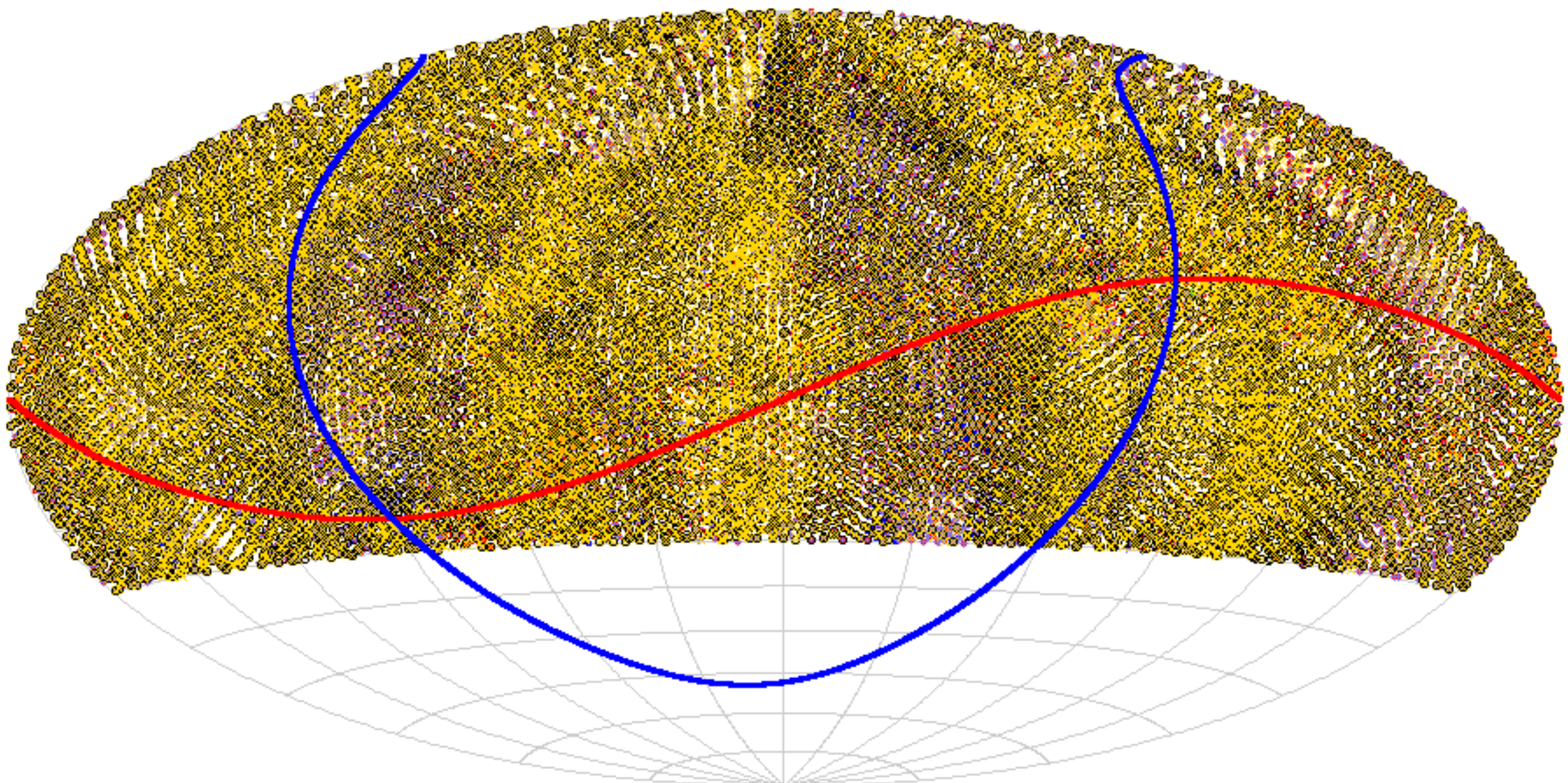
g band

Ecliptic plane coverage to Mar 1, 2012



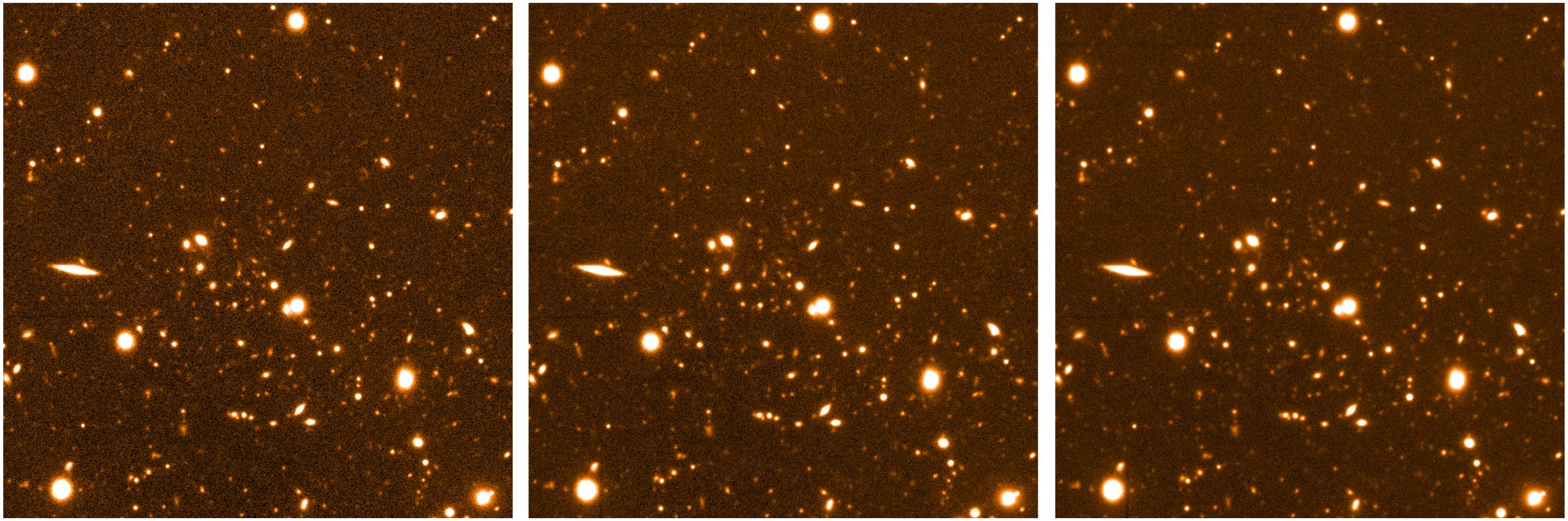
w band

Total 3pi sky coverage to Mar 1, 2012



grizy bands - more than 33 epochs on average, or >~ 6 per filter

MD04 – comparison of template and convolved



92 warps (0.9" FWHM), 206 warps (1.05"), 306 warps (1.15").

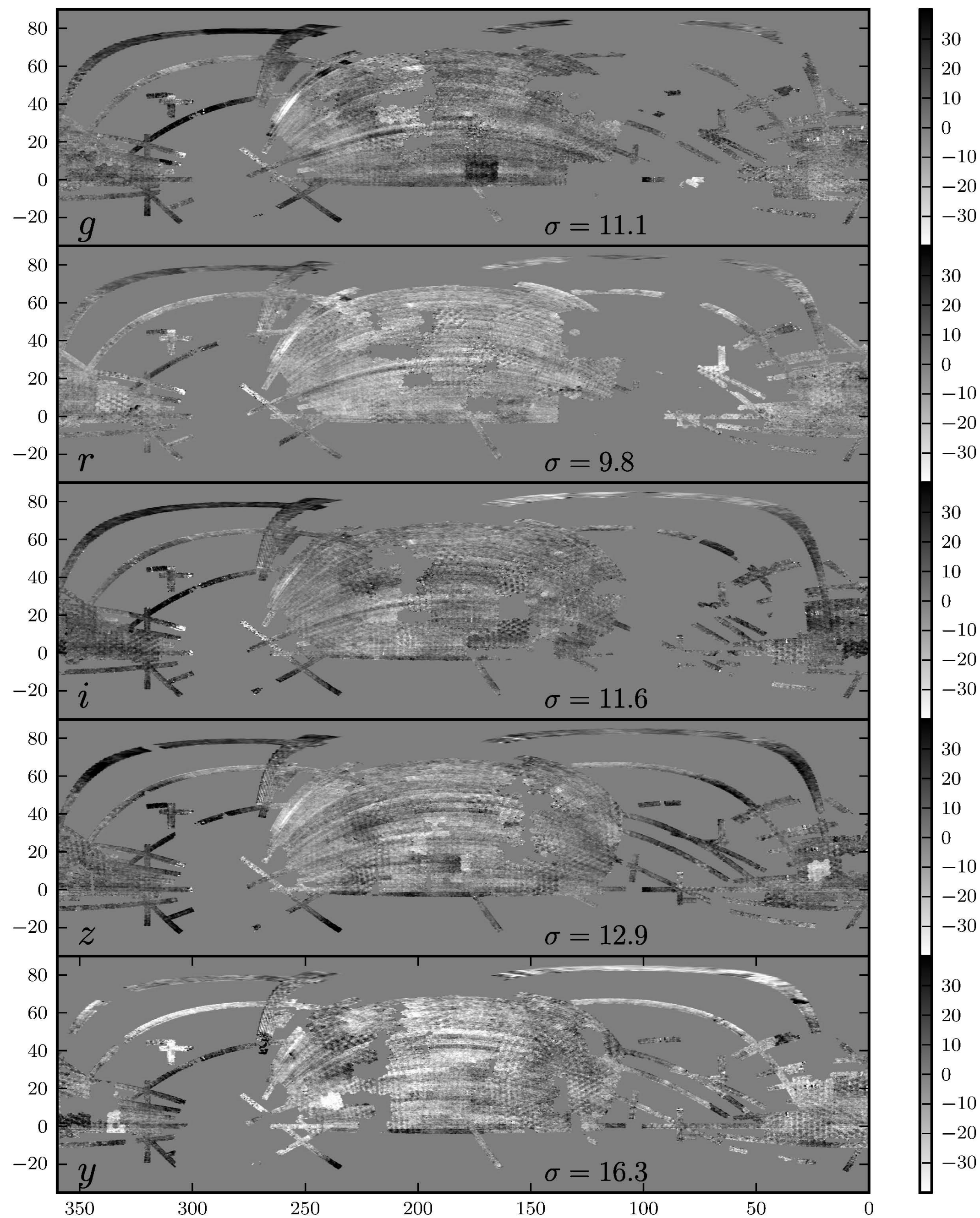
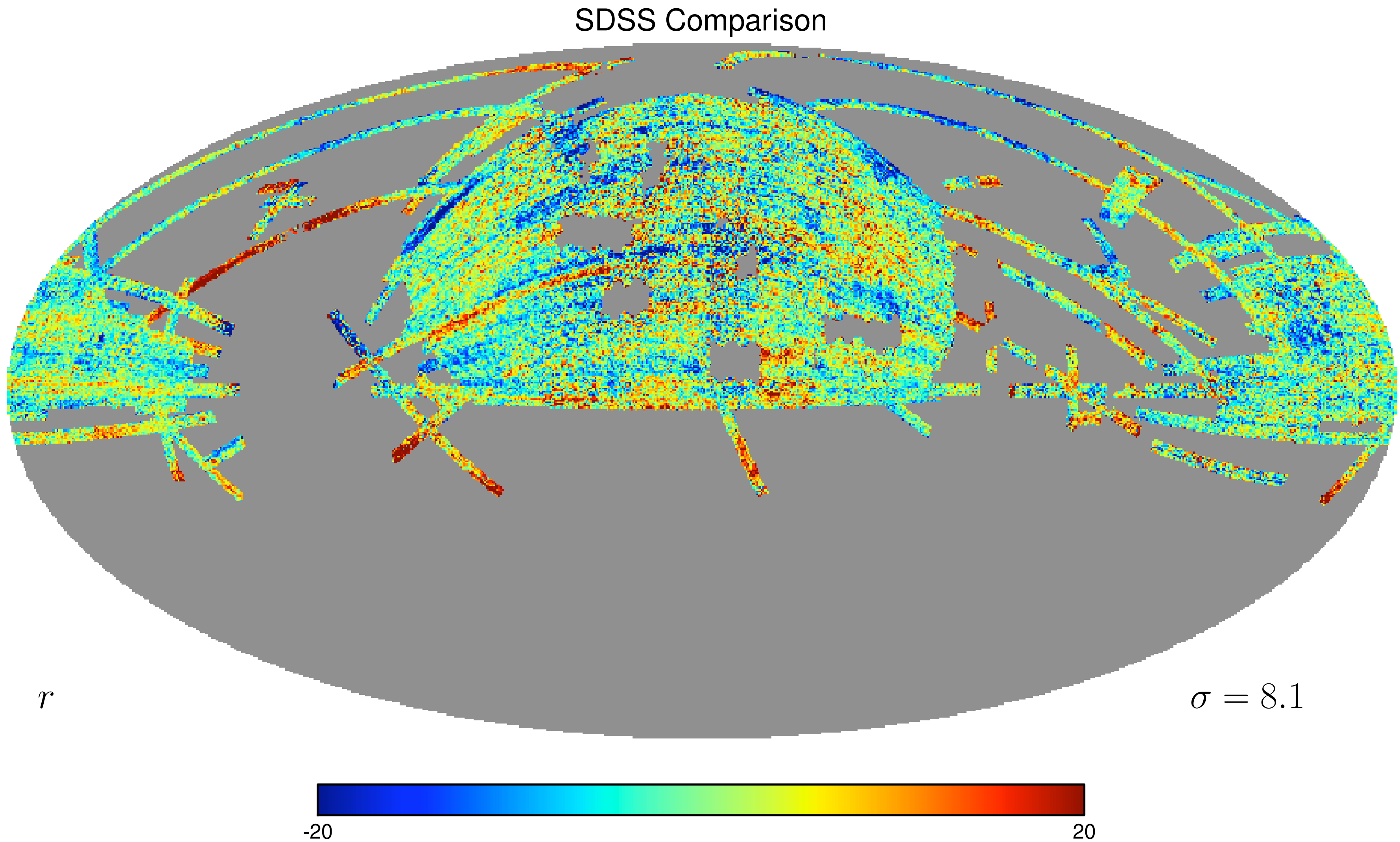
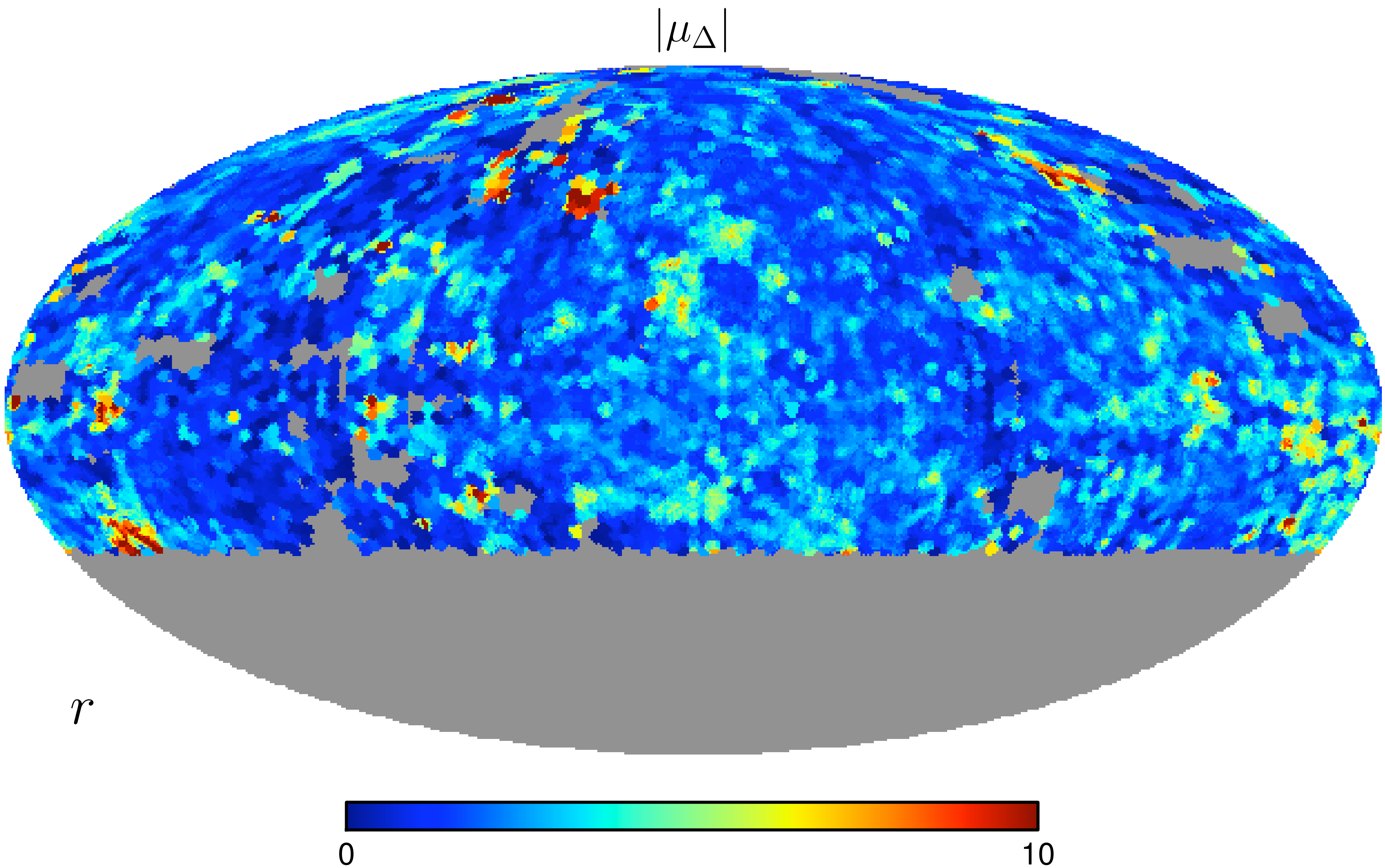


FIG. 5.— Maps of the difference between the color-corrected SDSS magnitudes of stars and the internally-calibrated Pan-STARRS1 magnitudes of the same stars in the filters $grizy_{\rm P1}$ (rows). The x-axes give right ascension and the y-axes give declination. The rms of the maps is about 10 mmag. Narrow stripes in right ascension are symptomatic of problems with the SDSS photometric calibration, while rectangles in right ascension and declination indicate problems with the PS1 calibration.


SDSS Comparison
r
σ = 8.1
-20
20

PS1 zero-point rms milli-mags (Jan 2012)



PS1 Operations

The PS1 System consists of:

PS1 Telescope and GIgapixel camera, at Summit of Haleakala

The observatory is operated from the PS1SC Remote Control Center at the ATRC, IfA in Pukalani, Maui

Reduced images and object catalogs, and data products are produced by the Image Processing Pipeline at the Maui High Performance Computing Center in Kihei,Maui.

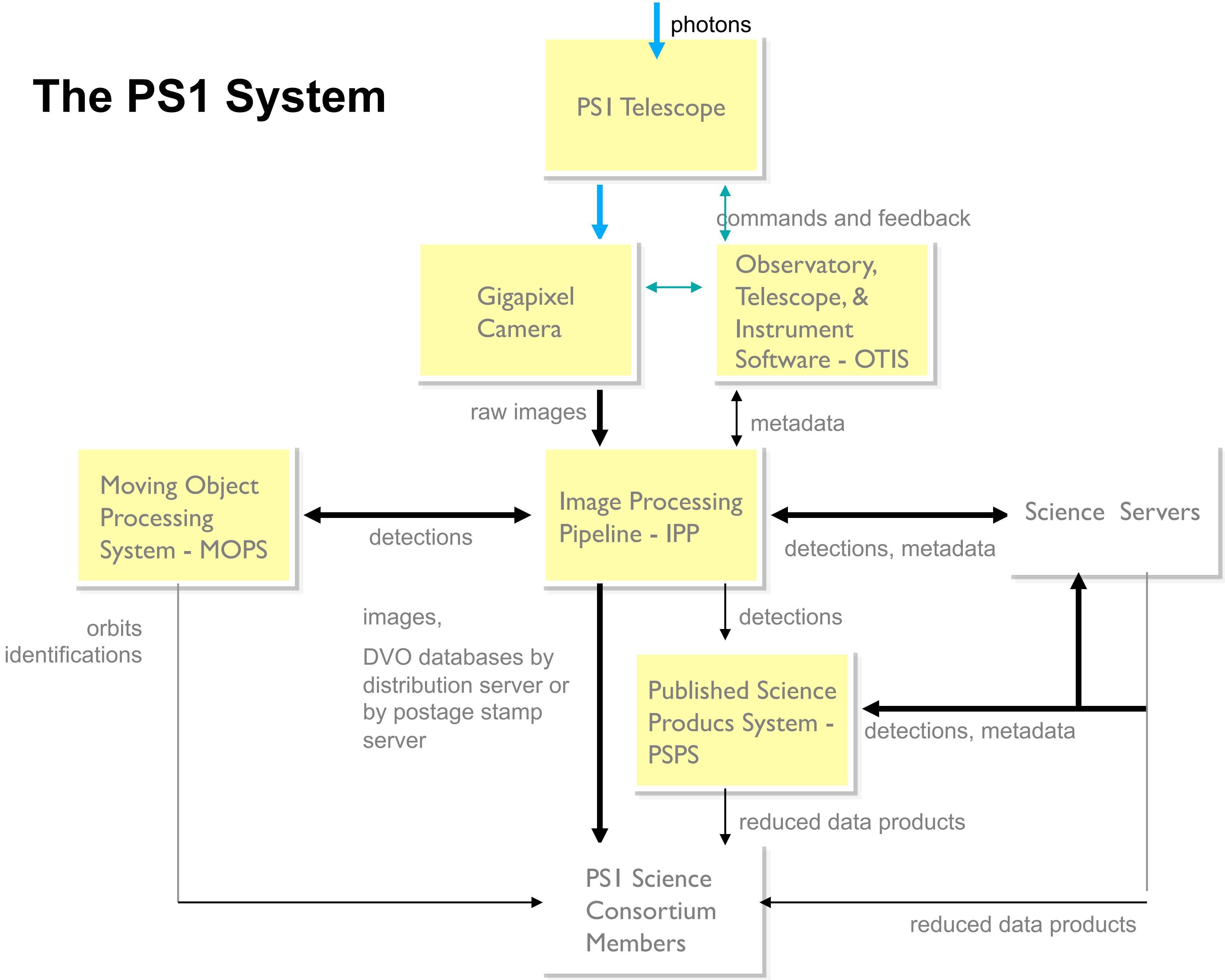
Data Reduction and Processing overseen from IfA Manoa on Oahu.

Data products sent by internet to Scientists of PS1SC

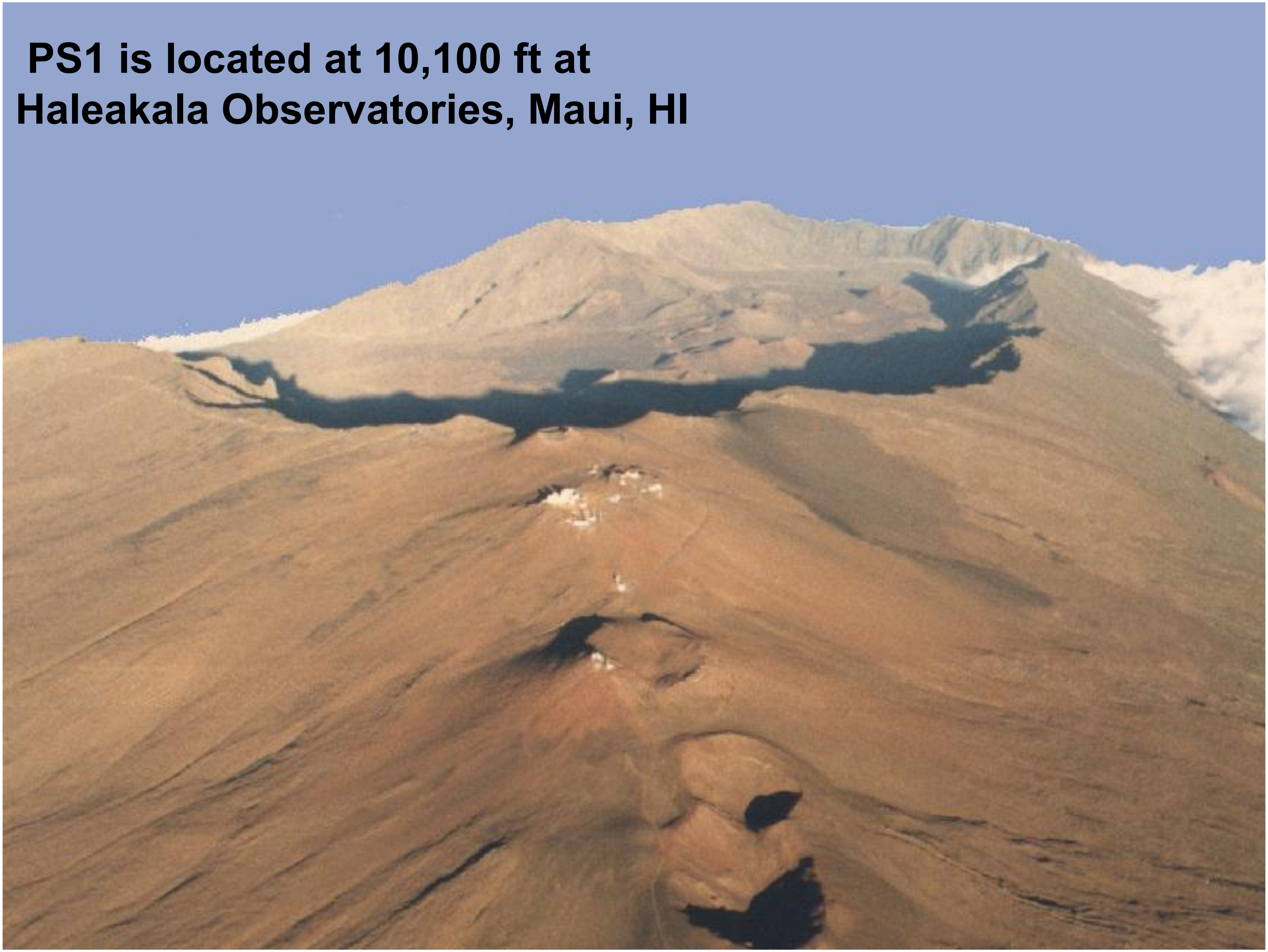
Pan-STARRS
PS1 Science Consortium

Data products **eventually** released to the world community.

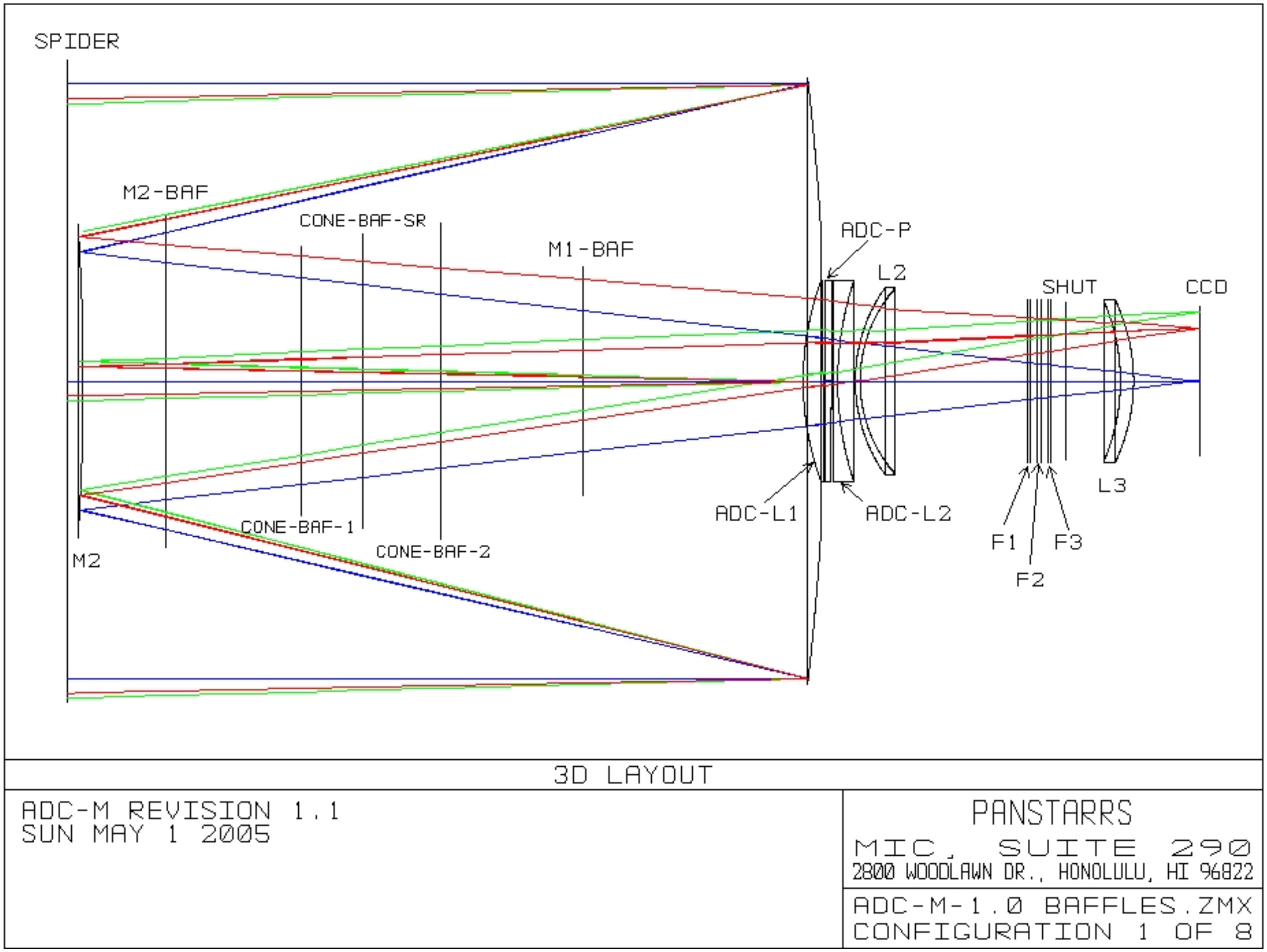
The PS1 System

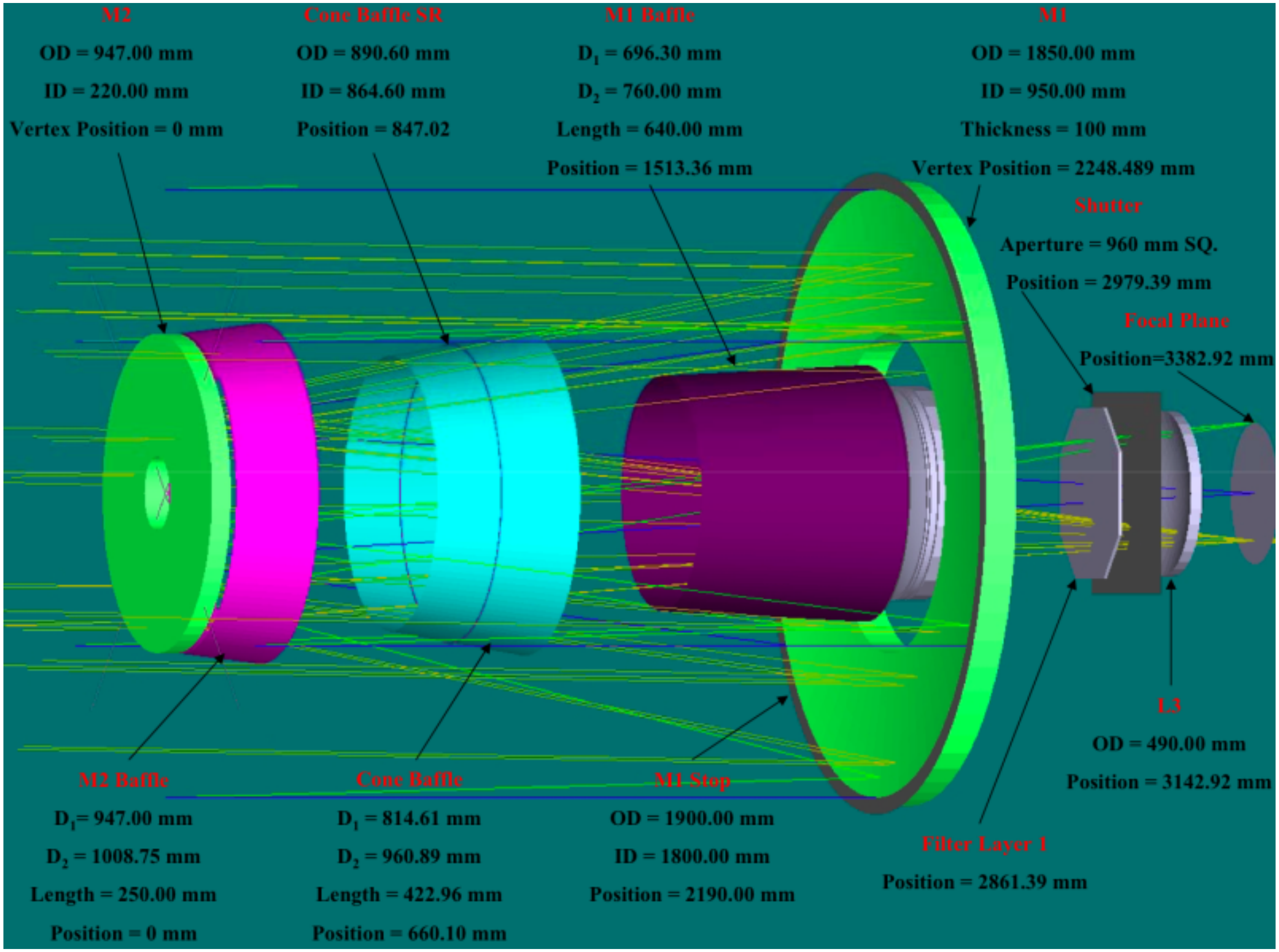


PS1 is located at 10,100 ft at Haleakala Observatories, Maui, HI



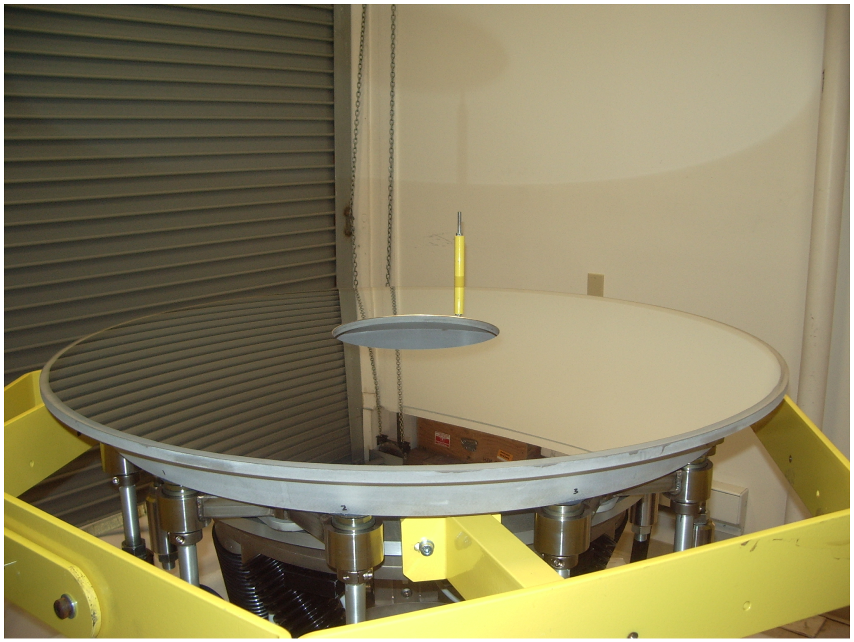
PS-1 Optical Desgin:
Ritchey-Chretien with 3 element Wide Field Corrector



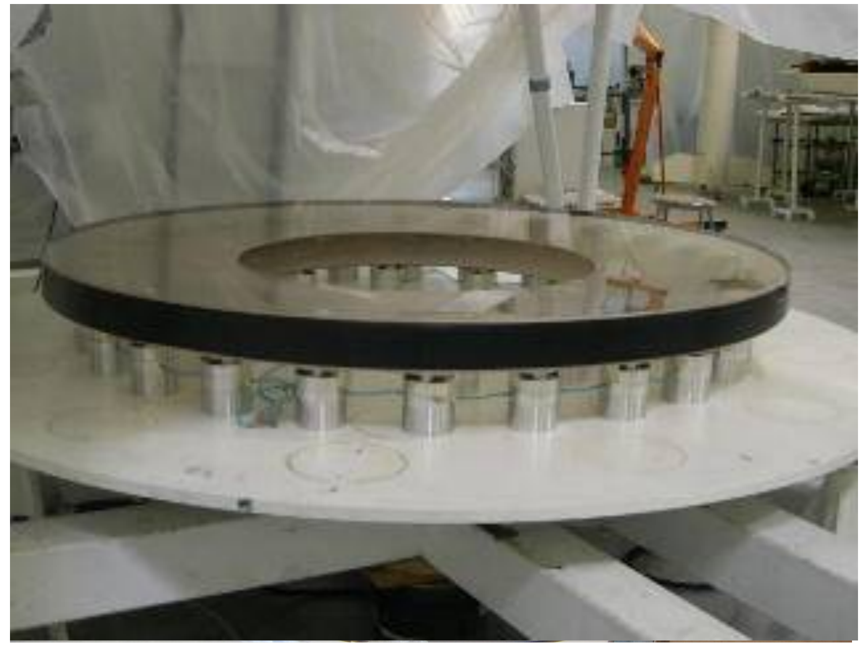


- The telescope has 2 mirrors and lenses and a focal plane giving a total of 5x5 + 3 -1 = 27 degrees of freedom for positioning.
- These elements need to be positioned to great precision (few hundred micron precision in some cases)

PS1 Optical Elements: Mirrors

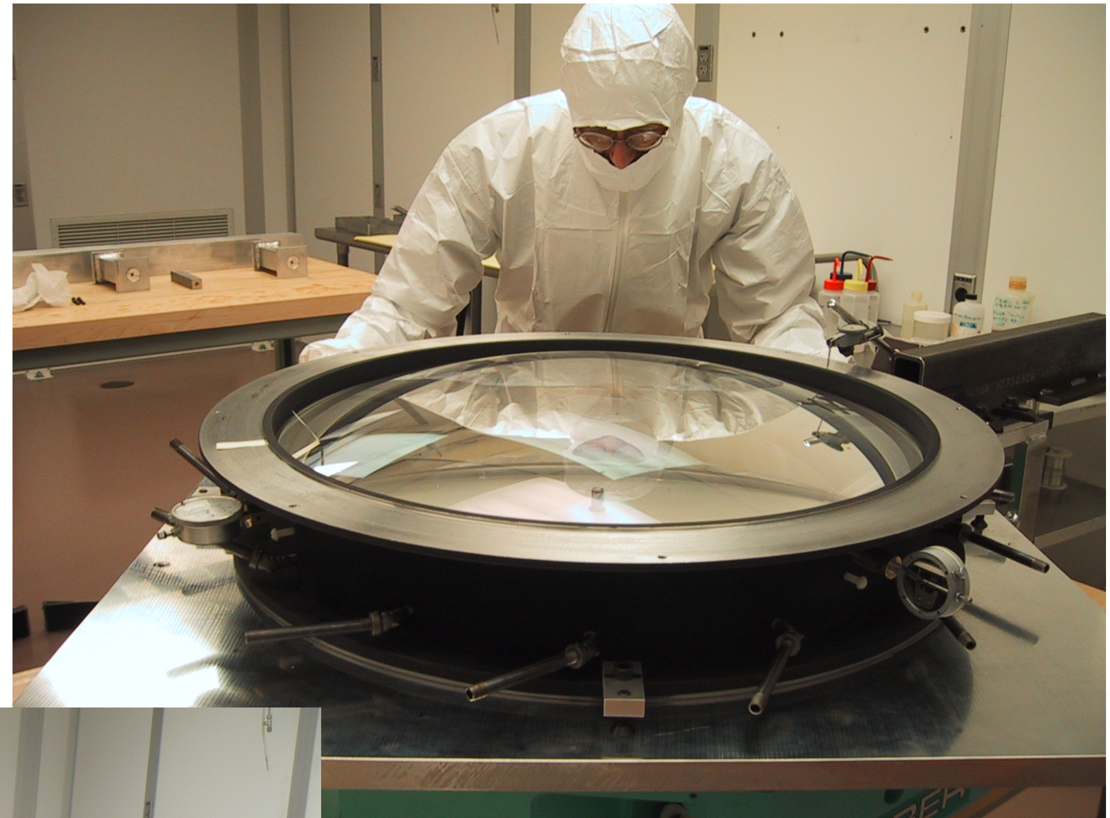


M2a Secondary Mirror after flexure bonding, being prepared for lift into enclosure
Protected silver coating.

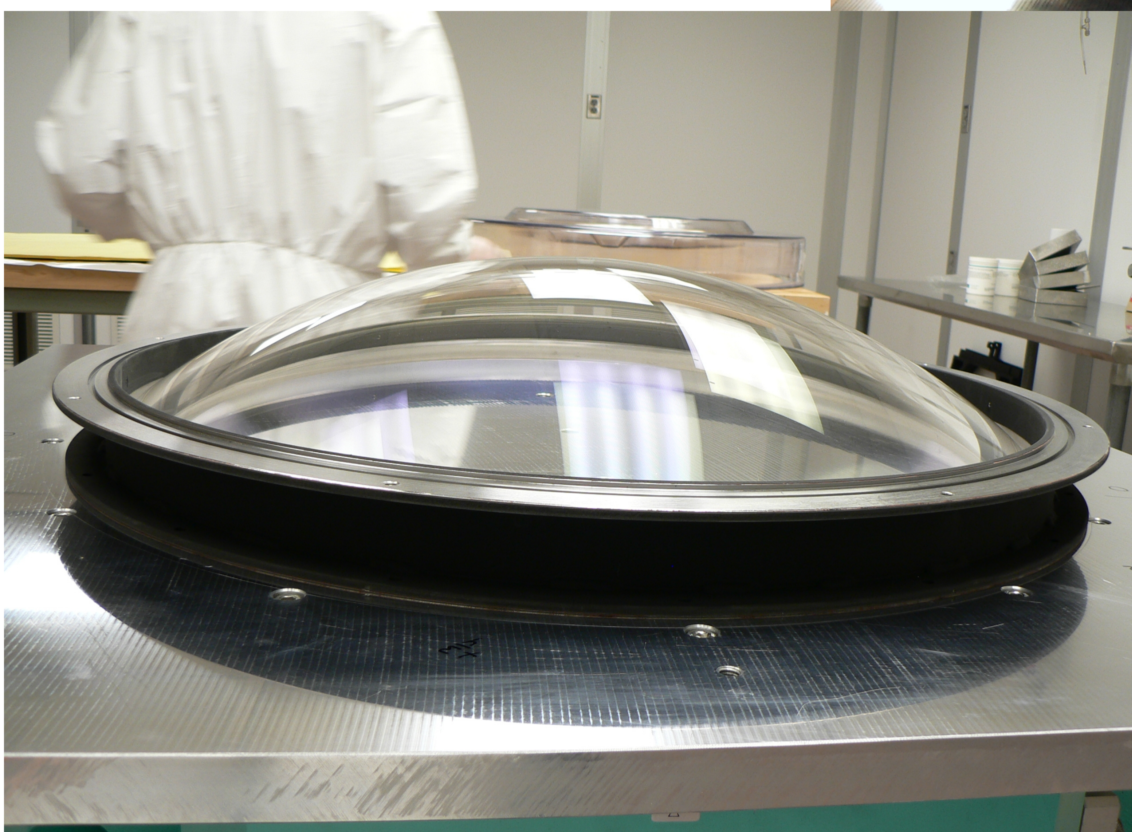


M1 Primary Mirror with protected aluminum coating prior to lift into enclosure

Corrector Optics

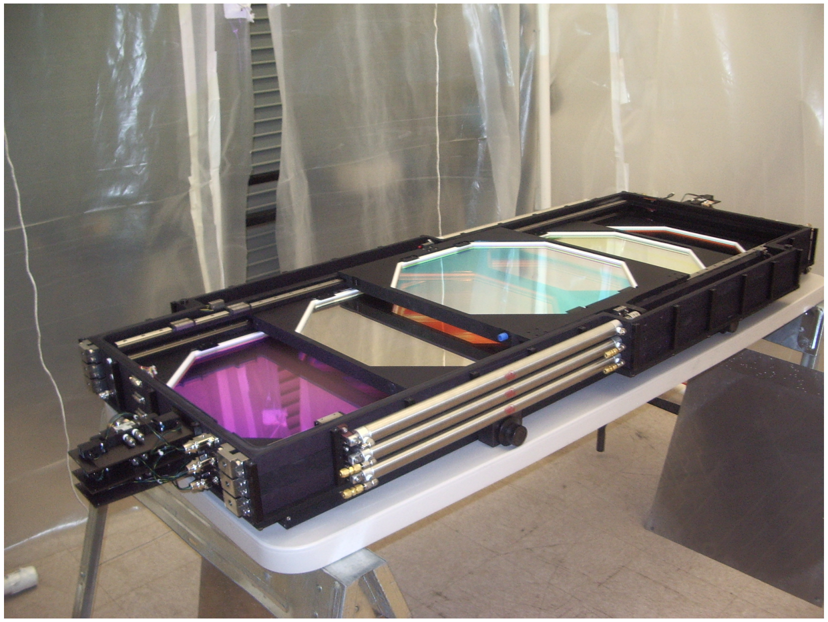


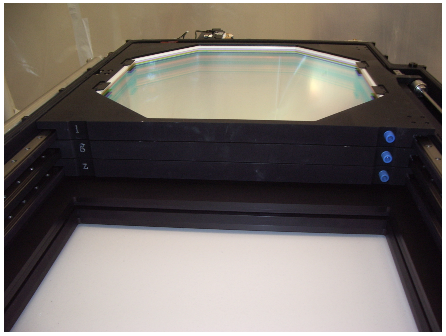
L1

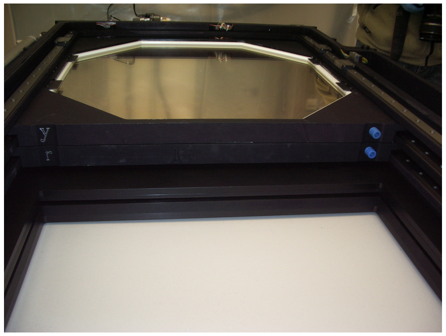


L2

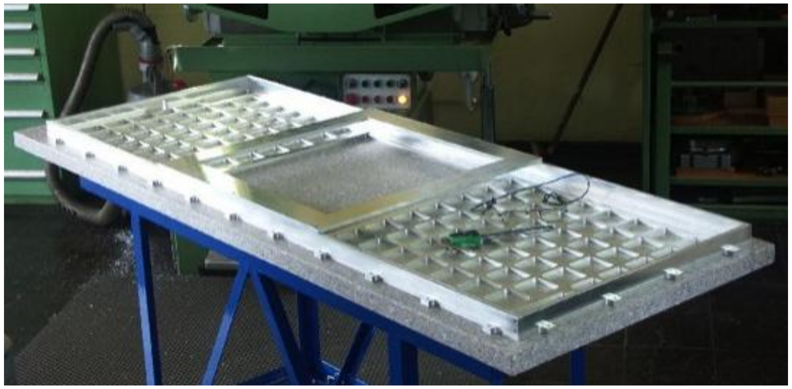
PS1 Filter Mechanism and interference filters







PS1 Precision Large Aperture Twin Blade Shutter



Carbon fiber construction

40 cm aperture

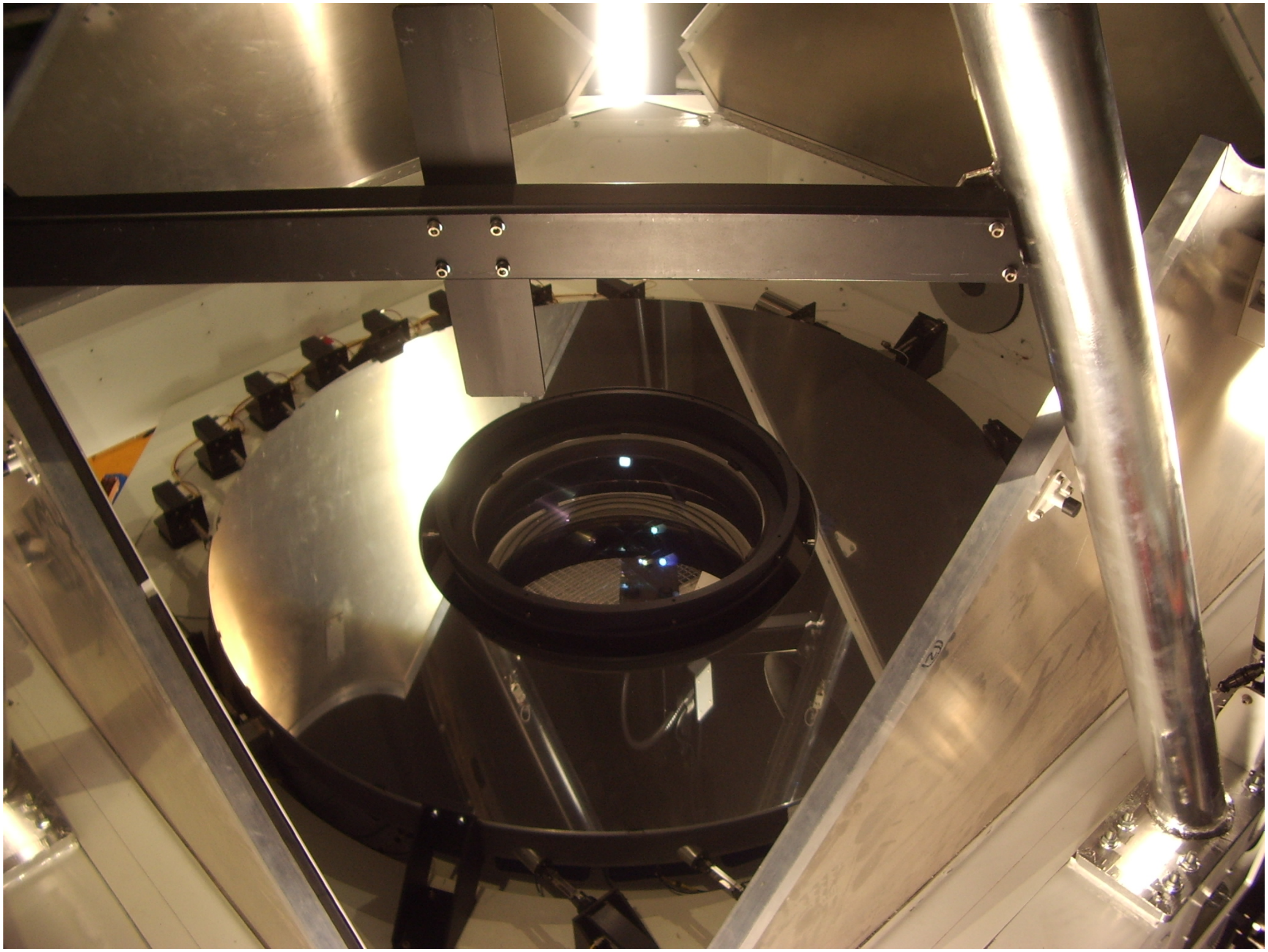
Blade trajectory repeatable

to 10 millisec!

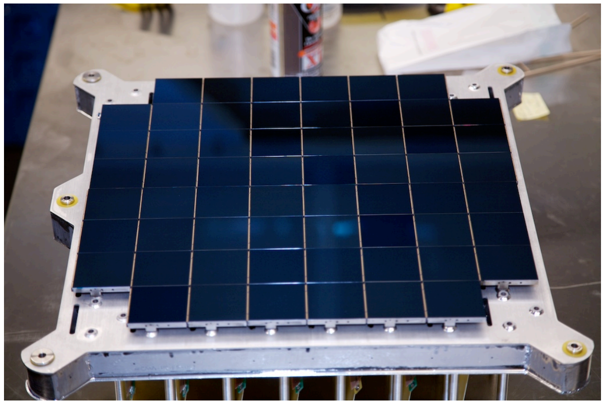
Timing interface with GPS

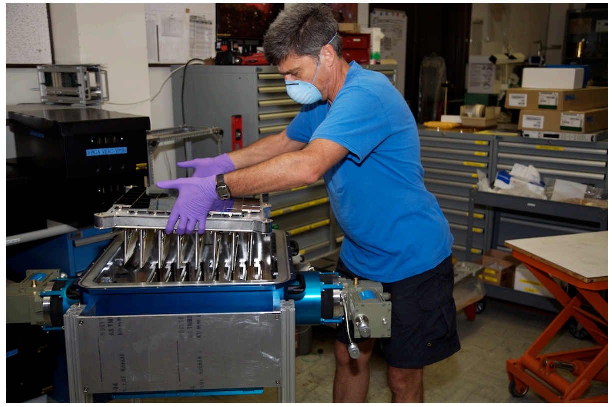
University of Bonn

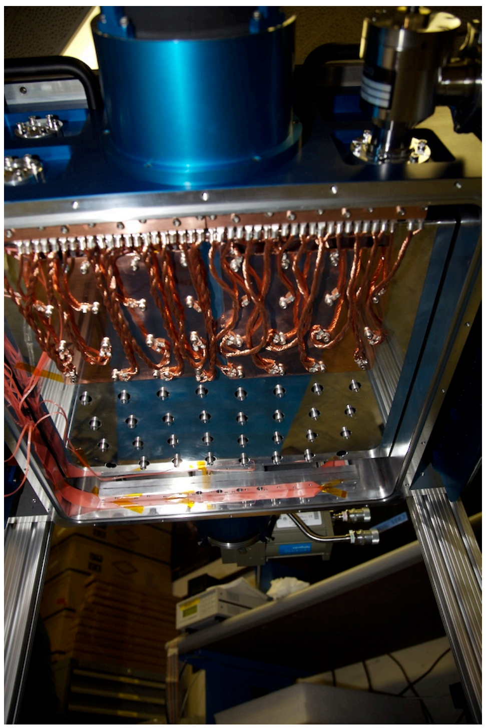
Integration of Upper Cass Core, L1, L2

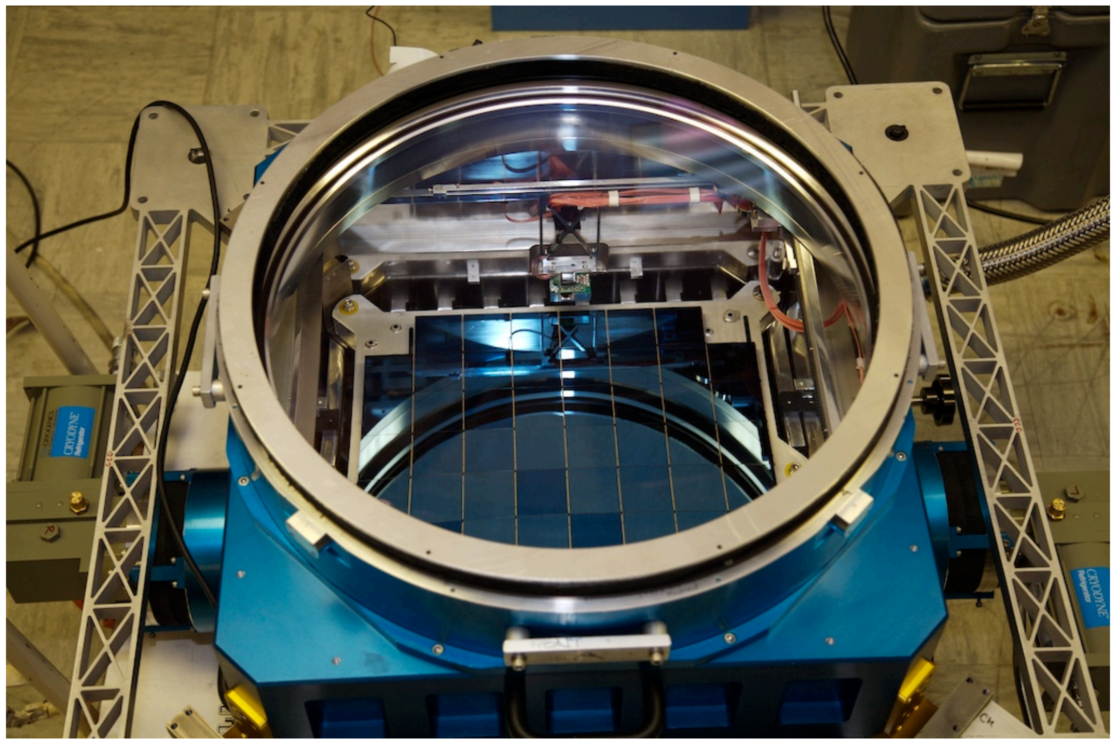


1.4 Gigapixel Camera Assembly with L3 Corrector Lens as Dewar Window

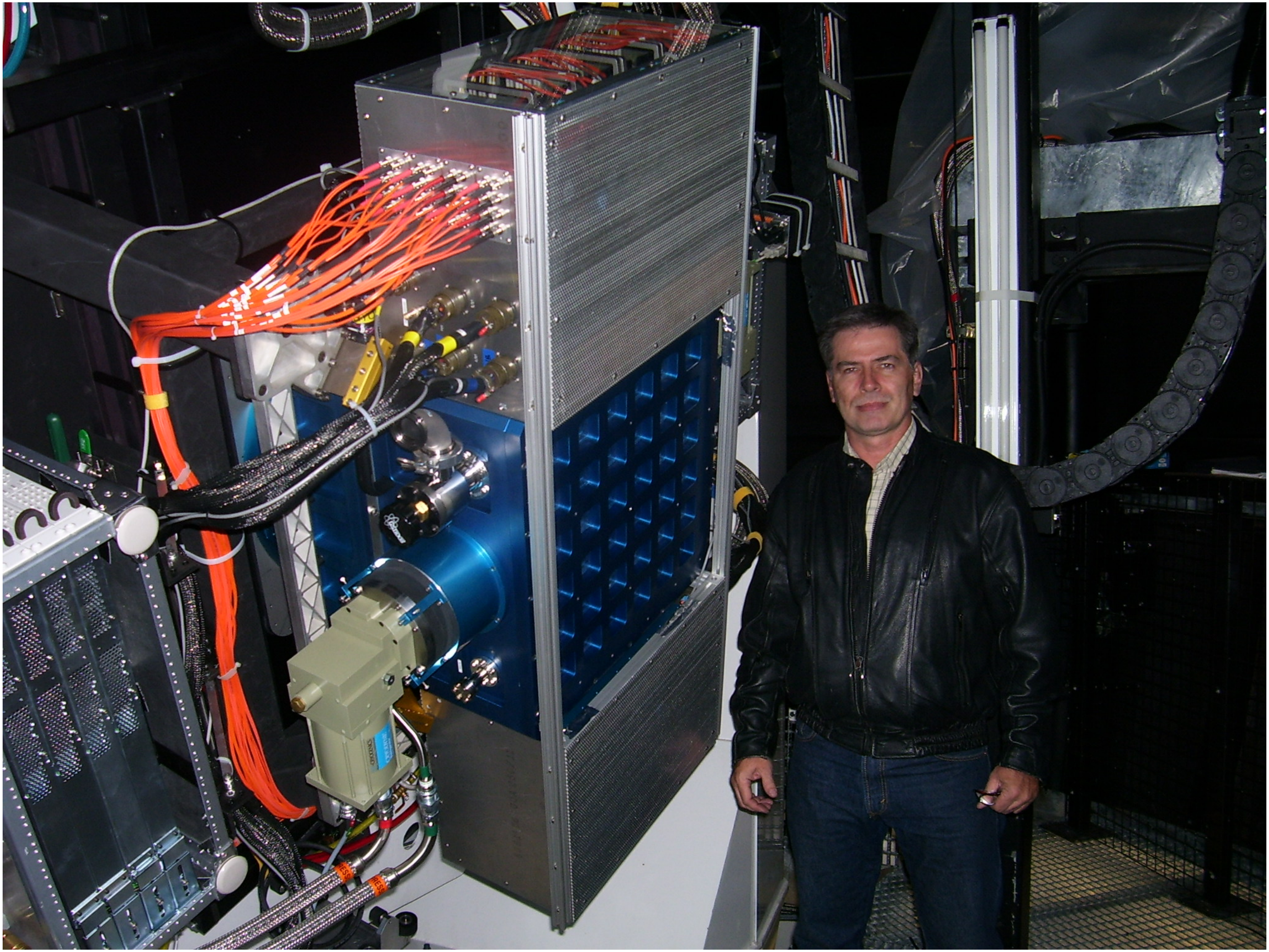




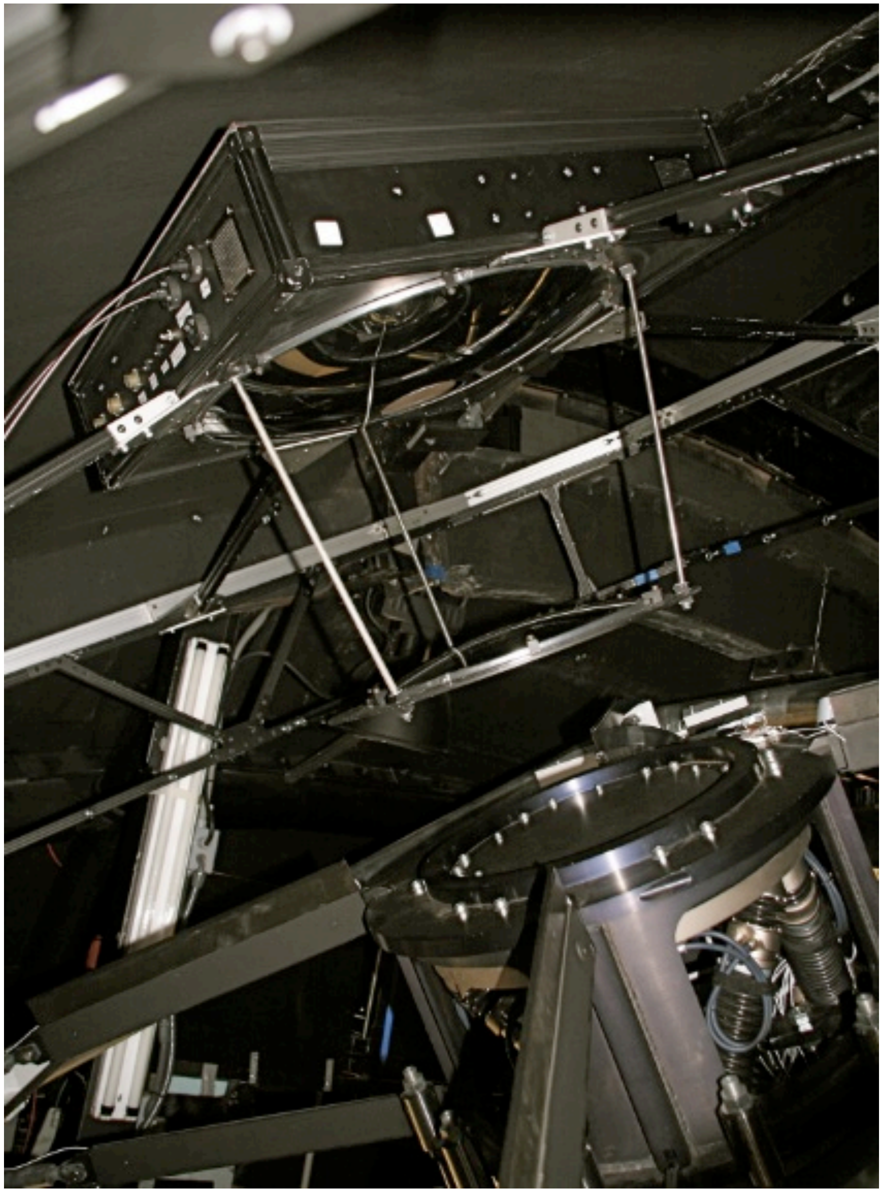


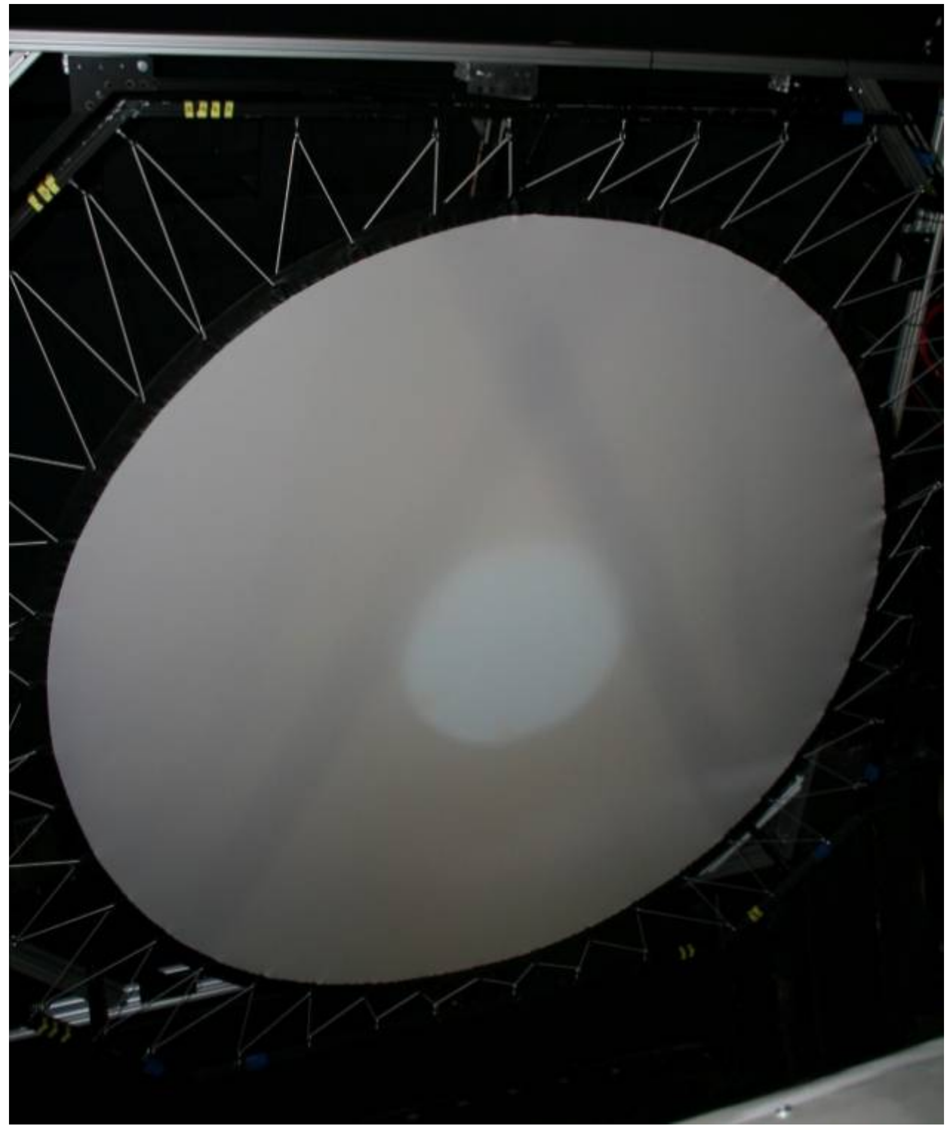


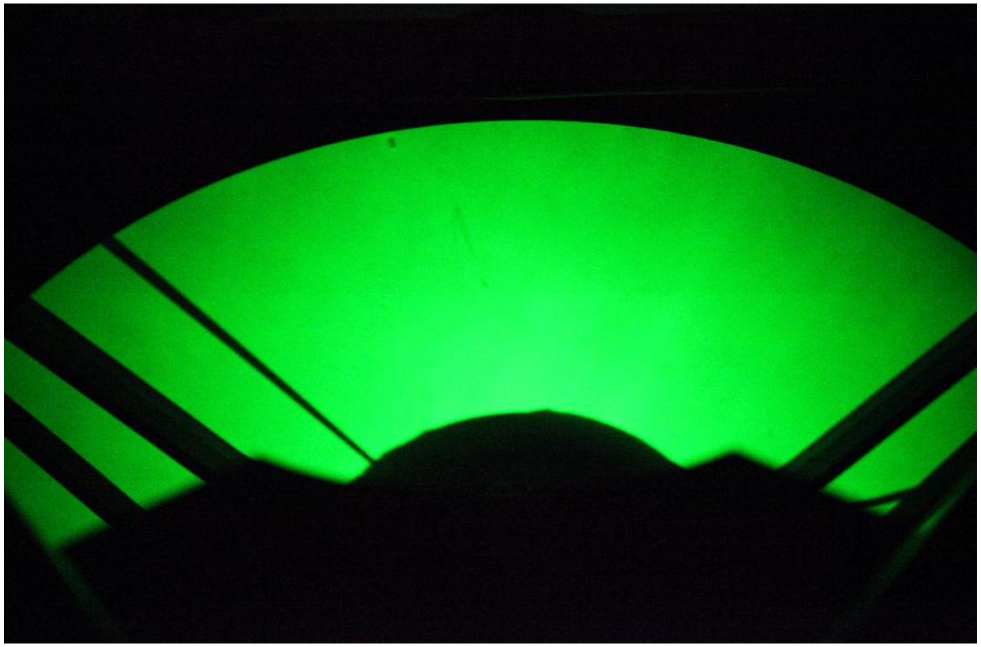

FRONT
FRONT

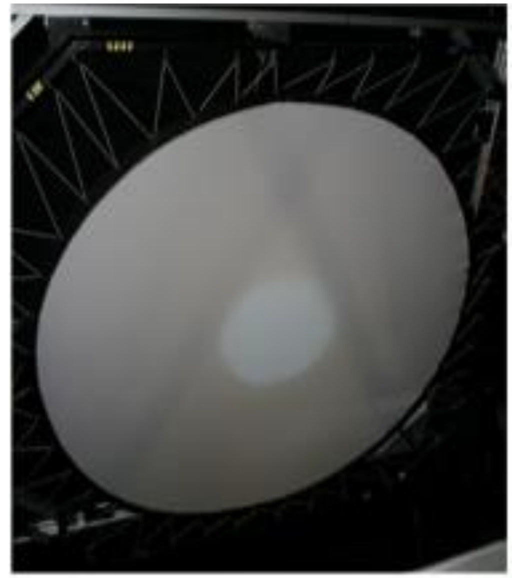


PS1 Calibration Unit – back illuminated screen with projector fiber fed from NIST tunable laser - Measure the system throughtput as a function of wavelength for every pixel every day.









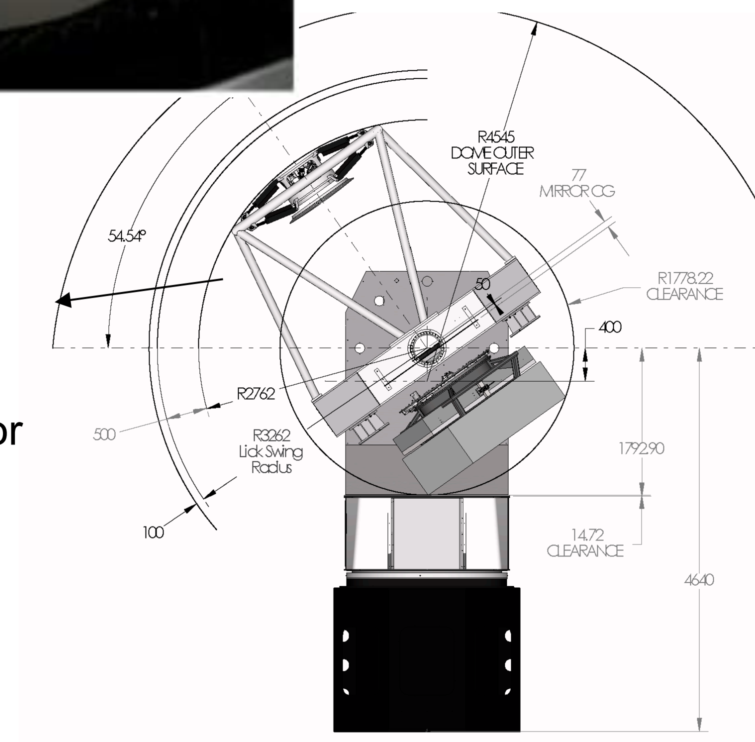
PS1 Calibration Screen
(Chris Stubbs + NIST)

Illuminate a screen with monochromatic light from NIST laser that can be tuned over the entire 400nm-1020nm wavelength range of PS1

Measure the system throughtput as a function of wavelength for every pixel.

Monitor with with white light flats.

->improved calibration

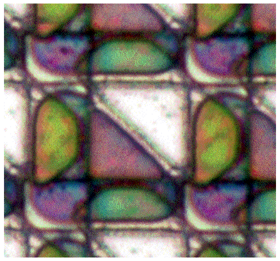


PS1 Remote Operations Center

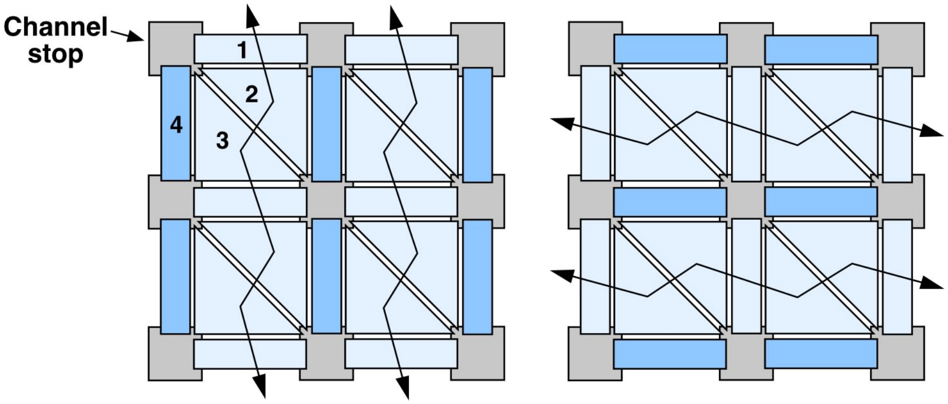
UH Institute for Astronomy
Advanced Technology Research Center, Pukalani , Maui

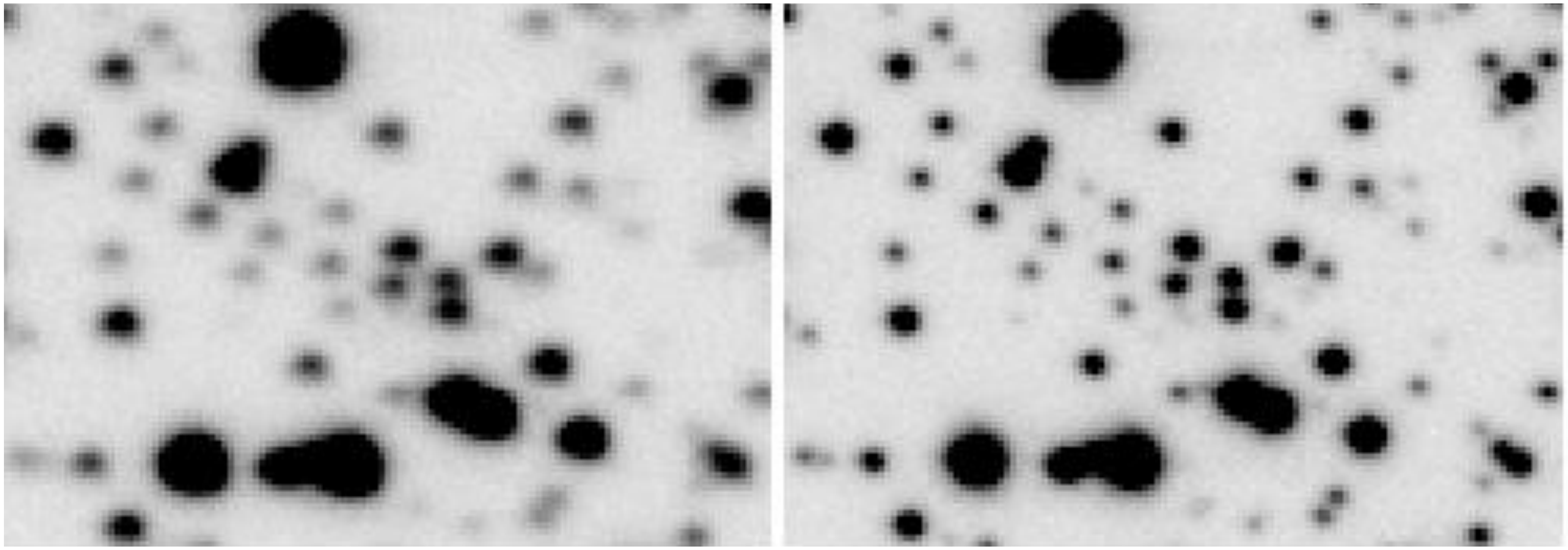
New Detector Technology with

Tonry’s Orthogonal Transfer Arrays



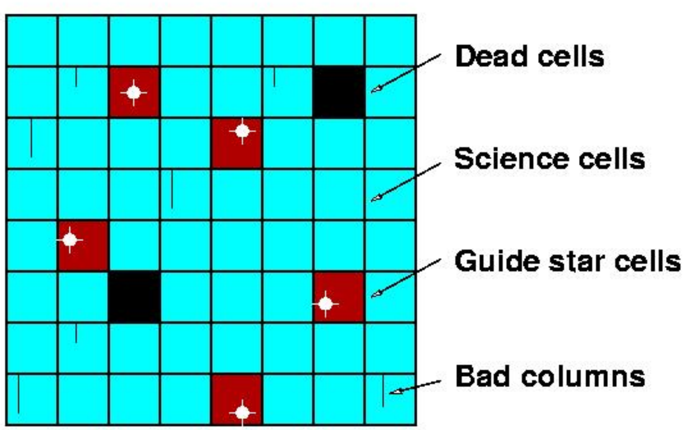
- Orthogonal Transfer Array: A new pixel/CCD chip design to noiselessly remove image motion at high speed (~10 usec)

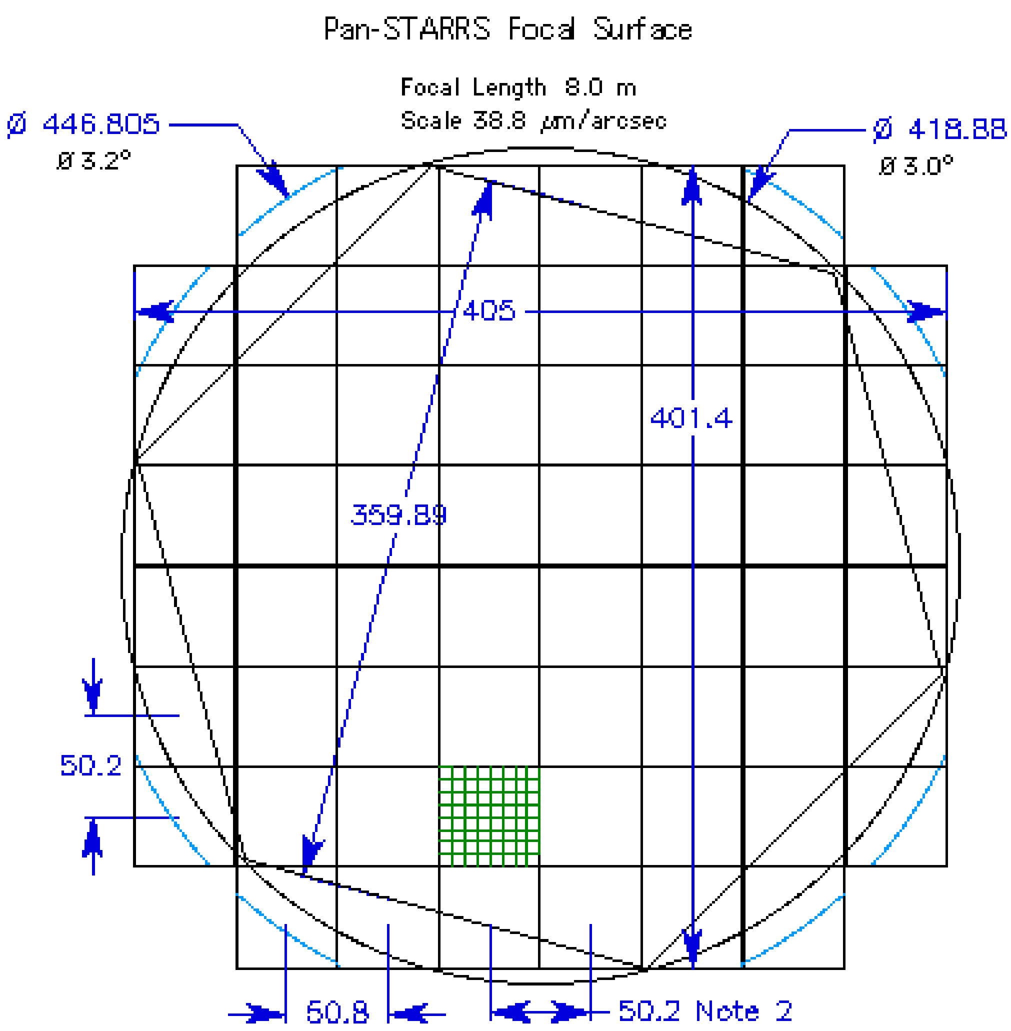




The PS1 Focal Plane

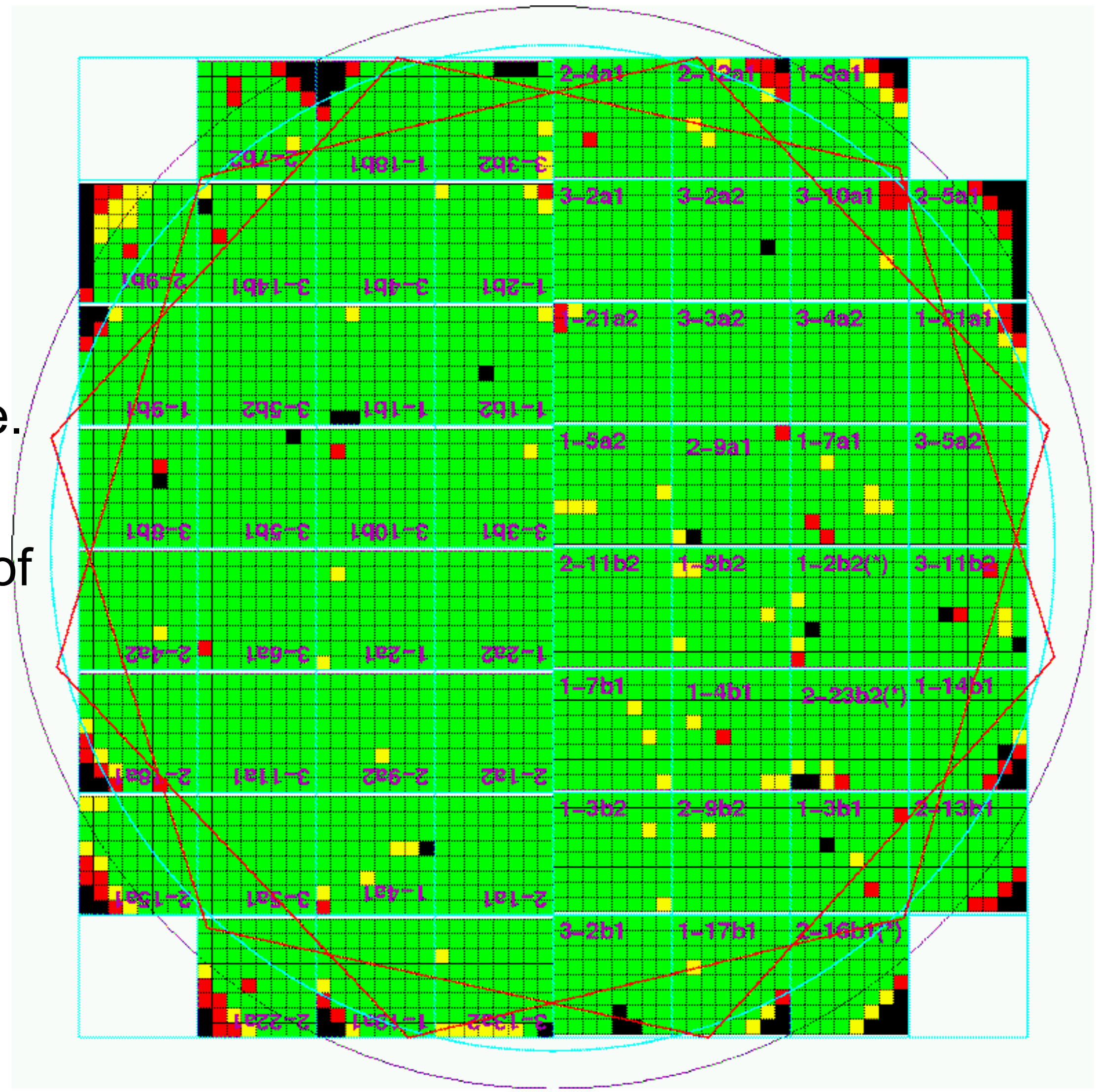
- The 1.4 Gigapixel Camera is an array of arrays.
- Each OTA chip can assign any 600x600 cell to be read at video rates for a guide star signal.
- Guide star signals can command local cells to track motion of guide stars.





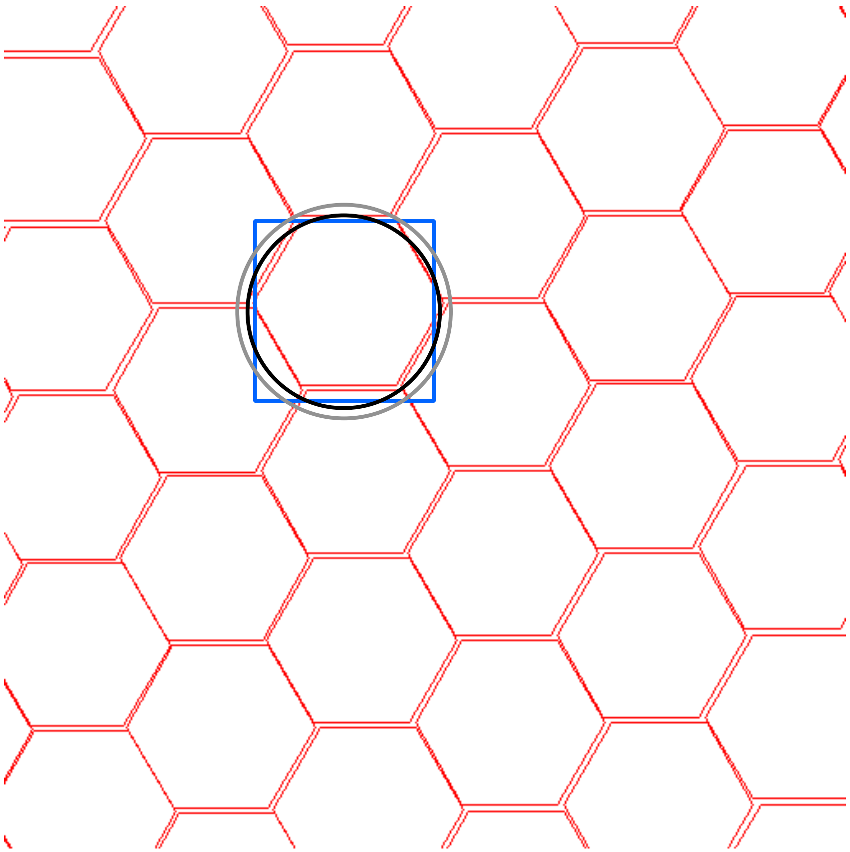
GPC1 Focal Plane and "Image" Format

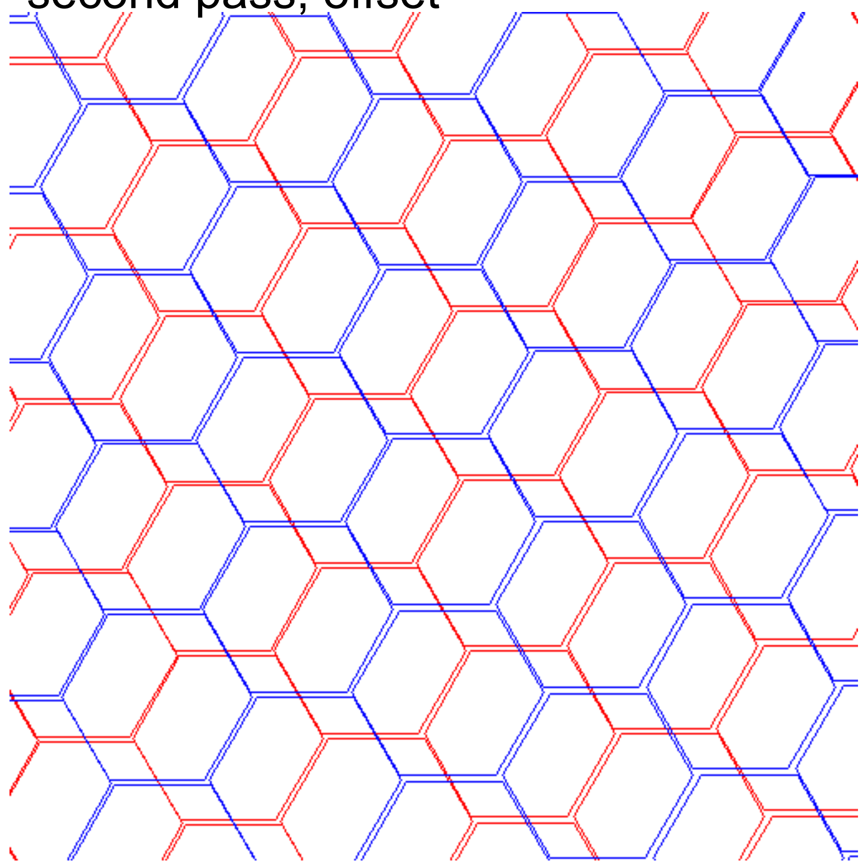
- A GPC "Exposure"
  - Data from 60 OT CCD's with 10 micron pixels
  - Each CCD, 64 cells
  - Up to one cell per CCD can be run in video mode.
  - "Image" is 60 fits files
  - Each FITS file is a cube of 64 images, one of which may itself be a cube of video images.
- Cyan circle = 3º
  - 1.7% loss
- Black circle = 3.3º
  - 3.4% loss



3pi Survey Observing Strategy : Extensive Dithers

- initial tesselation uses quasi-hexagonally spaced bore-sites
- each hex is 3.1 degree diameter
- maximum inscribed hex in focal plane (focal plane rotation)
- ~20% unvignetted area overlap with neighbors in same dither

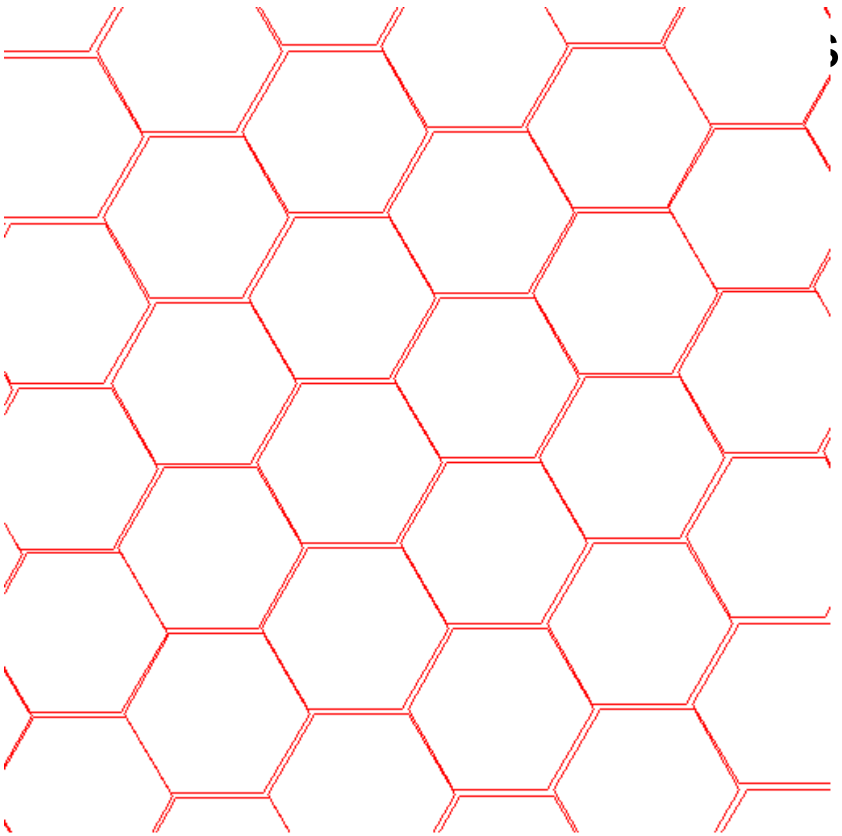




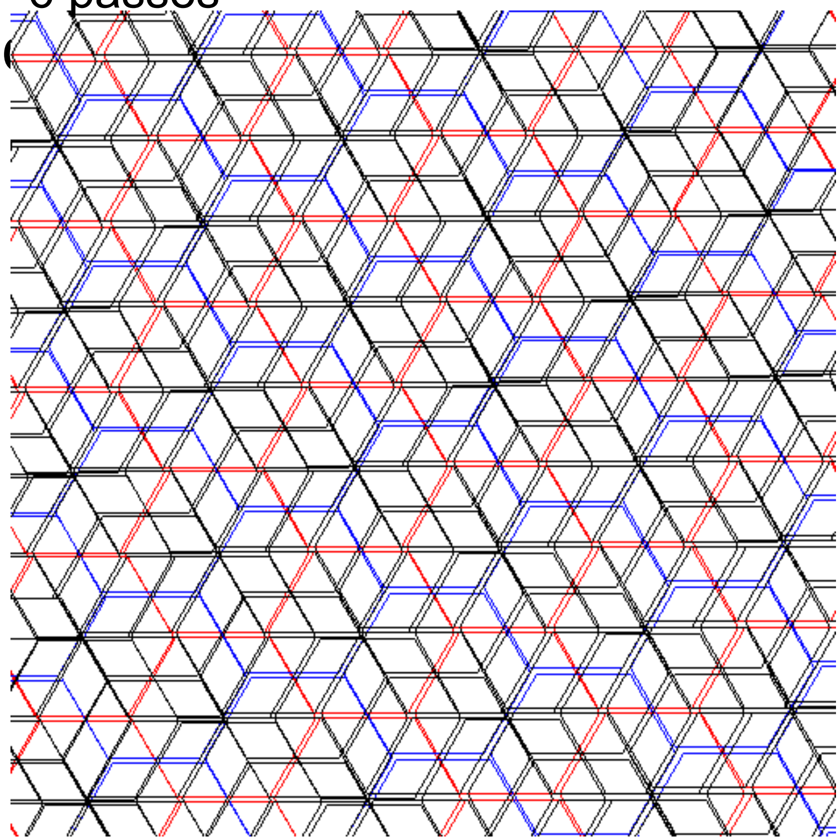
Observing Strategy : Extensive Dithers

- initial tesselation uses hexagon-spaced boresites
- each hex is 3.0 degree diameters (best IQ region)
- maximum inscribed hex in focal plane (focal plane rotation)
- … inc

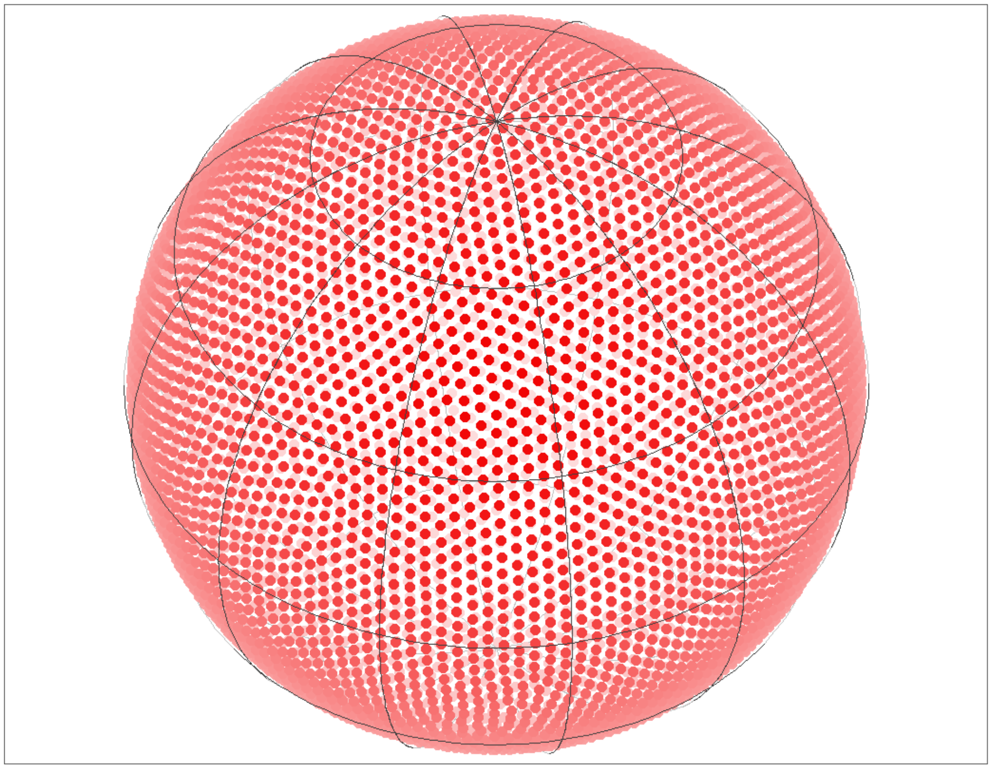
Initial tessalation



6 passes

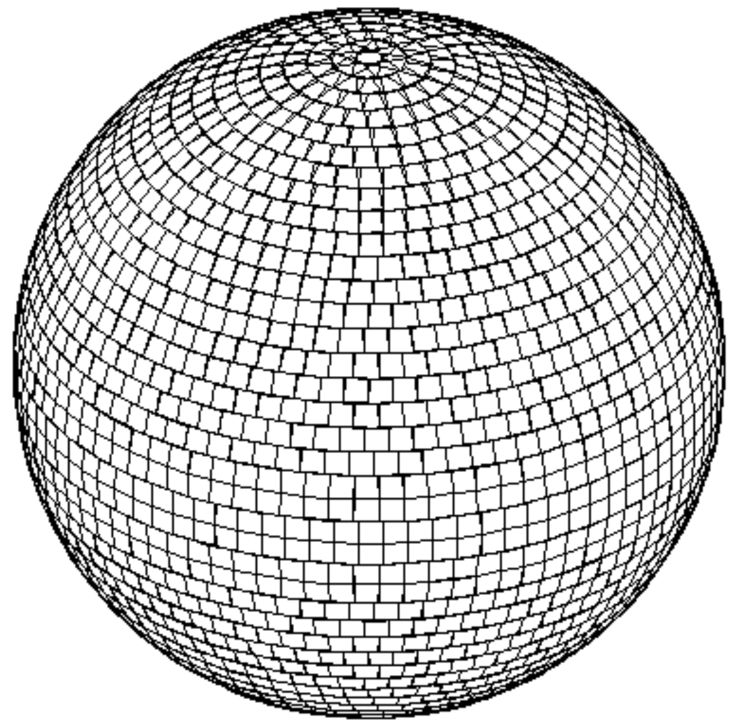


PS1 Observing Tessellation
Optimized to cover the sky
with as few camera footprints
(4432) as possible,
where camera footprints are
approximately hexagonal.



Asymmetric, need multiple realizations
of tesselation to insure overlap.
Camera is rotated to match tesselation,
pixels may have any orientation

PS1 Reduced Data
Sky Tessellation (Budavari Rings)
Optimized to cover the sky
with rectangular tangential projection
centers, and which overlap for analysis
of objects at boundaries.



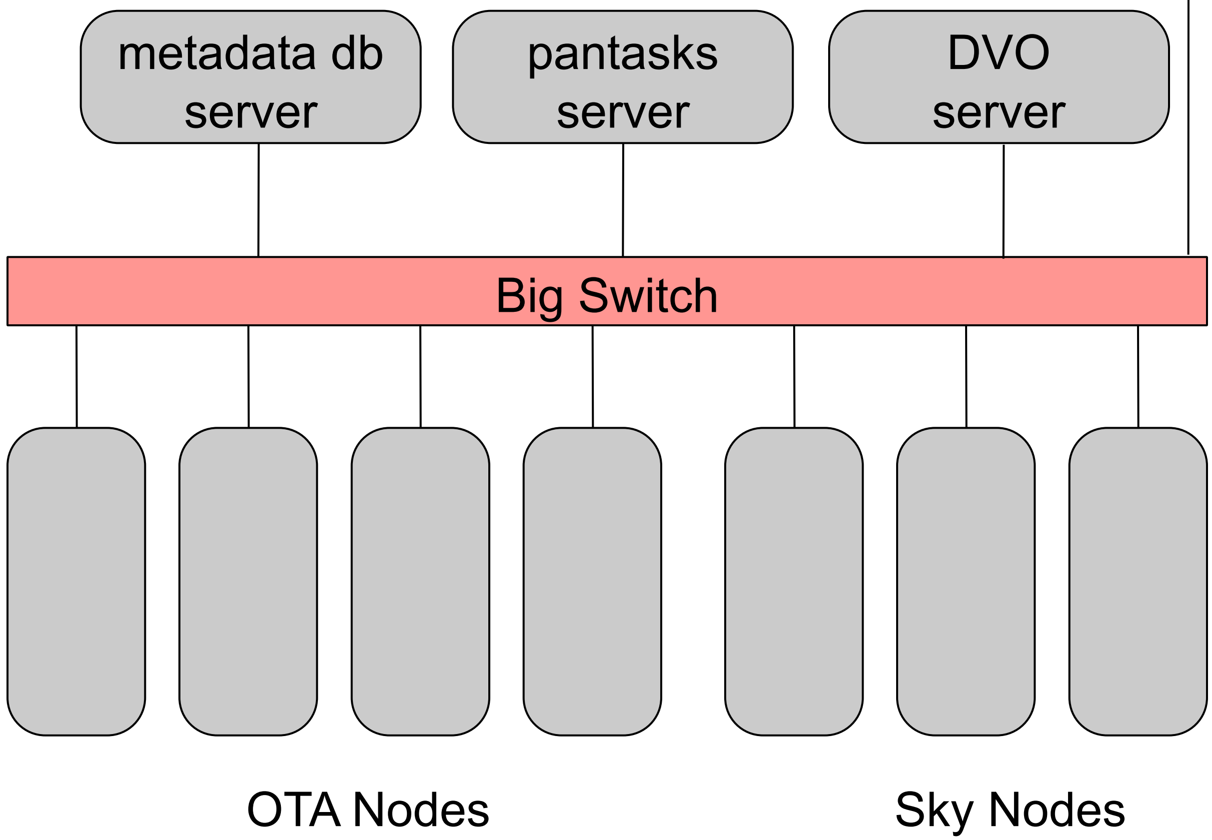
Symmetric, all data is warped on to
The same identical framework.
Pixels oriented in (RA, Dec).

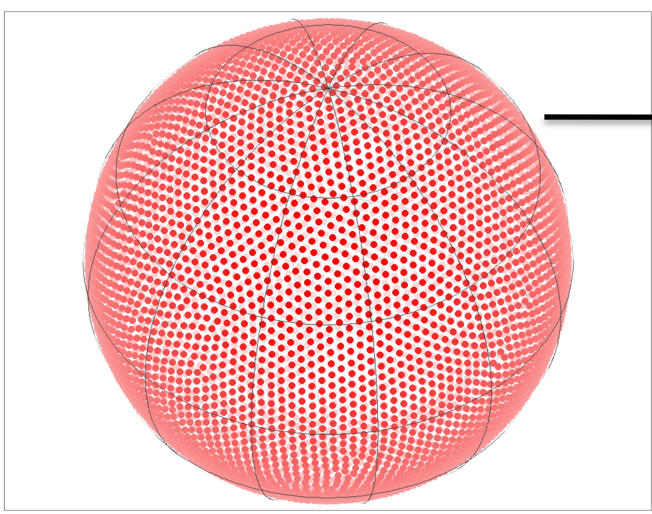
Image Processing Pipeline (IPP)

Currently 1368 CPU's at Maui High Performance Computing Center

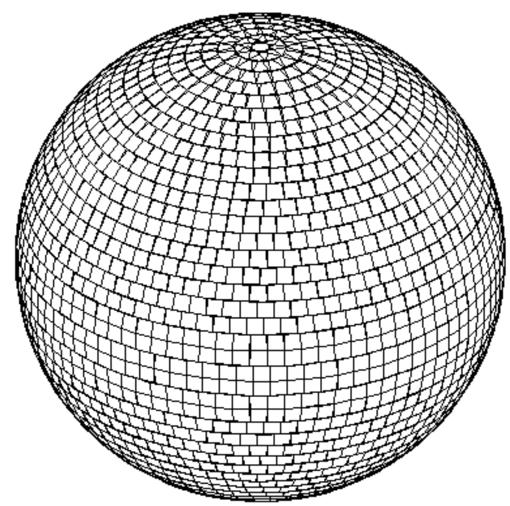
Storage = 2.5 Petabytes at MHPCC

Slow Mirror of raw data = 780 Terabytes at ATRC





All data must be "warped" on to identical regular astrometic grid. Then images can be stacked or subtracted.

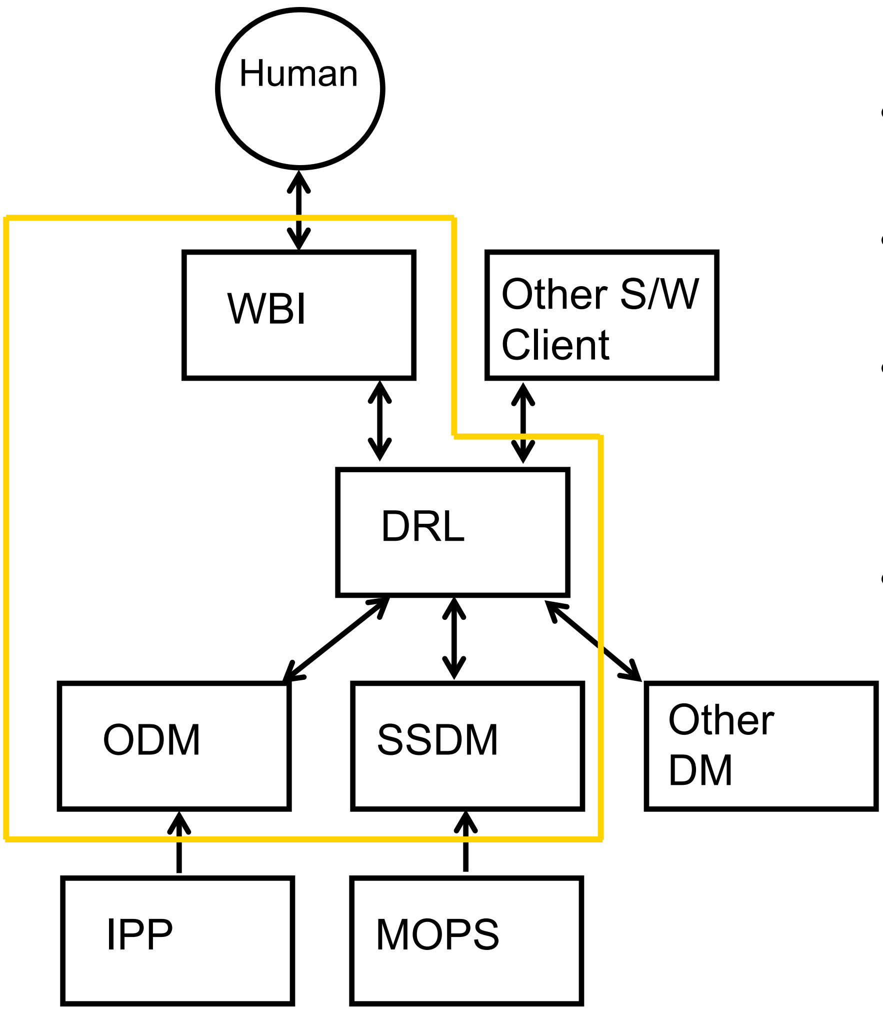


What are the stressing aspects of the problem?

- **Dynamic**
  - Continuous addition of new products, organized with existing products to support access
  - Continuous maintenance of celestial object properties based on time-history of detections
- **Fast**
  - ~10^8 new records per day, ~10^8 record updates per day
- **Spatial**
  - All records have a position on the surface of a sphere
  - Implicit distance calculations are important for many uses
- **Large**
  - One year: ~10^{11} records

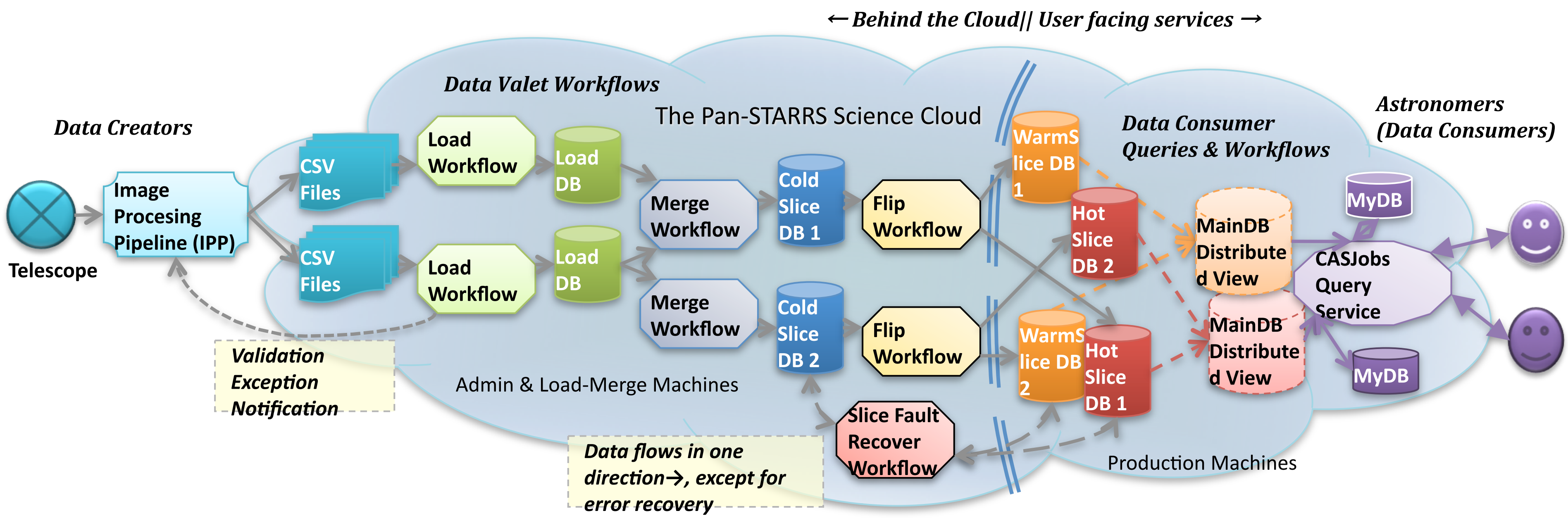
- **Simple**
- **Lenient**

PSPS – relational hierarchical database

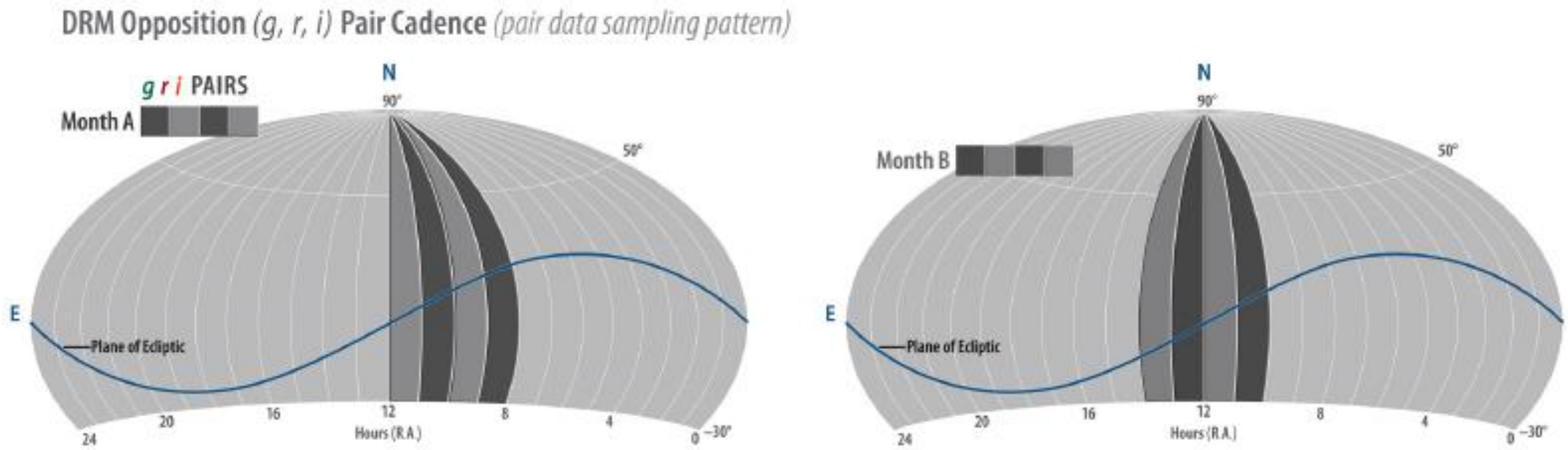


- Web Based Interface – the “link” with the human
- Data Retrieval Layer – the “gate-keeper” of the data collections
- PS1 data collection managers
  - Object Data Manager
  - Solar System Data Manager
- Other (future/PS4) data collection managers; e.g.,
  - “Postage stamp” cutouts
  - Metadata database (vice attributes managed in PS1 ODM)
  - Cumulative sky image server
  - Filtered transient database (or other special clients)

Pan-STARRS Data Flow

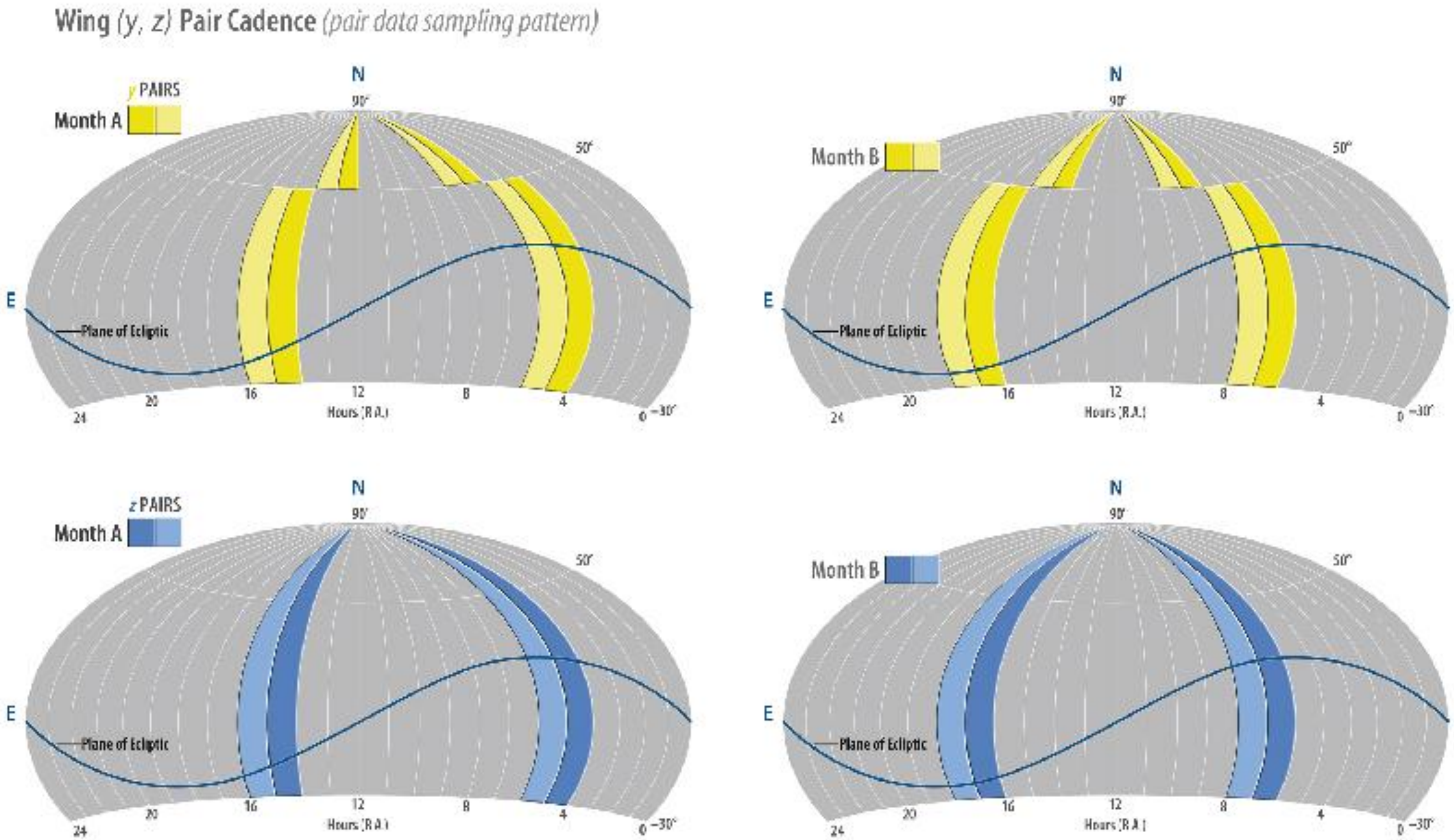


Original DRM "stripe" sky pattern and 2 month cadence for opposition fields, bands g, r, and i



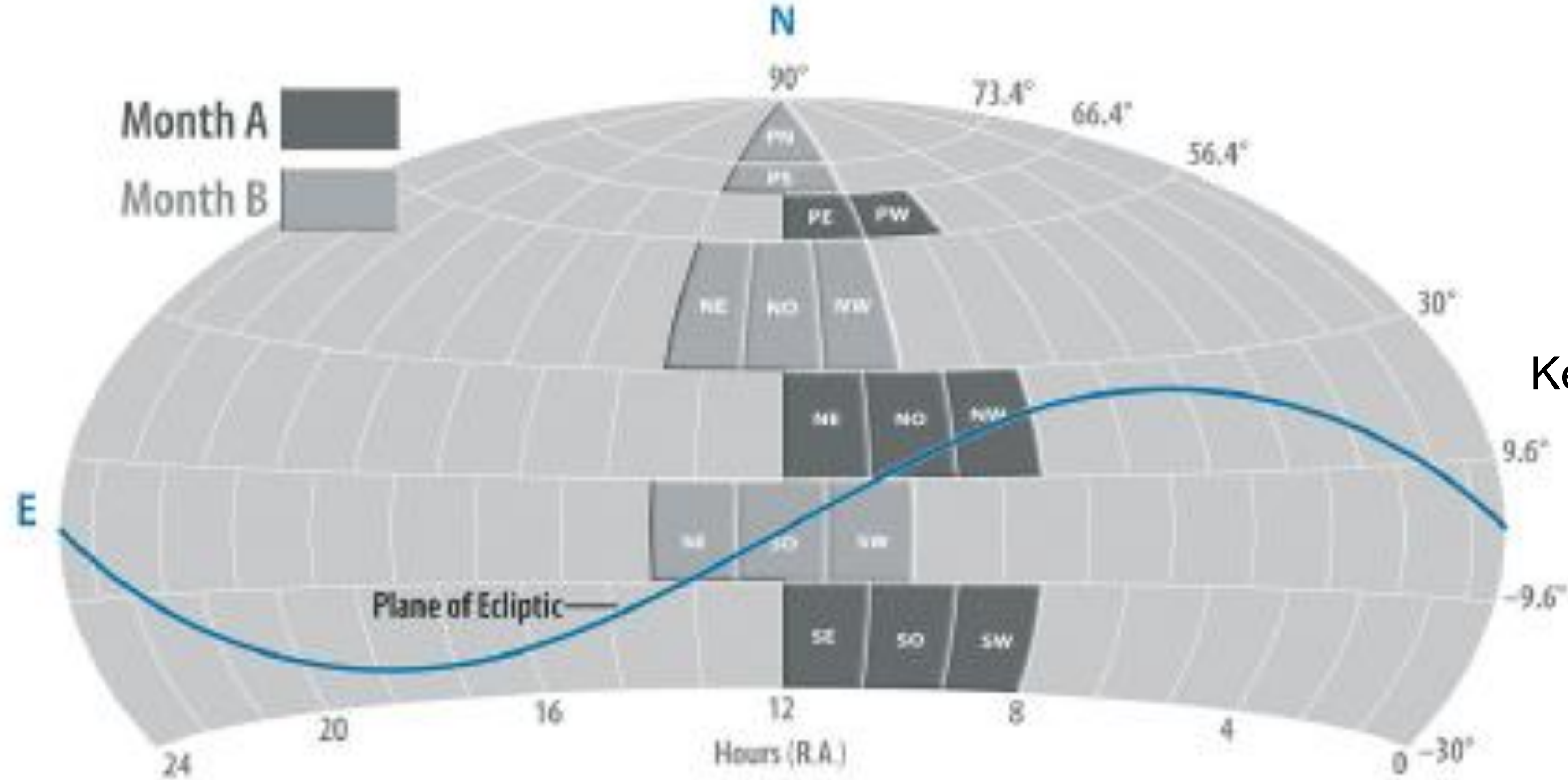
Motivations was to spread the observations of a given region over two lunations; to lessen the impact from episodic weather, and to provide intra-lunation linkages for NEO's.

DRM 3.0 “Wing” coverage



Motivations include paralax for brown dwarfs, and making best use of beginning and end of night.

MDRM “Brickwall” pattern



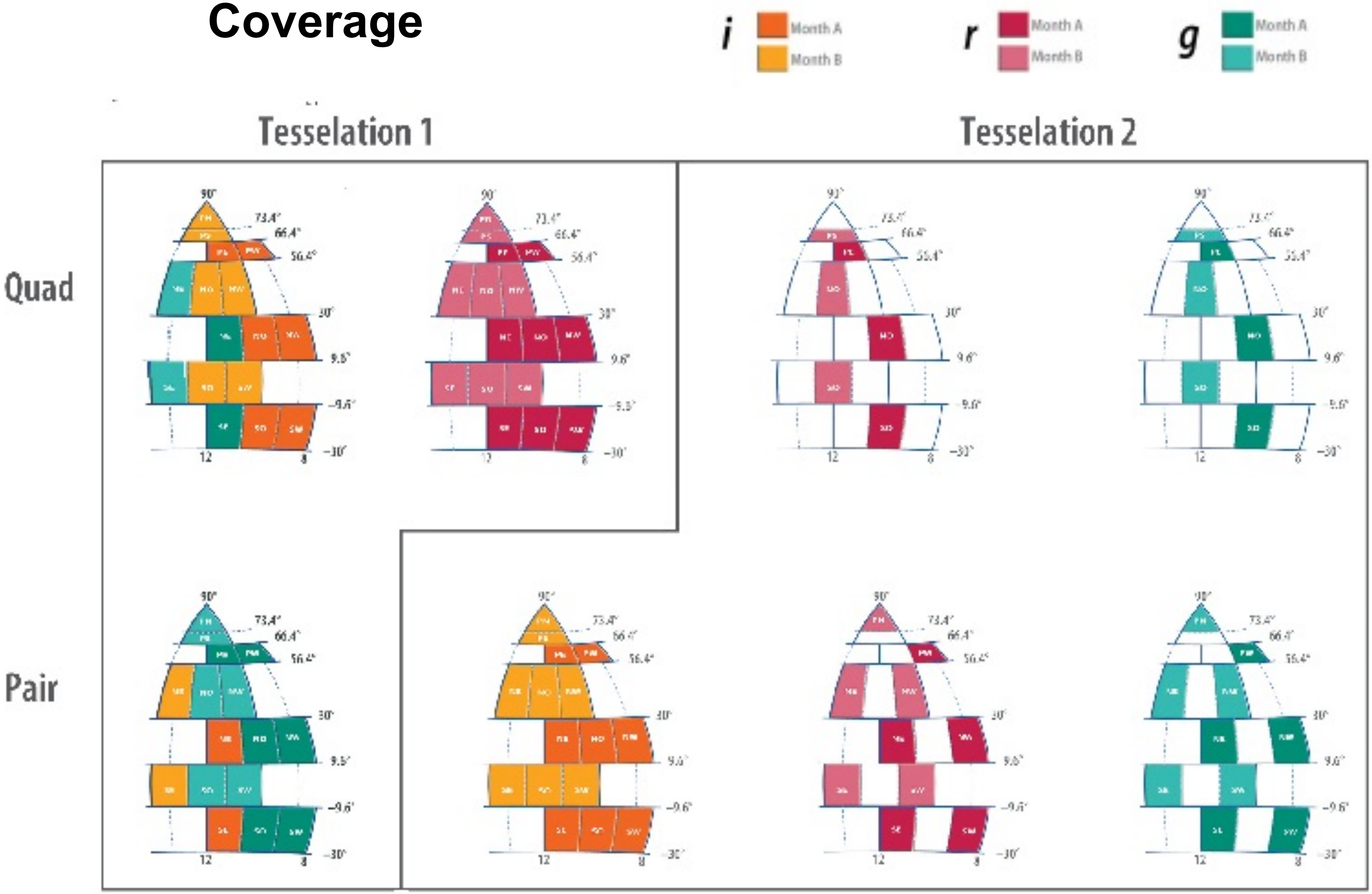
Keyhole

The number of exposures (4 per filter per year) is conserved.
The sky coverage is grouped into bricks, where all the 3pi data taken on a given area of the sky is taken in a single month. The bricks in “Month A” have the same area as those in “Month B”. In reality these are modulated with the length of the year and the need to fit in the STS survey in the summer.

NOTE: Each Declination Brick is divided into 3 sub-bricks.

MDRM Opposition Coverage

Every colored sub-brick represents a *pair* of observations, separated by ~ 25 min (TTI) .

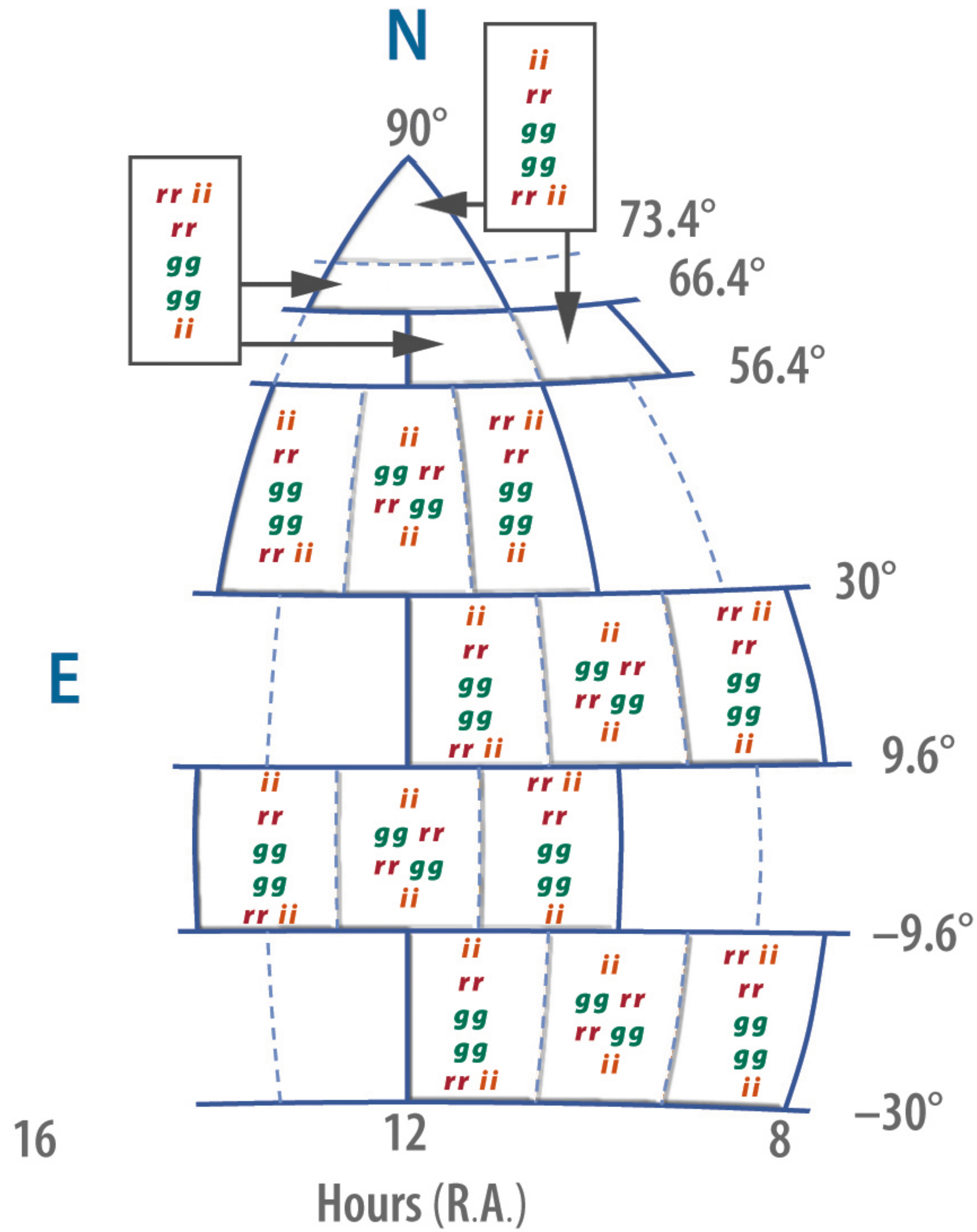


MDRM Opposition cadence

(20/45 x 3/5) + 2/5 = 2/3
(20/45) = 0.44 of gri data is taken in multi-color quads.

All of zy data (2/5 by filter) is Potentially taken in quads.

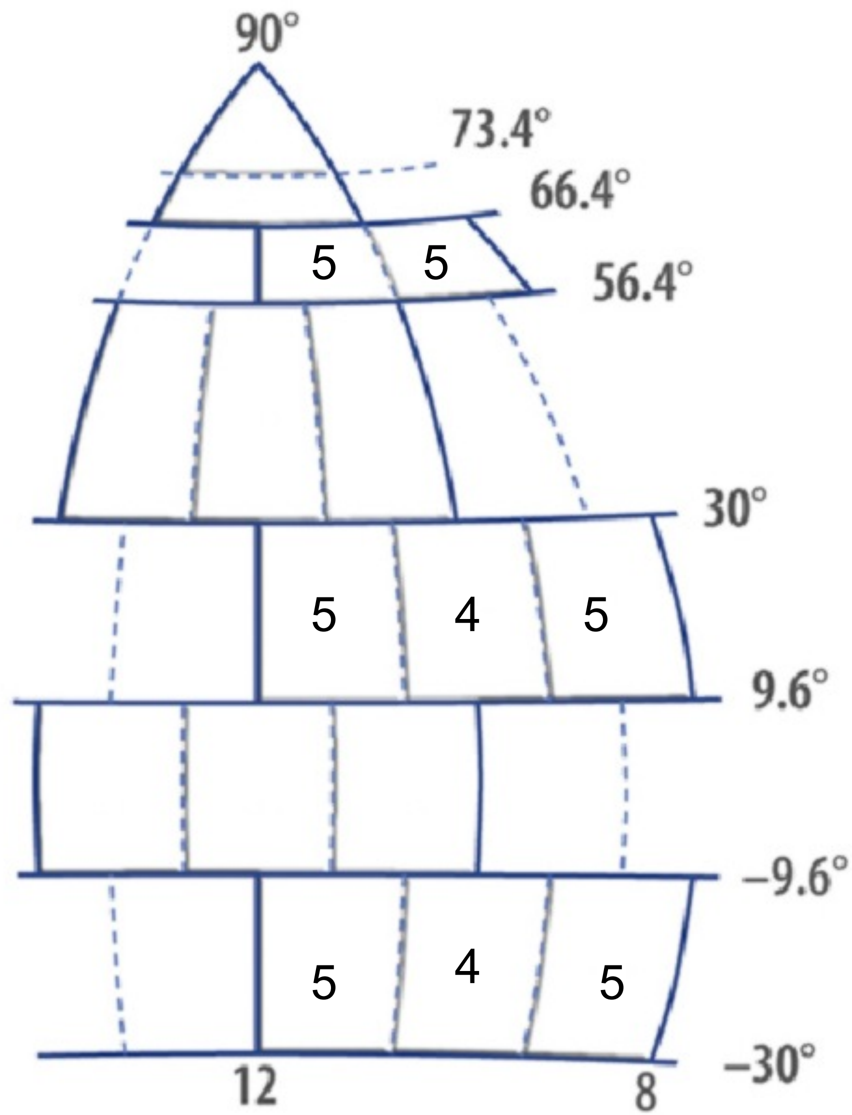
20/45 x 3/5) + 2/5 = 2/3 of 3pi data potentially taken in multi-color quads.



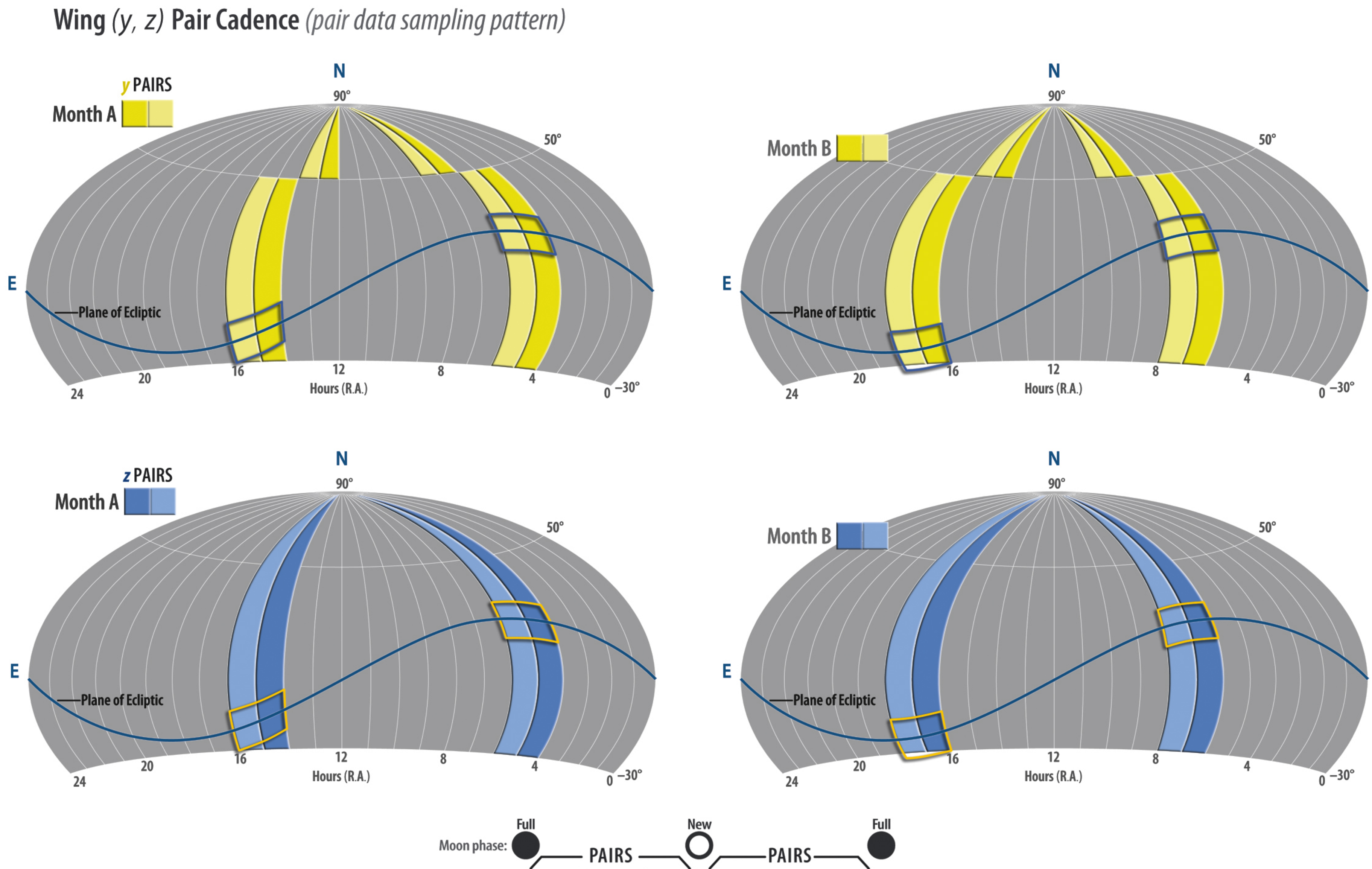
No. of Epochs in 3pi Opposition Survey

0.26 of 3pi area has
4 epochs in ~25 days.

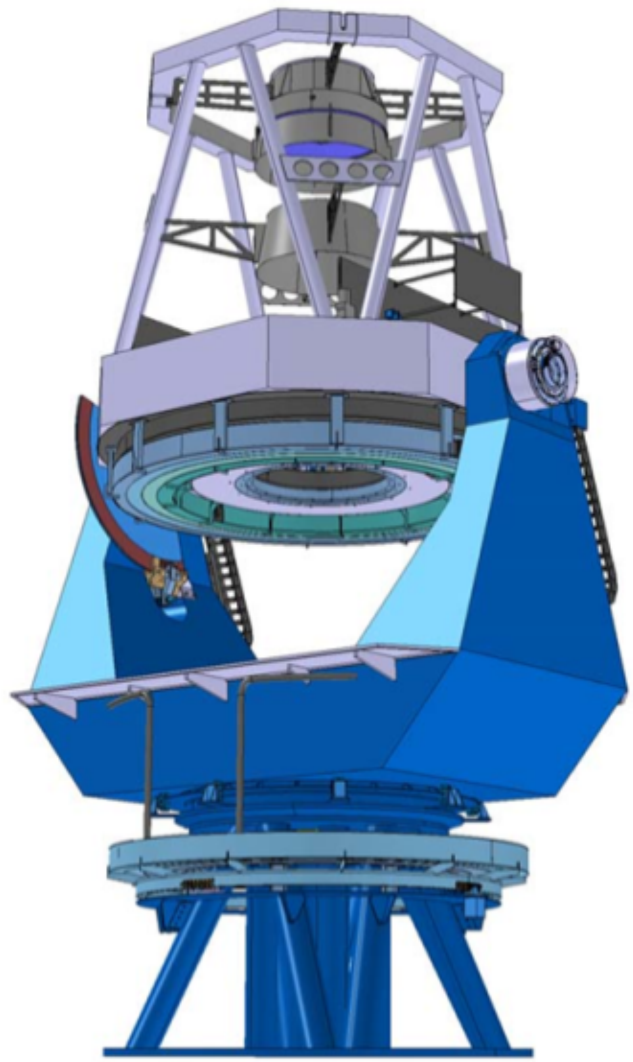
0.74 of 3pi area has
5 epochs in ~25 days.



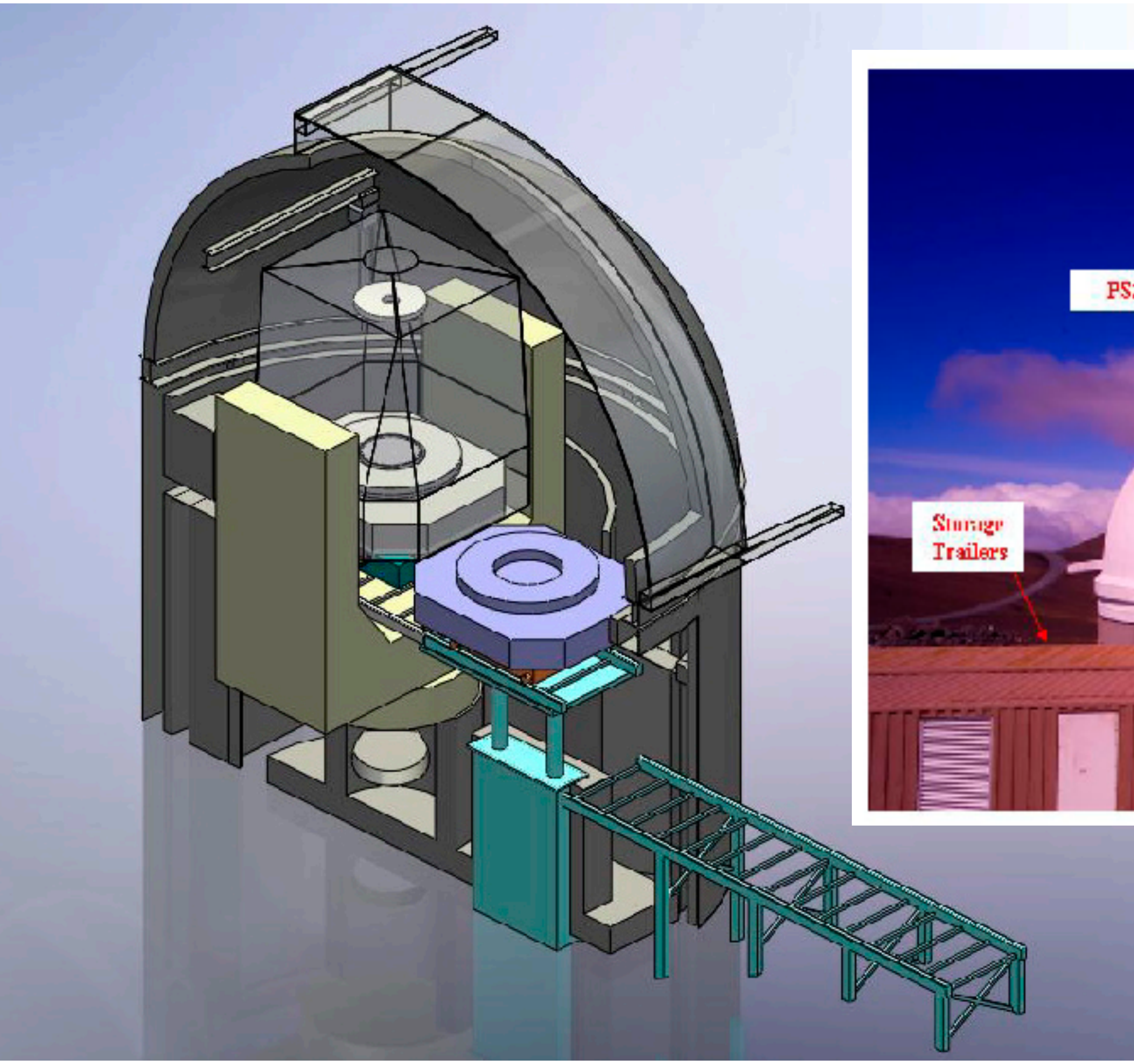
“wings” at solar elongation 120 observed as multicolor quads whenever possible, especially on the ecliptic

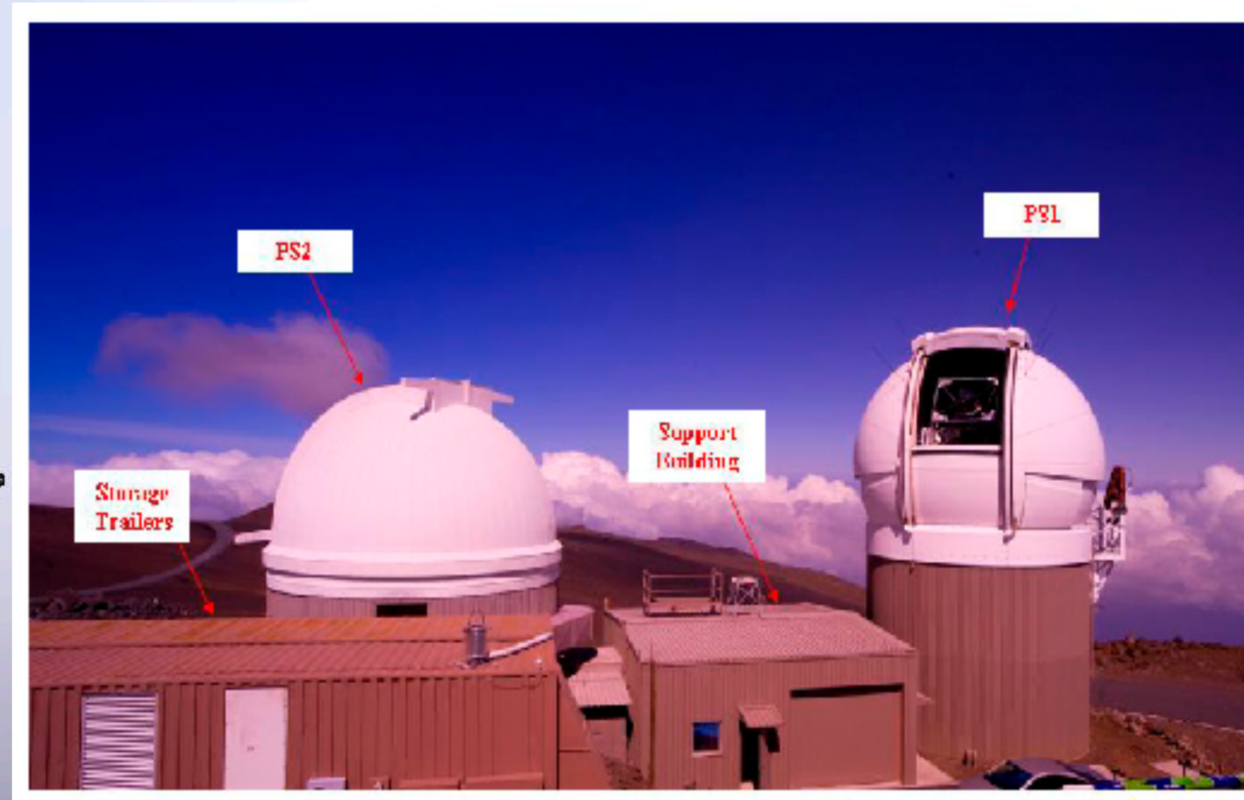


PS2 Telescope design from AMOS



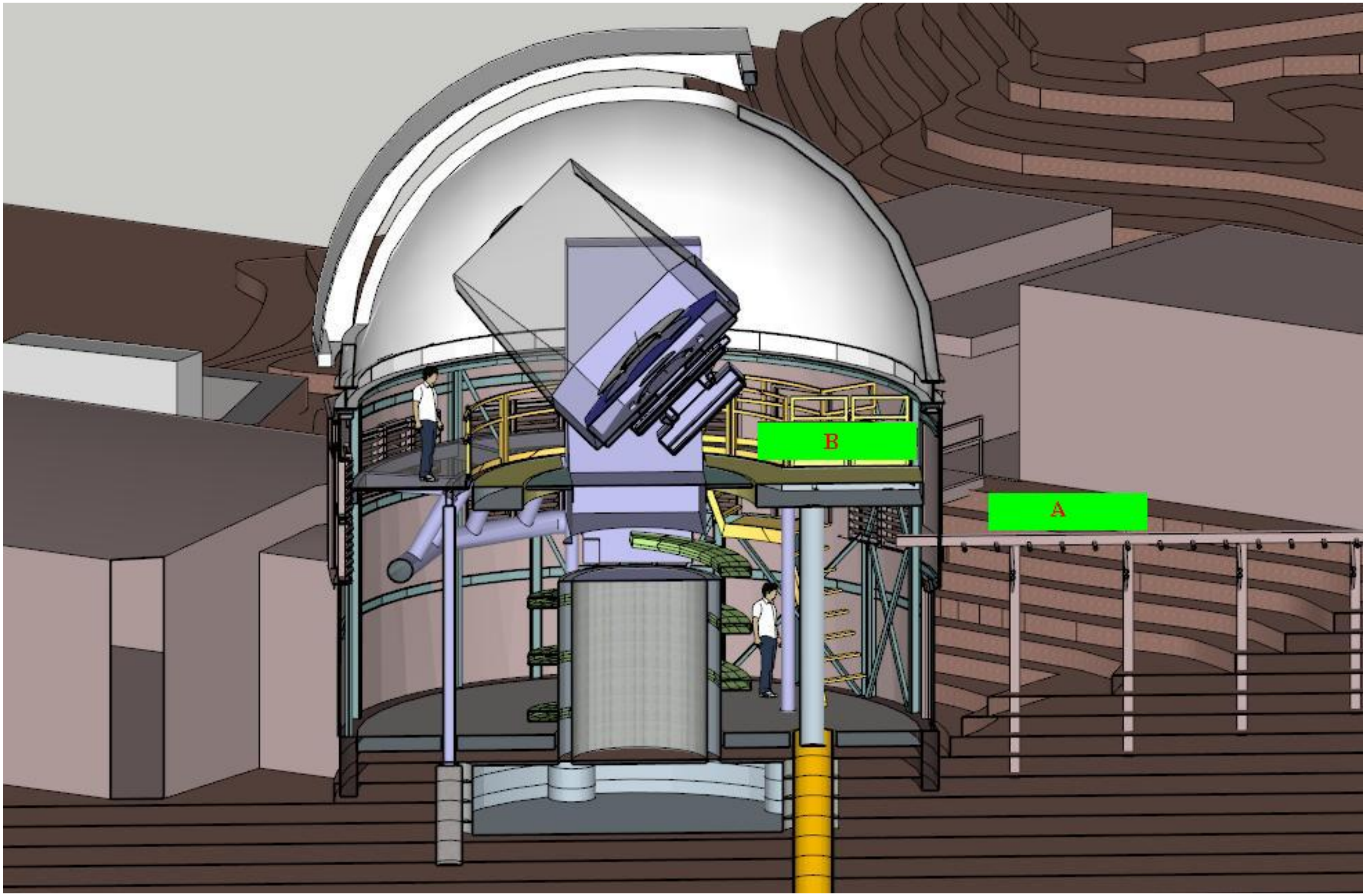
PS1 + PS2 Telescopes and Enclosures



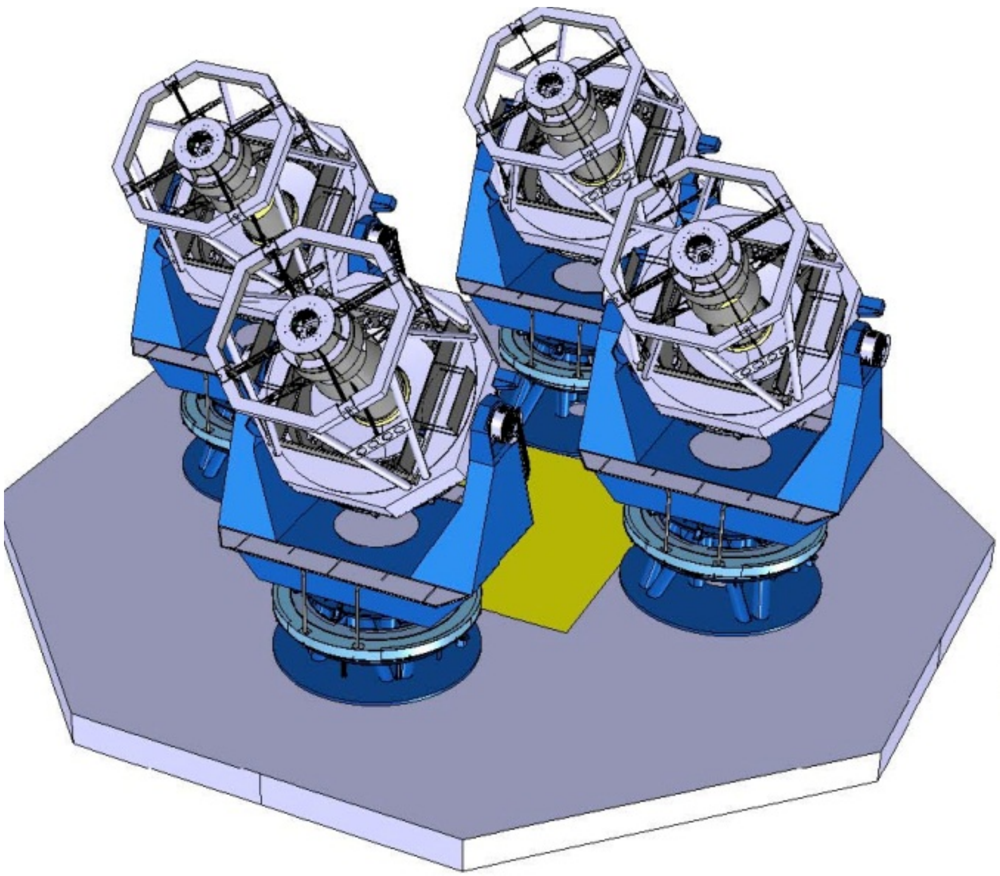


PS2 dome and telescope – cutaway view

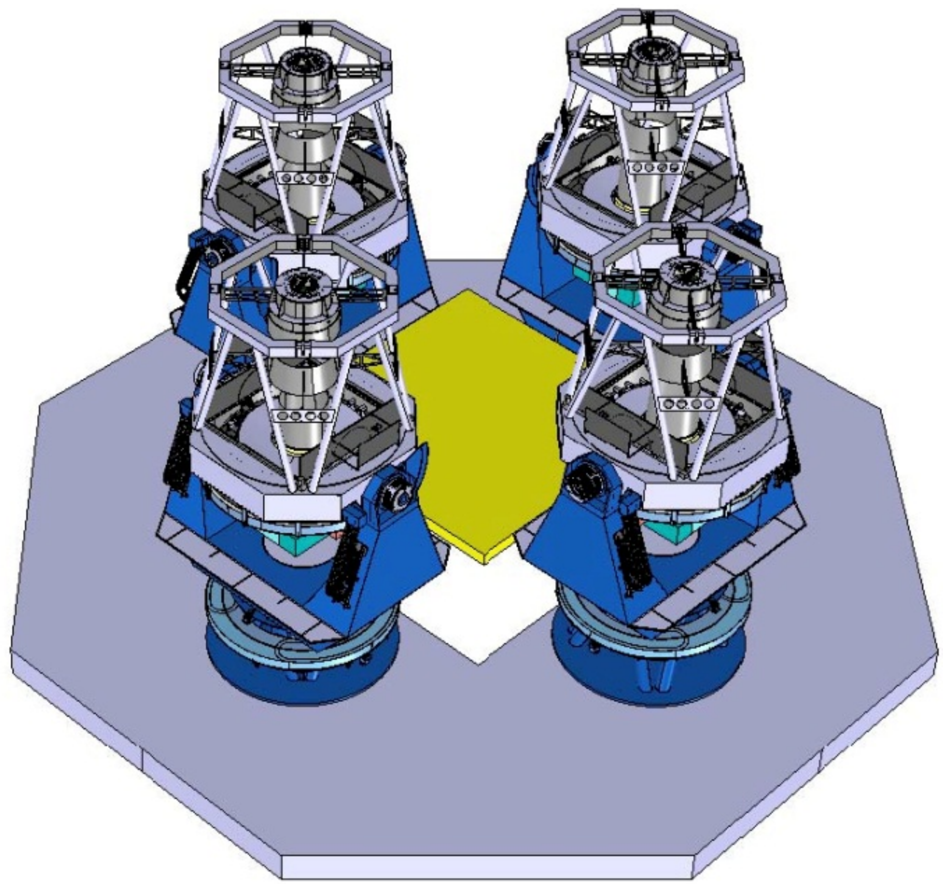
Updated Rendering of PS2 Observatory Interior (from M3 Eng.)



Proposed Telescope from PS2 Vendor AMOS (Belgium)

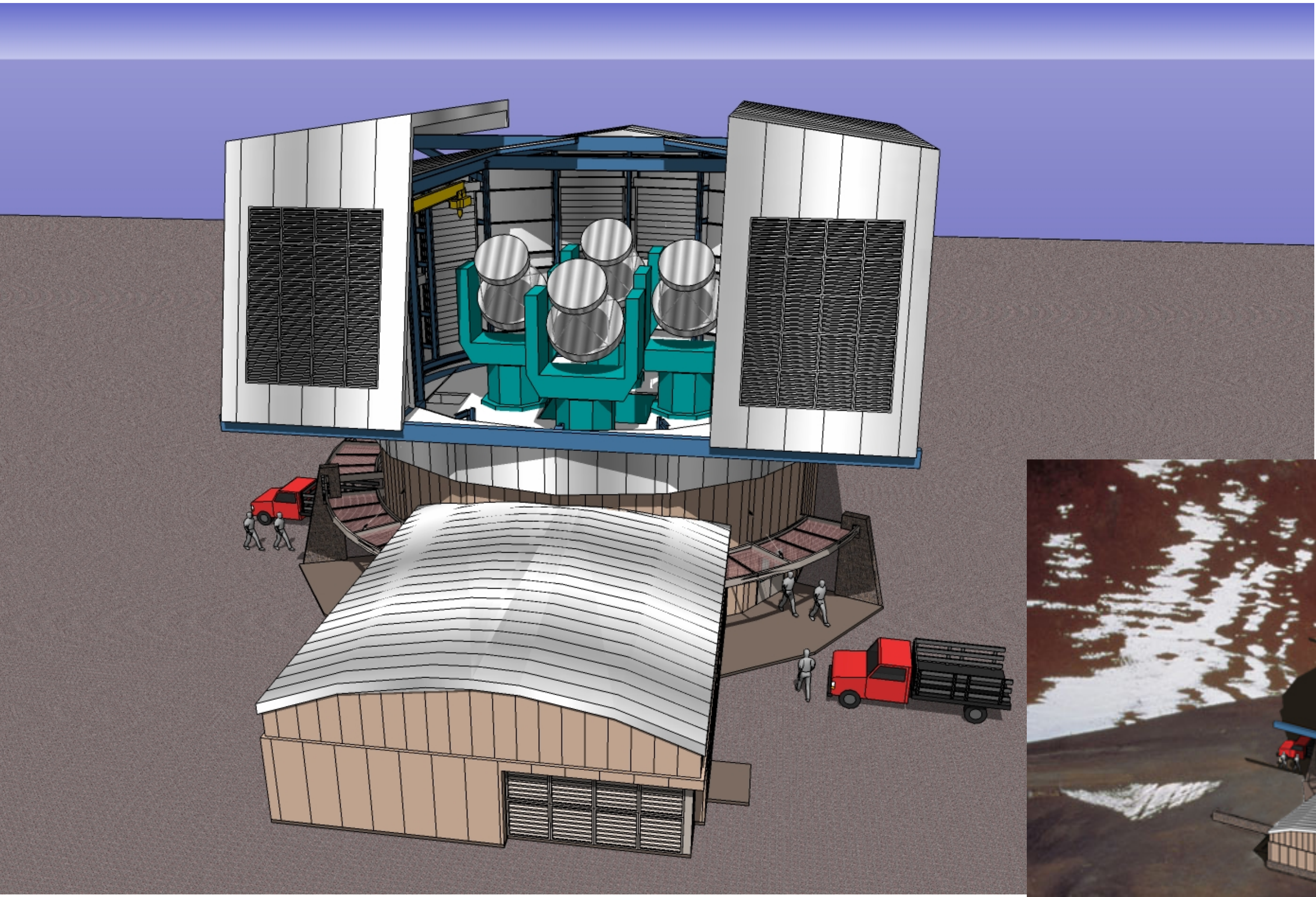


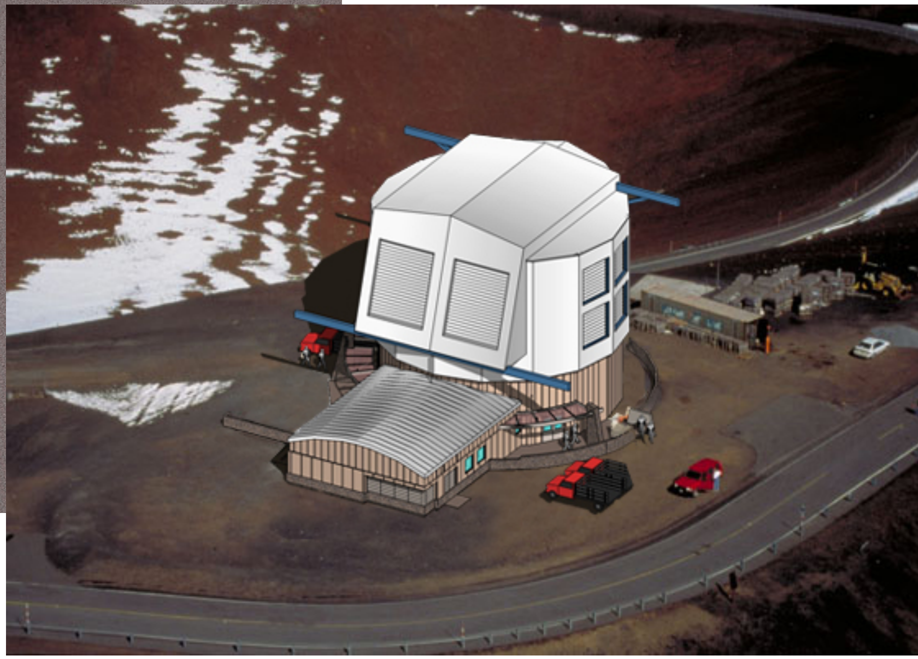
Observing position



Servicing position

PS4 Telescopes and Enclosure
On Mauna Kea 88inch Telescope site

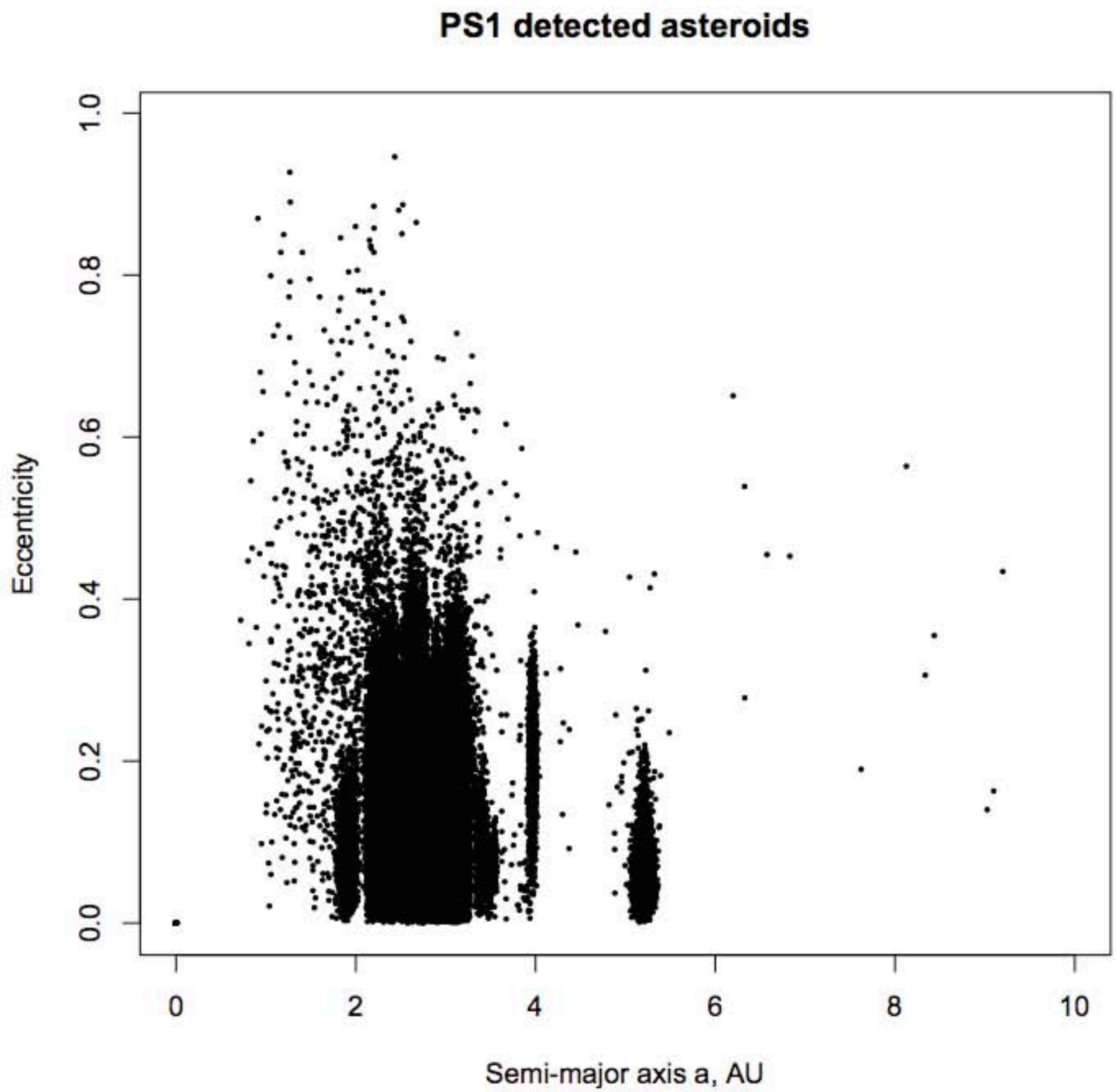




KP1 — Populations of objects in the inner solar system

Asteroids

- 13,777 discoveries
- 1,821,431 observations in Minor Planet Center database
  - 229,560 numbered asteroids
  - 63,239 unnumbered asteroids
  - 292,799 total asteroids observed


PS1 detected asteroids
Eccentricity
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
Semi-major axis a, AU

Near Earth Objects

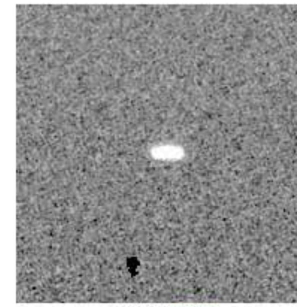
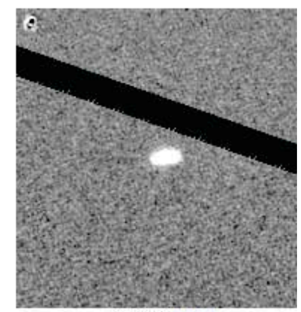
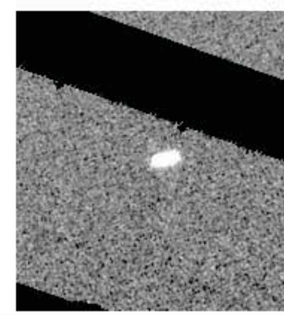
- 173 NEOs were discovered by PS1 in 2011
  - 11 with H magnitude brighter than 18.3 (diameter > approximately 1 km)
  - 16 Potentially Hazardous Asteroids (PHAs) (H < 22.0 (diameter > 150 m and passes closer than 0.05 AU to Earth)

NEO followup

- PS1 does not follow up its own discoveries
  - In general, follow up by others has been good
  - We have done some follow up ourselves using CFHT, UH 2.2-meter and Faulkes
  - Numerous fast moving NEO candidates have been lost

onsynthetic All | Nonsynthetic NEOs | Known Objects | Tabular (first 100) | Tabular (all) | e vs. a 10AU | 50AU | e vs. q 10AU 50AU

Tracklet ID	Status	Classification	Known As	V_{tot} (deg/day)	Pos Ang (deg)	Digest	GCR (arcsec
35107 MPCheck Digest MOPS | MPC | OORB | All Detections MPC | DES	UNATTRIBUTED	NONSYNTHETIC	N/A	1.776	83.5	100.0	0.20

Field ID	Detection ID	Epoch (MJD)	Δt	RA (deg)	Dec (deg)	S/N	Mag	Filter	V-Mag	Obscode	MOPS Object Name	Stamp .ZIP
o5635g0291o 137.3Pl.i.BSO3.P1 IQ	953439	55635.365941 2011-03-15 08:46:57.0 UT	--	160.733731 10h42m56.10s ±0.15"	-4.856054 - 4d51'21.79" ±0.15"	60.49	18.34 ±0.02	i	18.17 ±0.02	F51	NS	 Diff | FITS
o5635g0326o 137.3Pl.r.BSO3.Q1 IQ	970280	55635.390737 2011-03-15 09:22:40.0 UT	+35m	160.777773 10h43m06.67s ±0.15"	-4.851092 - 4d51'03.93" ±0.15"	60.75	18.13 ±0.02	r	17.81 ±0.02	F51	NS	 Diff | FITS
o5635g0343o 137.3Pl.r.BSO3.Q1 IQ	978083	55635.401292 2011-03-15 09:37:52.0 UT	+50m	160.796351 10h43m11.12s ±0.15"	-4.848983 - 4d50'56.34" ±0.15"	41.48	18.38 ±0.03	r	18.06 ±0.03	F51	NS	

Comets

- We search all moving objects for extended structure indicative of cometary activity
- PS1 discovered 9 comets in 2011
  - We missed 2 other comets (C/2011 UF 305 (LINEAR), and P/2011 Y2 (BOATTINI) for which we reported observations, but did not see cometary activity

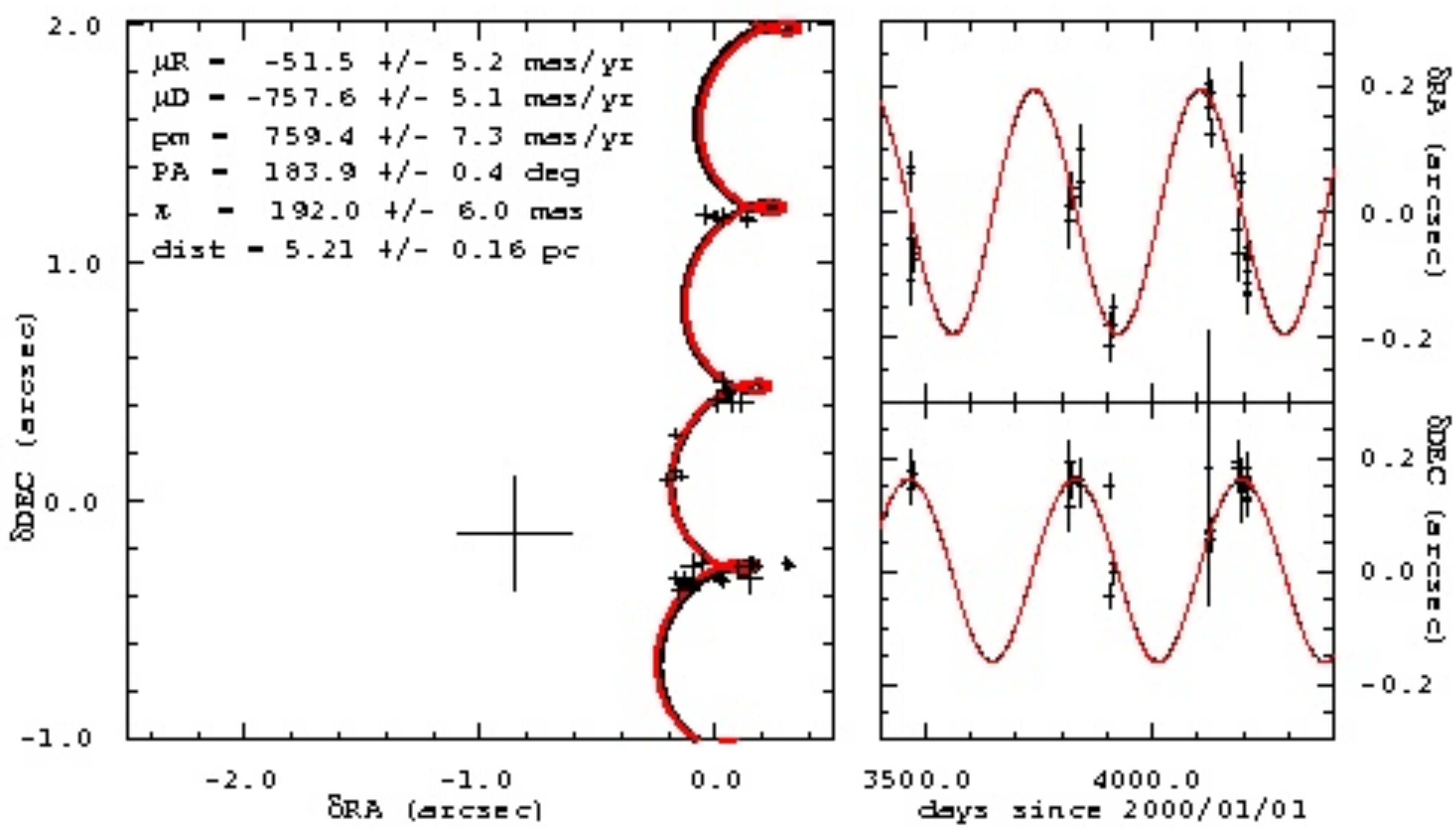
Long period Comets

- C/2011 U3 — q=1.1AU; small
- C/2011 Q1 — q=6.8 AU
- C/2012 A1 (?) — discovered Jan 2, 2012
  - Orbit still not well determined

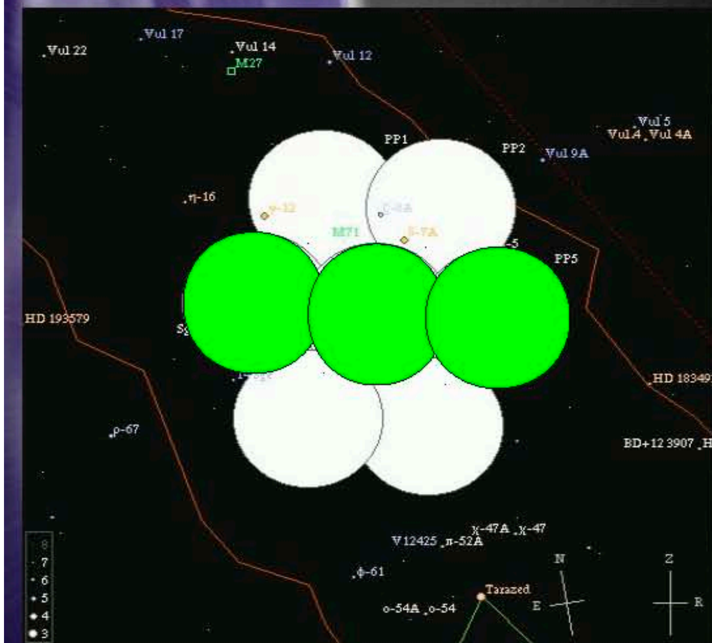
Comet C/2011 L4 (PANSTARRS)

- Perihelion at 0.3 AU on Mar 11, 2013
  - Predicted to be visible to the naked eye, low in the west after sunset in March 2013 (magnitude 0.5)
  - Presently behind the Sun (6 AU from Sun), and cannot be observed until February
  - We plan to obtain near-IR spectroscopy using Gemini starting in February to look for water ices

Parallax and Proper motion of BD



Pan-Planets (KP4/STS):



- Search for transiting extra-solar planets
- 4% of PS1 time
- Main focus on small radius host stars

  => deeper transits due to smaller R_*

- Observing strategy:

  3 overlapping fields in 2009/2010

  7 overlapping fields in 2011

Survey Metrics:

since May 2010: 106.6 hours (3.6% of survey time)

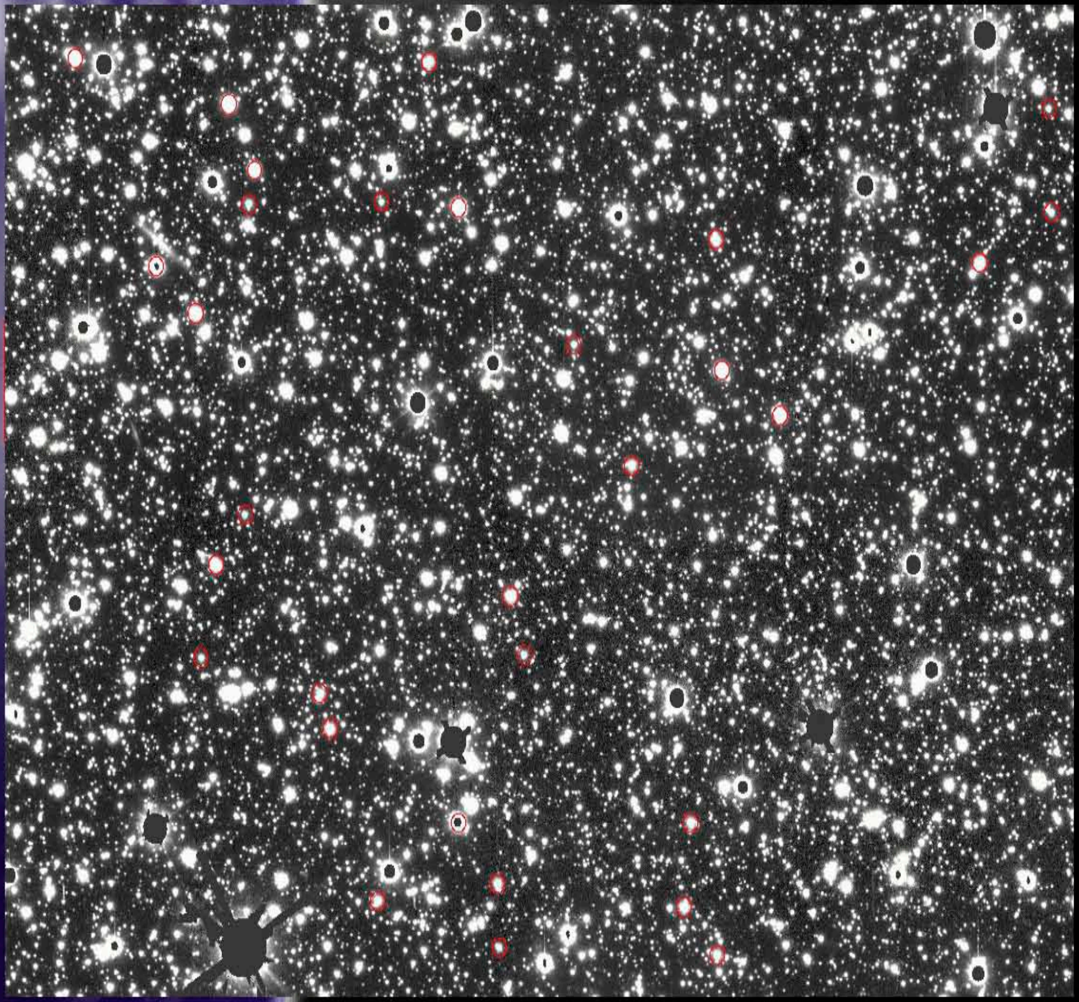
2009 (3 fields):	987 exposures
2010 (3 fields):	3859 exposures
2011 (3+4 fields):	4218 exposures
Total:	9064 exposures

=> ~2200 exp./old field

~600 exp./new field

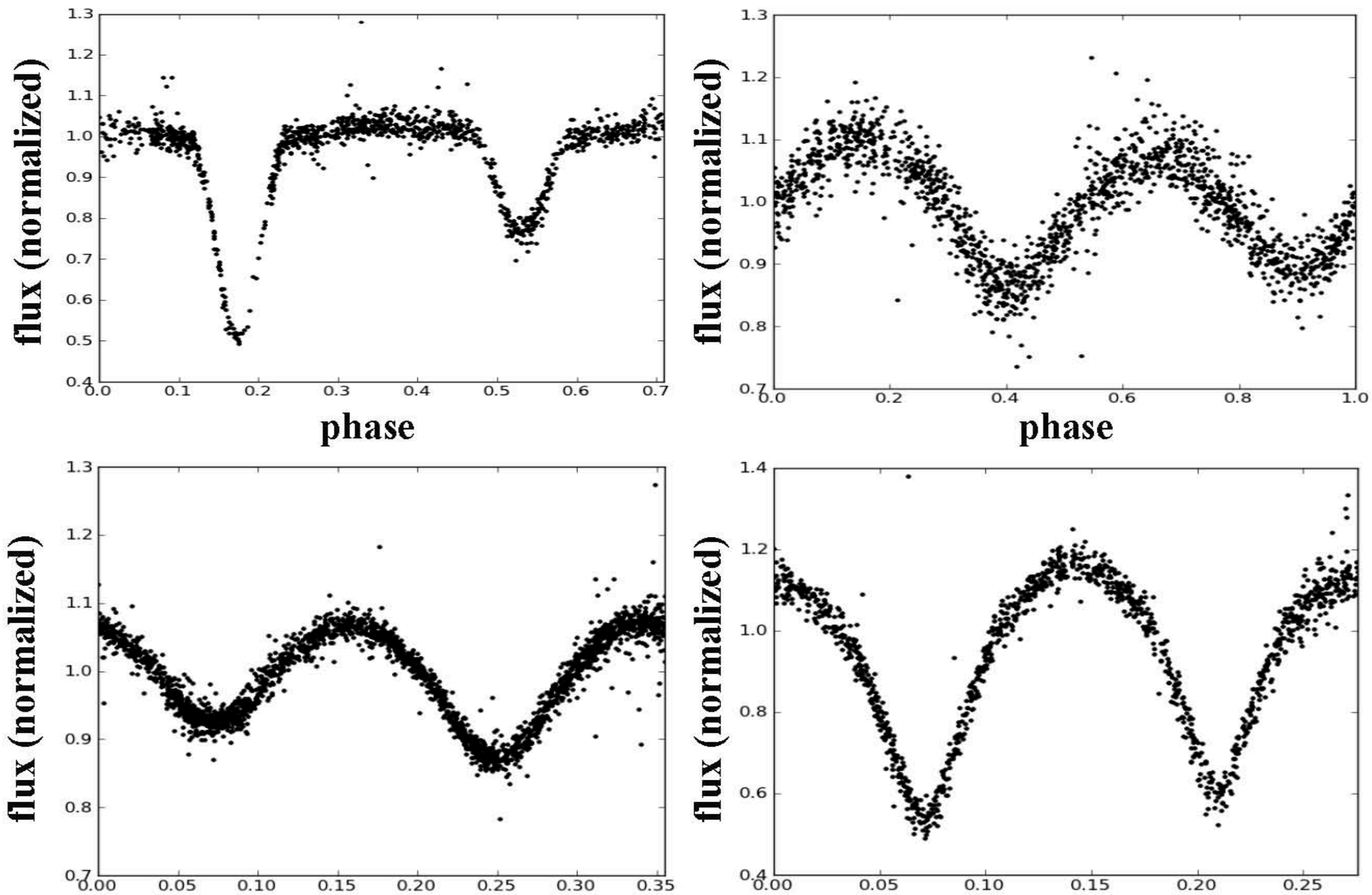
x2 in overlap regions

Reference Stack:

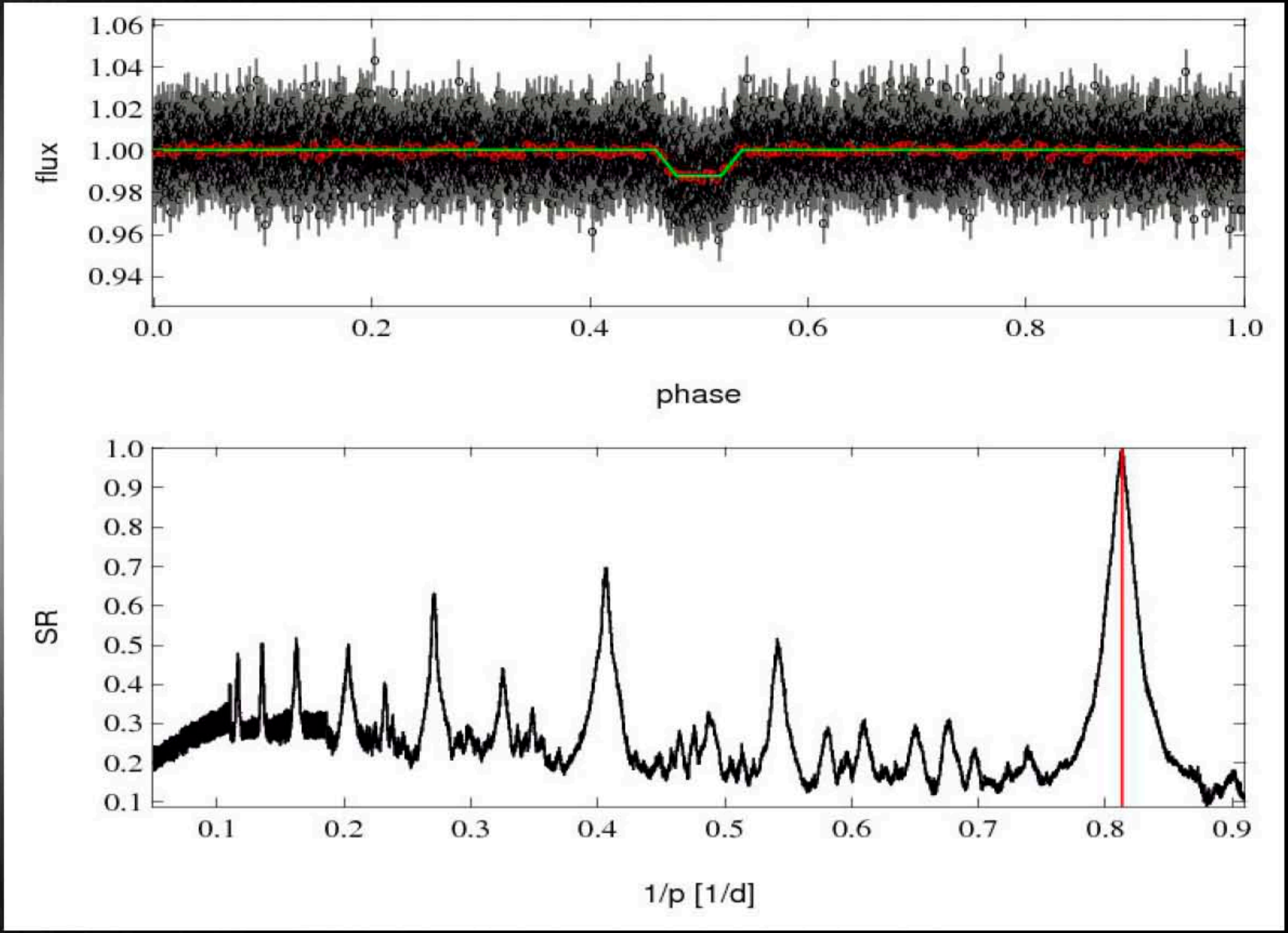


- stack of 100 best images
- 0.75...0.80" seeing
- replace masked pixels

Eclipsing Binaries:

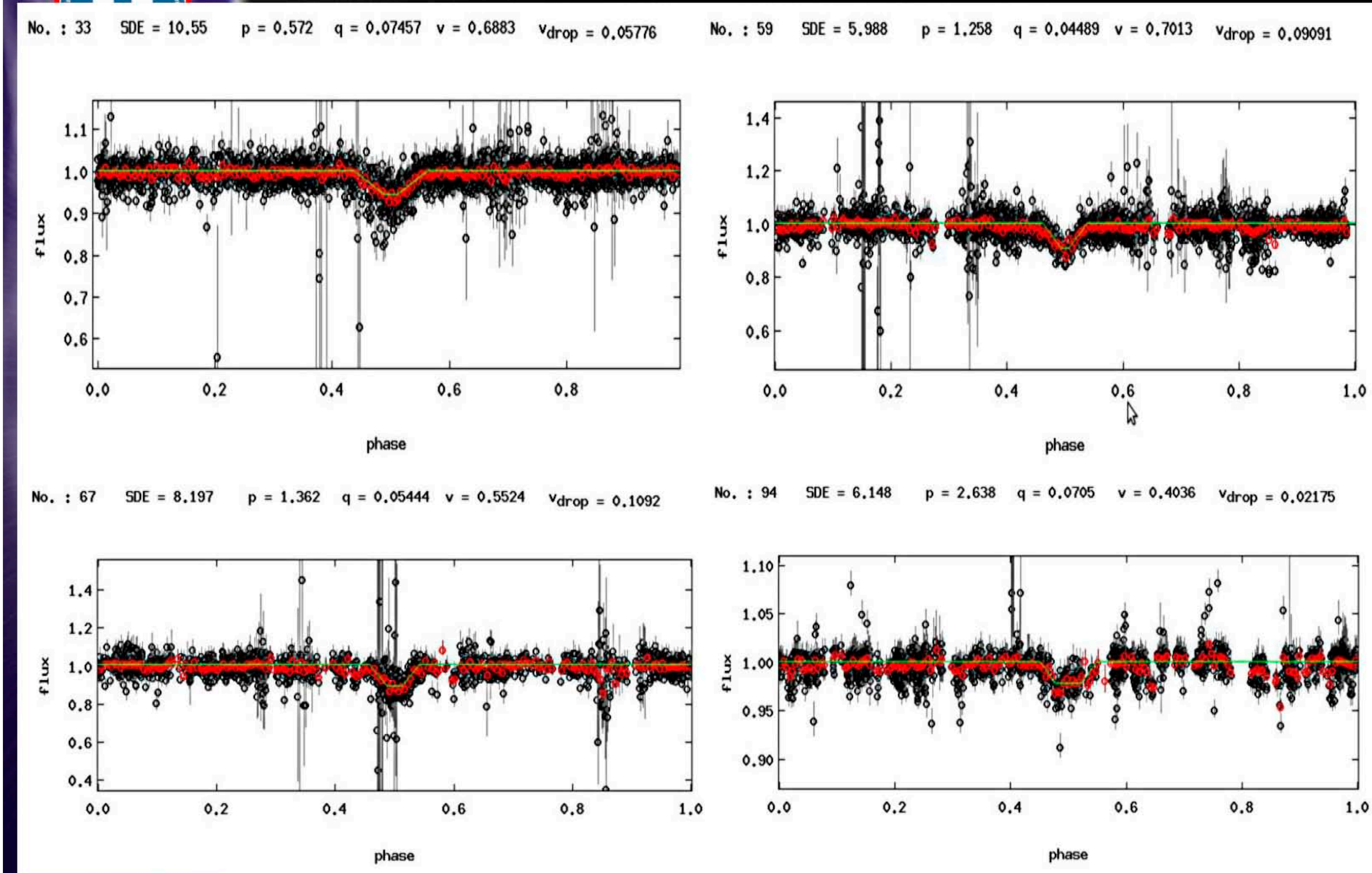


Search for transit events:



boxfitting algorithm (Kovacs et al. 2002)

'Candidates' (found so far):



PAndromeda – Pan-STARRS & Andromeda

Pan-STARRS - Panoramic Survey Telescope And Rapid Response System

PAndromeda
a dedicated deep survey of M31 with Pan-STARRS 1

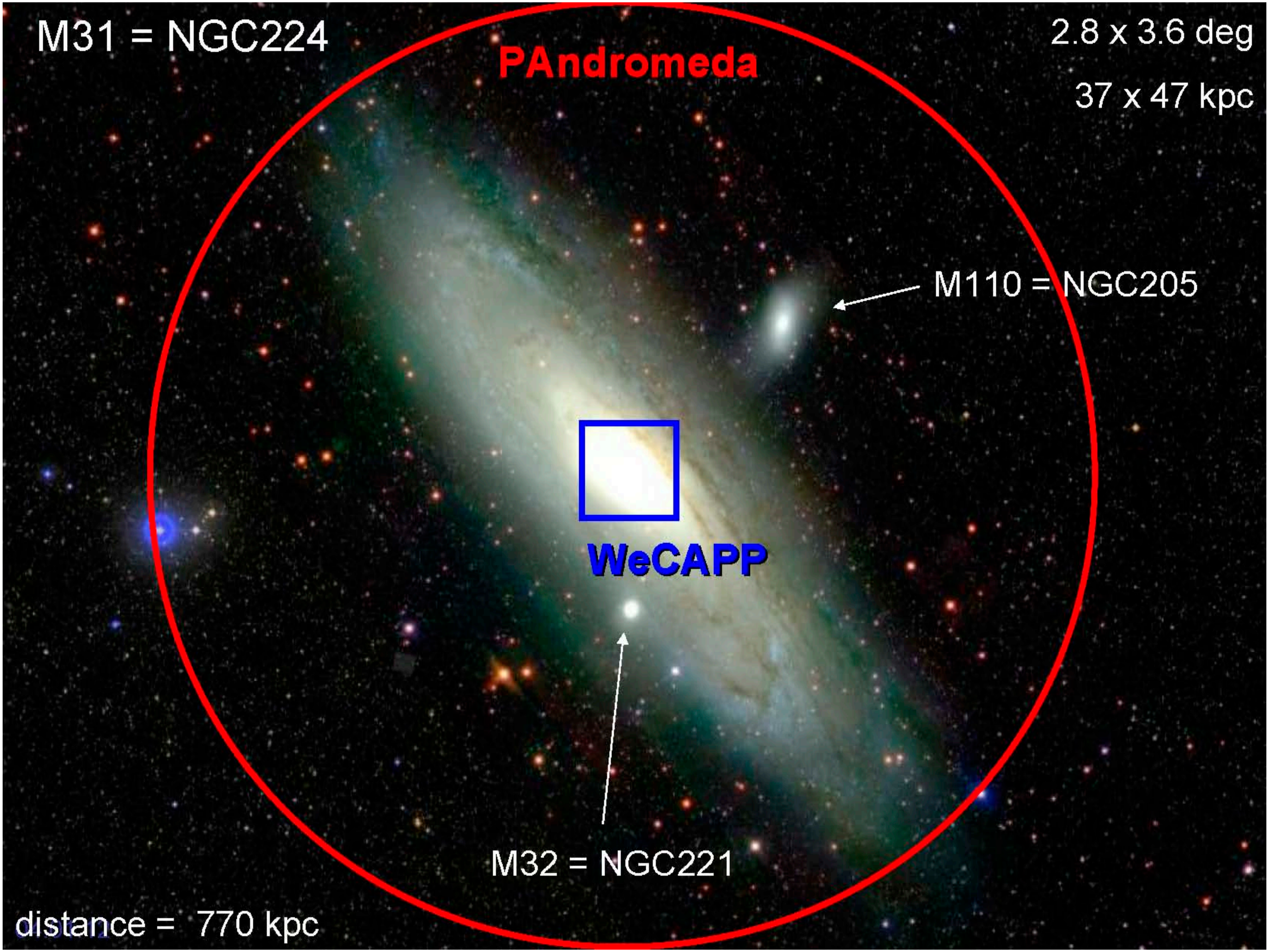
A. Riffeser - Honolulu 5/1/2011

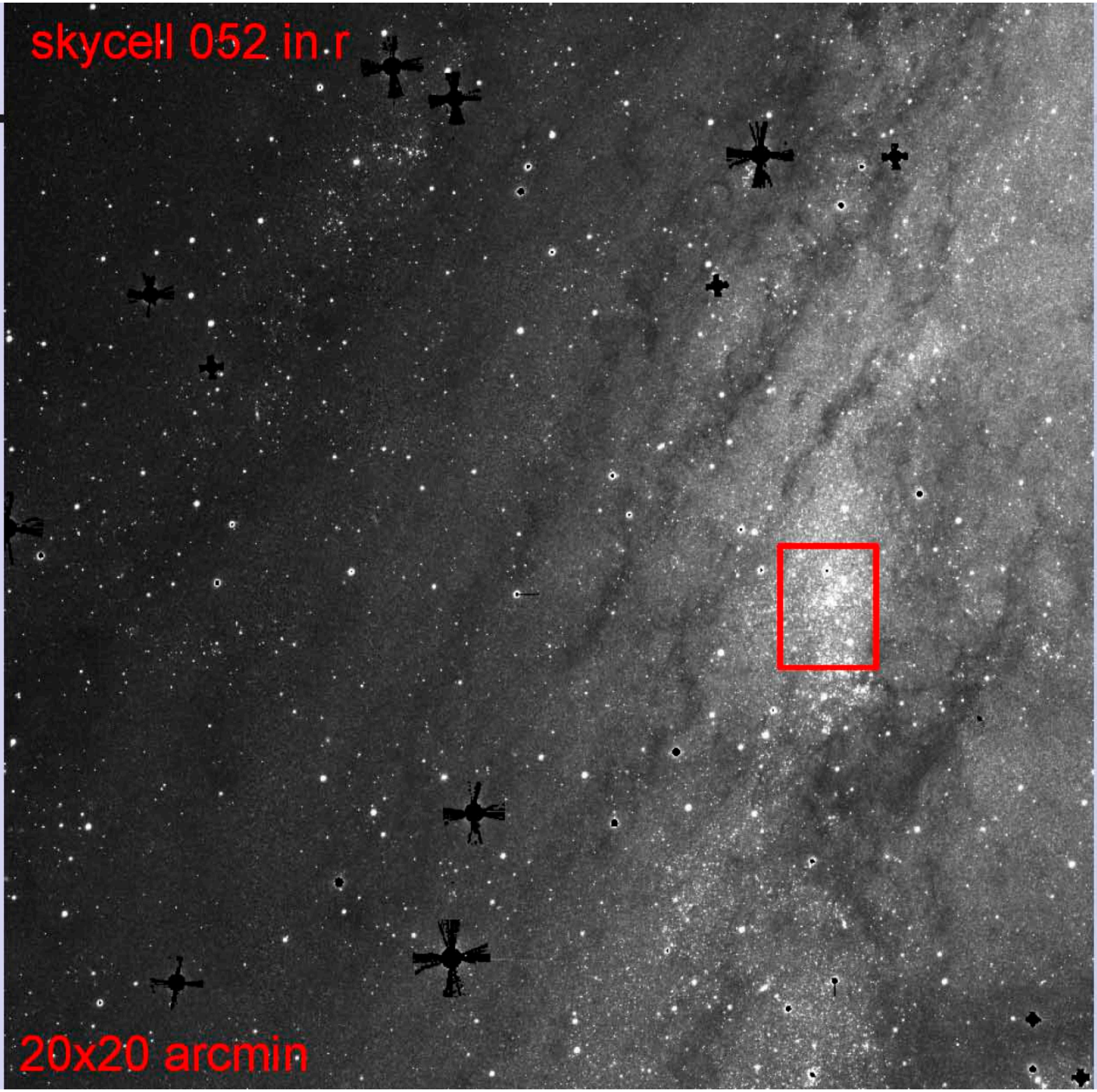
PIs: S. Seitz, R. Bender

J. Koppenhoefer, C.-H. Lee,

U. Hopp, C. Goessl, J. Snigula, M. Kodric

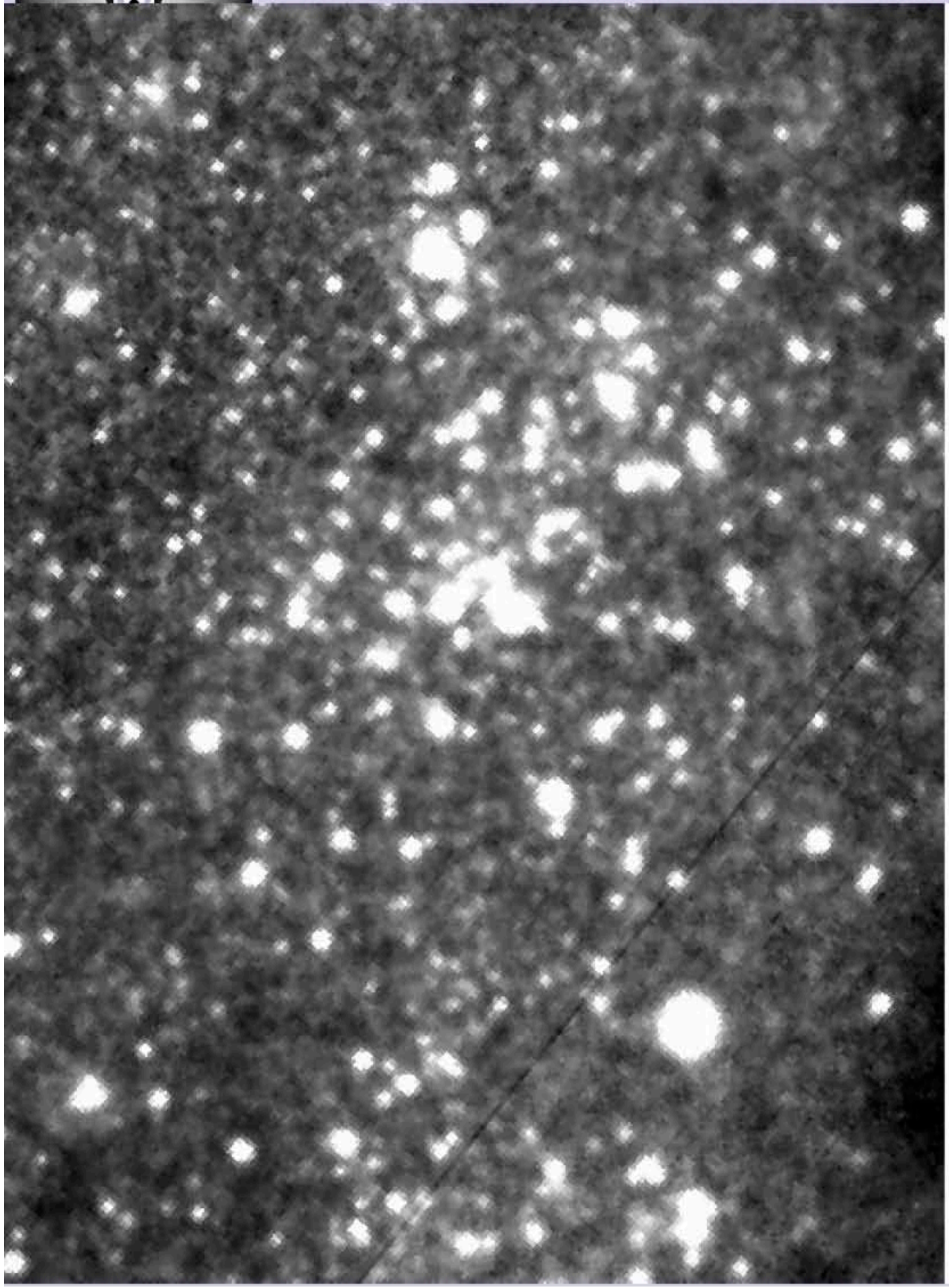
and the PS1 Science Consortium

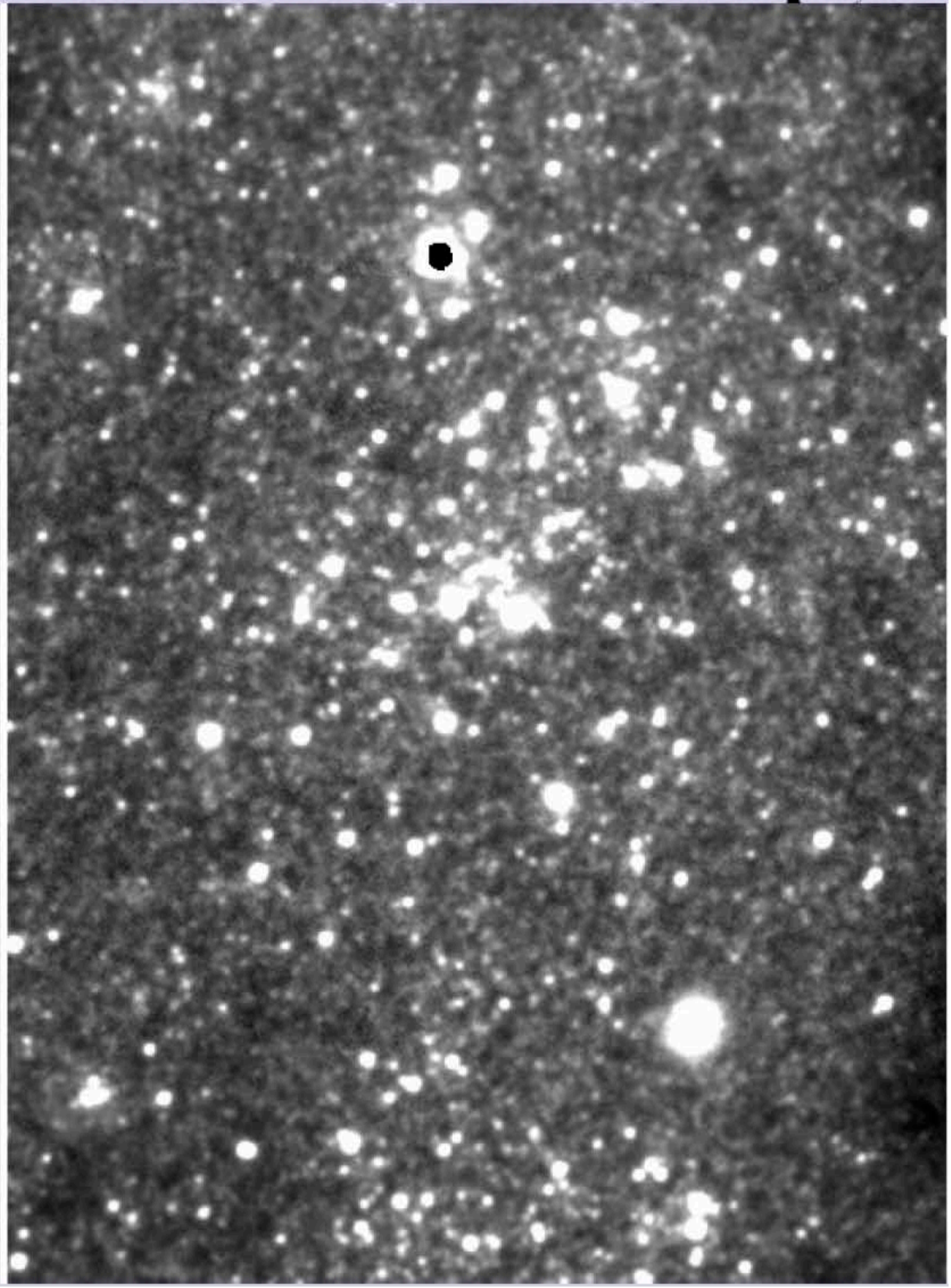

M31 = NGC224
PAndromeda
2.8 x 3.6 deg
37 x 47 kpc
M110 = NGC205
WeCAPP
M32 = NGC221
distance = 770 kpc


skycell 052 in r
20x20 arcmin

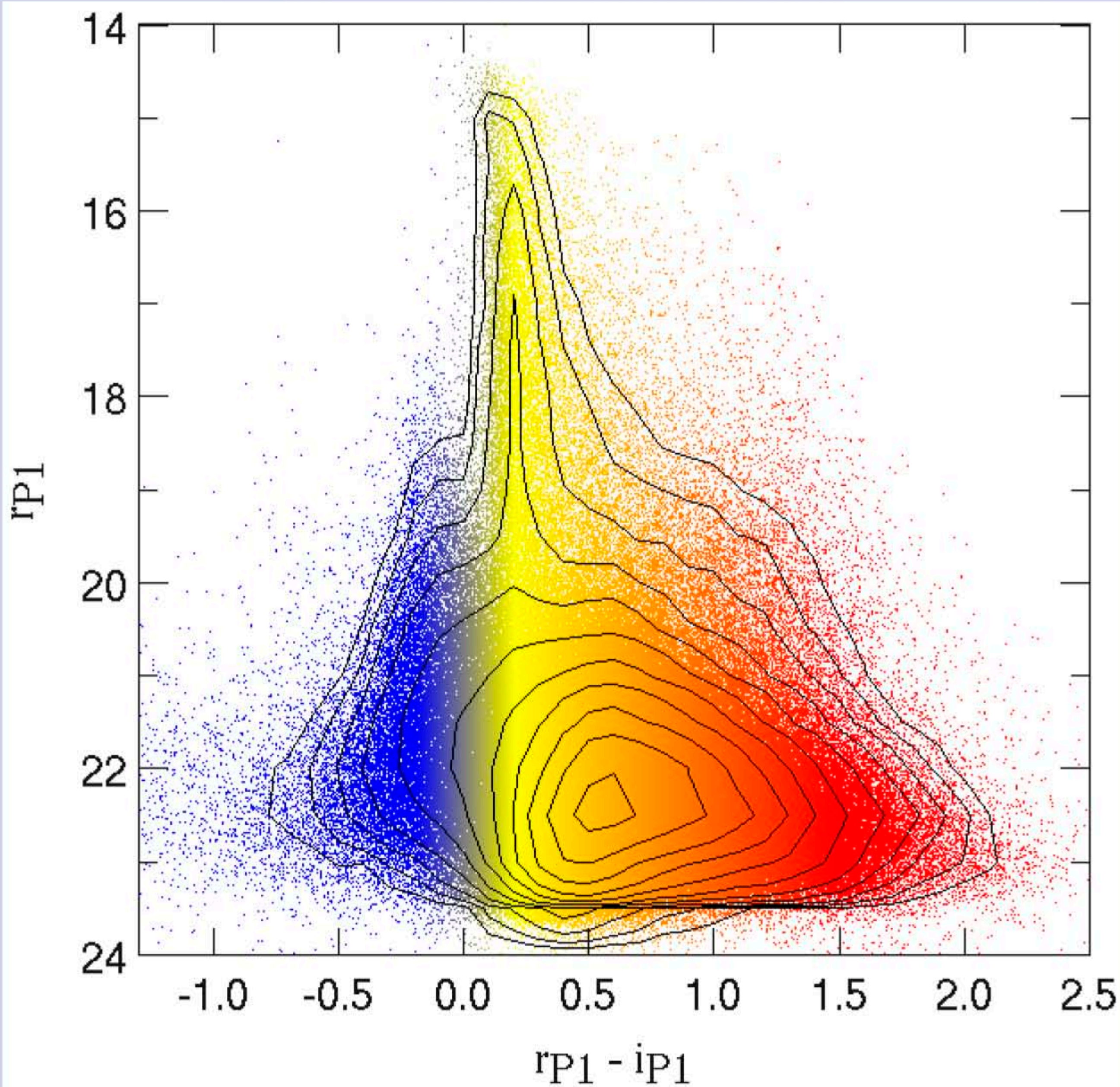
SDSS

PS1





PAndromeda: M31 color-magnitude diagram

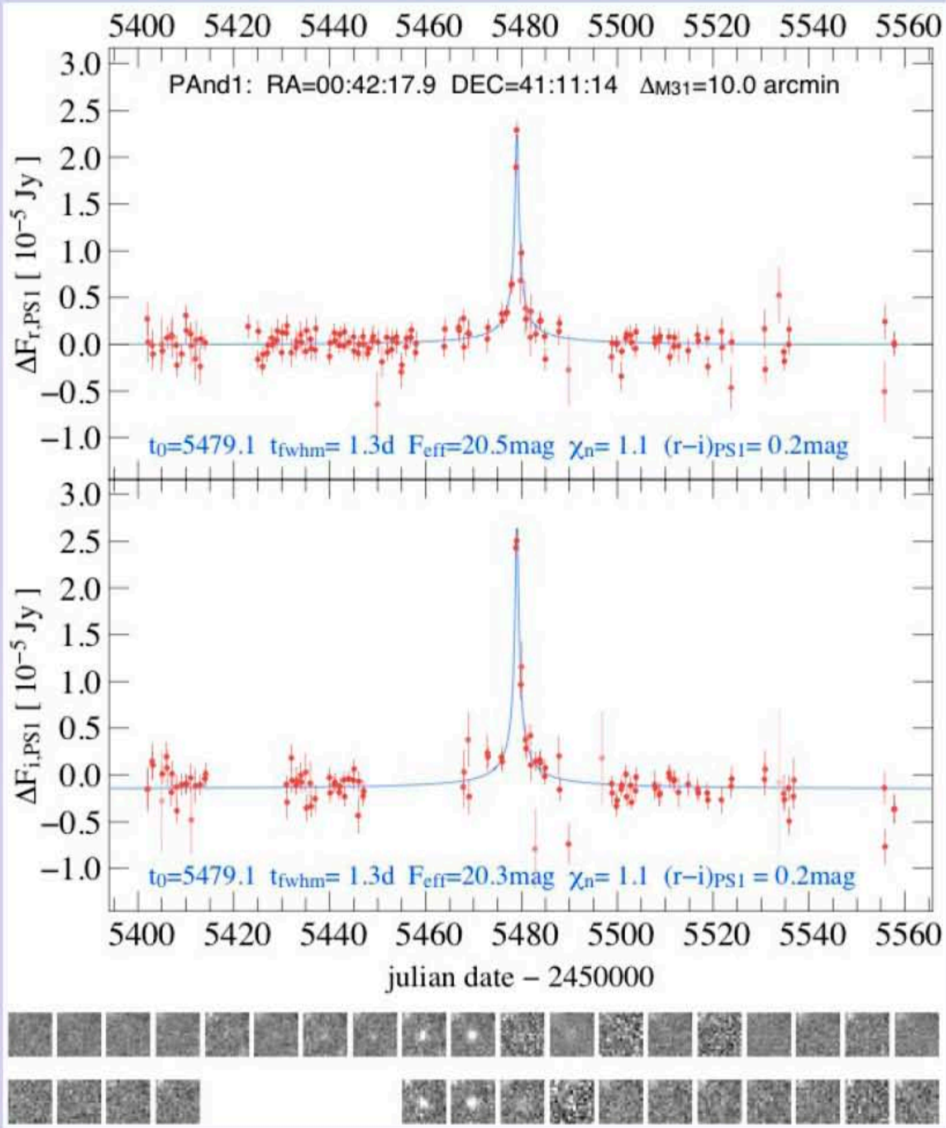


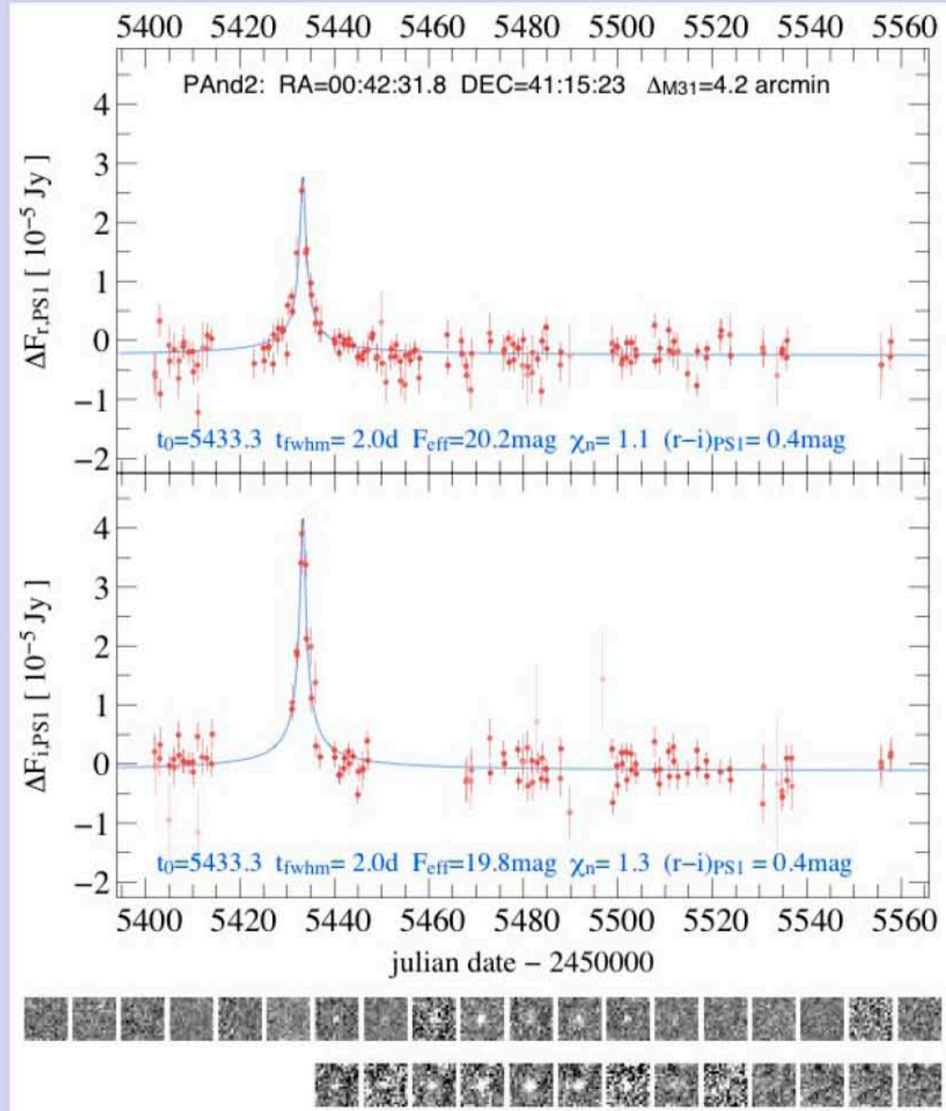
750,000 stars

countours: from 100 to 32000 in $\log_{10}$ intervals

homogeneous detection limit: r ~ 23 mag

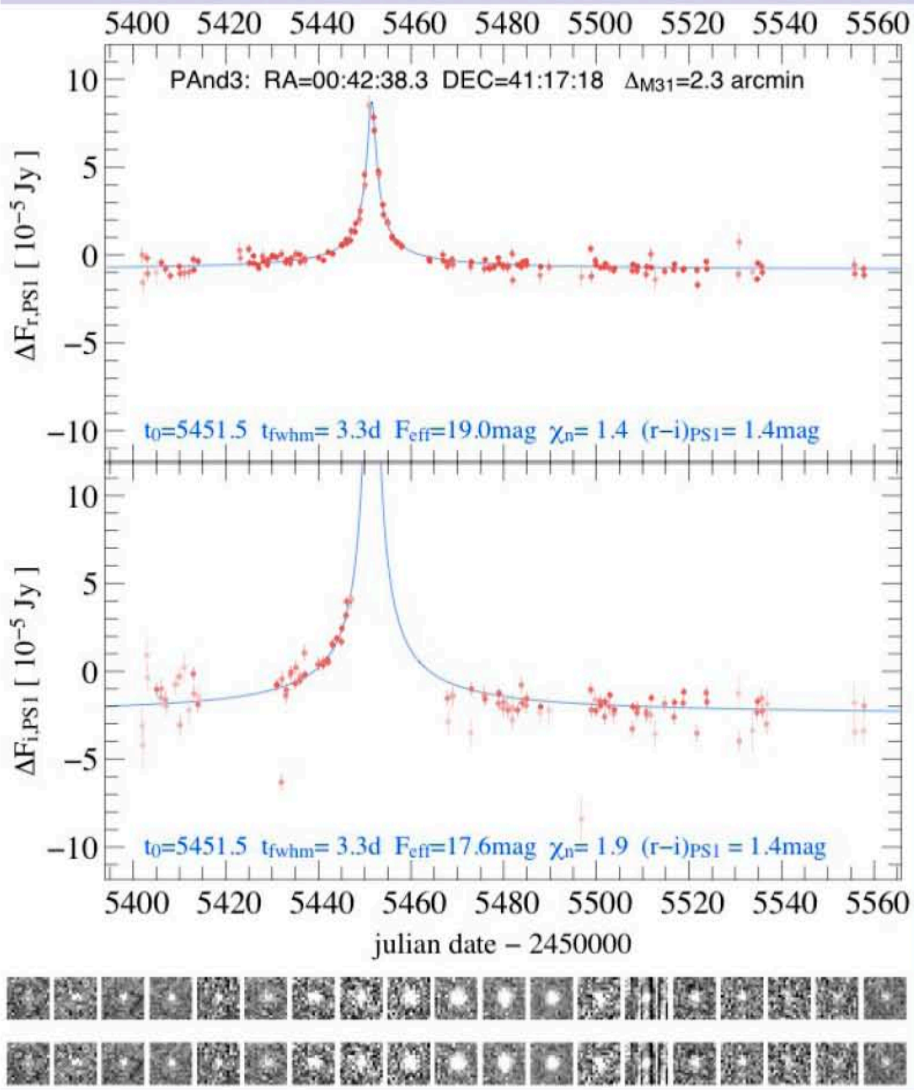
microlensing candidate PAnd 1 + 2

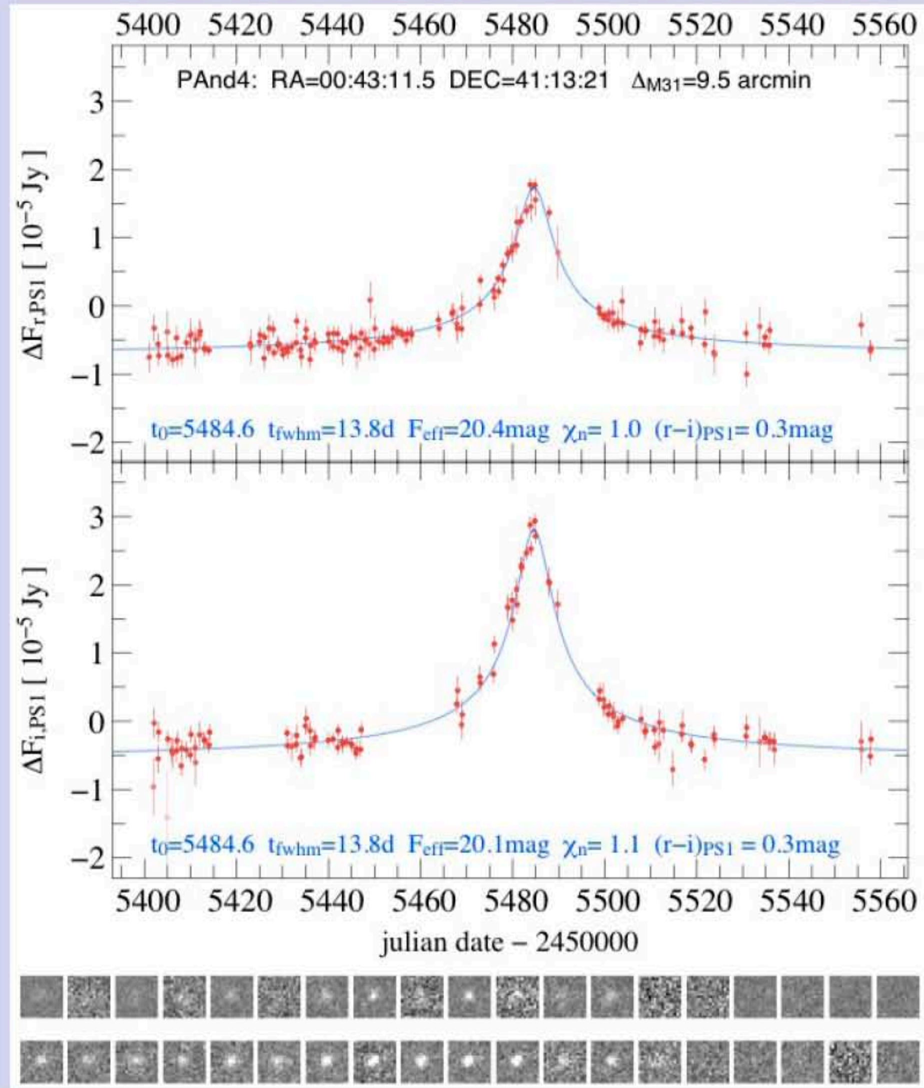




Lee (2011,arXiv,1109,6320)

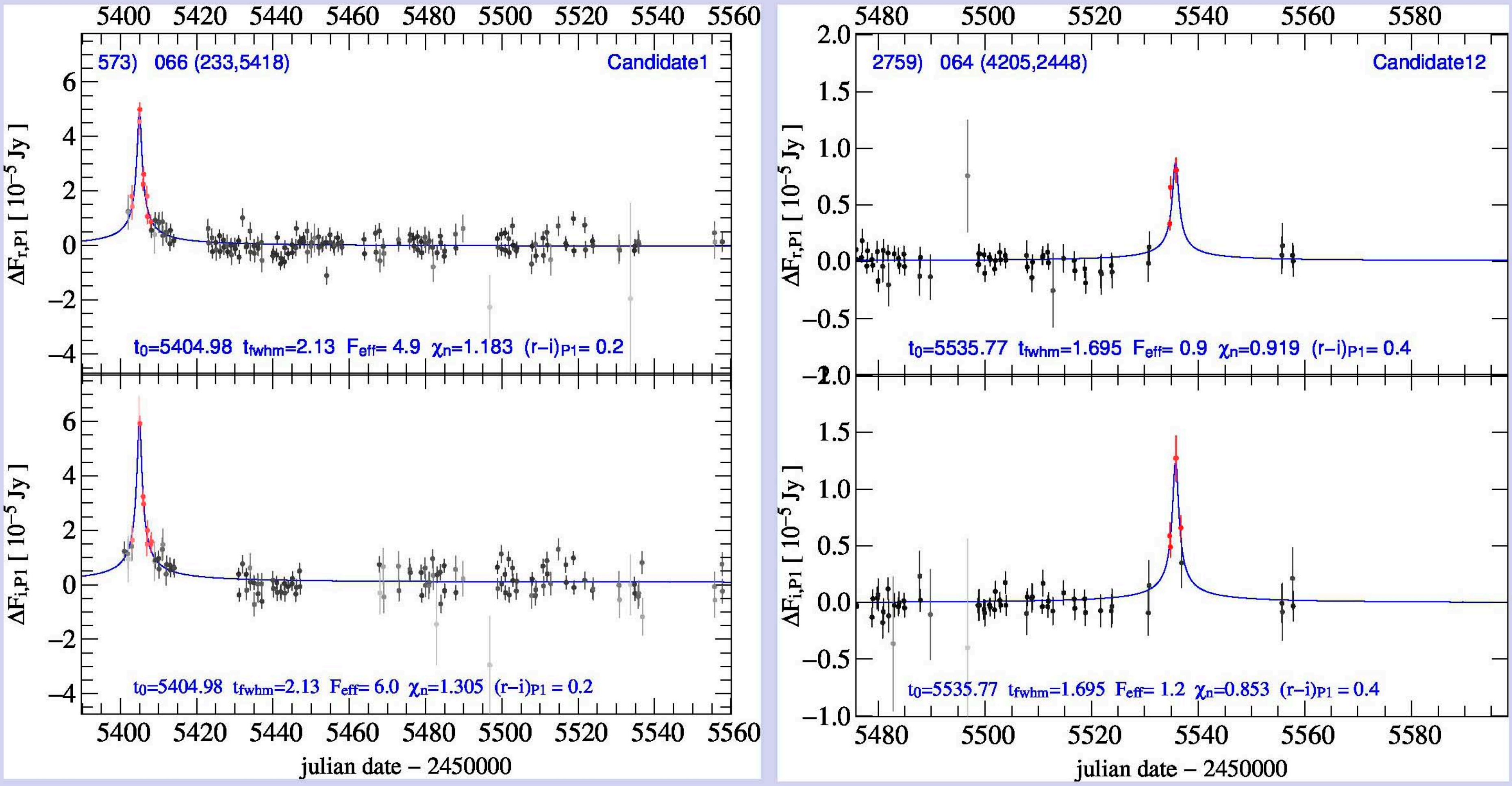
microlensing candidate PAnd 3 + 4





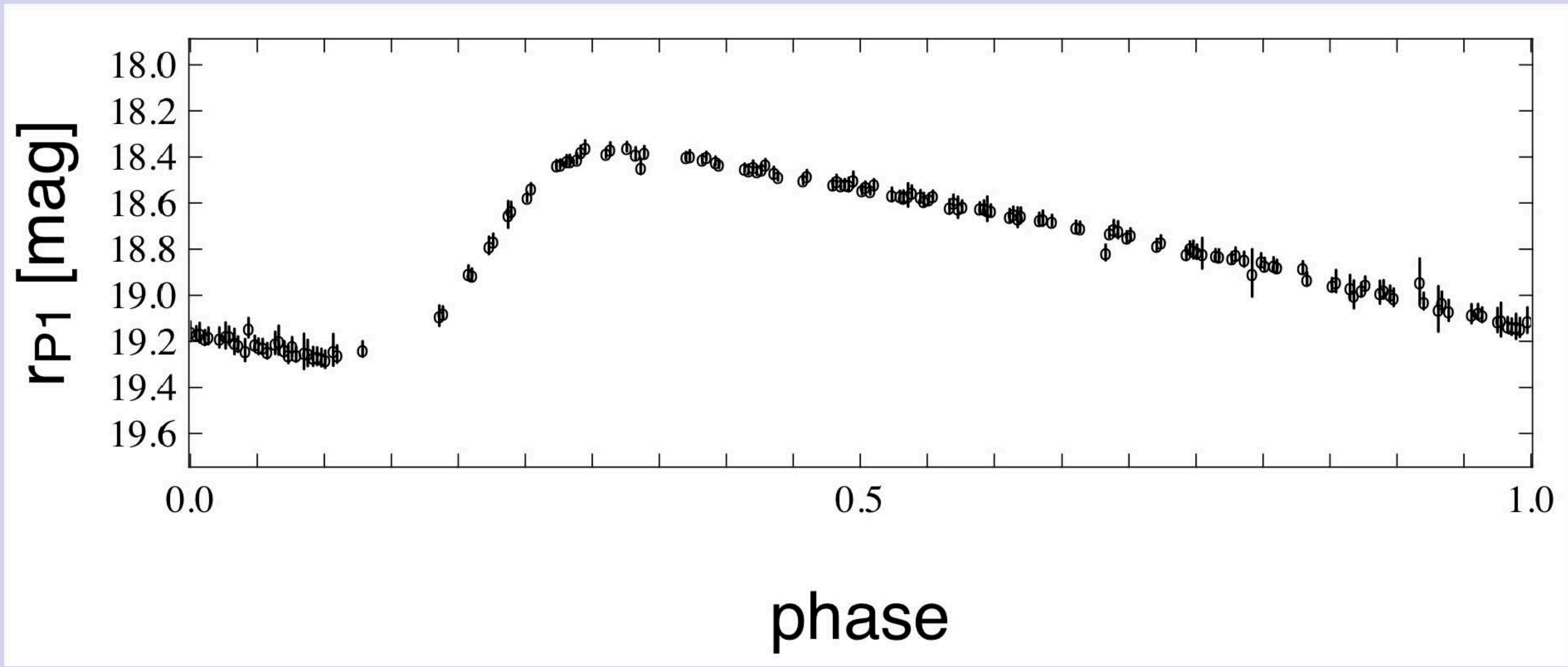
Lee (2011,arXiv,1109,6320)

preliminary: new disk candidates



cepheids

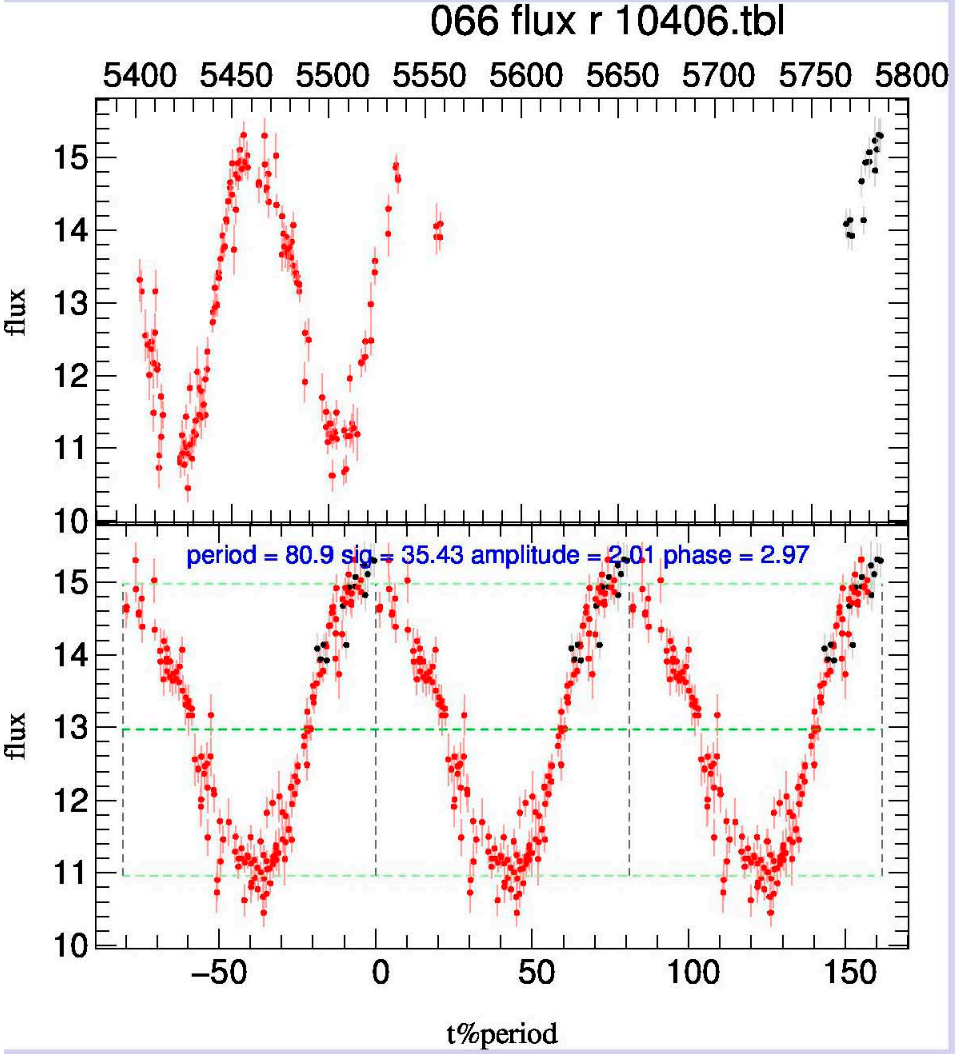
- responsible: Goessl (MPE)

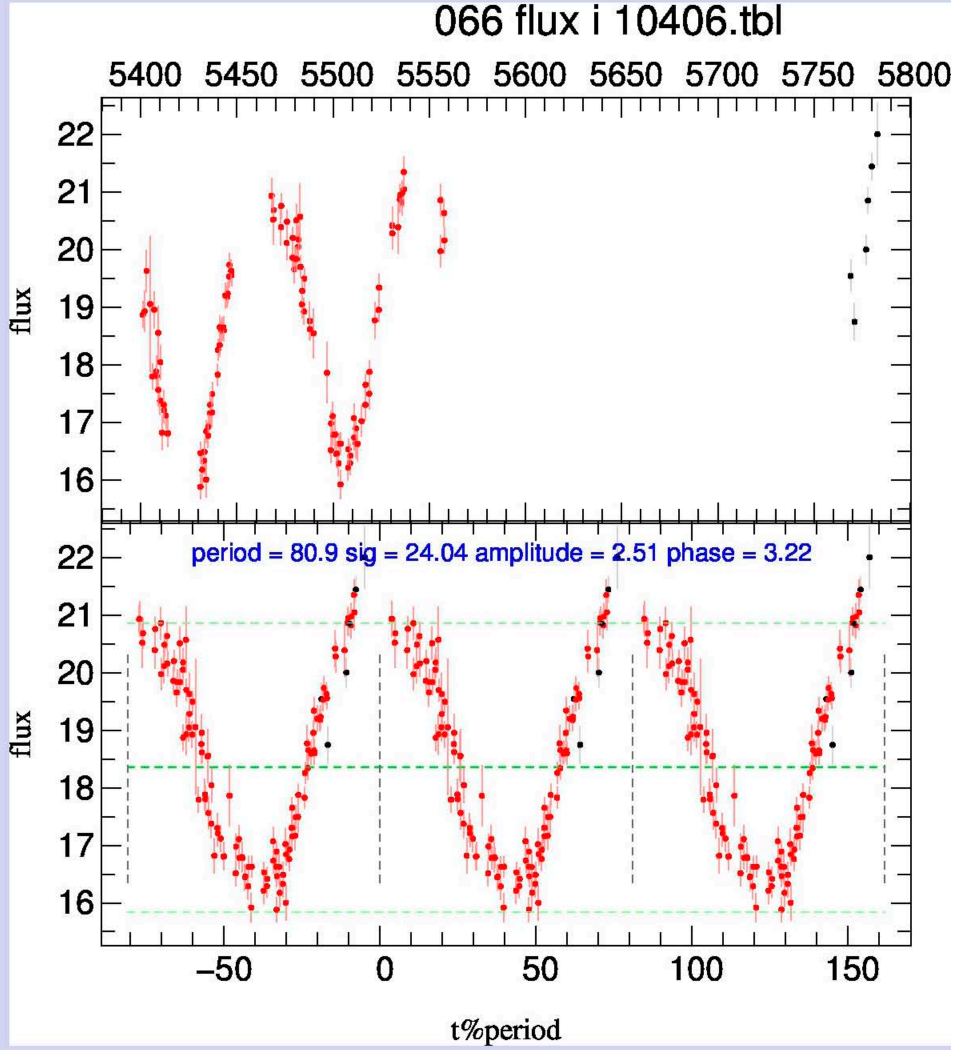


Folded r_{P1}-band light curve of our best Cepheid candidate at RA(J2000) = 10.2662 deg and Dec(J2000) = 41.1512 deg. The period is 45.6 days and the distance from the center of M31 is 20'.

Lee (2011,arXiv,1109,6320)

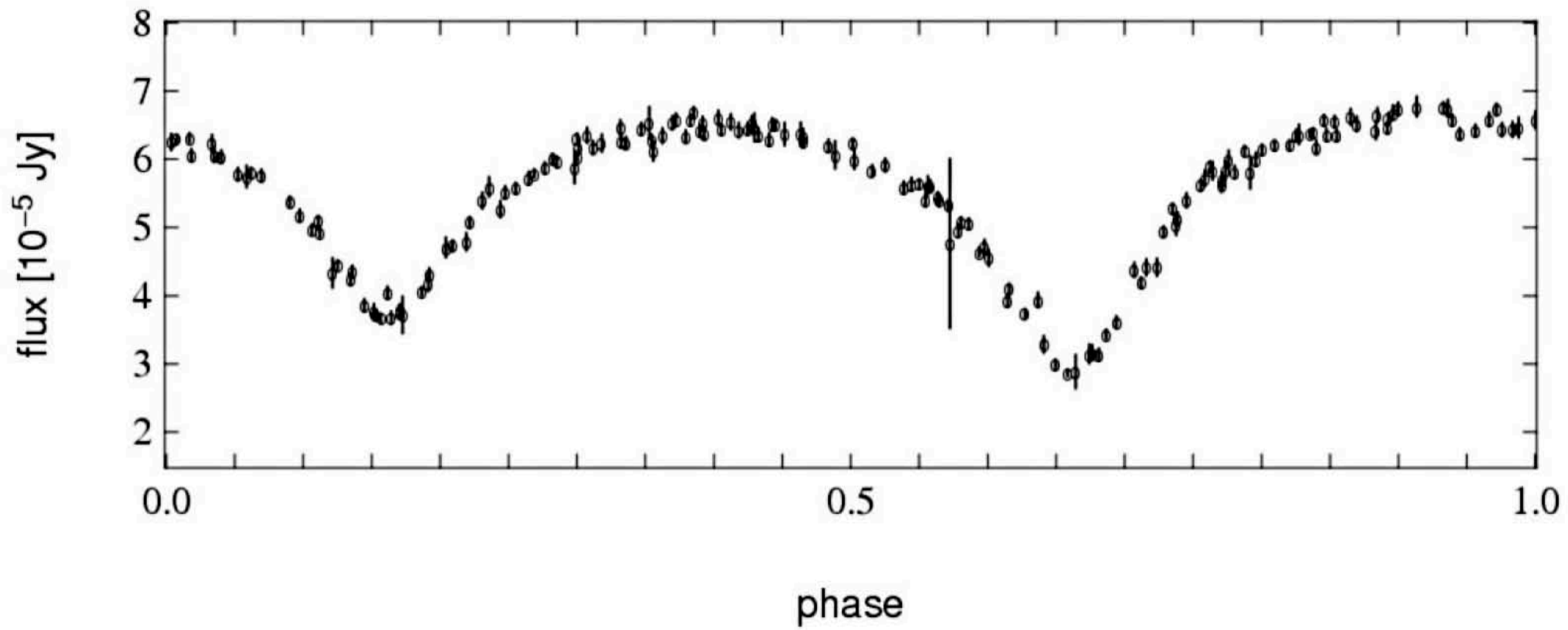
cepheids: period 81 days





eclipsing binaries

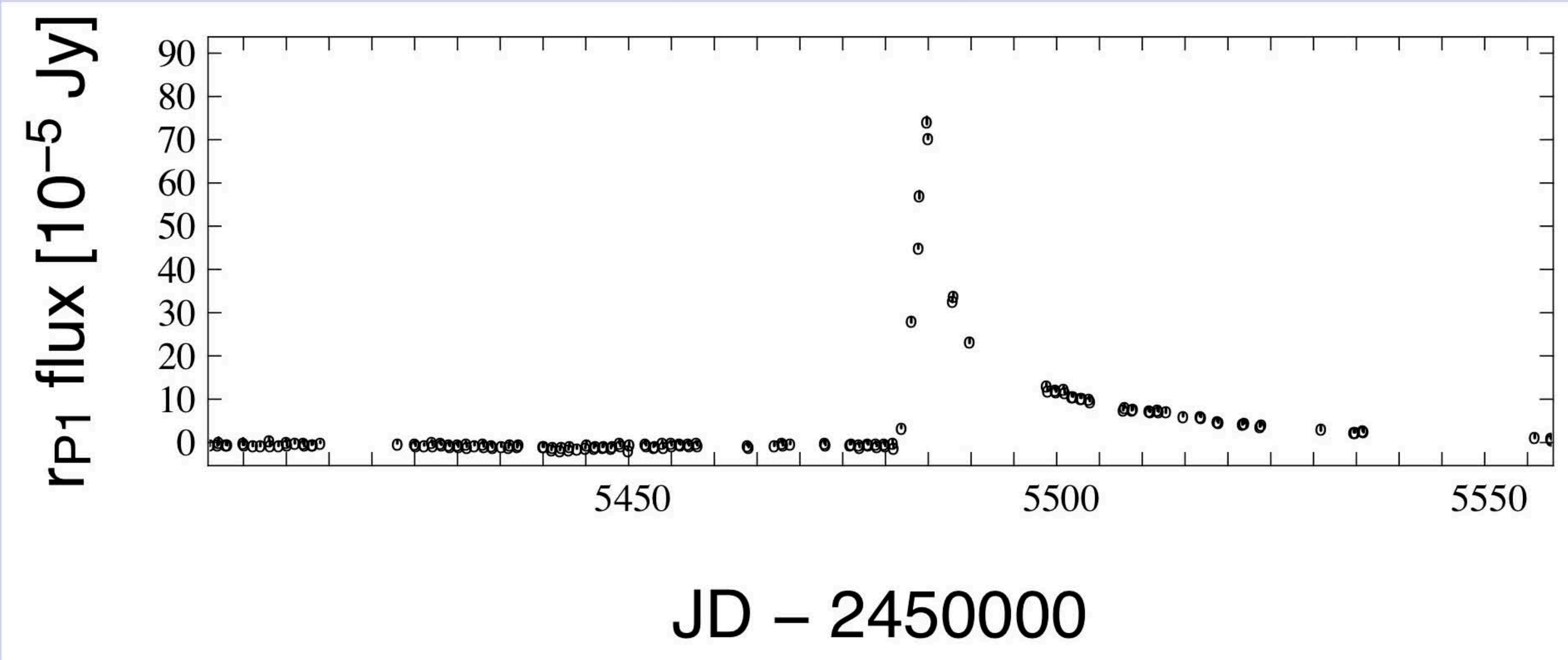
- Lee & Koppenhoefer



Folded r_{P1}-band light curve of a possible M31eclipsing binary variation 19.3 mag – 20.2 mag

Novae

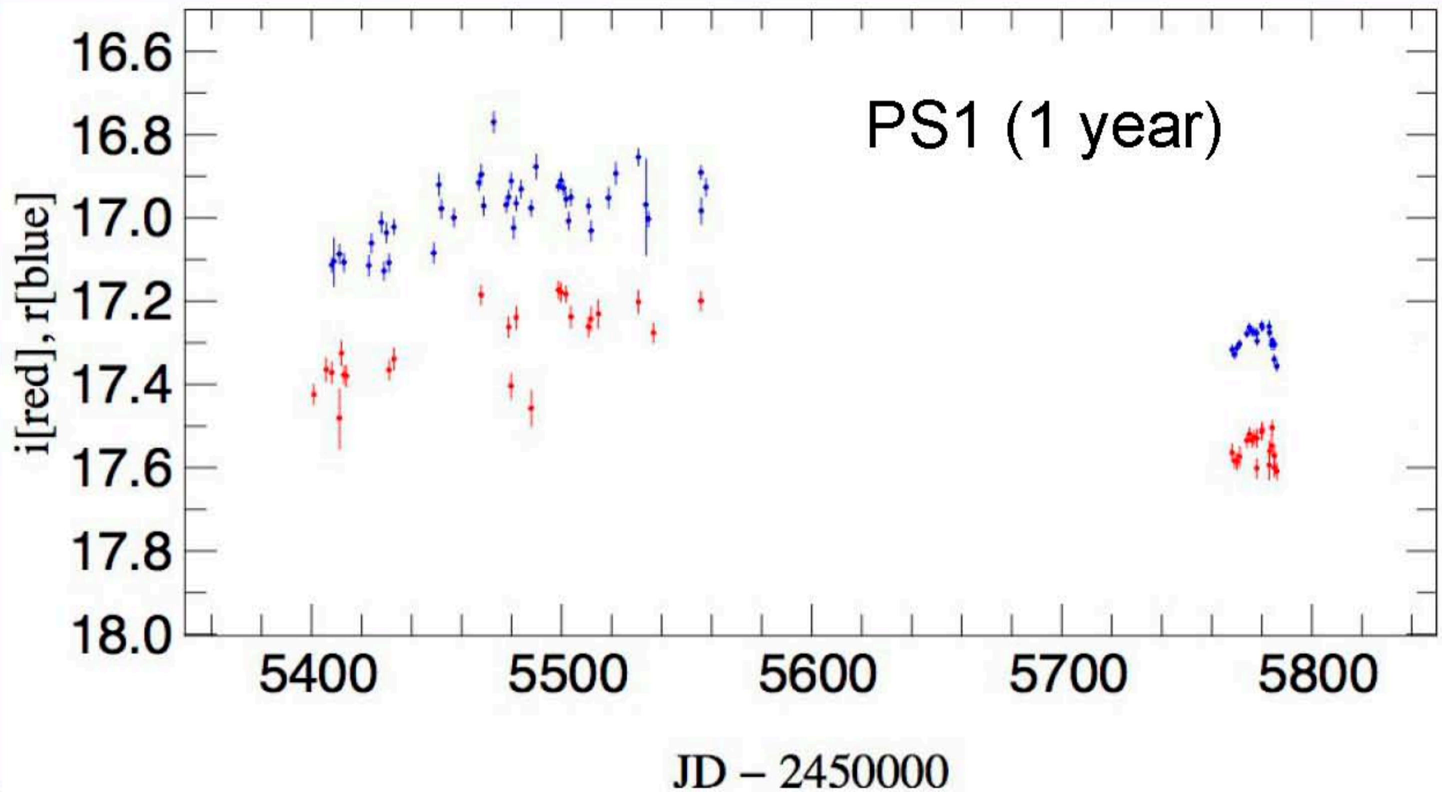
- Riffeser & Lee



r_{P1}-band light curve of the nova M31N-2010-10c from PAndromeda survey at RA(2000) = 11.1108 deg and Dec(2000) = 41.5205 deg.

Lee (2011,arXiv,1109,6320)

LBVs in M31 (Hubble-Sandage variables)



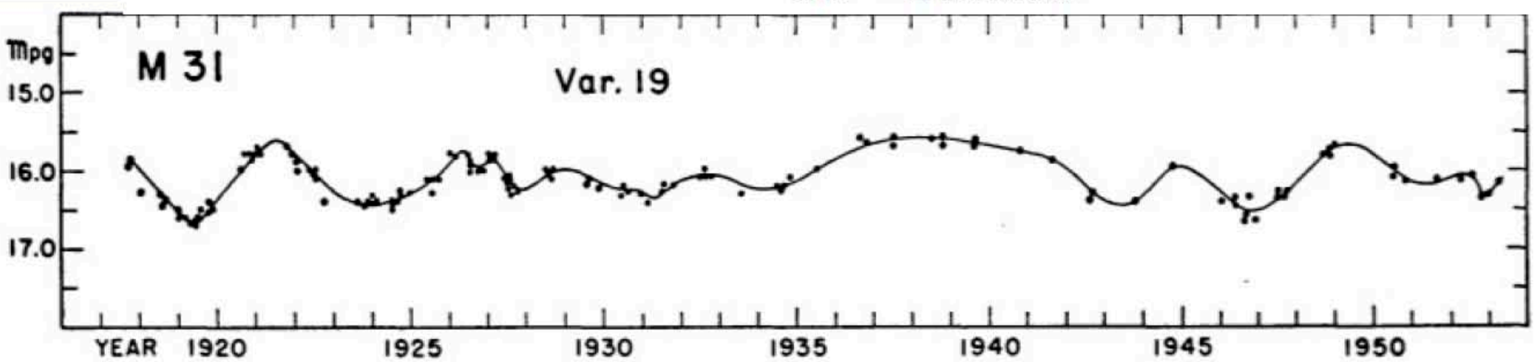


FIG. 5.—The light-curve for variable 19 in M31 from 1917 to 1953. The apparent photographic magnitude is plotted as ordinate.

Hubble (1953, ApJ, 118, 353)

FU Orionis (Kudritzki, Aspin)

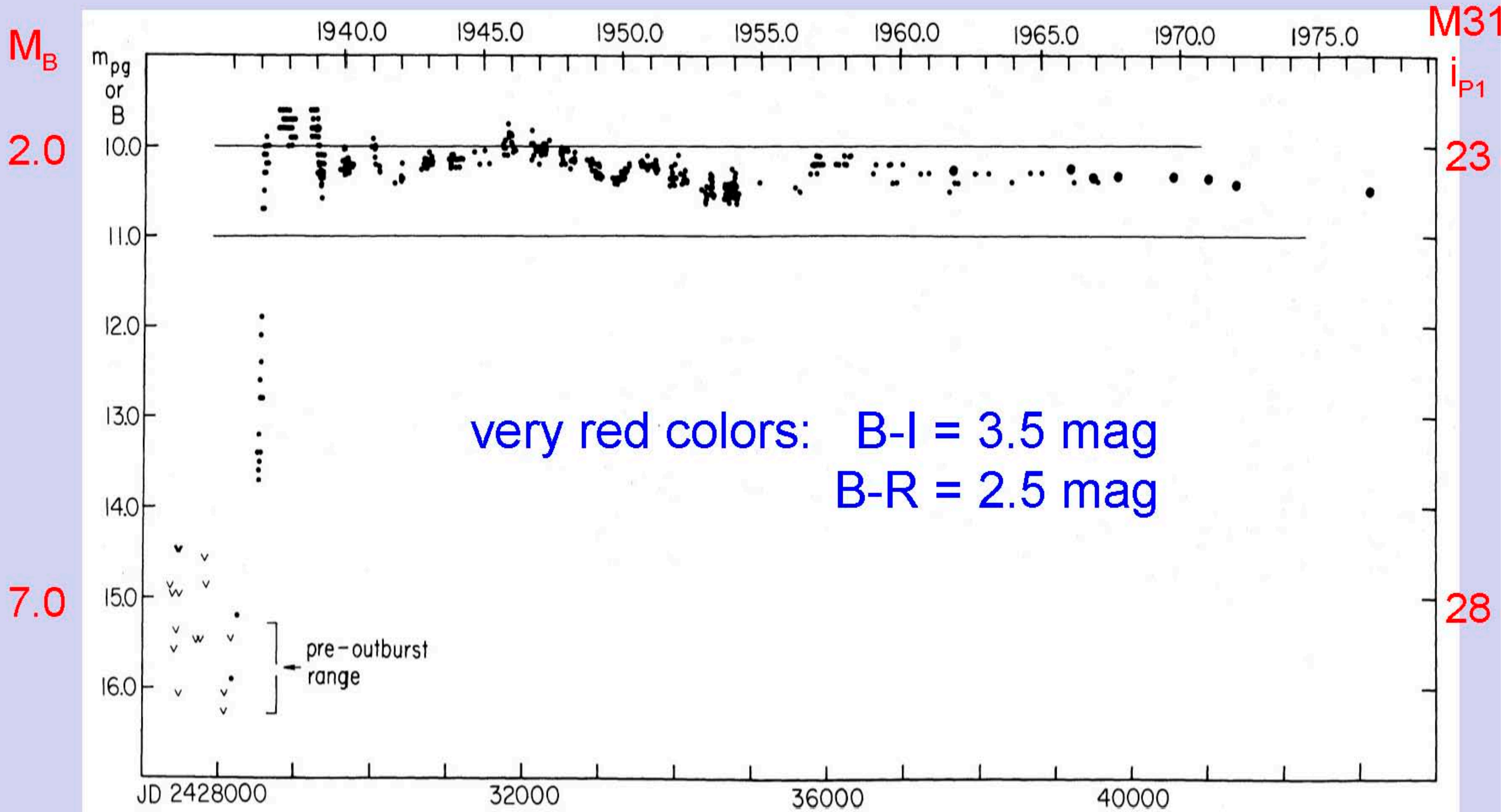
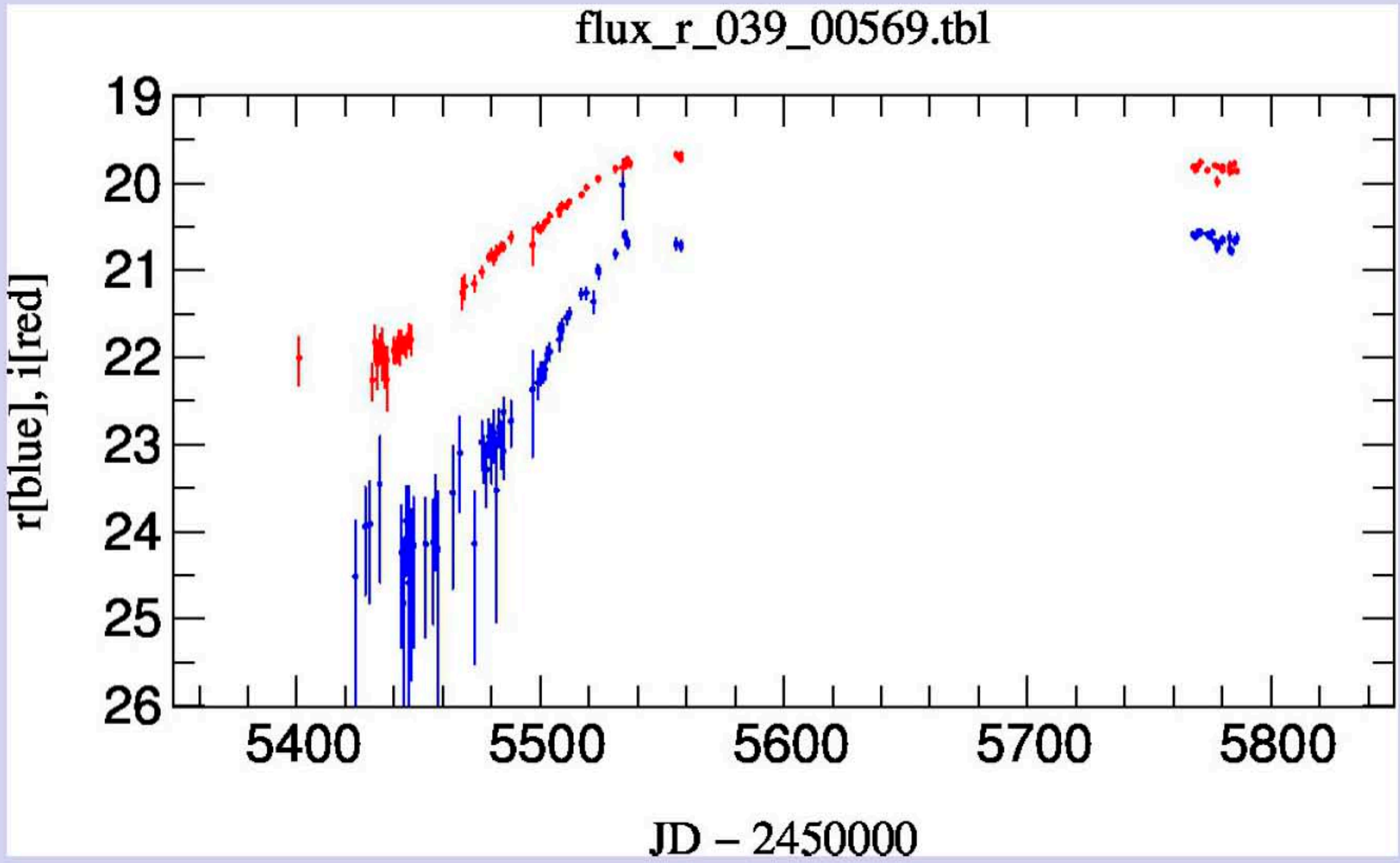


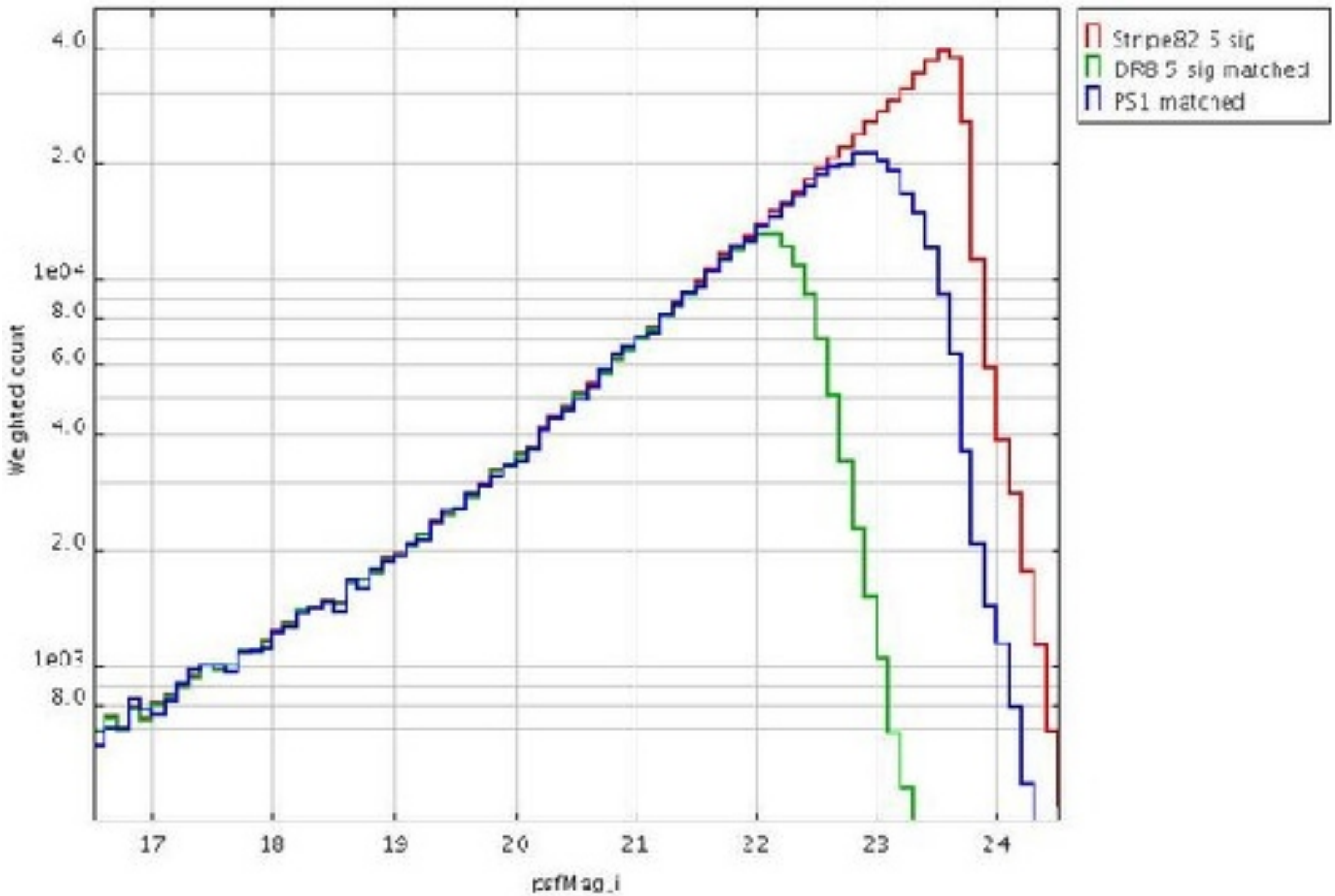
FIG. 1.—The photographic/*B* light curve of FU Ori through 1976. Small points represent photographic observations by Hoffleit (1939), Wachmann (1954), and Weber (1956, 1961, 1964, 1967). The larger points are photoelectric measures of *B* by Smak (Herbig 1966), Mendoza (1968), Dibai and Zaitseva (1968), Lee (1970), Lee and Low as quoted by Rieke *et al.* (1972), Landolt (1972), Schweitzer (1975, private communication), and Stone (unpublished).

Herbig (1977, ApJ, 217, 693)

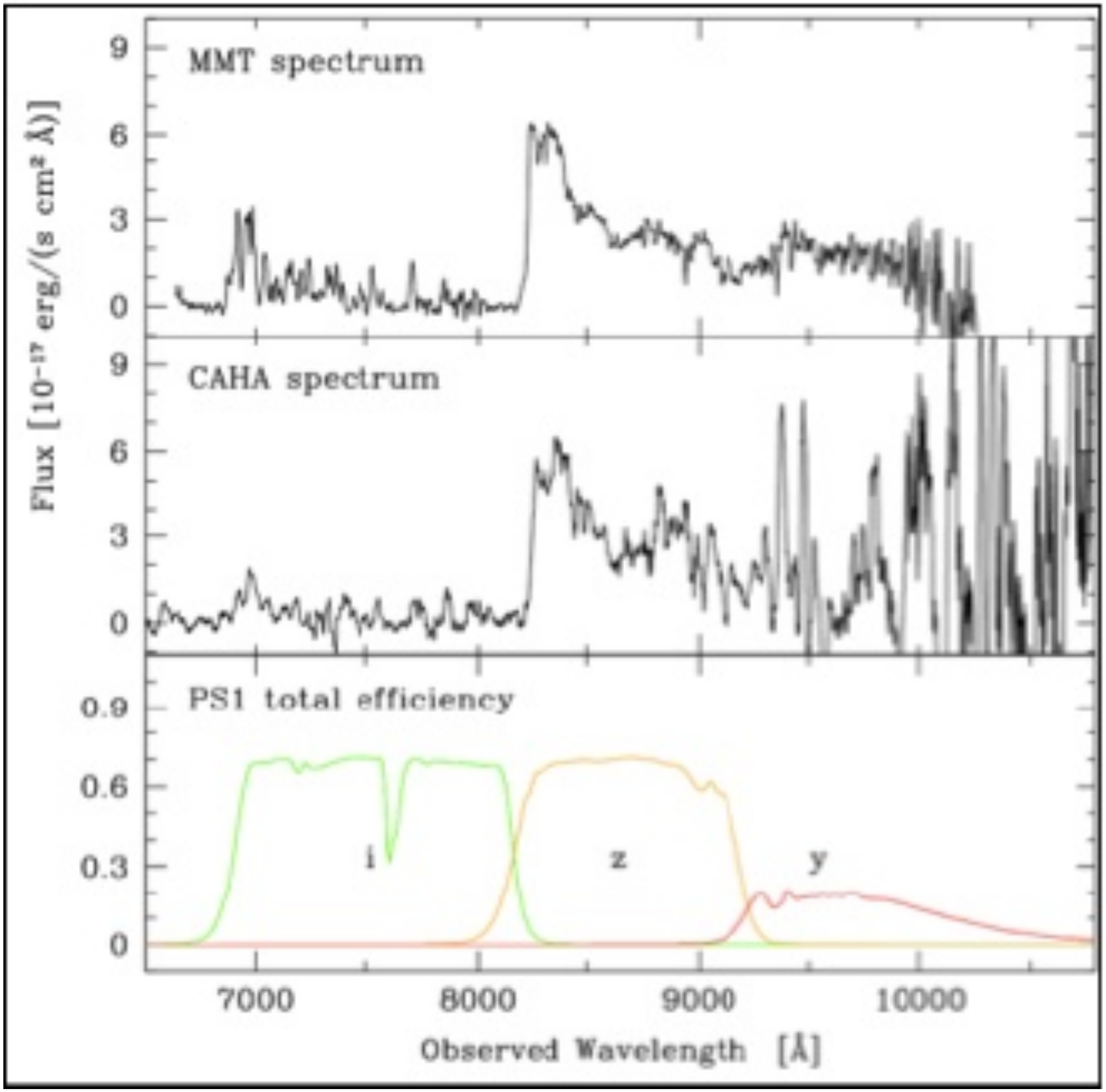
FU Orionis candidate



Galaxy number counts in test of 3 year survey – "small area survey" = 100 deg^2



First PS1 high z quasar



Supernovae and Transients with the Pan-STARRS1 survey

Queen's University Belfast :

S.J. Smartt , M. McCrum, R. Kotak, K. Smith, A. Pastorello, S. Valenti, M.T. Botticella, M. Fraser, S. Mattila (Turku) E. Kankare (Turku), D. Young

CfA , Harvard:

E. Berger, L. Chomiuk, R. Chornock, G. Narayan, R. Foley, A. Soderberg, R. Kirshner, N. Sanders, P. Challis, C. Stubbs, I. Czekala, A. Rest (STScI), M.W. Vasey (Pittsburgh), R. Chevalier (U. Virginia)

JHU :

S. Rodney, A. Riess, D. Scolnic, S. Gezari

IFA:

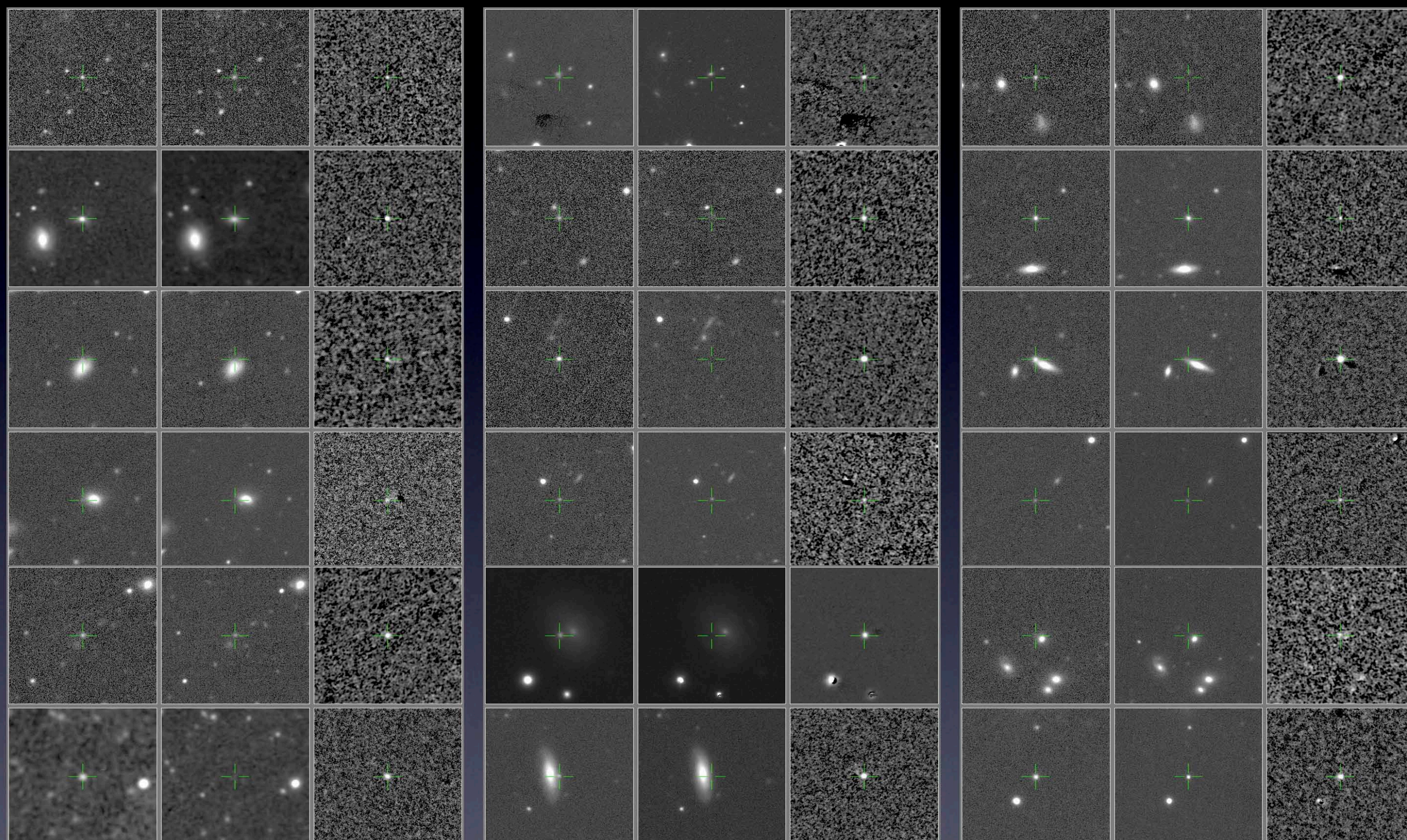
J. Tonry, M. Huber, K. Chambers, G. Magnier +PS1 Project team

LCOGT:

A. Howell

PS1 consortium members

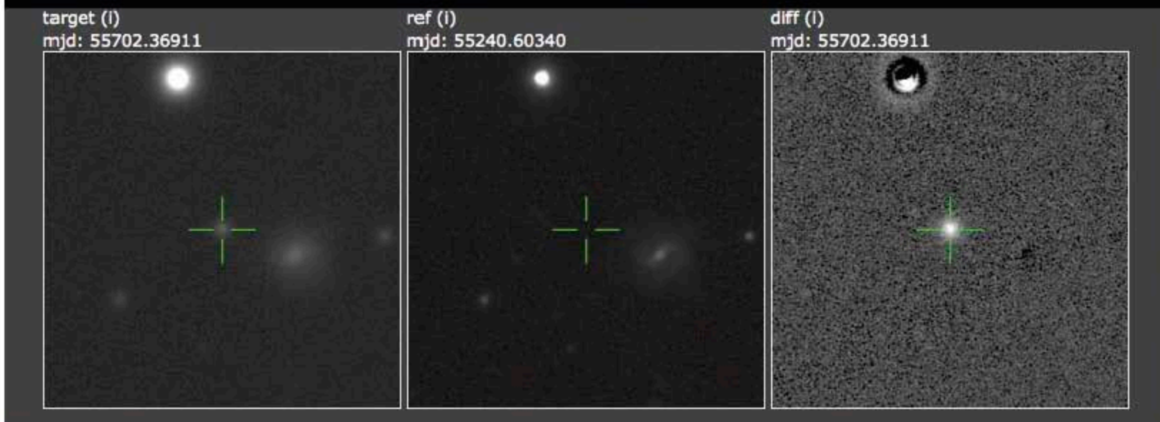
~3x10^3 *transients*, ~250 spectroscopically Confirmed SNe



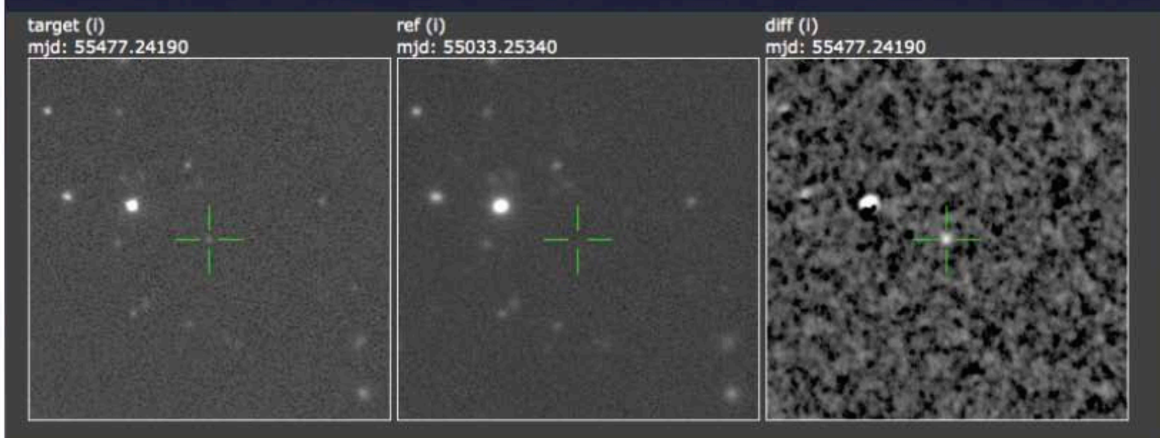
Photpipe team :Huber, Rest, Narayan, Stubbs, Wood-Vasey, Chornock, Foley, Berger, Rodney ++

QUB Team :Smartt,Smith, Kotak, McCrum, Fraser , Magil, Valenti, Botticella, Pastorello, Young

Search for Orphans



- PS1-11zd
- Type Ia, z=0.1 ; same as "host"
- Offset by ~25kpc



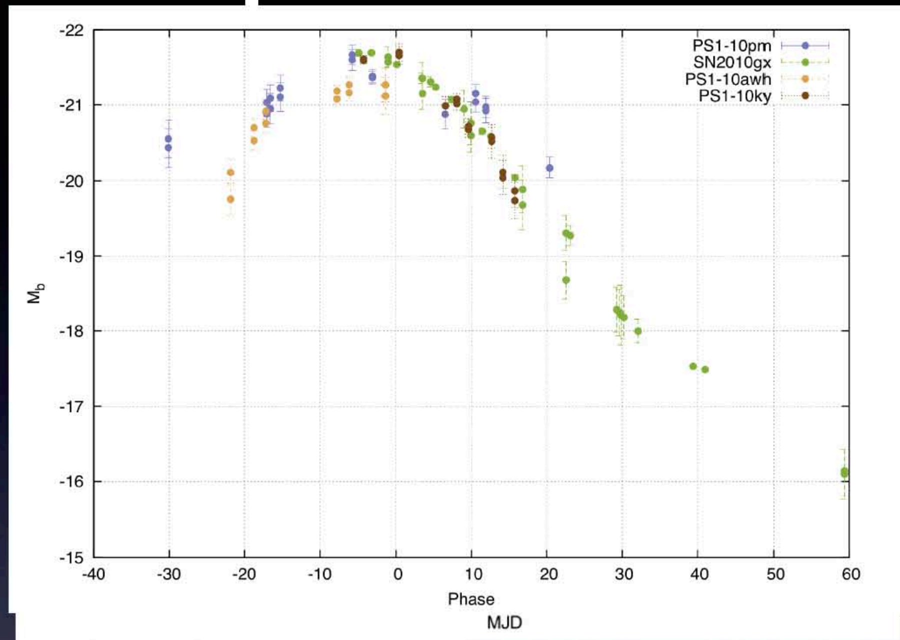
- PS1-10awh
- Type I SN at z=0.9
- No obvious host – even in deep stacks

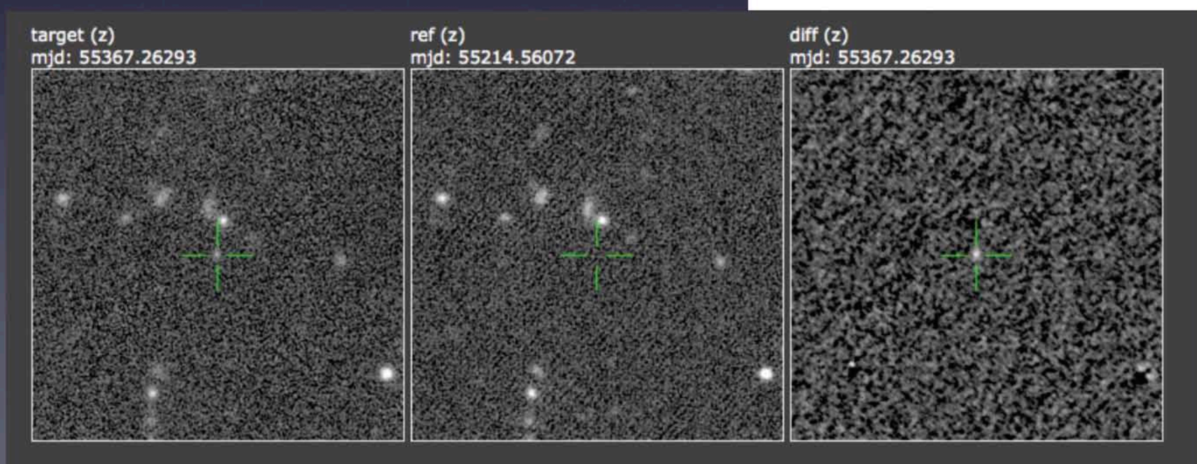
>3.5" from any catalogued star or galaxy, to $r \approx 23.5$

254 orphans from 1.25yr : Matt McCrum talk, paper in prep

High redshift orphans

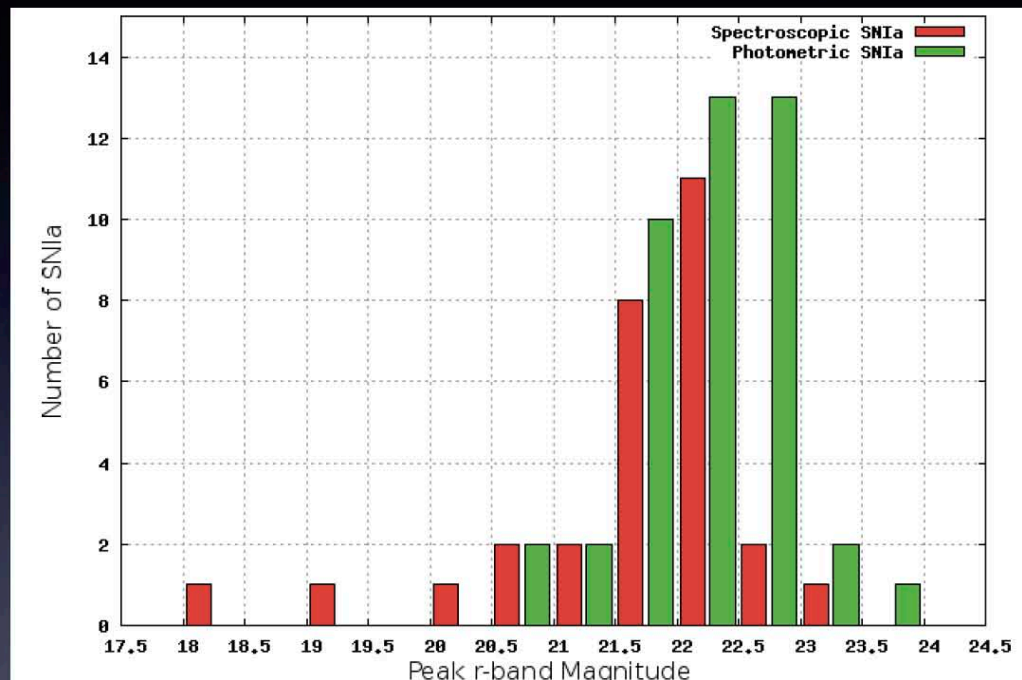
- *Peak at i_{P1} = 21.5*
- Mg II ISM host absorption : *z = 1.206*
- *M_U ~ -22 (rest frame)*
- *McCrum et al. 2012 in prep.*





Hostless type Ia SNe

- 96 are likely type Ia
- GMOS, MMT, WHT, Magellan, APO spectra of 30
- 48 lightcurves photometrically classified by SOFT (Rodney & Tonry) or SAKO classifer
- Analysis underway on hosts, offsets (dwarfs vs ejection from large galaxies)
- Tonry, Rodney et al.



Spectroscopic Programmes :
E. Berger, R. Chornock, R. Foley, CfA++
A. Pastorello, R. Kotak, S. Smartt,QUB++
M. Huber, S. Gezari, S. Rodney, JHU++
J. Tonry, F. Bresolin, R. Kudritzki, IfA

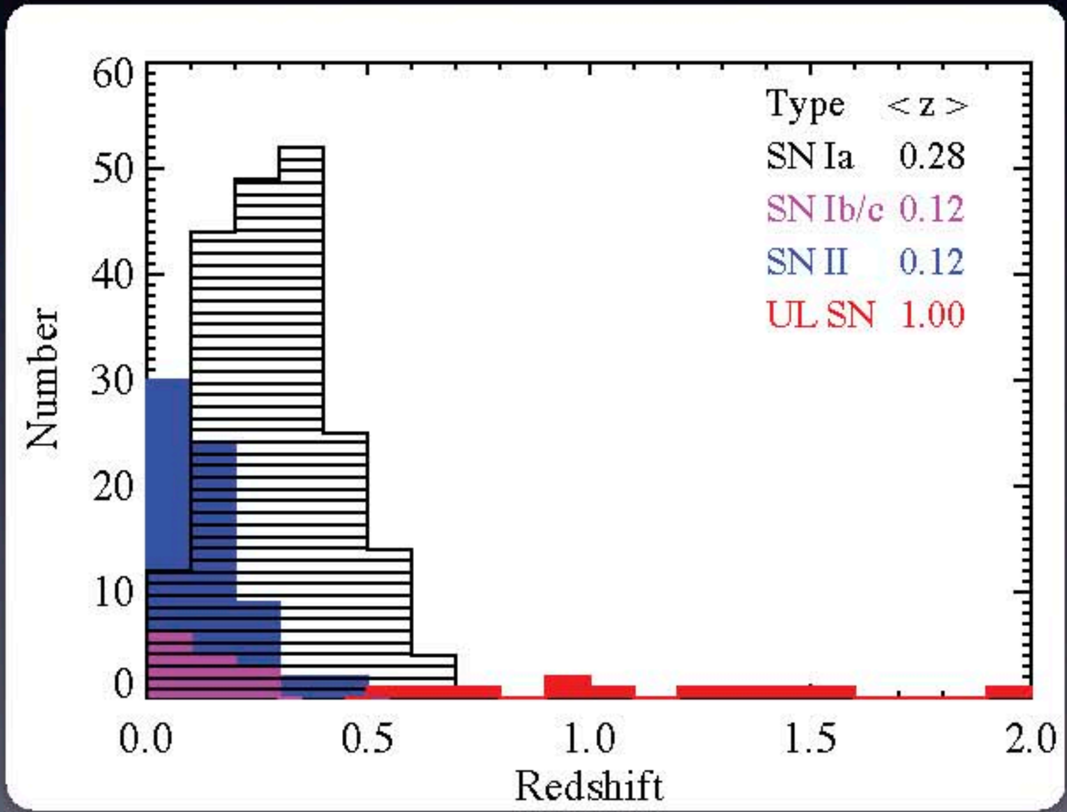
3Pi "Faint galaxy supernova survey"

- No PS1 difference imaging in 3Pi (apart from TTI pairs) : 1000 square degrees per night - wasted resource !
- New NEO cadence is good for discovery of young SNe
- <u>Catalogue matching</u> : Transient candidates in **Faint Galaxies** from the 3Pi images in the SDSS footprint.
- Scientifically designed by S. Valenti, S. Smartt – implemented by K. Smith

- We're finding ~100-150 new transients per month
- Spectroscopic followup from MMT/Blue Channel and Hectospec, Magellan, and Gemini

300 spectroscopically confirmed supernovae so far, mostly SNe Ia

(talk by Ryan Foley)

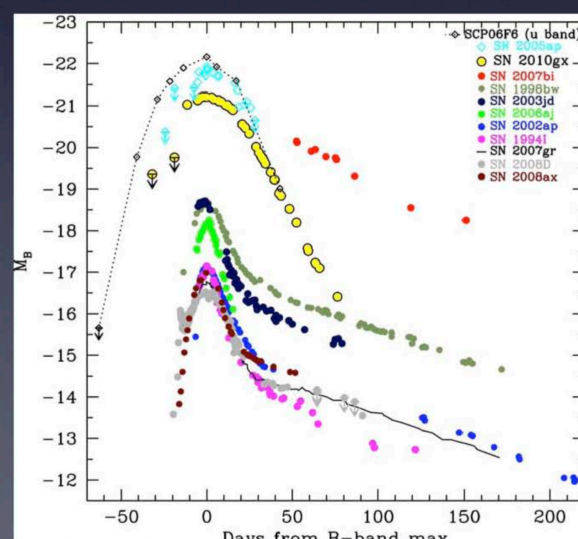


Normal Supernovae

- $E_\nu \sim 10^{53}$ erg
- $E_{Kin} \sim 10^{51}$ erg
- $E_{rad} \sim 10^{49}$ erg ($L \sim 10^{42}$ erg/s for 10^7 sec, or $L \sim 10^{43}$ erg/s for few $\times 10^6$ s)

Ultraluminous Supernovae

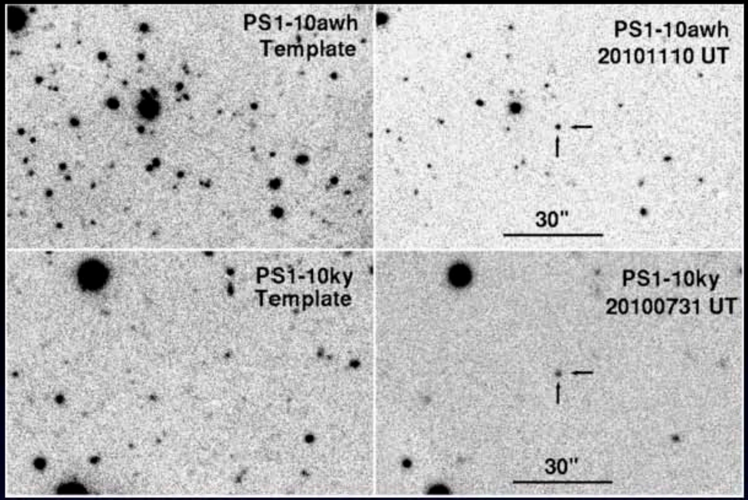
- L_{peak} < few x 10^{44} erg/s
- E_{rad} < few x 10^{51} erg
- $E_{Kin} \sim 10^{52}$ erg?

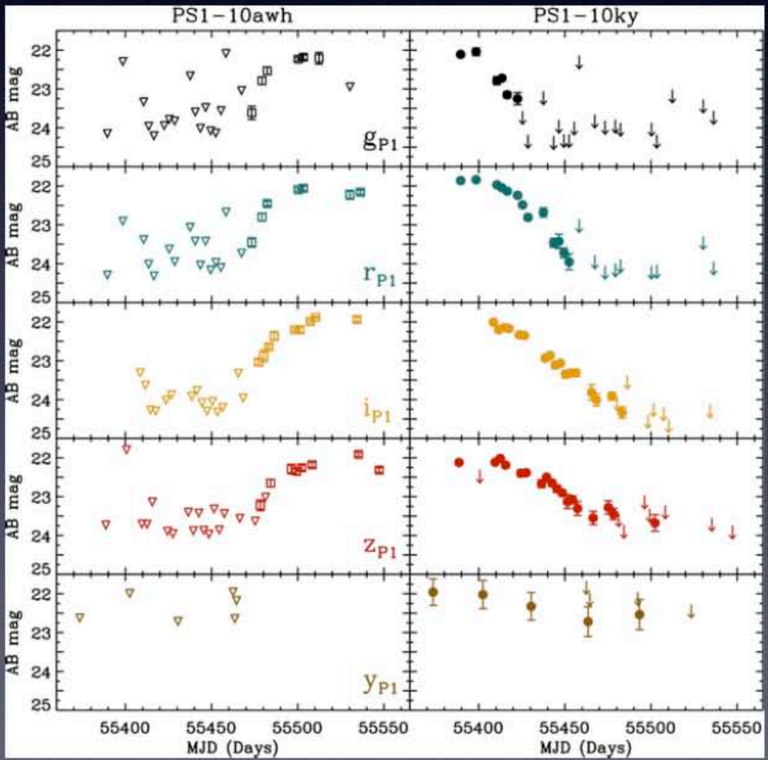


Pastorello et al. 2010

Our first two UL SNe

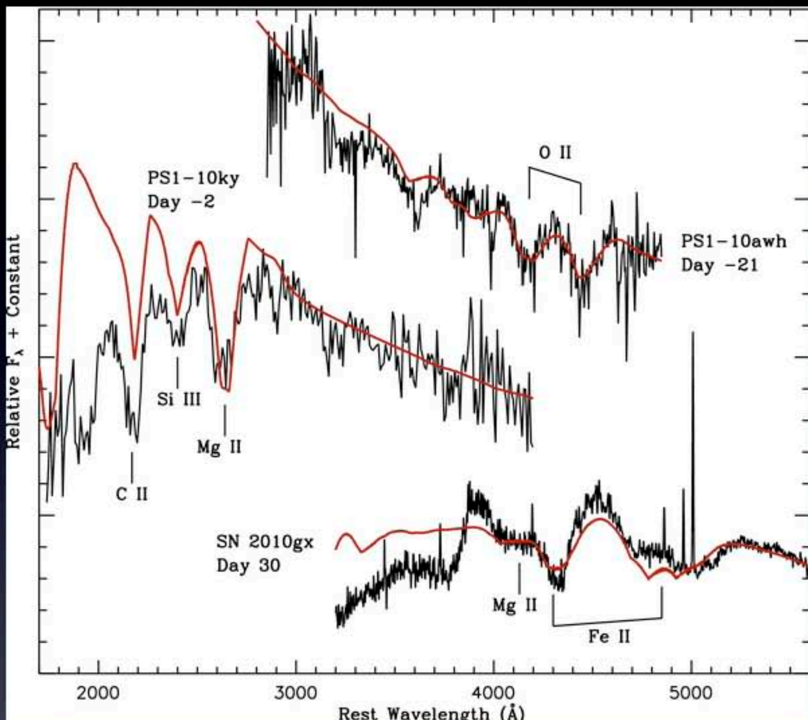
- PS1-10awh (z=0.908)
- PS1-10ky (z=0.956)

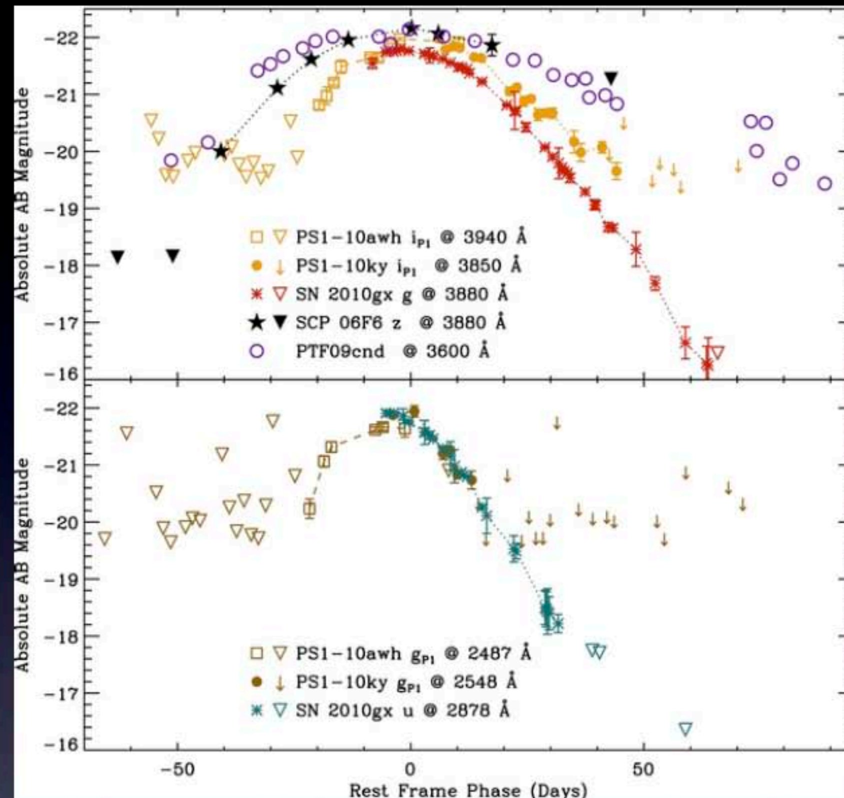




Chomiuk et al., 2011

Chomiuk et al., 2011





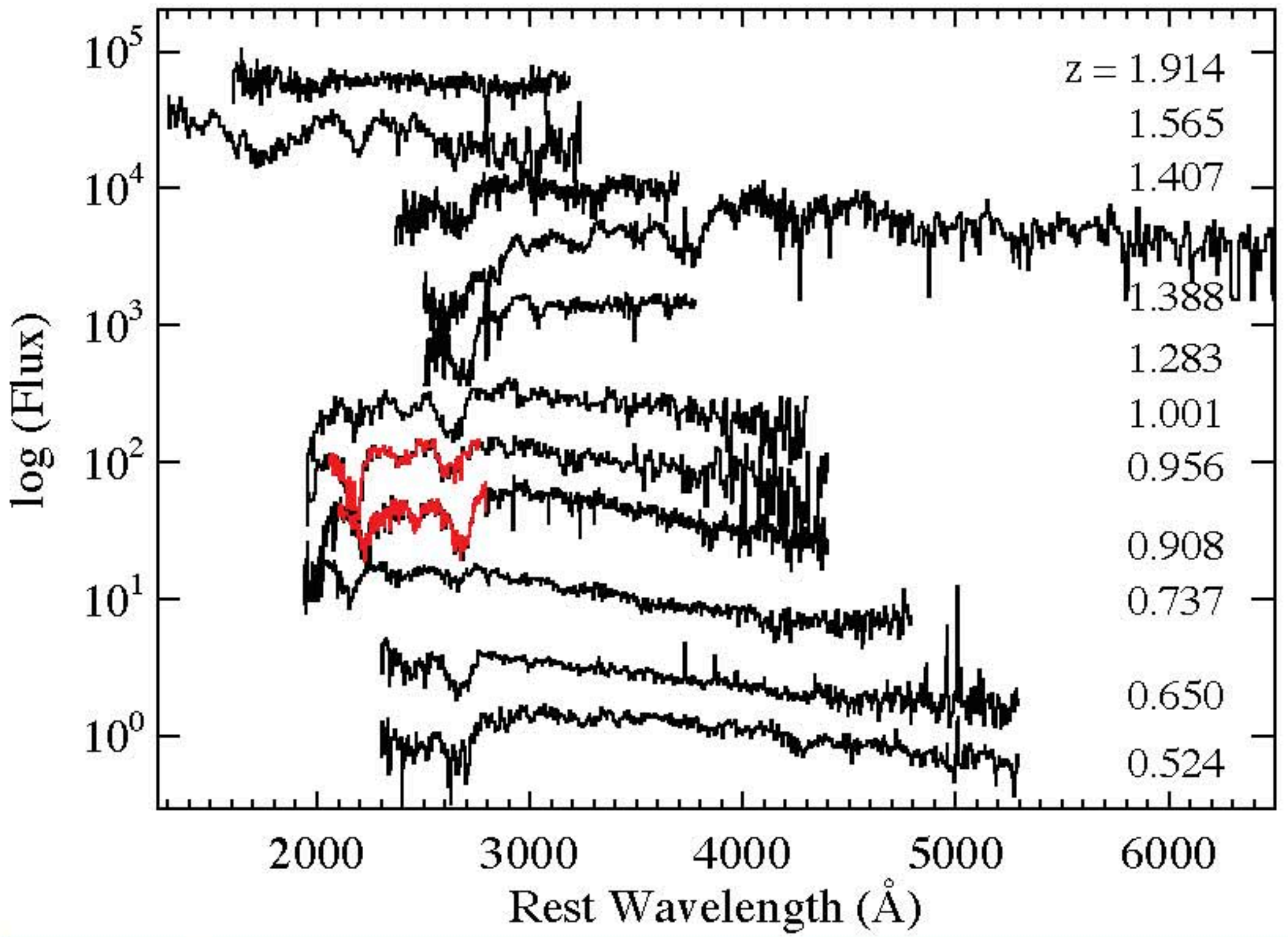
- High luminosities (M_{bol} ~ -22.5 mag)
- No H, He in spectra
- E_{rad} ~ (0.9-1.4) x 10^{51} ergs

What Powers These Objects?

- Radioactive decay? No! Peak luminosity inconsistent with shape of light curve ($M_{ej} < M_{Ni}$)
- Shock breakout through dense CSM? (e.g., Chevalier & Irwin 2011) Requires a circumstellar medium with ~6 $M_{\odot}$ within 3×10^{15} cm.
- Magnetar spindown? (Kasen & Bildsten 2010; Woosley 2010) Fit with: $B = 3 \times 10^{14}$ G, $P = 1.2$ ms (near maximal spin), $M_{ej} = 5\ M_{\odot}$

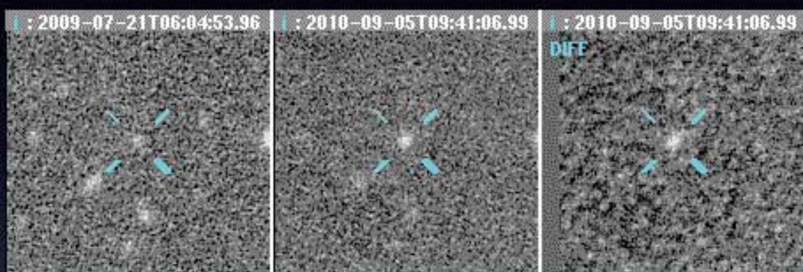
Chomiuk et al., 2011

Building a sample of UL SNe

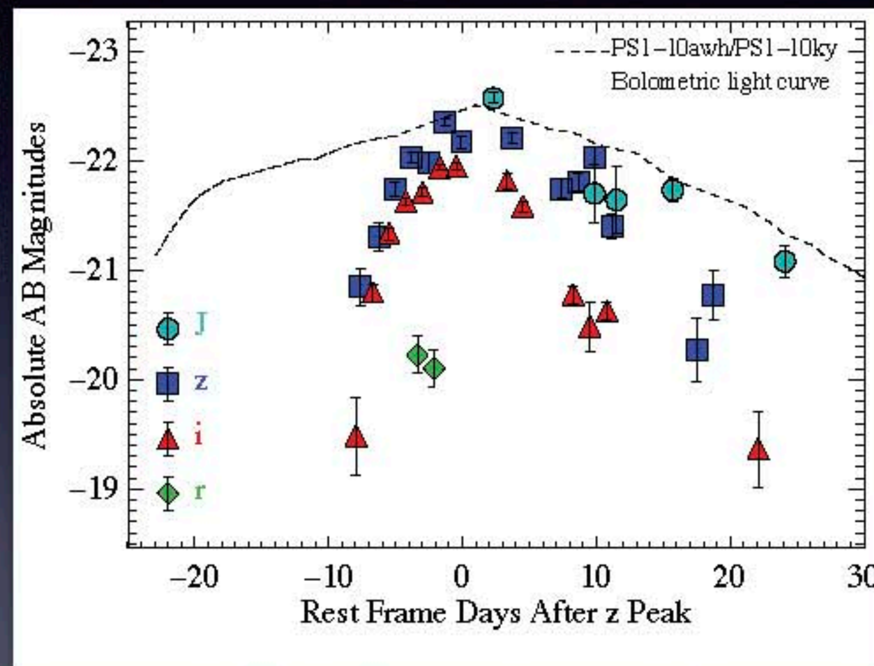


A New, Unique PS1 Discovery

PS1 i band



Template Image Difference

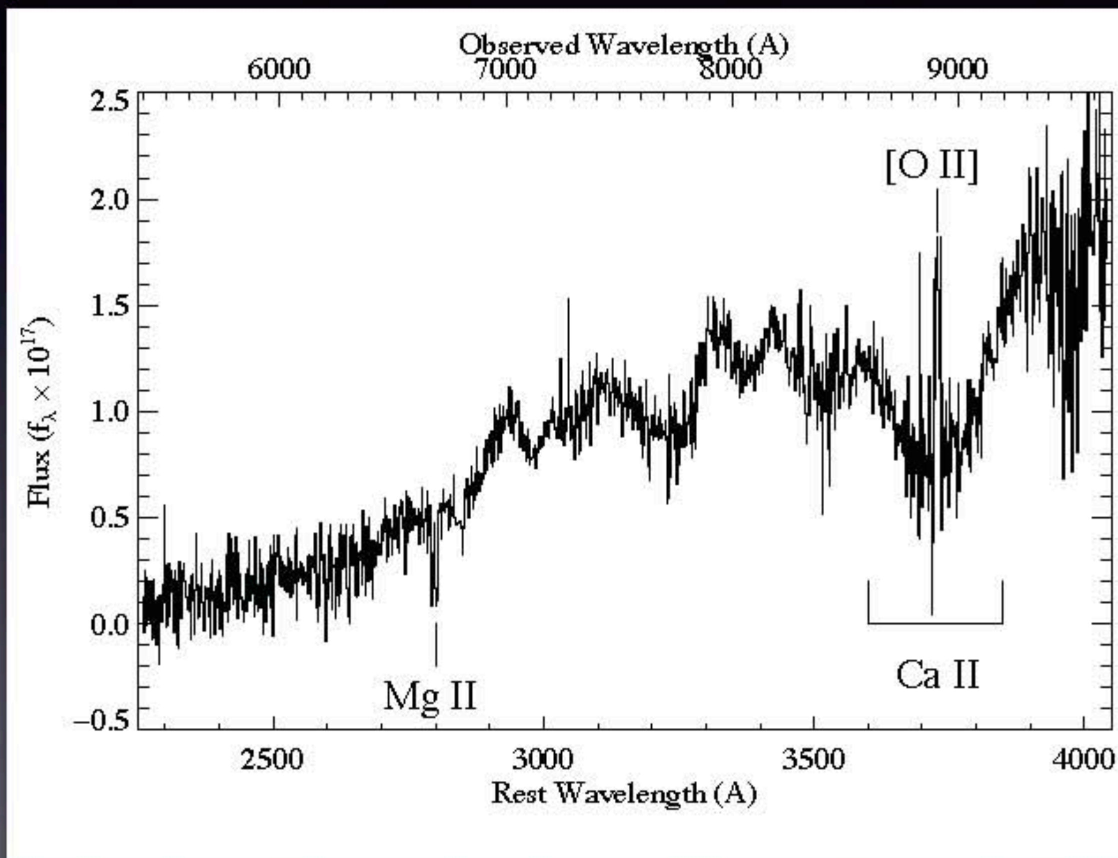


PS1-10afx

- Note red r-i color

Chornock et al., in prep.

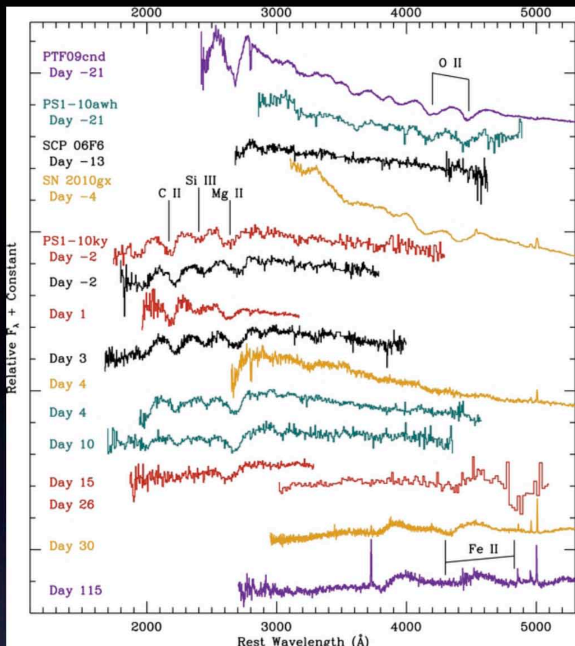
A High-Redshift SN!



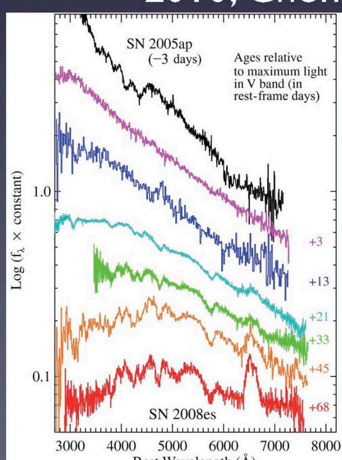
- z=1.388
- z_{peak}=21.6 (AB)
- m-M=45.0

For comparison:
HST04Sas at z=1.39 peaked
at M_{850LP} ~ 24.75 (Vega)
(Riess et al. 2007)

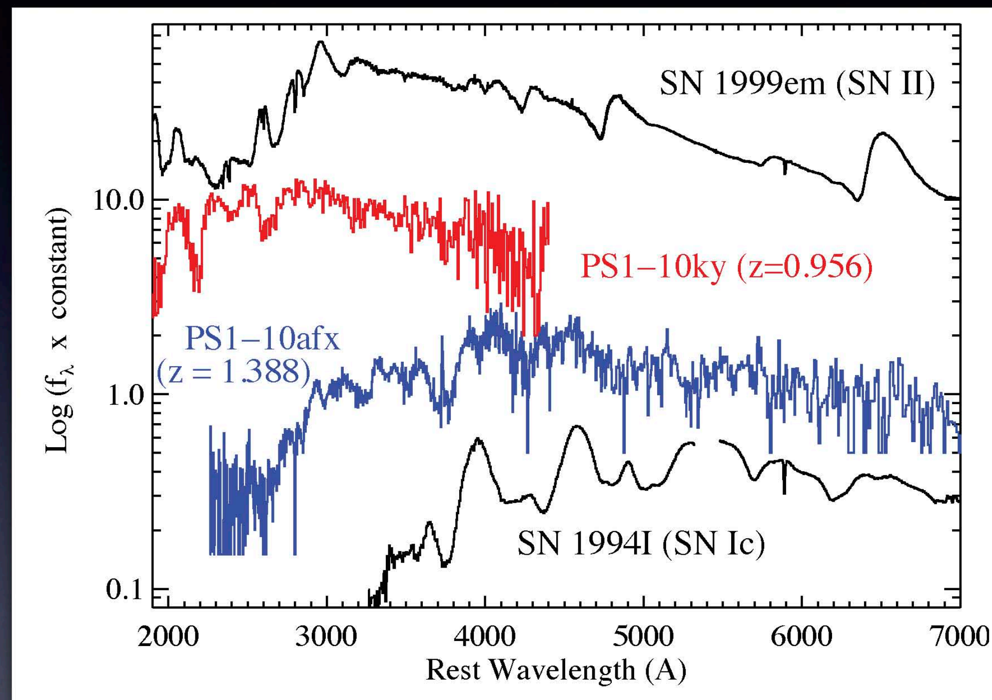
Unique spectrum



SN 2005ap-like objects: Barbary et al. 2008; Quimby et al. 2011; Pastorello et al. 2010; Chomiuk et al., 2011.



SN 2008es: Miller et al. 2009; Gezari et al. 2009



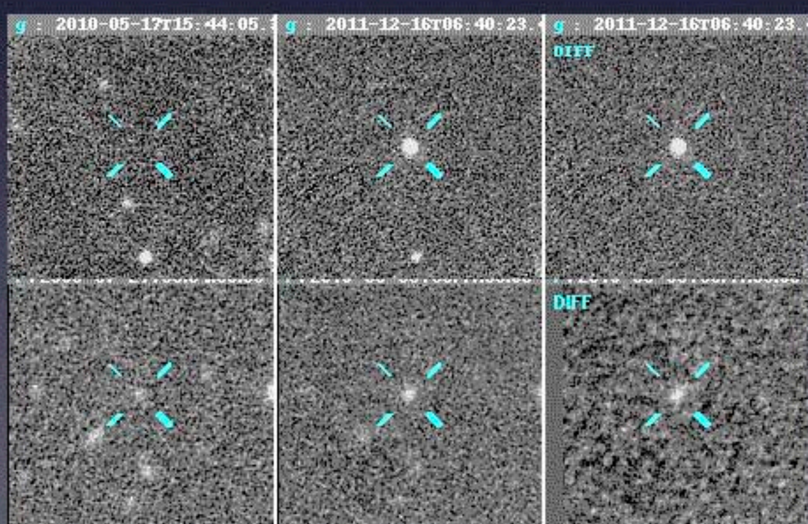
- Other ULSNe are bluer, lack Ca II H&K P-Cygni at early times

Faster Transients

- Using MDS data
- Focus on nights with two filters per field (usually *g* + *r*)
- Modify selection criteria to select transients not found on nearby nights
- Definitely some large M-star flares... anything else?

g

r



Template Image Difference

g=20.5 in stack

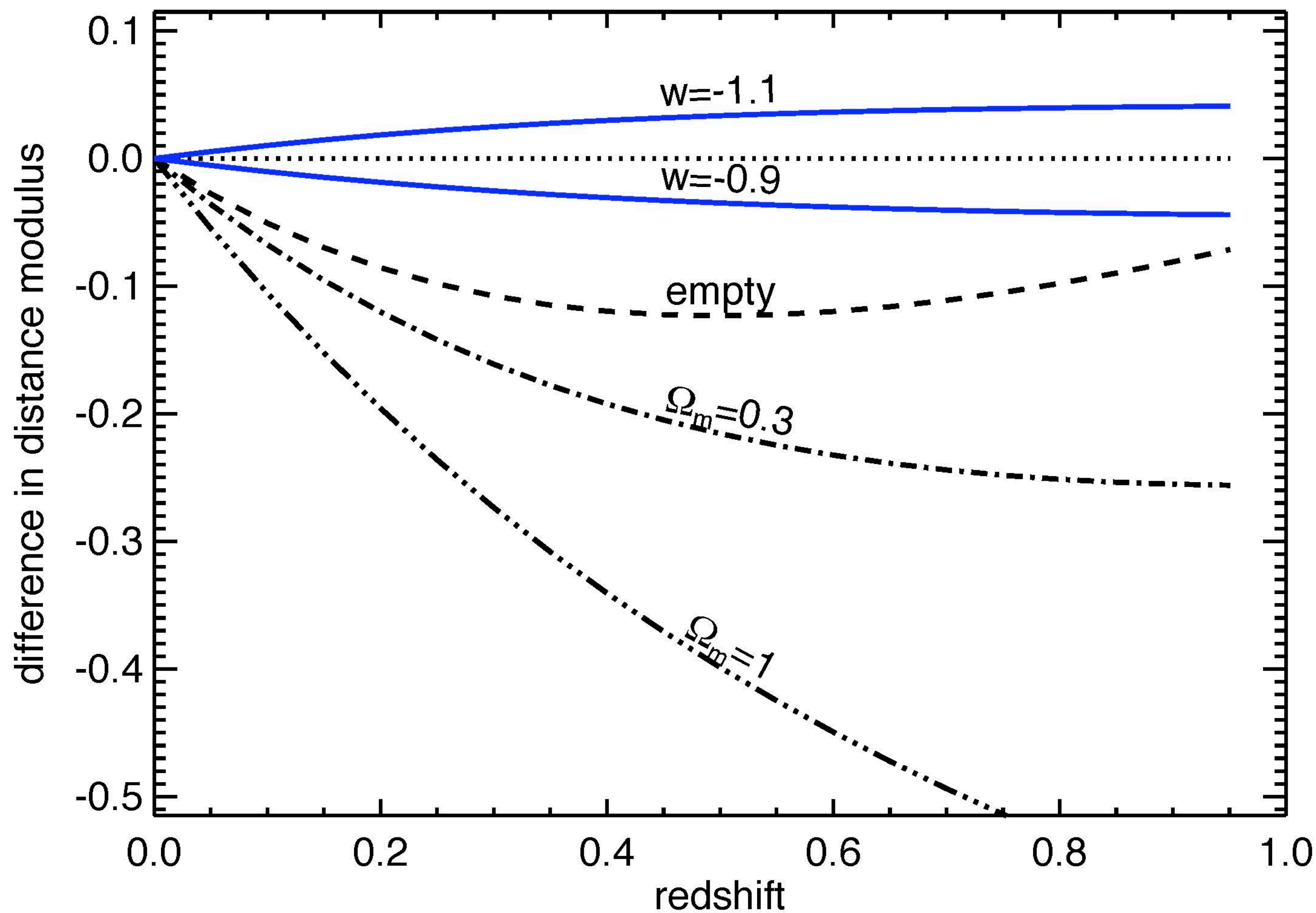
Camille Leibler, Armin Rest, Ryan Chornock, Edo Berger

PS1 Type Ia Supernovae

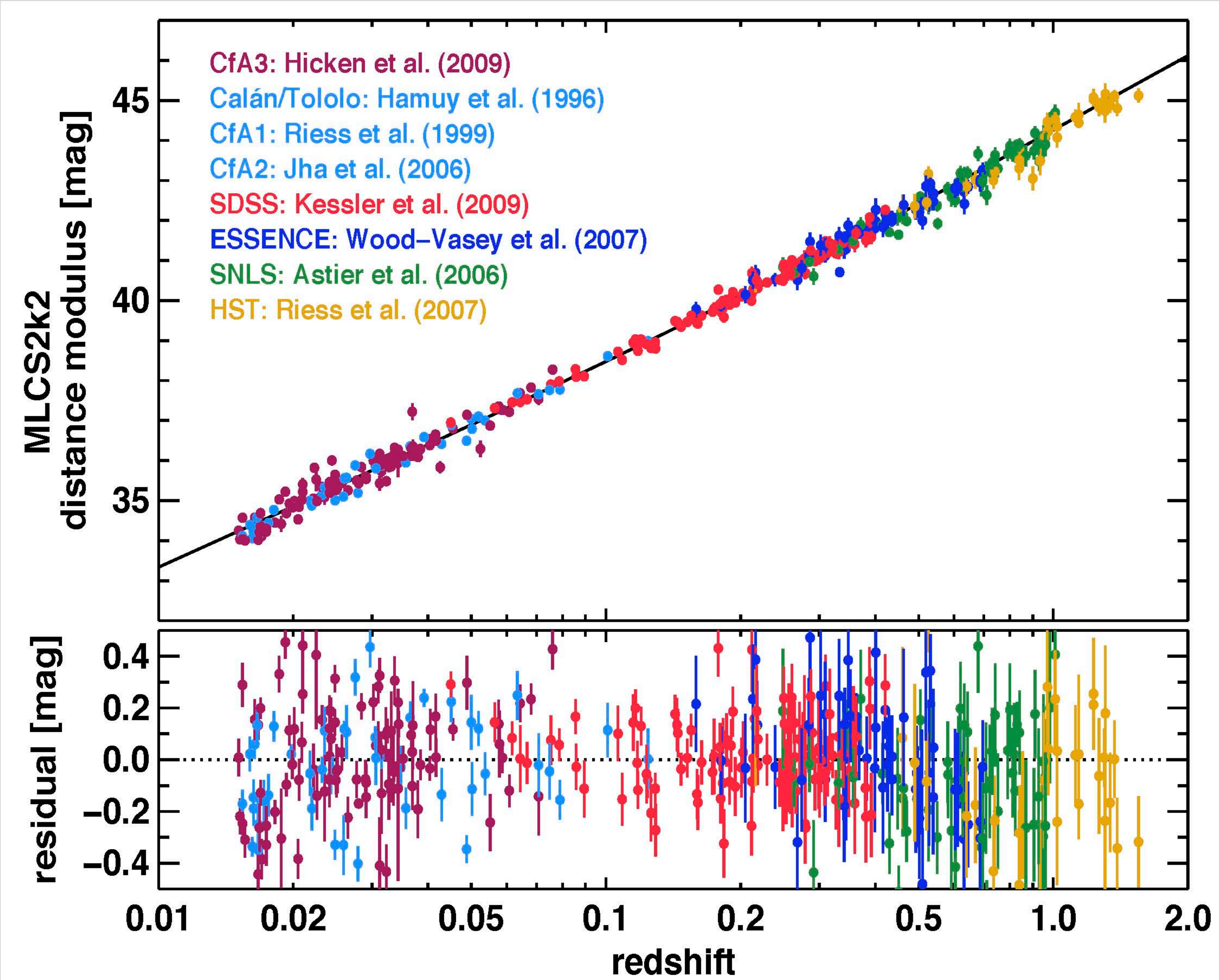
Ryan Foley
Clay Fellow
Harvard-Smithsonian
Center for Astrophysics

Armin Rest
Dan Scolnic
Ryan Chornock
Mark Huber
Gautham Narayan
Steve Rodney
John Tonry

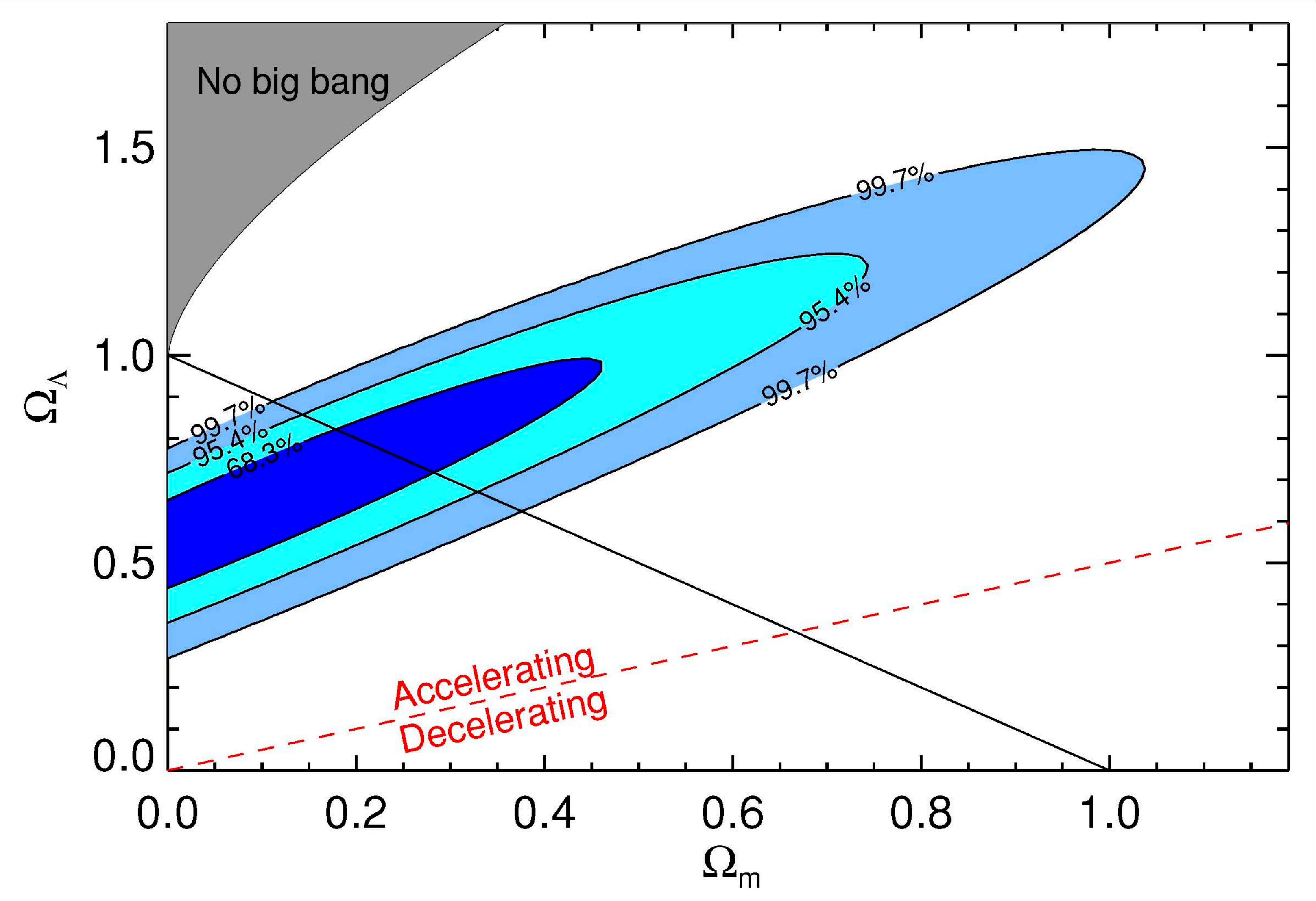
Measuring w is Hard



Recent Hubble Diagram

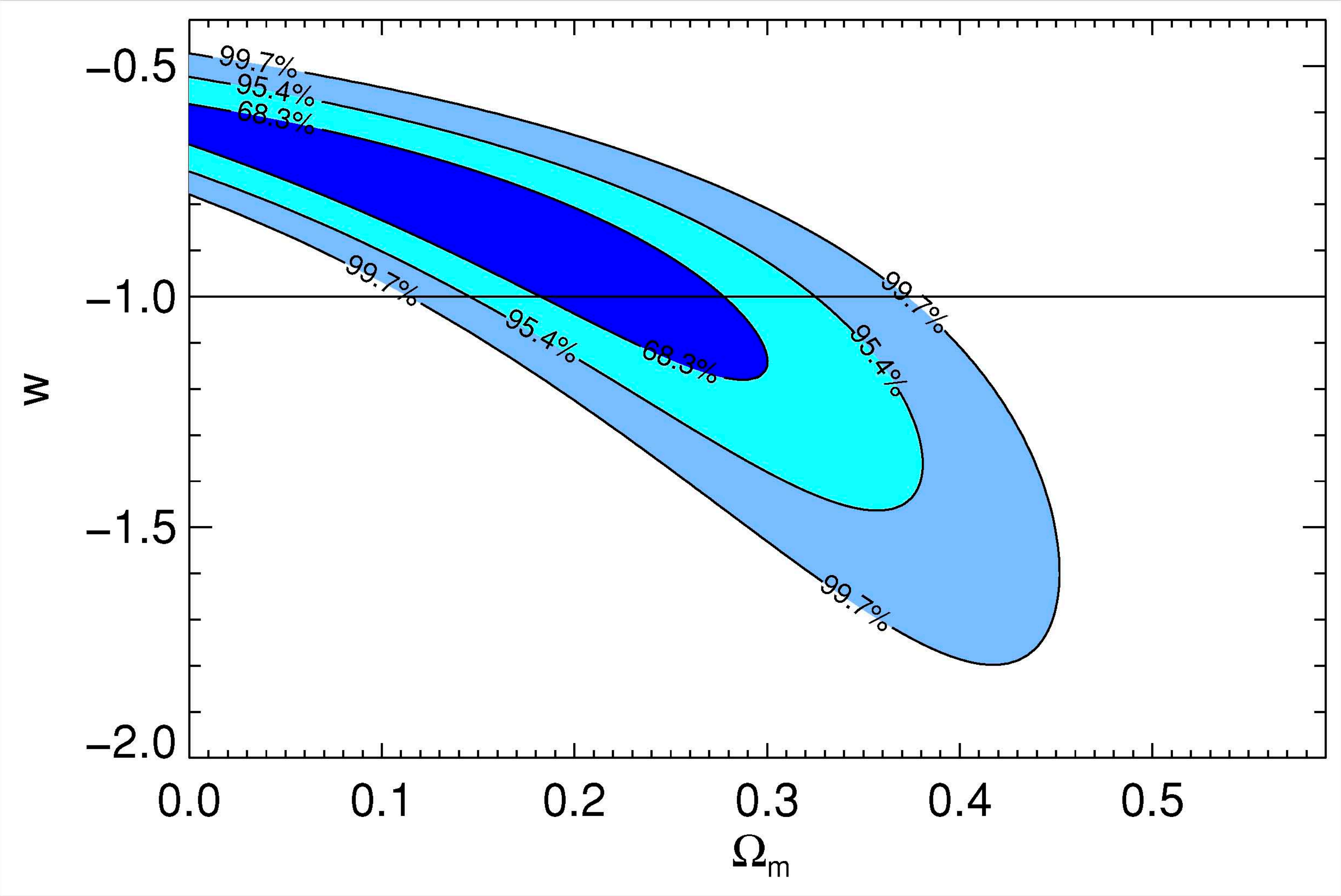


Supernovae Only (with Systematics)



Conley et al. 2011

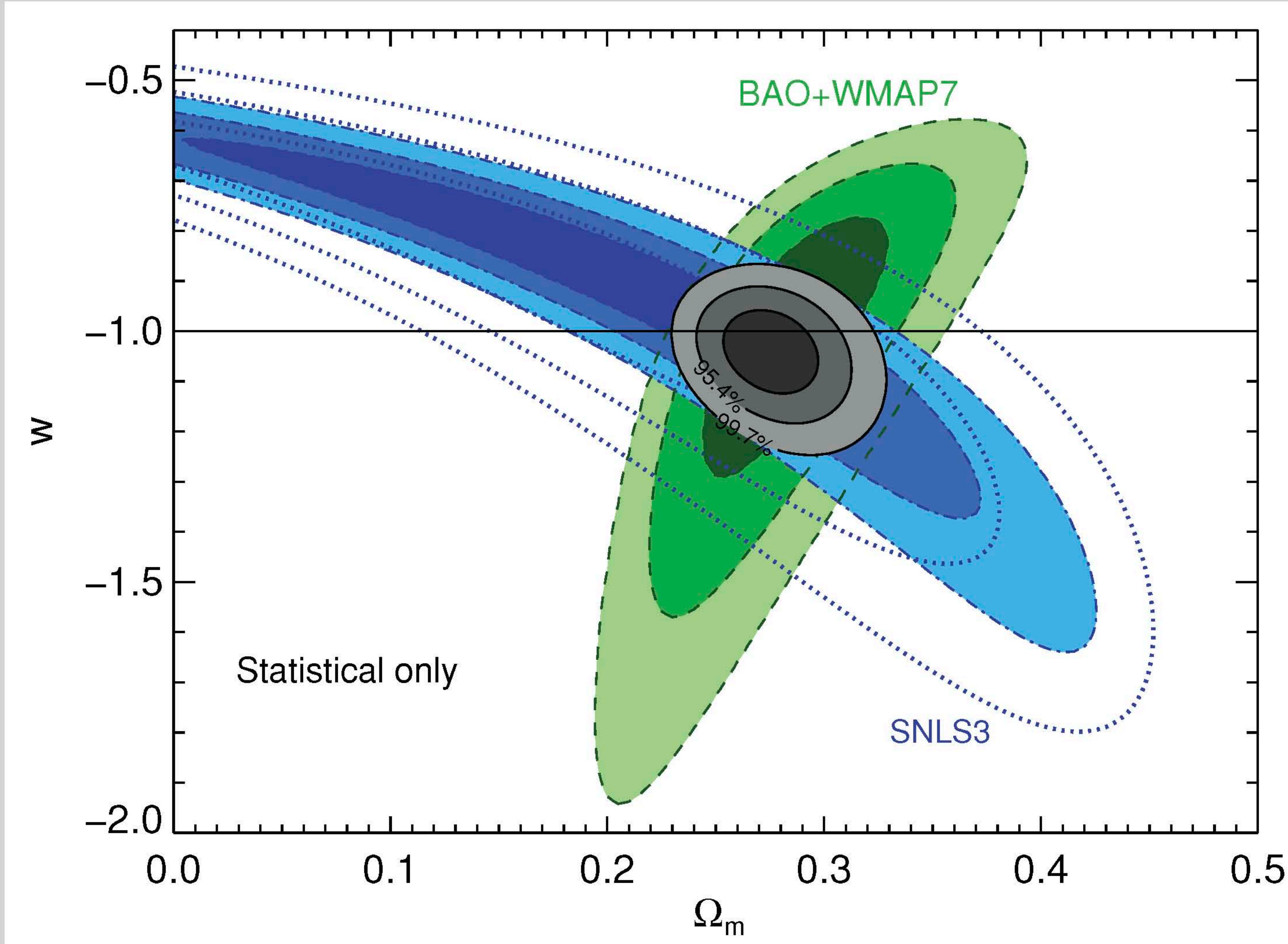
Supernovae Only (with Systematics)



$w = -0.91 \pm 0.18$ (stat) ± 0.11 (sys)

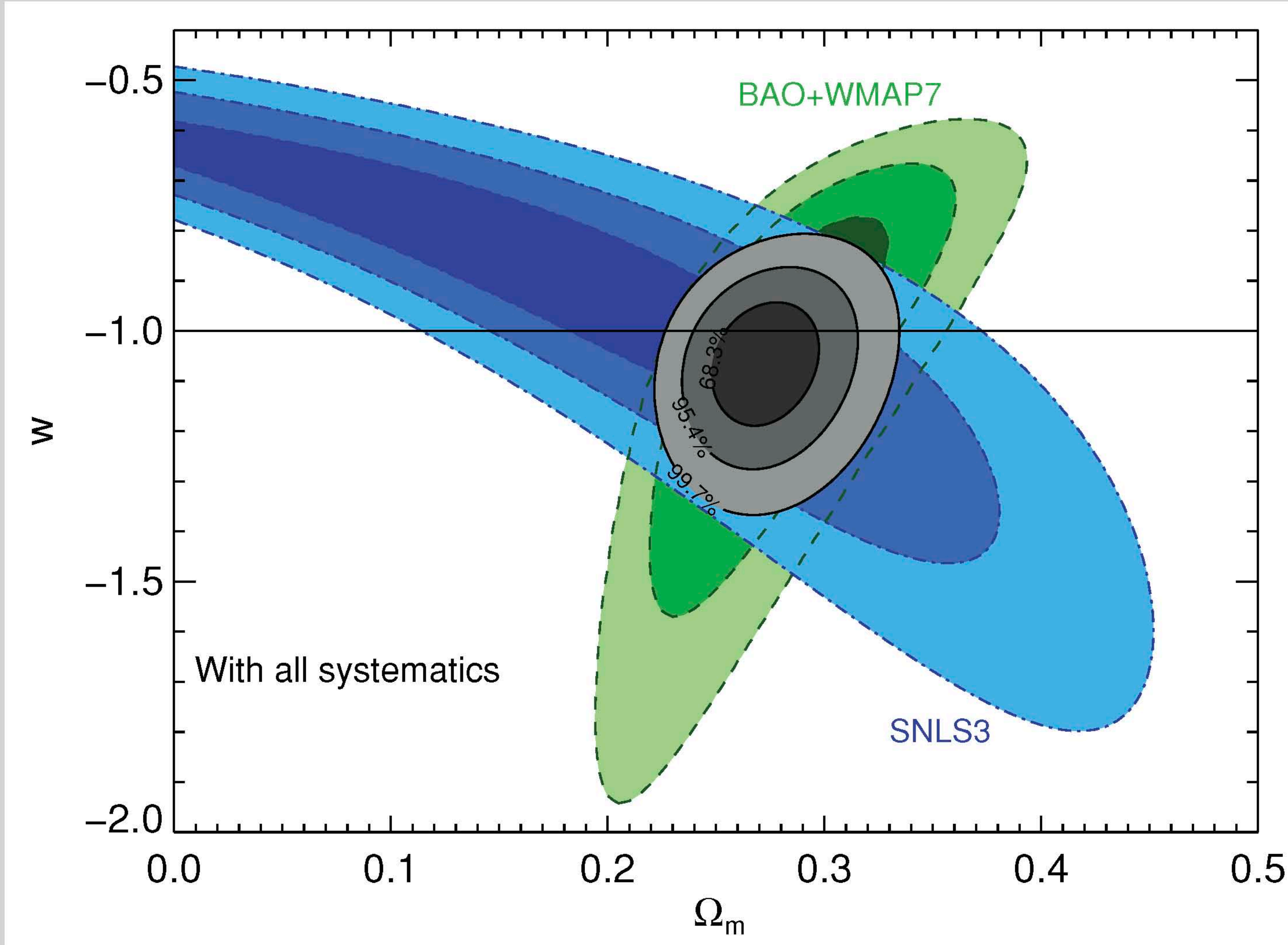
Conley et al. 2011

Constraints on w



Sullivan et al. 2011

Constraints on w (with Systematics)



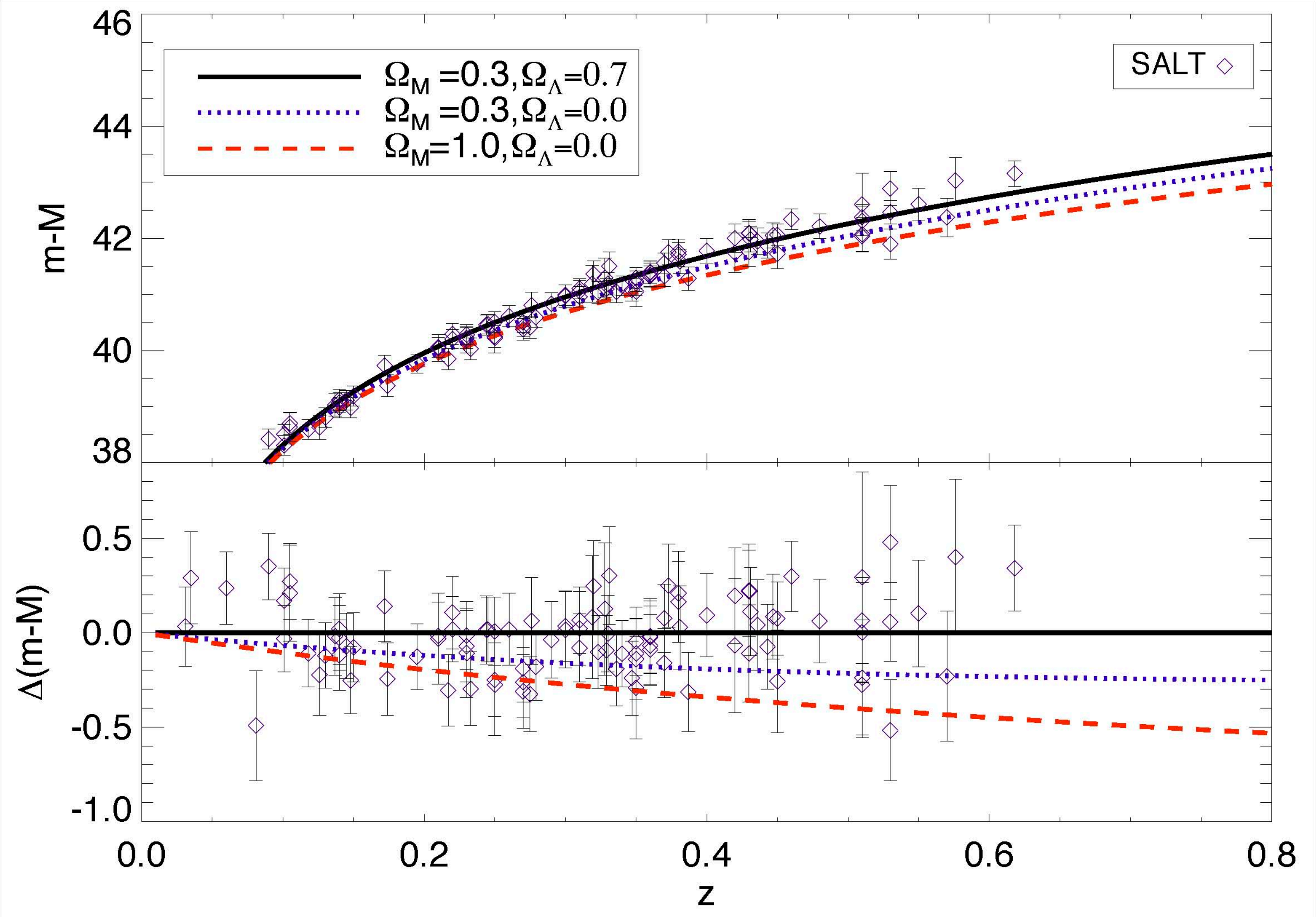
$w = -1.061 \pm 0.069$ (stat + sys)

Sullivan et al. 2011

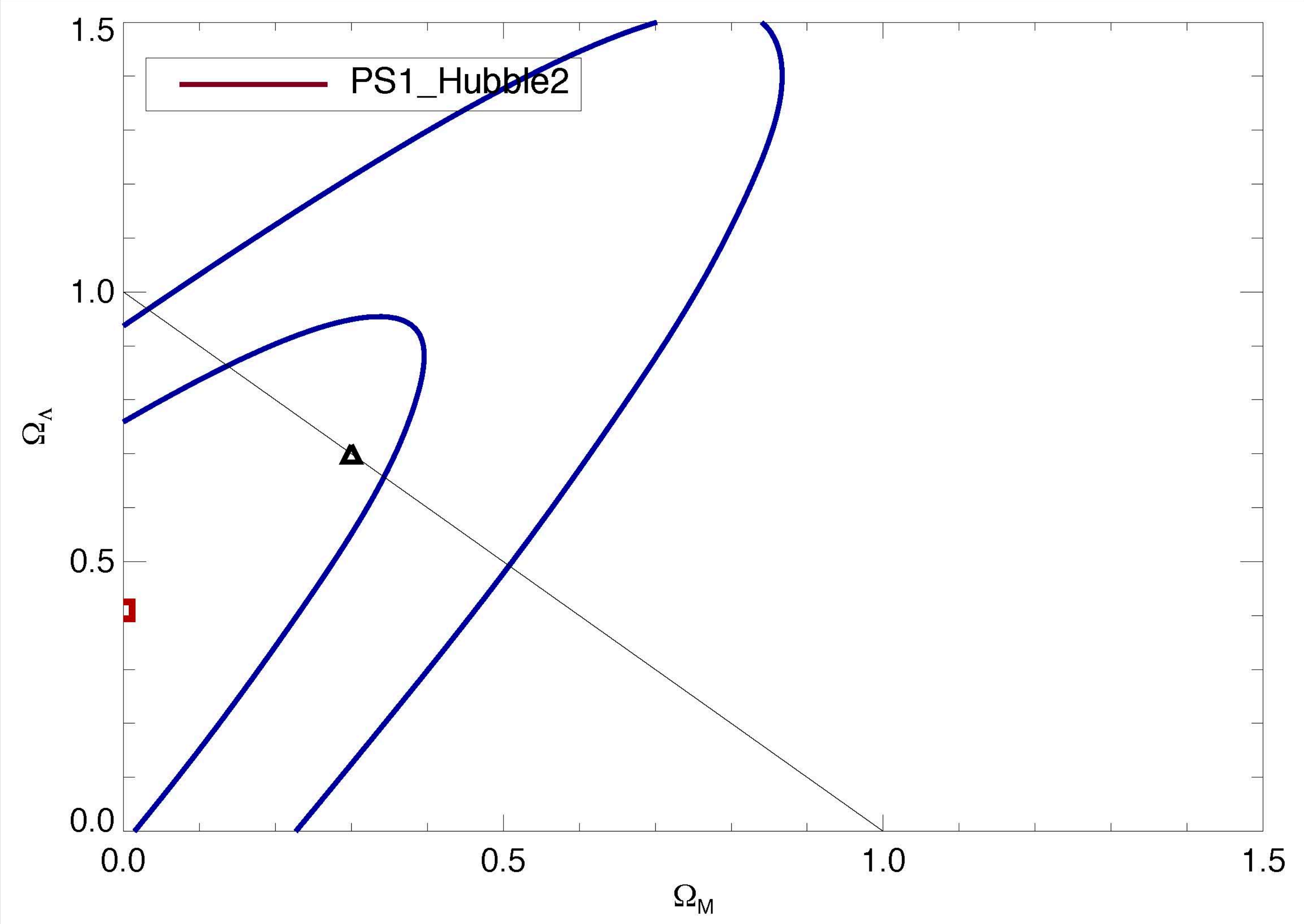
Calibration Errors

Source	Ω_m	w	Relative area[a]
Calibration:			
Colors of BD 17° 4708	$0.2719^{+0.0170}_{-0.0137}$	$-1.0720^{+0.0639}_{-0.0639}$	1.239
SED of BD 17° 4708	$0.2771^{+0.0170}_{-0.0138}$	$-1.0390^{+0.0623}_{-0.0630}$	1.205
SNLS zeropoints	$0.2767^{+0.0168}_{-0.0136}$	$-1.0421^{+0.0603}_{-0.0609}$	1.166
Low-z zeropoints	$0.2753^{+0.0164}_{-0.0133}$	$-1.0527^{+0.0578}_{-0.0586}$	1.078
SDSS zeropoints	$0.2767^{+0.0164}_{-0.0133}$	$-1.0411^{+0.0544}_{-0.0548}$	1.015
SNLS filters	$0.2789^{+0.0170}_{-0.0138}$	$-1.0330^{+0.0585}_{-0.0586}$	1.136
Lowz filters	$0.2766^{+0.0163}_{-0.0132}$	$-1.0402^{+0.0547}_{-0.0550}$	1.010
SDSS filters	$0.2770^{+0.0164}_{-0.0133}$	$-1.0396^{+0.0544}_{-0.0548}$	1.007
HST zeropoints	$0.2769^{+0.0164}_{-0.0133}$	$-1.0412^{+0.0544}_{-0.0548}$	1.007
NICMOS nonlinearity	$0.2767^{+0.0164}_{-0.0133}$	$-1.0418^{+0.0545}_{-0.0548}$	1.009

PS1-Only Hubble Diagram (117 SNe)

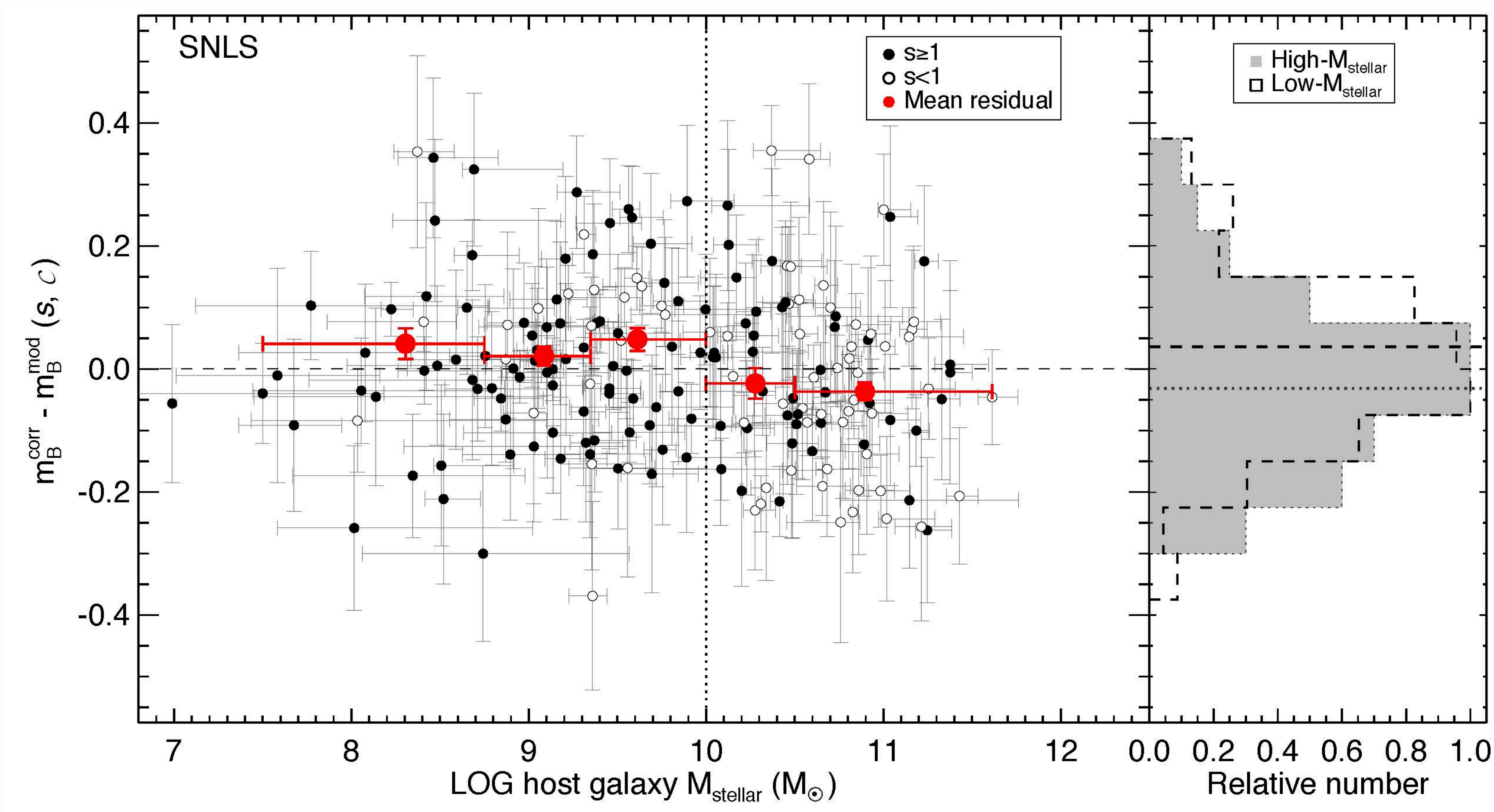


PS1-Only Banana Plot



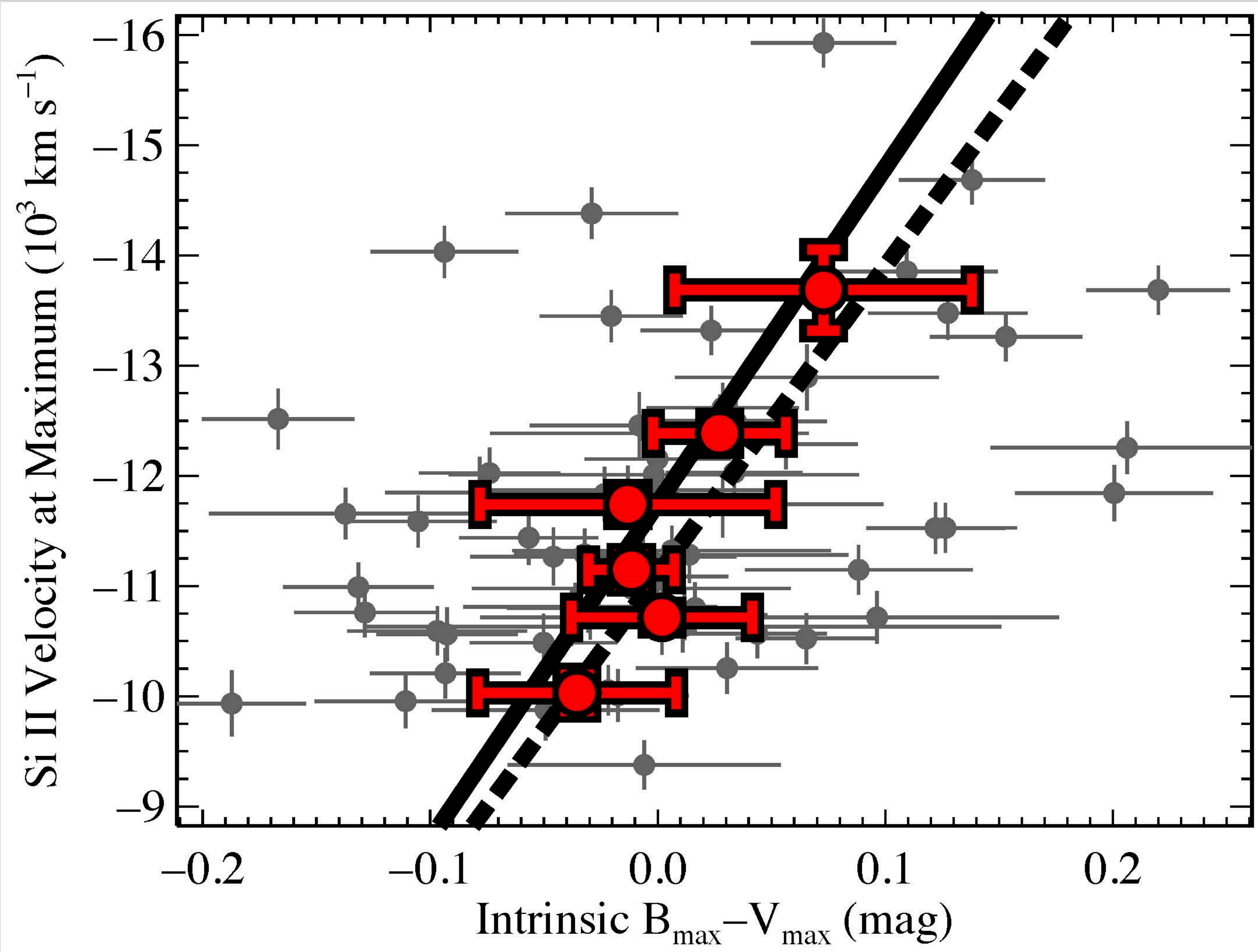
Survey	Redshift Range	SNe Today	SNe in 2015
Low-z	0 – 0.1	123	250
PTF	0 – 0.1	200	500
SDSS	0.1 – 0.4	93	400
SNLS	0.4 – 1	242	242?
DES	0.4 – 1	0	100 – 1000
HST	0.8 – 2	14	50
PS1	0 – 0.7	117 – 175	250 – 500

Host – Hubble Residual Relation



Sullivan et al. 2010

Color – Velocity Relation



Foley, Sanders, & Kirshner 2011

Pan-STARRS

PS1 Science Consortium

PS1 consortium members

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Max Planck Institute for Extraterrestrial Physics
Max Planck Institute for Astronomy
JOHNS HOPKINS UNIVERSITY
Department of Physics and Astronomy
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University of Edinburgh
Durham University
Institute for Computational Cosmology
National Central University, Taiwan
Las Cumbres Observatory
Global Telescope Network