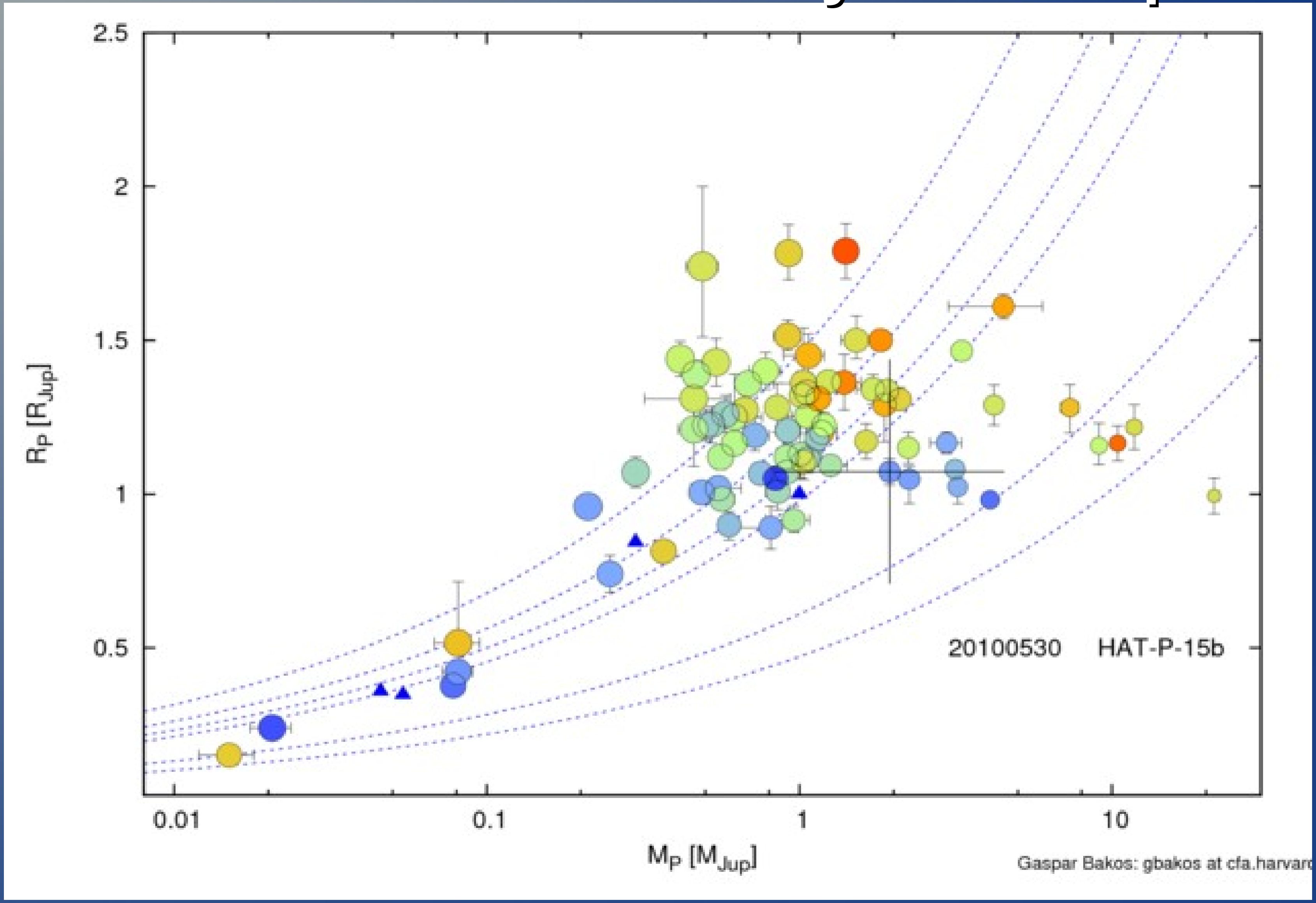
Ground-based Surveys for Exoplanets



Talk given at 2010 Sagan Exoplanet Summer Workshop
July 27, 2010

Gáspár Bakos
National Science Foundation Fellow
Harvard-Smithsonian Center for Astrophysics

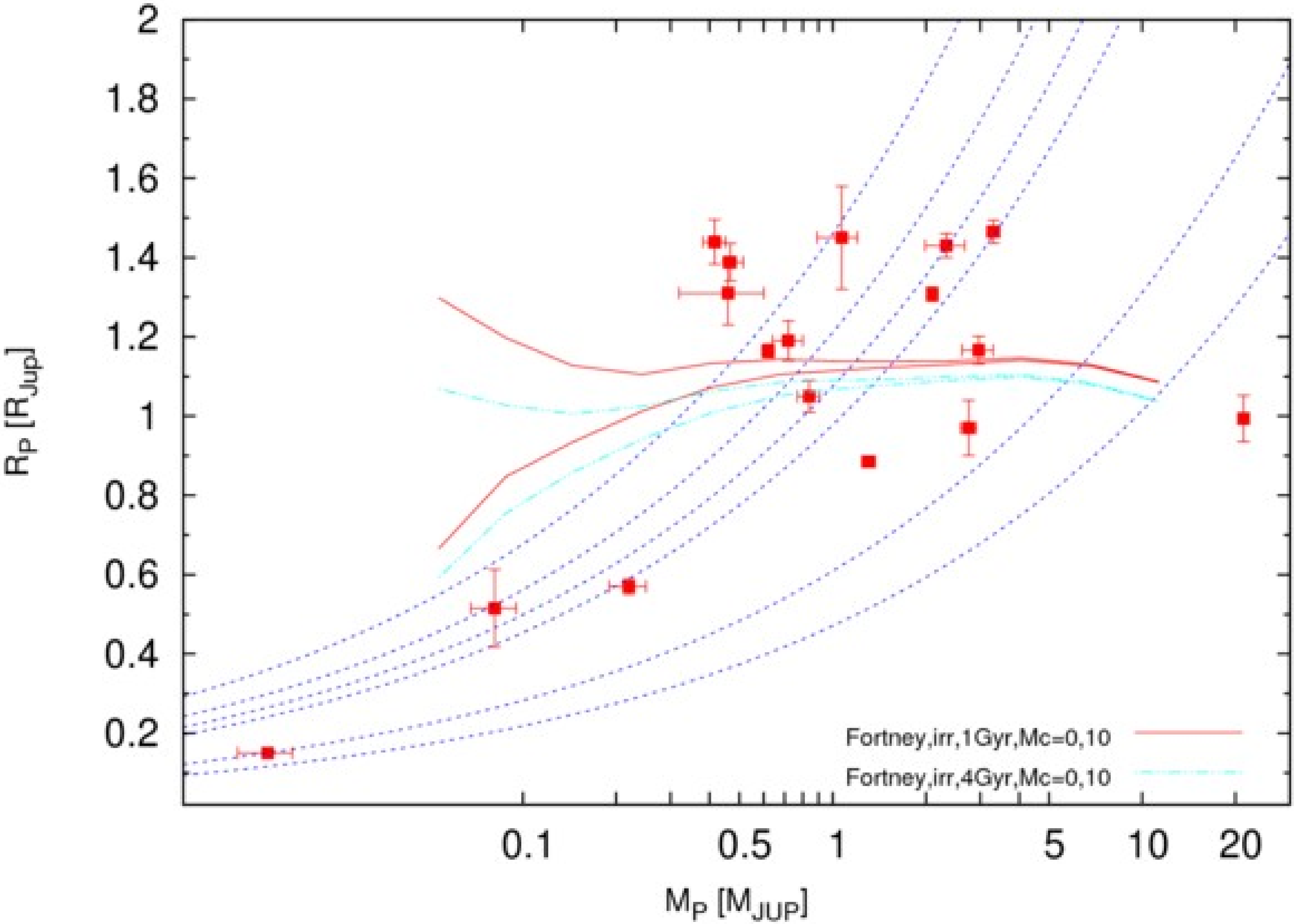
Outline of talk

- Current TEP statistics
- Role of ground-based projects
- Overview of ground-based transit-search projects
- How does a ground-based survey work?
- False alarm statistics
- Limitations of ground-based observations
- The current 86(-19) transiting exoplanets (TEPs)
- Null results and by-products
- Future prospects

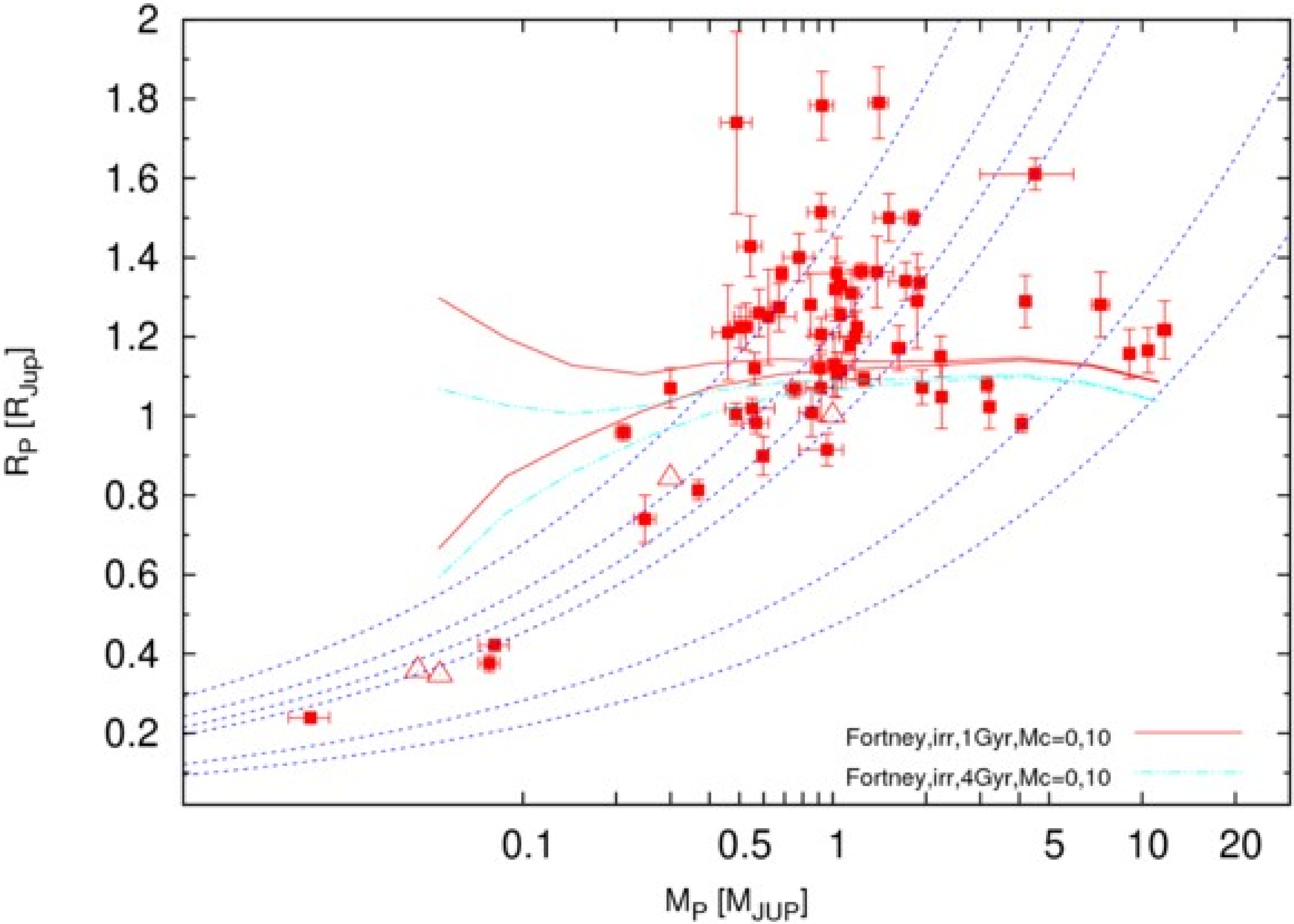
Ground versus space

- Ground-based surveys pioneered the discovery, characterization of TEPs, including most of the methodology used in the field, such as search methods, reconnaissance, and confirmation of planets.
- Space-based surveys (so far) primarily found planets around fainter host stars (but this is subject to change).
- Space-based surveys have the potential for extremely good light curve parameter determination (duration, depth, ingress/egress duration, etc).
- Space-based surveys have the sensitivity for TDV, TTV, exomoons, and long period planets.
- Ground-based surveys produced planets with better established mass (and, in general, smaller error-bars on quantities that depend on stellar parameters, or brightness of the host star)
- Ground-based surveys are cheap

Space-based discoveries



Ground-based discoveries



TEP statistics

- Altogether 86 confirmed, announced* TEPs
- RV discoveries with subsequent confirmation of the transit (6): HD-209458b, HD-149026b, HD-189733b, GJ-436b, HD-17156b, HD-80606b
  - RM-effect: HD-189733b
  - Spitzer observations: HD-80606b
- Transit (survey) discoveries (80)
- Ground-based: 67, space-based: 19

Science that has come out of TEPs

- Inclination, true mass, radius (if stellar radius and mass are known*) → density, structure
- Presenting targets for detection of planetary atmospheres via transmission spectroscopy or occultation spectroscopy
- Presenting targets for measurements of planetary surface temperature via the occultation of the planet (Spitzer)
- Sky projected angle of stellar spin axis and planetary orbital normal via the RM-effect → formation
- Refine (through a/R_* and RV) stellar parameters
- Confirmation and characterization of space-based discoveries
- Transit timing variations → perturber bodies

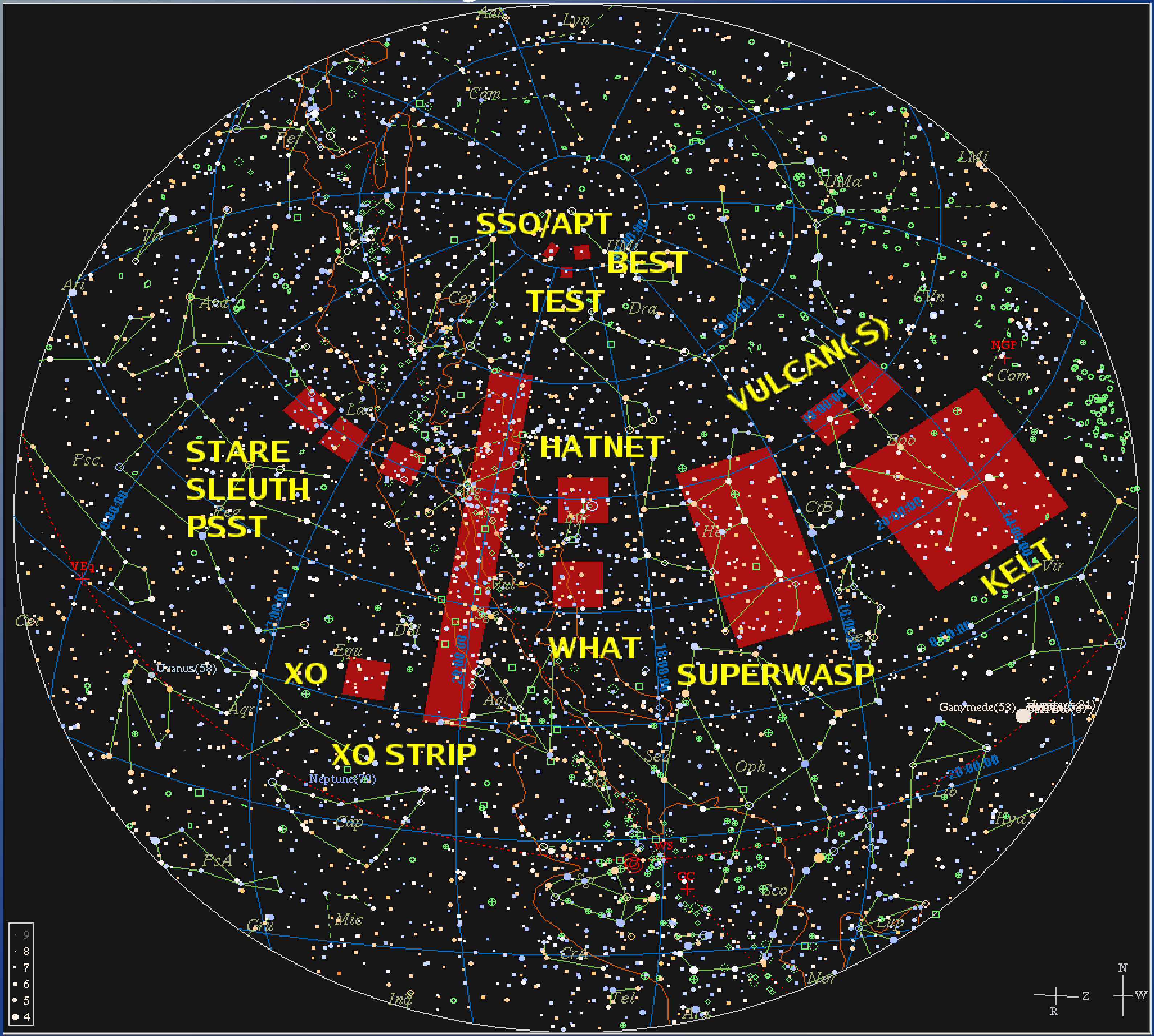
Transit Search Programmes

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	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

Note: most of these are not operational any more!

From Keith Horne, 2001

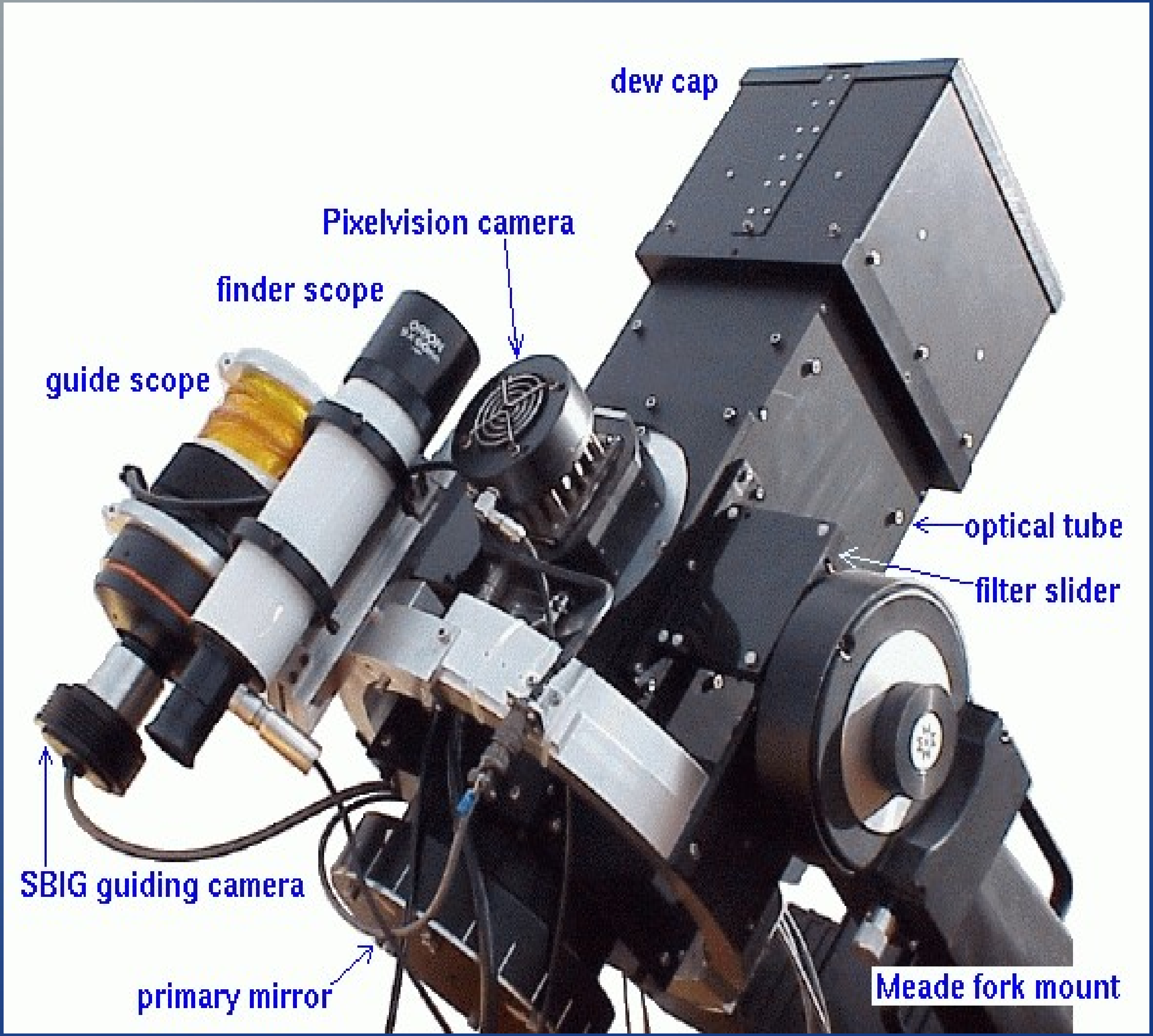
Project FOVs



Projects that found planets

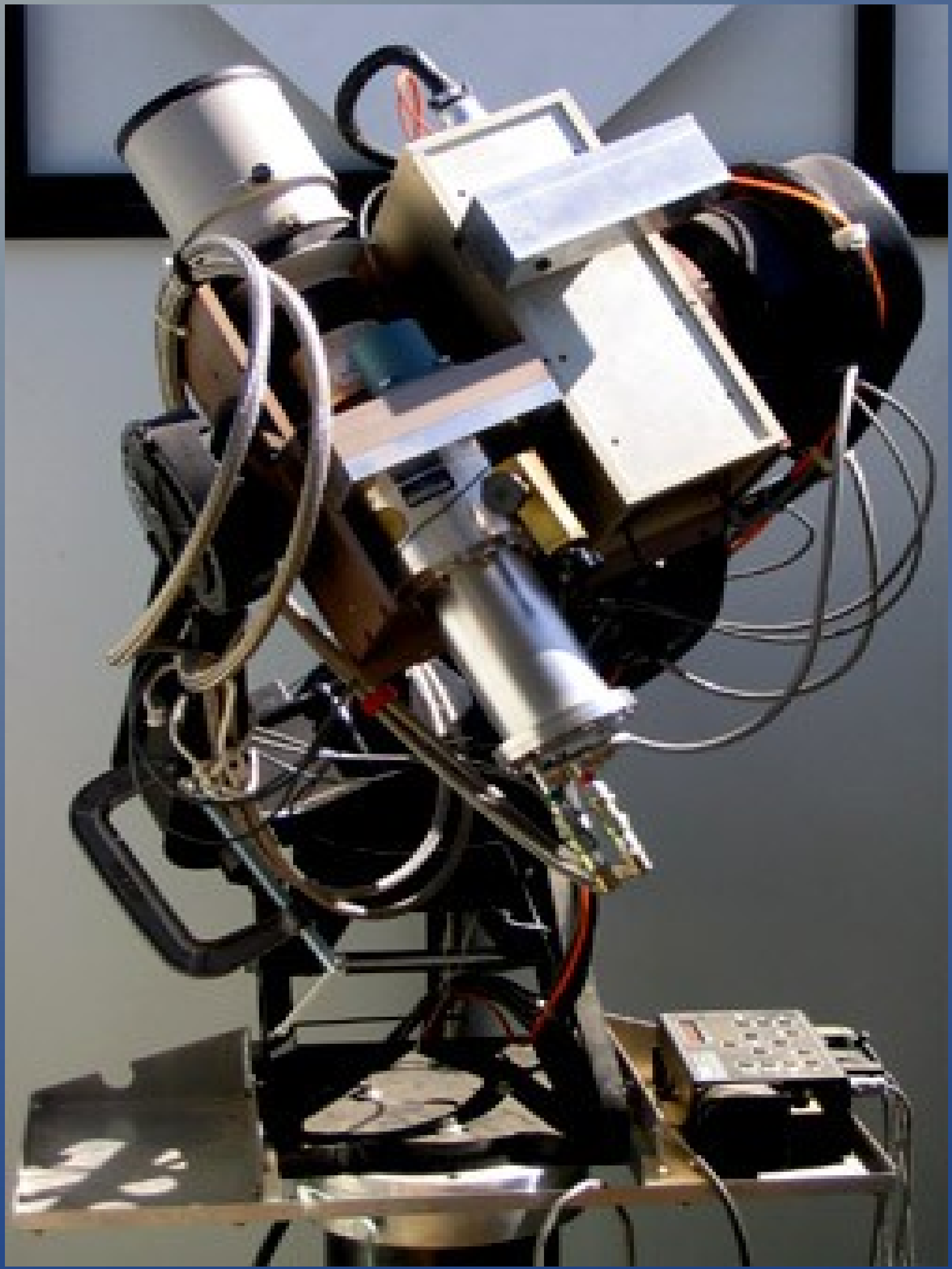
Las Campanas: OGLE

STARE +

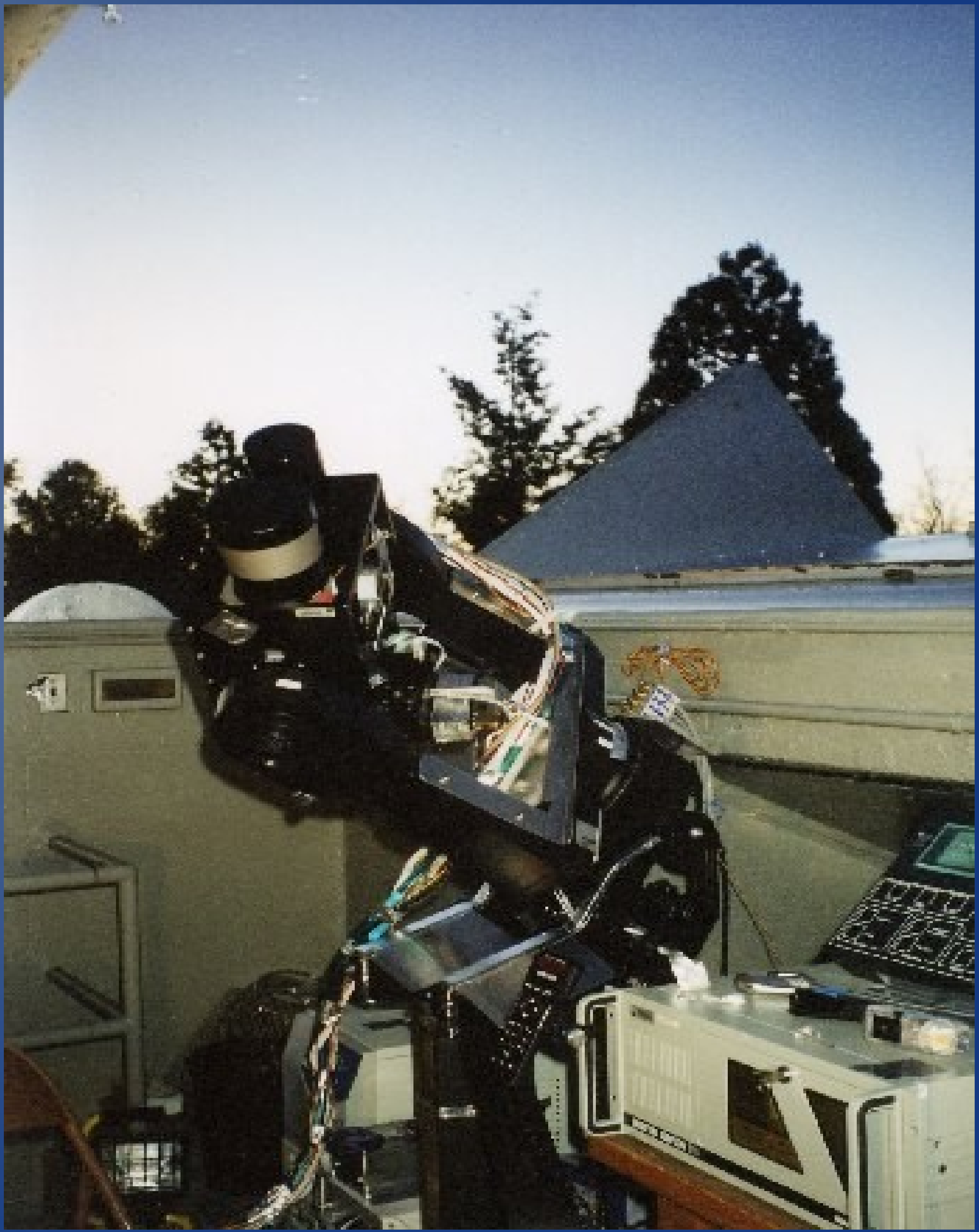


Tim Brown

PSST, Sleuth = TrES



Ted Dunham, Georgi Mandushev



Dave Charbonneau

XO + ET

Peter McCullough

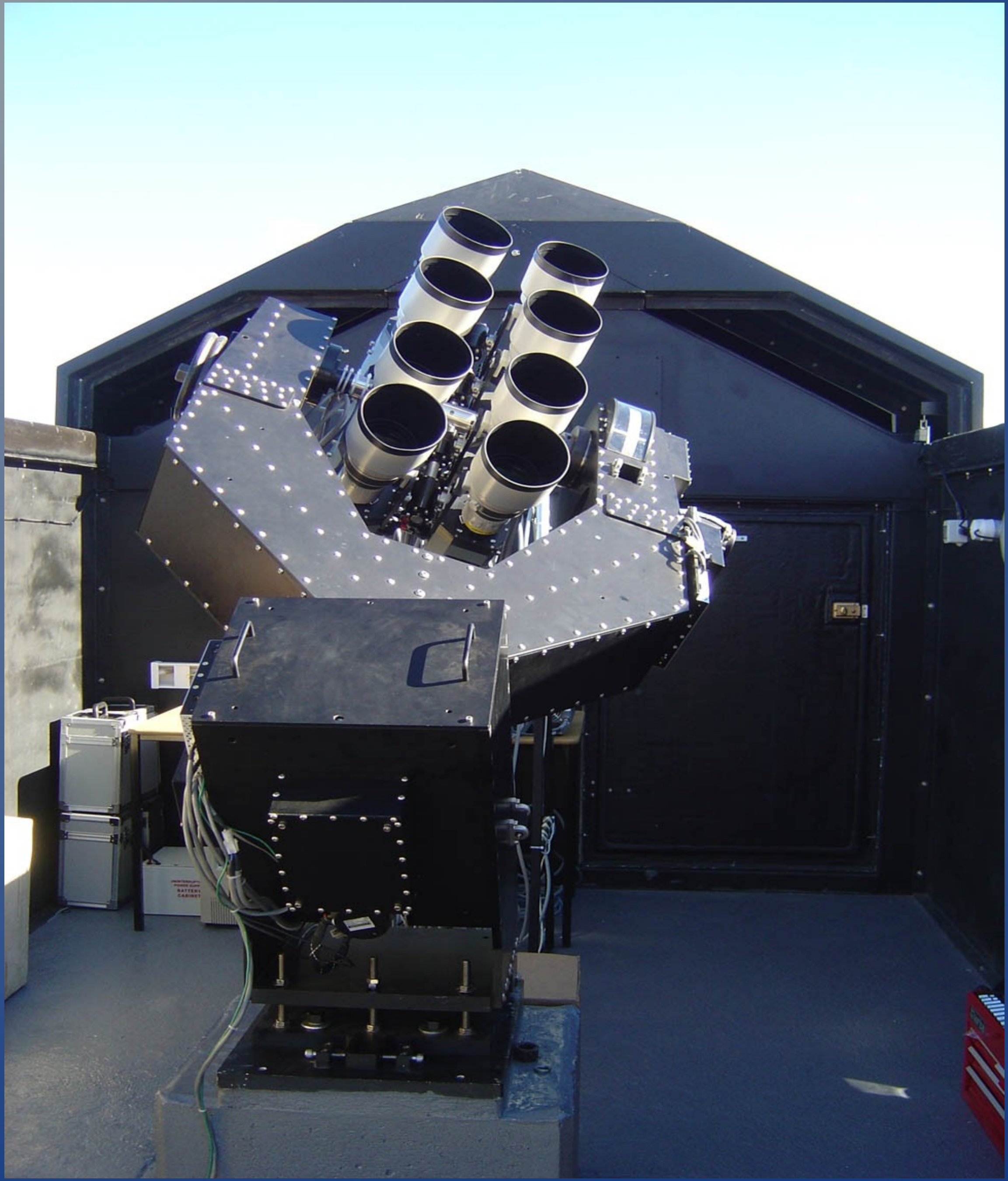
The HAT instrument (HATNet)

Gaspar Bakos et al.

The Wise-HAT telescope (WHAT)

Geza Kovacs, Tsevi Mazeh

SuperWASP (North + South)

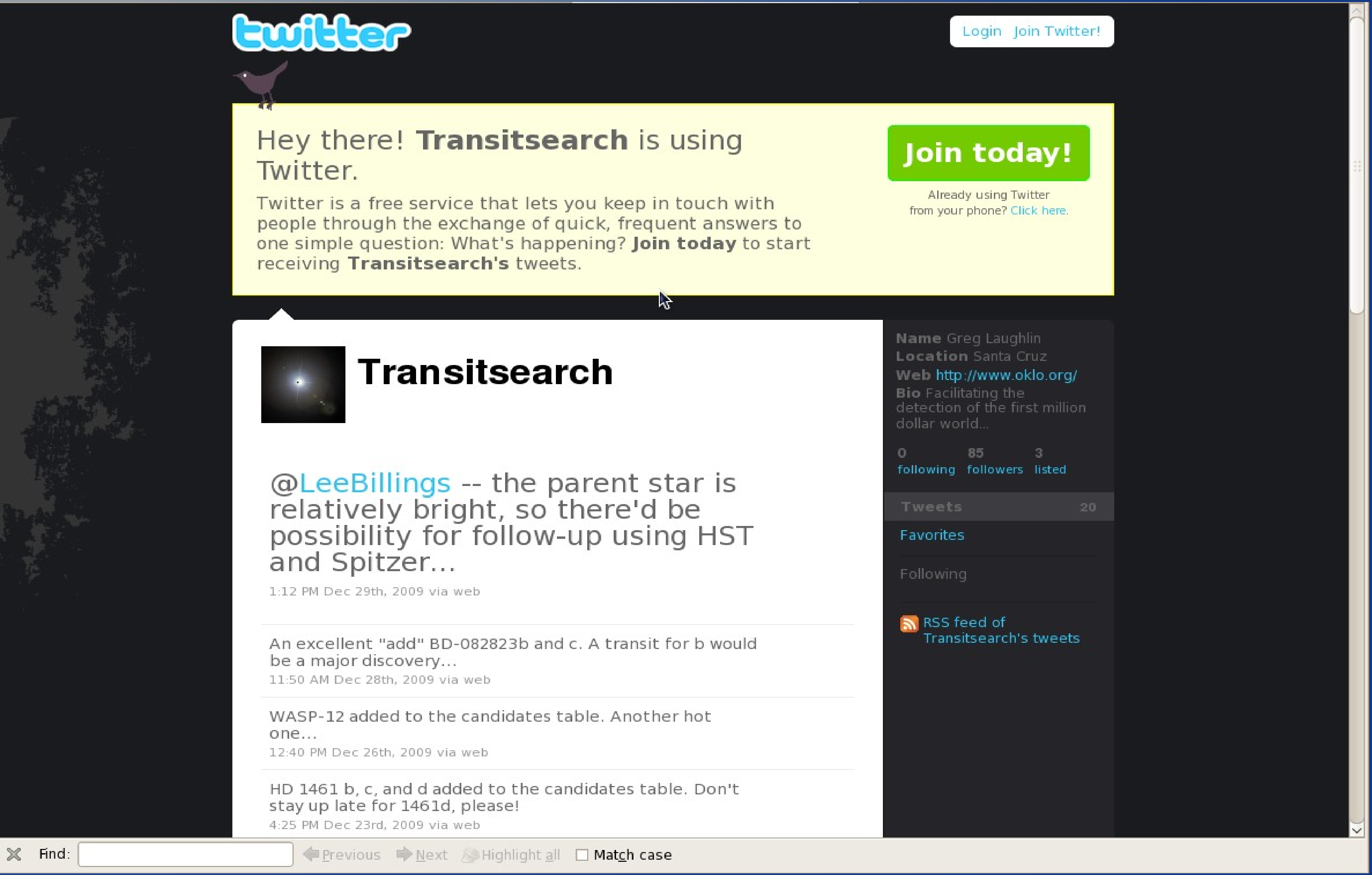


Don Pollacco,
Andrew Cameron
et al.

MEarth

Dave Charbonneau, Jonathan Irwin et al.

Transitsearch.org



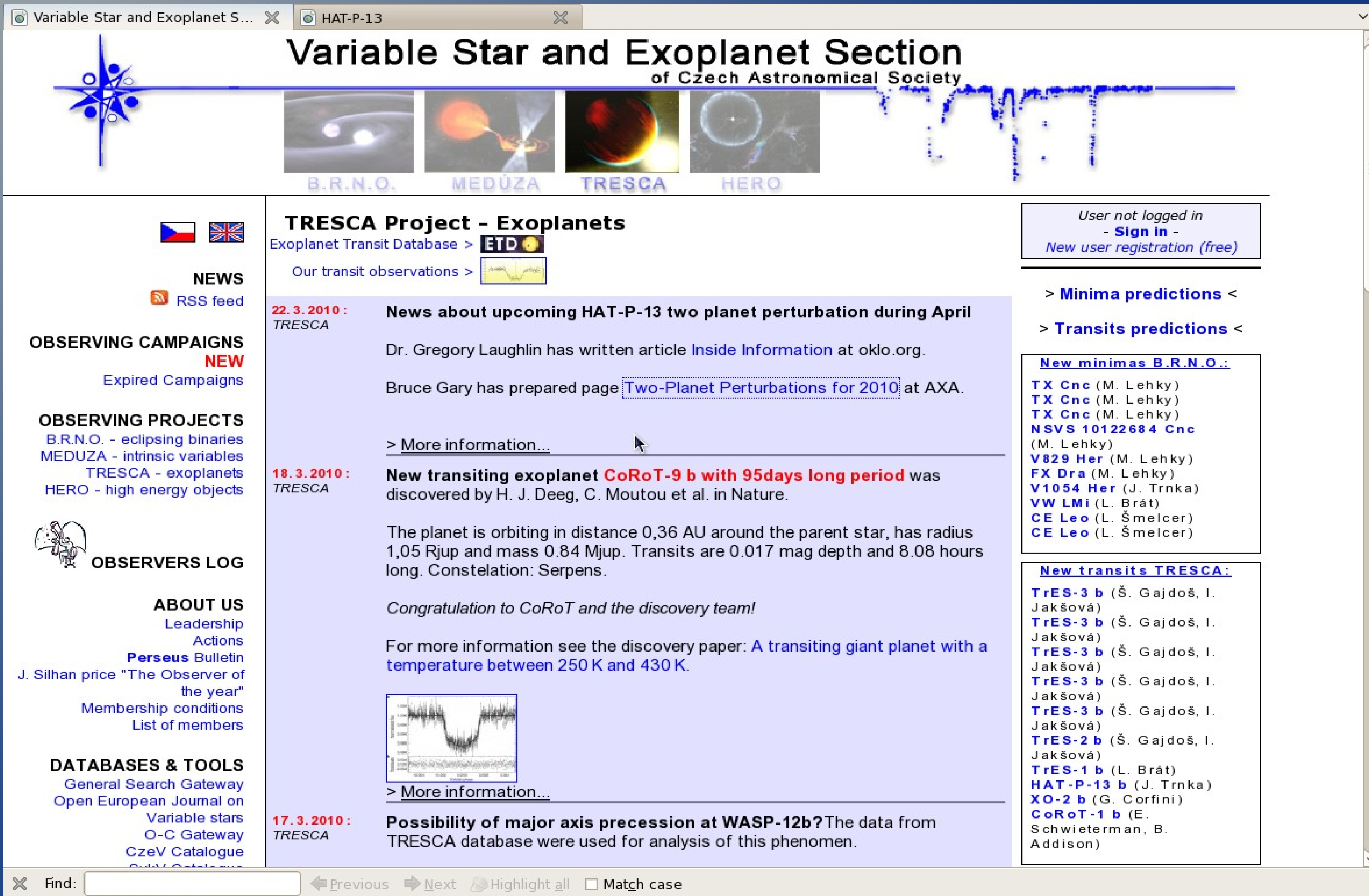
Another essential resource: www.oklo.org

AXA (Bruce Gary)

Amateur Exoplanet Archive (AXA)

##	Object	RA	Dec	V-mag	B-V	HJDo	Period [days]	Depth [mmag]	Length [hours]	b	Season [Month]	# Transit LCs (# OOT LCs)
37	WASP-12	06:30:33	+29:40.3	11.69	0.42	4506.9761	1.091423	16.5	2.95	0.36	01.0	0(0)
36	CoRoT-4	06:48:47	-00:40.4	13.7	0.??	4141.36416	9.20205	14.0	4.42	0.??	01.0	0(0)
35	CoRoT-3	19:28:13	+00:07.3	13.29	0.91	4283.1383	4.25680	5.2	3.77	0.55	07.1	0(0)
34	CoRoT-1	06:48:19	-03:06.1	13.6	0.57	4159.4532	1.5089557	24.8	2.46	0.??	01.0	1(0)
33	HAT-P-8	22:52:10	+35:26.8	10.26	0.??	4437.67582	3.076320	7.0	3.6	0.32	09.2	0(0)
32	WASP-11	03:09:29	+30:40.4	11.89	0.??	4729.90631	3.7224690	22.4	2.59	0.24	11.5	2(0)
31	HAT-P-9	07:20:40	+37:08.4	12.30	0.50	4417.9077	3.92289	14.0	3.3	0.52	01.3	0(0)
30	WASP-10	23:15:58	+31:27.8	12.7	0.??	4357.85803	3.0927600'	37	2.14	0.58	09.4	6(0)
29	WASP-14	14:33:06	+21:53.7	9.75	0.46	4465.81963	2.243756	11.7	2.78	0.51	05.1	1(0)
28	XO-5	07:46:52	+39:05.7	12.13	0.84	4485.6664	4.187732	13.8	3.05	0.55	01.5	7(0)
27	XO-4	07:21:34	+58:16.0	10.67	0.57	4485.9322	4.12502	09.7	4.58	0.18	01.4	8(1)
26	WASP-7	20:44:10	-39:13.5	9.51	0.??	3985.0149	4.954658	10	3.67	0.08	08.1	0(0)
25	HAT-P-7	19:28:59	+47:58.2	10.5	?.??	3790.2593	2.2047214'	07.1	3.88	0.37	07.4	8(0)
24	CoRoT-2	19:27:07	+01:23.0	12.57	?.??	4237.53562	1.7429964	35.2	2.27	?.??	07.4	12(1)
23	WASP-5	23:57:24	-41:16.6	12.26	?.??	4373.99598	1.6284279	12.5	2.37	0.31	09.8	0(0)
22	WASP-4	23:34:15	-42:03.7	12.5	?.??	4383.313070	1.3382324	34	2.12	0.06	09.7	1(0)
21	WASP-3	18:34:32	+35:39.7	10.64	?.??	4605.55915	1.846834	12.2	2.71	0.51	07.0	12(0)
20	HAT-P-6	23:39:06	+42:28.0	10.54	0.34	4035.67575	3.852985	10.1	3.42	0.60	09.5	2(0)
19	HAT-P-5	18:17:37	+36:37.3	12.03	0.62	4241.77663	2.788491	14.0	3.0	0.42	06.9	4(0)
18	HD 17156	02:49:45	+71:45.2	08.17	0.64	4438.4824'	21.21649'	06.6	3.05	0.55	11.3	8(3)
17	HAT-P-4	15:19:58	+36:13.8	11.21	0.57	4245.8154	3.056536	09.6	4.2	0.01	05.6	3(0)
16	TrES-4	17:53:13	+37:12.7	11.34	0.48	4230.9053	3.553888'	14.5	3.53	0.75	07.2	5(1)
15	HAT-P-3	13:44:22	+48:01.7	11.86	0.8	4218.7566'	2.90088'	16.8	2.04	0.49	04.5	13(0)
14	XO-3	04:21:53	+57:49.0	09.80	0.45	4449.8672'	3.1915228'	09.8	2.87	0.70	12.0	23(2)
13	GJ 436	11:42:11	+26:42.4	10.68	1.52	4280.78148	2.643904	08.1	0.95	0.92	03.5	38(9)
12	XO-2	07:48:08	+50:13.2	11.18	0.82	4147.74902	2.6158605'	14.2	2.67	0.16	01.5	32(3)
11	TrES-3	17:52:07	+37:32.8	12.40	0.71	4185.9107'	1.306186'	27.2	1.29	0.82	06.7	37(3)
10	HAT-P-2	16:20:36	+41:02.9	08.71	0.41	4213.4794	5.63341	05.5	3.46	0.54	06.0	0(0)
09	XO-1	16:02:12	+28:10.2	11.19	0.66	3808.91709'	3.941502'	23.5	2.91	0.73	05.9	38(4)
08	WASP-2	20:30:54	+06:25.8	11.98	1.02	3991.5138'	2.1522221'	19.5	1.74	0.39	08.0	18(5)
07	WASP-1	00:20:40	+31:59.4	11.65	0.54	3151.486	2.519955'	14.6	3.67	0.3	10.0	12(0)
06	TrES-2	19:07:14	+49:19.0	11.41	x.xx	3957.6372'	2.470600'	17.1	1.71	0.83	07.3	27(1)
05	HAT-P-1	22:57:47	+38:40.5	10.4x	0.6x	4363.94656	4.4652934	14	2.65	0.70	09.3	2(0)
04	HD 189733	20:00:43	+22:42.7	07.67	1.08	3988.8051'	2.2185629'	29.0	1.70	0.66	07.7	23(1)
03	HD 149026	16:30:30	+38:20.8	08.16	0.56	4327.37211	2.8758887	03.0	3.31	0.45	06.0	0(0)
02	TrES-1	19:04:10	+36:38.0	11.79	0.78	3898.87330'	3.0300703'	25.1	2.47	0.76	07.3	22(0)

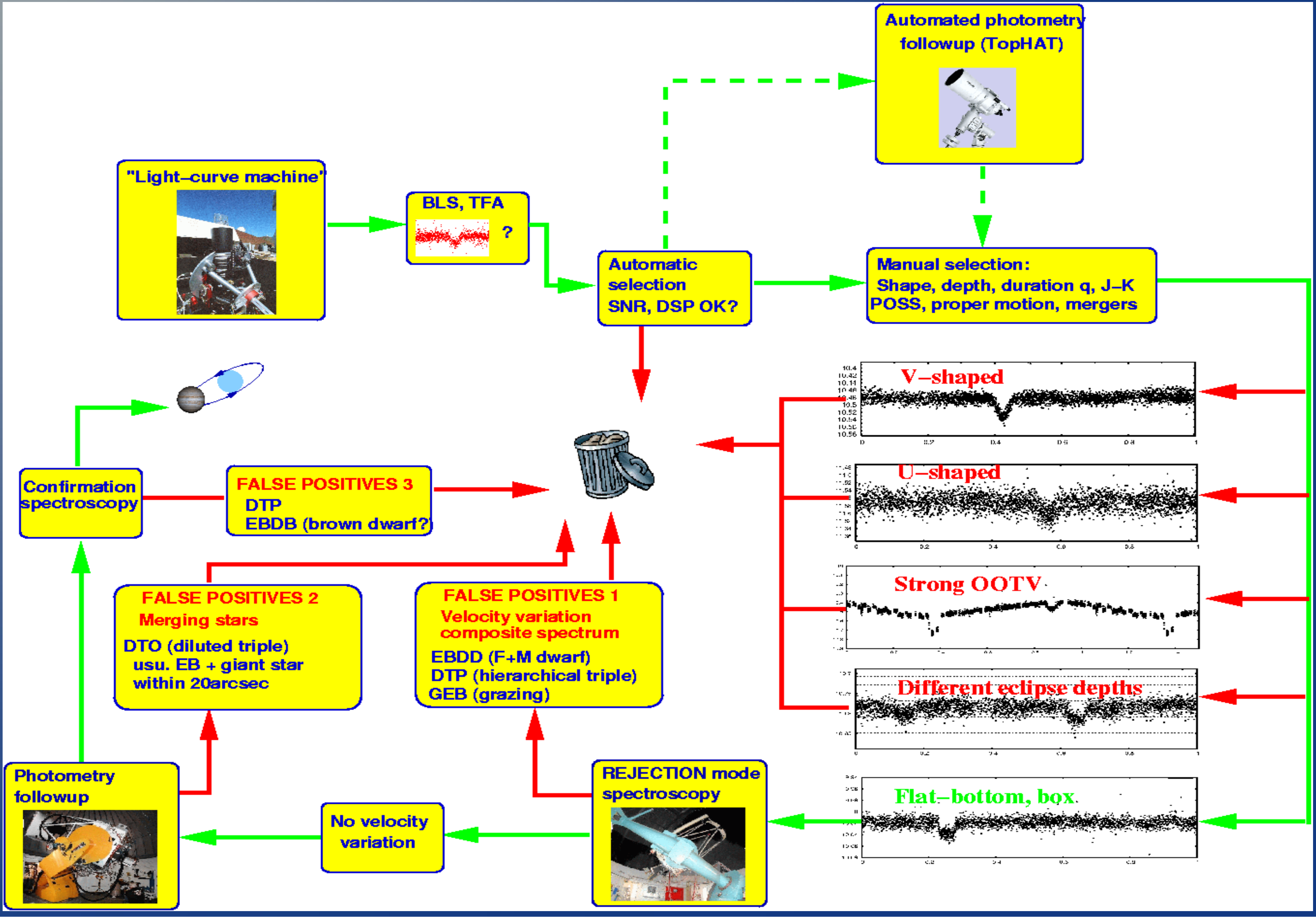
TRESCA and ETD (Czech)



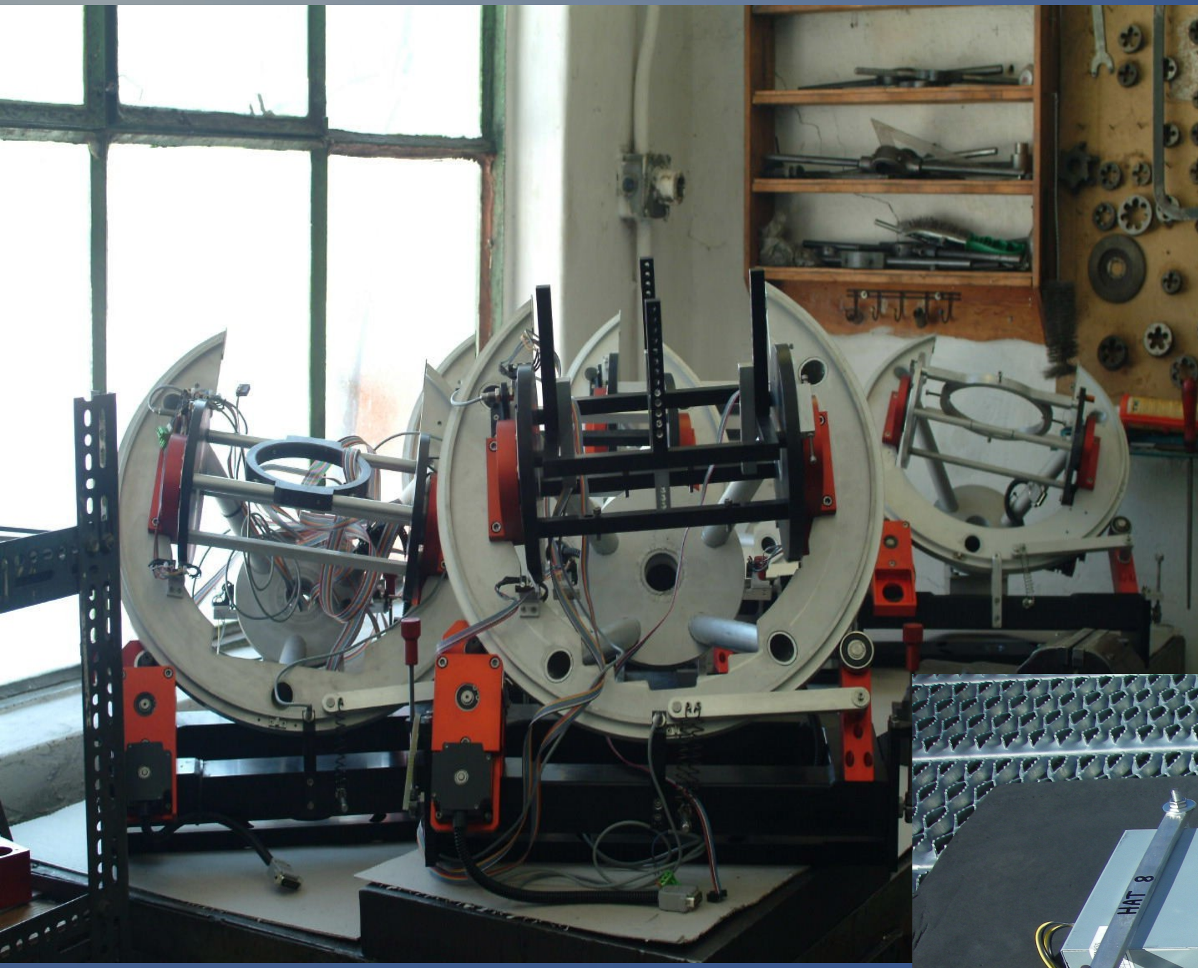
How does a ground-based survey work?

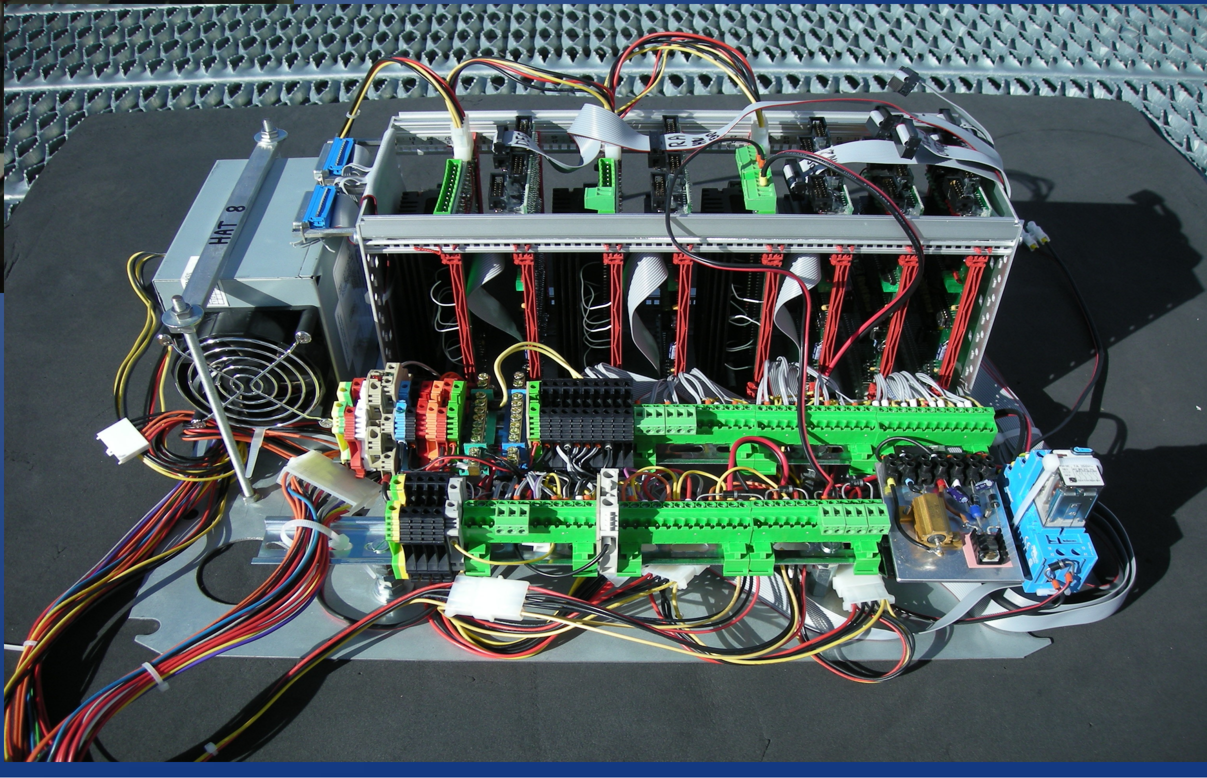
- Operations, data acquisition and transfer
- Data reduction: calibration, astrometry, photometry, light curve generation
- Trend filtering algorithms: TFA, Sysrem
- Candidate search: BLS
- Candidate evaluation: tools of all sort
- Reconnaissance follow-up phase (spectroscopy and photometry)
- Confirmation-mode follow-up (high precision RVs, blend analysis, activity)
- Analysis of results, physical interpretation
- Dissemination of results

Follow-up scheme



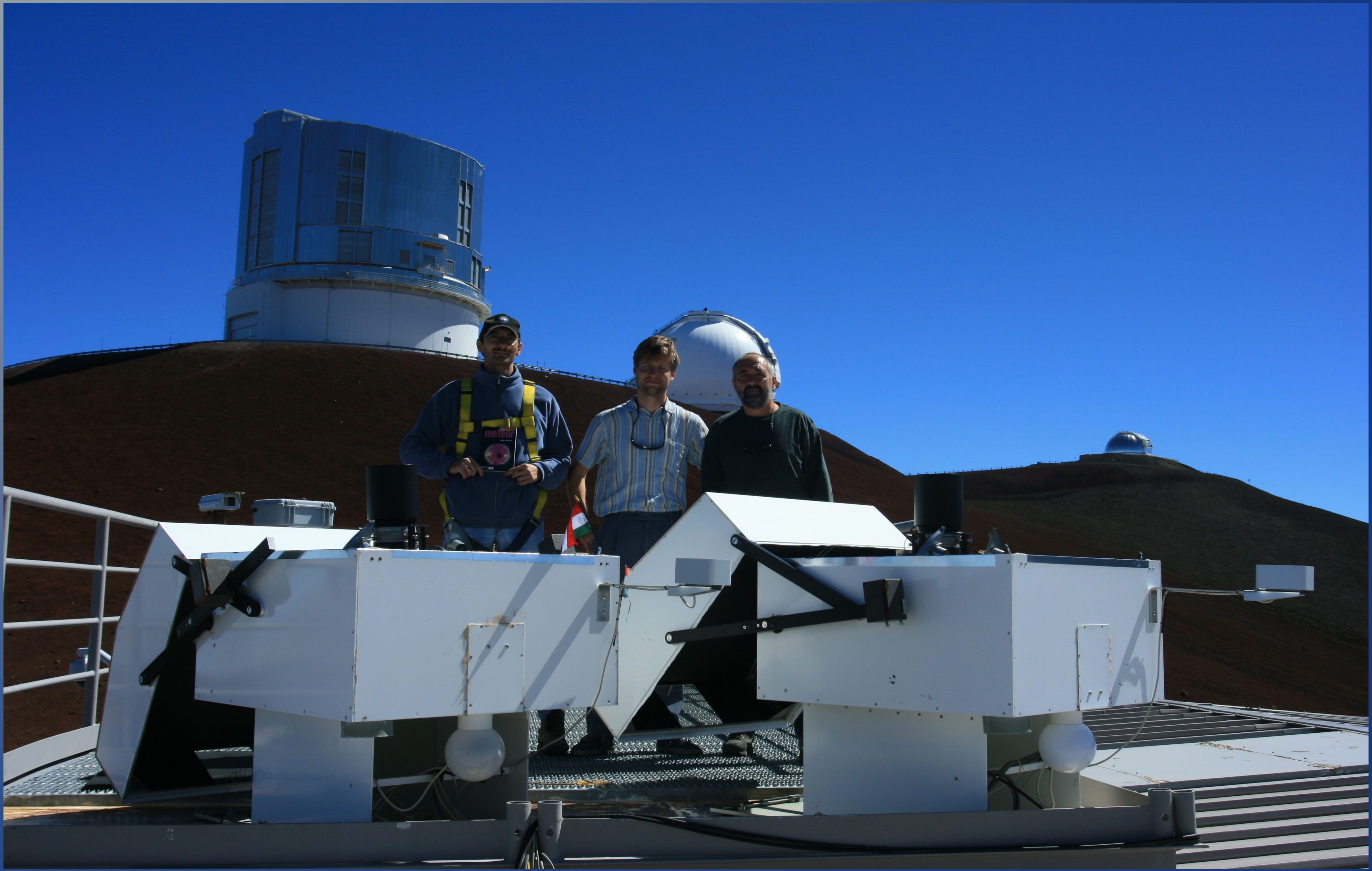
HATNet: an example






HAT 5
HAT 10

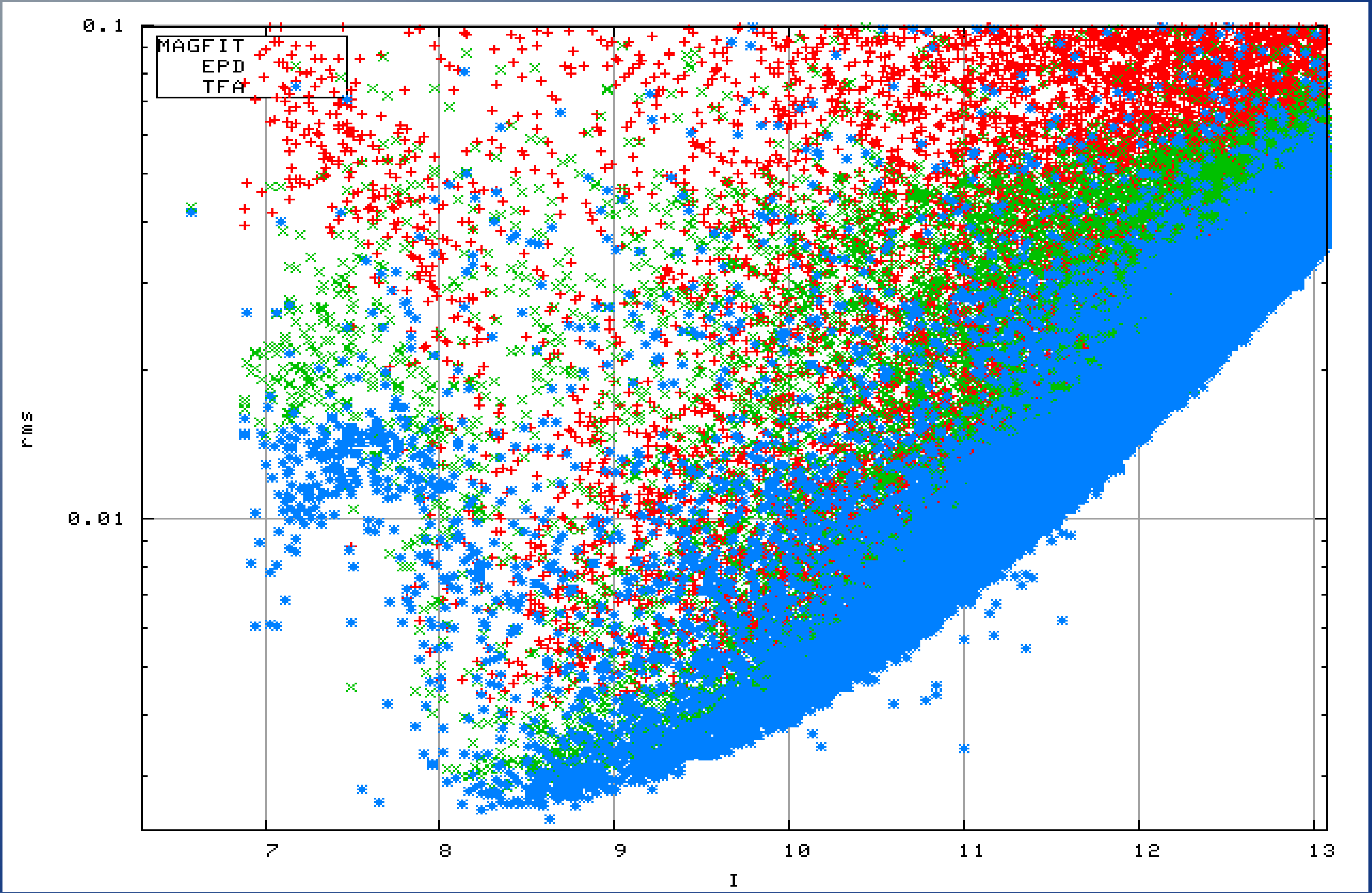
HATs at Mauna Kea



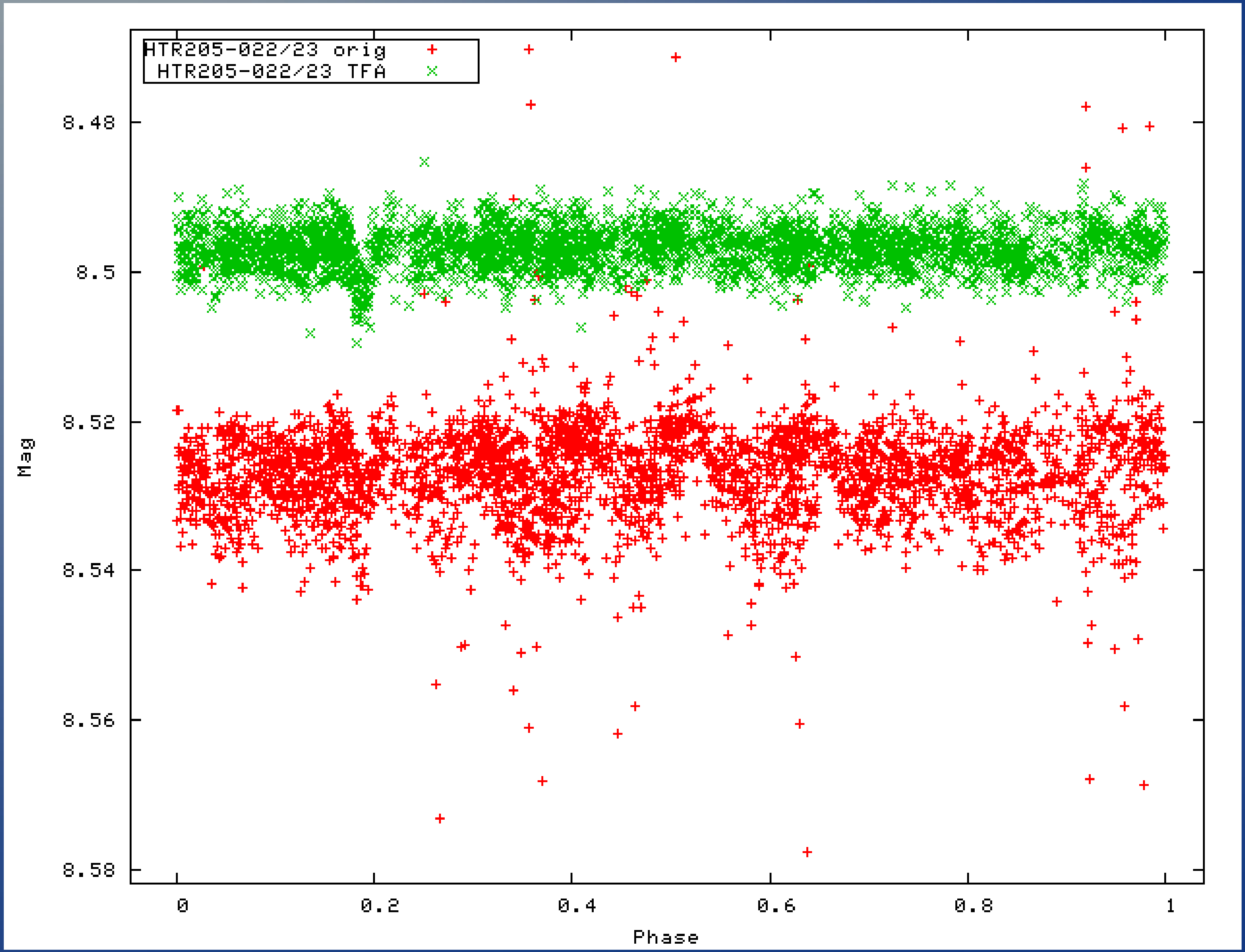
HAT-South first light image (1 chip out of 4)

HATNet and HATSouth computers

Photometric precision, systematics and trend filtering



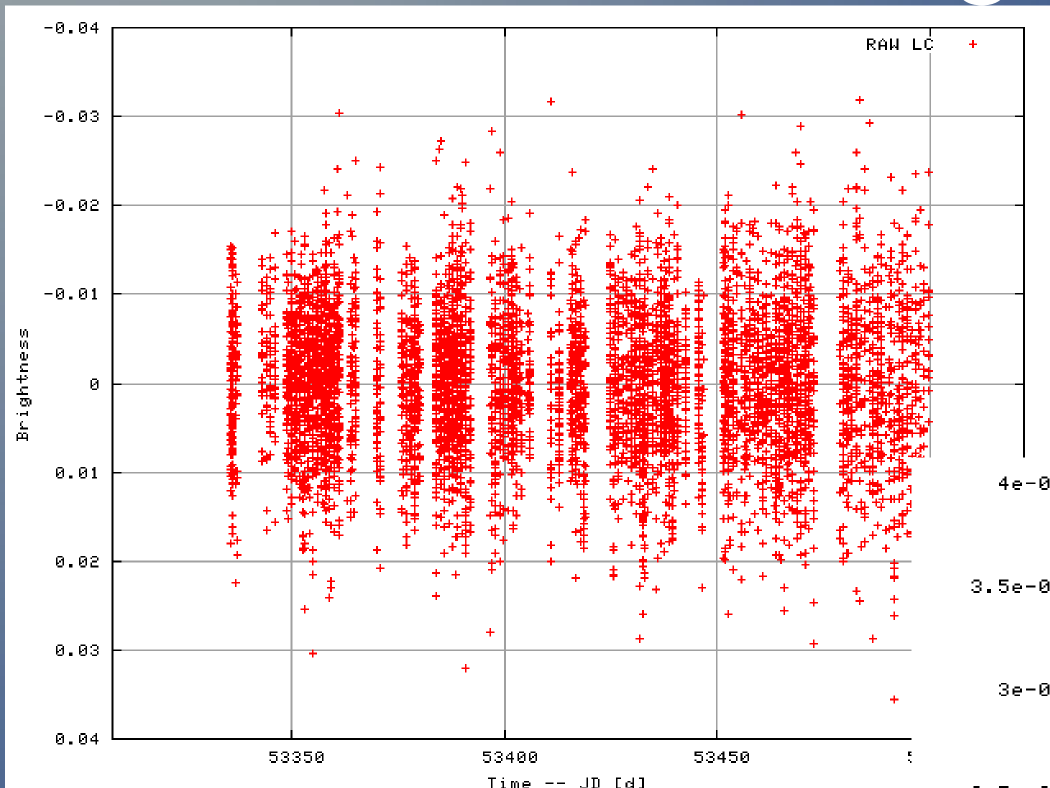
The Trend Filtering Algorithm

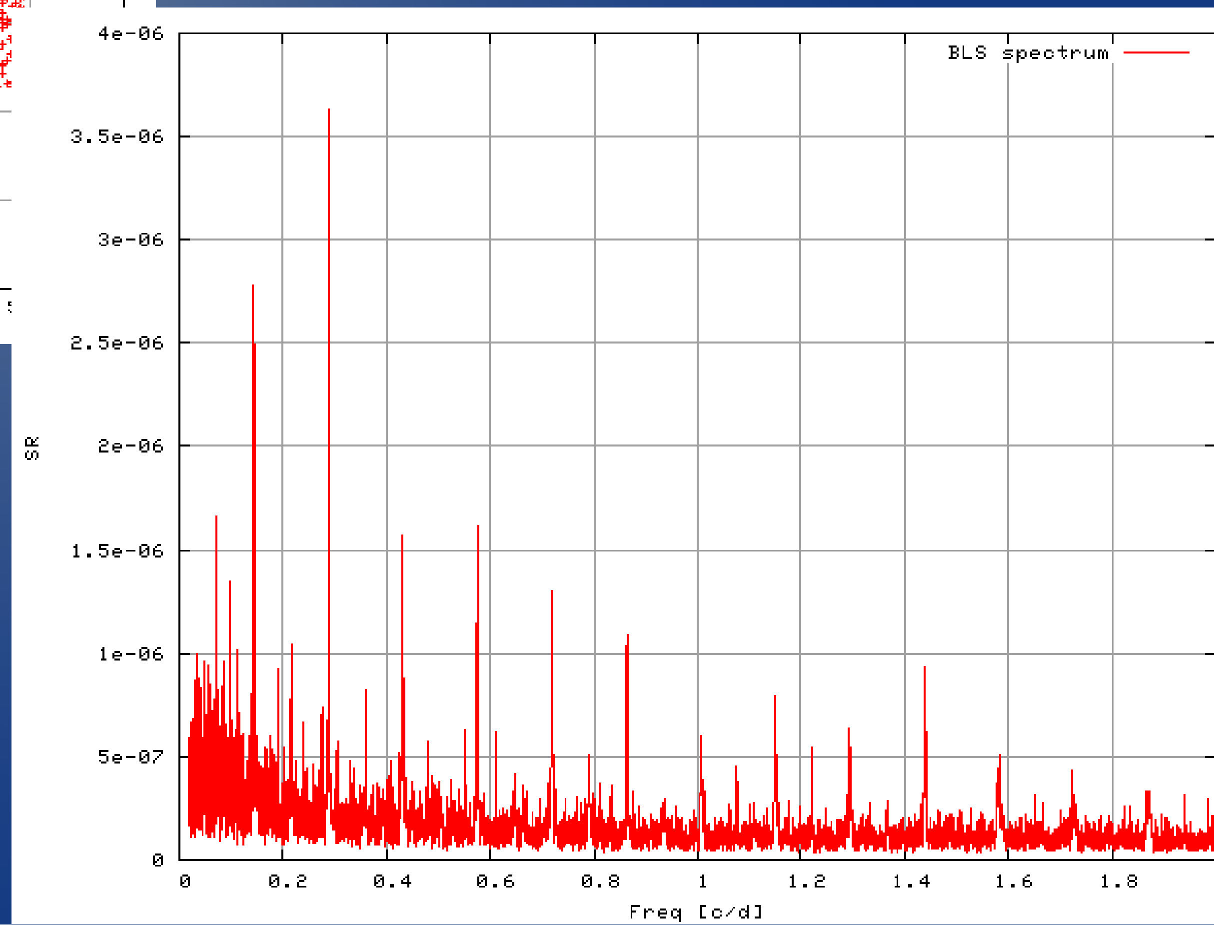


With TFA

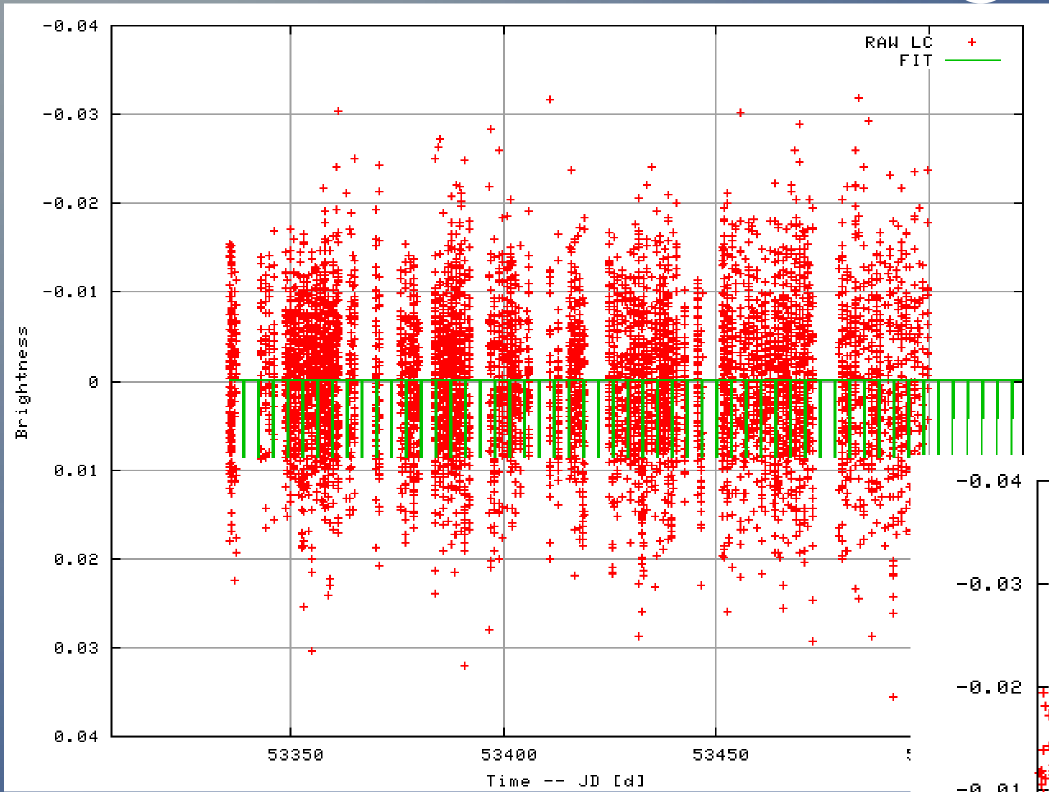
RAW

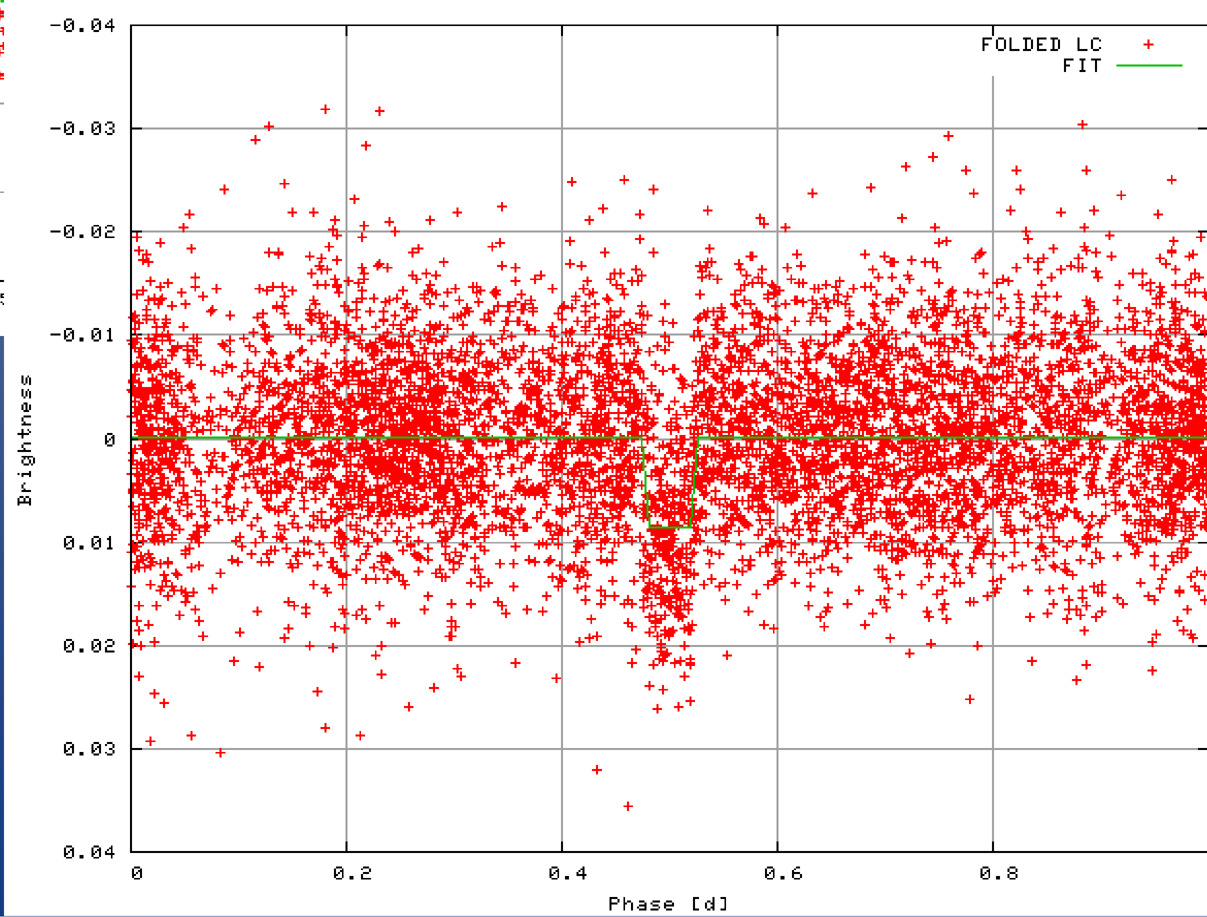
BLS: search algorithm for transits





BLS: search algorithm for transits





Follow-up observations

- HATNet has found ~1200 transiting planet *candidates*

- Intensive and coordinated follow-up effort to weed out false alarms: F+M binaries, grazing EBs, triples (52%), giants (18%), resolved blends (11%), false photometry (10%), rapid rotators (15%).

- Photometry follow-up with 0.25m TopHAT and 1.2m FLWO telescopes

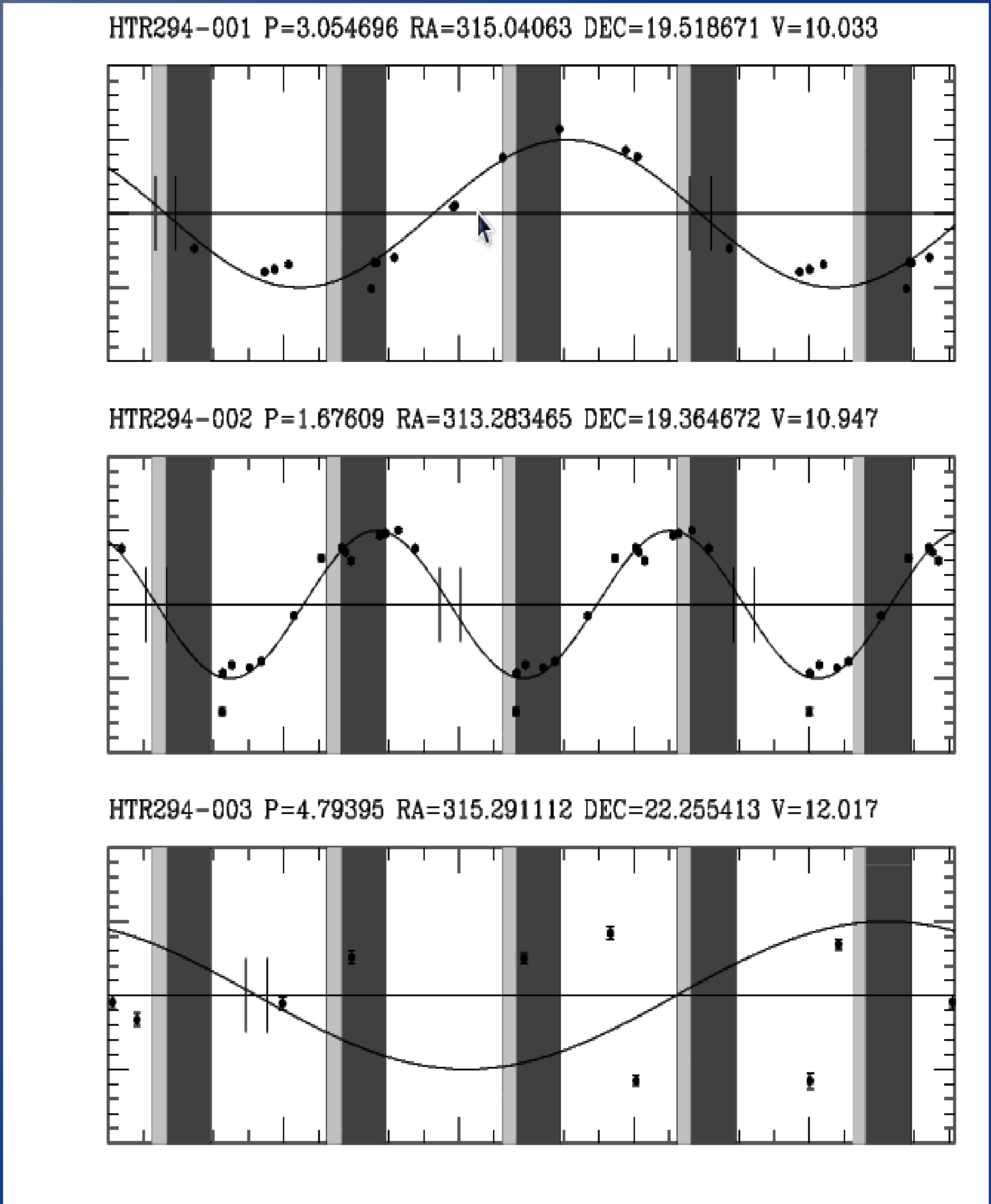
- High resolution low S/N “reconnaissance” spectroscopy with the 1.5m FLWO reflector + Digital Speedometer or TRES

- Additional low S/N spectroscopy: ANU 2.3m, DuPont 2.5m, NOT/FIES 2.3m.

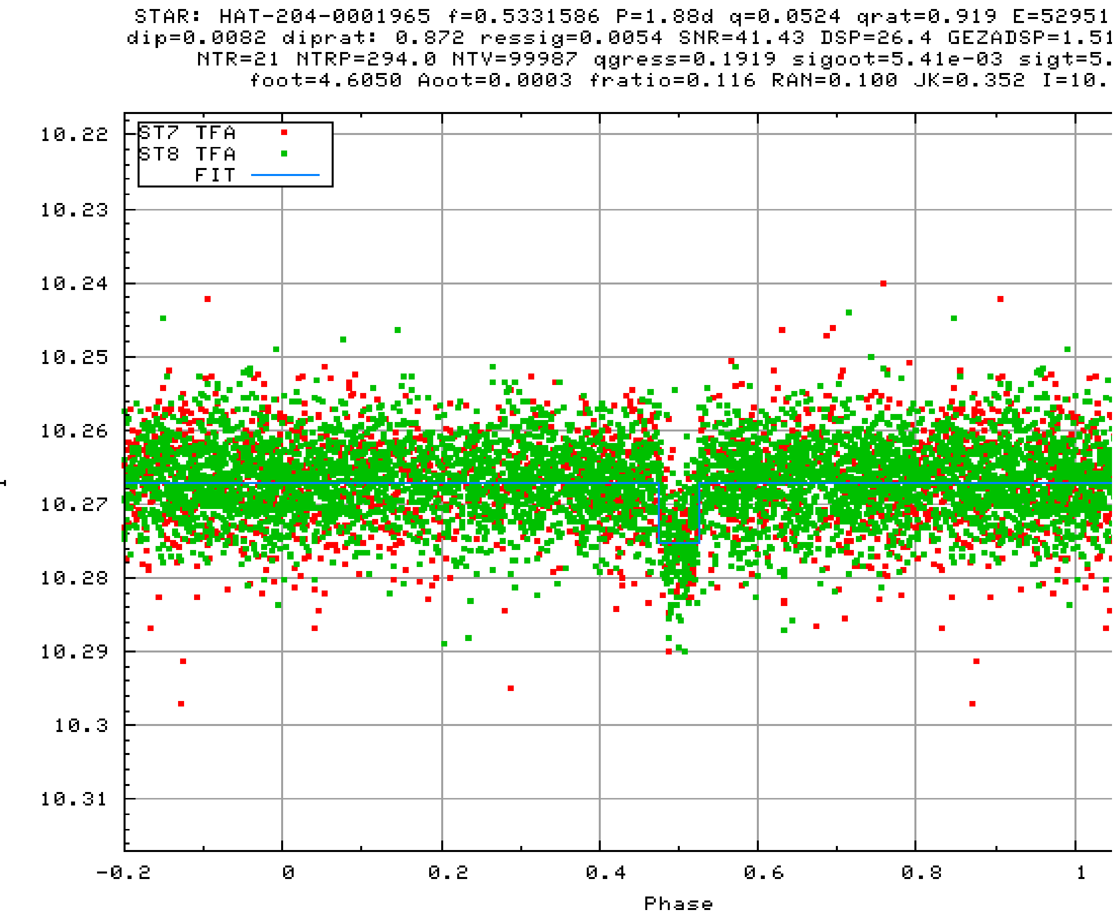
- About 1 in 20 candidates survives. These survivors reach Keck or FIES/NOT: the peak of the follow-up pyramid.

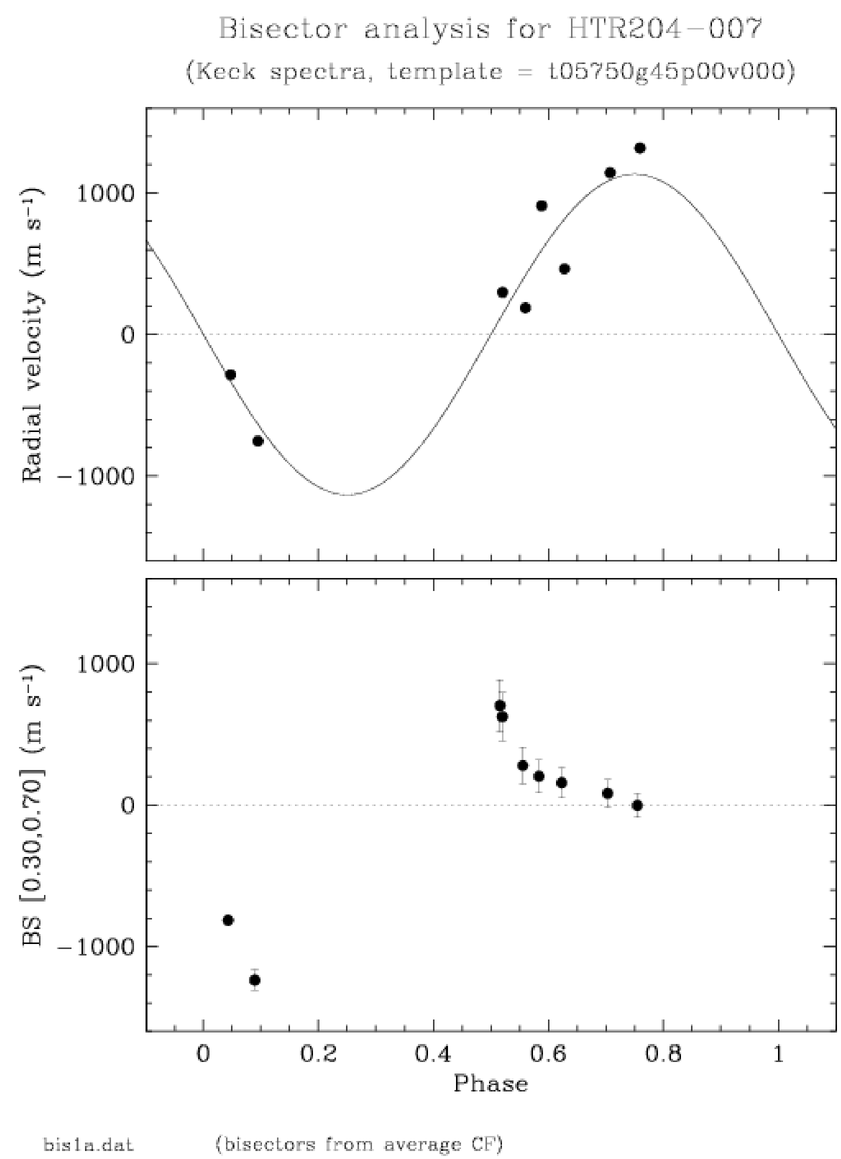
High precision RV observations of transit candidates

- Phase of expected RV curve known in advance!
- Highly optimized observing strategy, taking into account optimal phasing, visibility, priorities, prior history
- ~75% of Keck/FIES time is spent on targets that prove to be planet hosting stars
- Fast, “next-day” analysis helps in dynamic revision of the scheduling
- Outcome: atmospheric parameters (SME), RVs, bisector spans (BS),activity (S), high resolution snapshots



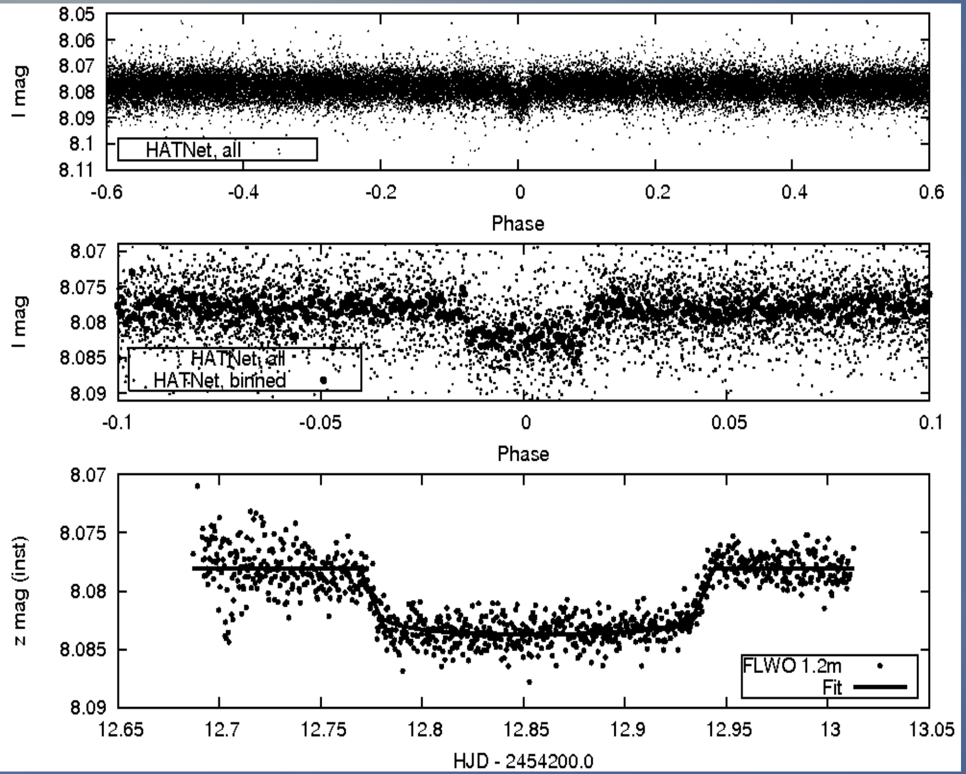
Example of a post-Keck impostor: HTR204-007

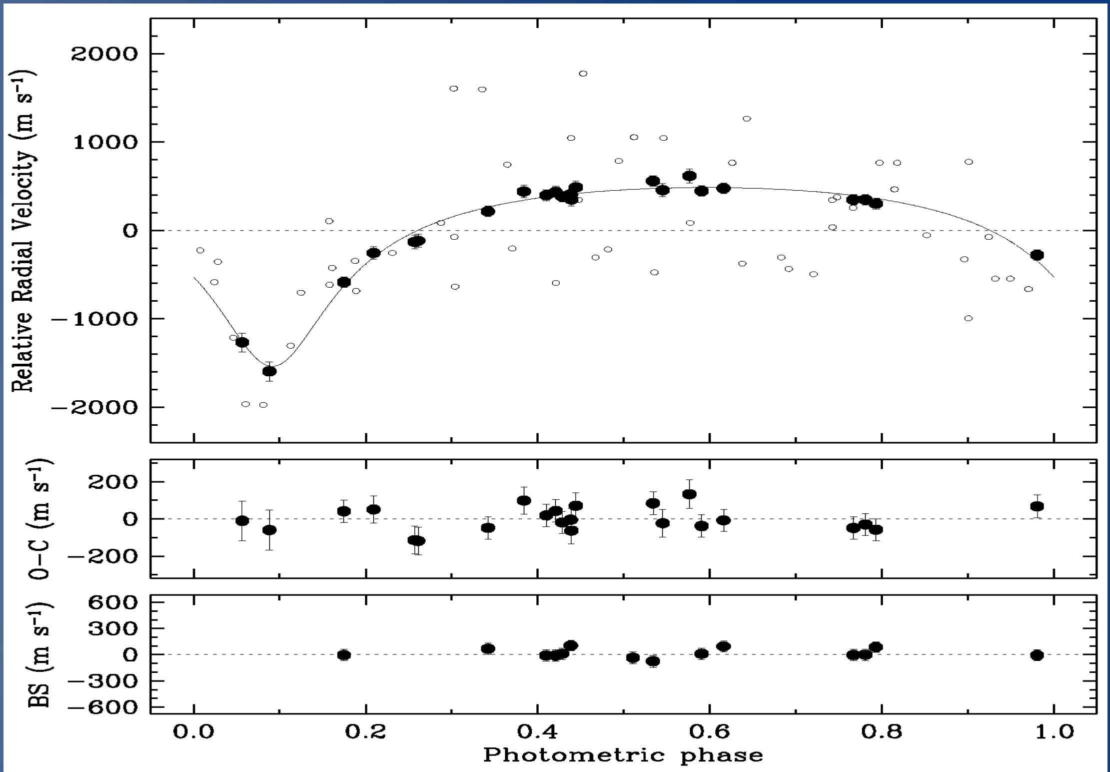




Strong bisector variations → triple

Example of a survivor: HAT-P-2b



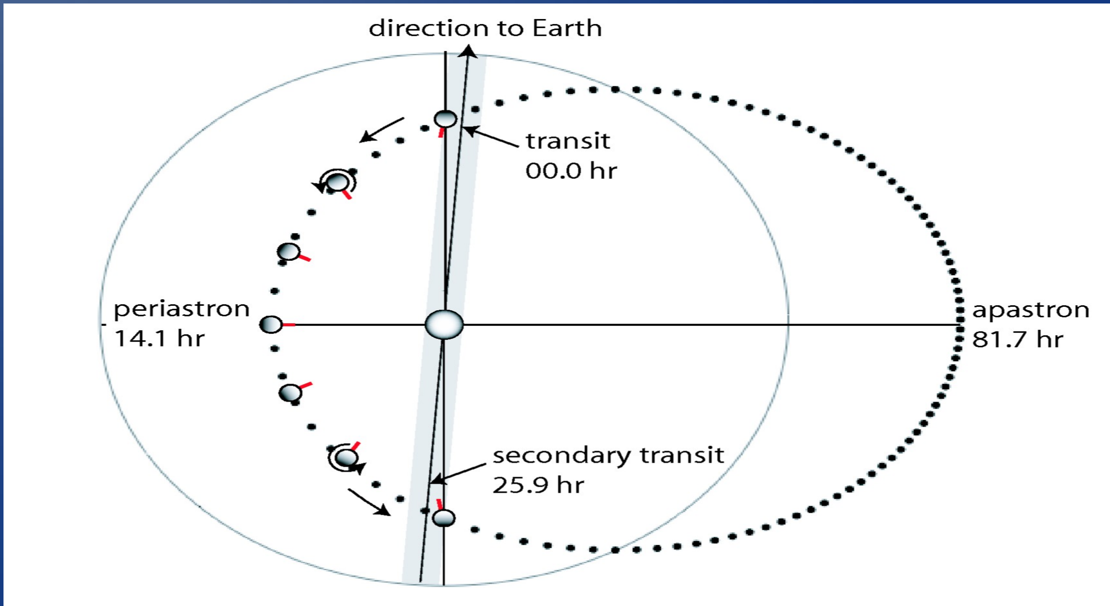


$R=1.16R_J$ $M=9.09M_J$

$\rho=7.6 g/cm^3$ $P = 5.6d$, $e=0.5$

Super-massive, compact hot Jupiter

See Bakos et al. 2007, ApJ



Limitations of ground-based surveys

- Duty cycle can be relatively low from a single site, or with poor weather. Result: gapped time series.
- Stability is worse than from space. Result: more systematics
- Effects of the atmosphere: (refraction), extinction, scintillation

Scintillation table for D=10cm, sea level

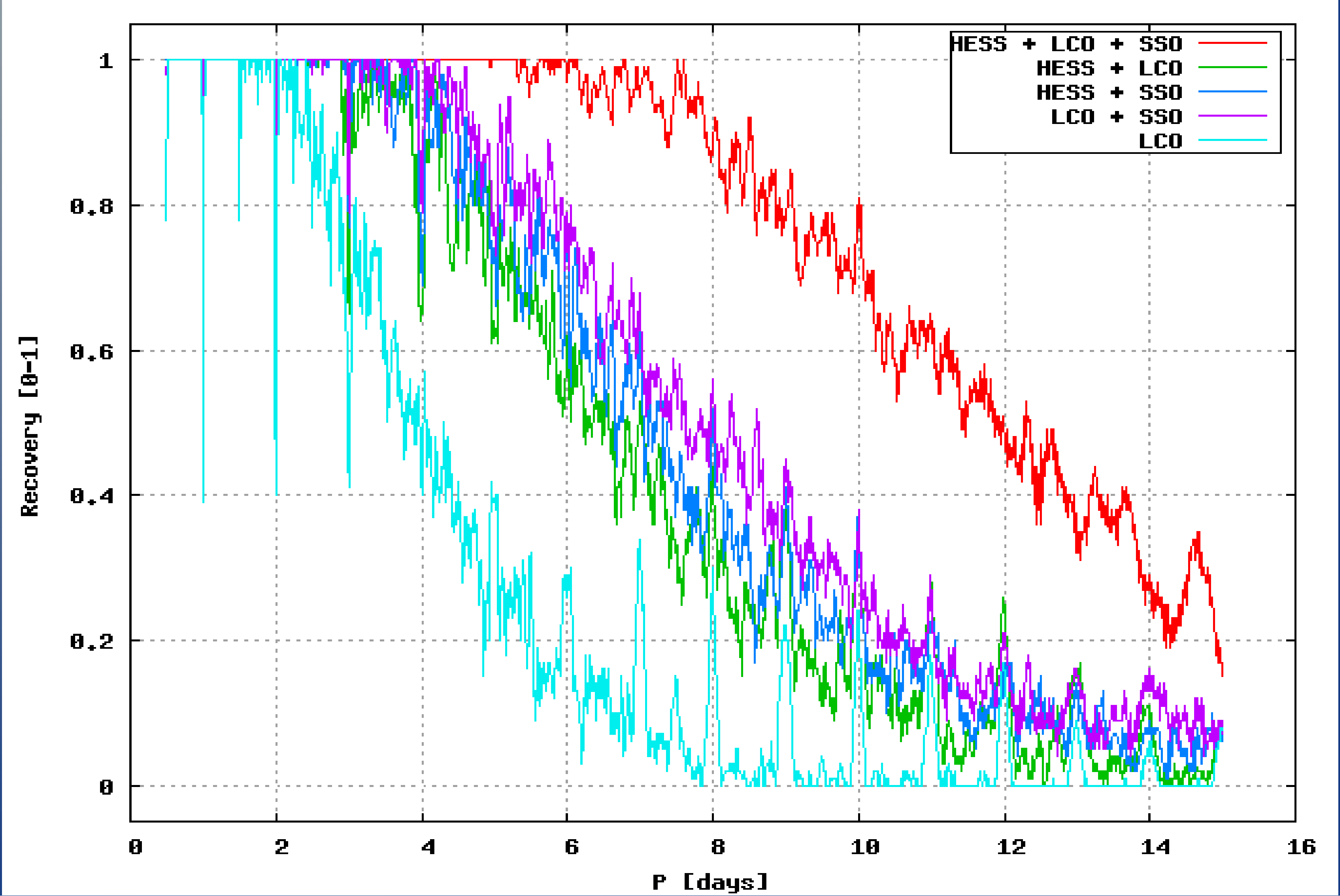
T/AM	1.0	1.2	1.4	1.7	2.0	2.4	2.8	3.5
200	0.00097	0.0013	0.0017	0.0025	0.0033	0.0045	0.0059	0.0087

Scintillation table for D=100cm, sea level

T/AM	1.0	1.2	1.4	1.7	2.0	2.4	2.8	3.5
20	0.00066	0.00091	0.0012	0.0017	0.0022	0.0031	0.004	0.0059

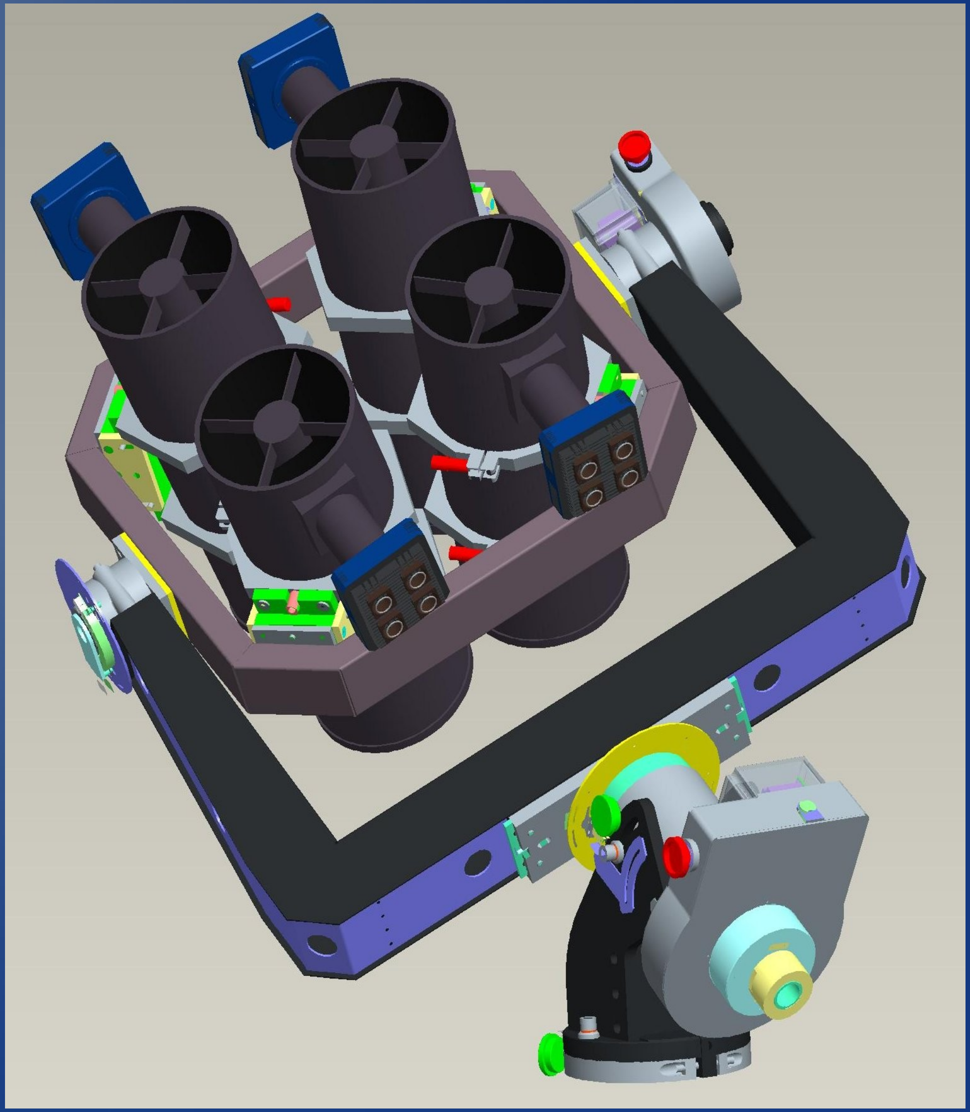
- Note, however, other limitations: RV precision, stellar jitter, stellar isochrones, parallaxes, blend analysis. These are limitations for both ground-based and space-based surveys.
- Transit depth from the ground: ~2mmag or deeper.

Transit recovery (HAT-South)



The HAT-South project

- Longitudinally spaced global network of fully automated telescopes in the Southern hemisphere
- Almost 24 hour coverage
- 128 □° field of view per site
- Long period transits (up to P=20 days)
- Shallow transits: hot Neptunes and super Earths
- Joint effort of the CfA, PUC, ANU, MPIA.
- 1500 cand/yr, 20 to 60 TEP/yr

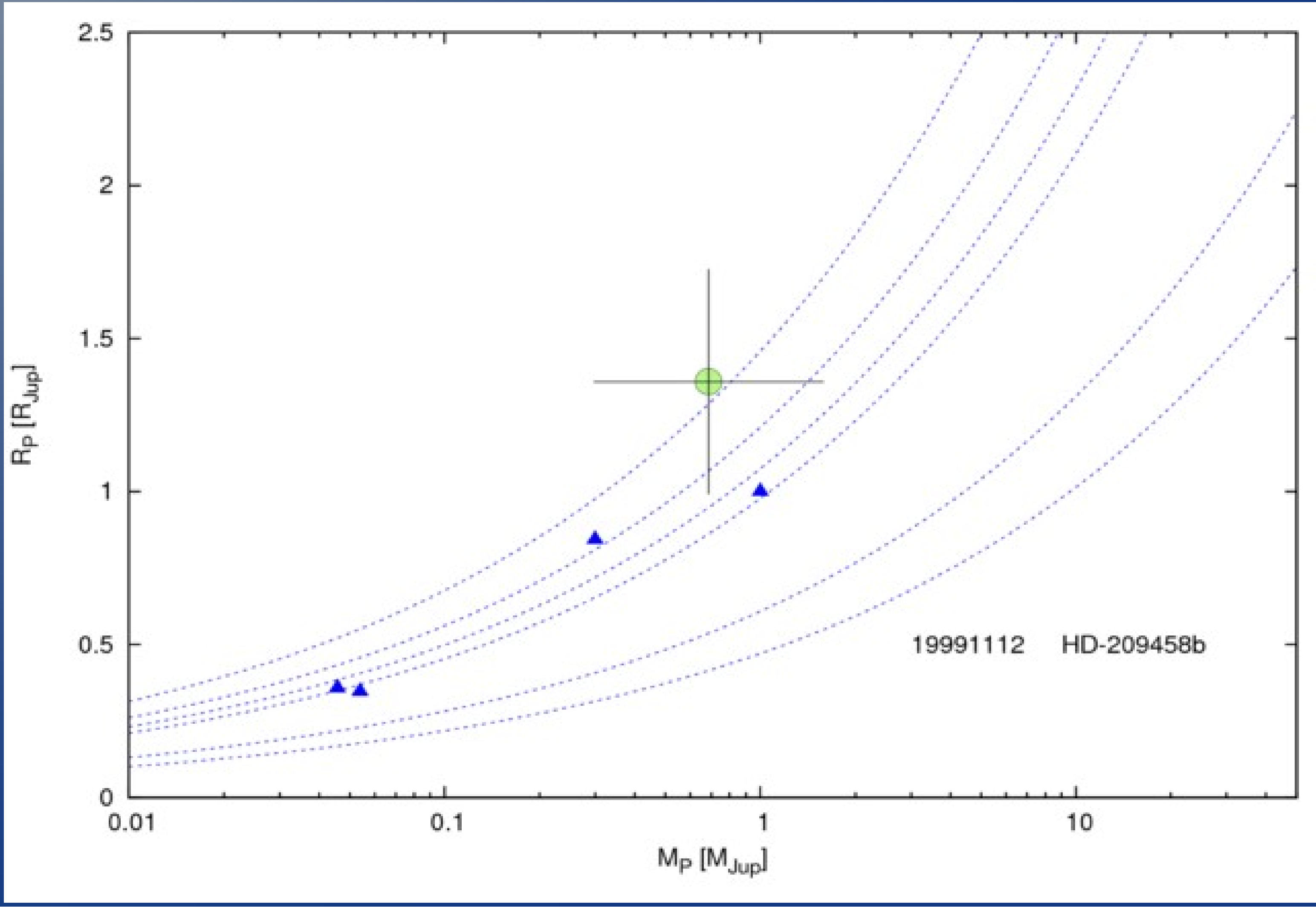


HAT-South units at LCO

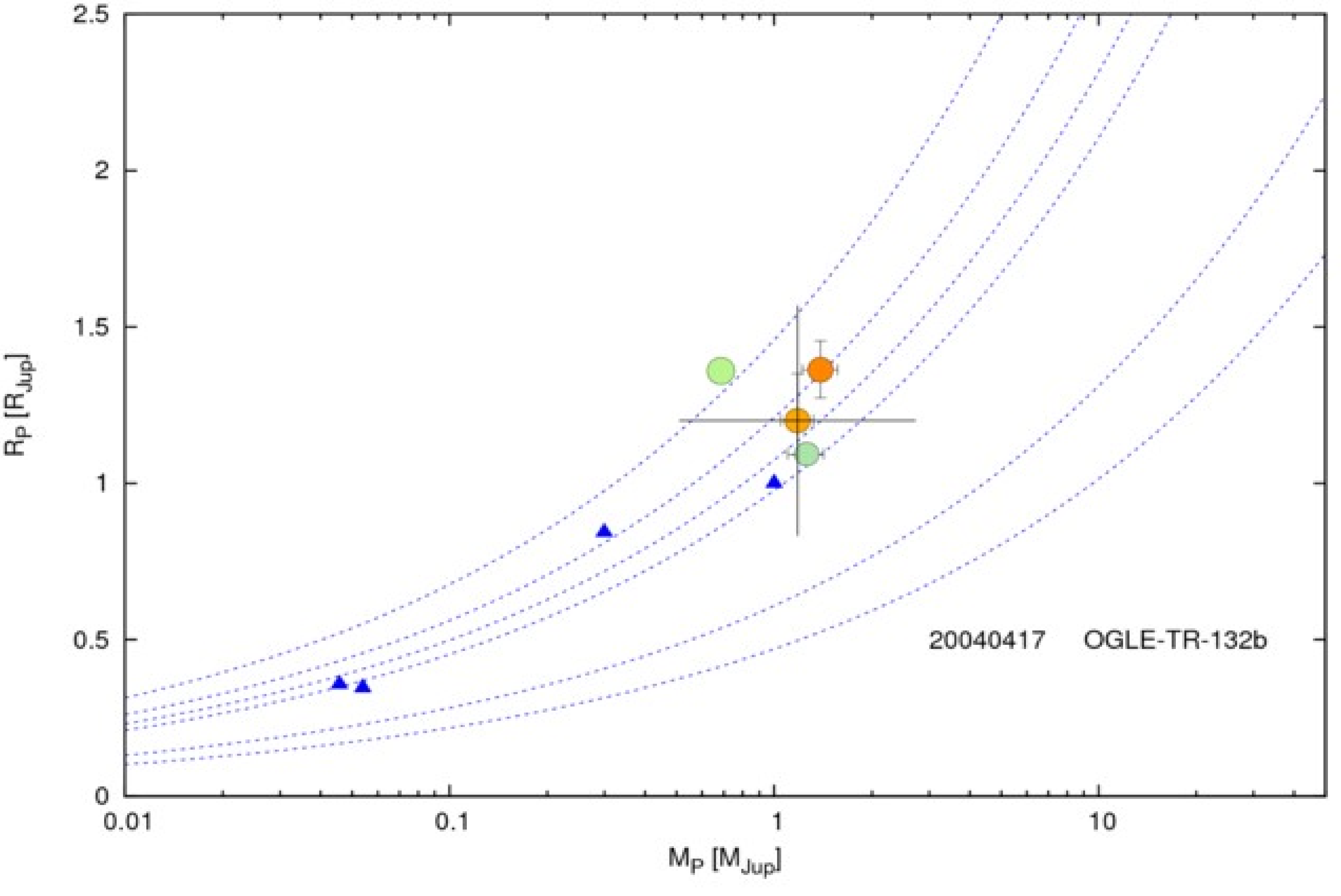
The brief history of TEPs

The following slides can be viewed as videos on youtube:

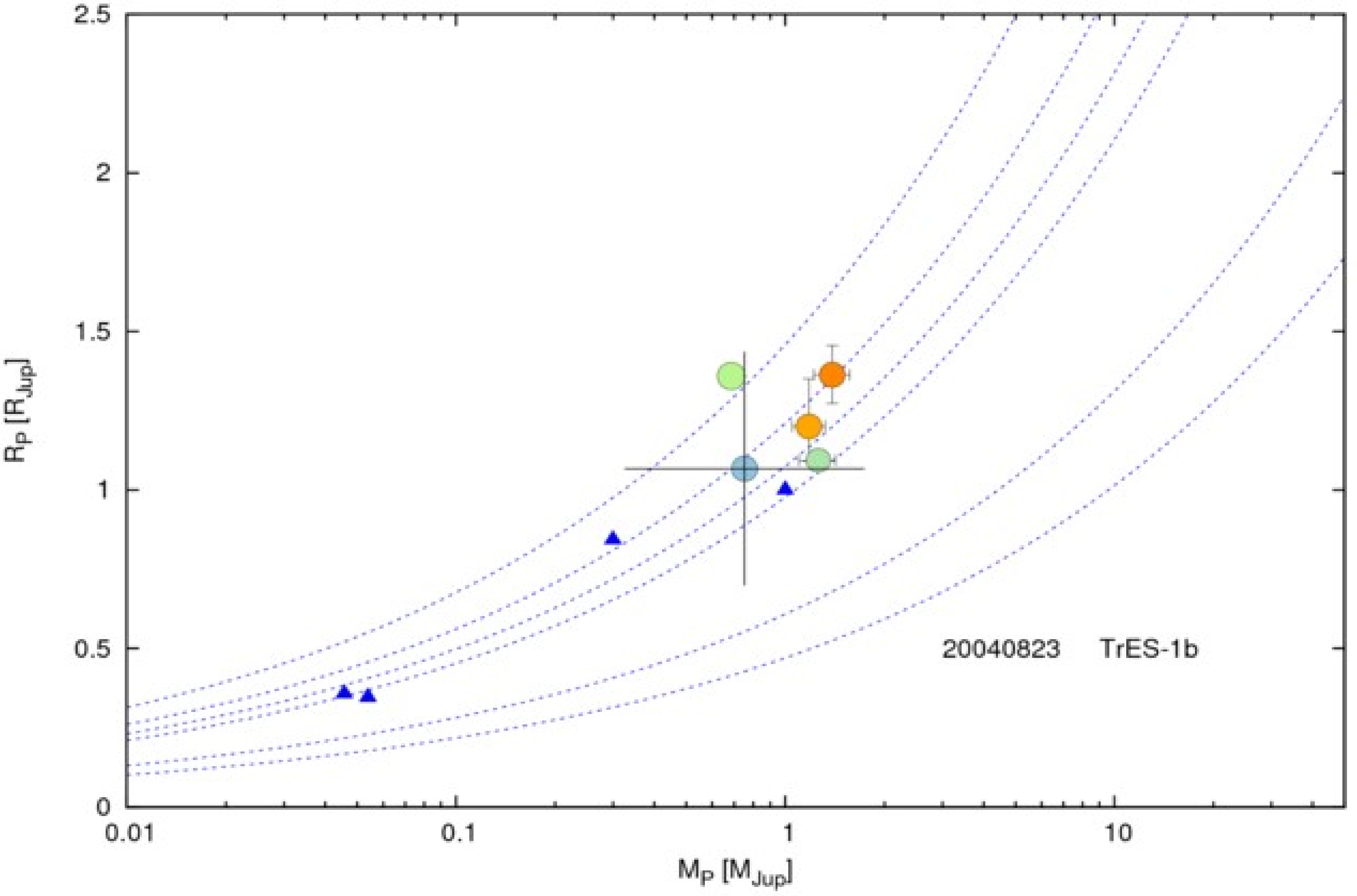
- http://www.youtube.com/watch?v=fsPVDBIL0eA
- http://www.youtube.com/watch?v=lzgoxa8bijc
- http://www.youtube.com/watch?v=pvfvY0oEKsc
- http://www.youtube.com/watch?v=TdUK04kG-6A



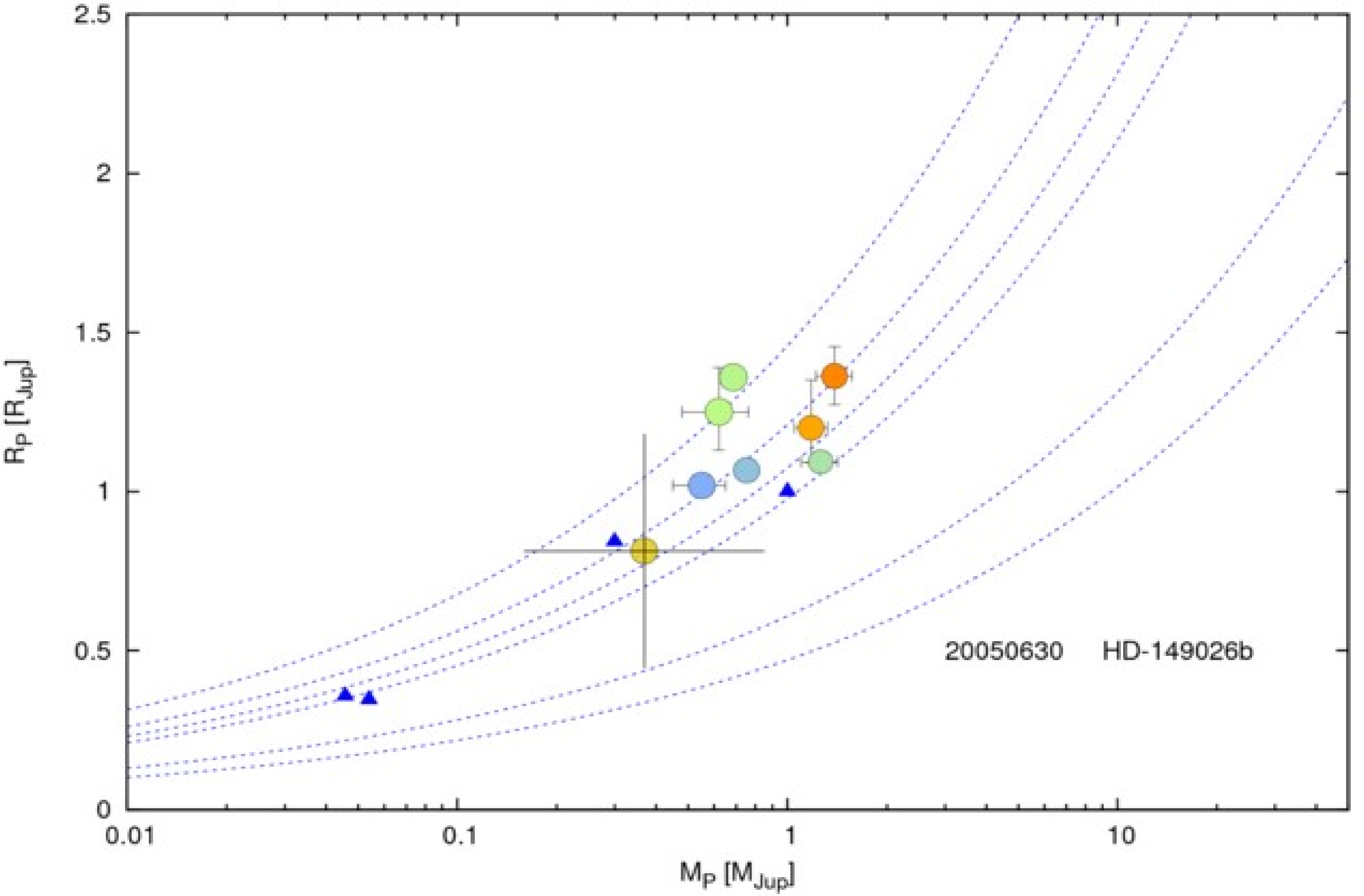
The brief history of TEPs: highlights



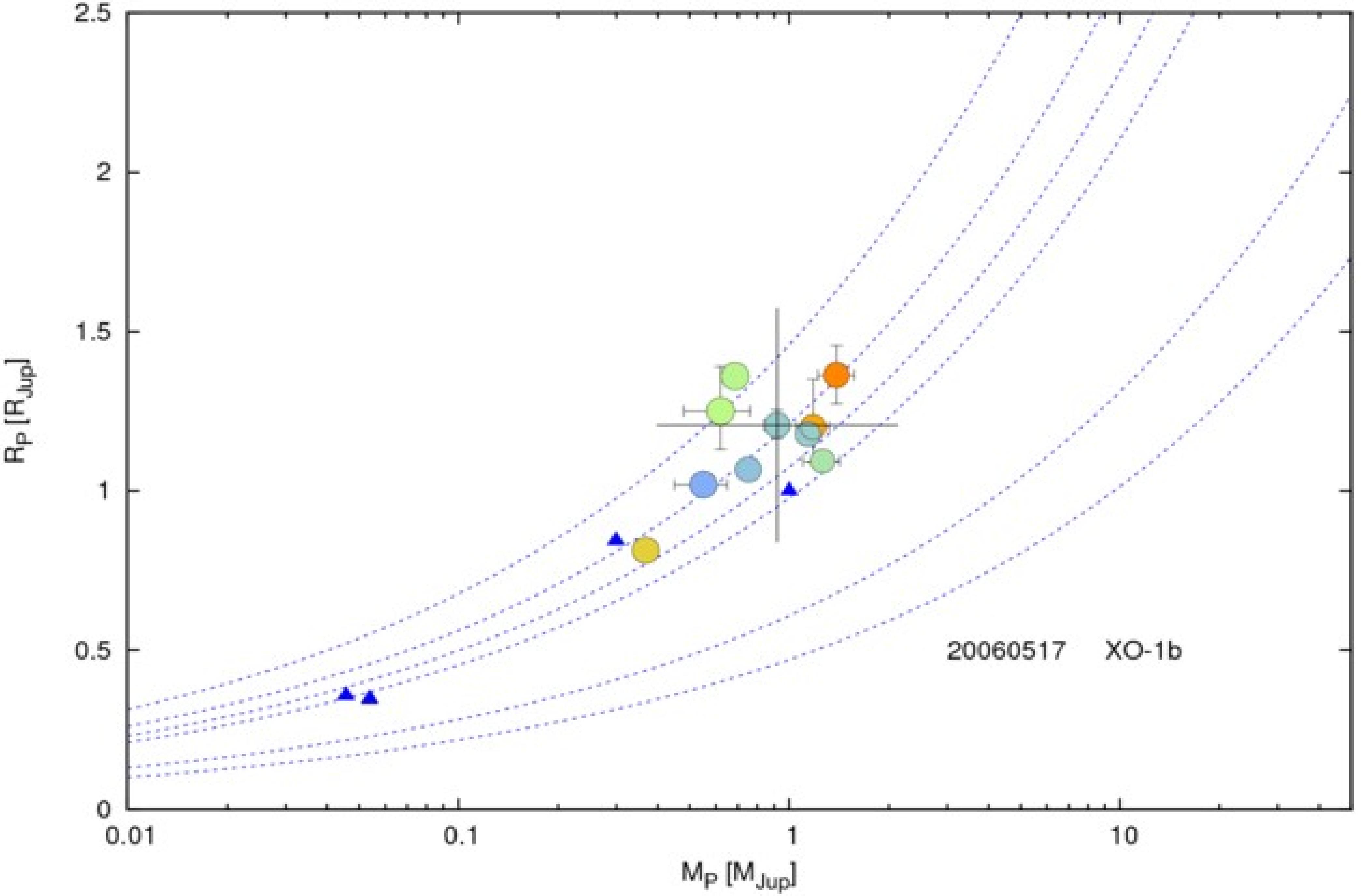
The brief history of TEPs



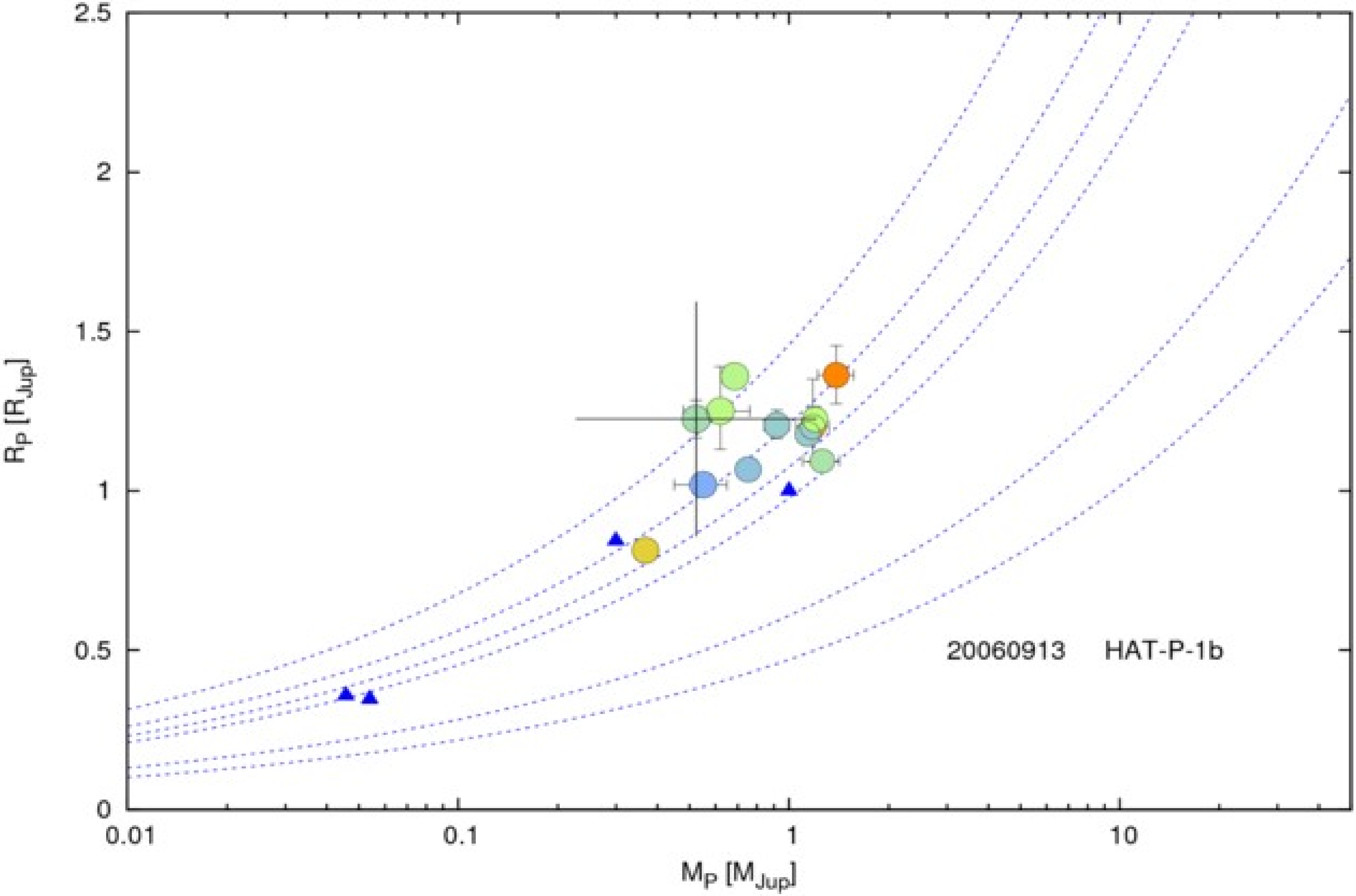
The brief history of TEPs



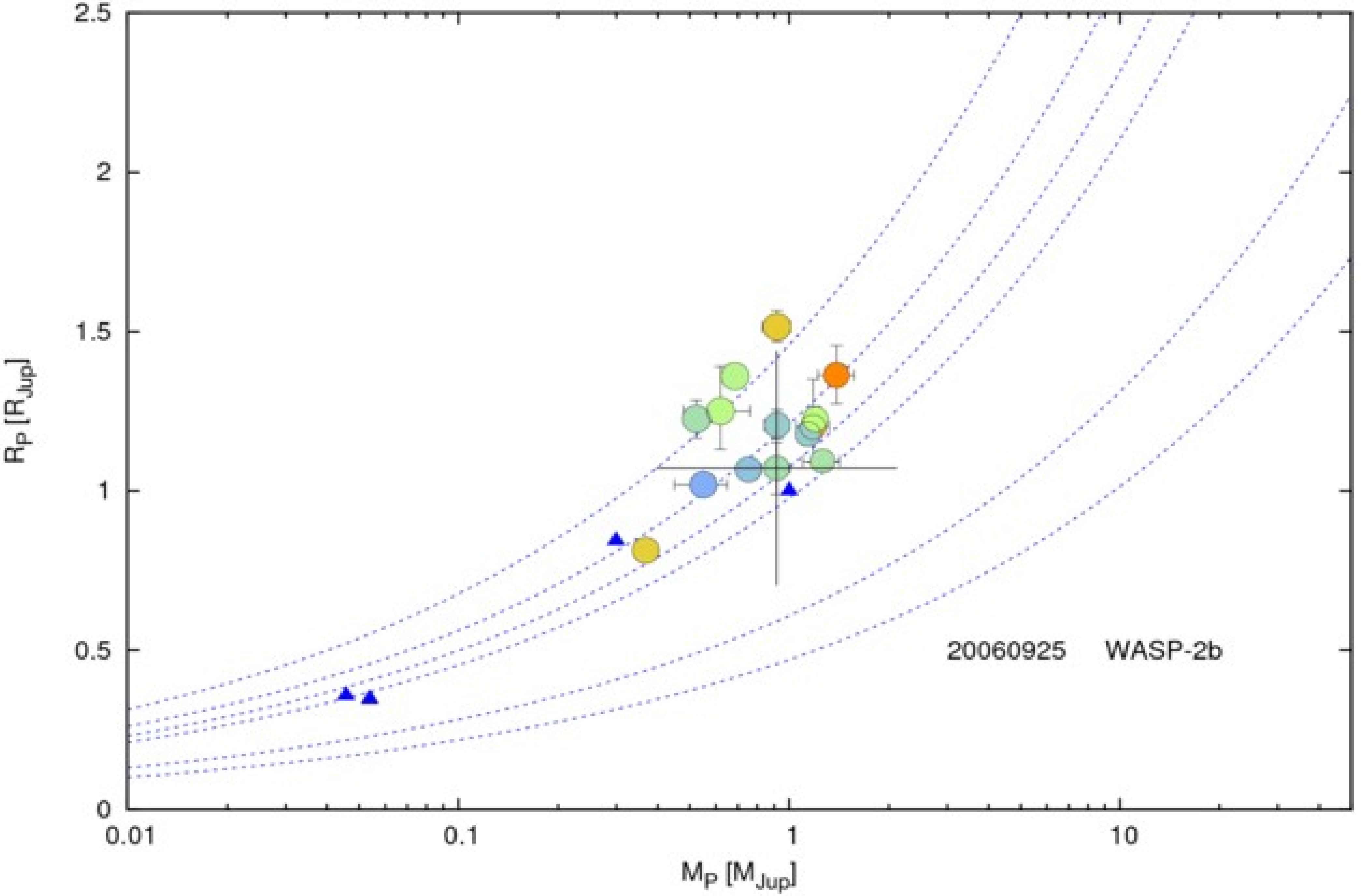
The brief history of TEPs



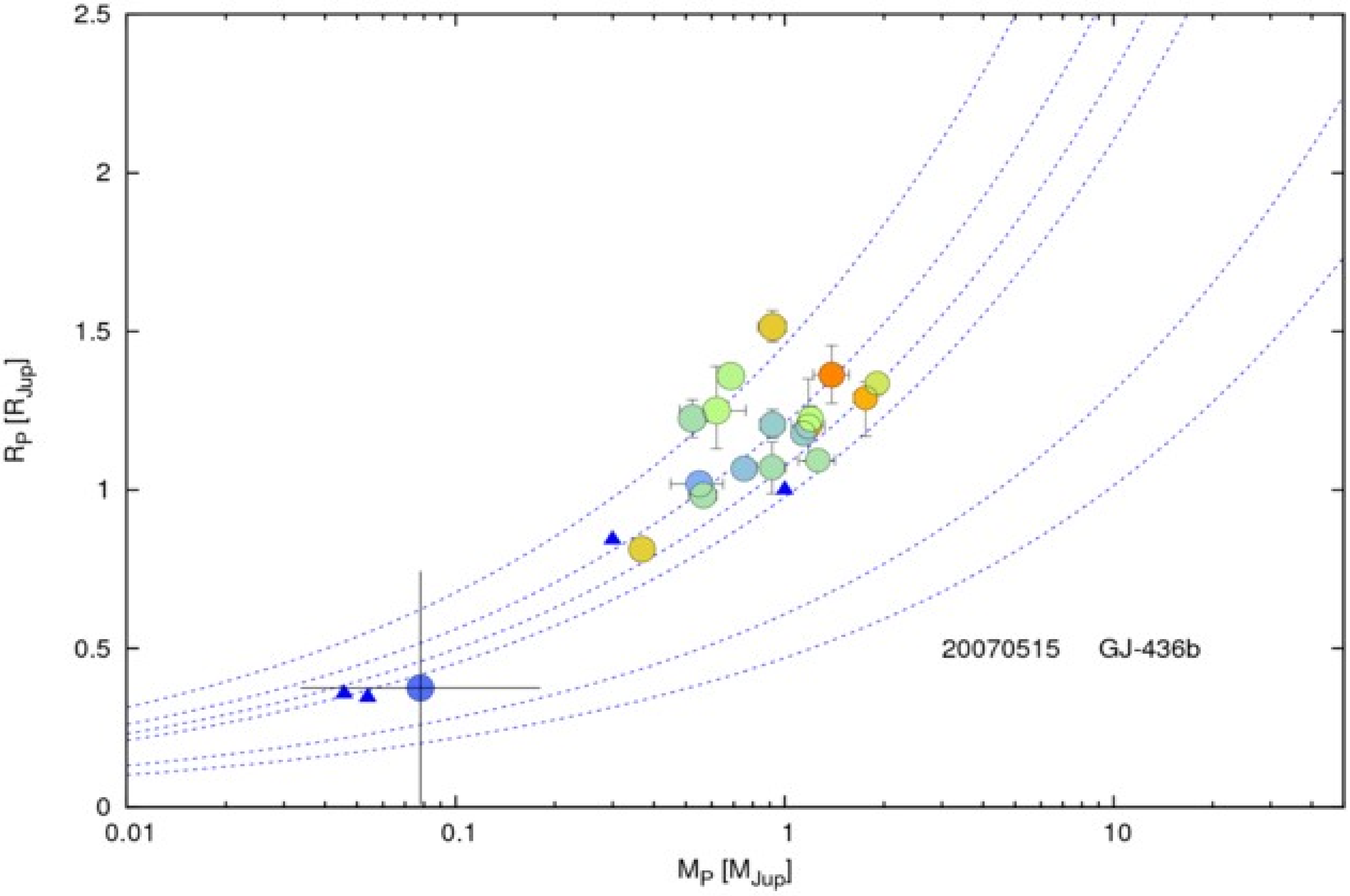
The brief history of TEPs



The brief history of TEPs



The brief history of TEPs



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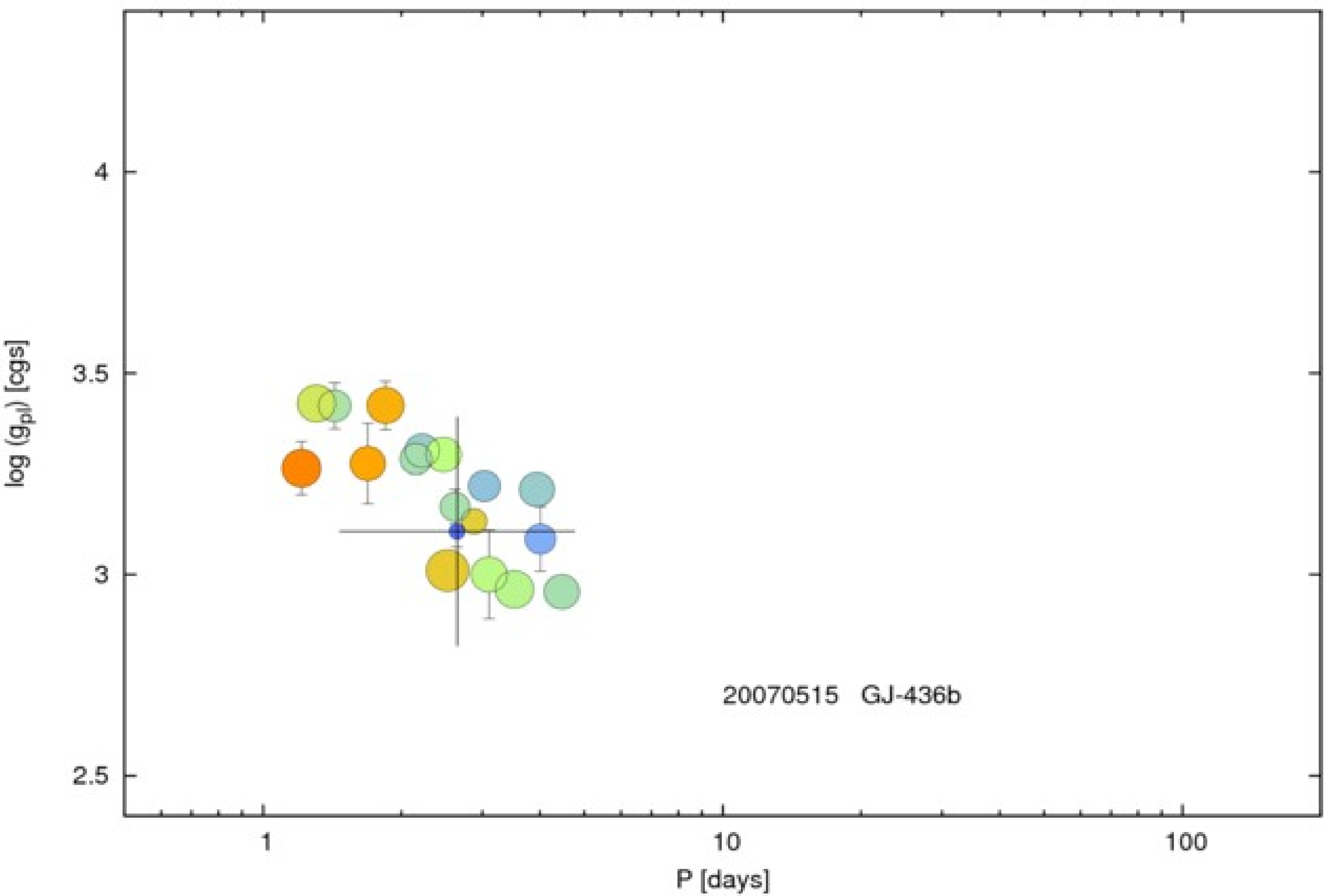

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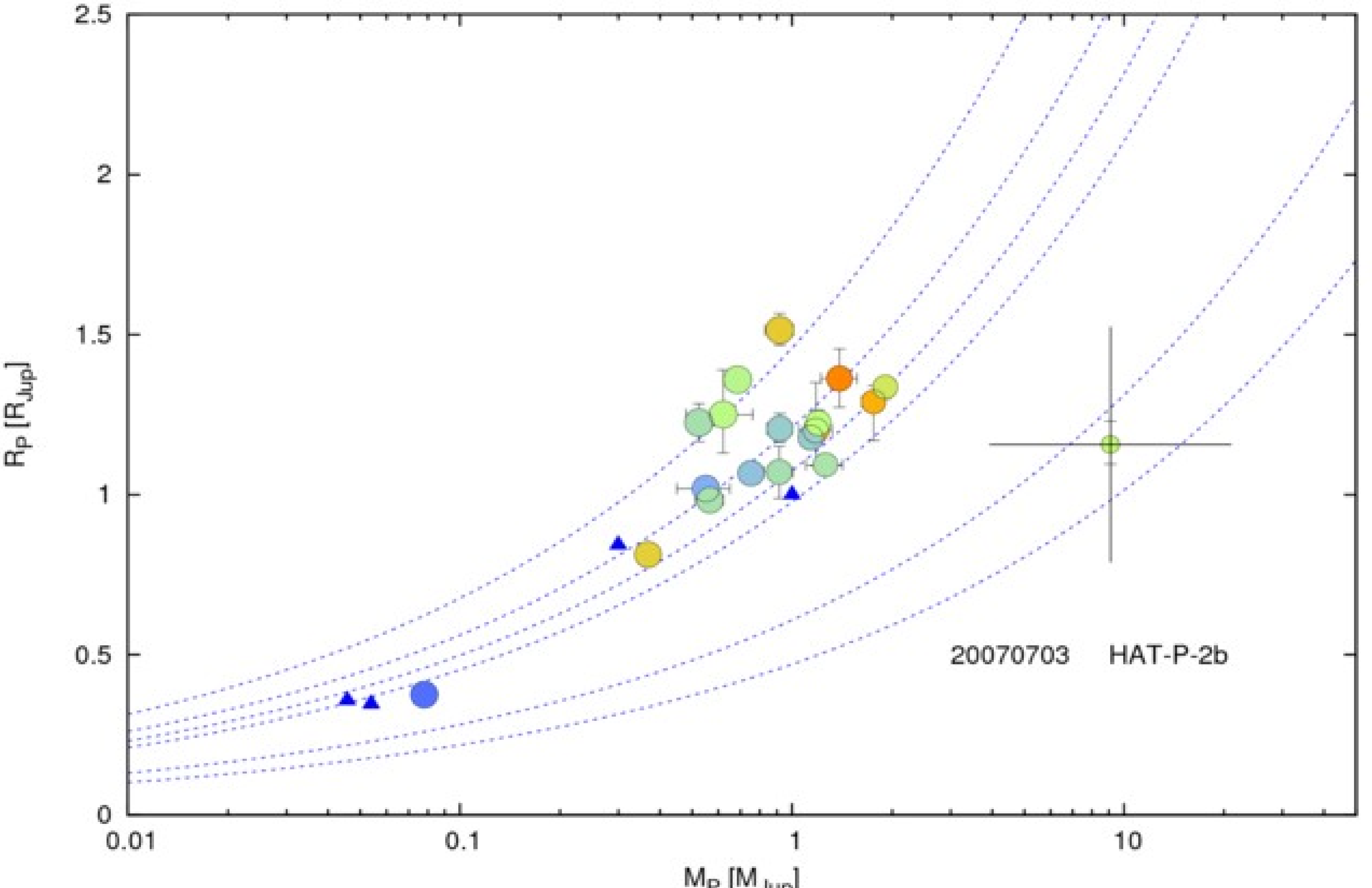
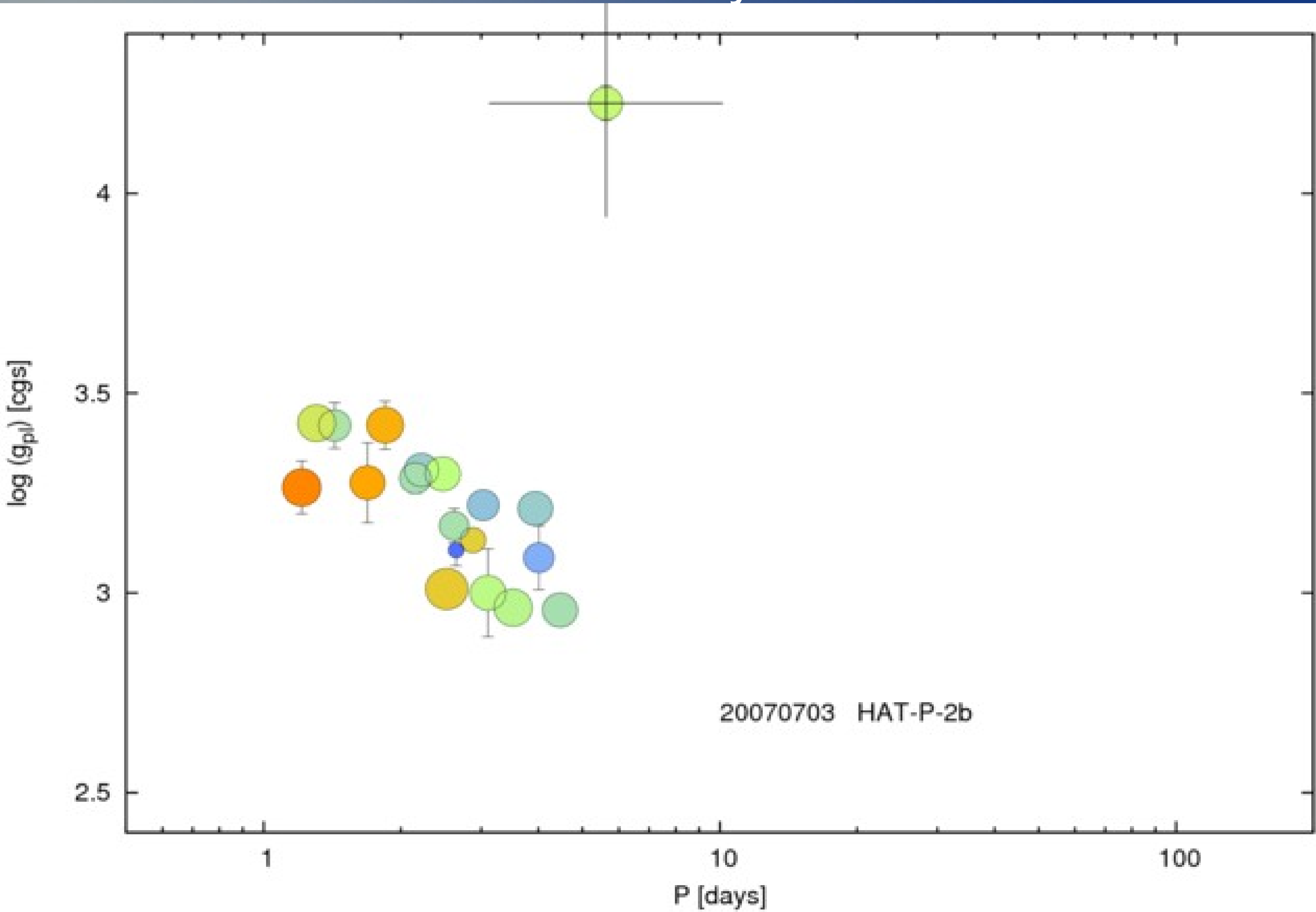


The brief history of TEPs



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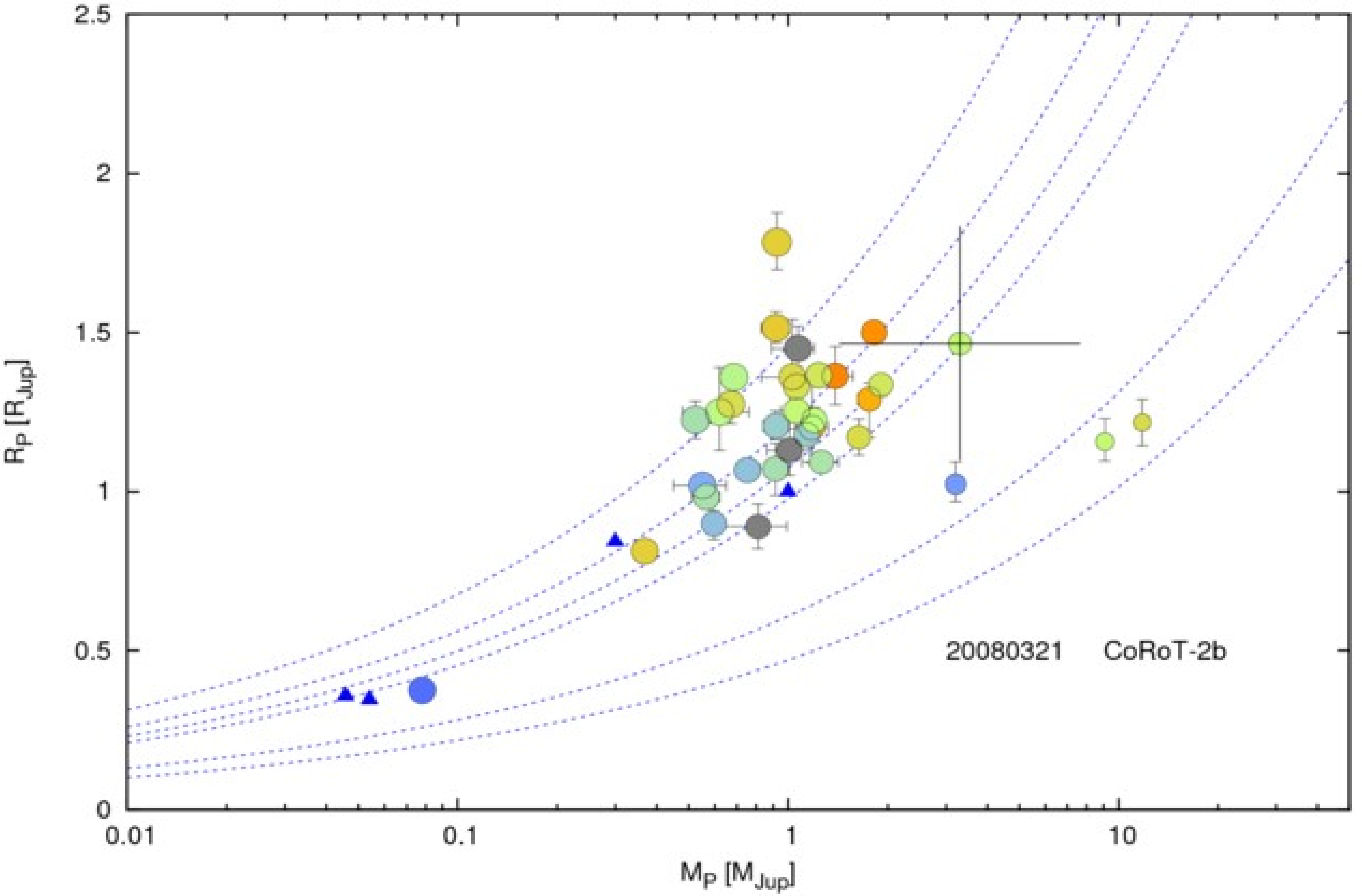

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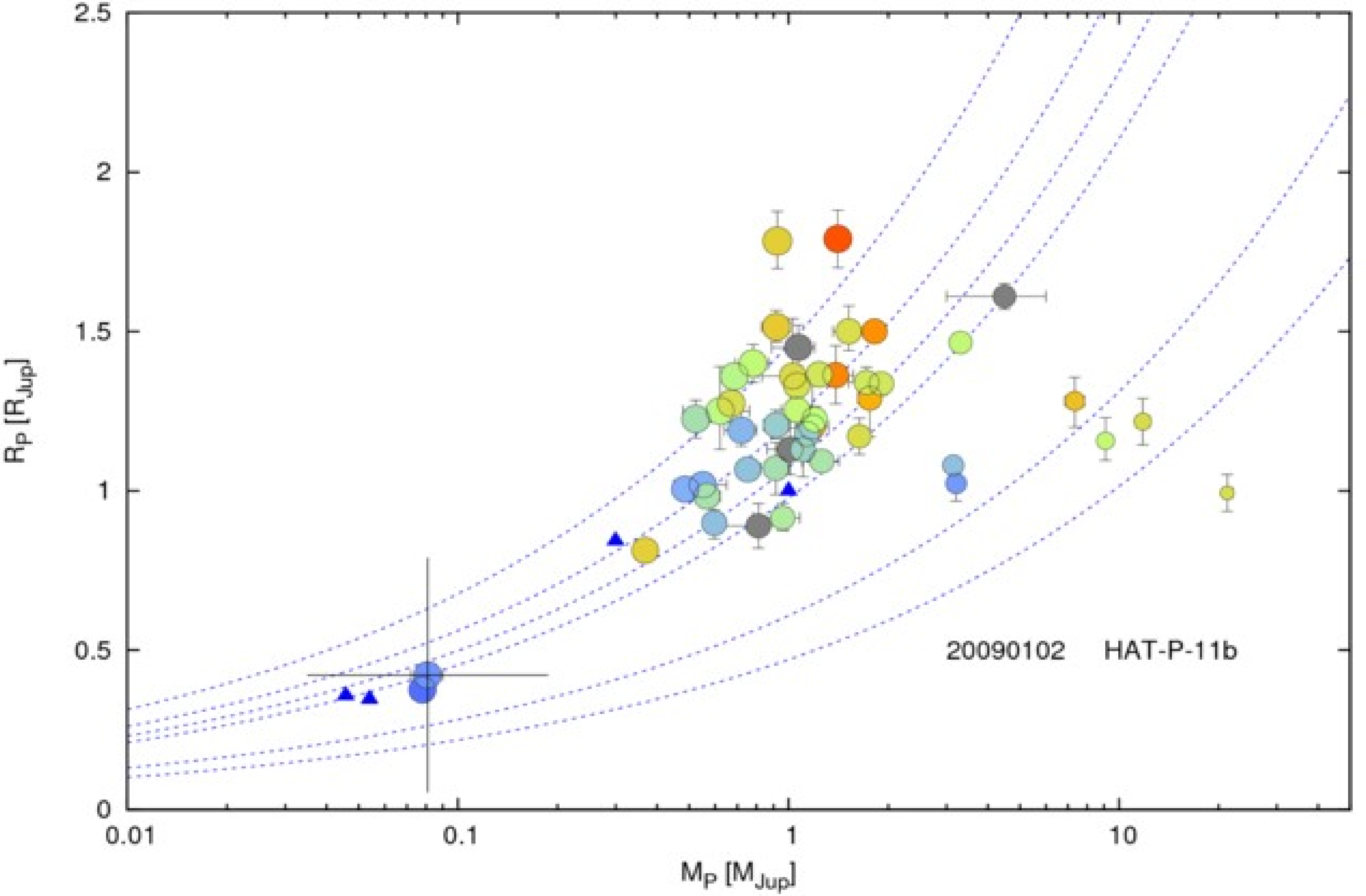
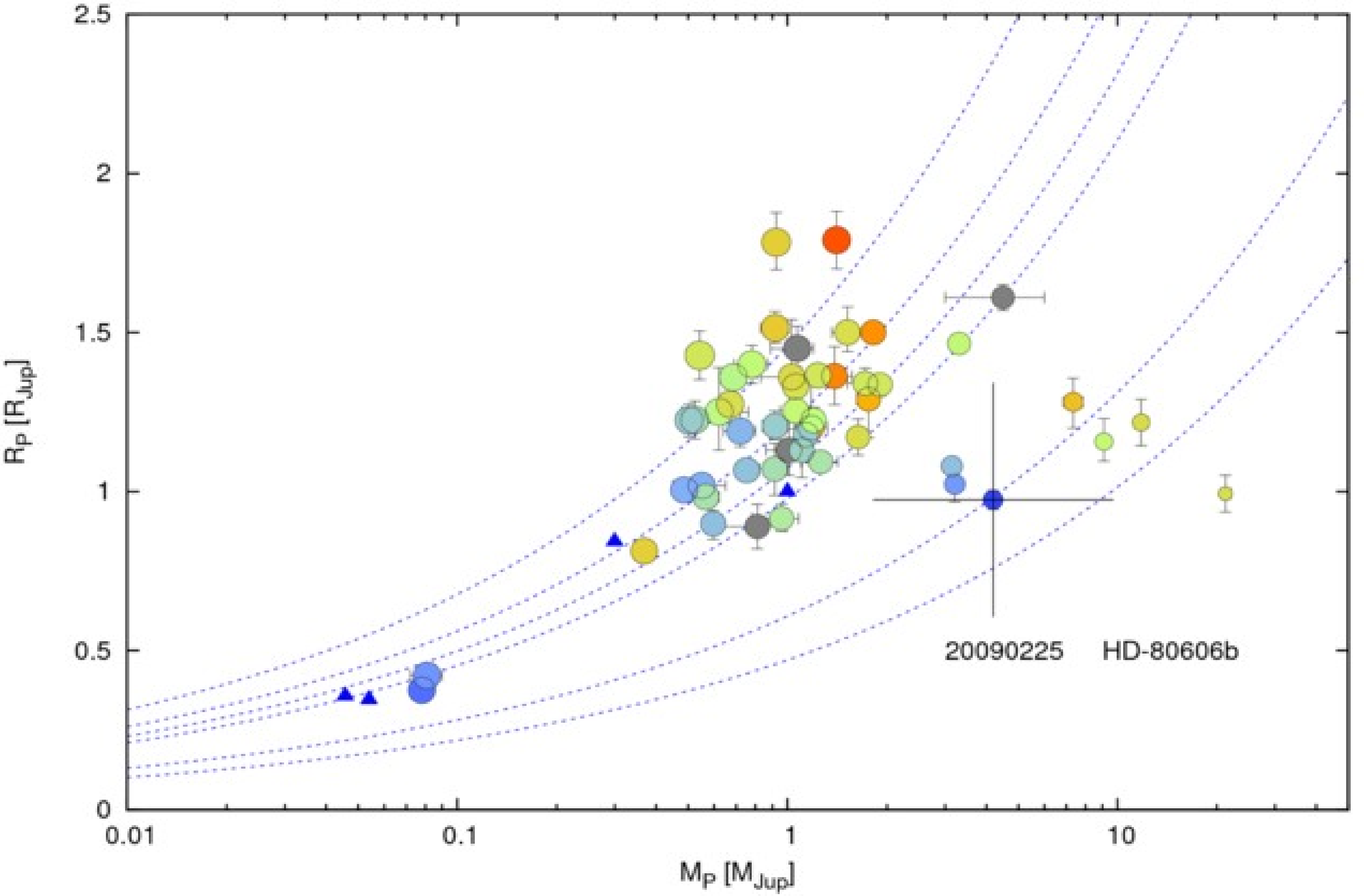


The brief history of TEPs



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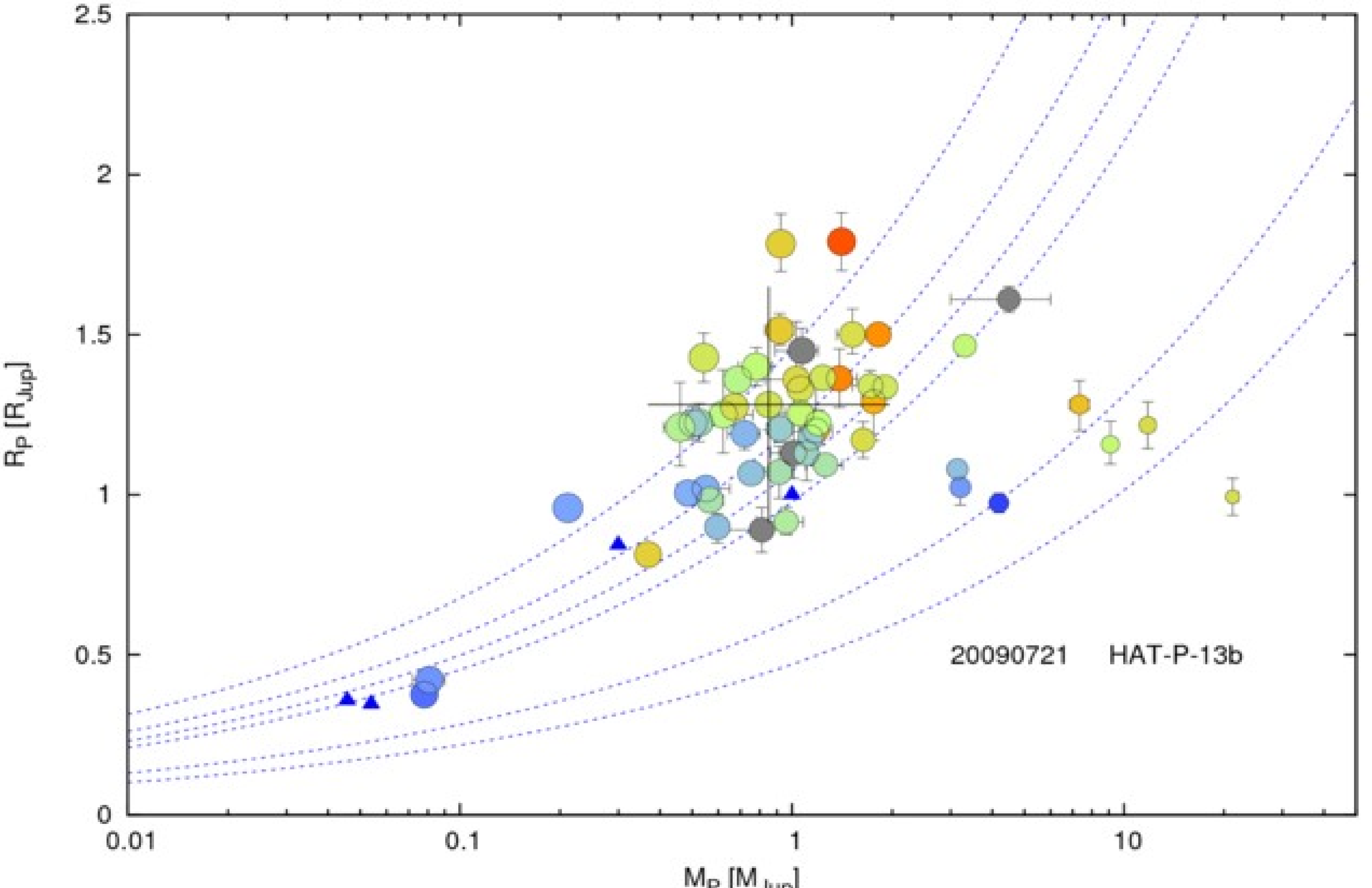

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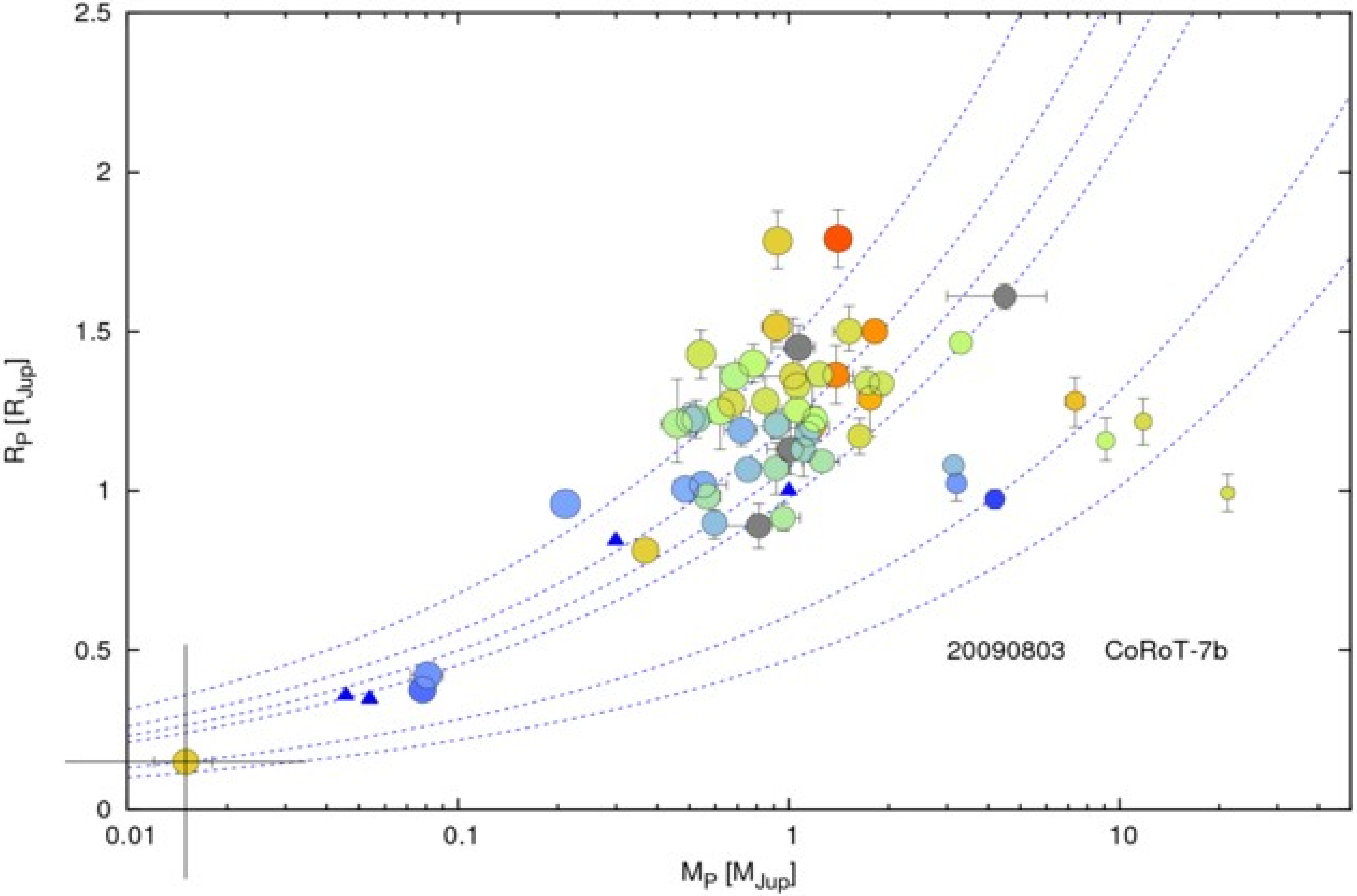
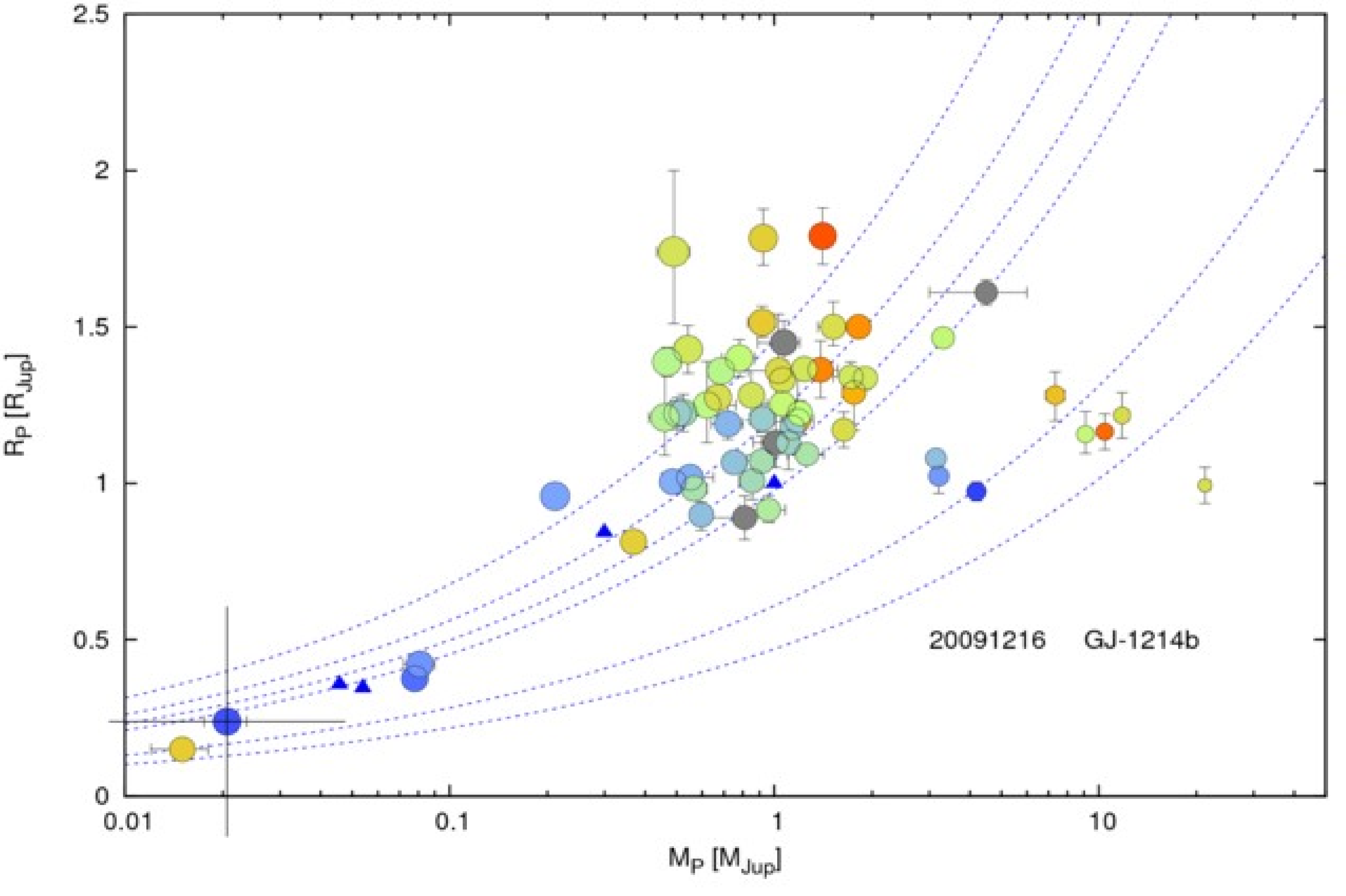
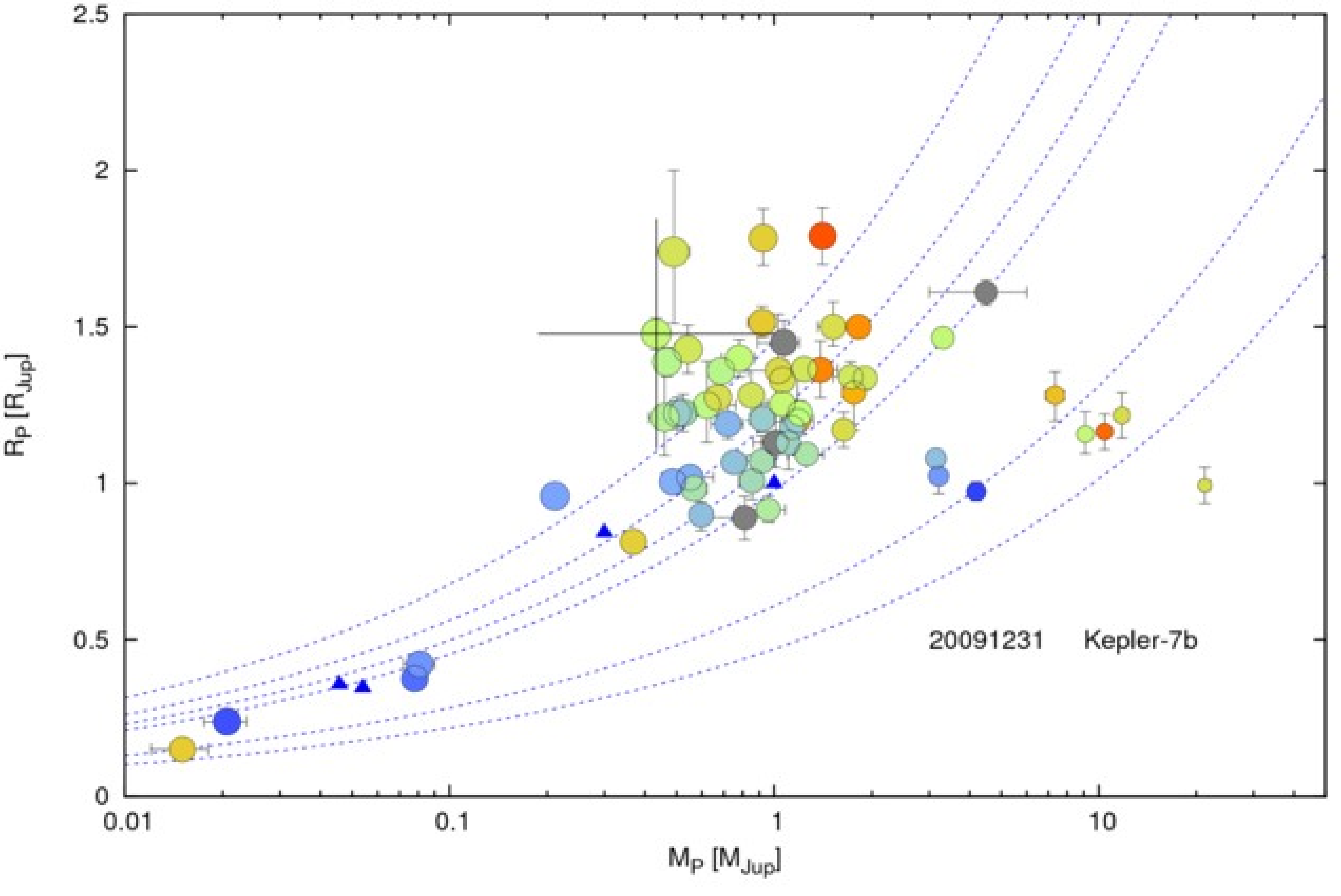


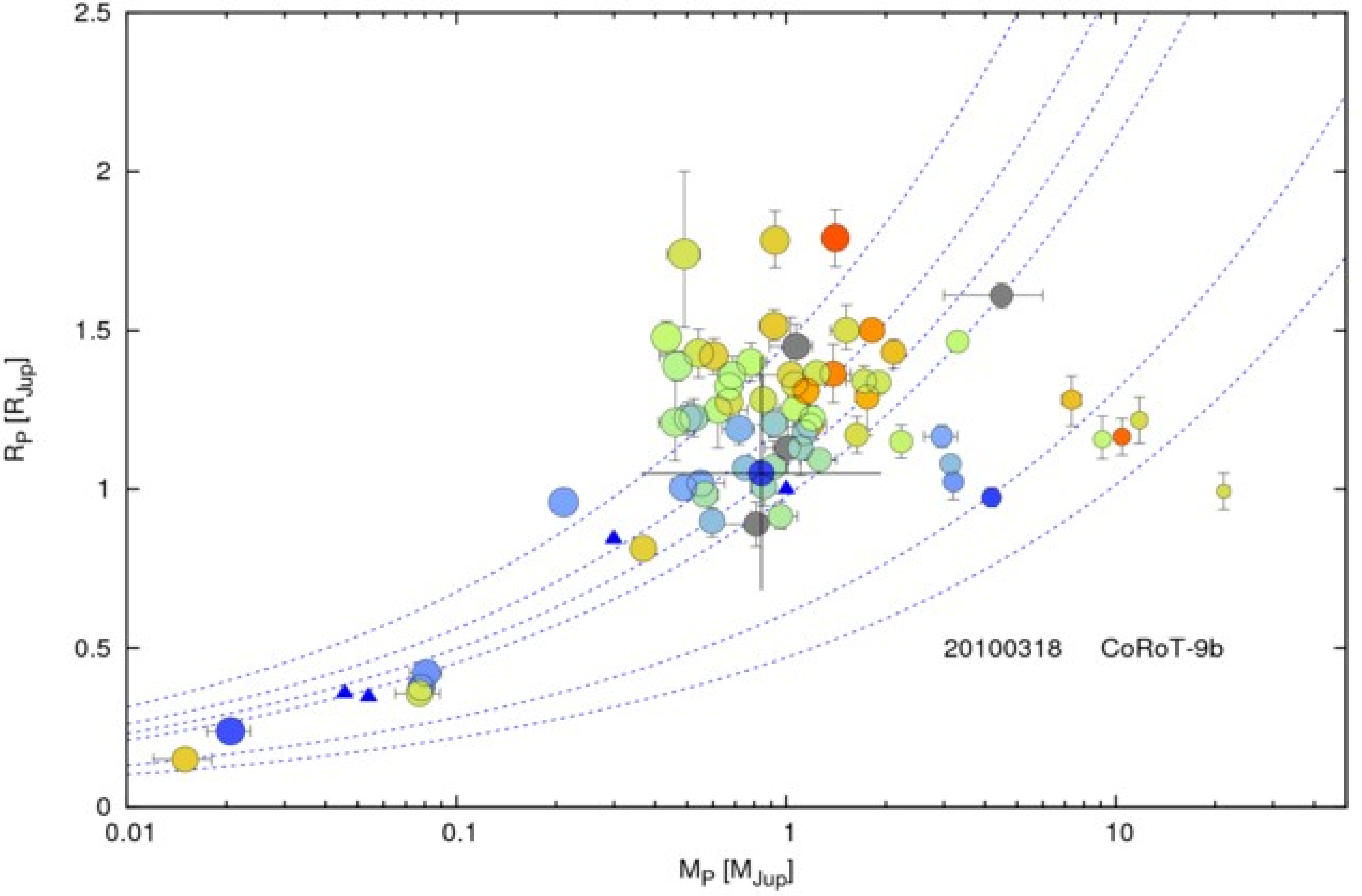
The brief history of TEPs



The brief history of TEPs



The brief history of TEPs



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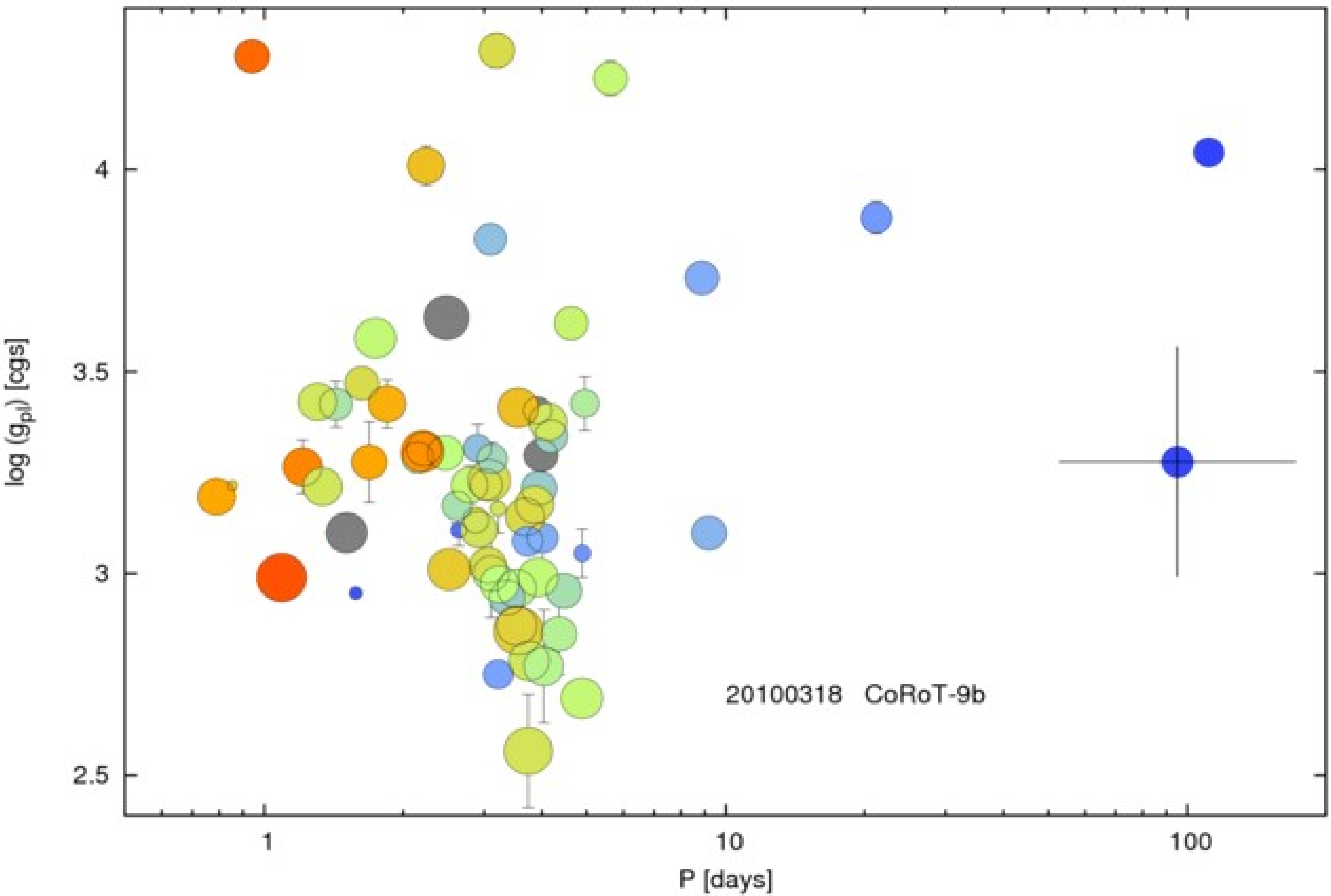

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- G. Marcy, A. Howard (UCB), D. Fischer (SFU), J. Johnson (Caltech)
- Géza Kovács (Konkoly)
- I. Papp, P. Sári, J. Lázár (H.A.S)

HAT-South:

- A. Jordán, M. Rabus, V. Suc (PUC)
- T. Henning, C. Afonso, B. Csák (MPIA)
- P. Sackett, D. Bayliss, P. Conroy (ANU)
- M. Holman, Z. Csubry, K. Penev, B. Béky (CfA)
- ... and many others

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- Staff at FLWO, Mauna Kea, LCO, SSO and HESS
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