Transit Searches for Extrasolar Planets

Properties, Pitfalls, Payoffs, and Promises

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Outline:

- Star and Planet Formation
- Migrating Planets
- Basic Properties of Planet Transits
- Challenges in Transit Surveys
- The Menagerie of Transit Surveys
- Field Searches – Properties and Implications
- Cluster Searches – Properties and Future Prospects
- Extrasolar Earths

Collaborators

- ***Chris Burke*** (OSU)
- Darren DePoy (OSU)
- *Susan Dorsher* (OSU)
- Andrew Gould (OSU)
- *Joel Hartman* (CfA)
- Matt Holman (CfA)
- Gabriela Mallen-Ornelas (CfA)
- *Joshua Pepper* (OSU)
- Sara Seager (DTM)
- Kris Stanek (CfA)

Jargon

- AU – Astronomical Unit.
  - Mean Earth-Sun Distance
- pc – "Parallax Second"
  - Distance at which an object's parallax would subtend one second of arc
- Metallicity
  - Mass fraction of elements above He
- Main Sequence/Giant Star

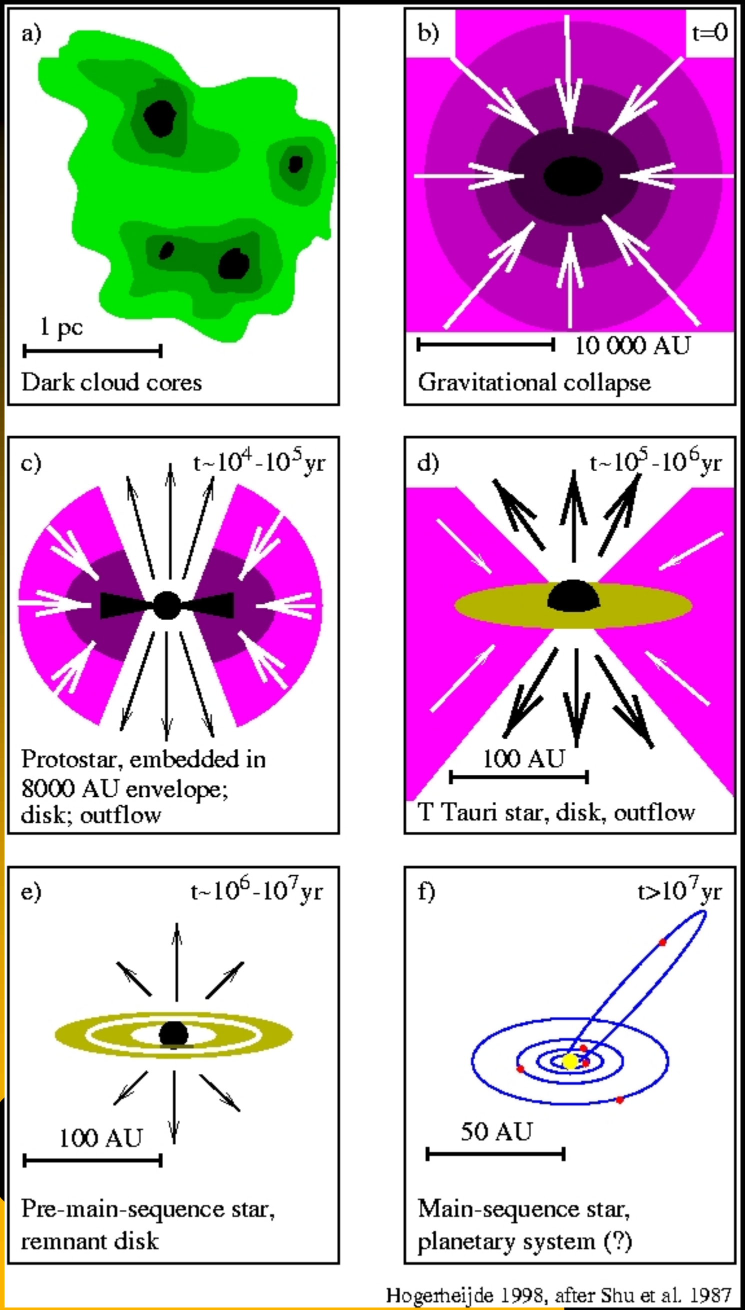
$$AU = 1.50 \times 10^{13}\, cm$$
$$pc = 3.09 \times 10^{18}\, cm$$

Constants

$$M_{Sun} = 1.99 \times 10^{33}\, g$$
$$M_J = 1.90 \times 10^{30}\, g \approx 10^{-3} M_{Sun}$$
$$M_{\oplus} = 5.97 \times 10^{27}\, g \approx 3 \times 10^{-6} M_{Sun}$$

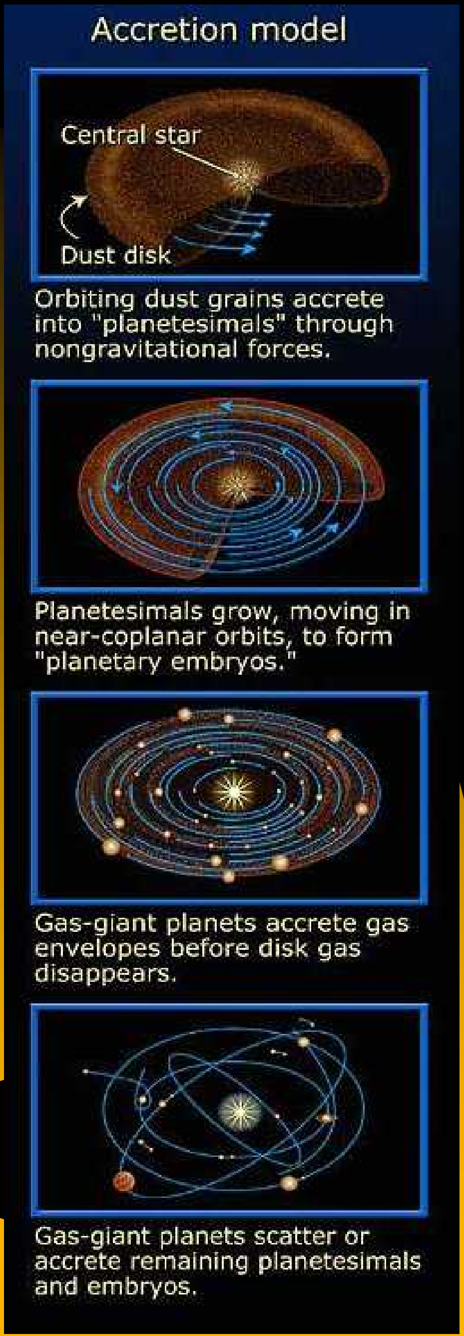
$$R_{Sun} = 6.96 \times 10^{10}\, cm$$
$$R_J = 7.15 \times 10^{9}\, cm \approx 0.1 R_{Sun}$$
$$R_{\oplus} = 6.38 \times 10^{8}\, cm \approx 0.01 R_{Sun}$$

Star Formation 101



Hogerheijde 1998

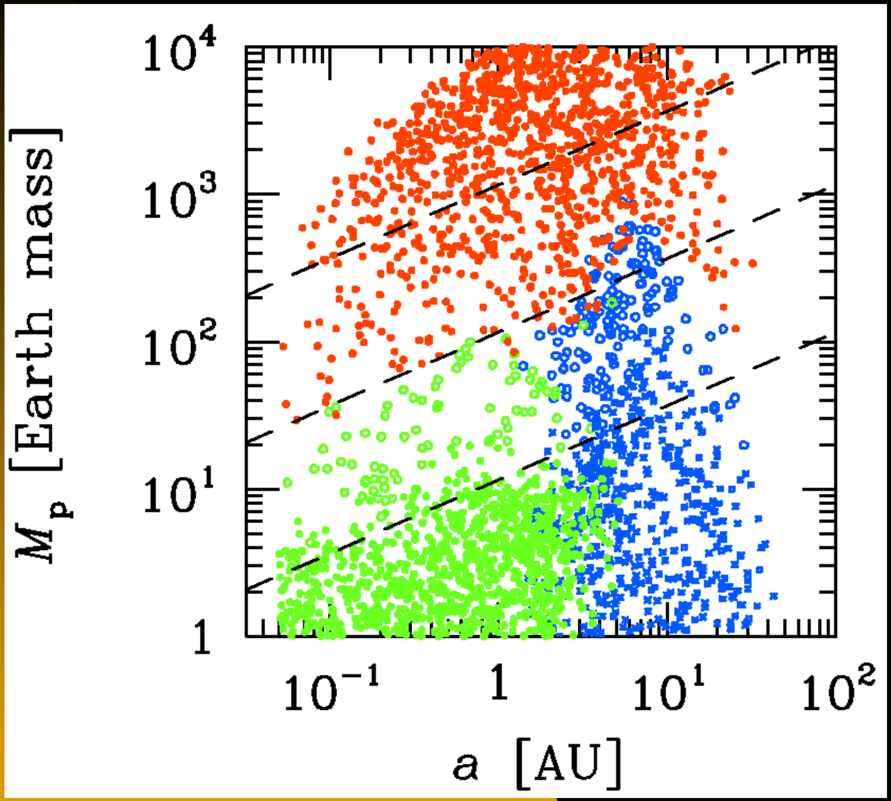
- Molecular Cloud
- Cores
- Collapse
- Ignition/Outflow
- Protoplanetary Disk
- Planetary System



Planet Formation 101

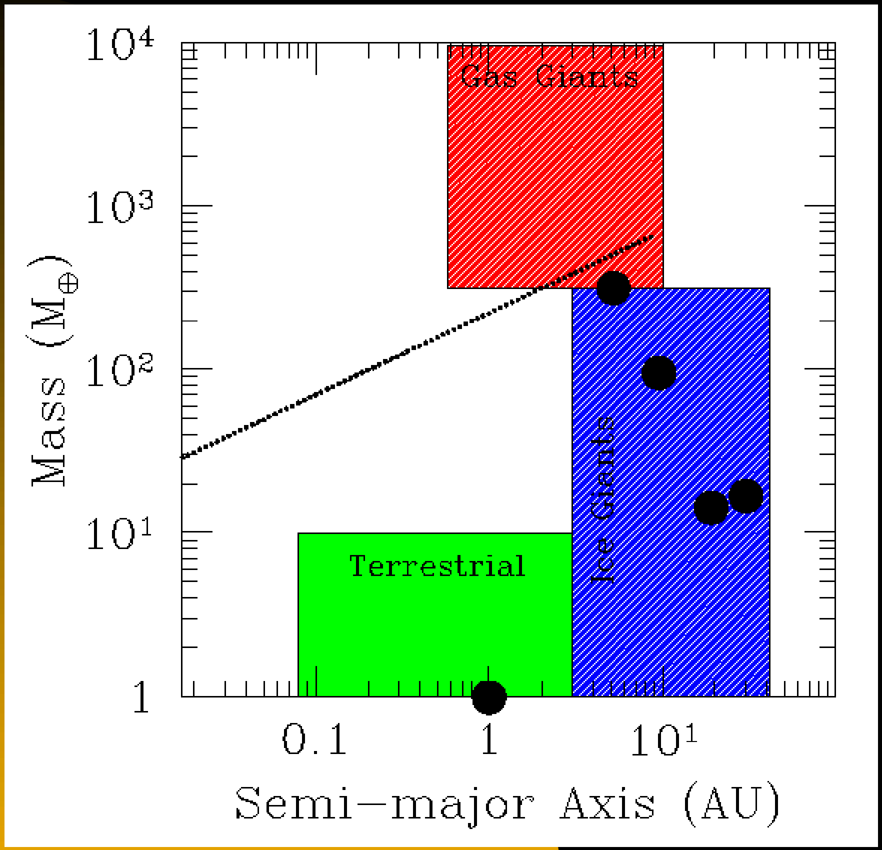
- Core-accretion Model
- Dust → Planetesimals (non G)
- Planetesimals → Protoplanets
- Protoplanets → Gas Giants (Outer Solar System)
- Protoplanets → Terrestrial Planets (Inner Solar System)

Predictions



(Ida & Lin 2004)

- Three types of Planets
  - Terrestrial Planets
  - Gas Giants
  - Ice Giants
- Segregation in Mass/Separation



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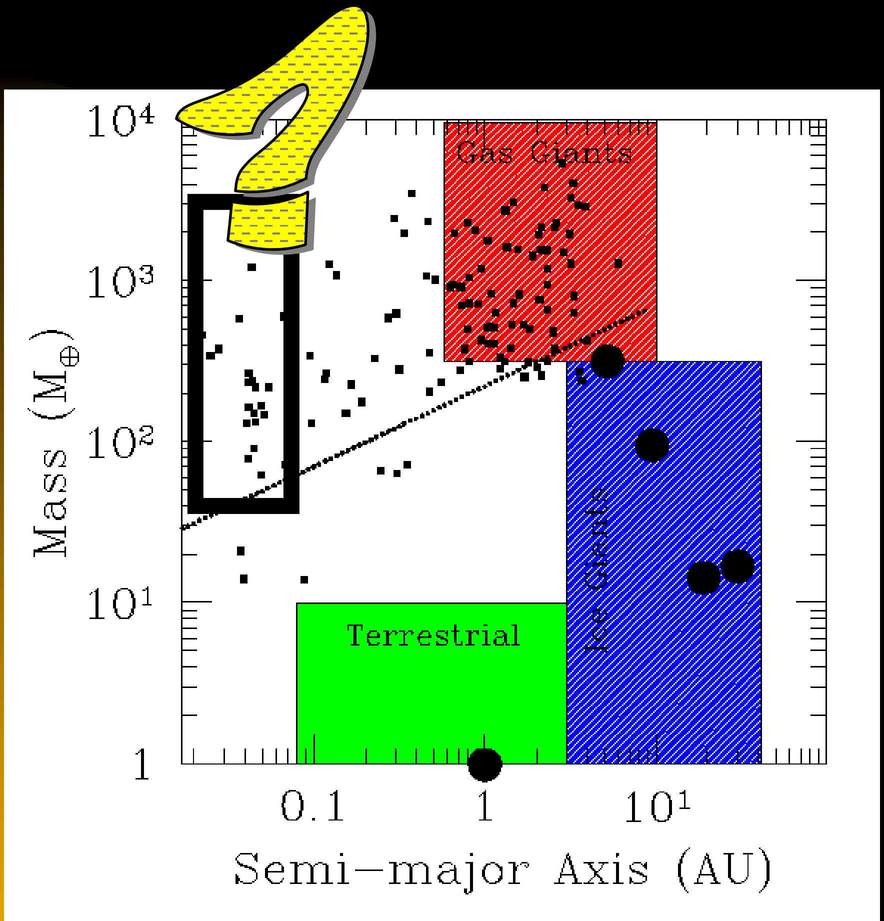
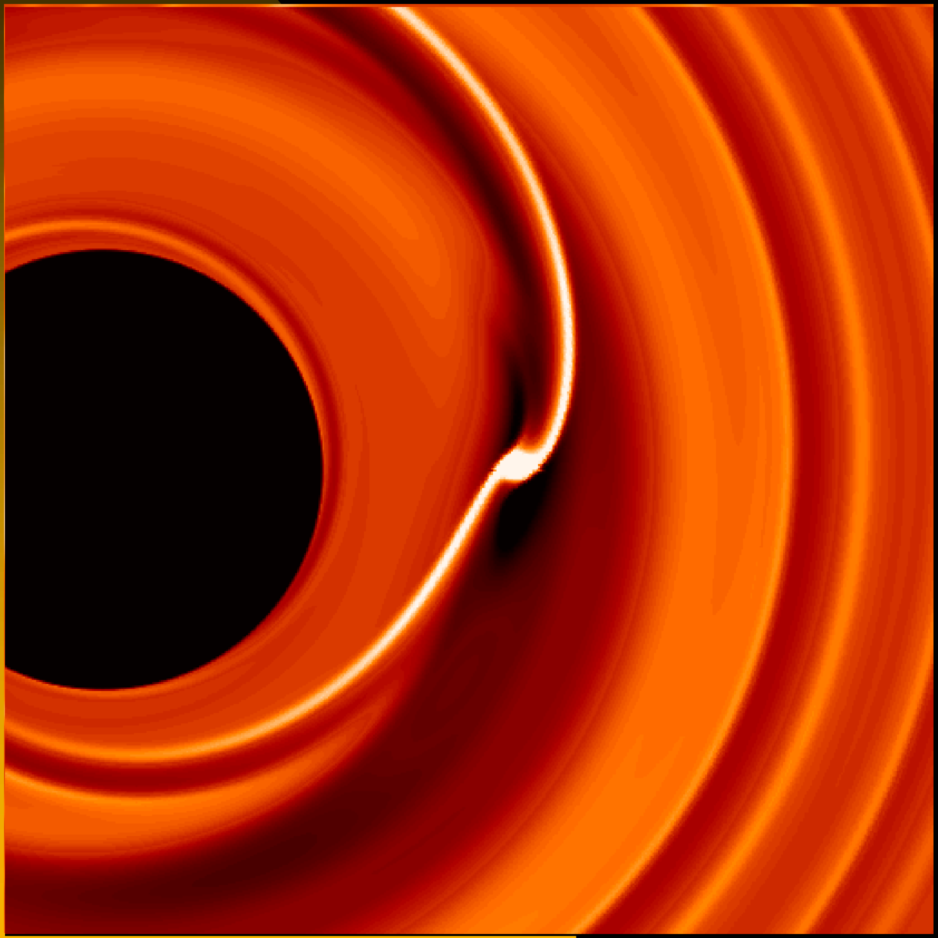


Reality

- Close-In Planets
  → 'Hot Jupiters'
- Cannot have formed *in situ*
- How did they acquire their strange real estate?

Migration



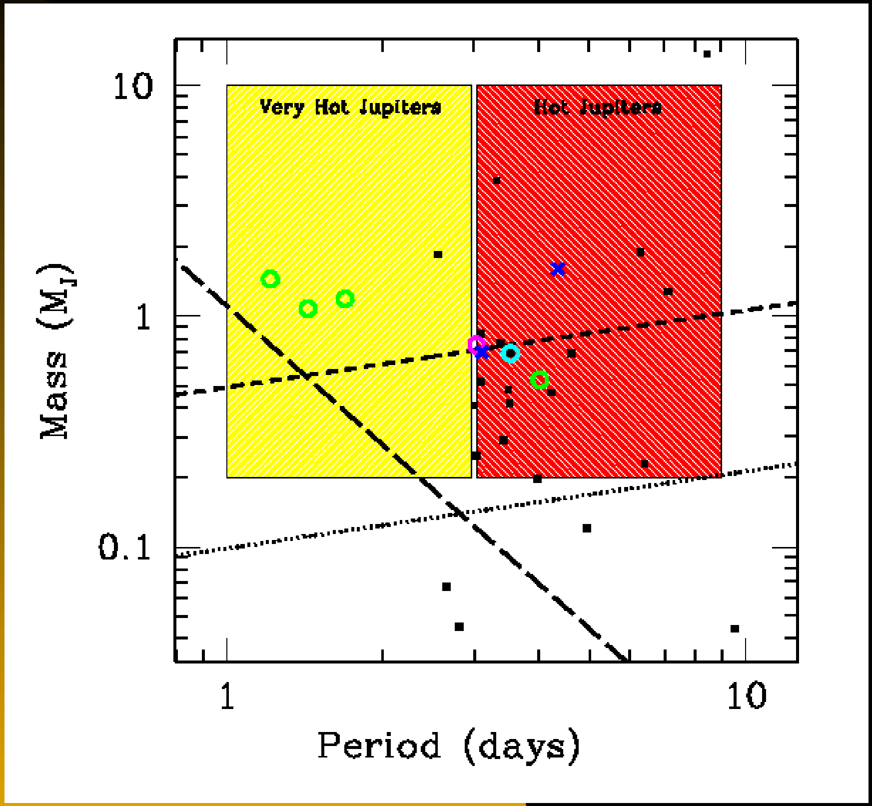
Frederic Masset

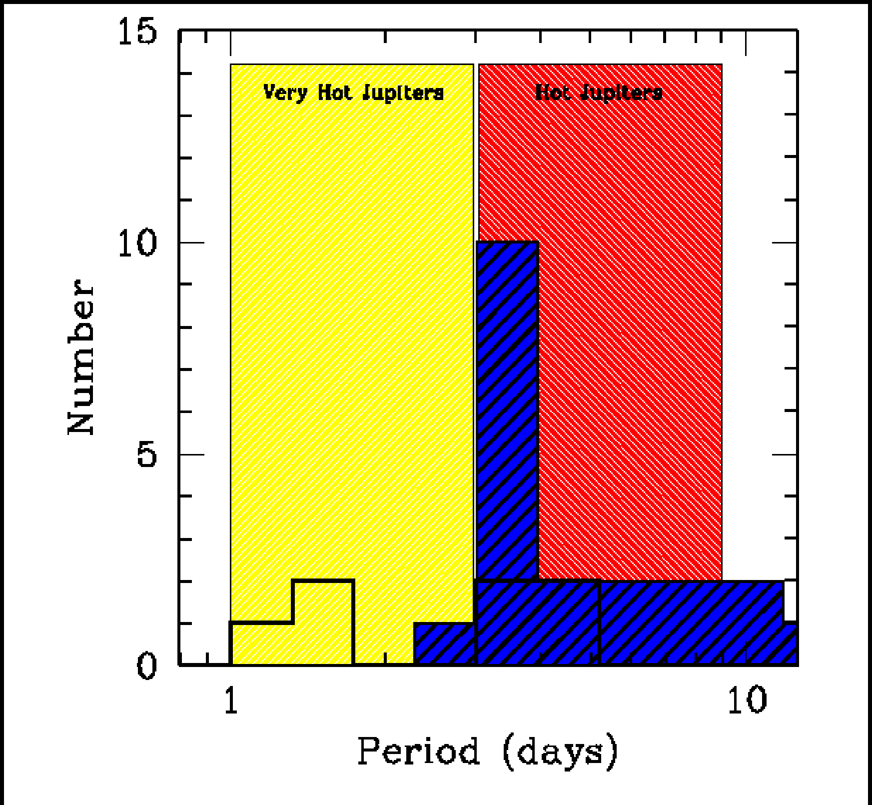
- Four Classes of Migration:
  - Type 0 –
    - Grains
      - Gas Drag
      - PR Drag
      - Yarkovsky Drag
  - Type I –
    - Protoplanets
      - Disk-Planet Torque
  - Type II –
    - Planets – Gap
      - Accretion
  - Type III –
    - Planets – Partial Gap

Open Questions

- What halts planetary migration?
- Which types of migration are most important?
- Migration ←→ Formation
- Migration ←→ Physical Properties

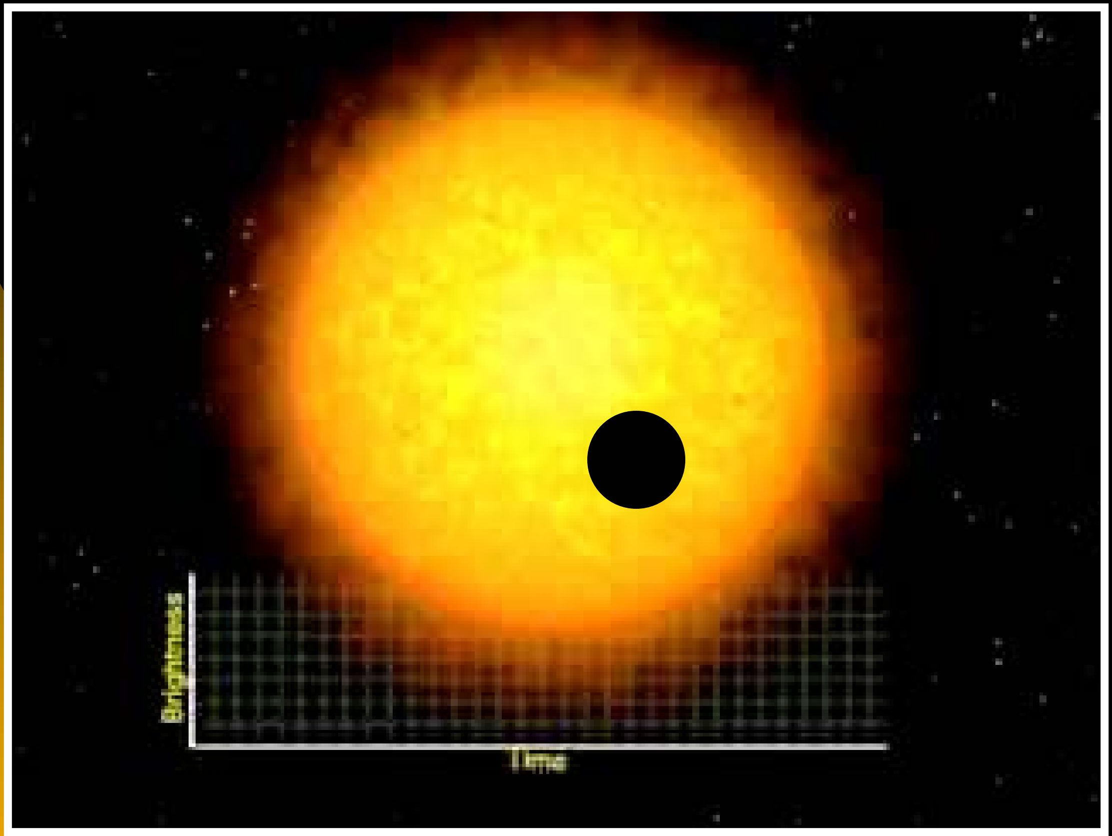
Close-In Planets





- Pile-Up at P ~ 3 days
- Dearth of Planets with P < 3 days
- Lack of High-Mass, Close-In Planets
- ‘Hot Neptunes’ with P < 3 days
- Massive, very close-in ‘Very Hot Neptunes’

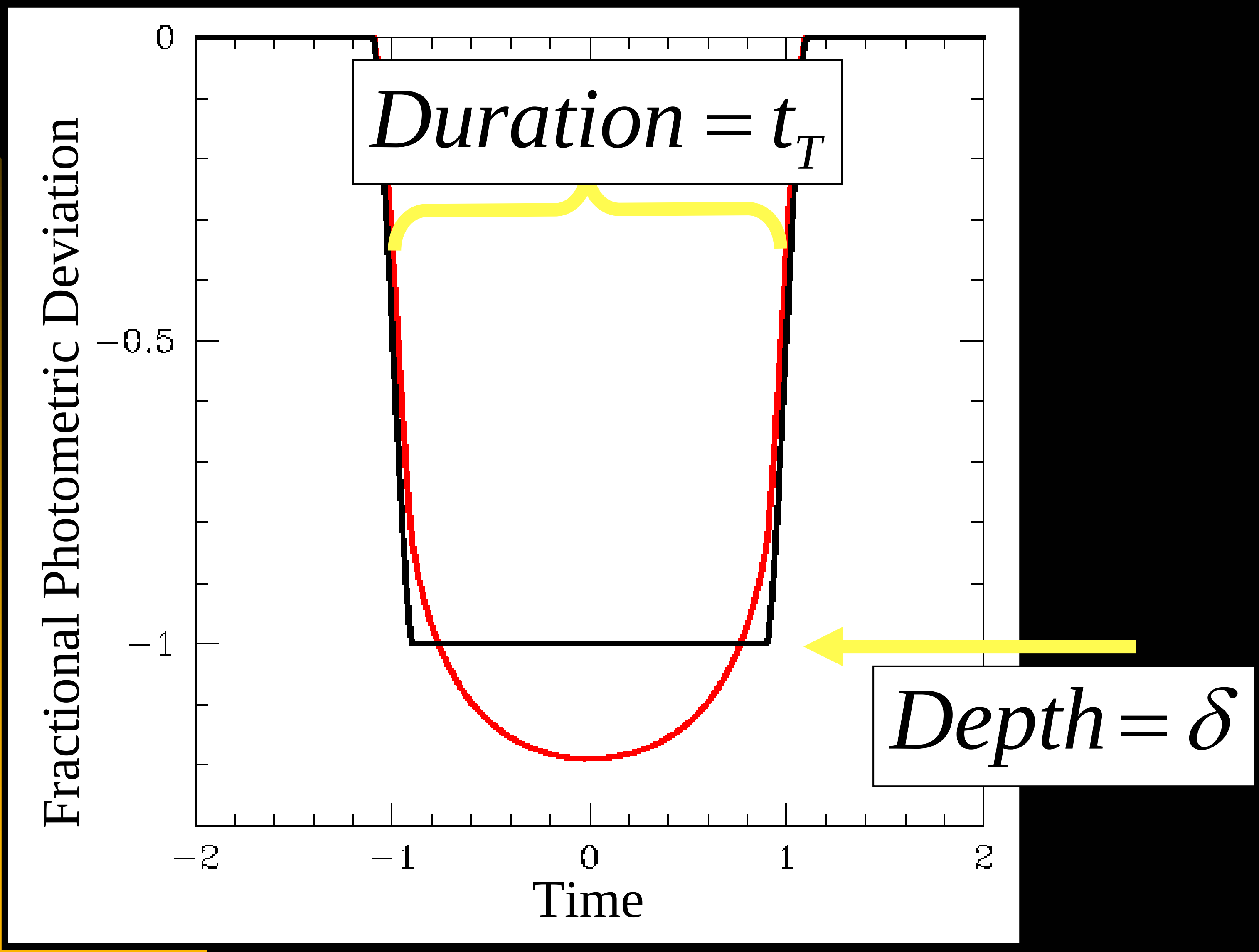
Transits - Observables



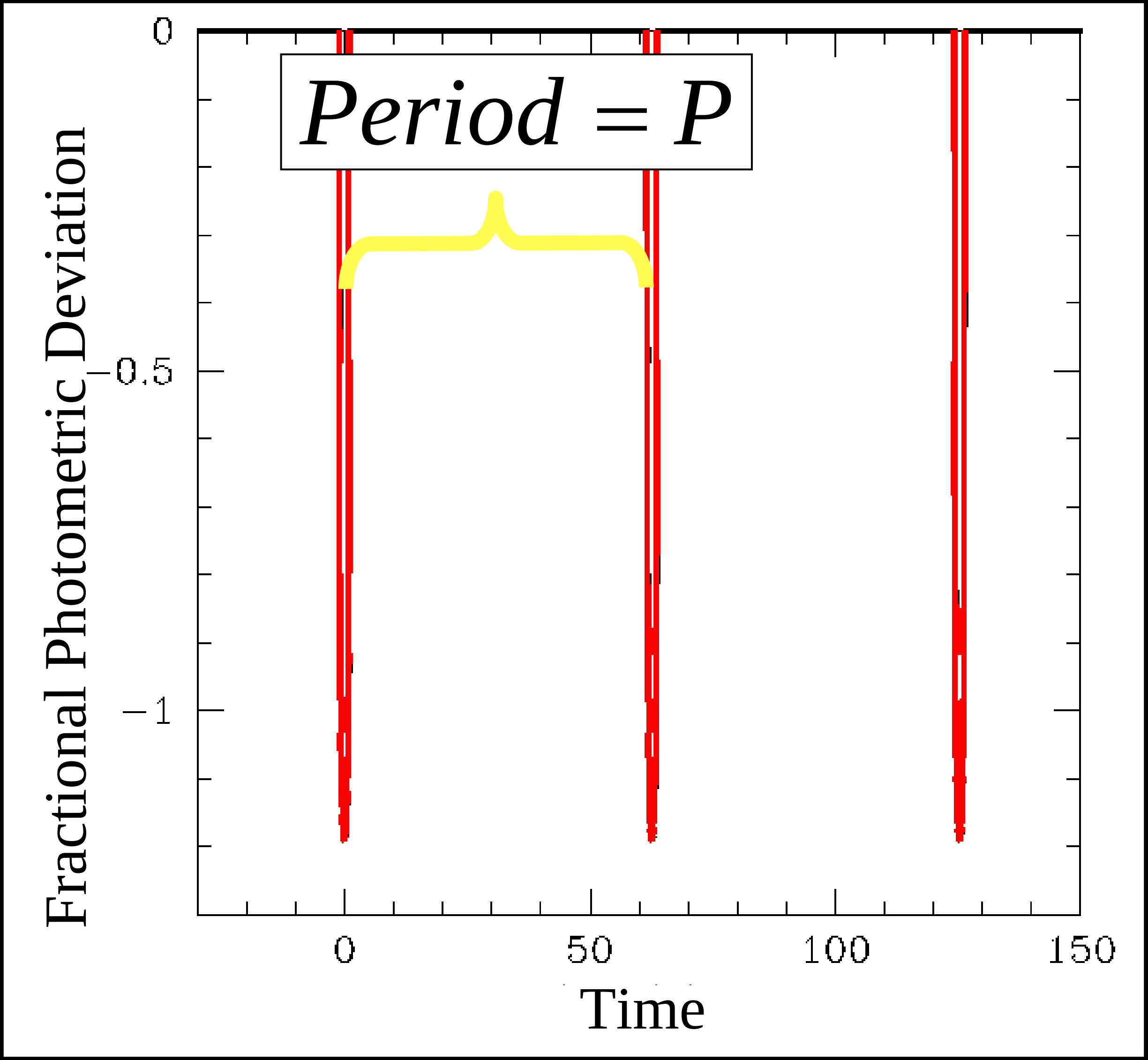
Given a small transit signature, what can we learn?

- Can we tell that it's a planet?
- Can we measure its radius, separation (semi-major axis)?

Transits - Observables



Transits - Observables



Transits – Parameters

Measure → **Infer**

δ, t_T, P → R_P, a

- Depth

$$\delta = \left(\frac{R_p}{R_*}\right)^2$$

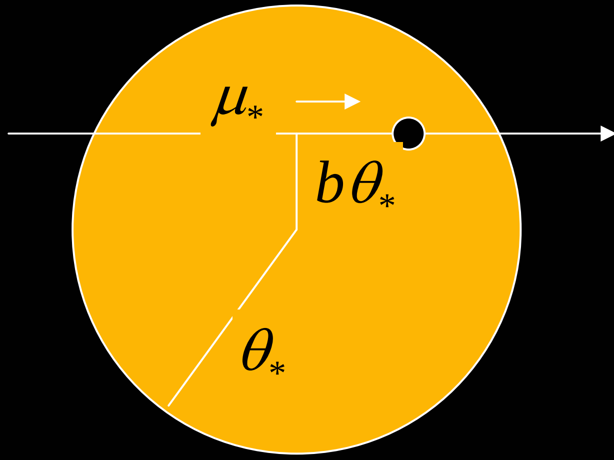
- Duration

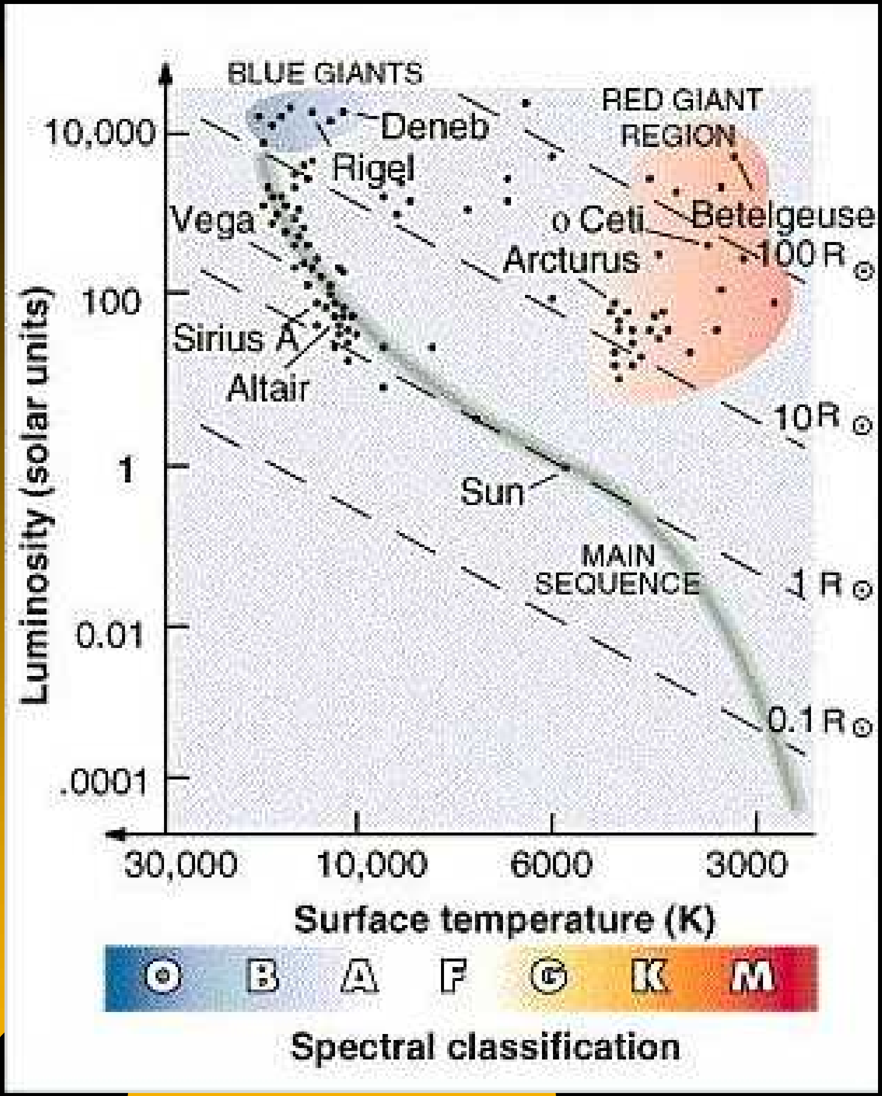
$$t_T \cong 2\frac{\theta_*}{\mu_*}\sqrt{1-b^2}$$

$$= \frac{R_*}{a}\frac{P}{\pi}\sqrt{1-b^2}$$

- Period

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





Stars 101

- Main Sequence
  - H Burning

$$R_* \propto M, L_* \propto M^{7/2}$$

- Giants
  - Exhausted H
  - Burning He or H in shell
- L,T → M,R,density
- Flux, Color → L,T
  - Need d, extinction.
- Spectrum → (T,g)
- Cluster → d,extinction

Transits – Parameters

$$\delta = \left(\frac{R_p}{R_*}\right)^2$$

$$t_T = \frac{R_*}{a}\frac{P}{\pi}\sqrt{1-b}$$

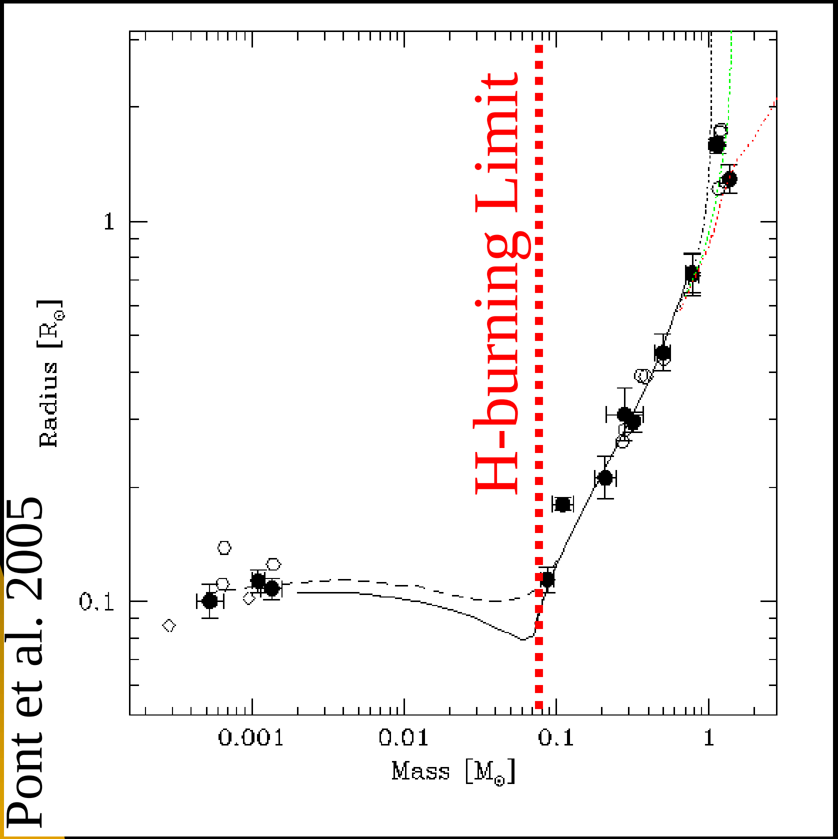
$$P = \frac{2\pi}{\sqrt{GM_*}}a^{3/2}$$

Measure		Infer
δ, t_T, P	→	0
δ, t_T, P, b	→	$\rho_*; (M_*, R_*); R_p, a$
(Accurate LC, M-R Relation)		
$\delta, t_T, P; (T, g)$	→	$(M_*, R_*); R_p, a$
(Spectroscopic Data)		

Transits – RV Follow-Up

Low Mass → Degeneracy Pressure

$$R \propto M^{-1/3}$$



High Mass → Ideal Gas + Ion Pressure

$$R \propto M$$

Need to measure mass of the planet – Radial Velocity

$$K = \frac{28.4\text{m/s}}{(1-e^2)^{1/2}} \left(\frac{M_p \sin i}{M_J} \right) \left(\frac{P}{1yr} \right)^{-1/3} \left(\frac{M_*}{M_{sun}} \right)^{-2/3}$$

Transits – Detection

- What is required to detect a planet orbiting a star via transits?
- What is the probability of detecting a planet around a star?
- How precise to my measurements need to be?
- How many stars to I need to look at?
- How long do I have to look at these stars?

Transits – Detection

$$P = P_T P_Q P_W$$

Gaudi (2000)

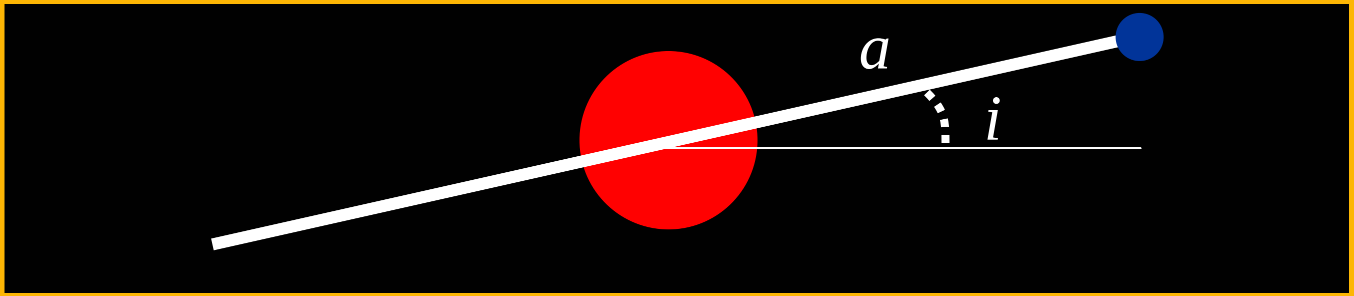
P_T → Probability that Planet Transits

P_Q → Probability of Exceeding S/N Requirement

P_W → Probability of Transit(s) Occurring in Window

Transits – Detection

$$P = P_T P_Q P_W$$

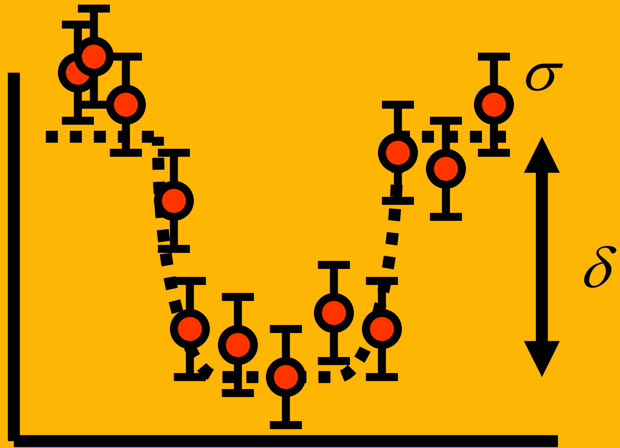


$$P_T = \frac{\int_0^{\cos i_{\min}} d(\cos i)}{\int_0^1 d(\cos i)} = \frac{R_* + R_p}{a} \approx \frac{R_*}{a}$$

Transits – Detection

$$P = P_T P_Q P_W$$

S/N = Signal to Noise Ratio → Must exceed some threshold



$$\frac{S}{N} = N_t^{1/2} \frac{\delta}{\sigma}$$

Transits – Detection

$$P = P_T P_Q P_W$$

$$\delta = \left(\frac{R_p}{R_*}\right)^2 \leq 1\%$$

$$N_t = \frac{R_*}{\pi a} N_{tot}$$

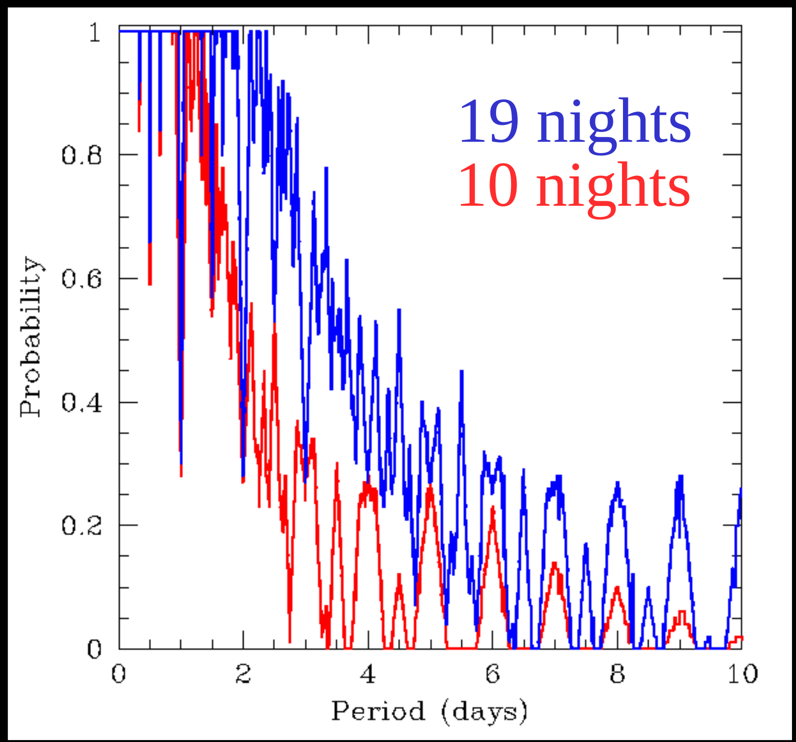
$$\sigma \propto F^{-1/2} \propto L^{-1/2} d$$

$$\frac{S}{N} \propto a^{-1/2} R_p^2 R_*^{-3/2} L_*^{1/2} d^{-1}$$

Transits – Detection

$$P = P_T P_Q P_W$$

"Window" Probability- probability that 2 transits occur during the observation windows.



$$\text{Duty Cycle} = \frac{R_*}{\pi a} \leq 5\%$$

Transits – Detection

$$P = P_T P_Q P_W$$

$P_T \approx 8\%$ (3d<P<11d, logarithmic)

$P_Q \approx 1$

$P_W \approx 20\%$ (3d<P<11d, logarithmic)

$$\left.\begin{aligned} &P_T \approx 8\% \\ &P_Q \approx 1 \\ &P_W \approx 20\% \end{aligned}\right\} P = 1.6\%$$

$$N_{\text{det}} = f N_* P \approx 1 \left(\frac{P}{1.6\%} \right) \left(\frac{N_*}{10^4} \right) \left(\frac{f_{a<0.1AU}}{0.5\%} \right)$$

Transits – Requirements

- Confirmation and Parameter Estimation
  - Accurate Light Curves
  - Follow-up
    - Spectroscopic
    - Radial Velocity
- Detection
  - Many Stars
  - Accurate Photometry
  - Lots of Observing Time
- Why Bother?
  - Possible Using Small Telescopes
  - Distant Targets
  - Large Fields of View + Dense Stellar Fields
  - Rare Objects, Distinct Populations

Transits – 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)

EXPLORE, OGLE
- Clusters

PISCES, EXPORT, STEPSS

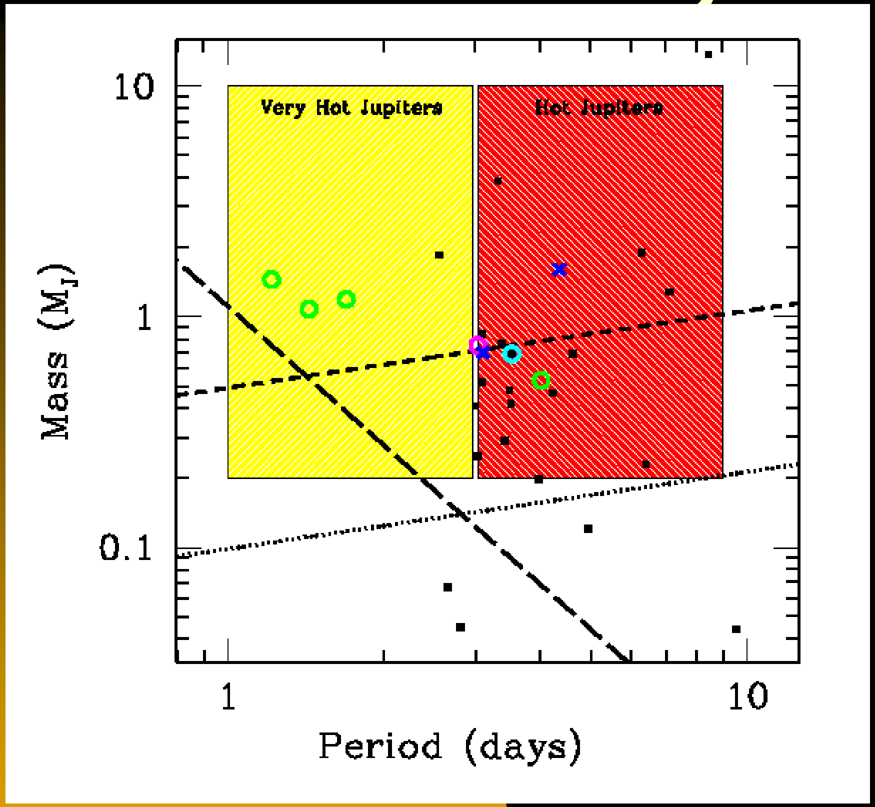
Not Amenable to Follow-up

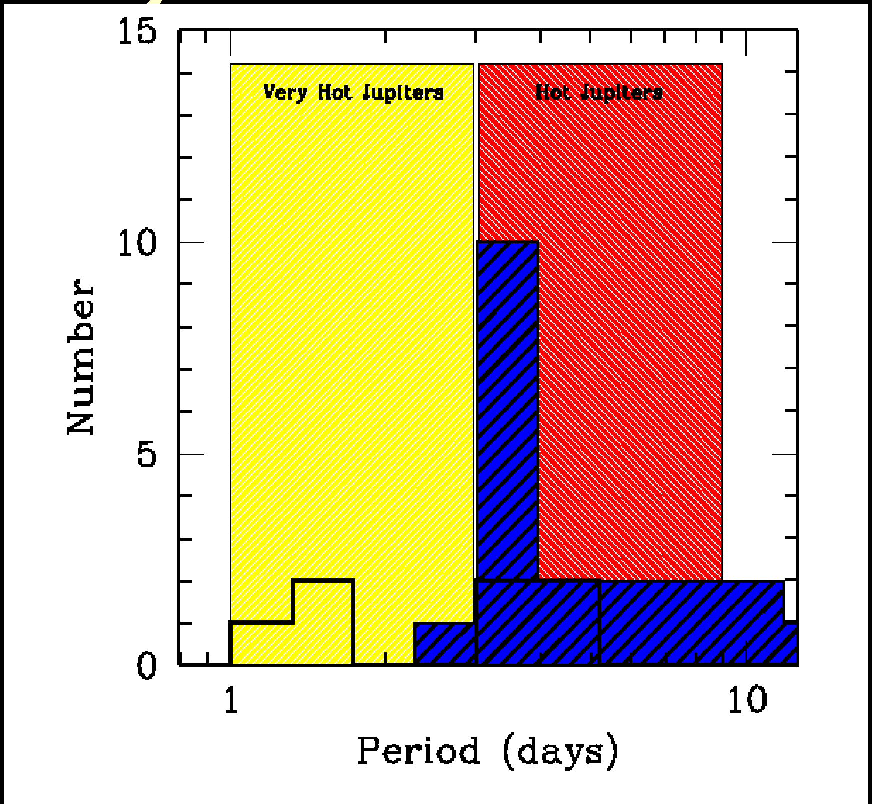
Primaries *too faint* for detailed follow-up

→ Masses and Radii only.

Why? Statistics!

Radial Velocity Surveys





~3000 FGKM Stars

123 Planets Found

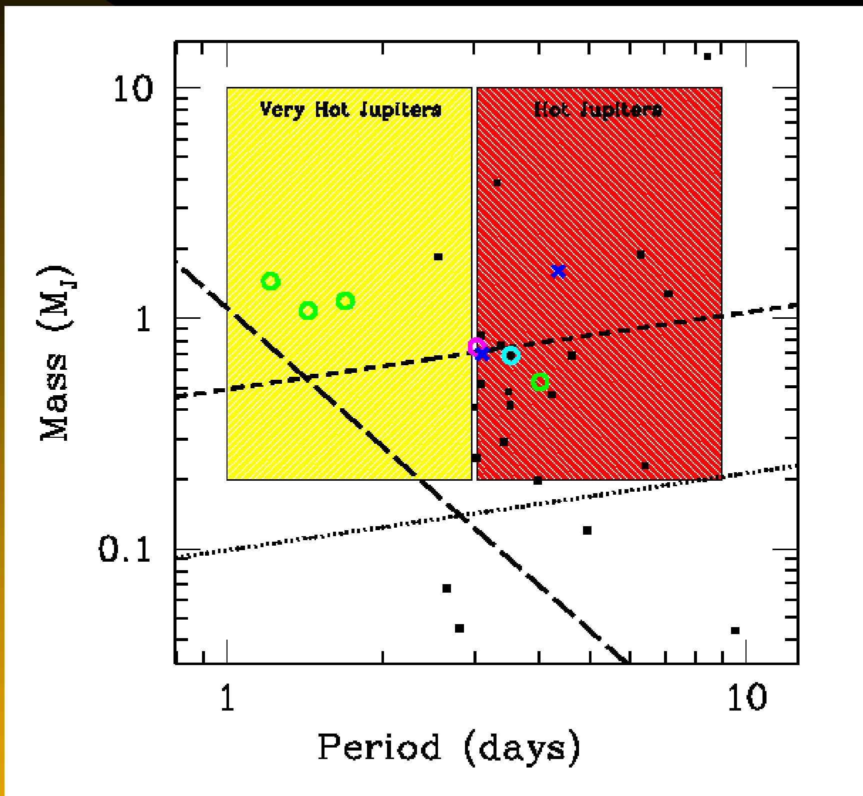
One Planet with P<3: $P = 2.55d$

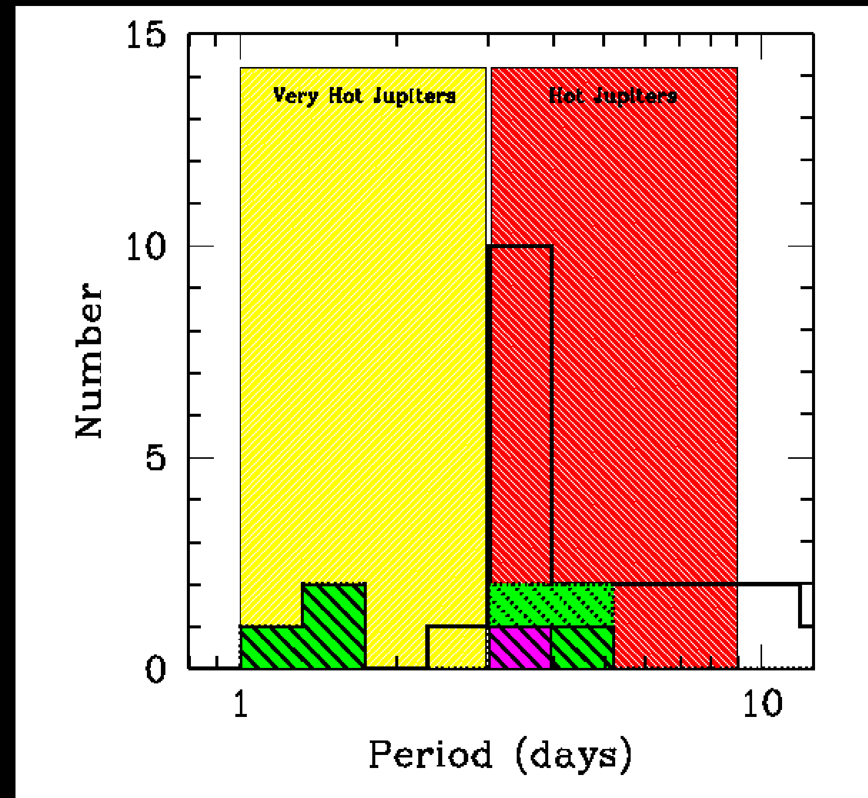
Single Measurement Precision $K = 1\text{m/s} - 3\text{m/s}$

Complete to $K \approx 20\text{m/s}$ → $M_p \sin i \geq 0.2 M_J$ for $P < 9d$

$$K = \frac{28.4\text{m/s}}{(1-e^2)^{1/2}} \left(\frac{M_p \sin i}{M_J} \right) \left(\frac{P}{1yr} \right)^{-1/3} \left(\frac{M_*}{M_{sun}} \right)^{-2/3}$$

Field Surveys - OGLE





~~4~~ 5 Planets Found by OGLE

Discovered Very Hot Jupiters $P \approx 1d$

Radial Velocity vs. Transits

Round 1

Radial Velocity	Transits
Very Hot Jupiters:	**Very Hot Jupiters:**
1	**3**
Hot Jupiters:	**Hot Jupiters:**
15	**1**
$r = 1/15 \approx 0.07$	$r = 3/1 = 3$

Inconsistency?

Very Hot Jupiters not real?

Transit Surveys Bogus?

Different Populations?

Sensitivity of a S/N-Limited Survey

$$N = P_t\, f n V_{\max} = P_t\, f n \frac{\Omega d_{\max}^3}{3}$$

Transit Probability

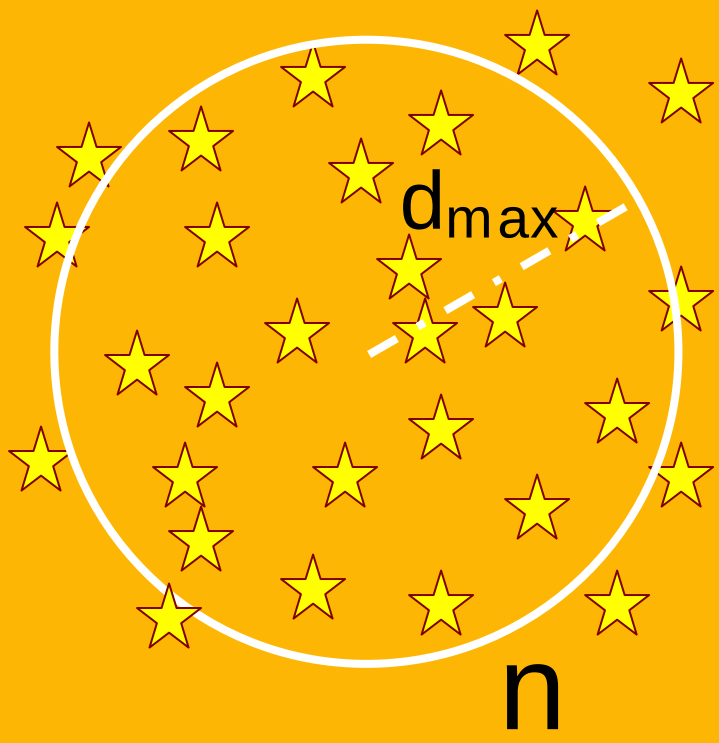
$$P_t = \frac{R_*}{a} \propto P^{-2/3}$$

Signal-to-Noise

$$\frac{S}{N} \propto a^{-1/2} d^{-1} \propto P^{-1/3} d^{-1}$$

At Limiting Signal-to-Noise:

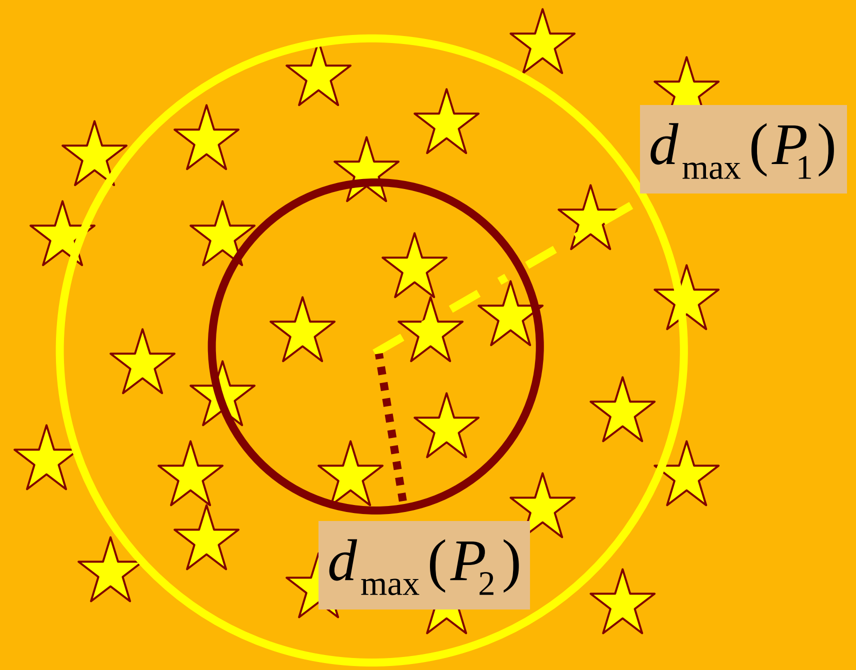
$d_{\max} \propto P^{-1/3}$ **and** $P_t \propto P^{-2/3}$



Sensitivity of a S/N-Limited Survey

$d_{max} \propto P^{-1/3}$ **and** $P_t \propto P^{-2/3}$

$$N \propto P_t f d_{max}^3$$



$$N \propto f(P) P_t d_{max}^3 \propto f(P) P^{-5/3}$$

Transit surveys are ~6 times more sensitive to 1 day period planets than 3 day period planets!

Radial Velocity vs. Transits

Round 2

Radial Velocity	Transits
Very Hot Jupiters: 1	**Very Hot Jupiters:** 3
Hot Jupiters: 15	**Hot Jupiters:** 1
$r = 1/15 \approx 0.07$	$r = 3/(1 \times 6) = 0.5$

Still Inconsistent?

Radial Velocity vs. Transits

Round 3

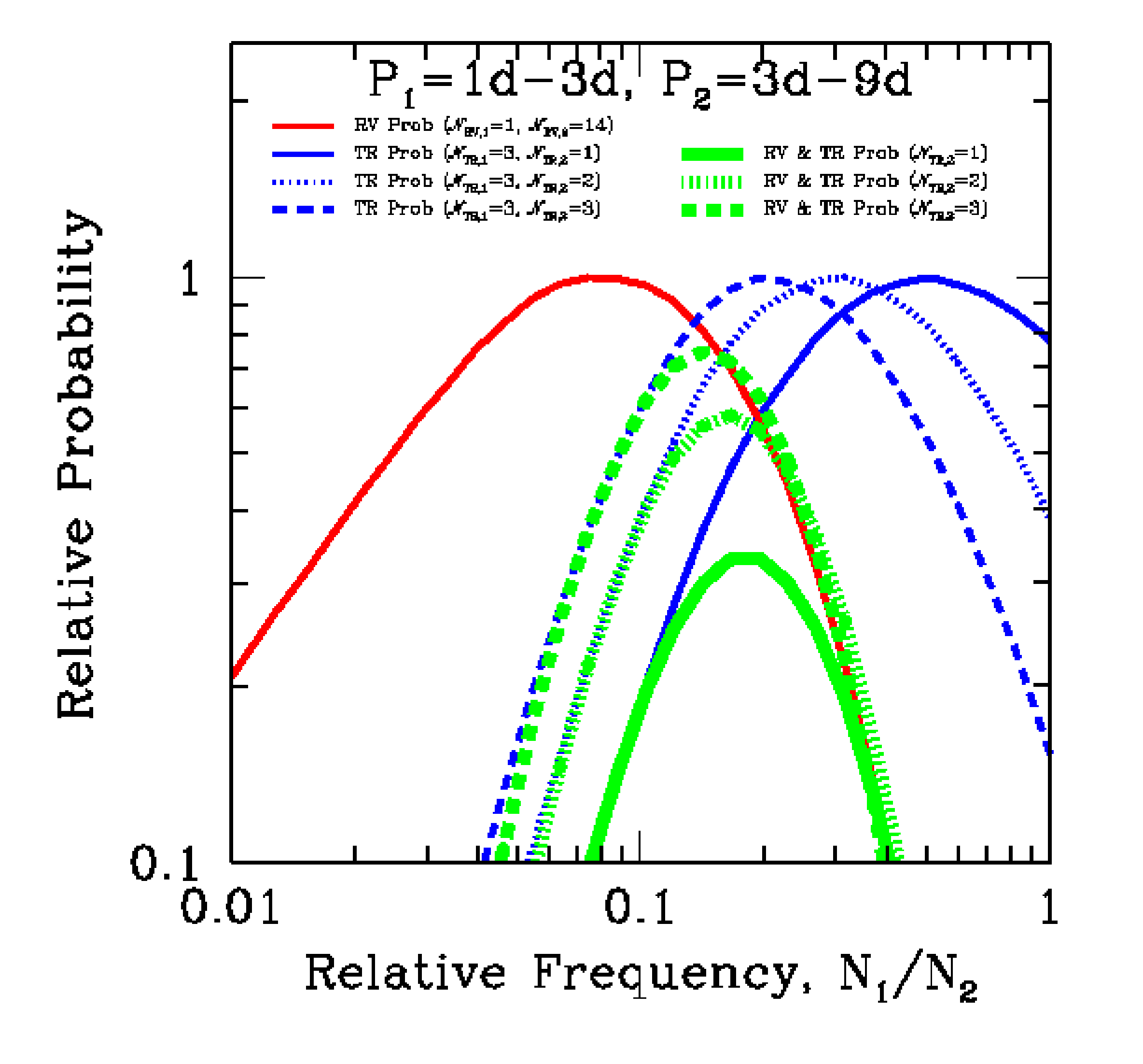
Poisson Distribution

$$P(N \mid M) = \frac{e^{-M} M^{N}}{N!}$$

$$r = 0.07^{+0.10}_{-0.05}$$

$$r = 0.5^{+1.5}_{-0.3}$$

Radial Velocity vs. Transits



Gaudi, Seager, & Mallen-Ornelas 2005

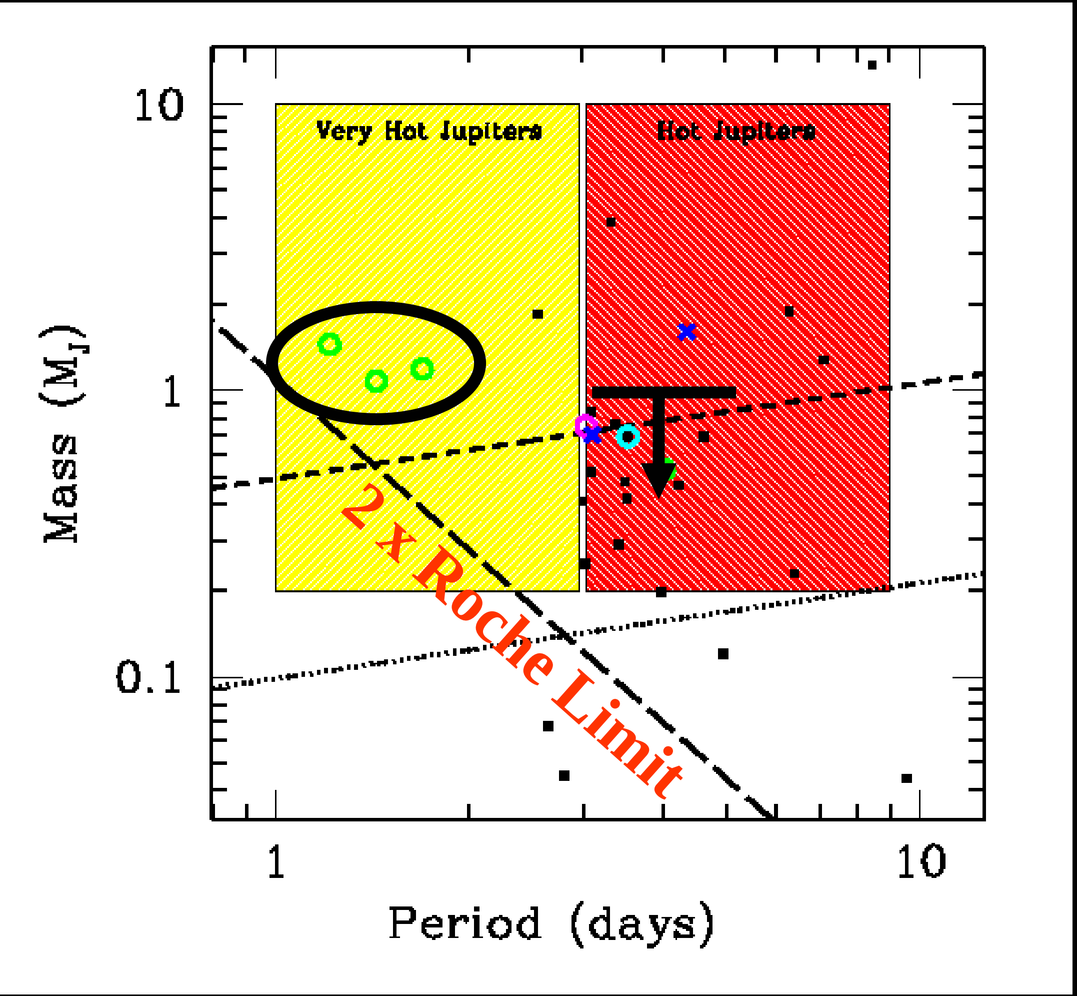
Relative Frequency of VHJ to HJ is ~ 10-20%

Radial Velocity vs. Transits

Additional Biases

Implications

- VHJ ~ transiting HJ
- One in ~500-1000 FGK Stars has a VHJ
- VHJs more massive?
- RV VHJ? (HD 73256b)
- Different (mass-dependent) parking mechanisms?
- Neptune-mass planets? (influenced by companions?)



Searches toward Stellar Systems

Advantages:

- *Primaries have common properties*
  Explore the effects of:
  - Stellar Density
  - Age
  - Metallicity [Fe/H]>0
- *Primaries have known properties*
  Statistics easy.
  Avoid many false positives.
- *Compact systems*
  Point-and-shoot

Disadvantages:

- *Relatively Faint Stars*
  Follow-up difficult
- *Small Number of Stars*
  Difficult to probe f<5%

Requirements:

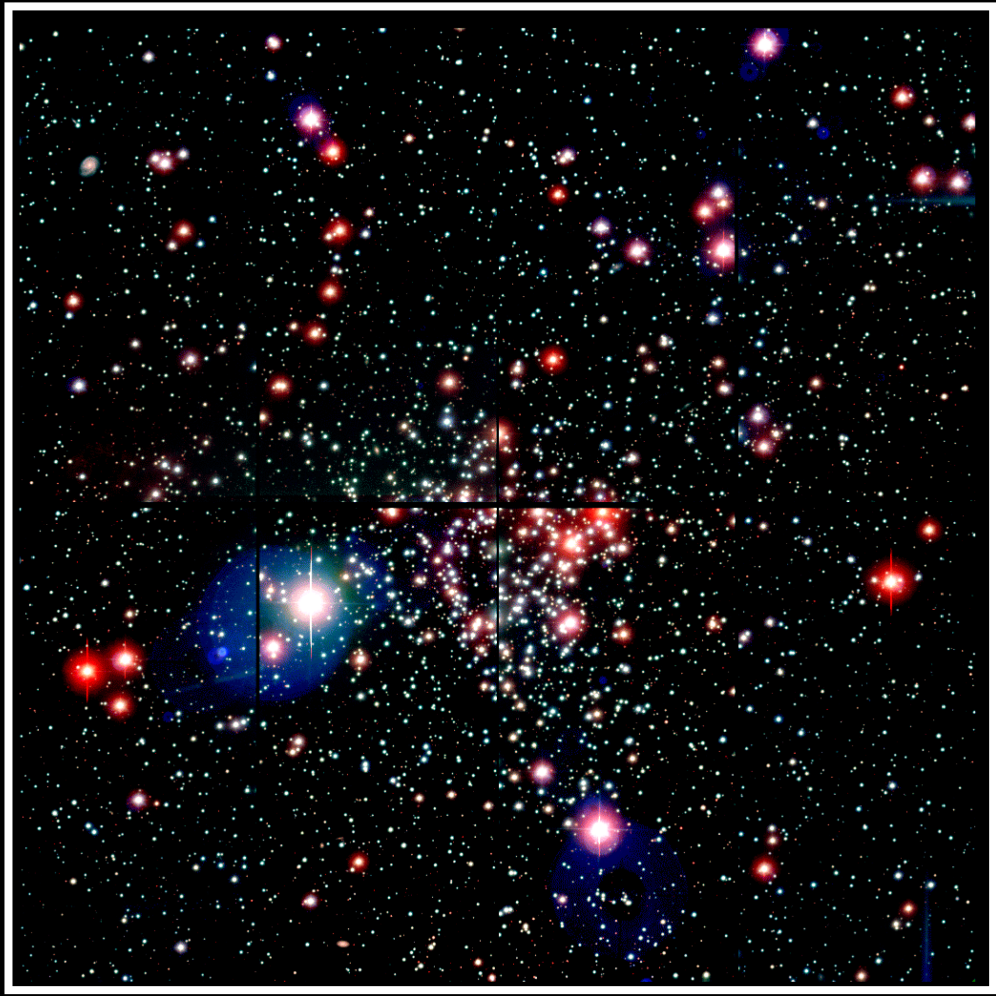
- Many (20) Consecutive Nights
- Relatively Large FOV
- Modest Aperture

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

(Open Clusters)

Setup
- MDM 1.3m & 2.4m
- 8192x8192 4x2 Mosaic CCD
- 25x25 arcmin^2
- 0.18"/pixel

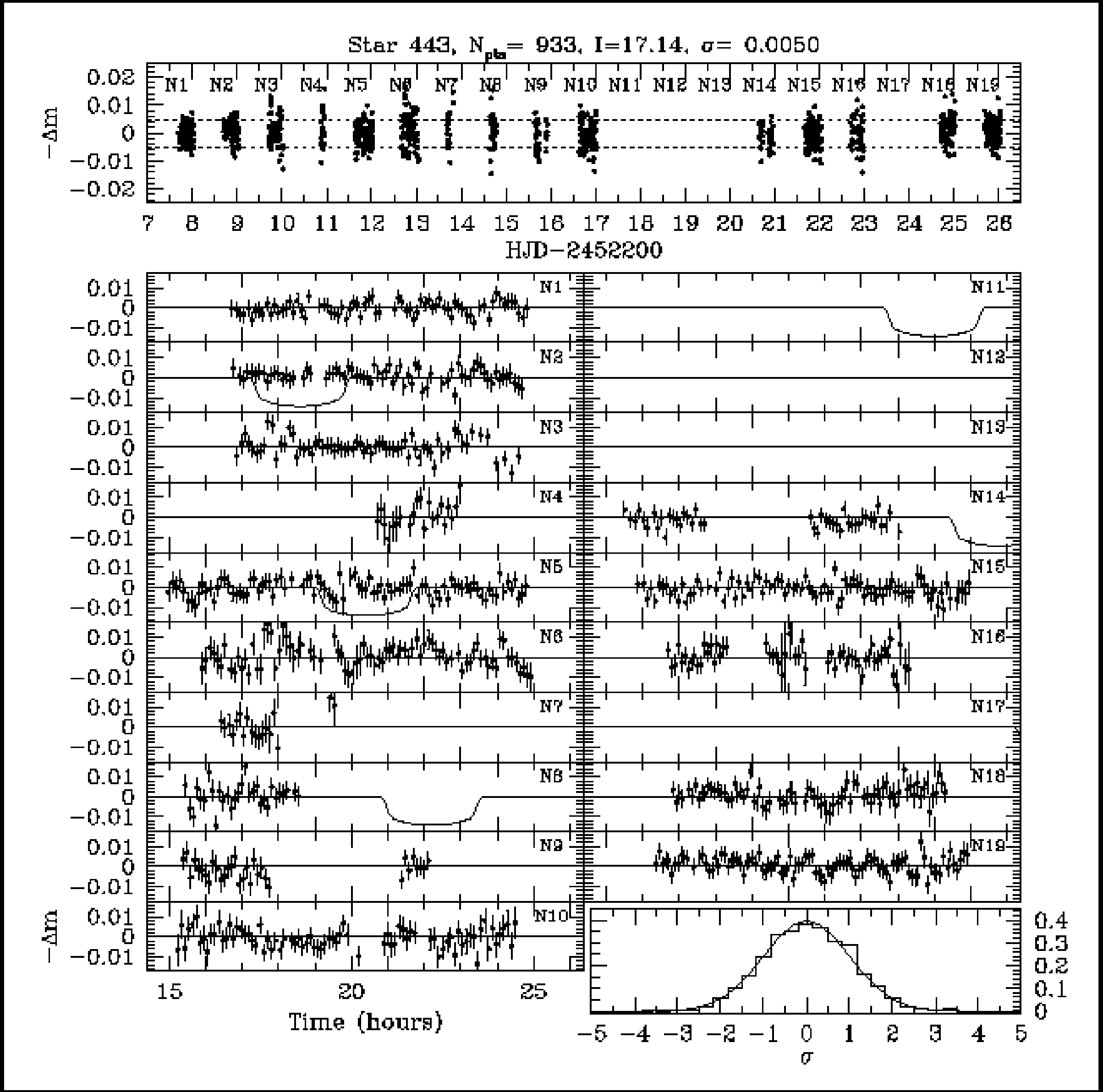
NGC1245
- 19 nights
- 1 Gyr
- [Fe/H]~0.0



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

Searches toward Stellar Systems

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



Burke et al., in prep

Searches toward Stellar Systems

- Sensitive to Jupiters for G0-M0 primaries

~1000 cluster members

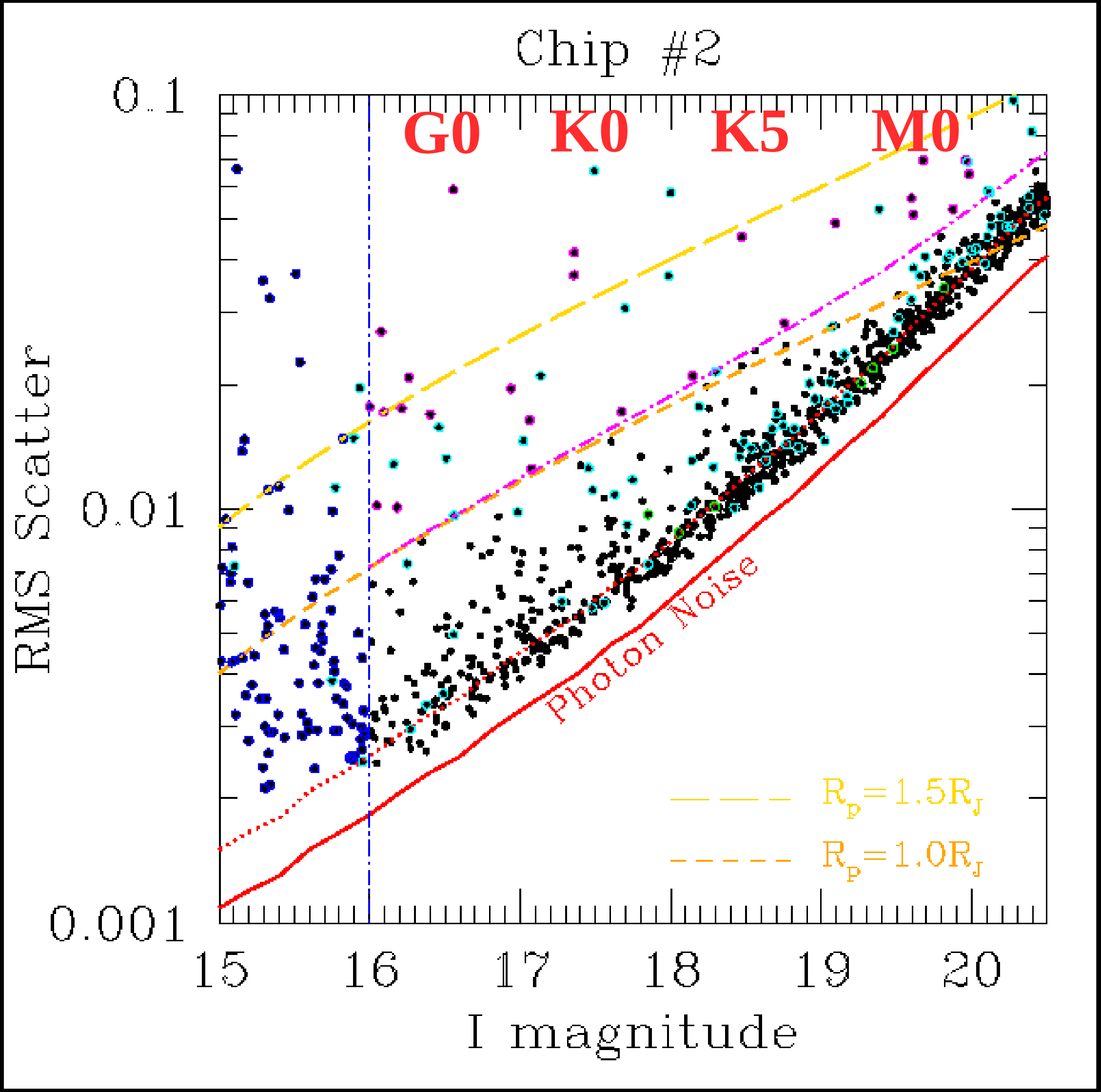
$$\frac{S}{N} \propto a^{-1/2} R_p^2 R_*^{-3/2} L_*^{1/2} d^{-1}$$

Main-Sequence Stars

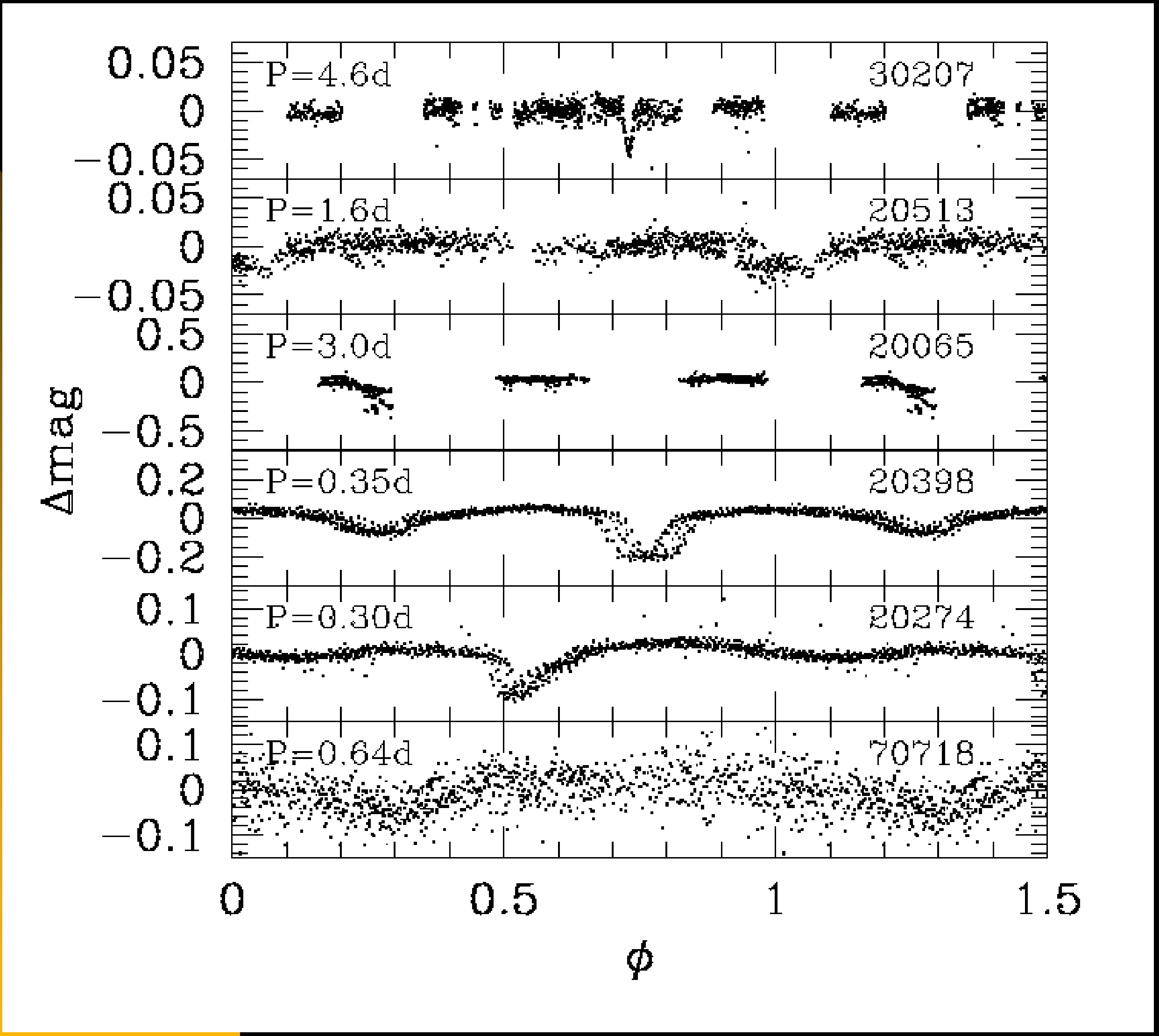
$$R_* \propto M \,, L_* \propto M^{7/2}$$

At Fixed a, R_p, d

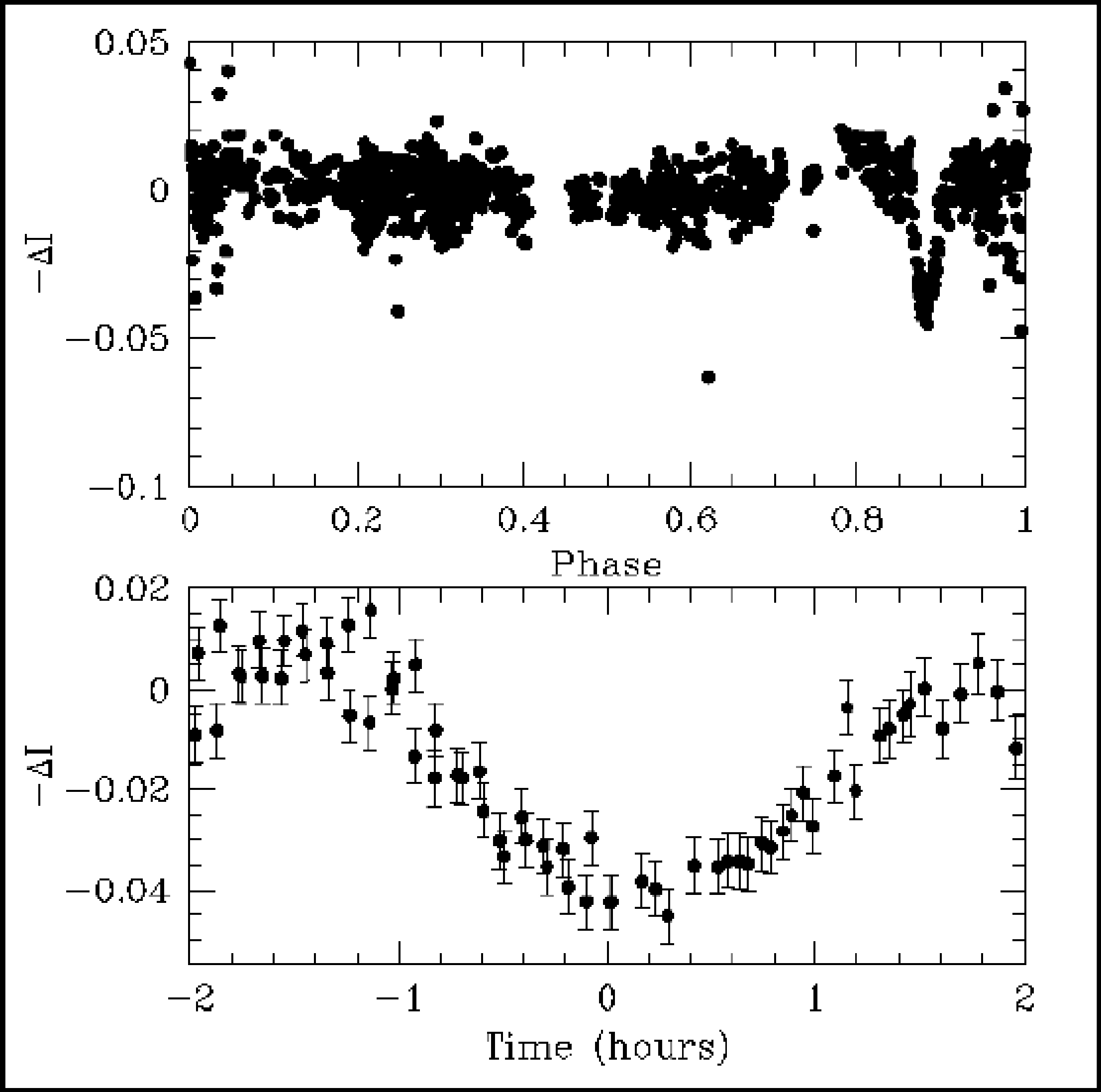
$$\frac{S}{N} \propto R_*^{-3/2} L_*^{1/2} \propto M_*^{1/4}$$



Searches toward Stellar Systems



Searches toward Stellar Systems

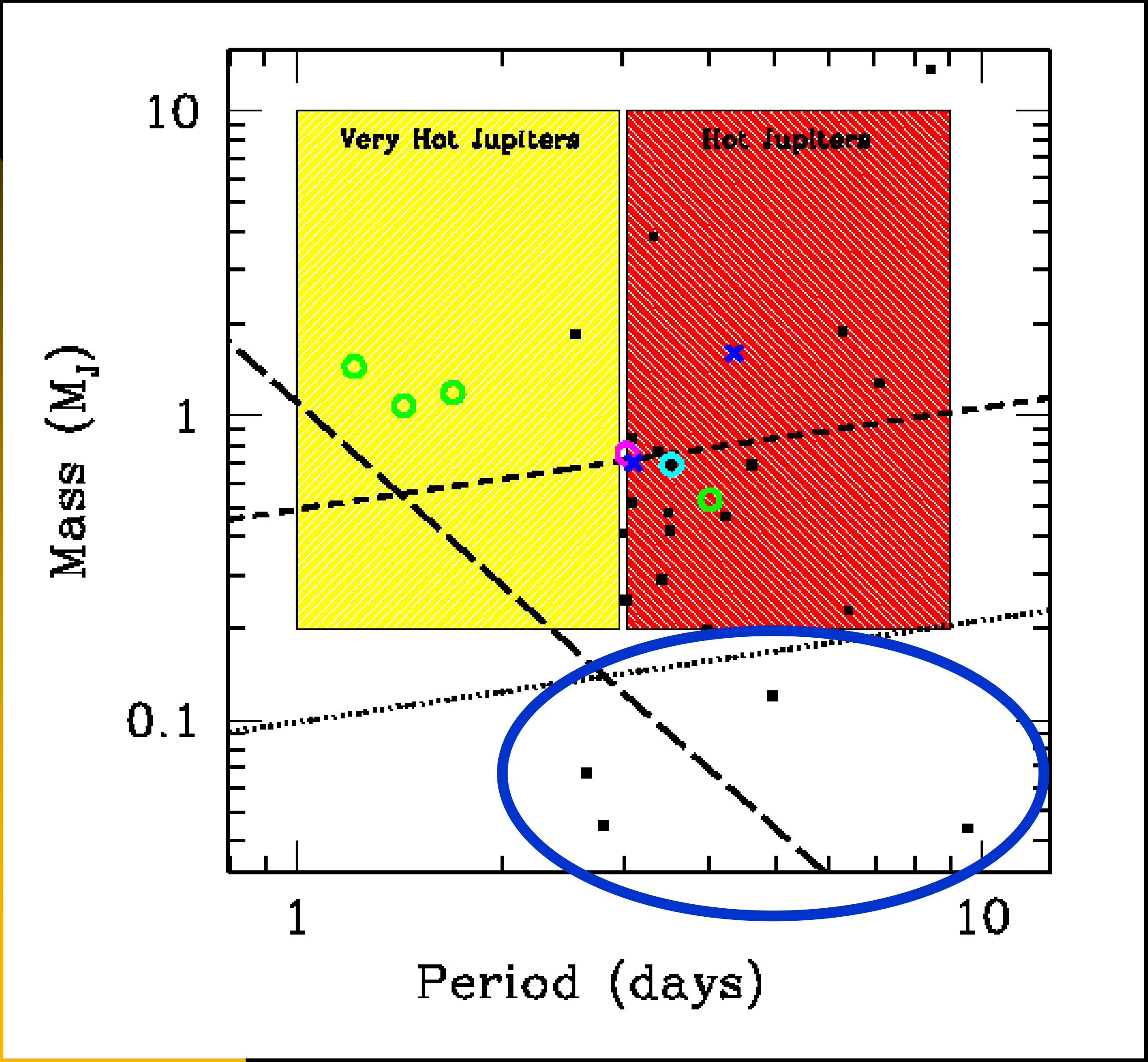


Period = 2.77 days, Depth ~ 4% ⟹ Grazing Binary

Searches toward Stellar Systems

- NGC 1245
  - Efficiency Calculation Underway
  - <5% VHJ, <30% HJ.
- NGC 2099
  - 37 nights
  - ~3000 Stars
  - Improved Statistics
- NGC 2682 (M67)
  - 20 nights
  - ~2000 Stars
- Future
  - 1-2 More Clusters

Future Prospects – Hot Neptunes?



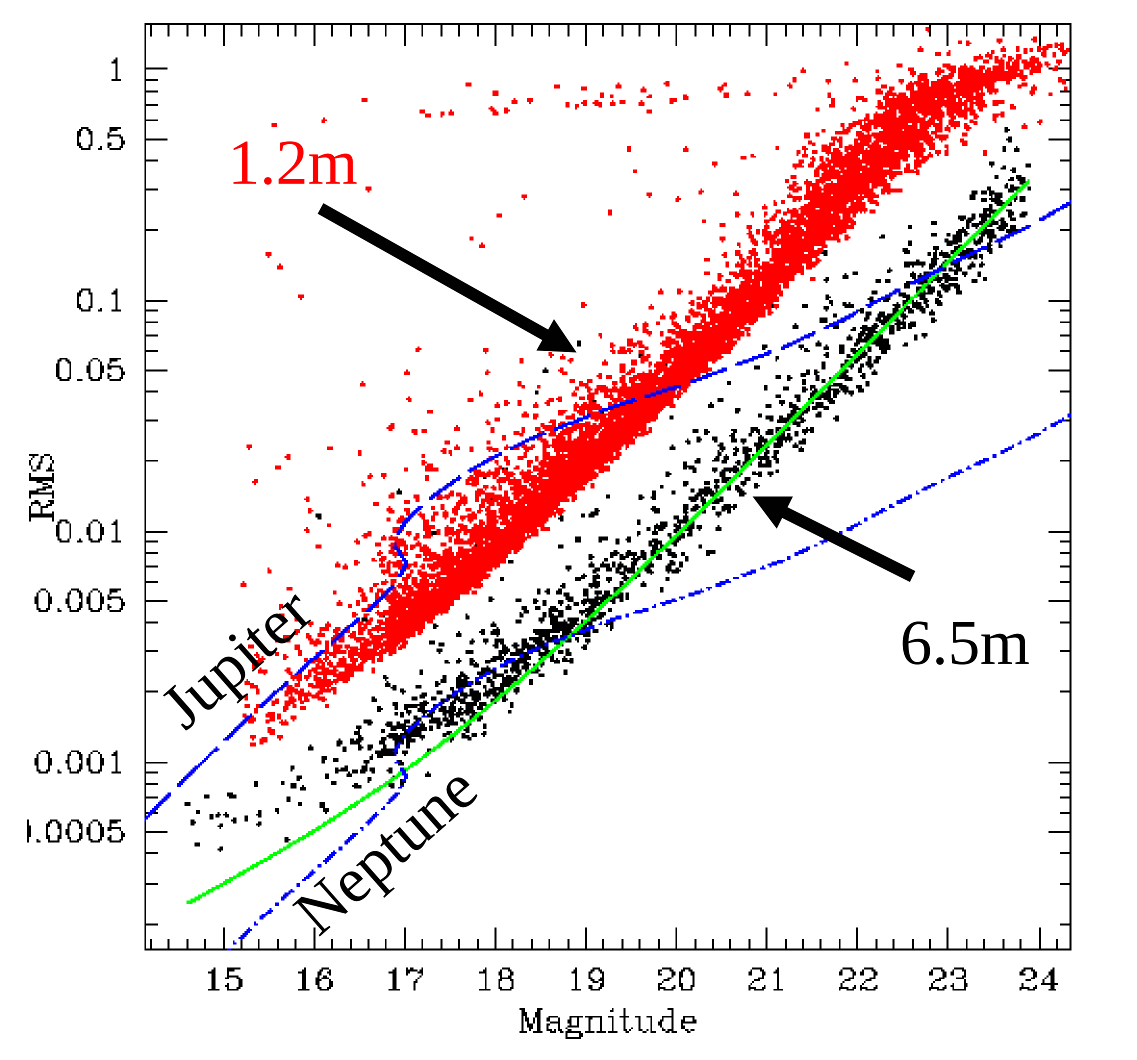
Future Prospects – Hot Neptunes?

- Hot Neptunes

$$R_N \approx 0.04 R_{Sun}$$
$$\delta \approx 2\times10^{-3}$$

  - <0.1% Photometry

- Large Telescopes
  - MMT 6.5m
  - NGC 6791
  - Better than 0.1%



Joel Hartman, Kris Stanek, Matt Holman, S.G

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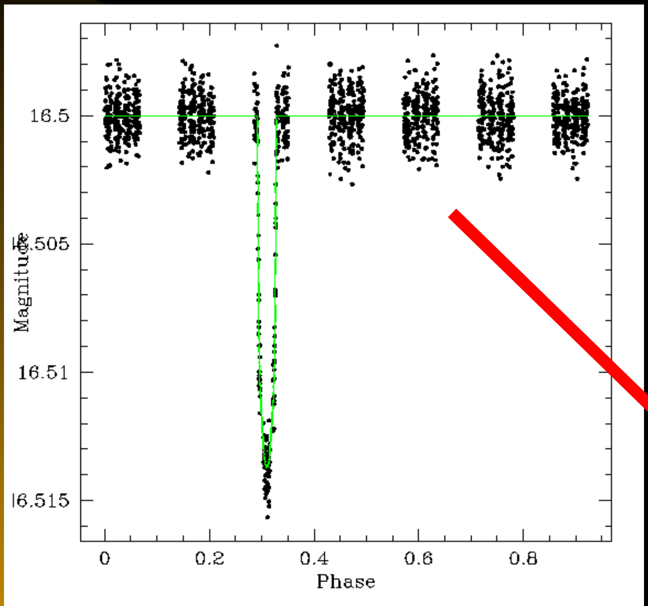
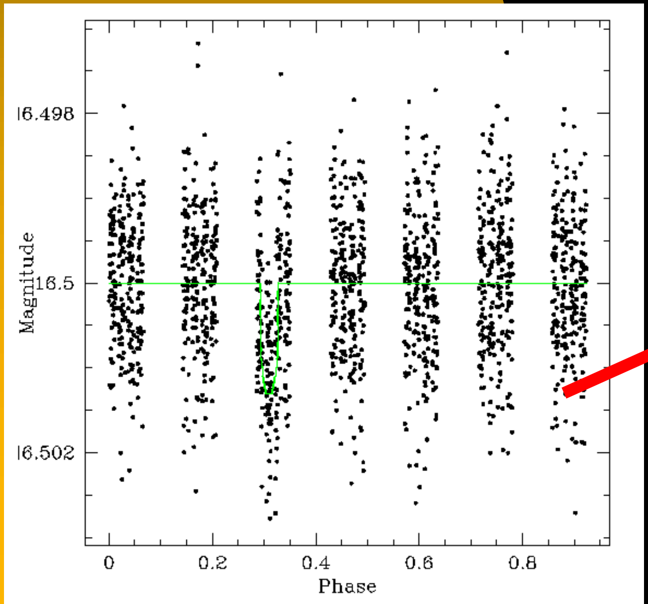
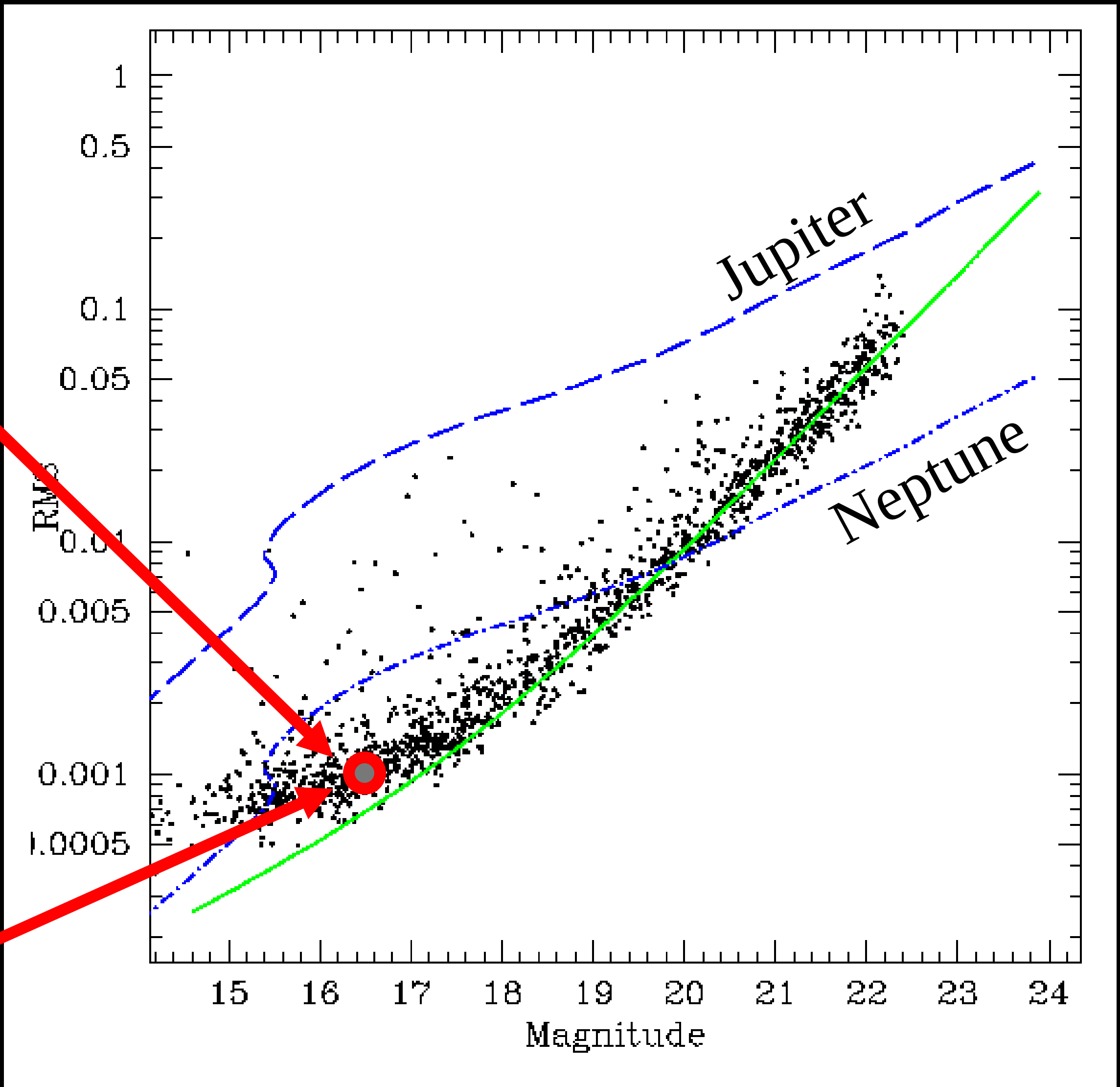


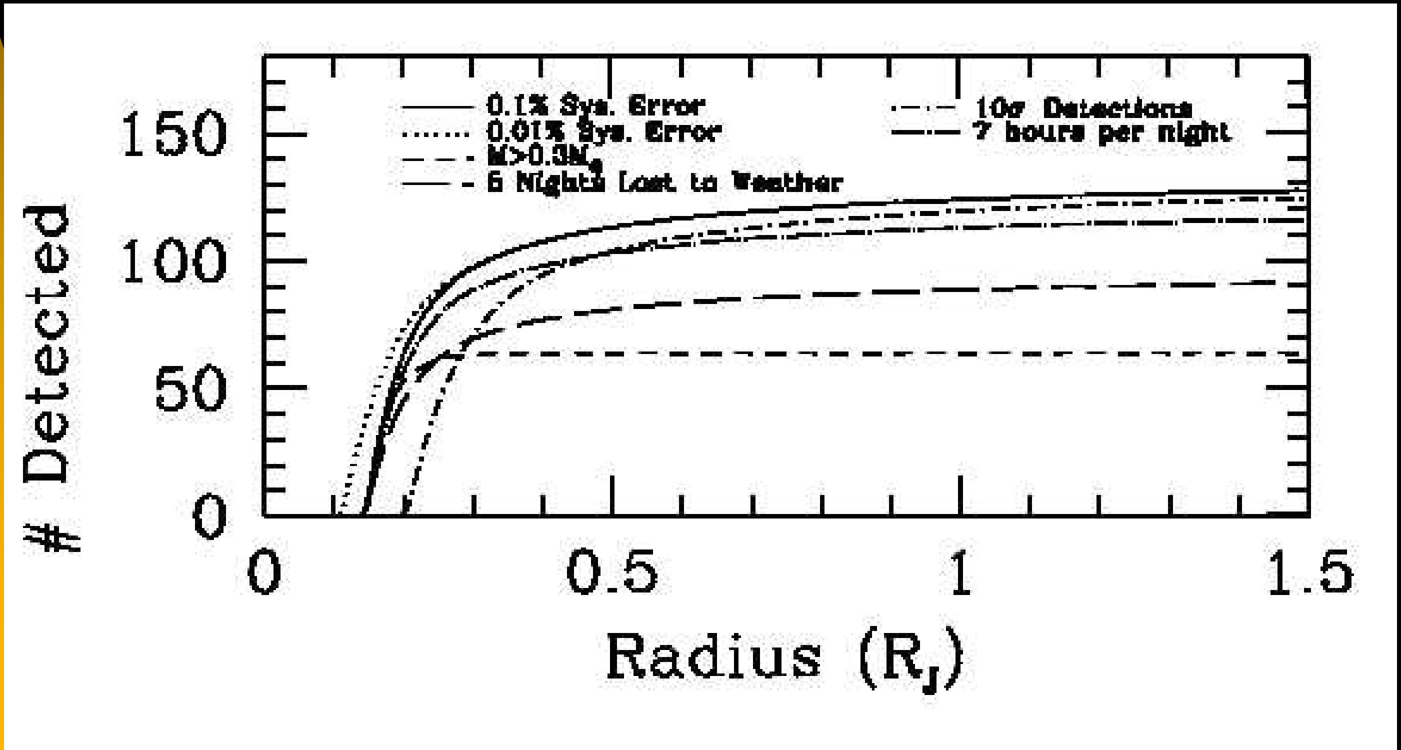




Joel Hartman, Kris Stanek, Matt Holman, S.G

Future Prospects – Hot Neptunes?

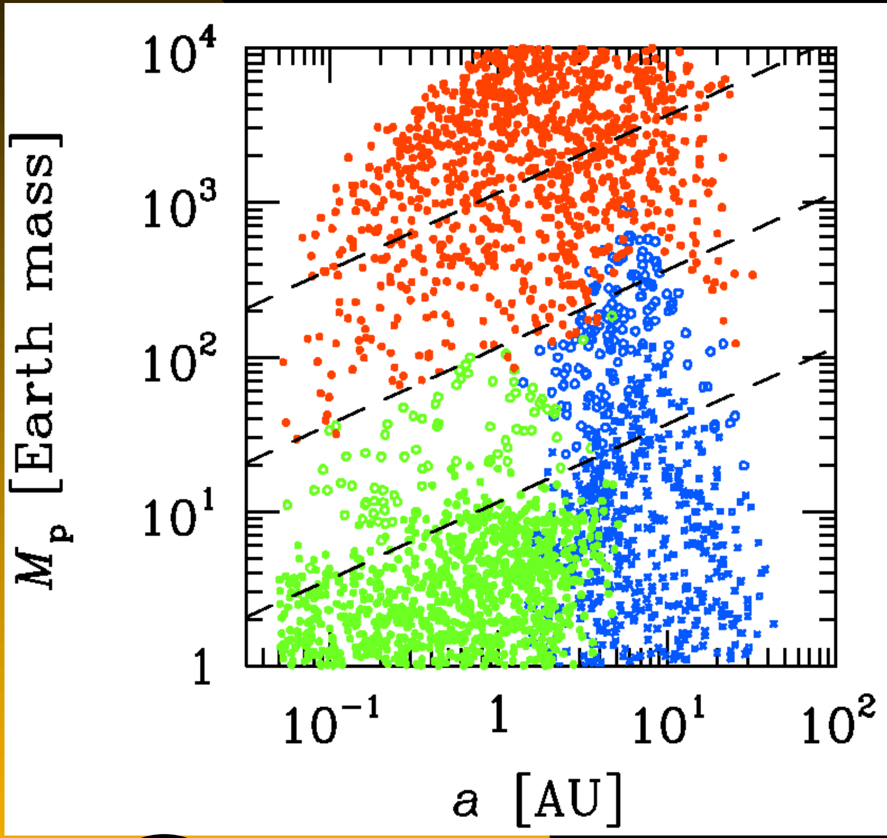
- Very Hot Neptune Search
  - Cluster Selection
  - ~20 Nights on MMT (or 6m Telescope)
  - Rising Mass Function?

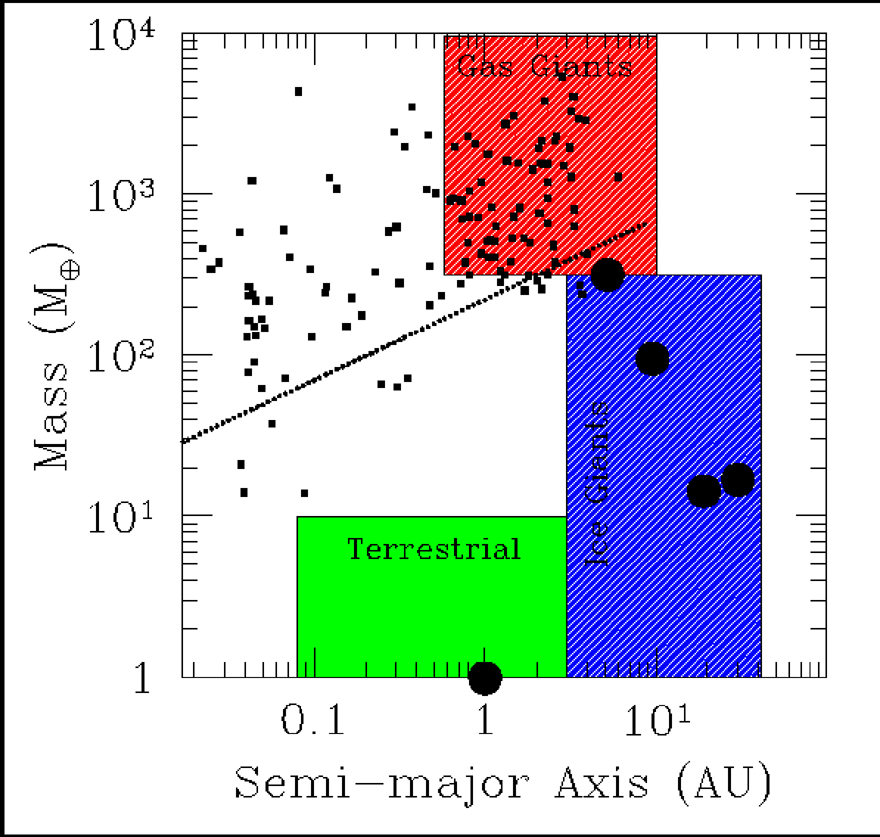


Conclusions:

- Transiting planets can tell us about migration → planet formation.
- Consideration of transit basics reveals:
  - Require accurate photometry
  - Follow-up for characterization & confirmation
  - Require ~10,000 stars
  - Long observational campaigns
- Understanding Field Surveys
  - RV and TR Surveys Consistent
  - VHJ are uncommon
- Hot Neptunes within reach.

Future Prospects – Extrasolar Earths?





(Ida & Lin 2004)

Future Prospects – Extrasolar Earths?

Radial Velocity: *Next Generation Survey?*

• 1 m/s limit?

- hard

+ ground based, flexible,cheap, unlimited observing time, nearby stars (TPF)

Astrometry: *SIM*

• 1 μas limit

- space-based, very expensive, hard to confirm

+ flexible, nearby stars (TPF)

Transits: *Kepler*

- spaced-based, expensive, distant stars, very difficult to confirm

+habitable, simple

Microlensing: *MPF, Ground Based?*

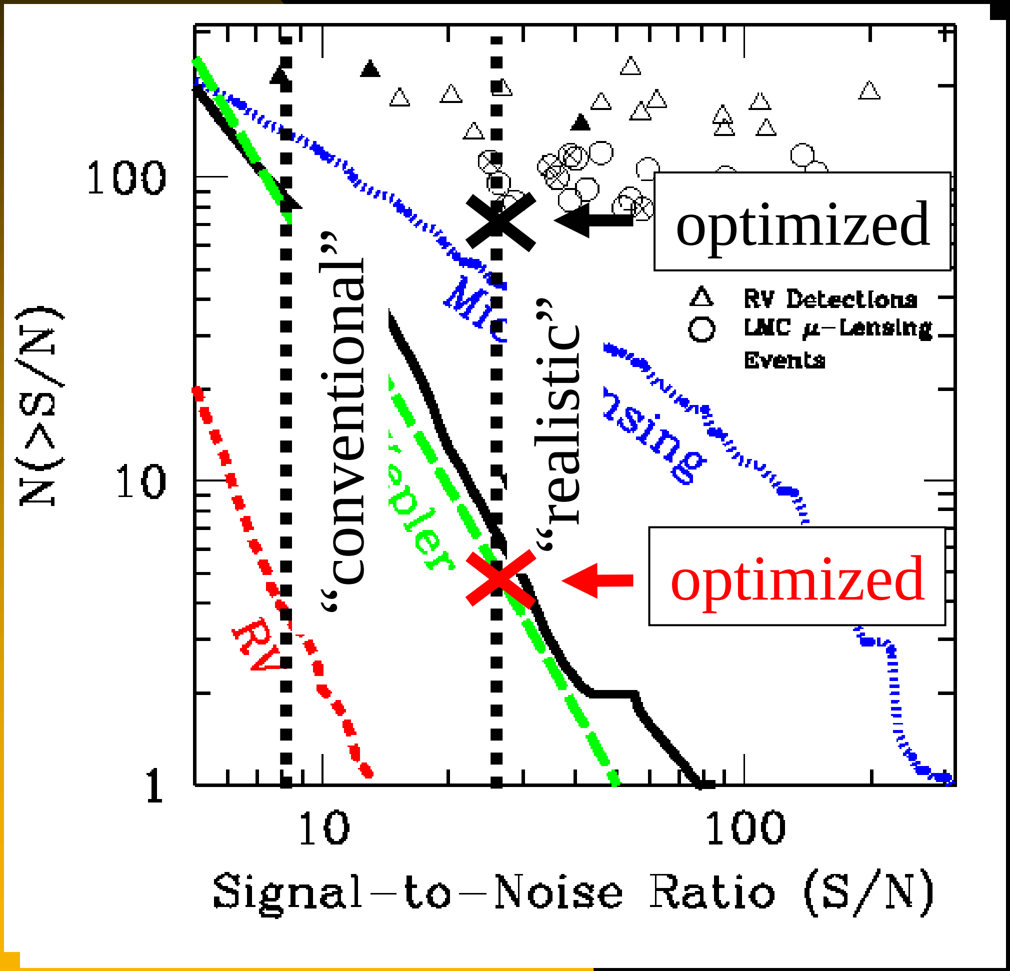
-expensive, distant stars, impossible(?) to confirm

+very low mass planets, robust statistics, many detections

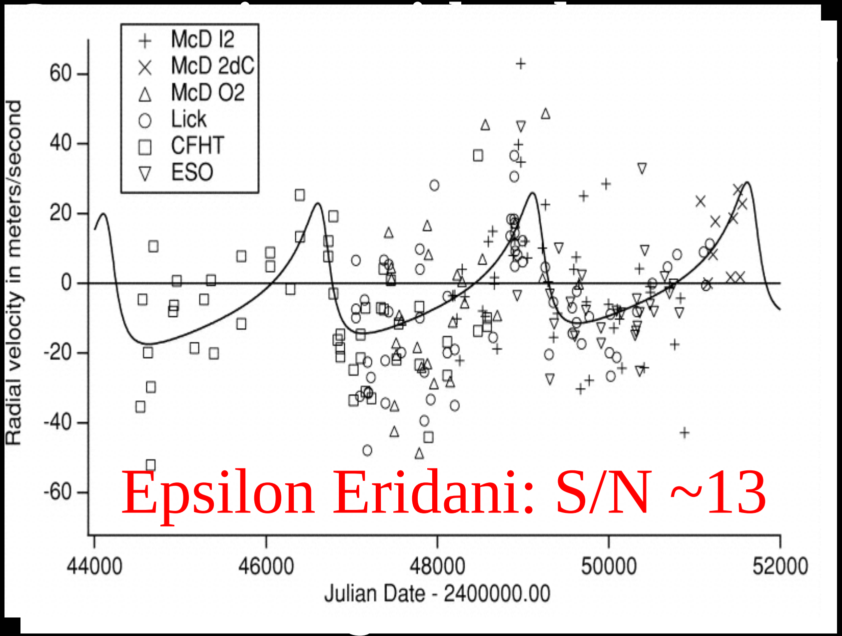
Direct: *TPF, Darwin*

Future Prospects – Extrasolar Earths?

Earth-mass planet sensitivities



(Gould, Gaudi, & Han 2004)



What S/N threshold?

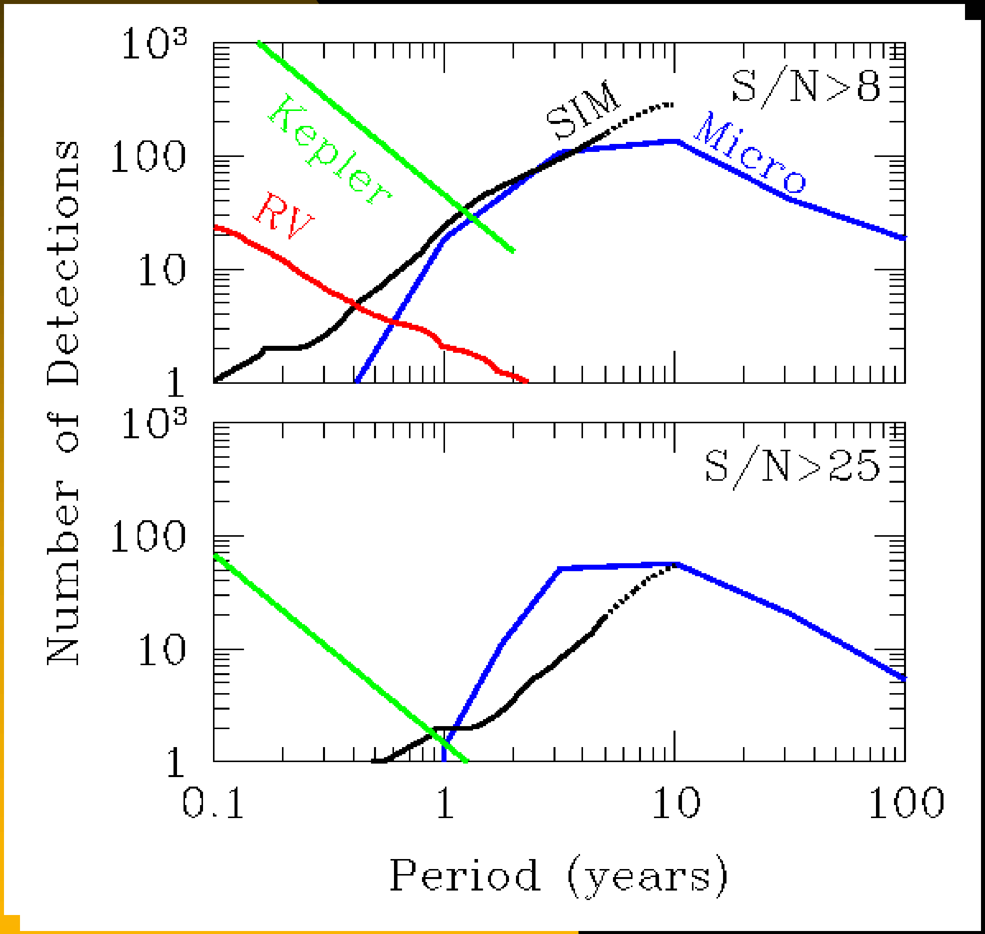
Conventionally: S/N ~ 8

Realistic: S/N ~25

Optimization

Future Prospects – Extrasolar Earths?

Earth-mass planet sensitivities



(Gould, Gaudi, & Han 2004)

Comparison with other methods, cont.

- Every star has a Earth-mass planet with period P
- Each technique is confronted with the same ensemble of planetary systems.

Even under *optimistic* assumptions, only ~5 Earth-mass planets with P=1 year detected with S/N > 25!

Efforts can and should be made to ensure and improve these statistics.

Conclusions:

- Earths are Hard