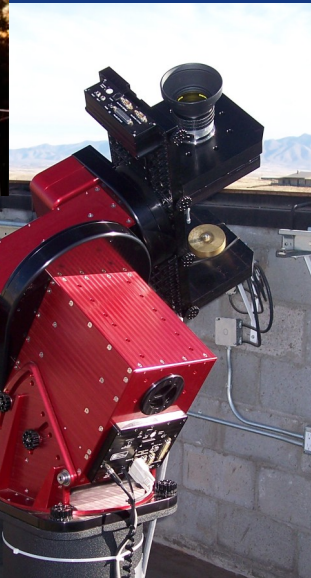
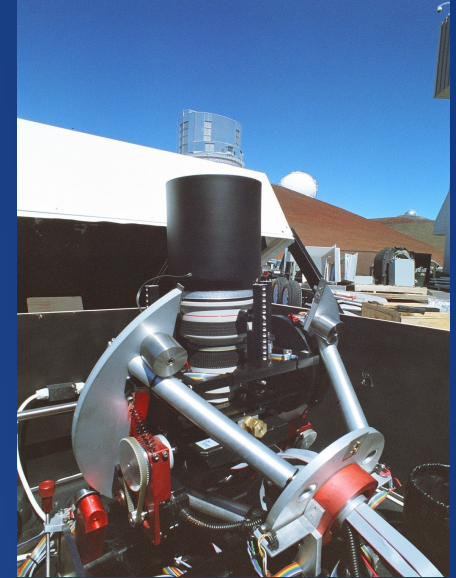
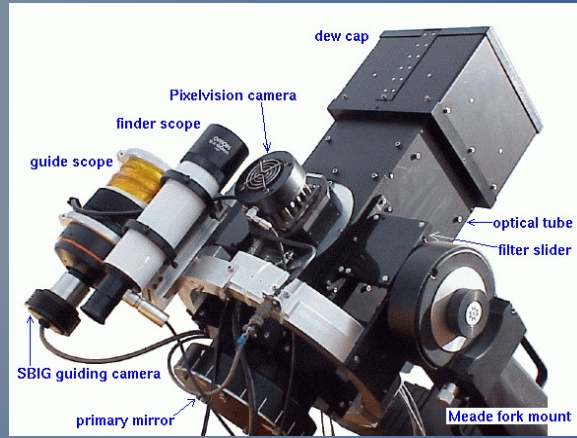


# Ground-based transit searches



# Expanding the parameter space

- 1. Massive (many stars)
- 2. High cadence (per minute)
- 3. Long time coverage (months, years)
- 4. High precision (sub percent)

photometry was not available before ground based transiting planet searches.

(but see flickering, globular and open cluster observations, and microlensing).

- Thanks to theoretical predictions of microlensing, transit discovery of HD209458b & Moore's law, 1+2+3+4 materialized in ~2000.
- Expanding the parameter space led to amazing (unexpected) discoveries. ( As always. )



# Ground-based transit searches – 2002

## Transit Search Programmes

Programme	D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	$N_x$ (kpix)	$N_y$ (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ( $\times 10^3$ )	planets /month	
<u>1</u>	<a href="#">PASS</a>	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
<u>2</u>	<a href="#">WASPO</a>	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
<u>3</u>	<a href="#">ASAS-3</a>	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
<u>4</u>	<a href="#">RAPTOR</a>	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
<u>5</u>	<a href="#">TrES</a>	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
<u>6</u>	<a href="#">XO</a>	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
<u>7</u>	<a href="#">HATnet</a>	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
<u>8</u>	<a href="#">SWASP</a>	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
<u>9</u>	<a href="#">Vulcan</a>	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
<u>10</u>	<a href="#">RAPTOR-F</a>	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
<u>11</u>	<a href="#">BEST</a>	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
<u>12</u>	<a href="#">Vulcan-S</a>	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
<u>13</u>	<a href="#">SSO/APT</a>	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
<u>14</u>	<a href="#">RATS</a>	67.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
<u>15</u>	<a href="#">TeMPEST</a>	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
<u>16</u>	<a href="#">EXPLORE-OC</a>	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
<u>17</u>	<a href="#">PISCES</a>	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
<u>18</u>	<a href="#">ASP</a>	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
<u>19</u>	<a href="#">OGLE-III</a>	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
<u>20</u>	<a href="#">STEPSS</a>	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
<u>21</u>	<a href="#">INT</a>	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
<u>22</u>	<a href="#">ONC</a>	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
<u>23</u>	<a href="#">EXPLORE-N</a>	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
<u>24</u>	<a href="#">EXPLORE-S</a>	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1

List from Keith Horne, ~2003

# Ground-based transit searches – 2002

## Transit Search Programmes

Programme	D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	$N_x$ (kpix)	$N_y$ (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ( $\times 10^3$ )	planets /month
1 <del>TRIS</del>	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
2 <del>WASP</del>	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3 <a href="#">ASAS-3</a>	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
4 <a href="#">RAPTOR</a>	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
5 <del>TRIS</del>	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6 <a href="#">XO</a>	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7 <a href="#">HATnet</a>	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8 <a href="#">SWASP</a>	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
9 <del>Vulcan</del>	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
10 <a href="#">RAPTOR-F</a>	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
11 <a href="#">BEST</a>	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
12 <del>TRIS 2</del>	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
13 <del>SWIFT</del>	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
14 <del>TRIS</del>	67.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
15 <del>TRIS 1</del>	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
16 <del>EXPLORE 00</del>	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
17 <del>TRIS 00</del>	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
18 <del>TRIS</del>	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
19 <a href="#">OGLE-III</a>	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
20 <del>TRIS 00</del>	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
21 <del>TRIS</del>	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
22 <del>TRIS</del>	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
23 <del>EXPLORE 01</del>	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
24 <del>EXPLORE 02</del>	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1



# Ground-based transit searches – 2002

## Transit Search Programmes

Programme	D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	$N_x$ (kpix)	$N_y$ (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ( $\times 10^3$ )	planets /month
1 <del>TRIS</del>	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
2 <del>WASP</del>	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3 <del>ASAS-2</del>	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
4 <del>KATFOR</del>	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
5 <del>TRIS</del>	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6 <del>XO</del>	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7 <del>HATnet</del>	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8 <del>SWASP</del>	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
9 <del>Vulcan</del>	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
10 <del>KATFOR</del>	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
11 <del>BEST</del>	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
12 <del>TRIS</del>	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
13 <del>SWIFT</del>	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
14 <del>TRIS</del>	67.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
15 <del>TRIS</del>	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
16 <del>EXPLORE-CC</del>	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
17 <del>TRIS</del>	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
18 <del>TRIS</del>	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
19 <del>EXPLORE-III</del>	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
20 <del>TRIS</del>	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
21 <del>TRIS</del>	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
22 <del>TRIS</del>	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
23 <del>EXPLORE-IV</del>	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
24 <del>EXPLORE-V</del>	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1

# Ground-based transit searches – 2002

## Transit Search Programmes

Programme	D (cm)	focal ratio	$\Omega^{0.5}$ (deg)	$N_x$ (kpix)	$N_y$ (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ( $\times 10^3$ )	planets /month
1 <del>TRIS</del>	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
2 <del>WASP</del>	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3 <del>ASAS-2</del>	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
4 <del>KATFOR</del>	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
5 <del>TRIS</del>	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6 <del>XO</del>	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7 <del>HATnet</del>	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8 <del>SWASP</del>	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
9 <del>Vulcan</del>	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
10 <del>KATFOR</del>	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
11 <del>BEST</del>	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
12 <del>Kepler 2</del>	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
13 <del>SOAR</del>	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
14 <del>KATFOR</del>	70.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
15 <del>Kepler 1</del>	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
16 <del>Kepler 3</del>	101.6	2.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
17 <del>Kepler 4</del>	120.0	2.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
18 <del>Kepler 5</del>	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
19 <del>Kepler 6</del>	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
20 <del>Kepler 7</del>	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
21 <del>Kepler 8</del>	250.0	3.3	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
22 <del>Kepler 9</del>	264.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
23 <del>Kepler 10</del>	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
24 <del>Kepler 11</del>	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1

QATAR

KELT

Mearth

HATSouth

GSTAR

ASTAR, ASTEP,

Solaris, PTF, APACHE, Dunlap

# Ground-based discoveries yielded:

- **True masses, radii** for many planets → **density**, structure [**~130**]. Taxonomy of exoplanets (inflated planets, super-Jupiters, Sapieters, etc). Mass—radius relation for  $M_p > 20M_E$ . Various other relations, e.g  $R_p$  vs  $(T_{eq}, [Fe/H]_*, \dots)$ .
- Detection of **planetary atmospheres** via transmission spectroscopy or occultation spectroscopy.
- Measurements of **planetary brightness temperature** via the occultation of the planet (Spitzer and ground-based). [**30+**]
- Sky projected **angle of stellar spin axis and planetary orbital normal** via the RM-effect → formation [**40+**]
- Multiple planetary systems (with one component transiting)
- Falling-in planets (e.g. WASP-18b)
- Ground-work for space-based discoveries: follow-up procedures, confirmation know-how, high precision RVs for faint stars, bisectors, planet parameter determinations, etc.



# Space-based discoveries yielded:

- First unambiguous transit timing variations → perturber bodies, and masses.
- Small radius planets, super-Earths, HZ planets.
- Multiple transiting planetary systems (architecture constraints on formation, evolution).
- Firm statistics on radius, period distribution and multiplicity. **Planets are plentiful.** Small ones and long period ones are even more.
- Orbital evolution (e.g. variable transit depths, durations, impact parameters).
- Circumbinary transiting planets (incl. spin—orbit alignment [Kep-16]).
- Optical signature of planets in Kepler light curves (e.g. phase function, reflection, occultation, measurement of albedos, beaming, ellipsoidal variation).

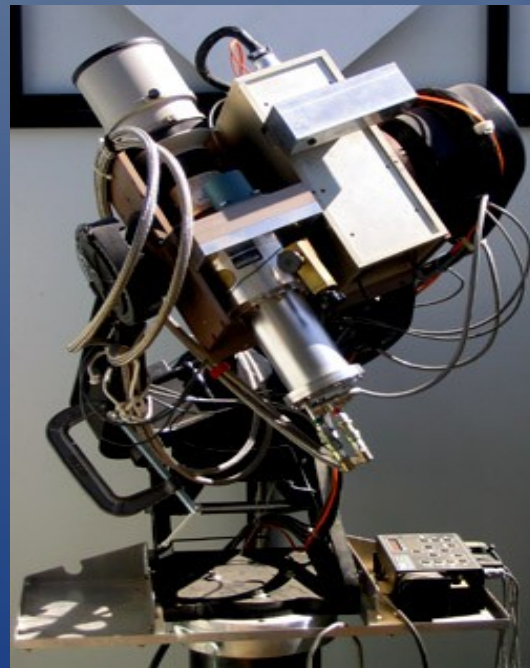
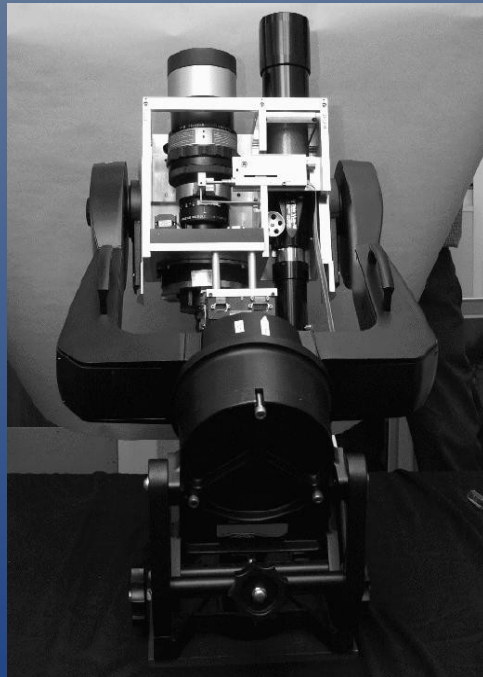
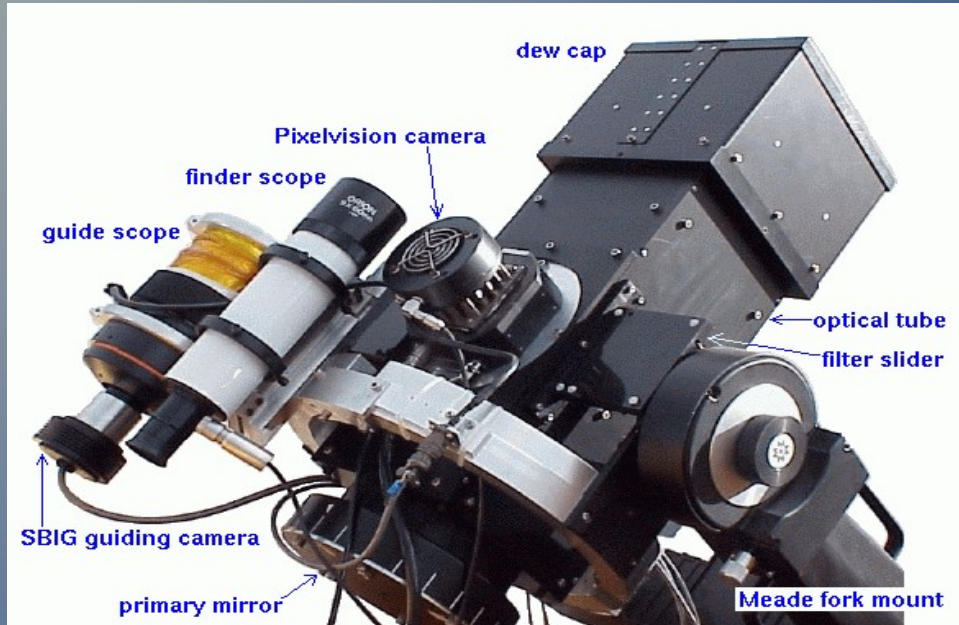
# Inventory of ground-based surveys – OGLE



- Not explicitly transit search project. Was in a unique position in ~2002 regarding FOV, data reduction techniques, expertise.
- PI: Andrzej Udalski
- 1.3m telescope. Current OGLE-4 has  $1.2^\circ \times 1.2^\circ$  FOV with  $16 \times 16$  Mpix.
- 8 planets (OGLE-TR-56b, 113b, 132b, 111b, 10b + 182b, 211b, L9b).
- $P \in [1.2, 4.01]$  days.
- OGLE-TR-56b is an ultra-short period “Very hot Jupiter” (an intrinsically rare object).
- In addition, discovery of 6 micro-lensing planets.
- Has become passive in TEP searches (due to faintness of targets with  $V > 15$ ).



# Ground-based surveys – TrES



- STARE + Sleuth + PSST, network of 3 telescopes.
- Tim Brown, Dave Charbonneau, Georgi Mandushev, Ted Dunham.
- Great success in the 'early times' (2004 – 2006).
- Winding down (if operational).
- 0.1m telescopes,  $6^\circ \times 6^\circ$  FOV with 4K – 16K Mpix.
- 5 planets (and initial detection of HD209458b by STARE)
- $P \in [1.3, 3.55]$  days.
- $V < 13$  targets. Follow-up primarily by Dave Latham's team.



# Ground-based surveys – XO



- Installed at Maui.
- PI: Peter McCullough
- 2 x 0.11m telescopes,  $7^\circ \times 7^\circ$  FOV with 4K Mpix.
- 5 planets (one in common with HAT).
- $P \in [2.6, 4.18]$  days.
- $V < 13$  targets. Follow-up primarily by Extended Team (ET).
- Strip scan mode ( $7^\circ \times 63^\circ$ )



# Ground-based surveys – HATNet



- FLWO/Arizona (4) and SMA/Mauna Kea/Hawaii (2)
- Operational: 2003 – present
- 6 x 0.11m telescopes,  $10^\circ \times 10^\circ$  FOV, each with 16K Mpix, sloan r filter.
- First network of identical hardware.
- 40\* transiting planets (+1 in common with WASP, +1 with XO, +1 KELT, +1 Kepler, +1 TrES).
- $P \in [1.21, 10.86]$  days.
- $V < 13.5$  targets. Follow-up primarily with Dave L team, then NOT, Subaru, Keck.
- $M_p \in [0.08, 10] M_J$ . 2 exo-Neptunes, number of super-Jupiters ( $M > 4 M_J$ ).
- 1<sup>st</sup> and 2<sup>nd</sup> TEP in a multi-planet system (HAT-P-13b, -17b) with full (including P) orbital solution.

\*: submtted to a refereed journal, posted on astro-ph.



# Ground-based surveys – WASP



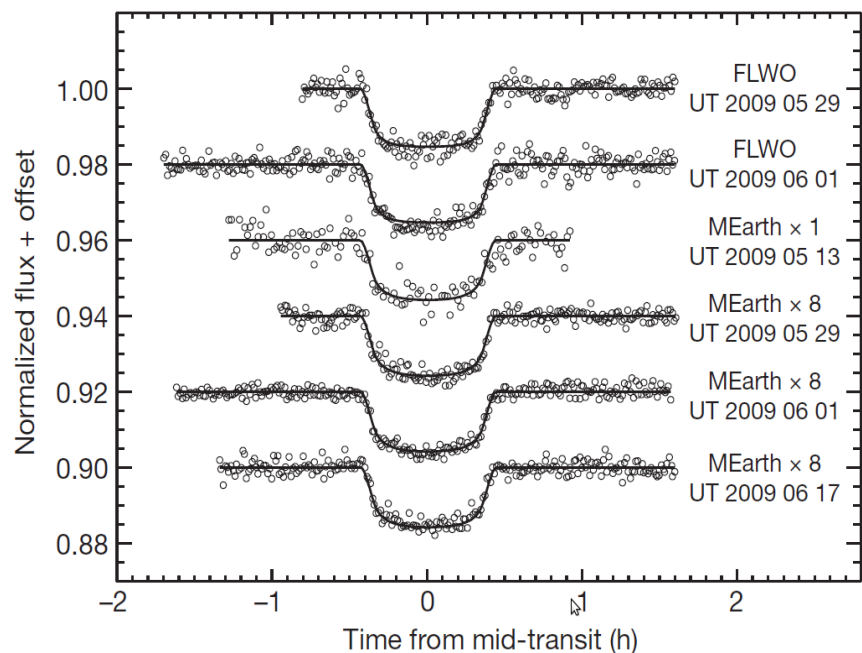
- 2 stations: La Palma (Canary Islands) and SAAO (South Africa).
- Operational: 2004 – present
- Don Pollacco, Andrew Cameron, Coel Hellier, Geneva team et al.
- 2 x (8 x 0.11m) telescopes,  $16^\circ \times 32^\circ$  FOV, each with 4K x 16K pix BI CCD, no filter.
- Massive, professional hardware.
- 53 planets (+2 in common with HAT, +possibly others common with other projects.).
- $P \in [0.78, 8.15]$  days.
- $V < 13.5$  targets. Follow-up with OHP and Geneva team (Coralie, HARPS).
- $M_p \in [0.25, 60] M_J$ .
- Very-short period super-massive TEPs (- 18b:  $P=0.94d$ ,  $M=10.4 M_J$  !)
- Highly bloated planets. Planet around an early fast rotator (WASP-33). Tomography.



# Ground-based surveys – Mearth

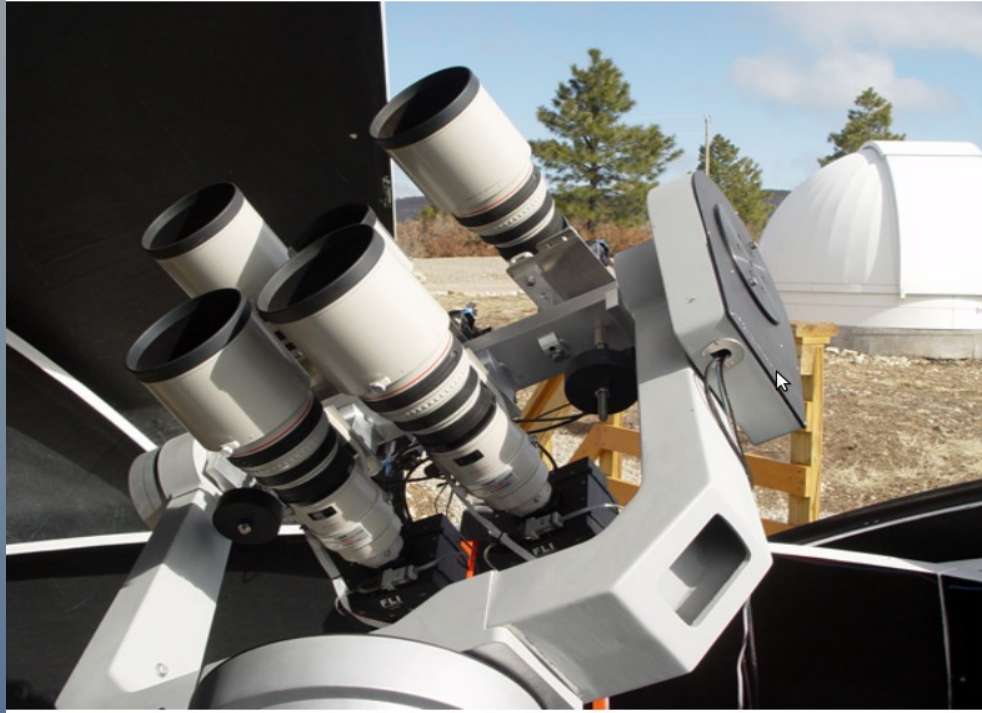


- Currently 1 station: FLWO, Arizona
- David Charbonneau, Jonathan Irwin
- Operational: 2008 – present
- 8 x 0.4m telescopes, 26' x 26' FOV, each with 2K x 2K pix BI CCD, wide filter.
- Off-the-shelf mounts, optics, CCDs, control software.
- 1 planet: GJ1214b (super-Earth? mini-Neptune?)
- Focused search on M dwarfs.
- Southern station at CTIO under construction.



Charbonneau et al. 2009

# Ground-based surveys – Qatar (QES)



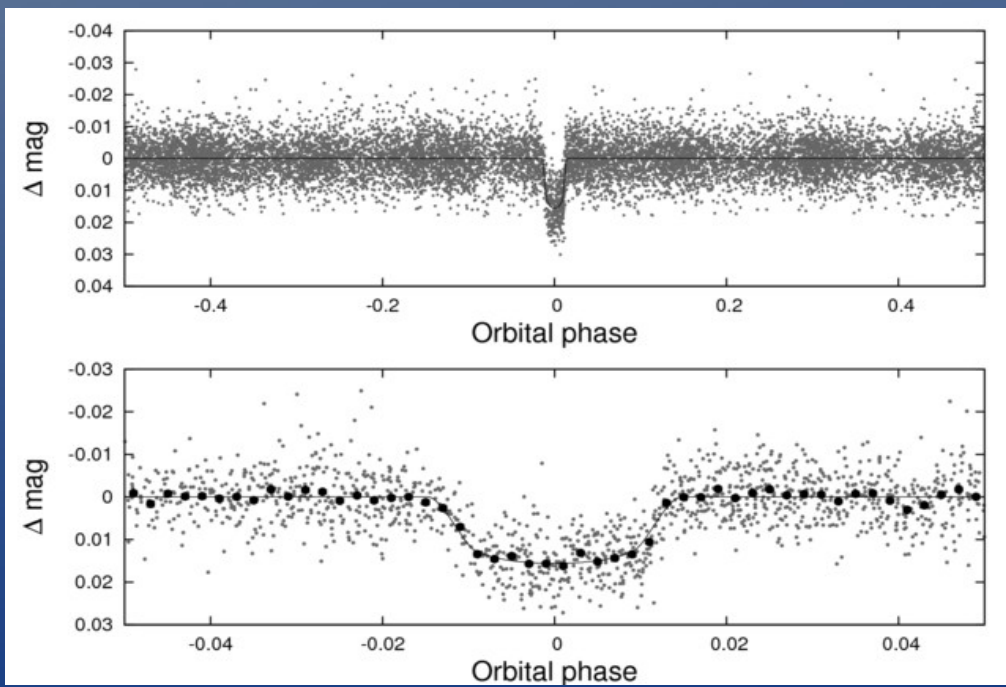
- 1 station: New Mexico
- Operational: ~2010 – present
- (4 x 0.14m + 1 x 0.11m) telescopes, 11° x 11° FOV, each with altogether 8K x 8K pix FI (FLI) CCD, no filter.
- Professional, off-the-shelf hardware (Mathis fork mount, FLI CCD, Canon 400mm lens, Macbooks)
- 2 planets, both around K dwarfs with  $P \sim 1.3d$ .
- $V < 14$  targets; goes somewhat fainter than HAT, WASP, KELT (see HATSouth).
- Follow-up & scientific analysis with Dave L. and members of the SuperWASP team.



# Ground-based surveys – HATSouth



- 3 stations: LCO (Chile), HESS (Namibia), SSO (Australia).
- Operational: 2010 – present.
- 6 x (4 x 0.2m) telescopes, each with 8° x 8° FOV, 8K x 8K pix FI CCD, sloan r filter.
- “Home-made” dome, mount, electronics, software.
- Off-the-shelf (Apogee) CCD, (Takahashi) optics, filters.
- 1 planet (HATS-1b) with  $P=3.44d$ .
- $V < 14.5$  targets. K and M dwarfs. Follow-up with extended team using multiple resources.
- Sensitive to long period and shallow transits.
- Princeton, MPIA, ANU, PUC collaboration.
- See Bakos et al. 2012, Penev et al 2012, *astroph*





# Ground-based surveys – KELT

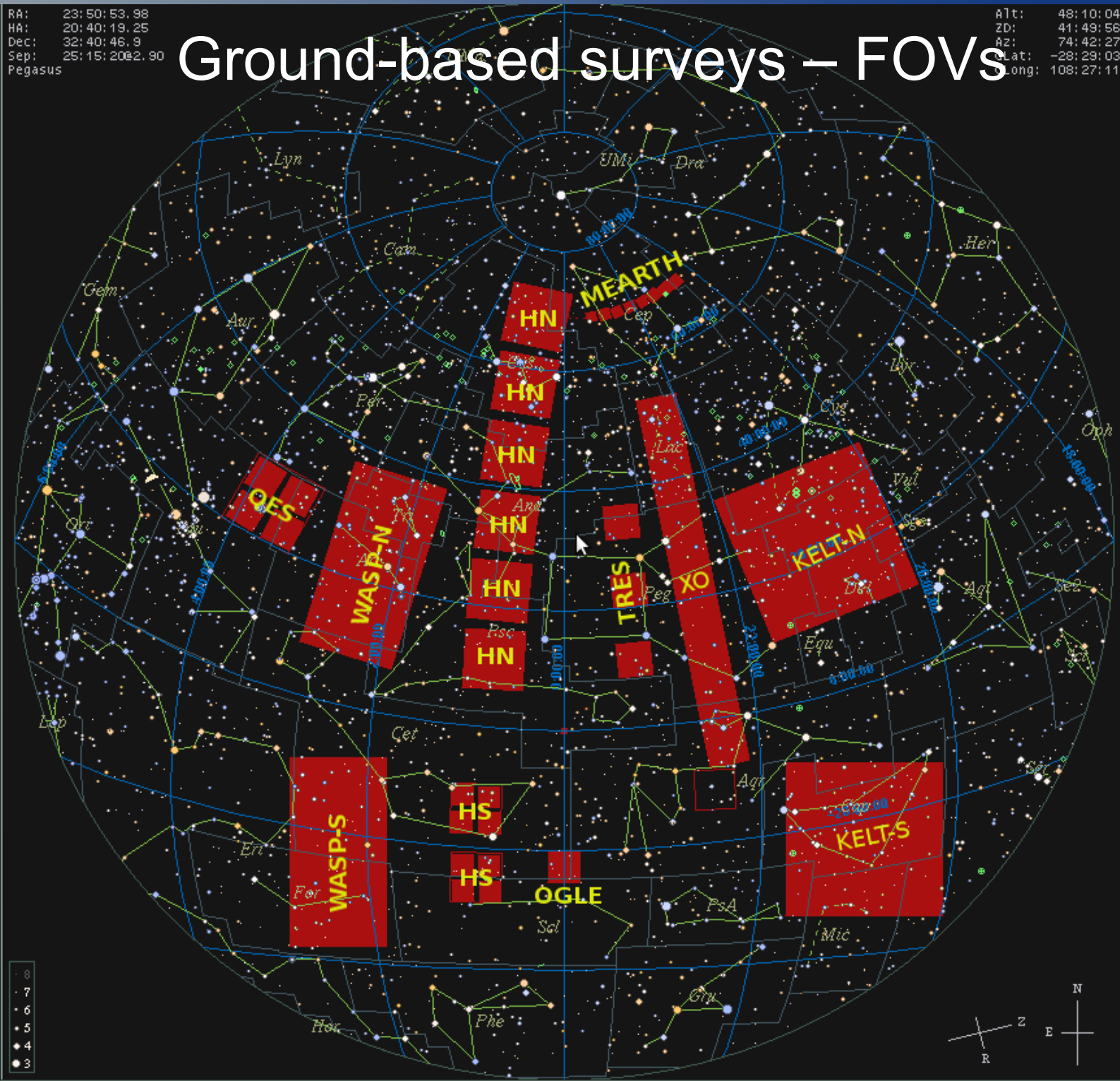


- 2 stations: Arizona and SAAO (South Africa).
- Operational: 2005? – present
- 2 x 0.05m telescopes,  $26^\circ \times 26^\circ$  FOV, each with 4K x 4K pix FI CCD, no filter.
- Massive mount, very wide angle, fast focal ratio optics.
- 2 planets. One is a  $27 M_J$  planet around a  $V=9$ , fast rotator star.
- $P \in [1.21, 4.11]$  days.
- $V < 12$  (bright) targets. Follow-up with Dave L. team.
- Very bright host stars, fast rotators.

RA: 23:50:53.98  
HA: 20:40:19.25  
Dec: 32:40:46.9  
Sep: 25:15:20.92, 90  
Pegasus

Alt: 48:10:04  
ZD: 41:49:56  
Az: 74:42:27  
Lat: -28:29:03  
Long: 108:27:11

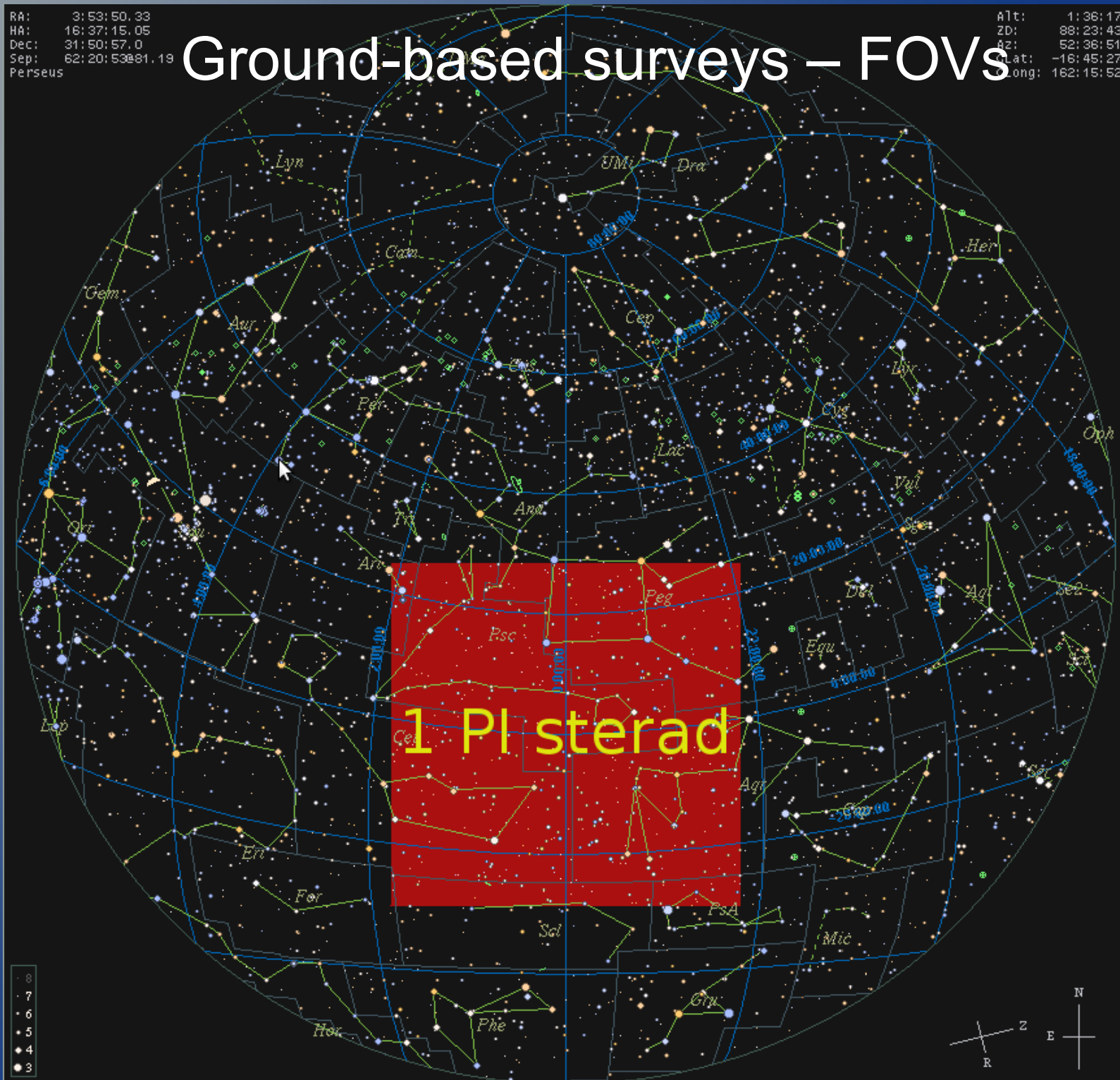
# Ground-based surveys – FOVs



RA: 3:53:50.33  
HA: 16:37:15.05  
Dec: 31:50:57.0  
Sep: 62:20:53@91.19  
Perseus

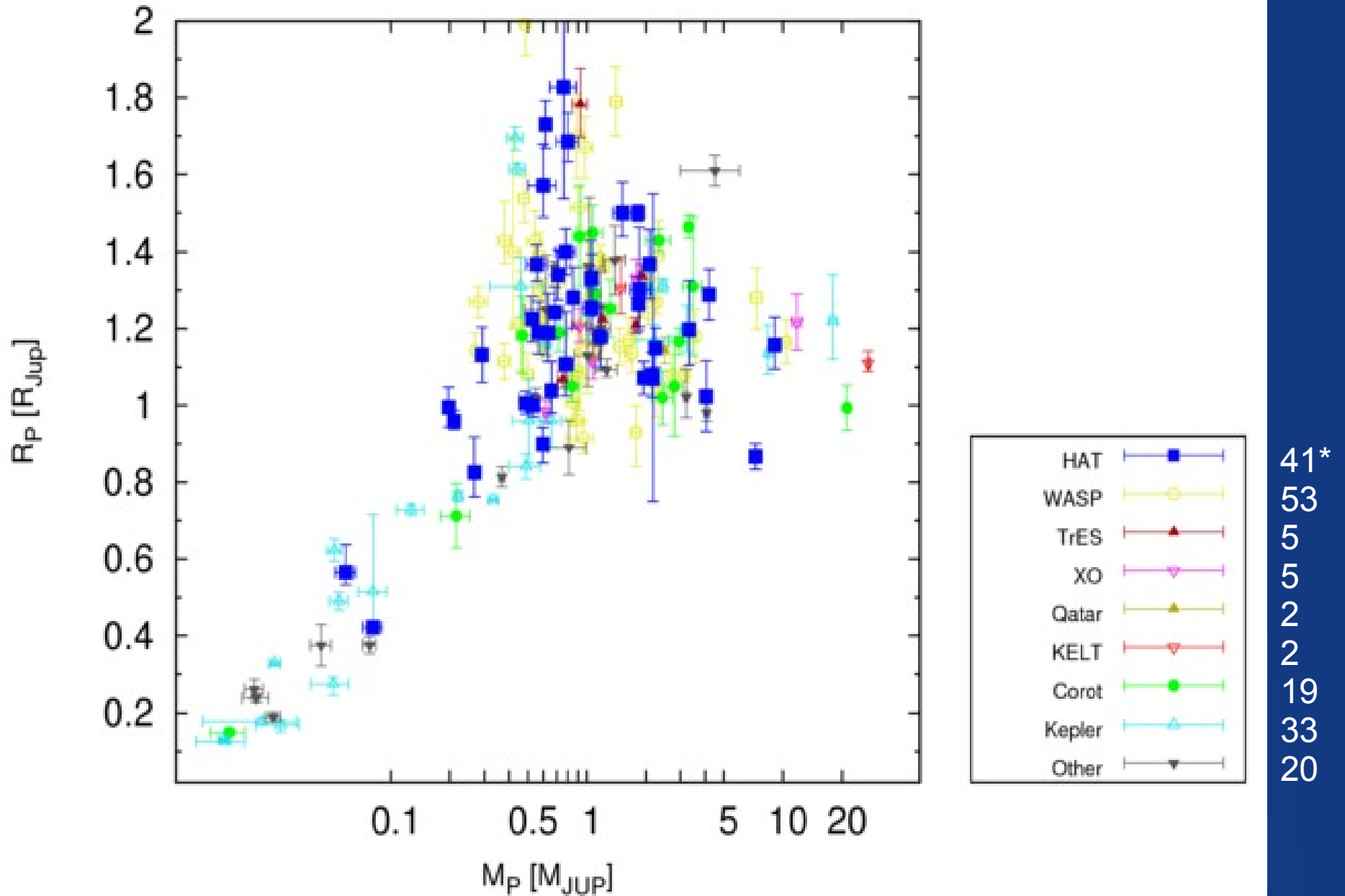
Alt: 1:36:17  
ZD: 88:23:43  
Az: 52:36:51  
Lat: -16:45:27  
Long: 162:15:52

# Ground-based surveys – FOVs



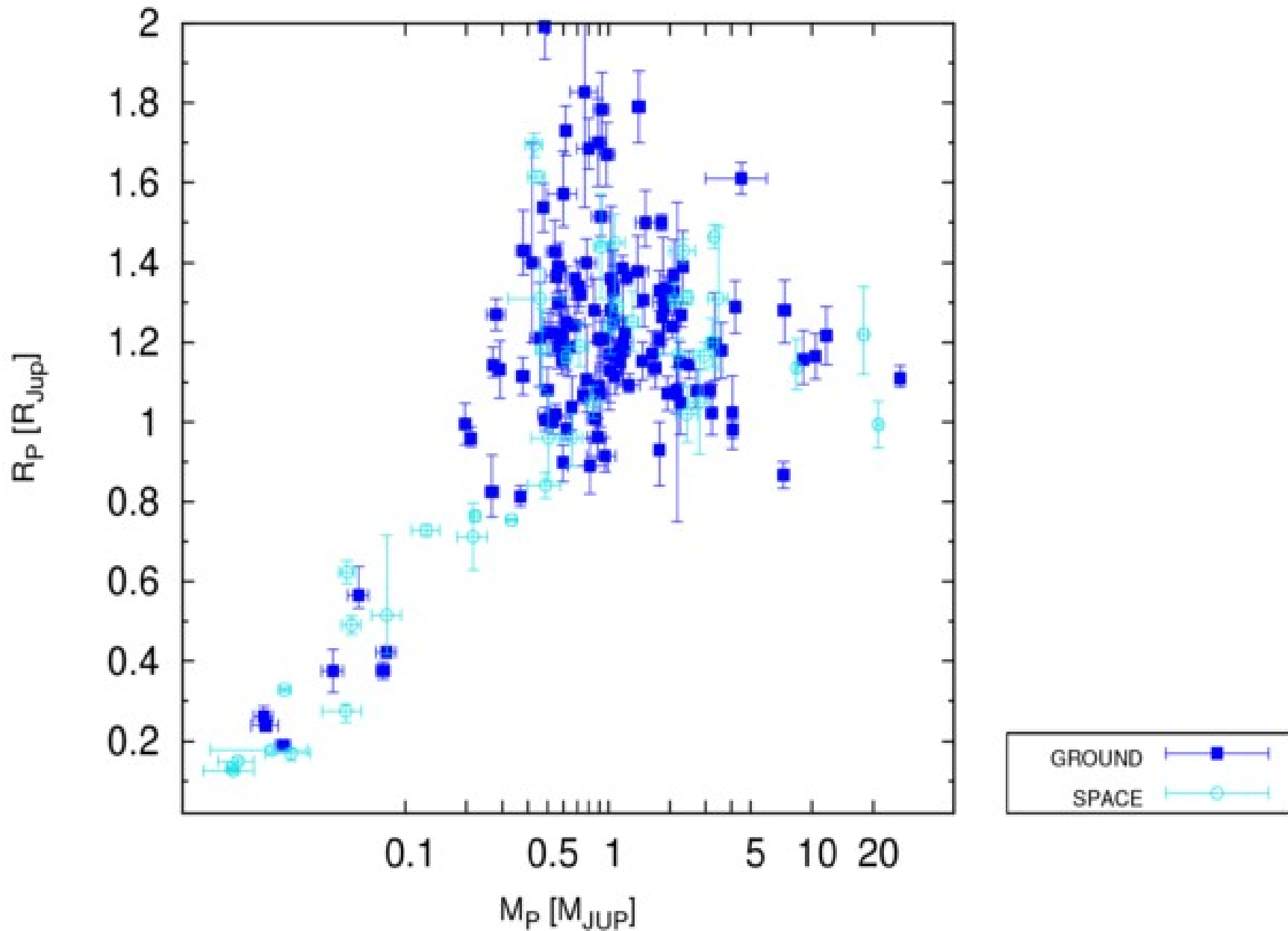


# Planetary mass—radius diagram, per project



\*Submitted to peer reviewed journal and posted on astro-ph

# Planetary mass—radius diagram, ground vs. space



128\*  
52

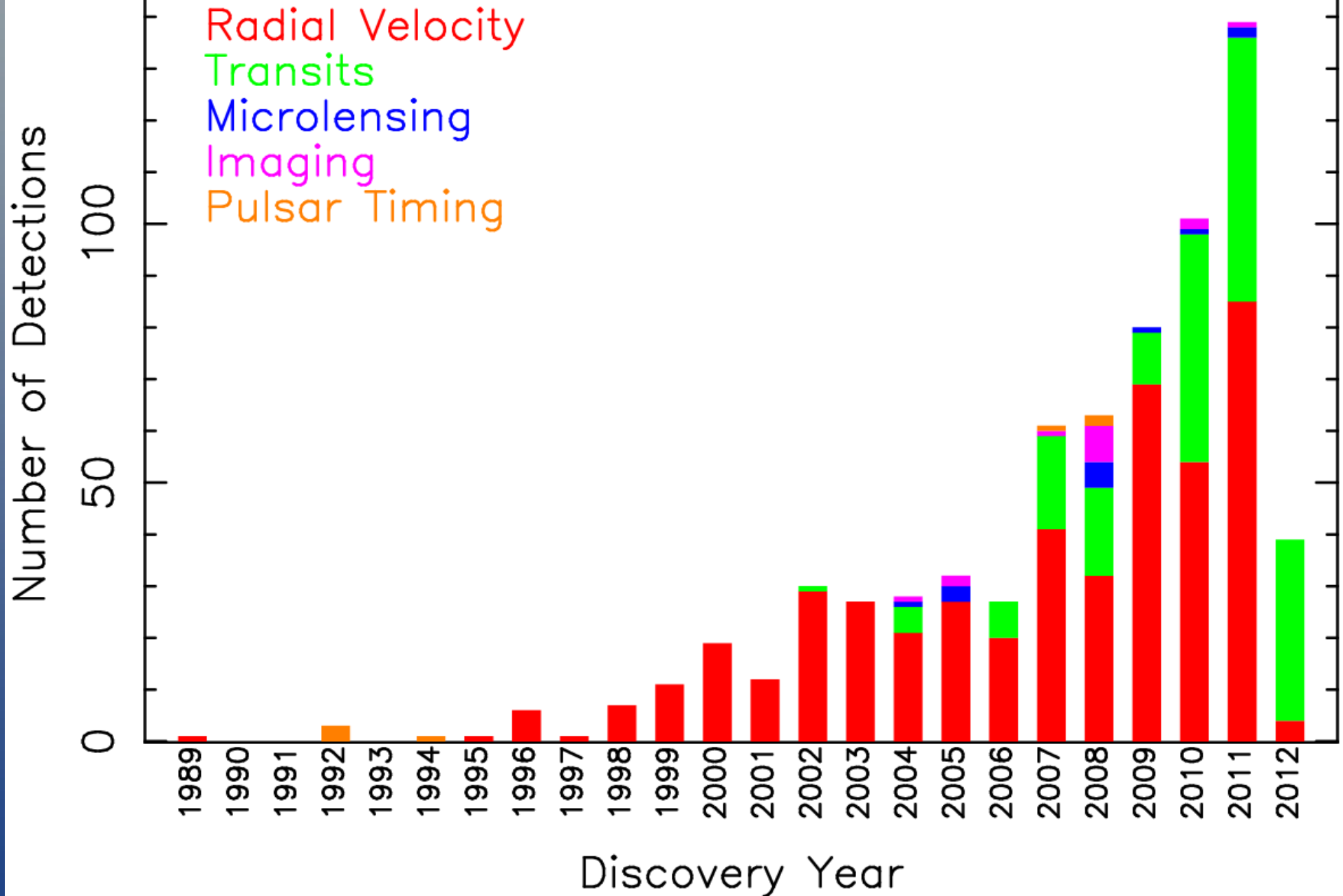


# Statistics

NASA Exoplanet Archive

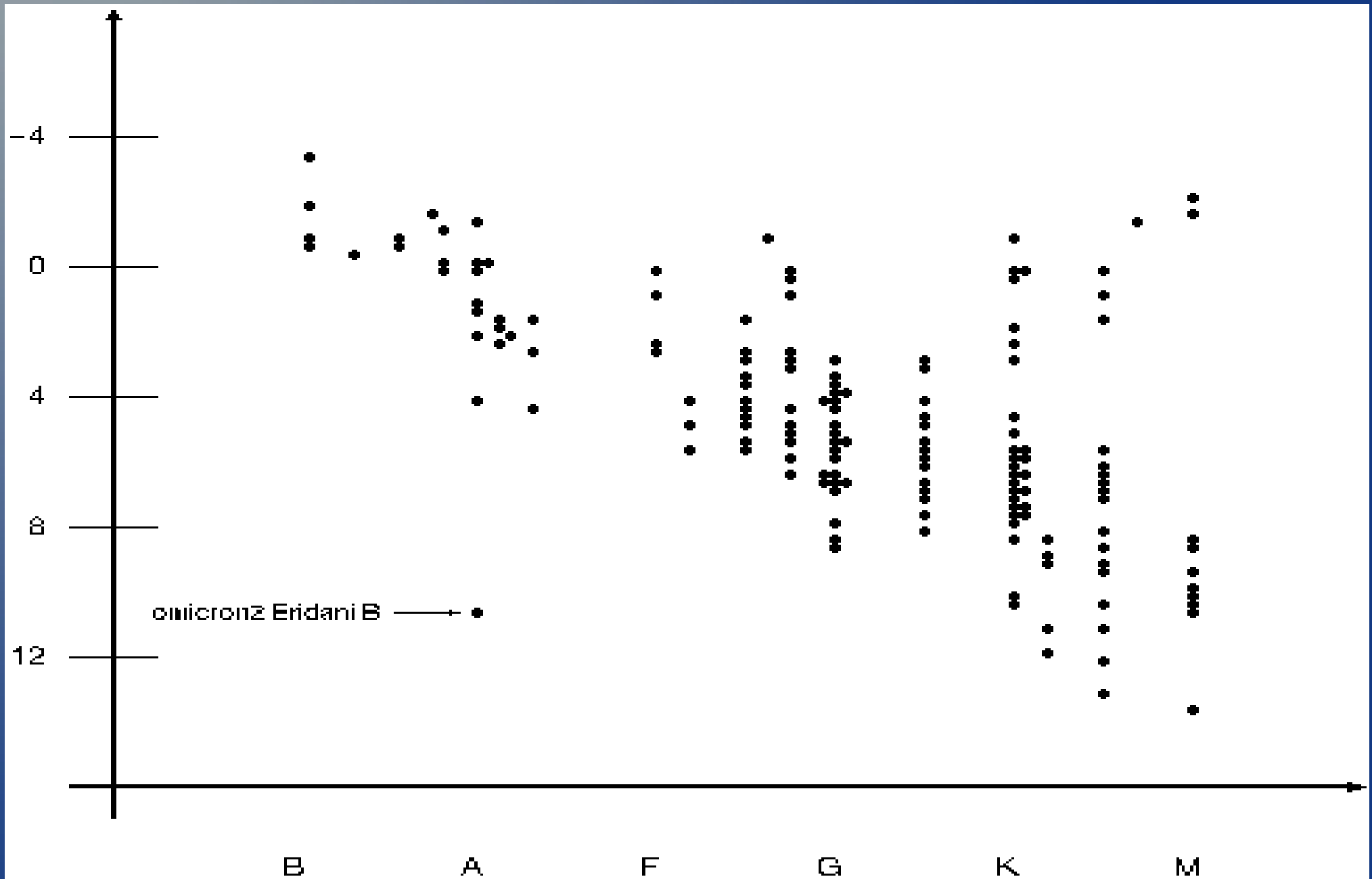
2012 July 25

exoplanetarchive.ipac.caltech.edu



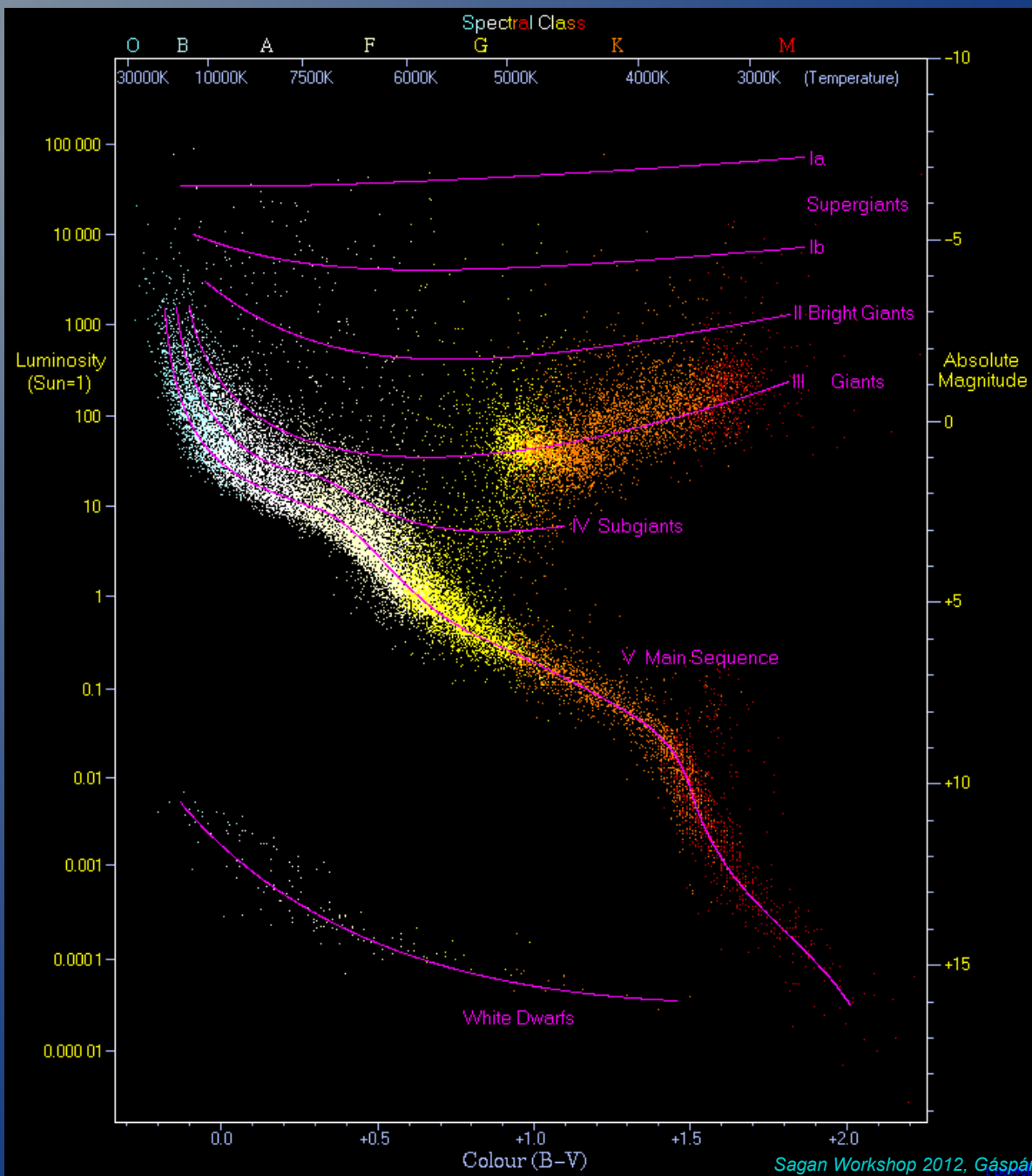
Thanks to Stephen Kane

# Russell's original "HR" diagram, 1911

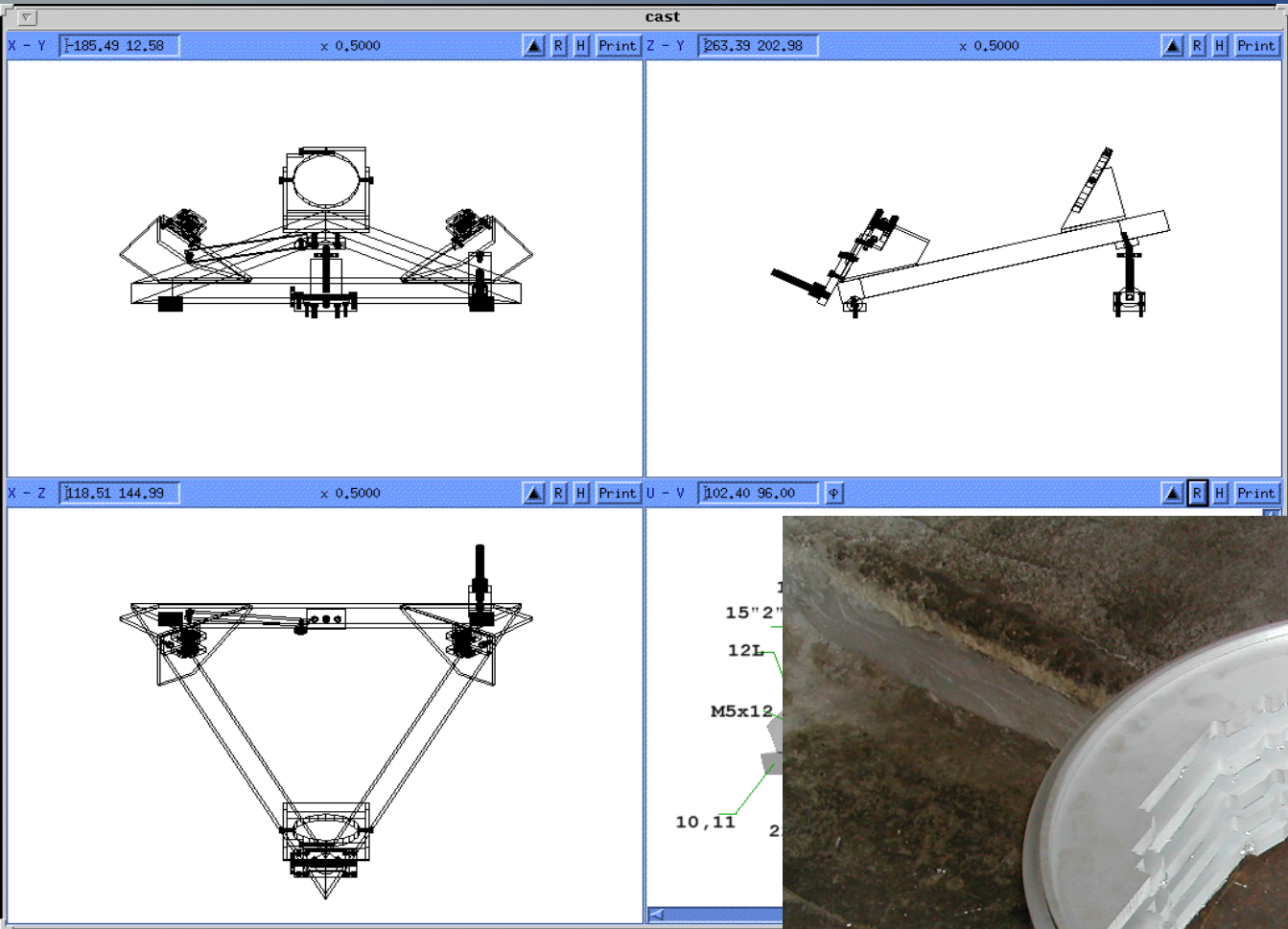




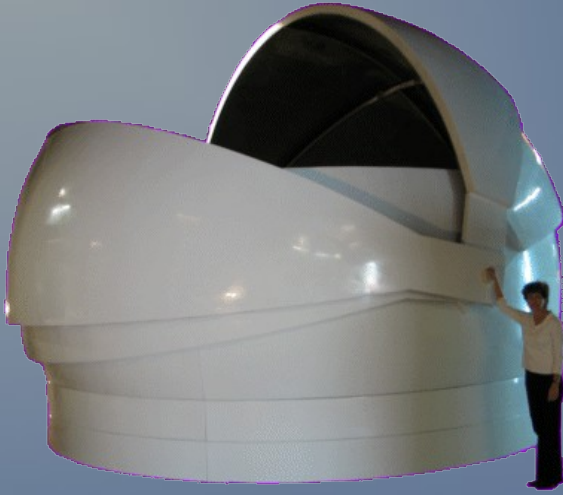
# Hipparcos HRD at circa 2000



# Evolution of hardware



# Add “transit-search-project to basket” era





# Present/planned surveys with no TEPs (yet) – APACHE



- 1 station: Astronomical Observatory of the Autonomous Region Aosta Valley (OAVdA)
- Operational: 2012? – present
- 4 x 0.4m telescopes, 26' x 26' FOV, each with 1K x 1K pix BI CCD
- Similar (almost identical?) to Mearth.

# Present/planned surveys with no TEPs (yet) – CSTAR

- 1 station: Dome A
- Operational: 2012? →
- 4 x 0.1m telescopes, 4° x 4° FOV, each with 1K x 1K pix frame txfer CCD



Multi-color

No moving parts.

Fig.7. CSTAR in Dome A (Installed by Prof. Xu Zhou and Zhenxi Zhu)

# Present/planned surveys with no TEPs (yet) – ASTAR

- 1 station: Dome A
- Operational: 2012? →
- 3 x 0.5m telescopes, 4° x 4° FOV. Schmidt telescope (-like).
- Multi-color
- First one installed to Dome A



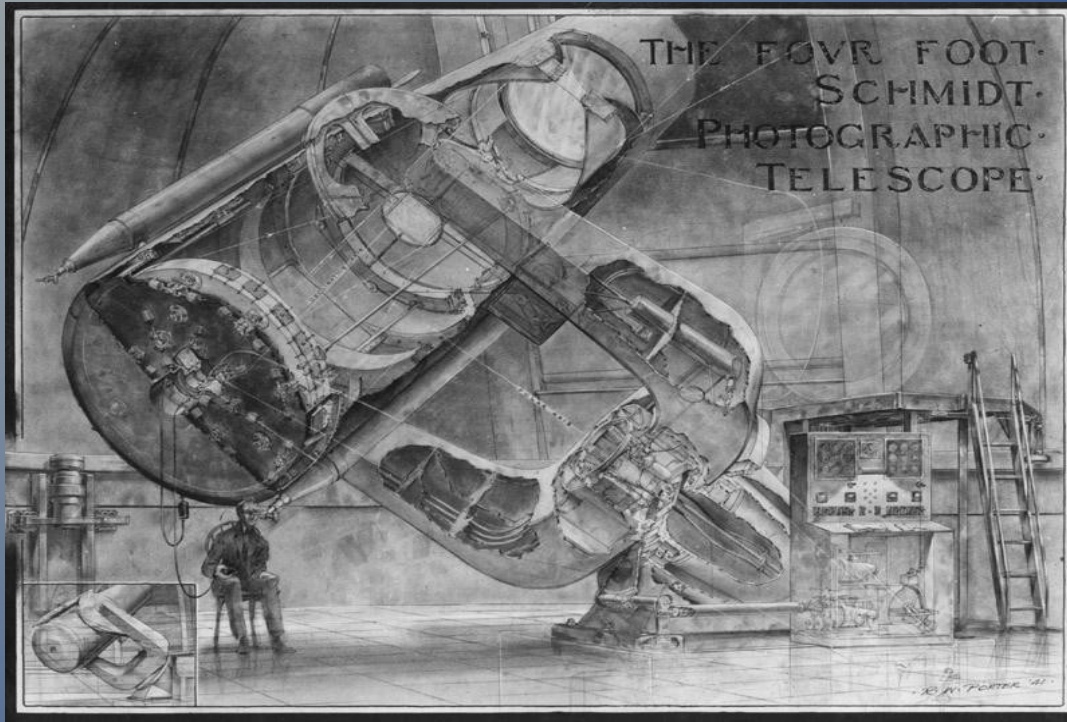


# Present/planned surveys with no TEPs (yet) – ASTEP

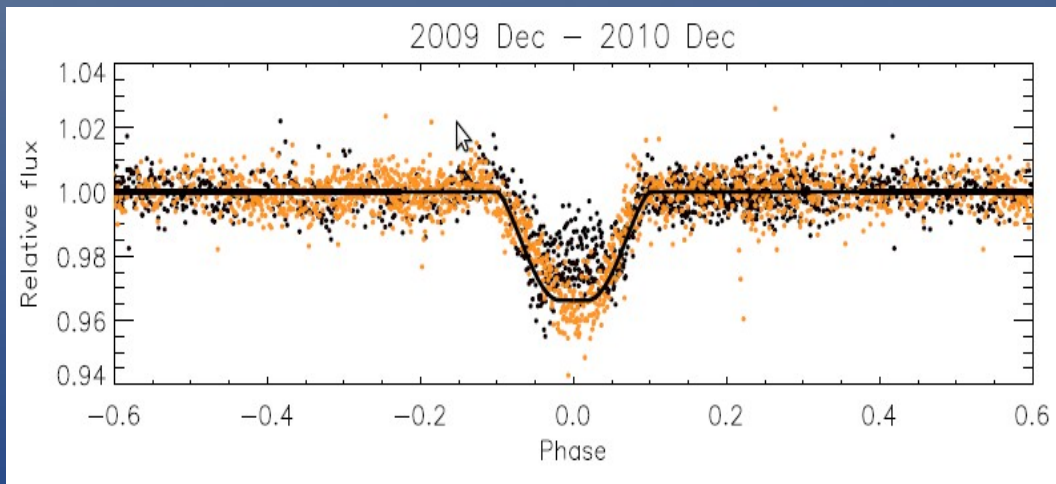


- Dome C
- PI: Tristan Guillot
- ASTEP-400: 0.4m telescope with  $1.2^\circ \times 1.2^\circ$  FOV, 2K x 2K BI CCD (Andor DW 436)
- Off-the-shelf mount, guiding.
- Optimized for low temperature.
- 2009 – present
- ASTEP-South: 0.1m telescope fixed, staring at the pole.

# Present/planned surveys with no TEPs (yet) – PTF

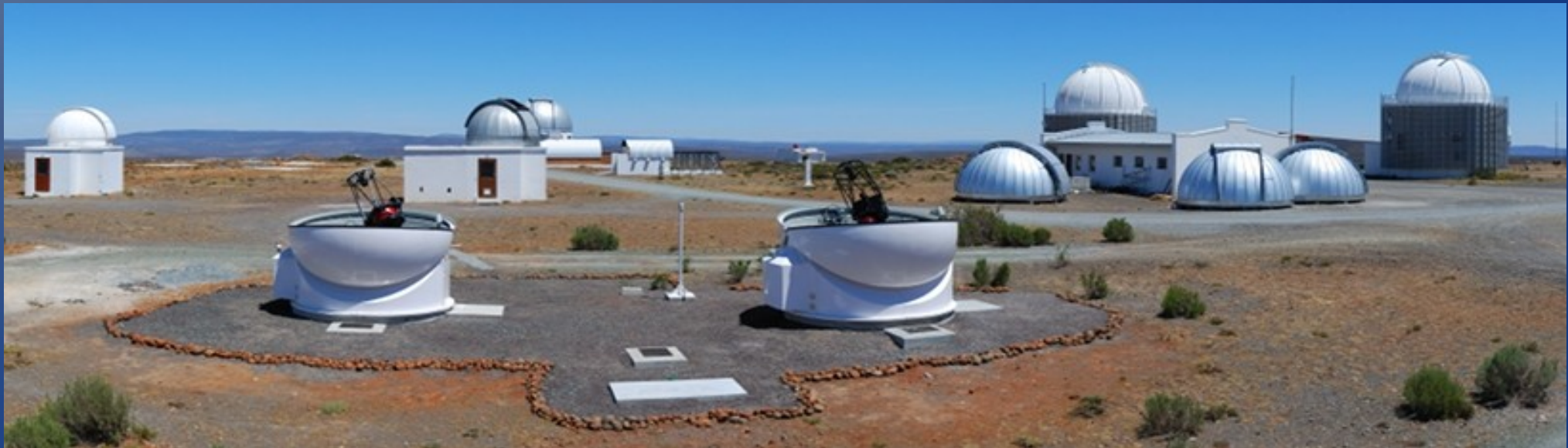


- Palomar Transient Factory, PTF/M dwarfs, PTF/Orion project.
- PI: Shri Kulkarni.
- Palomar 1.2m Schmidt telescope + giant mosaic CCD yielding  $2.7^\circ \times 2.7^\circ$  FOV
- 3000 M dwarfs per exposure, cycling through 8—10 fields.
- 2009 – present
- 14 eclipsing M dwarfs, one planetary transit candidate around a T Tauri star.



# Present/planned surveys with no TEPs (yet) – Solaris

- Planning 3 sites: Argentina, Australia, South Africa.
- PI: Maciej Konacki
- 0.5m telescopes, one per site (but 2 at SAAO).
- Off-the-shelf mount, optics, CCD, dome.
- Search for circumbinary planets by looking at eclipsing binaries.
- 2011/2012 – present.





# Dunlap Institute Arctic Telescope and Wide-field cameras in the High Arctic



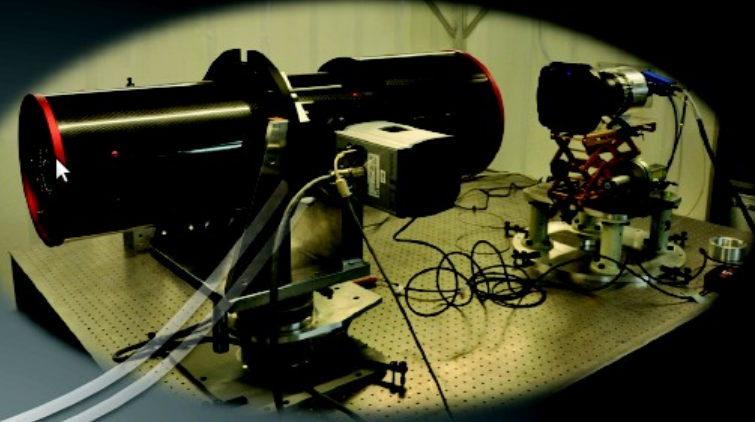
- 0.5m f/6.8 telescope,  $0.6^\circ \times 0.6^\circ$  field.
- PI: Nicholas Law
- Ellesmere Island, latitude  $80^\circ$
- 2012  $\rightarrow$  (?)
- Wide-field Cameras in the High Arctic:
- 85mm f/1.2 lenses, each  $22^\circ \times 22^\circ$  FOV



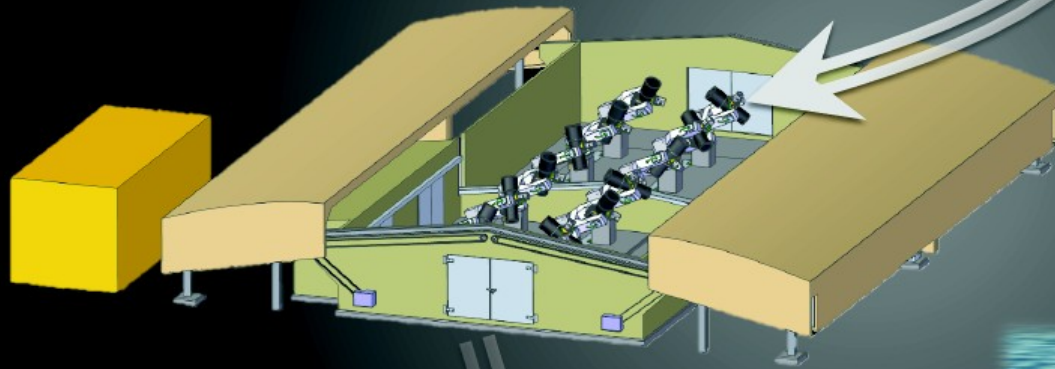
# Present/planned surveys with no TEPs (yet) – NGTS



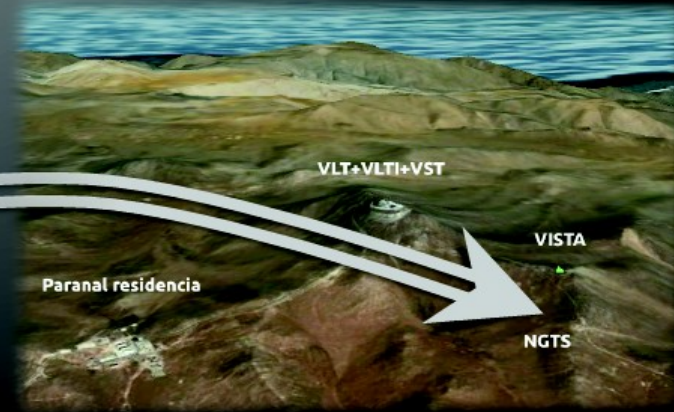
Ground-based transit survey aimed at detecting sub-Neptune sized exoplanets around bright stars



Robotic facility composed of 12 200mm telescopes equipped with 2Kx2K NIR sensitive detectors with a 8deg<sup>2</sup> FoV



First non-ESO experiment at Paranal

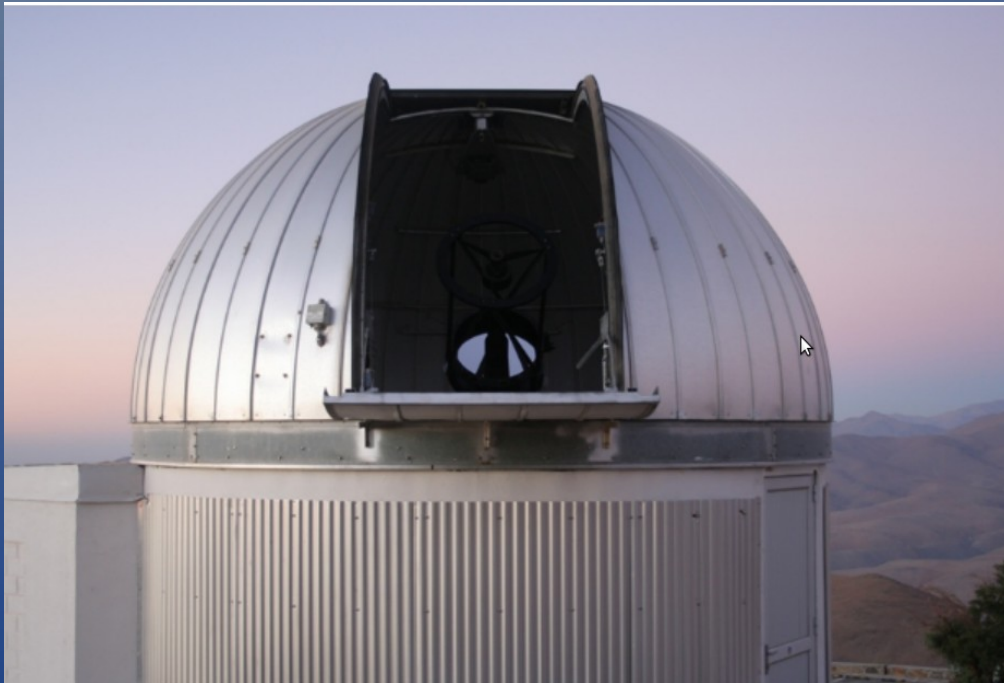


See poster from Neveu

# Dedicated to TEP follow-up – TRAPPIST



- 0.6m telescope, 22' x 22' field.
- PI: Michaël Gillon
- La Silla, Chile
- ~2010 → present
- High precision photometry follow-up, primarily of WASP targets.
- Off-the-shelf components: Astelco NTM-500 direct drive, FLI ProLine PL3041-BB CCD.





# St. Luc – GJ 436b



- 0.6m telescope
- Discovery of the transit of GJ 436b (Gillon et al.)

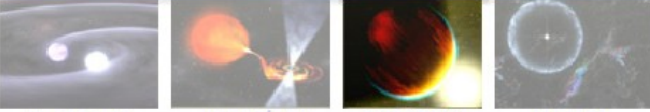
# Other transit search, confirmation & follow-up efforts

- Transit Ephemeris Refinement and Monitoring Survey (**TERMS**)  
(see papers from Kane, von Braun, Dragomir and collaborators)
- **TRESCA** (exoplanet transit database = ETD. Luboš Brát.).
- [transitsearch.org](http://transitsearch.org), [oklo.org](http://oklo.org), systemic (Laughlin et al.)
- Transit Light Curve (**TLC**) project (Winn, Holman et al.), primarily using the FLWO 1.2m telescope.
- ... and many others

# TRESCA

Variable Star and Exoplanet S... HAT-P-13

## Variable Star and Exoplanet Section of Czech Astronomical Society



B.R.N.O. MEDUZA TRESCA HERO

NEWS  
RSS feed

OBSERVING CAMPAIGNS  
NEW  
Expired Campaigns

OBSERVING PROJECTS  
B.R.N.O. - eclipsing binaries  
MEDUZA - intrinsic variables  
TRESCA - exoplanets  
HERO - high energy objects


OBSERVERS LOG

ABOUT US  
Leadership  
Actions  
Perseus Bulletin  
J. Silhan prize "The Observer of the year"  
Membership conditions  
List of members

DATABASES & TOOLS  
General Search Gateway  
Open European Journal on Variable stars  
O-C Gateway  
CzeV Catalogue  
CzeV Catalogue

### TRESCA Project - Exoplanets

Exoplanet Transit Database > **ETD**

Our transit observations > 

User not logged in  
- Sign in -  
New user registration (free)

> Minima predictions <  
> Transits predictions <

**22. 3. 2010:**  
TRESCA  
**News about upcoming HAT-P-13 two planet perturbation during April**

Dr. Gregory Laughlin has written article [Inside Information](#) at oklo.org.

Bruce Gary has prepared page [Two-Planet Perturbations for 2010](#) at AXA.

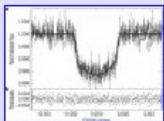
> [More information...](#)

**18. 3. 2010:**  
TRESCA  
**New transiting exoplanet CoRoT-9 b with 95days long period** was discovered by H. J. Deeg, C. Moutou et al. in Nature.

The planet is orbiting in distance 0,36 AU around the parent star, has radius 1,05 R<sub>Jup</sub> and mass 0.84 M<sub>Jup</sub>. Transits are 0.017 mag depth and 8.08 hours long. Constellation: Serpens.

*Congratulation to CoRoT and the discovery team!*

For more information see the discovery paper: [A transiting giant planet with a temperature between 250 K and 430 K.](#)



> [More information...](#)

**17. 3. 2010:**  
TRESCA  
**Possibility of major axis precession at WASP-12b?** The data from TRESCA database were used for analysis of this phenomenon.

**New minimas B.R.N.O.:**

- TX Cnc (M. Lehky)
- TX Cnc (M. Lehky)
- TX Cnc (M. Lehky)
- NSVS 10122684 Cnc (M. Lehky)
- V829 Her (M. Lehky)
- FX Dra (M. Lehky)
- V1054 Her (J. Trnka)
- VW LMI (L. Brát)
- CE Leo (L. Šmelcer)
- CE Leo (L. Šmelcer)

**New transits TRESCA:**

- TrES-3 b (Š. Gajdoš, I. Jakšová)
- TrES-3 b (Š. Gajdoš, I. Jakšová)
- TrES-3 b (Š. Gajdoš, I. Jakšová)
- TrES-3 b (Š. Gajdoš, I. Jakšová)
- TrES-3 b (Š. Gajdoš, I. Jakšová)
- TrES-3 b (Š. Gajdoš, I. Jakšová)
- TrES-2 b (Š. Gajdoš, I. Jakšová)
- TrES-1 b (L. Brát)
- HAT-P-13 b (J. Trnka)
- XO-2 b (G. Corfina)
- CoRoT-1 b (E. Schwieterman, B. Addison)

Find:  Previous Next Highlight all Match case

In 2011: 741 transit observations uploaded from 150 observers.  
Altogether more than 1500 transit light curves on 110 planets.



# Operation of ground-based surveys

- Operations are mostly “autonomous” (fully automated, pre-programmed in advance). As compared to robotic, remotely operated, and other levels of automation.
- Systems take calibration frames (biases, darks, skyflats).
- Observe every clear hour (minute) during the night using weather sensors (wind, humidity, precipitation, cloud cover, lightnings, etc).
- Make intelligent decisions depending on the conditions.
- Operations are optimized: perform astrometry, autofocusing in between exposures.
- Networked operations, combination of data from multiple sites.







# HATs at Mauna Kea

HATs at MK Tue Jan 11 10:23:28 2005





# HAT-South LCO weather station

Applications Places System 1GHz No alarms 7°C Mon Mar 1, 18:09:57 Gaspar Bakos

HAT South weather @ Chile - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://lcohsnode/~hatuser/wth/

Most Visited Gmail HatNet Project hat.cfa.harvard.ed... C hatWC W FC FW FP1 FP2 MC MW MP HC HN HR HS HC

## HSW @ LCO

current week month year

### Current weather overview

#### Temperature, last 24 hours

■ Device temp ■ Air temp ■ Shed int. temp.  
Current air: 13.6 °C  
Current dev.: 13.9 °C  
Current shed: 21.8 °C

#### Relative humidity, last 24 hours

■ Relative humidity  
Current: 50.2

#### Wind speed, last 24 hours

■ average ■ minimum ■ maximum  
■ Max. allowed wind speed  
Current avg.: 13.3 m/s  
Current max.: 15.6 m/s

#### Wind direction, last 24 hours

■ minimum ■ average ■ maximum  
Current: 53°

#### Relative sky temperature, last 24 hours

■ Relative sky temperature

#### Lightning strikes, last 24 hours

### HS sensors

- [Weather overview](#)
- [Väisälä weatherhead](#)
- [Boltwood cloud sensor](#)
- [Boltek lightning sensor](#)
- [Webcam and all-sky](#)
- [Webcam videos](#)
- [All-sky archive](#)

### LCO weather

- [Manguis ridge](#)
- [Magellan](#)

root@cfh... [Network ...] Terminal The Carne... Wireless ... HAT South... Workspace 6 HATCONTROL SW: PLFIT HS: ITR170-004 FU: PAPER



CASKETT all sky Camera @ Ico

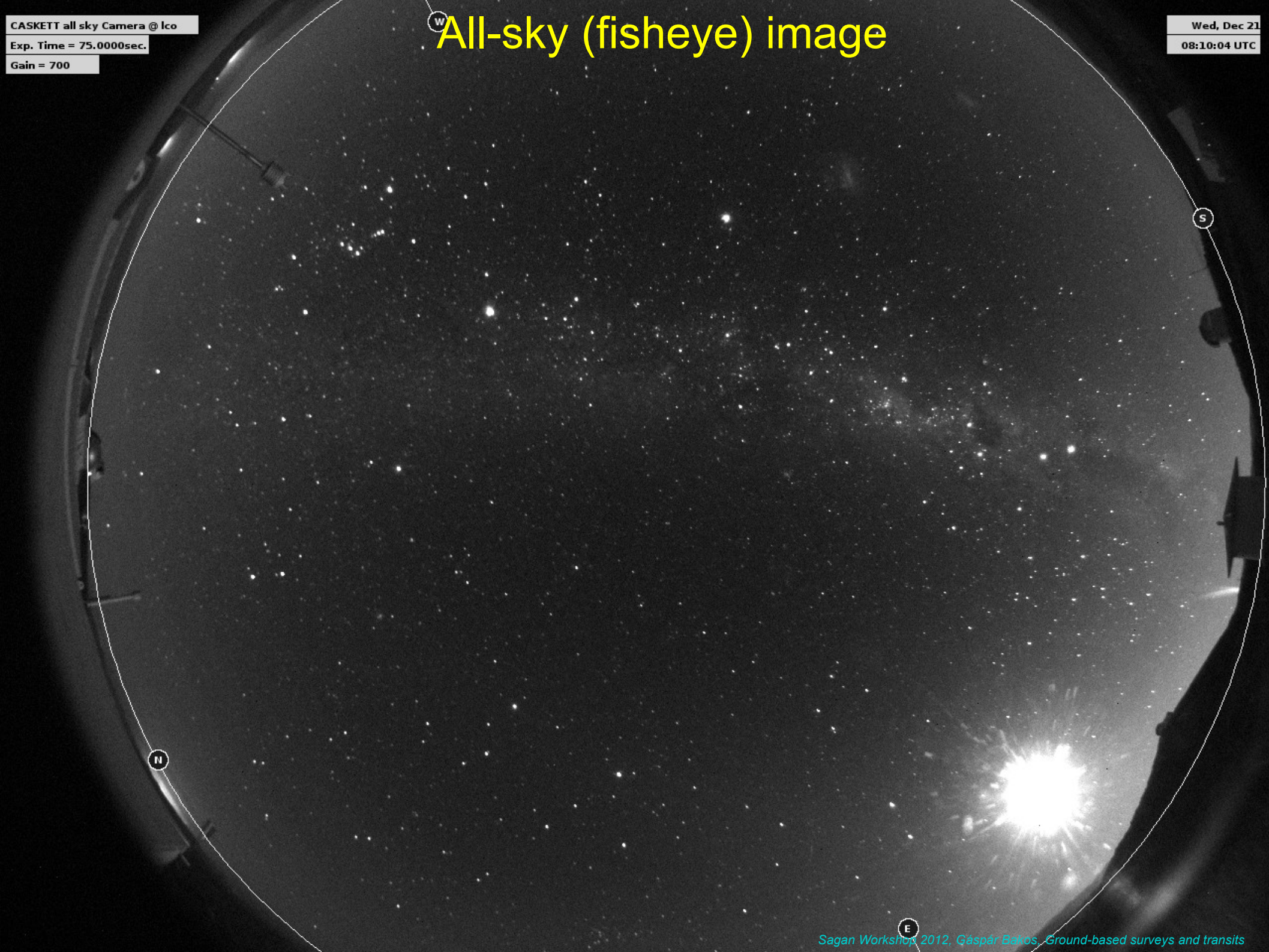
Exp. Time = 75.0000sec.

Gain = 700

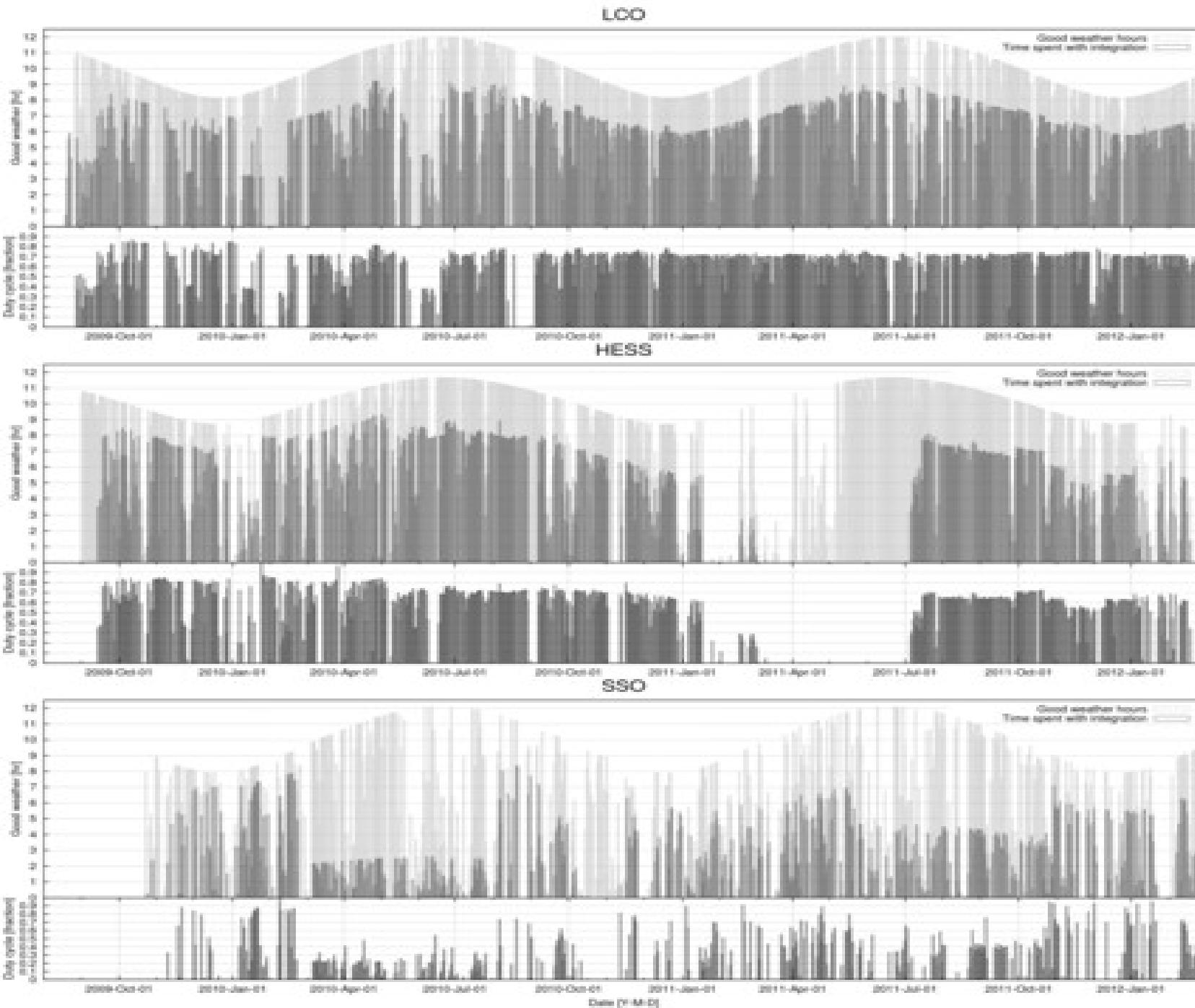
# All-sky (fisheye) image

Wed, Dec 21

08:10:04 UTC



# Detailed weather-logs



LCO: 8.48 hrs  
HESS: 7.15 hrs  
SSO: 4.64 hrs



BlackBerry

Snapshot - AXIS 221 Network Ca... EDGE



planet-only data

22552.75 ± 0



# Servicing, repairs and maintenance

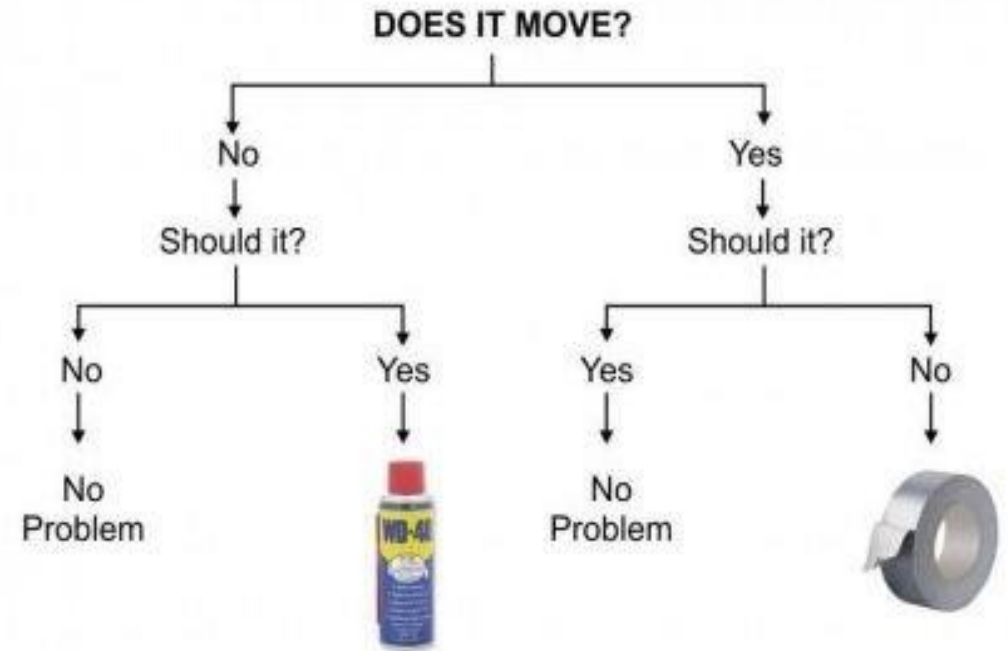
HATs at MK Mon Jan 3 13:40:23 2005



# Servicing, repairs and maintenance



## Engineering Flowchart

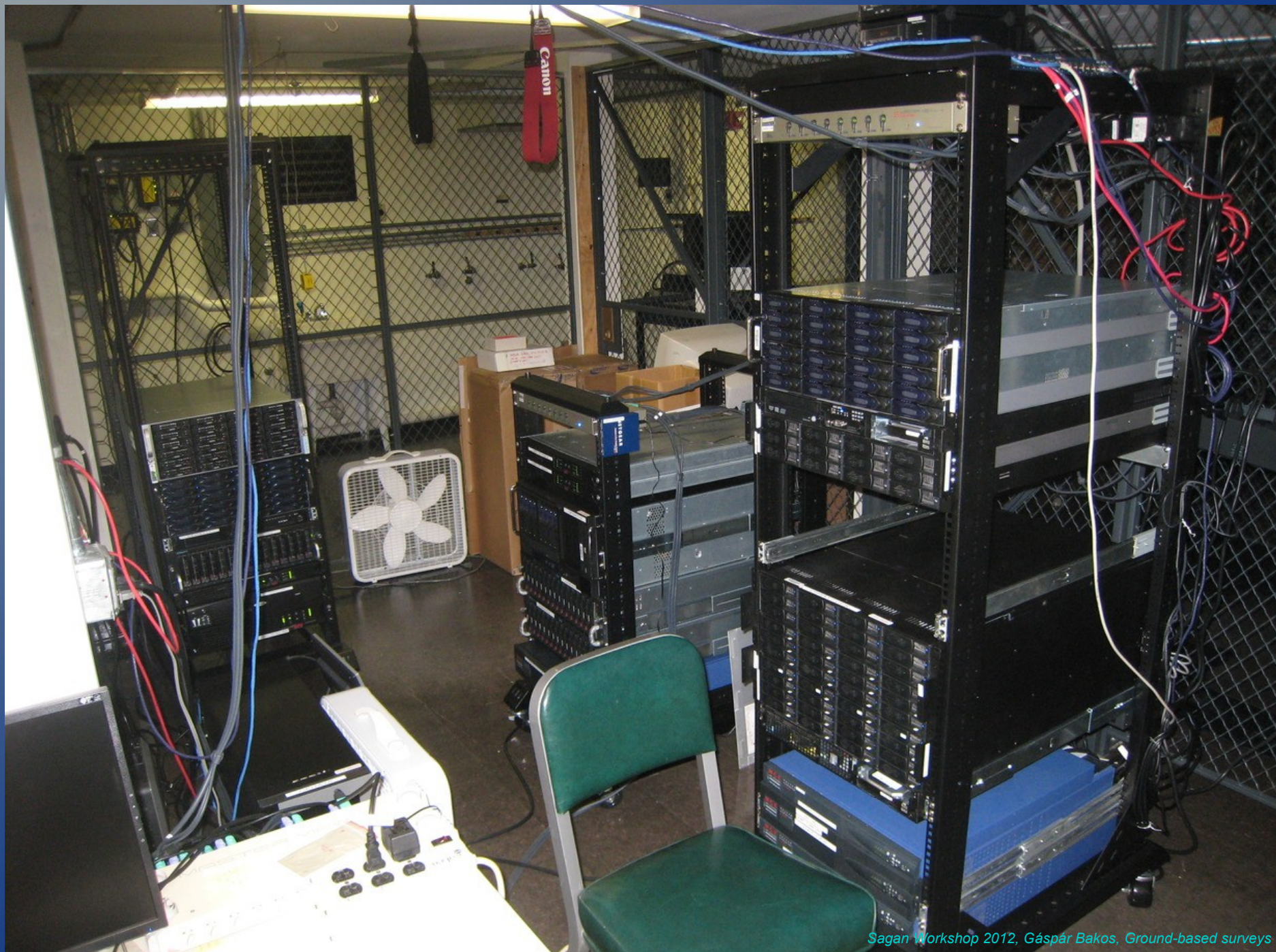


# Data reduction

- Wide field (up to 26 x 26 degrees), spatially variable PSF, highly distorted projection of sky (astrometric solutions).
- Under-sampled stellar profiles, often coupled with poor quality semi-professional front-illuminated (but affordable) CCDs.
- Extreme crowding.
- Time-variable: PSF, pointing, astrometry, CCD gain.
- Tricky calibration due to wide field and effects above.
- Peltier-cooled (+forced air, low-maintenance) systems with dark current and hot pixels.
- Classical astrometry/photometry packages were sub-optimal.
- Significant software development effort. See e.g. Image Subtraction (ISIS), initially developed for microlensing searches, in particular OGLE (→ 5 planets in 2002).
- TFA, BLS, SysREM, astrometry.net, etc.
- Data volume: hundreds of terabytes.

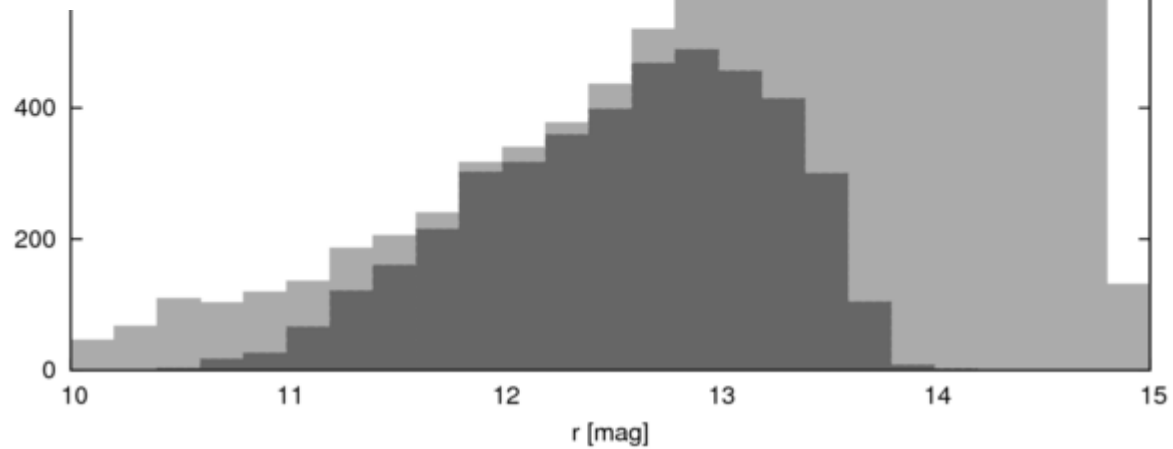
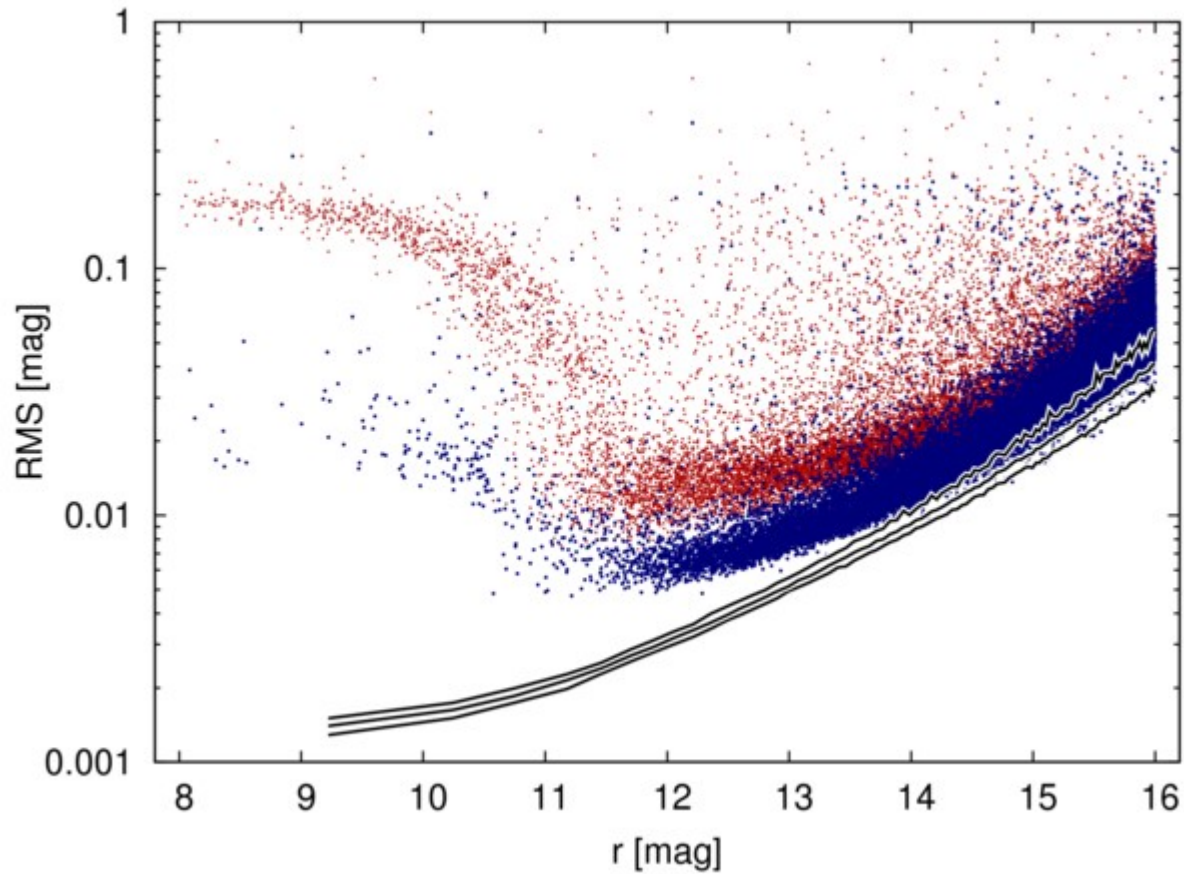


# Data volume can be daunting

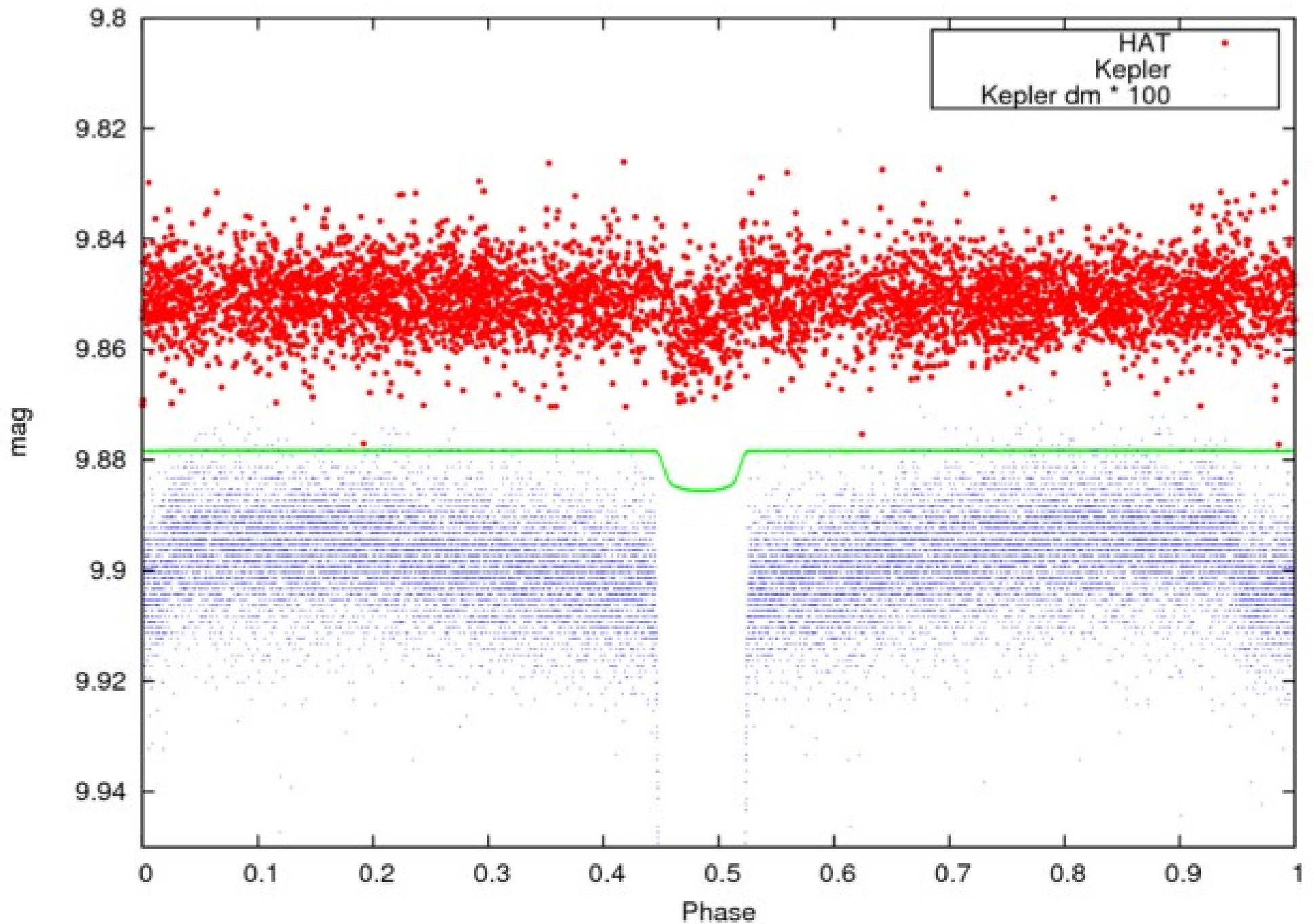




# Photometric precision



# HAT-P-7 ground vs space



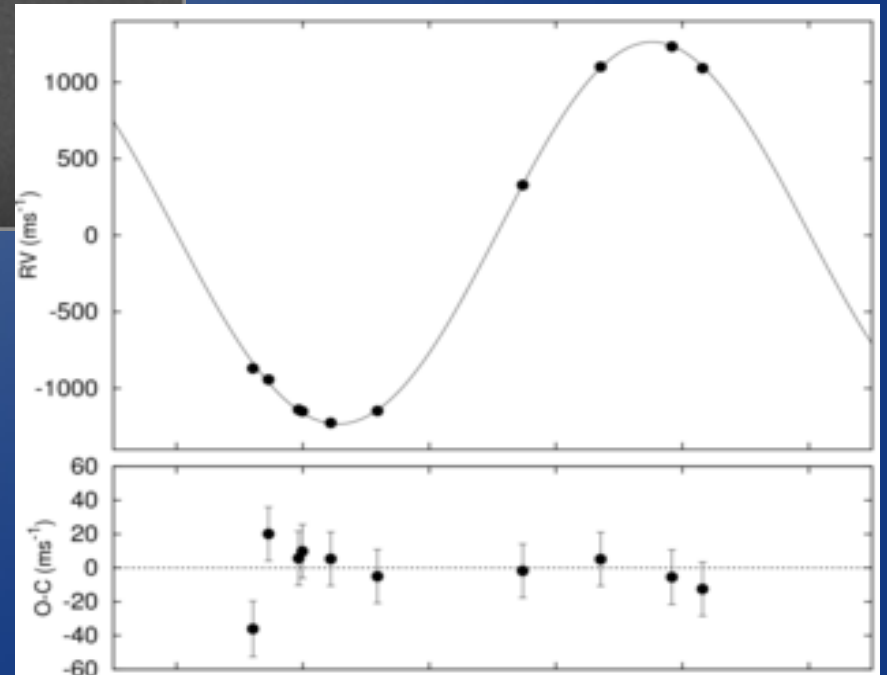
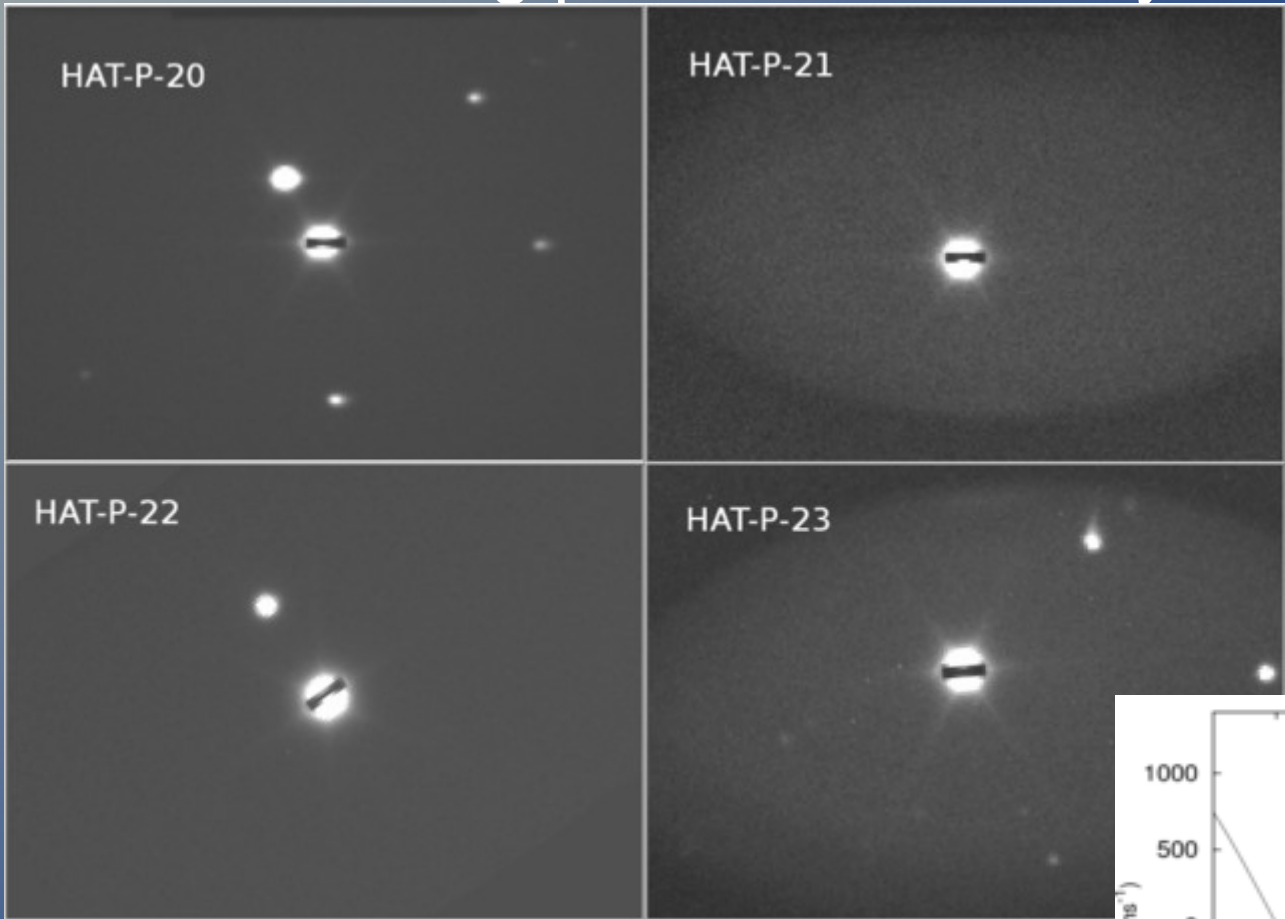


HAT-South  
first light  
image  
(1 chip out  
of 4)





# Transiting planets with binary stellar companions



*Bakos et al. 2010, ApJ*

# Showcasing two examples

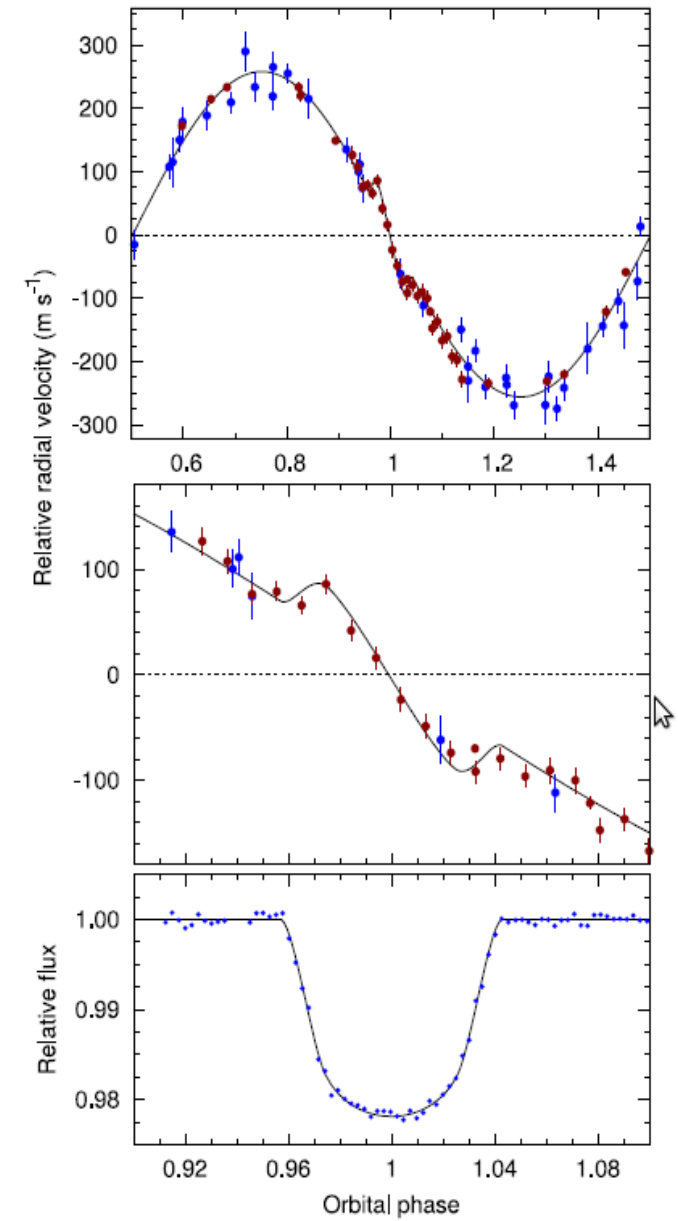
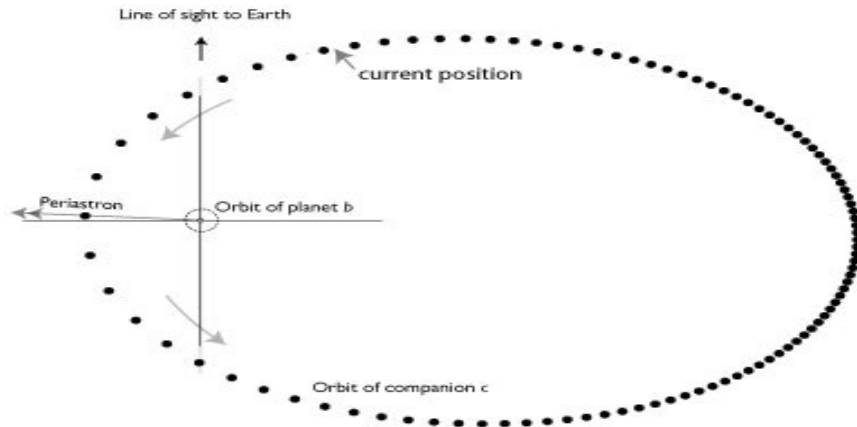
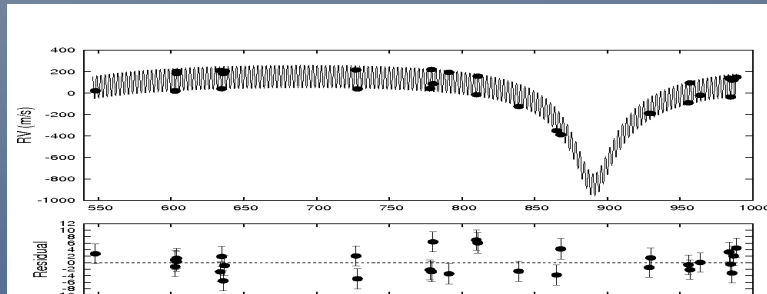
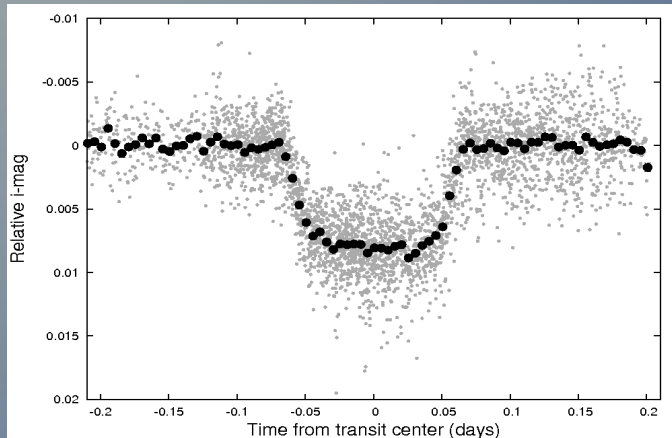
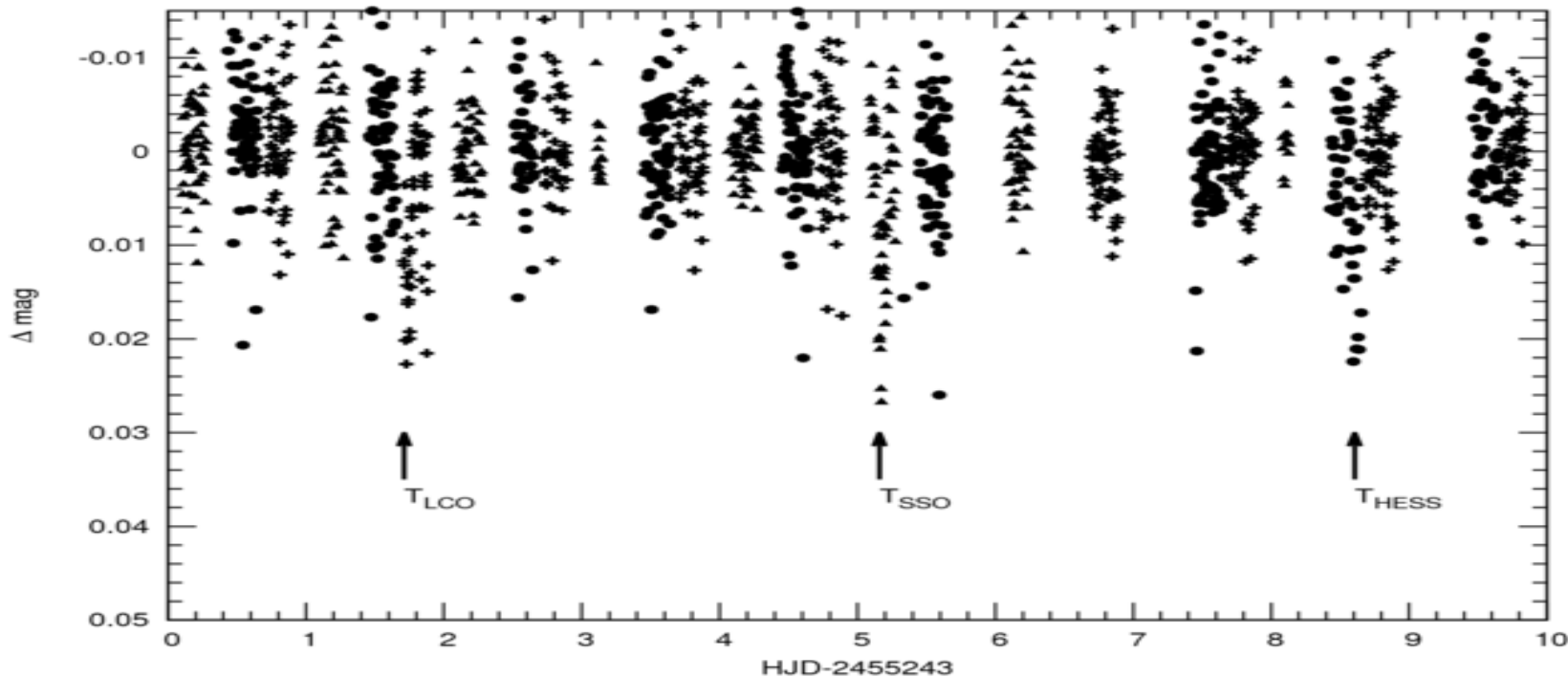
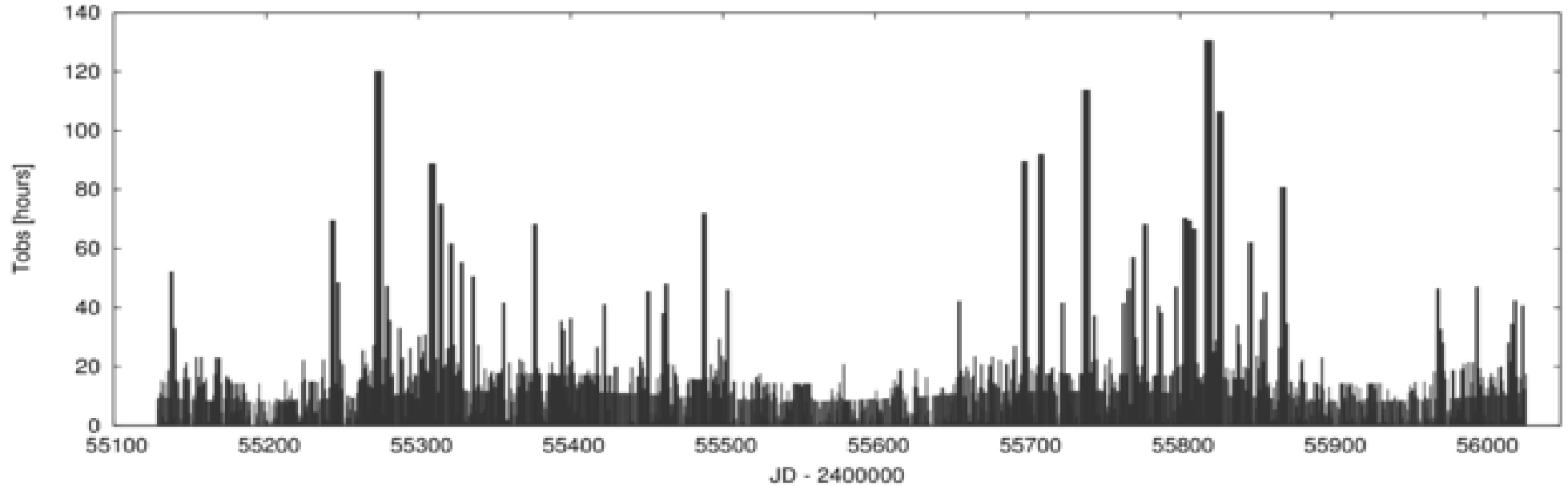


Figure 1. Top: the HARPS (brown) and CORALIE (blue) radial velocities of WASP-19 together with the fitted model. Middle: the transit region shown expanded. Bottom: the NTT transit light curve and fitted model. (A color version of this figure is available in the online journal.)

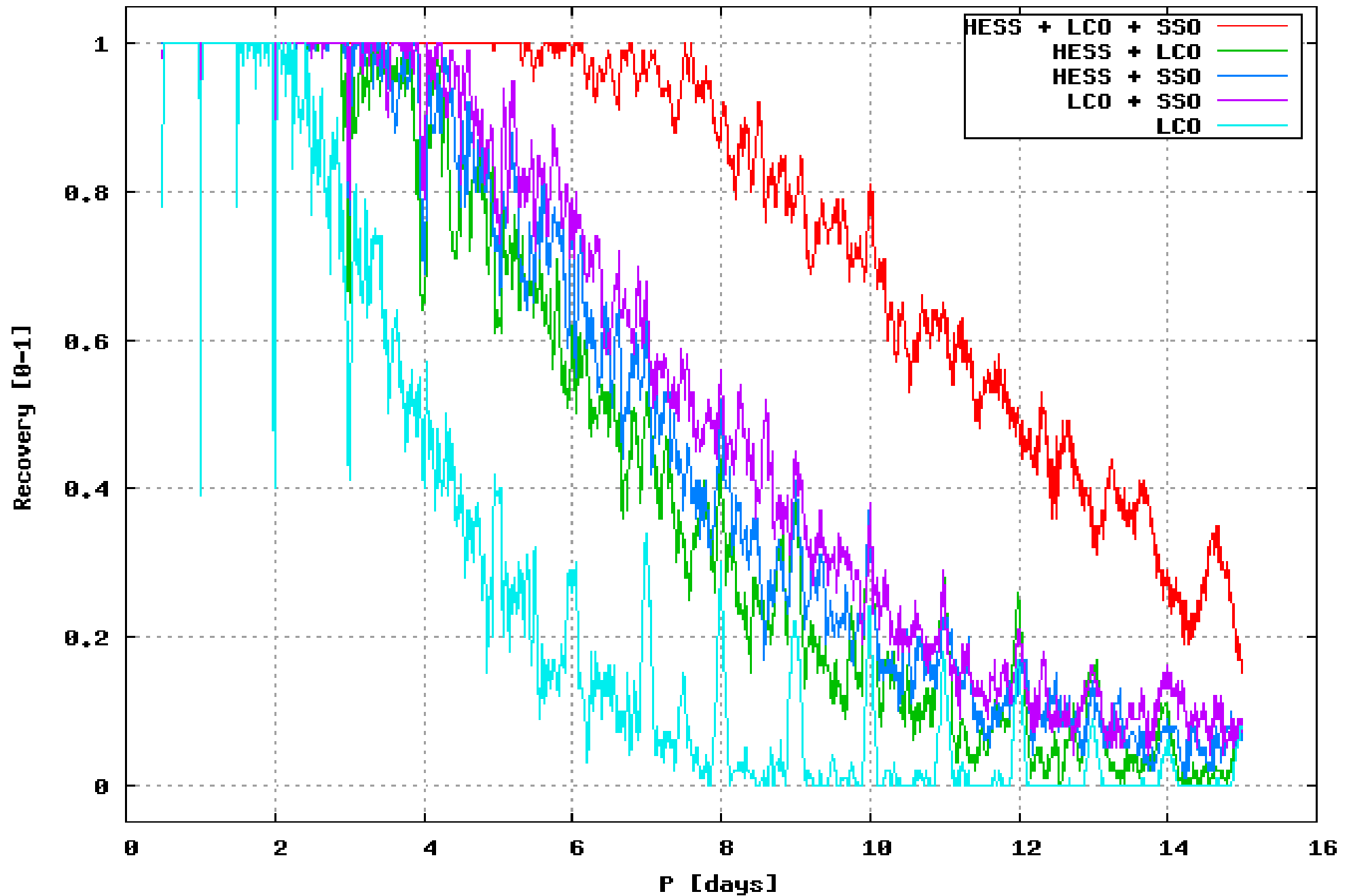


# Stretches of clear weather



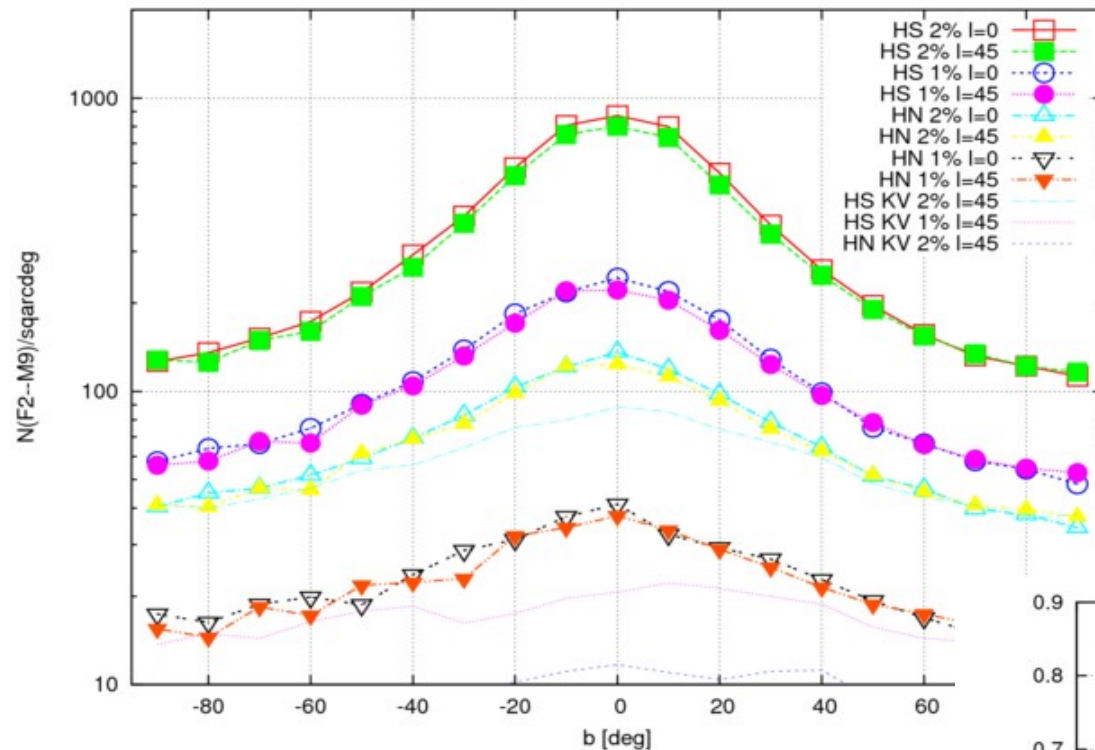
*From  
HATSouth.  
See  
Bakos  
et al. 2012,  
PASP  
and  
Penev et al.,  
2012, AJ*

# Transit recovery function



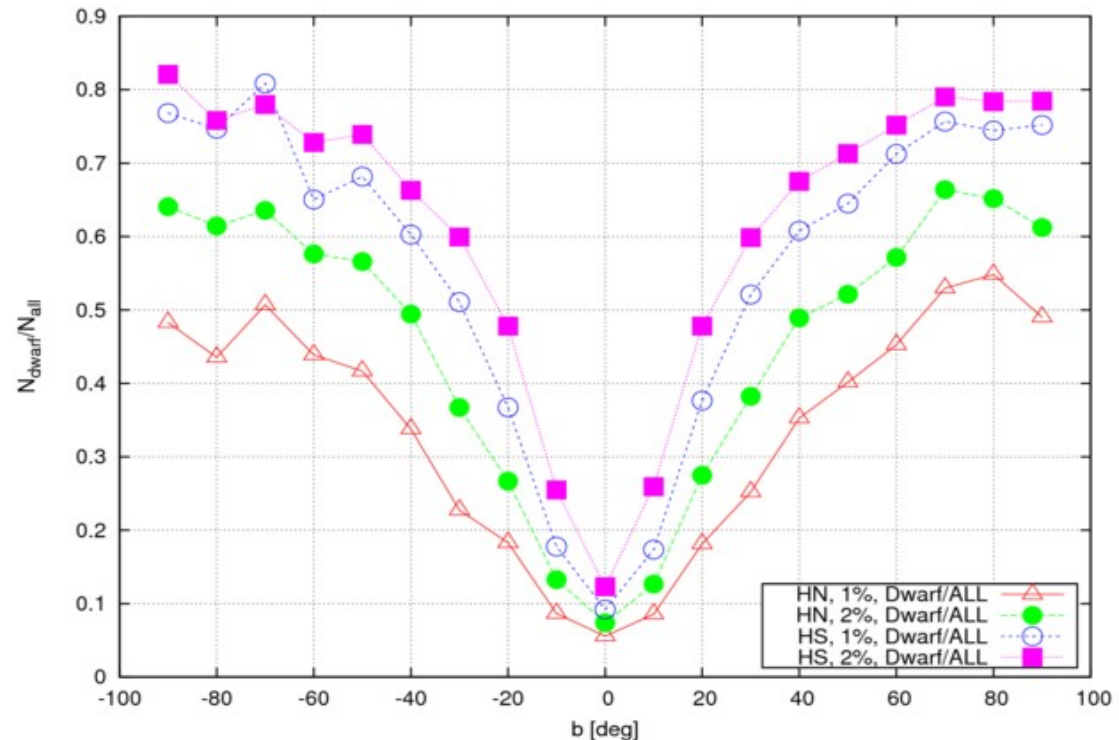
# Stellar populations

- $137/\square^\circ$  F2—M9 dwarfs with 1% photometric precision = 100,000/yr
- $374/\square^\circ$  with 2% rms = 290,000/yr
- 12,000 K dwarfs /yr @1%
- 770 M3V—M9V / yr @ 2%
- 1500 TEP candidates @  $\leq 2\%$



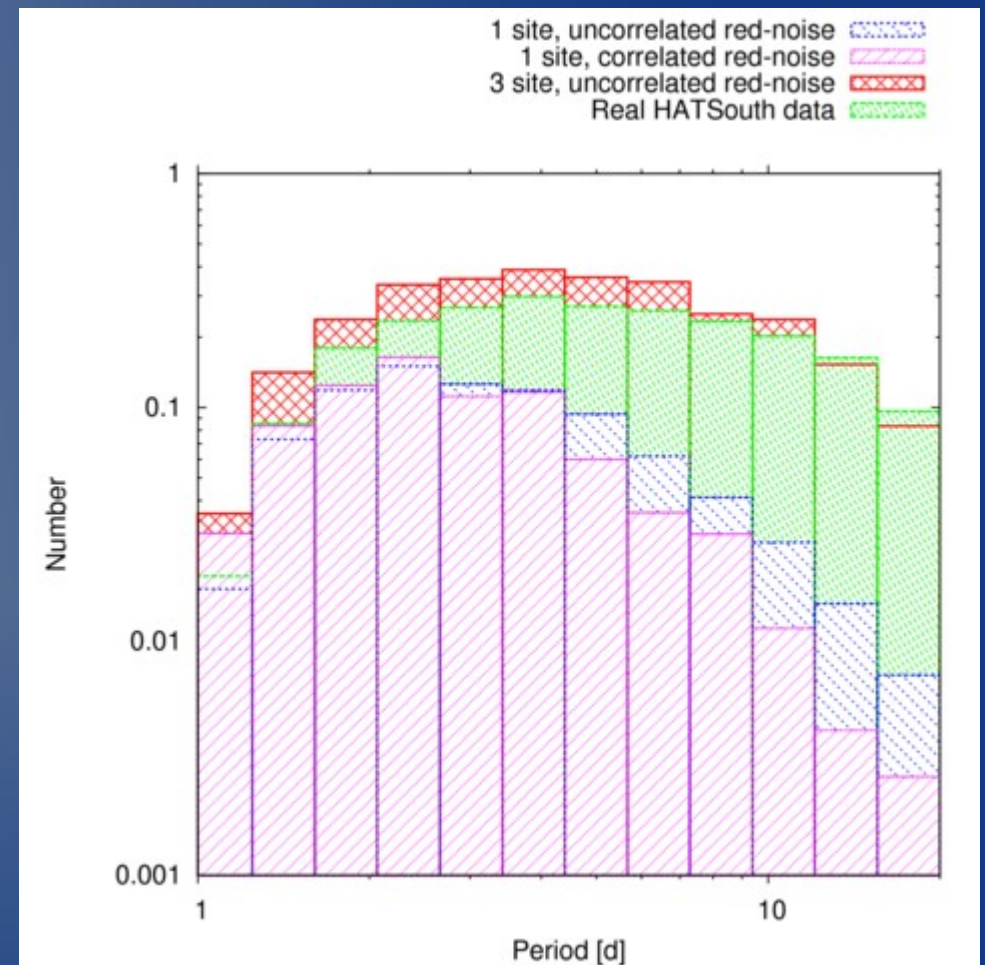
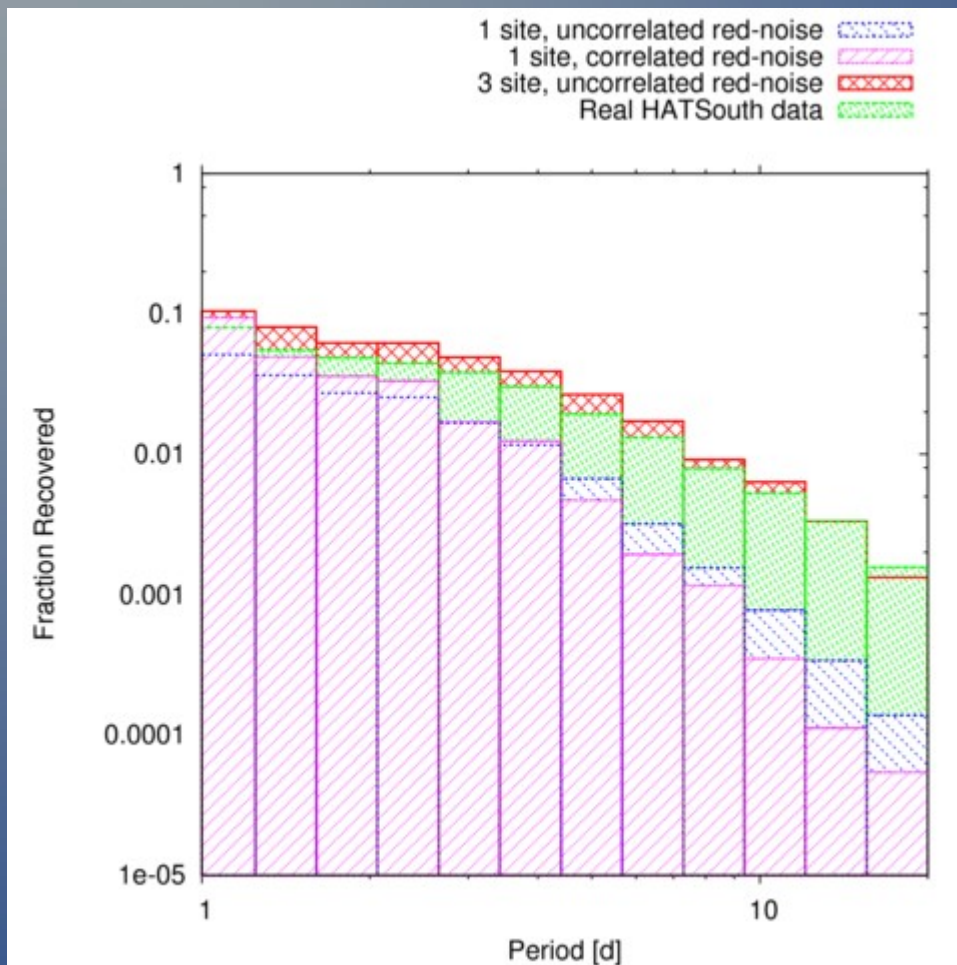
## Precision matters:

- TEP/candidate rate: 1/10 for 1% photometry
- TEP/candidate rate: 1/25 for 2%



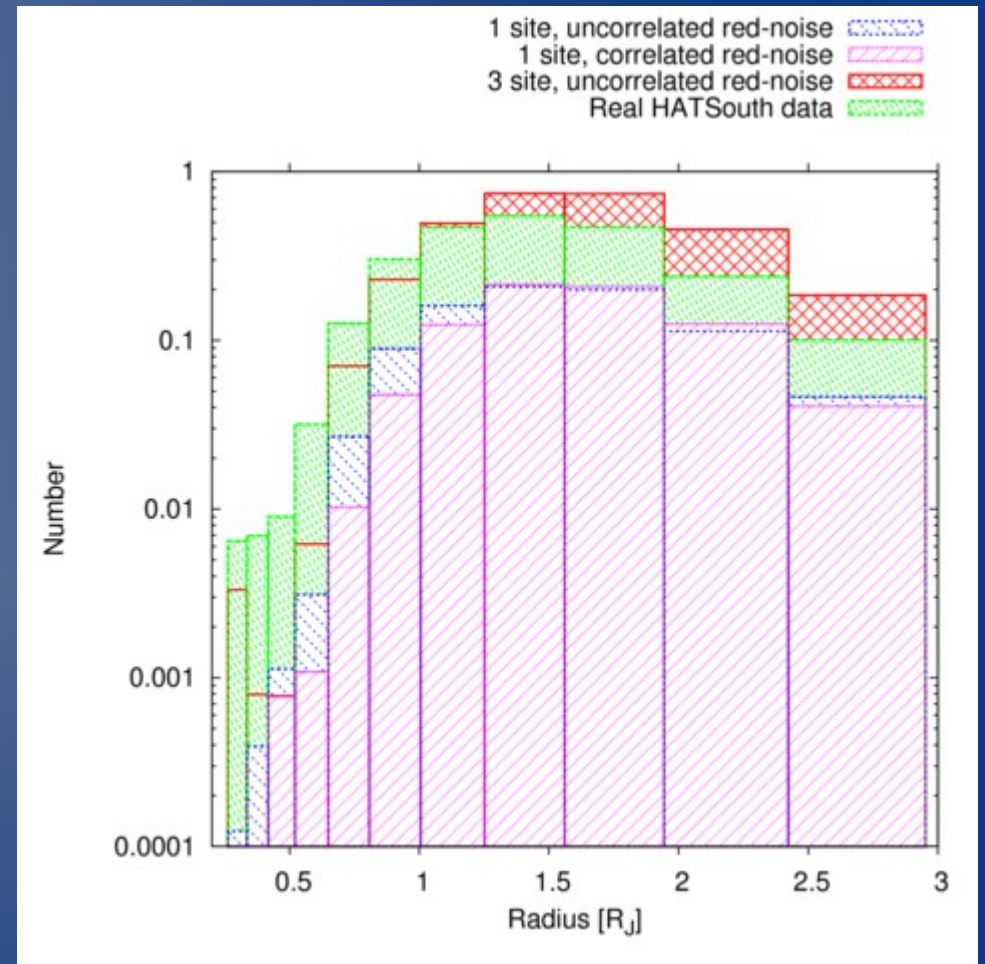
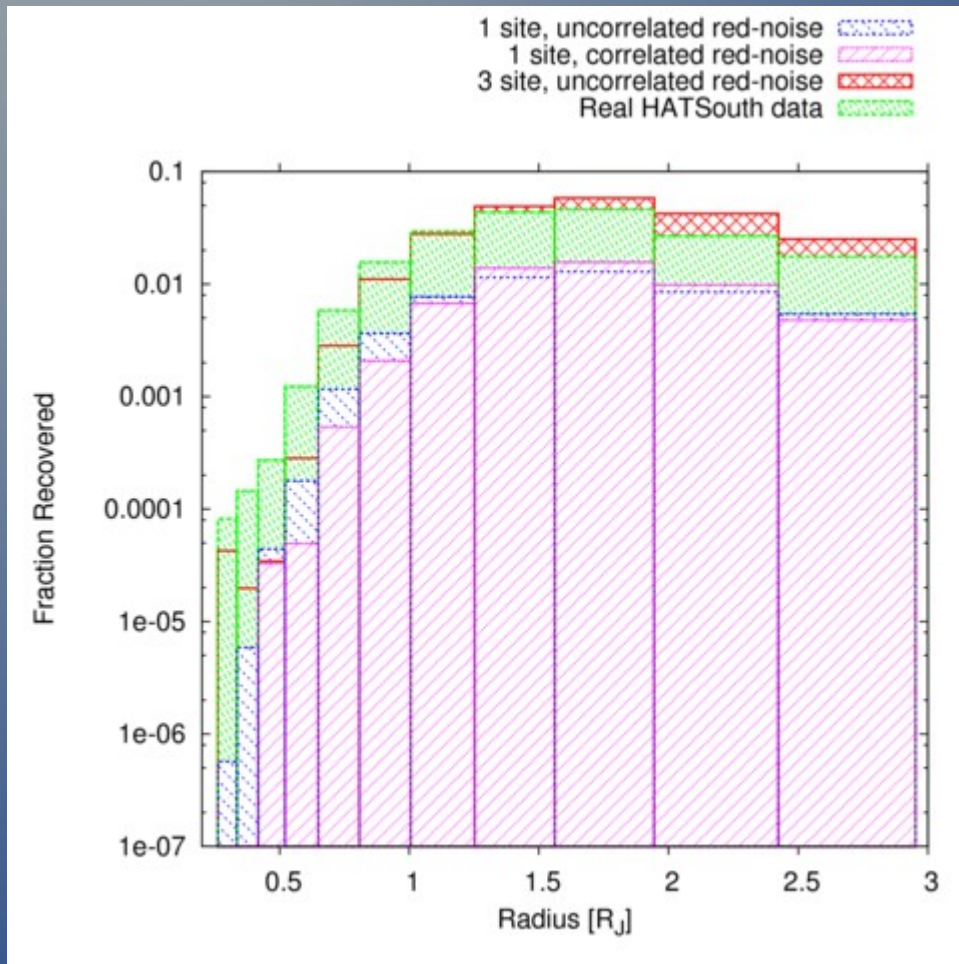


# Yield calculations



- Uses Besançon models
- Simulations take into account Kepler-based radius and period distribution.
- Corrected for geometric transit probability
- 2 month observing with realistic weather pattern (based on real data)
- Realistic noise model (“pink”),

# Yield calculations



# Future prospects

- Perhaps 1000 hot Jupiters all sky around  $r < 12.5$
- Many more transiting Neptunes and super Earths
- Some of these are within the reach of current, improved, and next generation surveys.
- Brightness of the host star is important
- Strong synergies between ground-based and space-based surveys.
- Ground-based surveys are going with full force, with more to come.