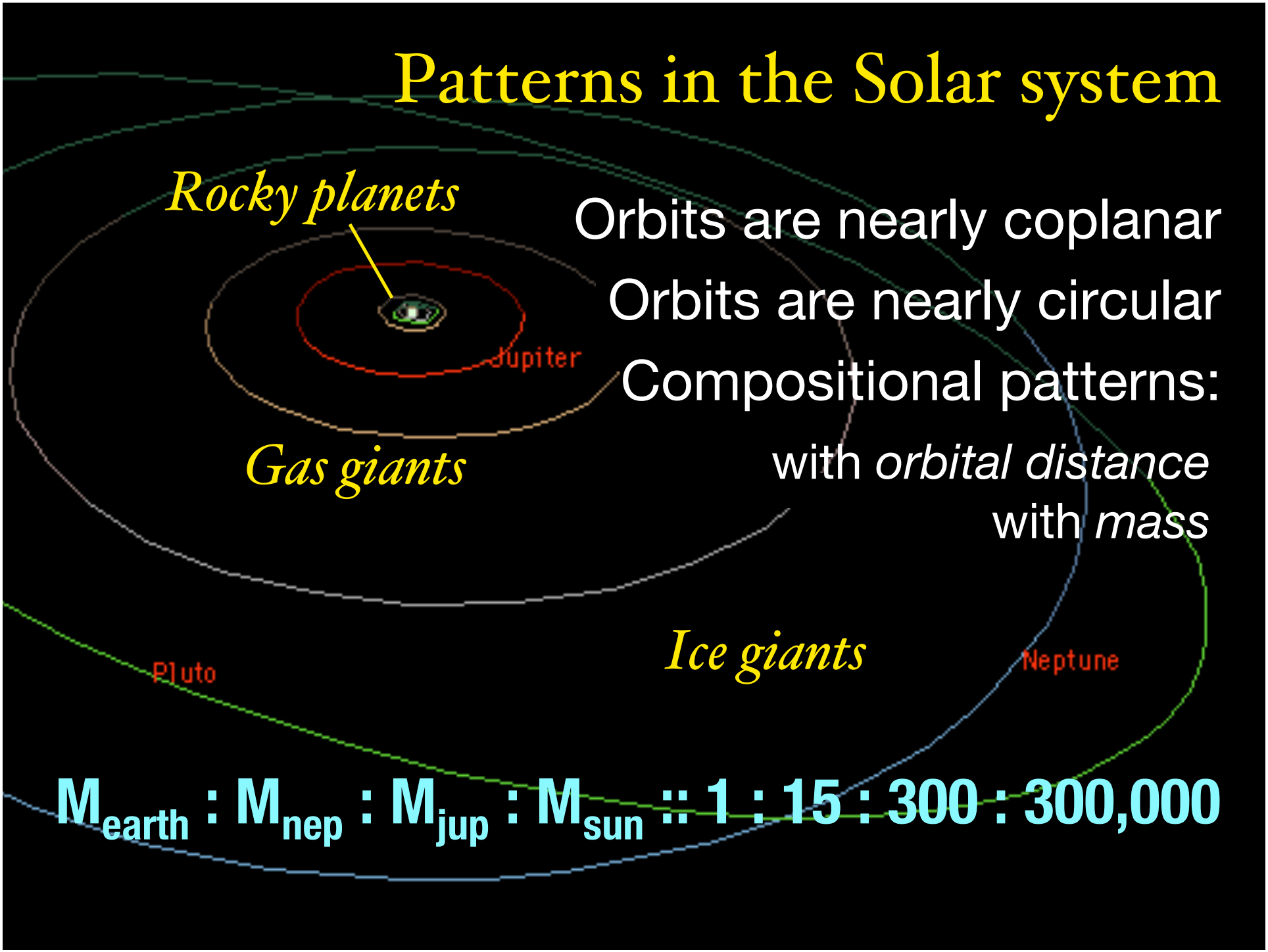
...previously, in 8.972...

Patterns in the Solar system



Orbits are nearly coplanar

Orbits are nearly circular

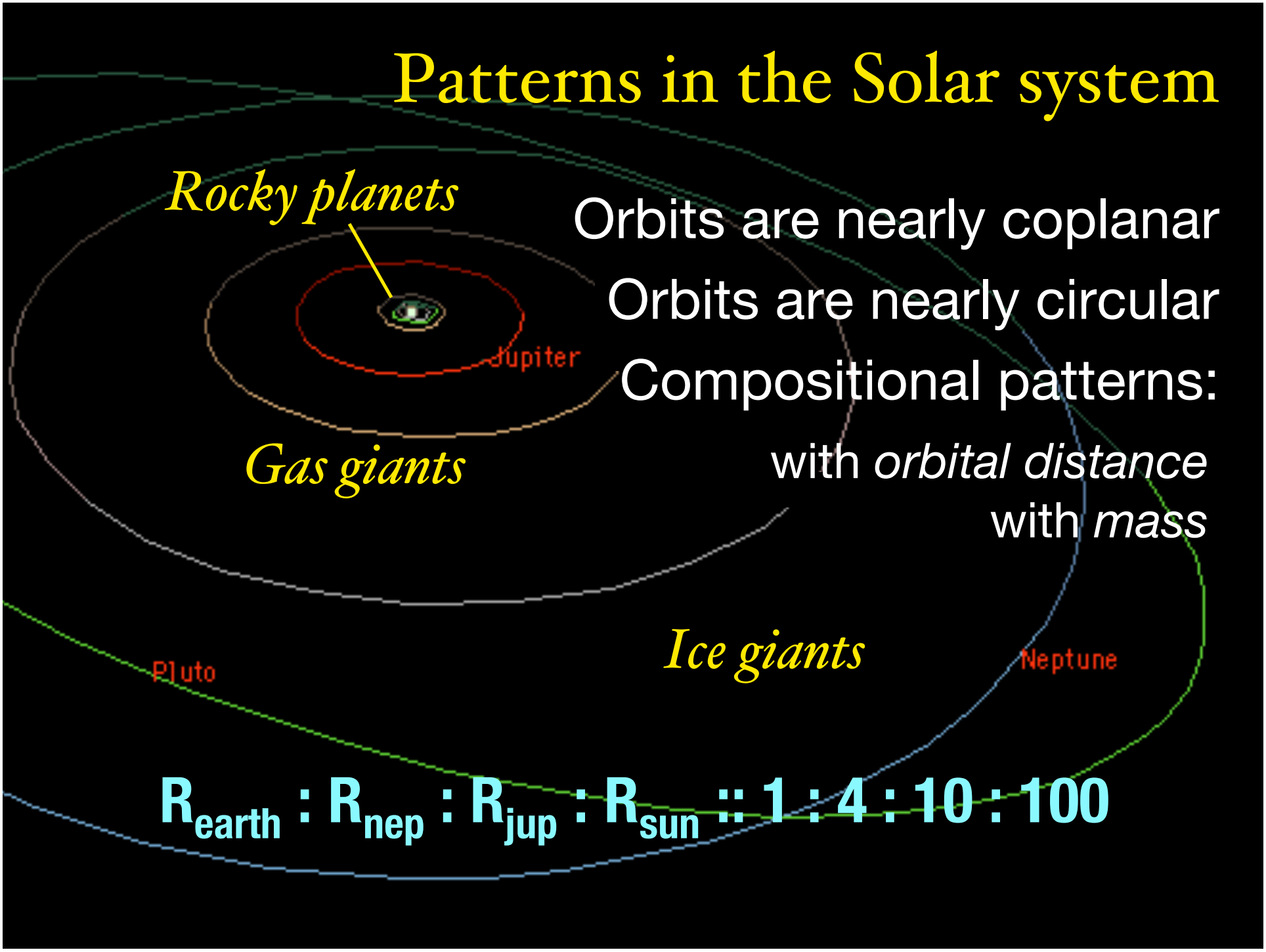
Compositional patterns:

with *orbital distance*

with *mass*

$M_{earth} : M_{nep} : M_{jup} : M_{sun} :: 1 : 15 : 300 : 300{,}000$

Patterns in the Solar system



Orbits are nearly coplanar

Orbits are nearly circular

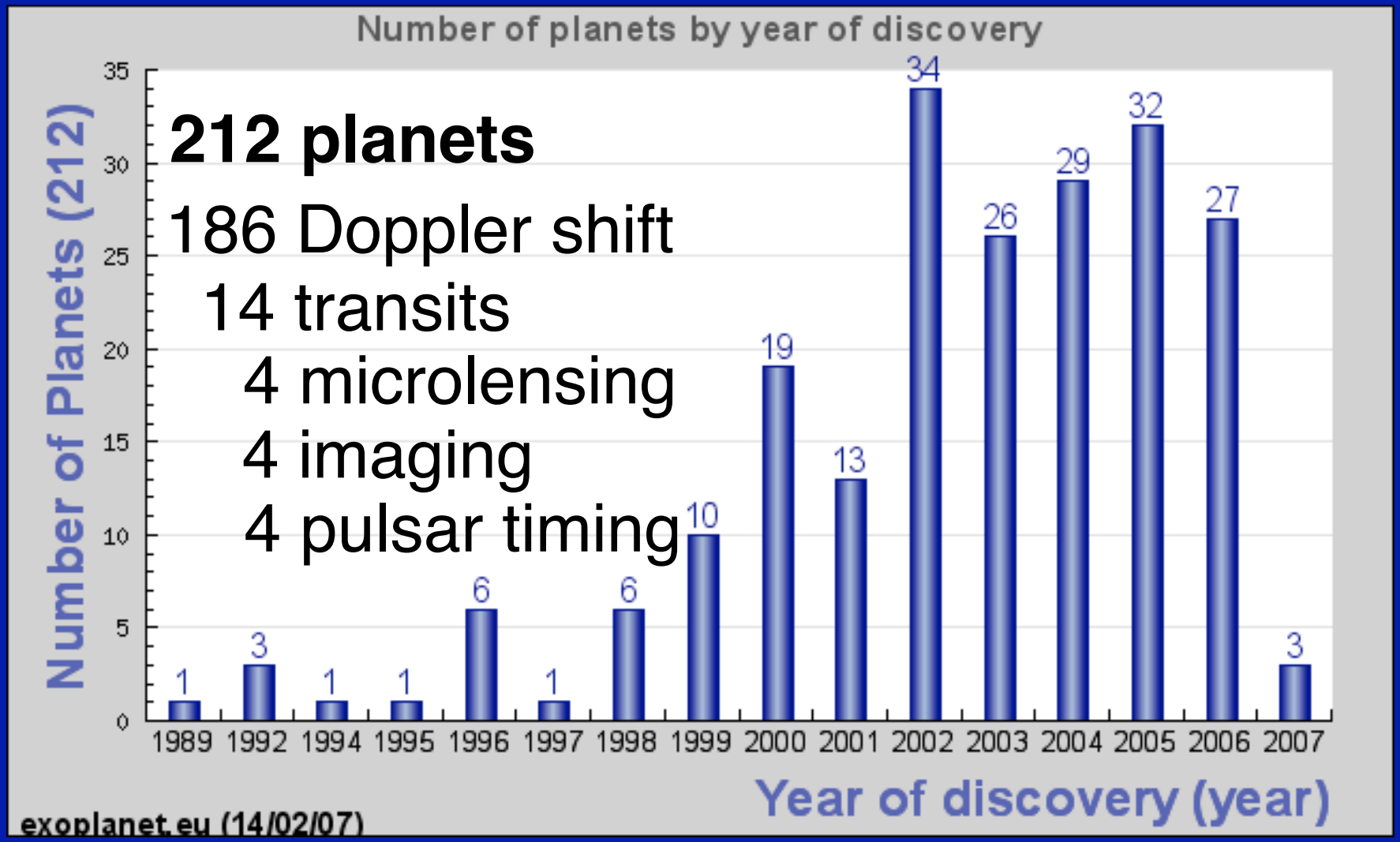
Compositional patterns:

with *orbital distance*

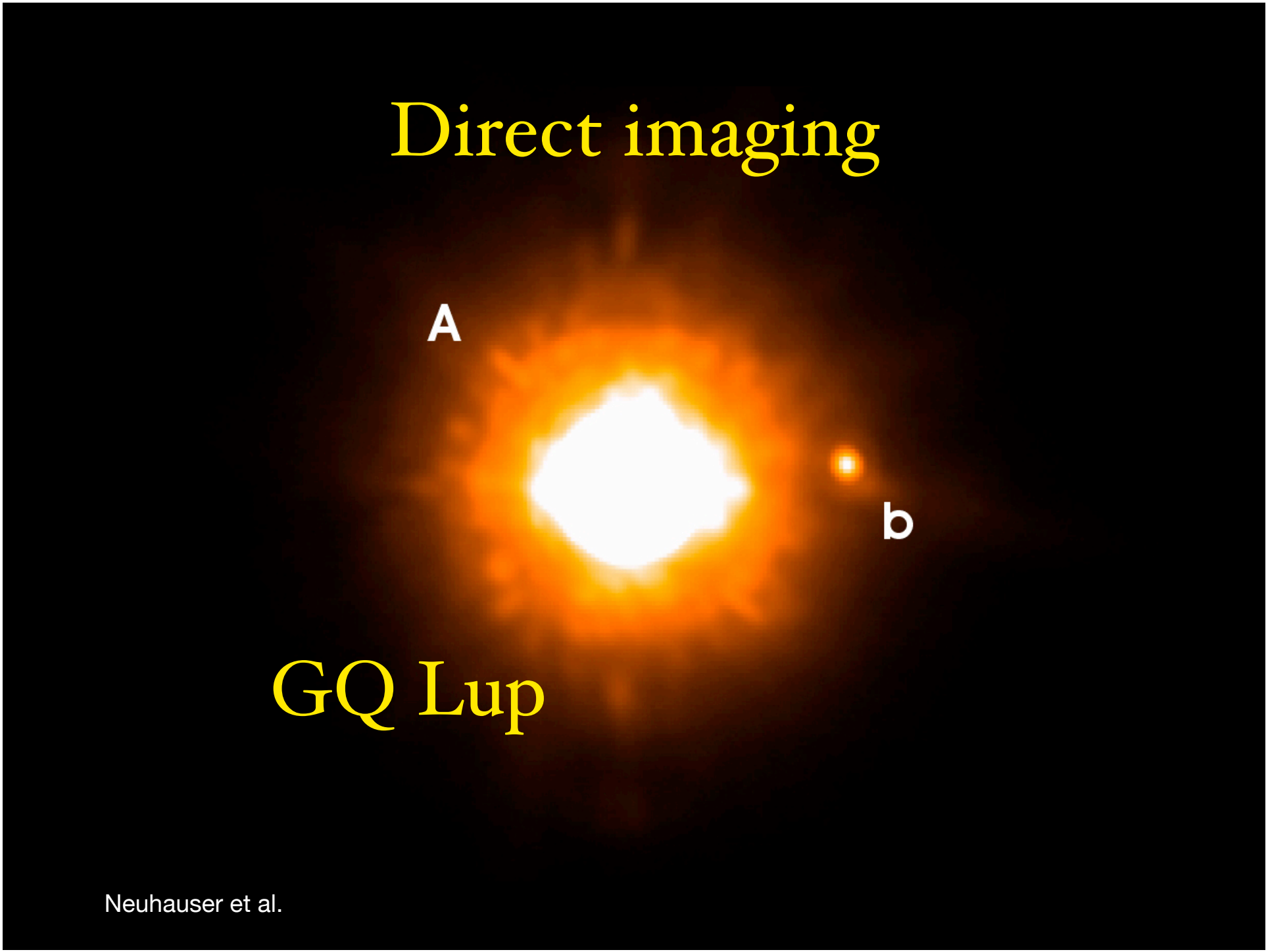
with *mass*

$R_{earth} : R_{nep} : R_{jup} : R_{sun} :: 1 : 4 : 10 : 100$

Exoplanet discoveries



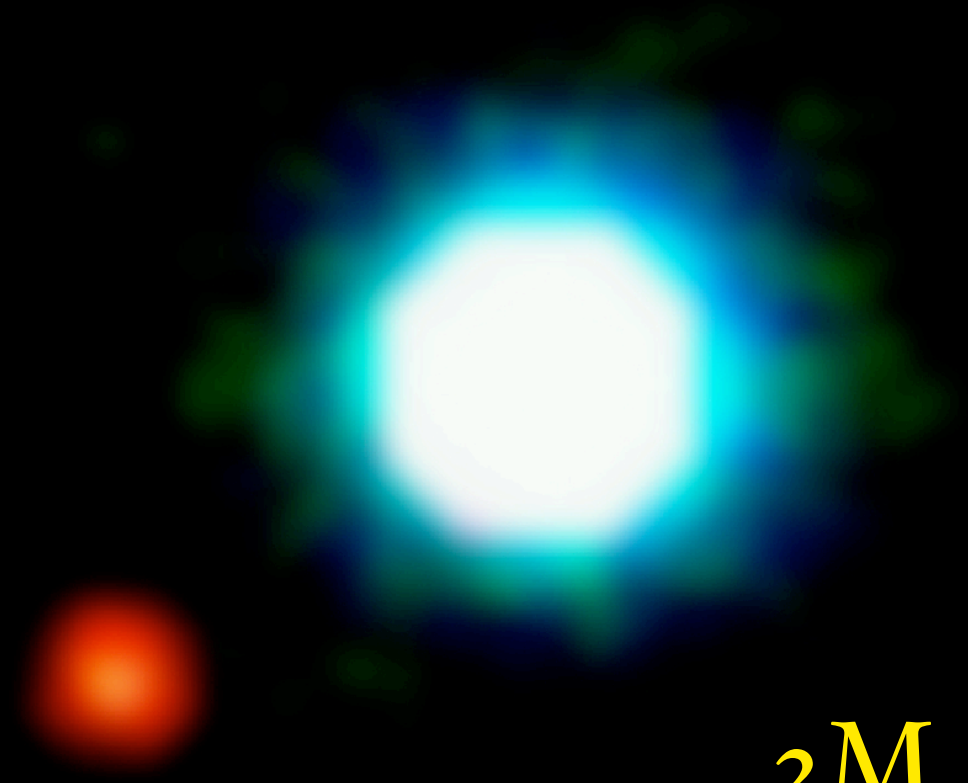
Direct imaging



GQ Lup

Neuhauser et al.

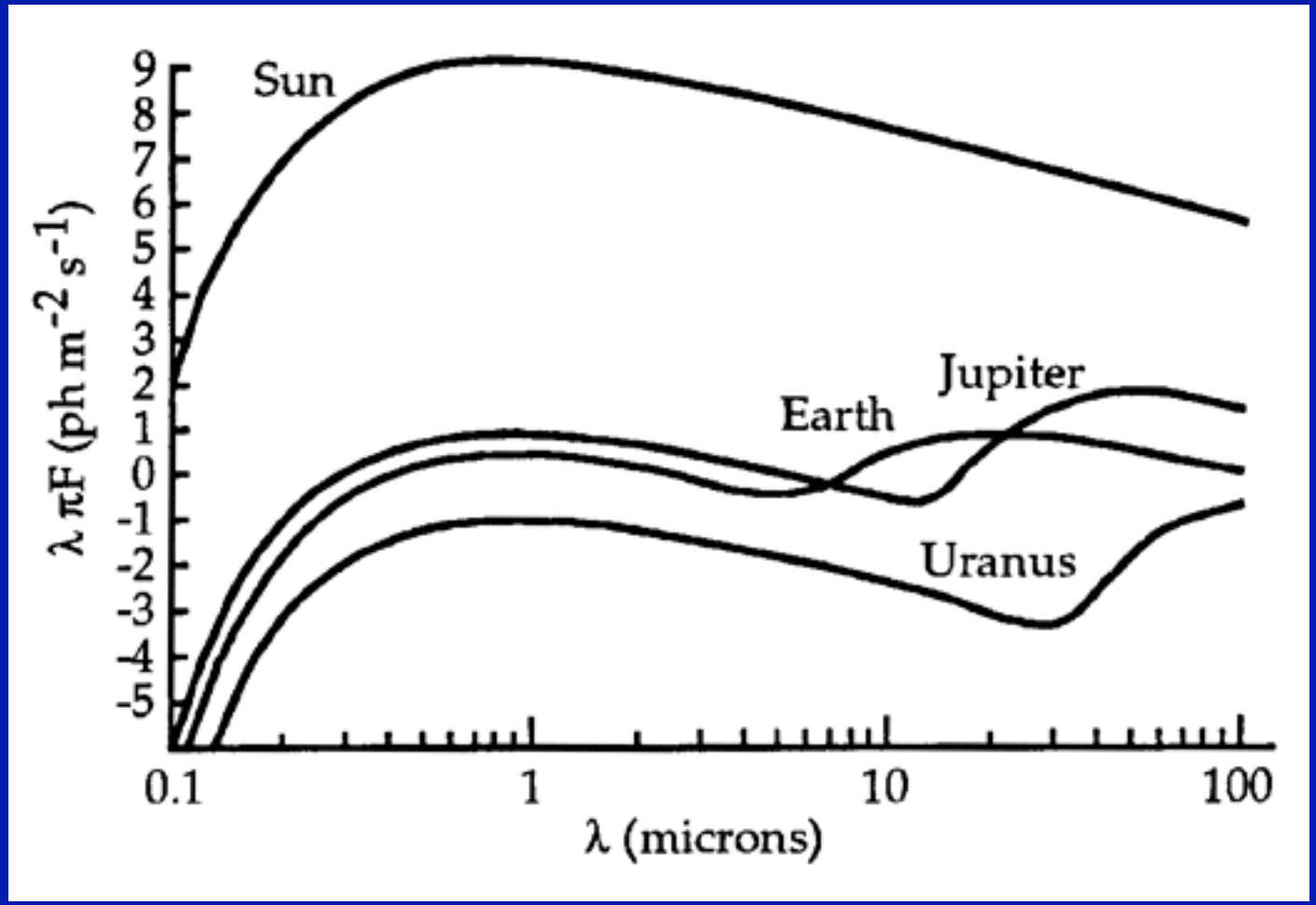
Direct imaging



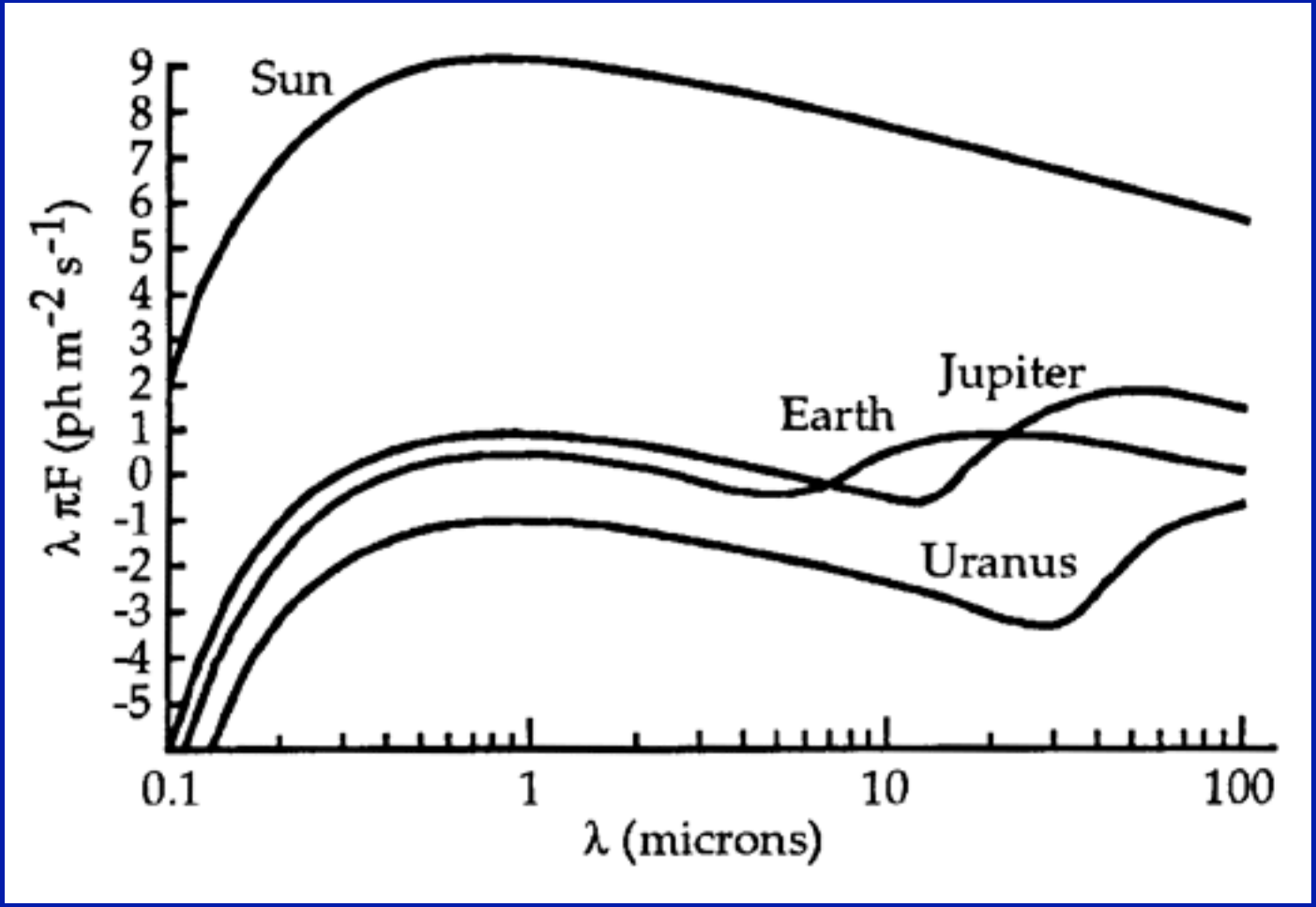
2M 1207

Chauvin et al.

The contrast problem

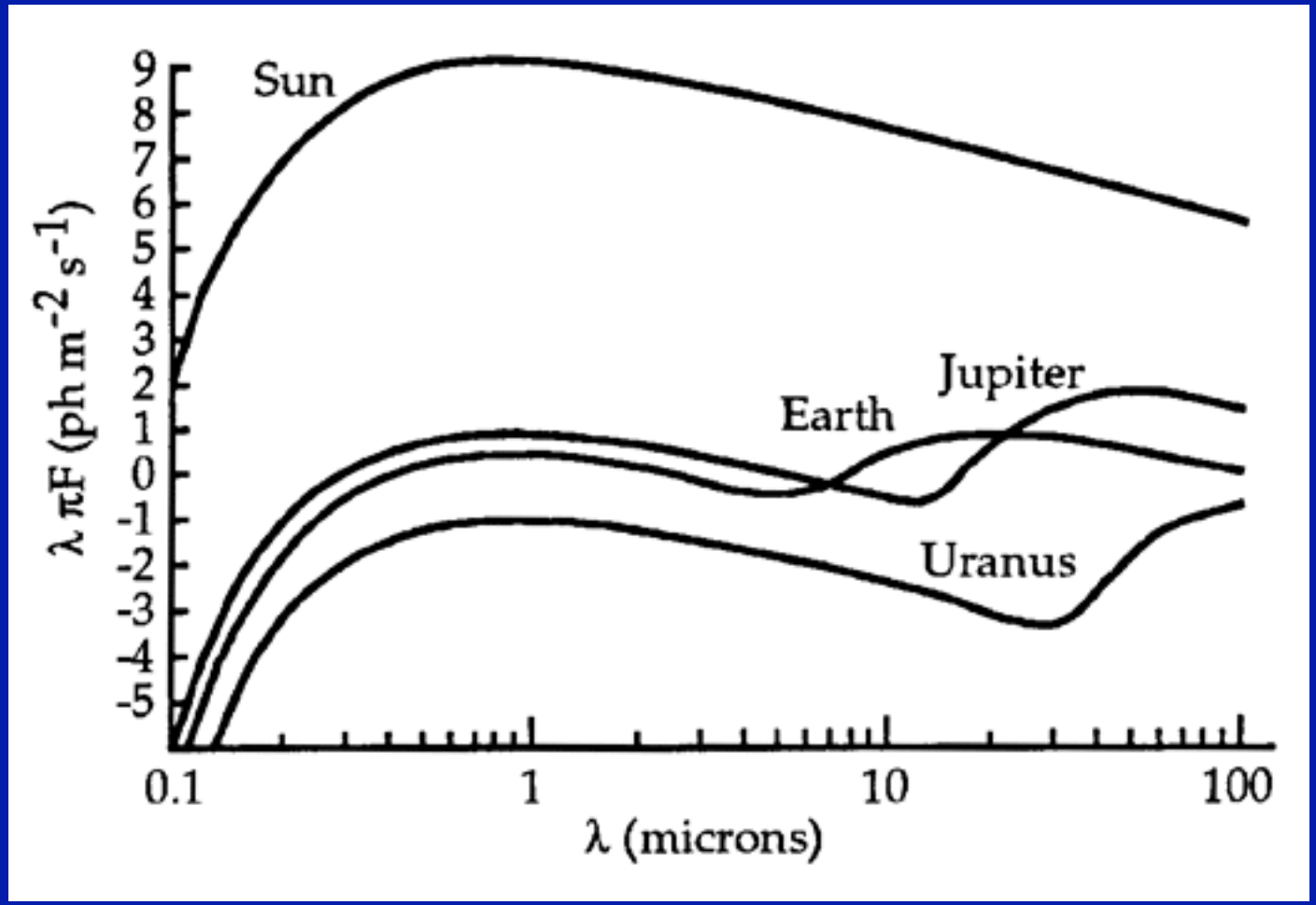


The contrast problem



Only works for hot, distant planets...

The contrast problem



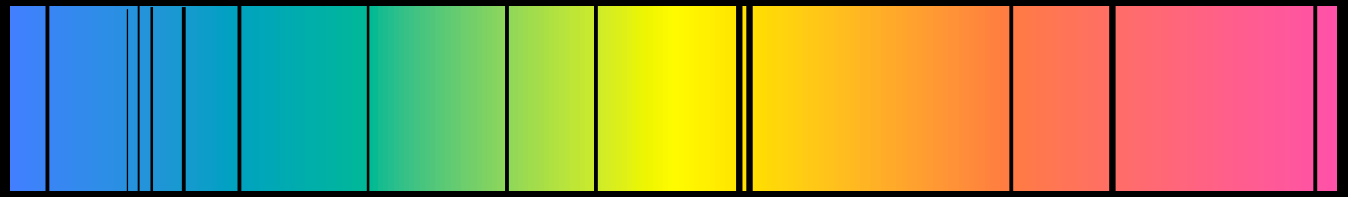
...and no direct measurement of M, R

Exoplanet detection

- Spectroscopy (Doppler shift)
- Astrometry (angular shift)
- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)

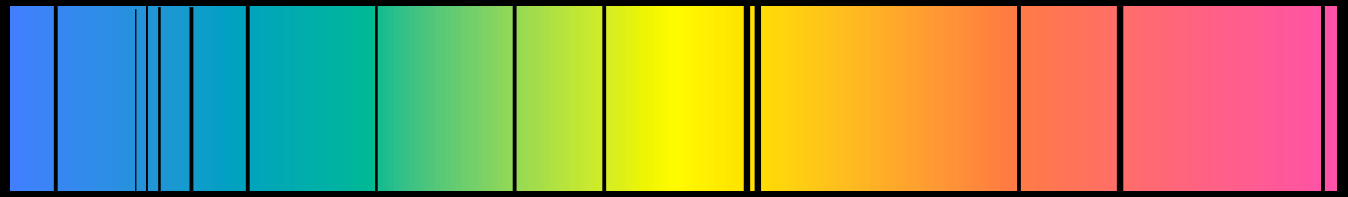


- Astrometry (angular shift)

- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)

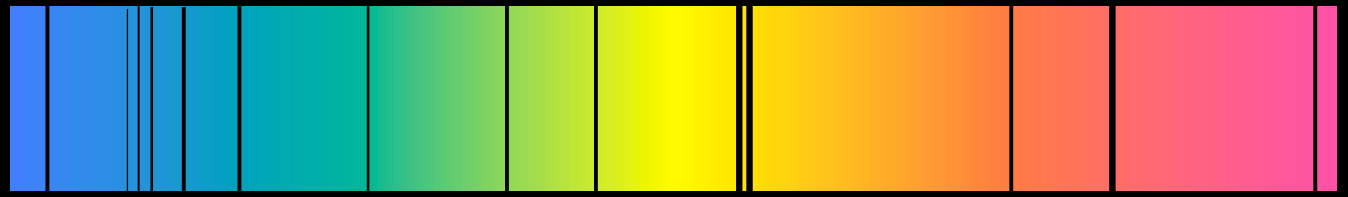


- Astrometry (angular shift)

- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)

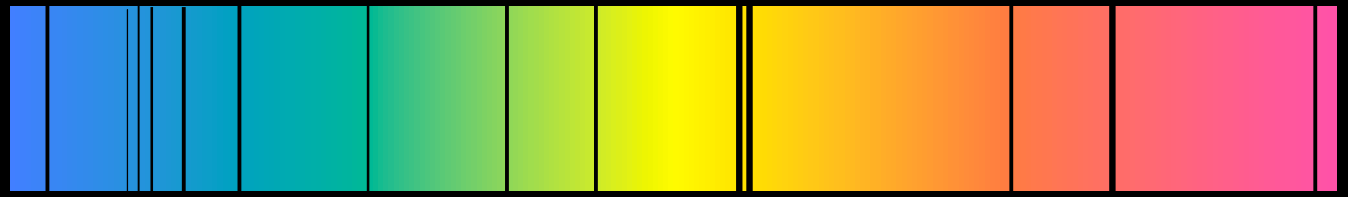


- Astrometry (angular shift)

- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)



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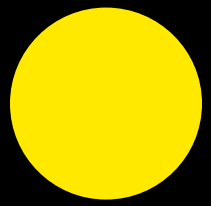
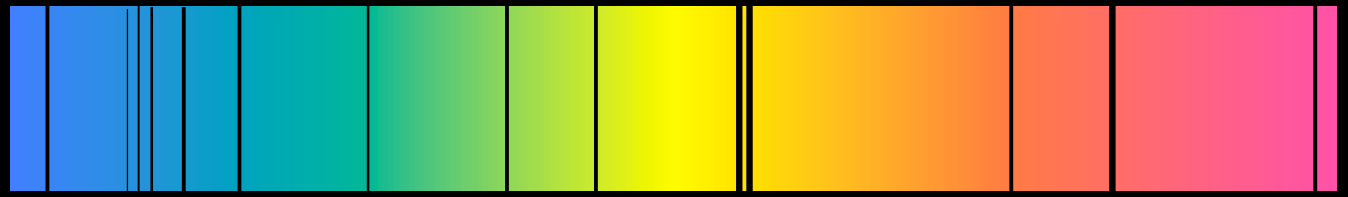


- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)



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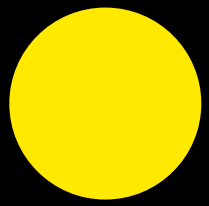
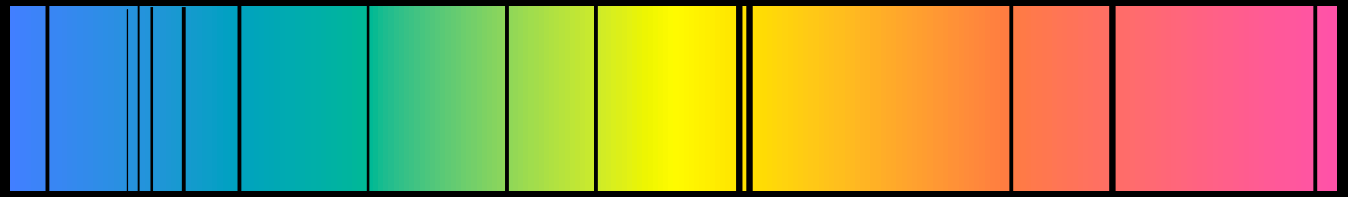


- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)



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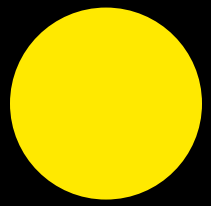
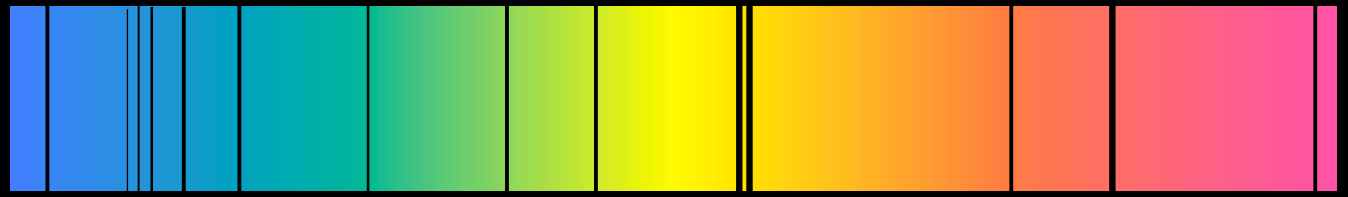


- Photometry (transits)

Exoplanet detection

- Spectroscopy (Doppler shift)



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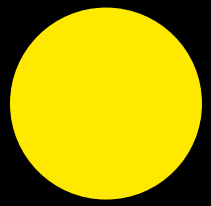
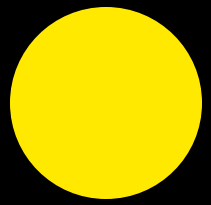


- Photometry (transits)



Exoplanet detection

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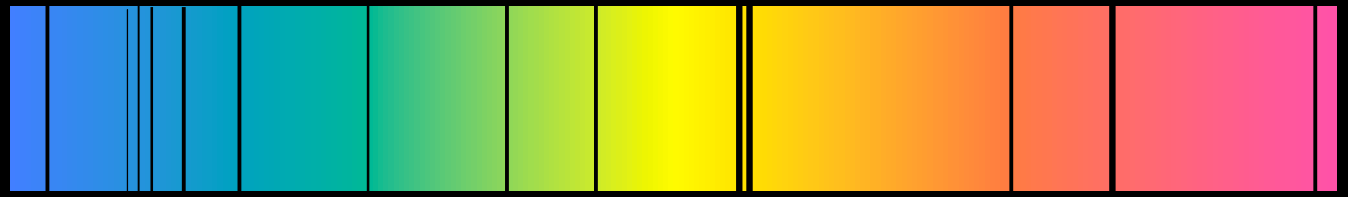

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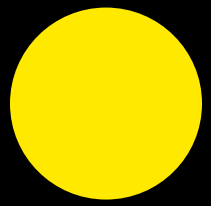

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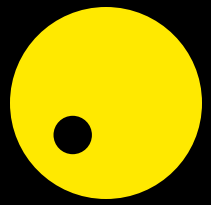
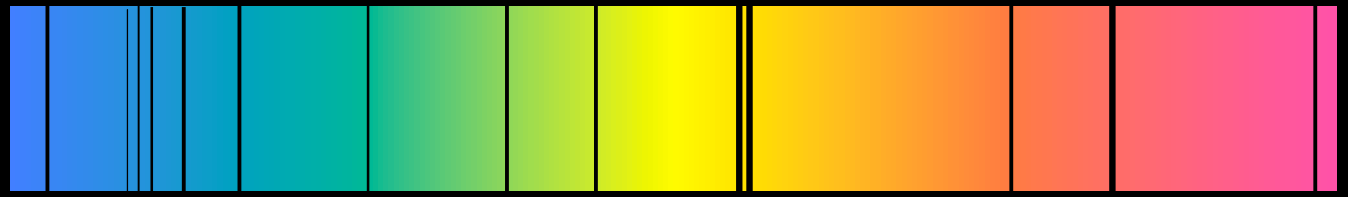


Exoplanet detection

- Spectroscopy (Doppler shift)



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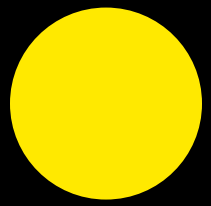

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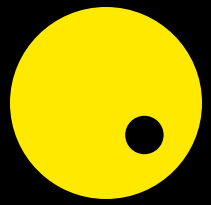


Exoplanet detection

- Spectroscopy (Doppler shift)

Exoplanet detection

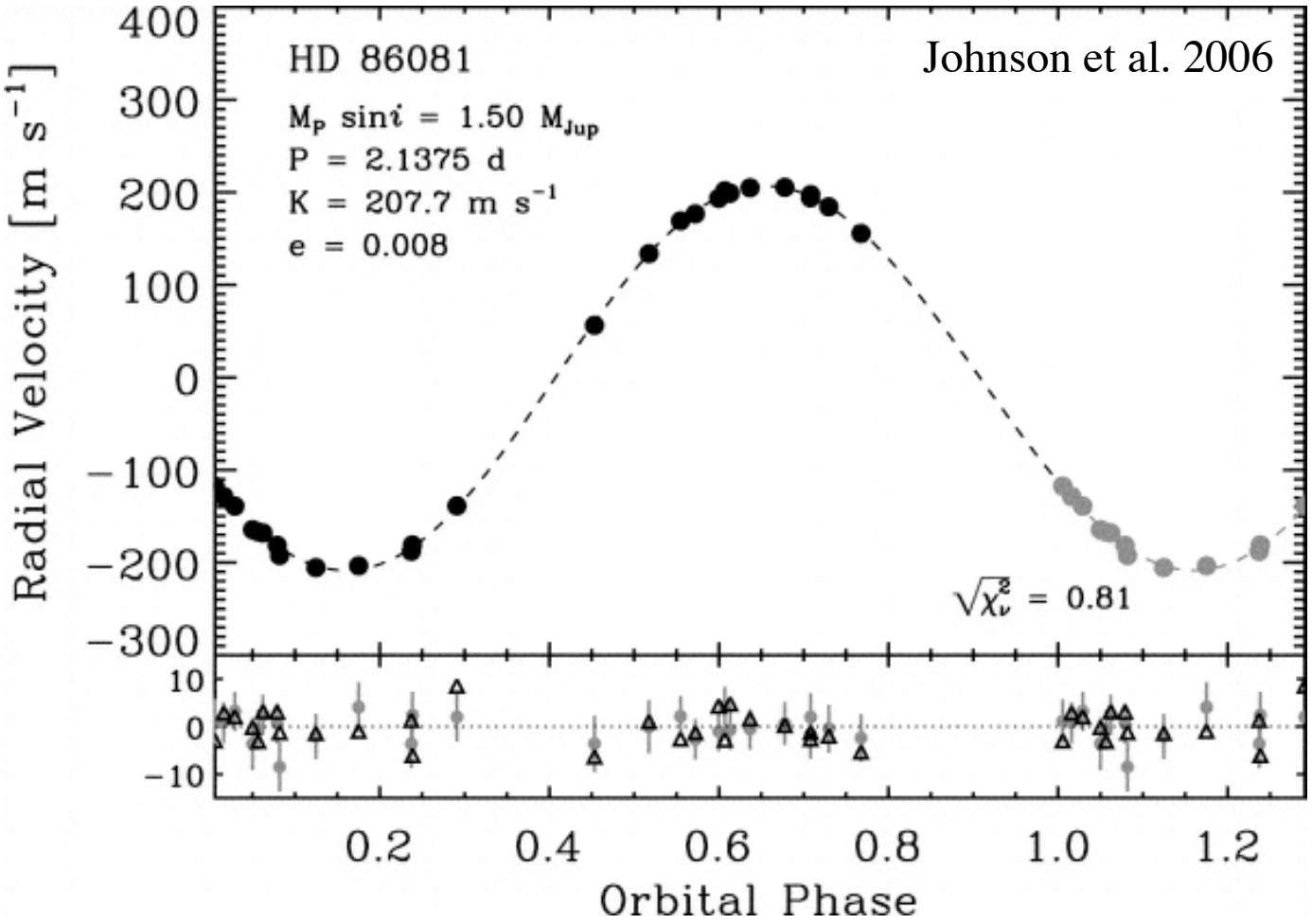
- Spectroscopy (Doppler shift)

$$\Delta V_{\max} = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_P \sin I}{(M_P + M_S)^{2/3}}$$

$$\approx (12 \text{ m s}^{-1}) \left(\frac{P}{12 \text{ yr}}\right)^{-1/3} \left(\frac{M_P \sin I}{M_{\text{Jup}}}\right) \left(\frac{M_S}{M_{\text{Sun}}}\right)^{-2/3}$$

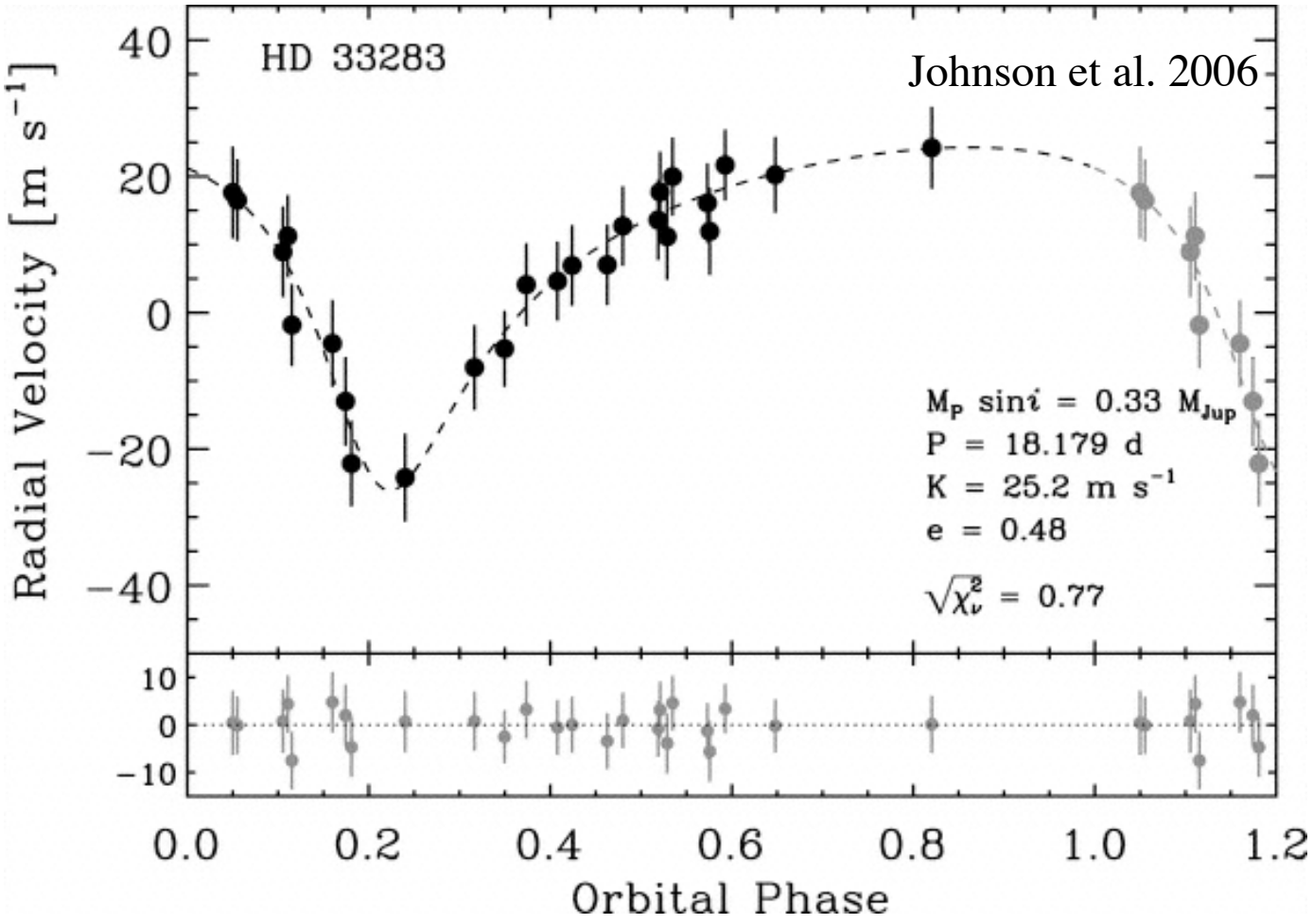
Exoplanet detection

- Spectroscopy (Doppler shift)



Exoplanet detection

- Spectroscopy (Doppler shift)



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state of the art: 0.5 m/s
(iodine cell, dual-fiber)

Exoplanet detection

- Spectroscopy (Doppler shift)

$$\Delta V_{\rm max} = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_P \sin I}{(M_P + M_S)^{2/3}}$$

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false positives: star spots, pulsations

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state of the art: 0.5 m/s
(iodine cell, dual-fiber)

false positives: star spots, pulsations

sin(I) ambiguity; radius unknown

Exoplanet detection

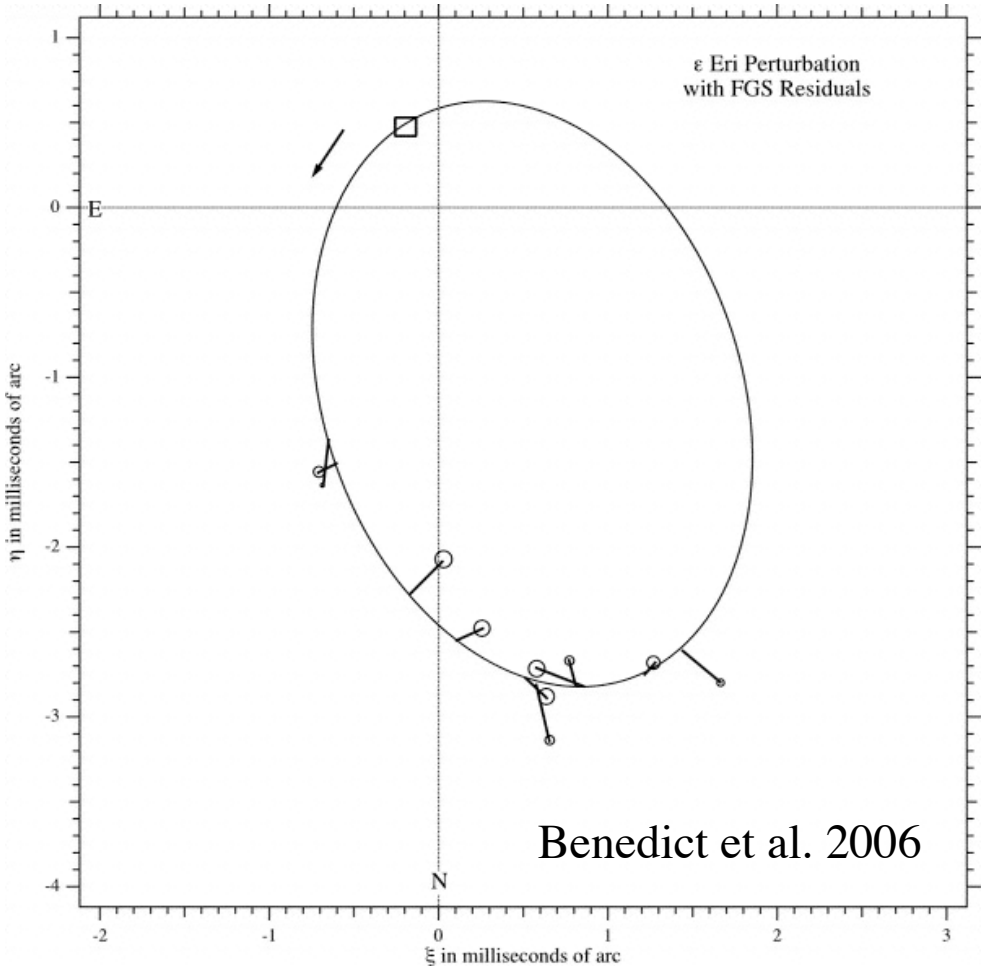
- Astrometry (angular shift)

$$\Delta\theta_{\rm max} = \left(\frac{M_P/M_S}{d}\right)\left(\frac{G(M_P+M_S)P^2}{4\pi^2}\right)^{1/3}$$

$$\approx 0.5\ {\rm mas}\left(\frac{P}{12\ {\rm yr}}\right)^{2/3}\left(\frac{M_P}{M_{\rm Jup}}\right)\left(\frac{M_S}{M_{\rm Sun}}\right)^{-2/3}\left(\frac{d}{10\ {\rm pc}}\right)^{-1}$$

Exoplanet detection

- Astrometry (angular shift)



Benedict et al. 2006

Exoplanet detection

- Astrometry (angular shift)

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state of the art: 0.01-0.5 mas

Exoplanet detection

- Astrometry (angular shift)

$$\Delta\theta_{\rm max} = \left(\frac{M_P/M_S}{d}\right)\left(\frac{G(M_P+M_S)P^2}{4\pi^2}\right)^{1/3}$$

$$\approx 0.5\ {\rm mas}\left(\frac{P}{12\ {\rm yr}}\right)^{2/3}\left(\frac{M_P}{M_{\rm Jup}}\right)\left(\frac{M_S}{M_{\rm Sun}}\right)^{-2/3}\left(\frac{d}{10\ {\rm pc}}\right)^{-1}$$

state of the art: 0.01-0.5 mas

false positives: star spots, ???

Exoplanet detection

- Astrometry (angular shift)

$$\Delta\theta_{\rm max} = \left(\frac{M_P/M_S}{d}\right)\left(\frac{G(M_P+M_S)P^2}{4\pi^2}\right)^{1/3}$$

$$\approx 0.5\ {\rm mas}\left(\frac{P}{12\ {\rm yr}}\right)^{2/3}\left(\frac{M_P}{M_{\rm Jup}}\right)\left(\frac{M_S}{M_{\rm Sun}}\right)^{-2/3}\left(\frac{d}{10\ {\rm pc}}\right)^{-1}$$

state of the art: 0.01-0.5 mas

false positives: star spots, ???

gets harder with distance; radius unknown

Exoplanet detection

- Photometry (transits)

$$\frac{\Delta F_{\rm max}}{F} \approx \left(\frac{R_P}{R_S}\right)^2 \approx 10^{-2}\left(\frac{R_P/R_S}{R_{\rm Jup}/R_{\rm Sun}}\right)^2$$

$$\text{duration} \approx \frac{R_S}{(2\pi a/P)} \approx 14\ \text{hr}\left(\frac{R_S}{R_{\rm Sun}}\right)\left(\frac{P}{11\ \text{yr}}\right)^{1/3}$$

$$\text{Prob.} \approx 0.1\%\left(\frac{R_S/R_{\rm Sun}}{a/5\ \text{AU}}\right)$$

Exoplanet detection

- Photometry (transits)

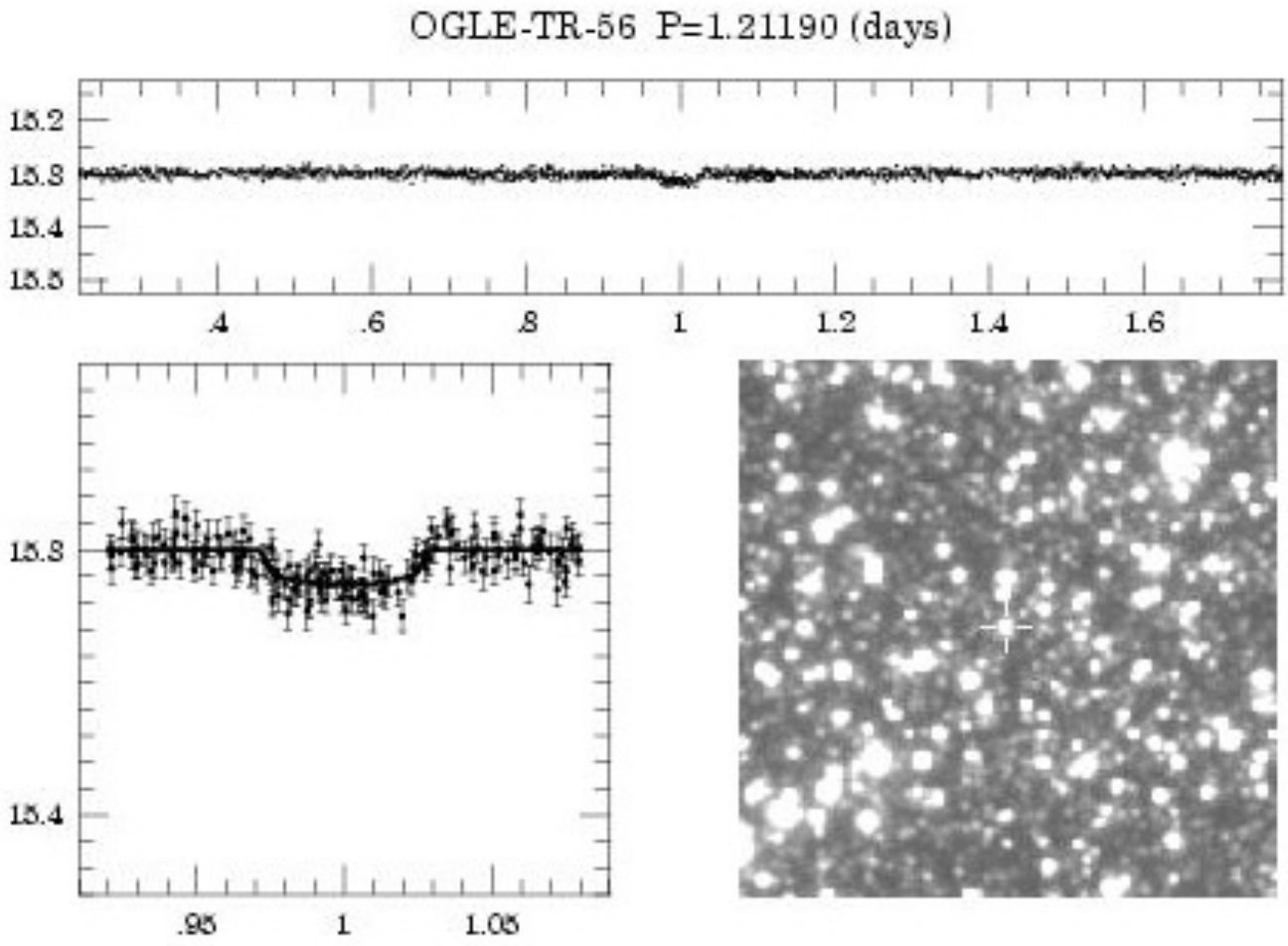
$$\frac{\Delta F_{\rm max}}{F} \approx \left(\frac{R_P}{R_S}\right)^2 \approx 10^{-2}\left(\frac{R_P/R_S}{R_{\rm Jup}/R_{\rm Sun}}\right)^2$$

$$\text{duration} \approx \frac{R_S}{(2\pi a/P)} \approx 1.3\ \text{hr}\left(\frac{R_S}{R_{\rm Sun}}\right)\left(\frac{P}{3\ \text{days}}\right)^{1/3}$$

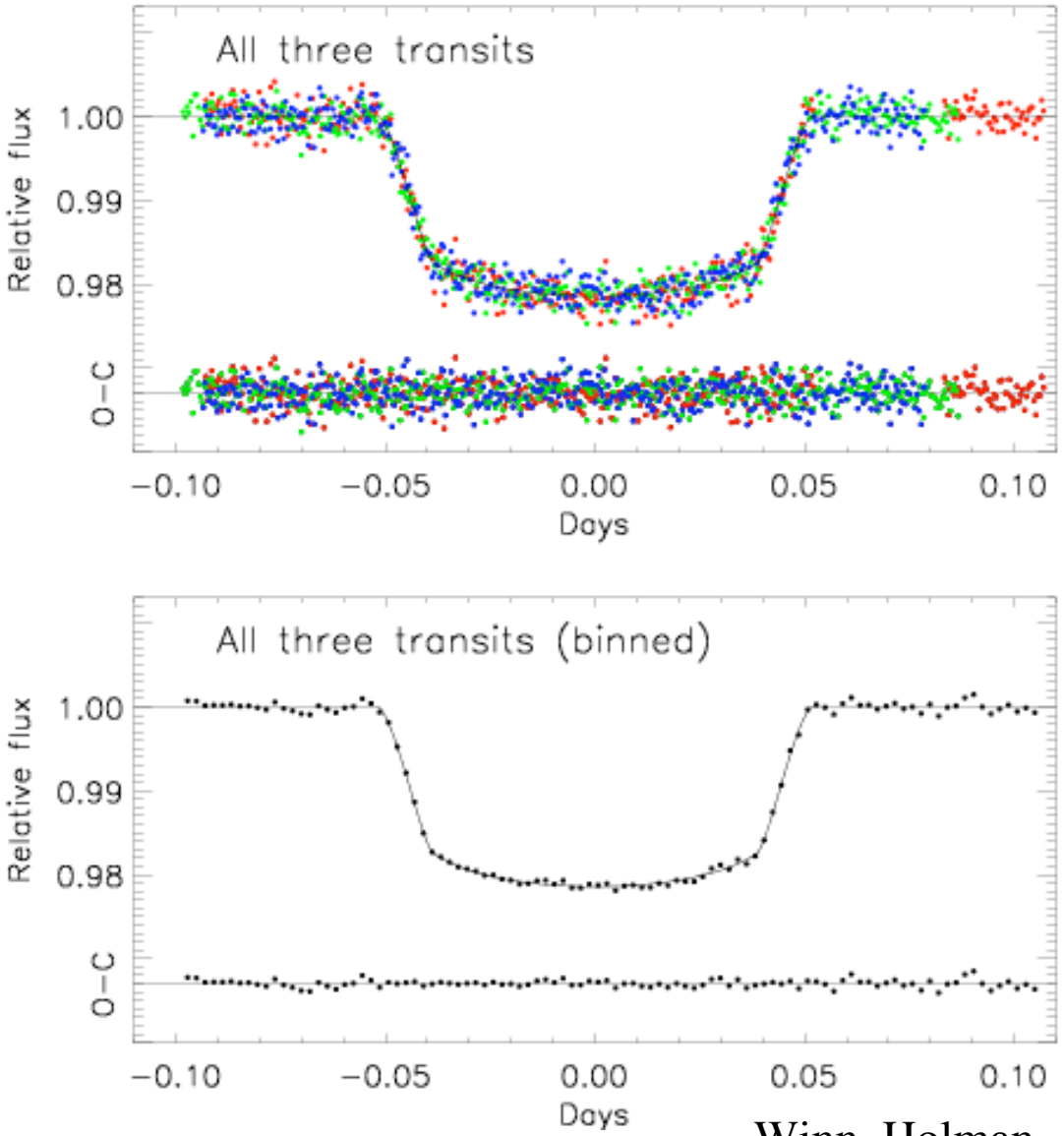
$$\text{Prob.} \approx 10\%\left(\frac{R_S/R_{\rm Sun}}{a/0.05\ \text{AU}}\right)$$

Exoplanet detection

- Photometry (transits)

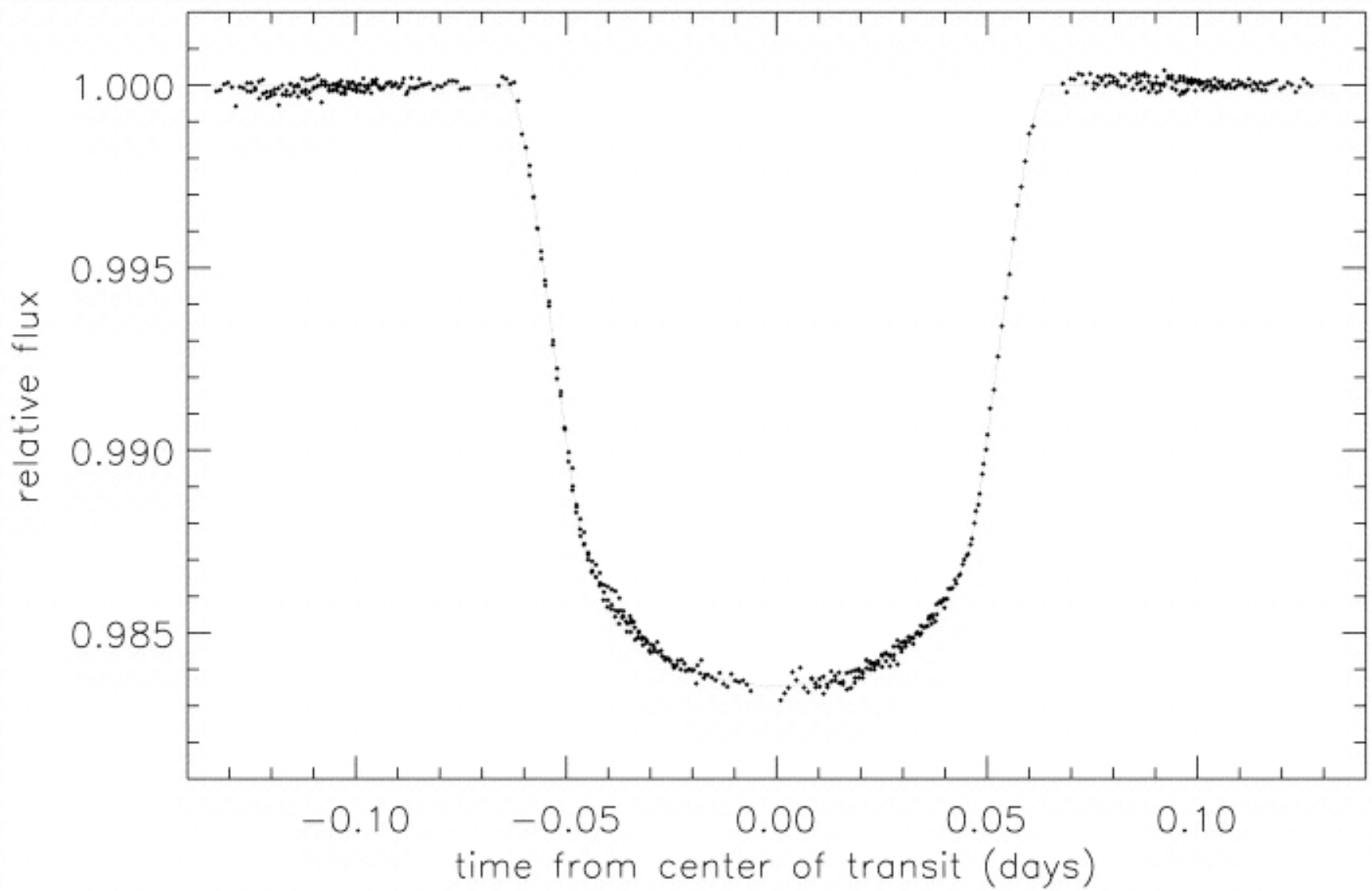


Exoplanet detection



Winn, Holman, & Roussanova 2007

Exoplanet detection



Brown et al. 2001

Exoplanet detection

- Photometry (transits)

$$\frac{\Delta F_{\max}}{F} \approx \left(\frac{R_P}{R_S}\right)^2 \approx 10^{-2}\left(\frac{R_P/R_S}{R_{\rm Jup}/R_{\rm Sun}}\right)^2$$

state of the art: 0.001 (for surveys)

Exoplanet detection

- Photometry (transits)

$$\frac{\Delta F_{\max}}{F} \approx \left(\frac{R_P}{R_S}\right)^2 \approx 10^{-2}\left(\frac{R_P/R_S}{R_{\rm Jup}/R_{\rm Sun}}\right)^2$$

state of the art: 0.001 (for surveys)

false positives: FM binaries, grazing eclipses, triple stars with eclipses

Exoplanet detection

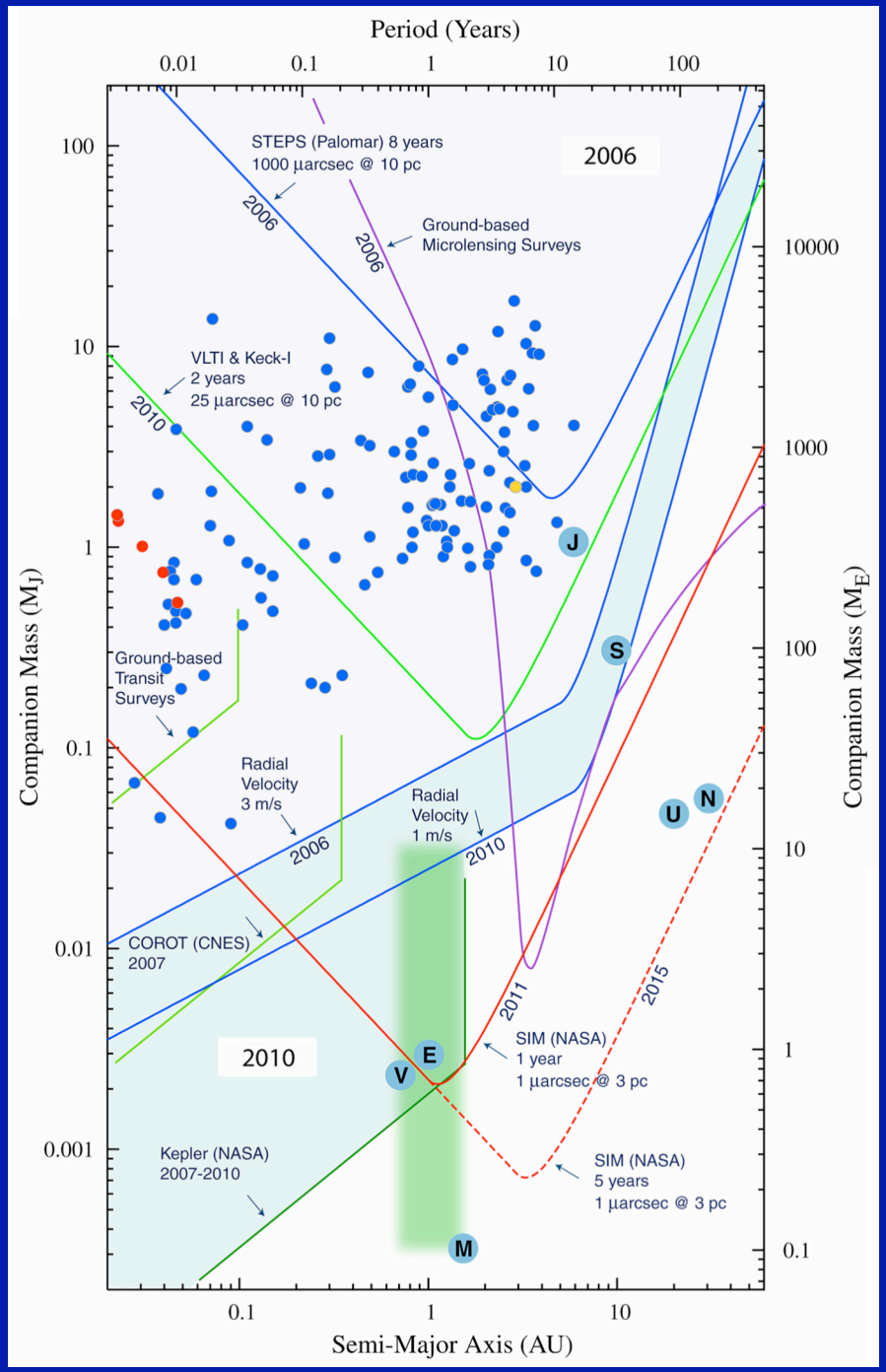
- Photometry (transits)

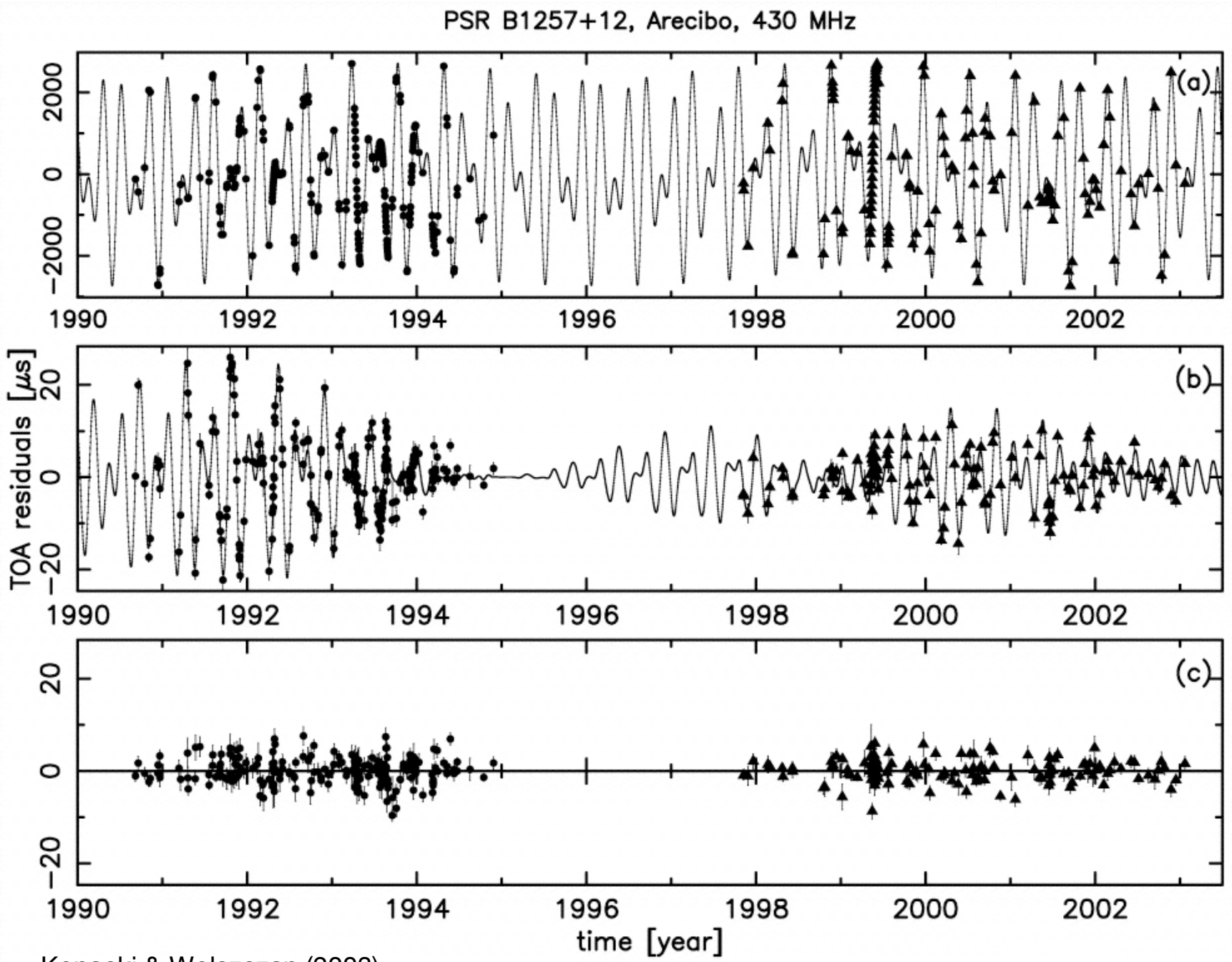
$$\frac{\Delta F_{\max}}{F} \approx \left(\frac{R_P}{R_S}\right)^2 \approx 10^{-2}\left(\frac{R_P/R_S}{R_{\rm Jup}/R_{\rm Sun}}\right)^2$$

state of the art: 0.001 (for surveys)

false positives: FM binaries, grazing eclipses, triple stars with eclipses

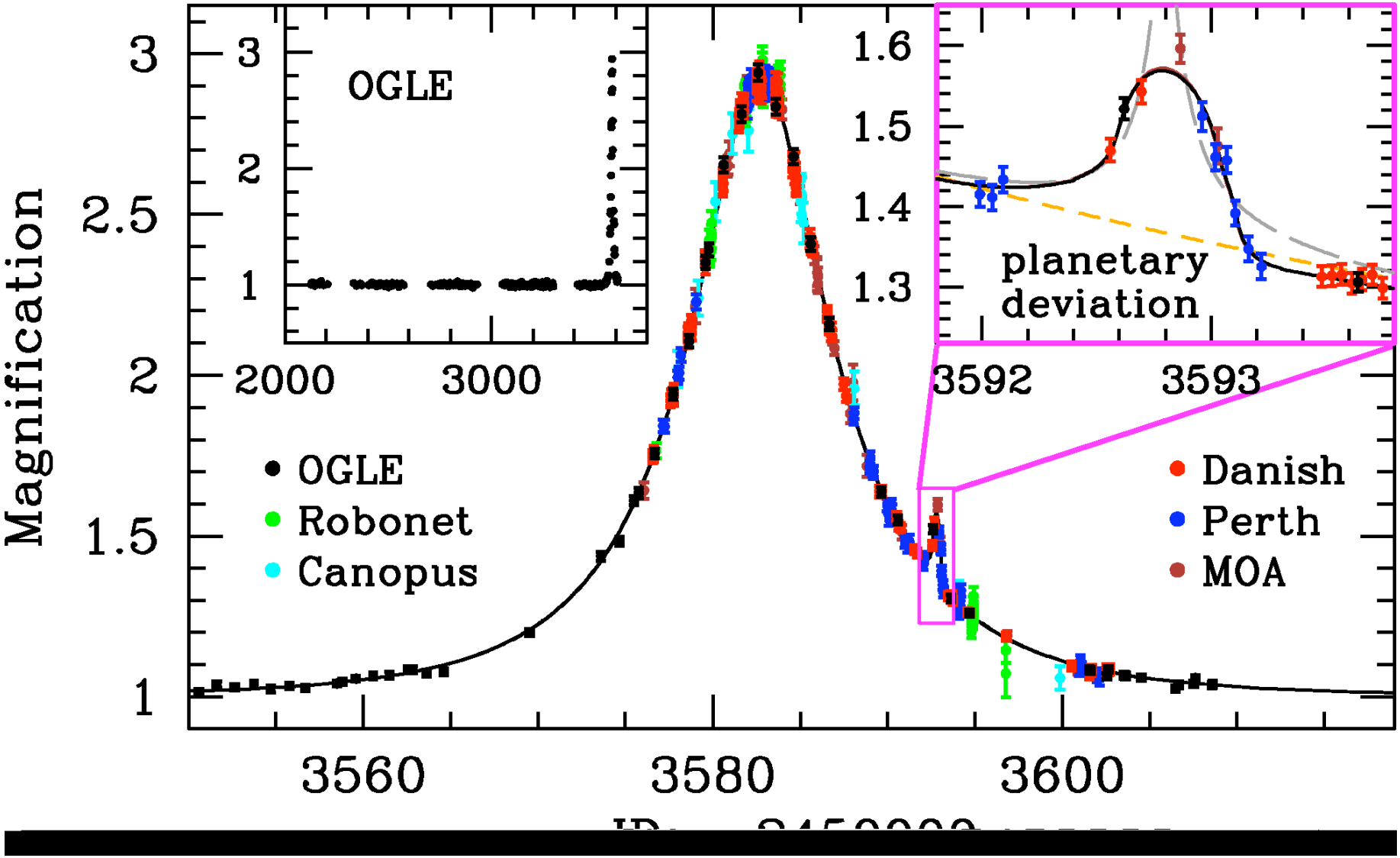
learn mass, incl, radius, temperature, more!


Period (Years)
0.01
0.1
1
10
100
STEPS (Palomar) 8 years
1000 µarcsec @ 10 pc
2006
2006
2006
Ground-based
Microlensing Surveys
VLTI & Keck-I
2 years
25 µarcsec @ 10 pc
2010
Ground-based
Transit
Surveys
Radial
Velocity
3 m/s
2006
Radial
Velocity
1 m/s
2010
COROT (CNES)
2007
2010
2011
2015
SIM (NASA)
1 year
1 µarcsec @ 3 pc
SIM (NASA)
5 years
1 µarcsec @ 3 pc
Kepler (NASA)
2007-2010
J
S
U
N
V
E
M
Companion Mass (M_J)
Companion Mass (M_E)
Semi-Major Axis (AU)
100
10
1
0.1
0.01
0.001
10000
1000
100
10
1
0.1
0.1
1
10



Konacki & Wolszczan (2003)

Gravitational lensing



Beaulieu et al. (2006)