Extrasolar Planets

John Menzies

SAAO

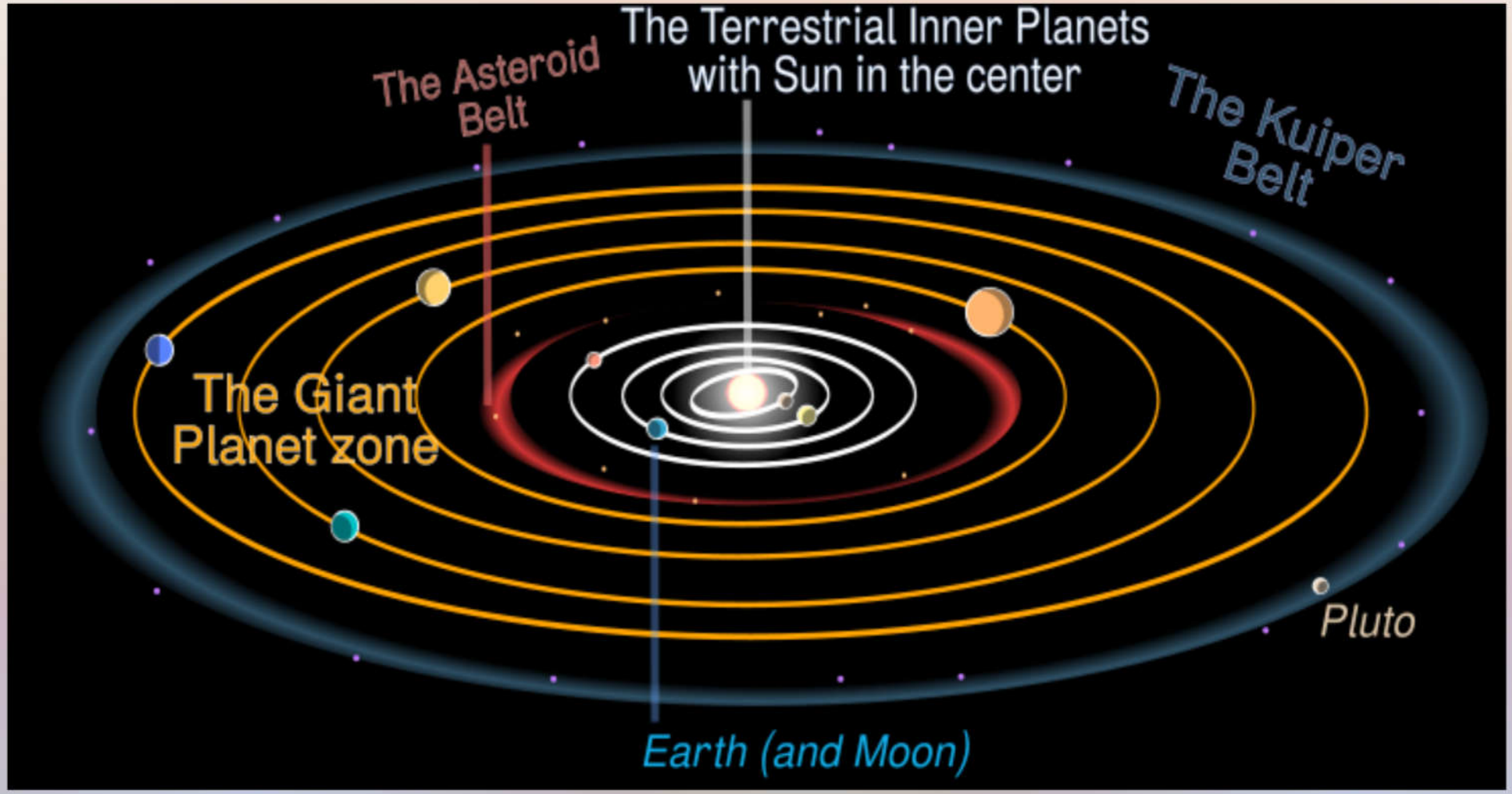
Outline

- **Solar System**
- **Exoplanets**
- **Search Methods**
  - **Transits**
  - **Microlensing**
  - **Timing**
- **Planet formation, habitable zone**

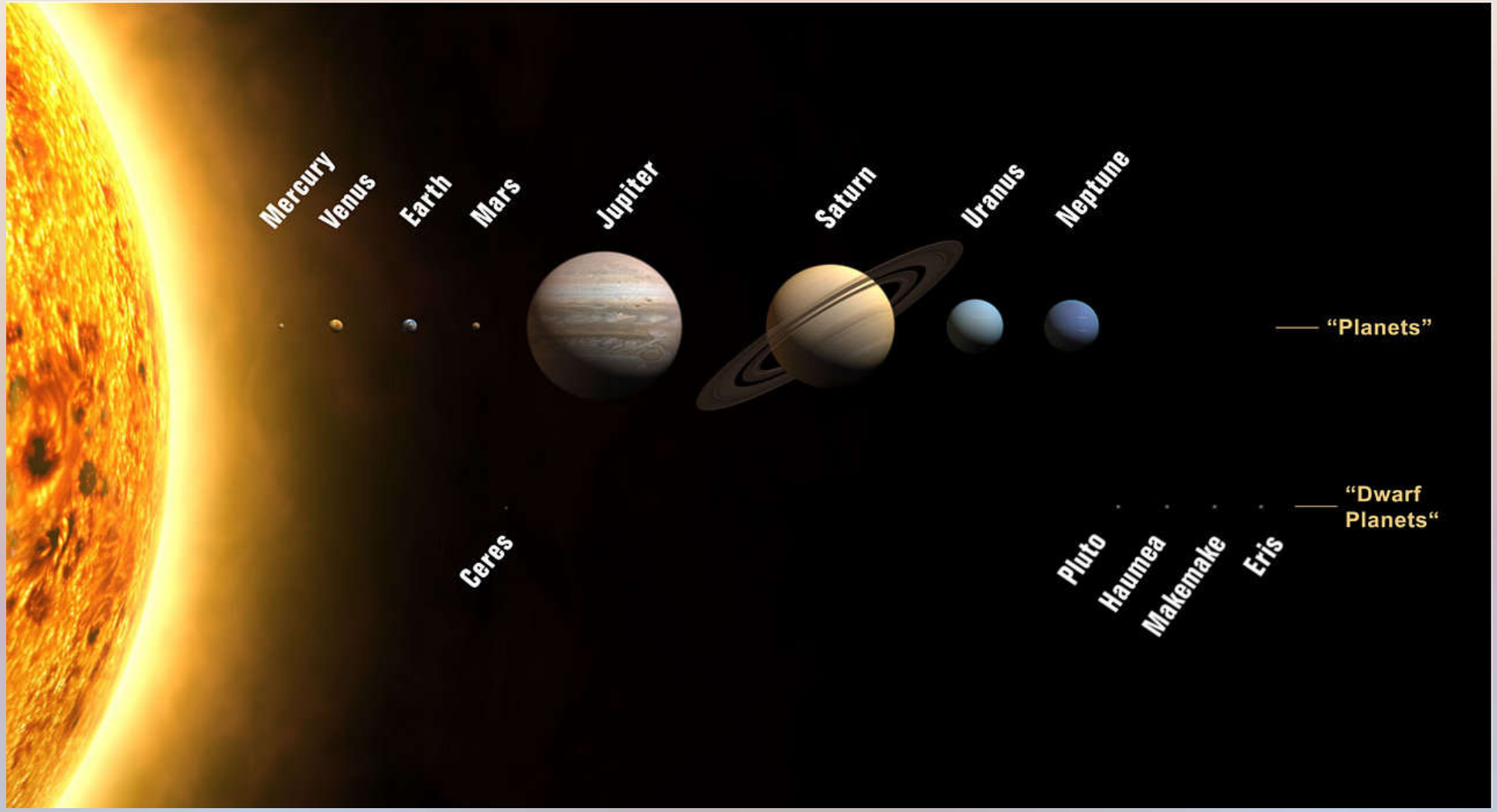
What is a Planet?

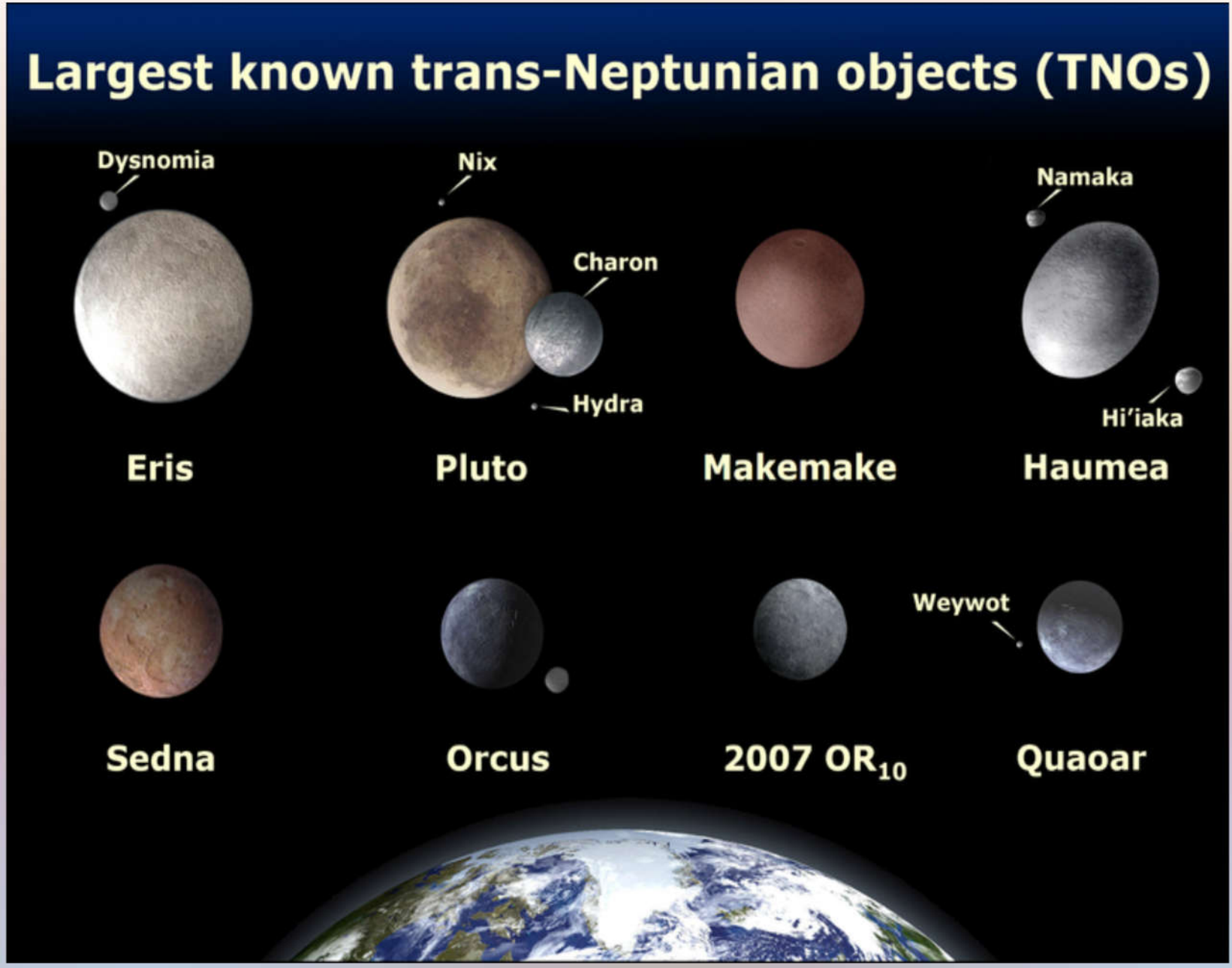
- Solar System Planet (IAU 2006)
  - orbits Sun,
  - massive enough to be round (hydrostatic equilibrium),
  - has cleared neighbourhood of debris,
  - not satellite of a larger object
- Dwarf planet
  - has not cleared neighbourhood
- Small Solar System Body
  - remnant of collision or failed assembly

- Extrasolar planet
  - Mass<13 $M_{Jupiter}$, orbiting star or stellar remnant
  - Not free floating


The Asteroid Belt
The Terrestrial Inner Planets with Sun in the center
The Kuiper Belt
The Giant Planet zone
Pluto
Earth (and Moon)

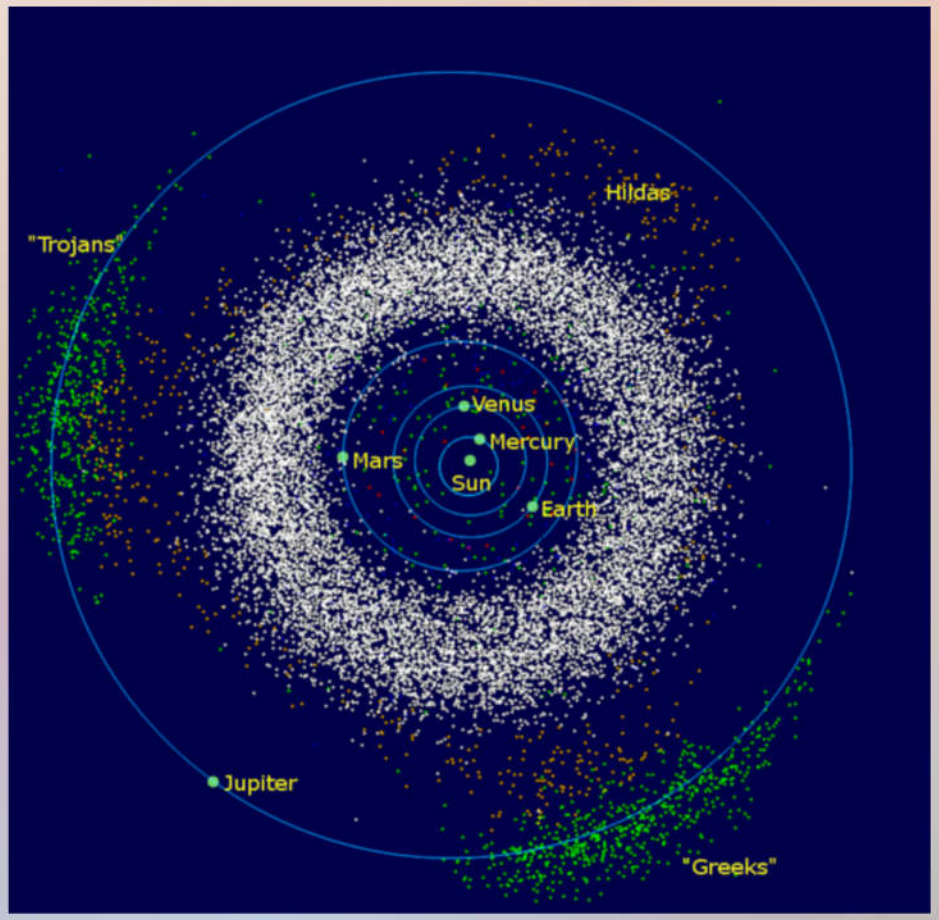
Solar System



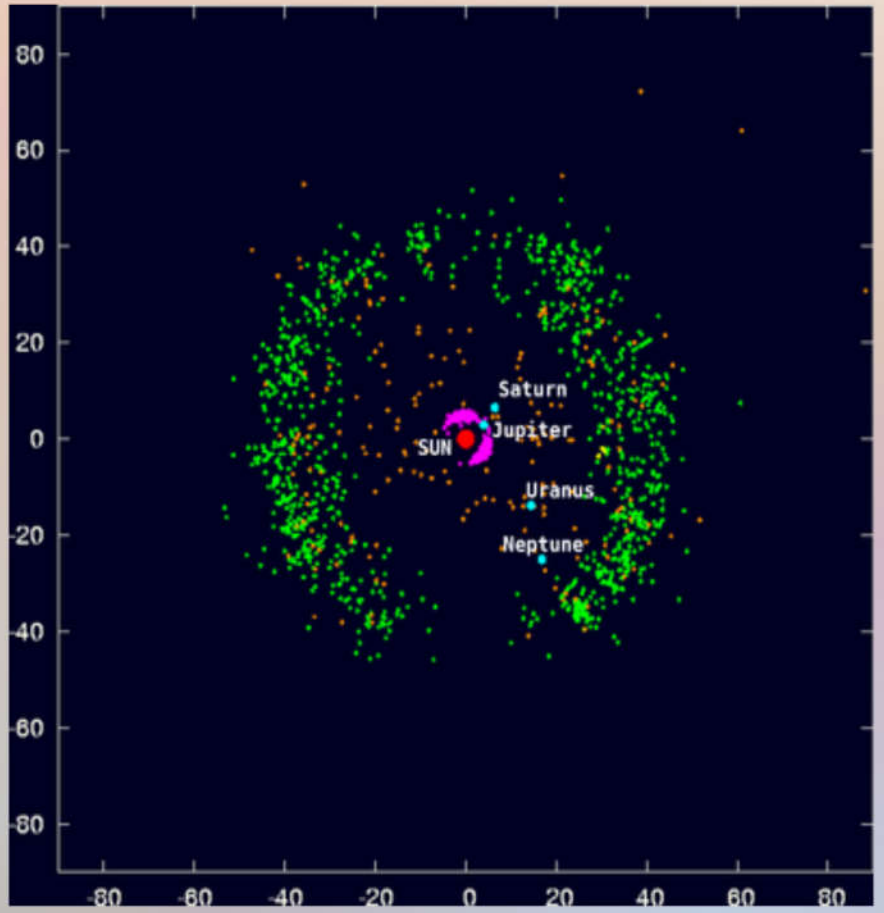

Largest known trans-Neptunian objects (TNOs)
Dysnomia
Nix
Charon
Hydra
Namaka
Hi'iaka
Eris
Pluto
Makemake
Haumea
Sedna
Orcus
2007 OR10
Weywot
Quaoar

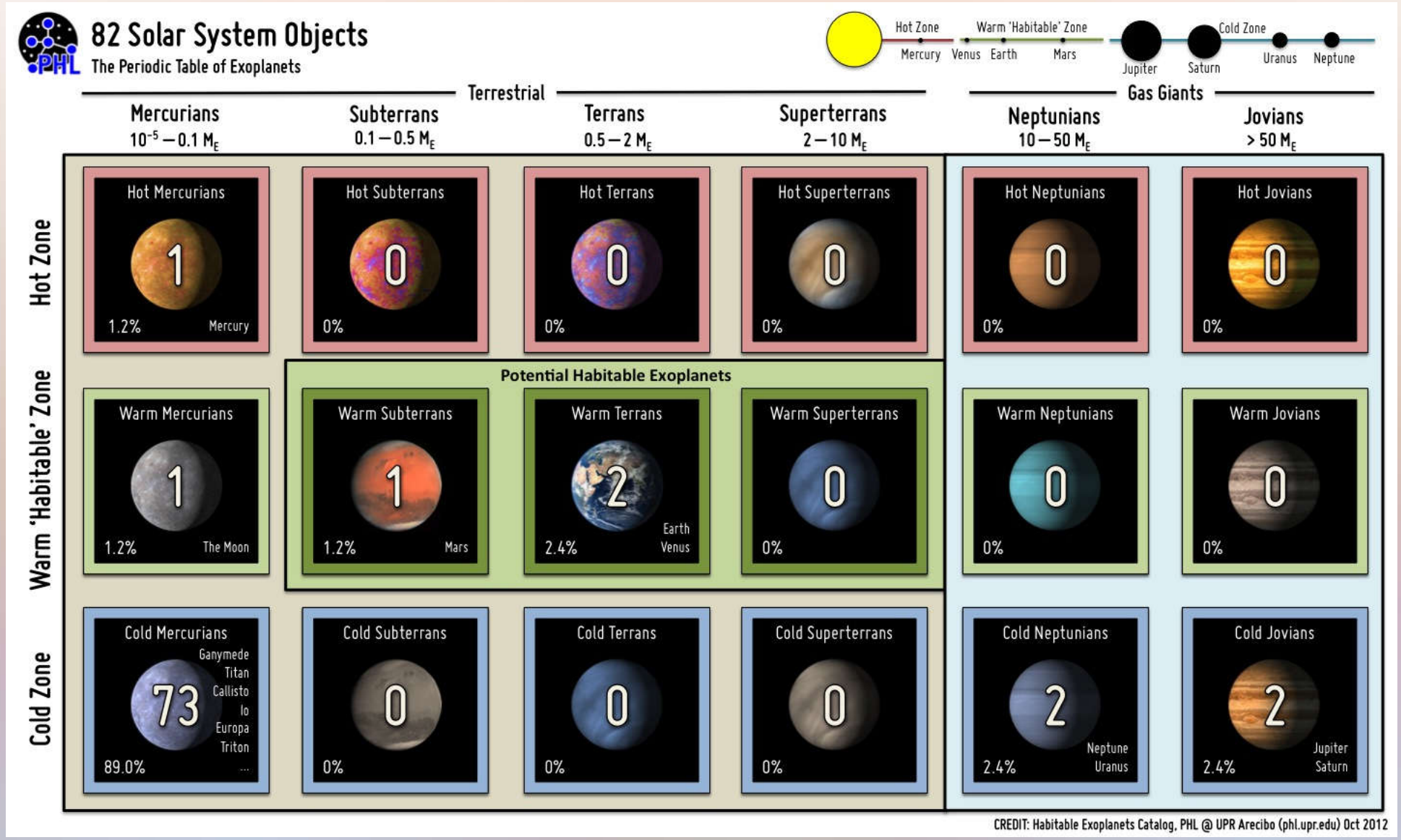
Planets have 'cleared out' their orbits

Inner planets + Jupiter



Outer planets




82 Solar System Objects
The Periodic Table of Exoplanets
Hot Zone
Warm 'Habitable' Zone
Cold Zone
Mercury
Venus
Earth
Mars
Jupiter
Saturn
Uranus
Neptune
Terrestrial
Gas Giants
Mercurians
10⁻⁵ — 0.1 M_E
Subterrans
0.1 — 0.5 M_E
Terrans
0.5 — 2 M_E
Superterrans
2 — 10 M_E
Neptunians
10 — 50 M_E
Jovians
> 50 M_E
Hot Zone
Warm 'Habitable' Zone
Cold Zone
Hot Mercurians
1
1.2%
Mercury
Hot Subterrans
0
0%
Hot Terrans
0
0%
Hot Superterrans
0
0%
Hot Neptunians
0
0%
Hot Jovians
0
0%
Potential Habitable Exoplanets
Warm Mercurians
1
1.2%
The Moon
Warm Subterrans
1
1.2%
Mars
Warm Terrans
2
2.4%
Earth
Venus
Warm Superterrans
0
0%
Warm Neptunians
0
0%
Warm Jovians
0
0%
Cold Mercurians
73
89.0%
Ganymede
Titan
Callisto
Io
Europa
Triton
...
Cold Subterrans
0
0%
Cold Terrans
0
0%
Cold Superterrans
0
0%
Cold Neptunians
2
2.4%
Neptune
Uranus
Cold Jovians
2
2.4%
Jupiter
Saturn
CREDIT: Habitable Exoplanets Catalog, PHL @ UPR Arecibo (phl.upr.edu) Oct 2012

Solar System comparisons

Name	Mass	Period (year)	Orbital Radius (AU)
Sun	1000	-	-
Mercury	0.00016	0.24	0.4
Earth	0.003	1	1
Jupiter	1	11.9	5.2
Neptune	0.05	165	30

- We know there are extrasolar planets
- Are there extrasolar planetary systems like the Solar System?
- Are there Earth-like planets, or planets in the habitable zone?

What is a Planet?

- **Extrasolar planet** (controversial)
  - Mass<13 $M_{Jupiter}$ orbiting star or stellar remnant
  - Minimum mass for Deuterium burning
  - 75 $M_{Jupiter}$ minimum mass for H burning
  - Brown dwarf
  - Depends on how assembled (gas collapse or rock/ice accretion)
  - Not free floating

Search Methods

- **Direct imaging**

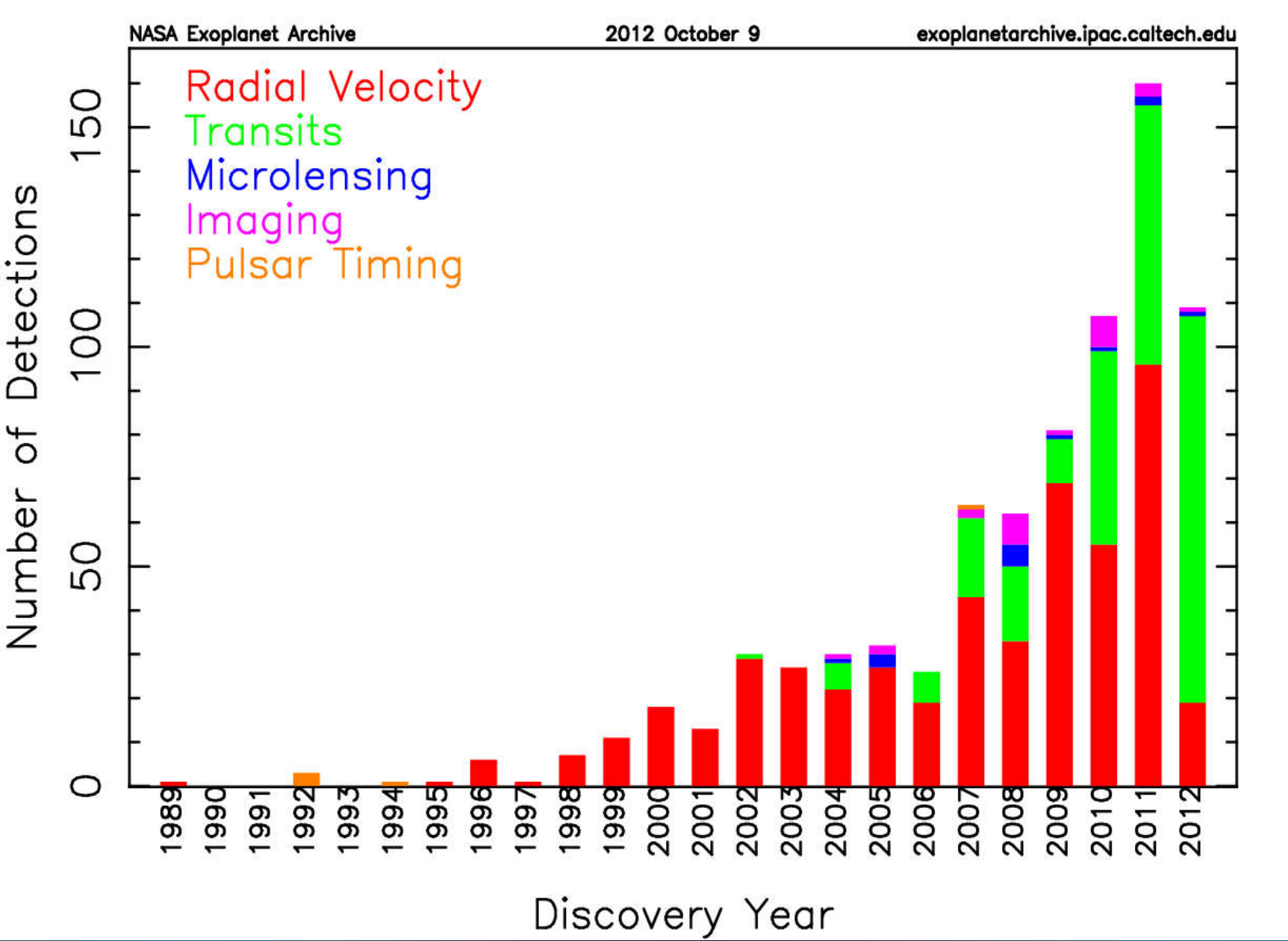
- **Dynamical methods**
  - Radial velocity – motion along line of sight
  - Astrometry – motion in plane of sky

- **Photometric methods**
  - Transits – photometry of parent star
  - Microlensing – photometry of background star

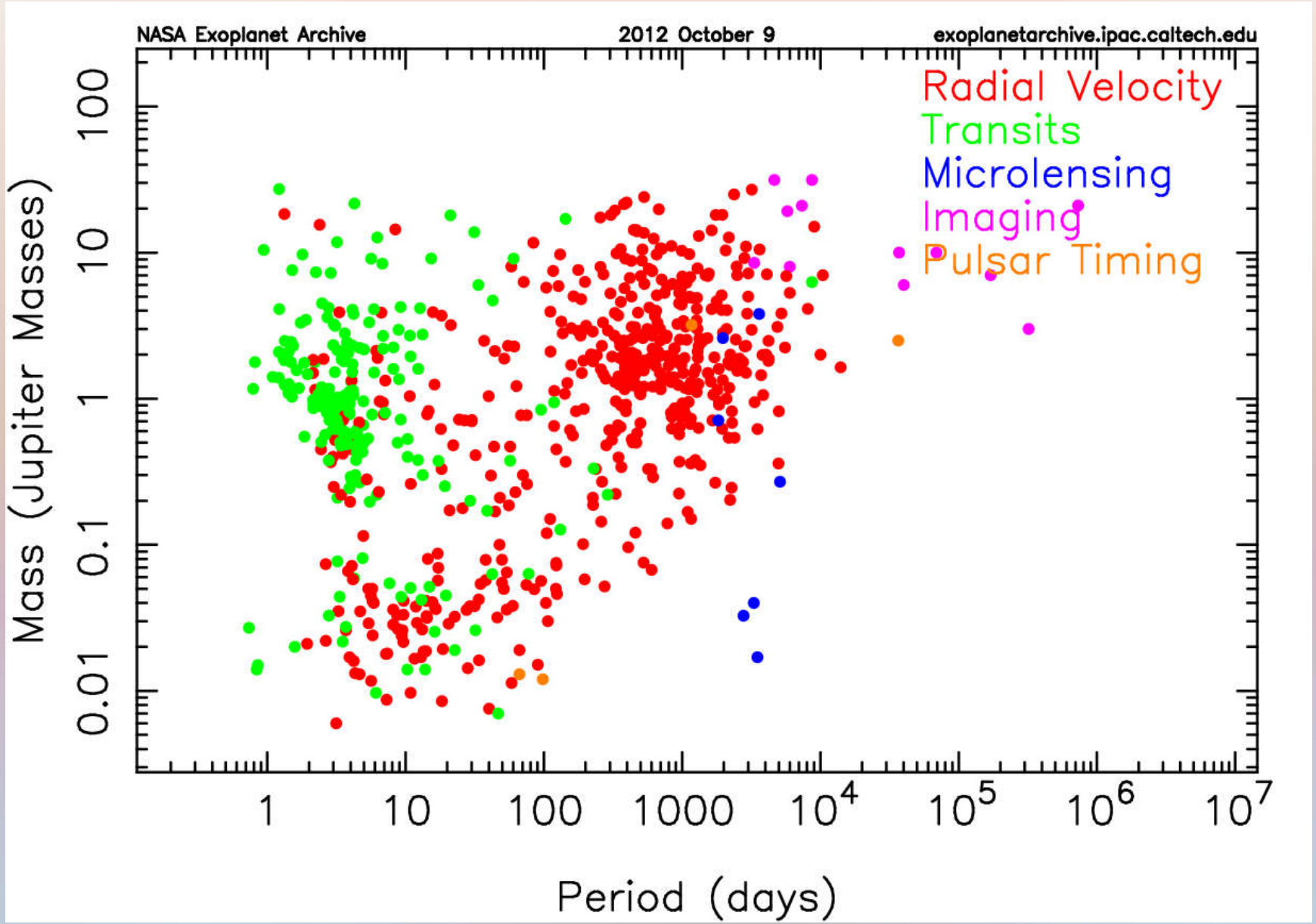
- **Timing** – variation in periodic behaviour of object, e.g. pulsar binary, variable star, eclipsing binary

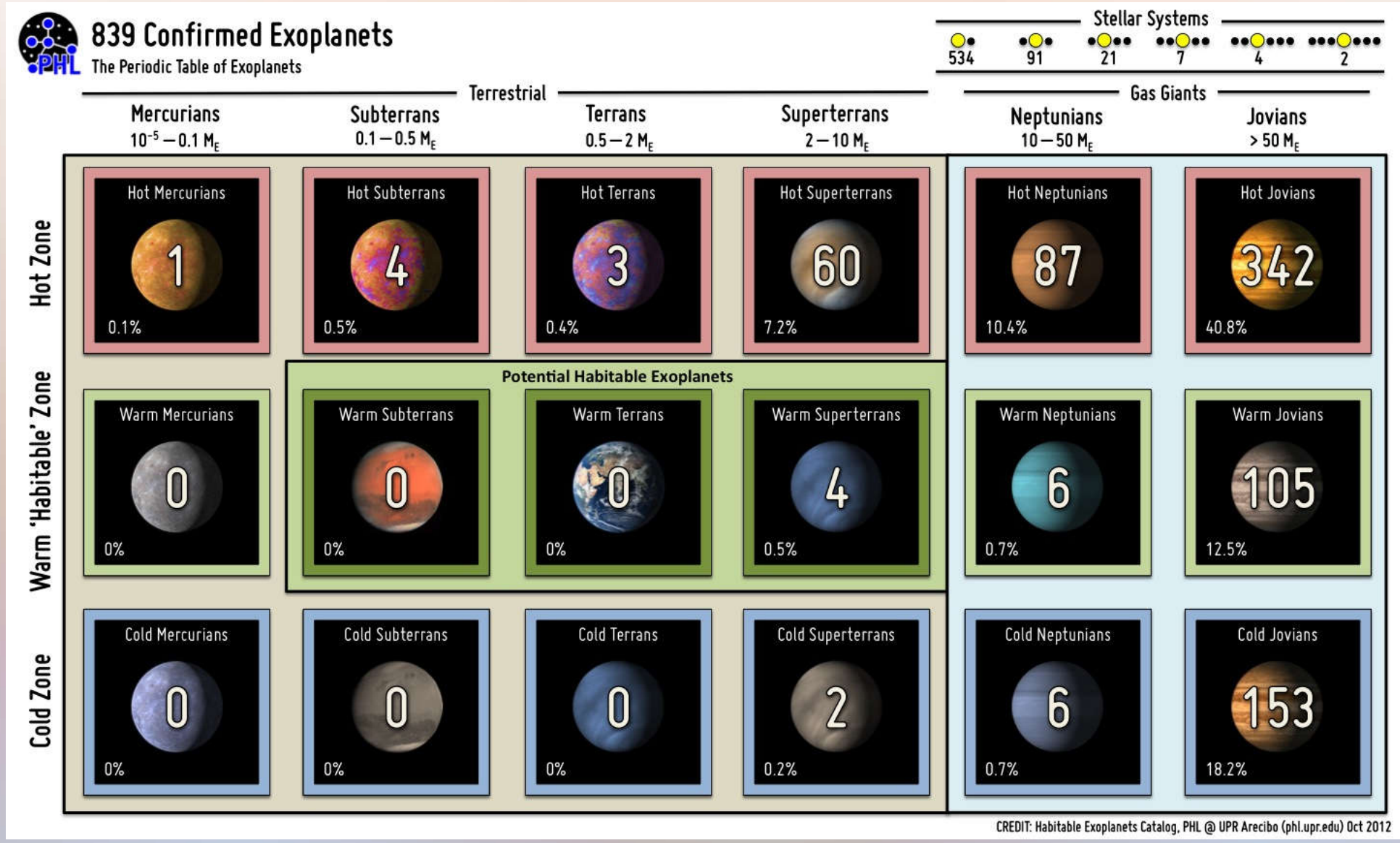
- **Polarimetry** – asymmetric mass distribution, light scattered off planet may be polarised

797 Exoplanets / 629 Stars



Distribution of Mass with Period



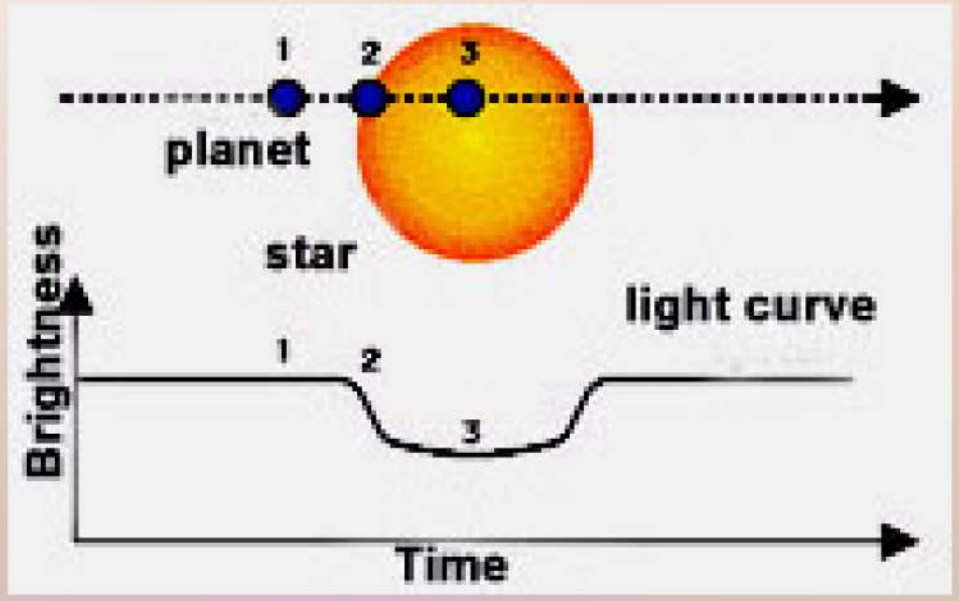

839 Confirmed Exoplanets
The Periodic Table of Exoplanets
Stellar Systems
534
91
21
7
4
2
Terrestrial
Gas Giants
Mercurians
10⁻⁵ — 0.1 M_E
Subterrans
0.1 — 0.5 M_E
Terrans
0.5 — 2 M_E
Superterrans
2 — 10 M_E
Neptunians
10 — 50 M_E
Jovians
> 50 M_E
Hot Zone
Warm 'Habitable' Zone
Cold Zone
Potential Habitable Exoplanets
Hot Mercurians
1
0.1%
Hot Subterrans
4
0.5%
Hot Terrans
3
0.4%
Hot Superterrans
60
7.2%
Hot Neptunians
87
10.4%
Hot Jovians
342
40.8%
Warm Mercurians
0
0%
Warm Subterrans
0
0%
Warm Terrans
0
0%
Warm Superterrans
4
0.5%
Warm Neptunians
6
0.7%
Warm Jovians
105
12.5%
Cold Mercurians
0
0%
Cold Subterrans
0
0%
Cold Terrans
0
0%
Cold Superterrans
2
0.2%
Cold Neptunians
6
0.7%
Cold Jovians
153
18.2%
CREDIT: Habitable Exoplanets Catalog, PHL @ UPR Arecibo (phl.upr.edu) Oct 2012

Planetary Transits

- Planet moves in front of parent star
  - Reduction in light received (~1-2%)
  - Requires almost edge-on orbit

- Derived parameters:
  - Period, diameter of planet, revolution axis, semi-major axis
  - atmospheric properties, surface temperature, chemical composition
  - With mass from RV can find density

Transit Photometry



(Spectrum ⇨ L_*, M_*, R_*)

$\Delta L/L_* = (R_{pl}/R_*)^2$ ⇨ R_{pl}

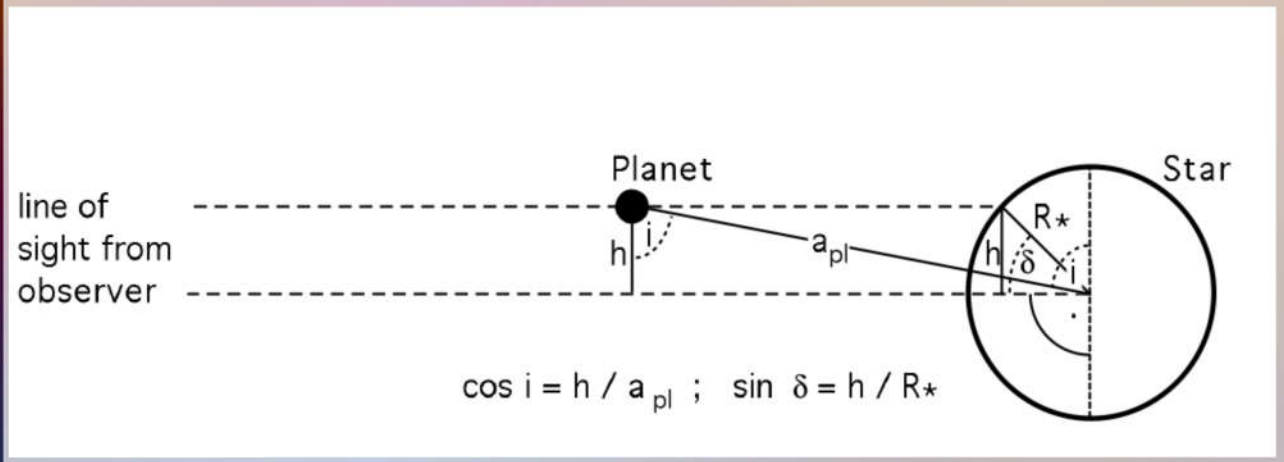
P_{pl}, M_* + Kepler's Law ⇨ a_{pl}

$t_{tr} = P_{pl}\,(R_* \cos\delta + R_{pl})/(\pi\, a_{pl})$

⇨ δ

$\cos i = R_* \sin\delta / a_{pl}$ ⇨ i

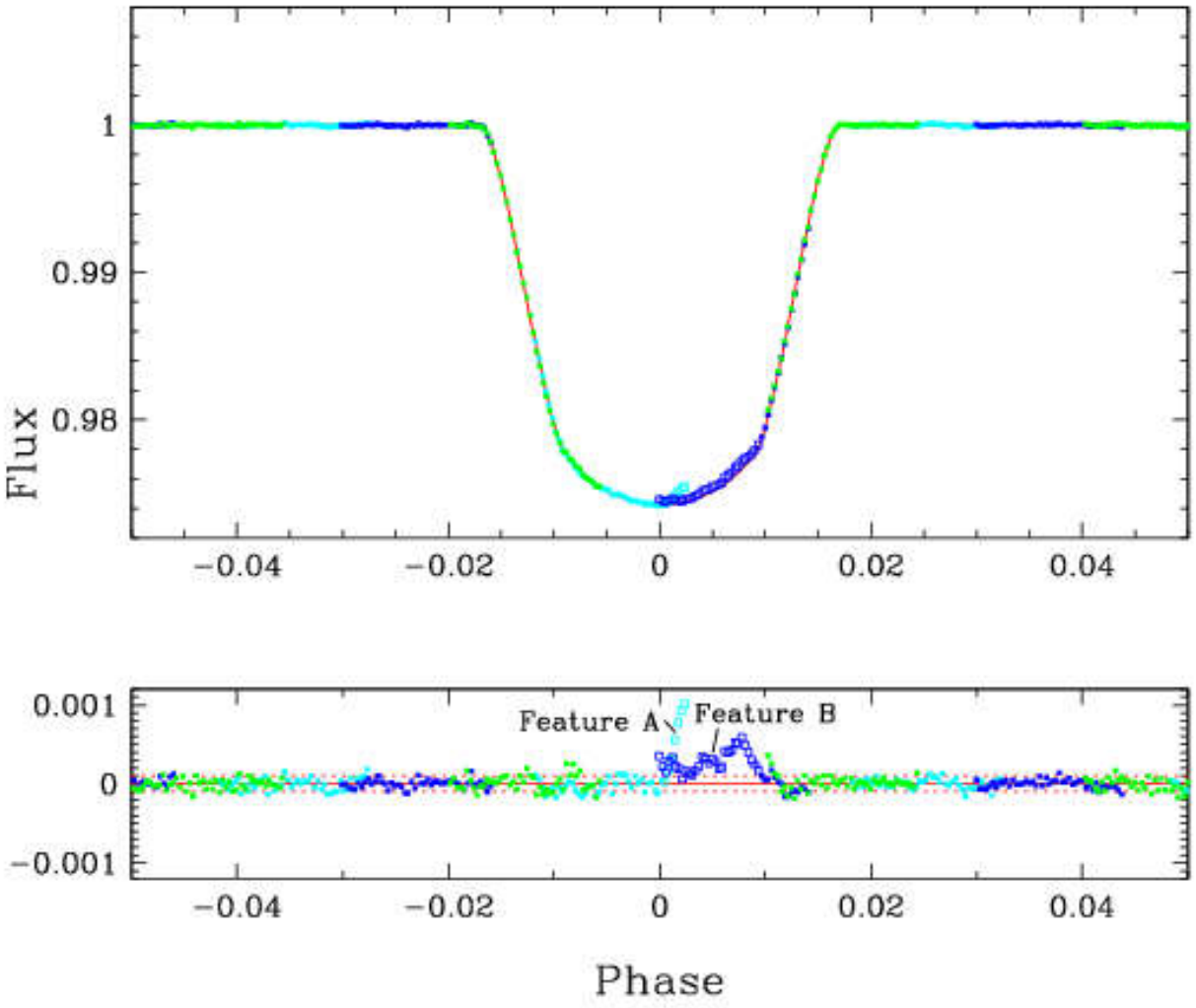
$(\delta = 90^o \rightarrow i_{min})$



M_*, i, RV amplitude ⇨ M_{pl}

M_{pl}, R_{pl} ⇨ ρ_{pl}

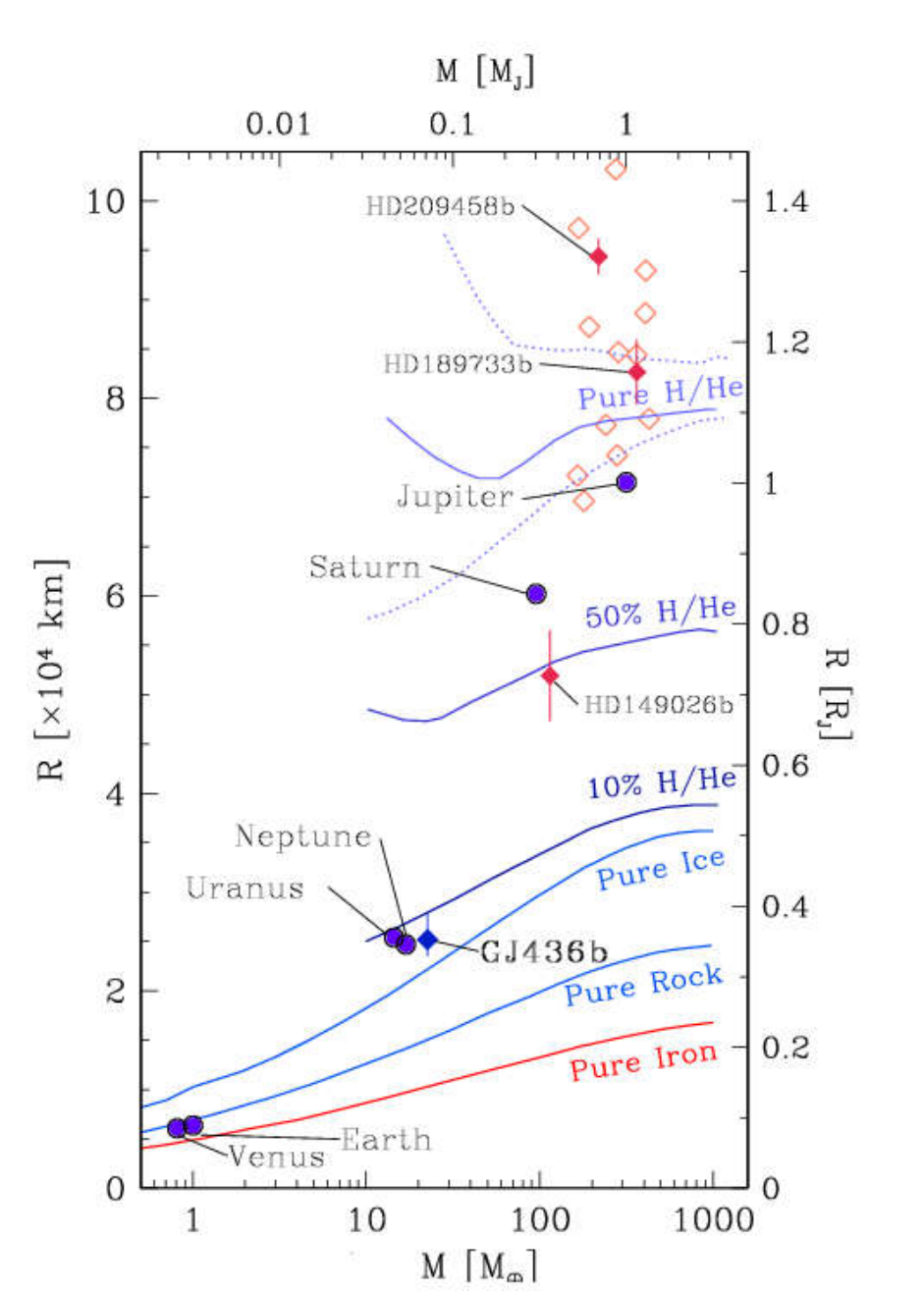
HD209458b



Parent Star:
G star, 154 lyr Pegasus

Planet:
a = 0.045 AU
P = 3.52474541 (25)day
i = 86°

M = 0.69 M_J
R = 1.35 R_J
T = 860 °C



Nature of Planet

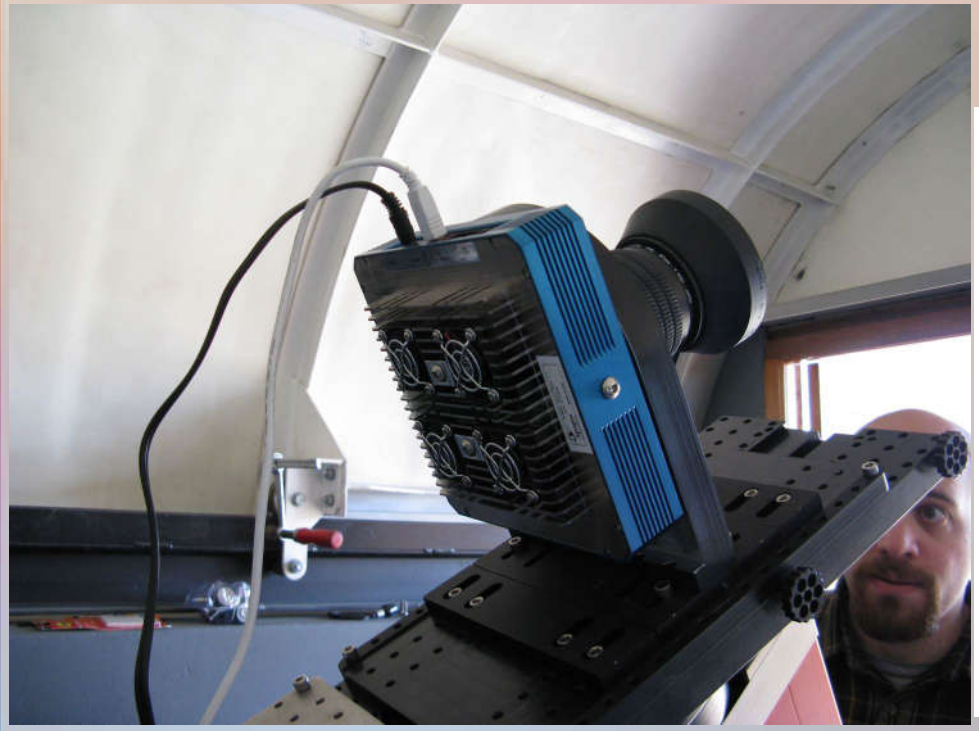
Models with likely composition of planets, calibrated wrt Solar system

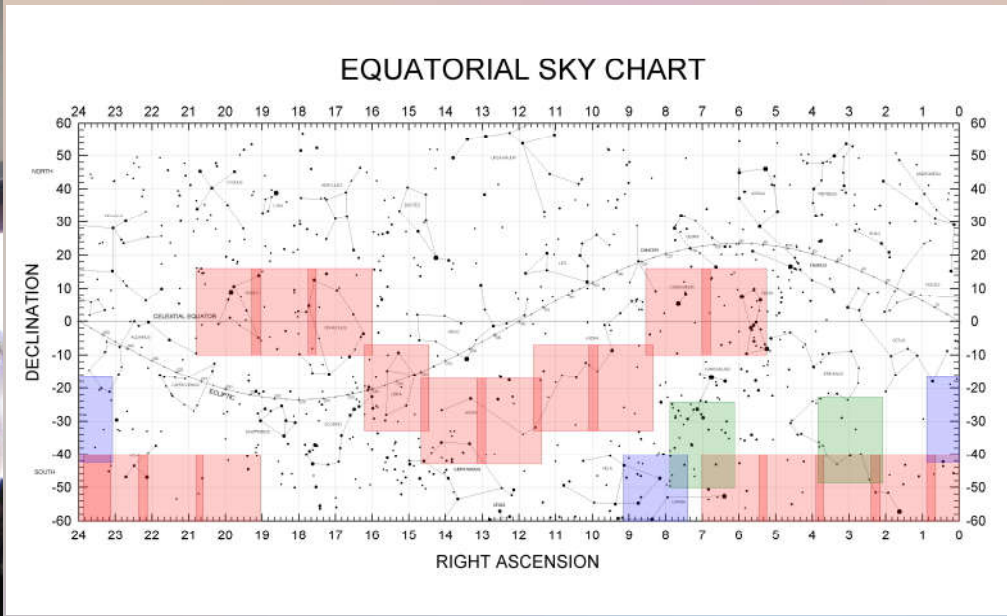
Allows gross characteristics of planet to be determined

Most are ‘hot’ Jupiters, but rocky planets are now being found

KELT-South
(Vanderbilt U)

- Robotic
- 42mm f1.9
- 26° x26° field
- ~100000 stars/image
- V=6-12, 150 sec
- ~80000 useable

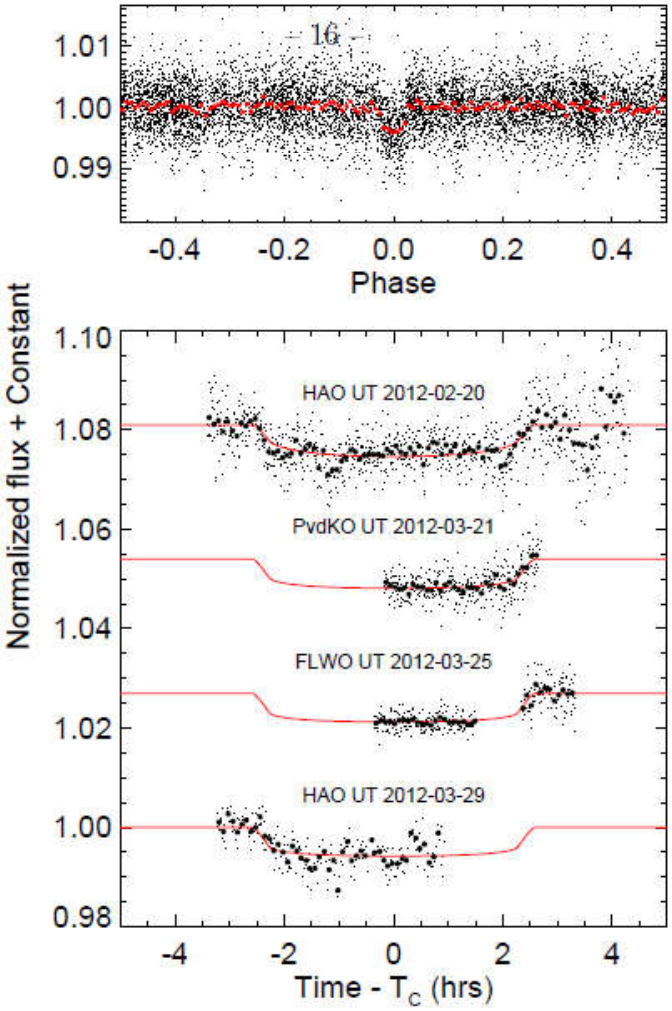




KELT-2Ab

V=8.8 F star P=4.11day, M=1.5M_J

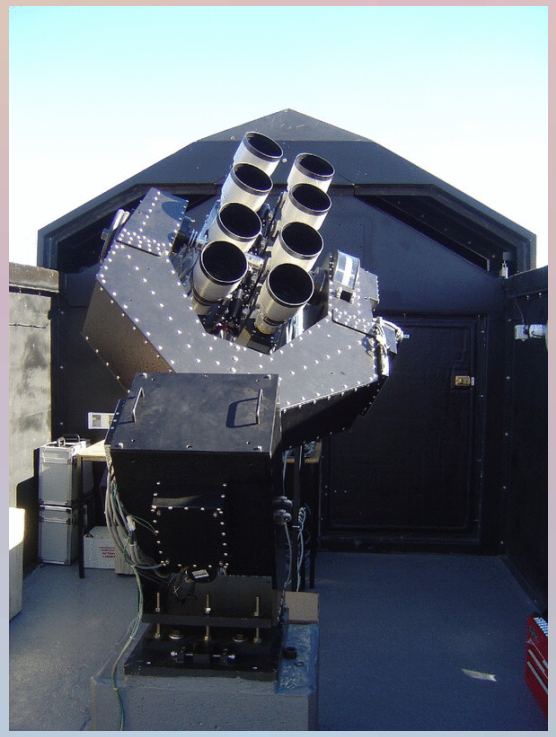
(7837 obs)

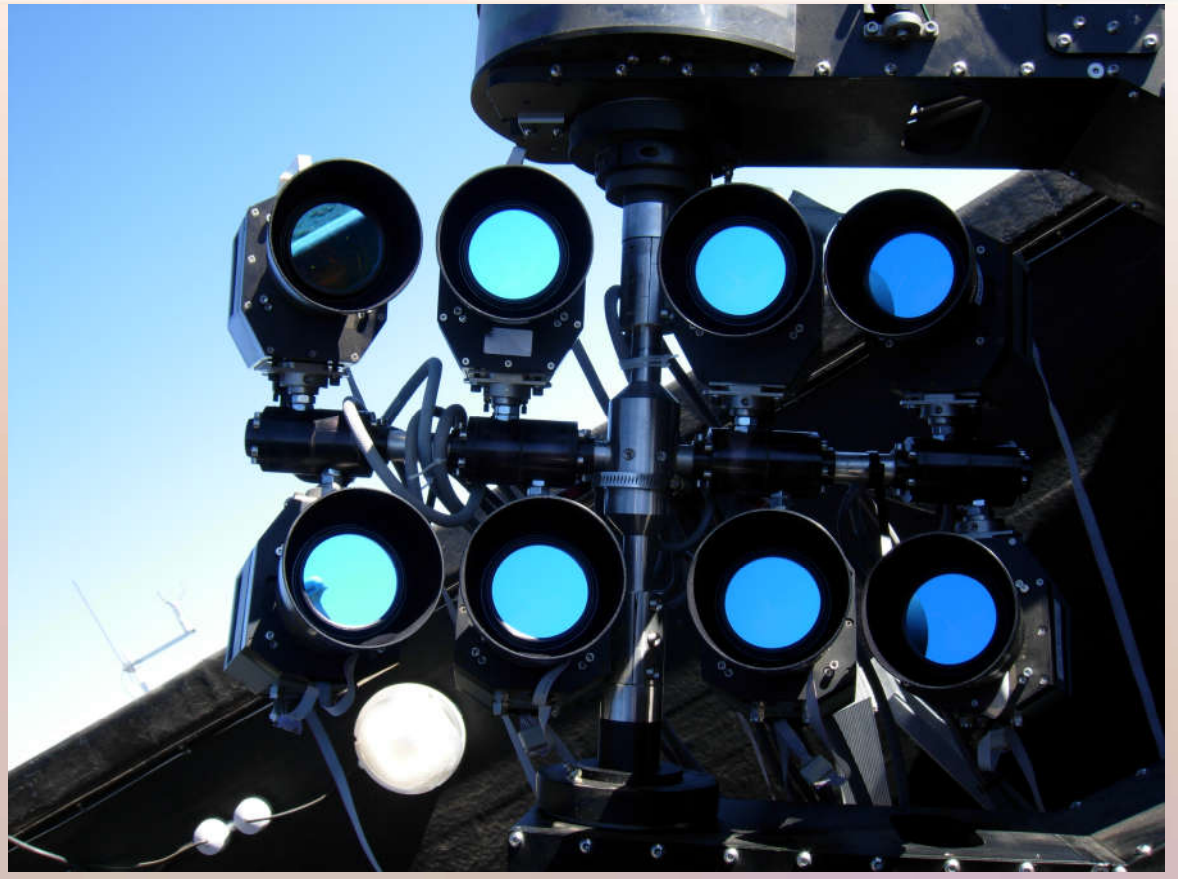


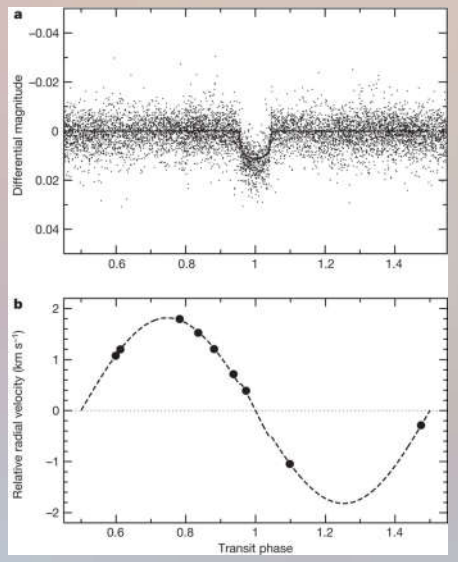
SuperWASP South

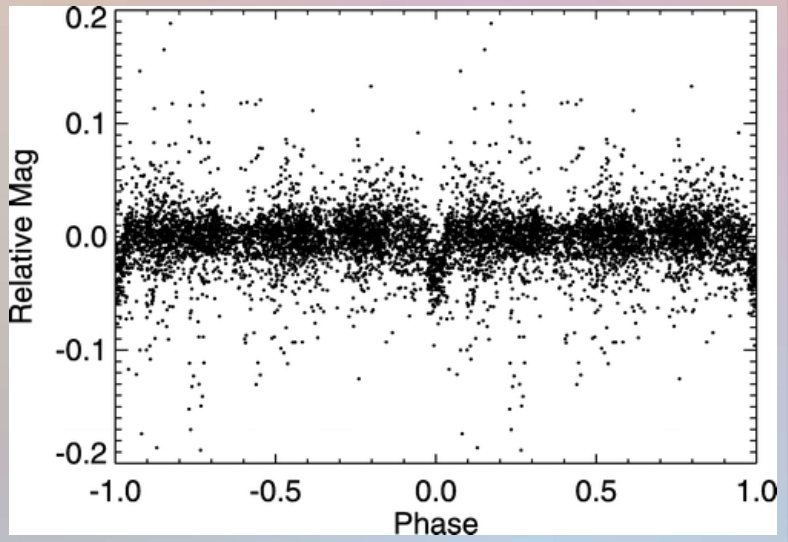
- 8x111mm f1.8

- 85mm f1.2 r-band
- 18° x 18° per camera
- V=7.5 – 9.5





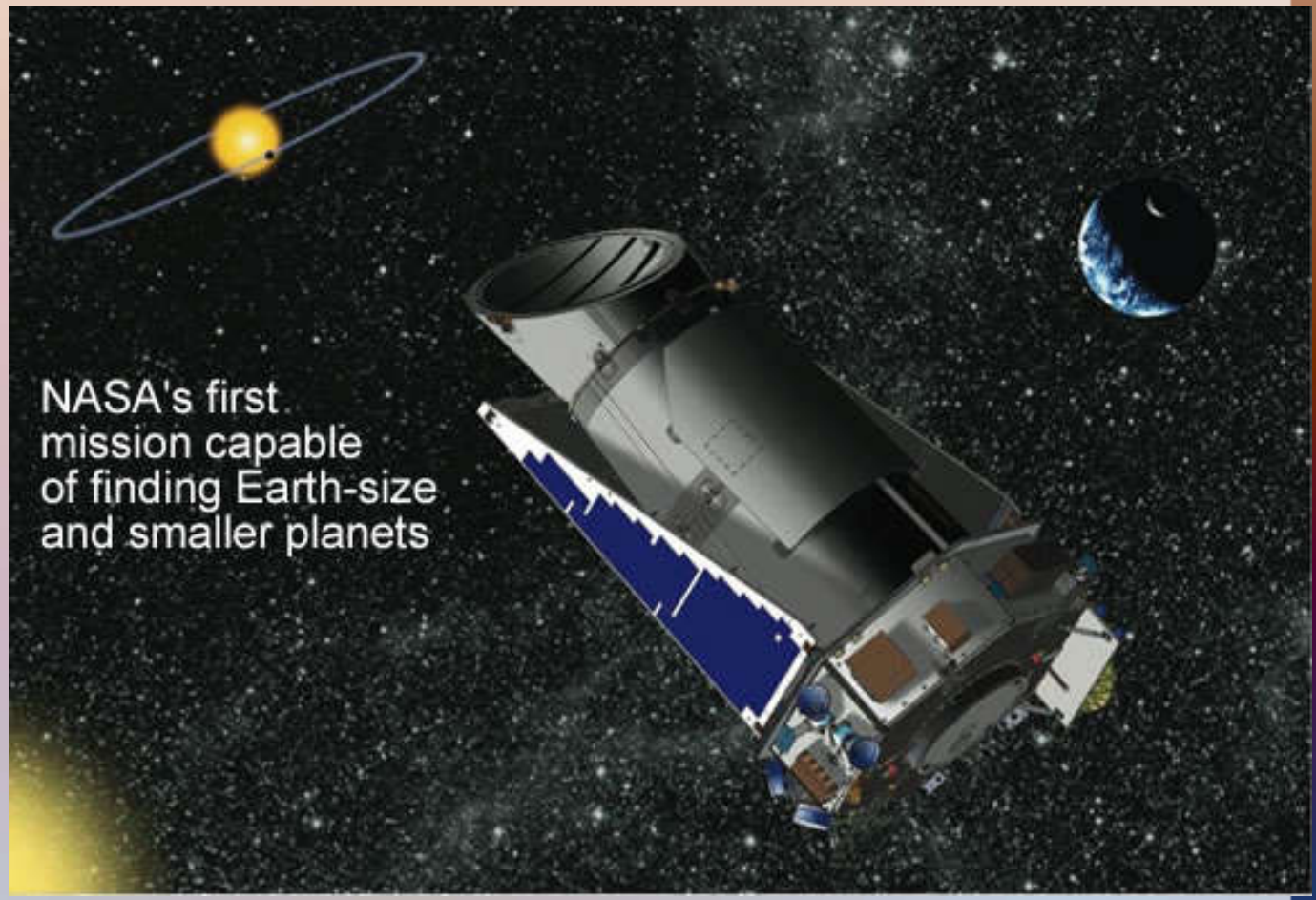


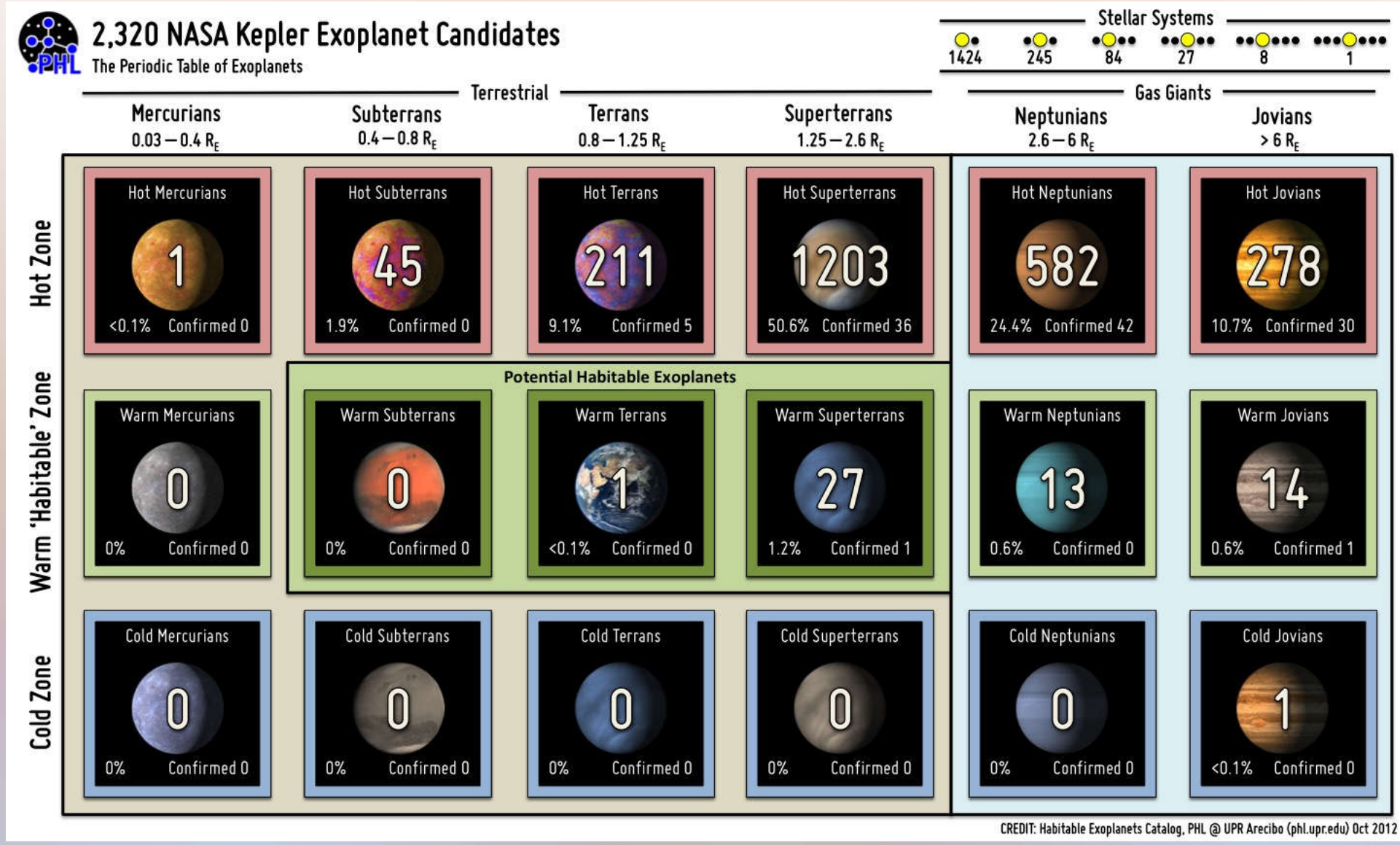


Kepler

. **7.5 year mission**
• **100000 stars**
• **Transits**
(need 3 eclipses to verify transit)
• **Can detect Earth-mass planets**

• **Launched May 2009**




2,320 NASA Kepler Exoplanet Candidates
The Periodic Table of Exoplanets
PHL
Stellar Systems
1424
245
84
27
8
1
Terrestrial
Gas Giants
Mercurians
0.03 — 0.4 R_E
Subterrans
0.4 — 0.8 R_E
Terrans
0.8 — 1.25 R_E
Superterrans
1.25 — 2.6 R_E
Neptunians
2.6 — 6 R_E
Jovians
> 6 R_E
Hot Zone
Warm 'Habitable' Zone
Cold Zone
Potential Habitable Exoplanets
Hot Mercurians
1
<0.1% Confirmed 0
Hot Subterrans
45
1.9% Confirmed 0
Hot Terrans
211
9.1% Confirmed 5
Hot Superterrans
1203
50.6% Confirmed 36
Hot Neptunians
582
24.4% Confirmed 42
Hot Jovians
278
10.7% Confirmed 30
Warm Mercurians
0
0% Confirmed 0
Warm Subterrans
0
0% Confirmed 0
Warm Terrans
1
<0.1% Confirmed 0
Warm Superterrans
27
1.2% Confirmed 1
Warm Neptunians
13
0.6% Confirmed 0
Warm Jovians
14
0.6% Confirmed 1
Cold Mercurians
0
0% Confirmed 0
Cold Subterrans
0
0% Confirmed 0
Cold Terrans
0
0% Confirmed 0
Cold Superterrans
0
0% Confirmed 0
Cold Neptunians
0
0% Confirmed 0
Cold Jovians
1
<0.1% Confirmed 0
CREDIT: Habitable Exoplanets Catalog, PHL @ UPR Arecibo (phl.upr.edu) Oct 2012

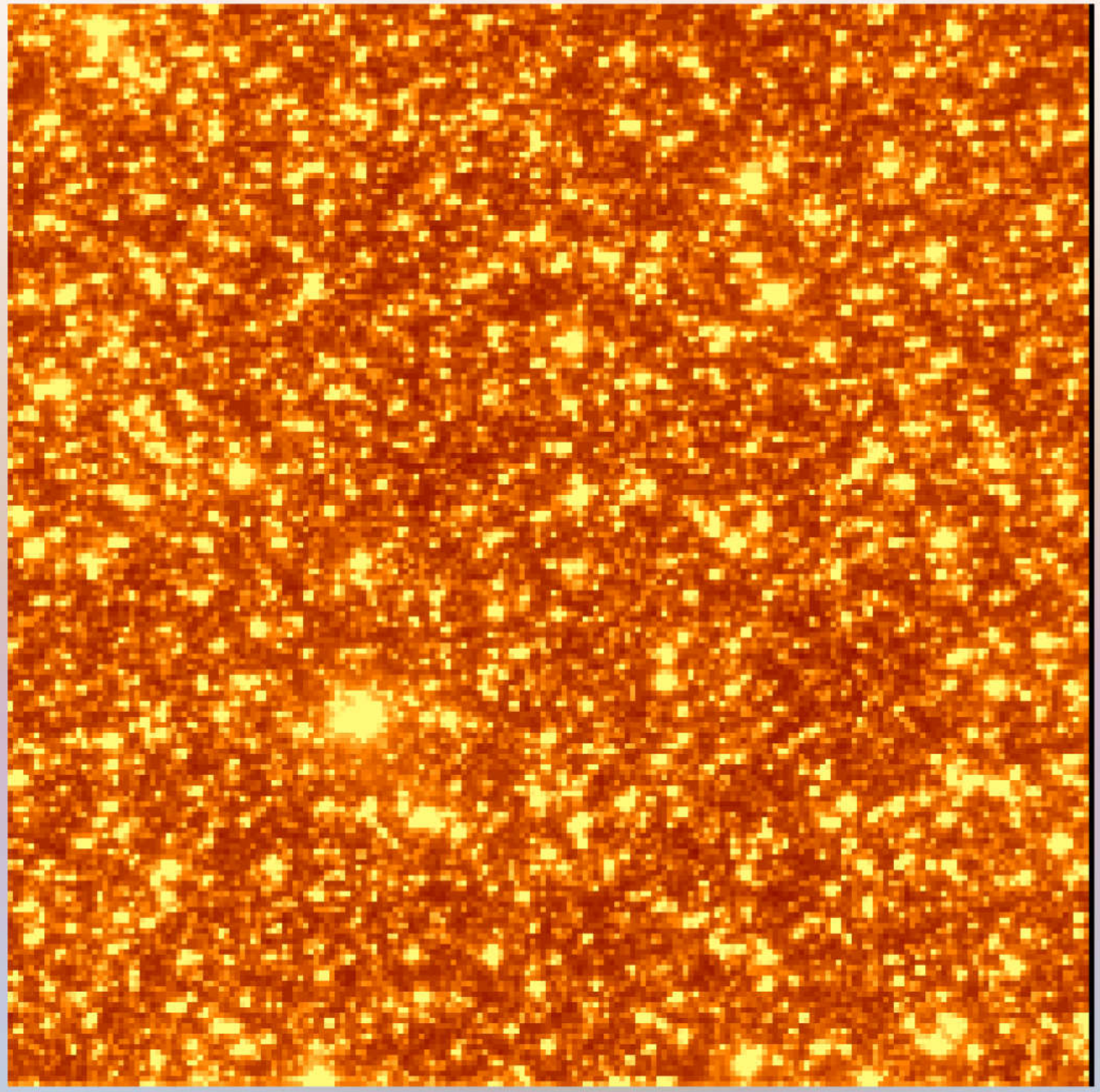
Microlensing

- Deflection of light from background star by intervening mass
- Einstein (1936) stellar lensing; General Relativity
  - Probability 10^{-8} in nearby general field

    (observe 10^{8} stars guarantees 1 event)

    "*Of course, there is no hope of observing this phenomenon directly.*"

- Technical advances:
  - image large areas with CCDs,
  - increased computing power,
  - realtime photometry of millions of stars with high precision in crowded fields (probability ~10^{-6})
  - realtime modelling of ongoing events



Microlensing Geometry

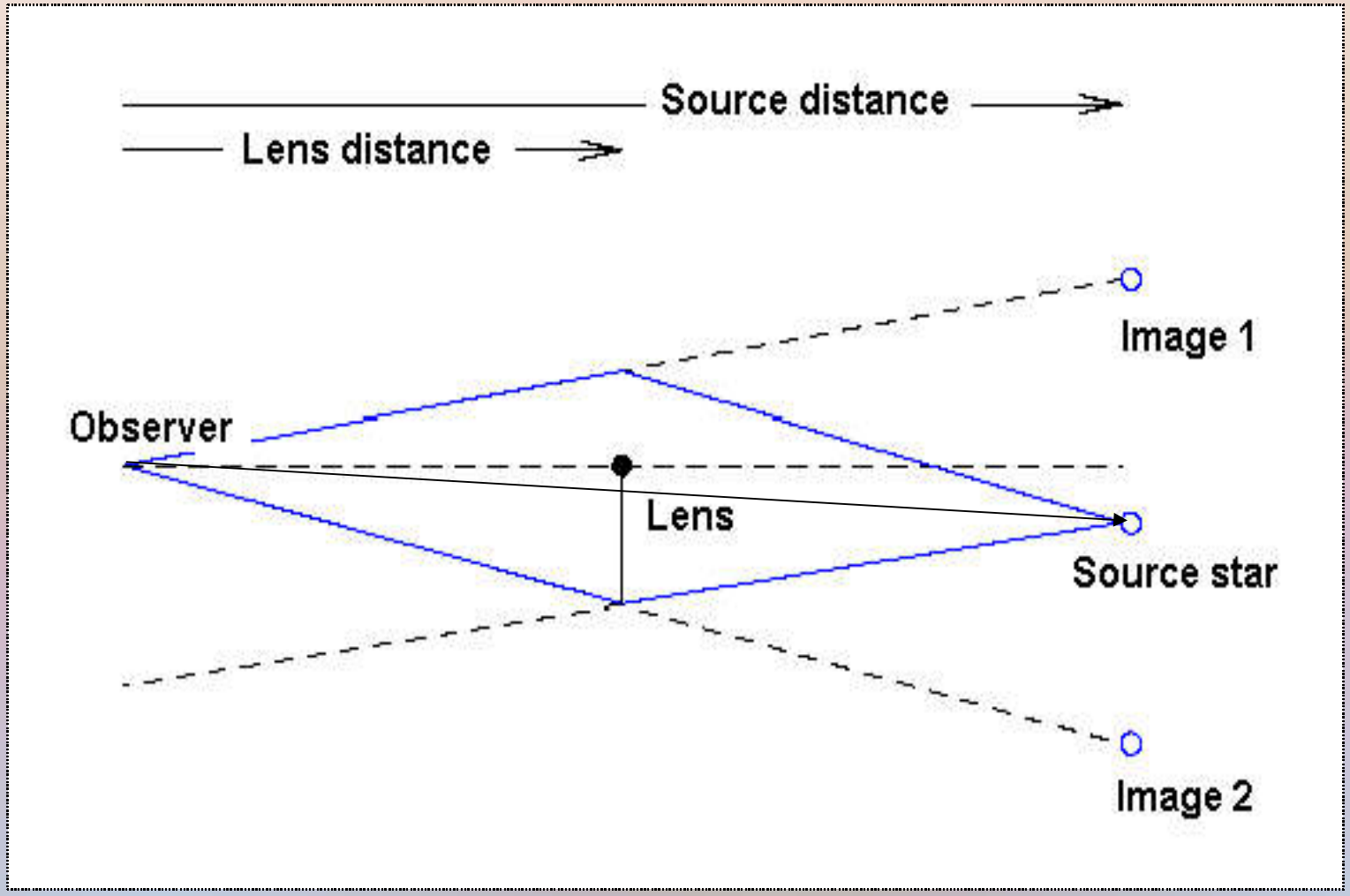
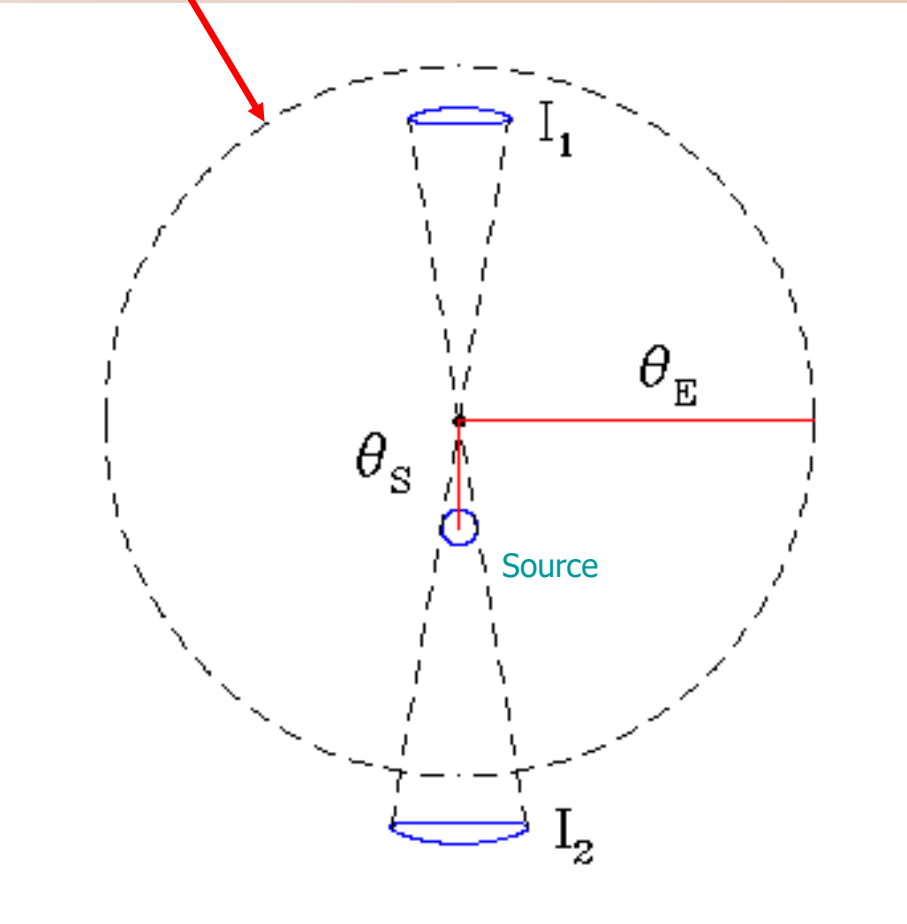


Image shapes

Einstein ring

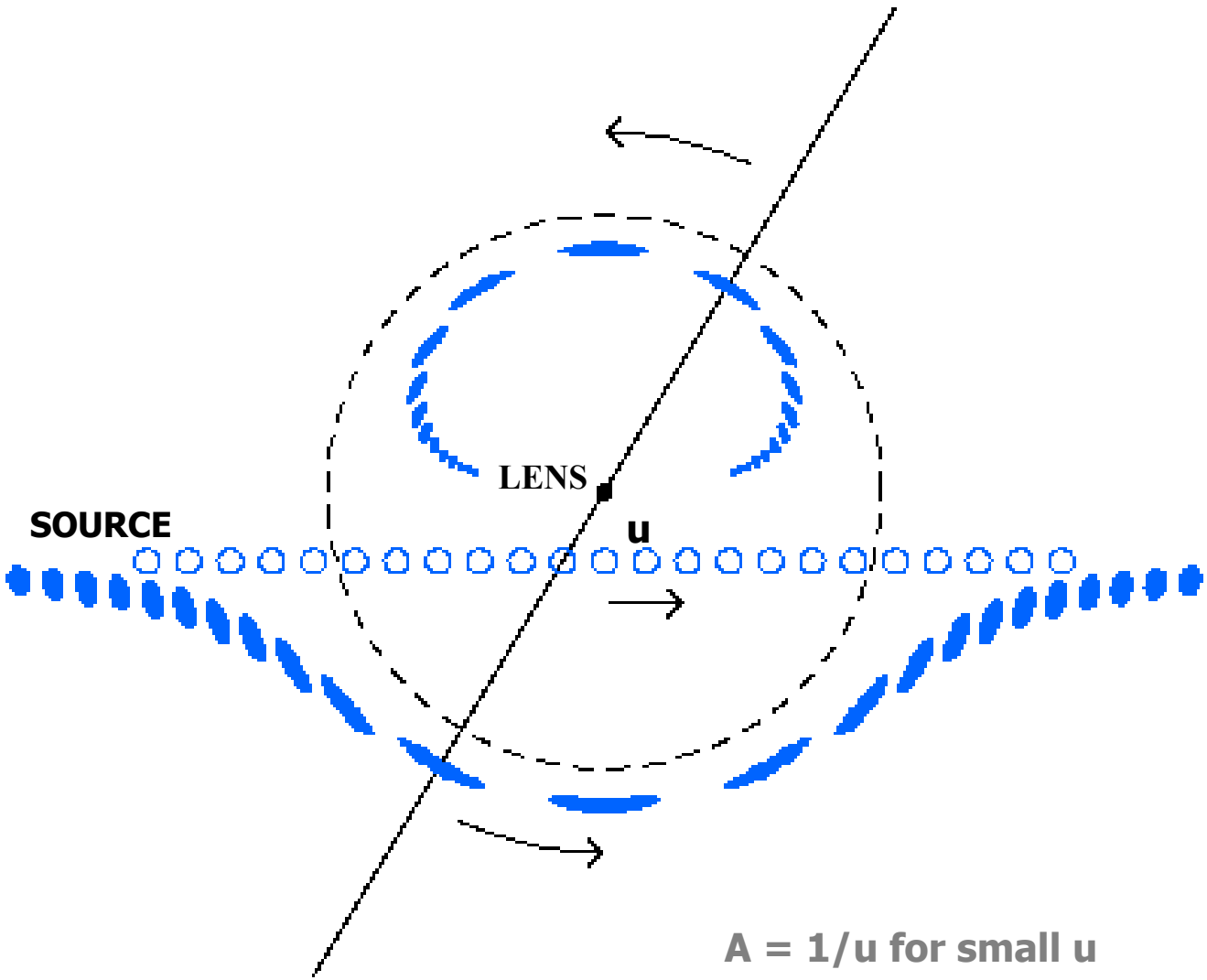


For Source at ~8 kpc
Lens ~ 4 kpc

Diameter of Einstein ring
~ 0.001 arcseconds

Best resolution ~0.1 arcsec
Only see combined light
Amplification

Light Curve – Source, Lens in relative motion

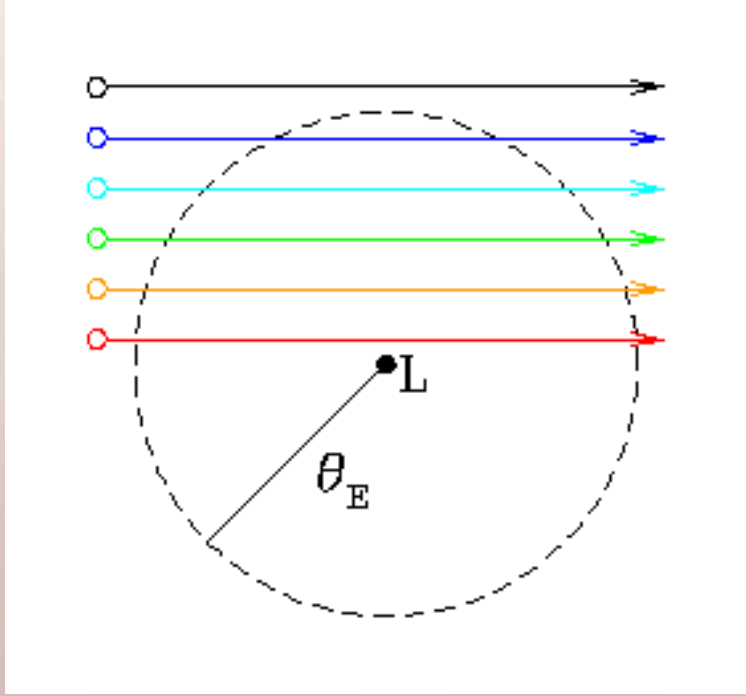


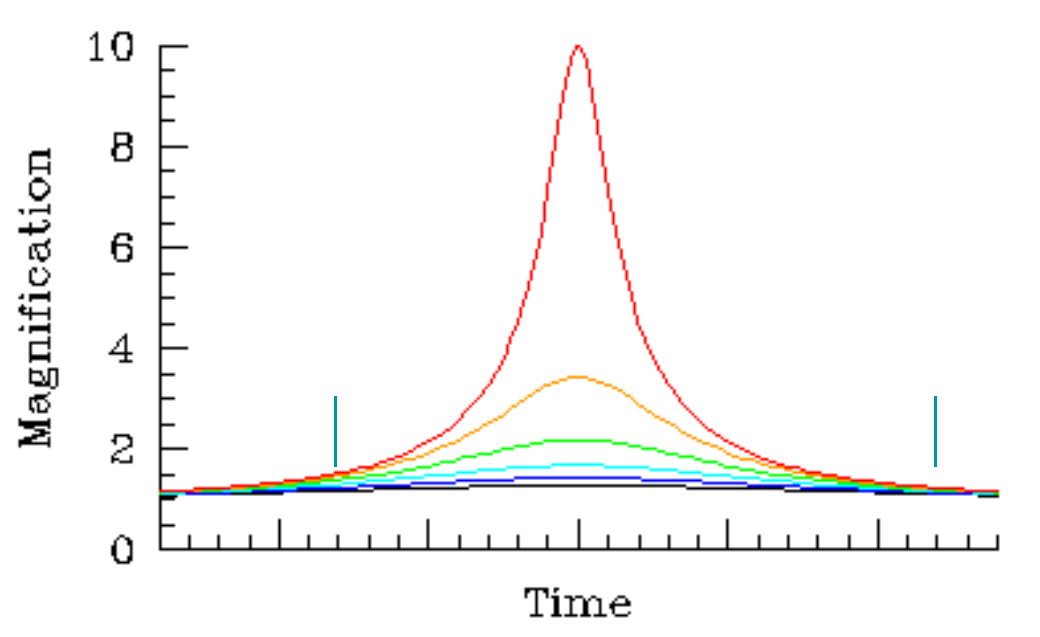
Only sum of 2 images observable.

Amplification

$$A = \frac{u^2 + 2}{u\sqrt{u^2 + 4}}$$

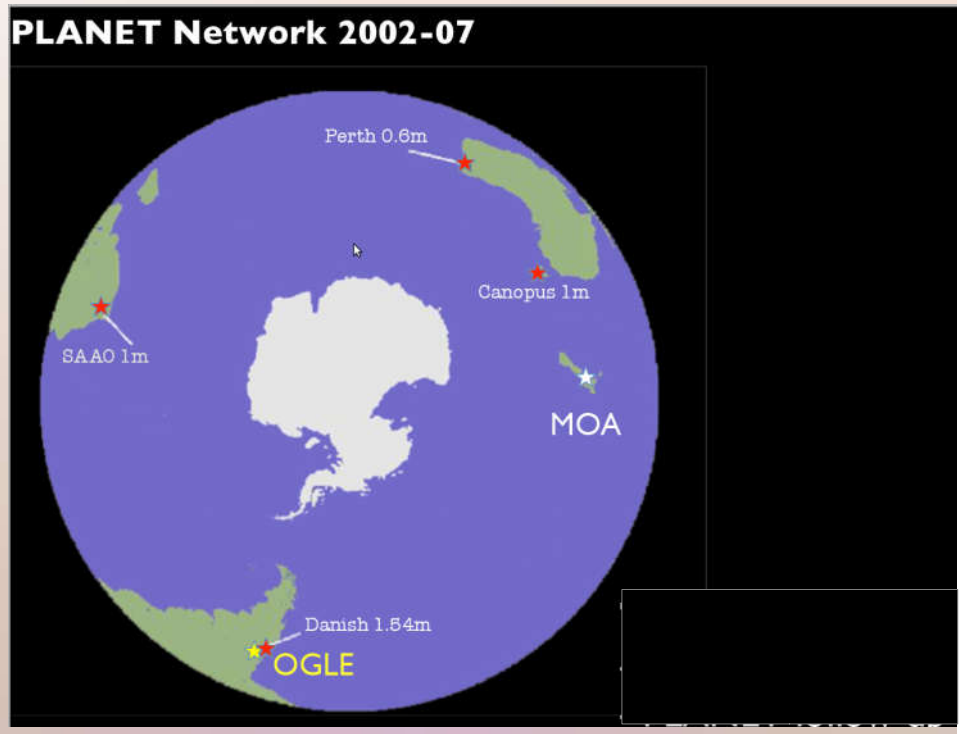
A_{max} depends only on distance of closest approach

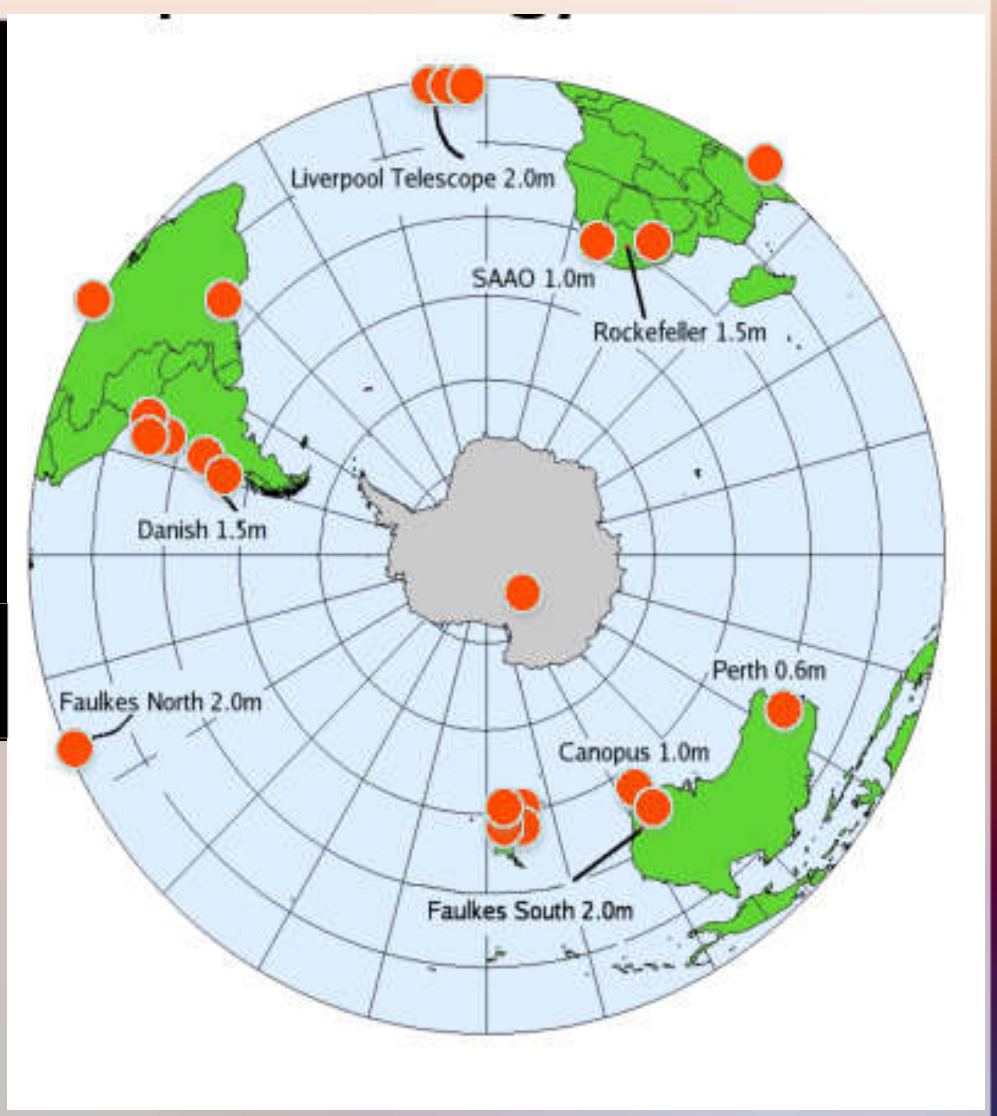




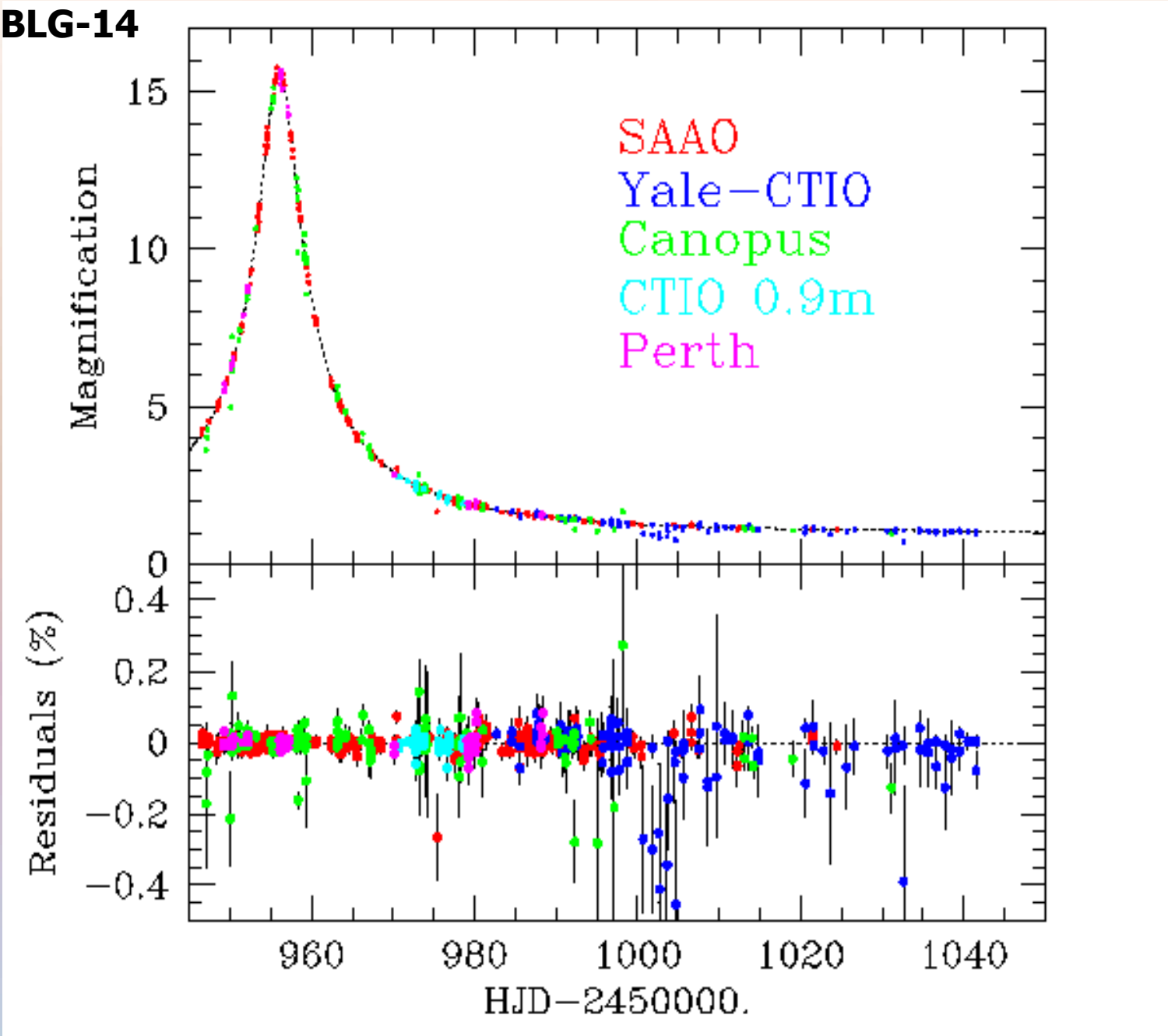
$$\text{Duration} = \frac{2\,D_L\,\theta_E}{v_L} = \frac{2\,D_L}{v_L}\sqrt{\frac{4\,G\,M\,[1-\frac{D_L}{D_S}]}{c^2\,D_L}}$$

Typically ~30-50 days for Bulge source, stellar lens; ~1 day for Jupiter mass


PLANET Network 2002-07
Perth 0.6m
Canopus 1m
SAAO 1m
MOA
Danish 1.54m
OGLE

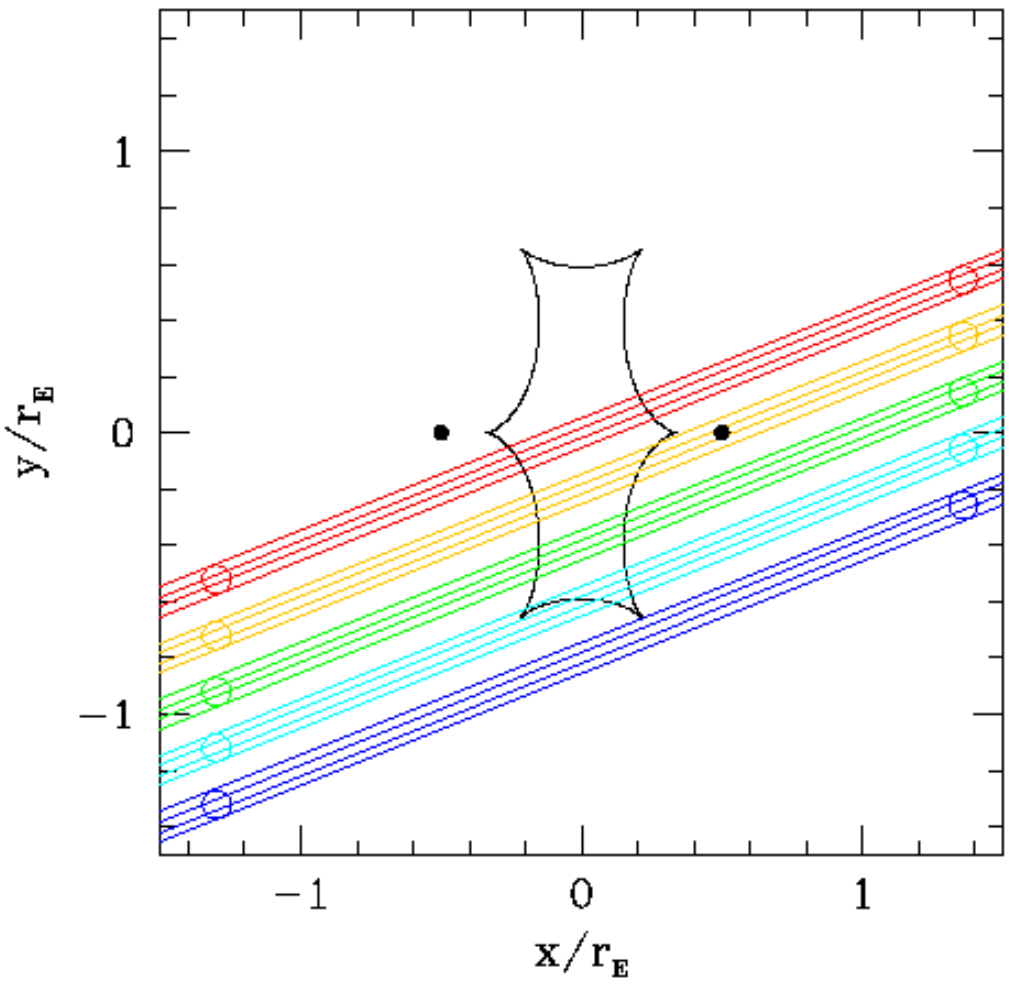

Liverpool Telescope 2.0m
SAAO 1.0m
Rockefeller 1.5m
Danish 1.5m
Faulkes North 2.0m
Perth 0.6m
Canopus 1.0m
Faulkes South 2.0m

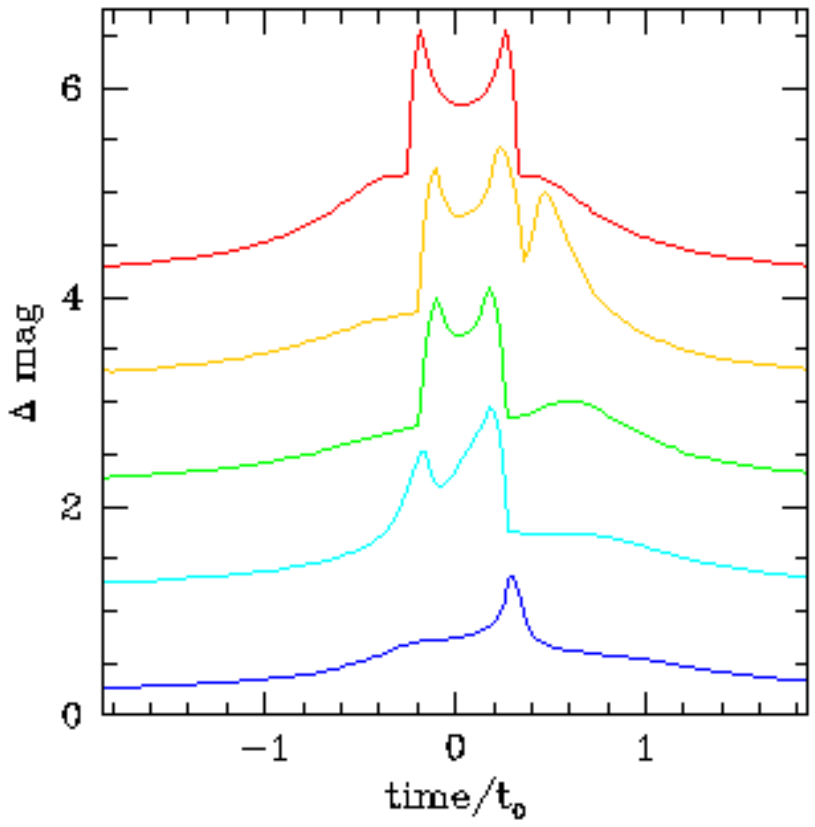
OGLE-1998-BLG-14



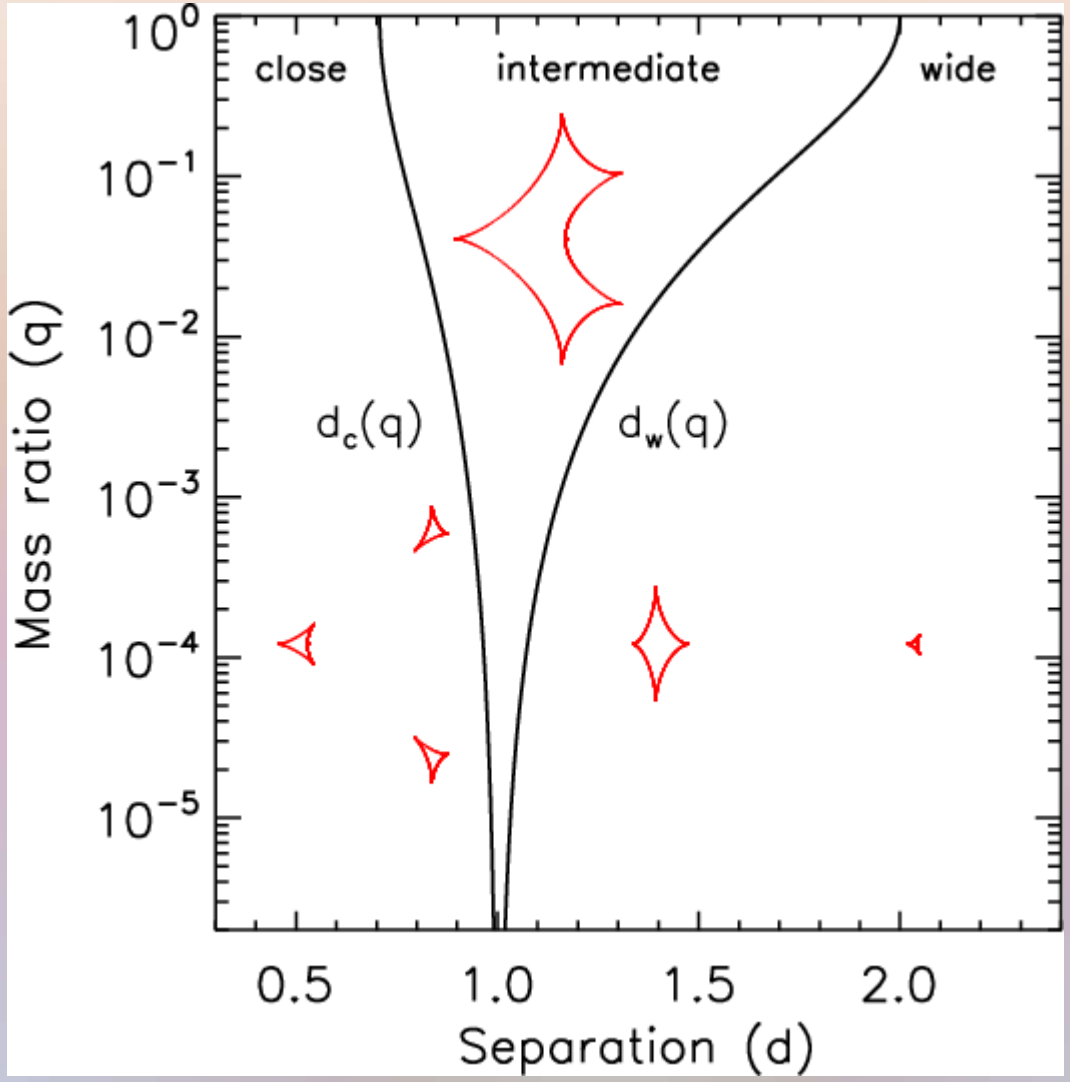
Binary Lens

mass ratio q=1.0





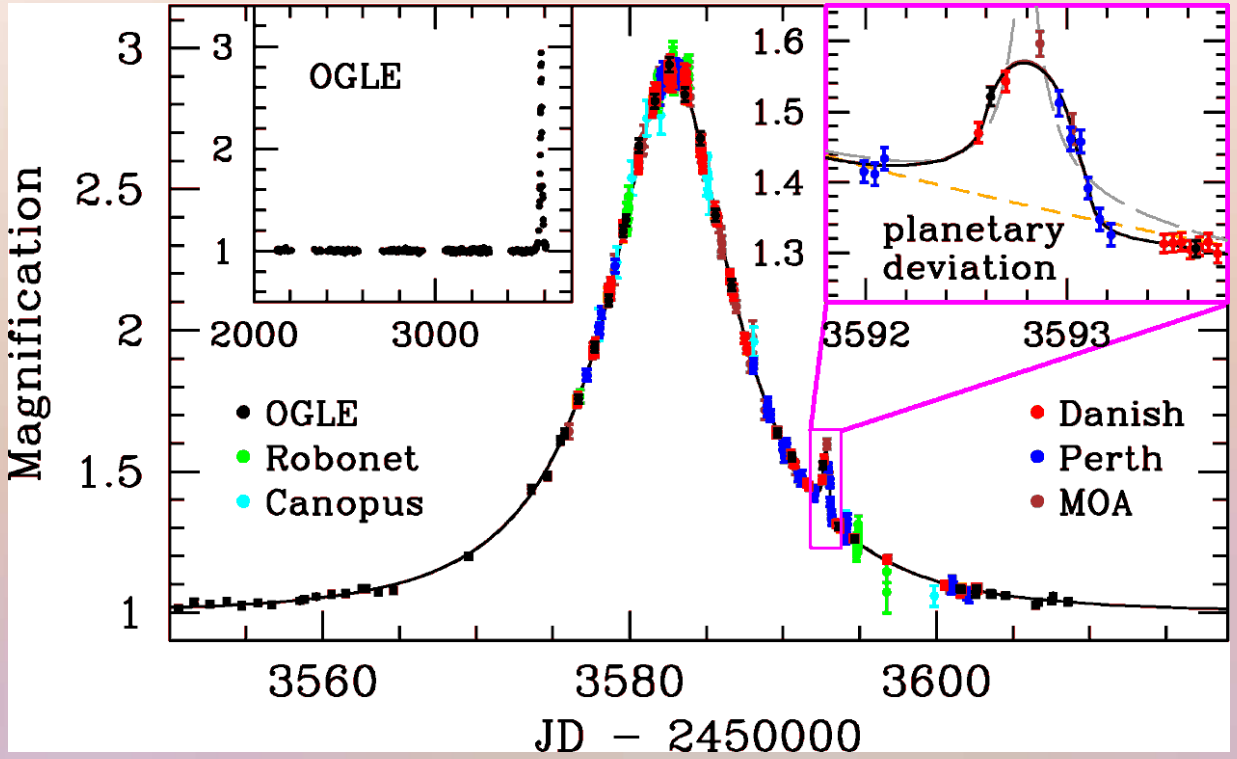
Binary separation effects



$q=M_2/M_1=10^{-2}$

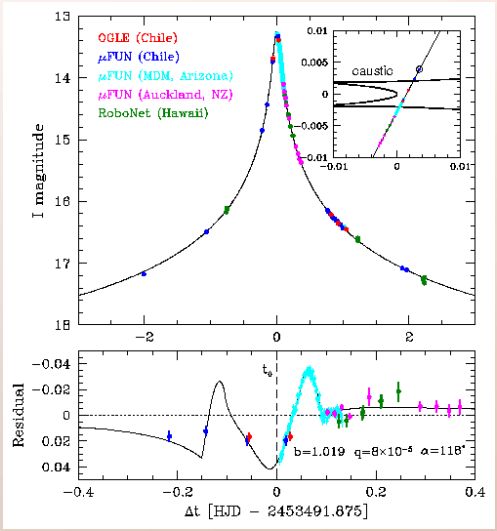
	D/R_E
Close	0.6
Inter	1.0
Wide	1.6

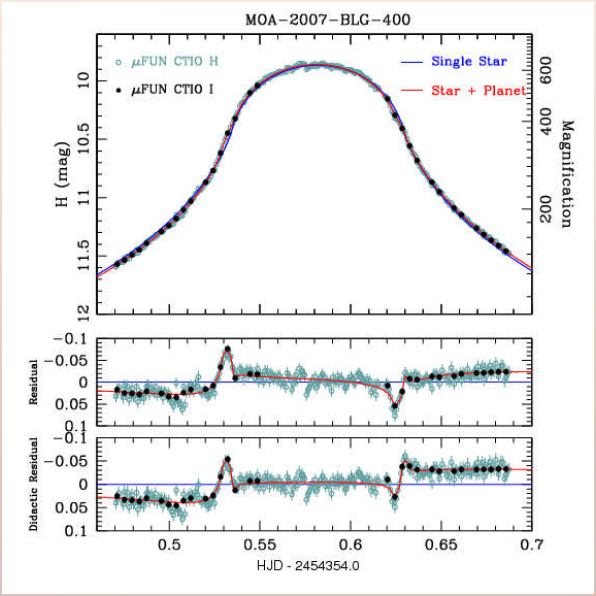
OGLE-2005-BLG-390

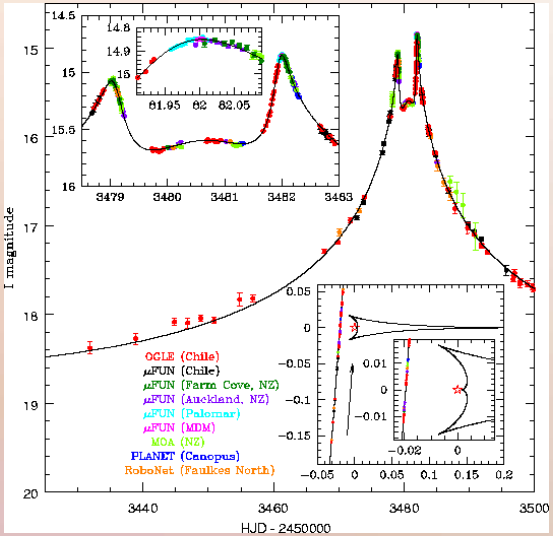


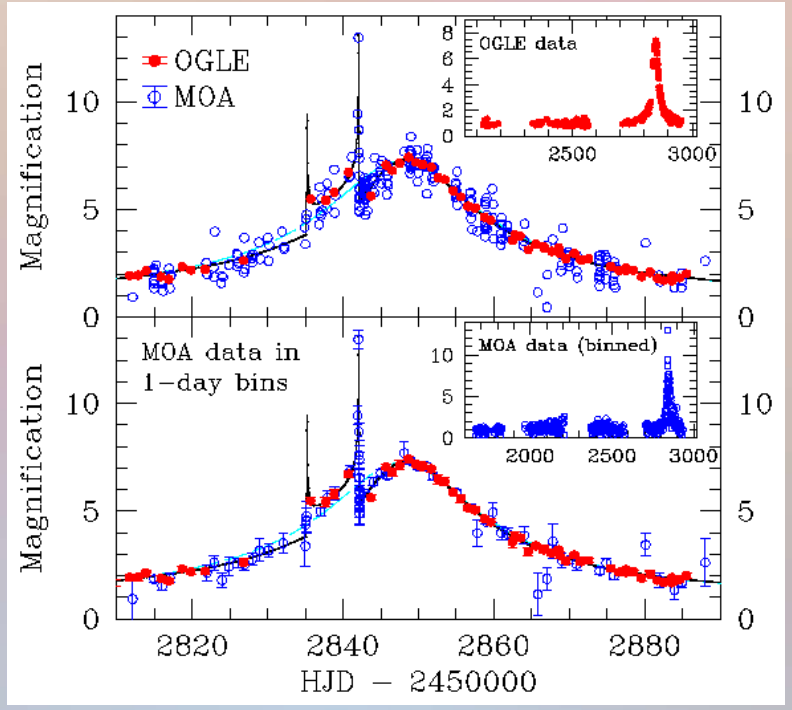
Planetary signal –

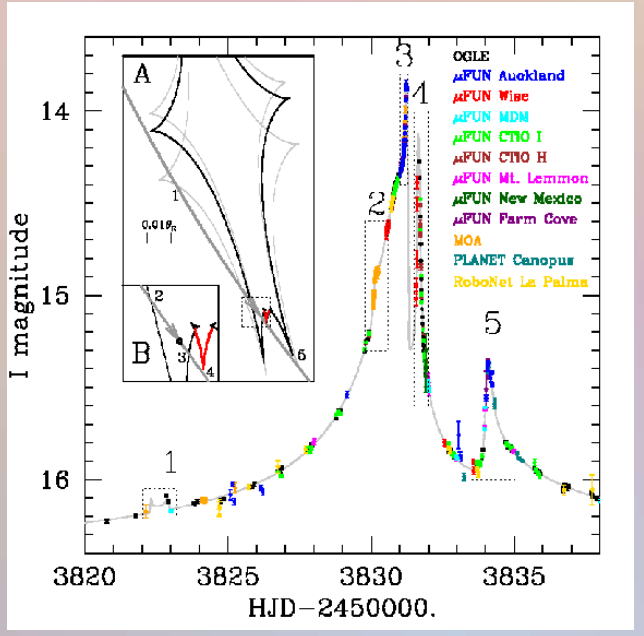
small deviation from ideal point source, point lens model
In this case owing to a ~5 Earth mass planet (0.015M_J)
at a distance of ~3 AU from the parent star (M type)

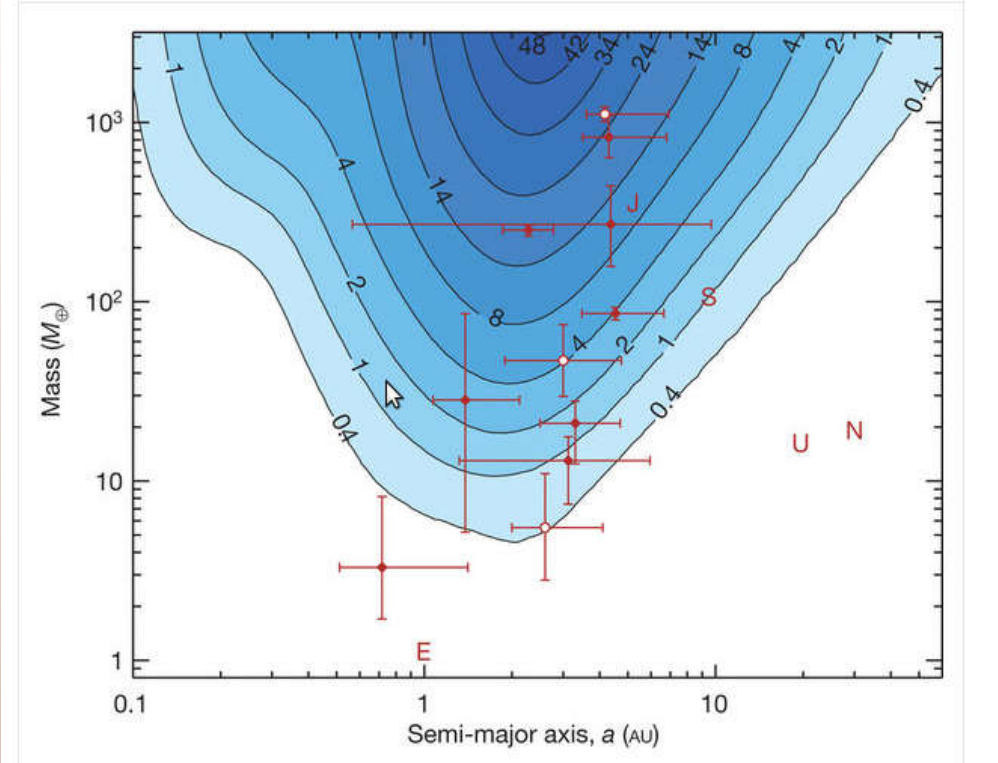

OGLE (Chile)
μFUN (Chile)
μFUN (MDM, Arizona)
μFUN (Auckland, NZ)
RoboNet (Hawaii)
caustic
I magnitude
Residual
b=1.019 q=8×10⁻⁵ α=118°
Δt [HJD − 2453491.875]


MOA−2007−BLG−400
μFUN CTIO H
μFUN CTIO I
Single Star
Star + Planet
H (mag)
Magnification
Residual
Didactic Residual
HJD - 2454354.0

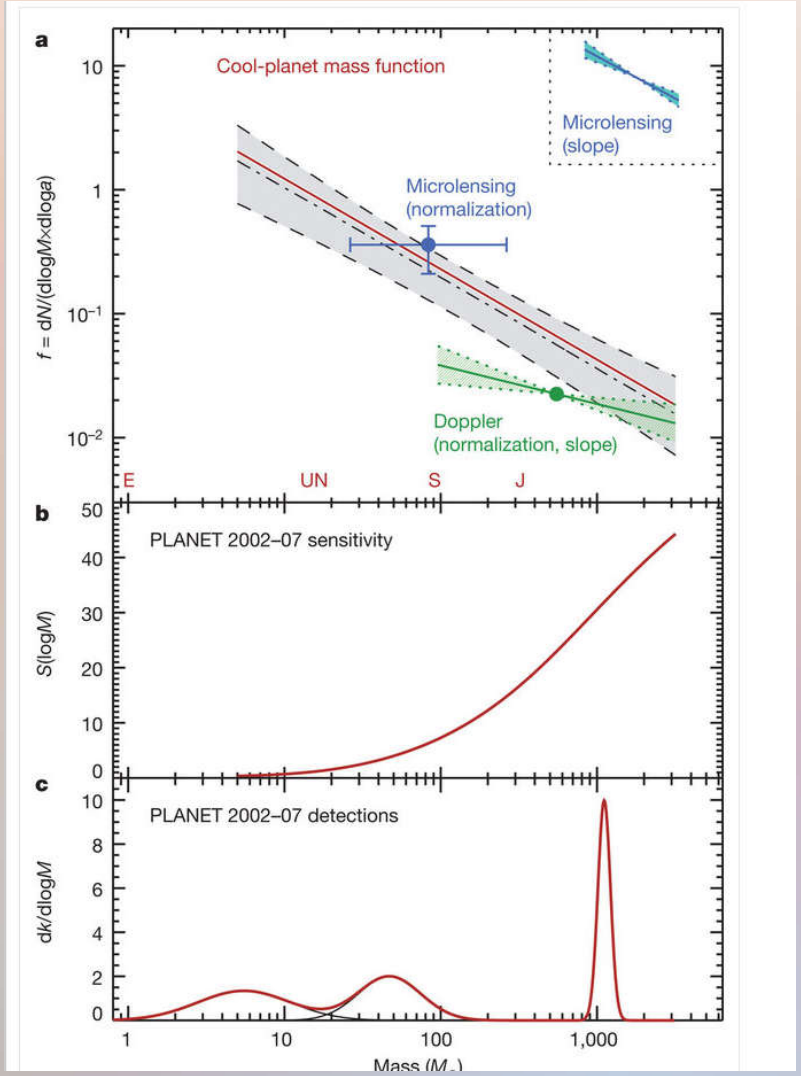

I magnitude
OGLE (Chile)
μFUN (Chile)
μFUN (Farm Cove, NZ)
μFUN (Auckland, NZ)
μFUN (Palomar)
μFUN (MDM)
MOA (NZ)
PLANET (Canopus)
RoboNet (Faulkes North)
HJD - 2450000


OGLE
MOA
OGLE data
MOA data in
1−day bins
MOA data (binned)
Magnification
HJD − 2450000


OGLE
μFUN Auckland
μFUN Wise
μFUN MDM
μFUN CTIO I
μFUN CTIO H
μFUN Mt. Lemmon
μFUN New Mexico
μFUN Farm Cove
MOA
PLANET Canopus
RoboNet La Palma
I magnitude
HJD−2450000.



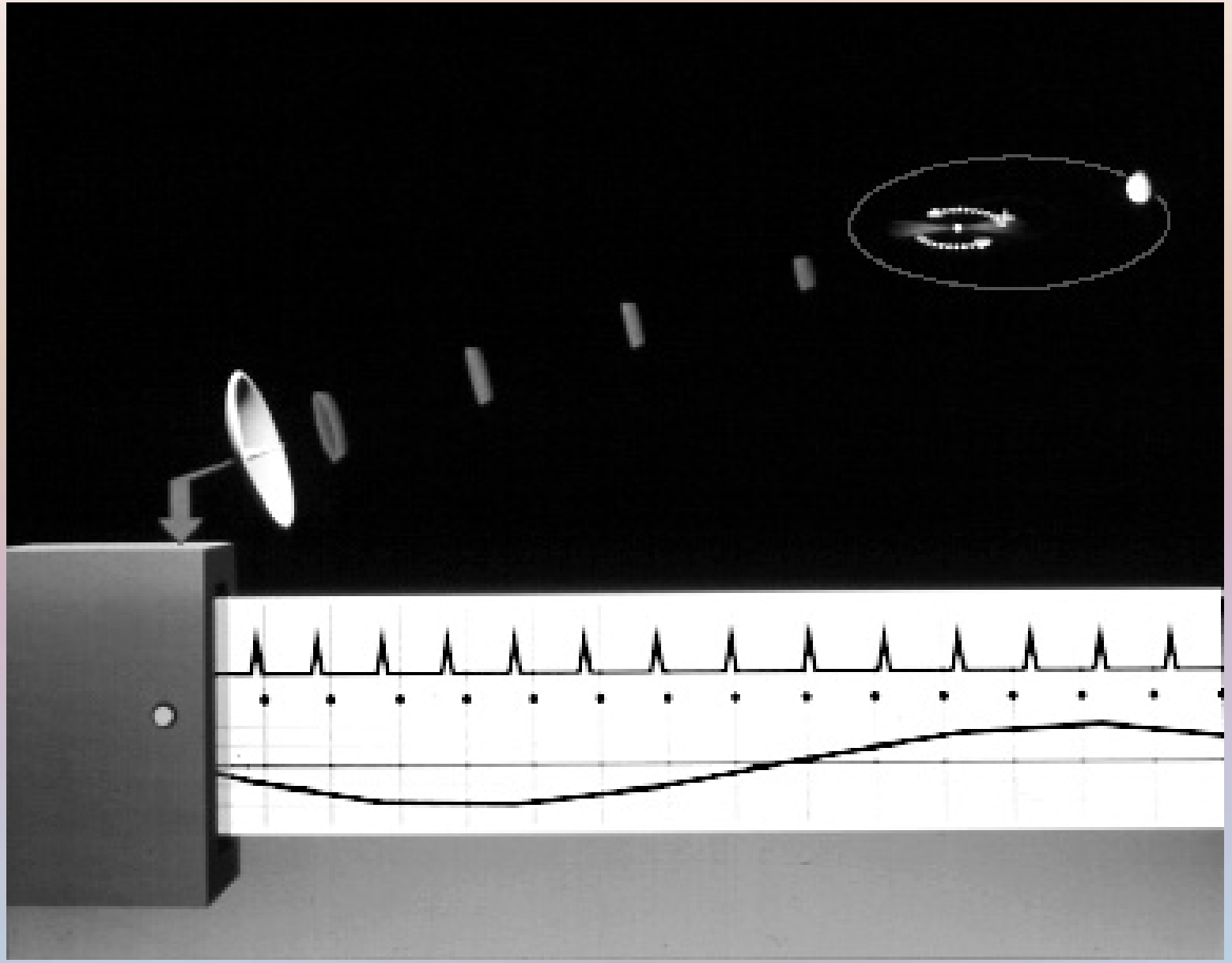
PLANET microlensing result



Within 0.5 – 10au:
17% on average host a Jupiter (.3-10M_J)
52% Neptune (10-30M_N)

1.6 planets (5M_E-10M_J) per star in Galaxy!!

Pulsar Timing



Project Solaris

GLOBAL TELESCOPE NETWORK

SOLARIS

SOLARIS-HQ
NICOLAUS COPERNICUS ASTRONOMICAL CENTER
TORUN, POLAND

SOLARIS-4
COMPLEJO ASTRONÓMICO EL LEONCITO
ARGENTINA
ELEV. 2591 M
COORD. 31°47 14.46" S, 69°18' 23.16" W

SOLARIS-3
SIDING SPRINGS OBSERVATORY
AUSTRALIA
ELEV. 1100M
COORD. 31°16'20.64", S149°3' 42.88" E

SOLARIS-1 AND SOLARIS-2
SOUTH AFRICAN ASTRONOMICAL OBSERVATORY
REPUBLIC OF SOUTH AFRICA
ELEV. 1783M
COORD. 32°22'41.88" S, 20°48'37.8" E

http://www.projectsolaris.eu

Ministry of Science and Higher Education
Republic of Poland

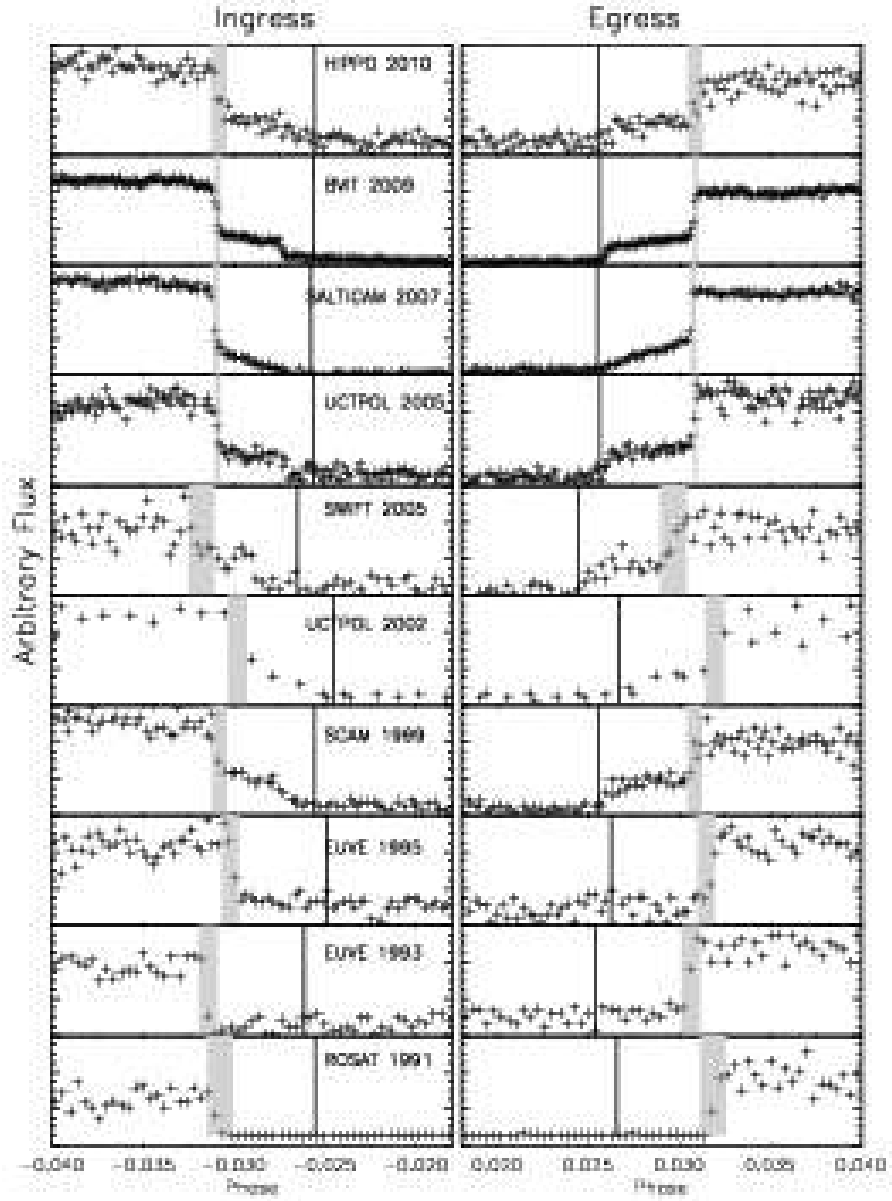
ZPORR

erc

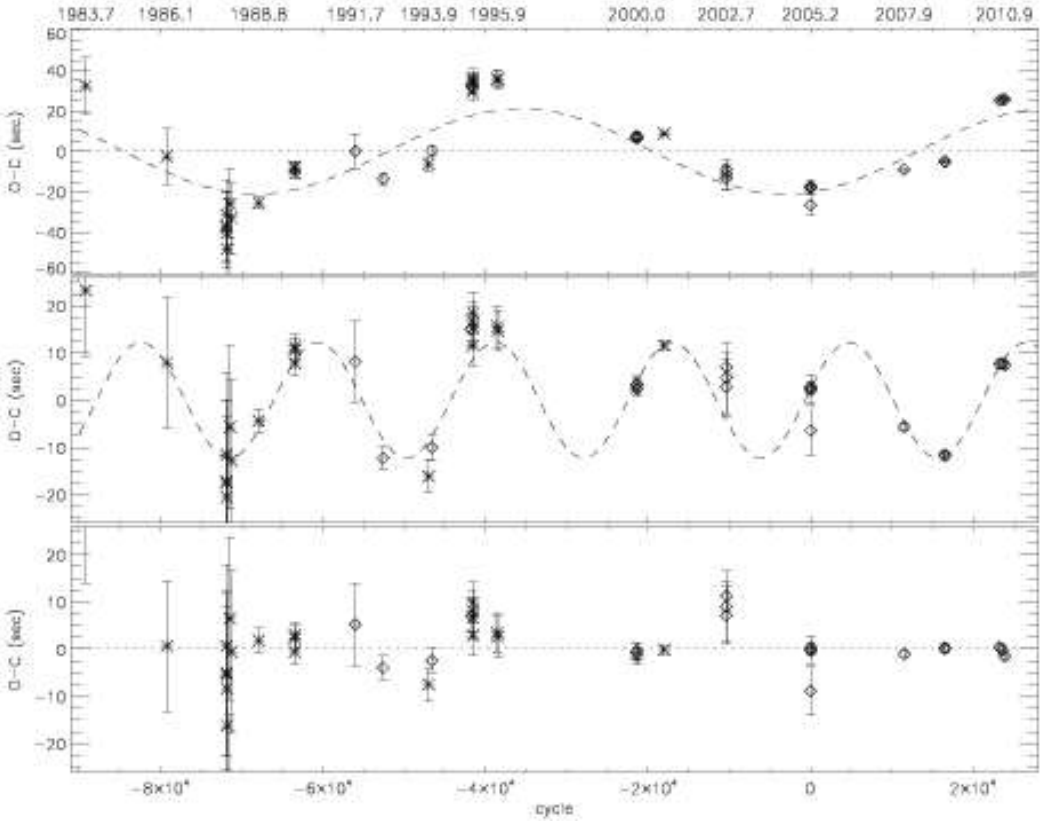
FNP

Eclipsing Polar, UZ For

(period=126.6 min)



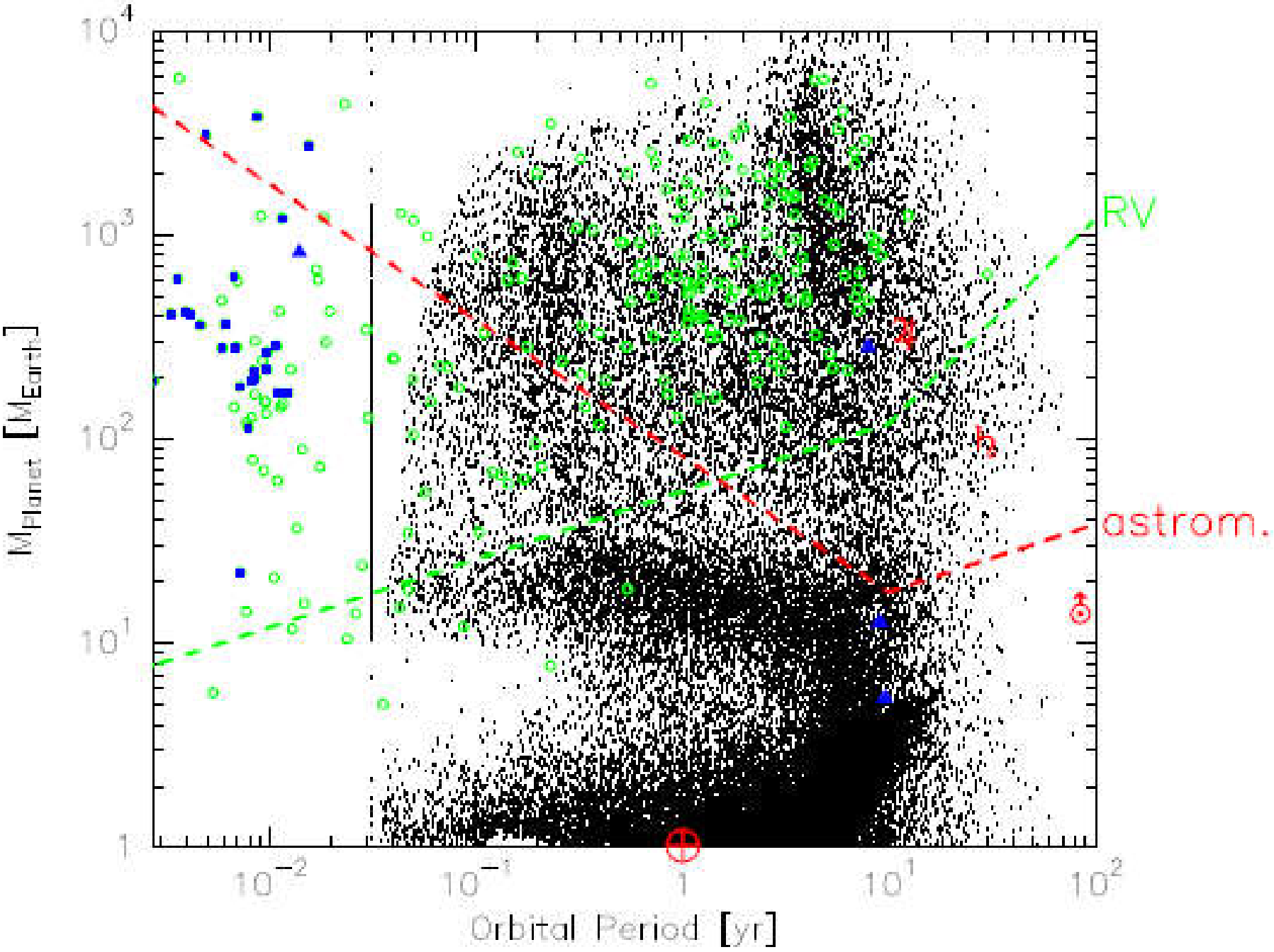
Eclipse timing variations ⇨ 2 giant planets

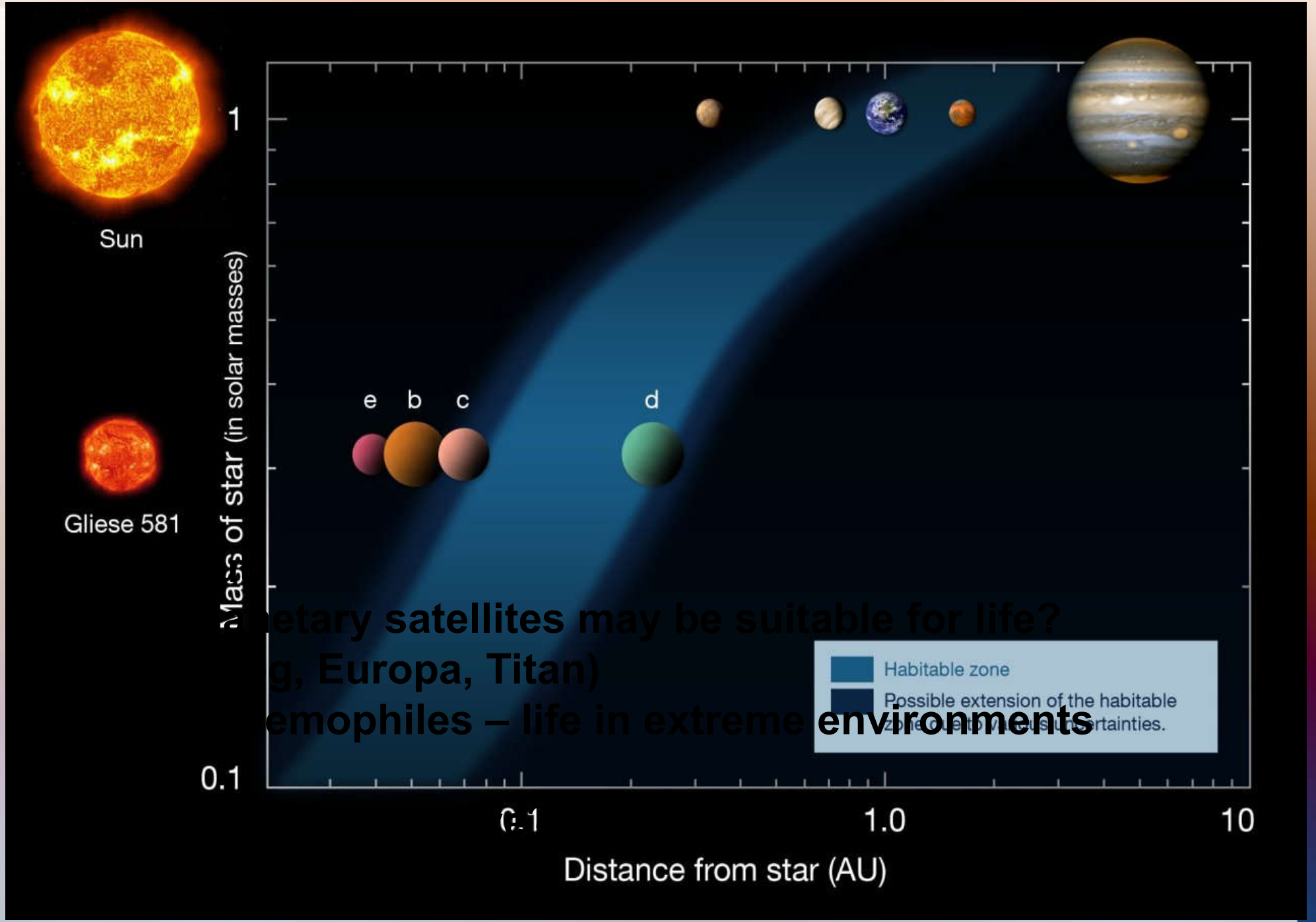


P_1 ~16 yr M_1 ~ 6.3M_J

P_2 ~5.25 yr M_2 ~ 7.7M_J

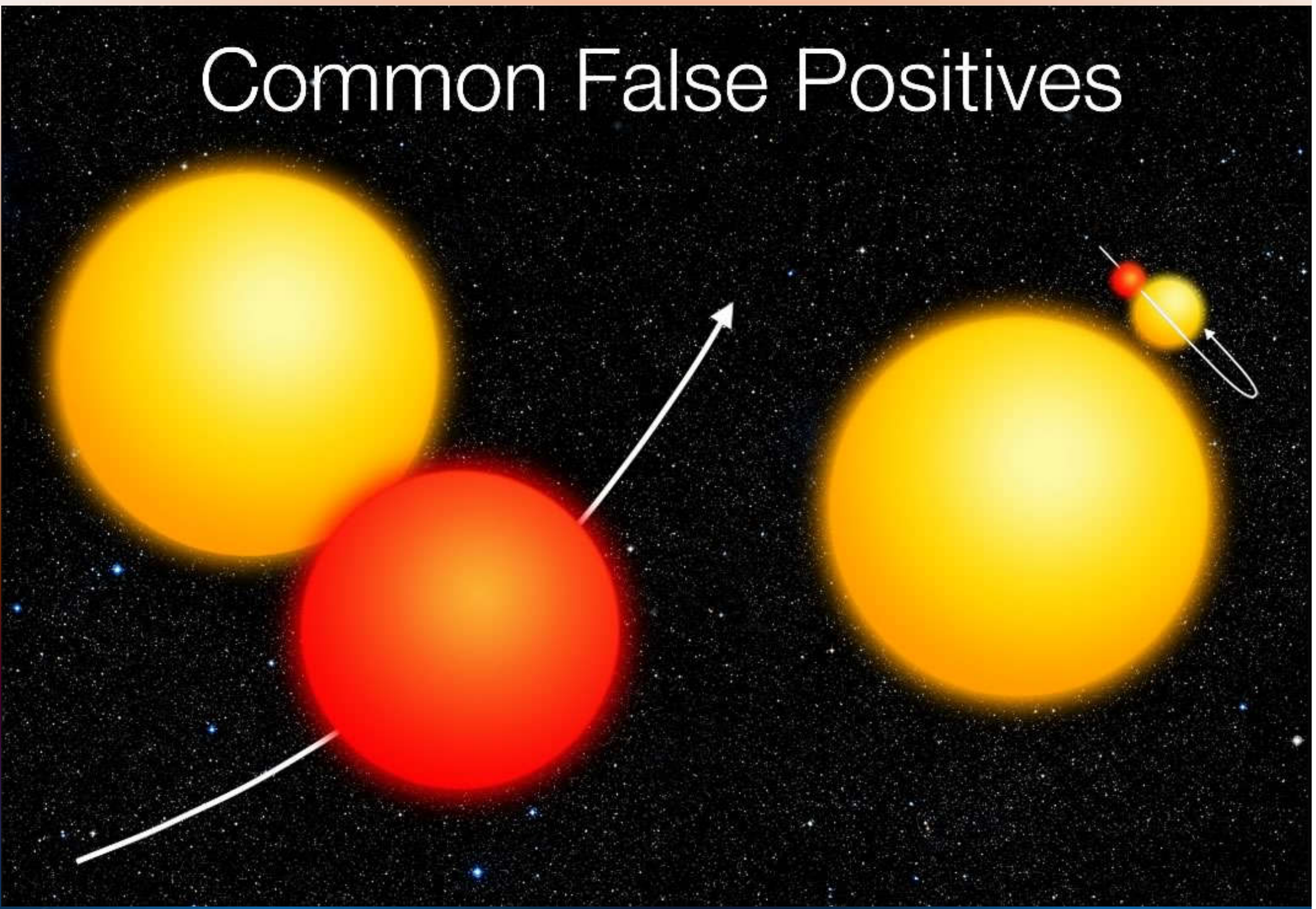
Potter et al, 2011


10^4
10^3
10^2
10^1
1
M_{Planet} [M_{Earth}]
10^{-2}
10^{-1}
1
10^1
10^2
Orbital Period [yr]
RV
astrom.
Jupiter
Saturn



etary satellites may be suitable for life?
g, Europa, Titan)
emophiles – life in extreme environments

END


Common False Positives

Extraterrestrial life