Hot Jupiters & Cool Neptunes

Exploring Planetary Systems with Transits and Microlensing

B. Scott Gaudi, Institute for Advanced Study

Available @ http://www.sns.ias.edu/~gaudi/presentations.html (soon)

Conclusions:

Transits and Microlensing offer complementary methods of exploring extrasolar planetary systems.

Transits & "Hot Jupiters"

- Need precise photometry, *many* (>20) *consecutive* nights.
- Optimal targets are homogeneous, compact, populous (#>3000) systems.
- Open clusters provide good (but not ideal) targets.
- NGC1245 (1 Gyr, [Fe/H]~ 0) f < 10% (95 c.l.) **Preliminary!**
- 1-2 clusters per year.

Microlensing & "Cool Neptunes"

- <33% of M-dwafs in the Bulge have Jupiter-Mass companions between 1.5-4 AU
- Probe fractions of 5% down to Neptune Mass in 5 Years with OGLE-III Alerts.
- Possible to push sensitivity to Earth-mass planets (but hard!)

Collaborators:

•Probing Lensing Anomalies NETwork (**PLANET**)

Penny Sackett, PI

http://mplanet.anu.edu.au/

•Microlensing Follow-Up Network (m**FUN**)

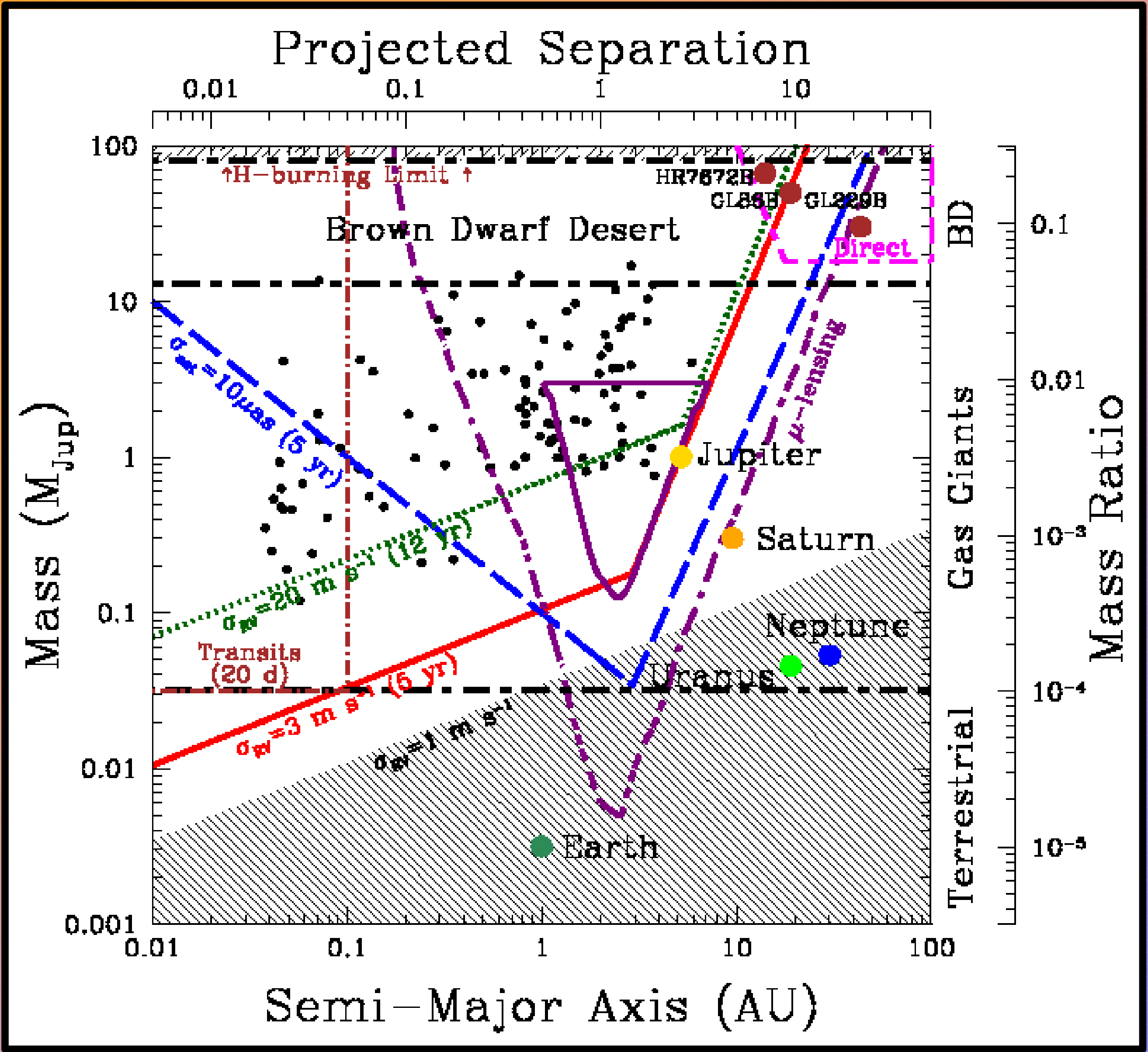
http://www.astronomy.ohio-state.edu/~microfun

•Search for Transiting Extrasolar Planets in Stellar Systems (**STEPSS**)

Chris Burke, S.G., Darren DePoy, Rick Pogge, Jennifer Marshall

http://www-astronomy.mps.ohio-state.edu/~cjburke/STEPSS/

The Search for Planets



100 known planets via RV

Features:

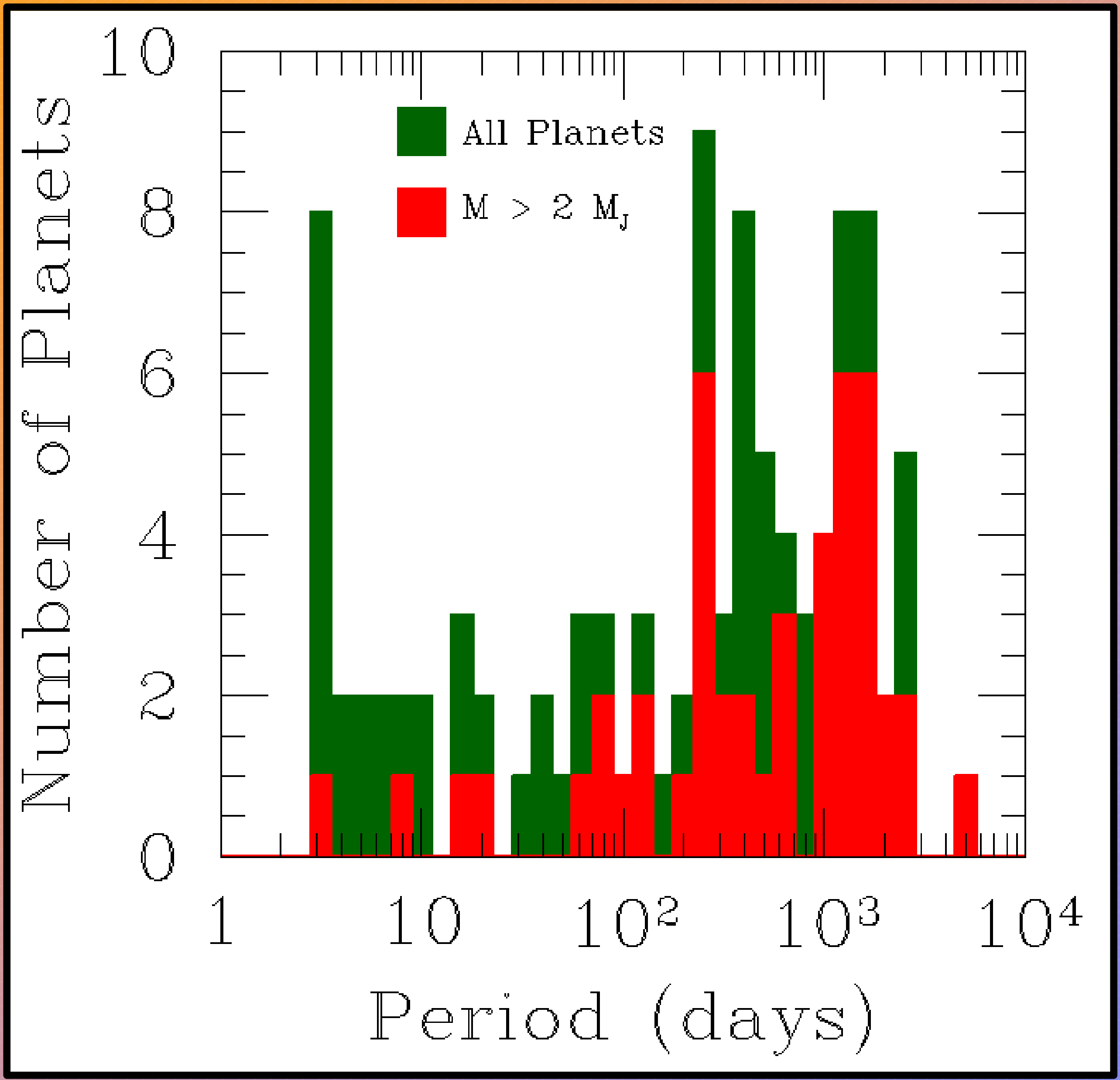
- BD Desert
- “Hot Jupiters”
- Freq. vs. [Fe/H]
- Piling Up at P=3d
- Lack of Massive, Close-in Planets

Terrestrial Planets?

Currently Undetectable via RV, Transits, Astrometry

http://exoplanets.org/

The Search for Planets



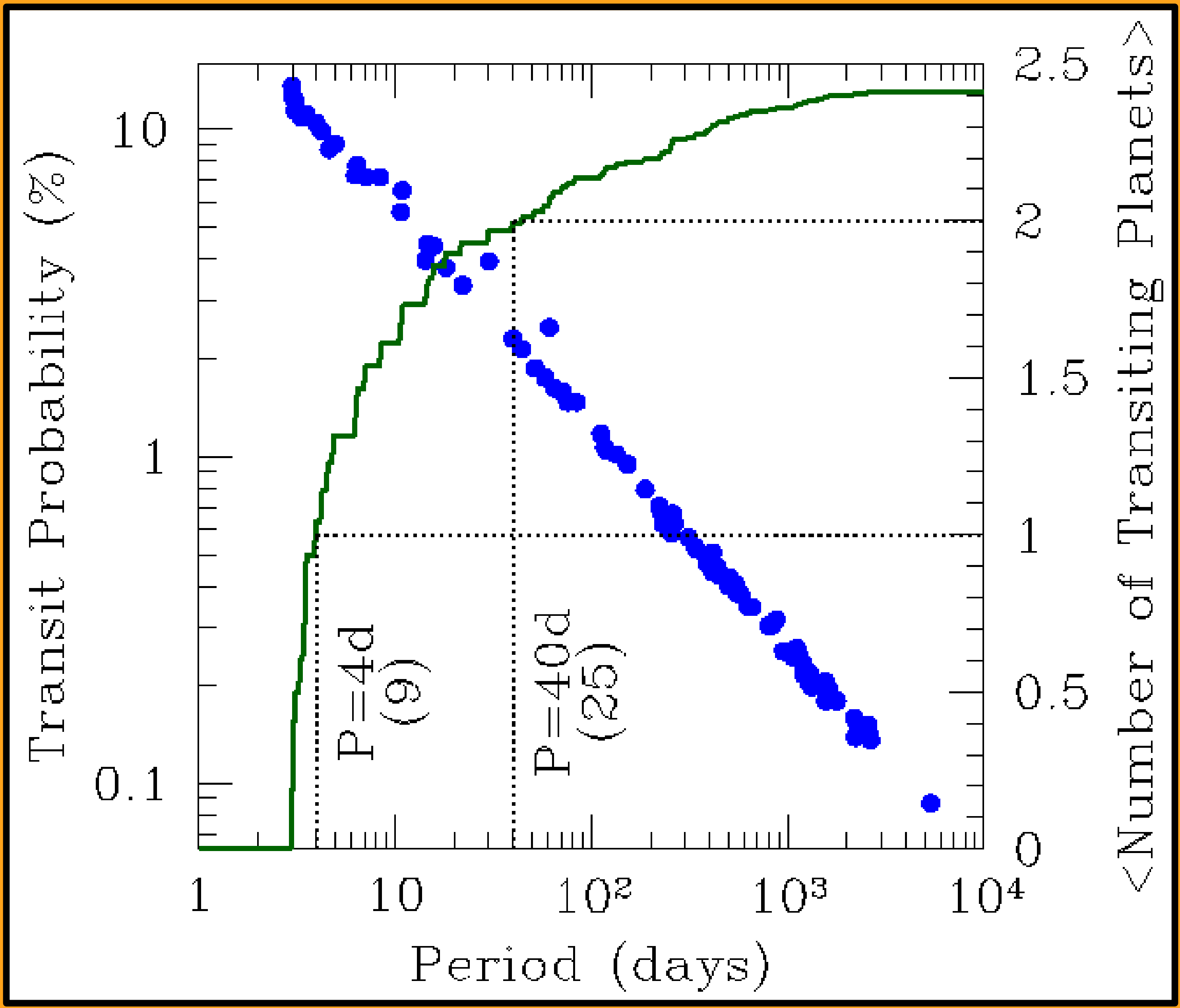
Piling up at P=3d

- Consequence of Migration?

Paucity of Giant, Close-In Planets

- Related to BD Desert?

How Many Transiting Planets?



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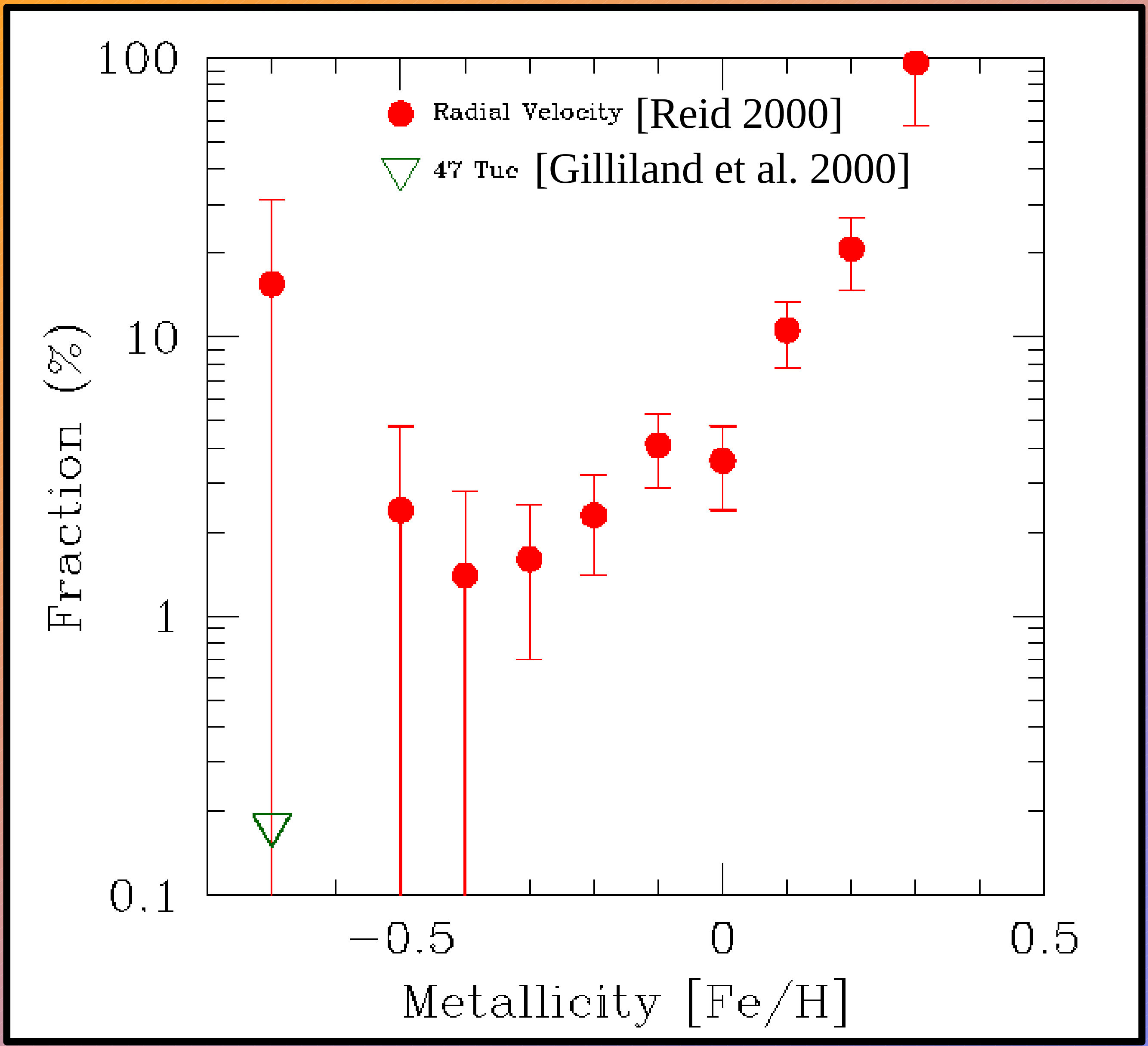


Frequency Increases with Metallicity

Gonzalez (1997), Laughlin (2000) Santos et al. (2001), Reid (2002)

Nature?

- Planet(esimal) Accretion?

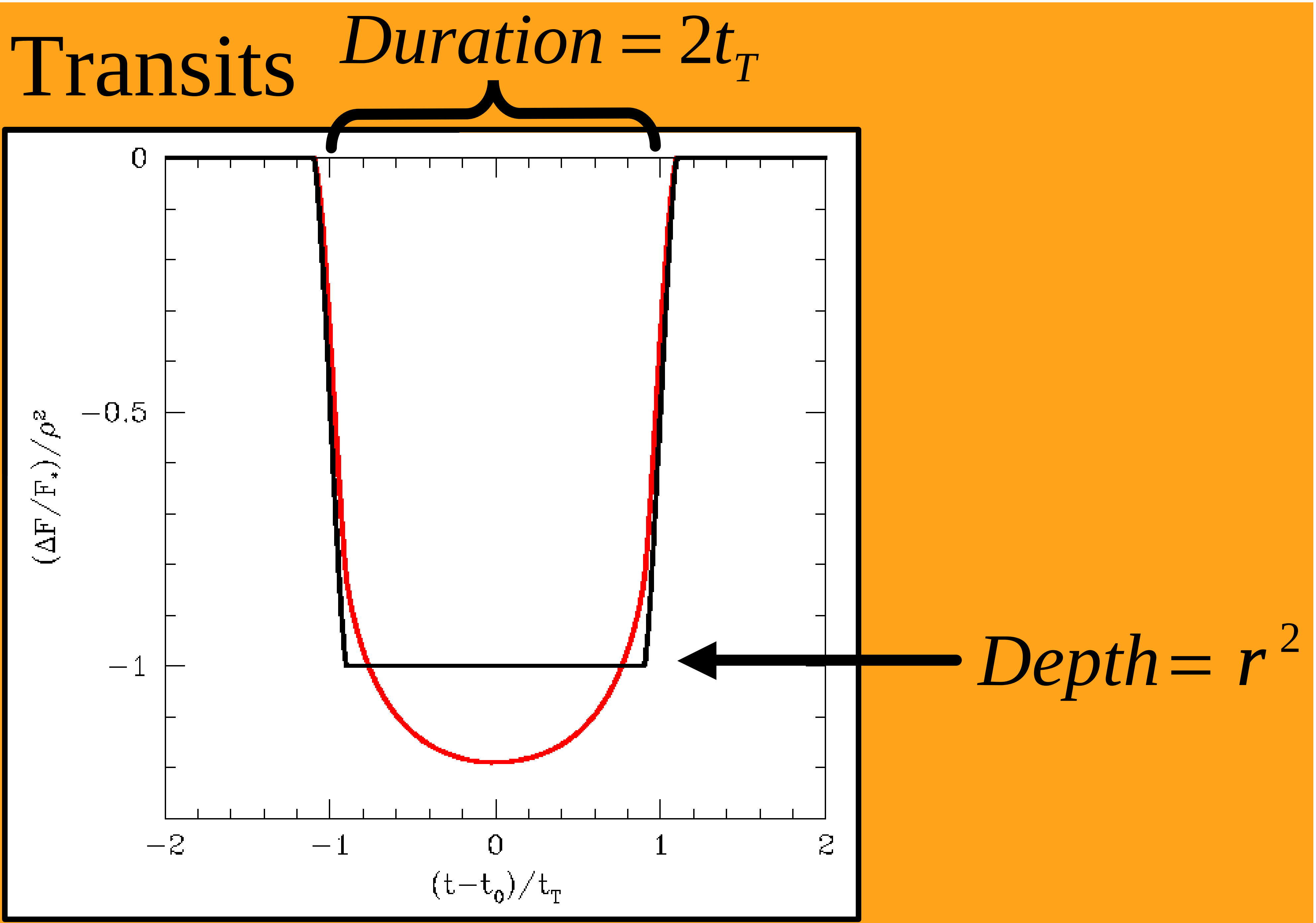
Nurture?

- Low metallicity inhibits formation.

47 Tuc?

- Stellar density

Transits



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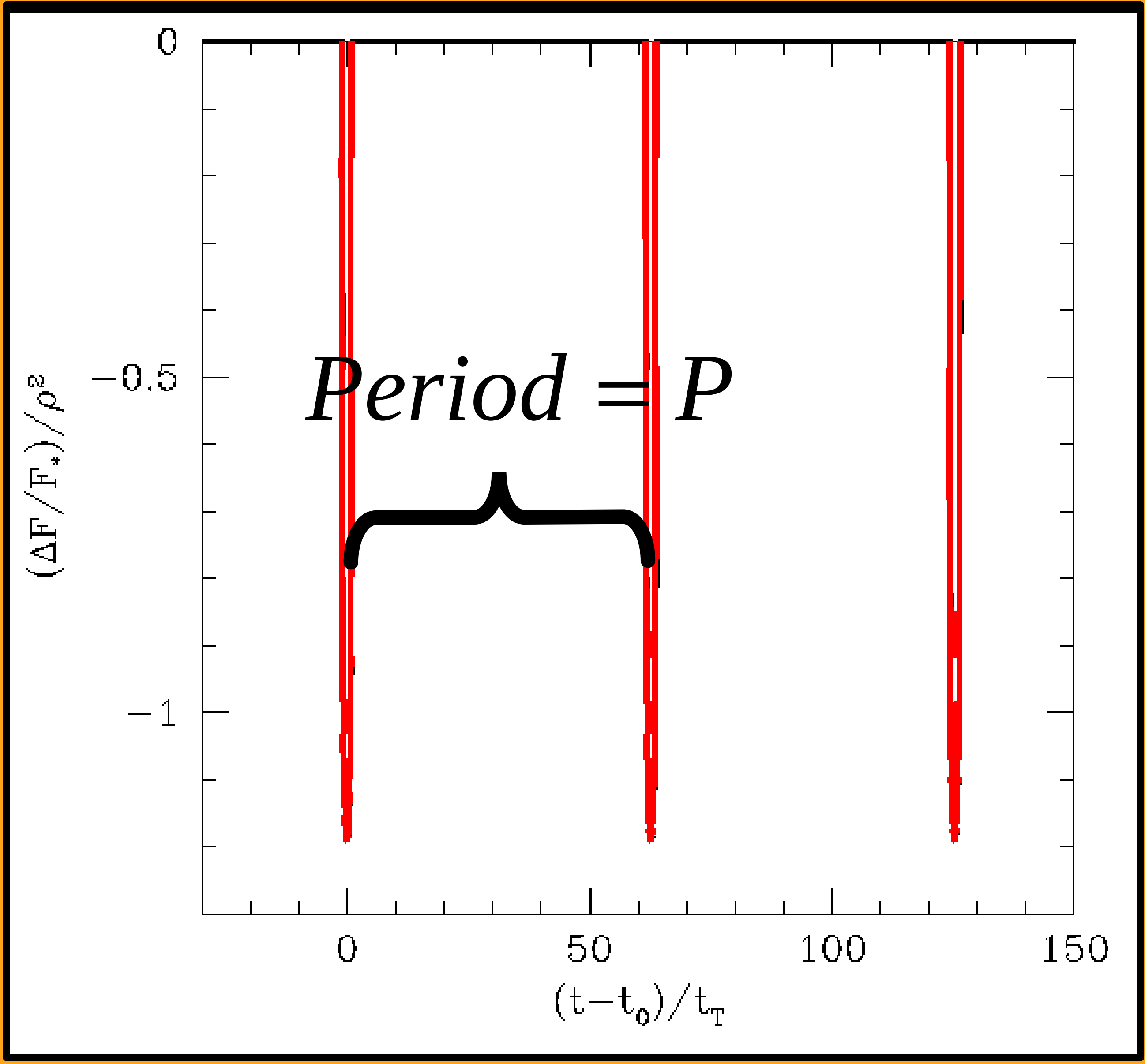
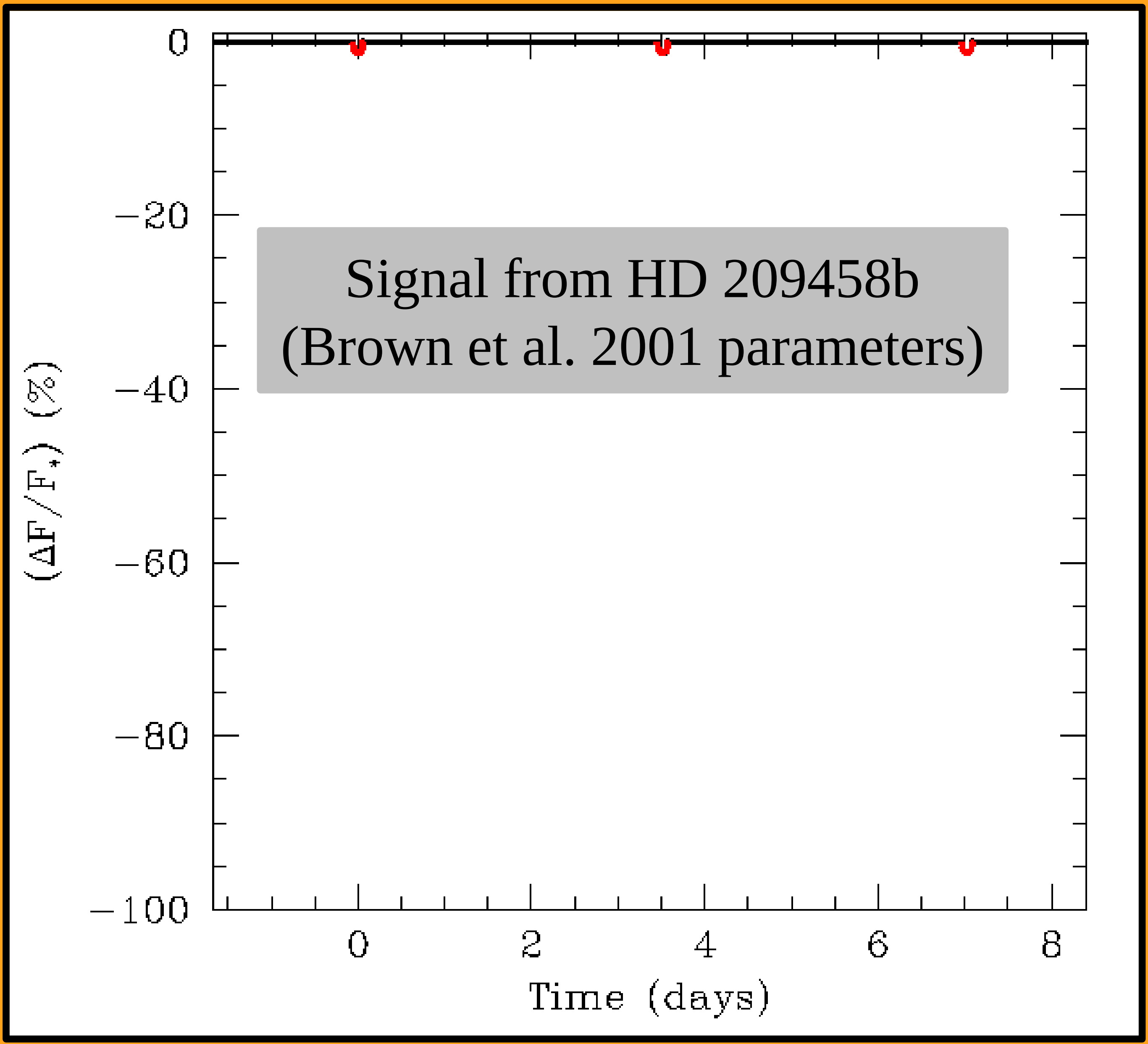


Transits



Signal from HD 209458b
(Brown et al. 2001 parameters)
0
−20
−40
−60
−80
−100
(ΔF/F*) (%)
0
2
4
6
8
Time (days)

Transits – What can we measure?

Measure

$$r, t_T, P$$

(also inclination, limb darkening)

- Depth

$$r = \frac{R_p}{R_*}$$

- Duration

$$t_T \cong \frac{q_*}{m_*} = \frac{R_*}{a}\frac{P}{2p}$$

- Period

$$P = \frac{2p}{\sqrt{GM_*}} a^{3/2}$$

Infer

$$R_P, a$$

(if R_*, M_* are known, or very precise lightcurve)

Need to know the properties of the primary

→ **Need absolute magnitude & color**

Late M dwarfs, BD, giant planets have similar radii

→ **Need RV follow-up of candidates.**

Transits - Detection

$$P = P_T P_Q P_W$$

P_T → Probability of Transit

P_Q → Probability of Exceeding S/N Requirement

P_W → Probability of Transit(s) Occurring in Window

Transits - Detection

$$P = P_T P_Q P_W$$

$$P_T = \frac{\int_0^{\cos i_{\min}} d(\cos i)}{\int_0^1 d(\cos i)} = \frac{R_* + R_p}{a} \approx \frac{R_*}{a}$$

$$\longrightarrow a$$

Transits - Detection

$$P = P_T P_Q P_W$$

$$P_Q = \Theta(Q - Q_{\min})$$

Where Q is the signal-to-noise

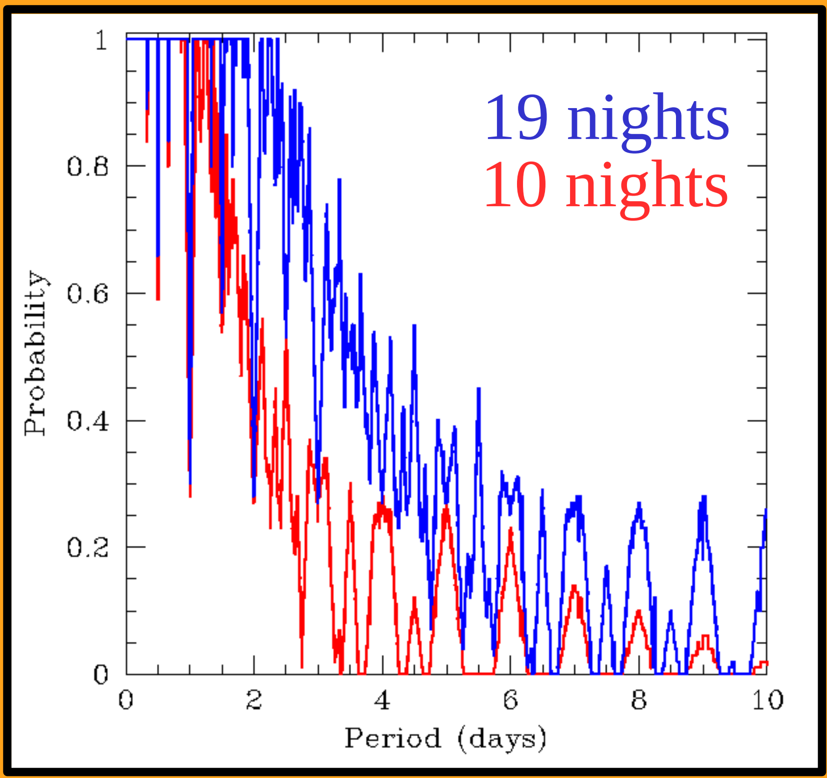
$$Q = \sqrt{N}\frac{r^2}{s} = \sqrt{\frac{2t_T}{t_{\exp}}}\frac{r^2}{s}$$

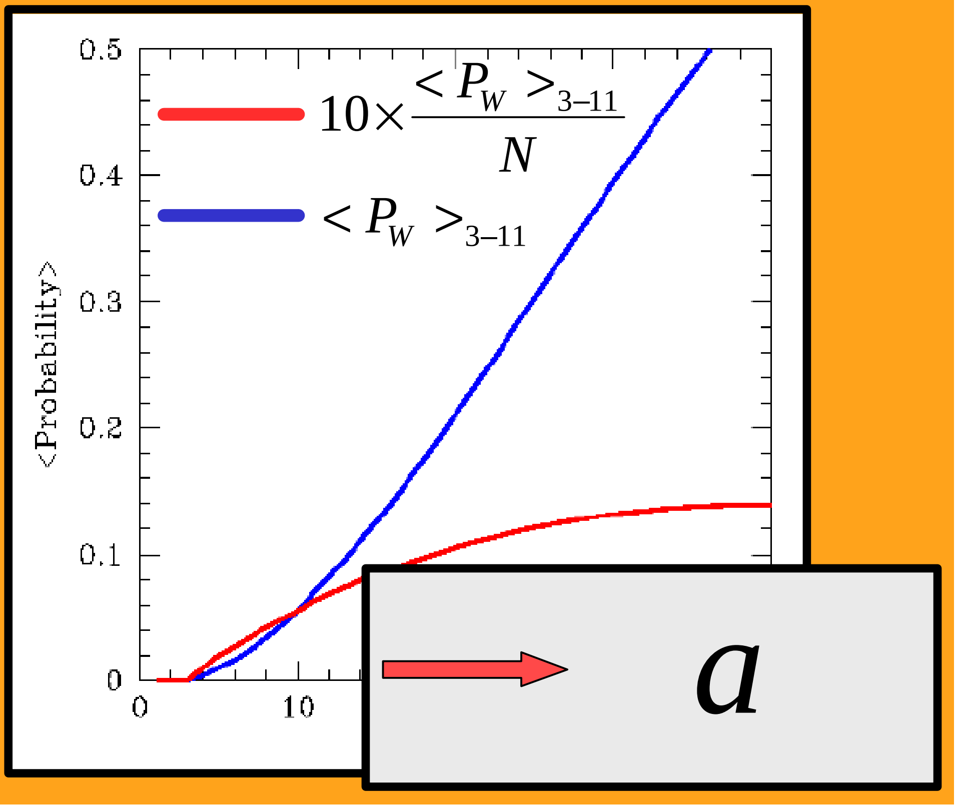
$$\rightarrow \frac{R_p}{R_*}, a^{1/4}$$

Transits - Detection

$$P = P_T P_Q P_W$$

“Window” Probability- probability that n transits occur during the observation windows.





Transits - Detection

$$P = P_T P_Q P_W$$

$P_T \approx 8\%$ (uniform for 3d<P<11d)

$P_Q \approx 1$

$P_W \approx 20\%$ (uniform for 3d<P<11d)

$\Big\}\ P = 1.6\%$

$$N_{\text{det}} = fN_* P = 3\left(\frac{P}{1.6\%}\right)\left(\frac{N_*}{3750}\right)\left(\frac{f_{a<0.1AU}}{5\%}\right)$$

Transit Searches - Flavors

Bright Targets

- RV Follow-up ☆
- All-Sky

Intermediate Targets

- Large FOV
  STARE, Vulcan, WASP

Amenable to Follow-up
{RV, Oblateness, Atmospheres, Rings, Moons, etc.}

Faint Targets

- Field Stars (Galactic Disk, Bulge)
  EXPLORE, OGLE
- Clusters*
  PISCES, EXPORT, STEPSS

Not Amenable to Follow-up
Primaries *too faint* for precise mass measurement.
→ Confirmation (limits) only.

Why? Statistics!

Survey for Transiting Extrasolar Planets in ~~Stellar Systems~~ (STEPSS)

(Open Clusters)

Advantages:

•*Primaries have common properties*

Explore the effects of:

Stellar Density

Age

Metallicity [Fe/H]>0

•*Primaries have known properties*

Statistics easy.

•*Compact systems*

Point-and-shoot

Disadvantages:

•*Relatively Faint Stars*

Follow-up difficult

•*Small Number of Stars*

Difficult to probe f<5%

Requirements:

•Many (20) Consecutive Nights

•Relatively Large FOV

•Modest Aperture

Members: **Chris Burke**, S.G., Darren DePoy, Rick Pogge, Jennifer Marshall

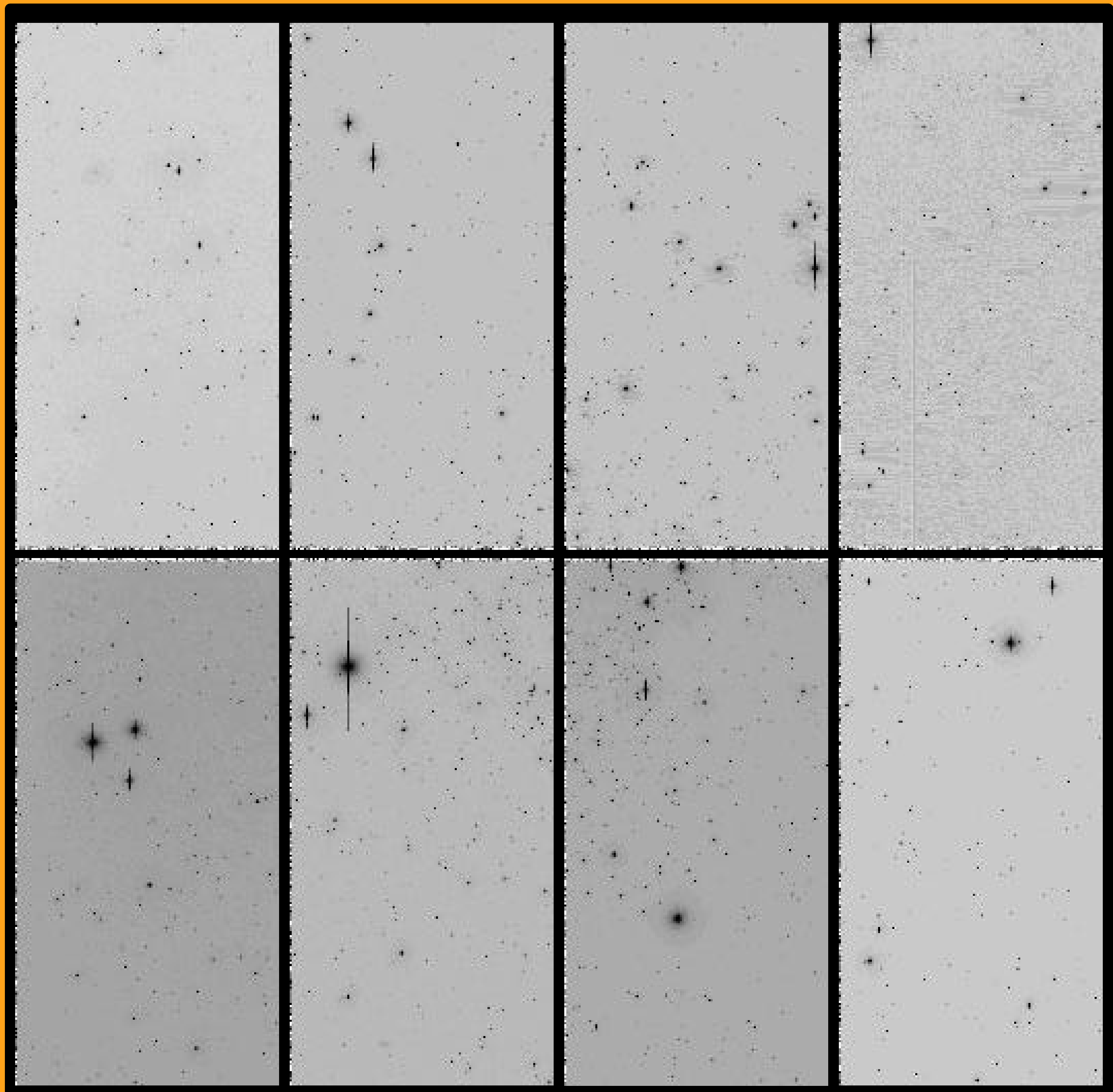
STEPSS

- MDM 2.4m
- 8192x8192 4x2 Mosaic CCD
- 25x25 arcmin^2
- 0.18”/pixel

Fall 2001
- 19 nights
- NGC 1245

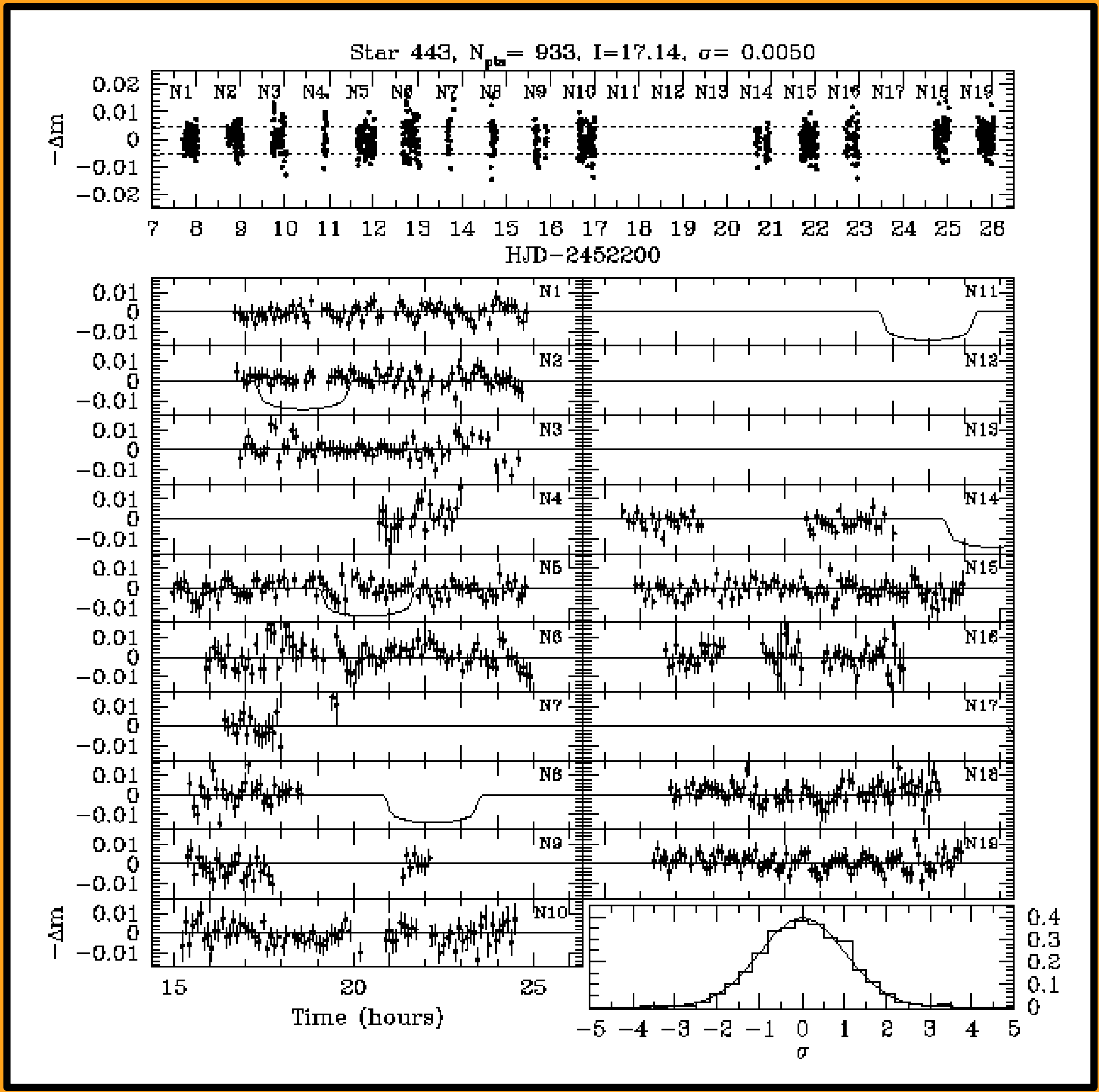
  1 Gyr

  [Fe/H]~0.0?



NGC 1245

- •4-5 minute sampling
- •15 nights with data
- •9 full nights
- •0 photometric nights



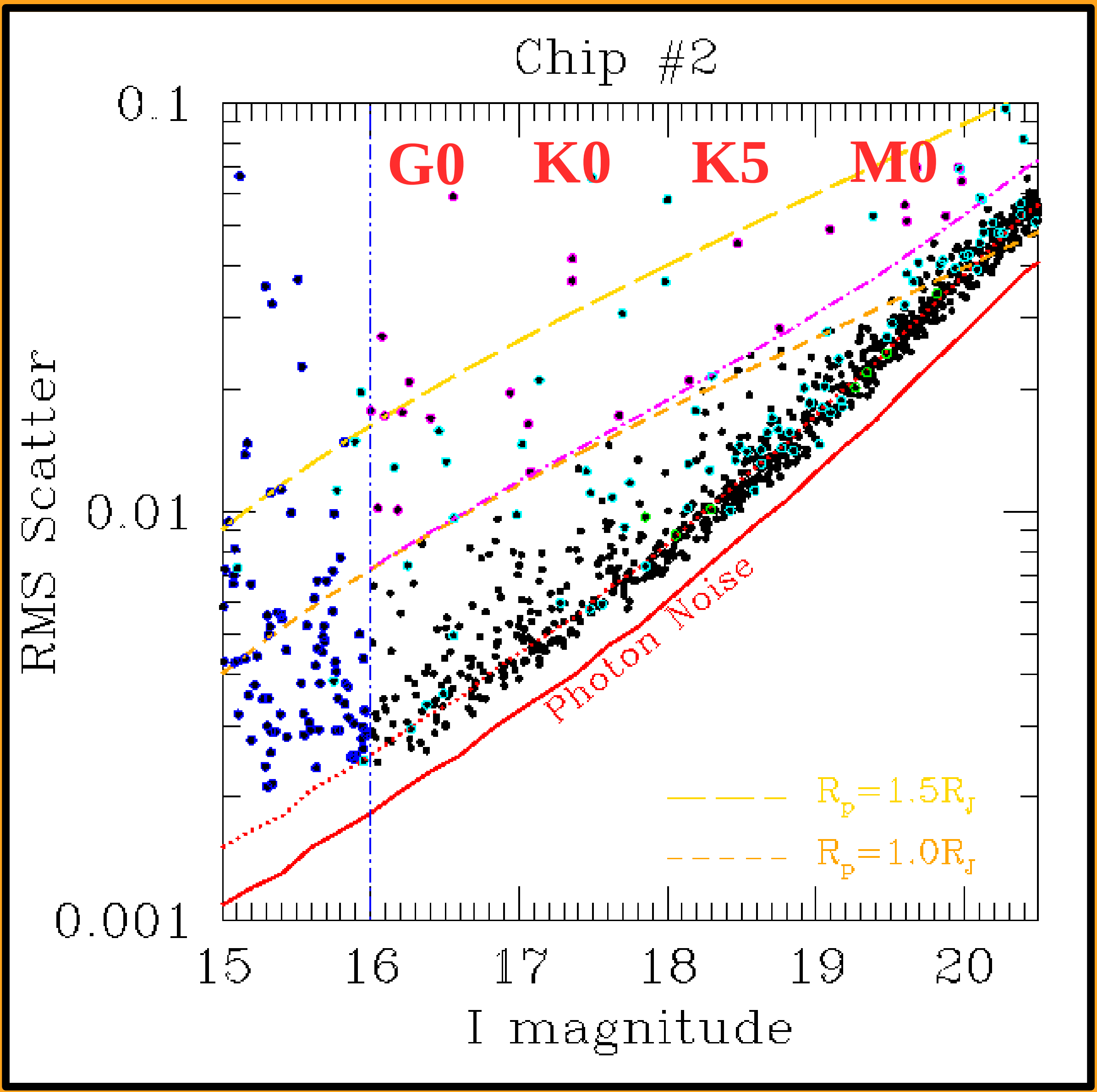
NGC 1245

- Saturate at I=16
- Sensitive to Jupiter-size for G0-M0 primaries

- 6881 objects
  - -259 variable
  - -519 saturated
  - -652 blended
  - - 43 too faint

 5408 pass all cuts

~2500 cluster members



NGC 1245

Ideal Sampling:

19 Nights

8 Hours per Night

$< P_W >_{3-11} = 19\%$ (uniform)

$< P_W >_{3-11} = 24\%$ (log)

Actual Sampling:

19 Nights

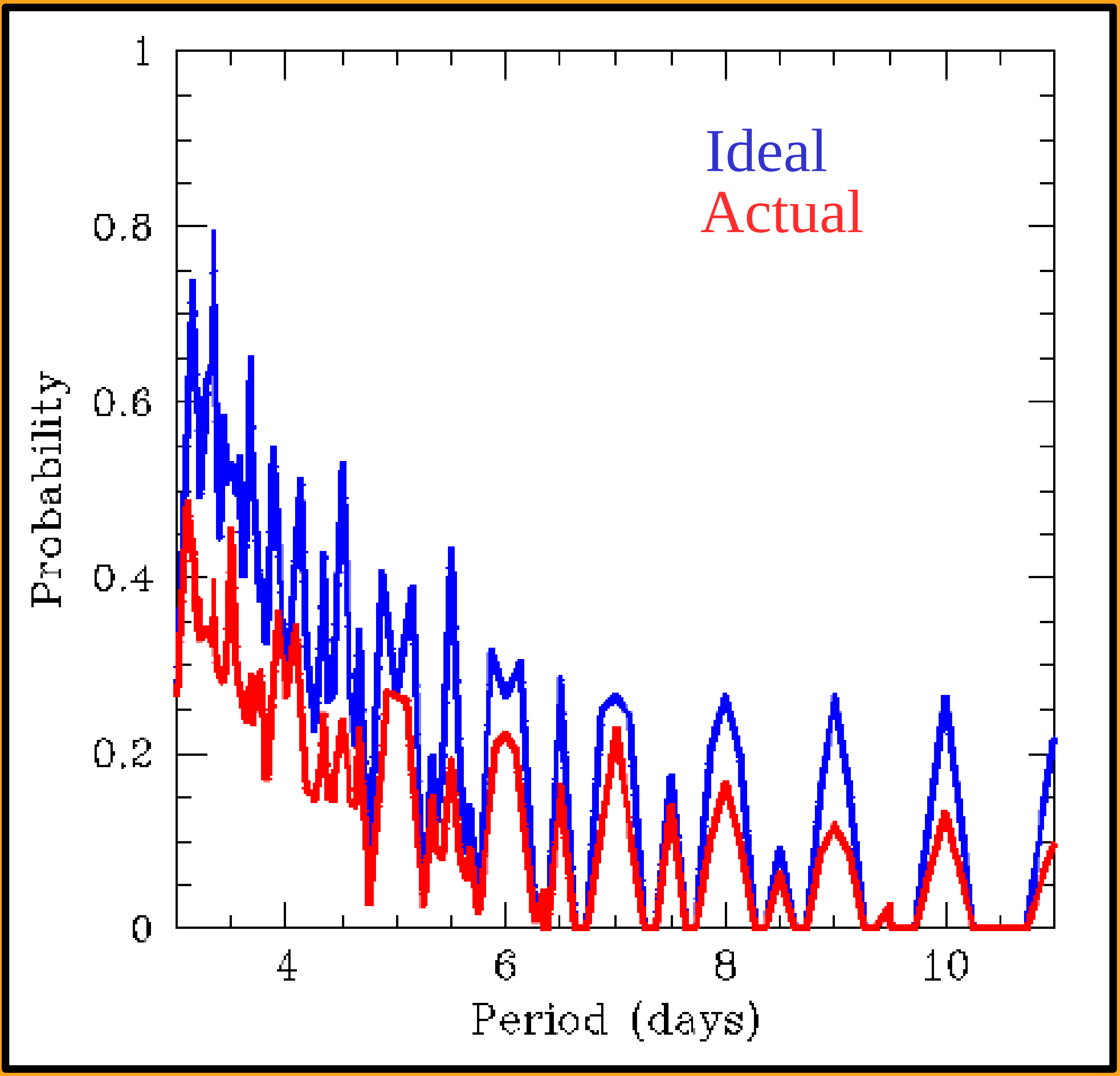
8 Hours per Night

$< P_T >_{3-11} = 12\%$ (uniform)

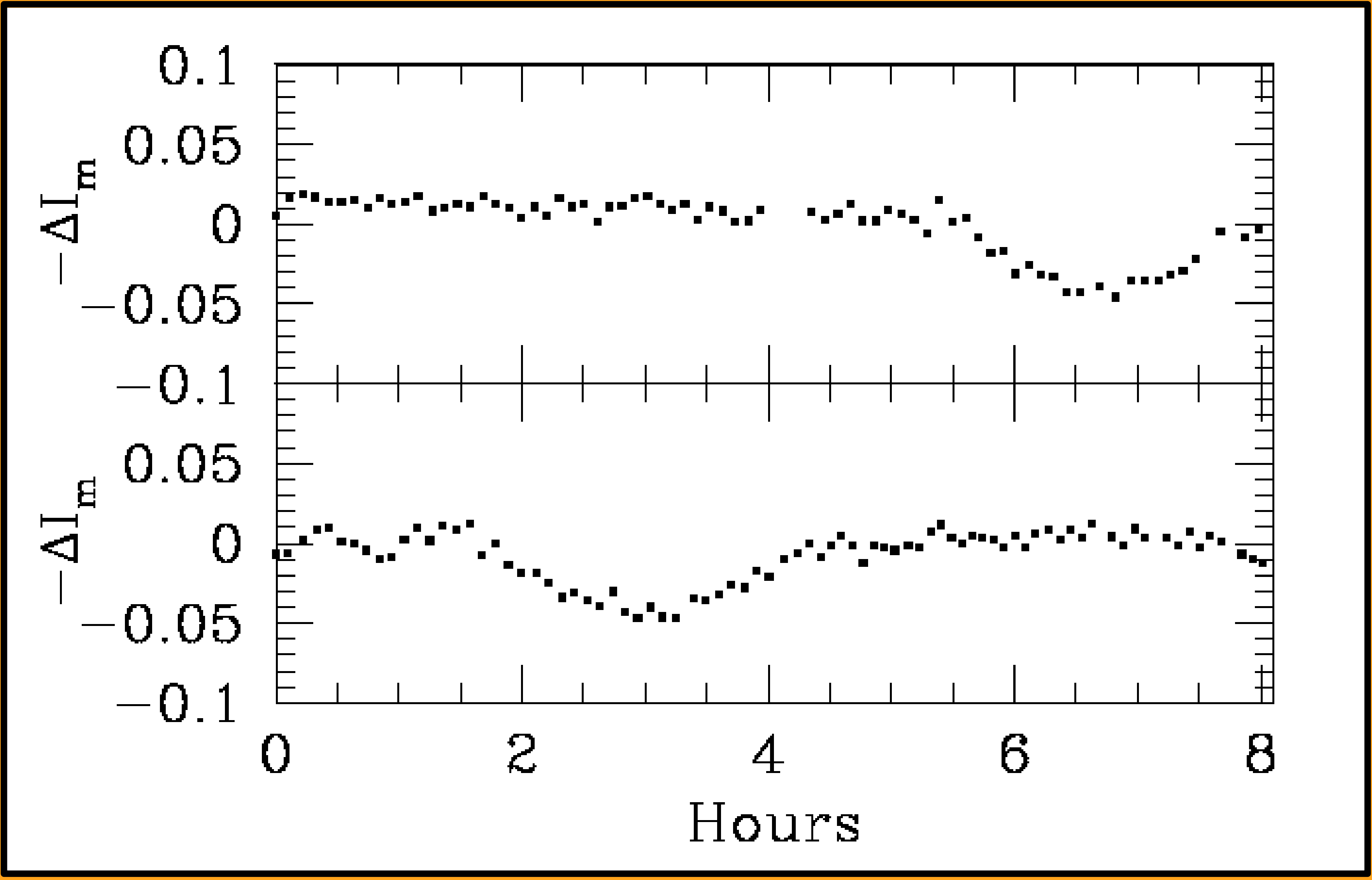
$< P_T >_{3-11} = 15\%$ (log)

Expect ~2 transits
for f=10% (uniform)

Expect ~3 transits
for f=10% (log)



NGC 1245



Period = 3.2 days, Depth ~ 4% → Grazing Binary

STEPSS – Results & Future Prospects

NGC 1245

• $f_{3-10} \leq 10\%$

•Fe/H]=??

NGC 2099

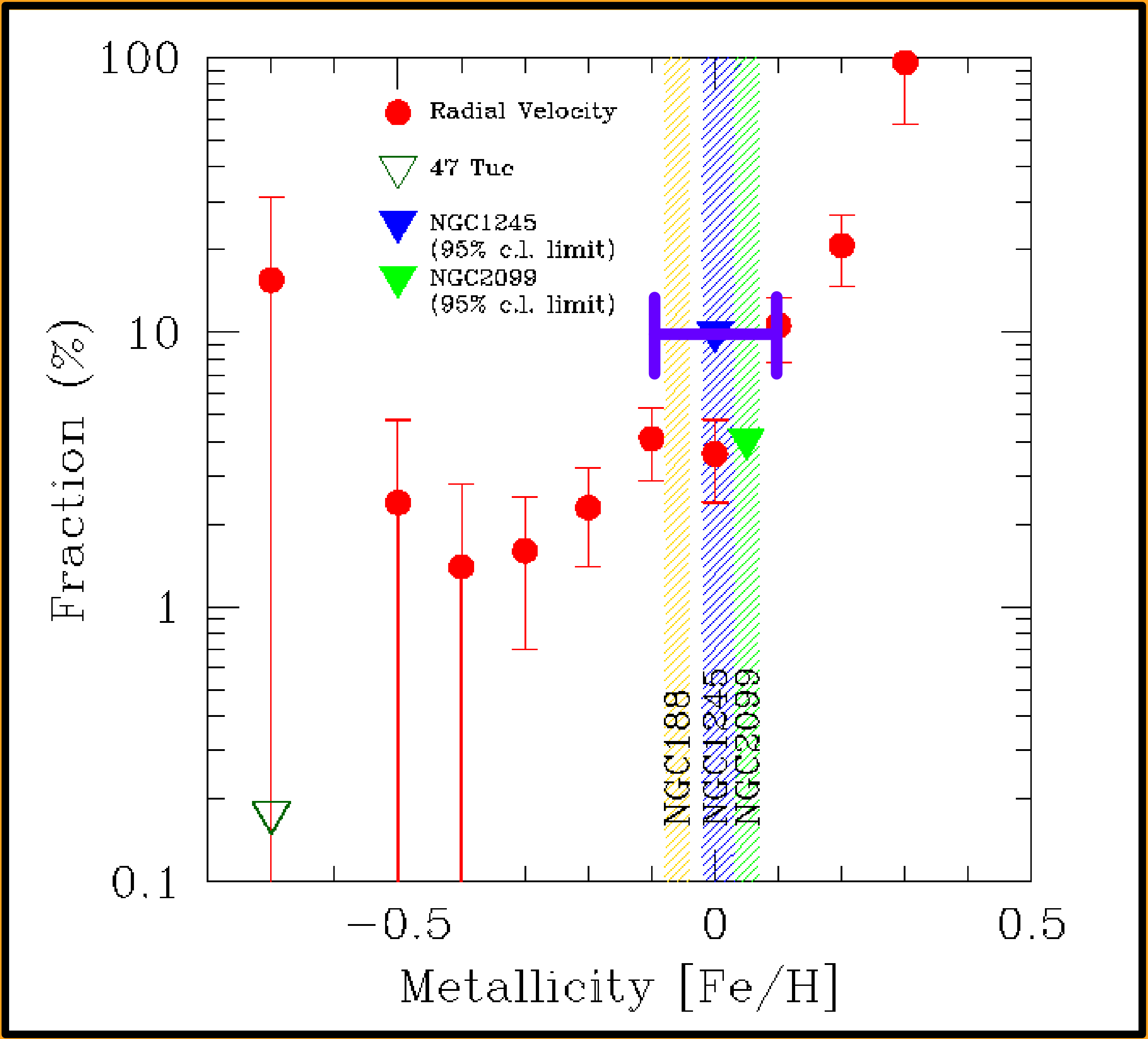
•[Fe/H]=0.05

•35 nights (now!)

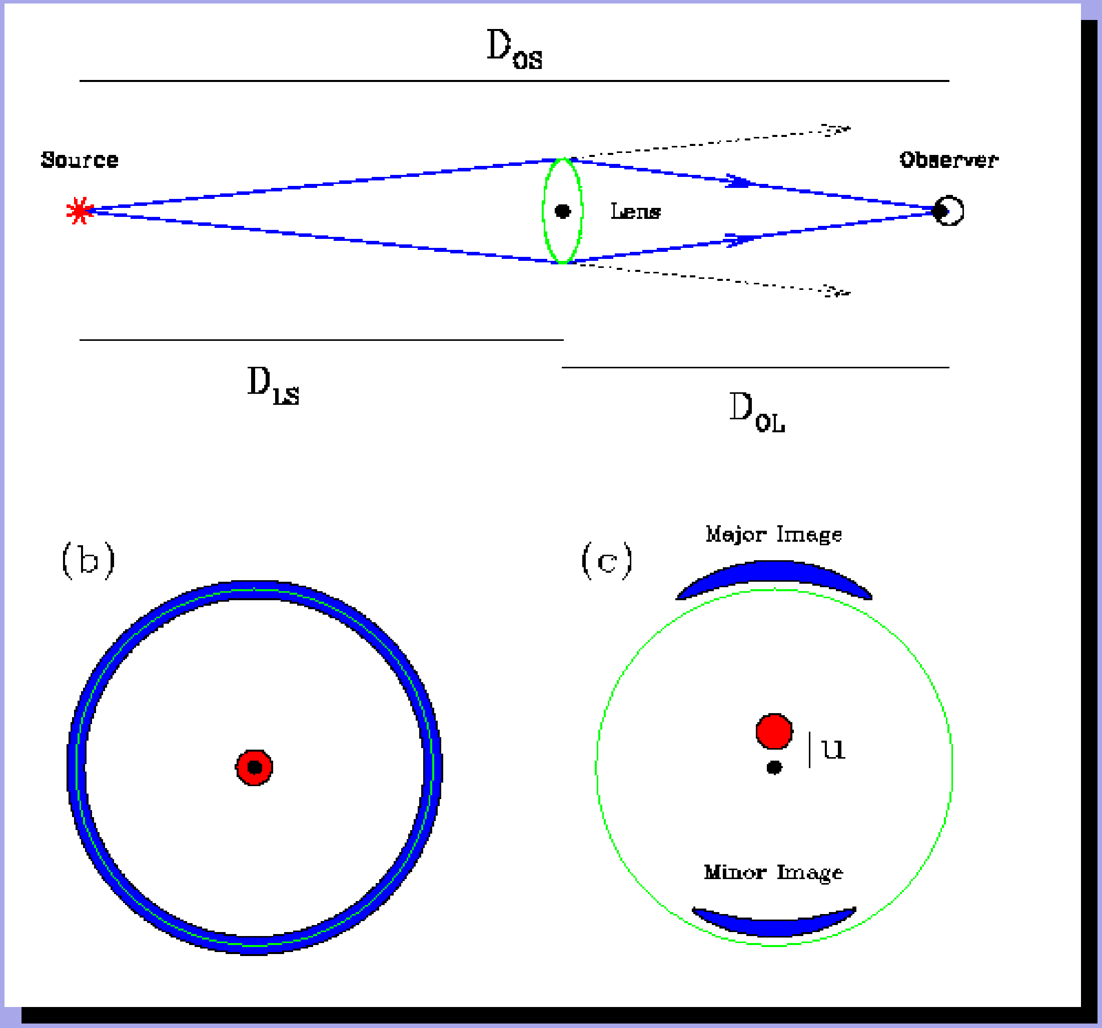
Future:

•1-2 Clusters/Year

•Metallicity determinations



Microlensing and Planets



Lens Equation:

$$\beta = \theta - \theta_E^2/\theta$$

Angular Einstein Ring Radius

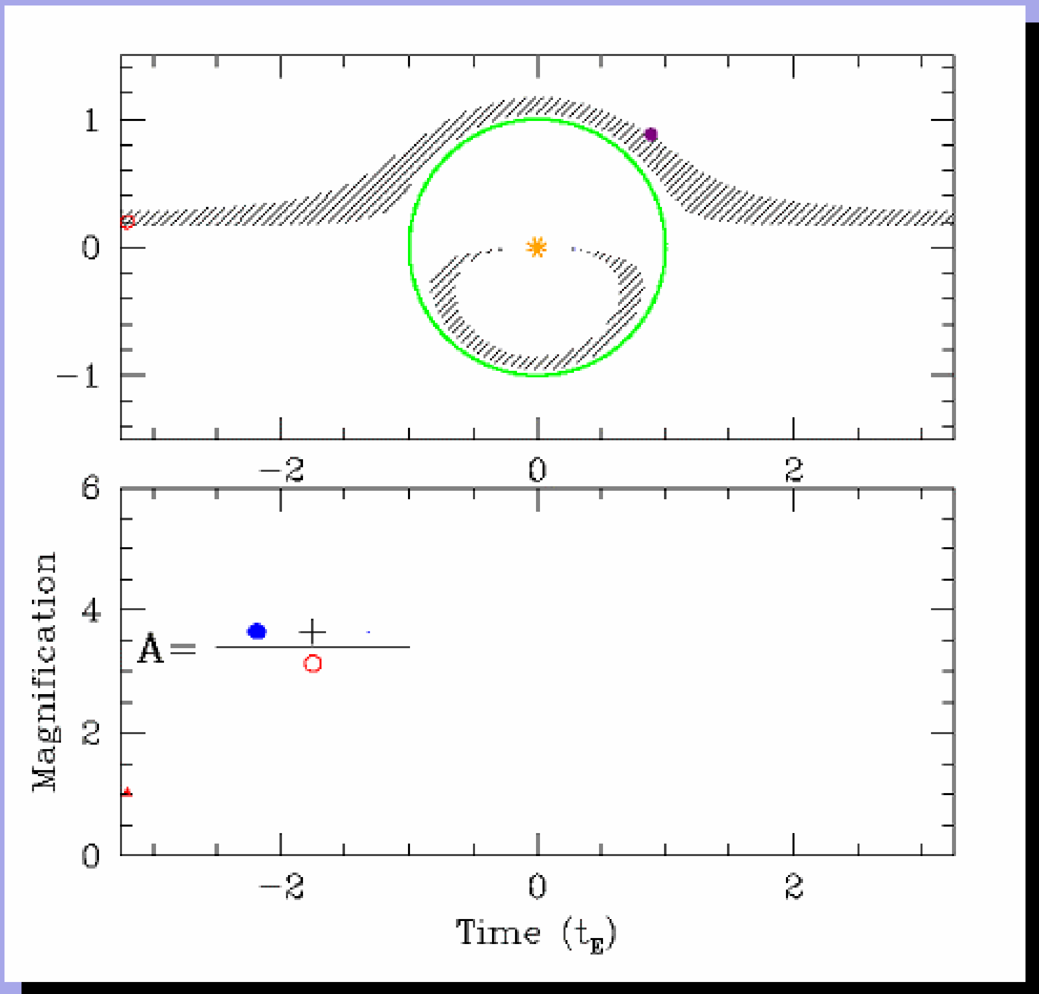
$$\theta_E = \sqrt{\frac{4GM}{c^2}\frac{D_{LS}}{D_{OL}D_{OS}}}$$

$$\approx 300mas\sqrt{\frac{M}{0.3M_\odot}}$$

Physical Radius

$$r_E = \theta_E D_{OL} \approx 2\mathrm{AU}$$

Microlensing and Planets



Single Lens Parameters:

- Impact parameter
- Time of Maximum Mag.
- Timescale

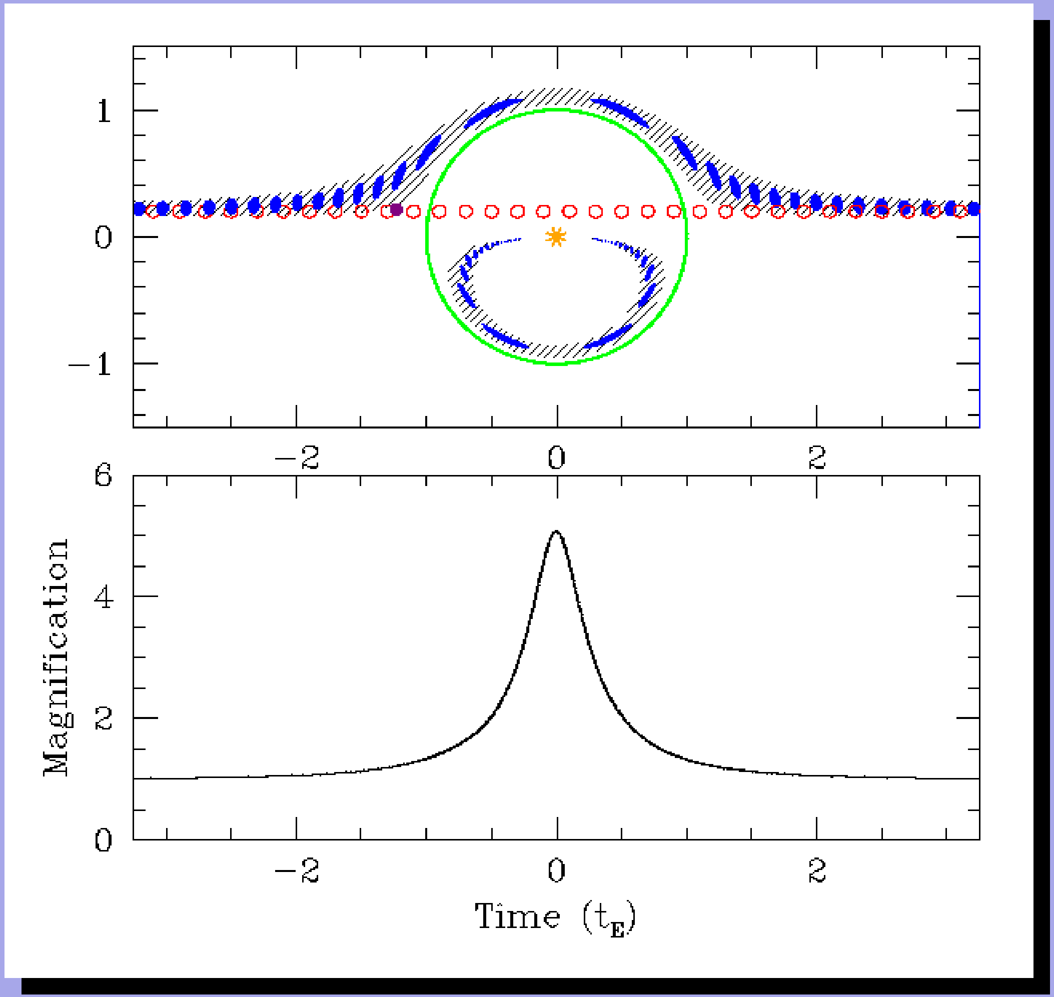
$$t_E = \frac{q_E}{m} \approx 20\text{days}\sqrt{\frac{M}{0.3M_\odot}}$$

Planet Parameters:

- Angle wrt Binary Axis
- Projected Separation
- Mass Ratio - q

$$t_p = \sqrt{q}\,t_E \approx 1\text{day}\sqrt{\frac{M_p}{M_J}}$$

Microlensing and Planets



Detection Efficiency:

Naïve Estimate:

$$\approx \frac{q_p}{q_E} \approx 3\% \sqrt{\frac{q}{10^{-3}}}$$

Enhanced Probability:

$$\approx A \frac{q_p}{q_E} \approx 15\% \sqrt{\frac{q}{10^{-3}}}$$

High-Magnification Events

➡ Higher Efficiencies

Maximized at $a \approx r_E$

Mao & Paczynski 1991,
Gould & Loeb 1992,
Griest & Safizadeh 1998

Microlensing and Planets

Advantages:

Sensitive to Jupiters at 1-10 AU.
Extend Sensitivity to Lower (>Mars!) Masses.

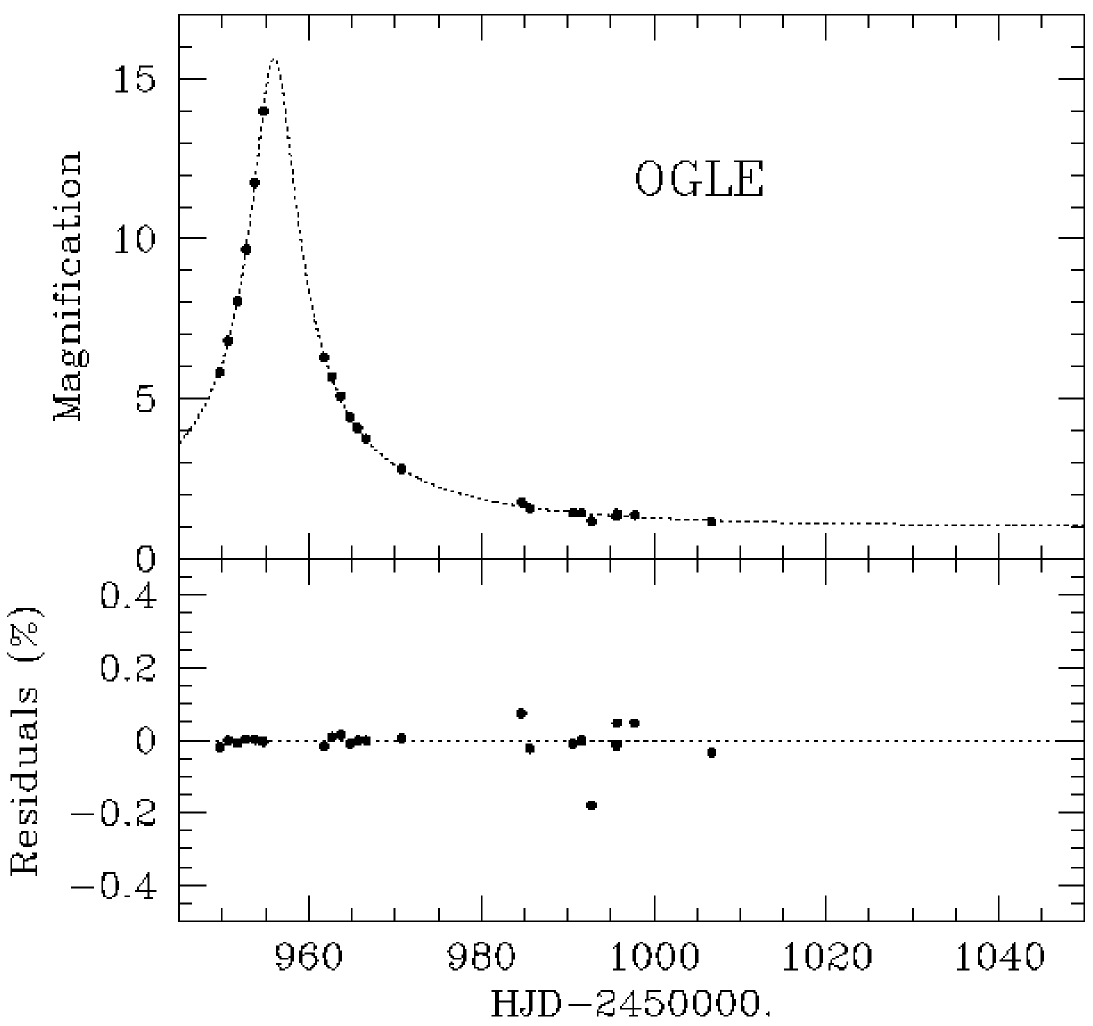
Disadvantages:

Follow-up Difficult (almost purely statistical information).
Non-repeatable.
Short Timescale Perturbations.

Basic Requirements:

Nearly Continuous Sampling.
Good Photometry for Detection.

Alerts and Follow-up



“Survey” Collaborations

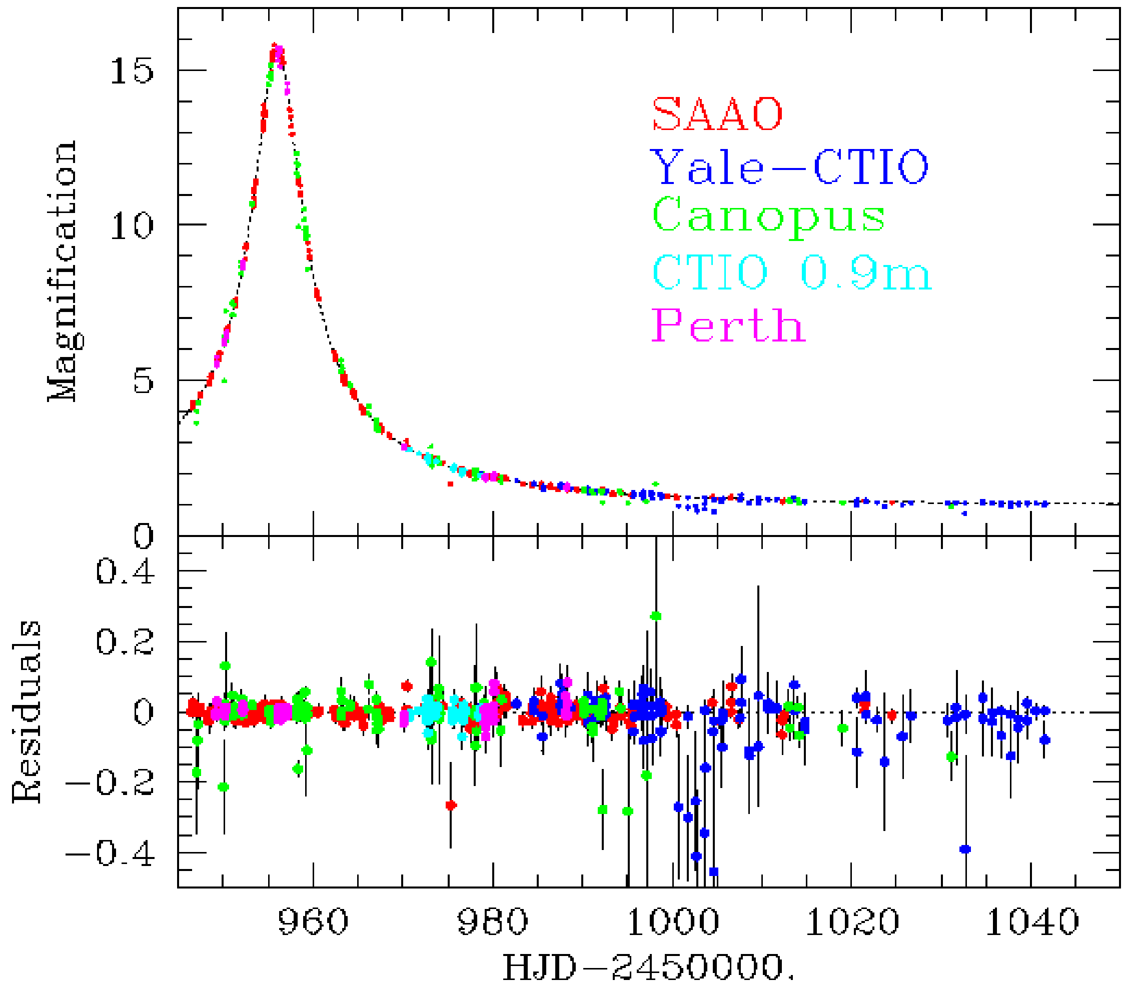
- Insufficient Sampling
- Real-time Alerts

Current and Past Alerts

- EROS
- MACHO*
- MOA
- OGLE III

(500 per year?)

Alerts and Follow-up



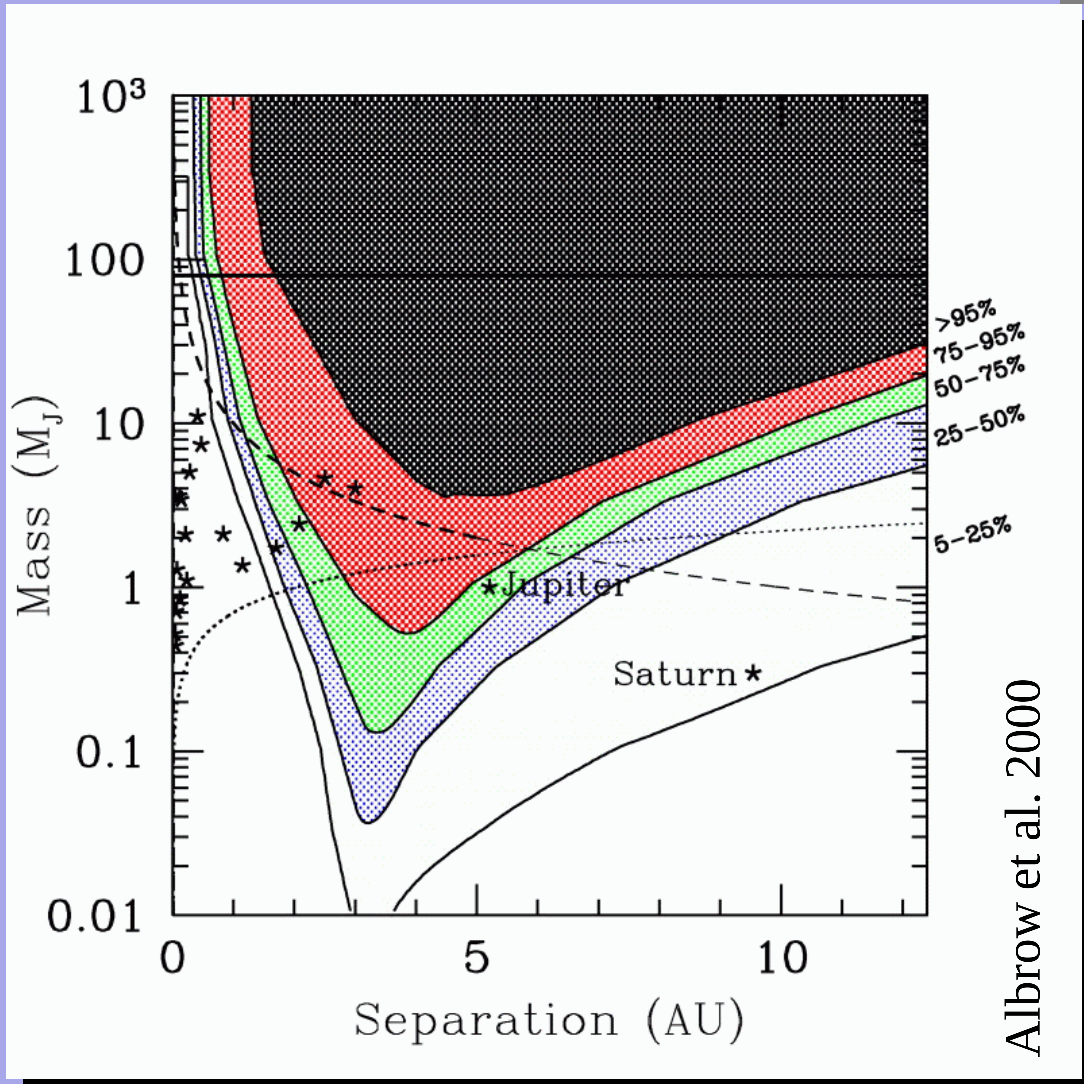
Follow-up Collaborations

- High Temporal Sampling
- Good Photometry

Current Collaborations

- EXPORT
  (Tsapras et al. 2001)
- μFUN
  (new collaboration)
- MOA
  (Bond et al 2002)
- MPS
  (Rhie et al. 2000)
- PLANET
  (Albrow et al. 1998)

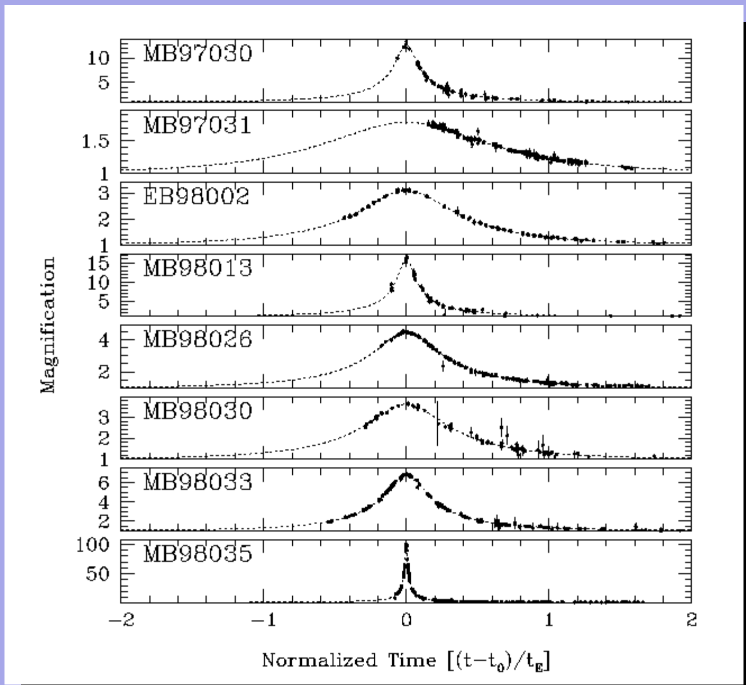
Detection and Efficiency



Albrow et al. 2000

Microlensing sensitive to Jupiters from 1-10 AU

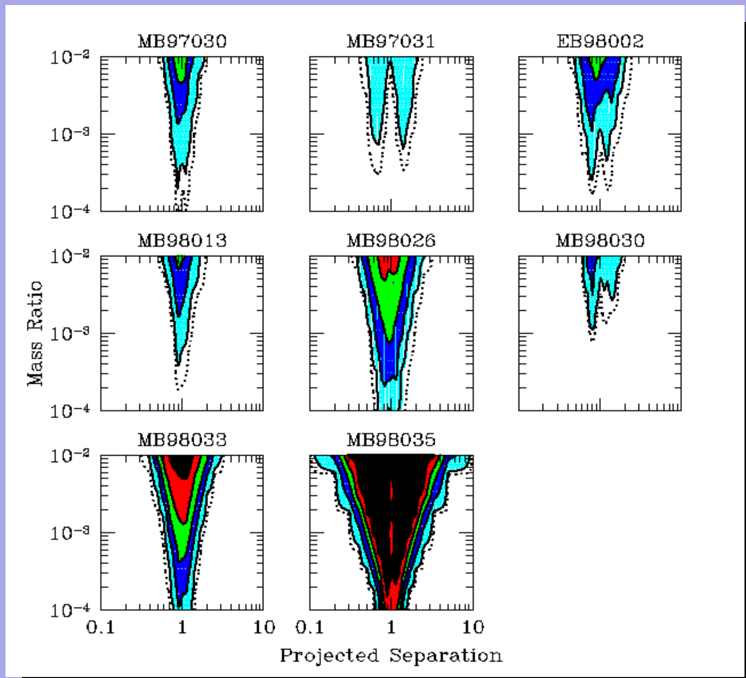
Five Years of PLANET Data



95-99 PLANET Sample

•43 Events

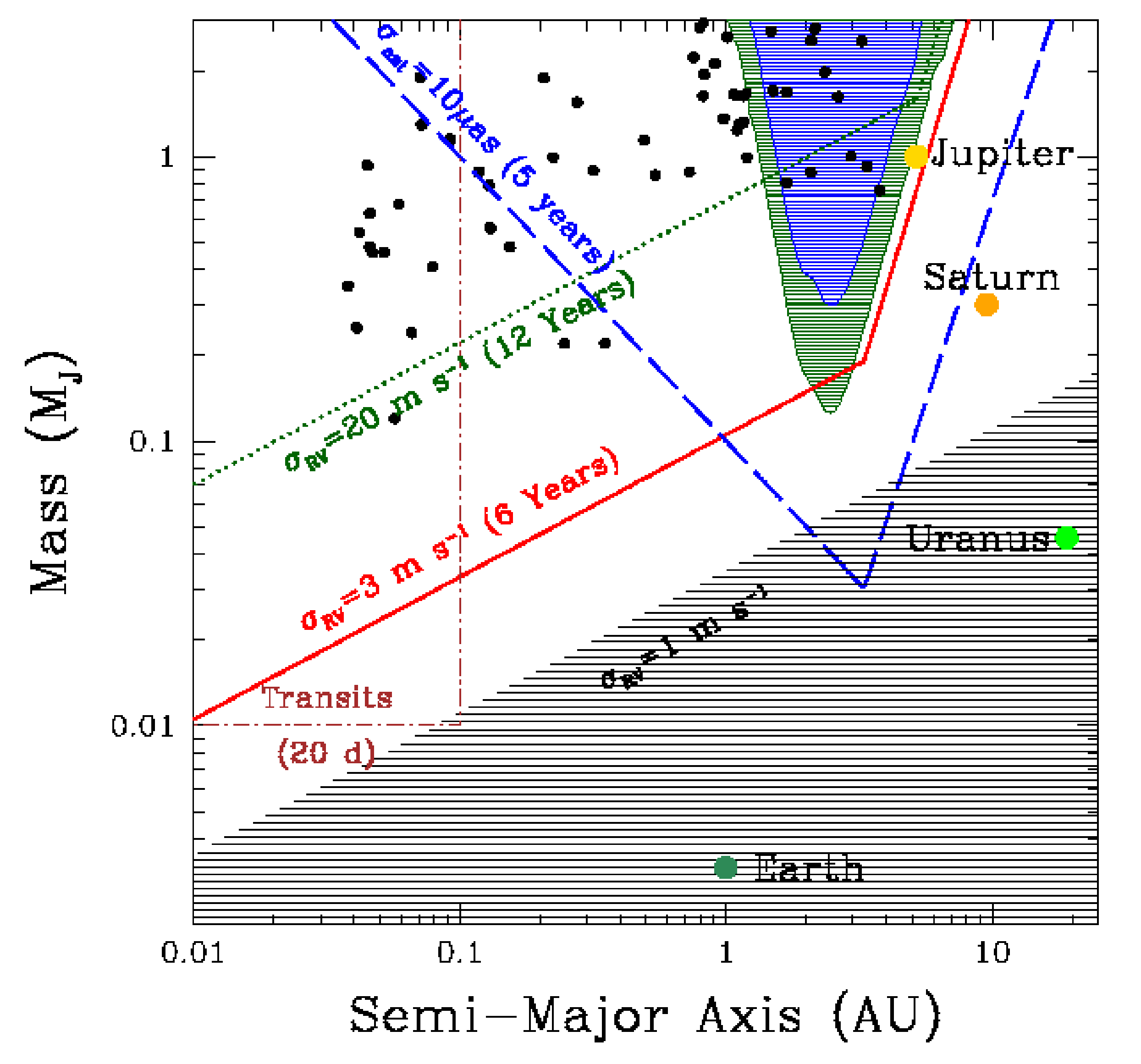
Albrow et al. 2001
Gaudi et al. 2002



Search for Planets

- $-4 < \log(q) < -2$
- $-1 < \log(d) < 1$

No Viable Detections



<33% Have Jupiter-mass companions between 1.5-4 AU
<45% Have 3 x Jupiter-mass companions between 1-7 AU

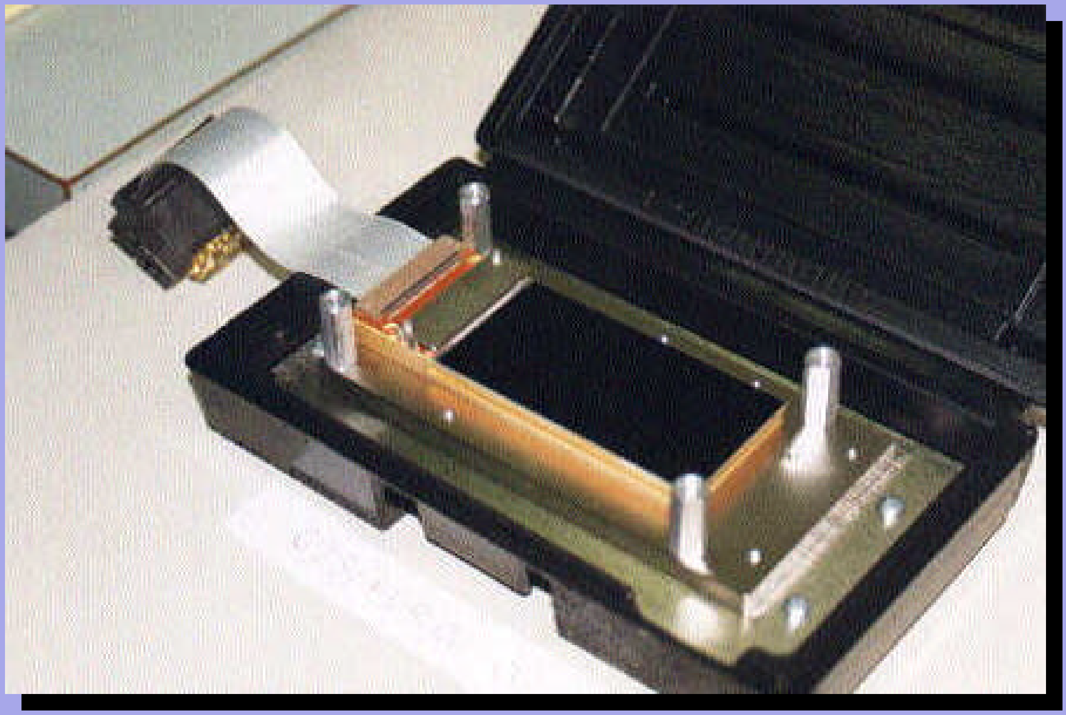
Future Prospects - Ground

Pushing to Lower Fractions

- More Efficient Monitoring
- Image Subtraction Processing

} Factor of 3 improvement (Gaudi & DePoy in prep)

- Increasing the Number of Alerts (OGLE III)

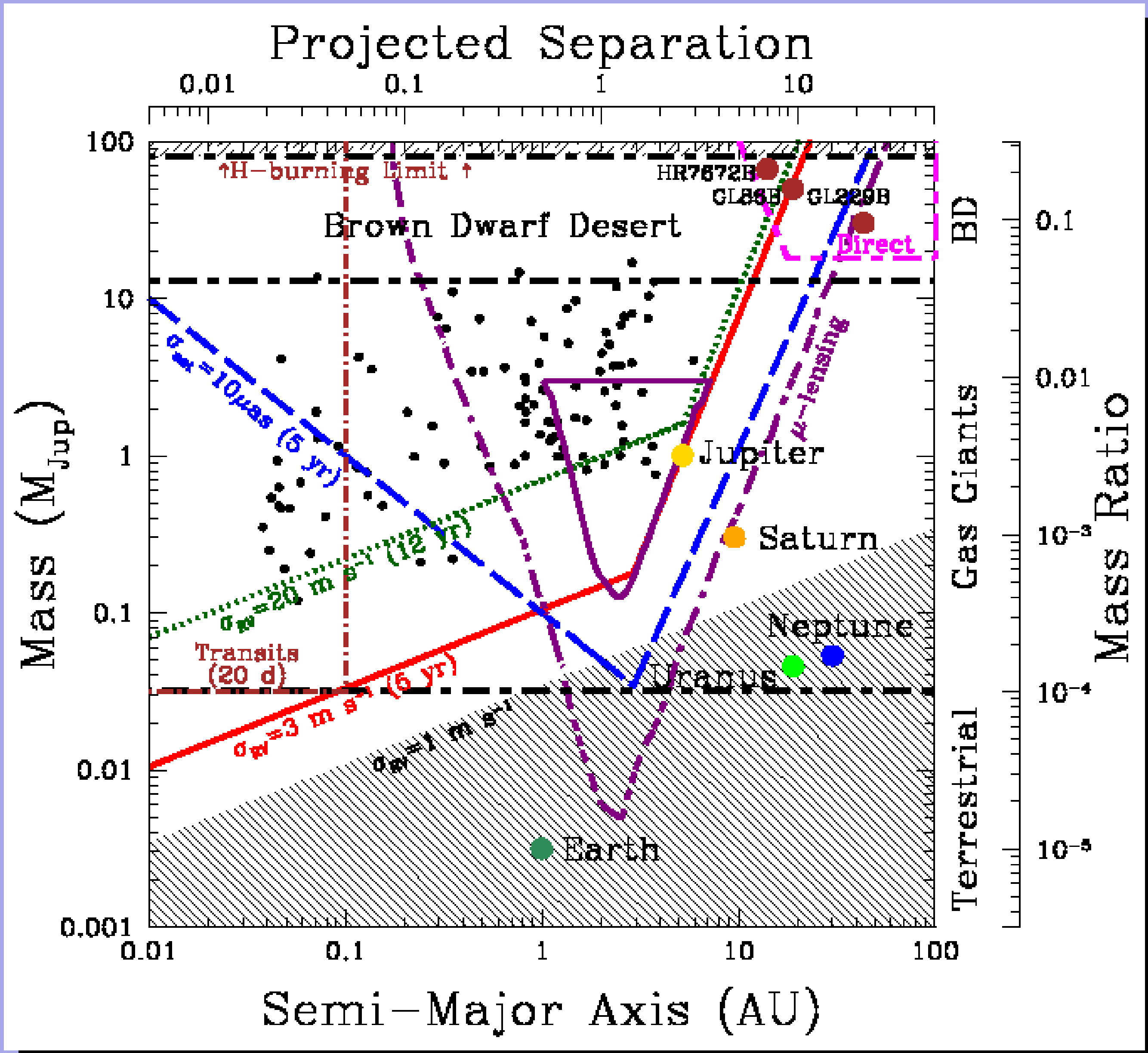


OGLE-III Camera

- 8 2045x4096 CCDs
- 35’ x 35’ field-of-view
- ~500 alerts per year

$$R_{exp} \approx 1\,\mathrm{yr}^{-1}\left(\frac{q}{10^{-3}}\right)^{1/2}\left(\frac{f}{5\%}\right)\left(\frac{R_{alert}}{500\mathrm{yr}^{-1}}\right)^{1/2}$$

Future Prospects - Ground



P=25% for A>10

- BD from 0.5-30 AU
- mass ratio to 10^{-5}

"Cool Neptunes"

$M_p = 0.05 M_J, a = 2AU$

Expect N~10f/year

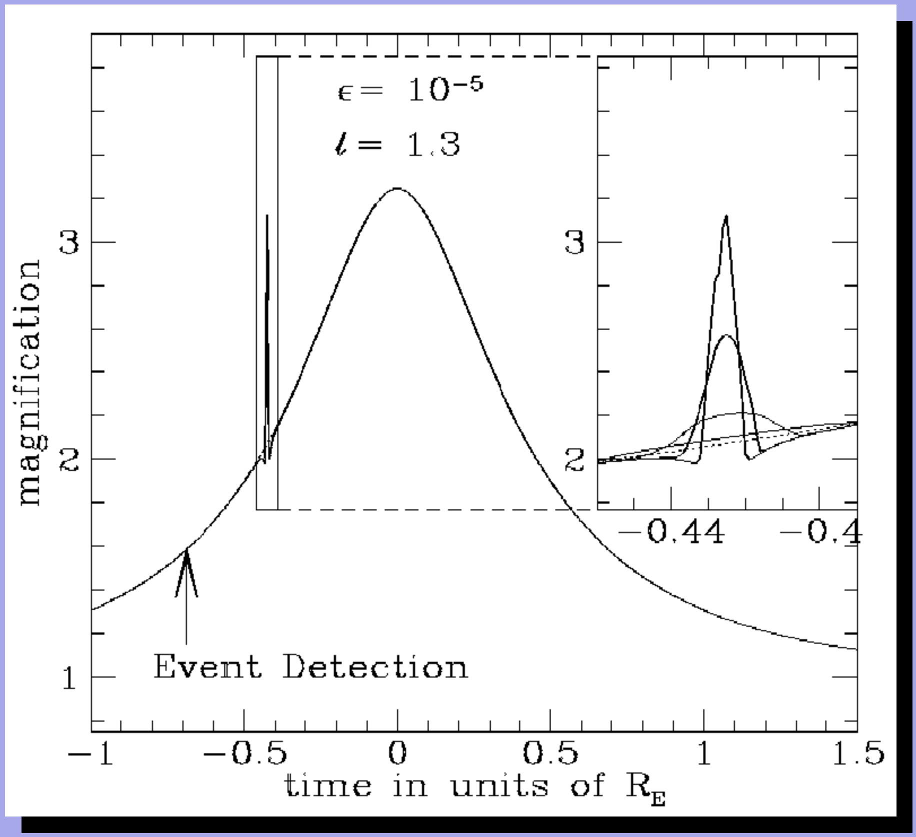
Future Prospects - Ground

Pushing to Lower Fractions

- Increasing the Number of Alerts (OGLE III)
- More Efficient Monitoring
- Image Subtraction Processing

Pushing to Earth Masses

- Main Sequence Alerts



Bennett & Rhie (1996)

→ Need Main Sequence Sources

Future Prospects - Ground

Pushing to Lower Fractions

- Increasing the Number of Alerts (OGLE III)
- More Efficient Monitoring
- Image Subtraction Processing

Pushing to Earth Masses

- Main Sequence Alerts
- Larger Apertures?
- Difficult with 2-tier approach

Next Generation/Space Based?

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