Variables in Pan-STARRS data

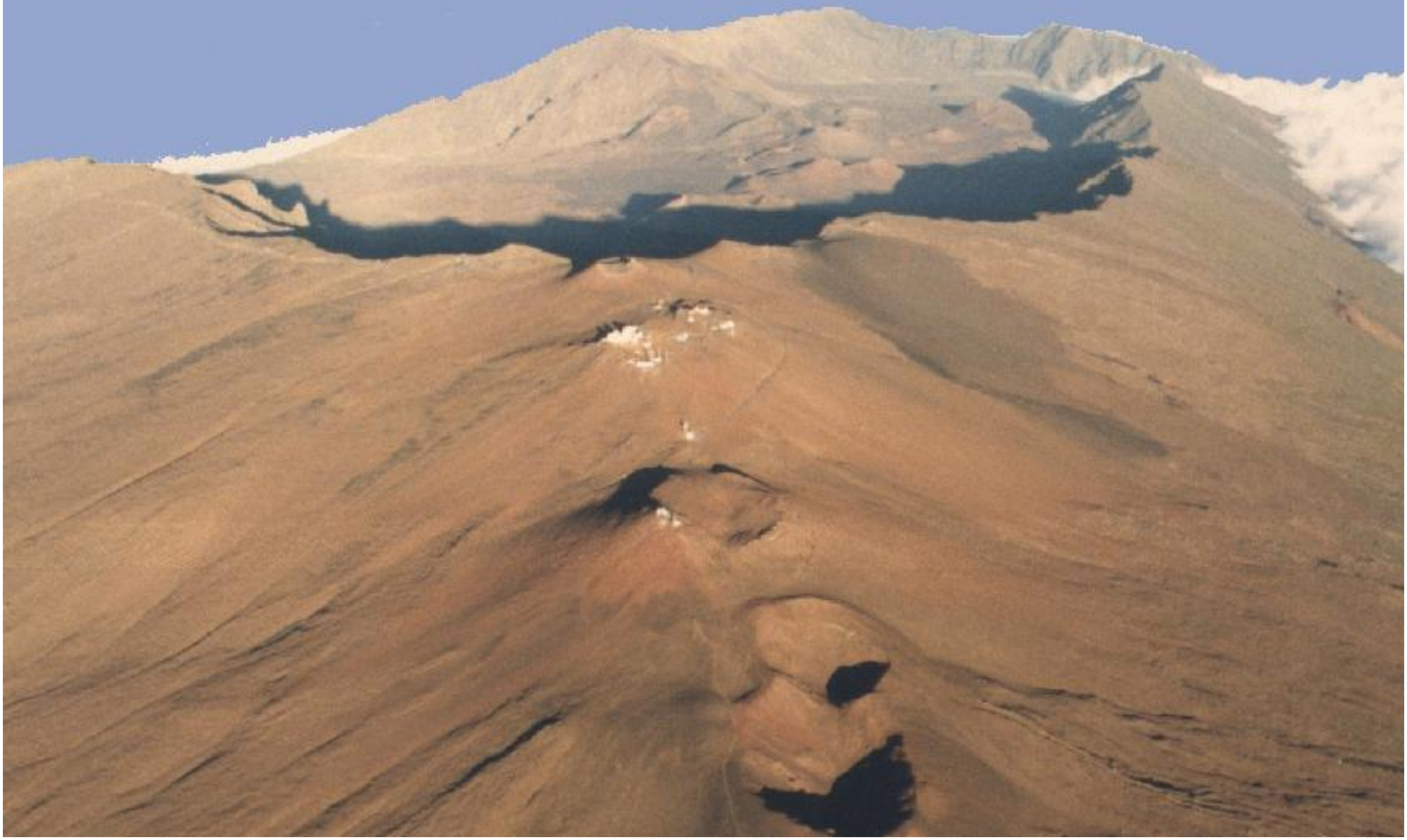
Heather Flewelling

Outline

- What is PanSTARRS1
- A bit about the different surveys
- A bit about PS1 / PS2
- public release (ie why Heather is always busy…)
- Searches for Variable Stars in PanSTARRS Medium Deep data


Pan-STARRS
PS1 Science Consortium
NSF
NASA
SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA
UNIVERSITY OF MARYLAND
1856
UNIVERSITAS BUDAPESTINENSIS DE ROLANDO EÖTVÖS NOMINATA
University of Hawai'i
UH Institute for Astronomy
Max Planck Institute for Extraterrestrial Physics
MPE
Max Planck Institute for Astronomy
JOHNS HOPKINS UNIVERSITY
Department of Physics and Astronomy
VERITAS
Harvard-Smithsonian Center for Astrophysics
Queen's University Belfast
Queen's University, Belfast
THE UNIVERSITY OF EDINBURGH
University of Edinburgh
Durham University
Durham University
Institute for Computational Cosmology
National Central University, Taiwan
Las Cumbres Observatory
Global Telescope Network
Las Cumbres Observatory
Global Telescope Network

The Pan-STARRS Observatories
are located at 10,100 ft
on Haleakala, Maui, HI



The Pan-STARRS Observatories:

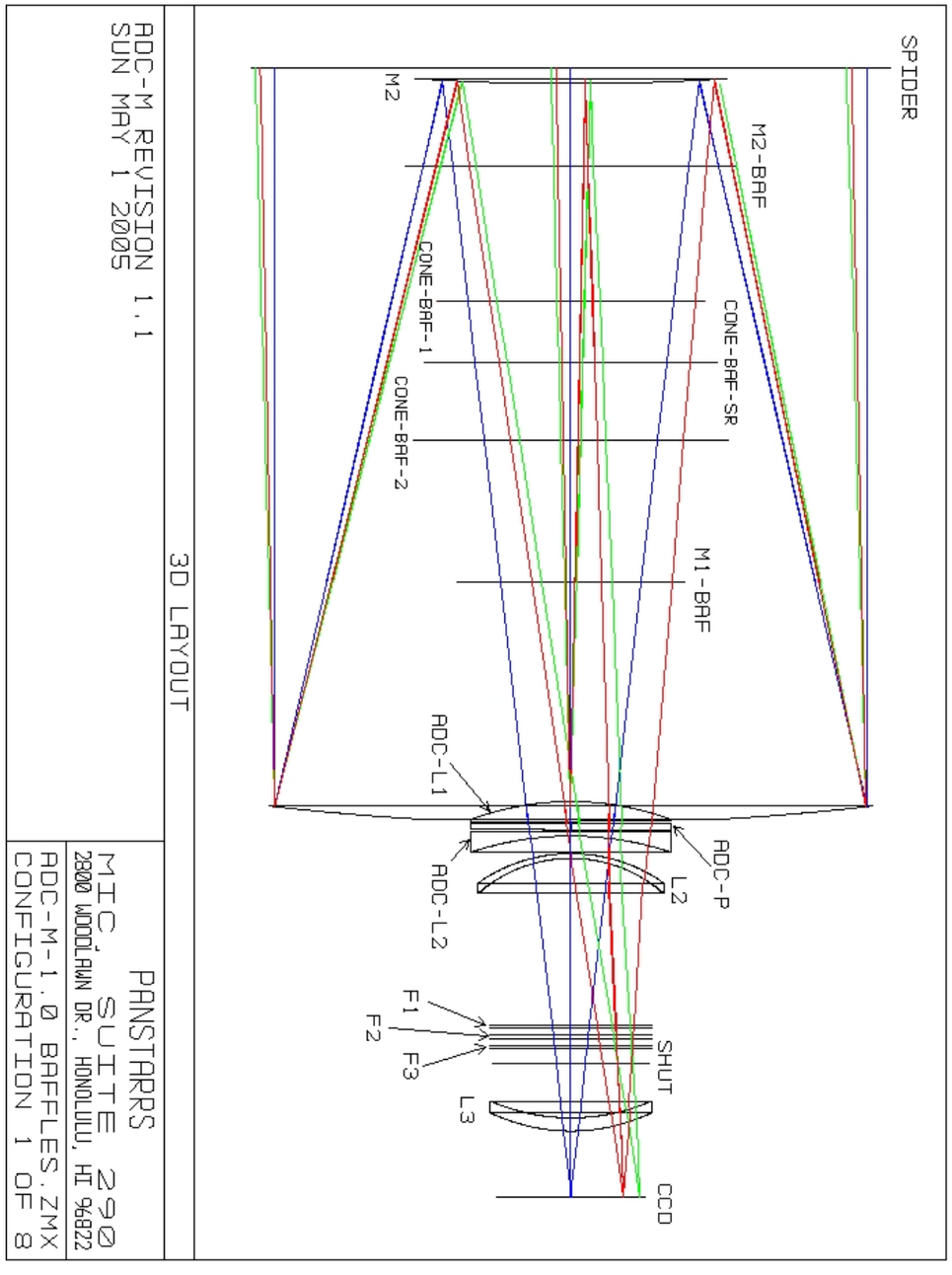
PS1 & PS2 built on the site of the 1970's Lunar Ranging Experiment (LURE Observatory)

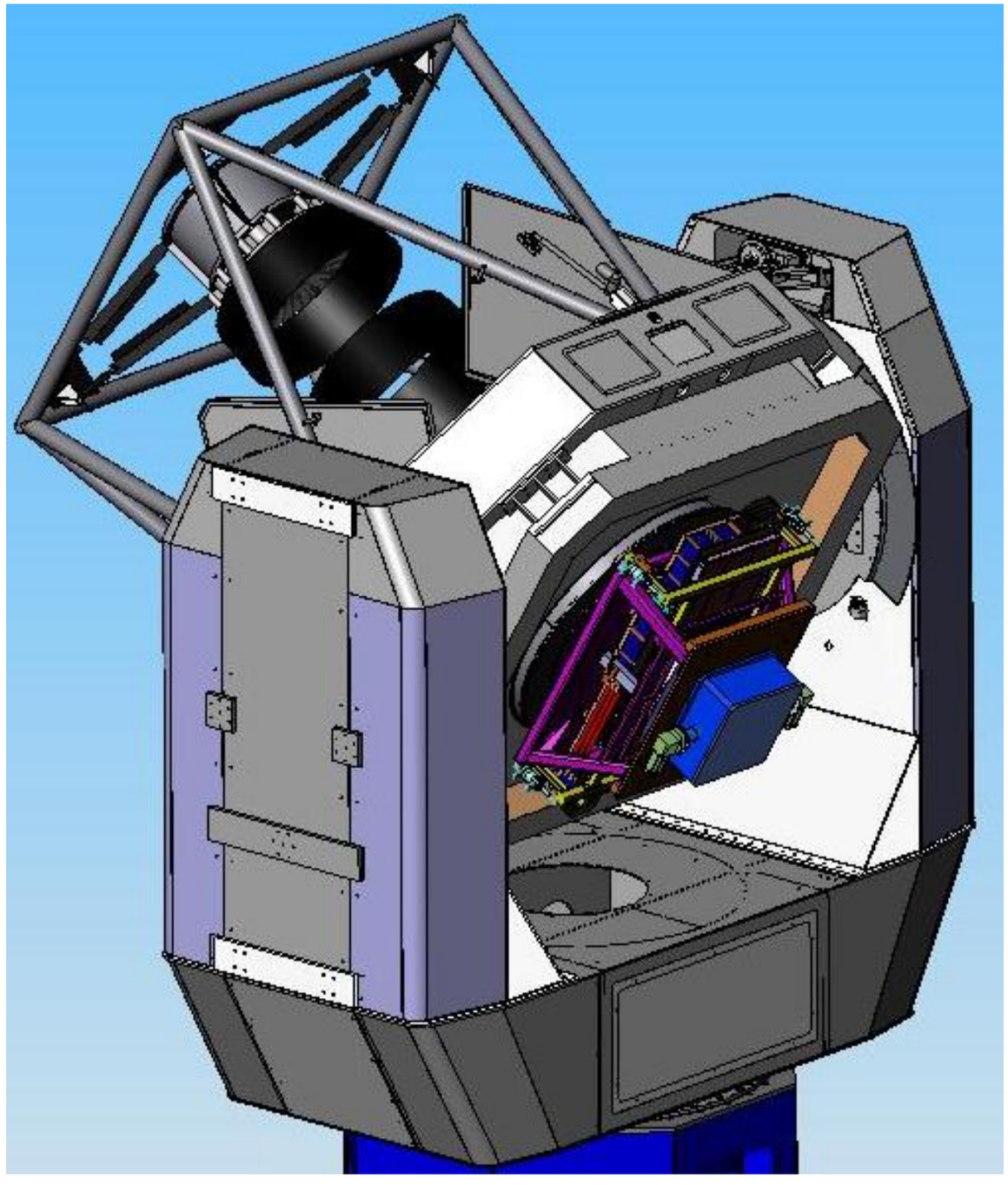
PS1

PS2

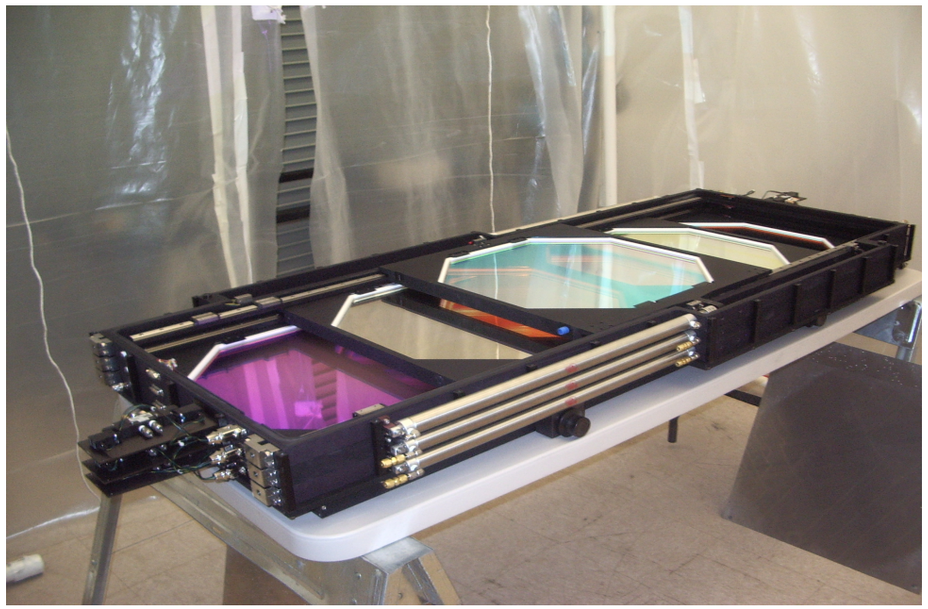
- PS1 wide field survey telescope
- 1.8 meter aperture at f/4.4
- Ritchey-Chretien with 3-element corrector
- 3.3 degree field-of-view

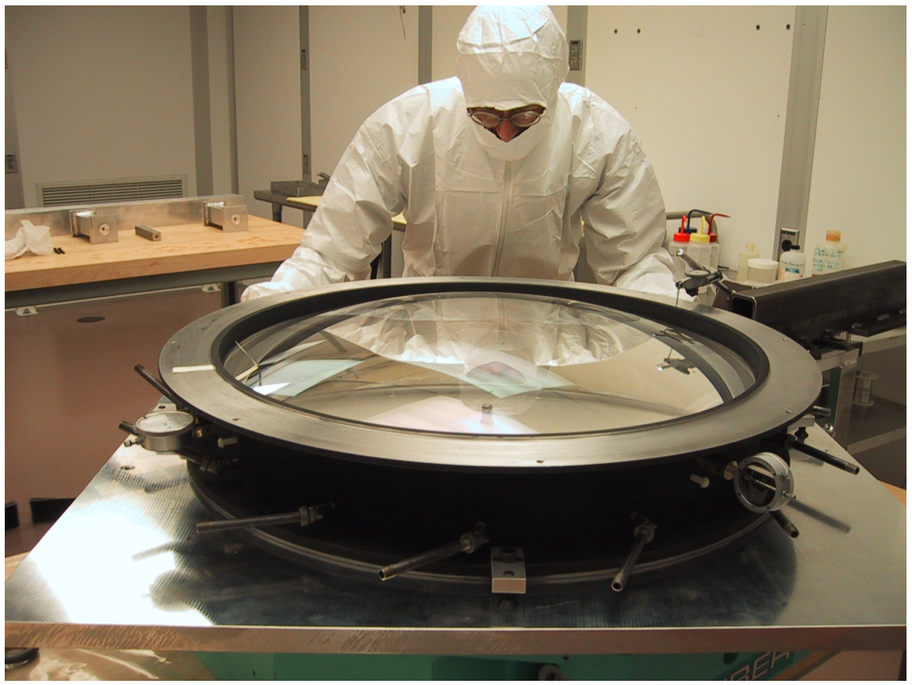
- 1.4 Gigapixel Camera
- 0.25 arcsec pixels
- 10 sec overhead (read/write/slew)
- 8 e- read noise

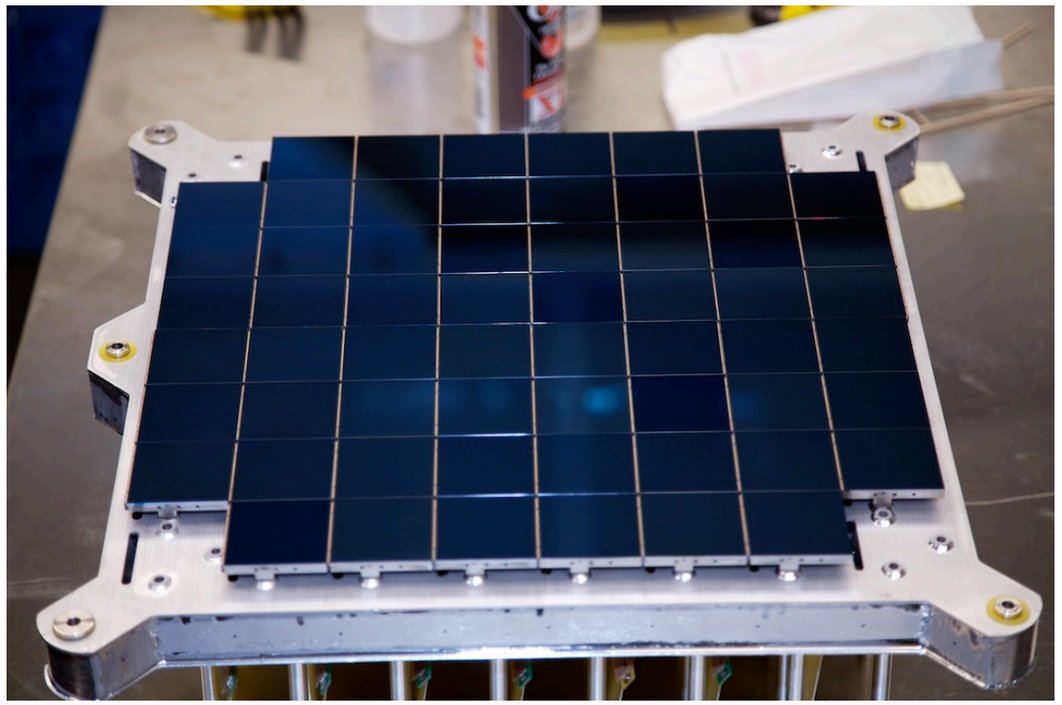


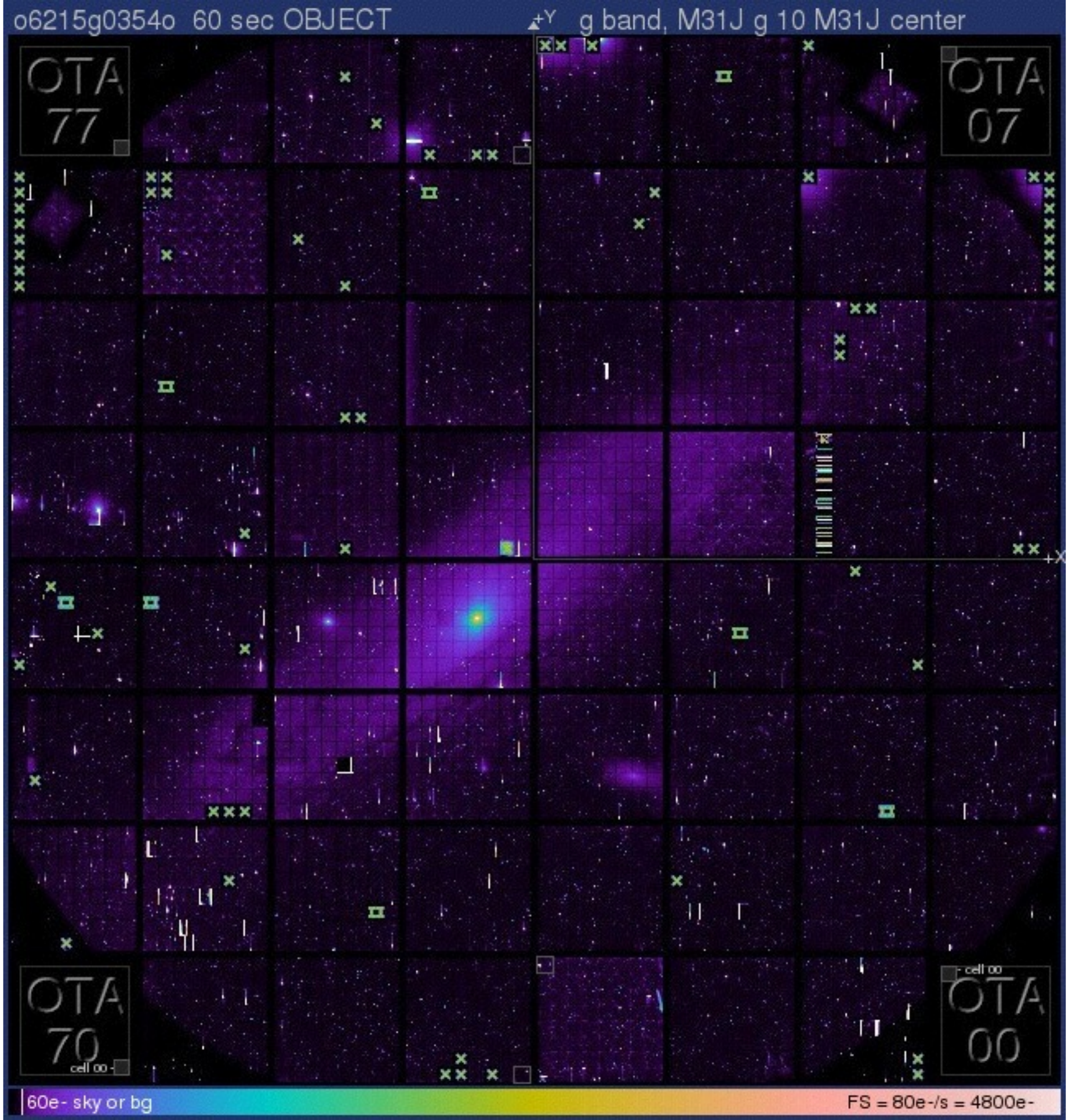


PS1 Filters, Optics, Shutter, 1.4 Gigapixel Focal Plane



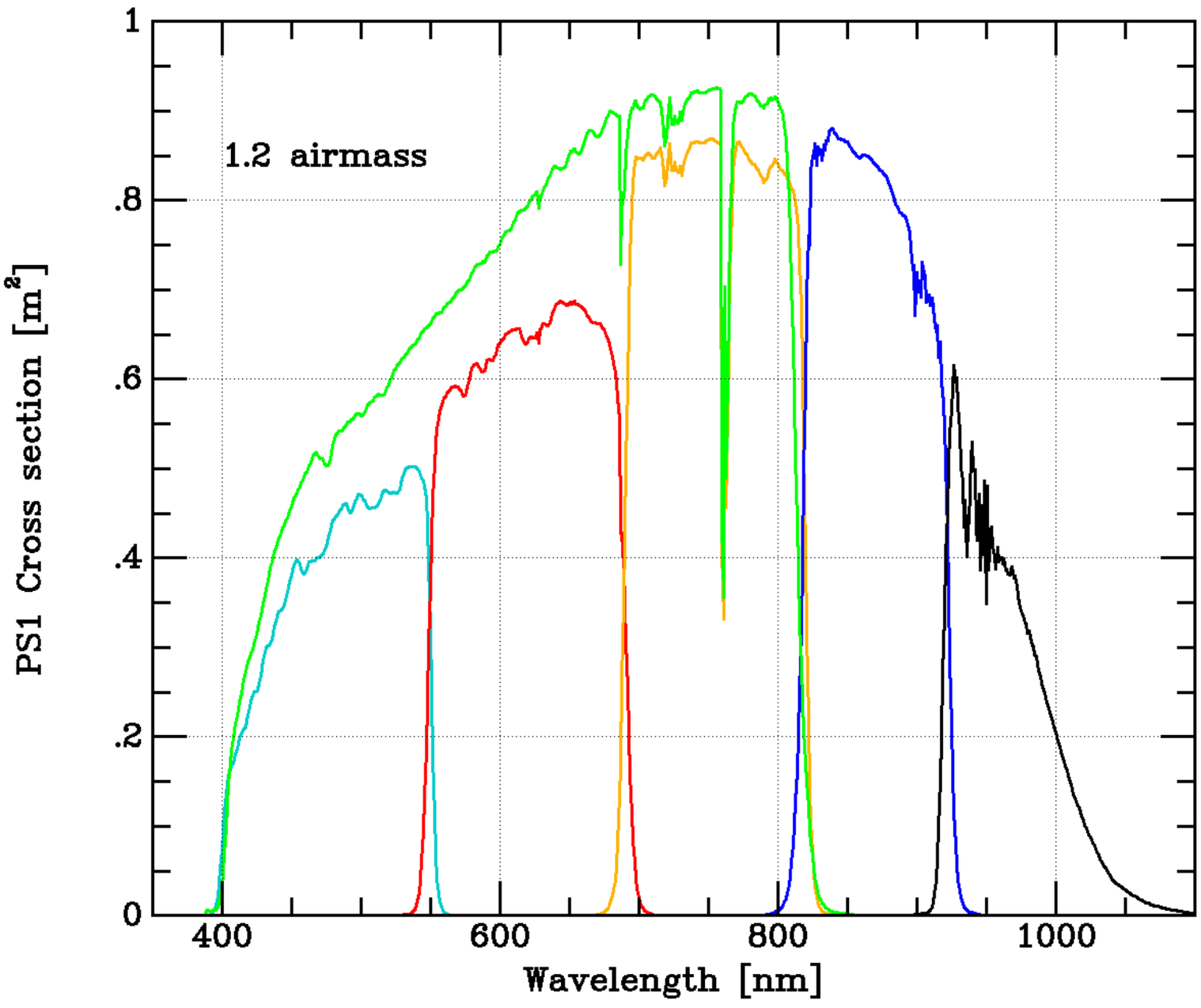





o6215g0354o 60 sec OBJECT
+Y
g band, M31J g 10 M31J center
OTA 77
OTA 07
OTA 70
cell 00
cell 00
OTA 00
60e- sky or bg
FS = 80e-/s = 4800e-

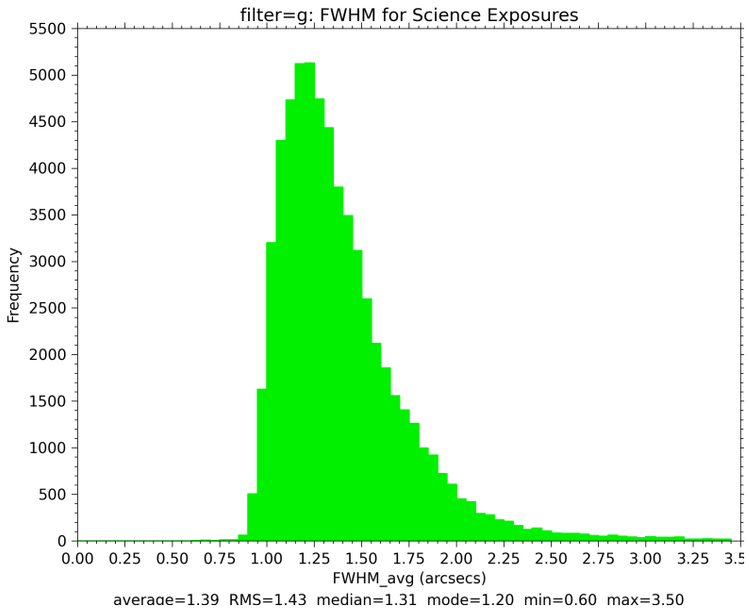
PS1 Filter System

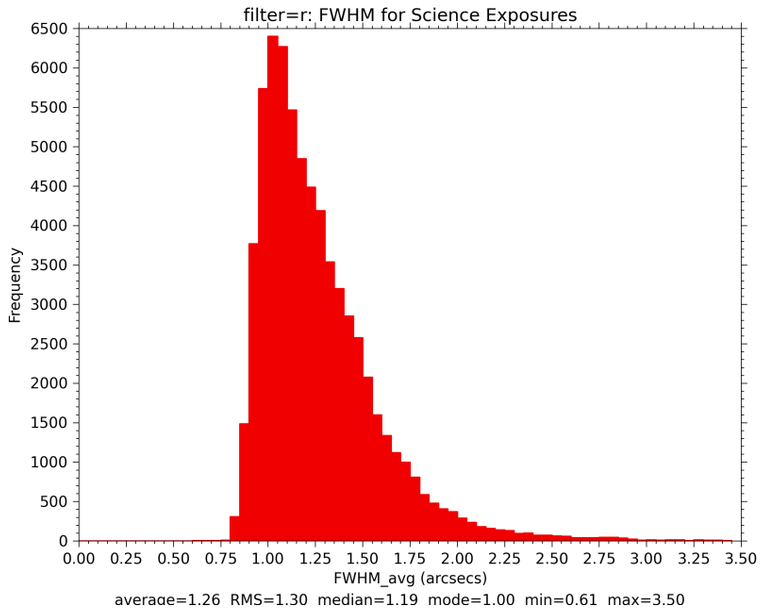
g r i z y, w (=wide)

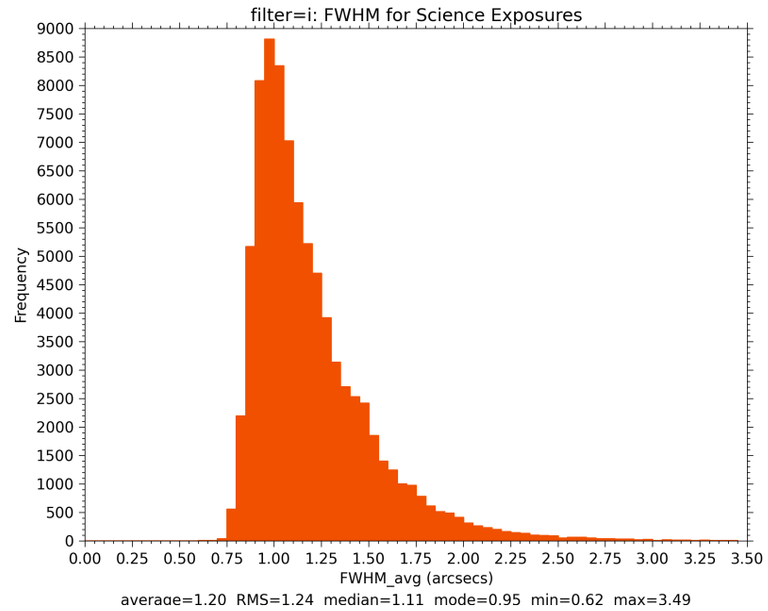


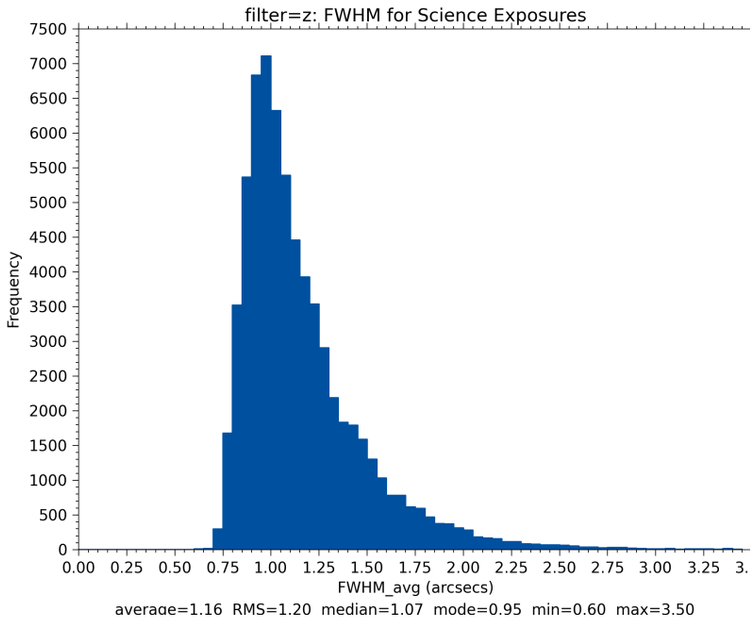
The Pan-STARRS1 Photometric System
Tonry et al. 2012, ApJ 750, 99

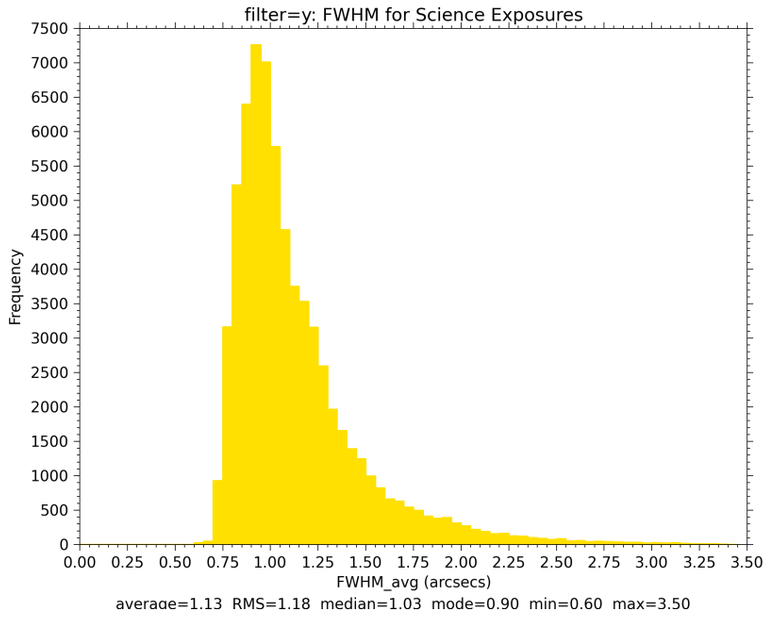
PS1 has 1 arcsec image quality

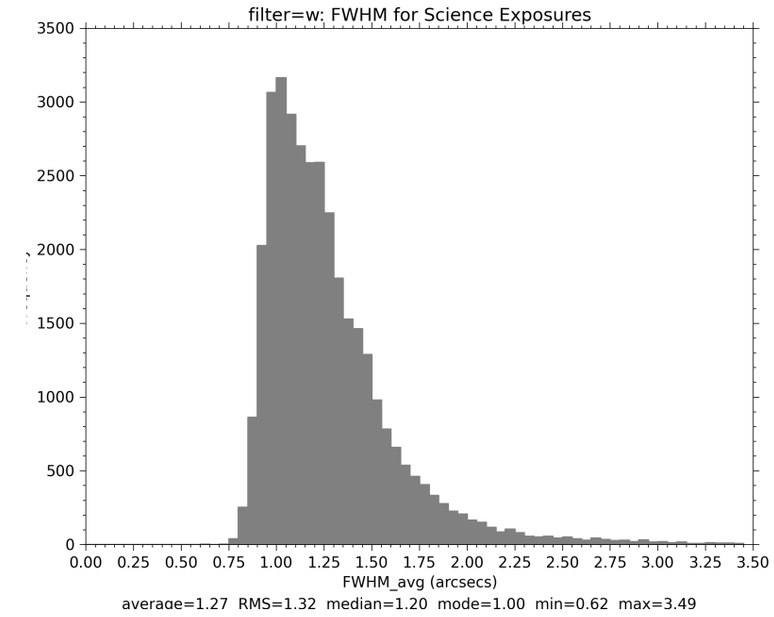












	g	r	i	z	y	w
FWHM Average	1.39	1.26	1.20	1.16	1.13	1.27
FWHM Median	1.31	1.19	1.11	1.07	1.03	1.20
FWHM Mode	1.18	1.02	0.96	0.96	0.96	1.02

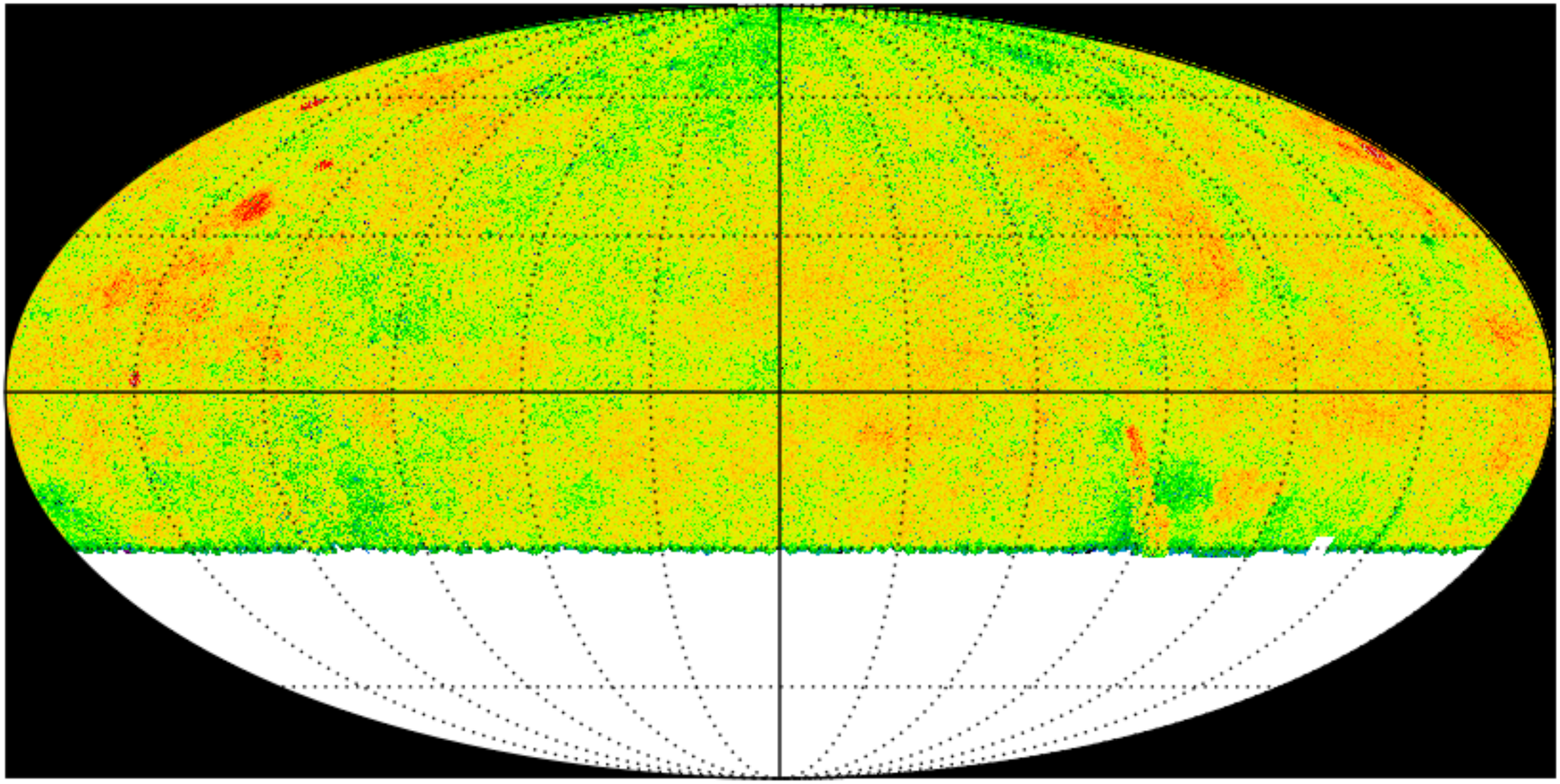
PS1 Science Consortium was founded to carry out and exploit the PS1 Sky Surveys

The PS1 Sky Surveys 2010-2014

PS1 Survey	Filter bands	Fraction of time
3pi Steradian Sky Survey (30,000 sq deg)	g r I z y	58 %
Calibration - spectrohotometric standards and the Celestial North Pole	g, r, i, z, y, w, open g,r,i,z,y	1 % 2012-2014
Medium Deep Survey (10 x 7 sq deg)	g r i z y	25 %
Solar System Survey	w band = g+r+i	5% ->11% Nov 2012
Pan-Planets: high cadence Stellar Transit Survey (50 sq deg)	i	4% 2010 - 2012
PAndromeda: M31 time domain survey	r i	2% 2010 - 2012

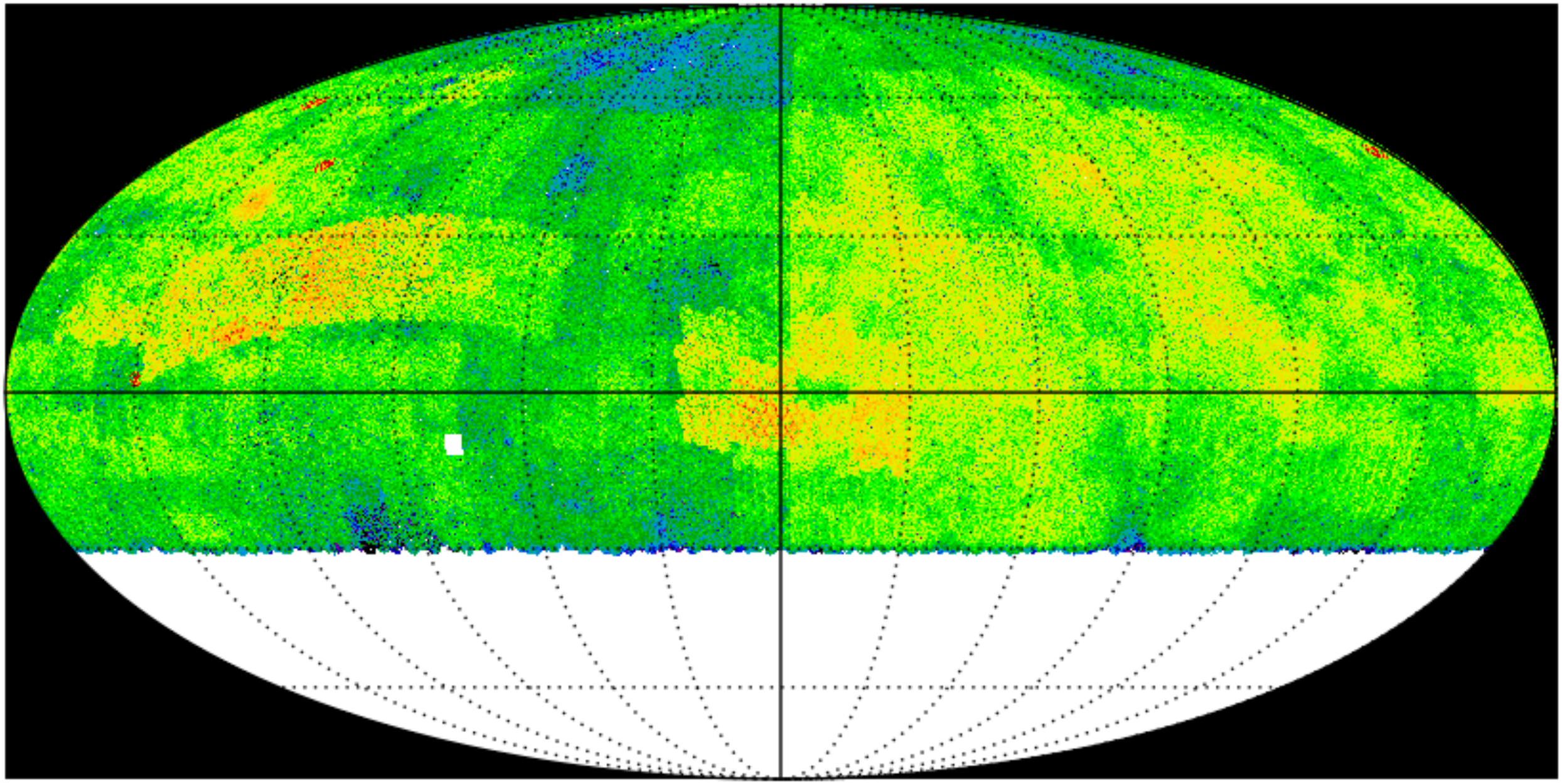
The PS1 Sky Surveys were funded by the PS1 Science Consortium

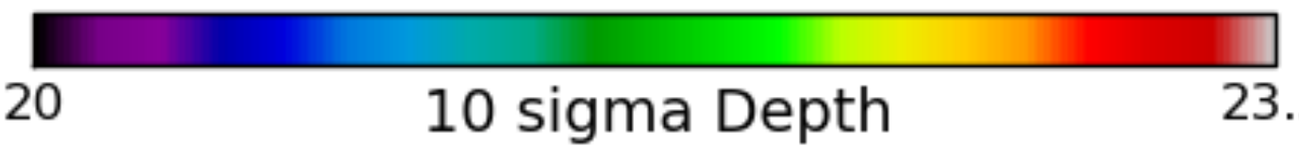
10 Sigma Depth Map g-band for 3.0 arcsec diameter aperture



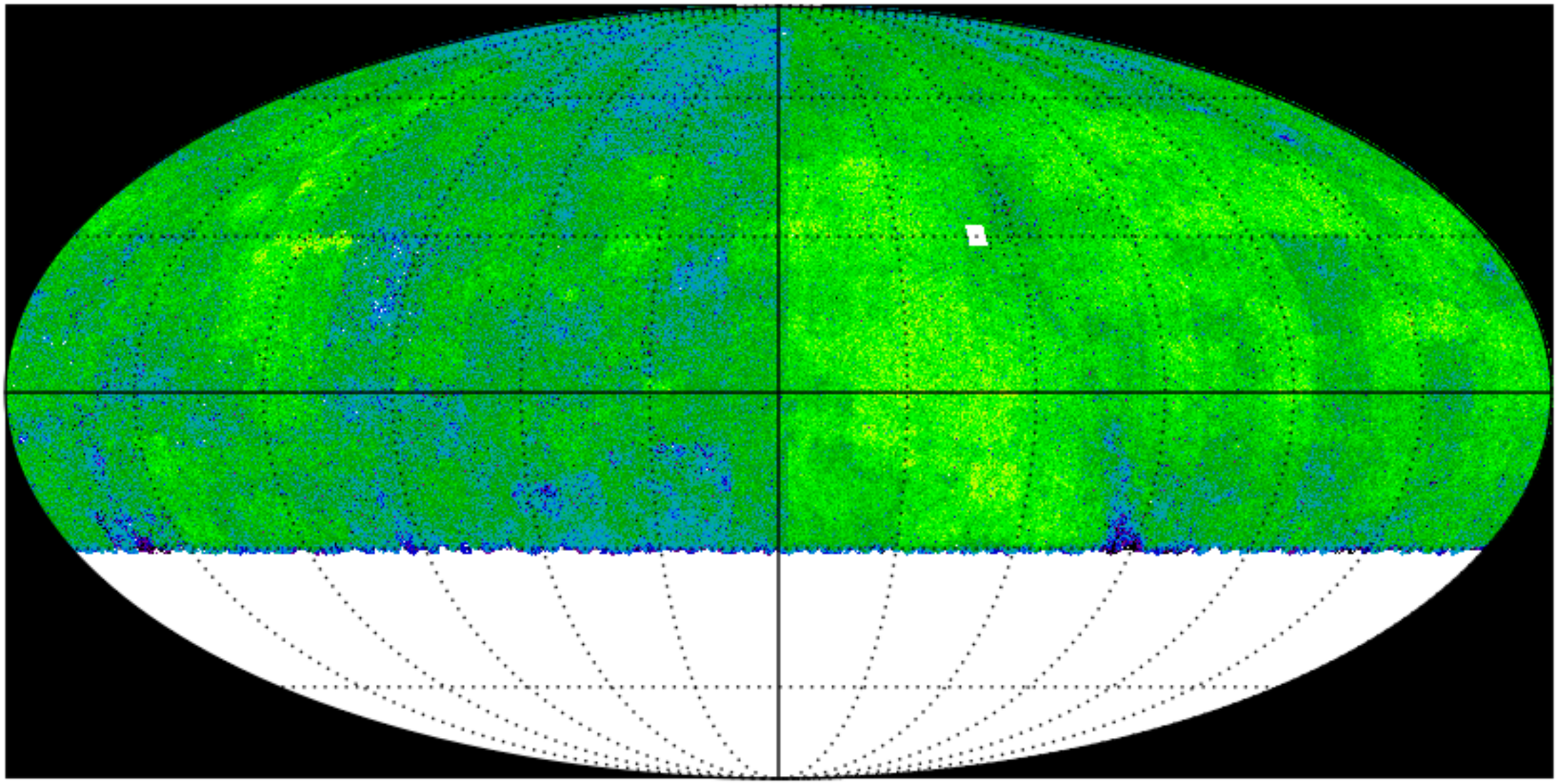
20 10 sigma Depth 23.5

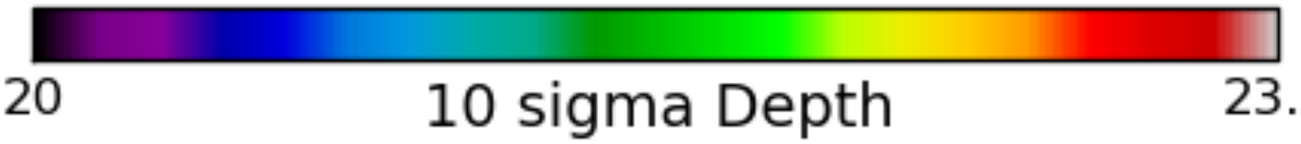
10 Sigma Depth Map r-band for 3.0 arcsec diameter aperture



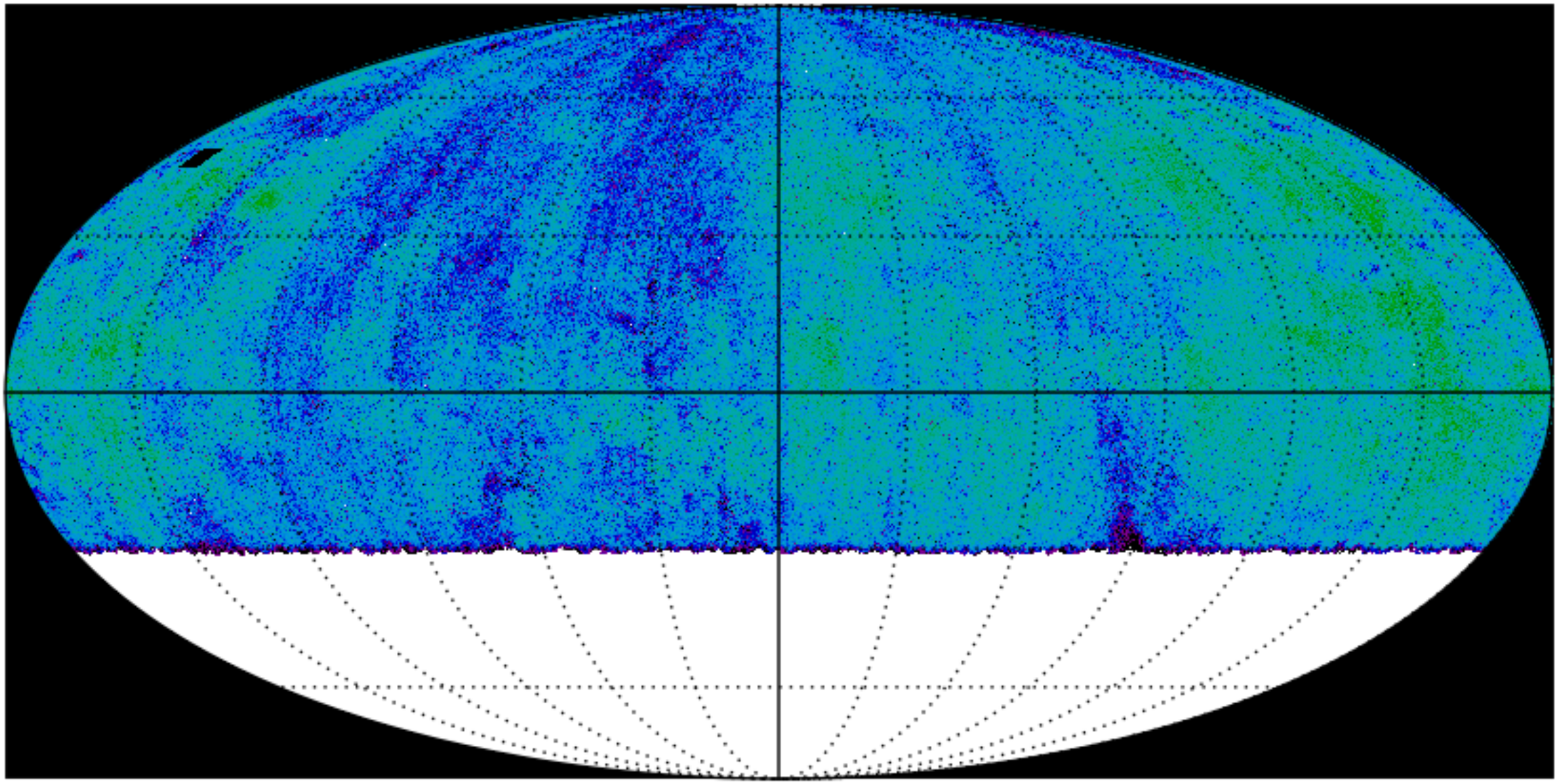


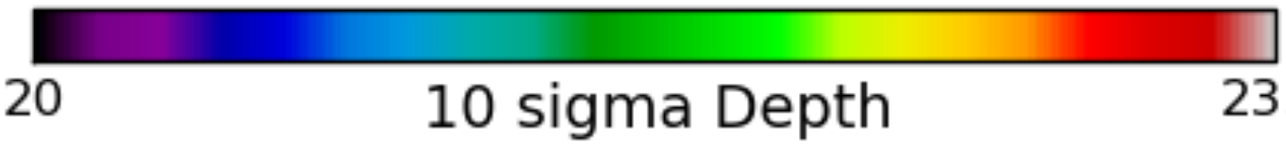
10 Sigma Depth Map i-band for 3.0 arcsec diameter aperture



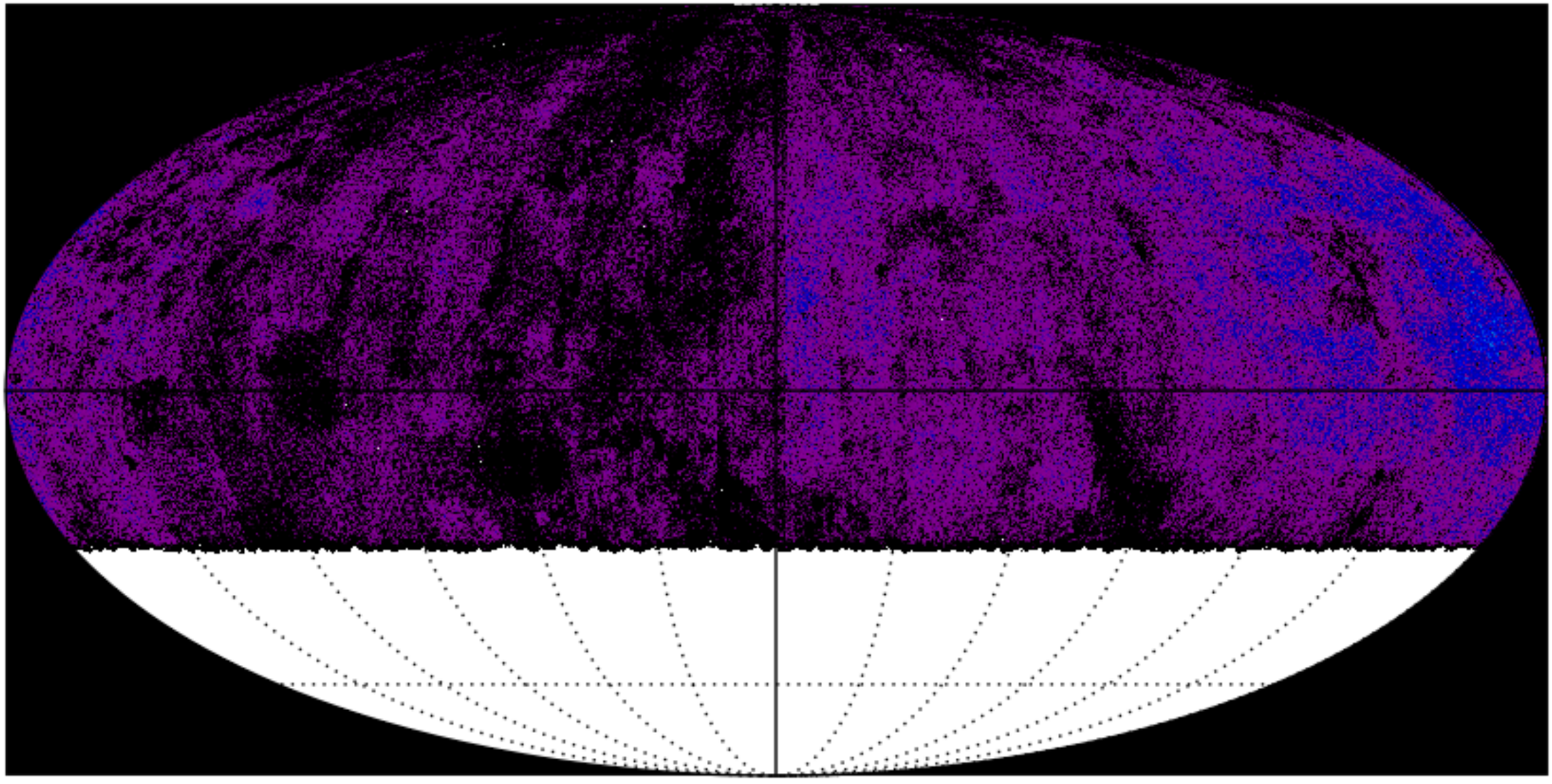


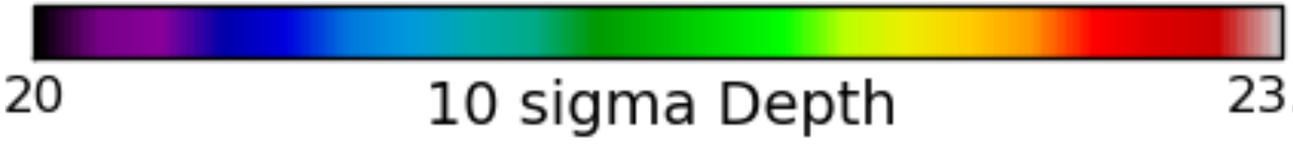
10 Sigma Depth Map z-band for 3.0 arcsec diameter aperture





10 Sigma Depth Map y-band for 3.0 arcsec diameter aperture

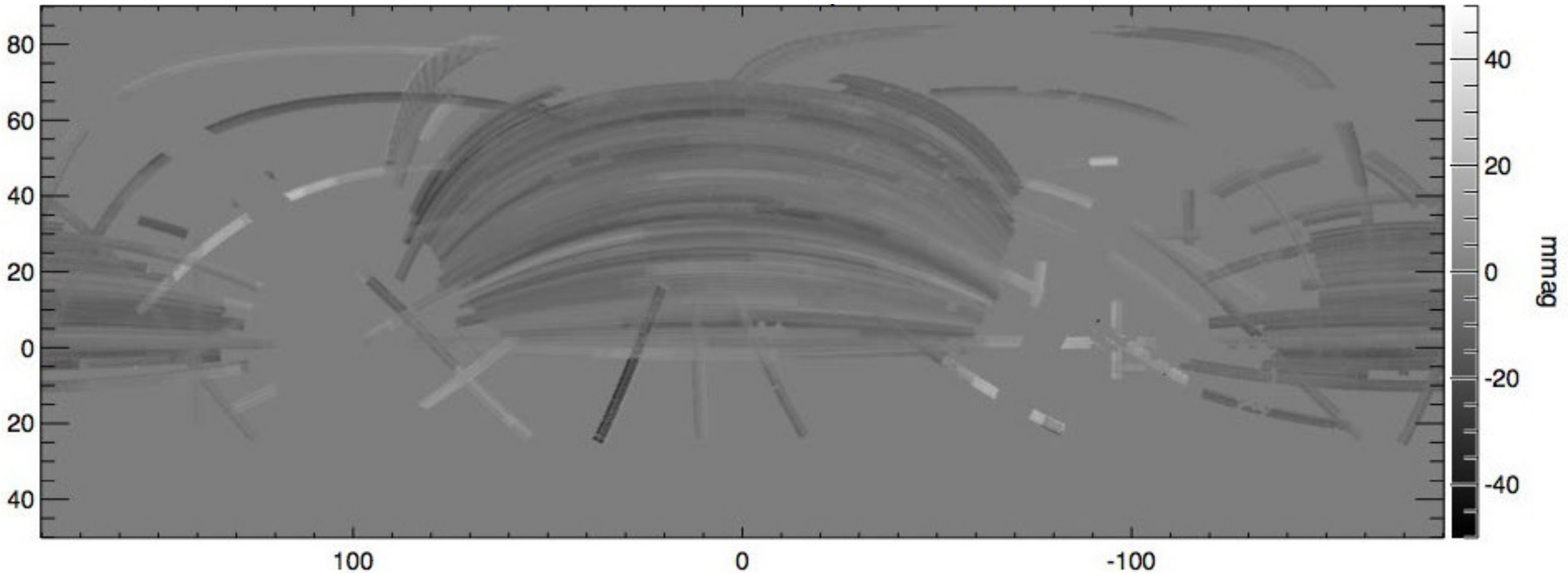




PS1 is the best-calibrated optical survey: <1%

Overlap- and repeat observations enable accurate self-calibration ("übercal")
Based on minimizing the variance of repeat observations

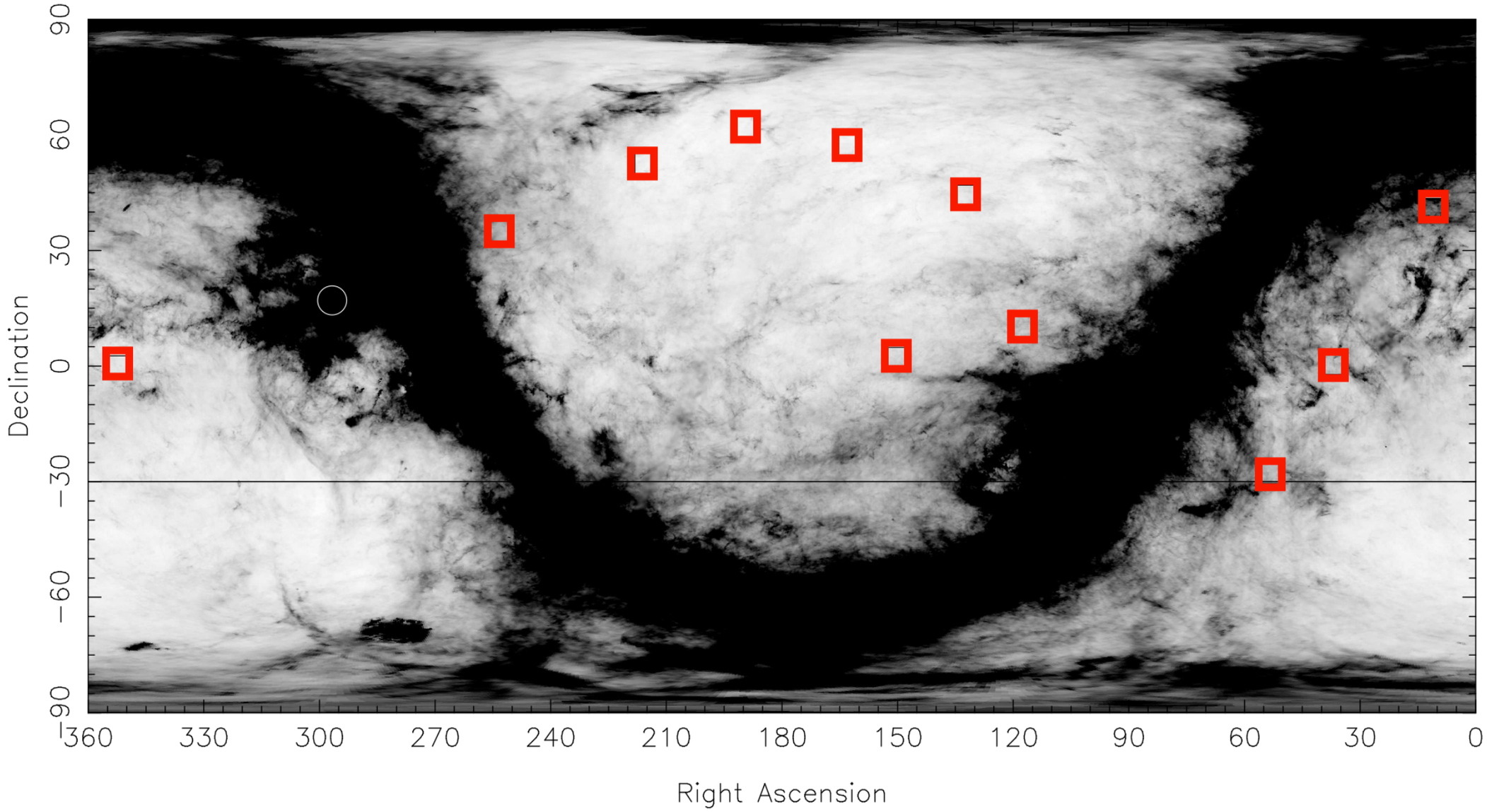
D.Finkbeiner, E. Schlafly, G. Magnier



e.g. r-band photom. zero-point PS1 vs SDSS: 0.004 mag variance

Medium Deep Survey (MDS) fields

10 fields, 7 square degrees each

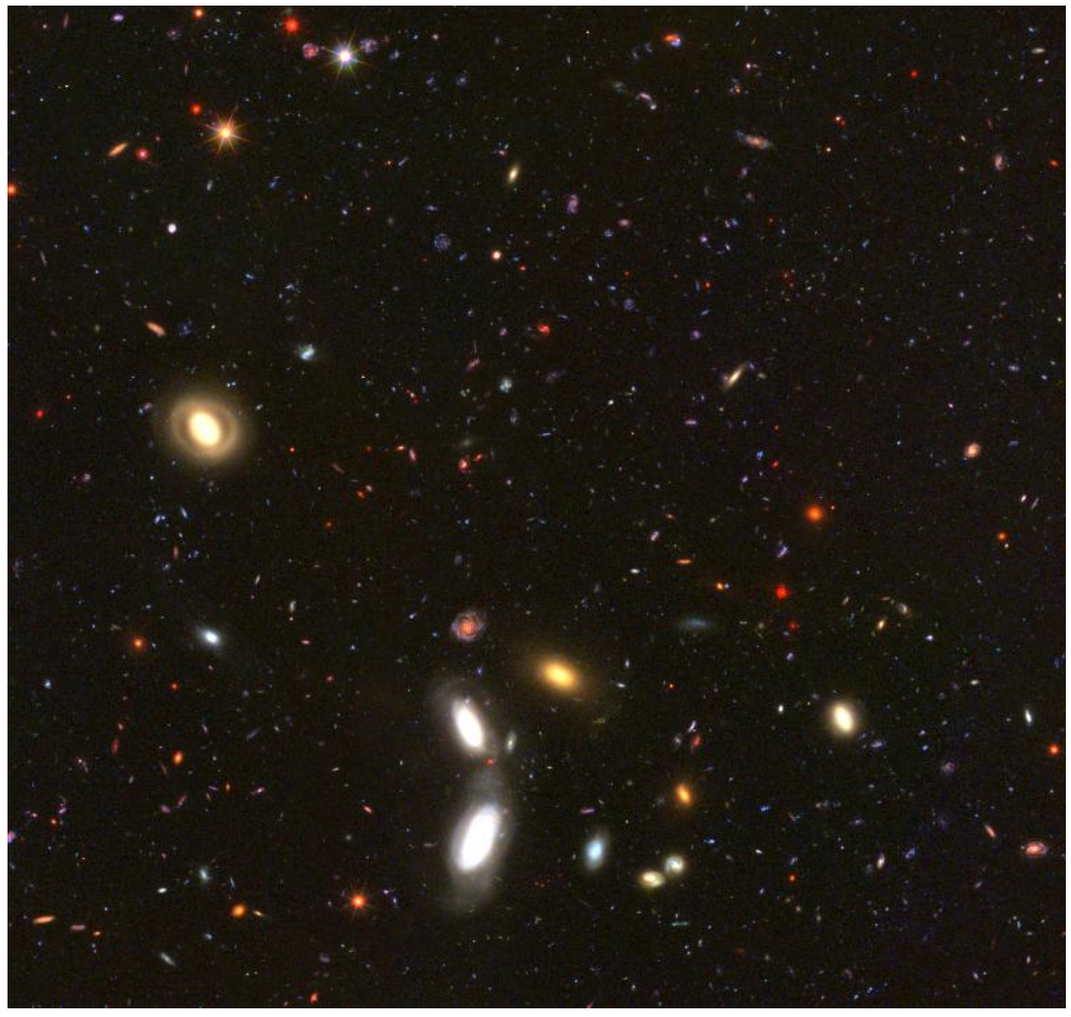


Nearly nightly observations in at least one band, “when field is up”

+ Pandromeda: monitoring M31

+ Pan-Planets: stellar transit monitoring

Comparison of PS1 MD fields and GOODS Survey



HST GOOD-S z/r/g
< 0.1 square degree
A few epochs

PS1 Medium Deep Survey
- **70 square degrees**
- **Several hundred epochs**

Comparison courtesy Rick White

Initial takeaways:
PS1 has done an enormous amount of brick and mortar astronomy:

- Photometry:

  Better than 1% photometry over 30,000 square degrees.
  (better than Landolt standards). You don't ever need to spend observing time calibrating anymore: everything in your field of view is already calibrated better than the usual standards.

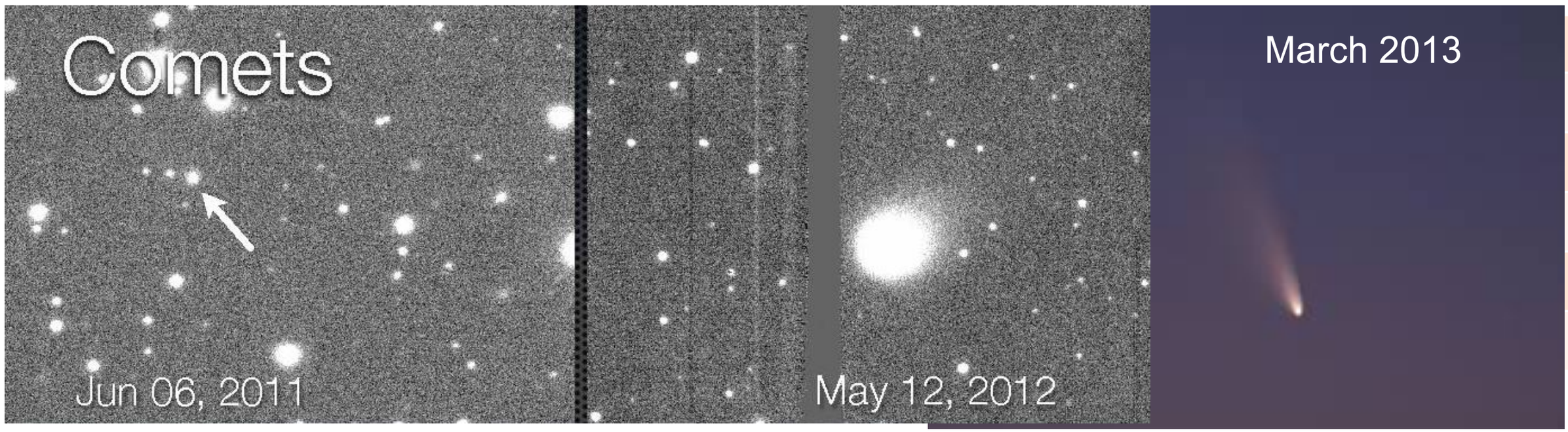
- Astrometry:

  PS1 has 3-4 milliarcsec relative astrometry
  Absolute astrometry is better than 10 milliarcsec.
  Will improve, active area of research. Unprecedented prior to Gaia, and will extend Gaia frame > 3 magnitudes deeper;
  e.g. successfully gone from PS1 catalog to DEIMOS mask with very good results. HST data is being re-astrometrized.

  Ground-based astronomy has entered the regime of precision physics.

Inner Solar System Discoveries

Potentially Hazardous Asteroids	**116**
Near Earth Objects	**1293**
Comets	**70**
Asteroid Tracklets	**3,650,842**



Wainscoat, Deneau, et al.

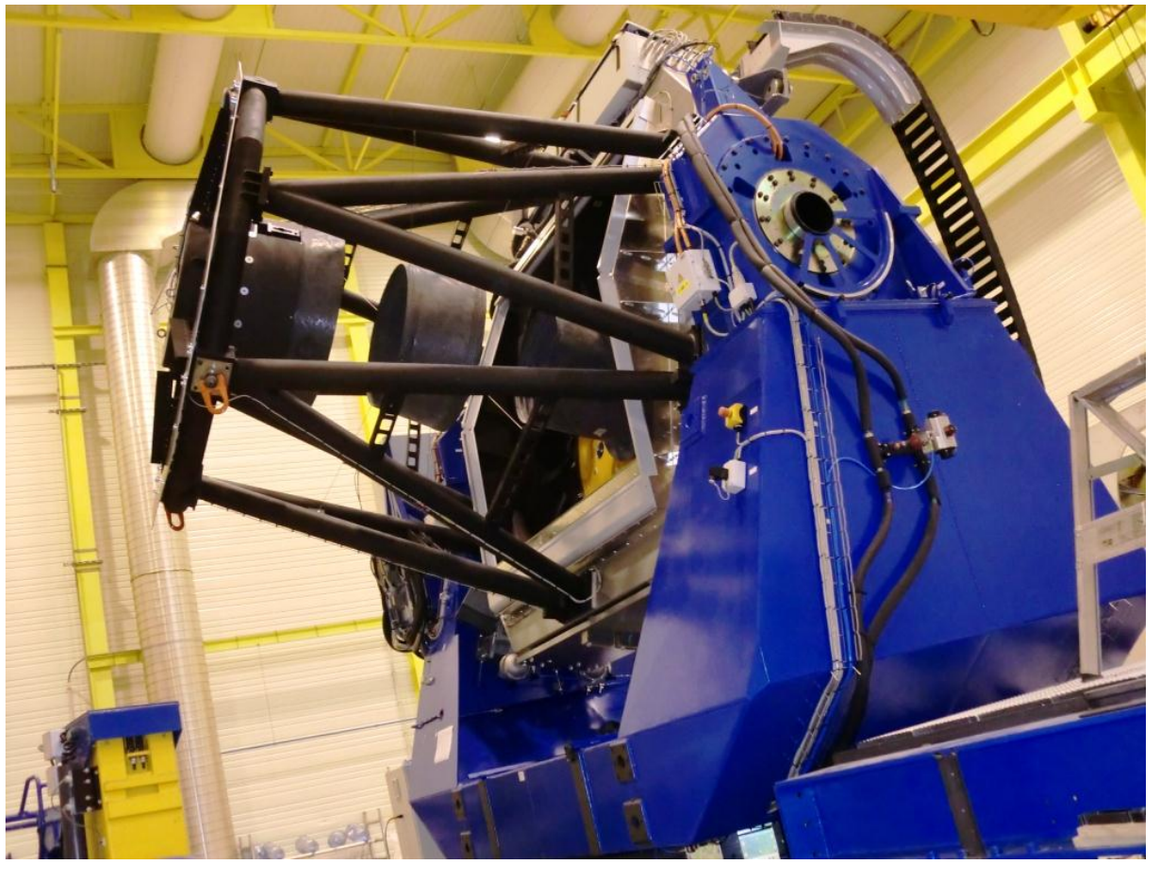
Ps1 - discovery machine in the solar system

- 2013/14 : now the leading telescope for Near Earth Objects and Potentially Hazardous Asteroids (PHAs)
- Discovering ~40% of new comets – image quality is key
- 90% of 1km objects were thought to be known
  But discoveries are continuing … tension with the solar system model
- Thousands of KBO's / TNO's in final release

Wainscoat, Denneau, Jedicke, Fitzsimmons et al.

Status of PS2

- PS2 has the same optics design as PS1, with hopefully superior fabrication of L2 optic
- Aside from optical design, PS2 is a completely different telescope from PS1.
- Construction is done, signifies the completion of the Pan-STARRS Project
- The GPC2 Camera is currently only partially populated, but the new chips look good.
- Commissioning including collimation & alignment, observing software, completion of GPC2 and integration is underway by ops team.
- Expect full functionally of PS2 & integrated operations with PS1 by the summer 2015.



PS2 telescope w/o optics on the factory floor at AMOS, Belgium.

PS2 telescope w/ optics assembled inside PS2 dome on Haleakala.

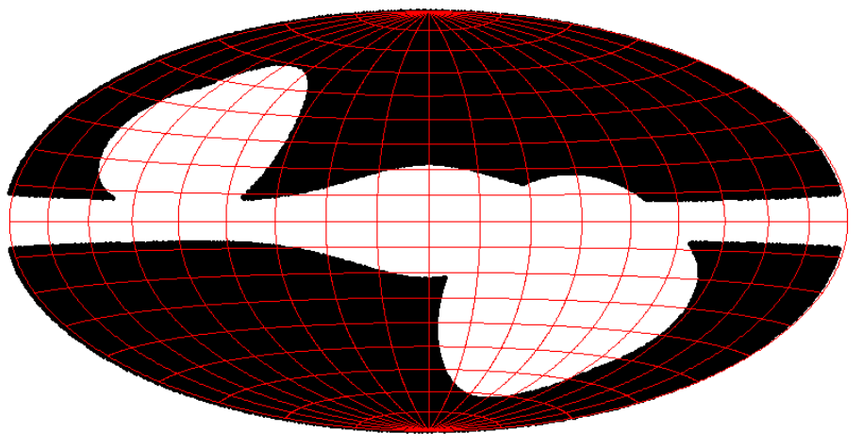
PS1 & PS2 2014-2017:

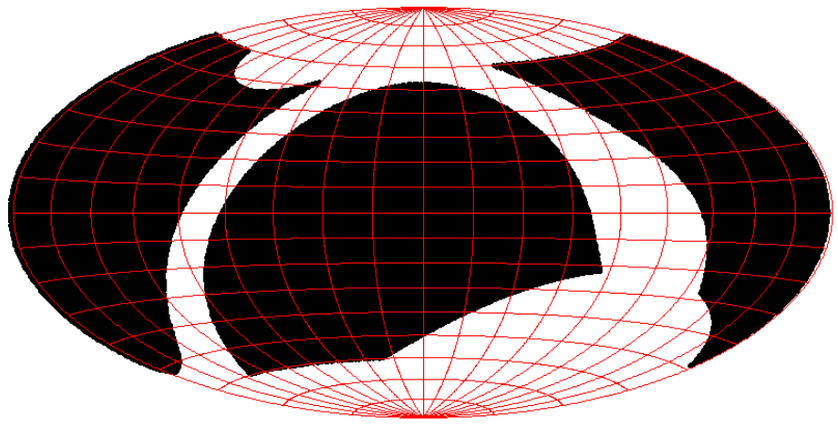
A sky survey optimized for NEO detection

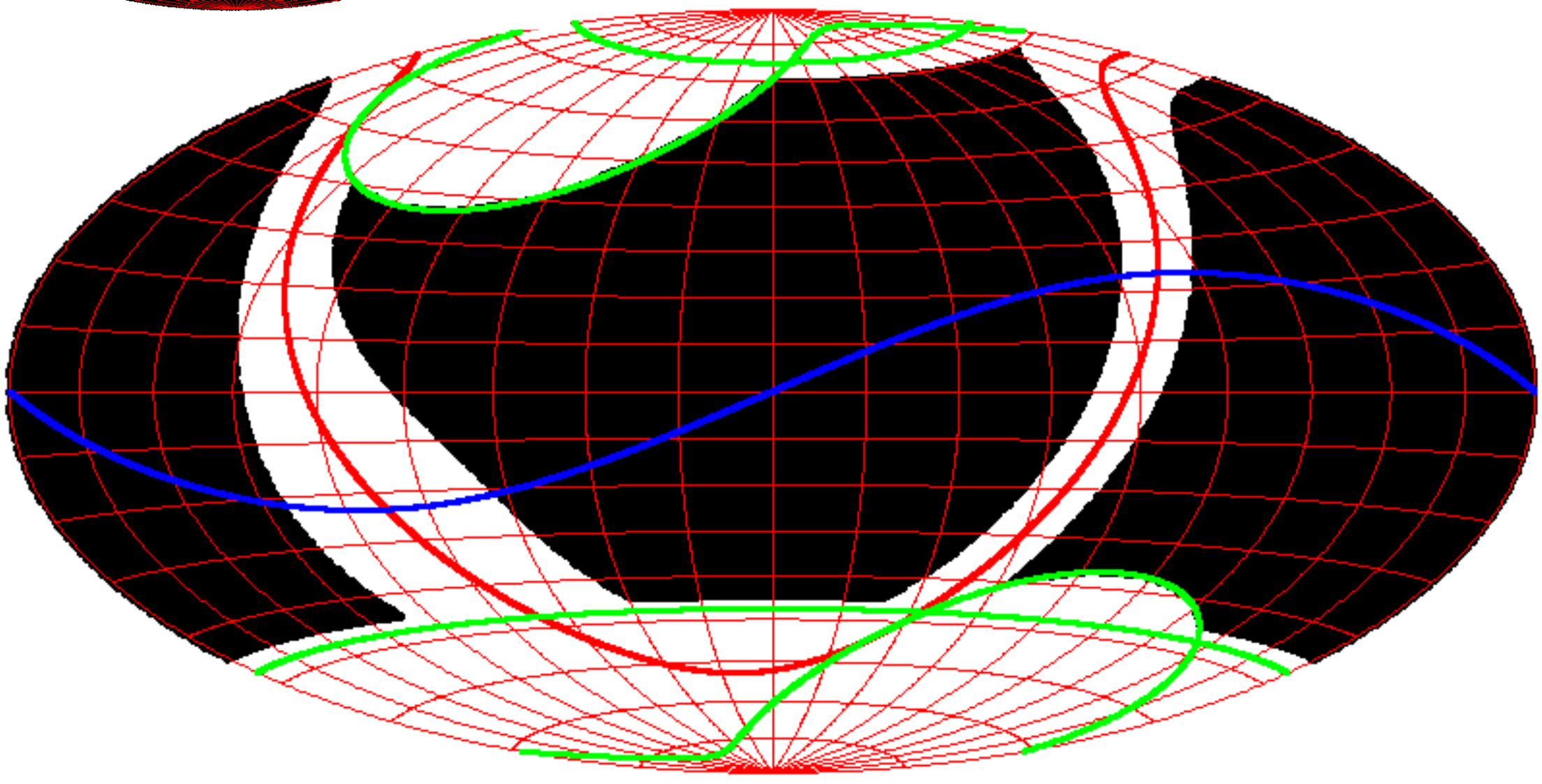
- The NASA NEO program is supporting the commissioning of PS2 and the Operations of PS1 & PS2 for 3.5 years for a ~ all sky survey.
- Program will use wide filters for greater instantaneous sensitivity.
  - W filter = g + r + I in dark time
  - Currently i and r band in bright time
  - Transition to x ~ i + y + z filters in bright time.
  - 4 exposures spaced by ~ 30 minutes

Pan-STARRS NEO Survey

26,000 square degrees
excludes Galactic plane
And Ecliptic poles





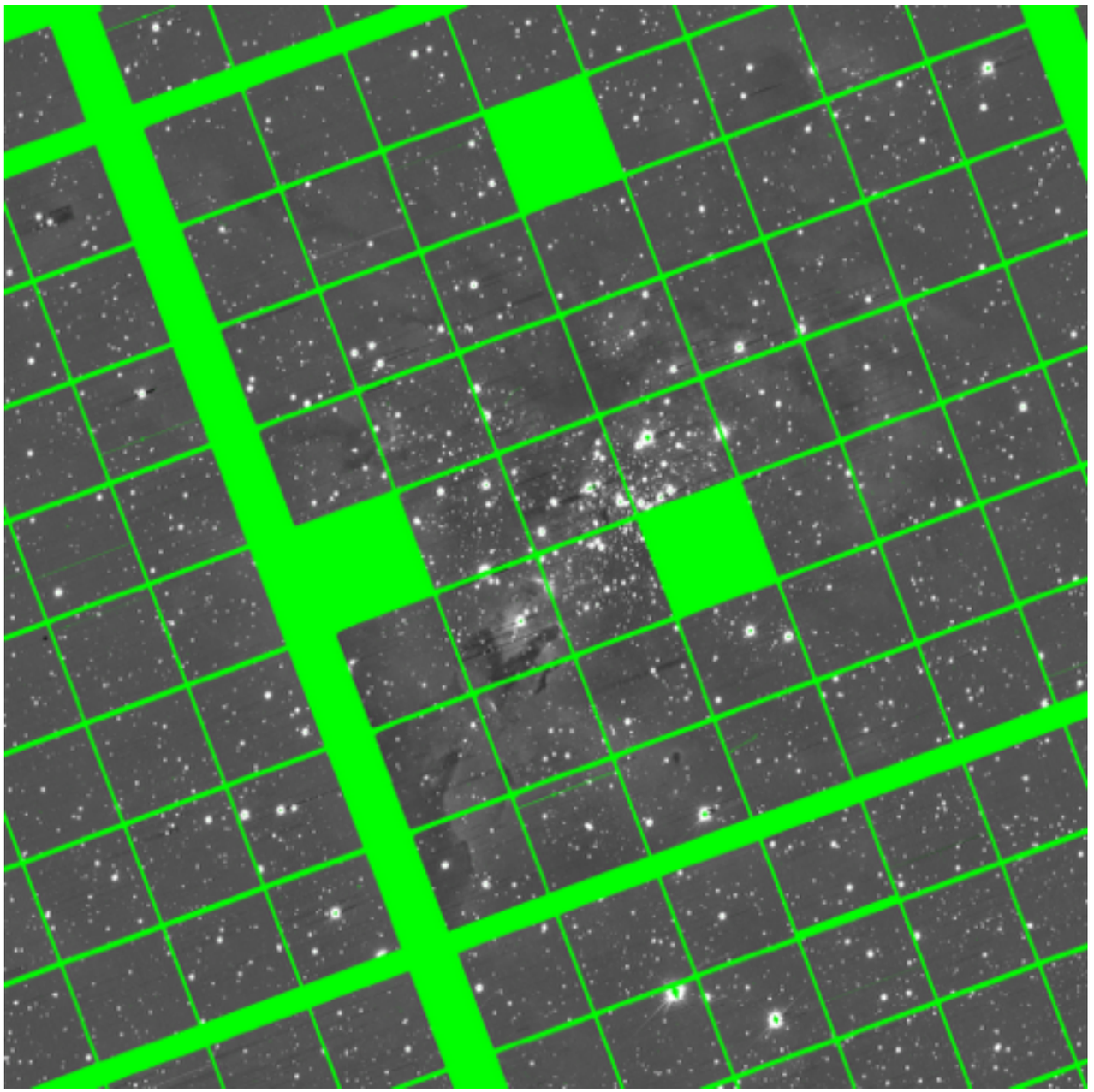


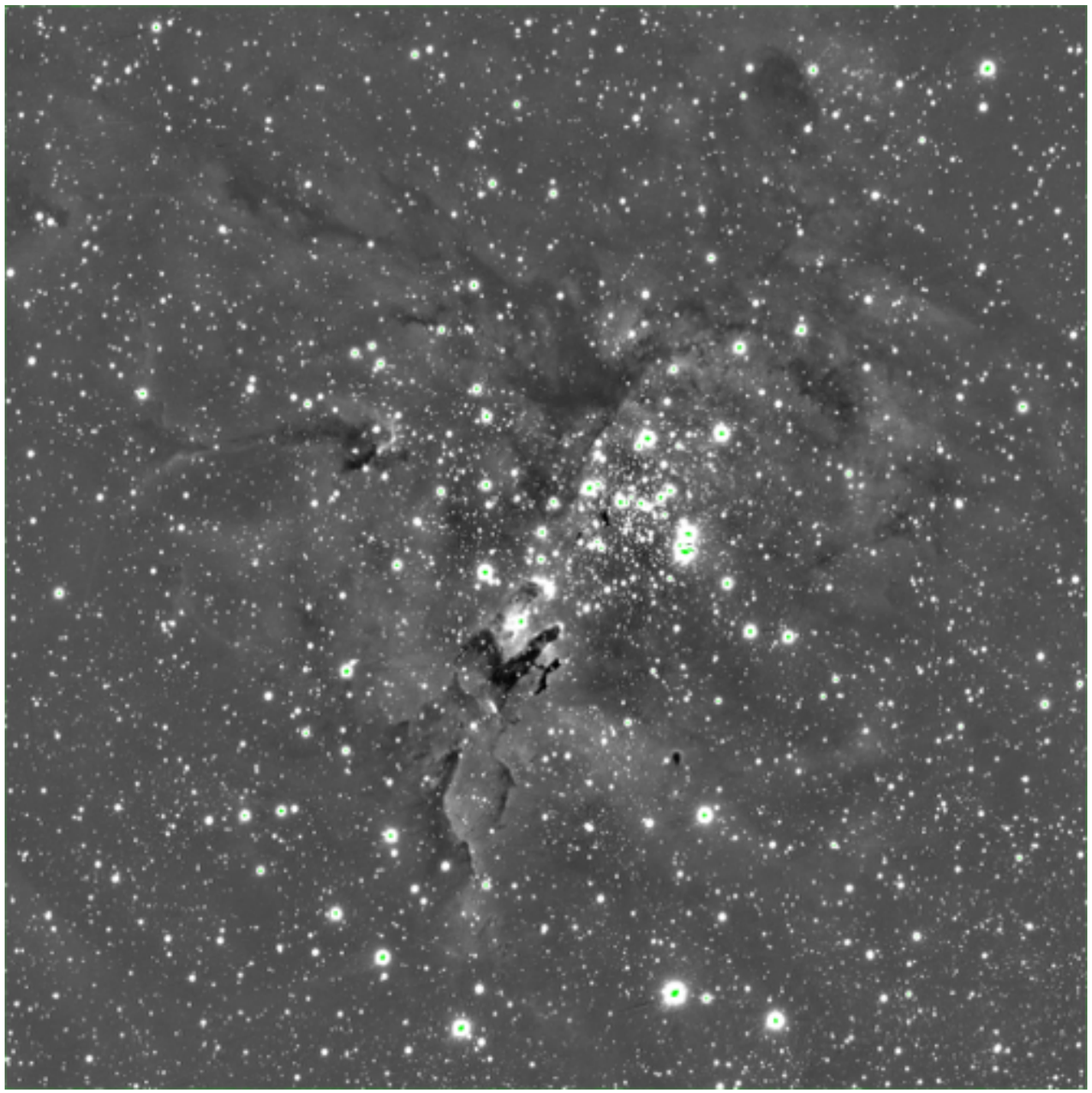
MAST: Mikulski Archive for Space Telescopes

- NASA's archive center for optical/UV data
  - Started with Hubble data in 1990
  - Multi-mission since 1997
  - Active missions:
    - Hubble, Kepler/K2, Swift UVOT, XMM-OM, JWST
  - Many legacy missions:
    - GALEX, IUE, FUSE, etc.
  - New missions:
    - TESS, WFIRST-AFTA
  - Catalogs:
    - Guide Star Catalog-2, GALEX, etc.

PS1 data to be served by MAST @ STScI

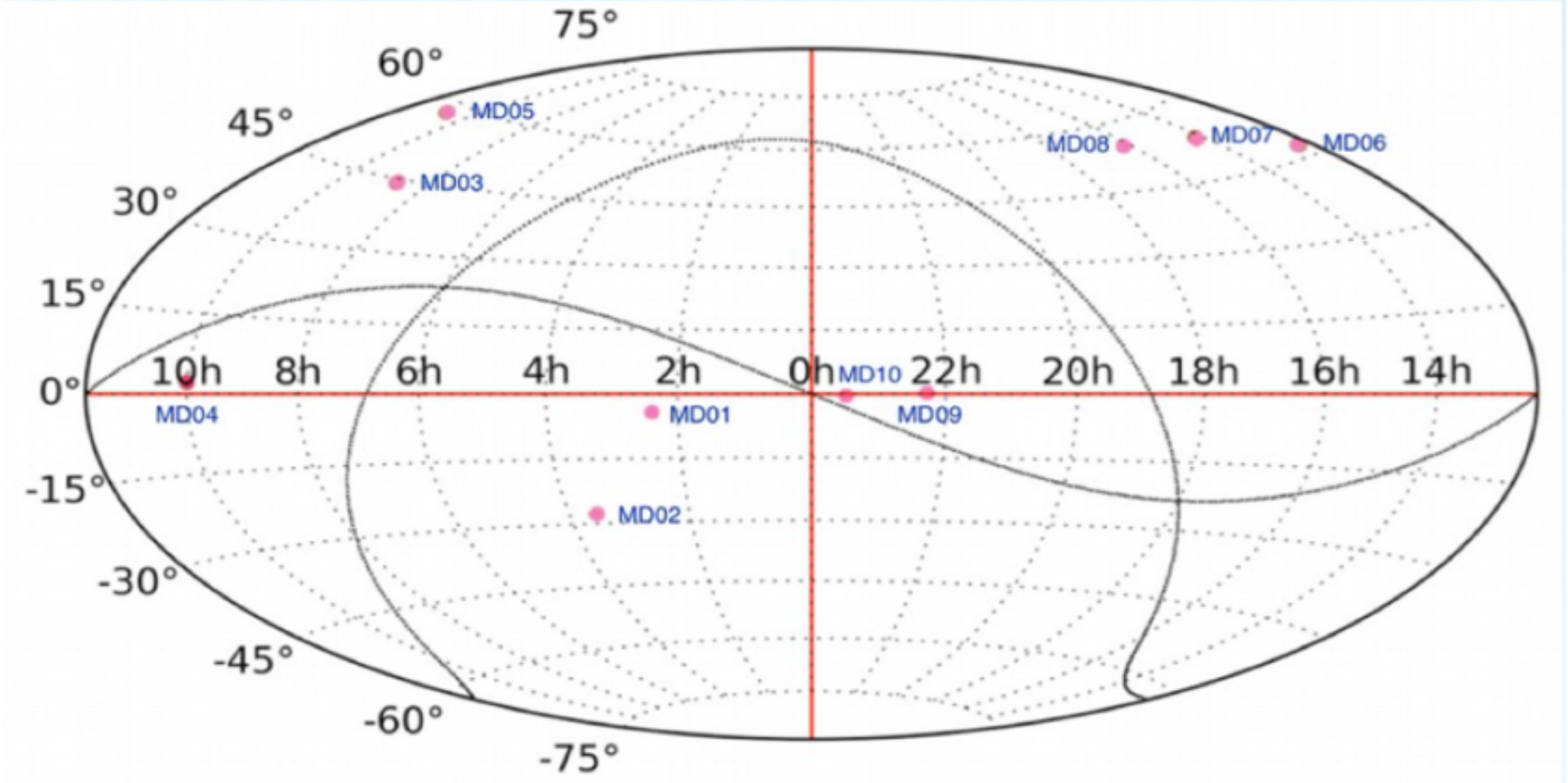
- Catalog databases
  - Including stack detections, single-epoch detections, forced photometry & objects (linking multiple epoch detections)
  - Total database volume ~100 TB
    - Most database volume is in single-epoch detections
    - 3PI database (PV1: ~90% of 3PI sky area, still incomplete in plane):
      - 29.4×10^9 detections
      - 5.9×10^9 objects
      - 1.4×10^9 objects with nDetections > 1
      - For comparison, SDSS DR9: 469 M objects (14,000 sq deg)
      - Difference detections from (warp – stack)
- Images – 2Petabytes
  - Individual warps
  - Stacks





Medium Deep Fields

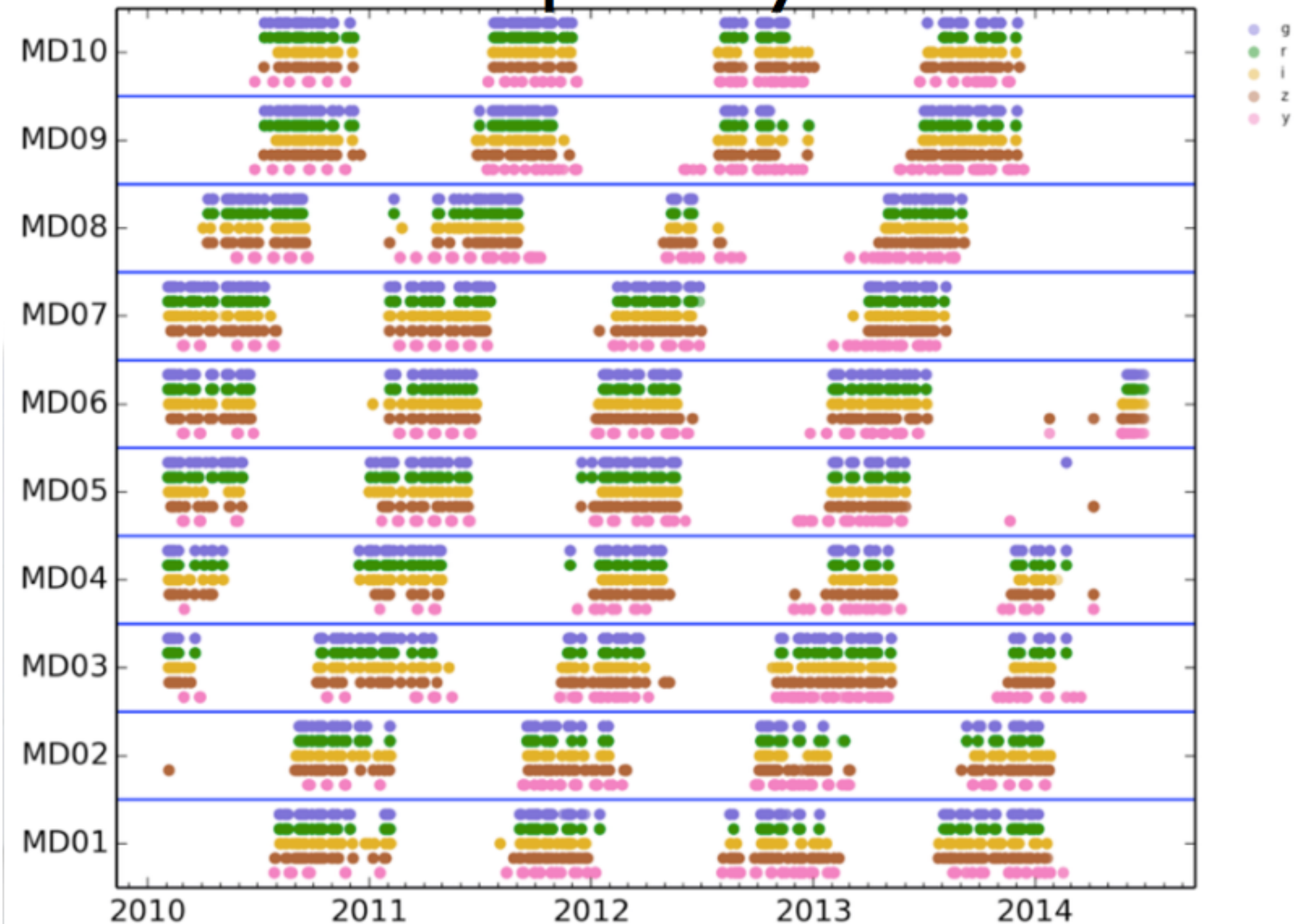
MD01	XMM-LSS-DXS/VVDS-02h	036.2074	-04.5833
MD02	CDFS/GOODS/GEMS	053.1000	-28.1333
MD03	IFA/Lynx	130.5917	+44.3167
MD04	COSMOS	150.0000	+02.2000
MD05	Lockman-DXS	161.9167	+58.0833
MD06	NGC 4258	185.0000	+47.1167
MD07	DEEP2 Field 1	213.7051	+53.0834
MD08	EliasN1-DXS	242.7875	+54.9500
MD09	SA22-DXS/VVDS-22h	334.1875	+00.2833
MD10	DEEP2-Field3	352.3125	-00.4333


75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
10h
8h
6h
4h
2h
0h
22h
20h
18h
16h
14h
MD01
MD02
MD03
MD04
MD05
MD06
MD07
MD08
MD09
MD10

MD04 Depth (PV2, 5σ)	g (N)	r (N)	i (N)	z (N)	y (N)
Night (typical)	23.6 (8)	23.6 (8)	23.8 (8)	23.2 (8)	22.0 (8)
IQ	24.7 (25)	24.7 (25)	24.8 (25)	24.3 (25)	23.3 (25)
Reference (yr1)	25.1 (70)	25.1 (66)	25.3 (66)	24.6 (66)	23.7 (66)
Deep	25.8 (507)	25.7 (506)	25.8 (636)	25.4 (594)	24.0 (386)

MD04 FWHM (PV2, “)	g	r	i	z	y
IQ	0.95	0.90	0.81	0.74	0.75
Reference (yr1)	1.01	0.91	0.82	0.77	0.79
Deep	1.21	1.09	0.95	0.95	1.10

Medium Deep Survey Cadence



Number of times observed

Name – (num exp)	Name – (num exp)
MD01 – 3798	MD06 – 4050
MD02 – 3433	MD07 – 4066
MD03 – 4659	MD08 – 4083
MD04 – 3393	MD09 – 3684
MD05 – 3836	MD10 – 3852

Perfect for variable searches

We observe each field 8x per filter, a few filters per night, with only a few seconds between exposures. We are sensitive to short period variables (on the order of minutes), as well as longer period variables (months).

Heather's Variable Star Pipeline

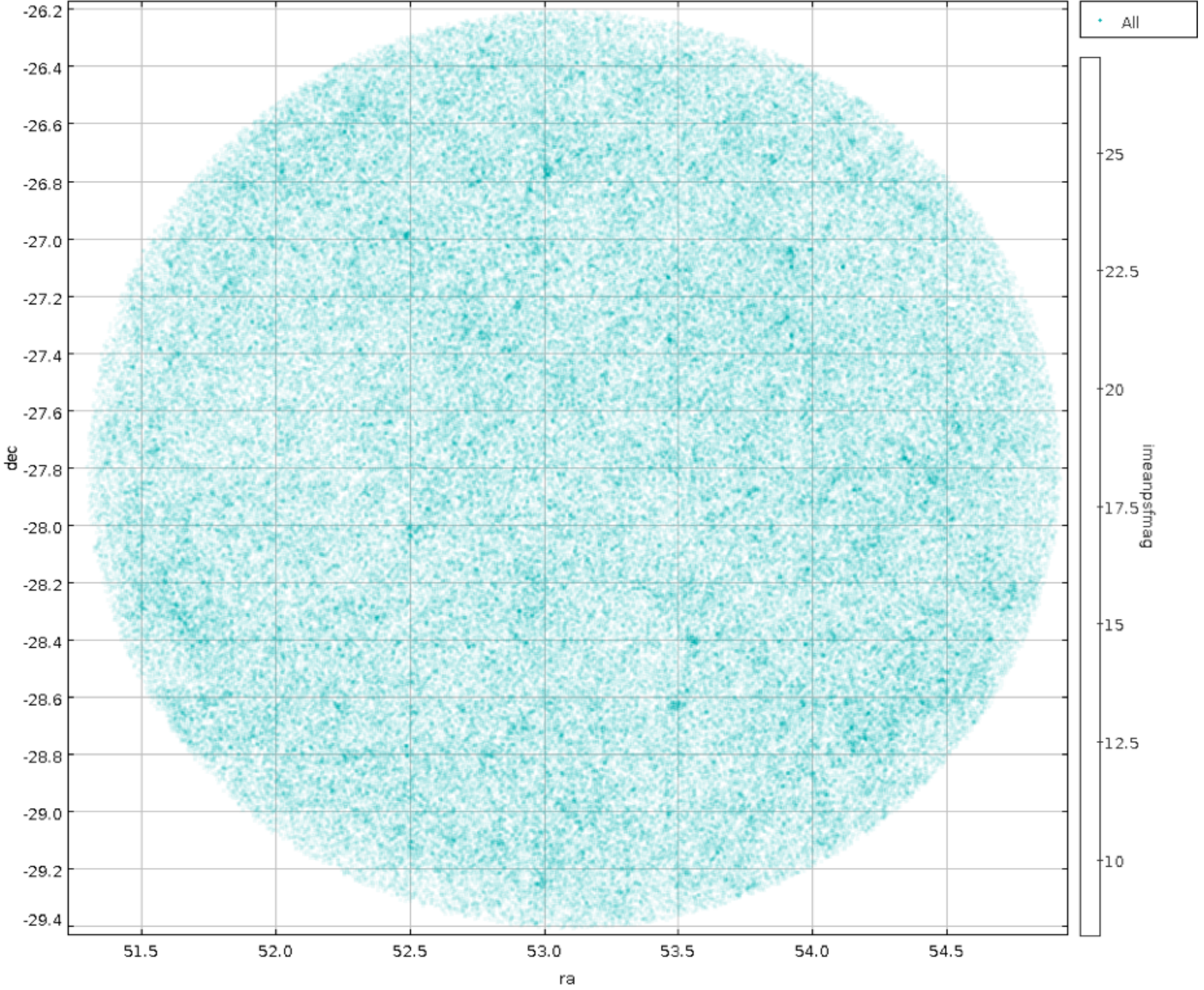
(this was after some small investigations with others, they had cuts on magnitude / color, which I didn't agree with - why not look at all the stars?)

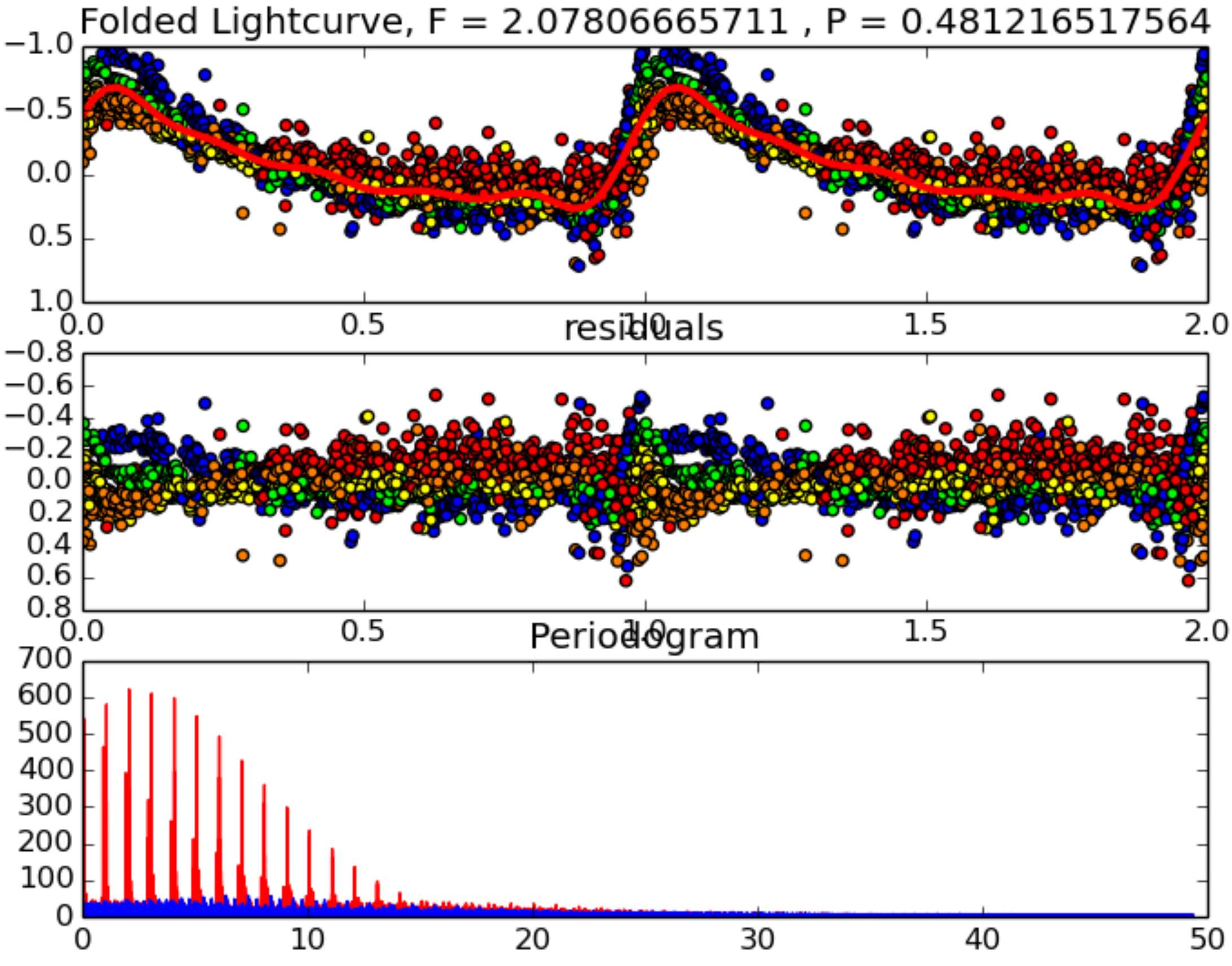
Take a MD field

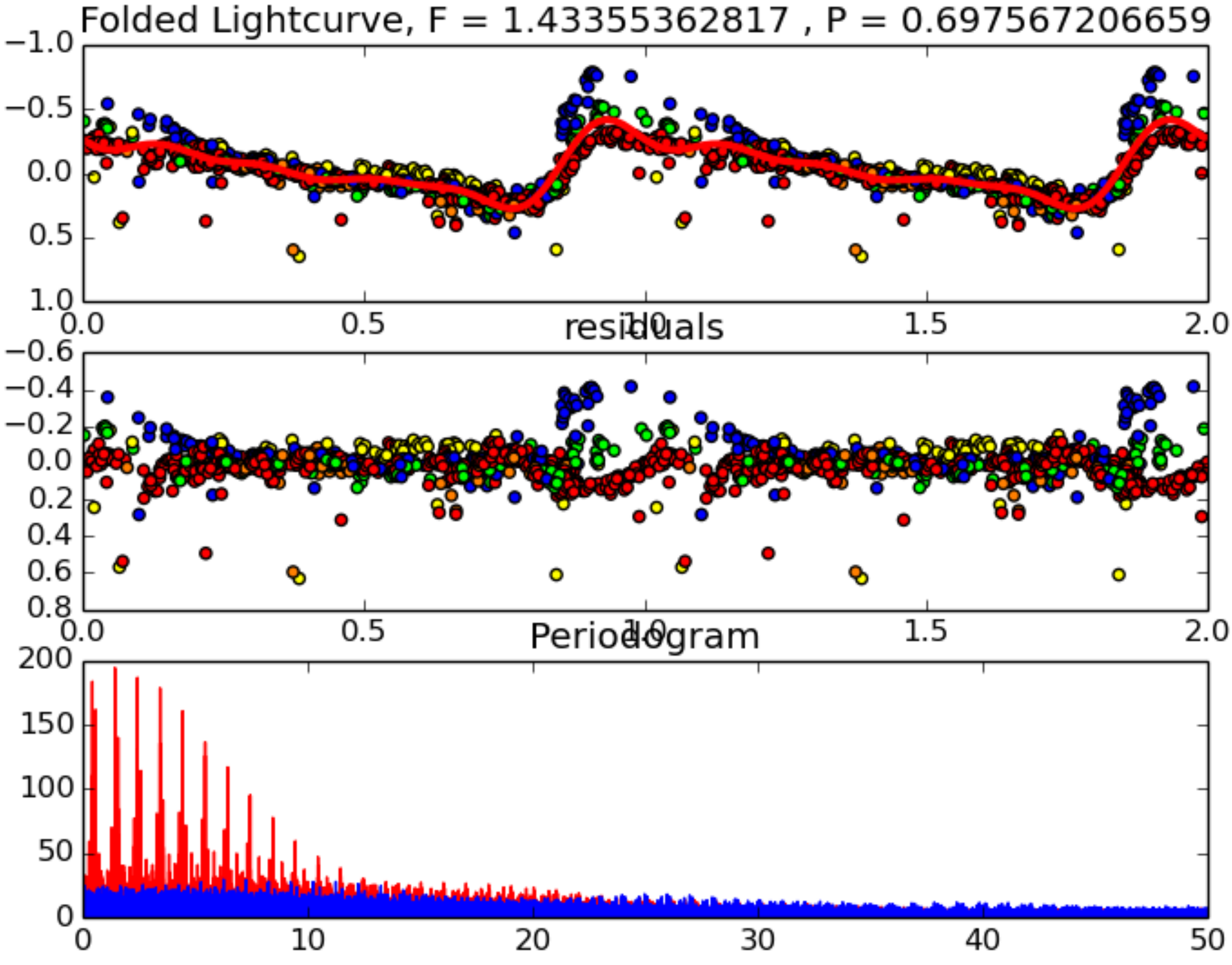
Find all the objects > 200 detections (~197000 for MD02, 2.5 million for all MD)

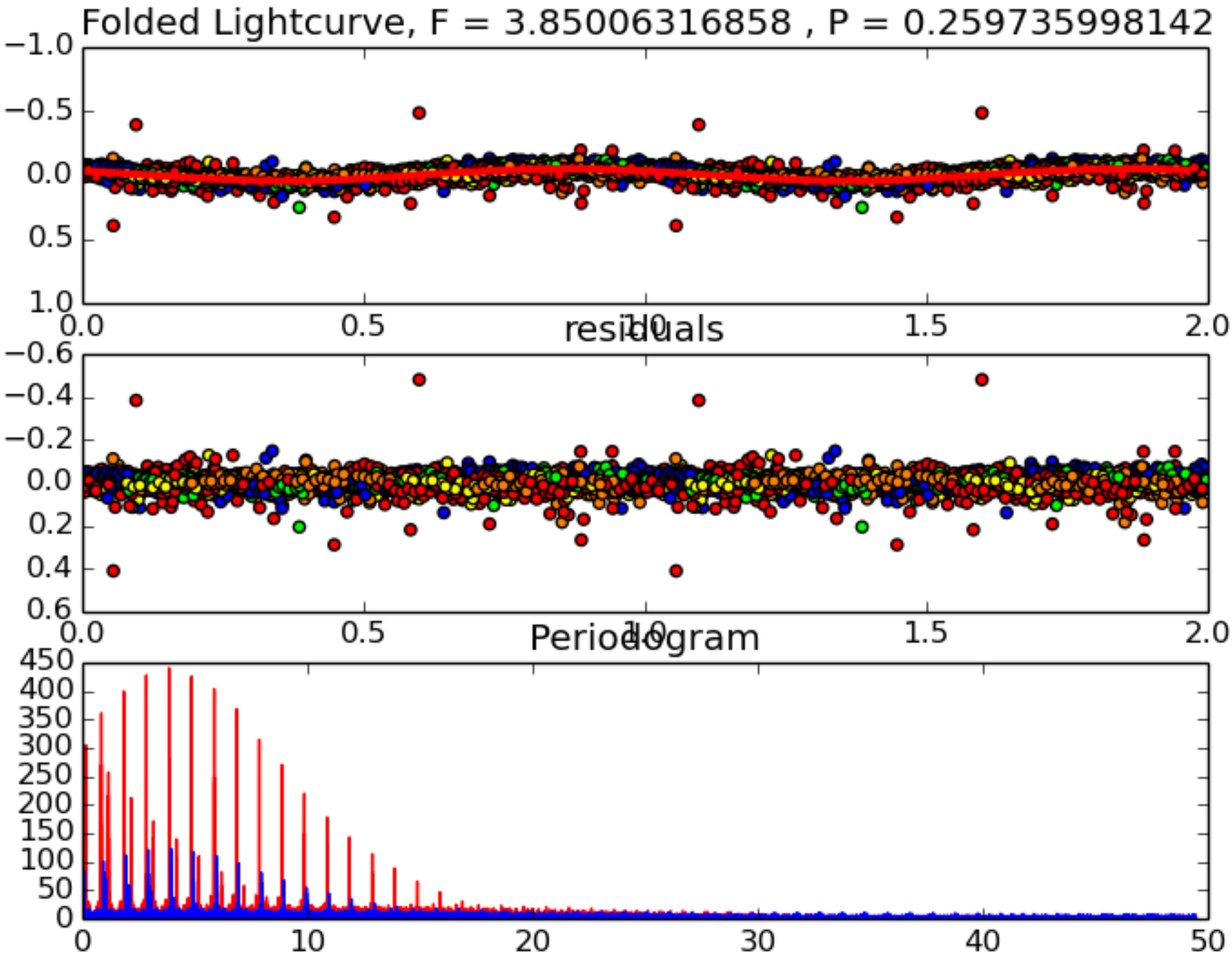
Run lomb scargle on those (basically FFT for unevenly spaced data)

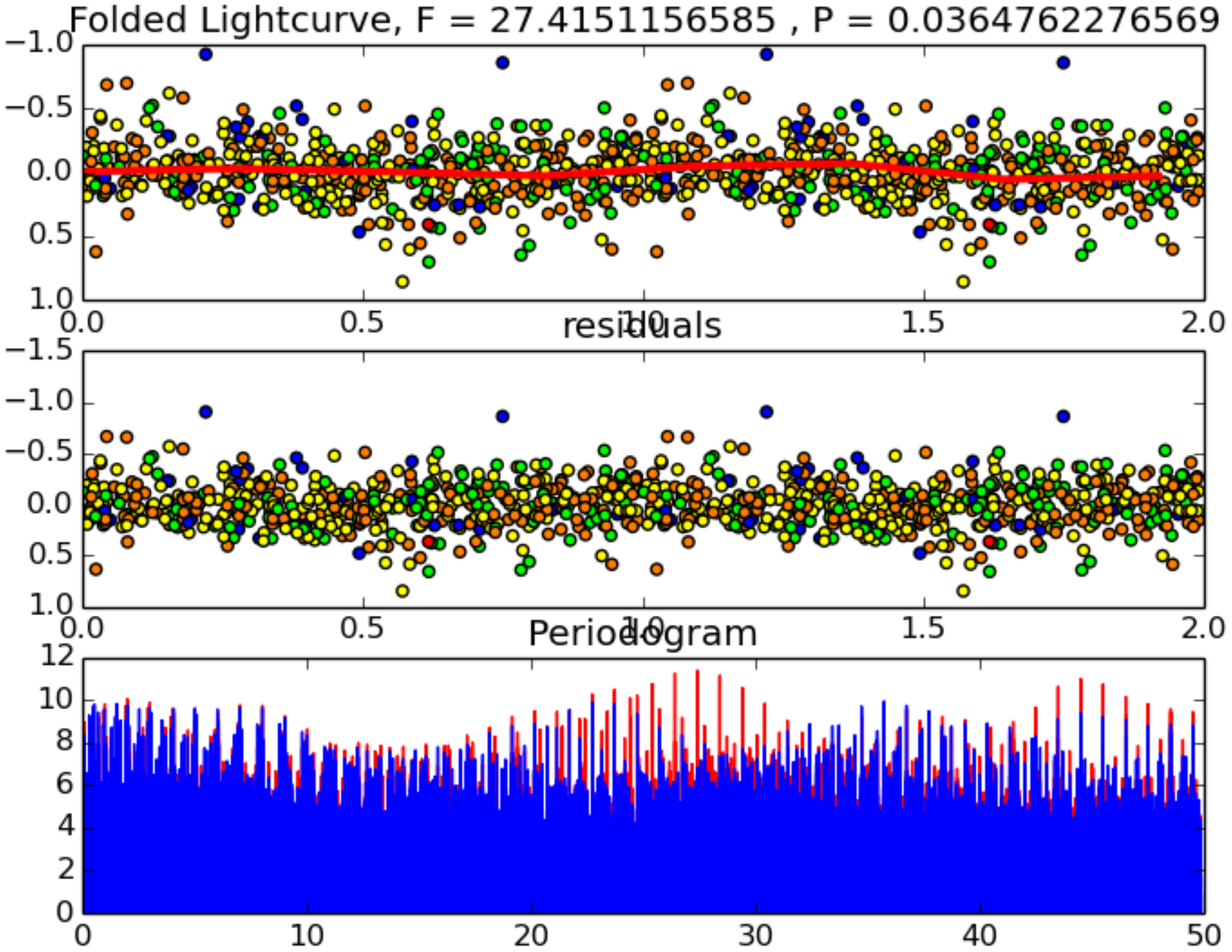
determine if periodic make catalog


All
-26.2
-26.4
-26.6
-26.8
-27.0
-27.2
-27.4
-27.6
-27.8
-28.0
-28.2
-28.4
-28.6
-28.8
-29.0
-29.2
-29.4
dec
51.5
52.0
52.5
53.0
53.5
54.0
54.5
ra
25
22.5
20
17.5
15
12.5
10
imeanpsfmag


Folded Lightcurve, F = 2.07806665711 , P = 0.481216517564
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
residuals
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
0.0
0.5
1.0
1.5
2.0
Periodogram
700
600
500
400
300
200
100
0
0
10
20
30
40
50

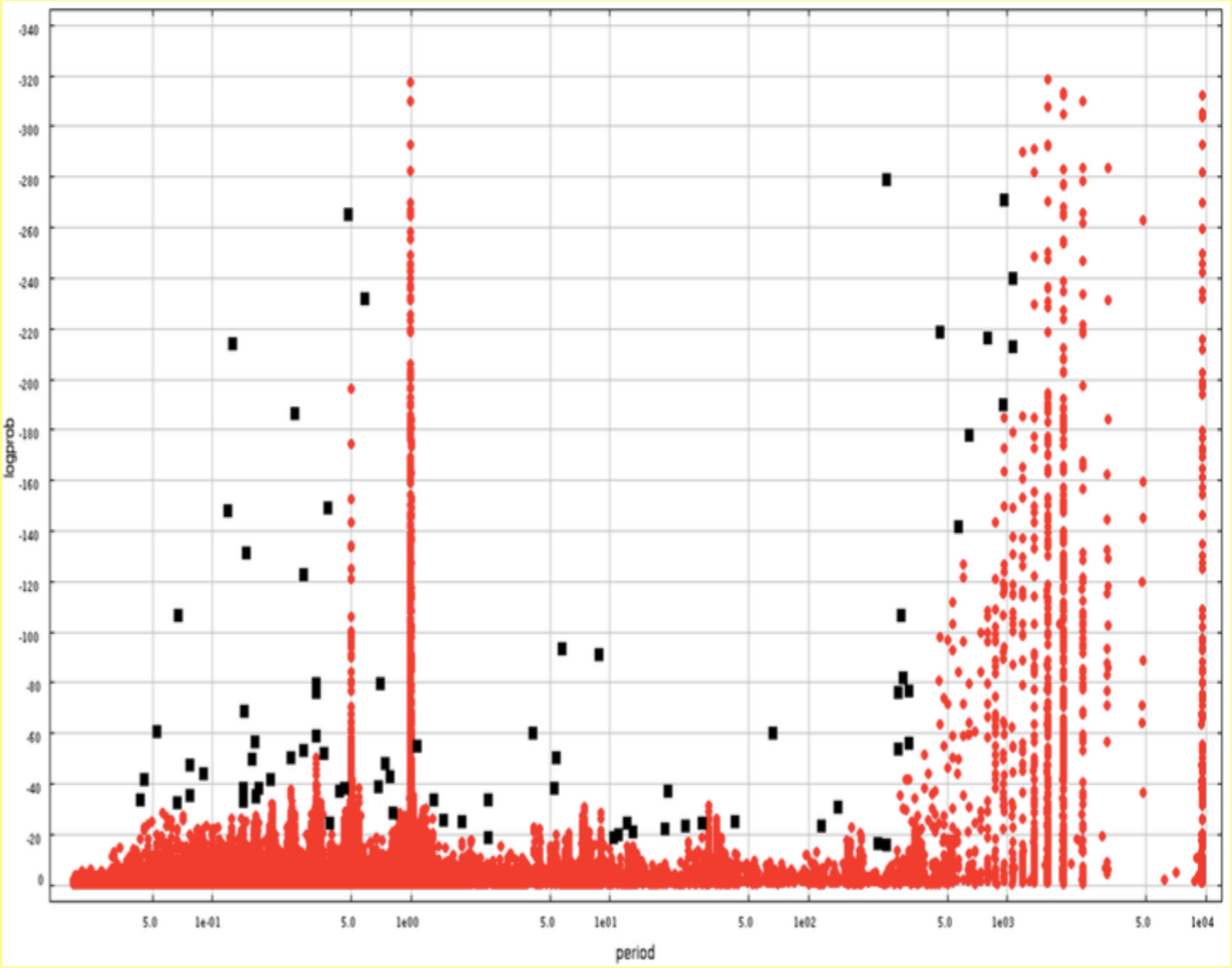

Folded Lightcurve, F = 1.43355362817 , P = 0.697567206659
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
residuals
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
0.0
0.5
1.0
1.5
2.0
Periodogram
200
150
100
50
0
0
10
20
30
40
50


Folded Lightcurve, F = 3.85006316858 , P = 0.259735998142
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
residuals
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.0
0.5
1.0
1.5
2.0
Periodogram
450
400
350
300
250
200
150
100
50
0
0
10
20
30
40
50


Folded Lightcurve, F = 27.4151156585 , P = 0.036476227656
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
residuals
−1.5
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
Periodogram
12
10
8
6
4
2
0
0
10
20
30
40
50

higher

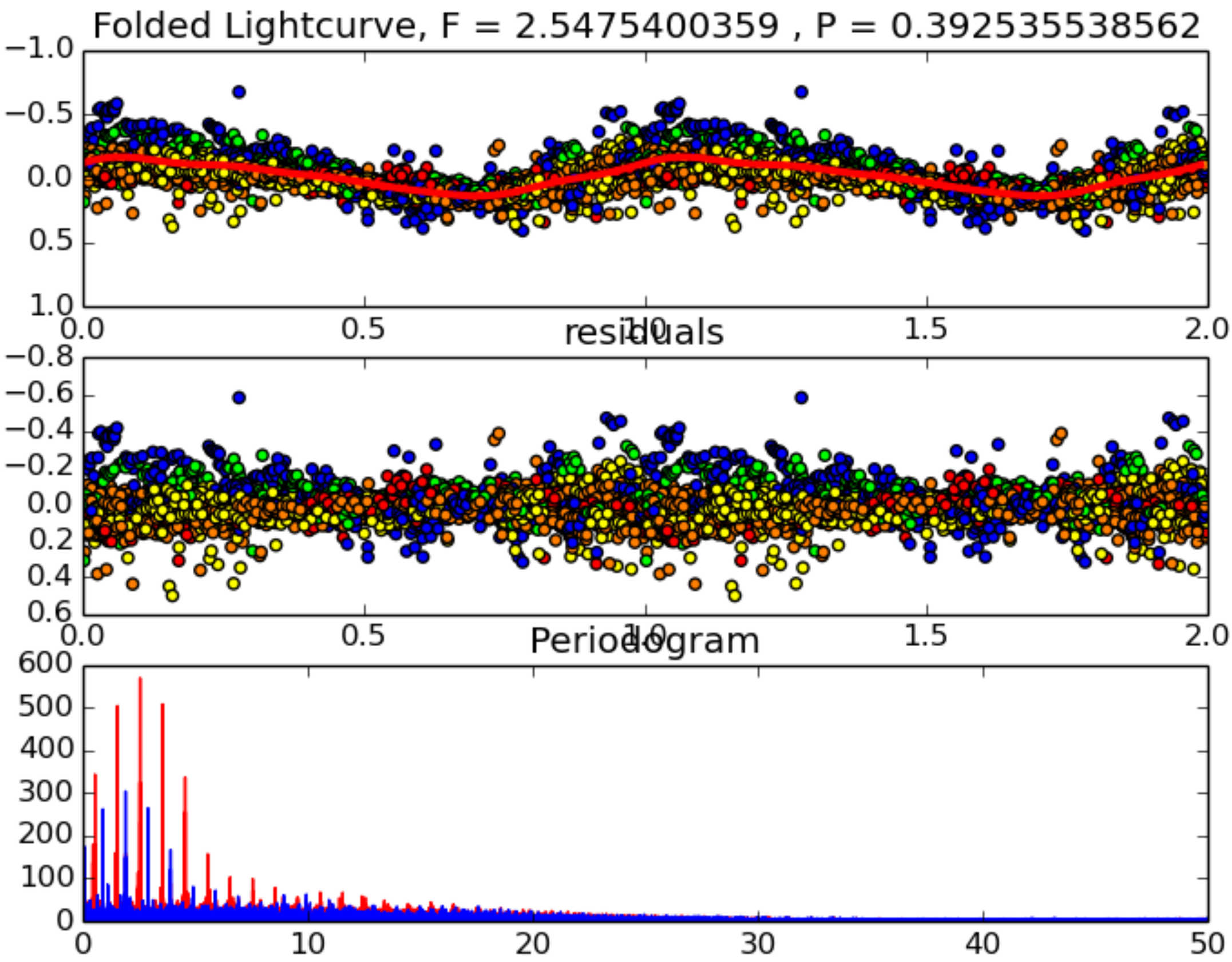
Probability it is periodic

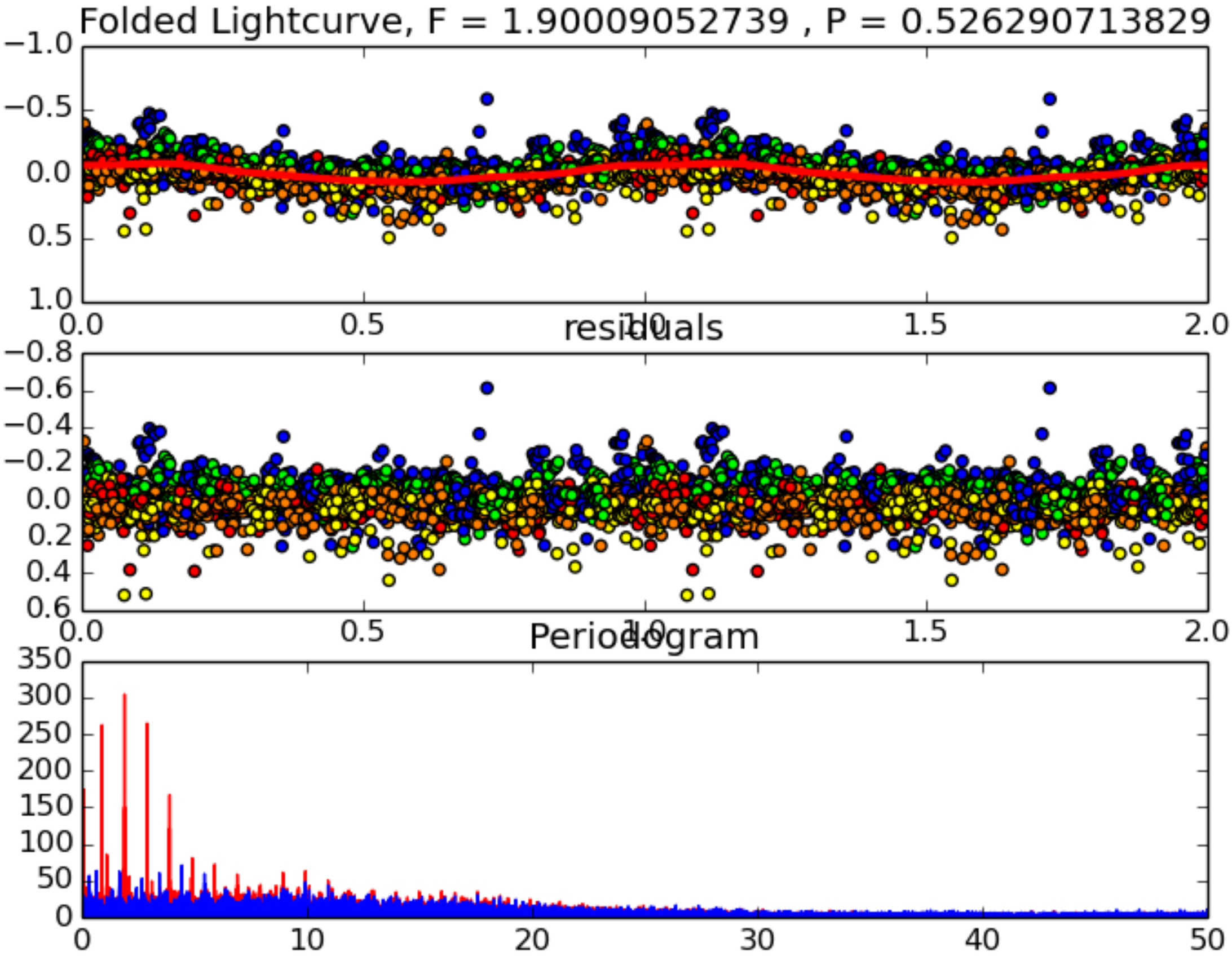


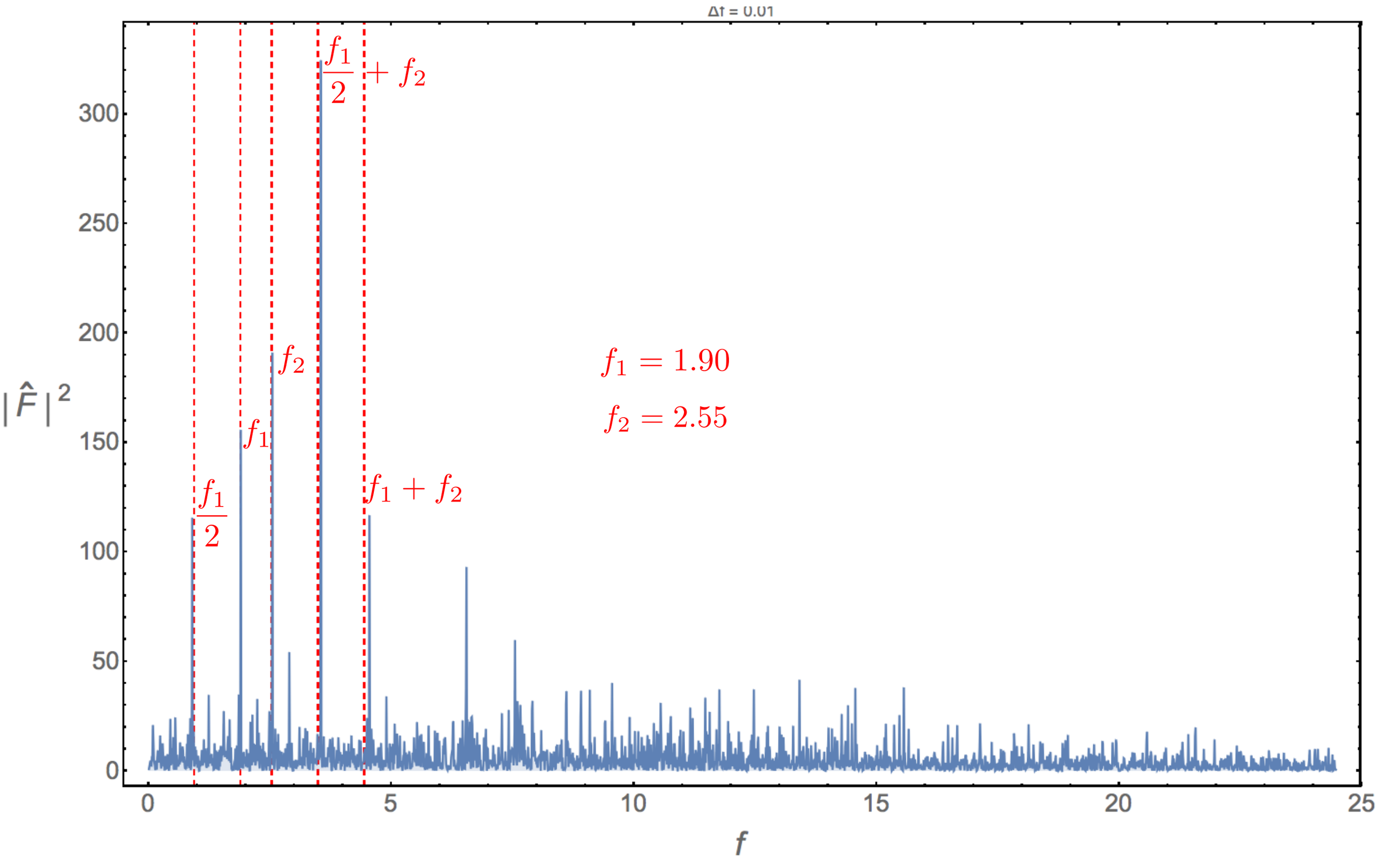
lower

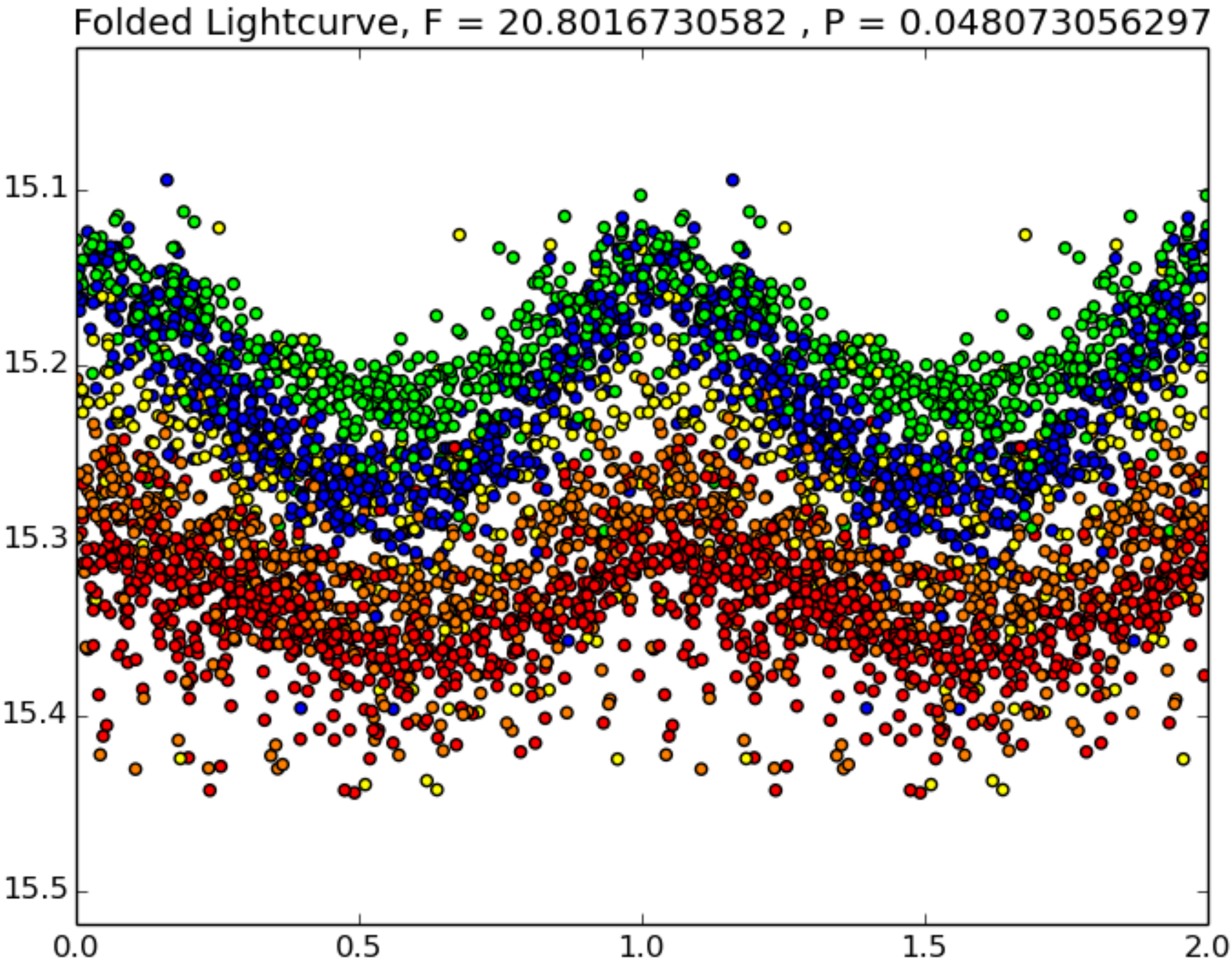
Short period

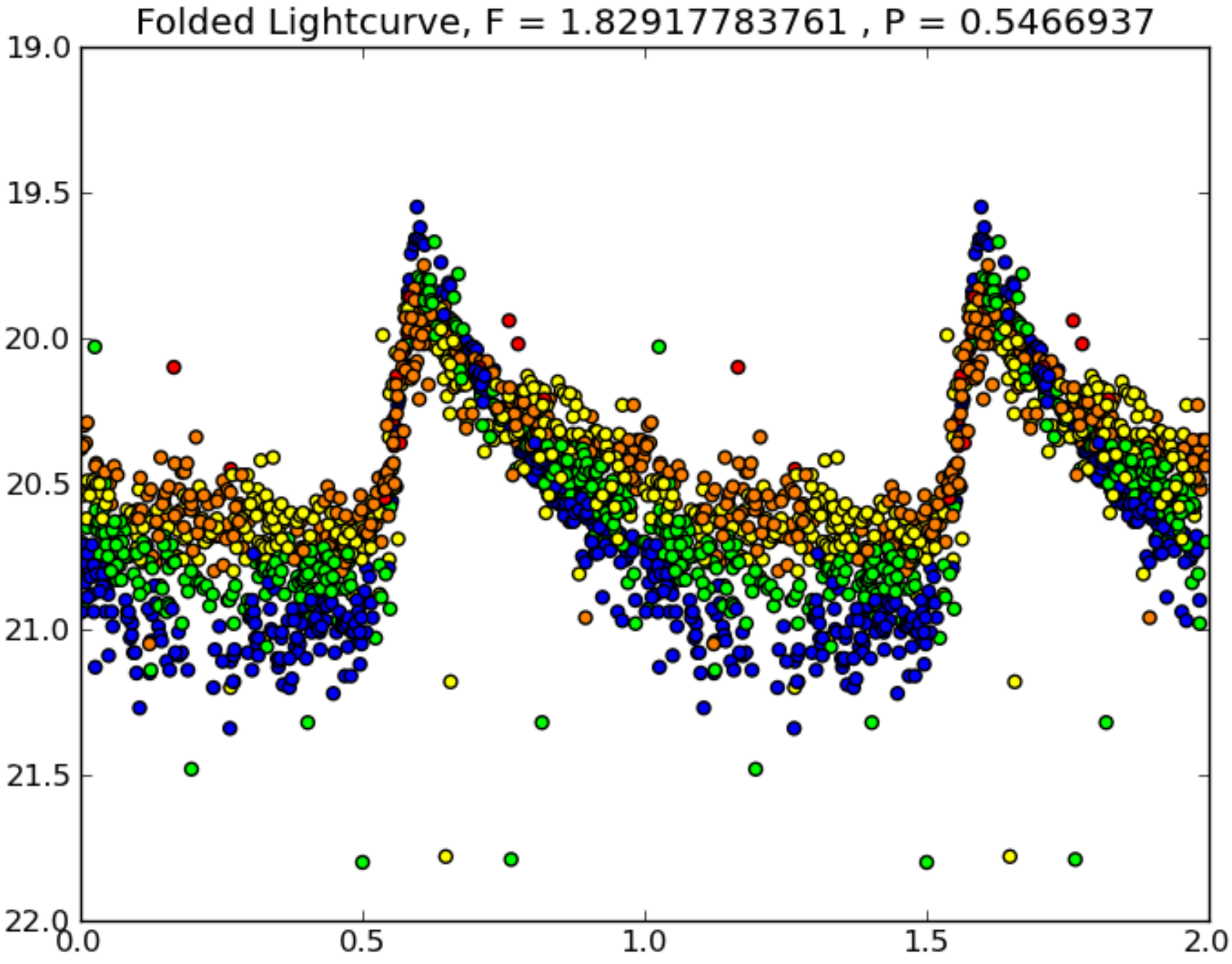
Long period


Folded Lightcurve, F = 2.5475400359 , P = 0.392535538562
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
residuals
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.0
0.5
1.0
1.5
2.0
Periodogram
600
500
400
300
200
100
0
0
10
20
30
40
50

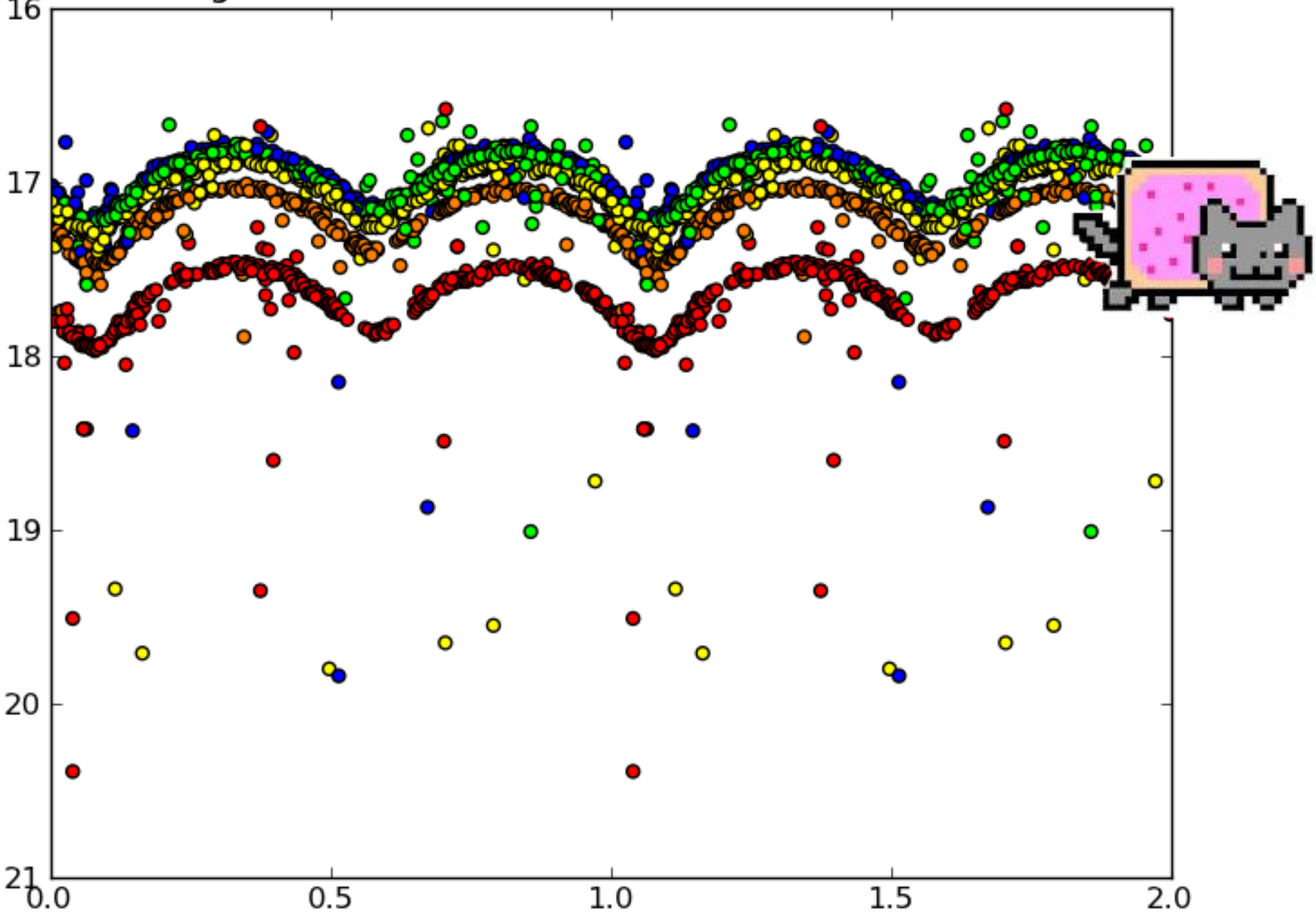

Folded Lightcurve, F = 1.90009052739 , P = 0.526290713829
−1.0
−0.5
0.0
0.5
1.0
0.0
0.5
1.0
1.5
2.0
residuals
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.0
0.5
1.0
1.5
2.0
Periodogram
350
300
250
200
150
100
50
0
0
10
20
30
40
50


Δt = 0.01
$\frac{f_1}{2} + f_2$
f_2
f_1
$\frac{f_1}{2}$
$f_1 + f_2$
$f_1 = 1.90$
$f_2 = 2.55$
$|\hat{F}|^2$
300
250
200
150
100
50
0
0
5
10
15
20
25
f


Folded Lightcurve, F = 20.8016730582 , P = 0.048073056297
15.1
15.2
15.3
15.4
15.5
0.0
0.5
1.0
1.5
2.0


Folded Lightcurve, F = 1.82917783761 , P = 0.5466937
19.0
19.5
20.0
20.5
21.0
21.5
22.0
0.0
0.5
1.0
1.5
2.0

Folded Lightcurve, F = 3.15140298762 , P = 0.317318985839



Heather's Future Plans

- Finish public release of panstarrs 3pi data (in a couple of months- this takes priority over everything)

- Heather's release variable star catalog for medium deep fields (from processing version 2, pv2 not going to be public)

- public release of medium deep images / catalogs (processing version 3)

- other science with these vars? (I am no expert..)