Extra-Solar Planets

The Ongoing Discovery Era
and
Planet Formation Theory

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SUPA, St.Andrews

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1965-2005

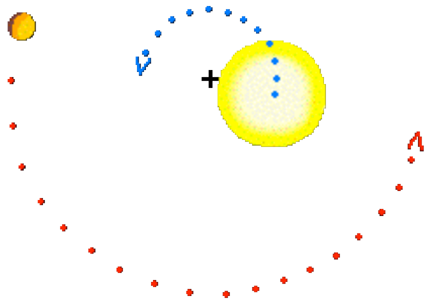
(avalanche)

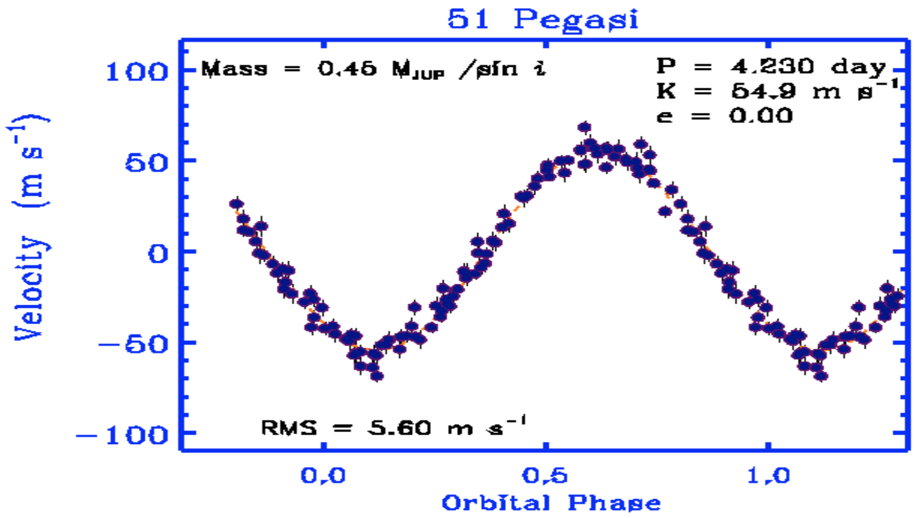
Extra-Solar Planets
The Discovery Era

- < 1995 Solar System planets
- 1995 first extrasolar planet
- (51 Peg) a Hot Jupiter!
- 2005 ~150 Hot-Cool Jupiters
- 2010-15 Habitable Earths -- common or rare?
- 2015-25 Are we alone? Extra-solar Life?

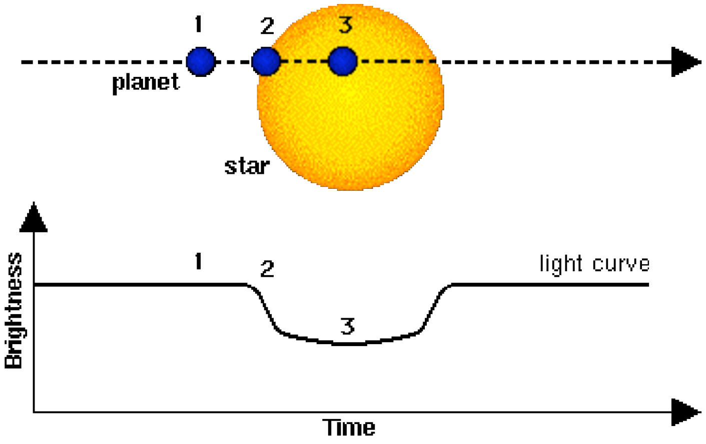
Exo-Planet Discovery Methods

- Doppler Star Wobbles:

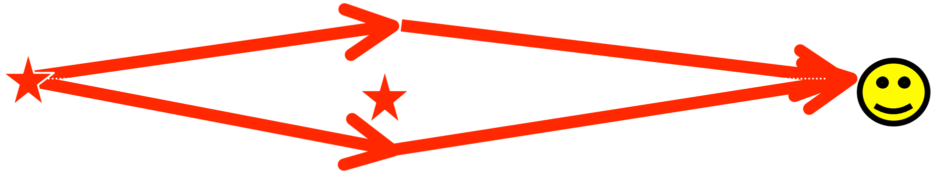


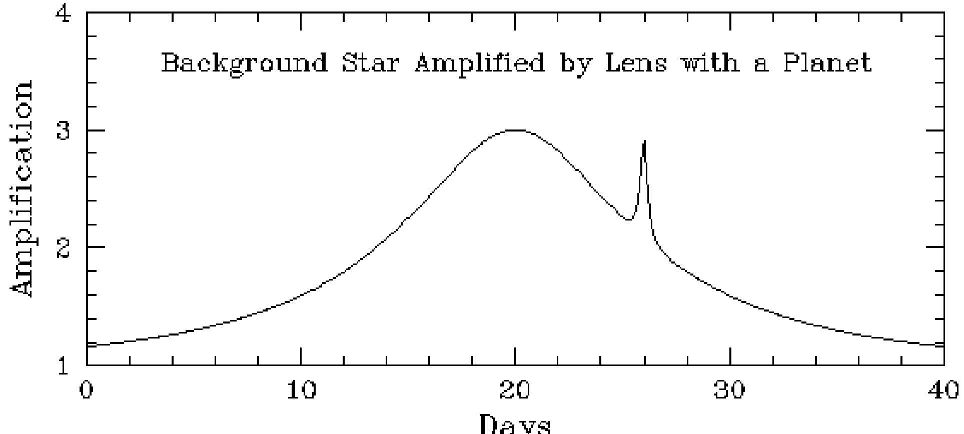


- Transits:



- Microlensing:



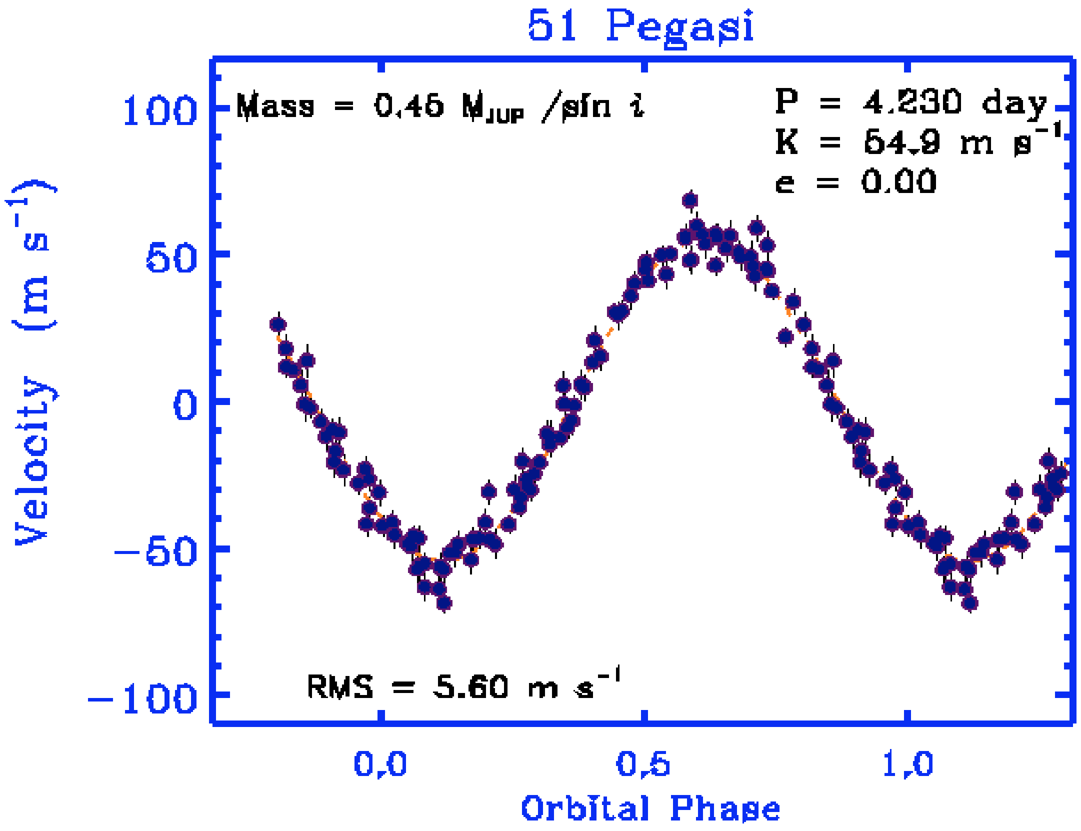


1995: First Doppler Wobble Planet: 51 Peg

Discovered by accident:
Mayor & Queloz (1995)

Quickly confirmed:
Marcy & Butler (1995)

P = 4.2 days (!)
a = 0.05 AU
T ~2000K
m sin(i) = 0.5 m_J



New type of Planet: "Hot Jupiter"

Doppler Wobble Planets 2004 May

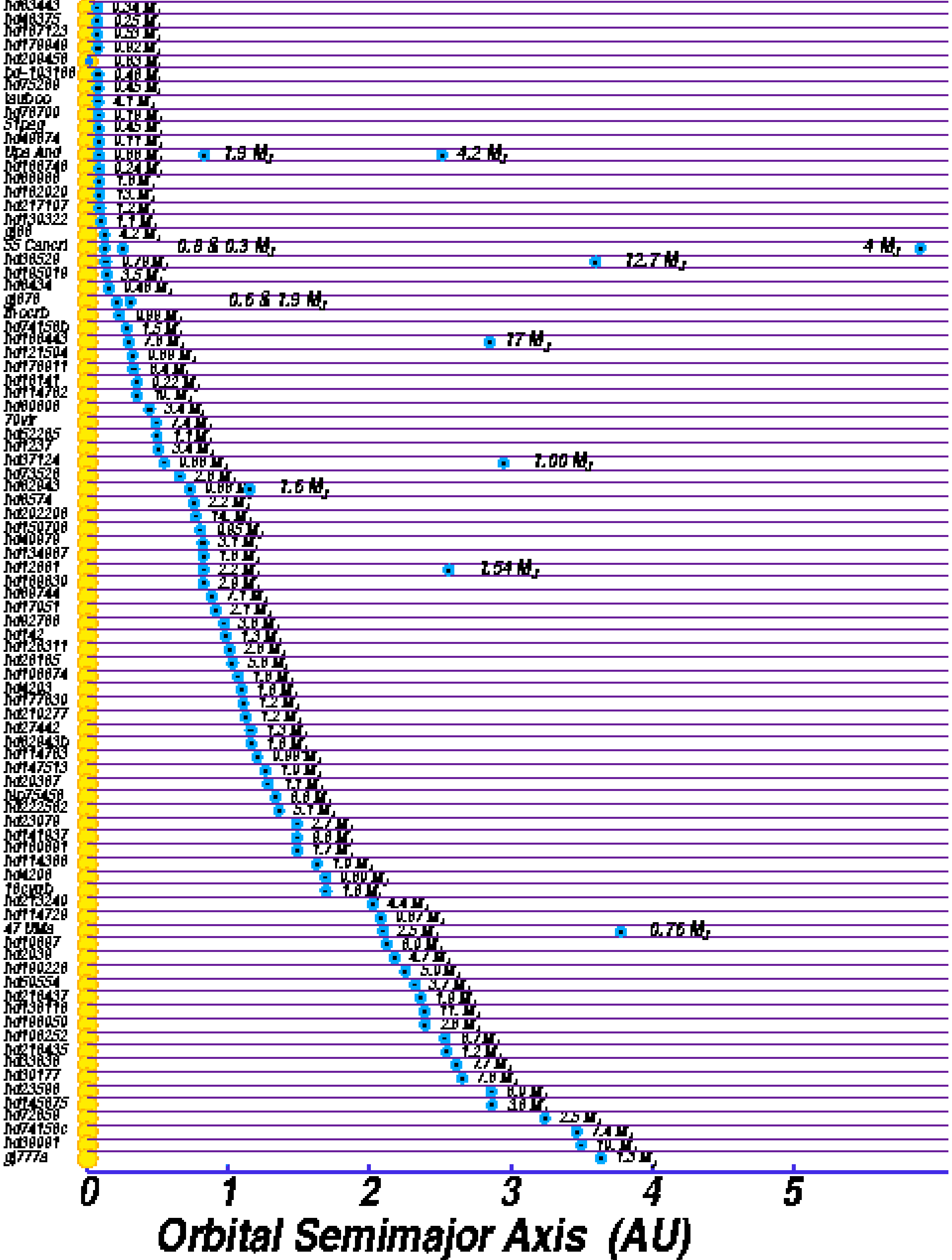
102 stars

122 planets

13 multi-planet
. systems

~5% of stars "wobble"

1-2 planets / month

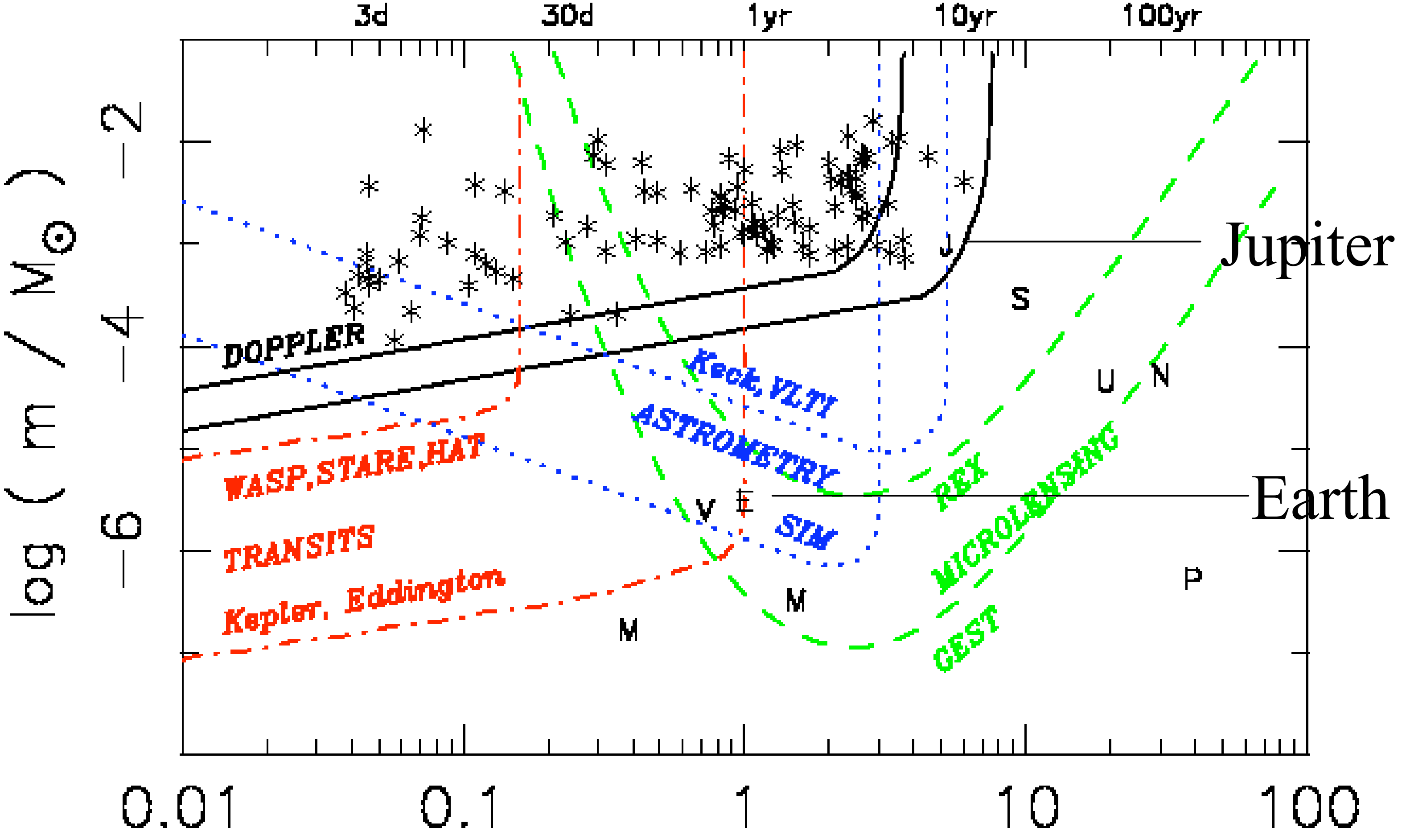


Wide range of planet masses and orbit sizes

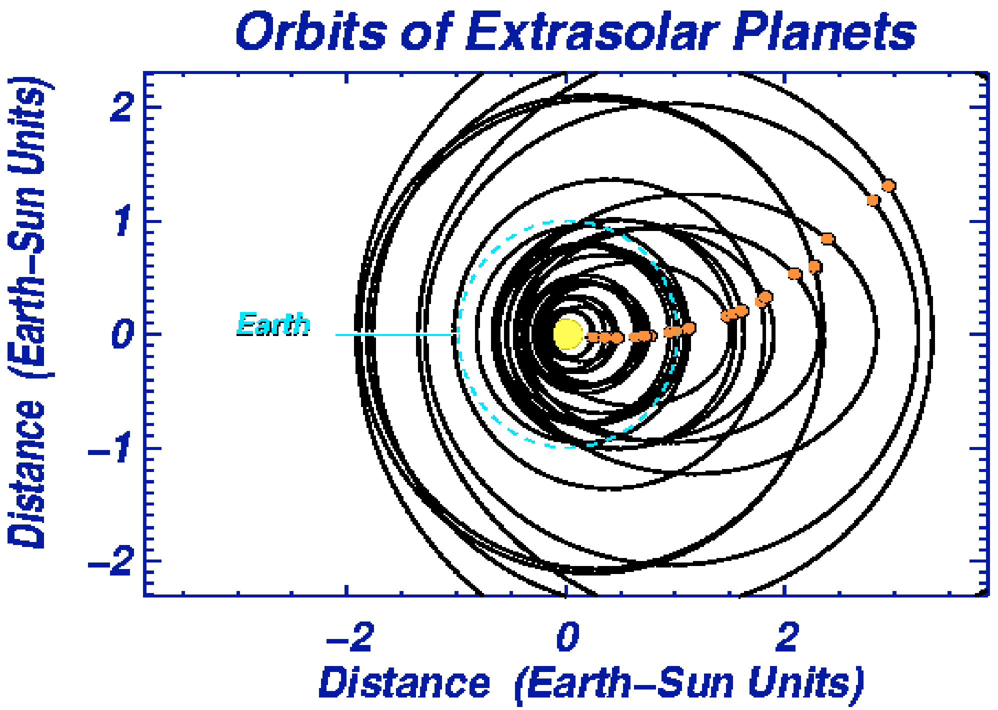
$m < 10\, m_{\mathrm{Jup}}$

$P > 3\mathrm{d}$

~100 Doppler wobble planets



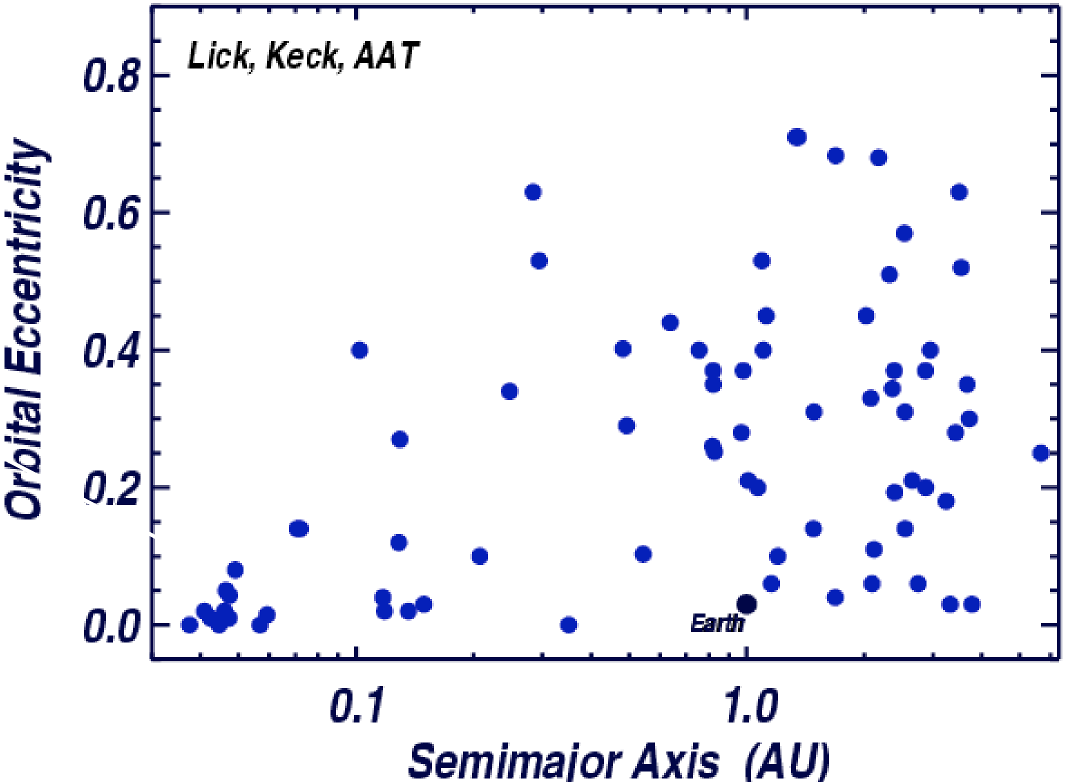
Eccentric Orbits



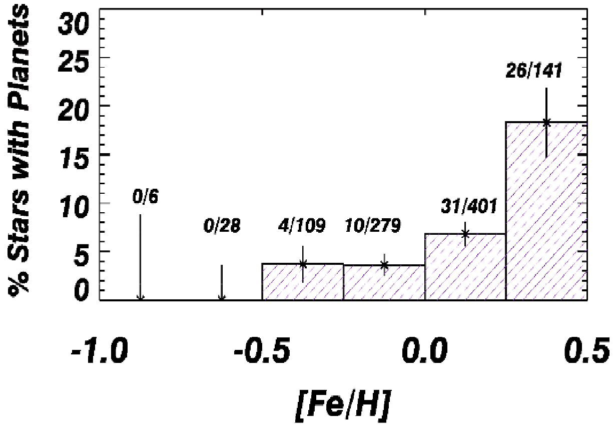
Planet-planet interactions

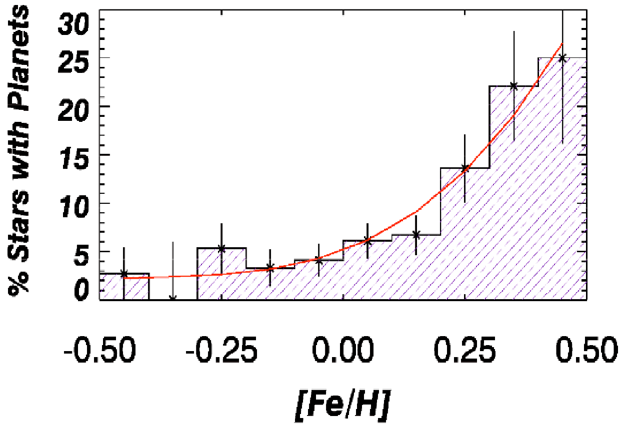
Small planets ejected

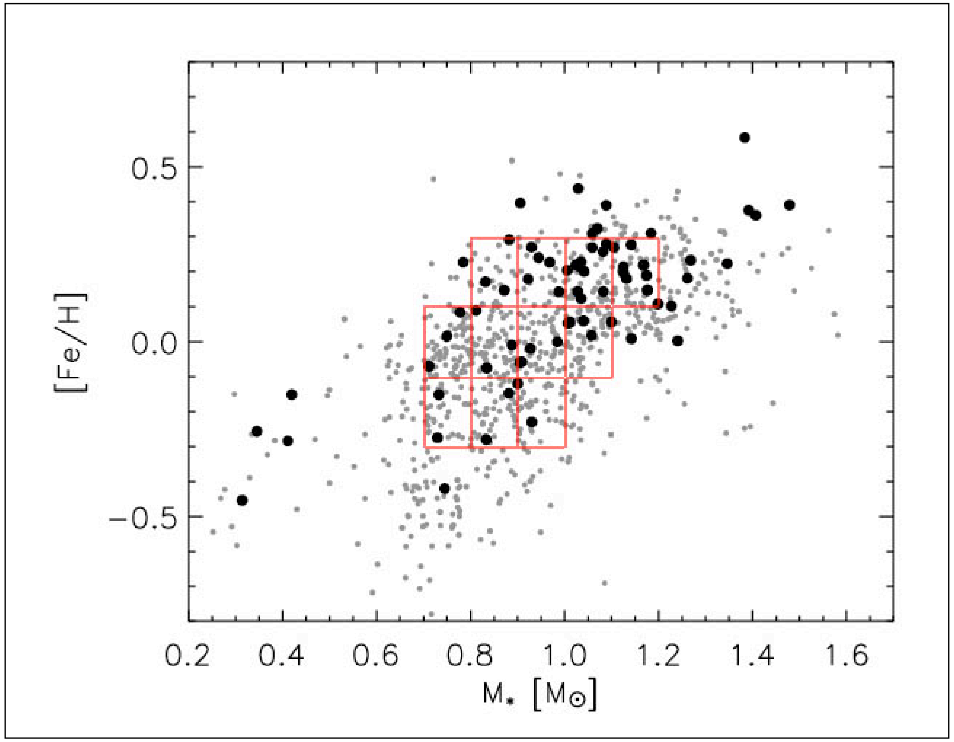
Tidal circularisation



High metalicity of planet host stars







planet abundance :

$$\eta_p = 0.065\,[\,\mathrm{Fe}/\mathrm{H}\,]^{6.2\pm 0.6}\; M_*^{\,0.7\pm 0.6}$$

Santos 2003

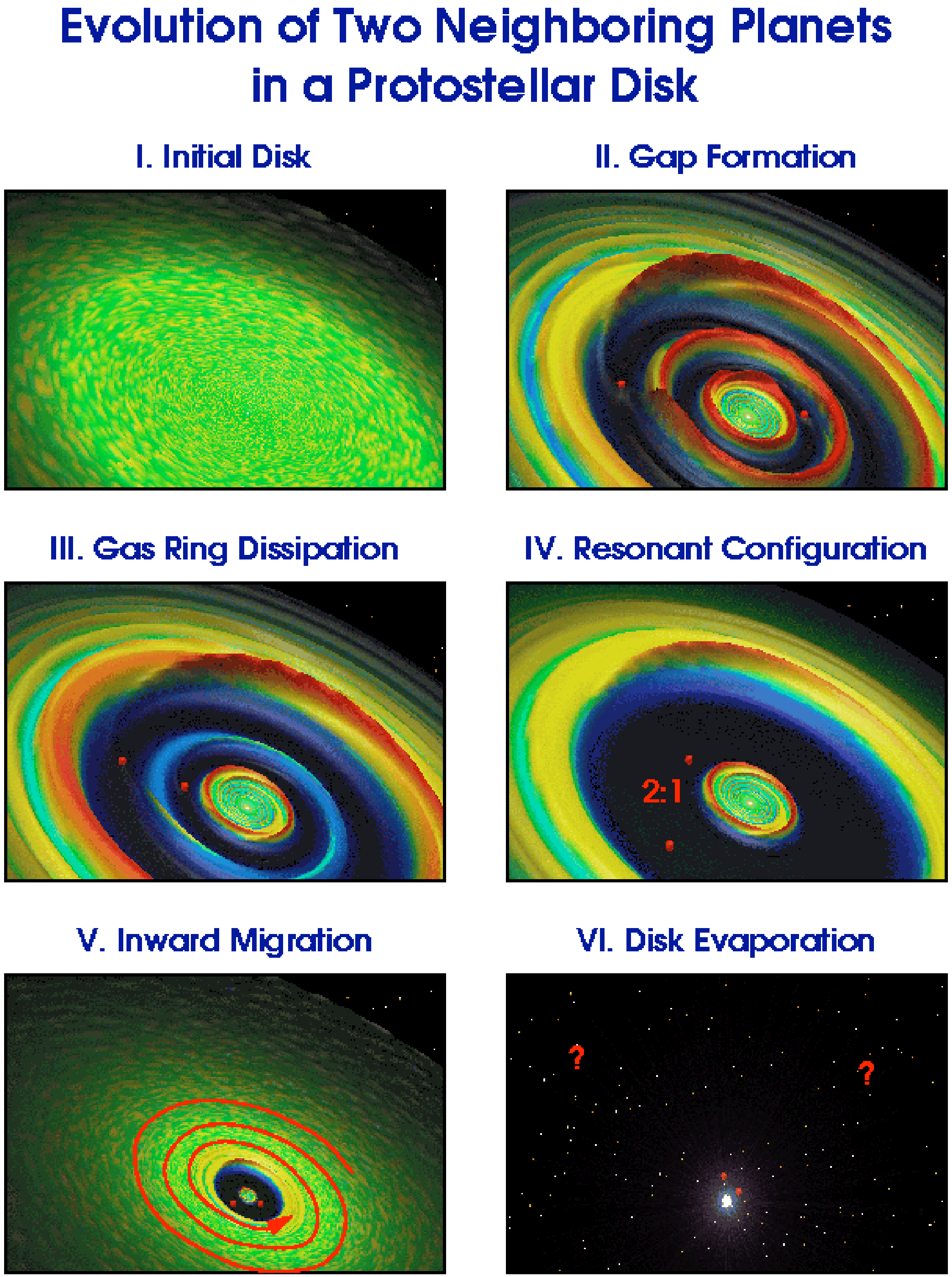
Fischer & Valenti 2004

John Johnson PhD thesis

Lessons from Doppler Wobbles

- > 6% of Sun-like stars host a Jupiter
- Metalicity matters
- Orbits differ from Solar System
  - wide range of orbit radii (P > 3d)
  - wide range of eccentricities
- New processes
  - migration
  - eccentricity pumping
  - ejection
- What about the other 94% ?
  - Is the Solar System typical or rare ?

New Planets, New Theories of Formation and Evolution



Evolution of Two Neighboring Planets in a Protostellar Disk

I. Initial Disk

II. Gap Formation

III. Gas Ring Dissipation

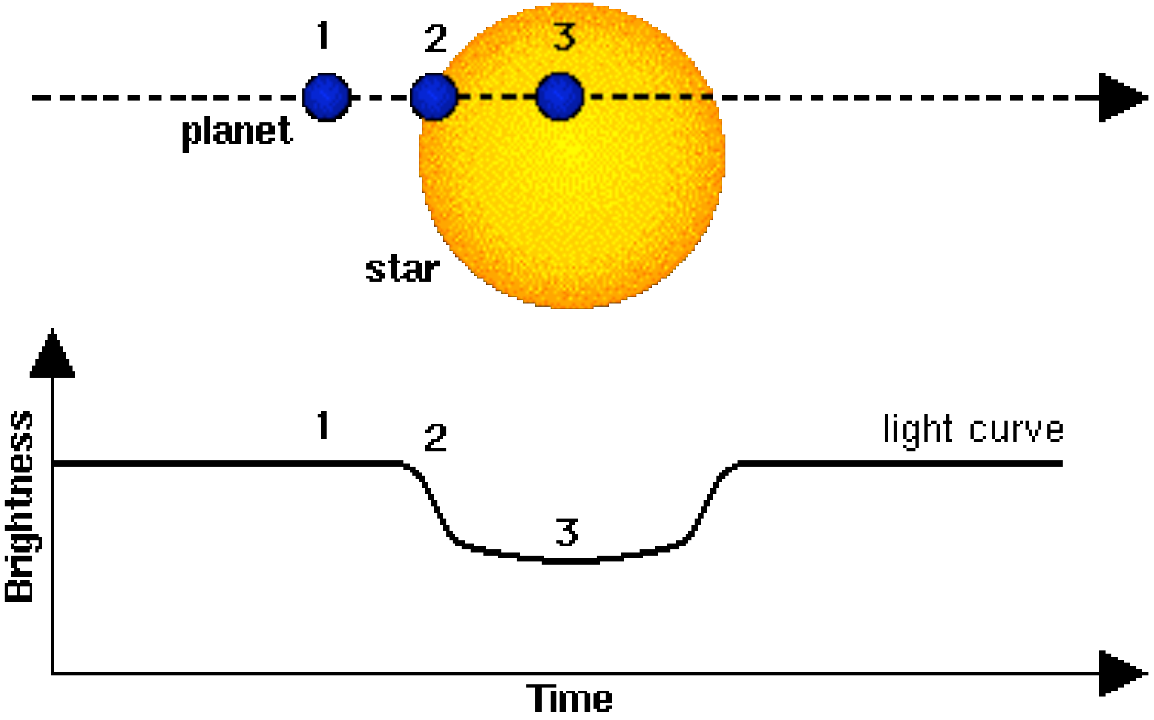
IV. Resonant Configuration

V. Inward Migration

VI. Disk Evaporation

Bryden/Lin 2001
http://www.ucolick.org/~bryden/2planet

Transit Lightcurves



$$r_{Jup} \approx 0.1\, R_{Sun}$$

Depth :

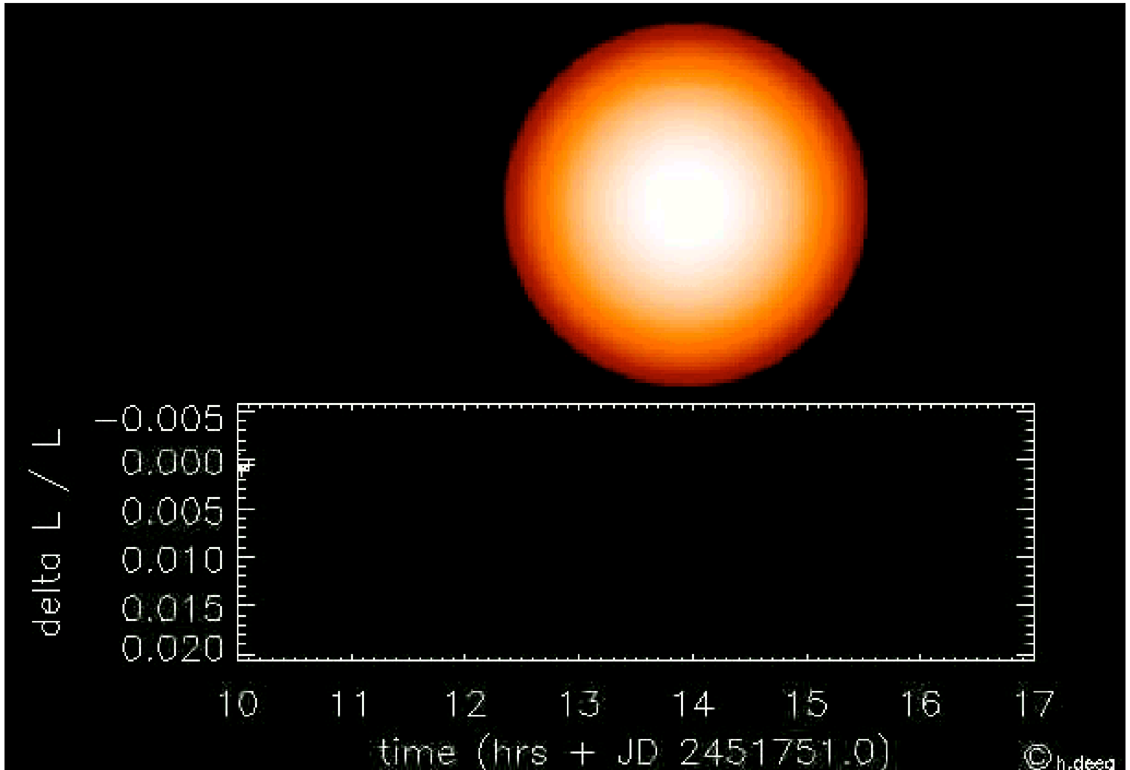
$$\frac{\Delta f}{f} \approx 1\% \left(\frac{r_p}{r_{Jup}}\right)^2 \left(\frac{R_*}{R_{Sun}}\right)^{-2}$$

Duration :

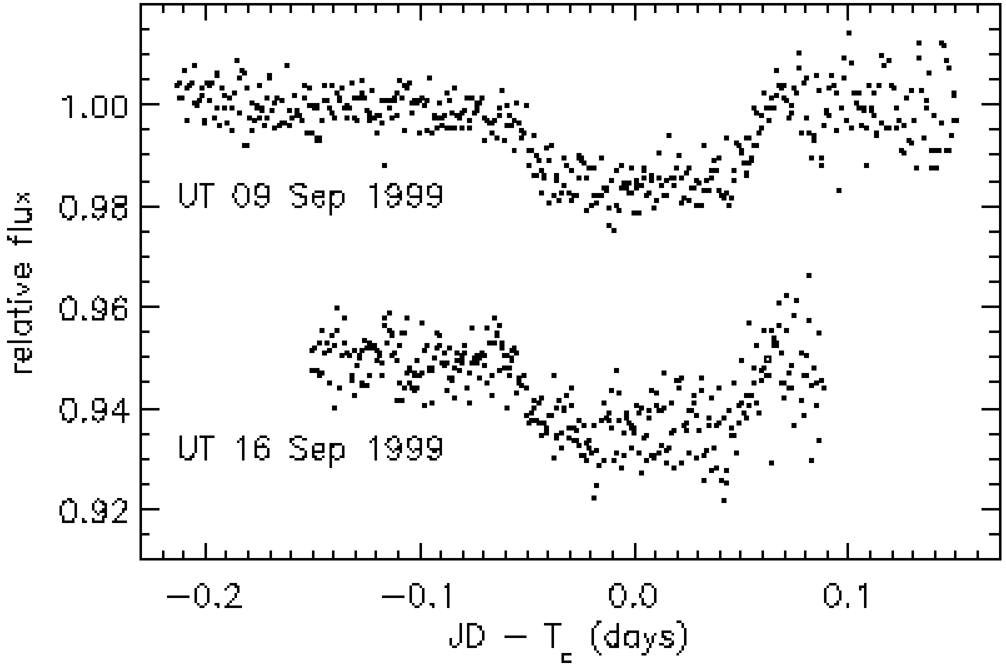
$$\Delta t \approx 3h \left(\frac{M_*}{M_{Sun}}\right)^{2/3} \left(\frac{P}{4d}\right)^{1/3}$$

Probability :

$$P_t \approx 10\% \left(\frac{R_*}{R_{Sun}}\right) \left(\frac{M_*}{M_{Sun}}\right)^{-1/3} \left(\frac{P}{4d}\right)^{-2/3}$$



1999 -- First Transiting Planet

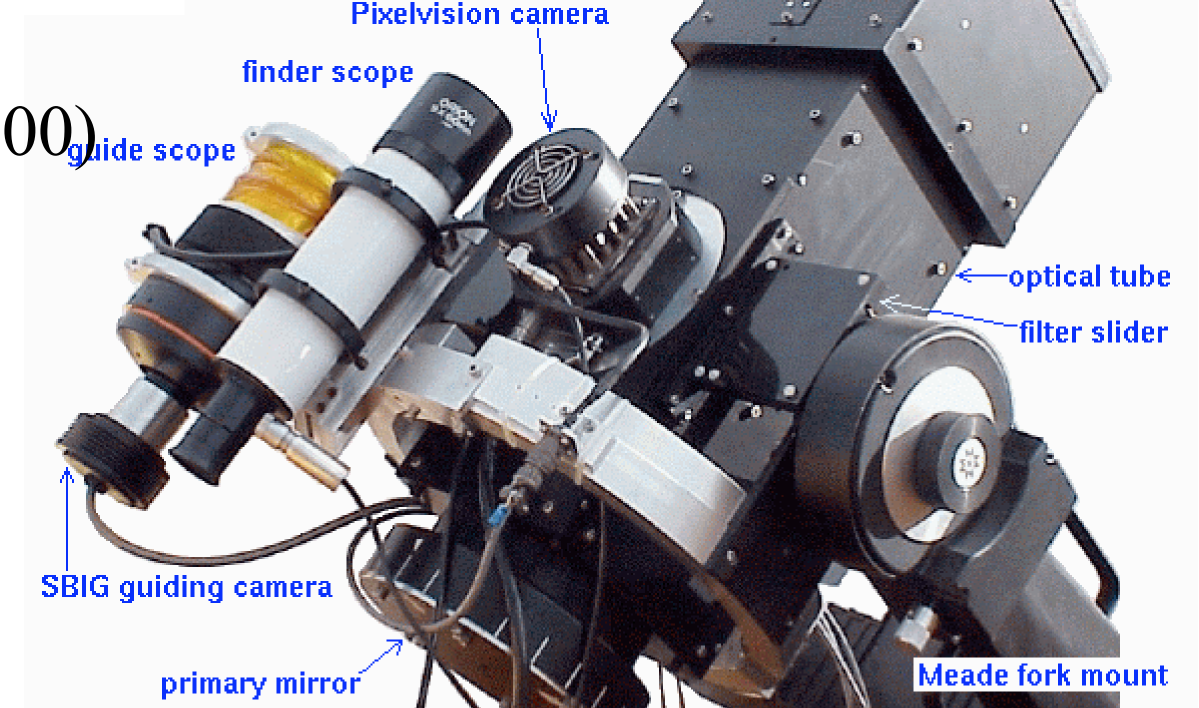


HD 209458
V=7.6 mag

1.6% “winks”
last 3 hours
repeat every 3.5 days

Charbonneau & Brown (2000)

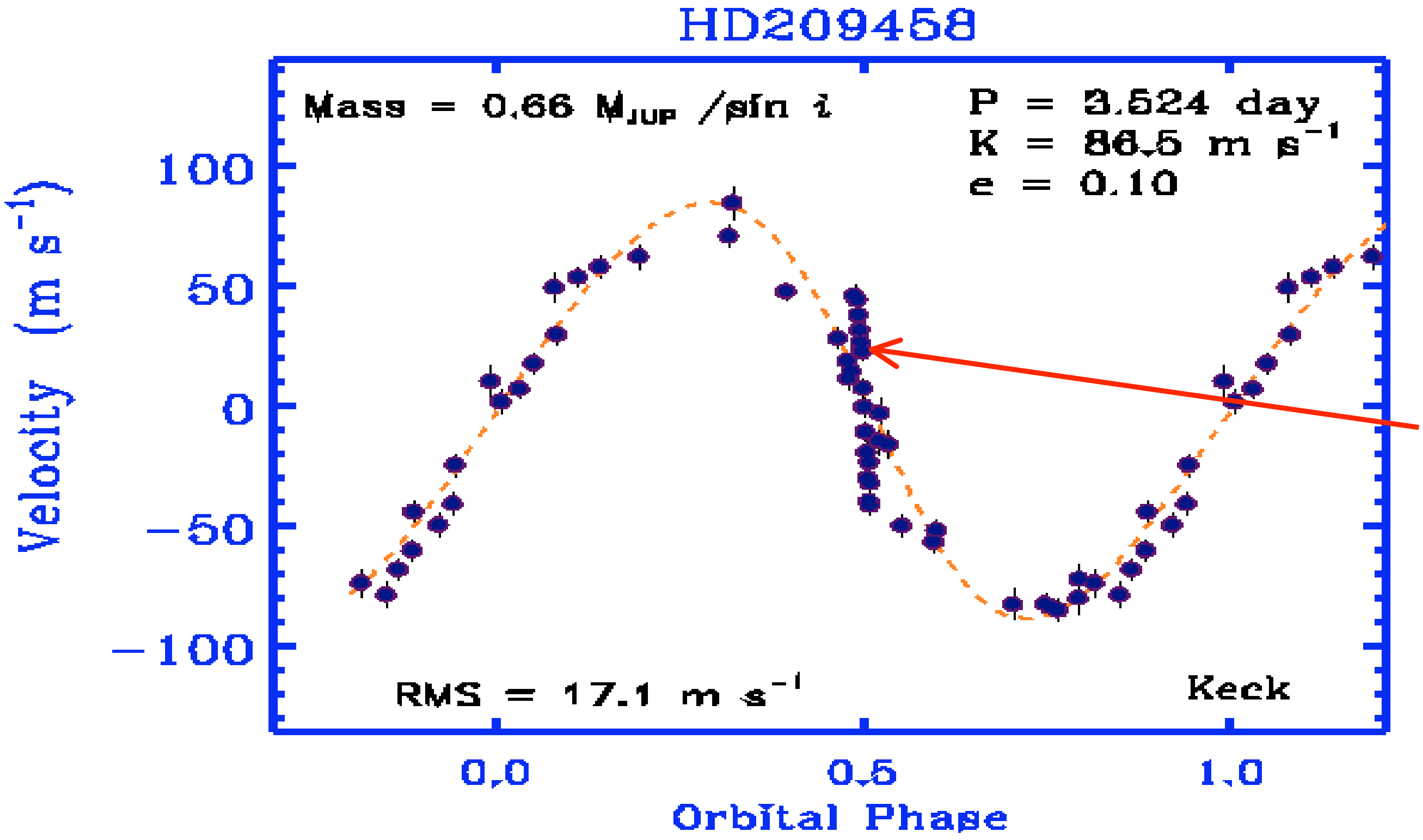
STARE 10 cm telescope



HD 209458b radial velocities

Doppler wobbles found first.

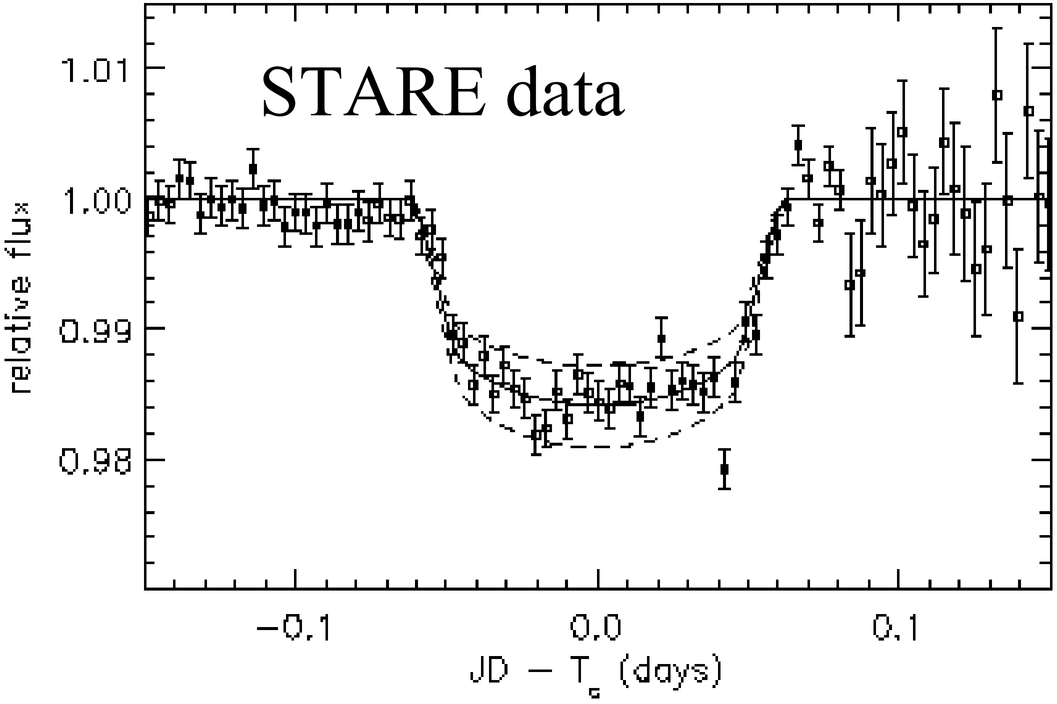
Transits then observed at predicted times.



Rossiter effect

planet transits
a rotating star

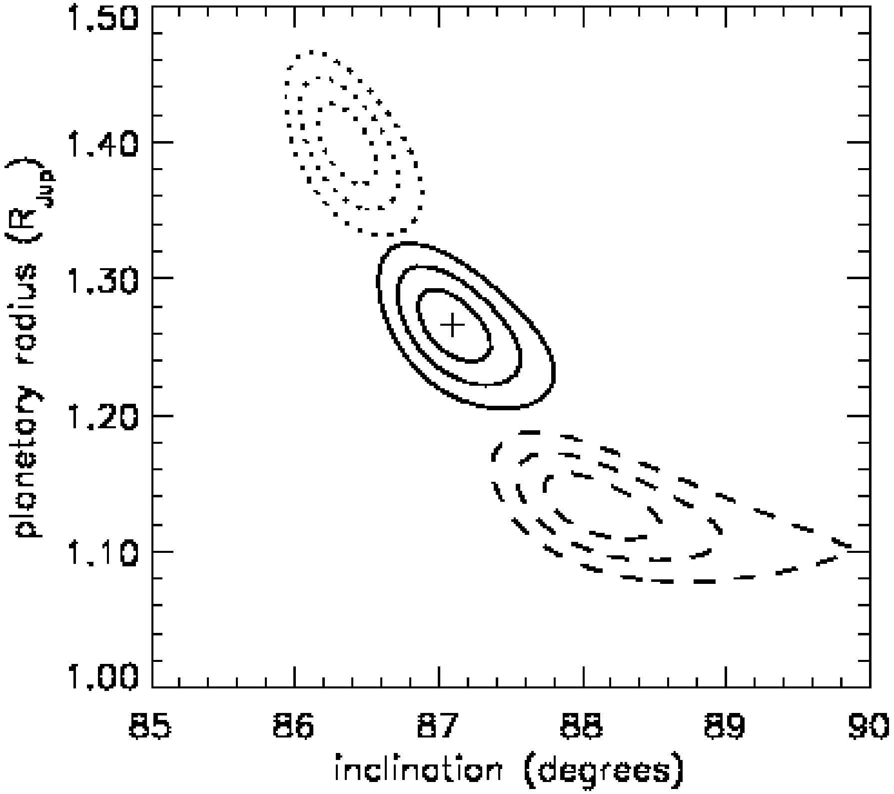
HD 209458 “Bloated” Gas Giant



$m \sim 0.63\ m_{Jup}$

$r \sim 1.3\ r_{Jup}$

$i \sim 87^o$

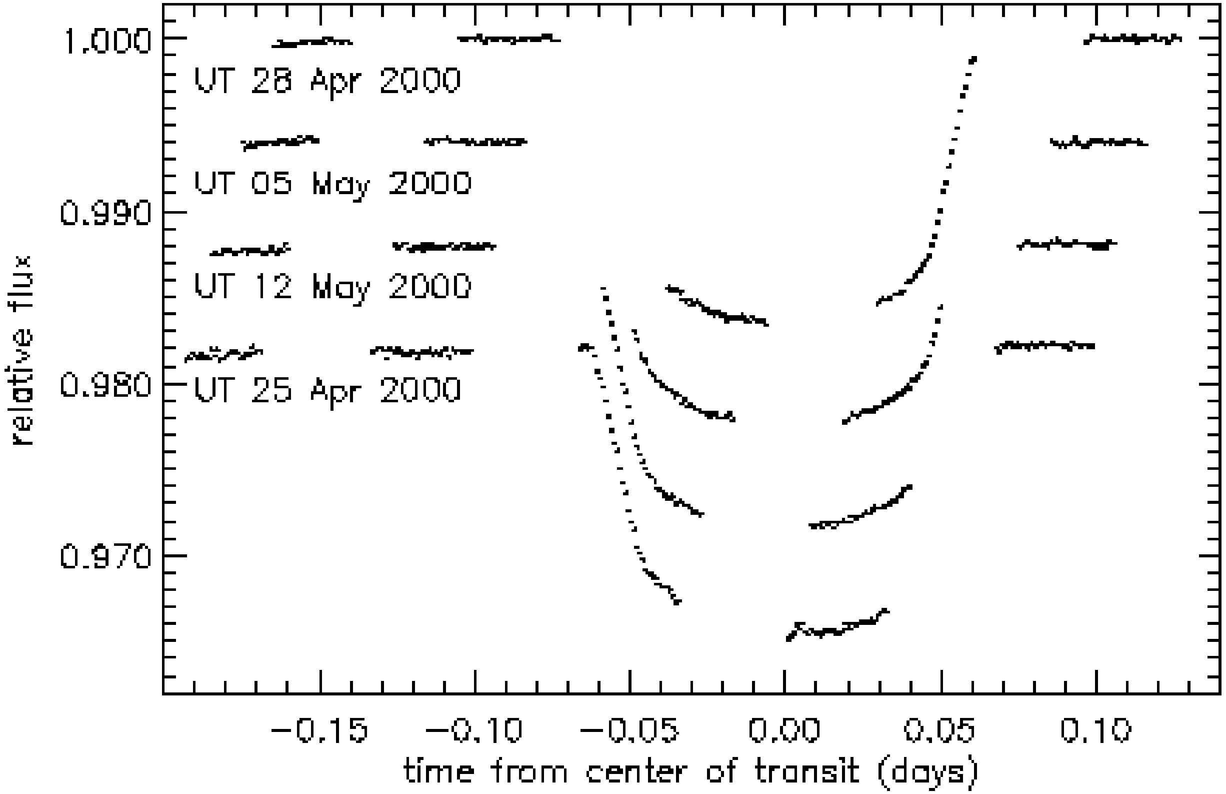


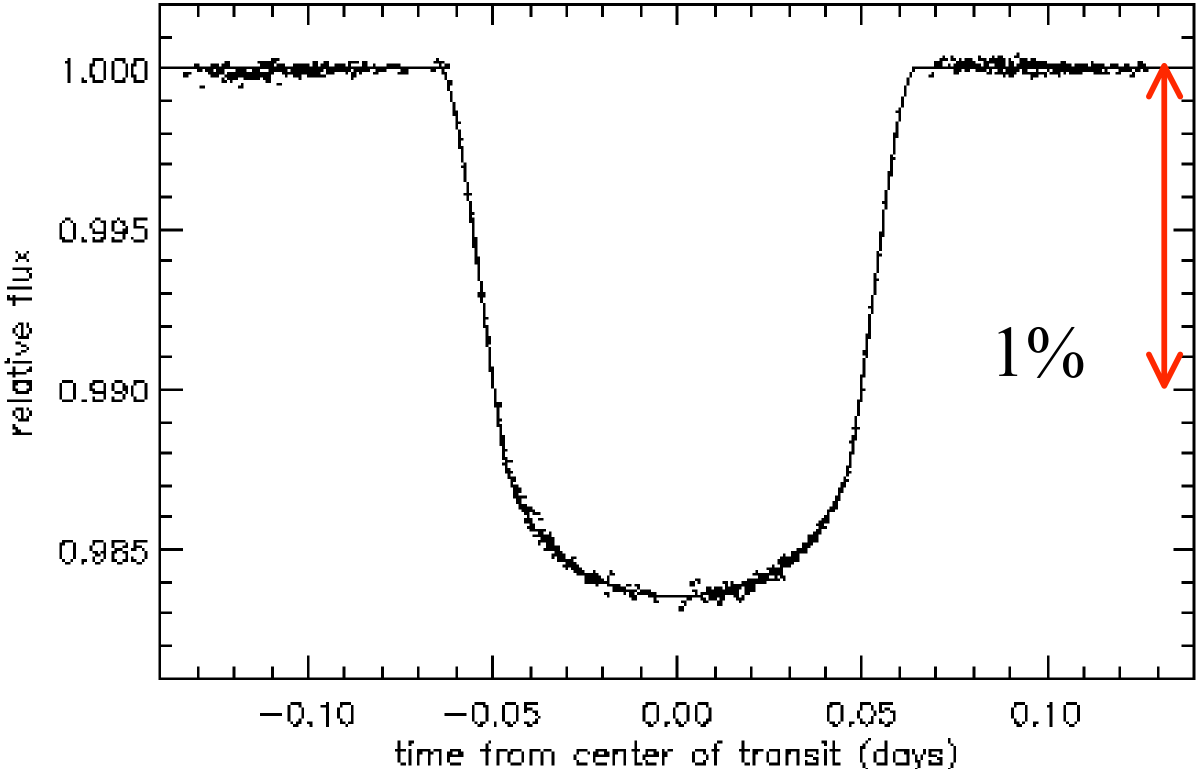
HST/STIS
HD 209458
Transits

Brown et al. (2001)

$r = 1.35 \pm 0.06\ r_{Jup}$

$i = 86^{o}.6 \pm 0^{o}.2$



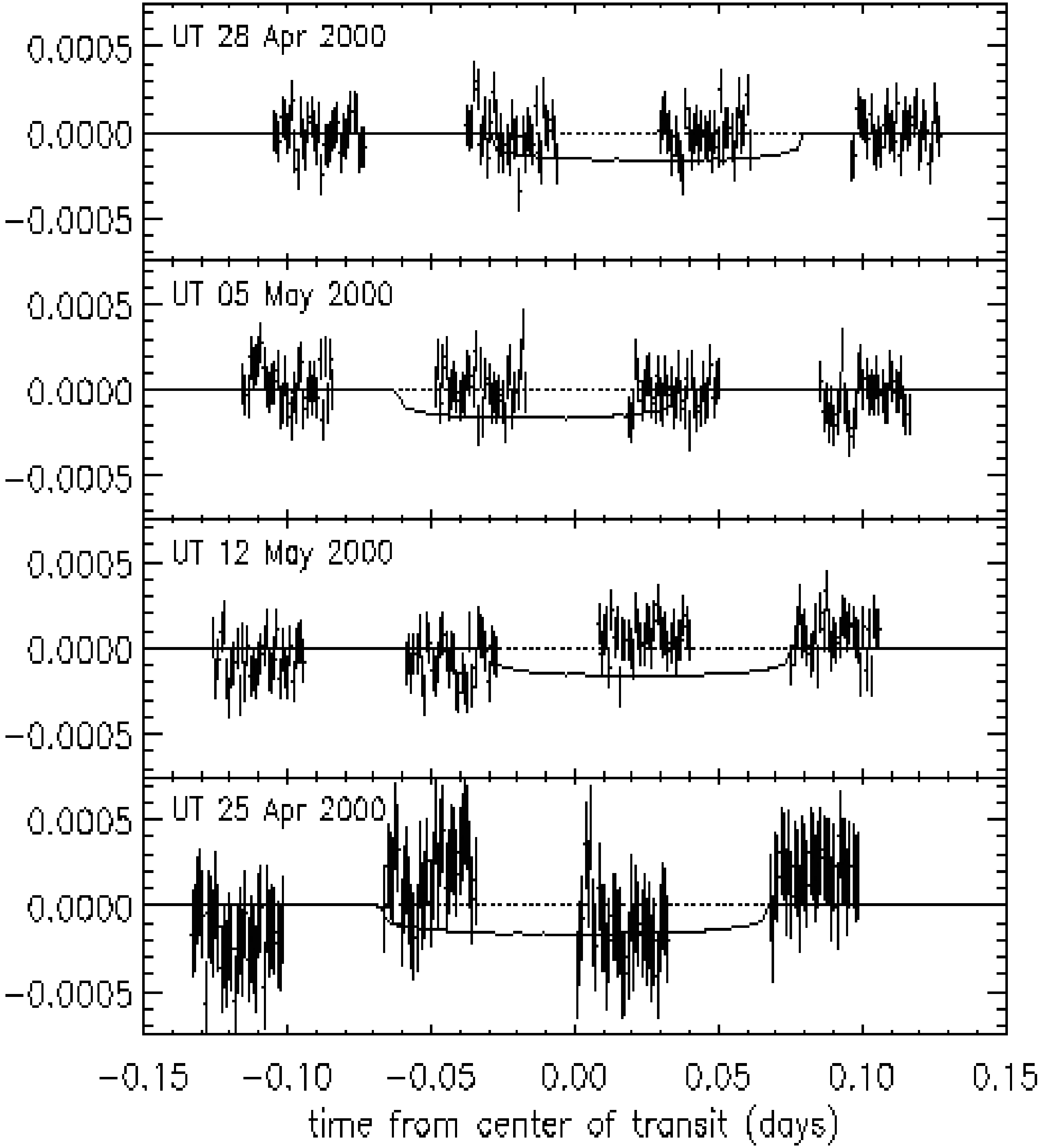


1%

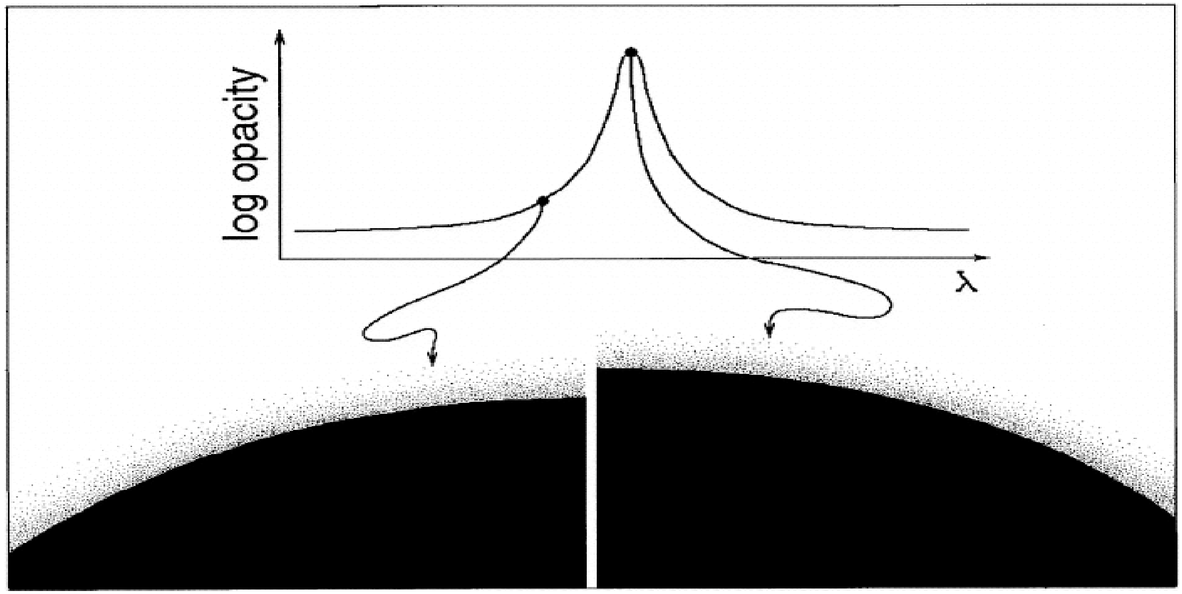
HST: Fit Residuals ~10^{-4}

No Moons
r > 1.2 r_{Earth}

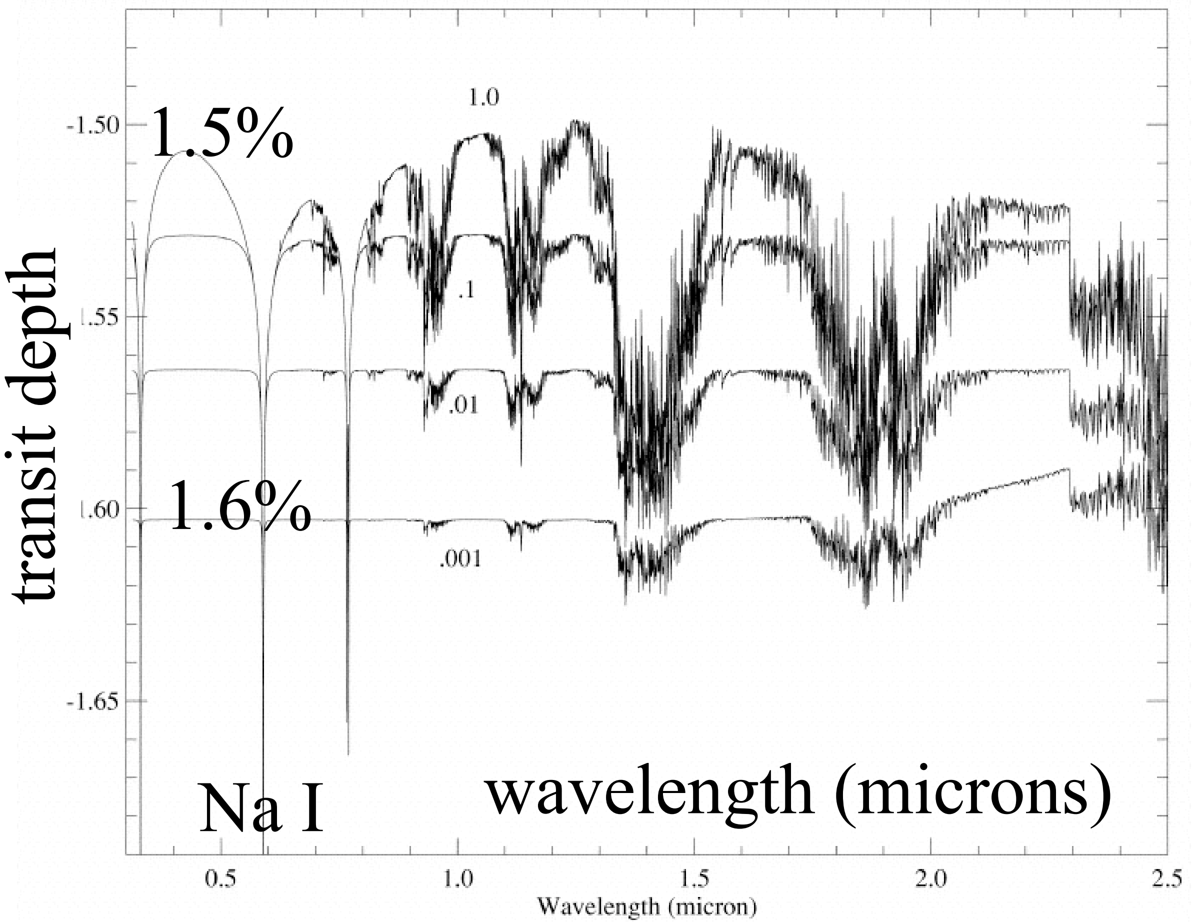
No Rings
r > 1.8 r_{Earth}



Transit Spectroscopy



Brown (2001)



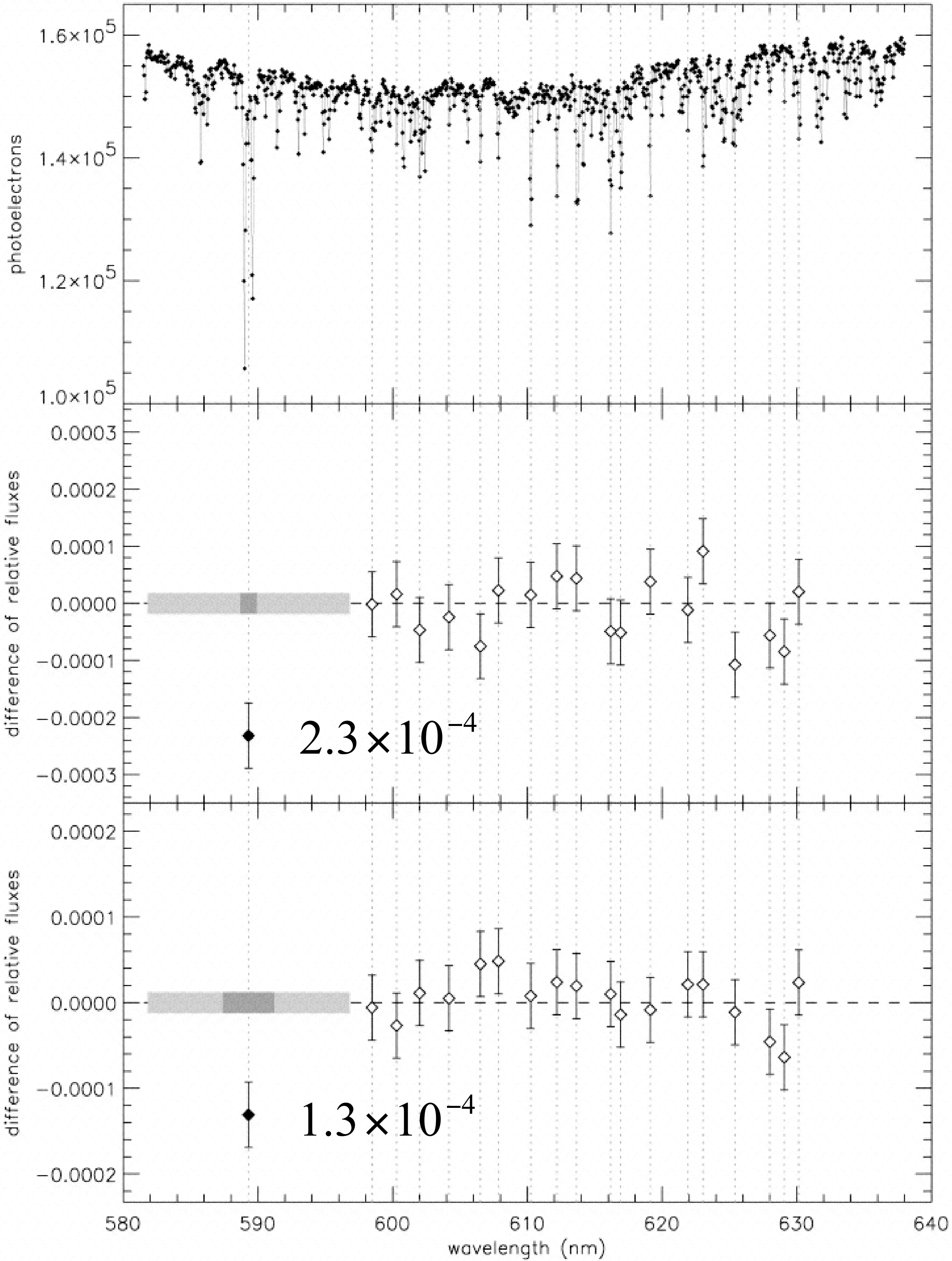
planetary atmosphere

composition

cloud decks

winds

HST Transit Spectroscopy detects Na I in the atmosphere of HD 209458b

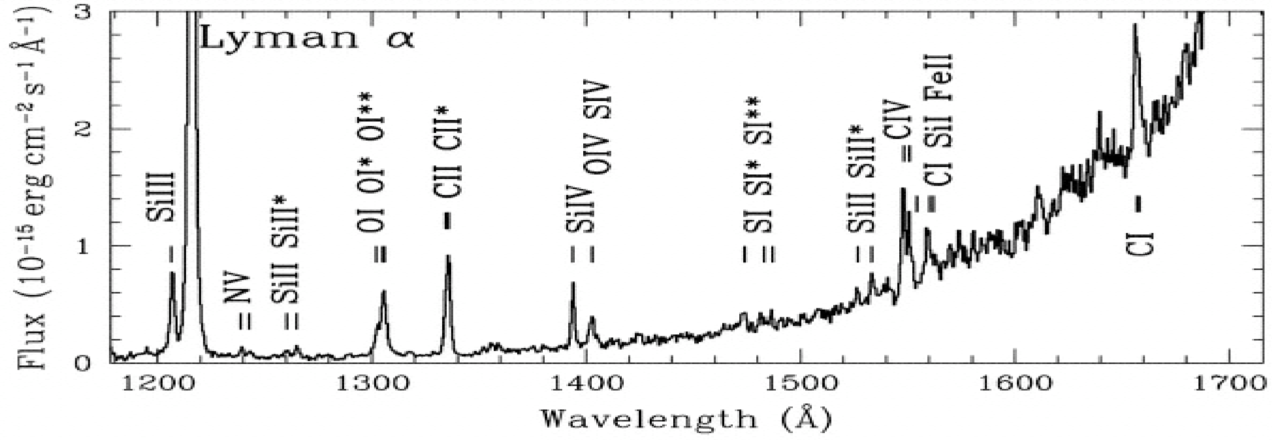


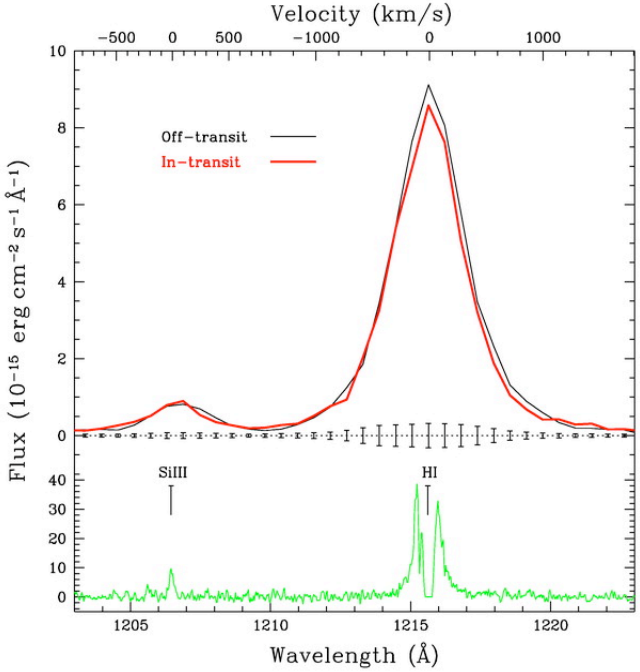
Charbonneau et al. (2002)

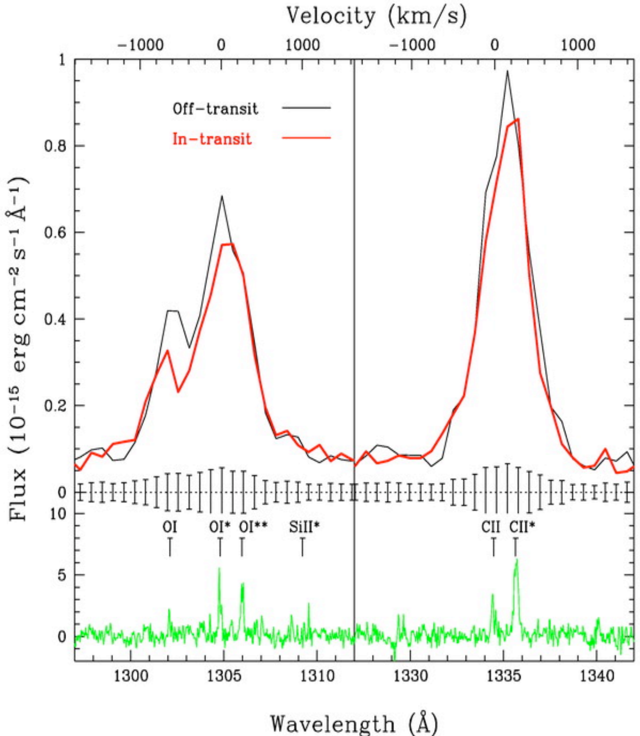
Evaporating Atmosphere

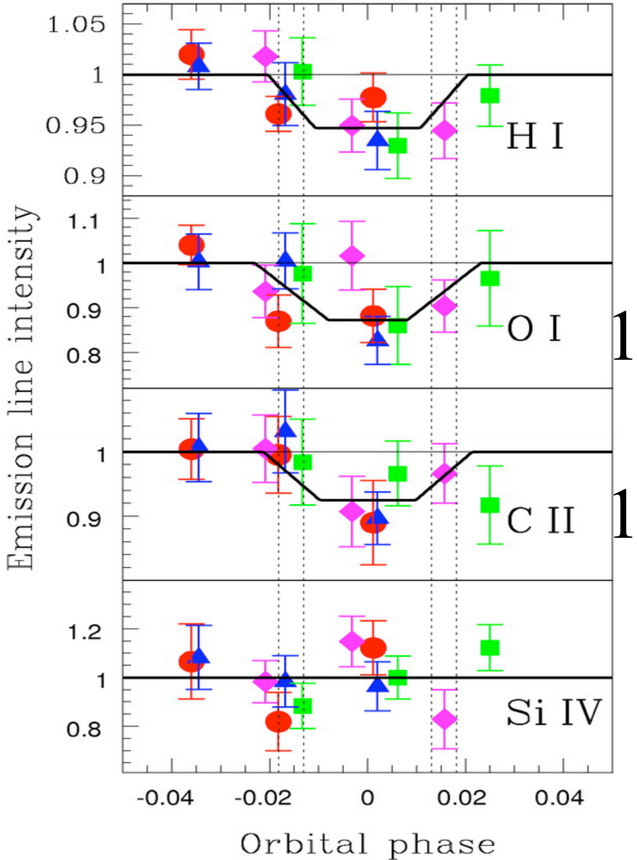
Vidal-Madjar et al. (2003)

ESA / A.Vidal-Madjar, CNRS / NASA







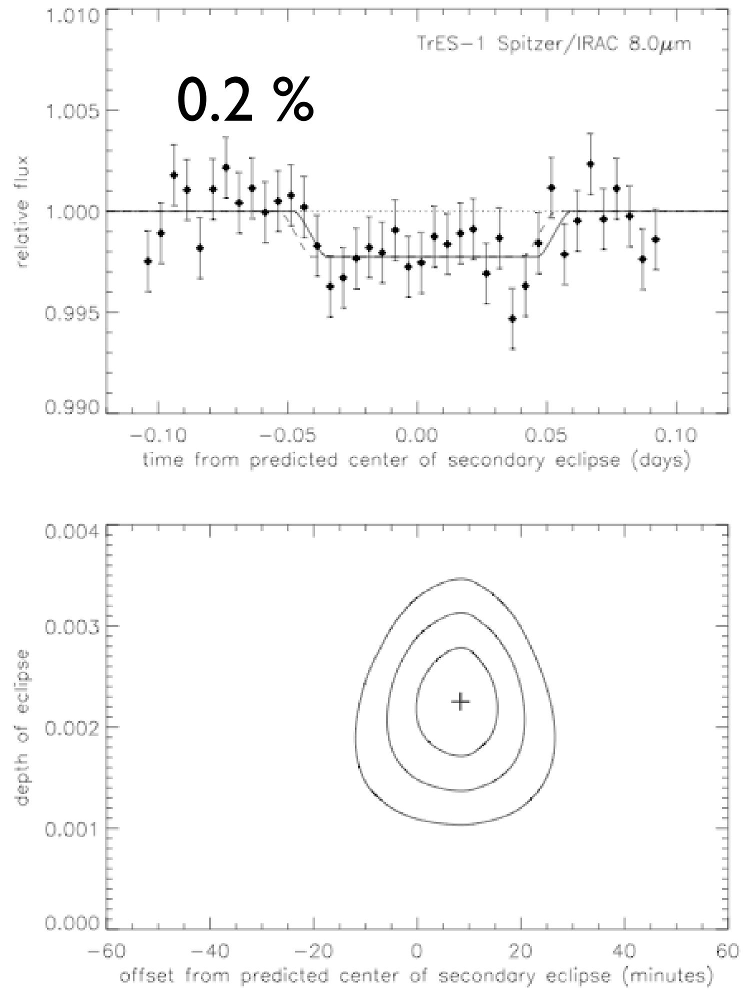


5%

10%

10%

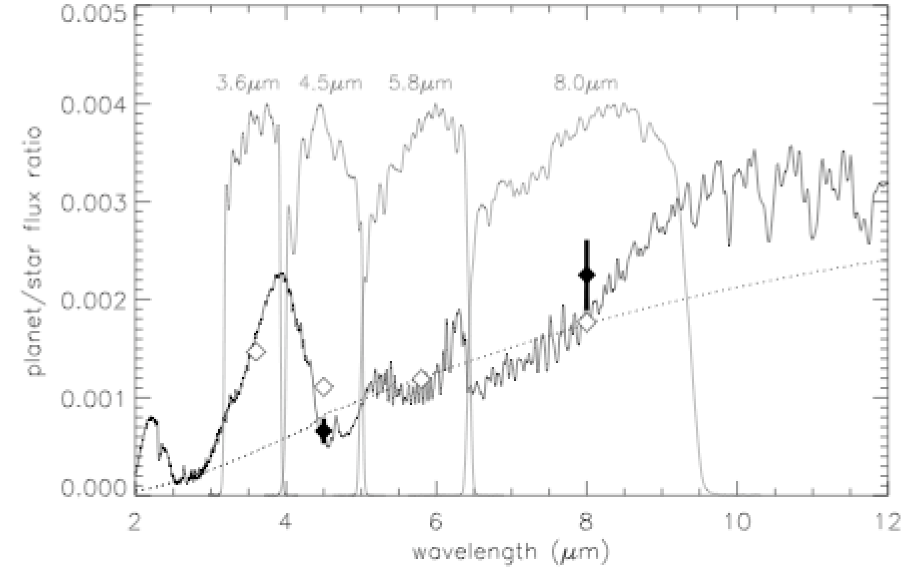
Star occults planet



TrES-1: Charbonneau et al. 2005

HD 209458: Deming et al. 2005

Spitzer/IRAC 4.5, 8.0 micron



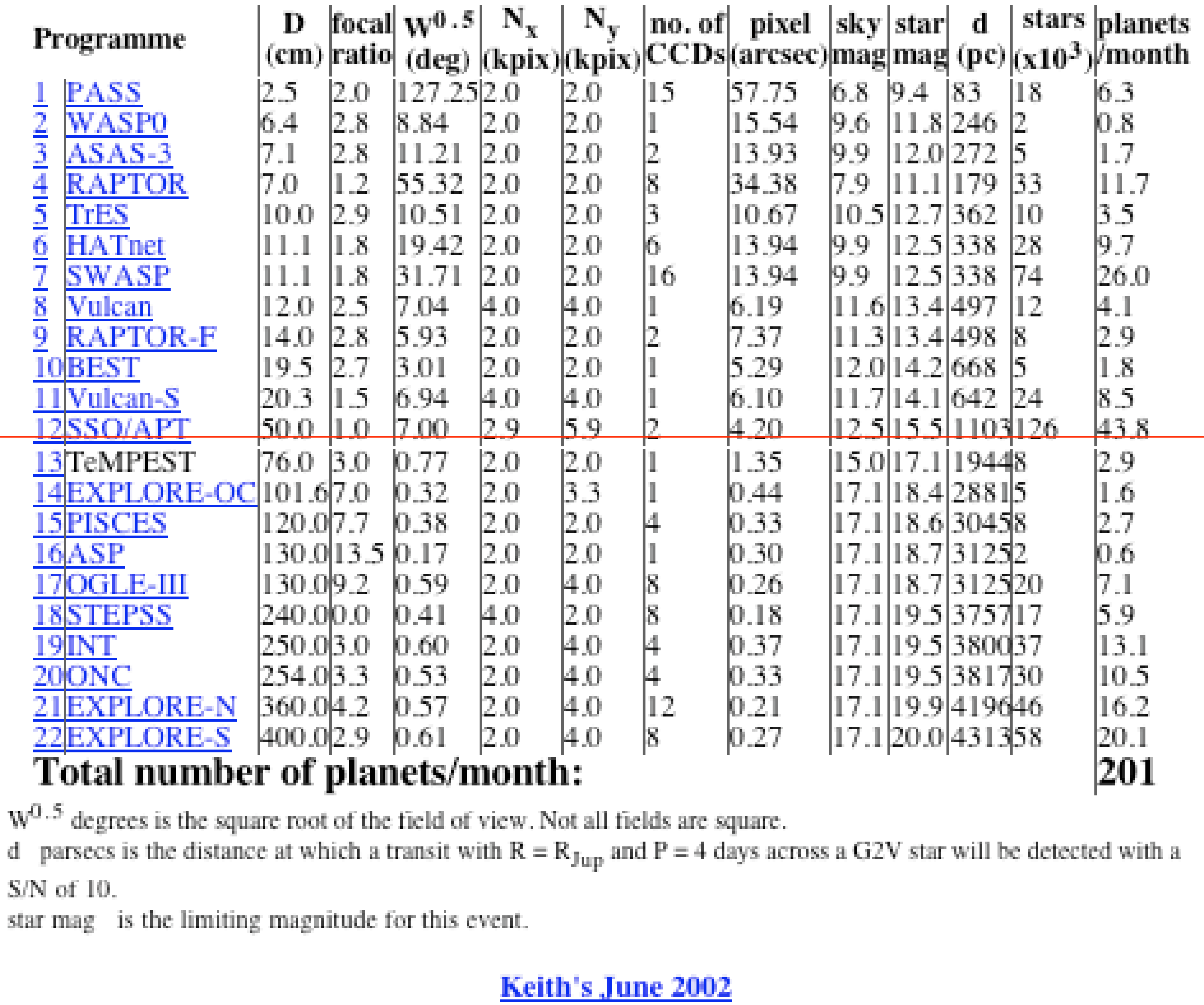
Direct detection of infrared light from planet

2005 Ground-based Transit Surveys

UK WASP

Wide

Deep



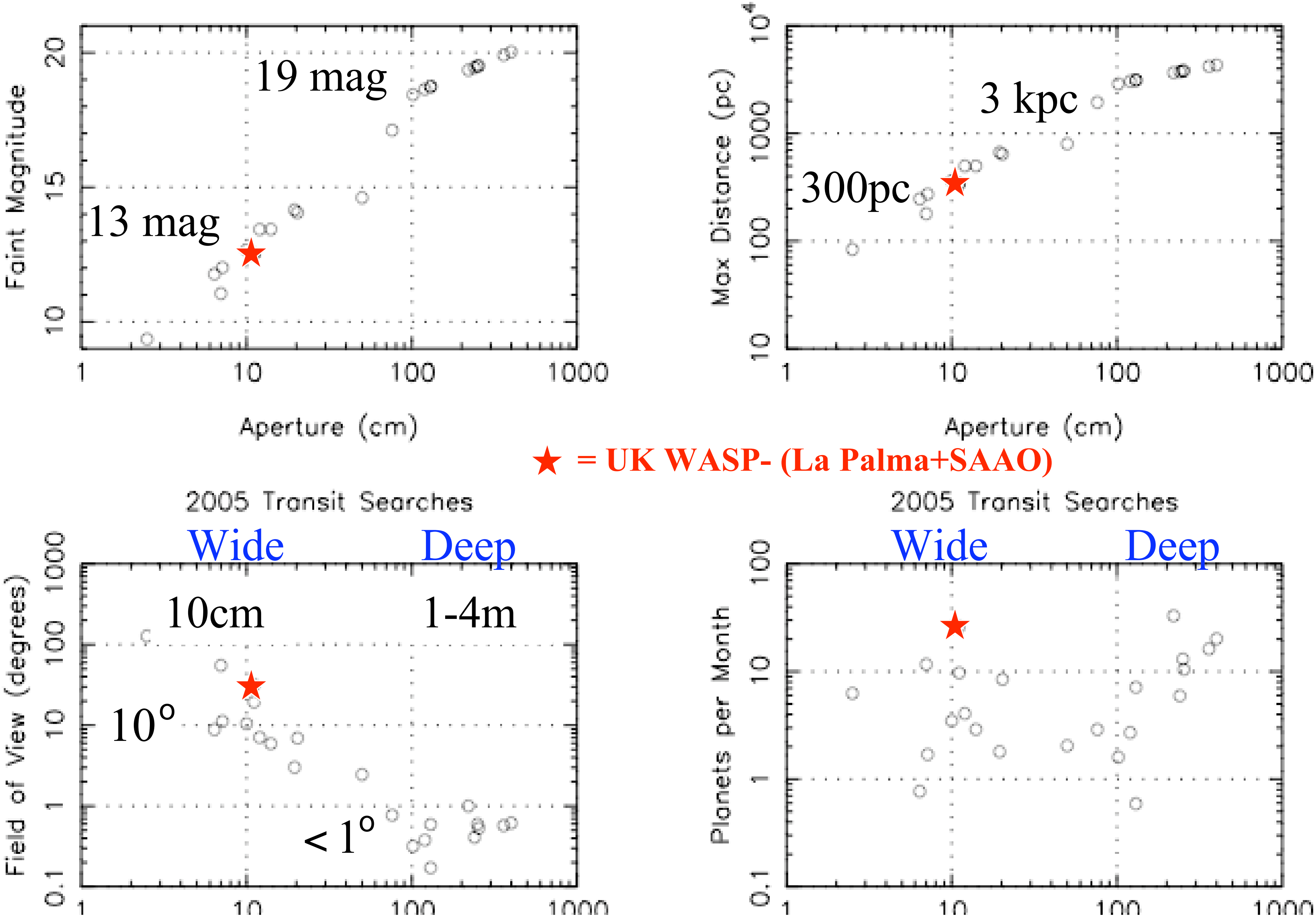
	Programme	D (cm)	focal ratio	$W^{0.5}$ (deg)	N_x (kpix)	N_y (kpix)	no. of CCDs	pixel (arcsec)	sky mag	star mag	d (pc)	stars ($x10^3$)	planets /month
1	PASS	2.5	2.0	127.25	2.0	2.0	15	57.75	6.8	9.4	83	18	6.3
2	WASP0	6.4	2.8	8.84	2.0	2.0	1	15.54	9.6	11.8	246	2	0.8
3	ASAS-3	7.1	2.8	11.21	2.0	2.0	2	13.93	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	HATnet	11.1	1.8	19.42	2.0	2.0	6	13.94	9.9	12.5	338	28	9.7
7	SWASP	11.1	1.8	31.71	2.0	2.0	16	13.94	9.9	12.5	338	74	26.0
8	Vulcan	12.0	2.5	7.04	4.0	4.0	1	6.19	11.6	13.4	497	12	4.1
9	RAPTOR-F	14.0	2.8	5.93	2.0	2.0	2	7.37	11.3	13.4	498	8	2.9
10	BEST	19.5	2.7	3.01	2.0	2.0	1	5.29	12.0	14.2	668	5	1.8
11	Vulcan-S	20.3	1.5	6.94	4.0	4.0	1	6.10	11.7	14.1	642	24	8.5
12	SSO/APT	50.0	1.0	7.00	2.9	5.9	2	4.20	12.5	15.5	1103	126	43.8
13	TeMPEST	76.0	3.0	0.77	2.0	2.0	1	1.35	15.0	17.1	1944	8	2.9
14	EXPLORE-OC	101.6	7.0	0.32	2.0	3.3	1	0.44	17.1	18.4	2881	5	1.6
15	PISCES	120.0	7.7	0.38	2.0	2.0	4	0.33	17.1	18.6	3045	8	2.7
16	ASP	130.0	13.5	0.17	2.0	2.0	1	0.30	17.1	18.7	3125	2	0.6
17	OGLE-III	130.0	9.2	0.59	2.0	4.0	8	0.26	17.1	18.7	3125	20	7.1
18	STEPSS	240.0	0.0	0.41	4.0	2.0	8	0.18	17.1	19.5	3757	17	5.9
19	INT	250.0	3.0	0.60	2.0	4.0	4	0.37	17.1	19.5	3800	37	13.1
20	ONC	254.0	3.3	0.53	2.0	4.0	4	0.33	17.1	19.5	3817	30	10.5
21	EXPLORE-N	360.0	4.2	0.57	2.0	4.0	12	0.21	17.1	19.9	4196	46	16.2
22	EXPLORE-S	400.0	2.9	0.61	2.0	4.0	8	0.27	17.1	20.0	4313	58	20.1
	Total number of planets/month:												**201**

$W^{0.5}$ degrees is the square root of the field of view. Not all fields are square.

d parsecs is the distance at which a transit with $R = R_{Jup}$ and $P = 4$ days across a G2V star will be detected with a S/N of 10.

star mag is the limiting magnitude for this event.

Keith's June 2002


Faint Magnitude
10
15
20
19 mag
13 mag
Aperture (cm)
1
10
100
1000
Max Distance (pc)
10
100
1000
10⁴
3 kpc
300pc
Aperture (cm)
1
10
100
1000
★ = UK WASP- (La Palma+SAAO)
2005 Transit Searches
Wide
Deep
10cm
1-4m
10°
< 1°
Field of View (degrees)
0.1
1
10
100
1000
1
10
100
1000
2005 Transit Searches
Wide
Deep
Planets per Month
0.1
1
10
100
1
10
100
1000

UK WASP Experiment
Wide-Angle Search for Planets

2004 SuperWASP La Palma
2005 SuperWASP SAAO

Robotic Mount
8 cameras / mount
11cm F/1.8 lens
2K x 2K E2V CCD
8^o x 8^o field
15 arcsec pixels

UK WASP Consortium: Belfast, St.Andrews, Keele, Open, Leicester, Cambridge, IAC, SAAO.   D.Pollacco = PI

Wide Transit Survey Discovery Potential

Assume HD 209458 (V=7.6 mag) is brightest.

mag	8	9	10	11	12	13
all sky	1	4	16	64	256	1k
16^{o}x16^{o}	-	-	0.1	0.4	1.6	7

How long to find them all ?

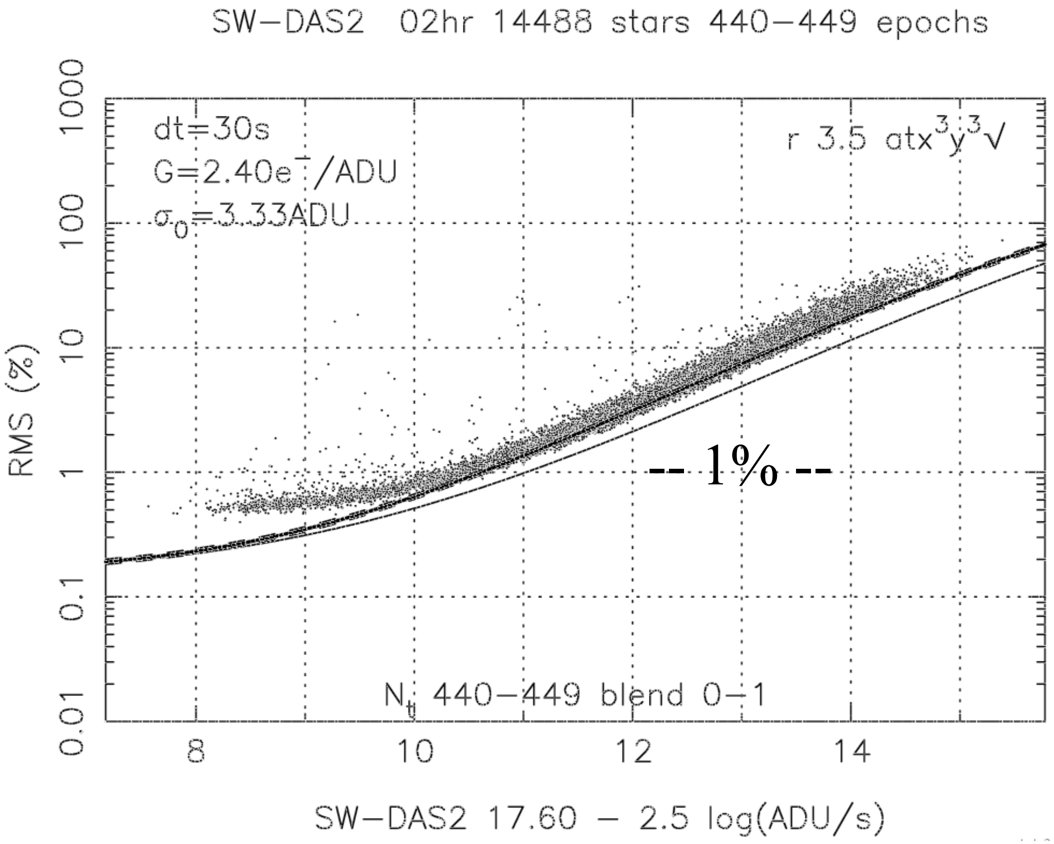
~ 150 16^{o}x16^{o} fields

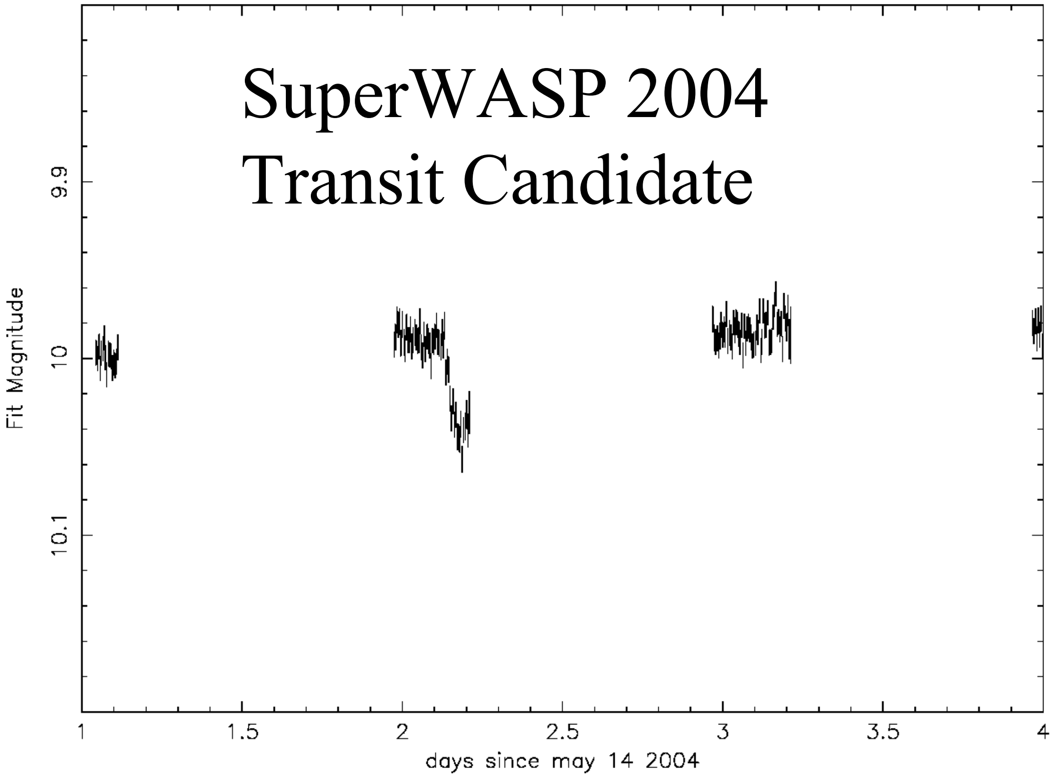
~ 2 months / field

~ 25/N years N = number of 16^{o}x16^{o} cameras

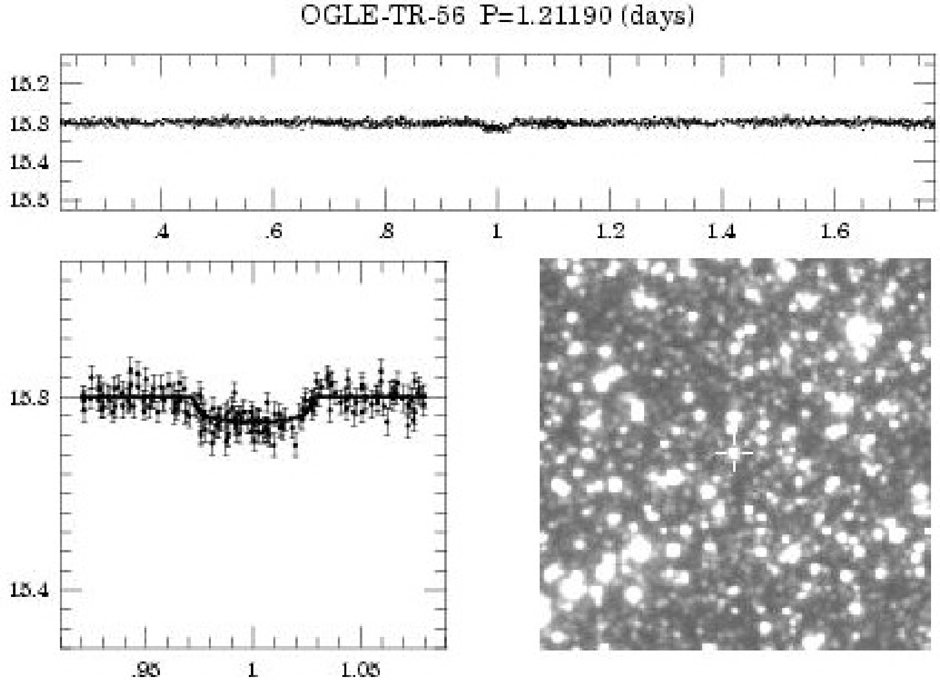
SuperWASP
2004 Data Under Analysis

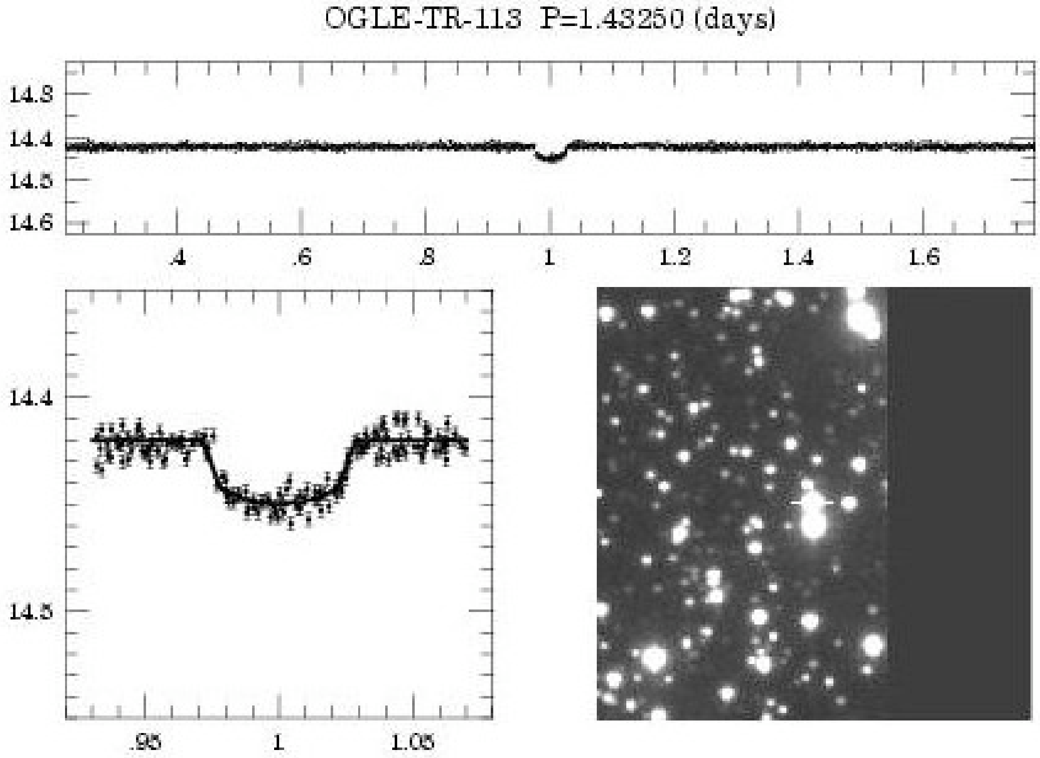
(B.Enoch poster)





OGLE III Transit Candidates





3m Las Campanas (microlens survey telescope)

Mosaic 8-chip CCD camera

2001 Galactic Bulge -- 64 candidates
2002 Carina -- 73 candidates

2004 Nov

Deep surveys of Galactic Plane fields yield **many false alarms**:

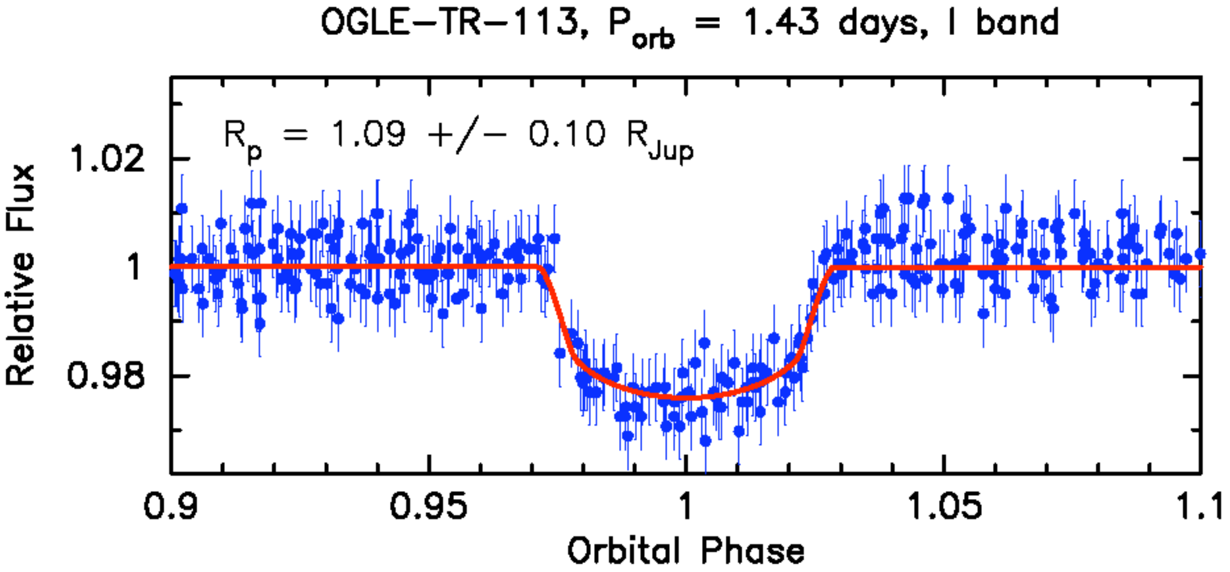
grazing or blended eclipsing binaries,

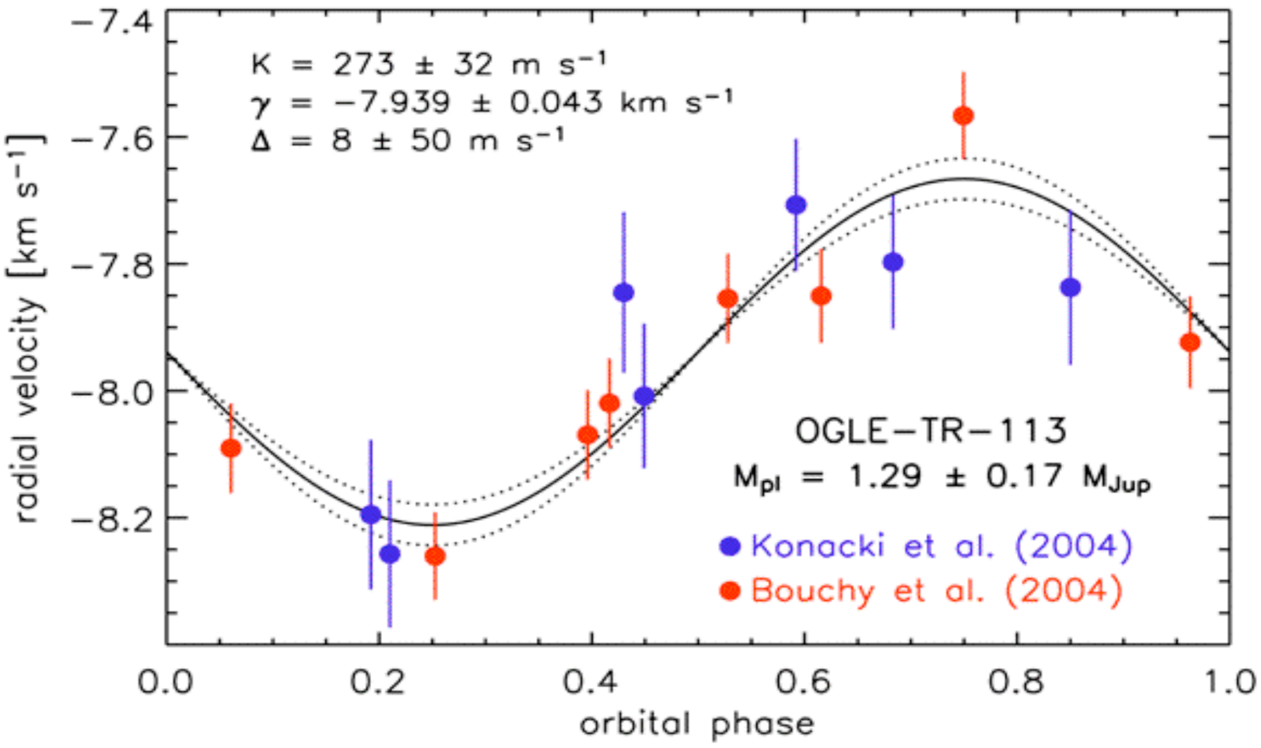
brown dwarf eclipses

6 planets discovered by transits

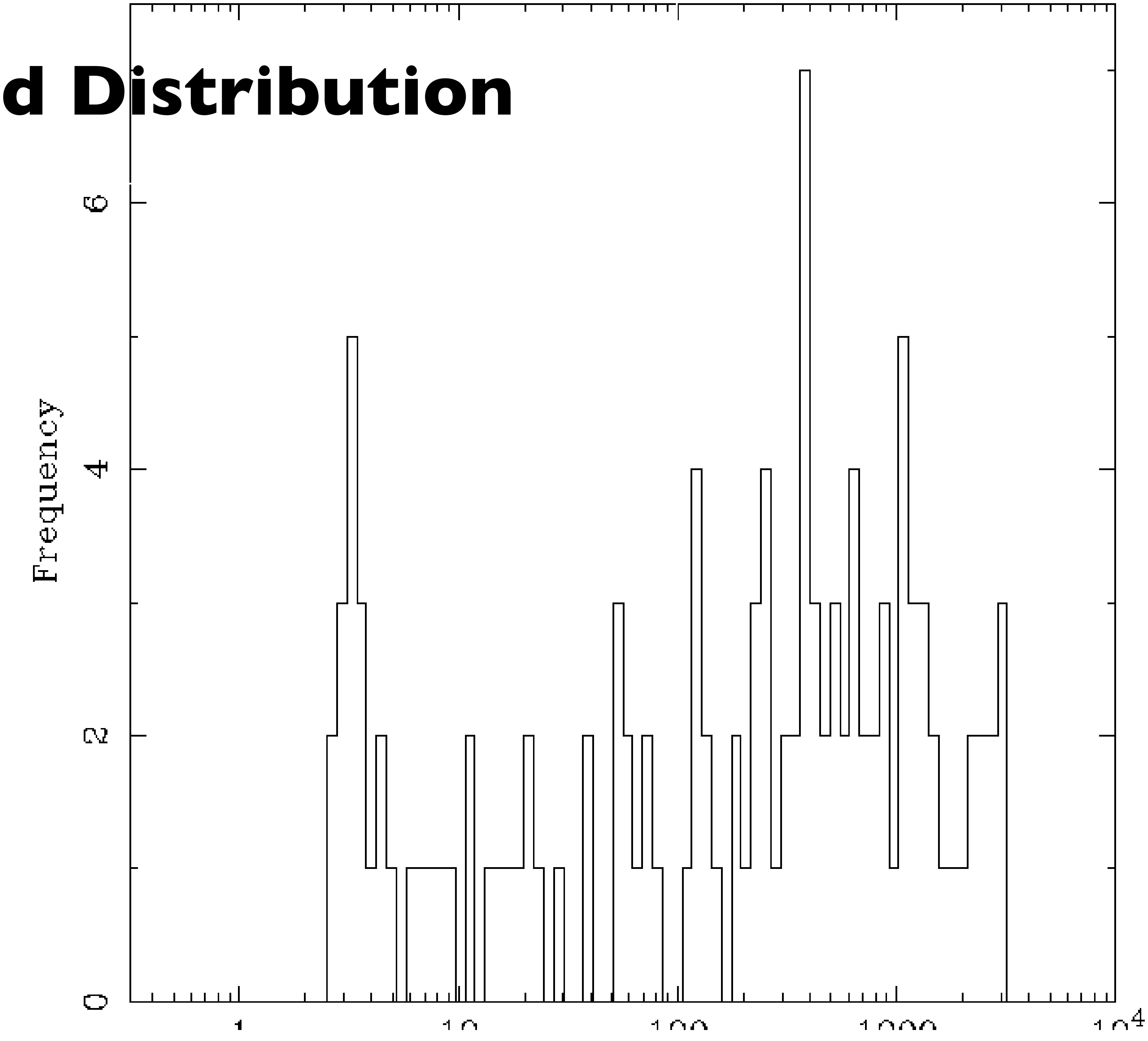
and confirmed by radial velocities

3 with P < 3d (?)





Period Distribution



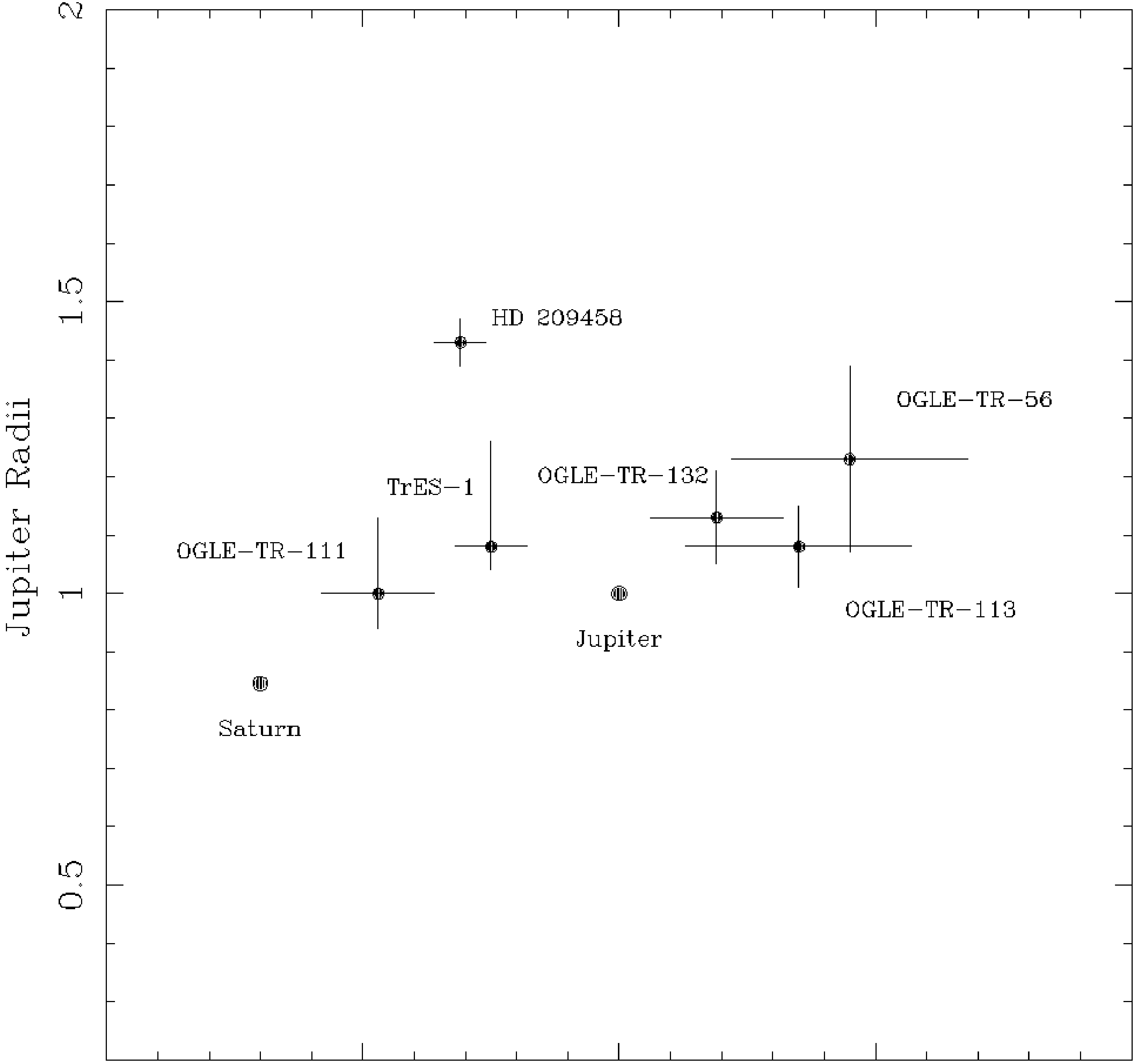
New class of
very-hot
Jupiters?

Different
selection
effects ?

Radius vs Mass

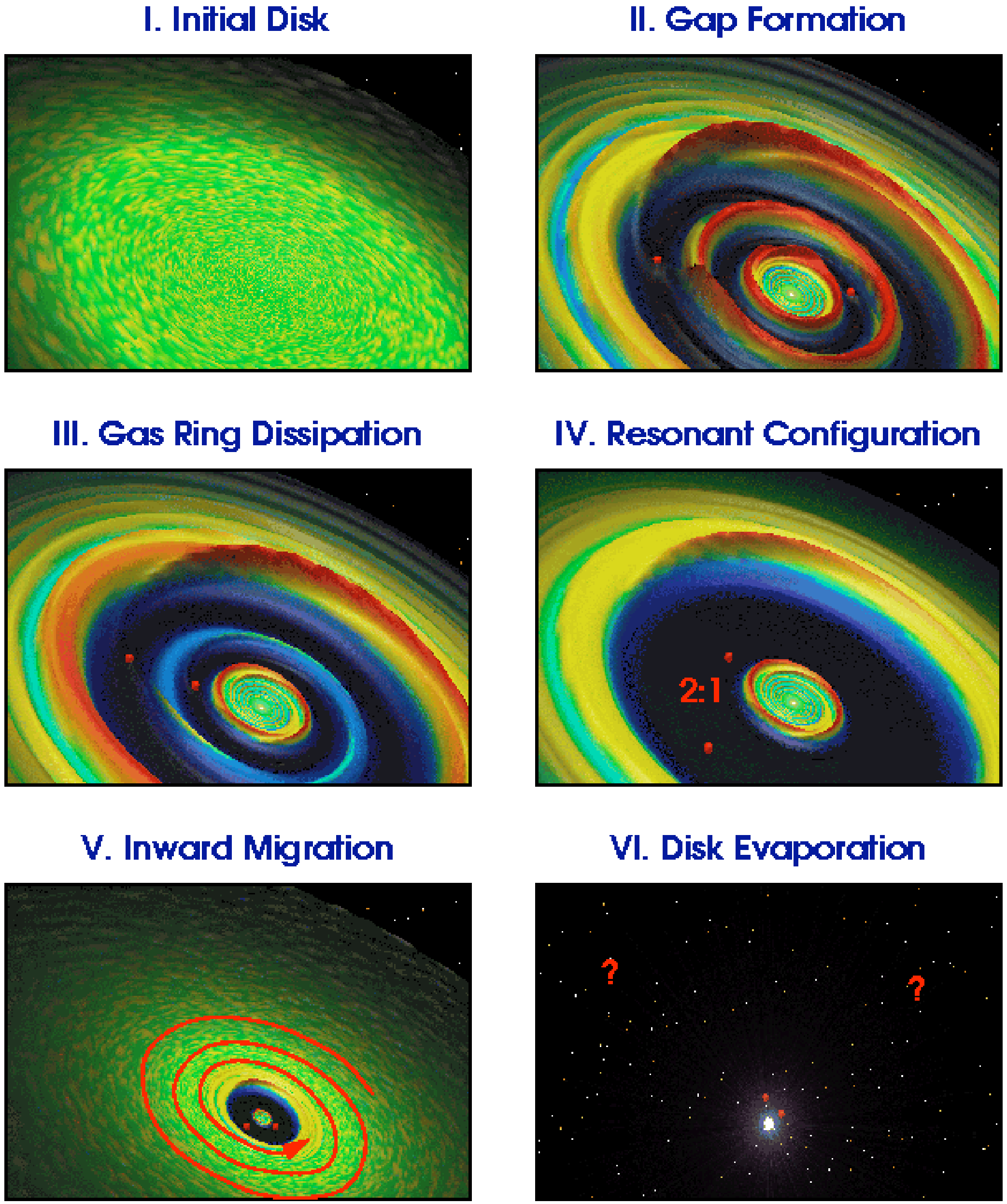
At least 2 parameters

Rapid inward migration -> no time to cool



New Planets, New Theories of Formation and Evolution

Evolution of Two Neighboring Planets in a Protostellar Disk



Bryden/Lin 2001
http://www.ucolick.org/~bryden/2planet

Planets form from dust and gas in Protostellar Accretion Disks

- **Evidence for dusty disks:**
- Solar system.
- Infrared excess from unresolved disks
- HST: protostellar disk images.
- SCUBA: debris disk images.

- **Disk Theory:**

Angular momentum flows out.
Matter spirals in.

Keplerian orbits: $V_K^2 = G\ M / R$

Thin if supersonic: $H / R \sim c_S\ / V_K$

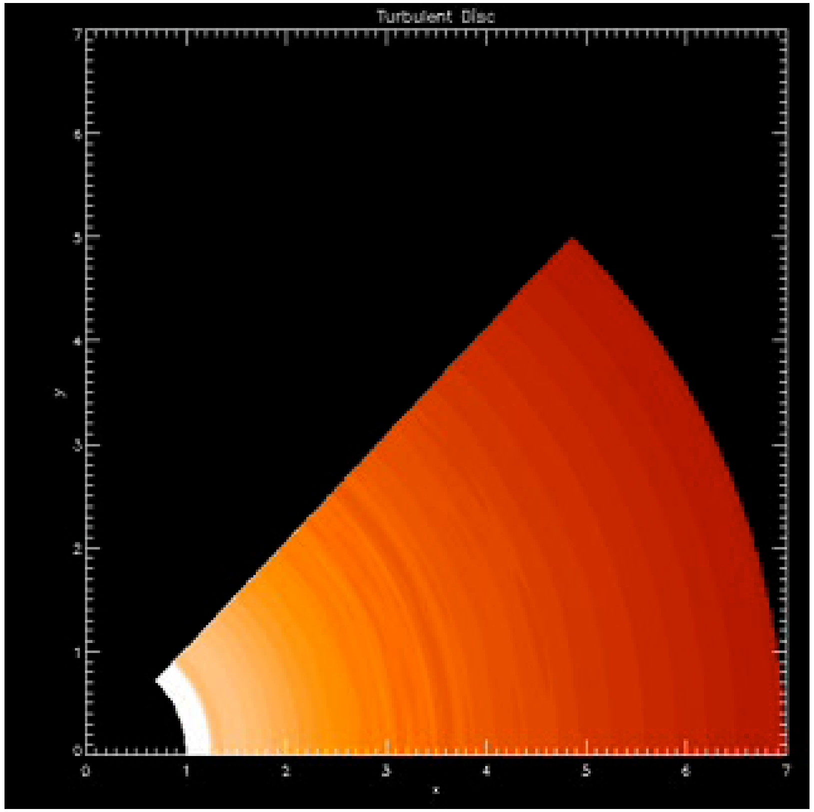
Anomalous viscosity => gas inspiral:

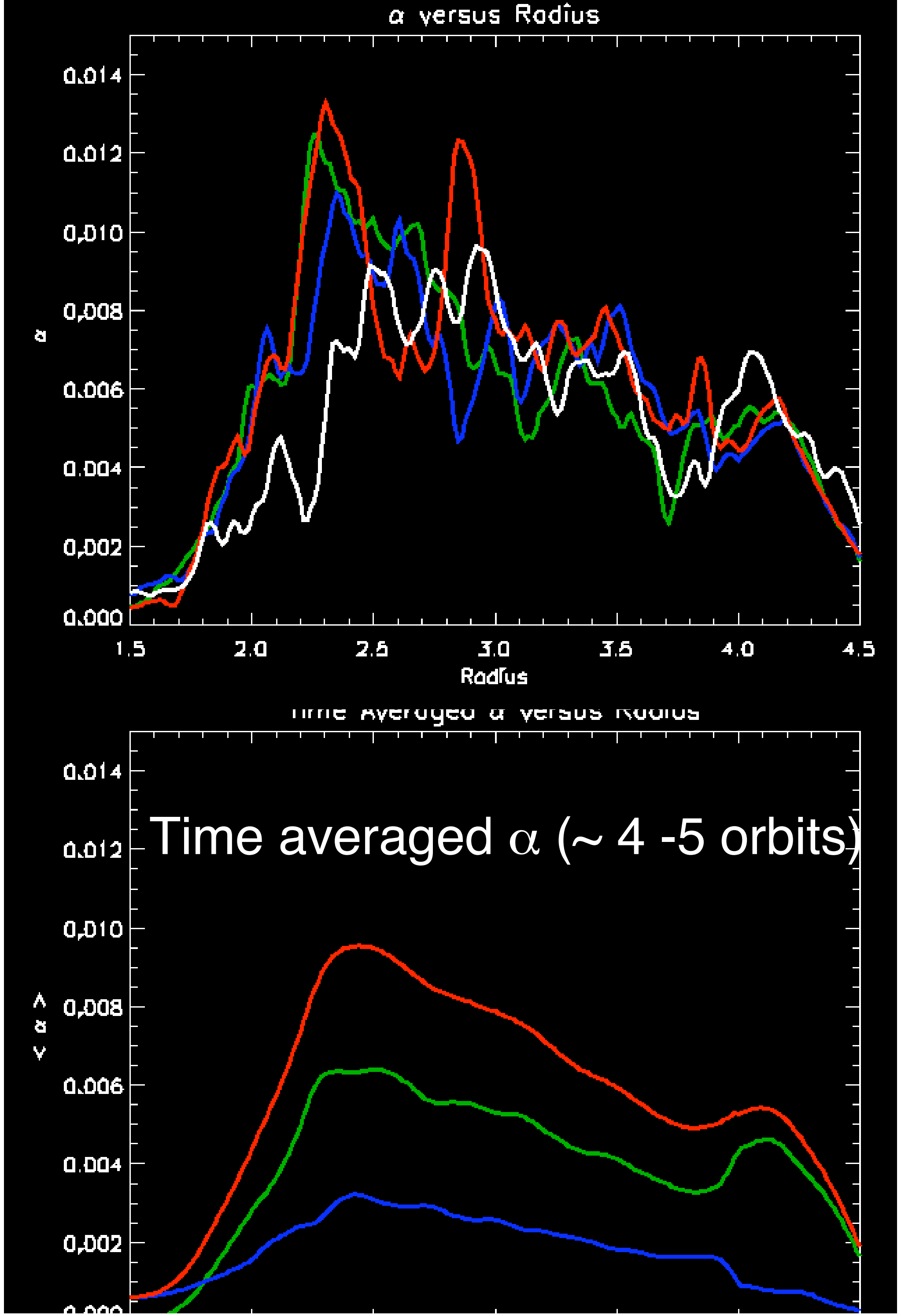
$$V_R = -\nu / R$$

$$\nu = \alpha\ c_S\ H$$

MHD turbulence

Magneto-Rotational
(Balbus-Hawley) instability



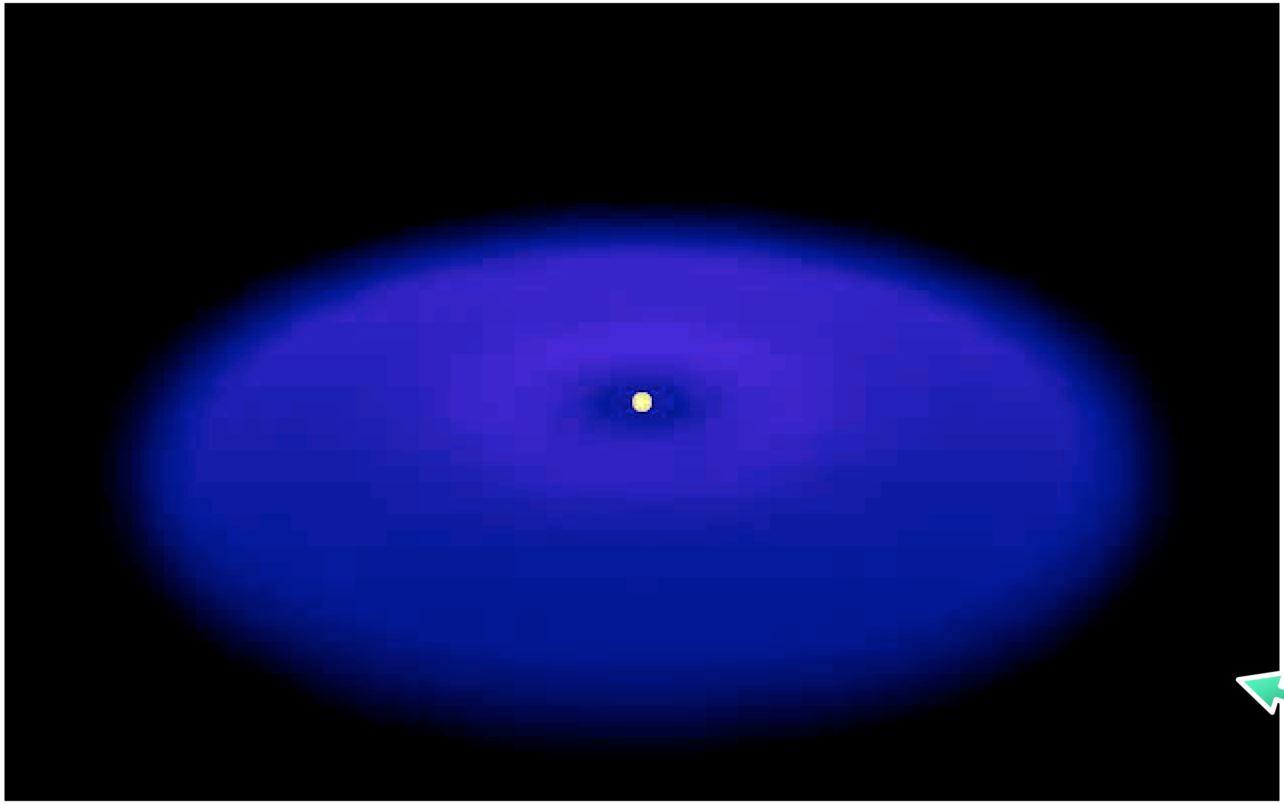


Time averaged α (~ 4 -5 orbits)

$$\alpha \sim 10^{-3}$$

Nelson, Papaloizou

Gravitational Instability



Kuiper 1951
Cameron 1978
DeCampli & Cameron 1979
Boss 1998
Boss 2000
Mayer et al. 2002
Pickett et al. 2003
Rice et al 2003a
Rice et al 2003b
Boss 2003
Cai et al 2004
Boss 2004
Mayer et al 2004
Mejia et al 2005

Requirements for **gravitational instability**:

1. (Toomre 1964) . $Q \equiv \frac{c_S \, \Omega}{\pi \, G \, \Sigma} < Q_{crit} \sim 1$

$$\boxed{M_{disk} > \frac{H}{R} M_*}$$

2. Cooling of fragments faster than orbit time (Gammie 2001).

Dust to planetesimals

- Sub-Keplerian gas orbits

$$V_\theta^{\ 2} = V_K^{\ 2} + \left(\frac{d \ln P}{d \ln R} \right) c_S^{\ 2}$$

  - Gas pressure decreases outward
- Gas drag on dust
  - Settling to mid-plane
  - Inspiral fastest for r = 10-100 cm "rocks"
  - Concentration by spiral waves, turbulence, vortices
- Growth of planetesimals

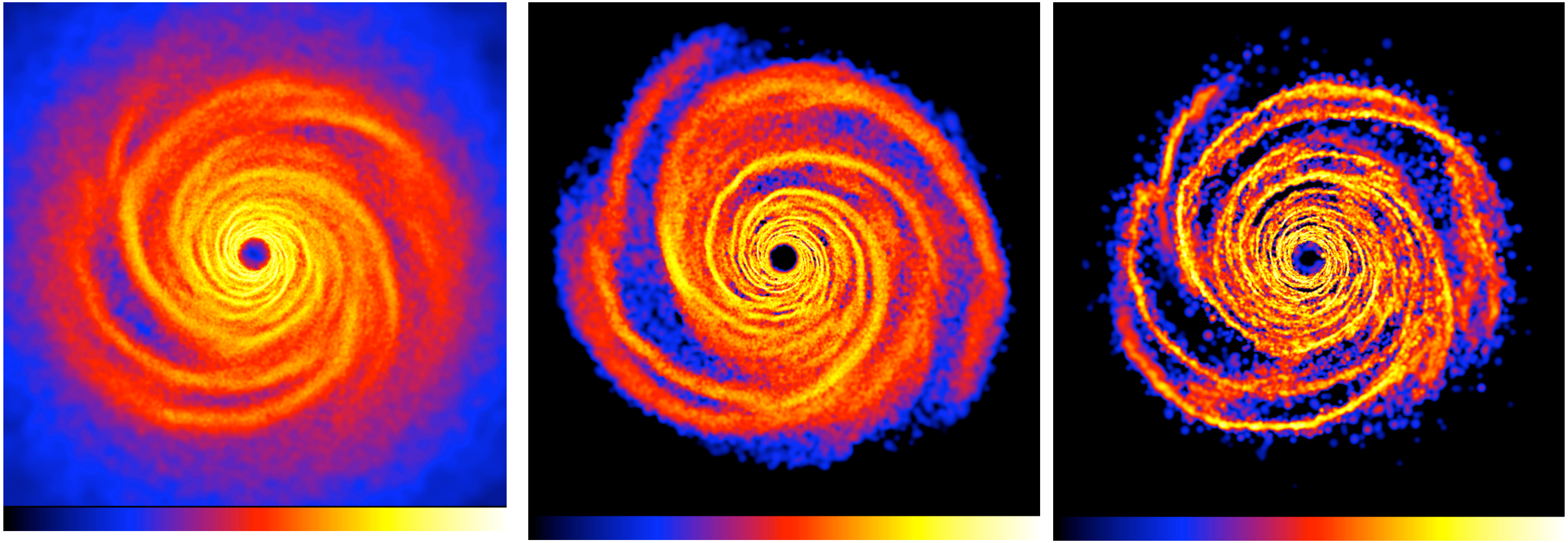
$$\dot{m} = \pi \ r^2 \ \rho_d \ \Delta V_d$$

  - **Need to concentrate dust**
- Outside the "Snow line"

$$R > R_{ice} \sim 3 \ M_*^{\ 2} \ \text{AU}$$

  - Ice mantles on grains
  - Snowballs tend to stick

Planetesimal dynamics in massive discs



Gas

$r = 10^3$cm

50cm

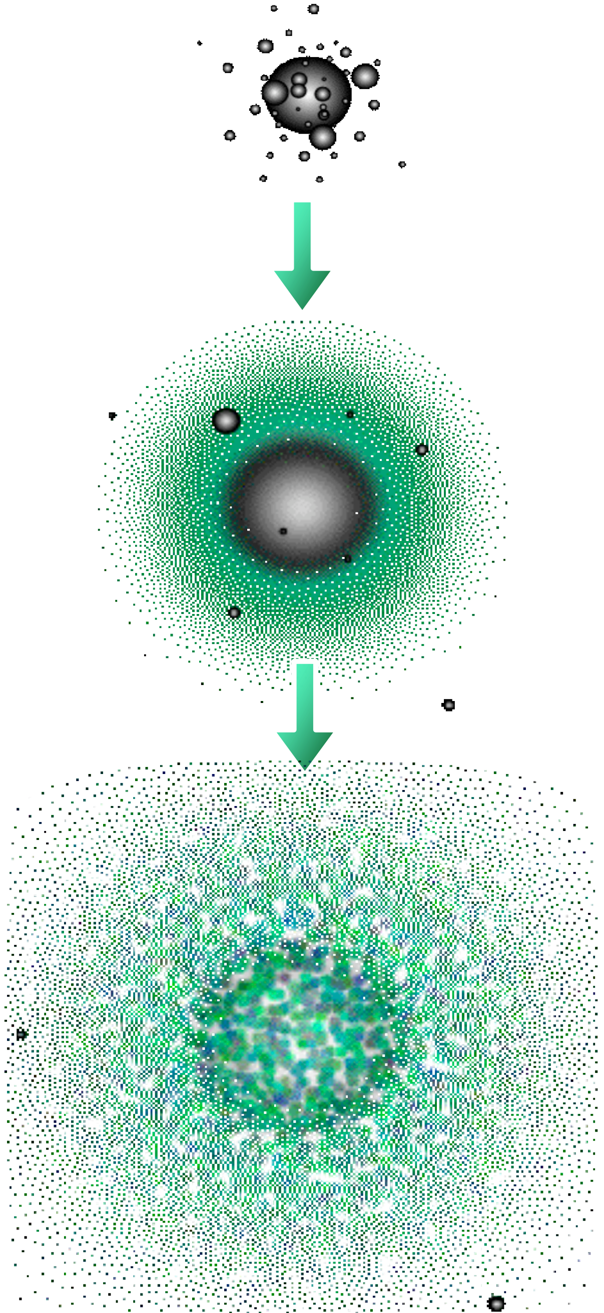
Planetesimals accumulate in the spiral arms

Rice, Lodato, et al. 2004

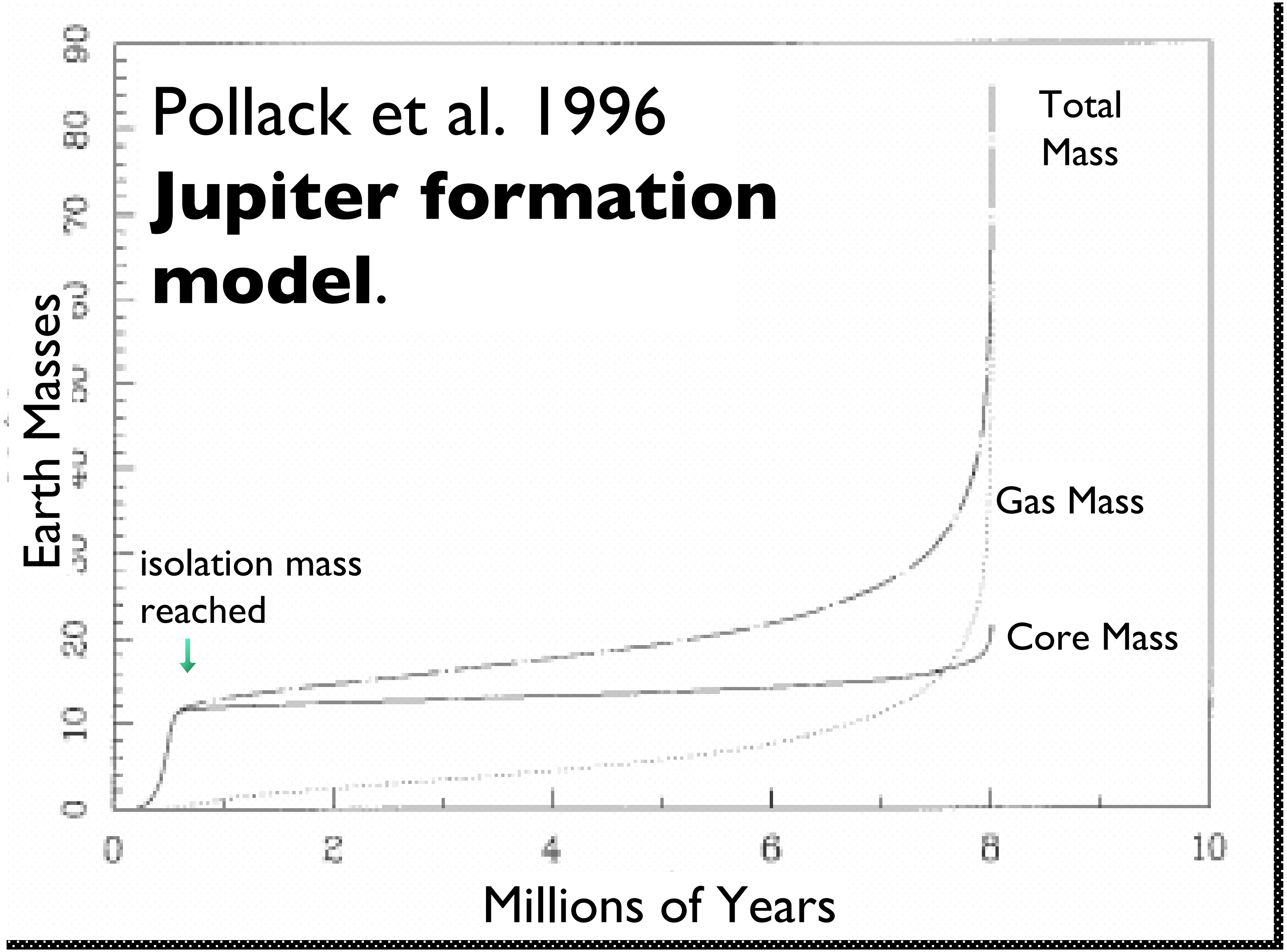
Core Accretion

Perri & Cameron 1974, Mizuno et al 1978, Mizuno 1980, Bodenheimer & Pollack 1986, Pollack et al 1996

1. Rapid growth of solid core by accreting planetesimals.
2. Feeding zone depleted. Slow growth of solid core. Accretion of gas envelope.
3. Runaway gas accretion starts when envelope and core masses roughly equal.



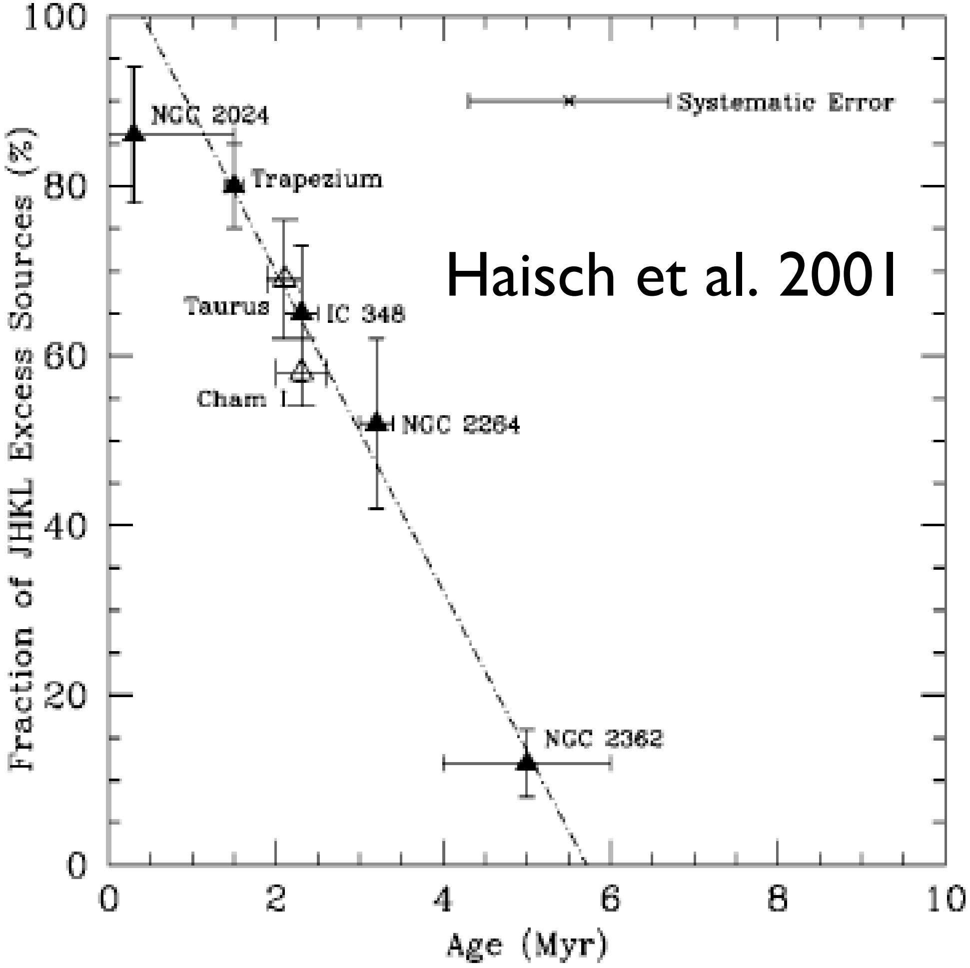
Pollack et al. 1996 **Jupiter formation model**.



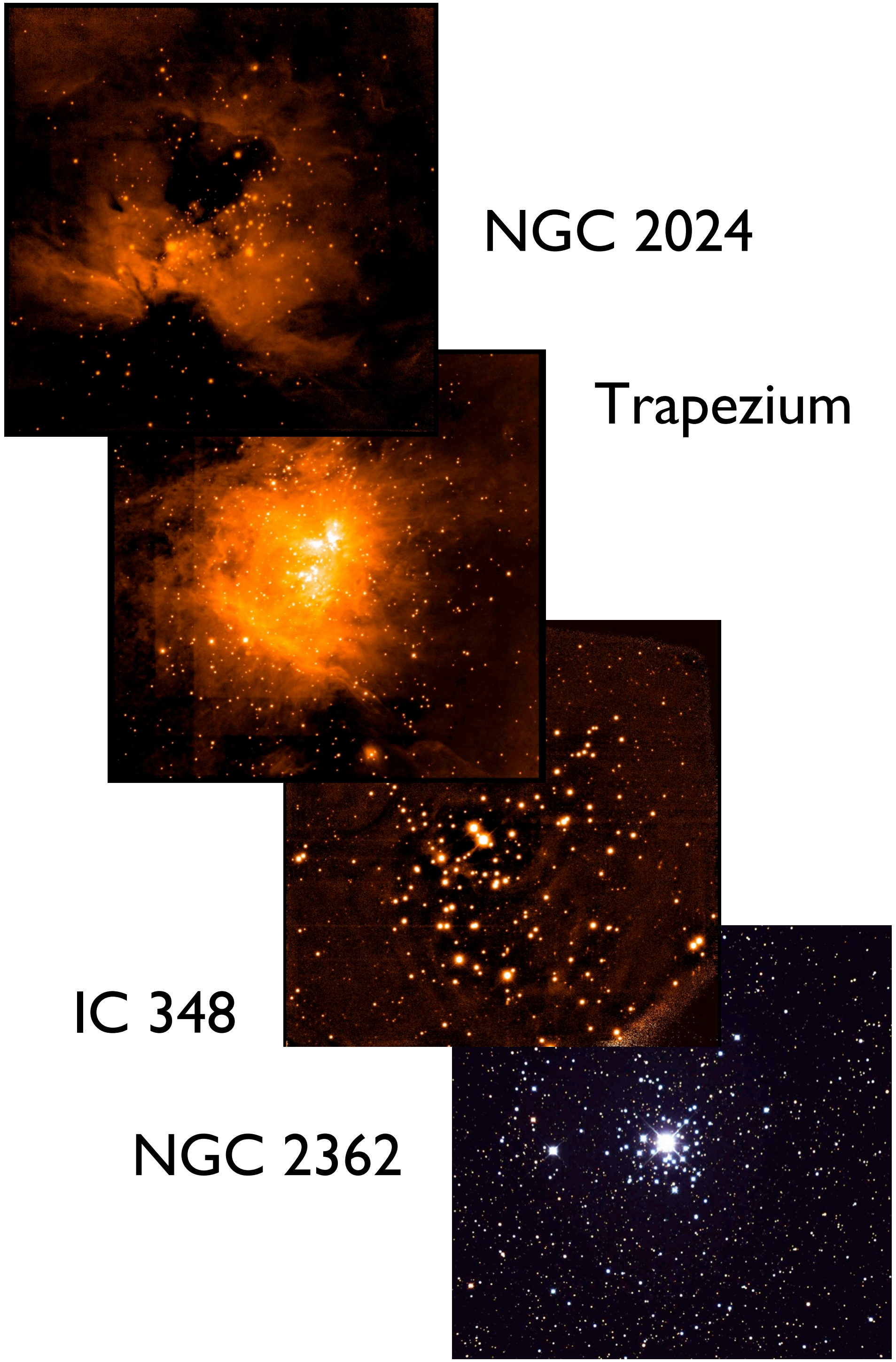
$$d = 5.2\,\mathrm{AU} \qquad \sigma_{solids} = 10\,\mathrm{g\,cm^{-2}}$$

$$T \qquad 150\,\mathrm{K} \qquad 5\times10^{-11}\,\mathrm{g\,cm^{-3}}$$

Disk lifetimes are short ~3Myr.



Haisch et al. 2001



~8 Myr required in the Pollack et al. (1996) standard case model.

Turbulent disc with giant protoplanet – migrates in ~ 10^5 yr

Growth slows when gap opens.

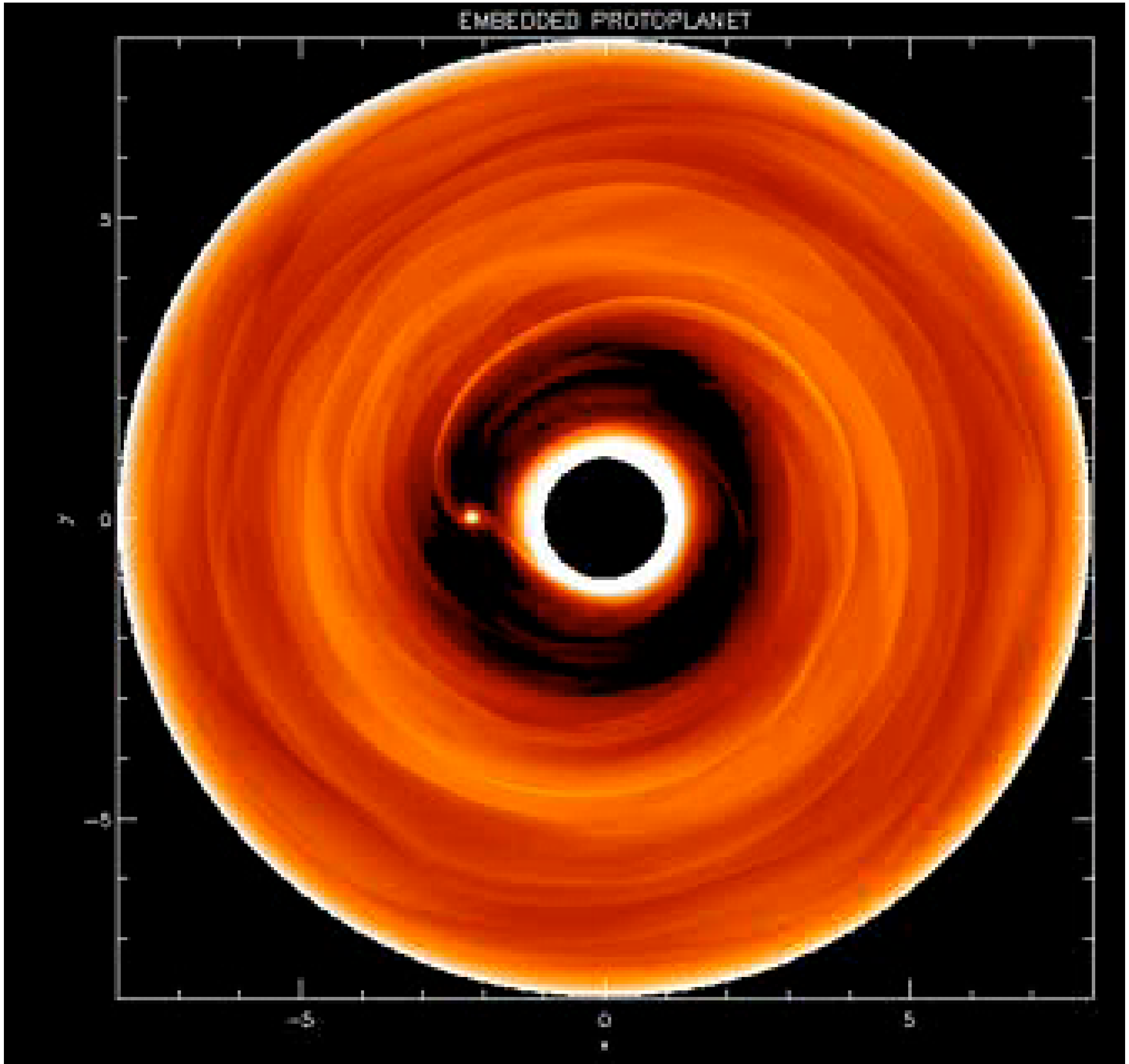
$R_H > H$

Gap width ~ 10 R_H

Hill radius:

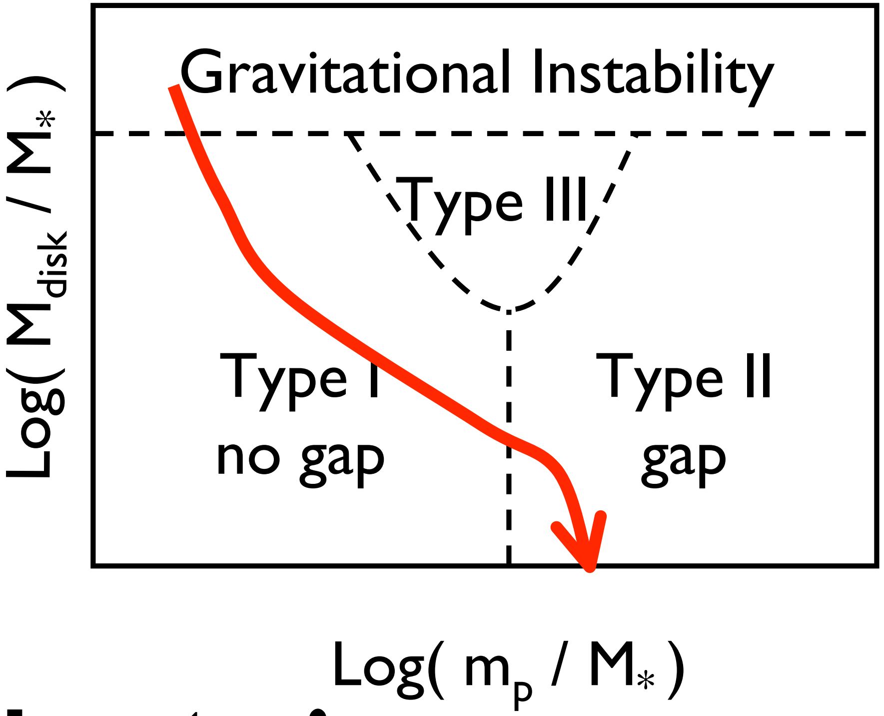
$$\frac{R_H}{a} = \left(\frac{m}{3M_*}\right)^{1/3}$$

Type II migration.



Orbital migration

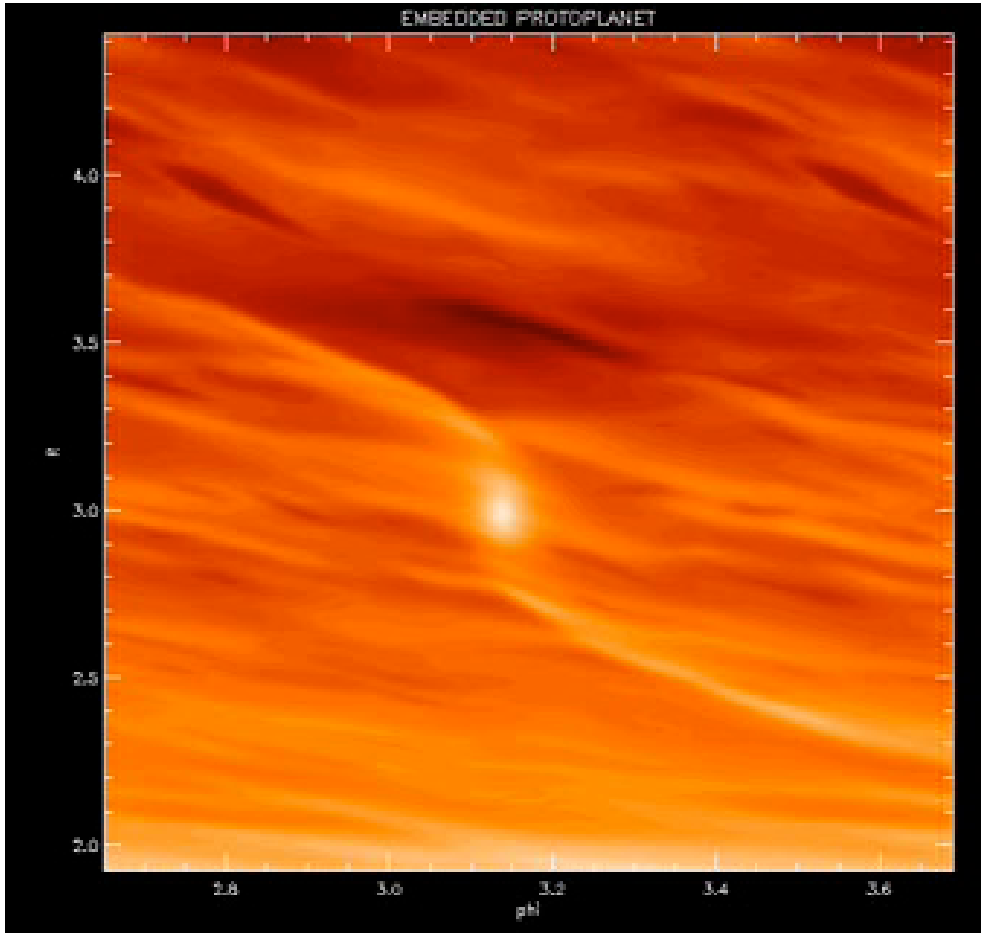
- Spiral waves induced by planet
  - Exchange angular momentum with disk
- Type I -- no gap. Fast.
  - m < Saturn
- Type II -- gap. Slow.
  - m > Saturn
- Type III -- runaway
  - m ~ Saturn
- **Planets migrate into the star!**
  - **Need to suppress Type I migration.**

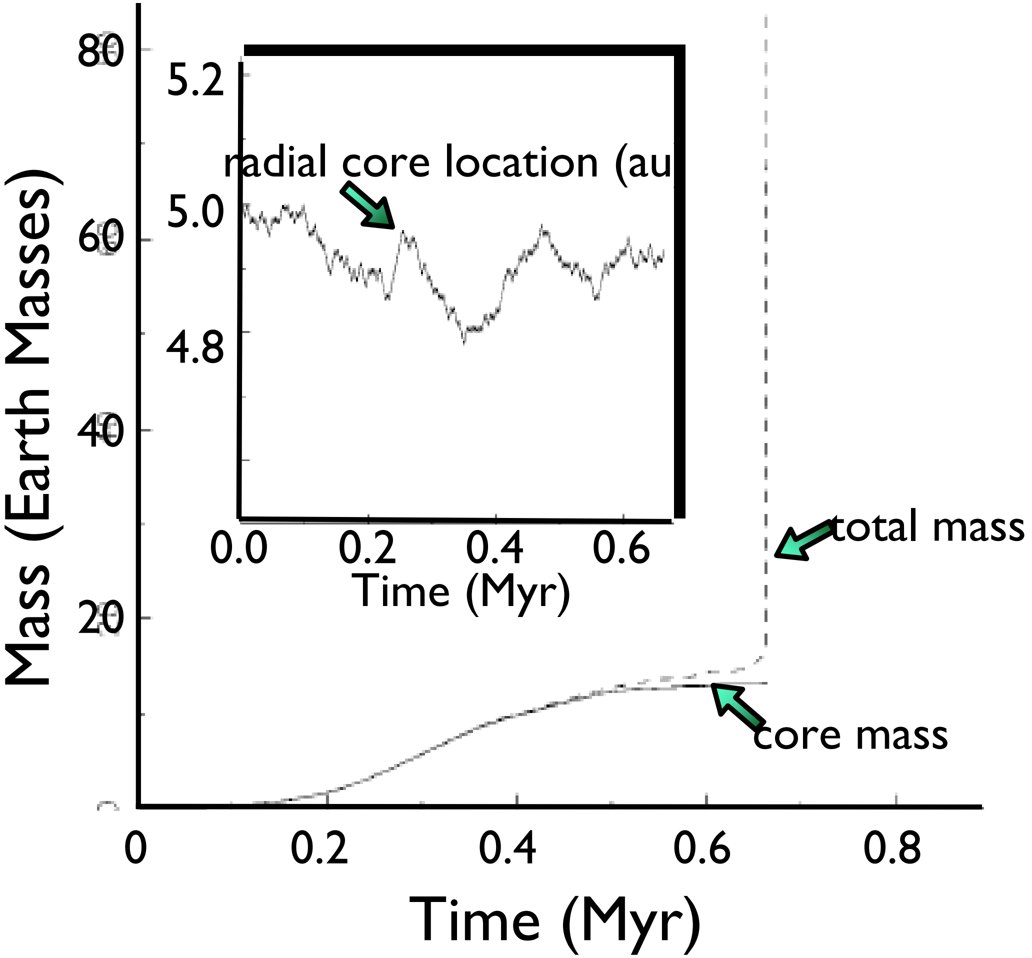


e.g. Masset & Papaloizou, 2003

MHD turbulence random walk migration

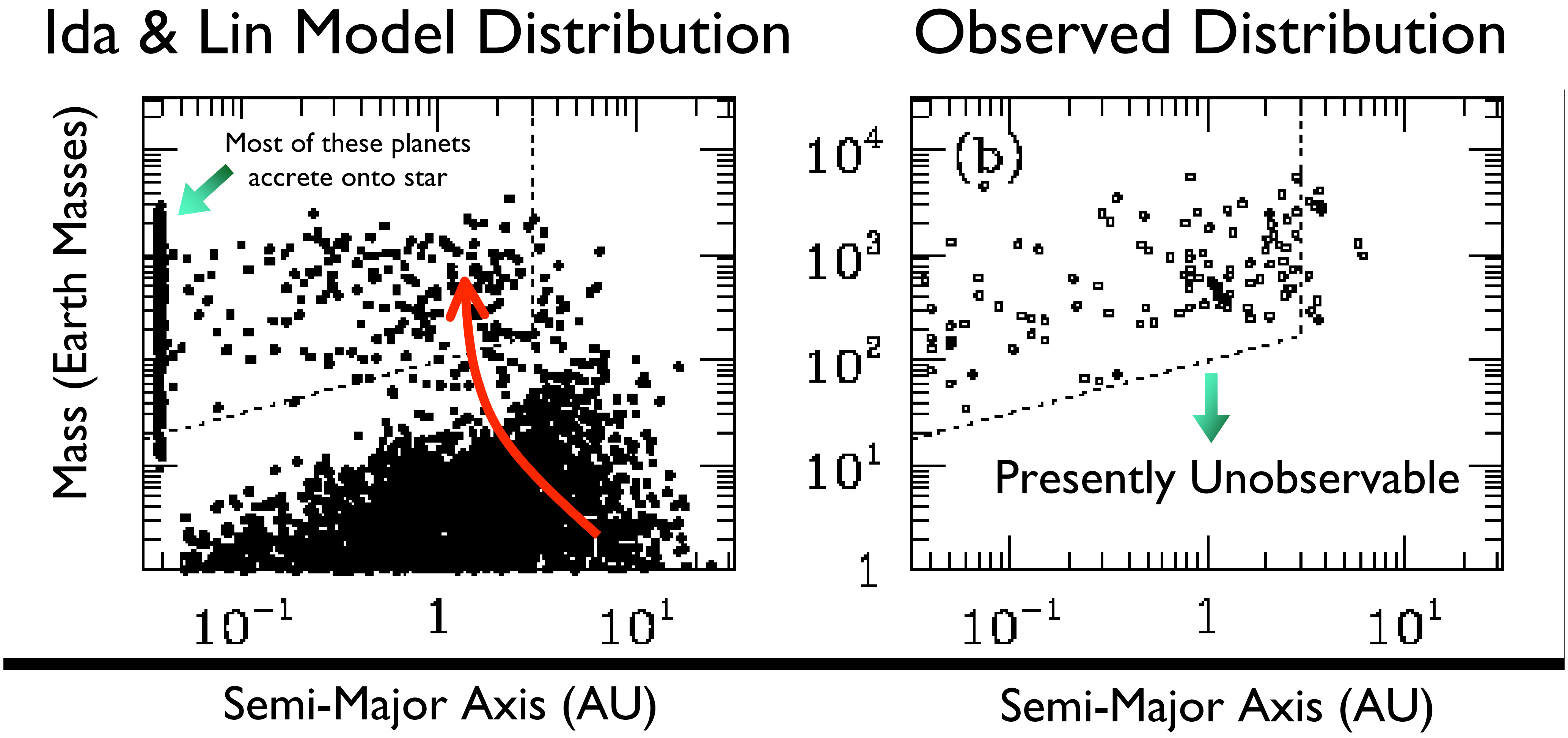
$m = 30\ m_J$





Papaloizou, Nelson, Snellgrove 2004

Rice & Armitage 2003



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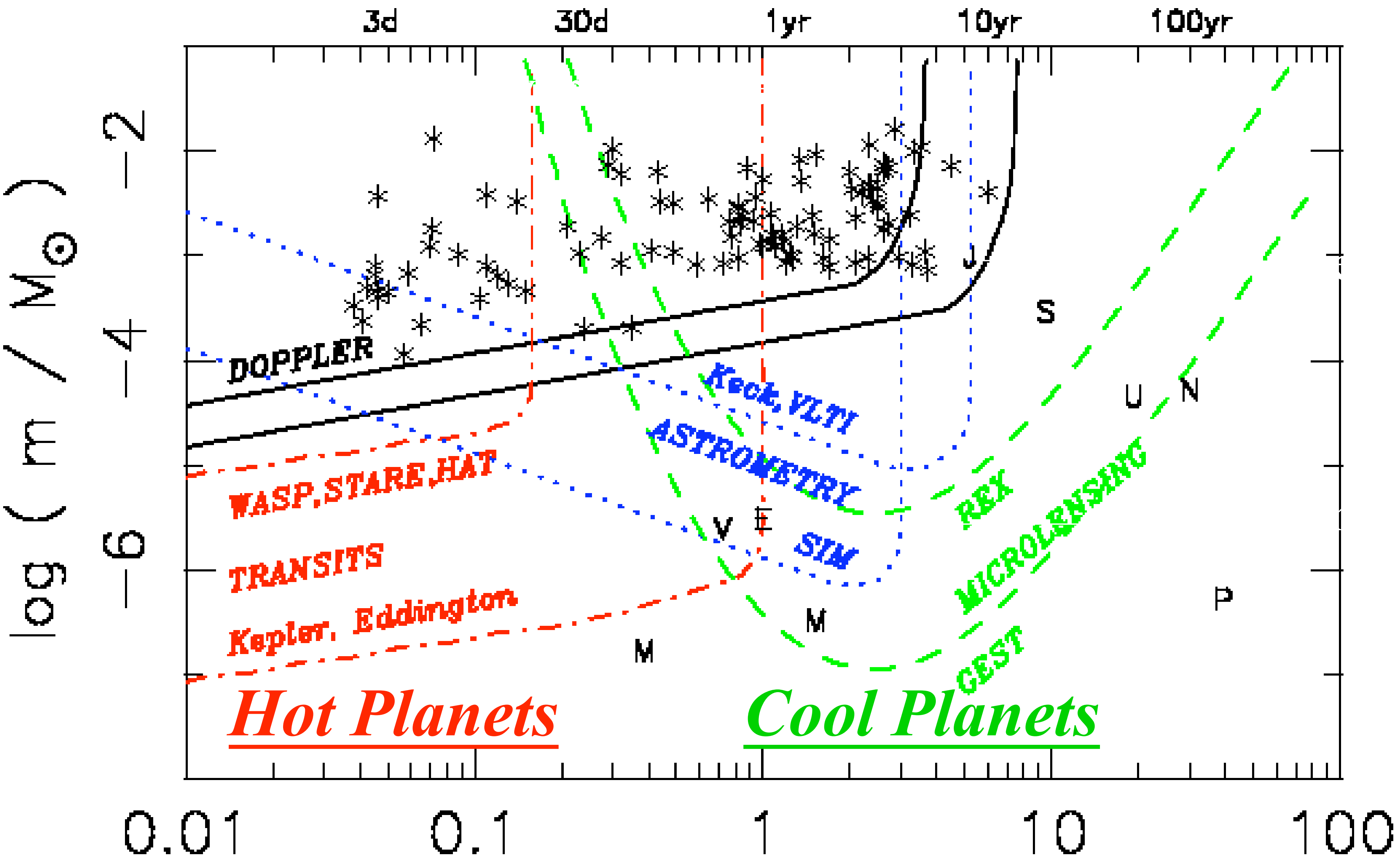
$$\tau_{mig} = \frac{a}{\dot{a}} = 10^6 \frac{1}{f_{(}g,0)} \exp^{t/\tau_{dep}} (\frac{M_p}{M_J})(\frac{a}{1\mathrm{AU}})^{1/2} \mathrm{yr}$$

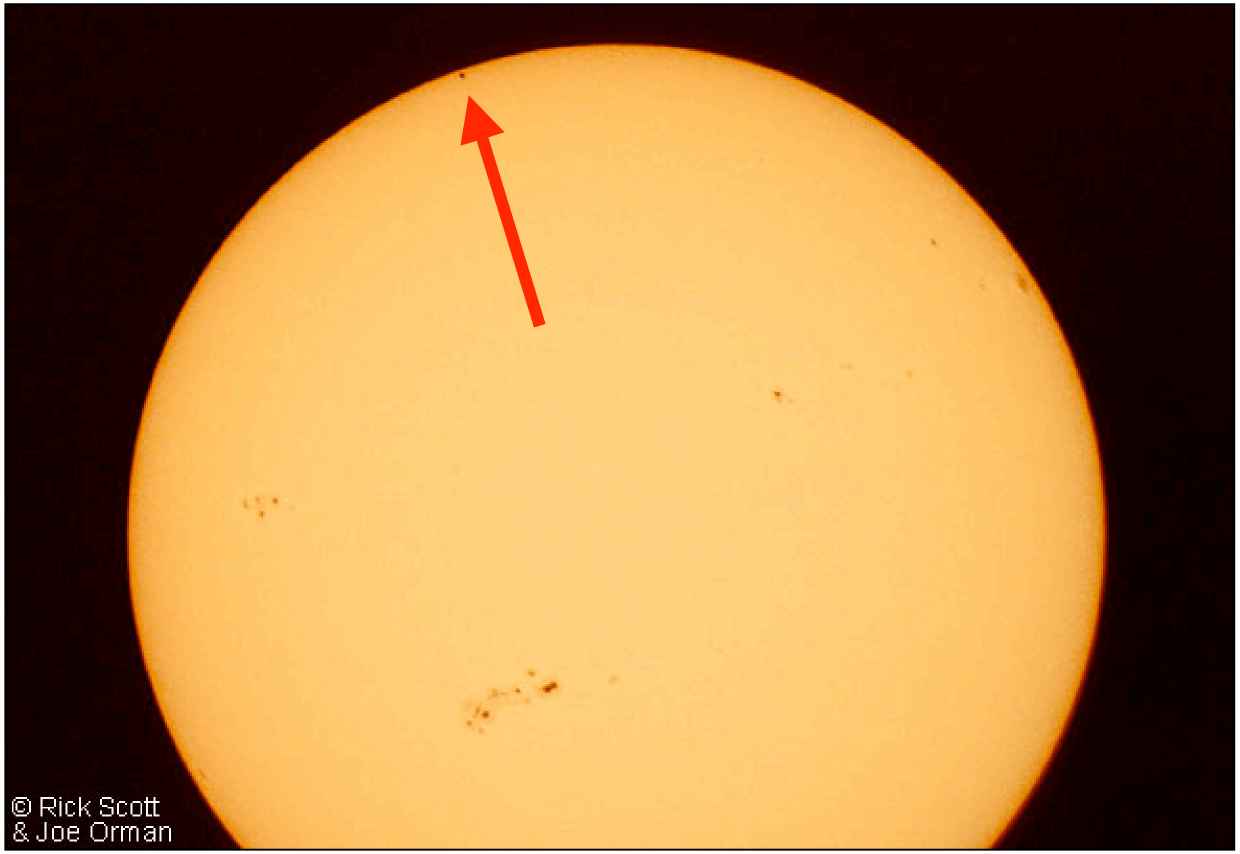
How to find Earths

- ***Hot Earths***: transits from space
  - 2006 … Corot
  - 2008 … Kepler ~~(Eddington?)~~
- ***Cool Earths***: microlensing
  - OGLE, MOA
  - PLANET, microFUN
  - RoboNet (--> REX)

Complementary Methods



Mercury transiting the Sun 1999 Nov 15



Earth transits:

$$\frac{\Delta f}{f} \sim 10^{-4}$$

HST results suggest this is feasible.

Mercury transits:

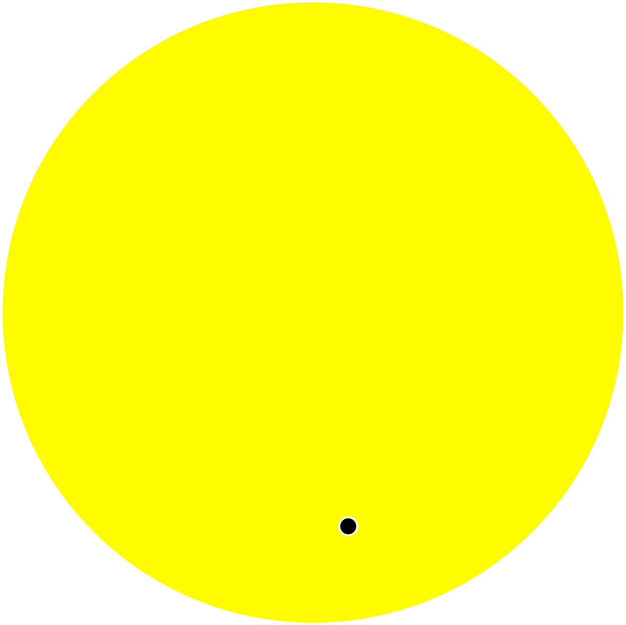
2003 May 07
2006 Nov 08

Venus transits:

2004 Jun 08
2012 Jun 06

Space Transit Missions

Designed to detect Earth analogs



$$r \sim r_{\oplus} \sim 0.01\ R_{sun}$$

$$T \approx 300\text{K}$$

$$P \sim 1\ \text{yr}$$

$$a \sim 1\ \text{au}$$

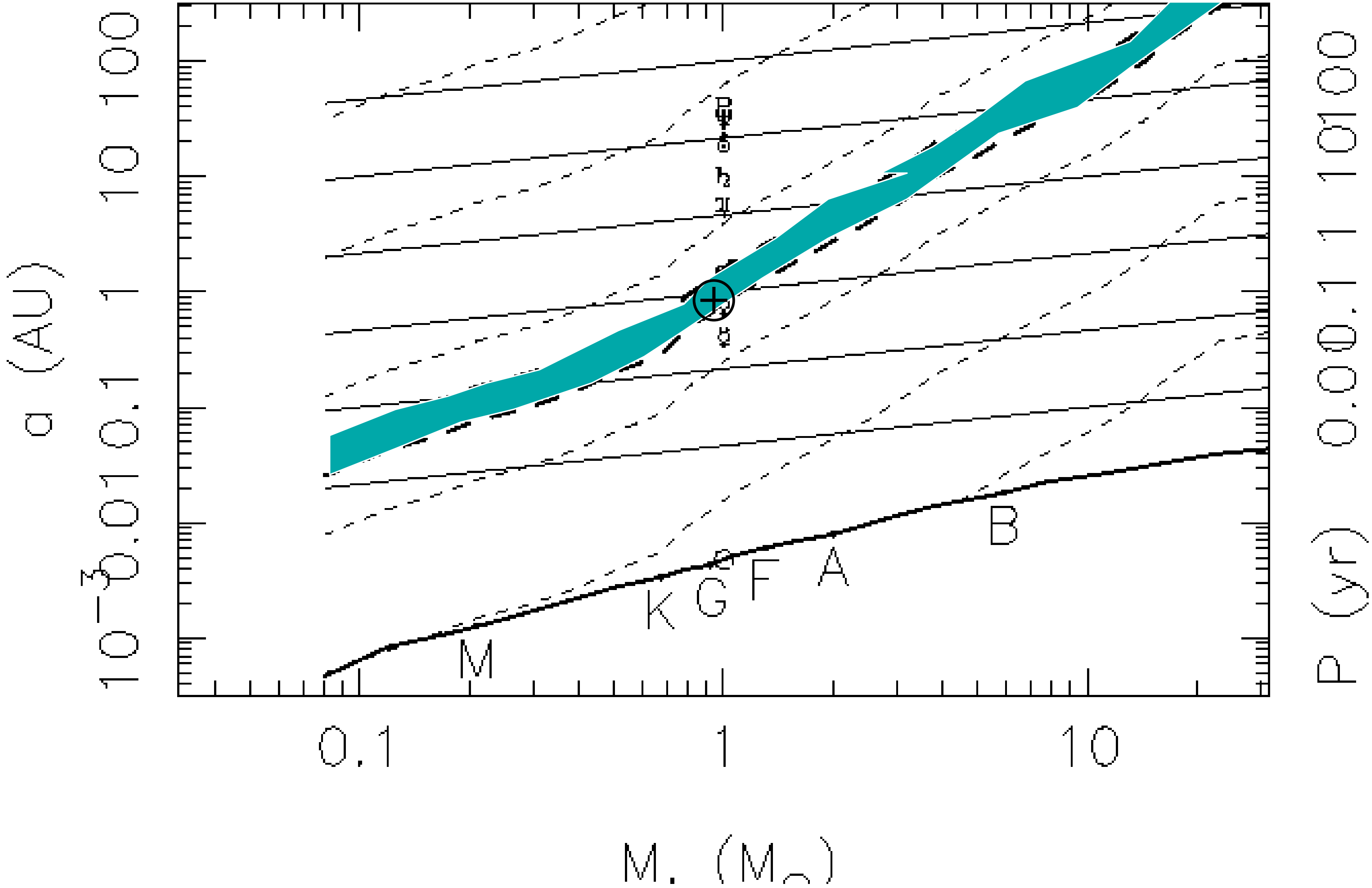
$$\Delta t \sim 13\ \text{h}$$

$$\Delta f\ /\ f \sim 10^{-4}$$

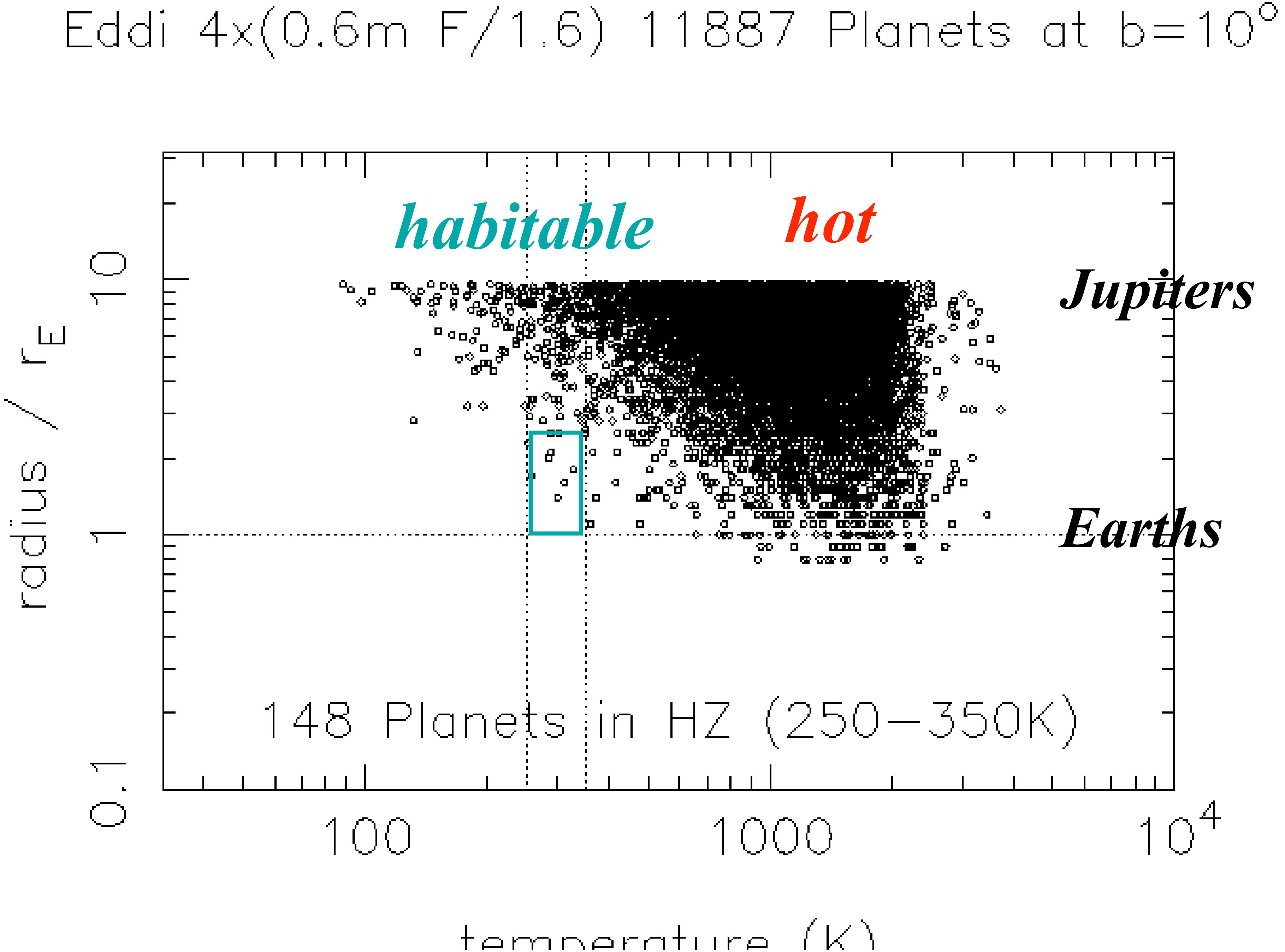
Transit probability: $P_t \sim 0.5\%$

"The Habitable Zone"

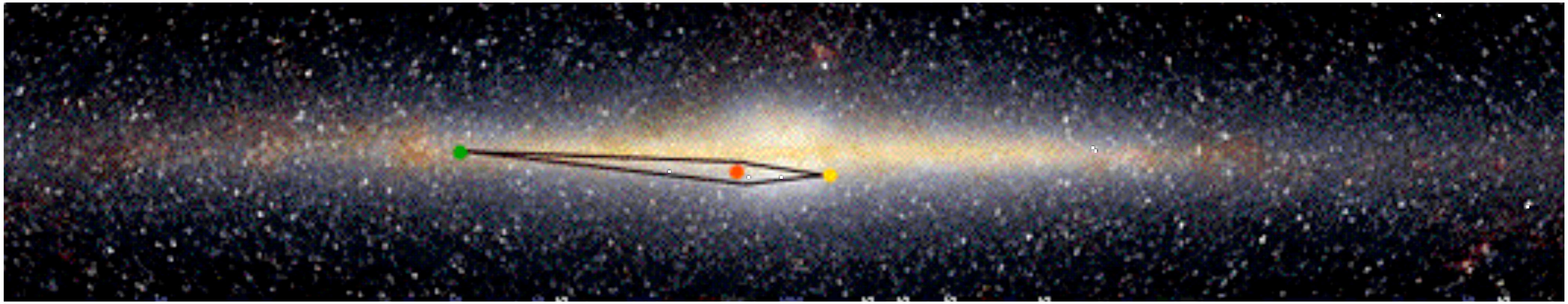
T~300K

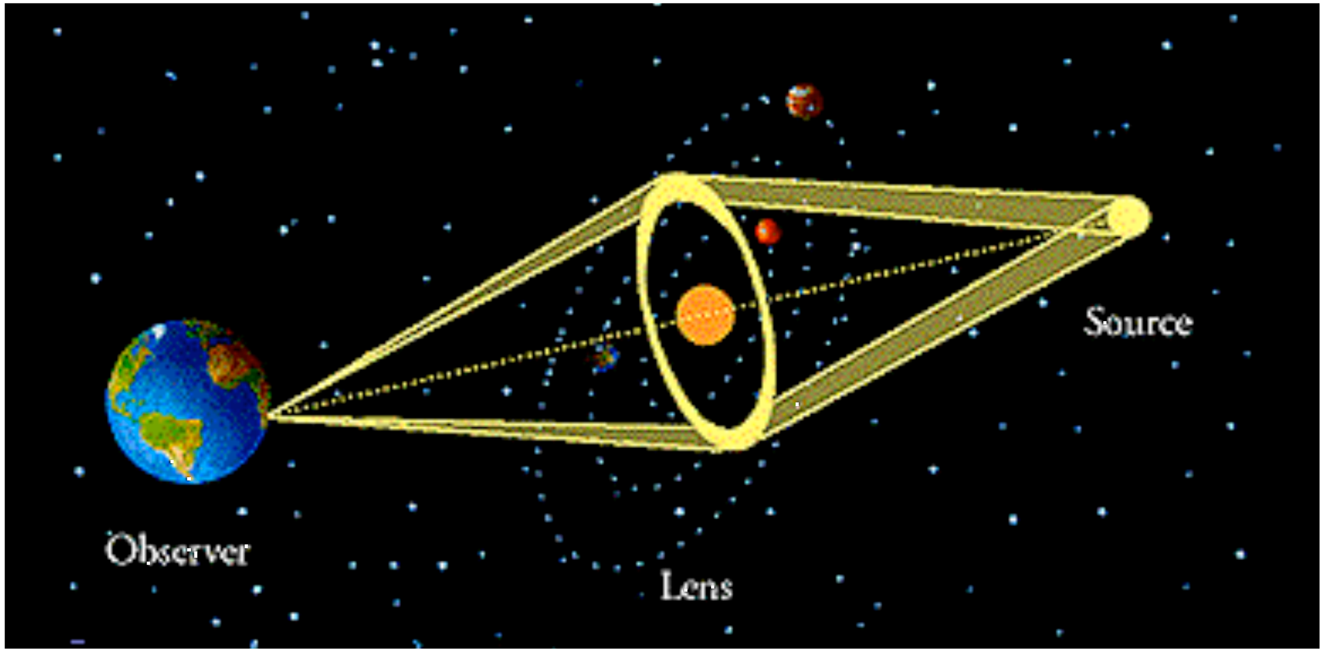


Eddington Planet Catch Simulation



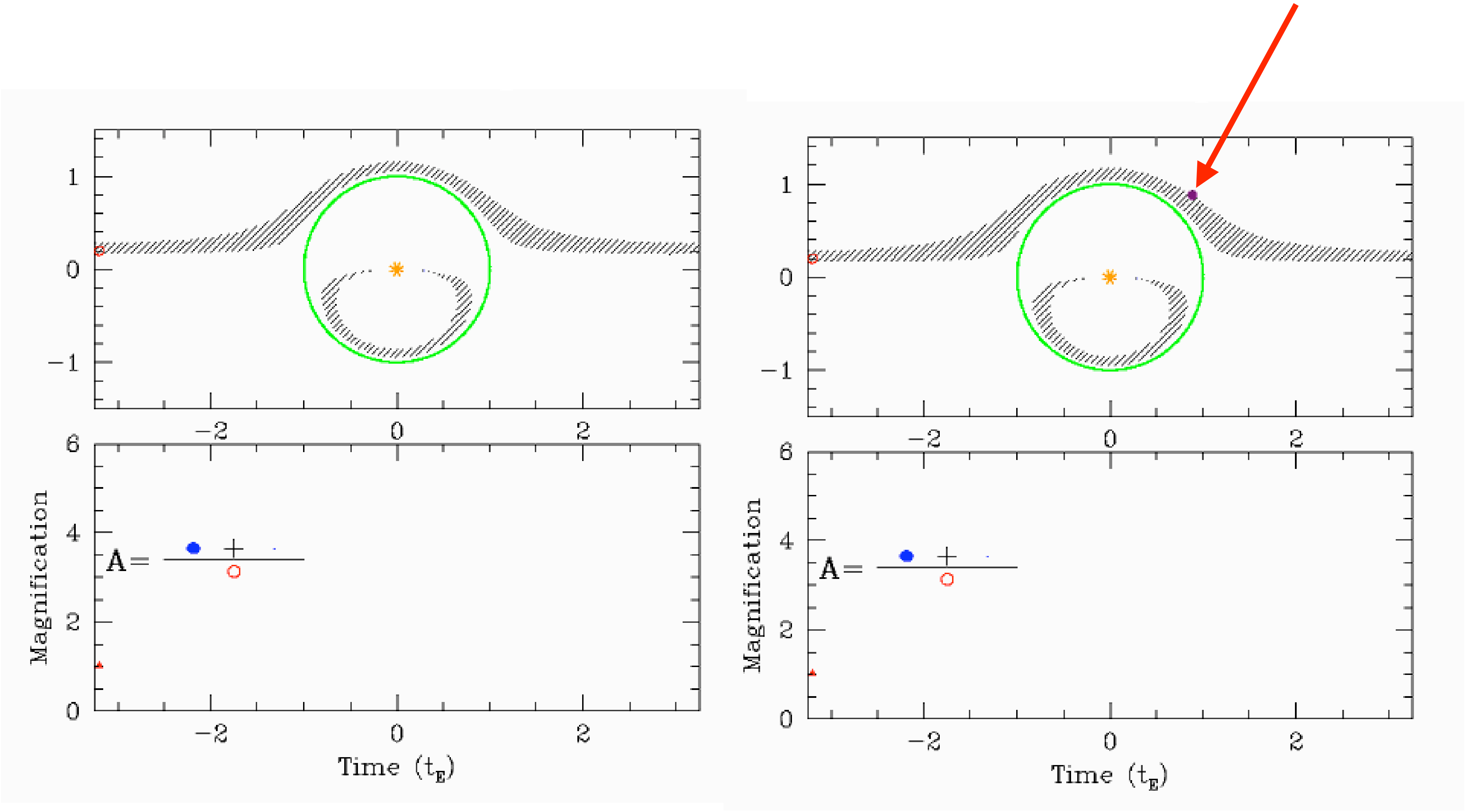
Gravitational Microlensing





Hunting for
Cool Planets
near the
Lens Star

Lensing by a Star with a Planet



~600 Galactic Bulge lensing events found each year

$M_{\text{lens}} \sim 0.3\, M_{\text{sun}}$ $R_E \sim 4$ AU $\sim 10^{-3}$ arcsec

(Animations by Scott Gaudi)

OGLE III Galactic Bulge Microlens Search Fields

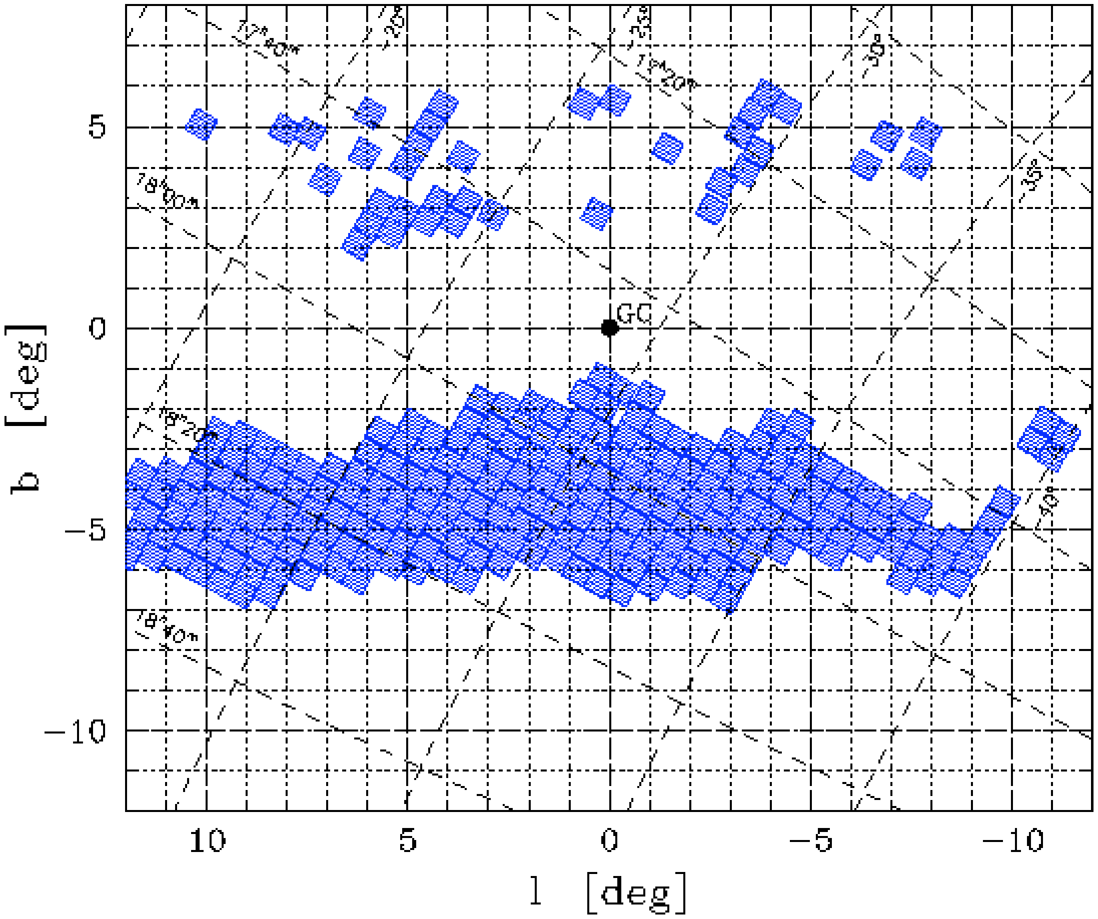
1.3 m Las Campanas

~ 150 million stars

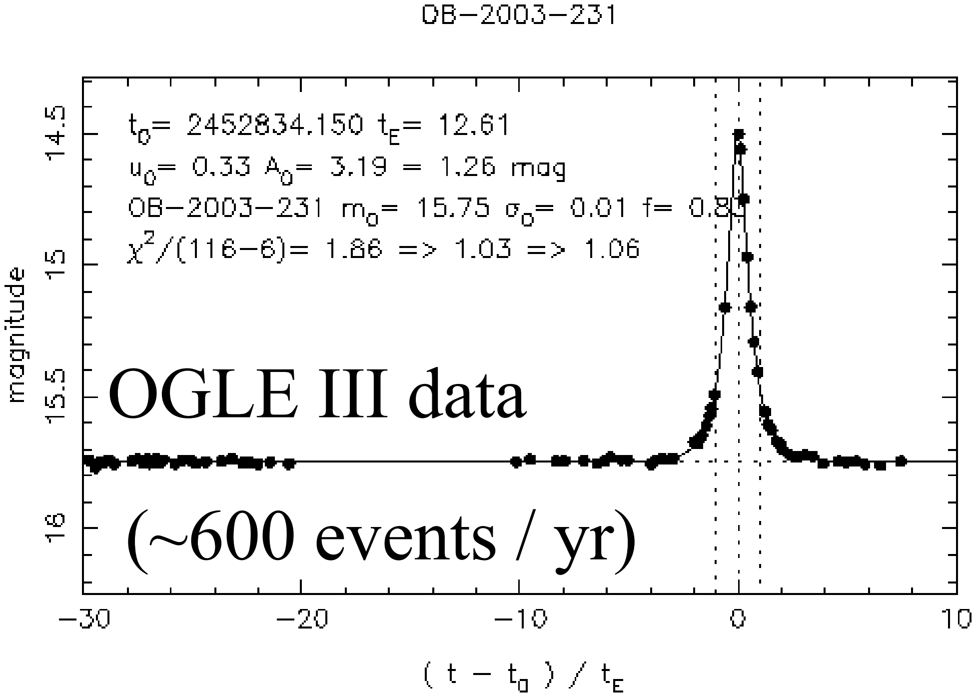
~ 4 day sampling

~ 600 microlens events
.   each year

Early Warning System
internet alerts

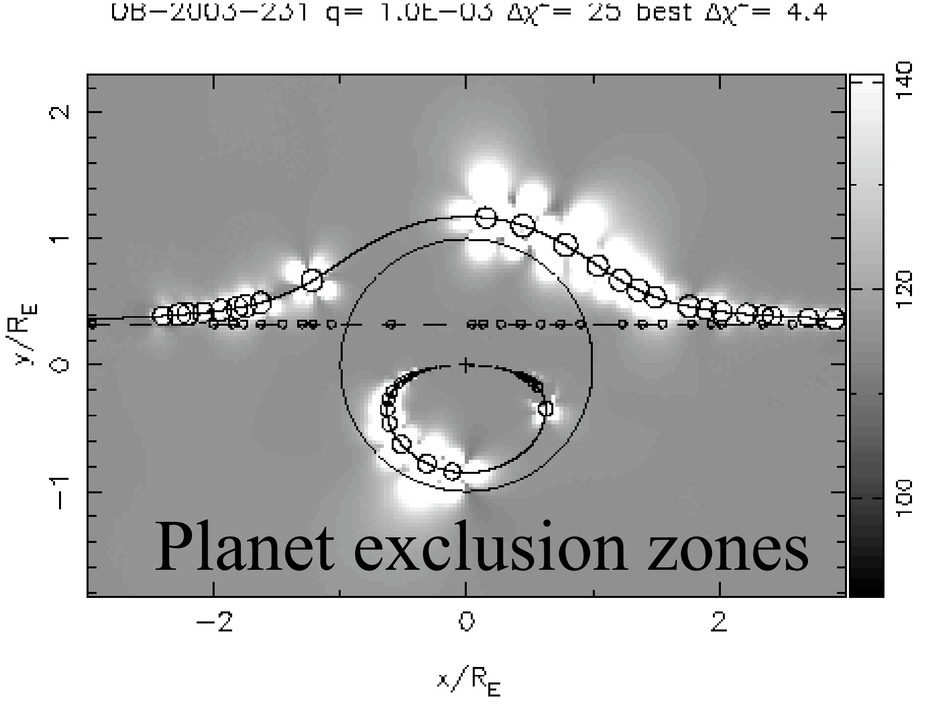


Planet Detection Zones

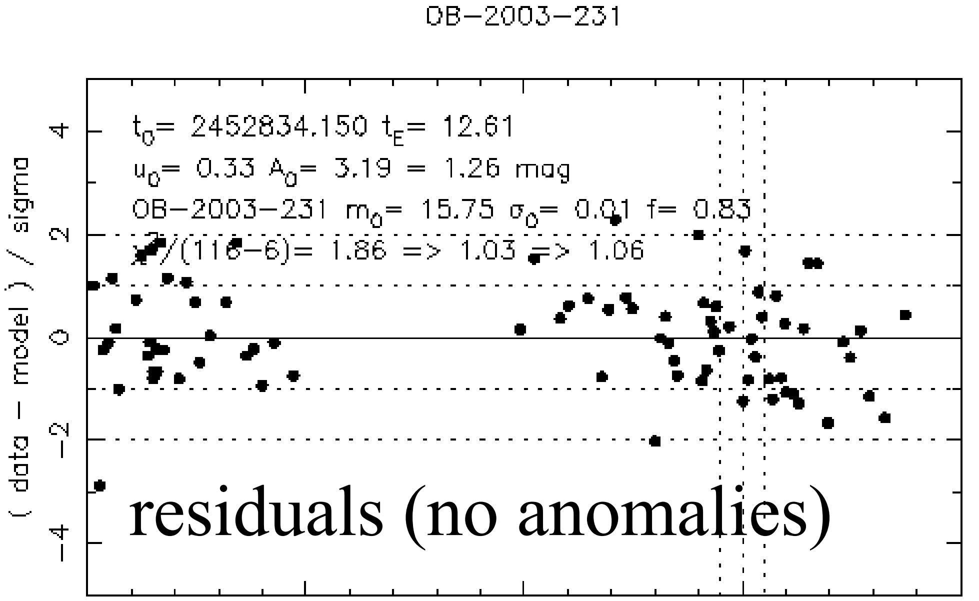


OGLE III data

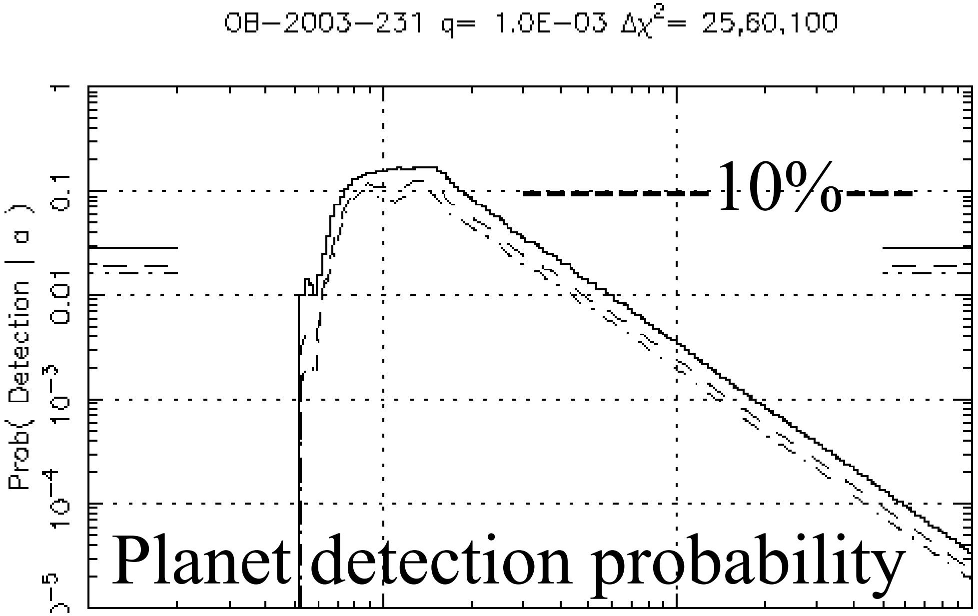
(~600 events / yr)



Planet exclusion zones



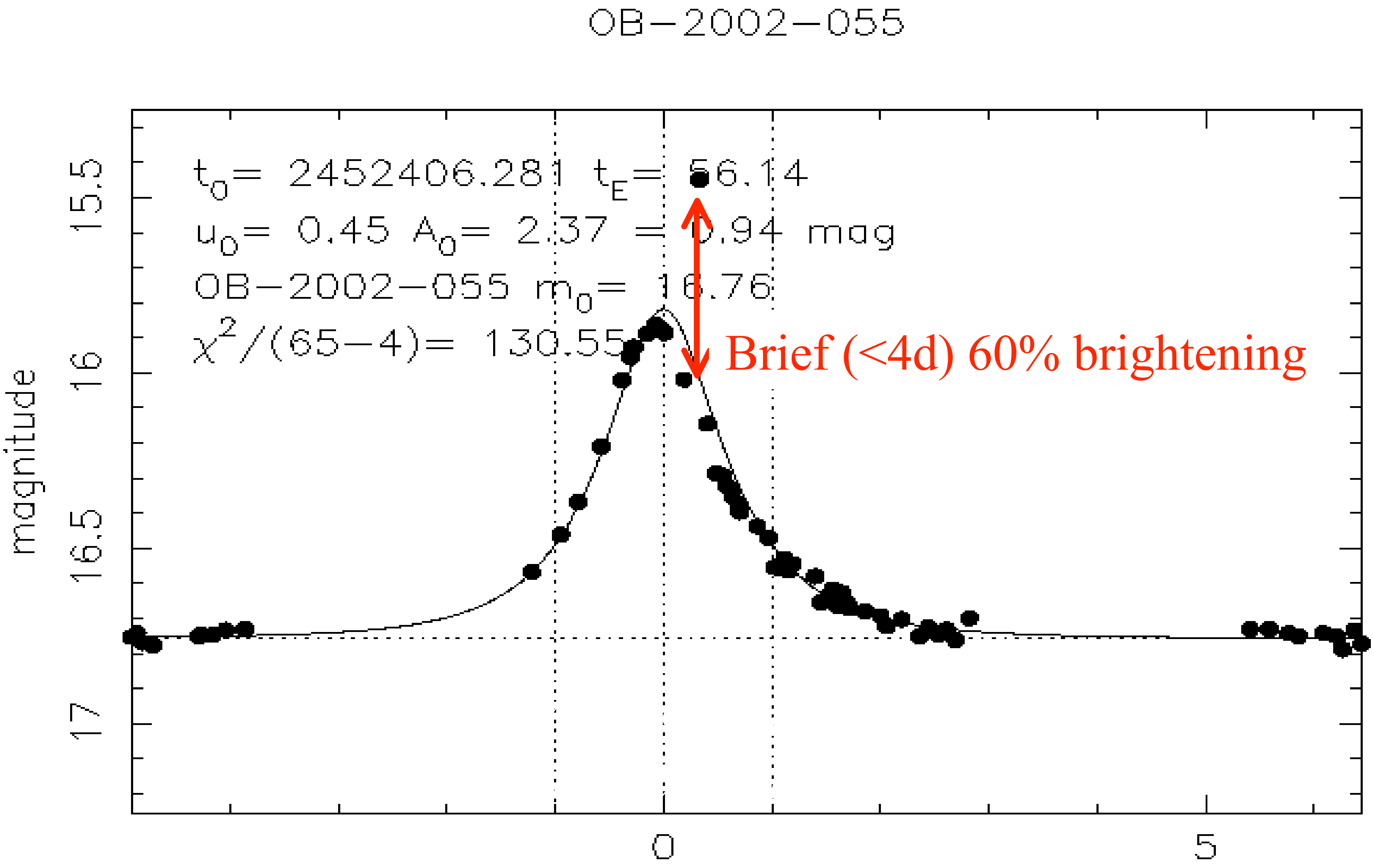
residuals (no anomalies)



10%

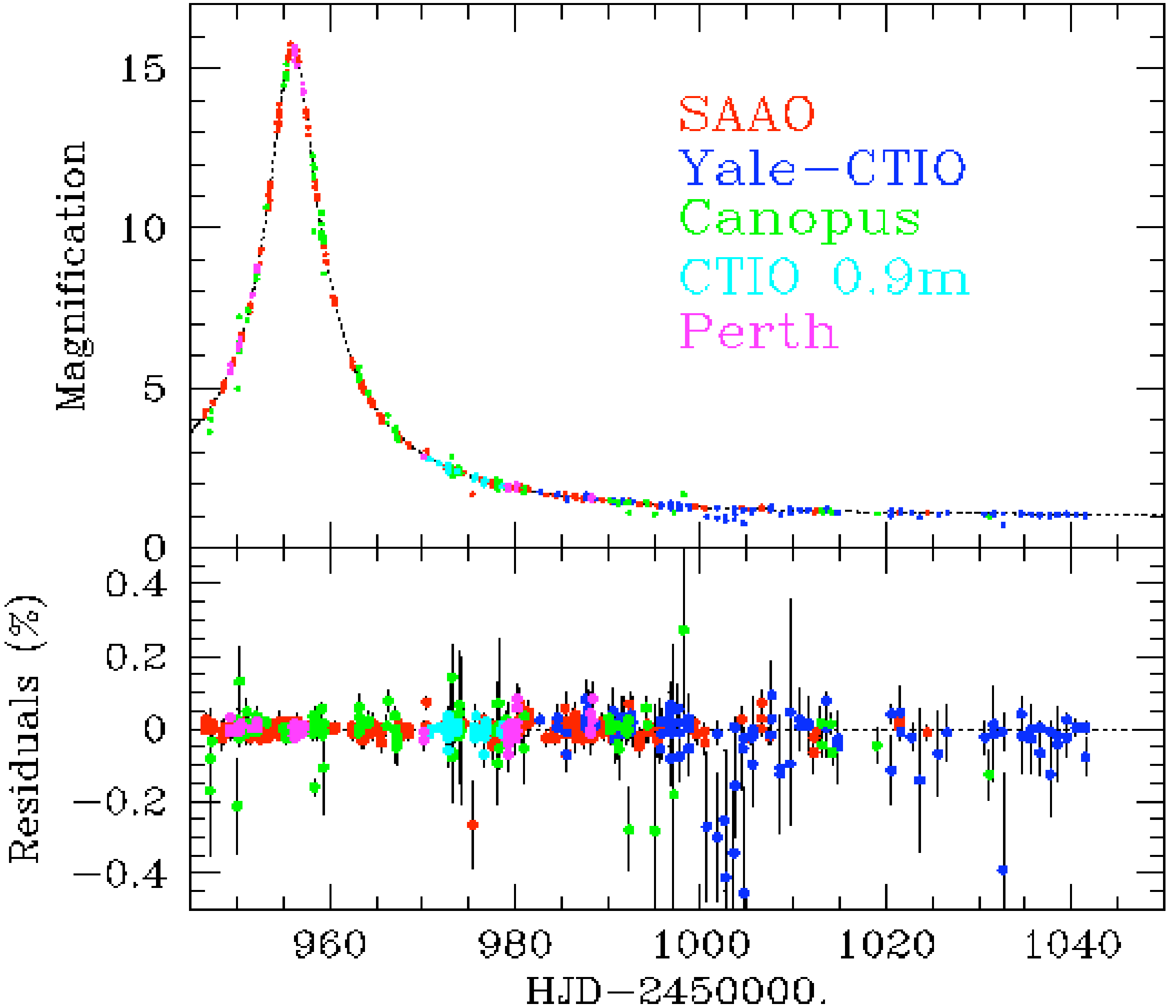
Planet detection probability

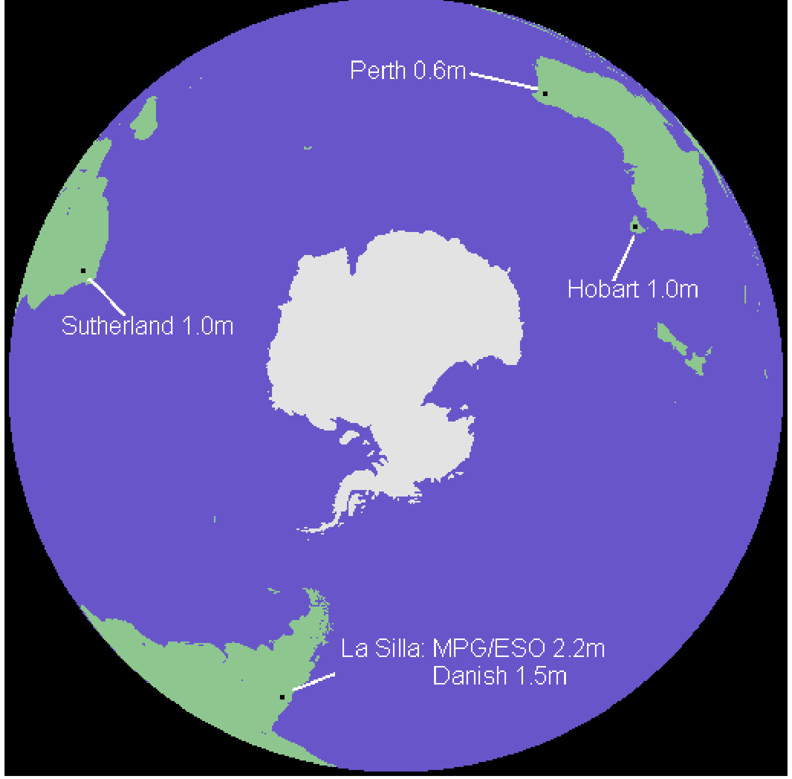
Planet-like Anomalies



Brief (<4d) 60% brightening

Probing Lensing Anomalies NETwork





PLANET

4 southern sites

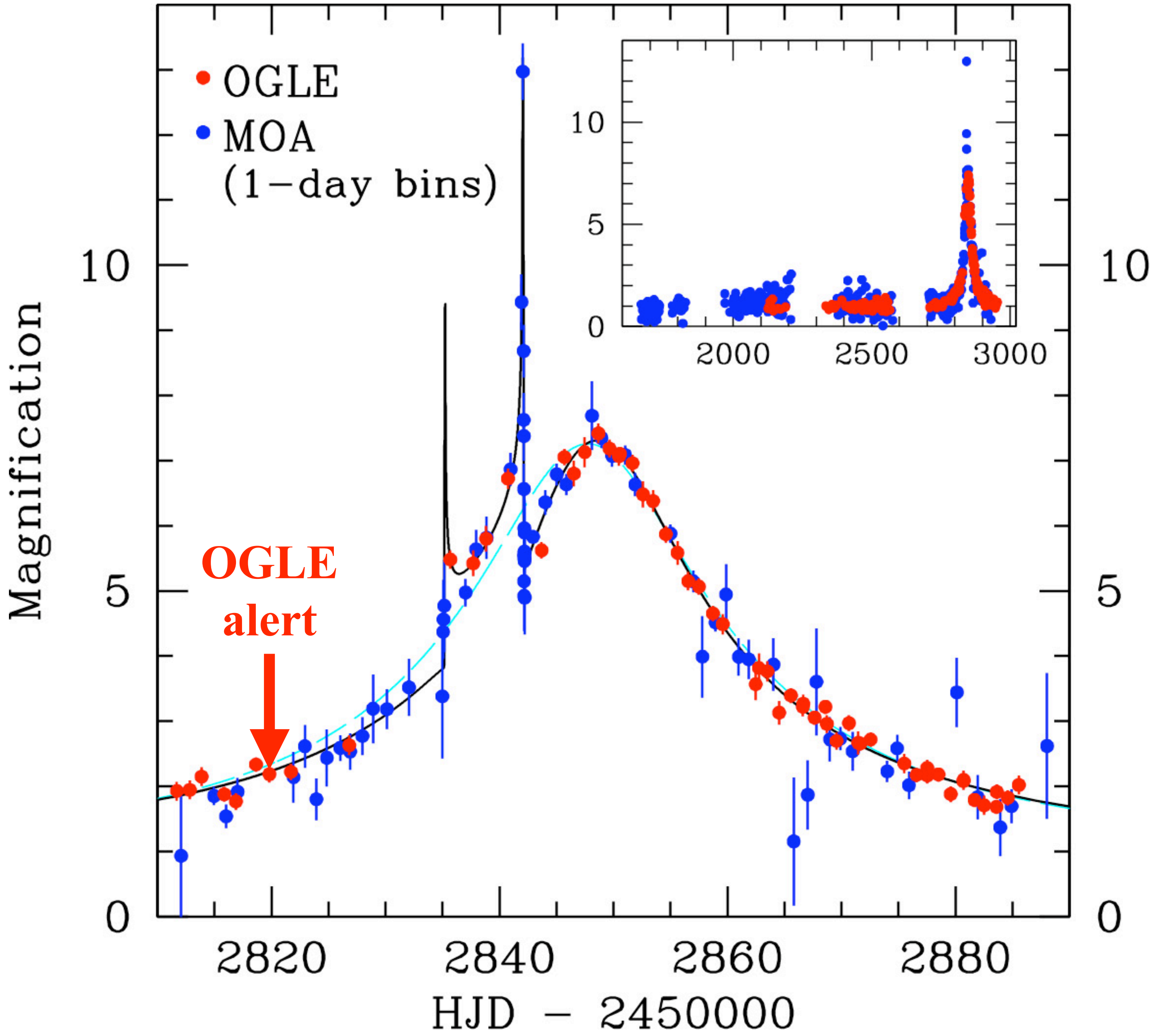
0.6-1.5 m telescopes

selected events
~24-hour coverage

2004 - first microlens planet

$m \sim 1.5\, m_{Jup}$

Bond et al.
2004
(MOA+OGLE)



Cool Planet Hunting with the UK's 2m Robotic Telescopes

Liverpool Telescope: La Palma

Faulkes Telescopes: FT-N, Maui

FT-S, Siding Springs

RoboNet I --> REX

REX *=* ***R****obotic* ***EX****oplanet discovery Network*

REX proposal for 2 more southern telescopes.

Dedicated to exoplanet hunting

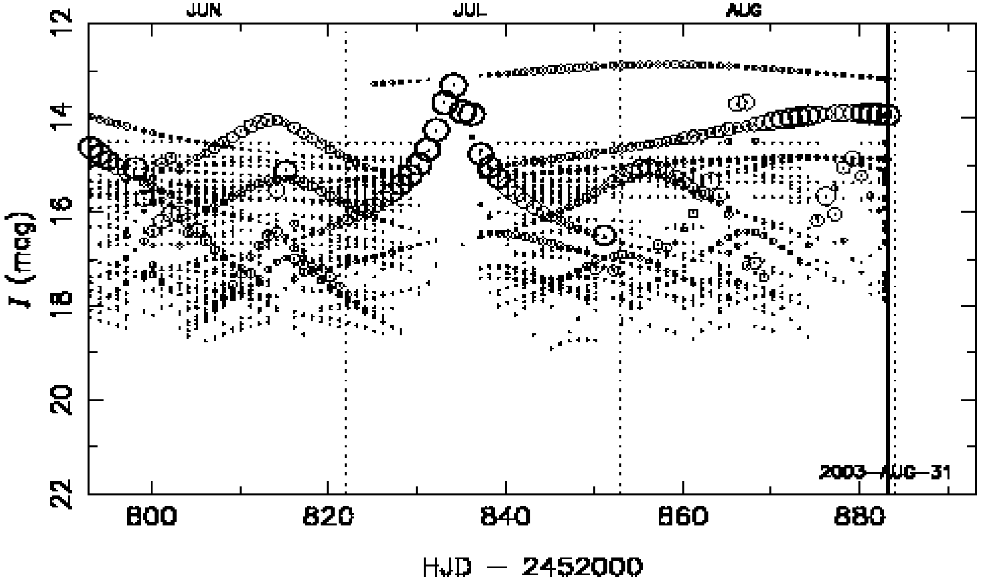
Doppler wobbles, transits, microlensing.

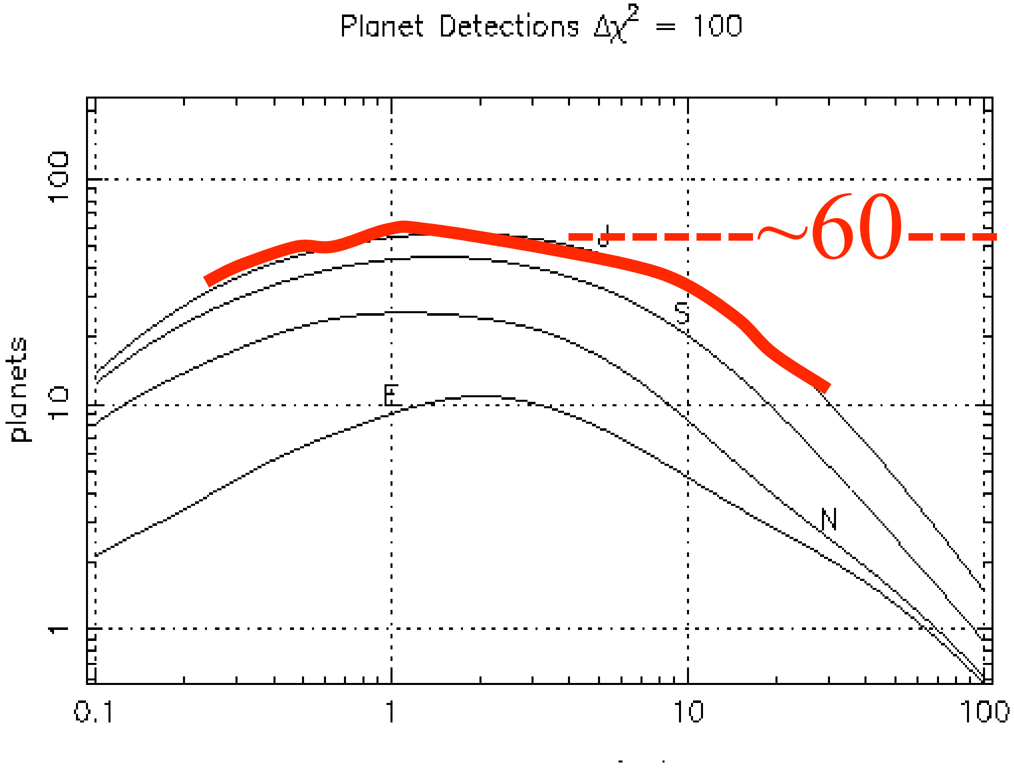
RoboNet-1 Microlens Planet Detection Capability

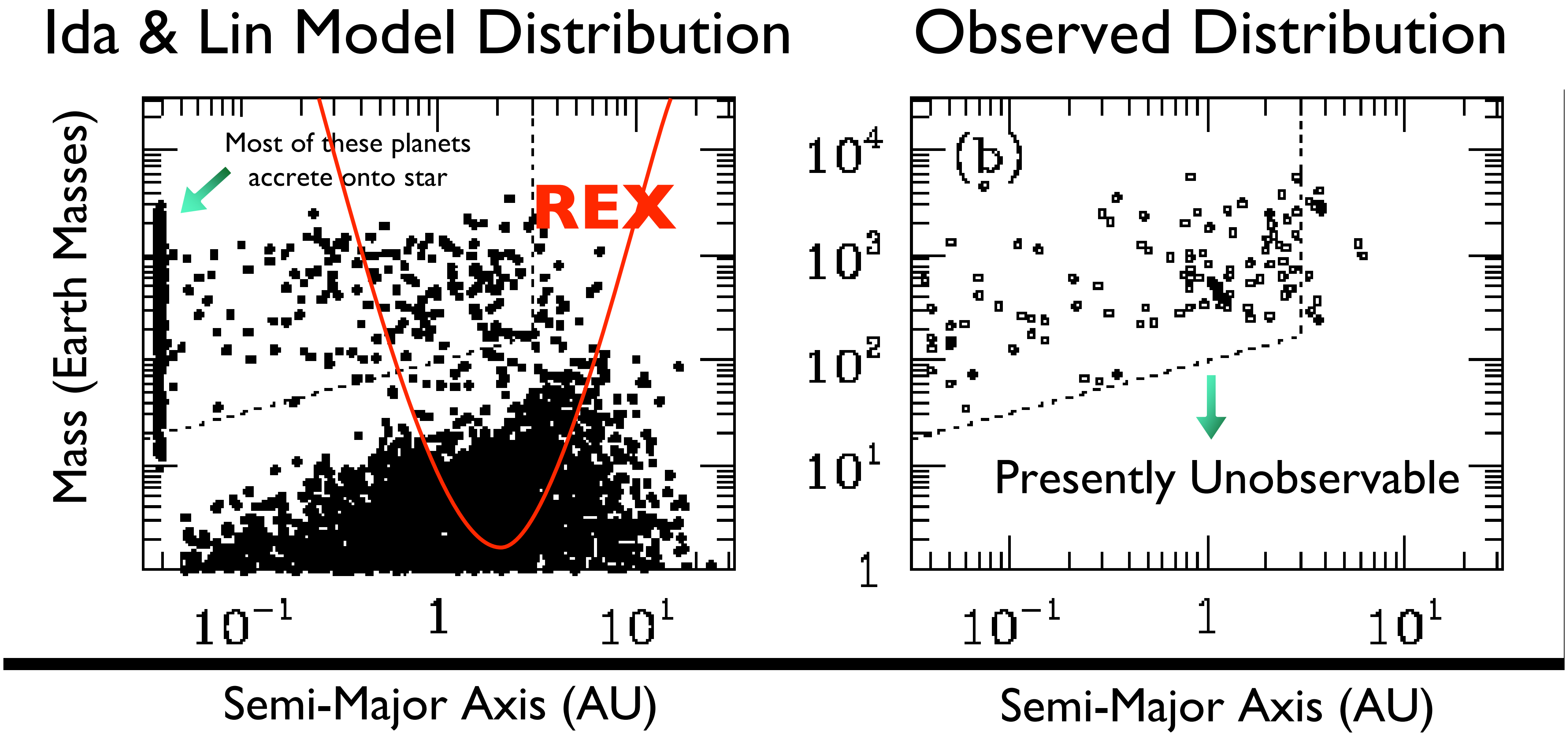
Observing strategy
optimised to maximise
planet discovery rate.

~ 60 P cool Jupiters / yr
~ 10 P cool Earths / yr
(if P planets per lens star)

Simulated observations:







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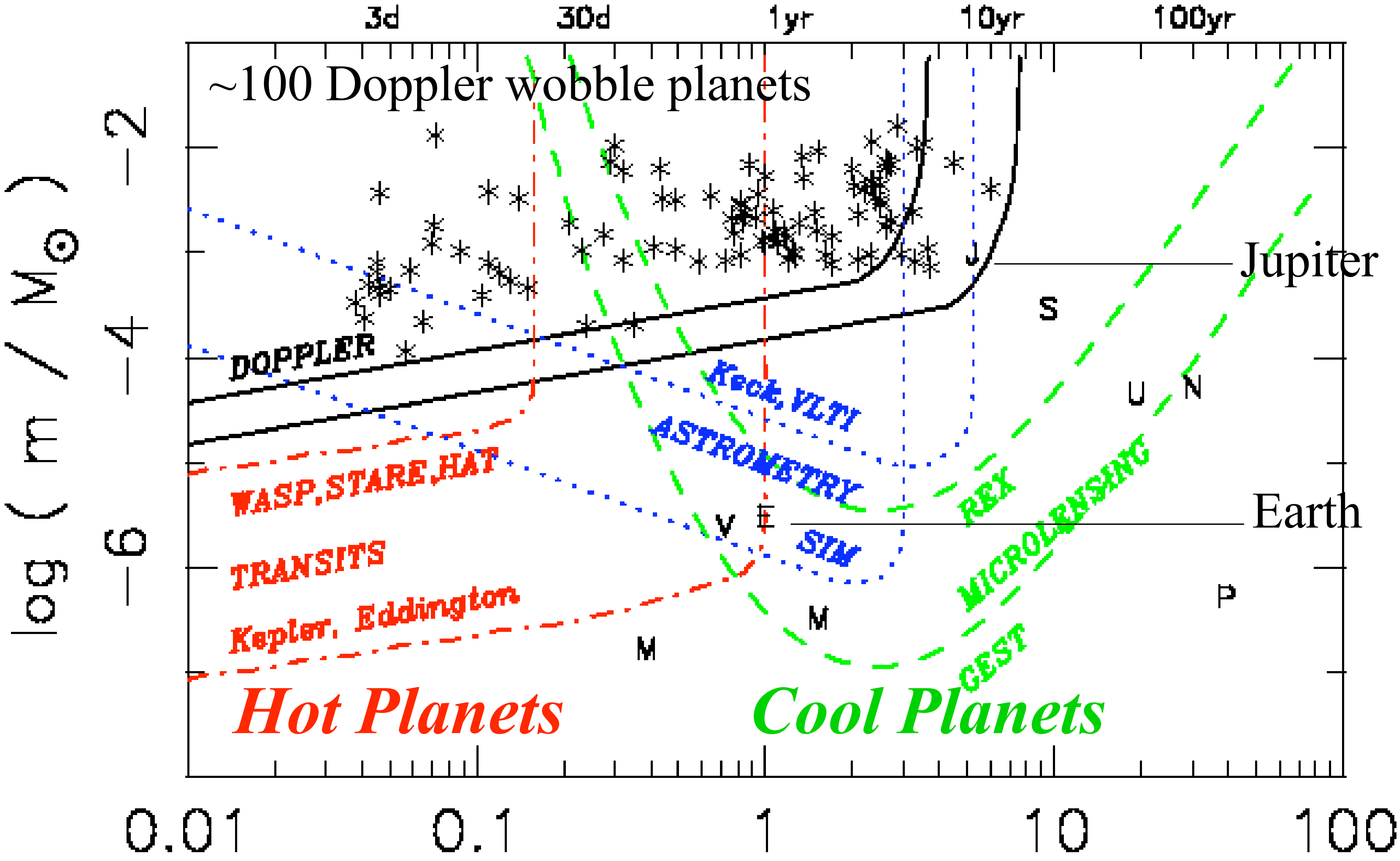
Abundance of Habitable Planets?



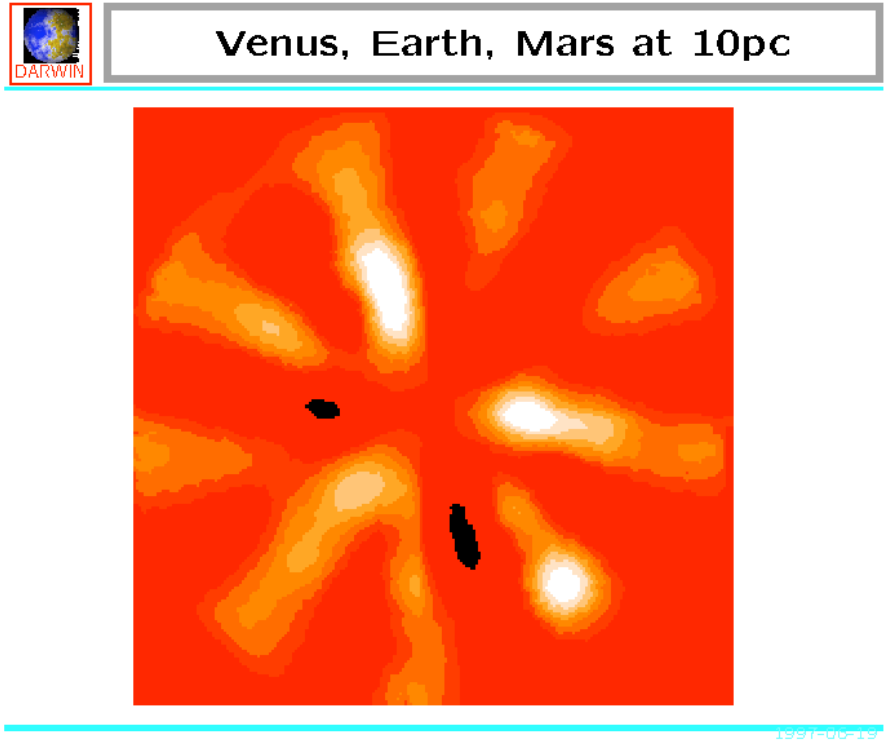
ESA: Darwin

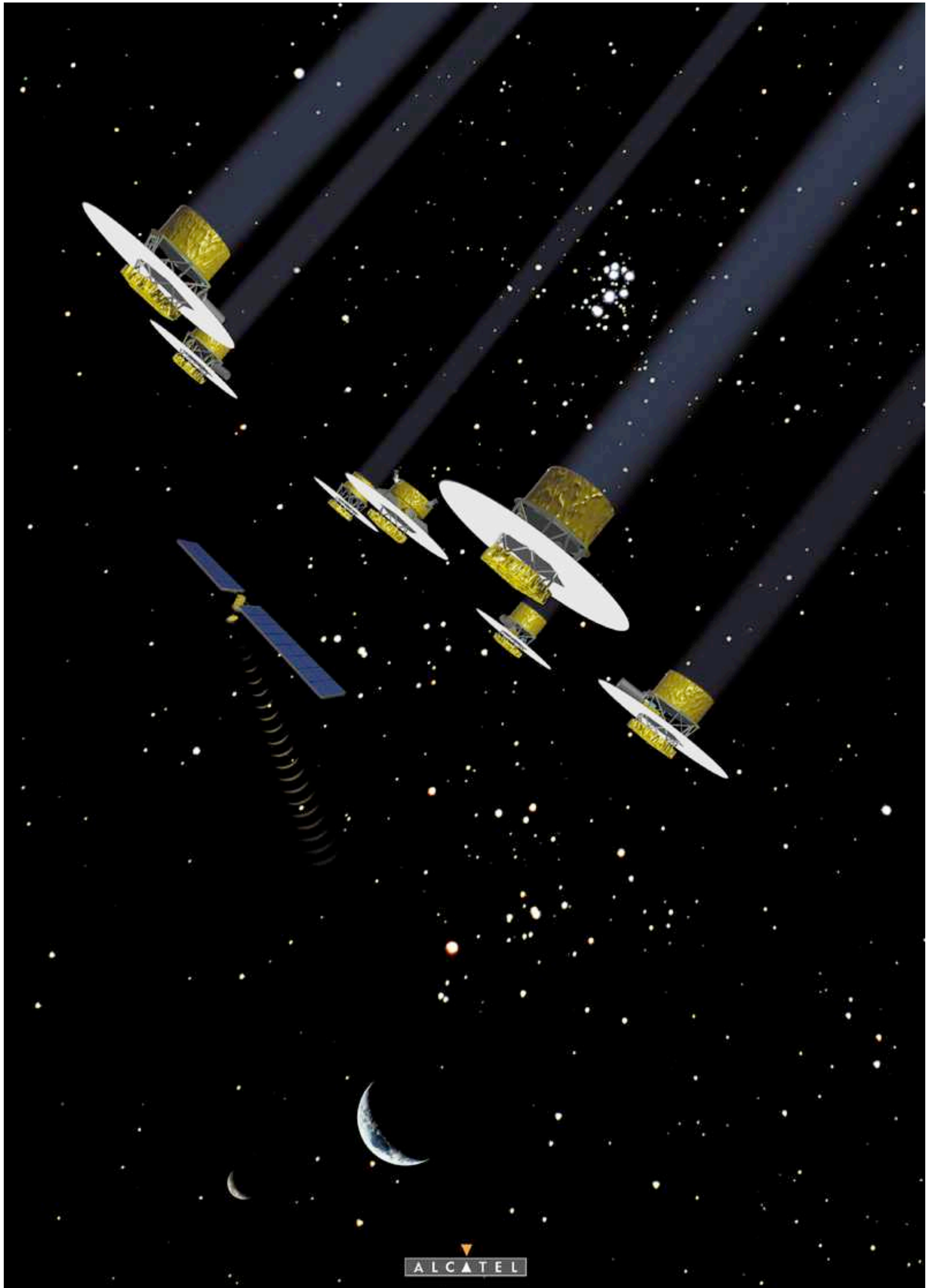
~ 2015-20?

infrared space interferrometer

destructive interference to null out the starlight

snapshot ~500 nearby systems
study ~ 50 in detail

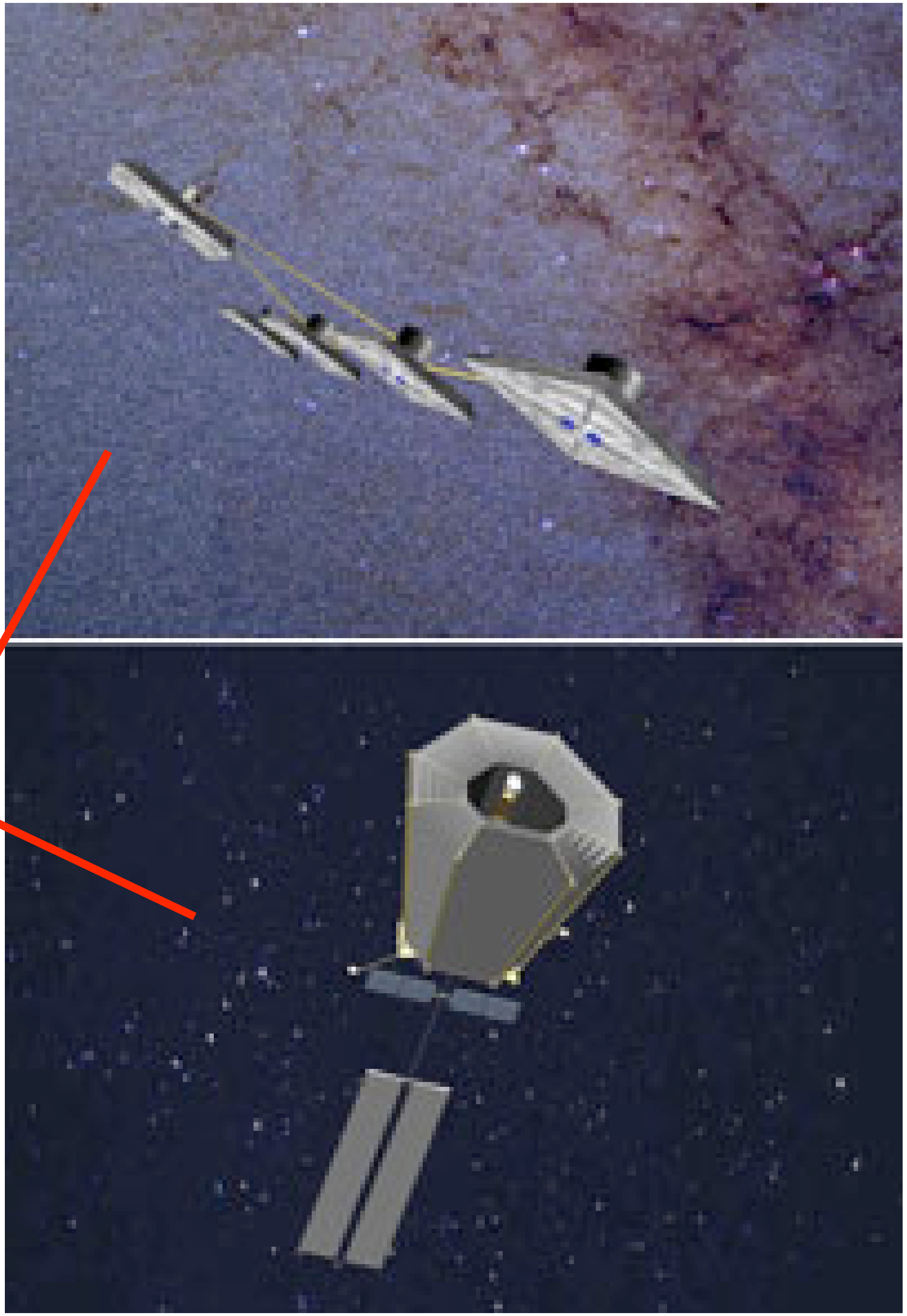




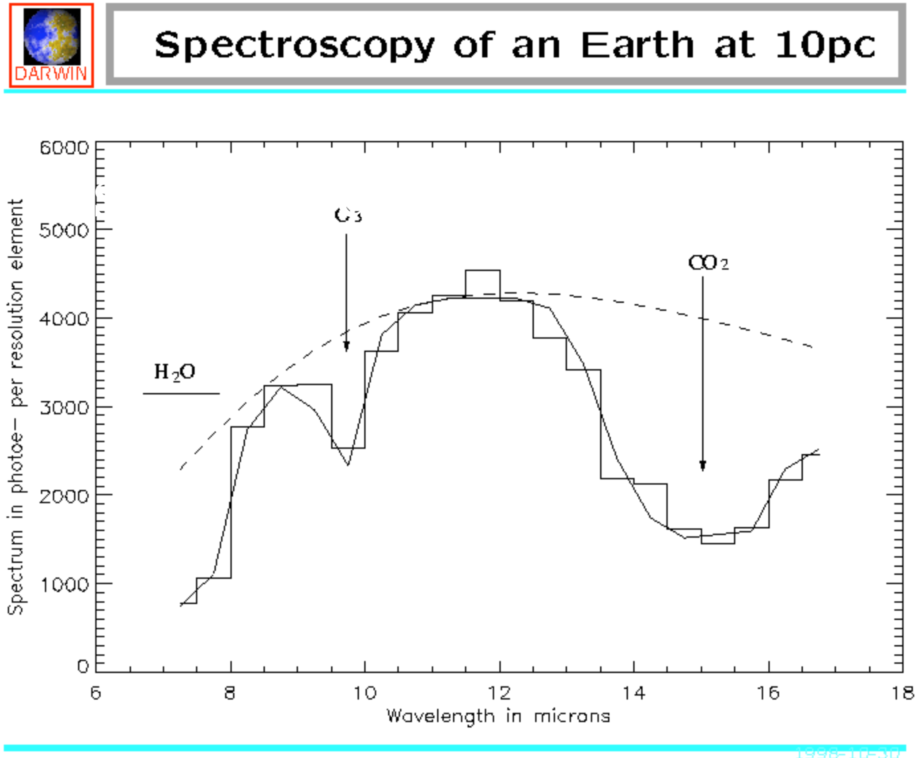
NASA:TPF (Terrestrial Planet Finder)

2014: TPF-C
4-6 m visible light coronagraph

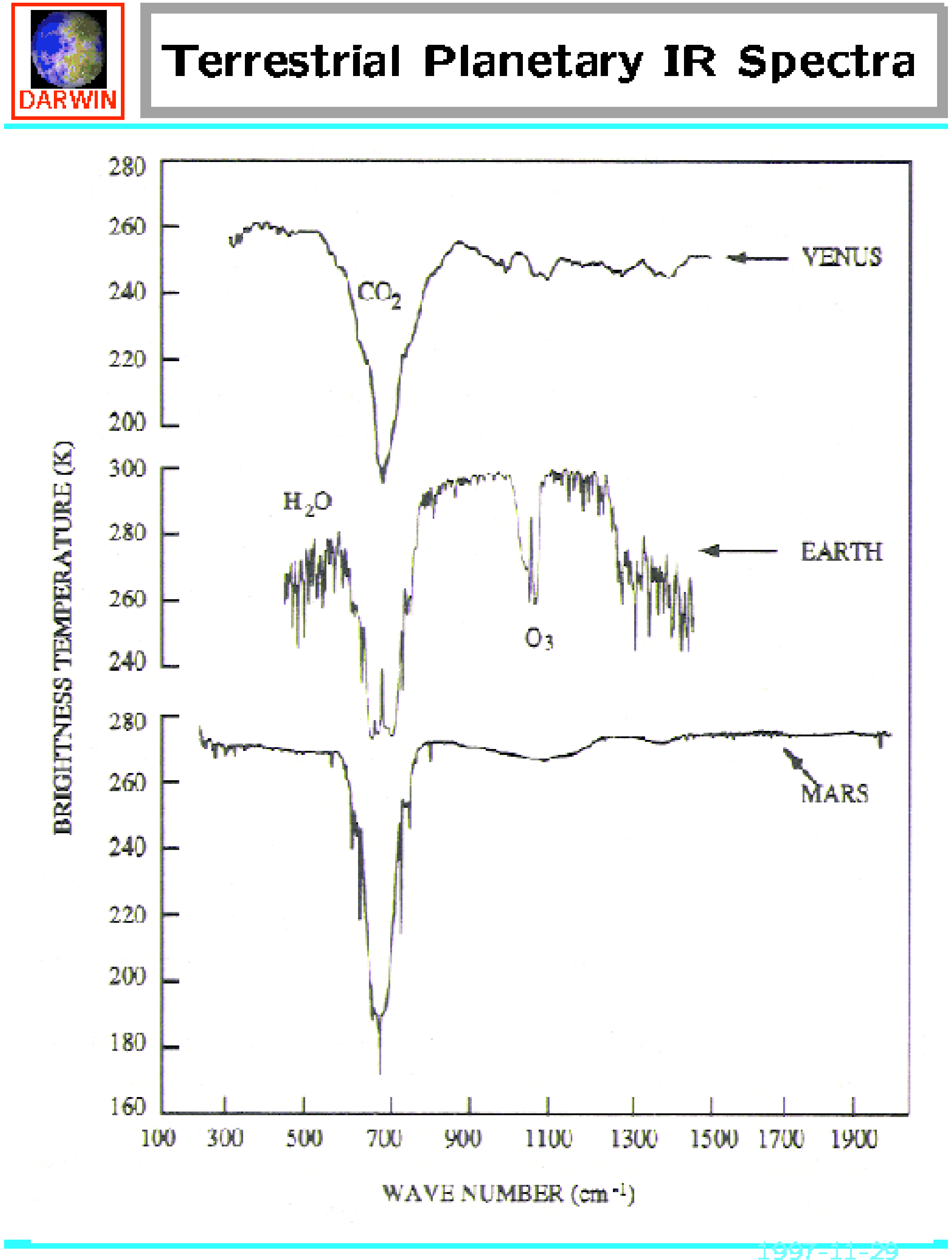
2020: TPF-I
3-4 m infrared interferrometer



Life's Signature:
disequilibrium atmosphere (e.g. oxygen-rich)



Spectroscopy of an Earth at 10pc



Terrestrial Planetary IR Spectra

The Road Ahead

- Doppler Wobbles
  - 2005 ... 150 --> 200 Jupiters
  - longer periods, multi-planet systems
- Transits
  - 2005-10 … WASP ~10^3 Hot Jupiters
  - 2006-08 … Corot Hot Earths
  - 2008-12 … Kepler Hot --> Habitable Earths
- Microlensing
  - 2005-15 … cool Jupiters --> Earths
- Darwin / TPF
  - 2015-2025 … direct images, spectra, Life?

Thanks for Listening!

And thanks to
G.Laughlin,G.Lodato, R.Nelson
for slides from previous talks.