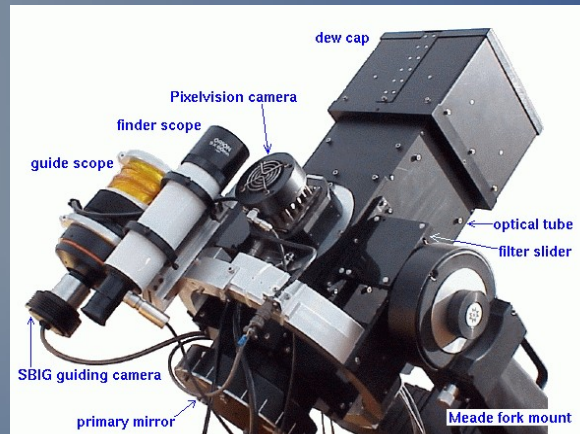
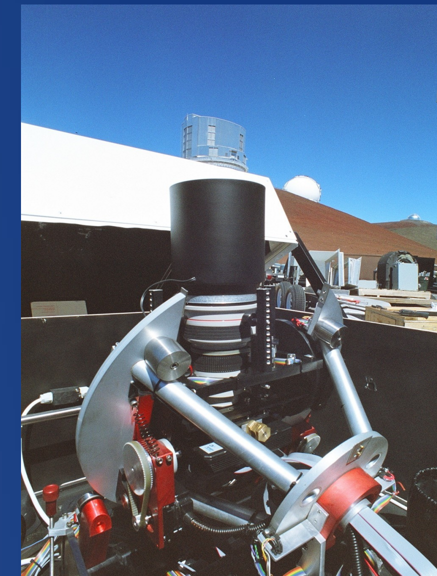
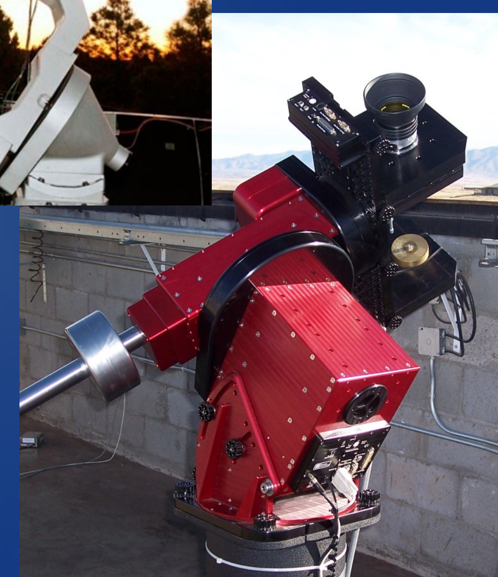
Ground-based transit searches







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 ($x10^3$)	planets /month
1	PASS	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
2	WASP0	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3	ASAS-3	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
4	RAPTOR	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
5	TrES	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
6	XO	11.0	1.8	10.06	1.0	1.0	2	25.00	8.6	11.9	258	3	1.2
7	HATnet	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
8	SWASP	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
9	Vulcan	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
10	RAPTOR-F	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
11	BEST	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
12	Vulcan-S	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
13	SSO/APT	50.0	1.0	5.05	2.9	3.1	2	4.20	12.5	15.5	1103	65	22.8
14	RATS	67.0	3.0	1.31	2.0	2.0	1	2.30	13.8	16.4	1548	12	4.2
15	TeMPEST	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
16	EXPLORE-OC	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
17	PISCES	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
18	ASP	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
19	OGLE-III	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
20	STEPSS	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
21	INT	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
22	ONC	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
23	EXPLORE-N	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
24	EXPLORE-S	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 ($x10^3$)	planets /month
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~~2~~	~~WASP0~~	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3	ASAS-3	7.1	2.8	11.21	2.0	2.0	2	13.93	9.9	12.0	272	5	1.7
4	RAPTOR	7.0	1.2	55.32	2.0	2.0	8	34.38	7.9	11.1	179	33	11.7
~~5~~	~~TrES~~	10.0	2.9	10.51	2.0	2.0	3	10.67	10.5	12.7	362	10	3.5
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~~21~~	~~INT~~	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
~~22~~	~~ONC~~	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
~~23~~	~~EXPLORE-N~~	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
~~24~~	~~EXPLORE-S~~	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

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QATAR
KELT
Mearth
HATSouth
CSTAR, 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, Sapiters, etc). Mass—radius relation for $M_P > 20 M_E$. Various other relations, e.g R_P vs (T_{eq} ,$[Fe/H]_*$,...).
- 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.

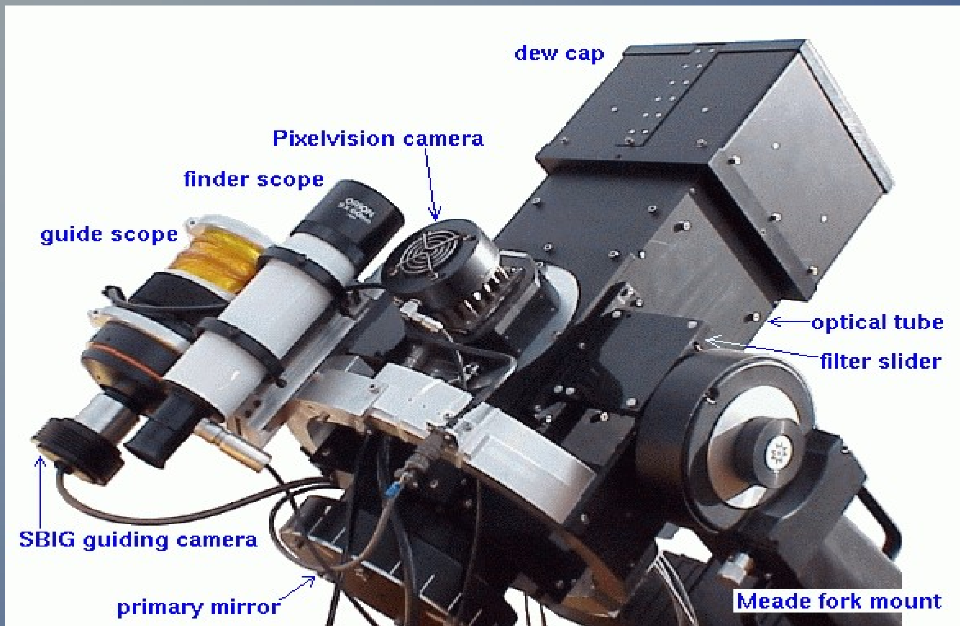
Space-based discoveries yielded:

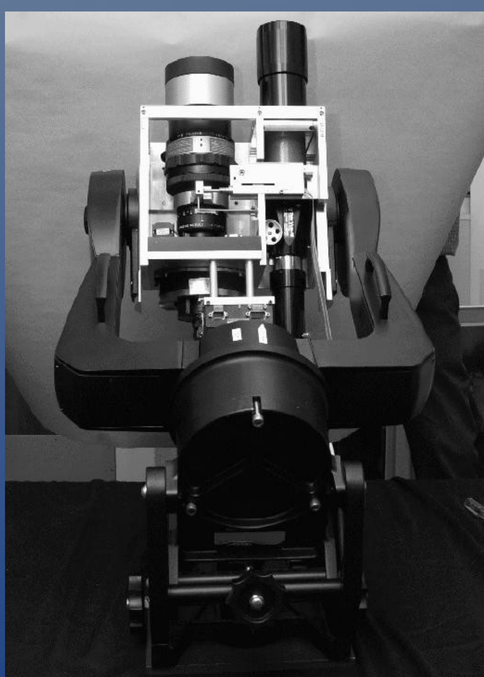
- First unambiguous transit timing variations → perturber bodies, and masses.
- Small radius planets, super-Earths, HZ planets.
- Multiple transiting planetary systems (architecture constraints on formation, evolution).
- Firm statistics on radius, period distribution and multiplicity. Planets are plentiful. 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).

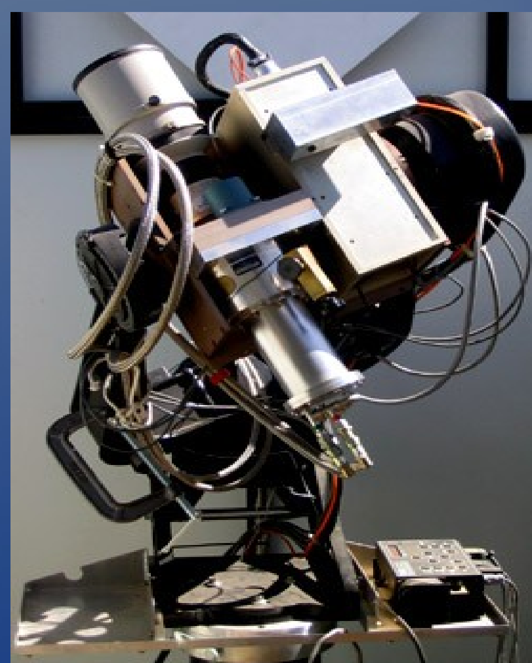
Inventory of ground-based surveys – OGLE

- 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° x 1.2° FOV with 16 x 16 Mpix.
- 8 planets (OGLE-TR-56b, 113b, 132b, 111b, 10b + 182b, 211b, L9b).
- P Є [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





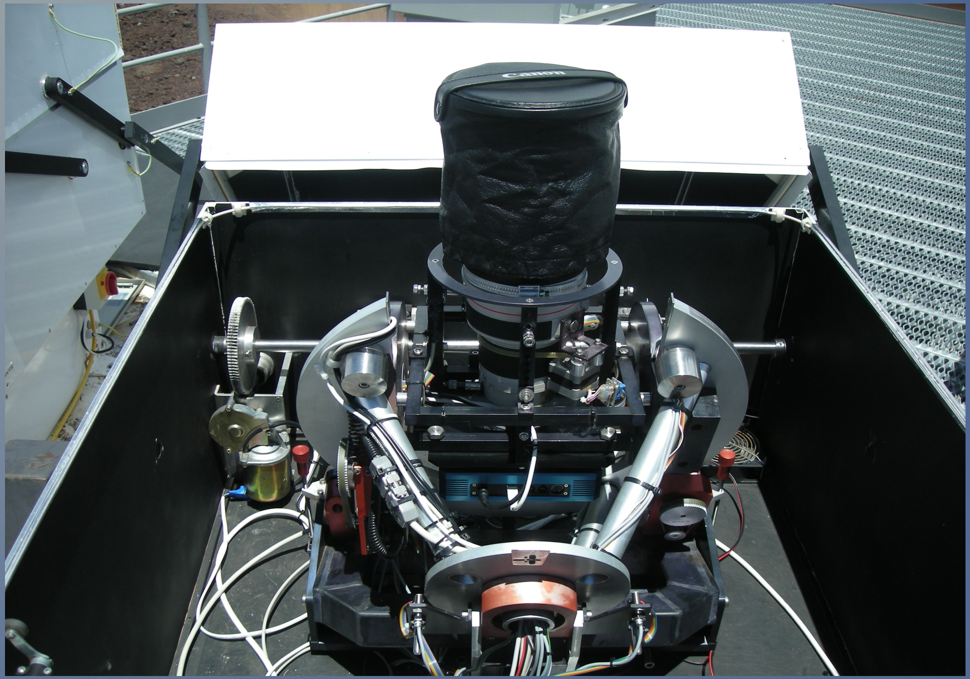


- STARE + Sleuth + PSST, network of 3 telescopes.
- Tim Brown, Dave Charbonneau, Georgi Mandushev, Ted Dunham.
- Great success in the 'early times' (2004 – 2006).
- Winding down (if operational).
- 0.1m telescopes, 6° x 6° FOV with 4K – 16K Mpix.
- 5 planets (and initial detection of HD209458b by STARE)
- P Є [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° x 7° FOV with 4K Mpix.
- 5 planets (one in common with HAT).
- P Є [2.6,4.18] days.
- V < 13 targets. Follow-up primarily by Extended Team (ET).
- Strip scan mode (7° x 63°)

Ground-based surveys – HATNet



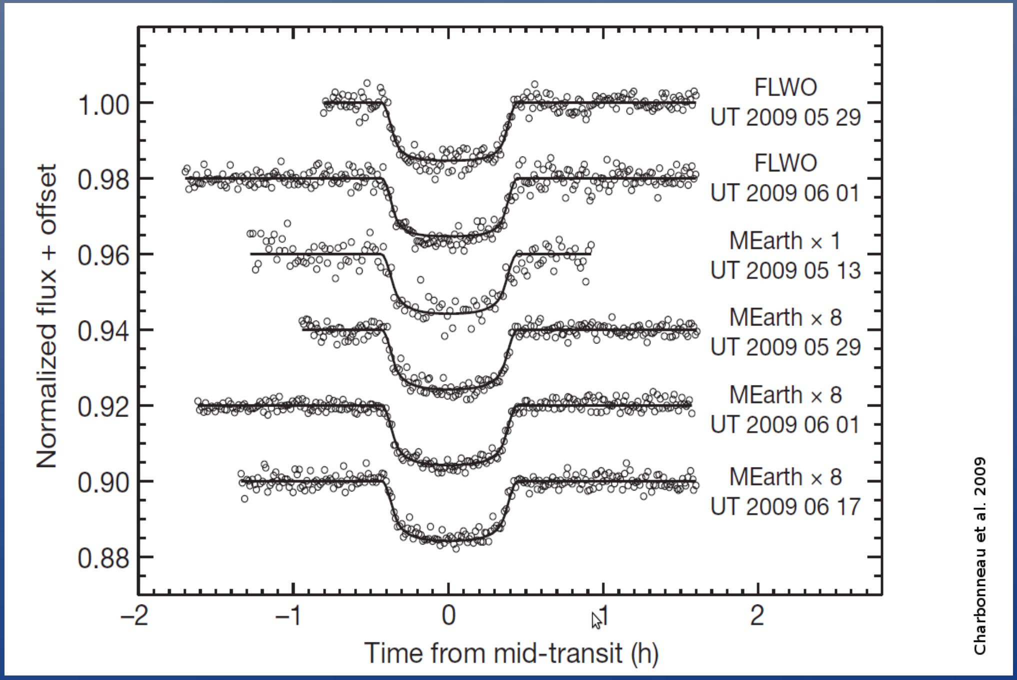
- FLWO/Arizona (4) and SMA/Mauna Kea/Hawaii (2)
- Operational: 2003 – present
- 6 x 0.11m telescopes, 10° x 10° FOV, each with 16K Mpix, sloan r filter.
- First network of identical hardware.
- 40* transiting planets (+1 in common with WASP, +1 with XO, +1 KELT, +1 Kepler,+1 TrES).
- P $\in$ [1.21,10.86] 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 ($M > 4\ M_J$).
- 1st and 2nd TEP in a multi-planet system (HAT-P-13b, -17b) with full (including P) orbital solution.

*: submtted to a refereed journal, posted on astroph.

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° x 32° 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

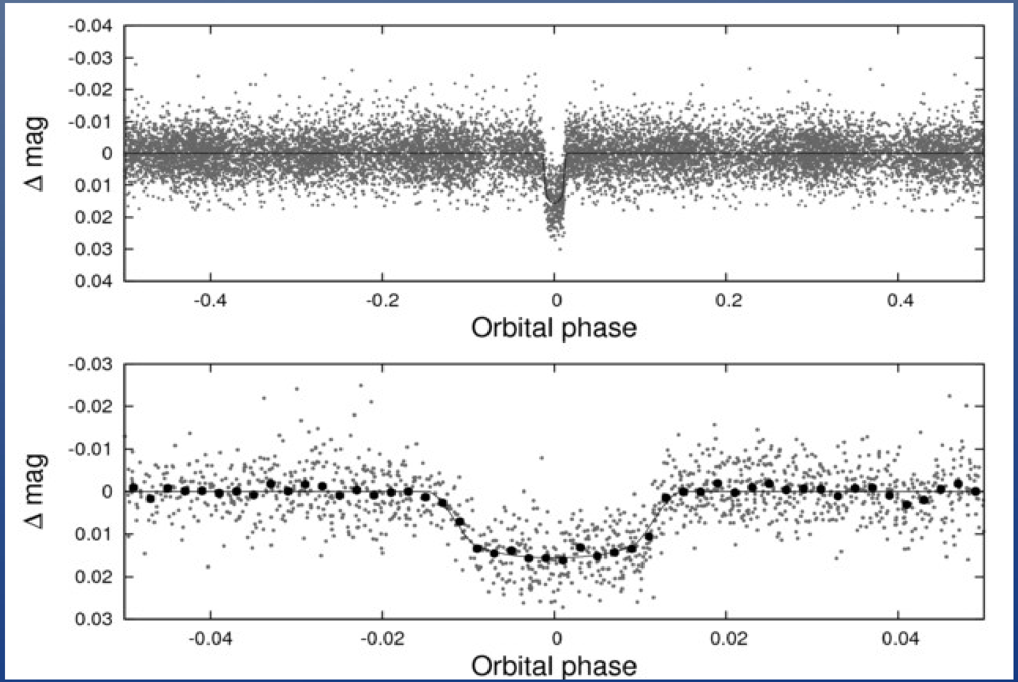


- Currently 1 station: FLWO, Arizona
- David Charbonneau, Jonathan Irwin
- Operational: 2008 – present
- 8 x 0.4m telescopes, 26' x 26' FOV, each with 2K x 2K pix BI CCD, wide filter.
- Off-the-shelf mounts, optics, CCDs, control software.
- 1 planet: GJ1214b (super-Earth? mini-Neptune?)
- Focused search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

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~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

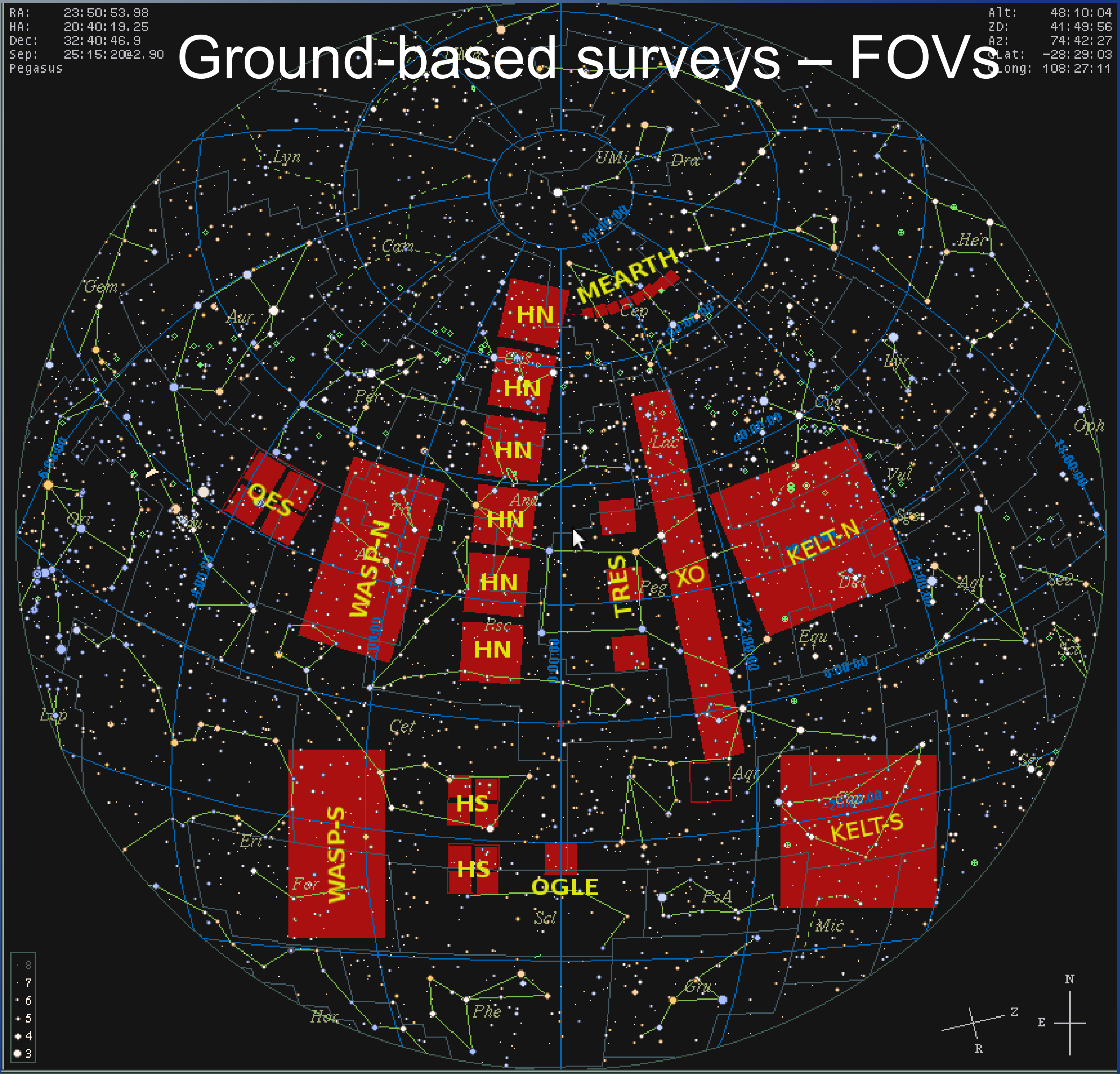


- 3 stations: LCO (Chile), HESS (Namibia), SSO (Australia).
- Operational: 2010 – present.
- 6 x (4 x 0.2m) telescopes, each with 8° x 8° FOV, 8K x 8K pix FI CCD, sloan r filter.
- “Home-made” dome, mount, electronics, software.
- Off-the-shelf (Apogee) CCD, (Takahashi) optics, filters.
- 1 planet (HATS-1b) 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

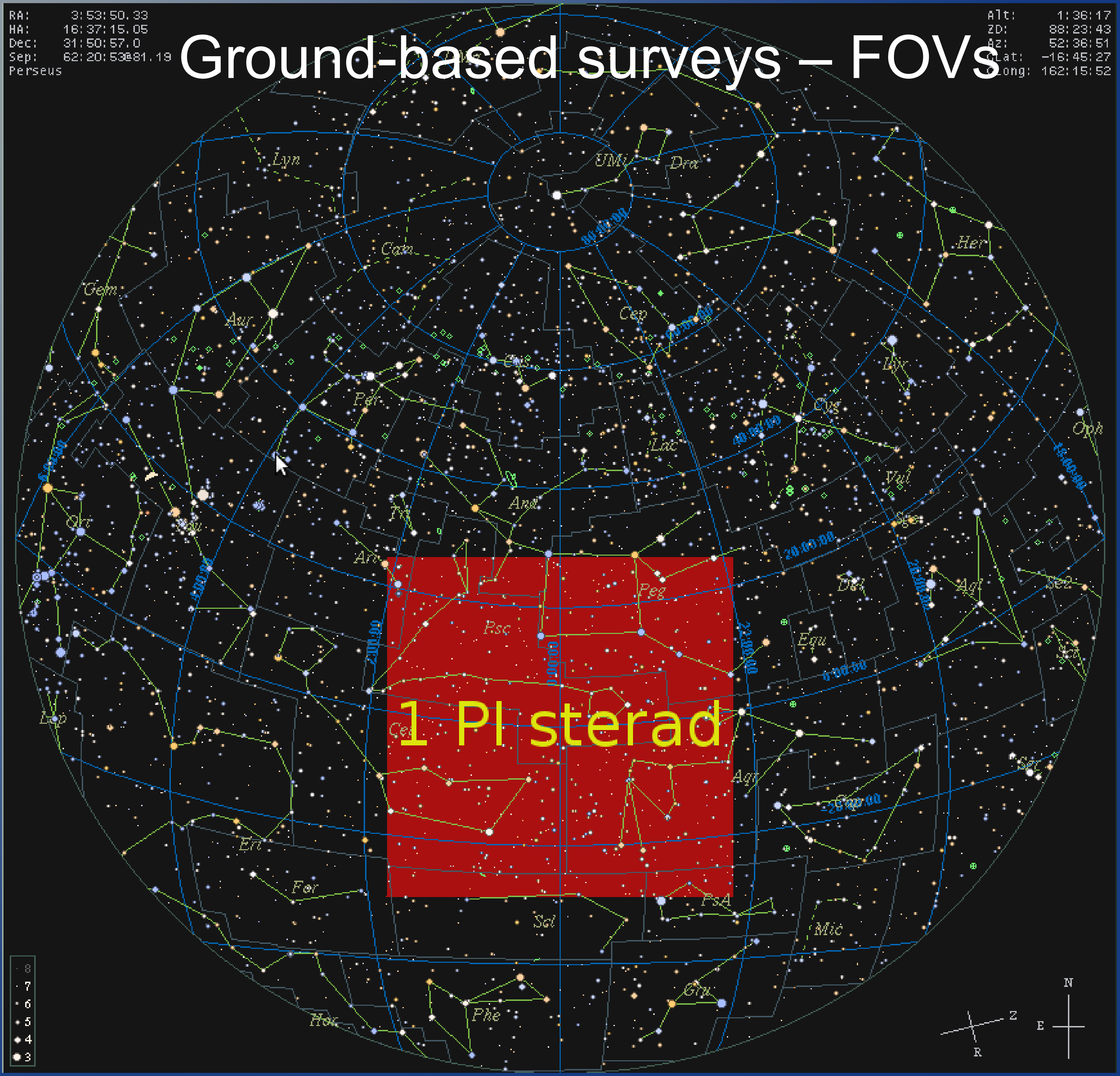
Ground-based surveys – KELT

- 2 stations: Arizona and SAAO (South Africa).
- Operational: 2005? – present
- 2 x 0.05m telescopes, 26° x 26° 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 Є [1.21,4.11] days.
- V < 12 (bright) targets. Follow-up with Dave L. team.
- Very bright host stars, fast rotators.

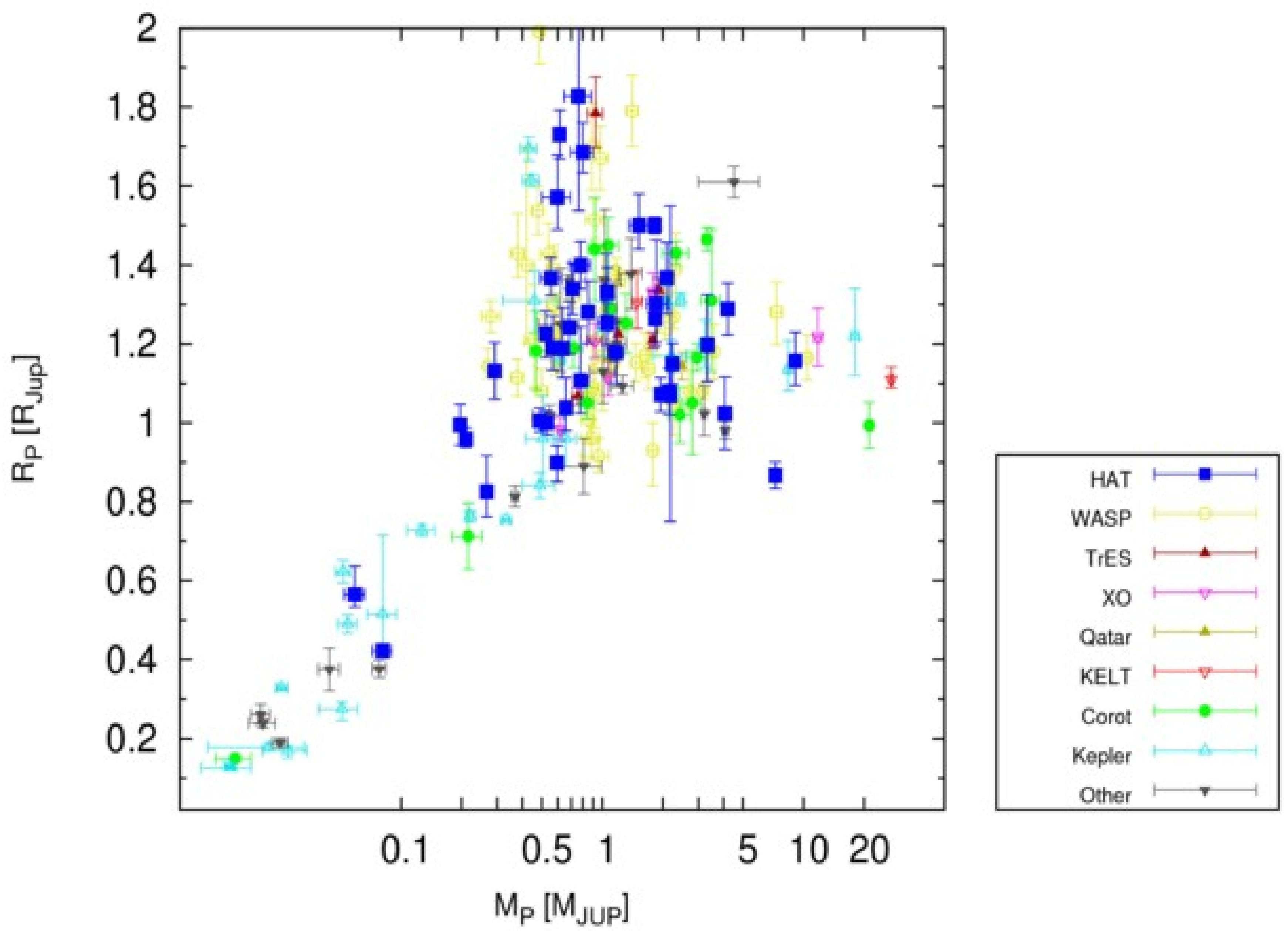
Ground-based surveys – FOVs



Ground-based surveys – FOVs



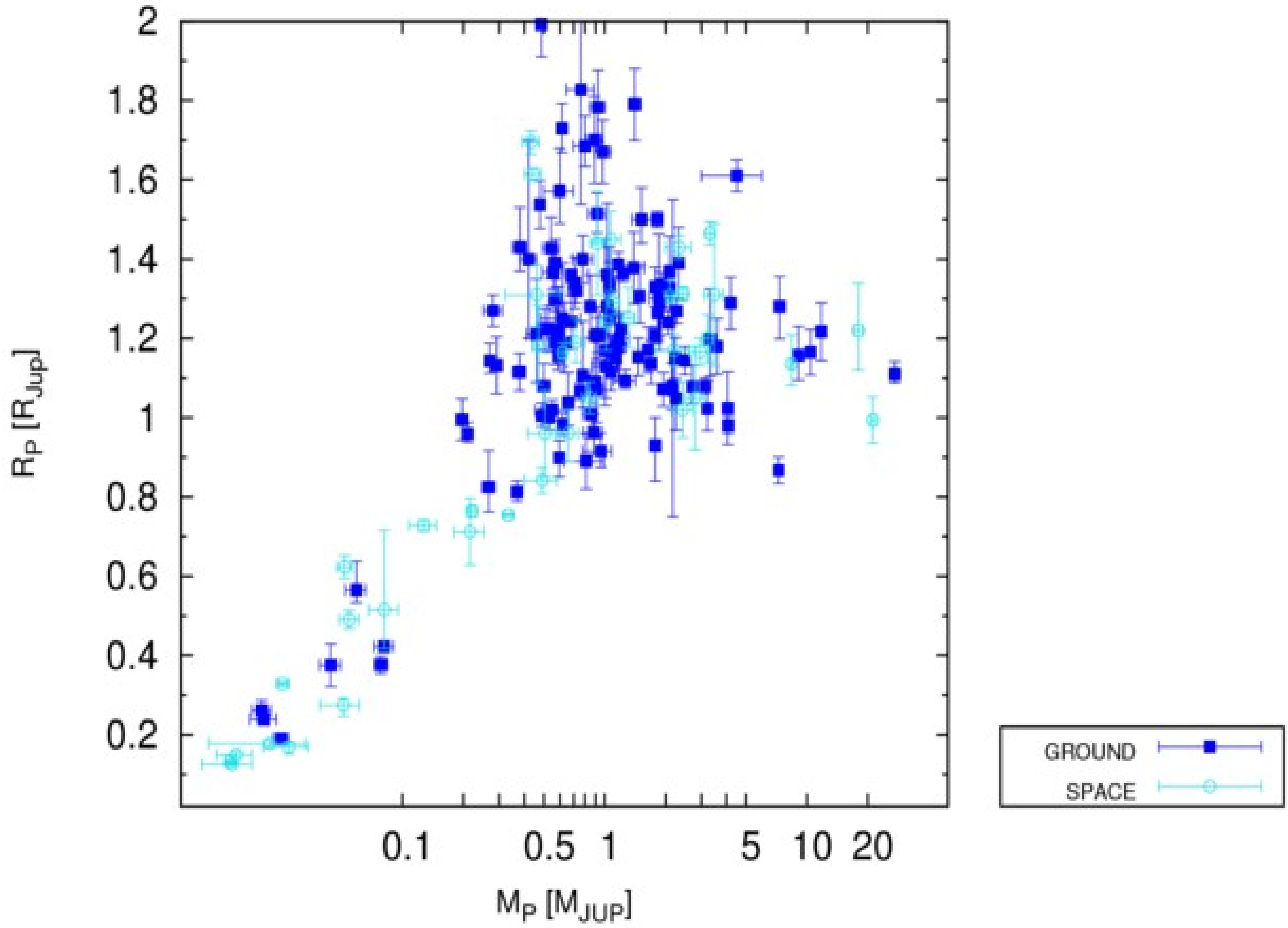
Planetary mass—radius diagram, per project



HAT	41*
WASP	53
TrES	5
XO	5
Qatar	2
KELT	2
Corot	19
Kepler	33
Other	20

*Submitted to peer reviewed journal and posted on astroph

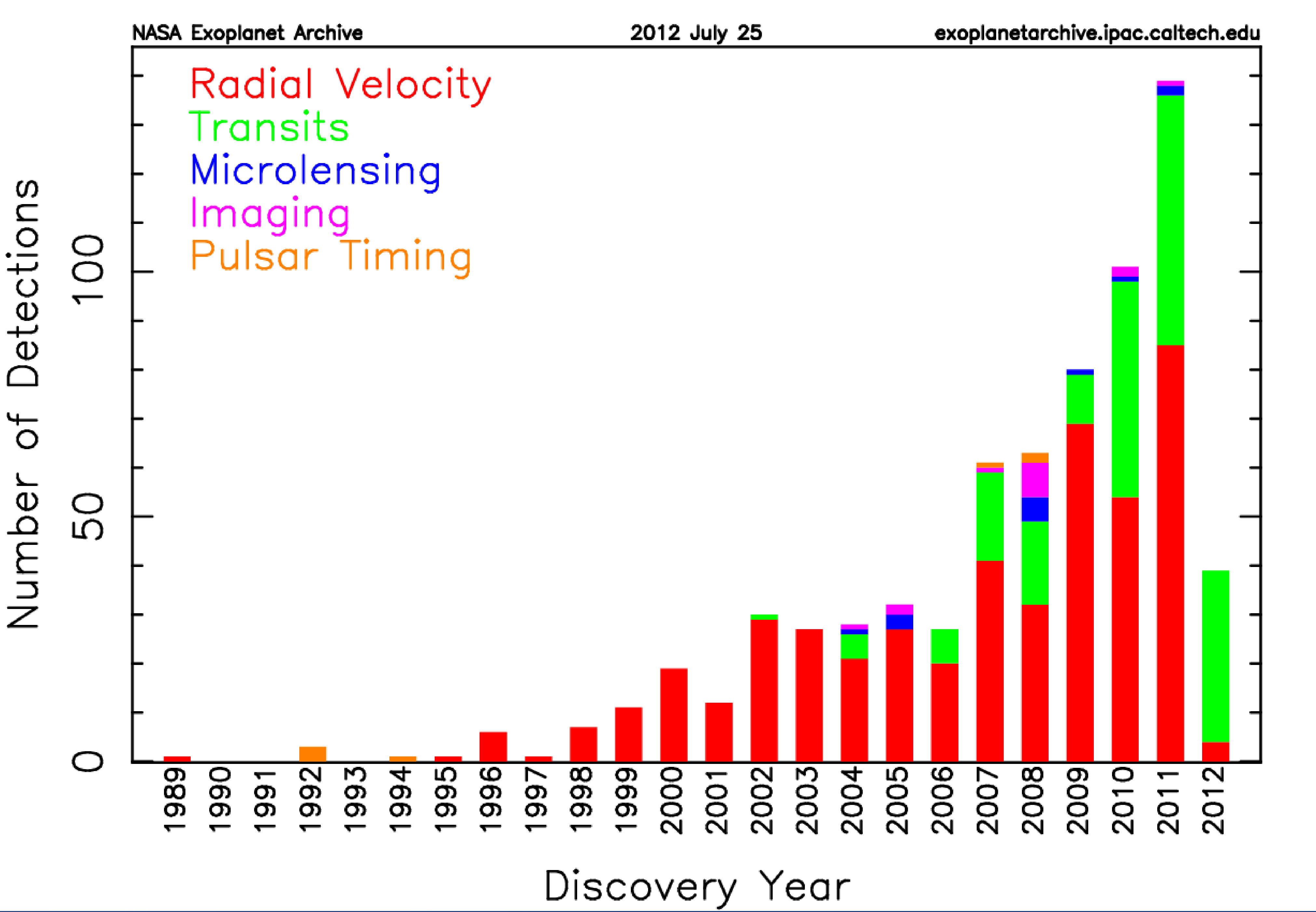
Planetary mass—radius diagram, ground vs. space



128*
52

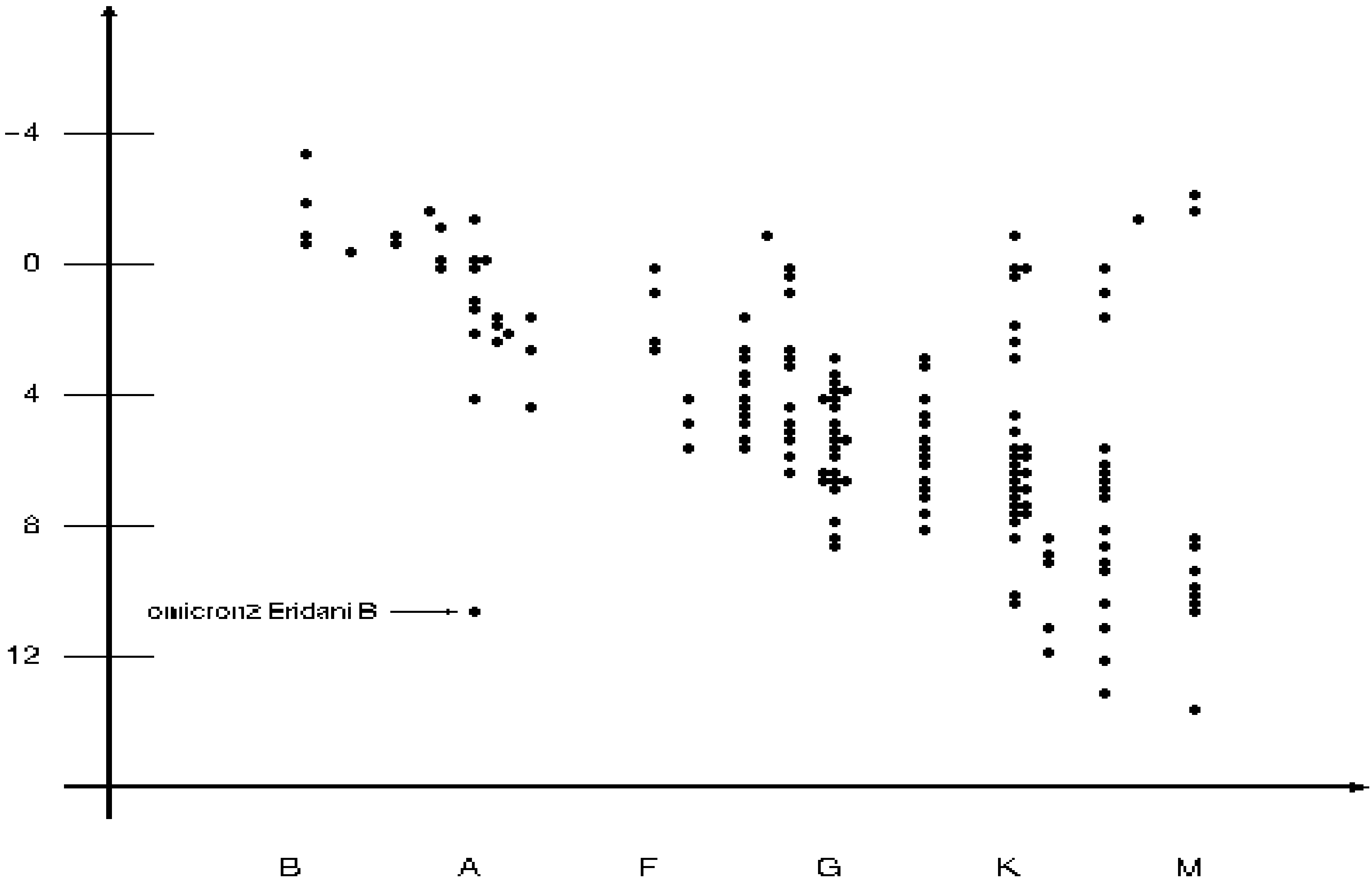
*Submitted to peer reviewed journal and posted on astroph

Statistics

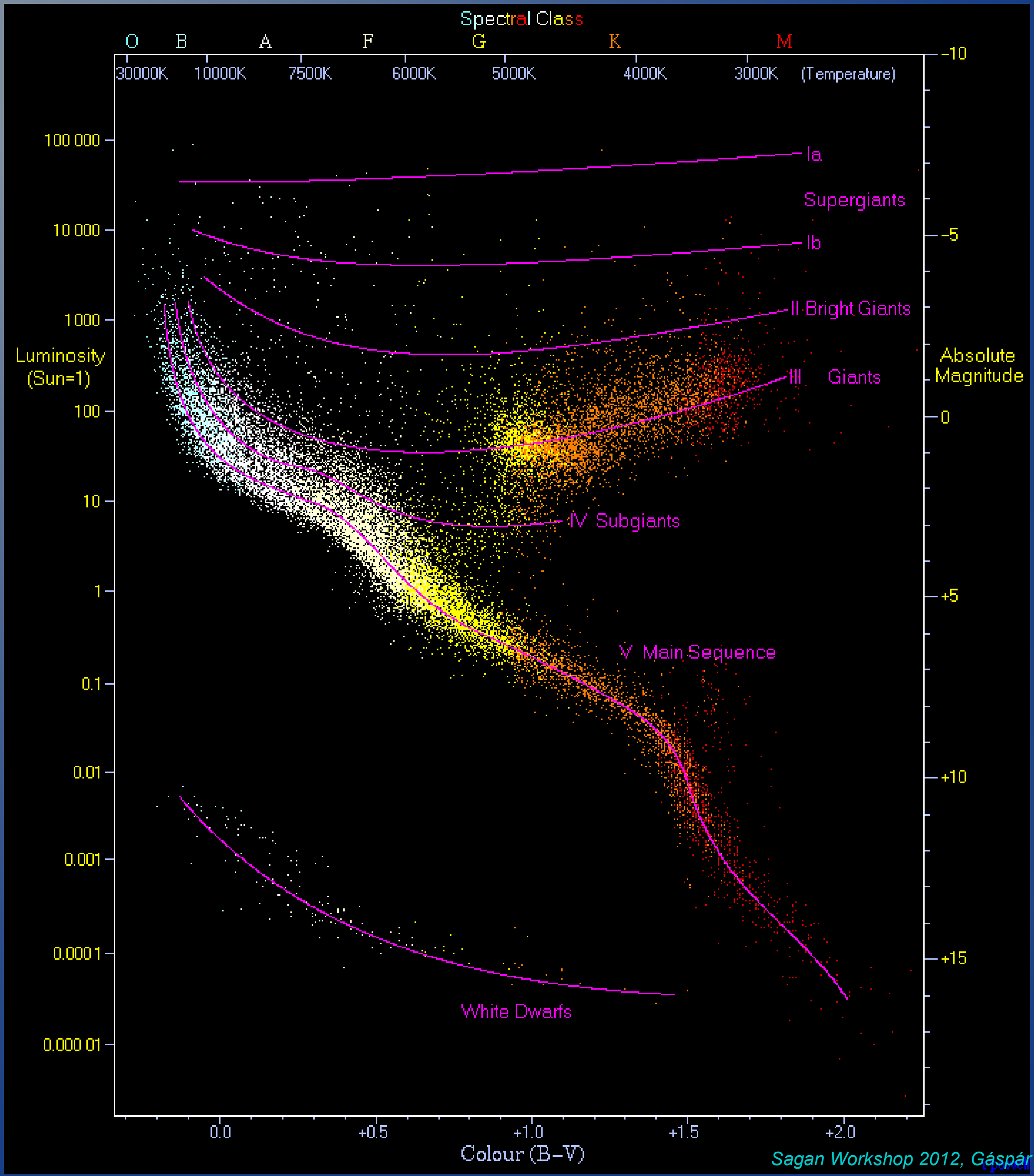


Thanks to Stephen Kane

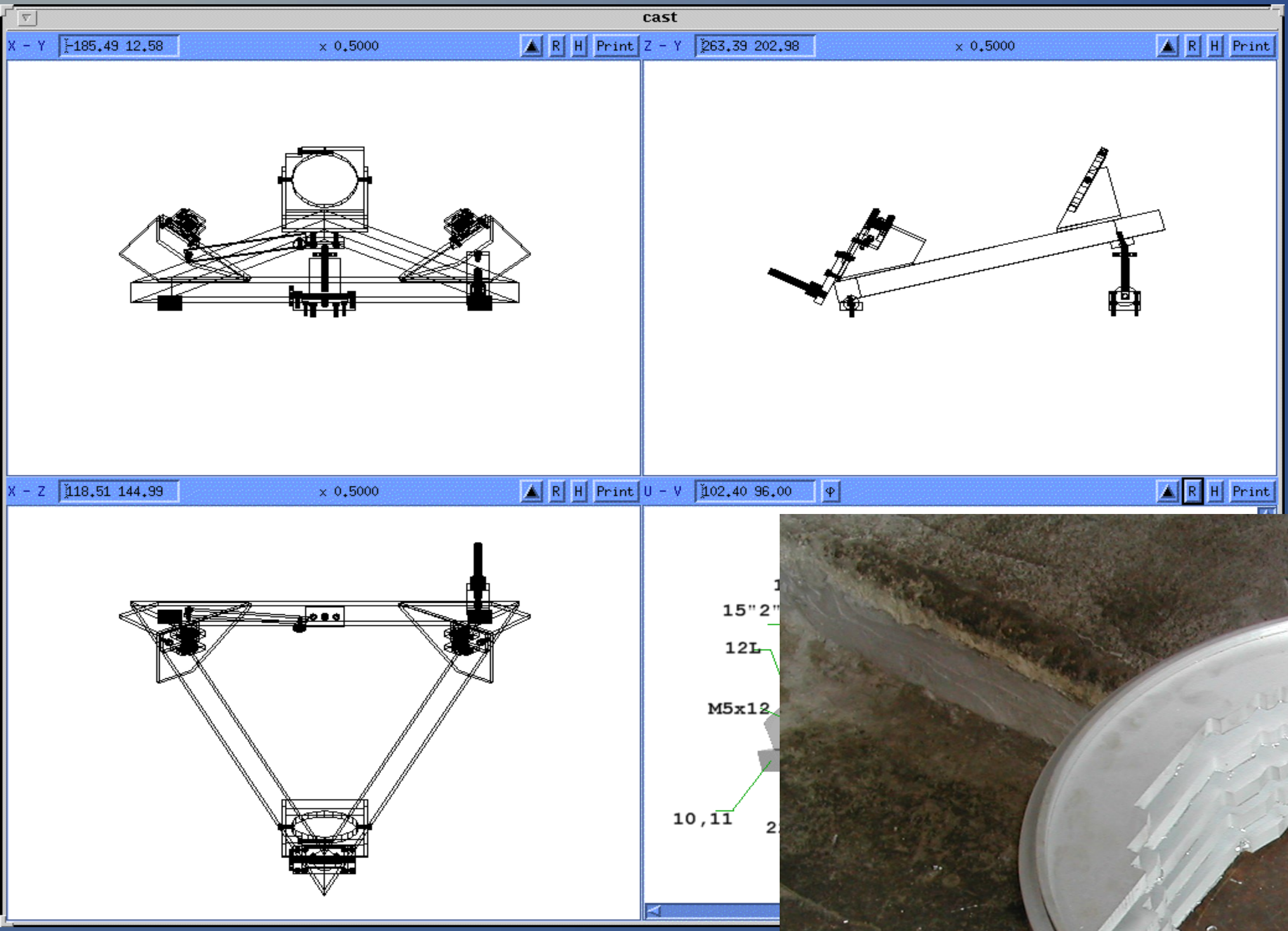
Russell's original “HR” diagram, 1911



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, 4º x 4º FOV, each with 1K x 1K pix frame txfer CCD
- Multi-color
- No moving parts.

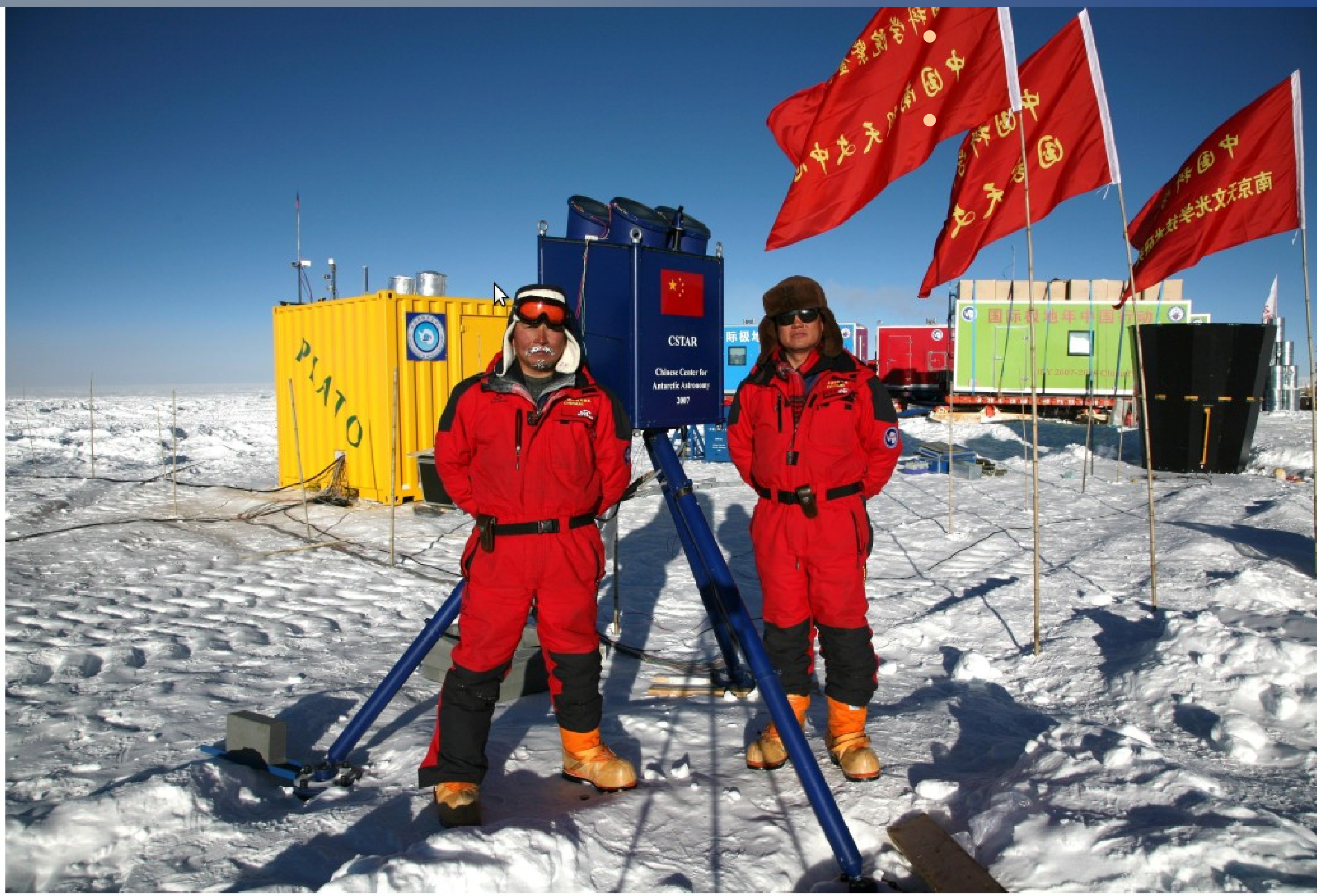


Fig.7. CSTAR in Dome A (Installed by Prof. Xu Zhou and Zhenxi Zhu)

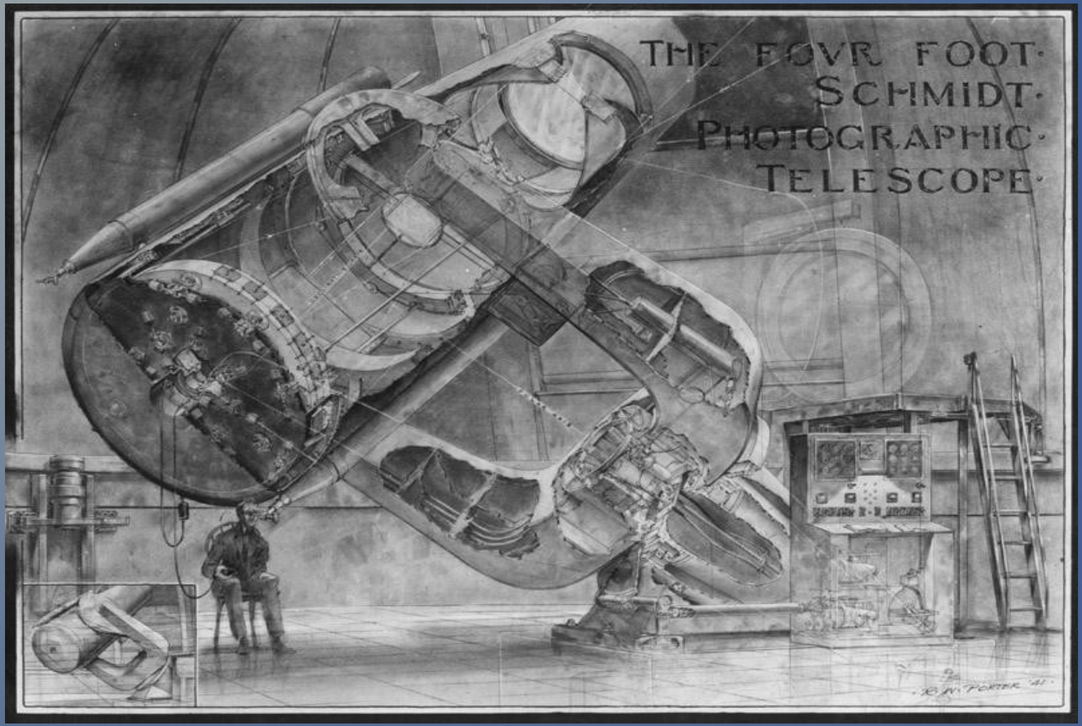
Present/planned surveys with no TEPs (yet) – ASTAR

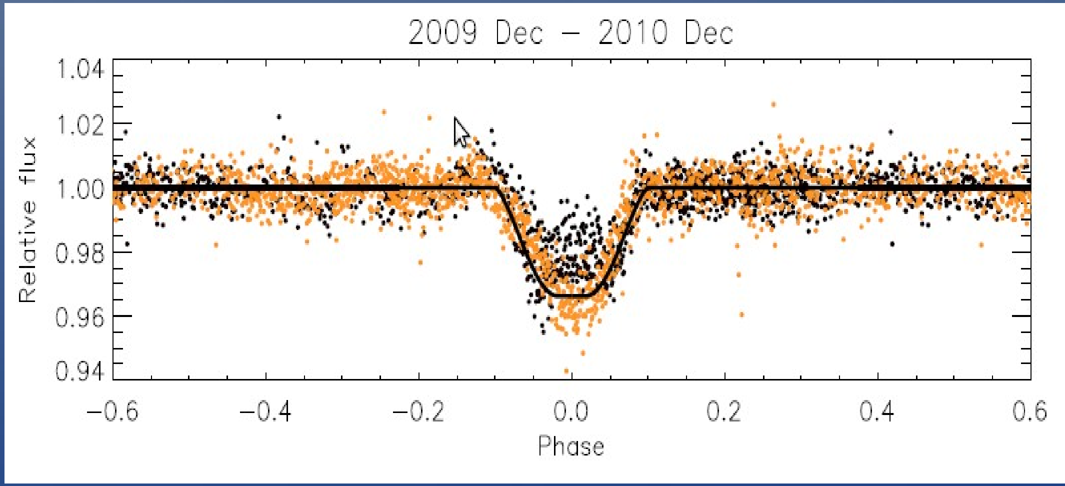
- 1 station: Dome A
- Operational: 2012? →
- 3 x 0.5m telescopes, 4º x 4º FOV. Schmidt telescope (-like).
- Multi-color
- First one installed to Dome A

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

- Dome C
- PI: Tristan Guillot
- ASTEP-400: 0.4m telescope with 1.2º x 1.2º 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

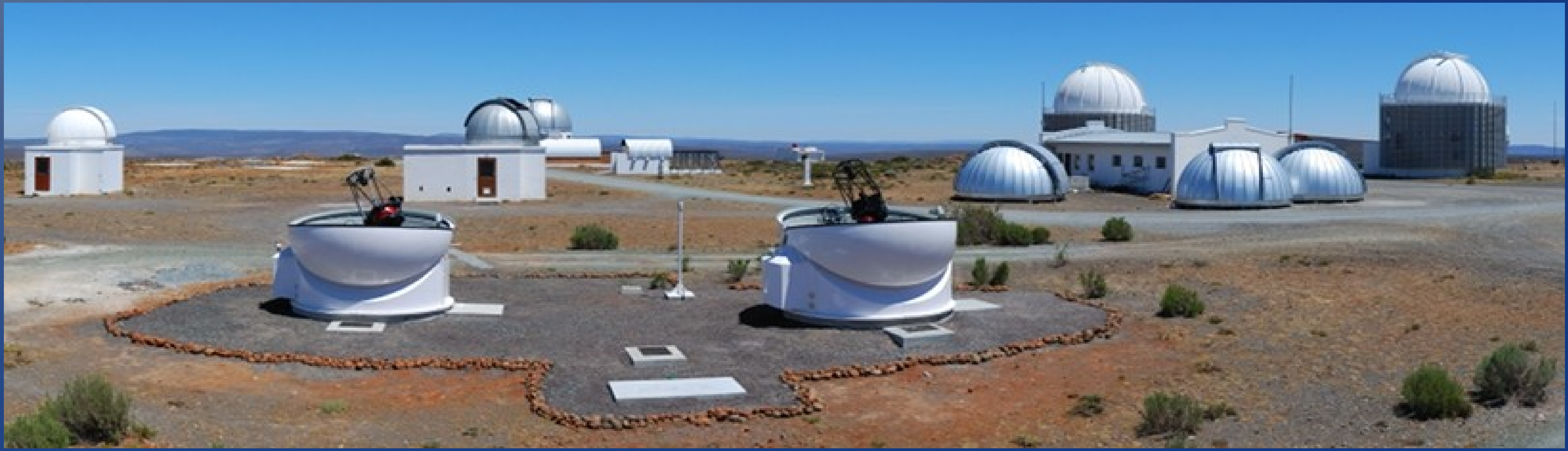




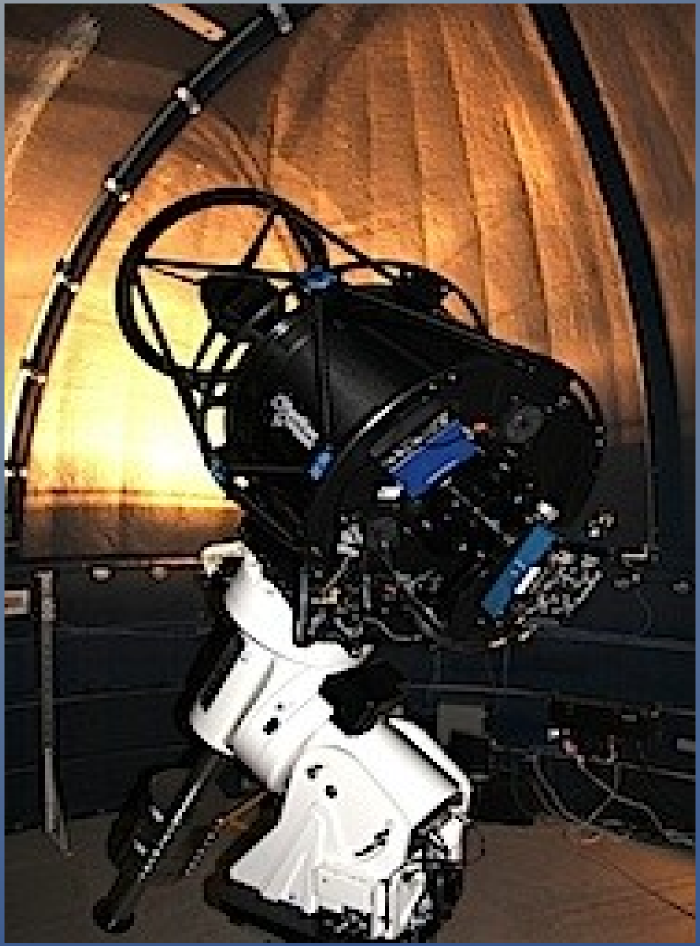
- Palomar Transient Factory, PTF/M dwarfs, PTF/Orion project.
- PI: Shri Kulkarni.
- Palomar 1.2m Schmidt telescope + giant mosaic CCD yielding 2.7º x 2.7º FOV
- 3000 M dwarfs per exposure, cycling through 8—10 fields.
- 2009 – present
- 14 eclipsing M dwarfs, one planetary transit candidate around a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

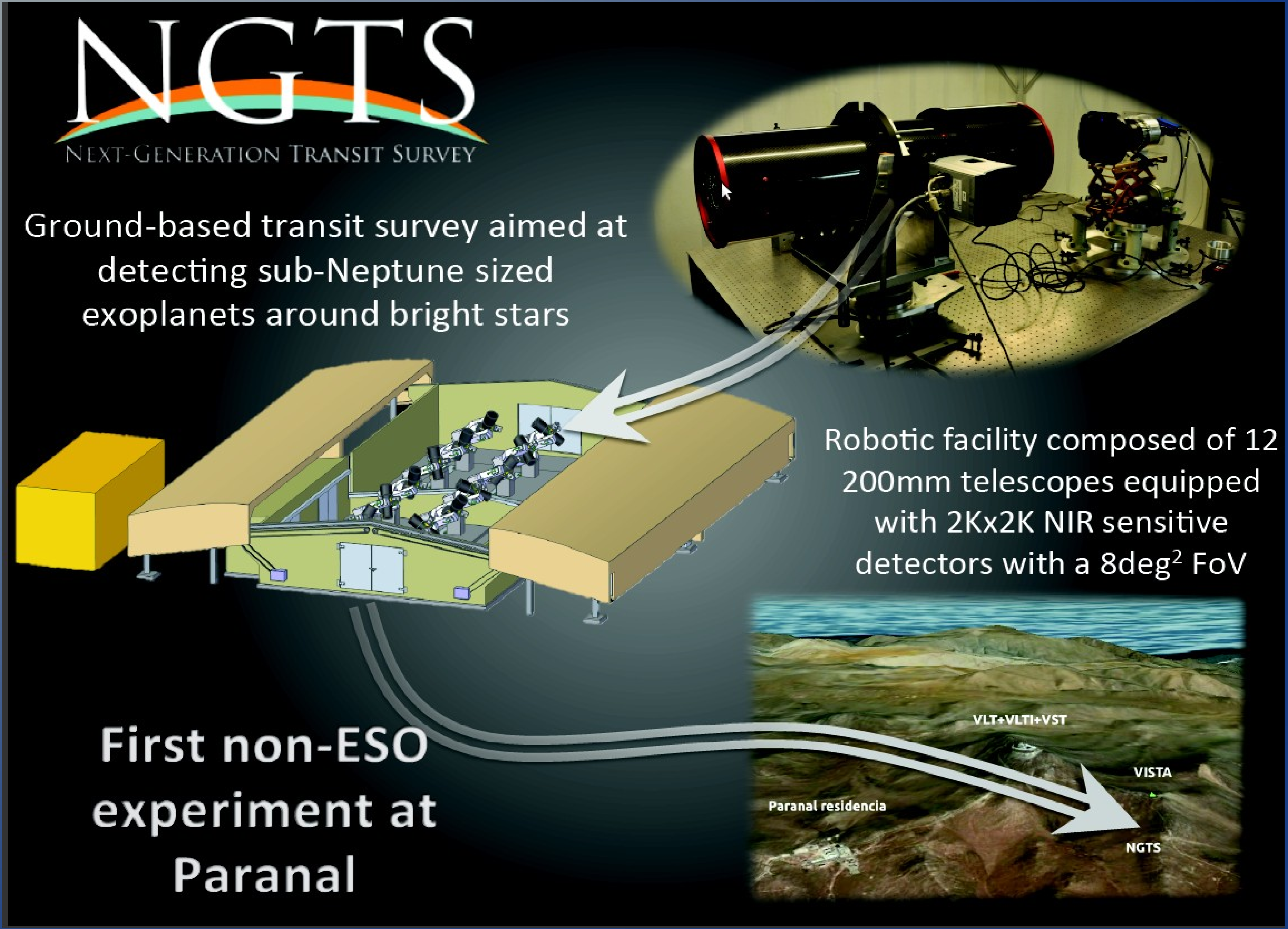


Dunlap Institute Arctic Telescope and Wide-field cameras in the High Arctic



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

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



See poster from Neveu

Dedicated to TEP follow-up – TRAPPIST

- 0.6m telescope, 22' x 22' field.
- PI: Michäel 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.

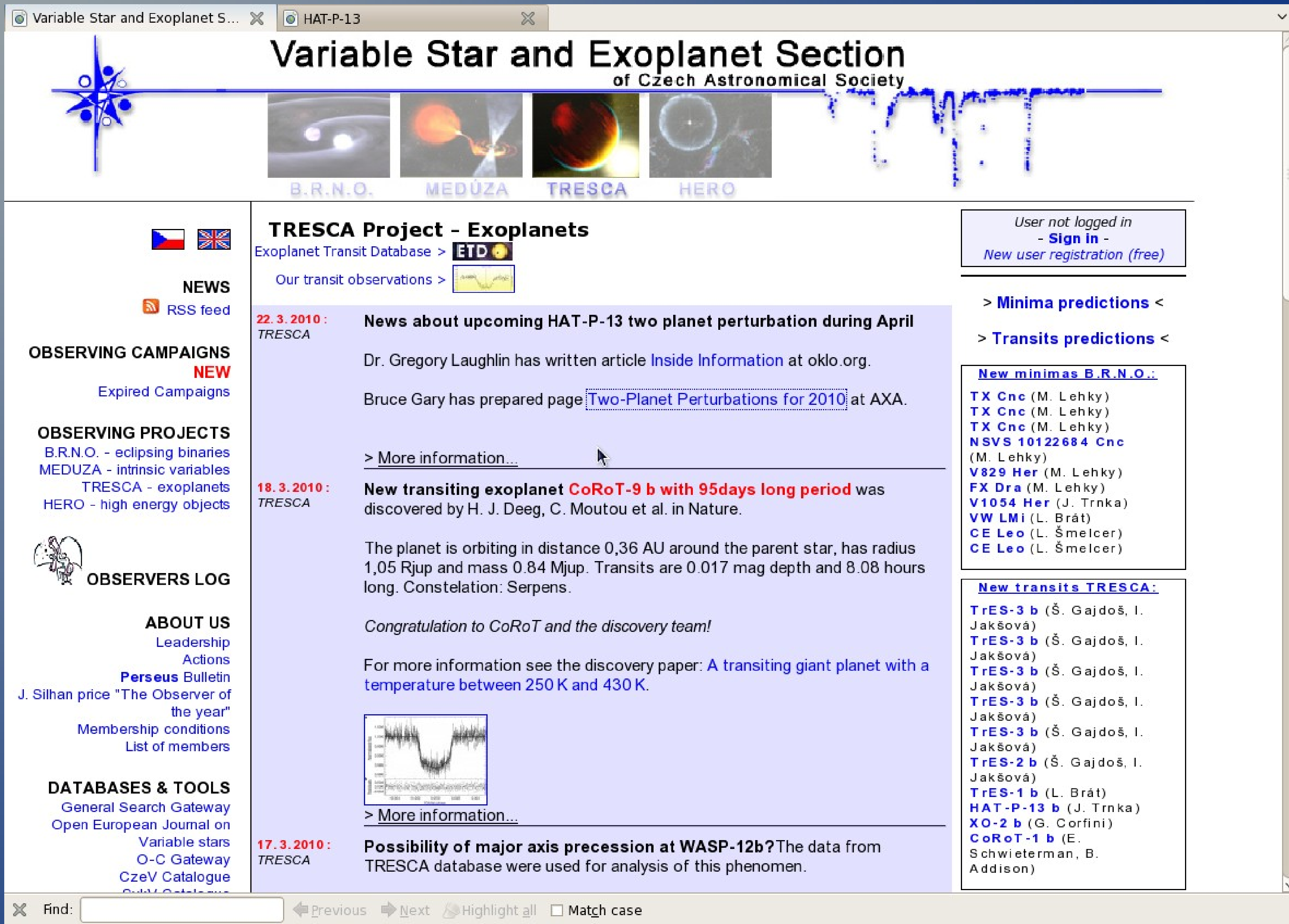
St. Luc – GJ 436b

- 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, 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



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.

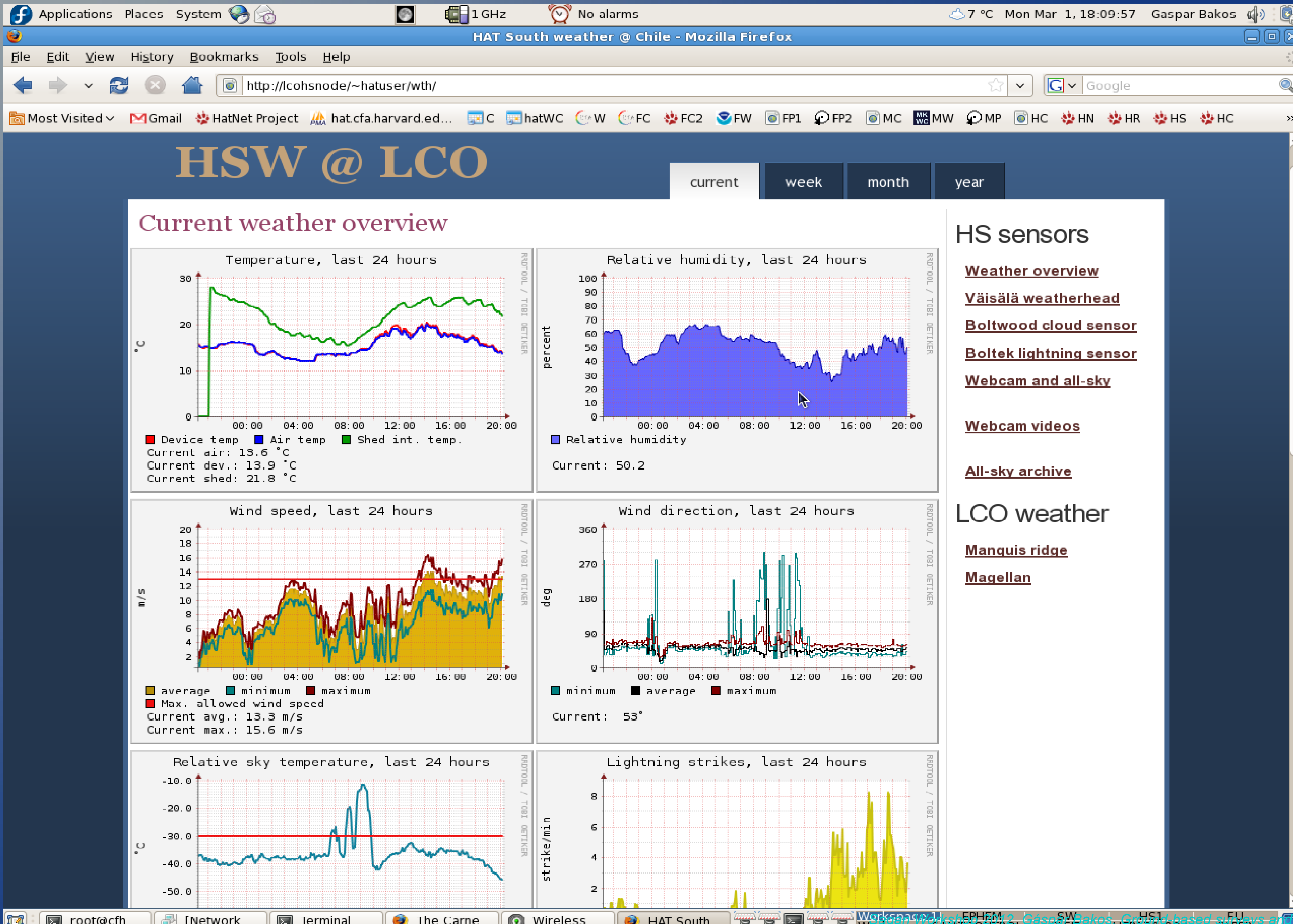

HATNet at FLWO 2010-01-24 08:33:00


HATSouth @ LCO 2011-06-06 12:45:10 (local time)

HATs at Mauna Kea

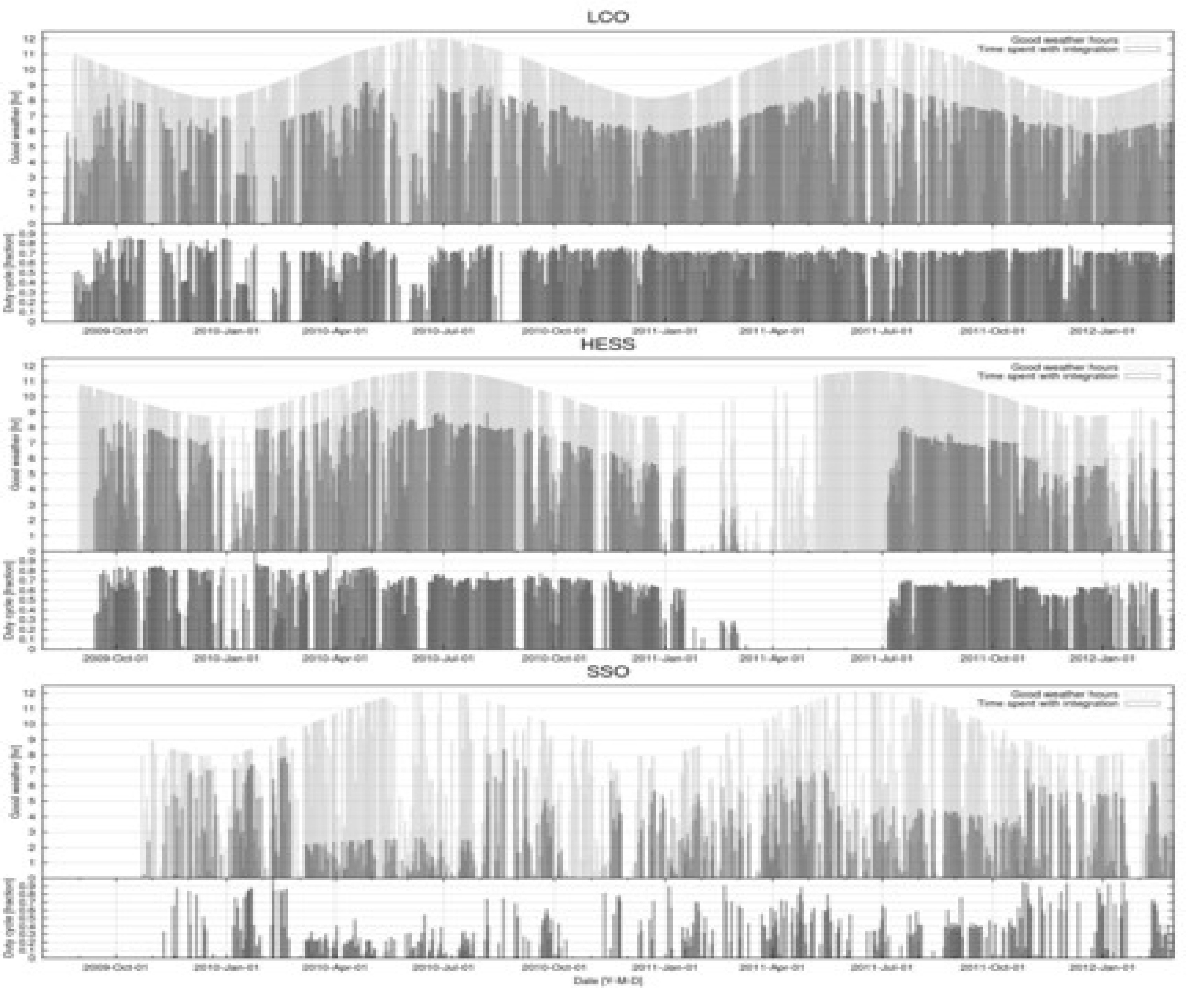

HATSouth @ Namibia 2011-04-20 03:19:23 (GMT+1 ; no local time zone!)

HAT-South LCO weather station

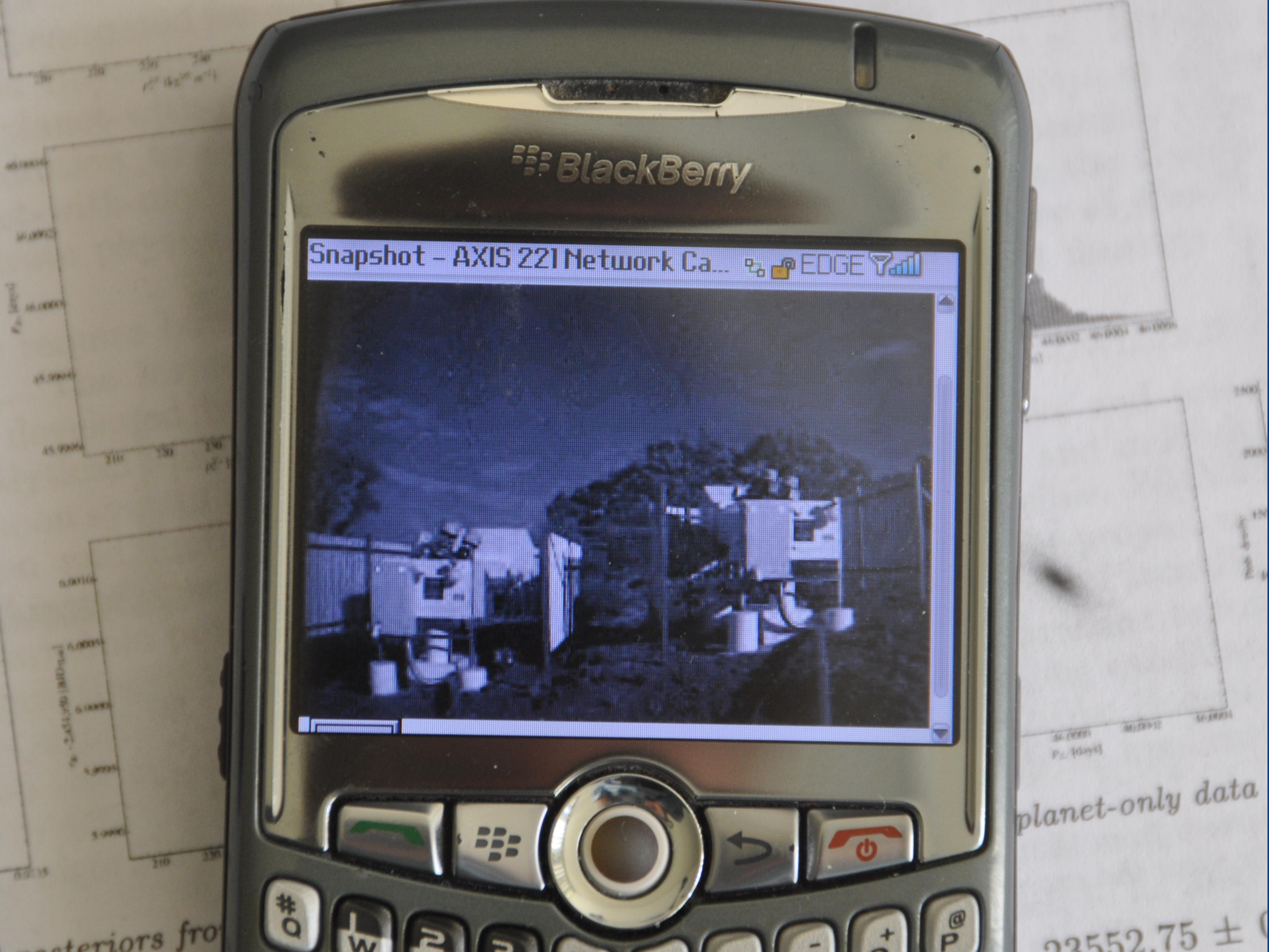


All-sky (fisheye) image

Detailed weather-logs

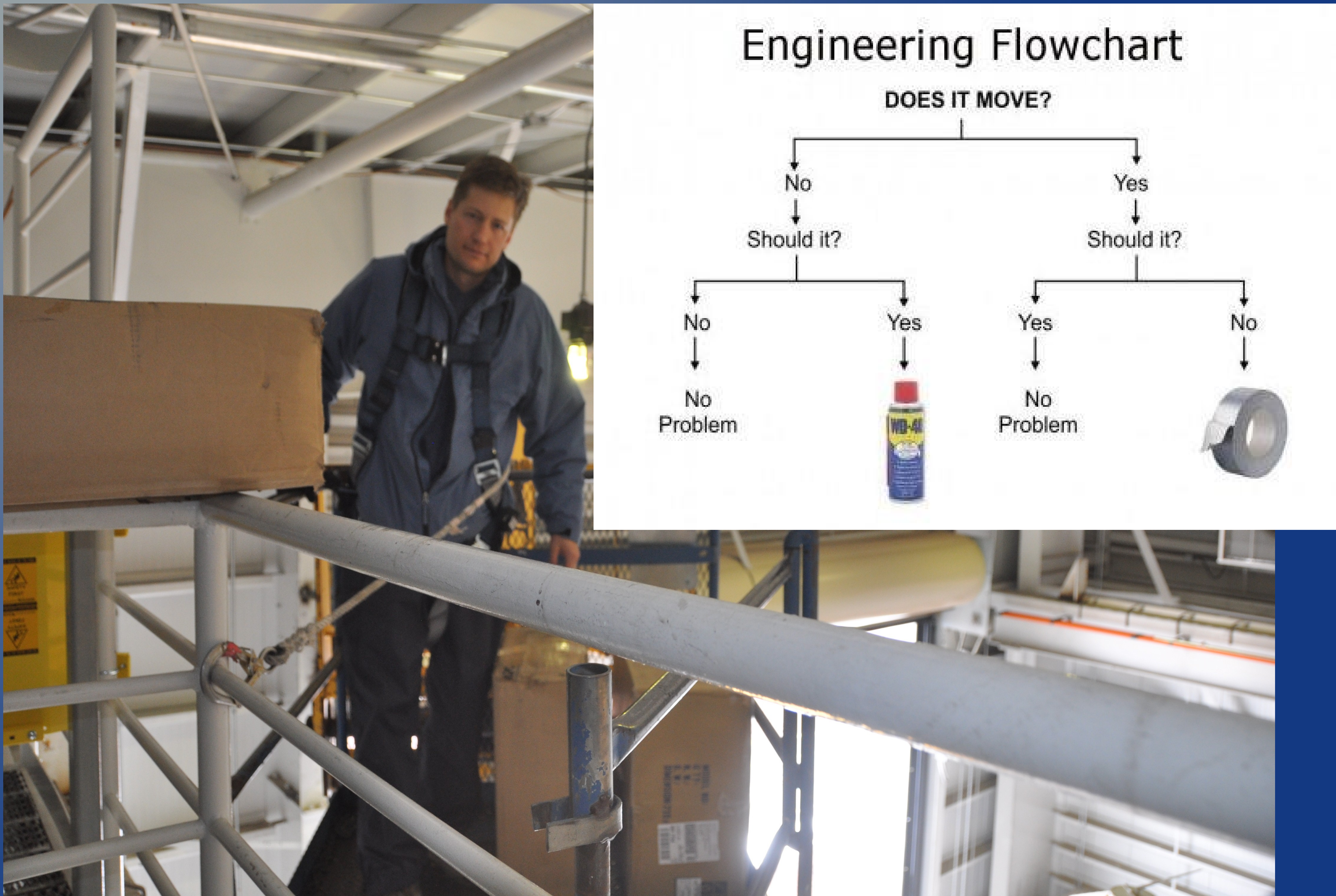


LCO: 8.48 hrs
HESS: 7.15 hrs
SSO: 4.64 hrs


BlackBerry
Snapshot - AXIS 221 Network Ca...
EDGE
planet-only data

Servicing, repairs and maintenance

Servicing, repairs and maintenance

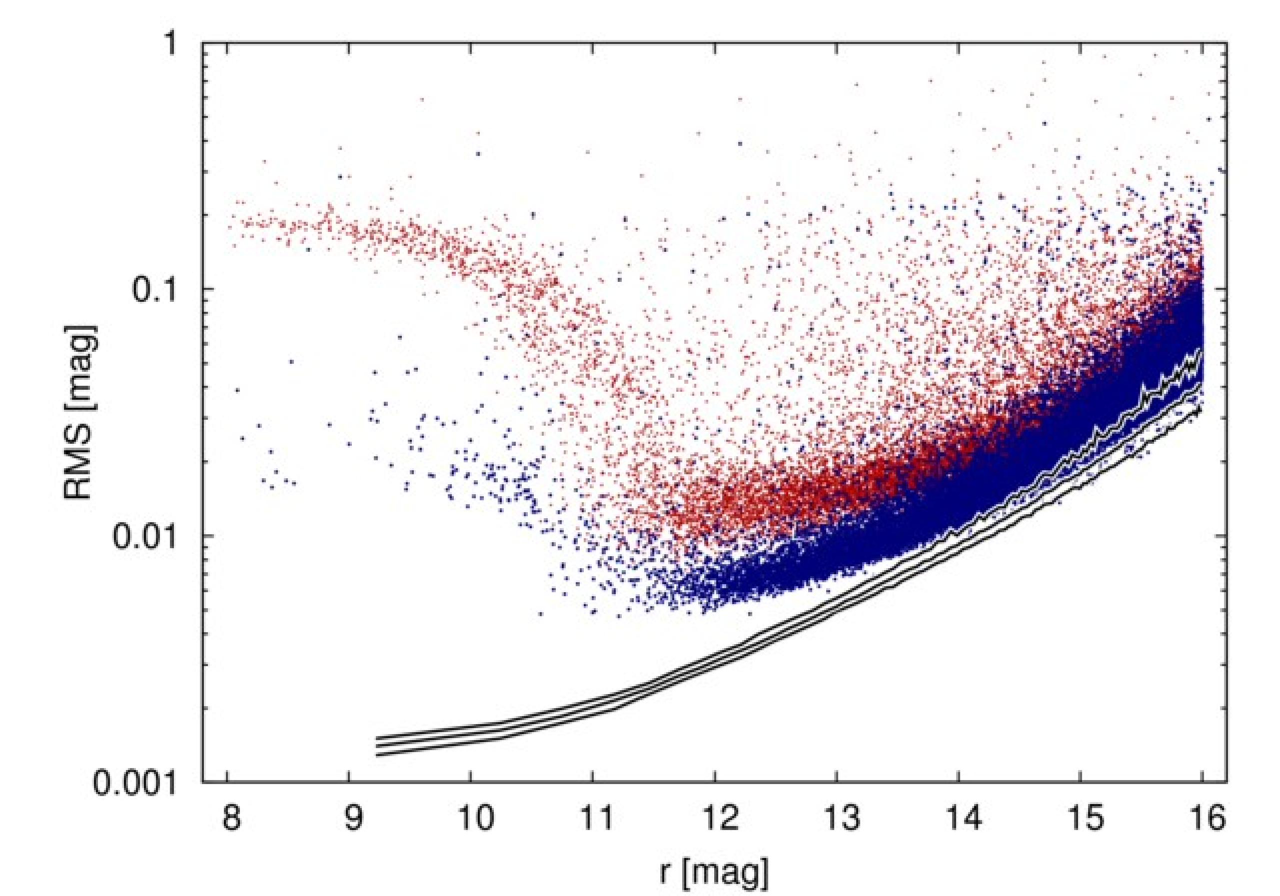


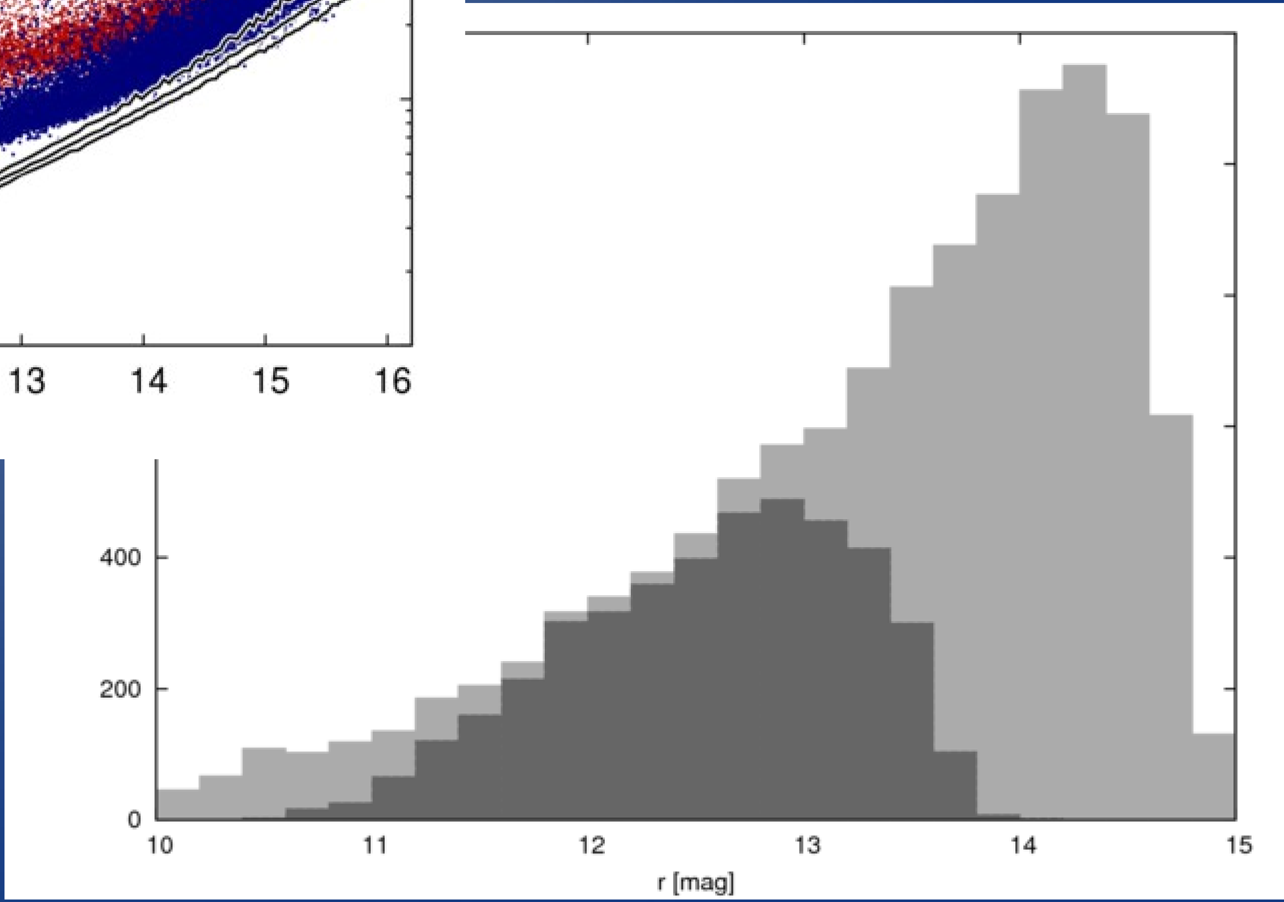
Data reduction

- 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.

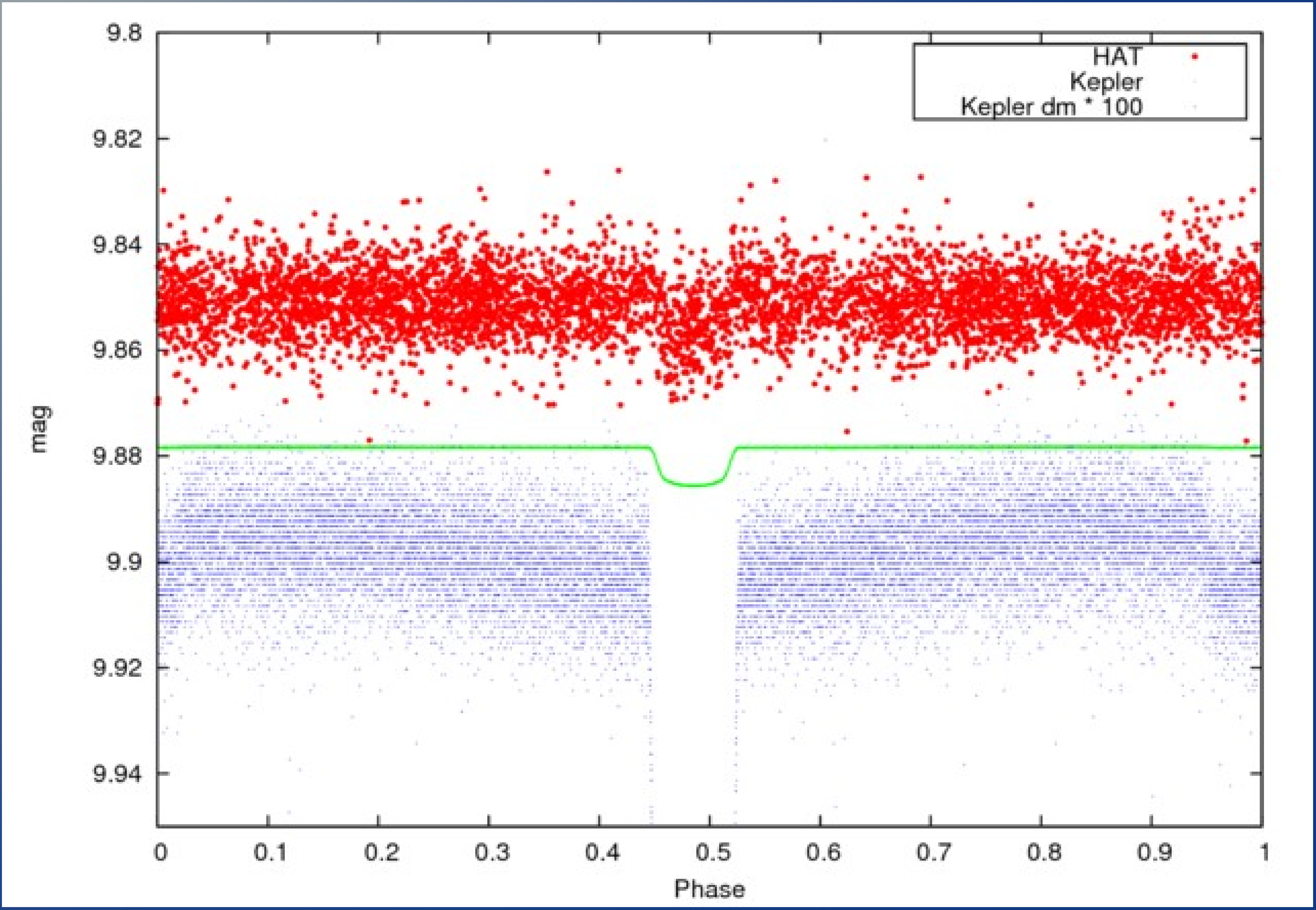
Data volume can be daunting

Photometric precision



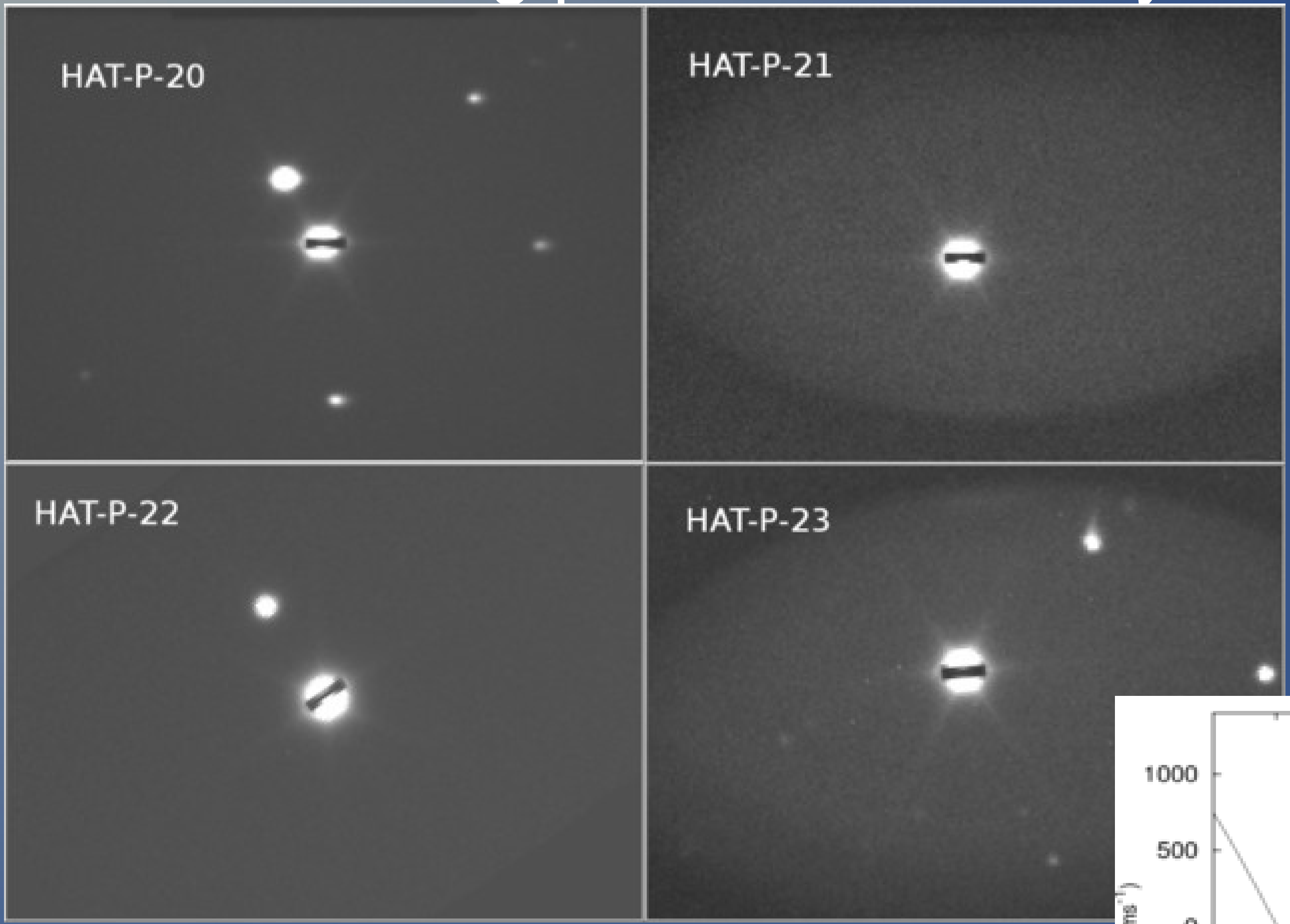


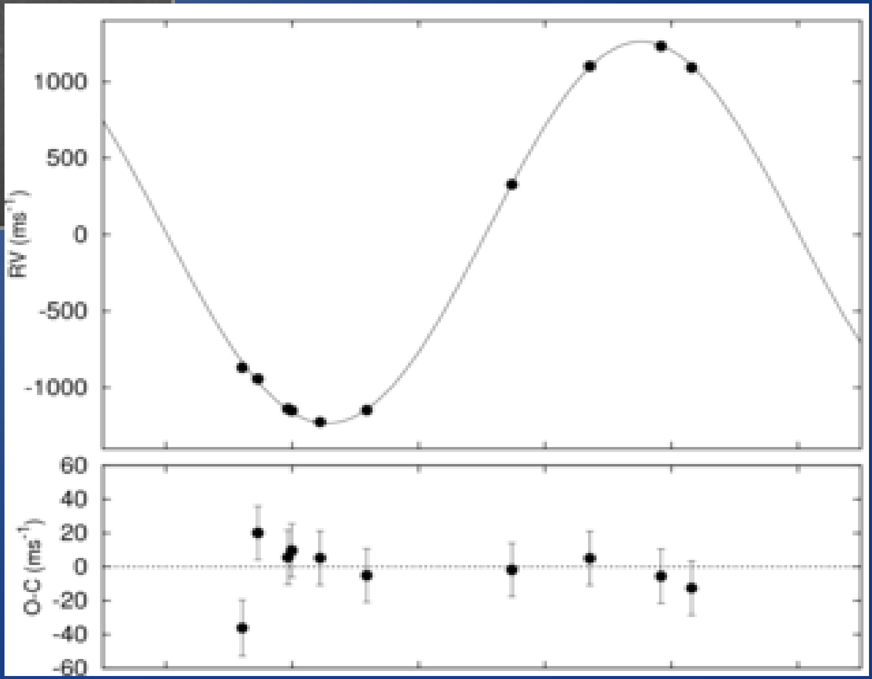
HAT-P-7 ground vs space



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

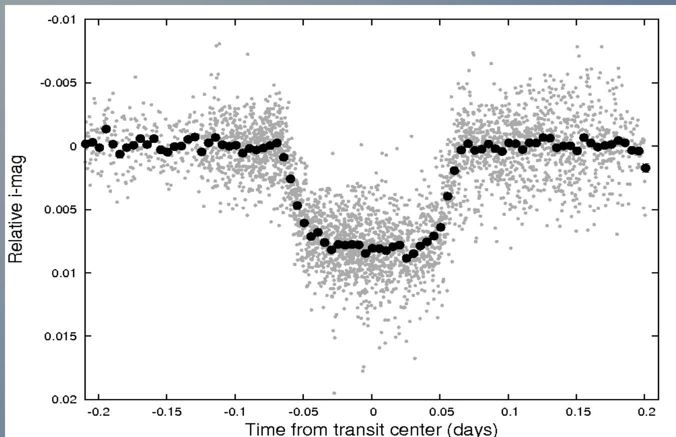
Transiting planets with binary stellar companions

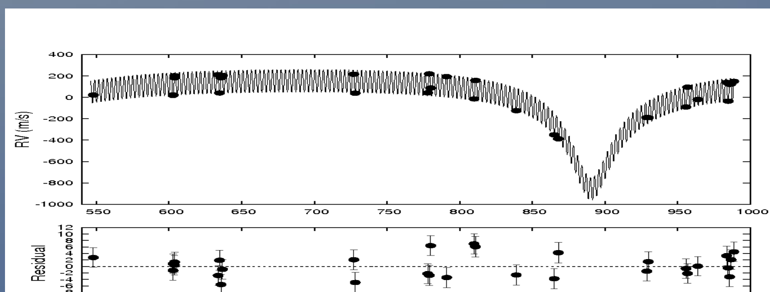


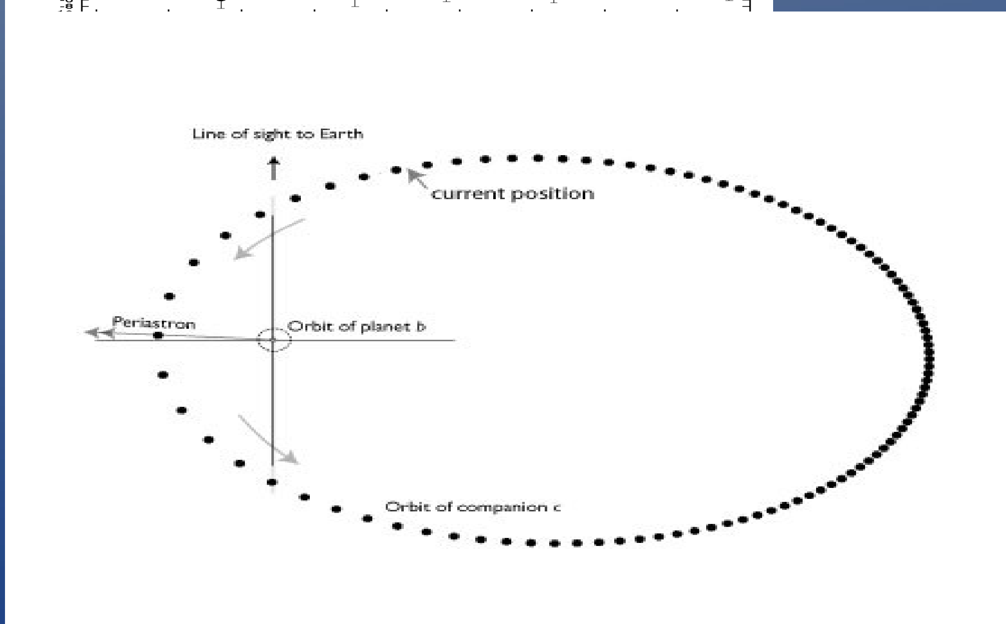


Bakos et al. 2010,ApJ

Showcasing two examples







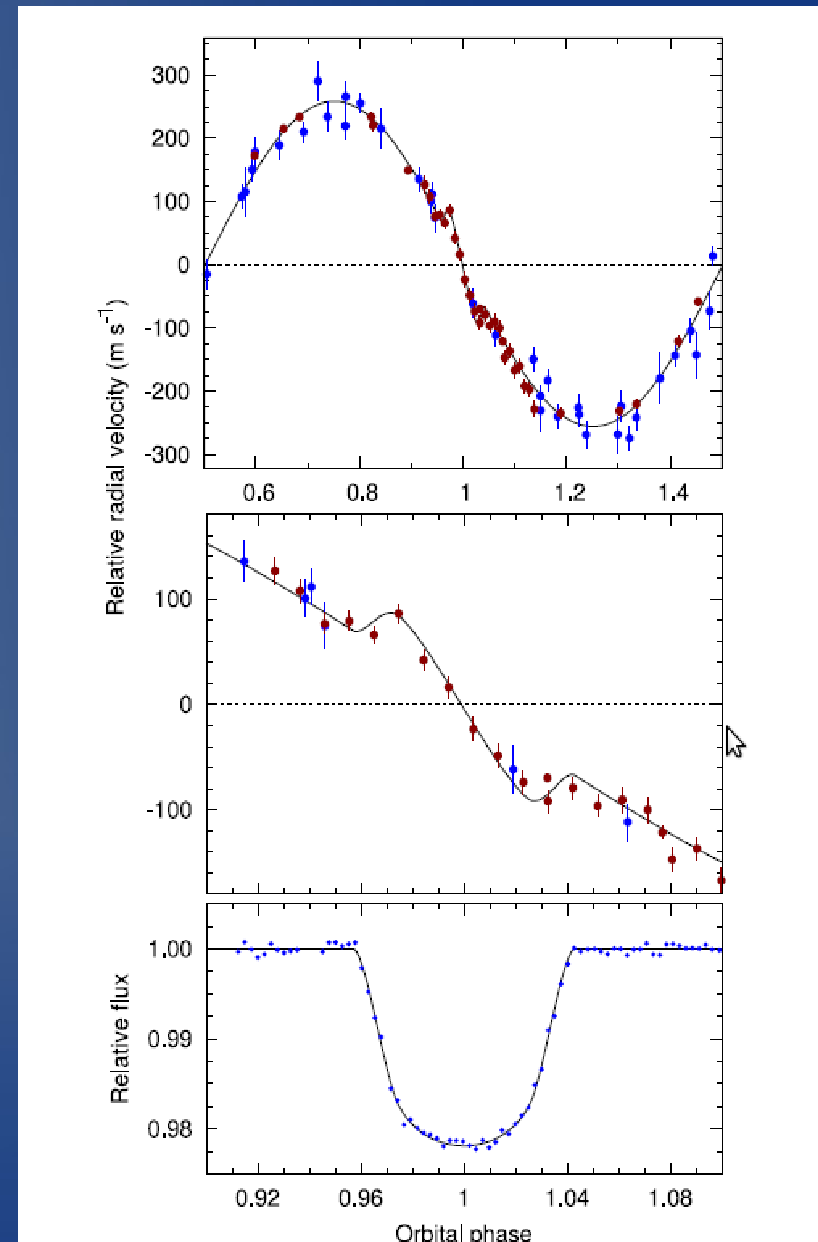
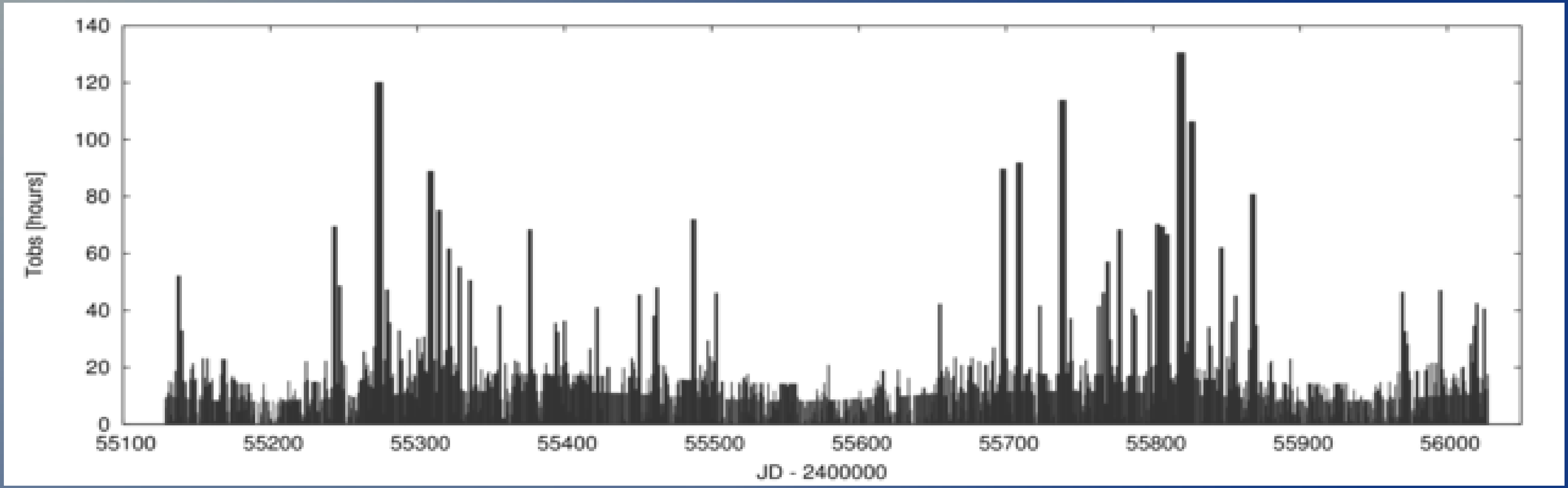
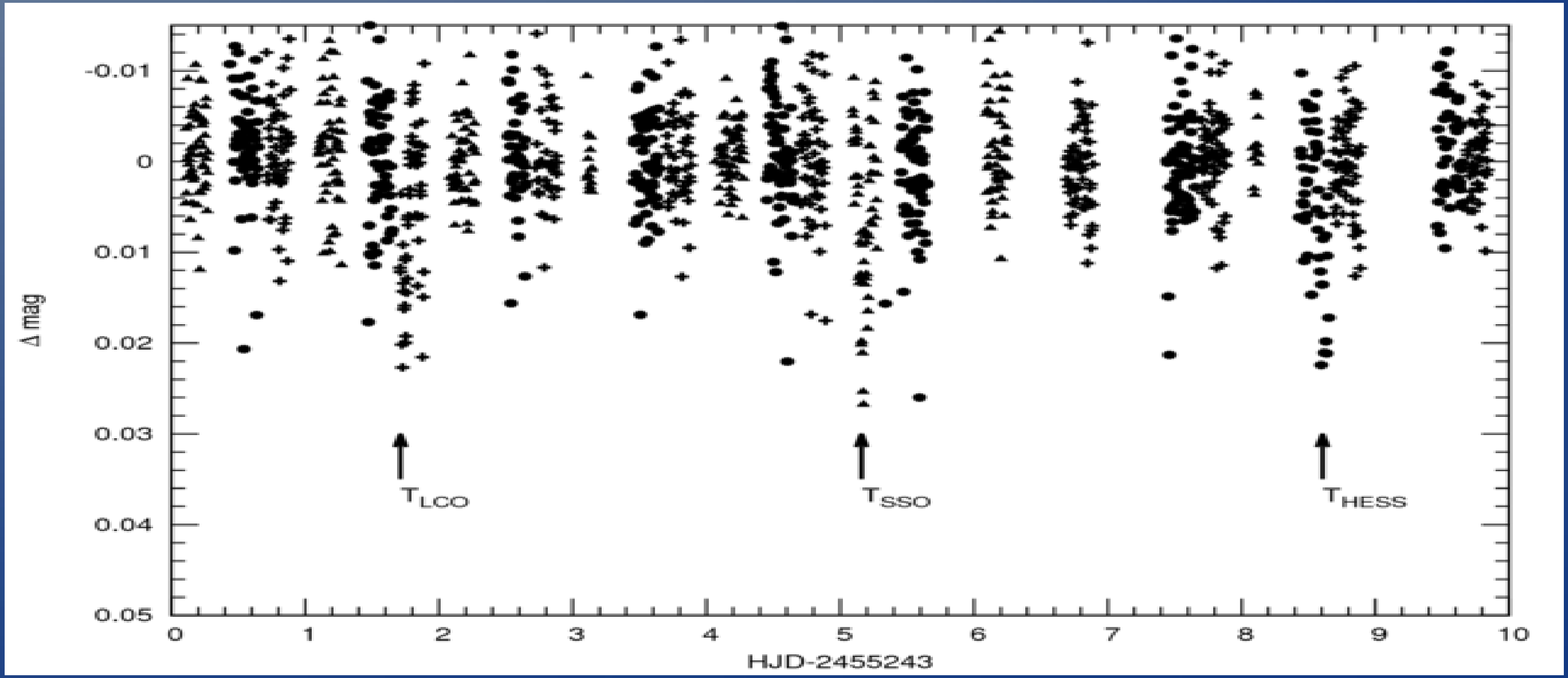


Figure 1. Top: the HARPS (brown) and CORALIE (blue) radial velocities of WASP-19 together with the fitted model. Middle: the transit region shown expanded. Bottom: the NTT transit light curve and fitted model.

(A color version of this figure is available in the online journal.)

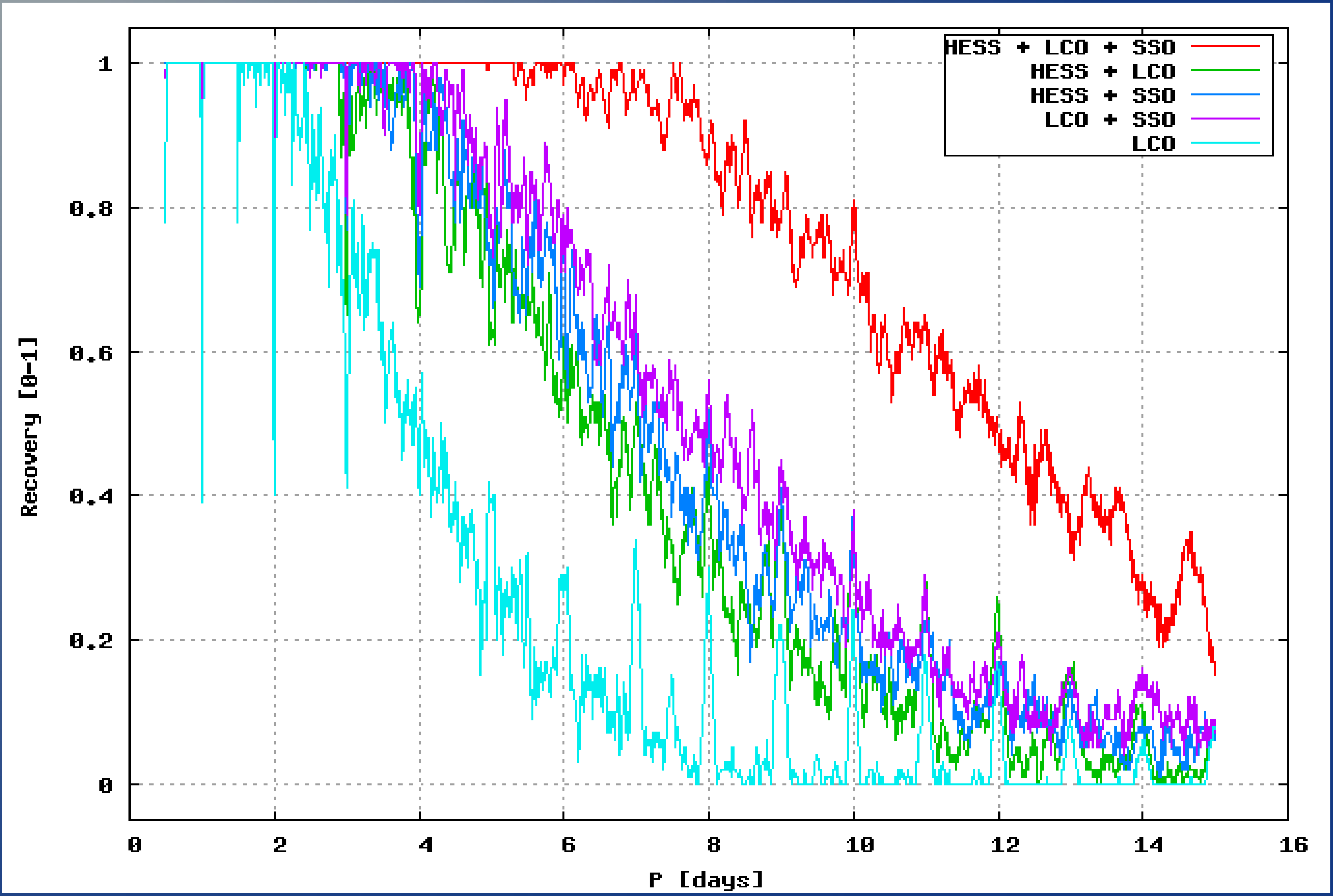
Stretches of clear weather



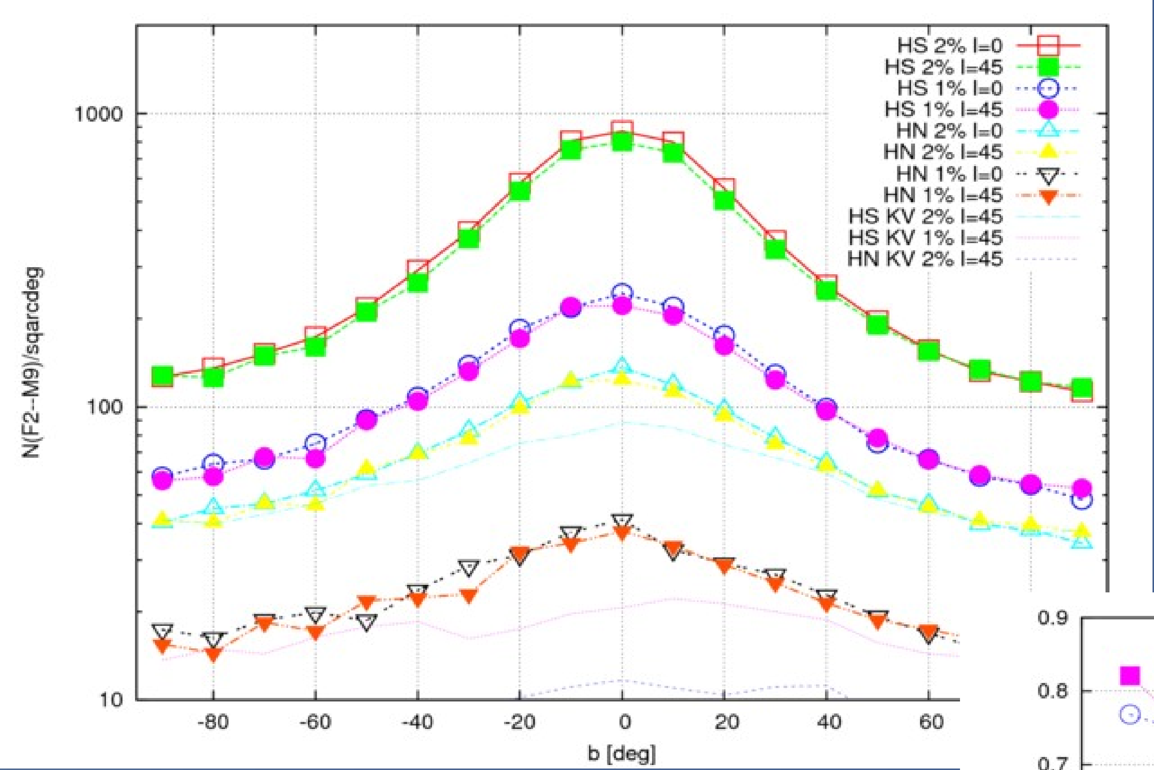


From HATSouth. See Bakos et al. 2012, PASP and Penev et al., 2012, AJ

Transit recovery function



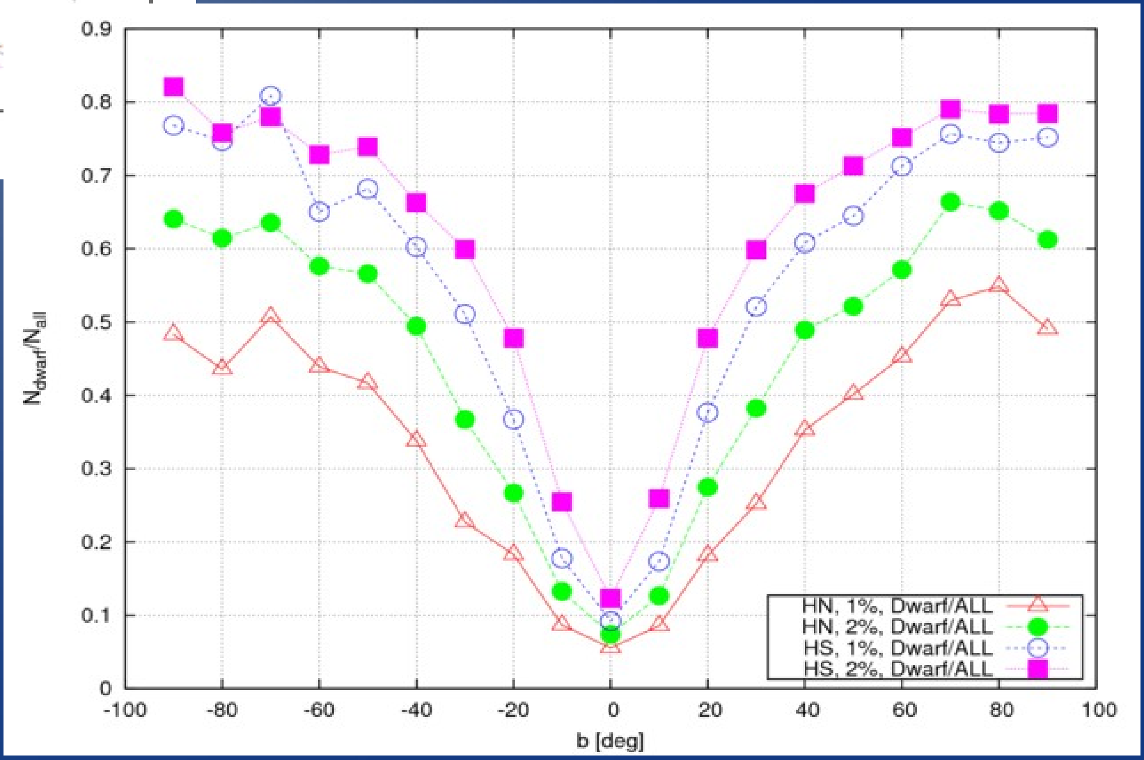
Stellar populations



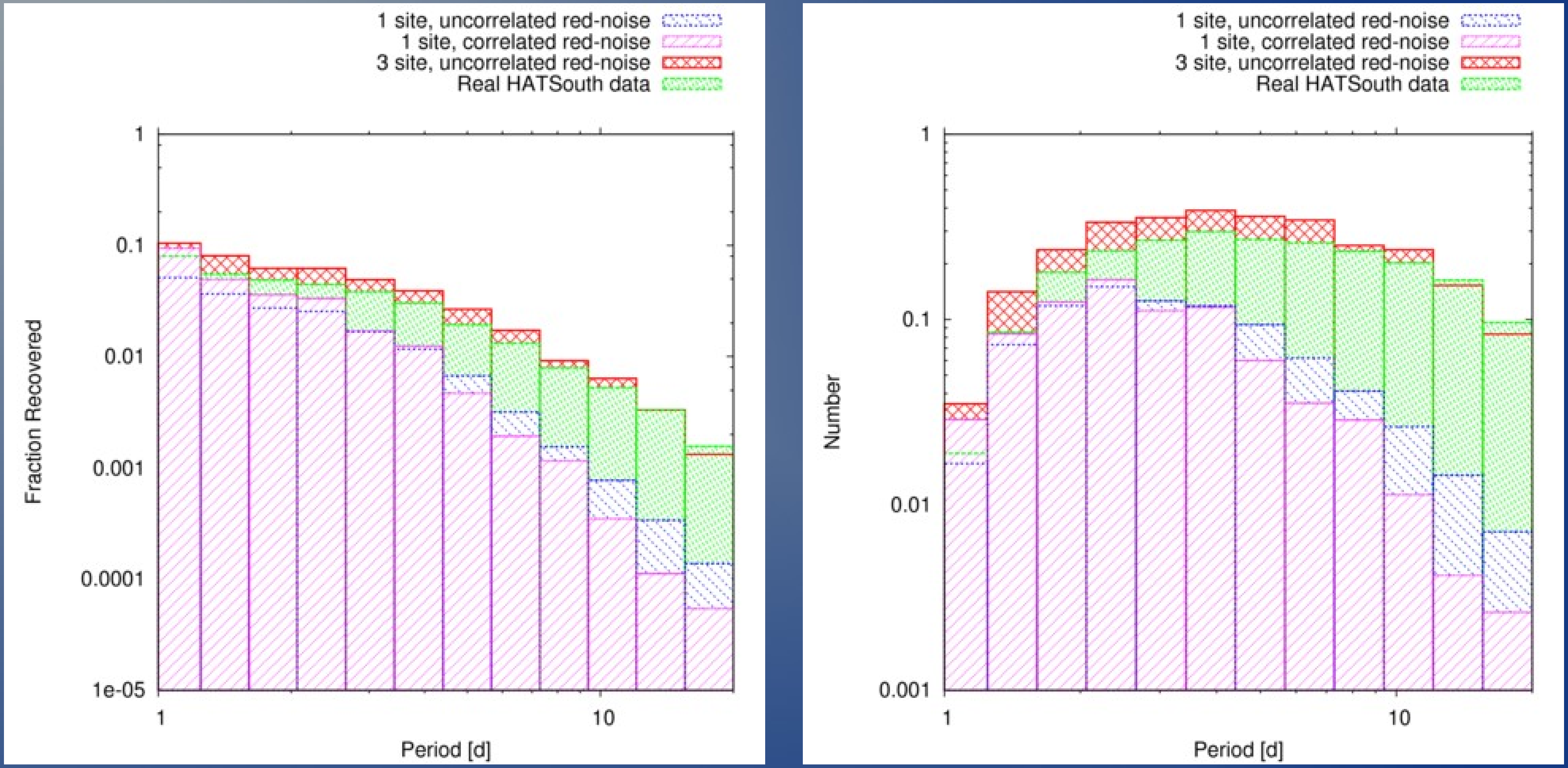
- 137/□° F2—M9 dwarfs with 1% photometric precision = 100,000/yr
- 374/□° with 2% rms = 290,000/yr
- 12,000 K dwarfs /yr @1%
- 770 M3V—M9V / yr @ 2%
- 1500 TEP candidates @ <= 2%

Precision matters:

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

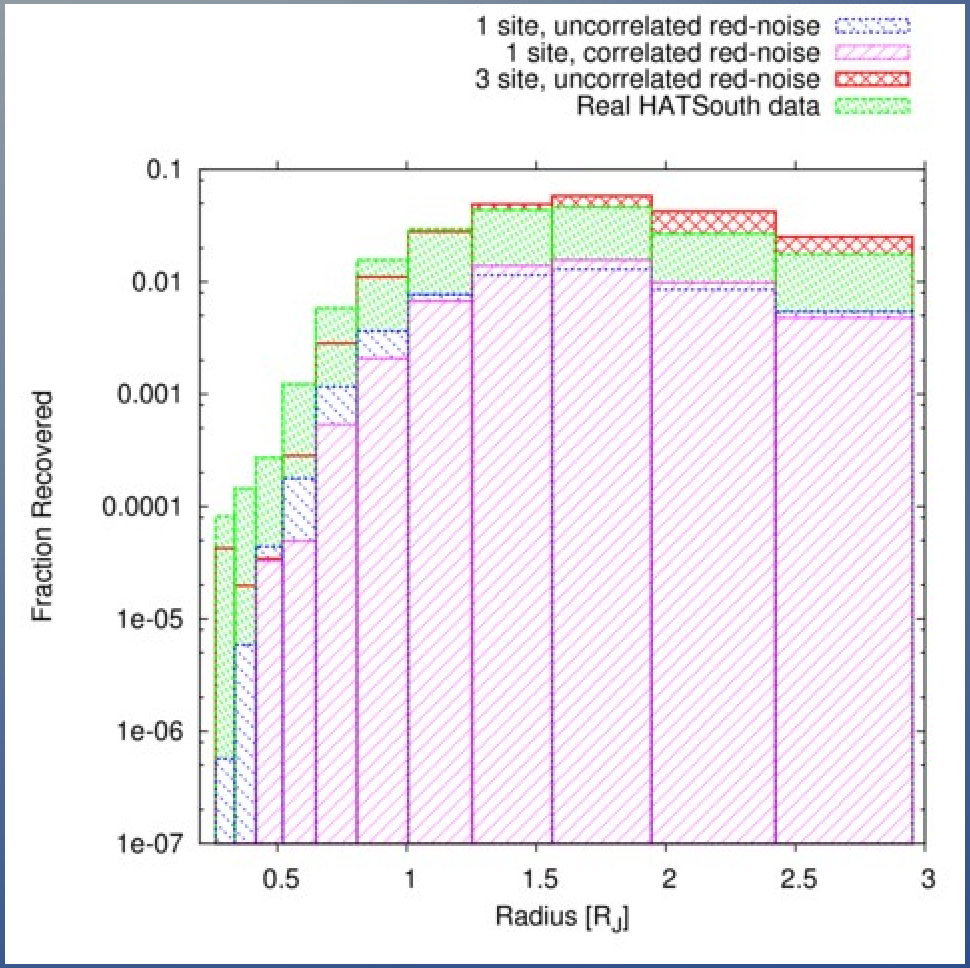


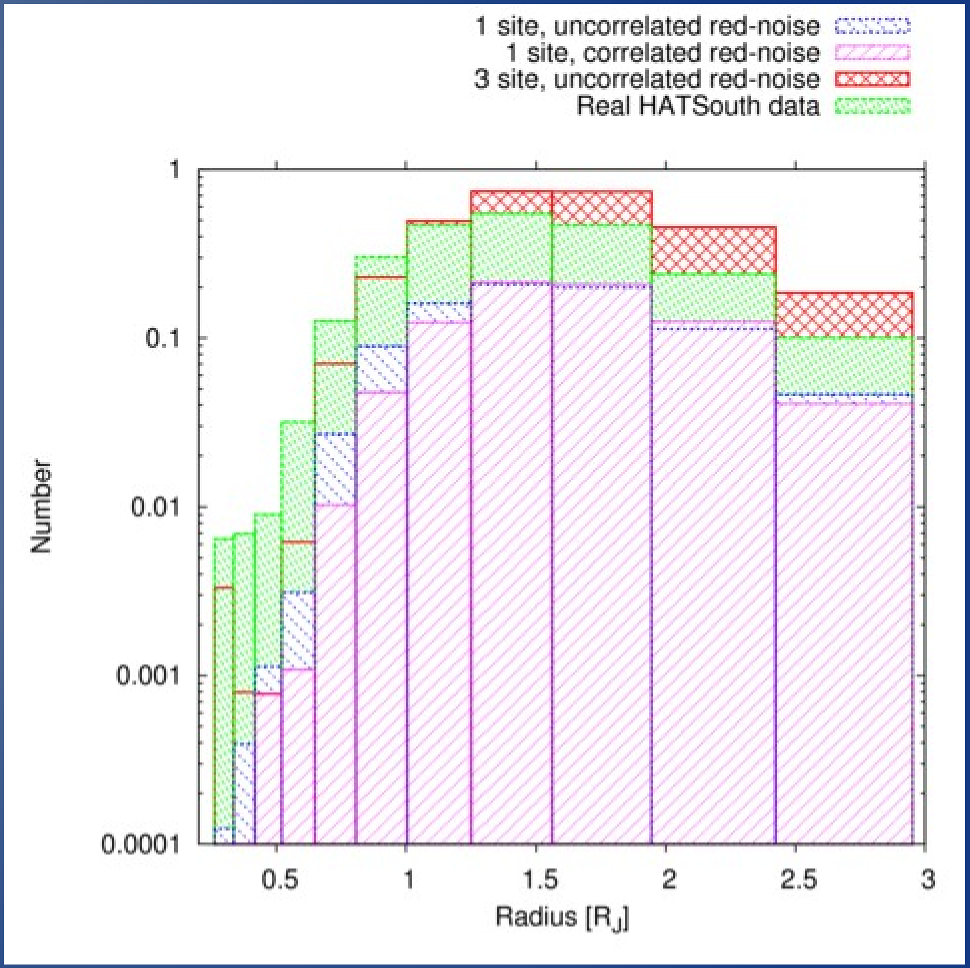
Yield calculations



- 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.