# YETI:
# Transits of young extra-solar planets and the formation of planets and stars

Ralph Neuhäuser et al.

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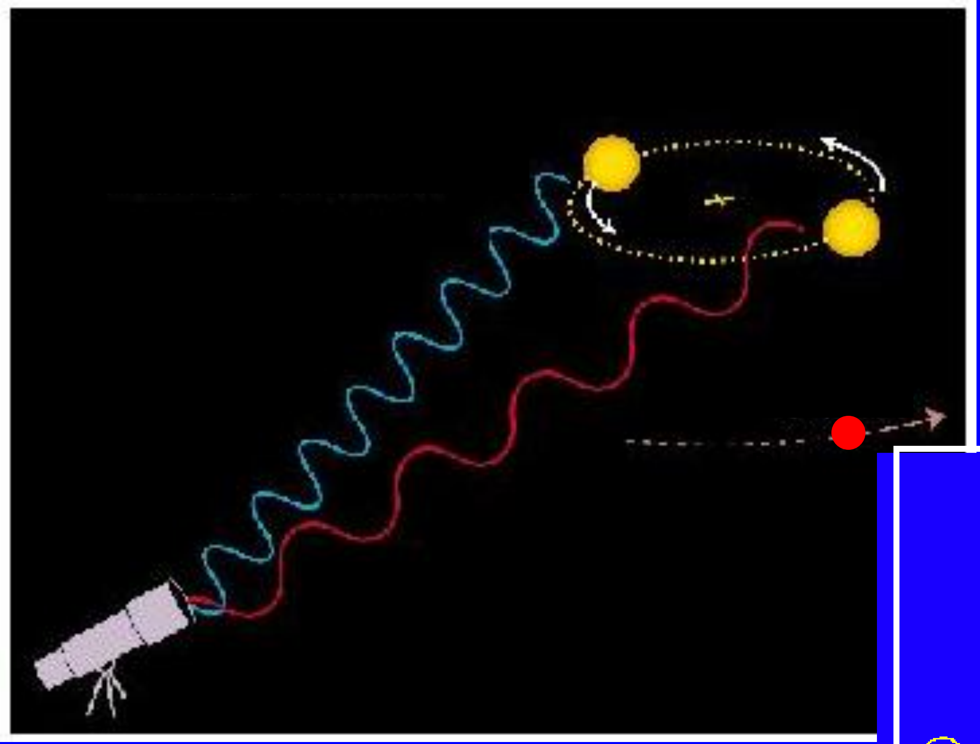
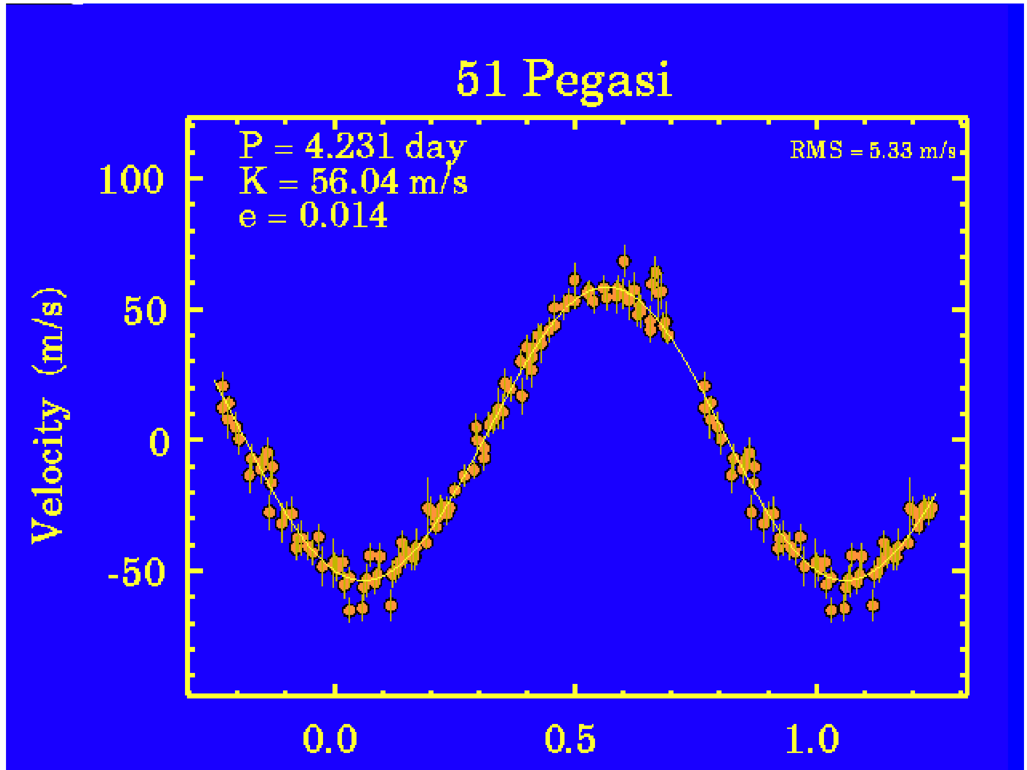
**Motivation: How did the solar system form ?**

# Extra-solar planets with radial velocity



First such radial velocity planet candidate:
HD 114762 b (Latham et al. 1989 Nature).




(Mayor & Queloz 1995 Nature)

Almost 1000 such objects.

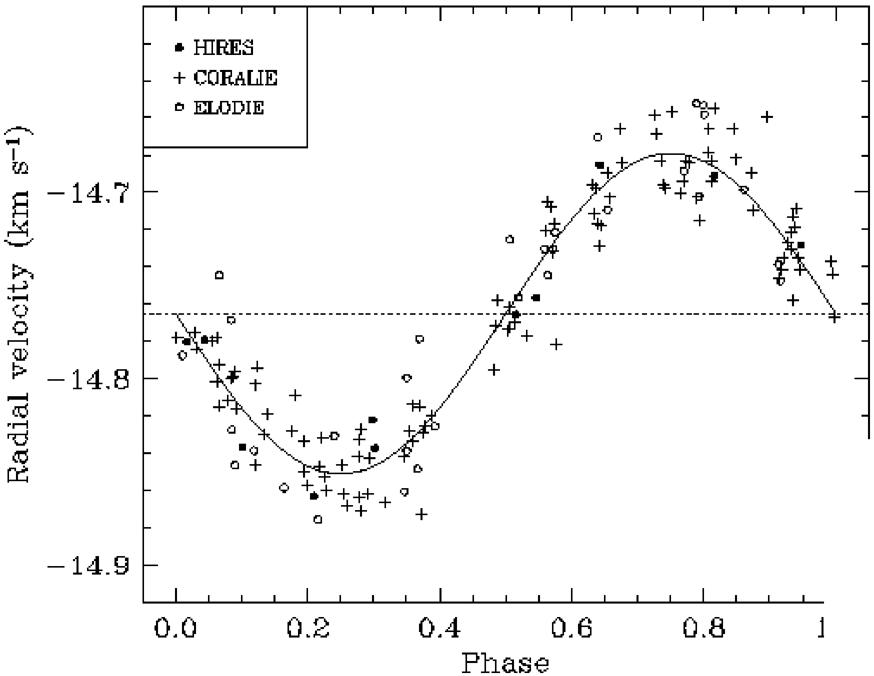
Orbital inclination often unknown.

➔ Only M sin i known.
Hence, planet *candidates* !

Confirmable by transit or astrometry

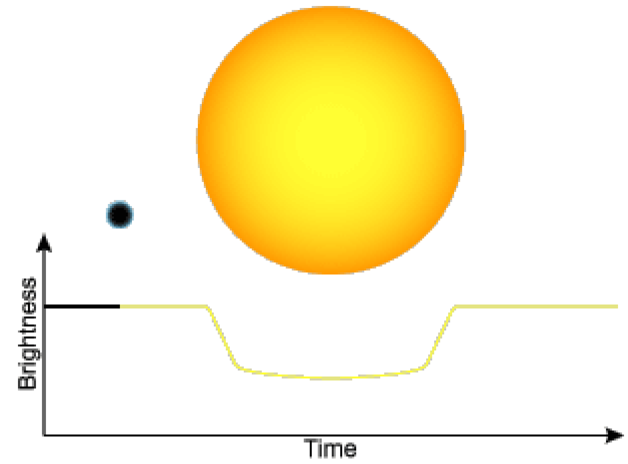
# Radial Velocity and Transit methods

(Mazeh et al. 2000 ApJ)

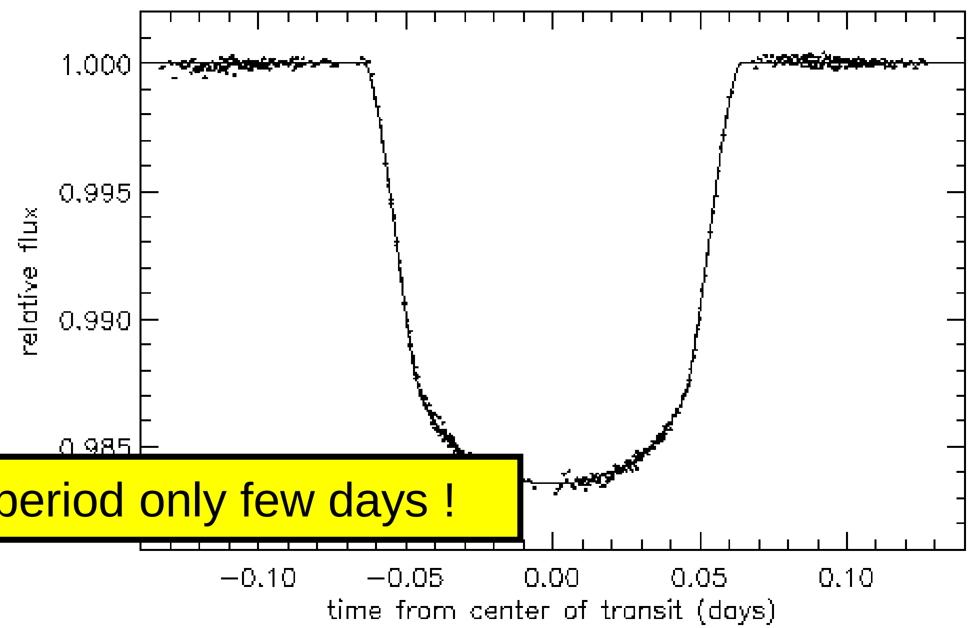



HD 209458

Light Curve of a Star During Planetary Transit



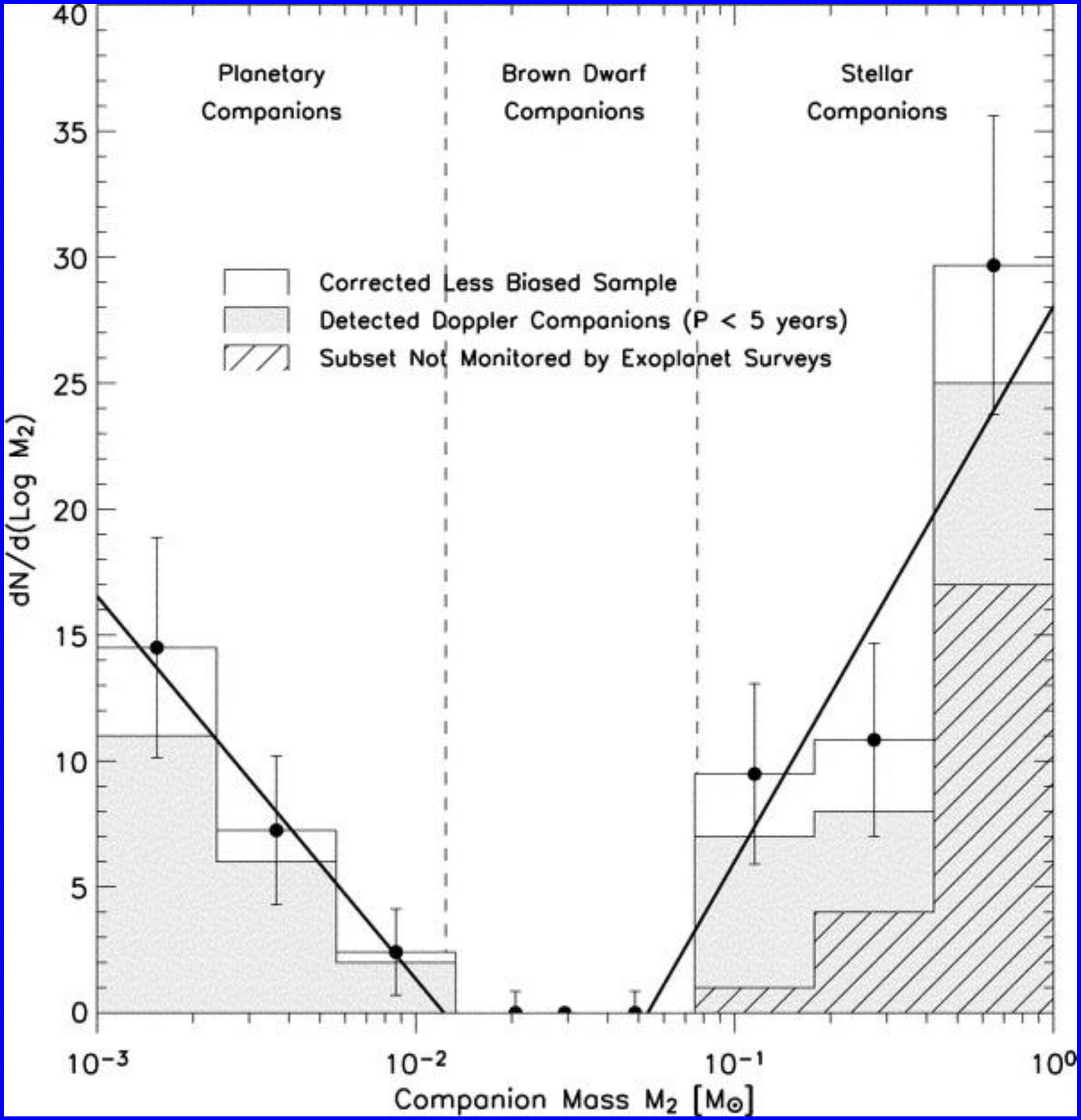

(Charbonneau et al. 2000 ApJ, Brown et al. 2001 ApJ)




**Planets often close to star: orbital period only few days !**

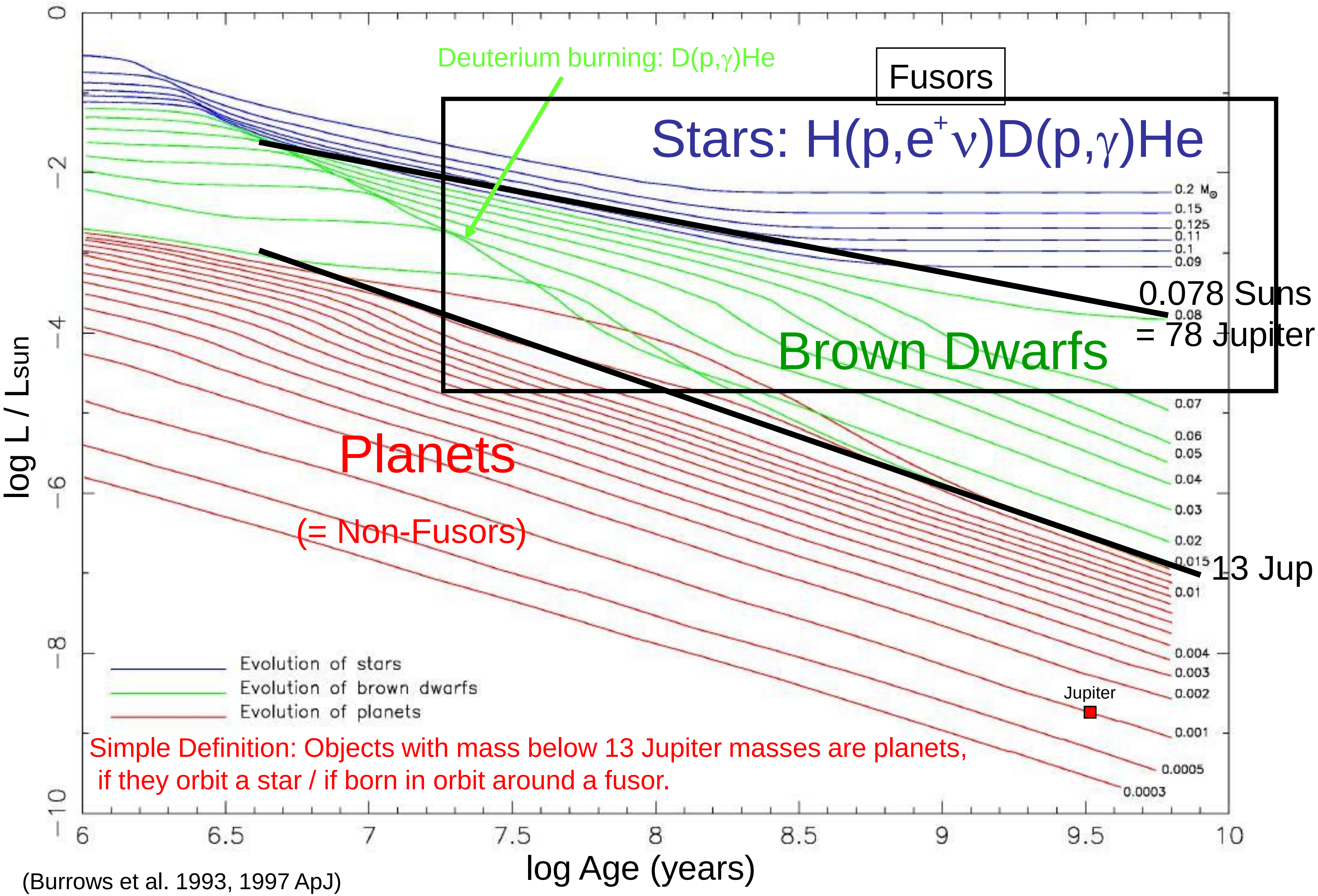
Transit ➔ orbital inclination and planet radius ➔ Mass and density of planets

# The brown dwarf desert:  20 to 50 Jup masses




Lineweaver & Grether 2006

# Luminosity vs. age (stars, brown dwarfs, and planets)

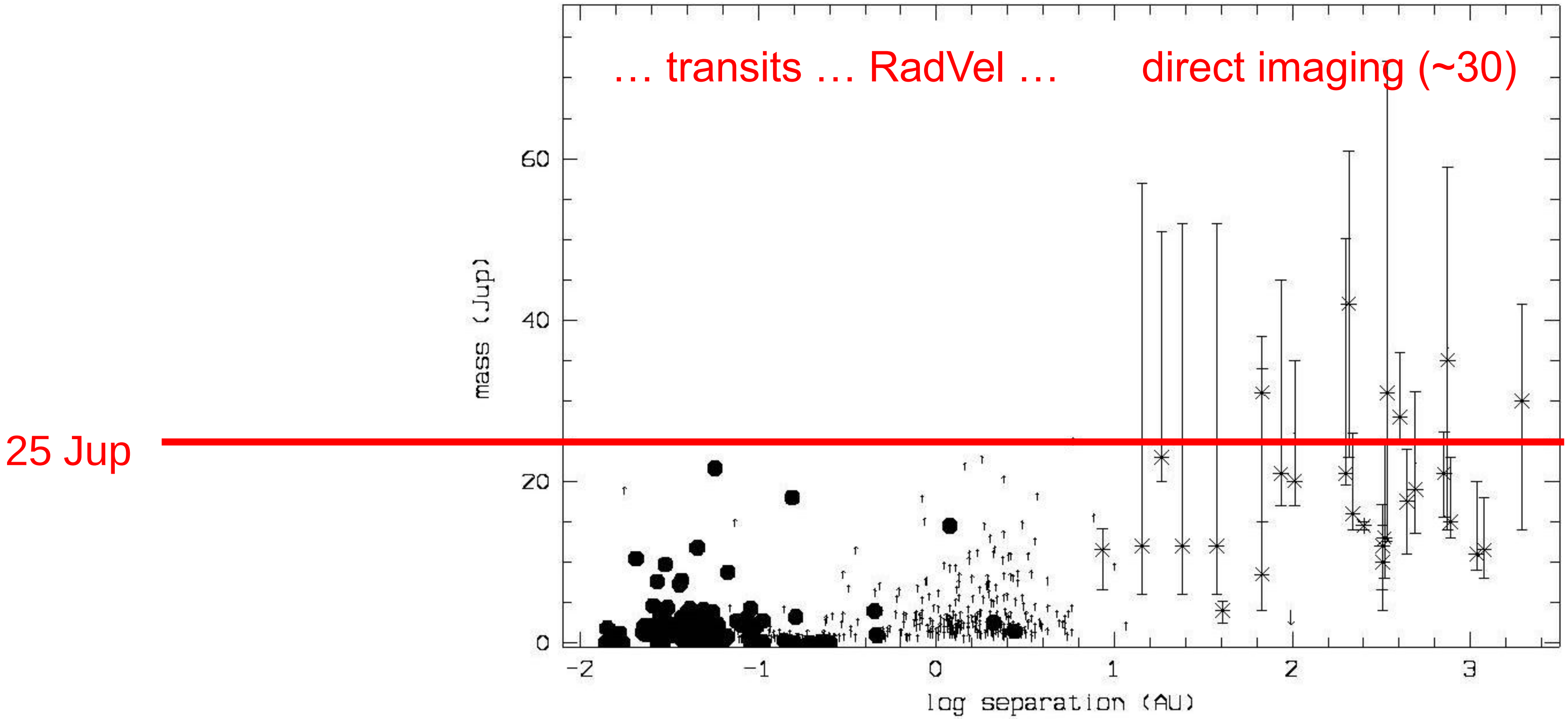



(Burrows et al. 1993, 1997 ApJ)

Mass (or m sin i) for planets (and planet candidates) with mass below 25 Jup
versus
Separation in au

For Rad Vel and transit planets (left) and directly imaged candidates (right)

Methods now meet at ~ 10 au




RV planet cands. at 9-12 au: ν Oph c, HIP 5158 b, HIP 70849 b, 47 UMa d

Imaged planet cands. at 9-18 au: b Pic b, HR 8799 e, PZ Tel b

Neuhäuser & Schmidt 2012 review

## Young Transiting Planets:

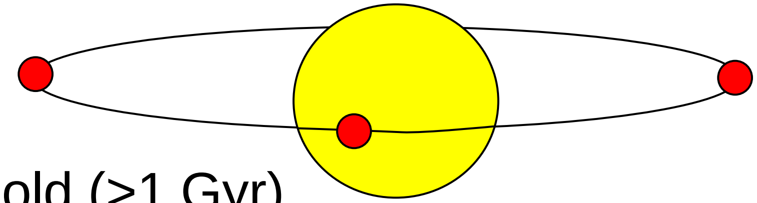
Directly imaged planets (and candidates) young, but mass determination difficult.

Different detection technique for young planets ?

Rad Vel difficult due to noise in young active stars.

➔ **Transit method**

# Transiting planets



most of the known extra-solar planets are old (>1 Gyr)

youngest transiting planets (until a few years ago):

Corot 2: 130 – 500 Myr from star spots
(or 30 – 40 Myr from planet radius)

- Corot 20: 100 – 800 Myr from Li-abundance
- Wasp 10: 200 – 350 Myr from gyro-chronology (Maciejewski + 2011)
- K2-33b Neptune-size (David et al. 2016), 5-10 Myr, P=5.4 d

→ younger transiting planets needed to study planet formation
(e.g. youngest planet found would constrain formation time-scale)

Previous attempts on transits of young planets in clusters:

MONITOR project (few clusters / short obs runs)
&
CoRoT (one cluster), but no planets reported yet

→ long continuous observation needed for detection

# Observatory of U Jena in Großschwabhausen near Jena

## 3 telescopes with 4 instruments

CCD for high
Time and spatial
Resolution: RTK
(20 cm)

CCD
*CTK* (25 cm)



CCD
Schmidt
Focus:
STK
(60 cm)

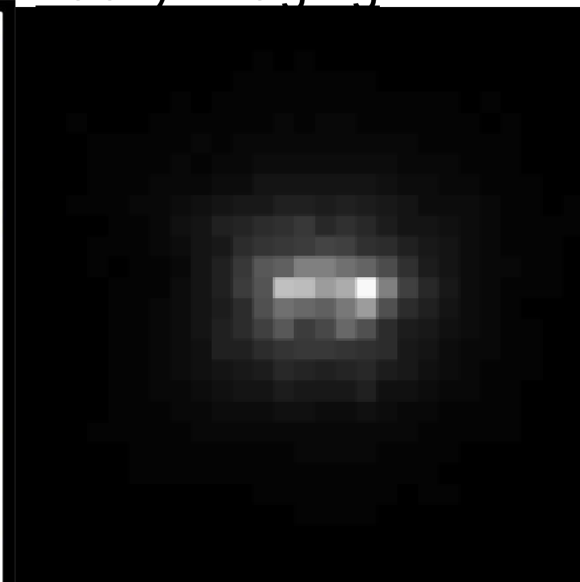
Fiber-
Spectrographs
*FIASCO and*
*FLECHAS*

# Observatory of U Jena in Großschwabhausen near Jena

## 3 telescopes with 4 instruments

CCD
*CTK* (25 cm)


Lucky Imaging



CCD for high
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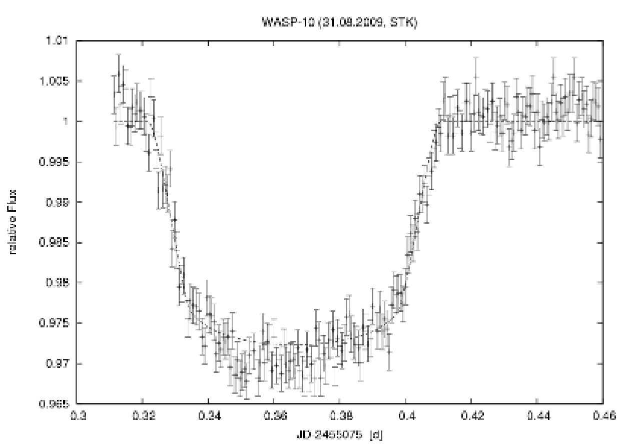
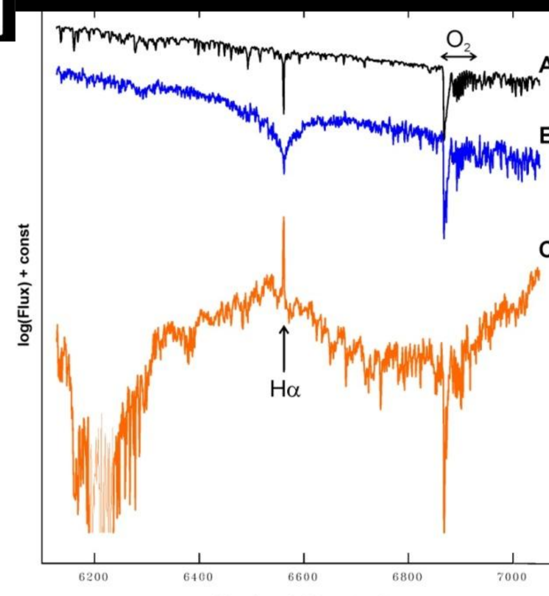
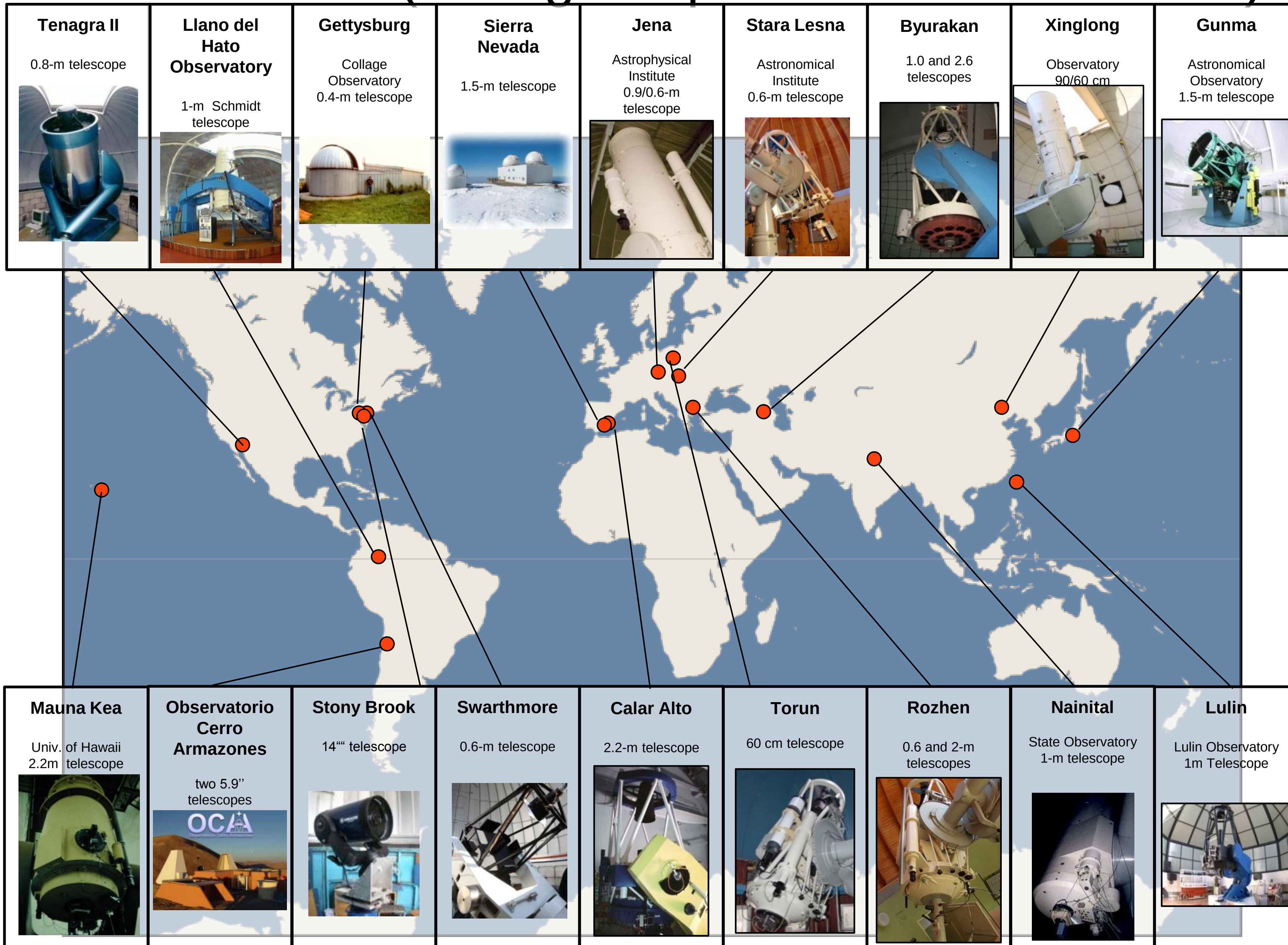
(60 cm)




Fiber-
Spectrographs
*FIASCO and*
*FLECHAS*

# YETI network (Young Exoplanet Transit Initiative)



## YETI project (Young Exoplanet Transit Initiative)

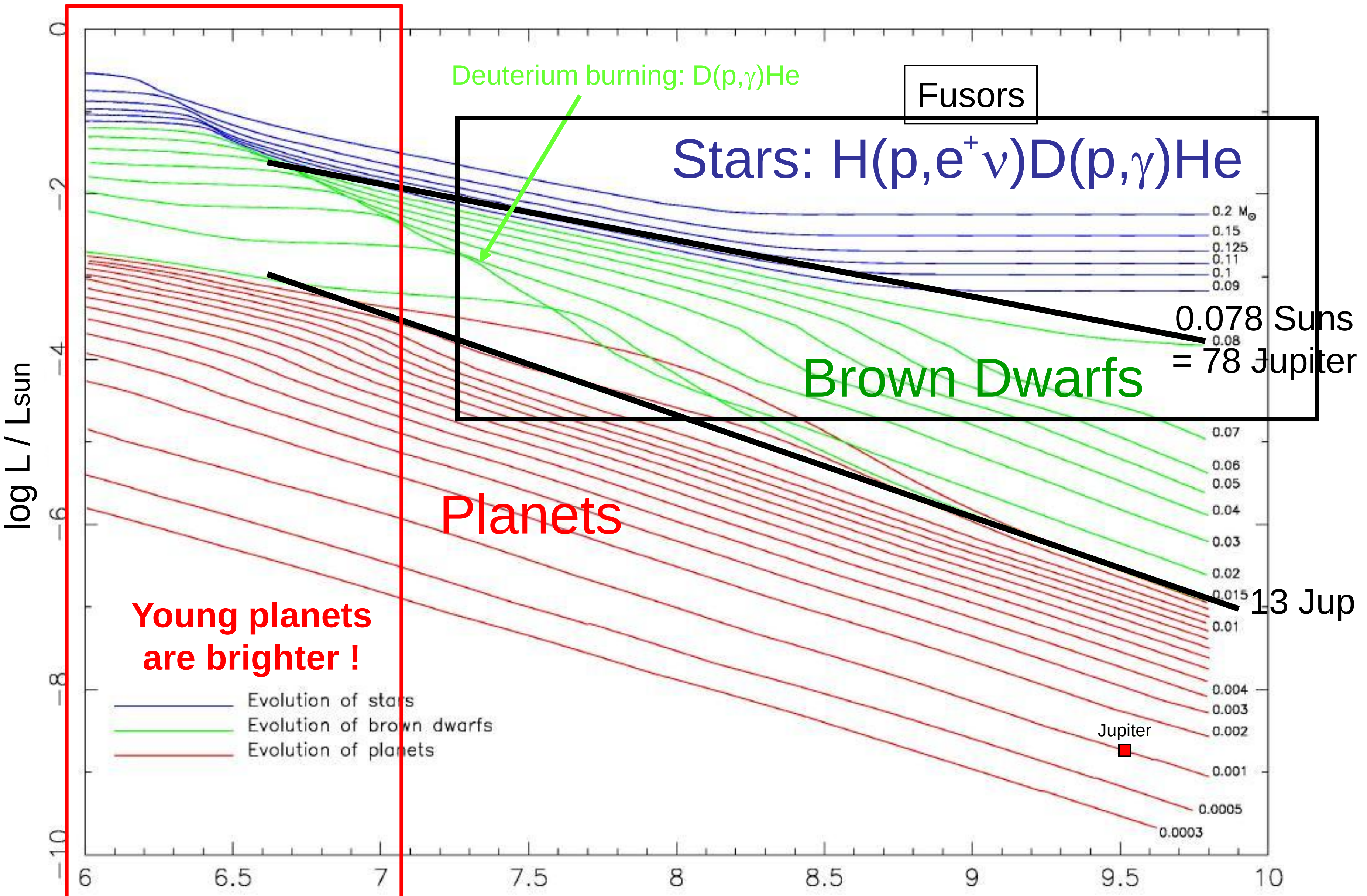
PI: R. Neuhäuser
with Co-PIs from each participating observatory

Target selection criteria (among others):
Young (< 100 Myr), nearby (< 2 kpc) stellar cluster,
many members with intermediate brightness,
about 1 square degree on sky, etc.

Each cluster observed for 3 years for 2-3 runs each year
(each run about 1-2 weeks), i.e. 24/7 monitoring around the world.

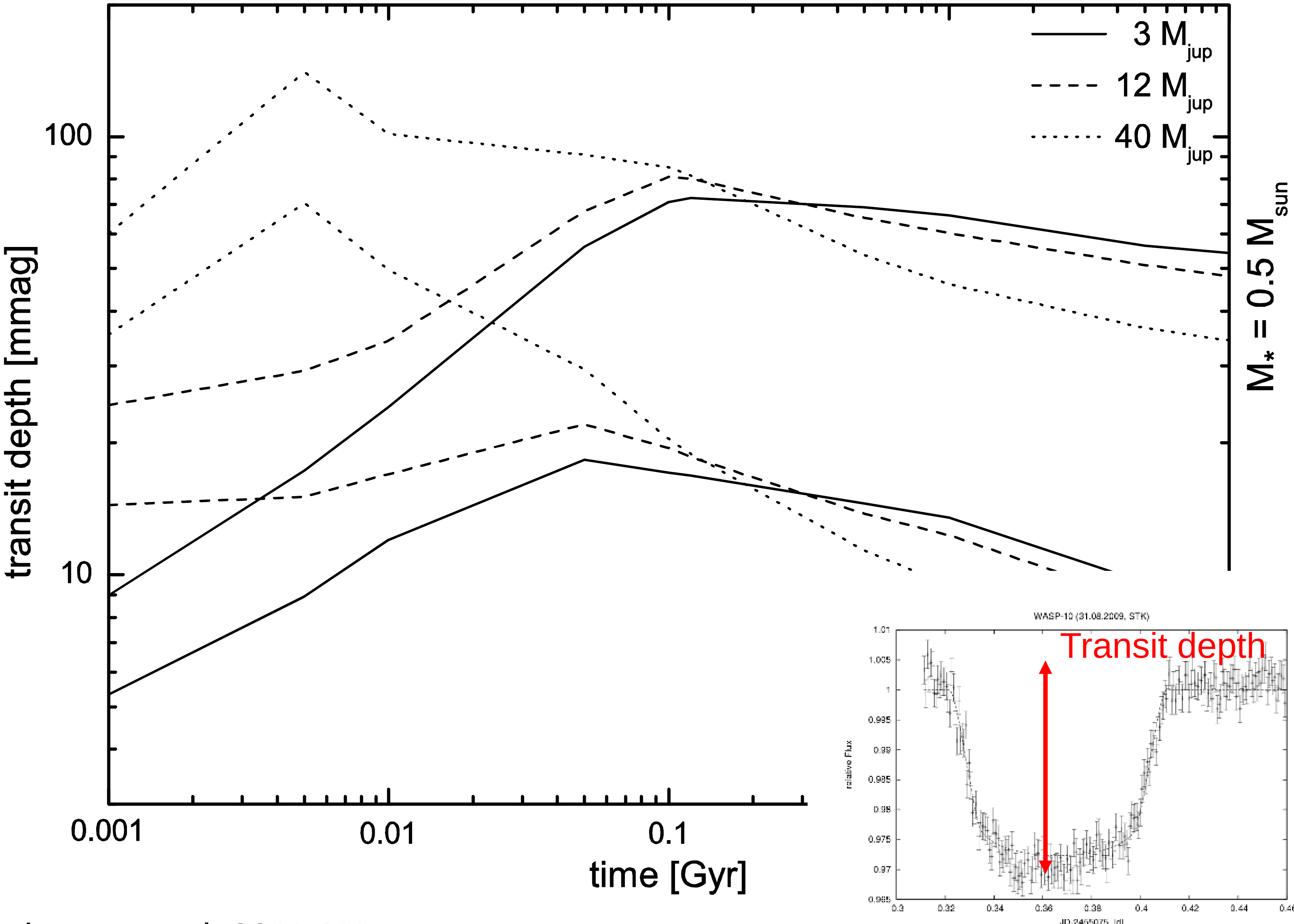
Each team can concentrate on certain topics, e.g.:
a certain cluster or eclipsing binaries, or flares, etc.

# Luminosity vs. age (stars, brown dwarfs, and planets)




(Burrows et al. 1993, 1997 ApJ)

Motivation to monitor young clusters at few to hundreds of Myr age:

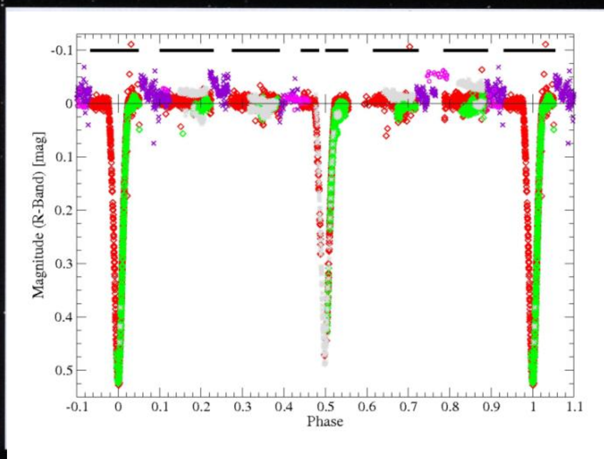



Neuhäuser et al. 2011 AN

# Astronomical Notes
## Astronomische Nachrichten

Founded by H. C. Schumacher in 1821

06
2011



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# The Young Exoplanet Transit Initiative (YETI)


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**Key words** planetary systems – surveys – techniques: photometric – techniques: spectroscopic



We present the Young Exoplanet Transit Initiative (YETI), in which we use several 0.2 to 2.6-m telescopes around the world to monitor continuously young ($\leq$100 Myr), nearby ($\leq$1 kpc) stellar clusters mainly to detect young transiting planets (and to study other variability phenomena on time-scales from minutes to years). The telescope network enables us to observe the targets continuously for several days in order not to miss any transit. The runs are typically one to two weeks long, about three runs per year per cluster in two or three subsequent years for about ten clusters. There are thousands of stars detectable in each field with several hundred known cluster members, e.g. in the first cluster observed, Tr-37, a typical cluster for the YETI survey, there are at least 469 known young stars detected in YETI data down to $R = 16.5$ mag with sufficient precision of 50 millimag rms (5 mmag rms down to $R = 14.5$ mag) to detect transits, so that we can expect at least about one young transiting object in this cluster. If we observe $\sim$10 similar clusters, we can expect to detect $\sim$10 young transiting planets with radius determinations. The precision given above is for a typical telescope of the YETI network, namely the 60/90-cm Jena telescope (similar brightness limit, namely within $\pm$1 mag, for the others) so that planetary transits can be detected. For targets with a periodic transit-like light curve, we obtain spectroscopy to ensure that the star is young and that the transiting object can be sub-stellar; then, we obtain Adaptive Optics infrared images and spectra, to exclude other bright eclipsing stars in the (larger) optical PSF; we carry out other observations as needed to rule out other false positive scenarios; finally, we also perform spectroscopy to determine the mass of the transiting companion. For planets with mass and radius determinations, we can calculate the mean density and probe the internal structure. We aim to constrain planet formation models and their time-scales by discovering planets younger than $\sim$100 Myr and determining not only their orbital parameters, but also measuring their true masses and radii, which is possible so far only by the transit method. Here, we present an overview and first results.




## 1 Introduction: Extrasolar planets

Beginning with the discovery of planets around a neutron star (Wolszczan & Frail 1992; Wolszczan 1994) and around


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# Trumpler 37

part of H-II region IC 1396 in Cepheus

distance: 800-900 pc (*)

age: 4 to 10 Myr (*)
→ formation of planets

Diameter: 1.5°

Extinction:

$A_V$ = 1.5 mag

Cluster velocity

v = -15.0 ± 3.6 km/s (*)

18000 stars,
500 known members

Errmann et al. 2013

central part of Trumpler 37 from 90/60cm Telescope Jena, R-Band 60s
FOV: 53' x 53'

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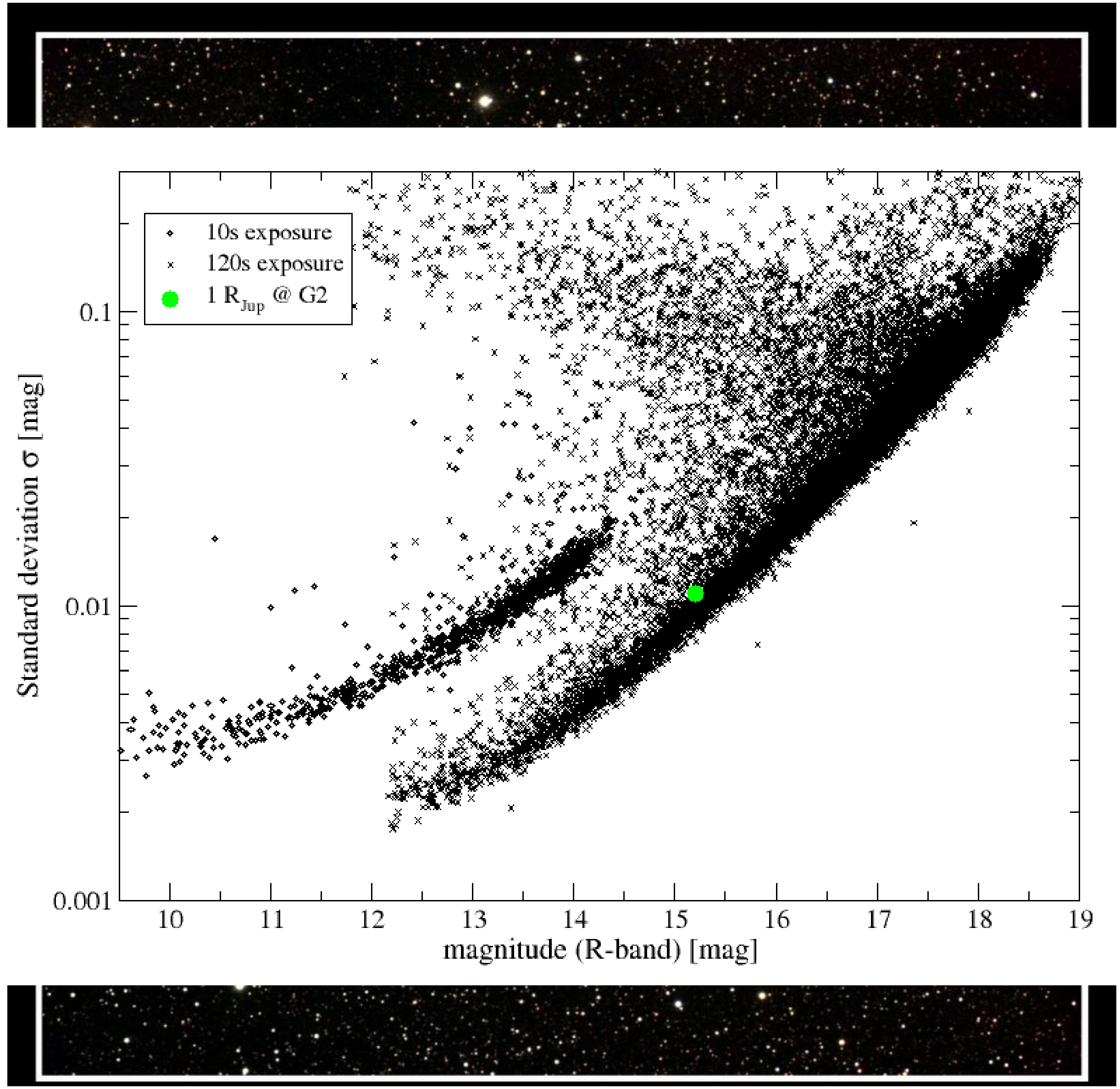
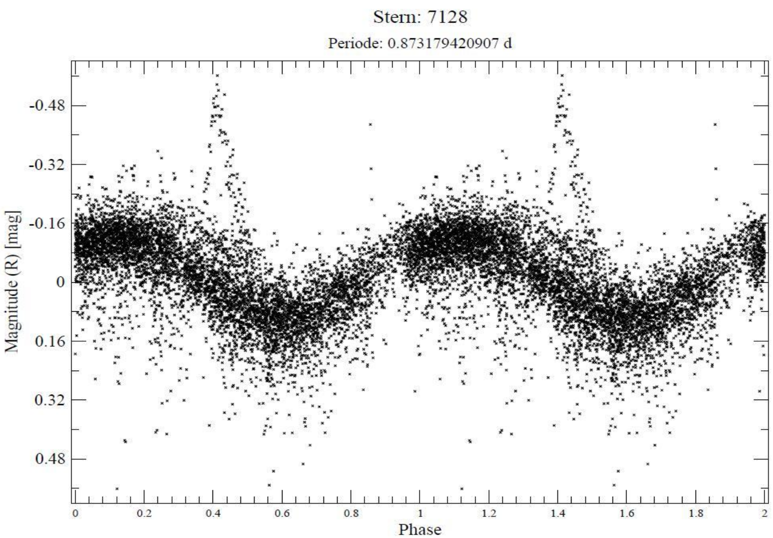


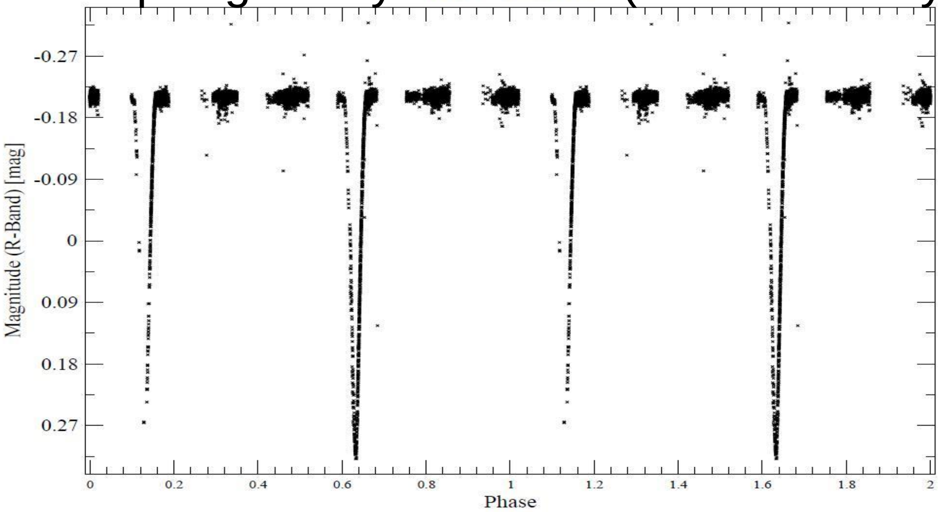

central part of Trumpler 37 from 90/60cm Telescope Jena, R-Band 60s
FOV: 53' x 53'

# Preliminary Results

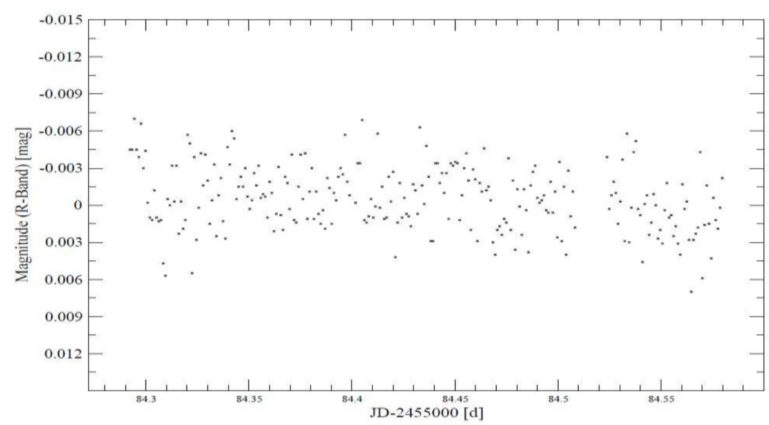
Rotating and flaring T Tauri star

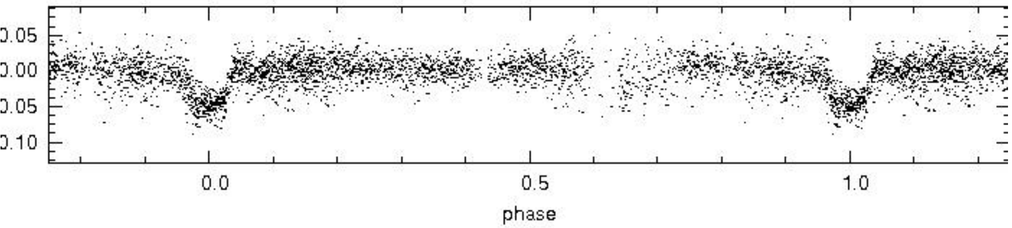



Eclipsing binary Stern: 118 Periode: 6.005194 d (3.0 or 6.0 day orbit?)




Constant star Nacht: 09_09_09/ , Stern: 243 σ=2.6 mmag




A first (planetary ?) transit candidate (?)

# Transit candidate

V = 15.55 mag
B-V = 1.02 mag
R = 15.1 mag

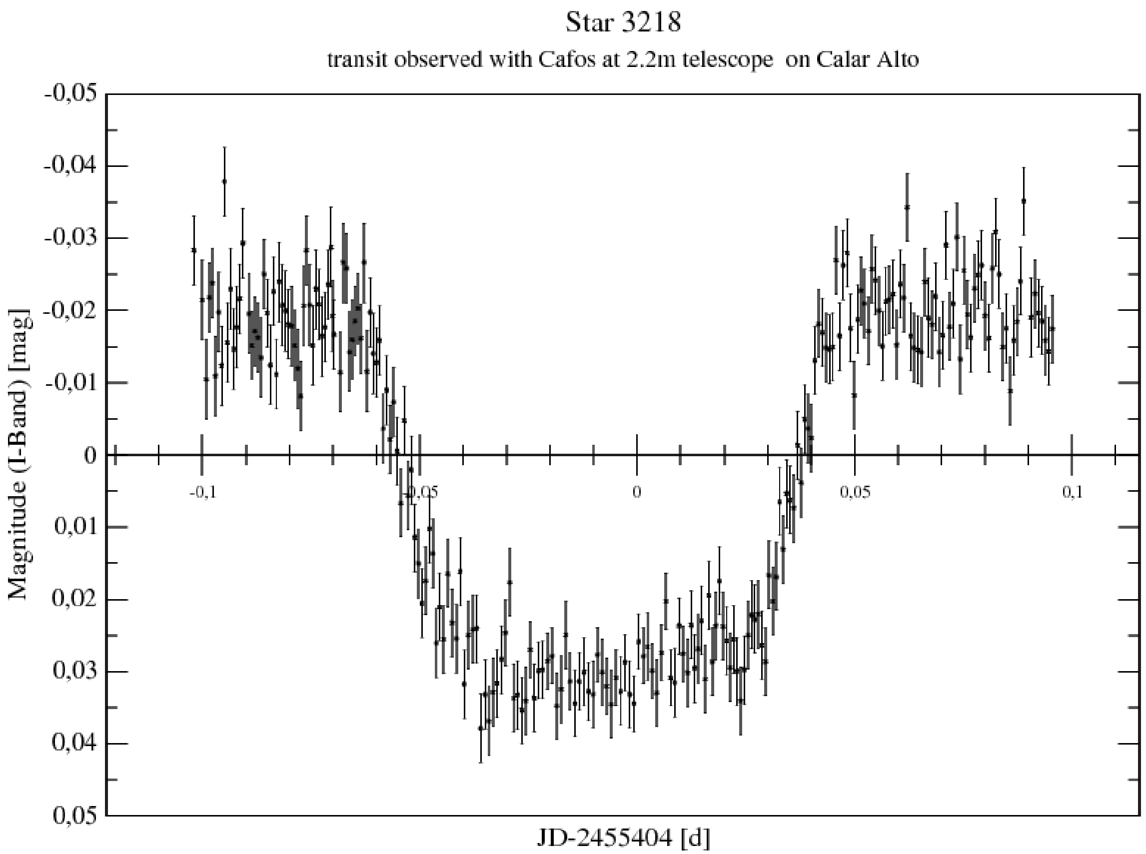
Transit depth ΔR ≈ 0.050 mag

First guess: probable member in the cluster from:
- HR diagram
- proper motion

photometric spectral type:
G8-K5

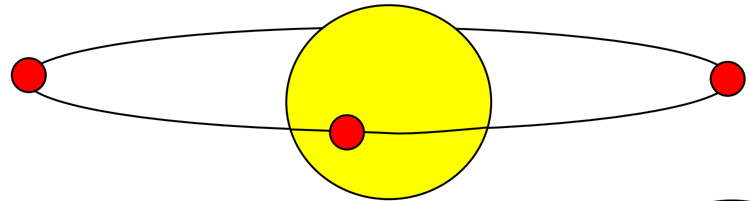
deep transit could be from young planet with ongoing contraction
$R \approx (1.7 \pm 0.4)\ R_{jup}$

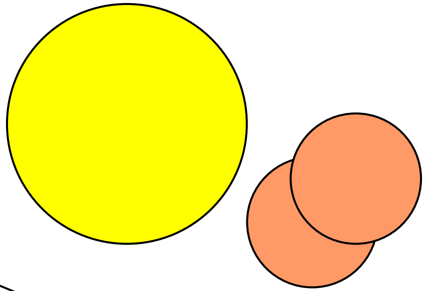
Photometry 2.2m Calar Alto:
ΔI = 0.052 mag



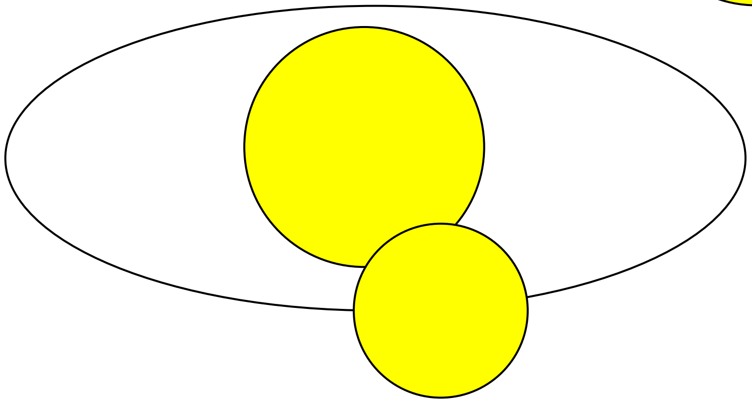
# Transit like light curve with flat-bottom dip can be due to either:

- real planet transit

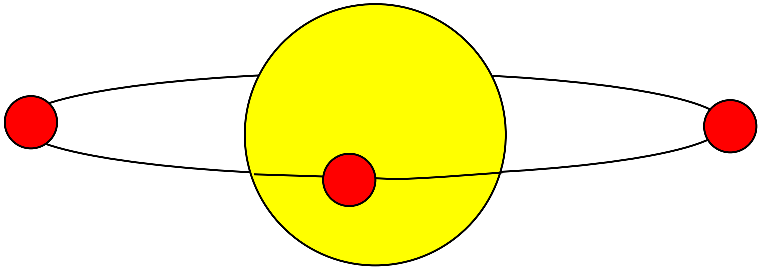




- or eclipsing background star in PSF (point spread function)



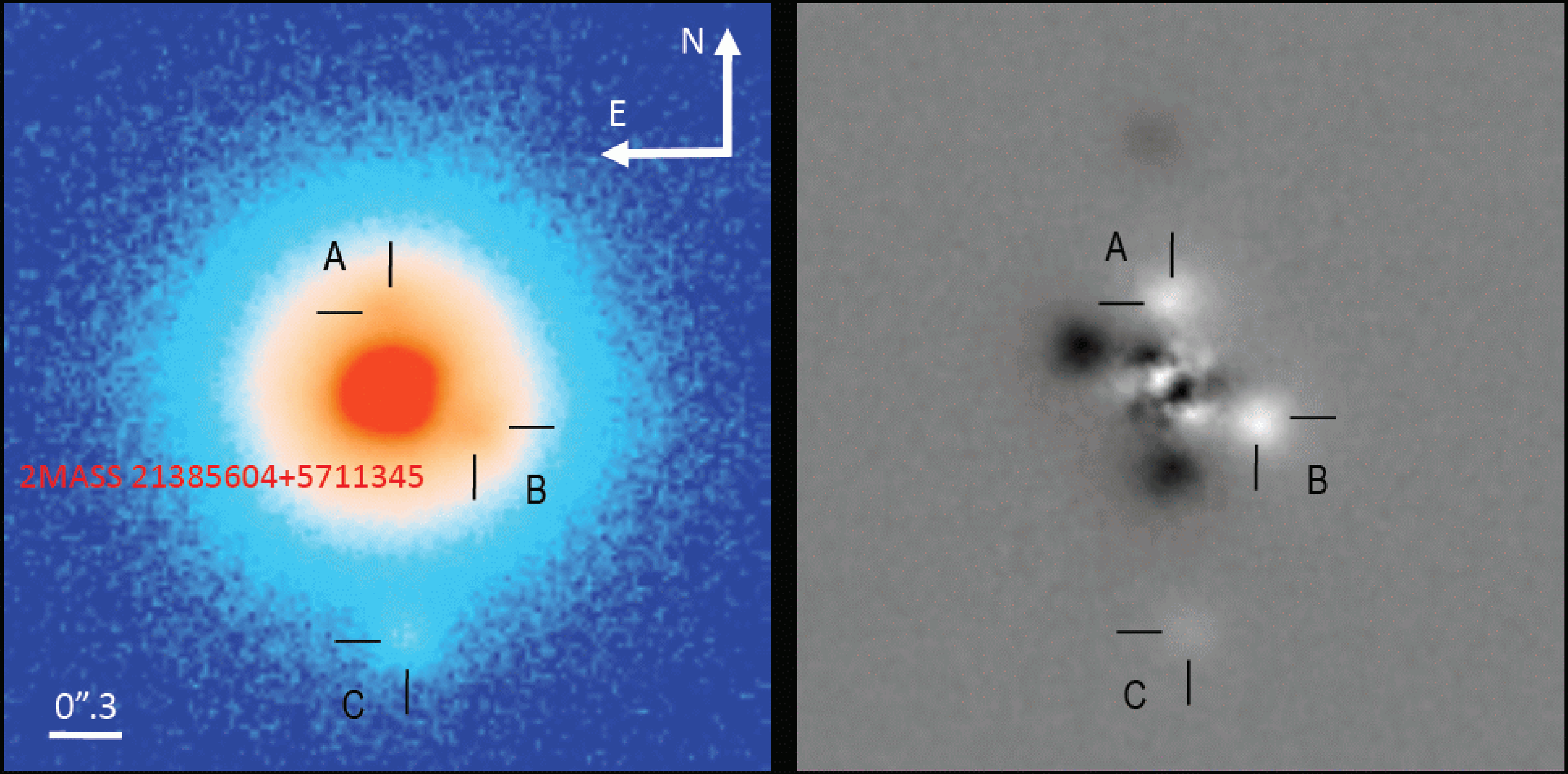
- or grazing eclipse of two stars



- or transiting brown dwarf or very low mass star

# IRCS+AO188 Observation of Possible Eclipsing Binary in Tr37

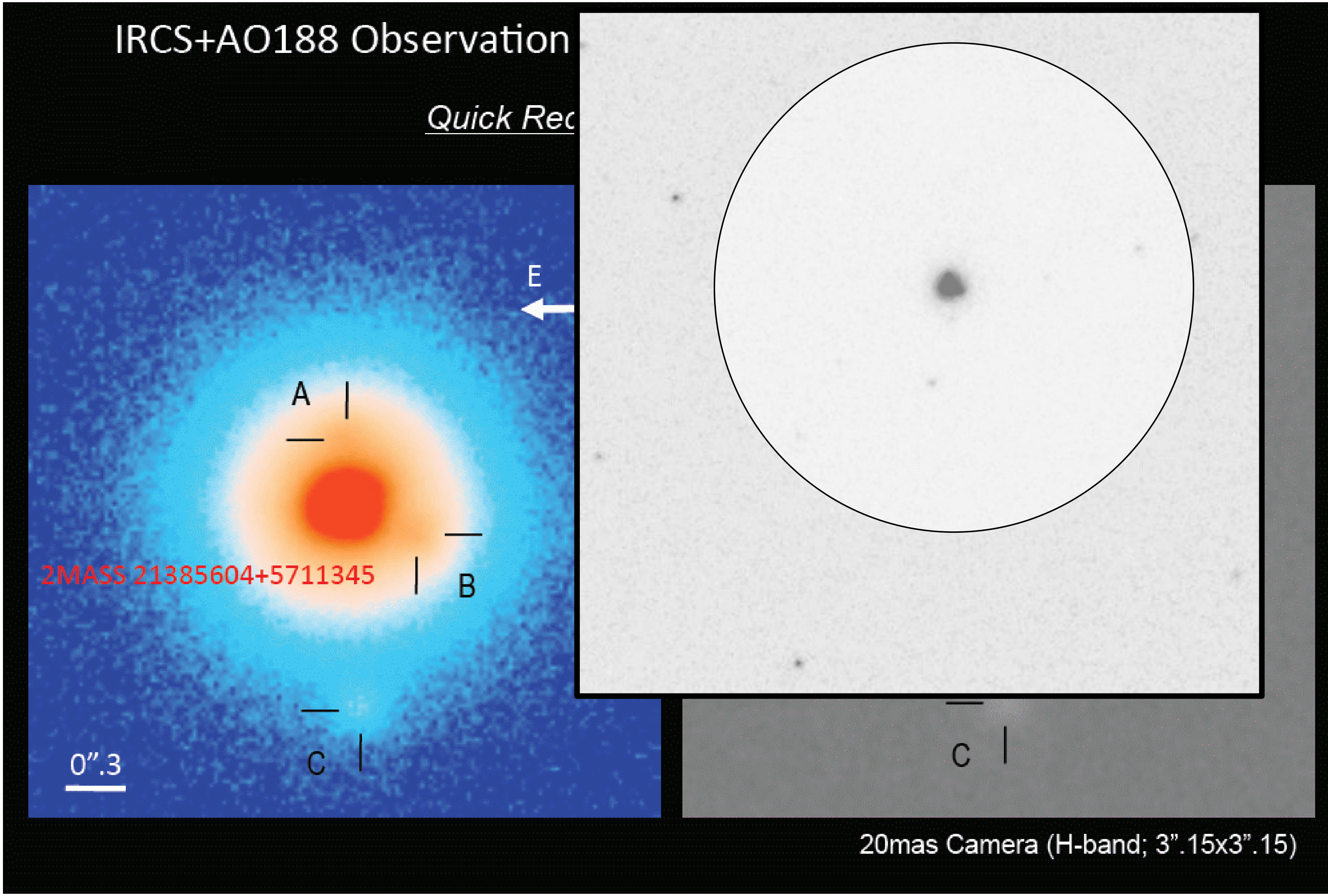
*Quick Reduction for H-band image*




20mas Camera (H-band; 3".15x3".15)

Hiroshi TERADA

# SUBARU AO188/IRCS

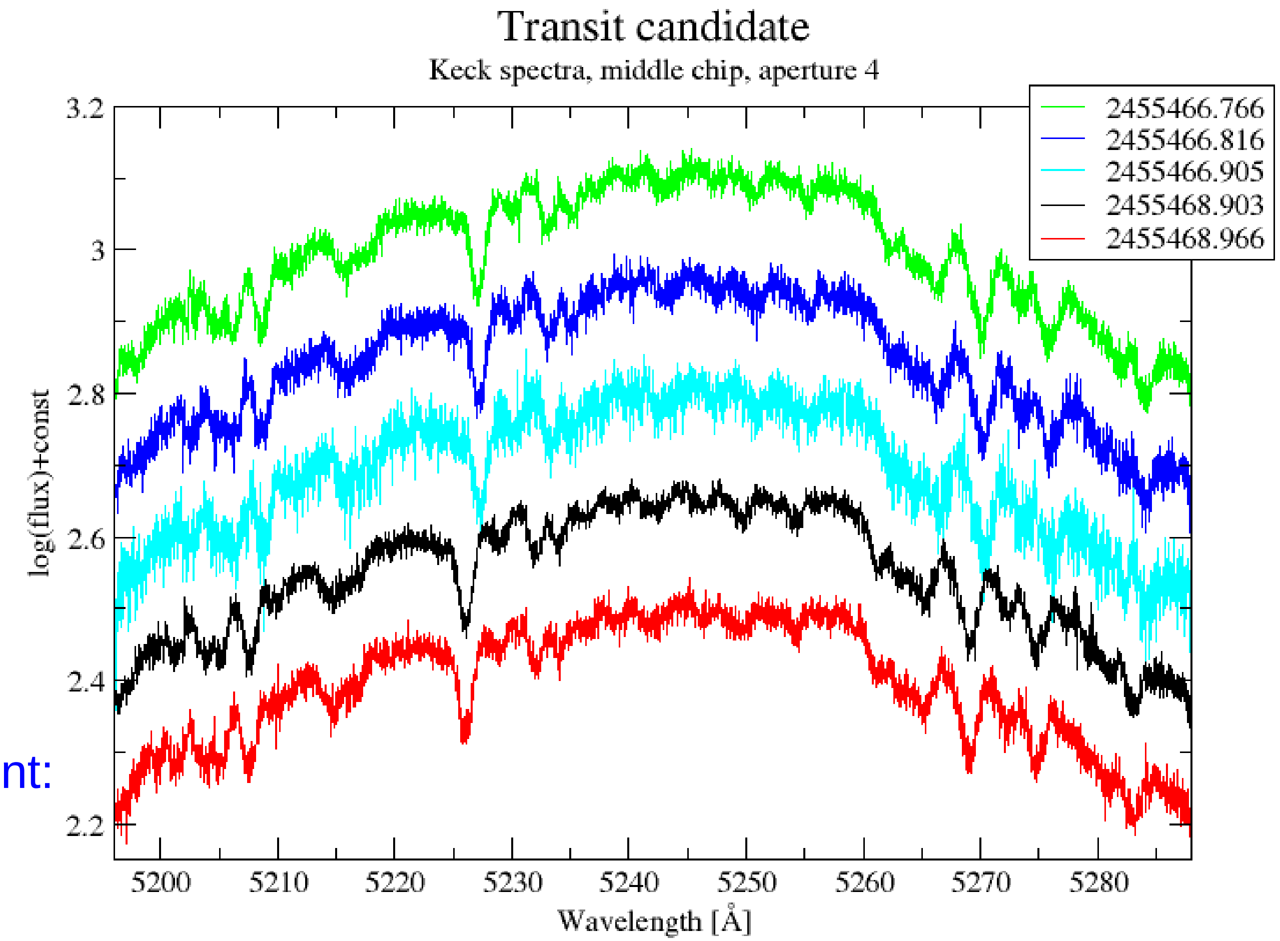



Hiroshi TERADA

# Follow-up - Keck

Radial velocity orbit for transit candidate:
HIRES spectrograph at 10m-Keck-I telescope

| HJD -2455000 | RV [km/s] |
|---|---|
| 466.74372 | 9.071 |
| 466.79397 | 10.548 |
| 466.88945 | 11.482 |
| 468.88121 | -47.398 |
| 468.94959 | -48.682 |
| 521.68193 | -3.242 |




Mass of the 2nd component:
$M_B$=0.16±0.02 $M_{sun}$
(M6 V)

(Errmann et al. 2014)

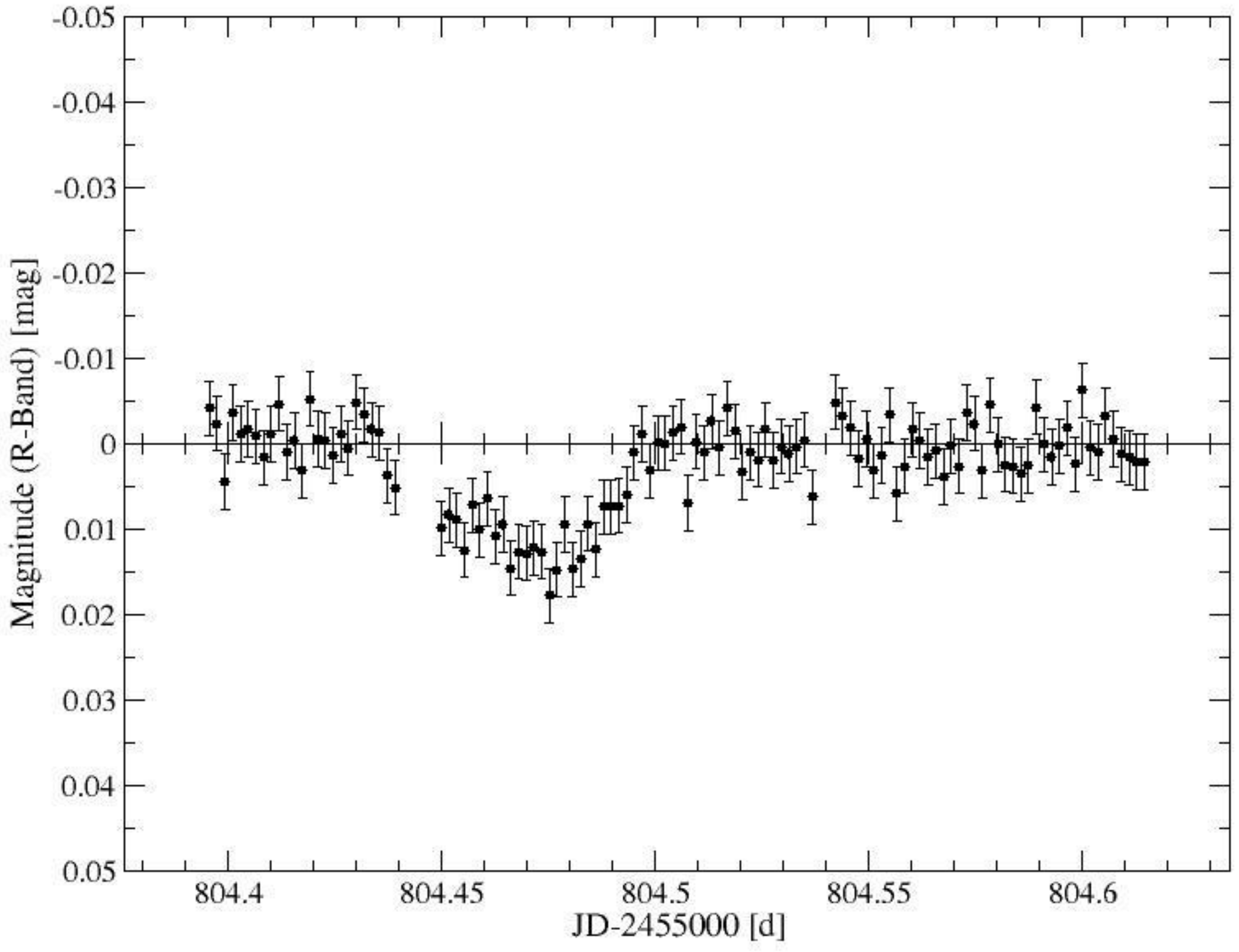
# New transiting candidate in Tr-37

R  =  13.4 mag
V  =  14.1 mag
B-V= 0.8 mag
≈ G4

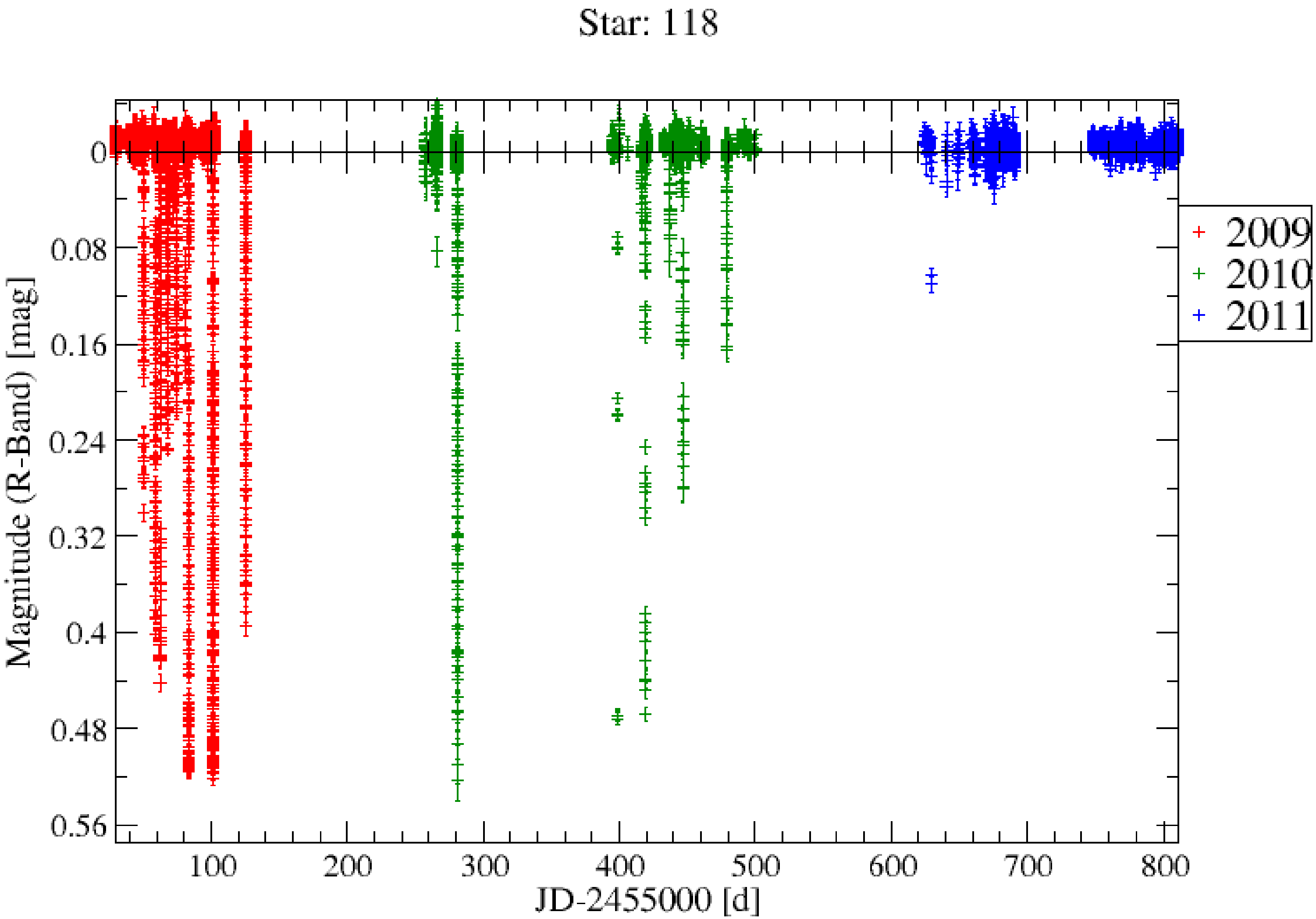
proper motion and color magnitude diagram → probable member

P ≈ 0.7367 d

Δm ≈ 15 milli-mag
t  ≈ 1.5 h



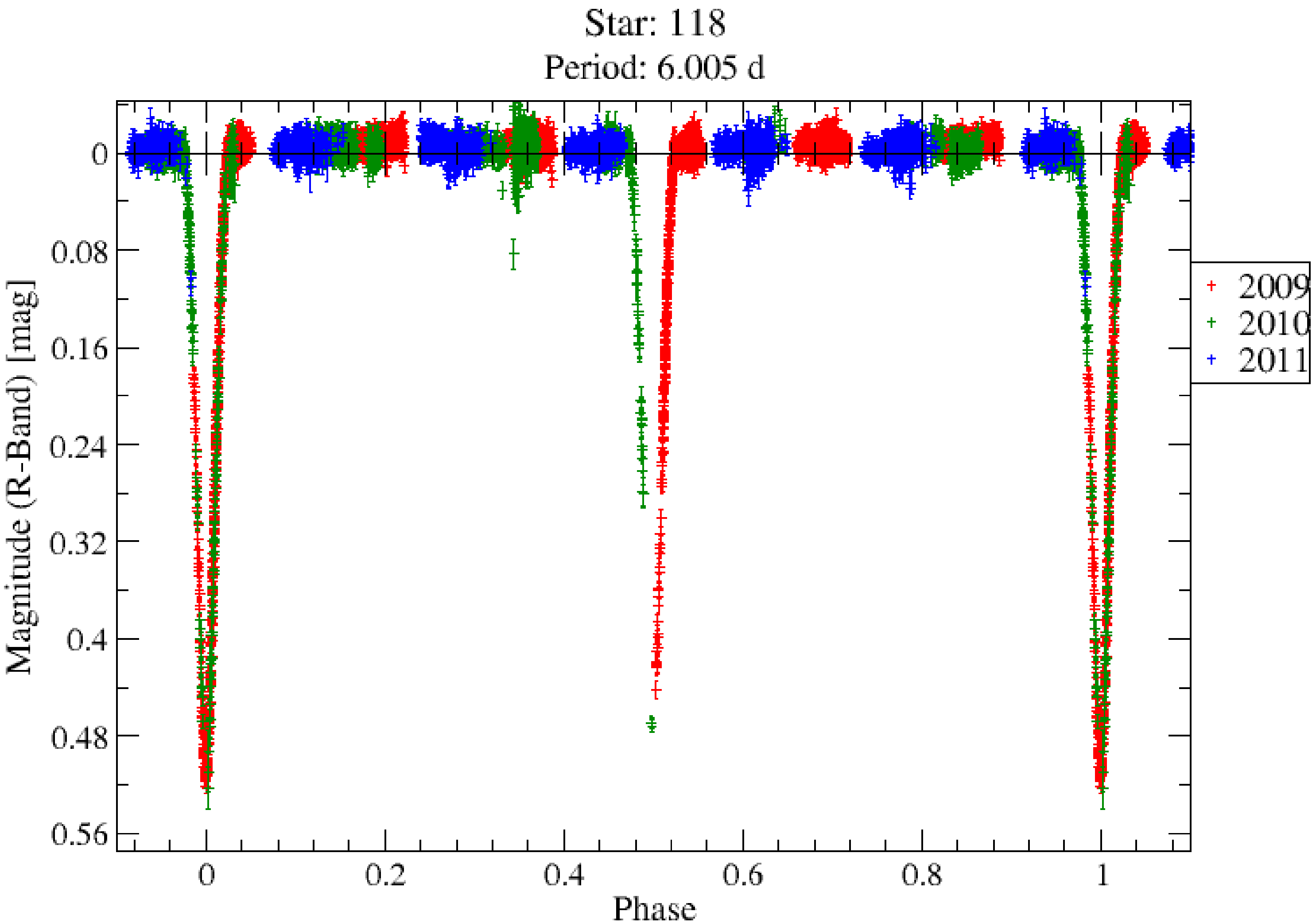
# Multi-site campaign on Trumpler 37




from 2011:
star is
constant

only Jena data

# Multi-site campaign on Trumpler 37



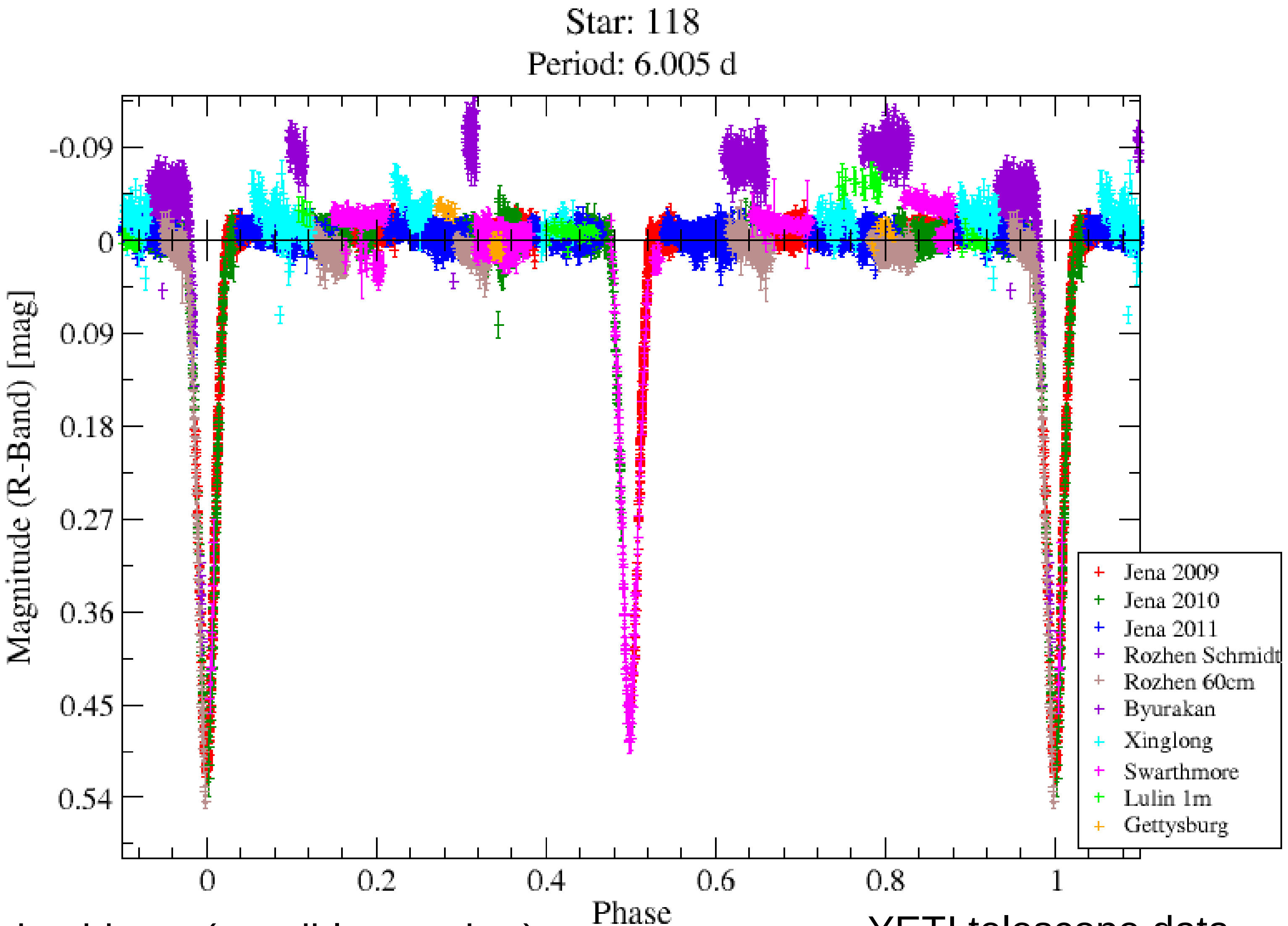

10 000 data points, but still gaps in the phase folded light curve

only Jena data

# Multi-site campaign on Trumpler 37

no gaps

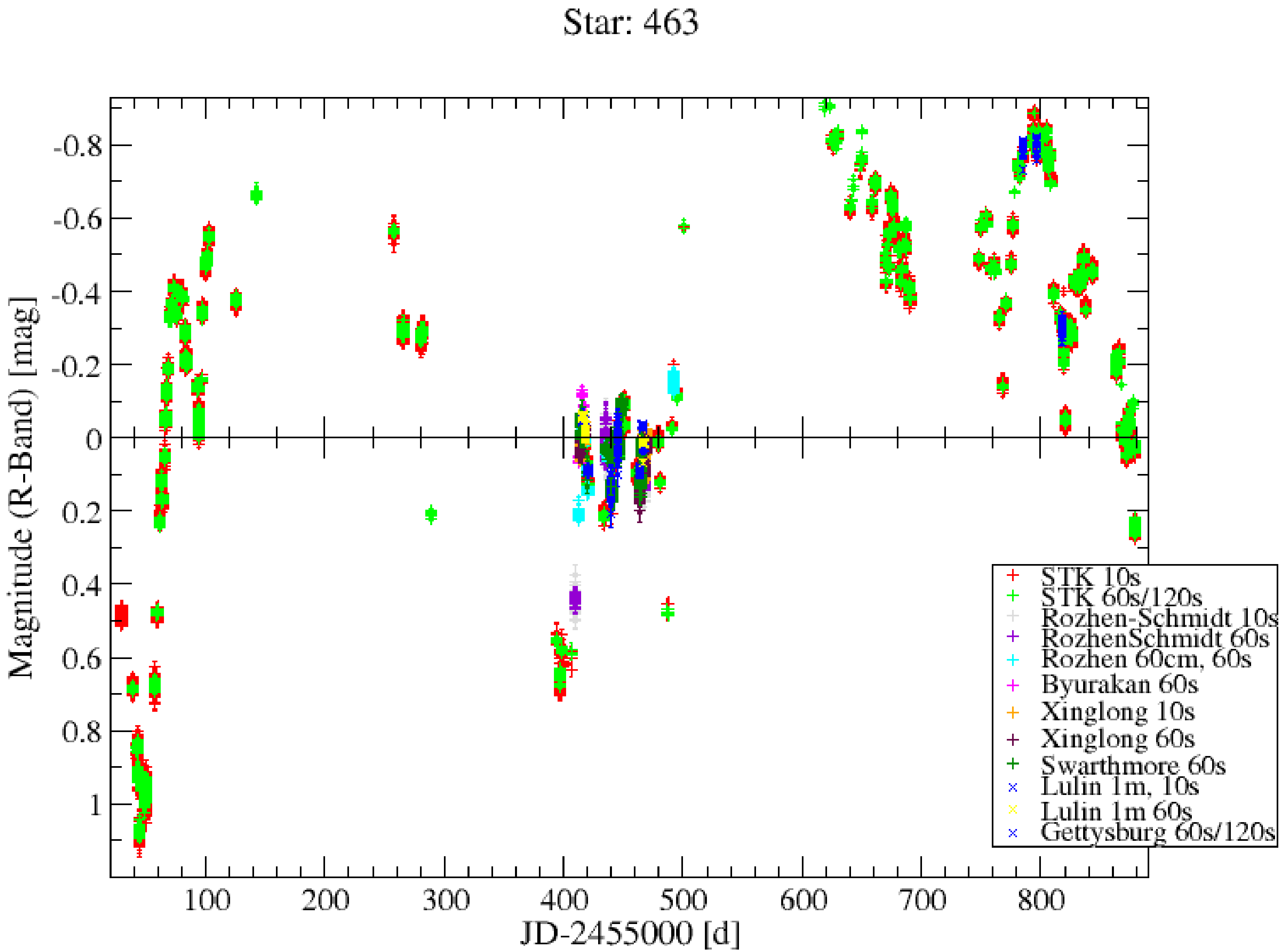
but need for some improvements in combining data from different telescopes




Star 118: eclipsing binary (possible member)

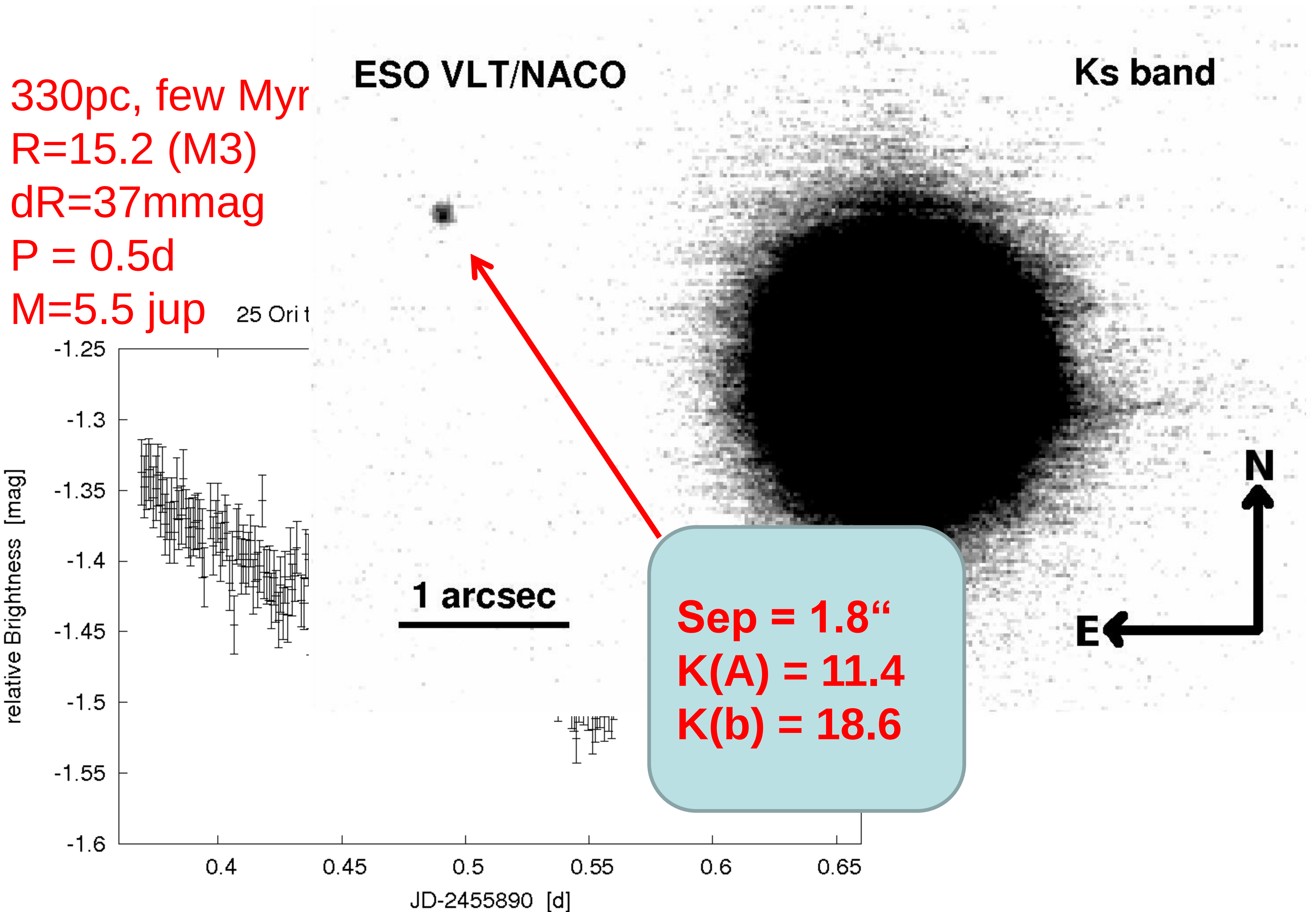
YETI telescope data

# GM Cep: very variable (Chen et al. 2012)



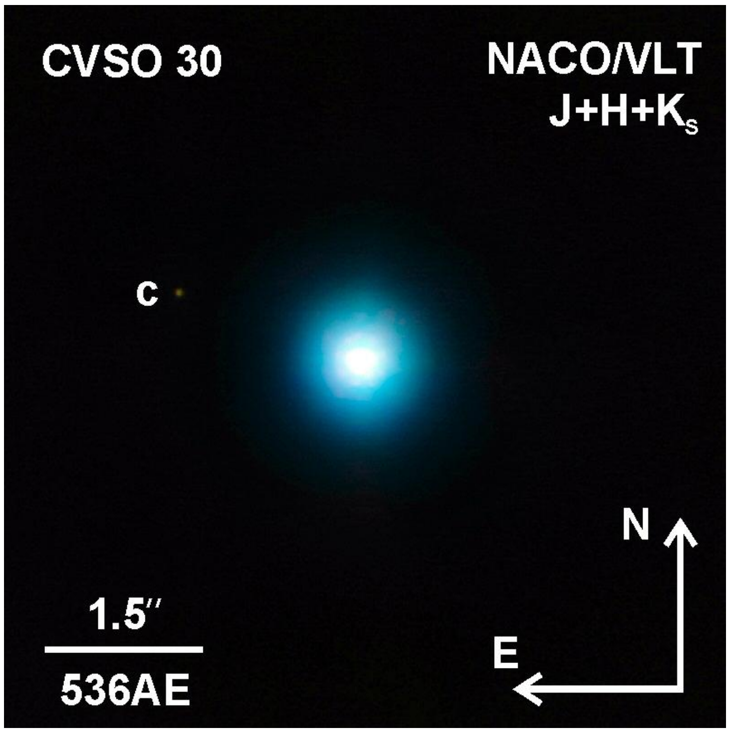
# **Young** transiting candidate in 25 Ori

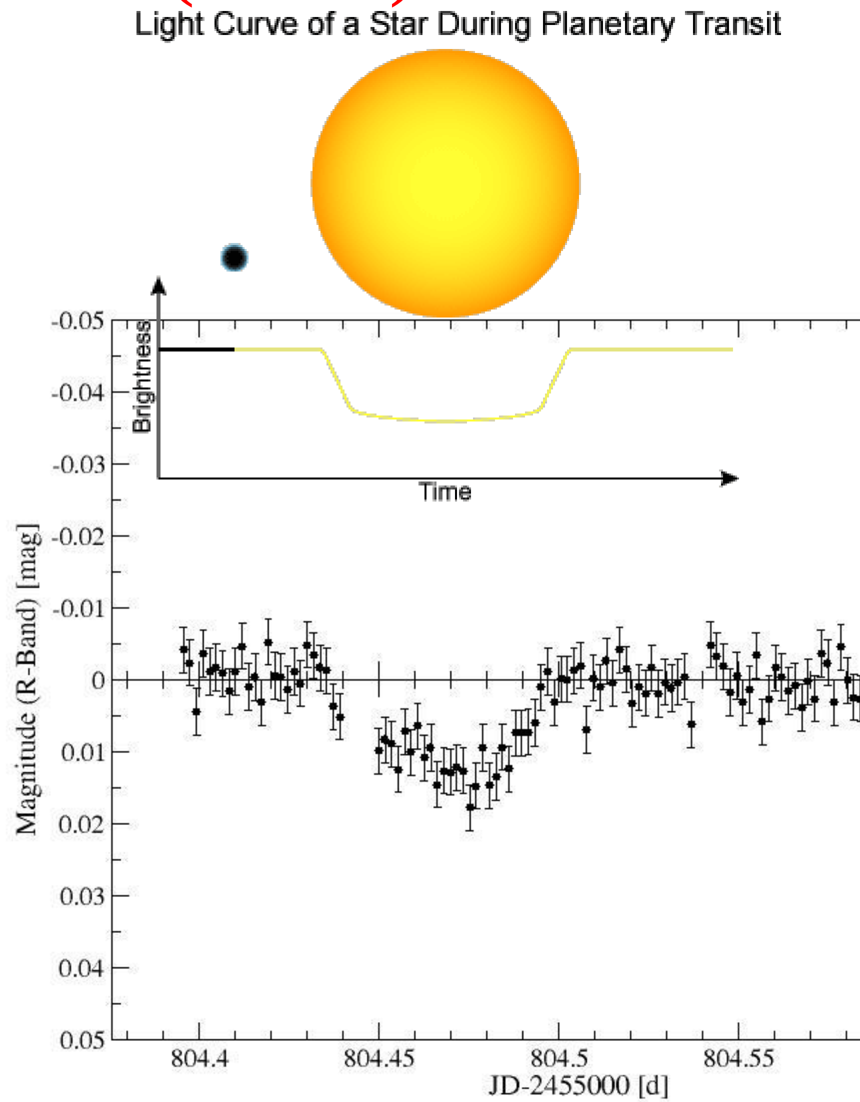
330pc, few Myr
R=15.2 (M3)
dR=37mmag
P = 0.5d
M=5.5 jup



# Young Exoplanet Transit Initiative (YETI)

**CVSO 30 b+c in 25 Ori:**
**Young star with**
**close-in transit planet**
**+ wide direct imaging planet**




Schmidt et al. 2016 A&A
(PhD U Jena → Paris → U HH)

Rätz et al. 2016 MNRAS
(PhD U Jena → ESA → U Tüb.)

# YETI project (Young Exoplanet Transit Initiative)

Tr-37 observed in 2010, 2011, and 2012
with 2 transiting candidates found so far, one rejected as M-dwarf
(PI Jena, R. Errmann, PhD student U Jena)

25 Ori observed in 2010/11, 2011/12, 2012/13 with one good candidate found so far, which appears variable, hence young
(PI Jena, S. Rätz)

λ Ori observed since 2012/13, 2013/14, and 2014/15 (PI C. Briceno)

IC 348 observed 2012, 2013, 2014 (PI Jena, D. Fritzewski et al.)

NGC 1980 observed 2012/13, 2013/14, 2014/15 (PI Chini, U Bochum)

NGC 7243 observed 2013, 2014, and 2015 (Garai, Pribulla et al., Slowakia)

h and χ Per, IC 4665 (PI Zielinski, Poland), IC 4665 observed last week

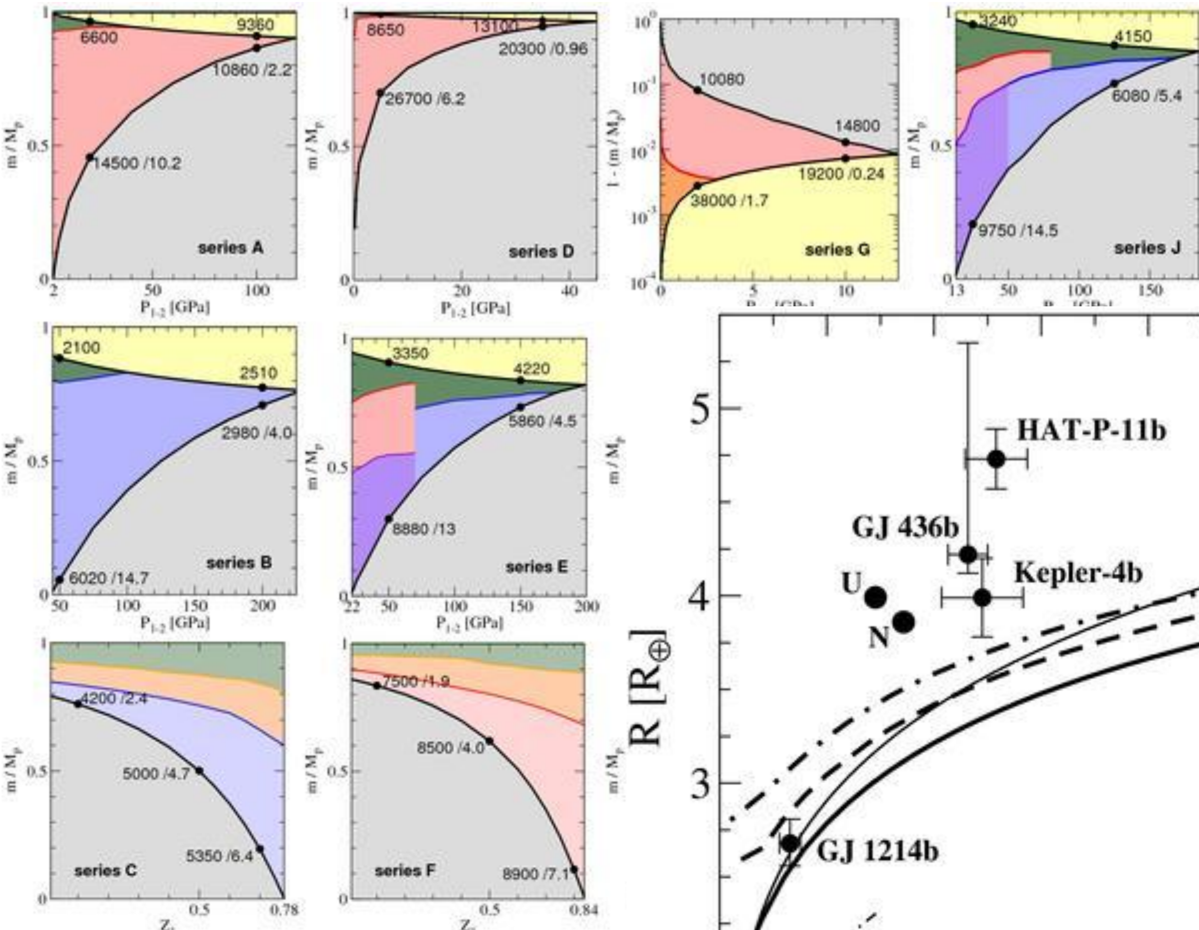
**Theoretical modeling on young transit panets: Redmer et al. (Rostock)**

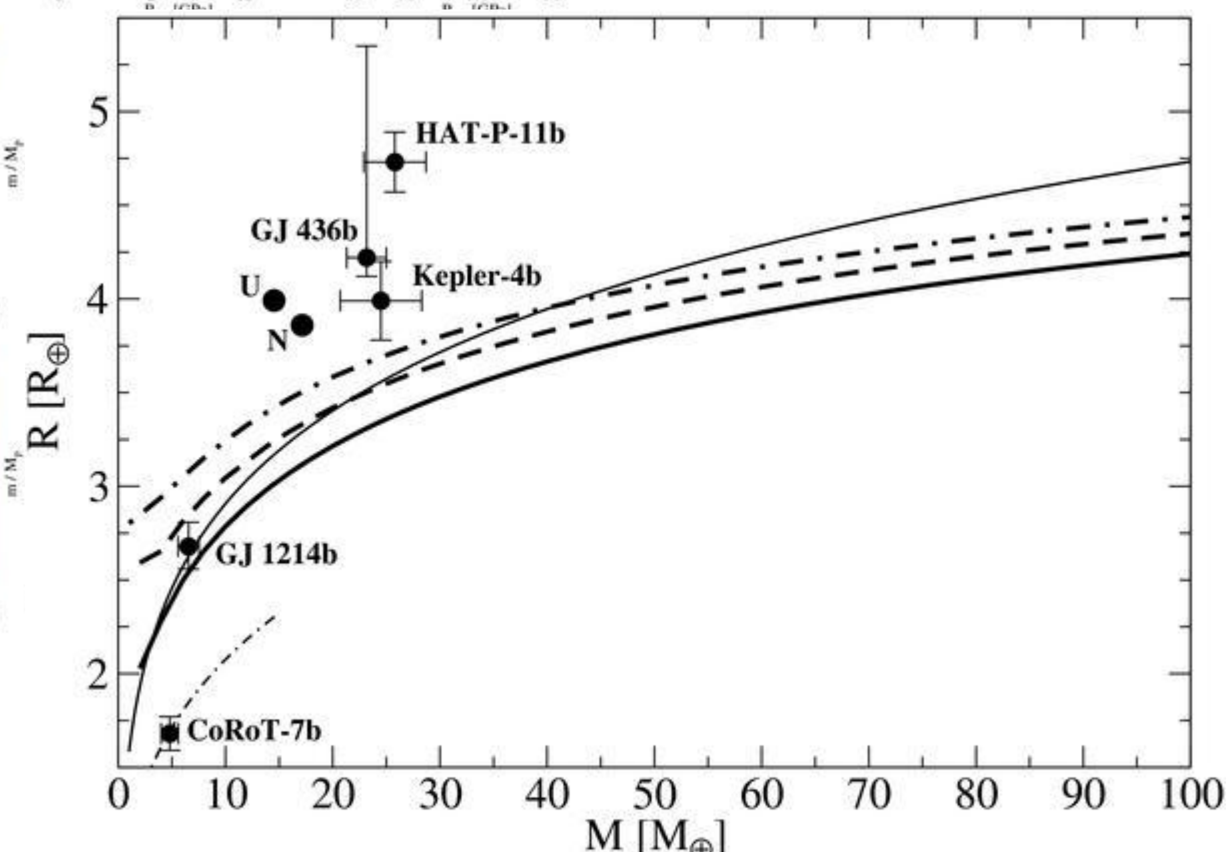
# If transits happen, we know mass and radius !

Theoretical model for transiting planets ➔ composition, interior, formation …

Nettelmann, Kramm, Redmer, RN (2010)

e.g. low-mass planet
GJ 436 b



# Further investigations

Reducing all remaining / new data from 2018

→ transit search

→ more transit candidates expected

Additional follow-up observations (membership, orbits, masses, ...)

… Richard Bischoff

Similar monitoring for more young clusters (?)

Goals: young planets to constrain

➔ formation models (e.g. time-scale of planet formation)

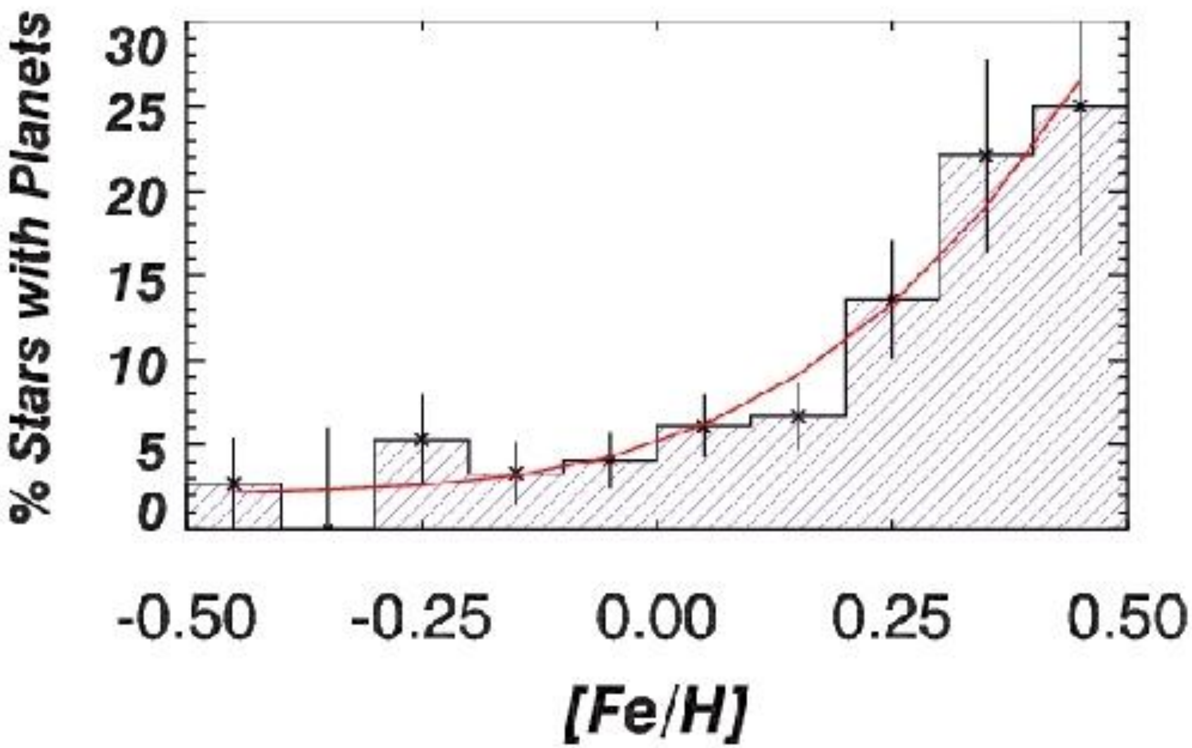
➔ planet radii and planetary interior

➔ architecture of young planetary systems (test migration theories)

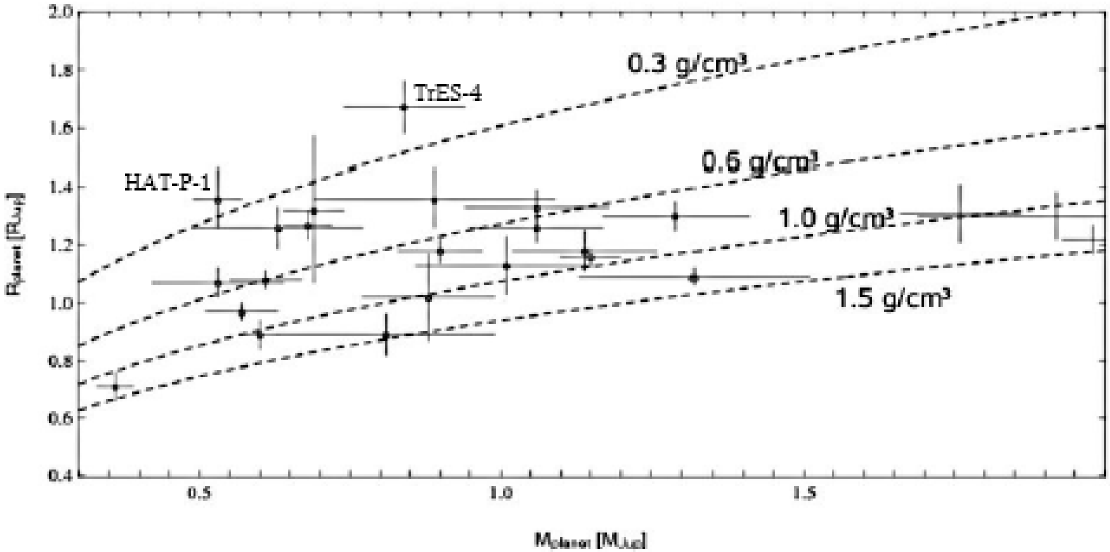
➔ to compare with solar system

# What did we learn about planet formation ?

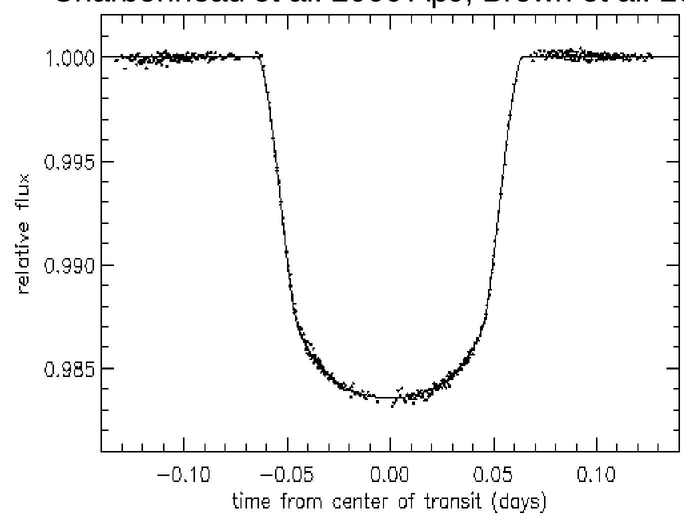
- ➔Planets often very close to their star ➔ Radial migration
- ➔Planets in close binary stars ➔ in-situ formation (?)
- ➔ More planets around metall-rich stars
- ➔ Transit planets give radii and densities (so far, all old)
- ➔ Spectra still quite poor




(Valenti & Fischer 2005)




Charbonneau et al. 2000 ApJ, Brown et al. 2001 A



# Open questions / problems

- ➔ Do all kinds of stars have planets ?
  How frequent are Earth-like planets ?

- ➔ Atmospheric composition and interior (cores, convection, mag.fields, …)

- ➔ Radial migration and/or in-situ formation ?

- ➔ Mass determination after direct detection / upper mass limit of planets
  What is a planet (definition) ? Metallicity of planets ?

- ➔ Time scale of planet formation: Myr or Gyr ?
  Fast by gravitational collapse or slow by dust growth ?

# YETI project (Young Exoplanet Transit Initiative)

Publications of observational data so far:

Neuhäuser et al. 2011 AN 332, 547 (~50 co-authors): Introduction to YETI

Chen et al. 2012 ApJ 751,118: Strong variability of GM Cep (in Tr-37)

Errmann (U Jena) et al. 2013: Introduction to Tr-37

Errmann (U Jena) et al. 2014:
Follow-up observations on the first YETI transit candidate
(one refereed proceedings + one refereed journal paper)

Raetz et al. 2016 MNRAS 460, 2834: CVSO 30b young transit planet 25 Ori

Schmidt et al. 2016 A&A 593, 75: CVSO 30c direct imaging planet (same star)

Garai (Slowakai) et al. 2016 AN 337, 261: NGC 7243

Fritzewski (U Jena) et al. 2016 MNRAS 462, 2396: IC 348 rotation periods

+ several papers on TTV (Maciejewski et al., Raetz et al., Seeliger et al.)
+ theory papers on internal structure, e.g. Nettelmann et al., Kramm et al.

# Young Exoplanet Transit Initiative (YETI)