The Transit Timing method: How to detect extrasolar planets?

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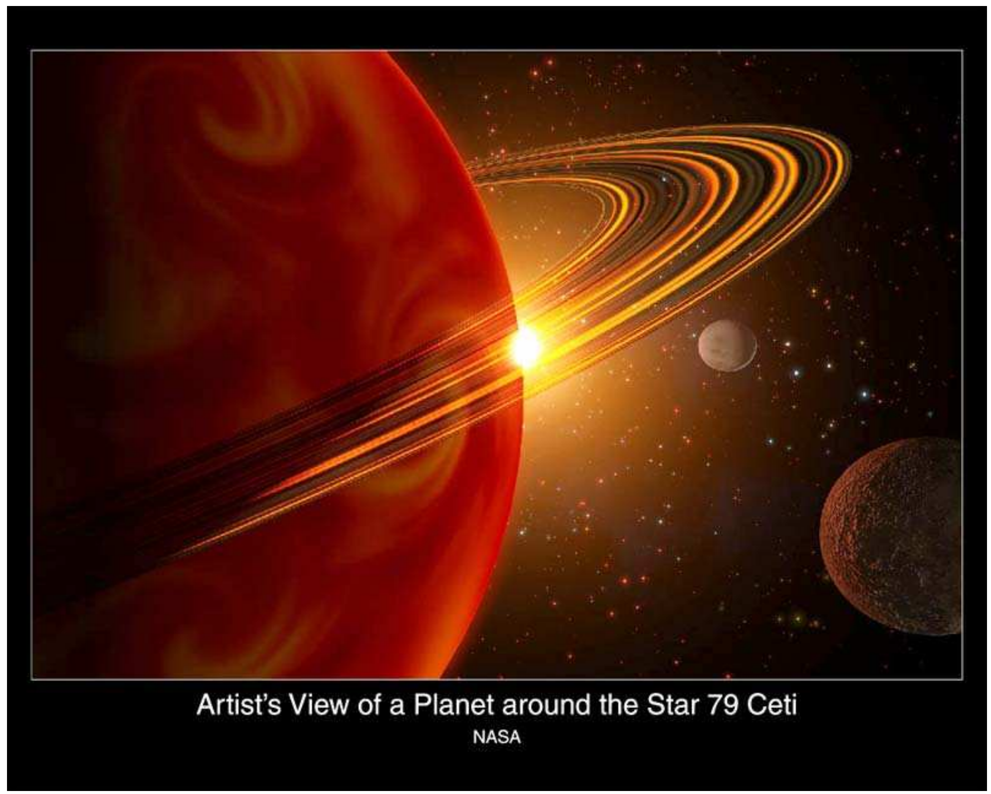
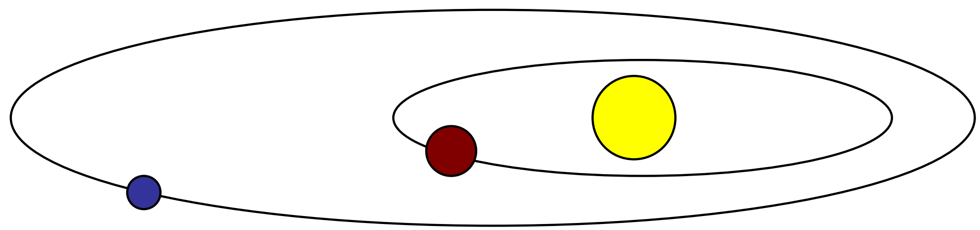


Artist's View of a Planet around the Star 79 Ceti
NASA

Canadian Institute for Theoretical Astrophysics
Institut d'Astrophysique de Paris

June 26th, 2006

Context



M. Holman, N. Murray (2005) and E. Agol et al (2005): one can detect extrasolar planets with the Transit Timing variations, and in some cases, terrestrial mass planets.

Introduction

Idea:

Transit timings are perturbated in case of a second planet.

Motivations:

•New method to discover extrasolar planets

•Spaced based mission Kepler

•Possibility to detect terrestrial mass planets

Problem:

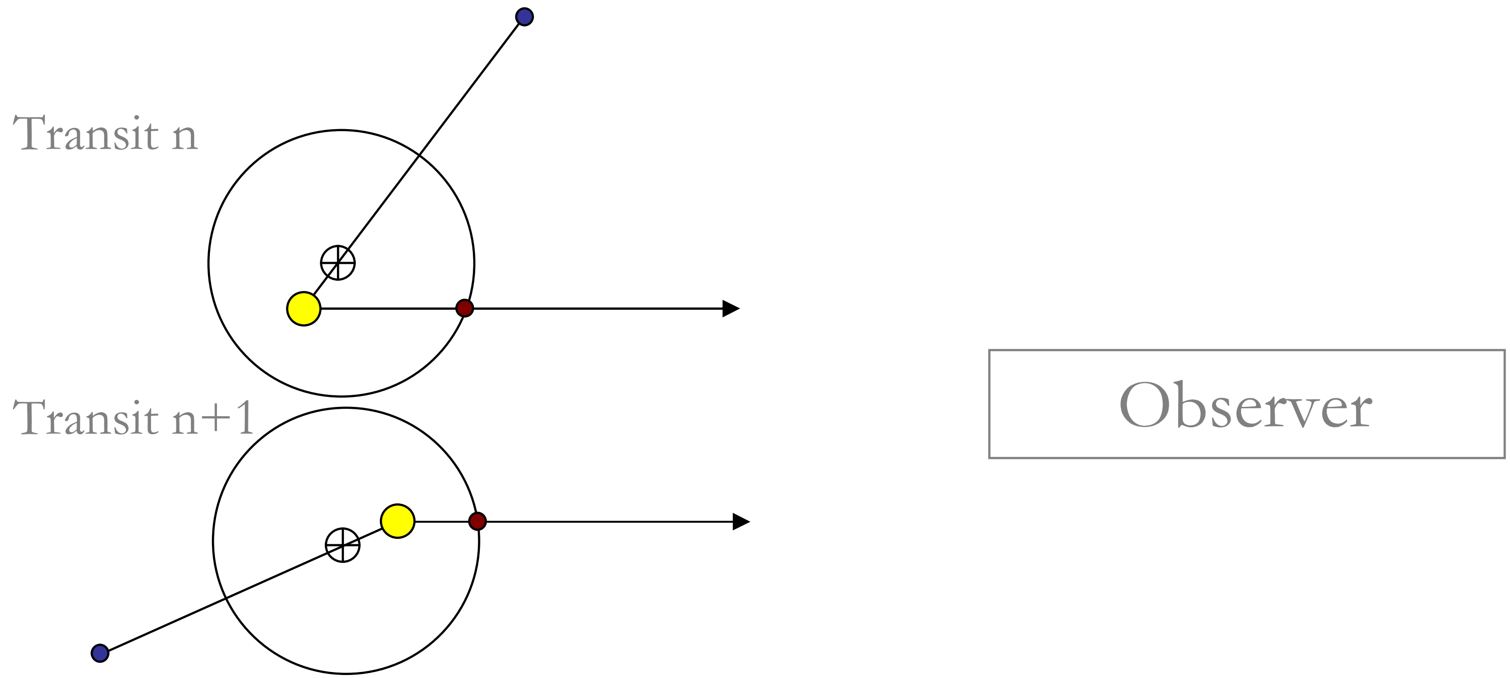
How to extract orbital elements and the mass of the perturbing planet?

Introduction

1. **Effects of a perturbing planet on the transit timings**
   - 1.1 Descriptions and assumptions
   - 1.2 Parameters dependencies
   - 1.3 Numerical results
2. **Estimation of the parameters of the perturbing planet**
   - 2.1 Method
   - 2.2 Planets on circular orbits
   - 2.3 Perturbing planet on an eccentric orbit
3. **Terrestrial mass planet in mean-motion resonance**
   - 3.1 New assumptions
   - 3.2 Numerical results
   - 3.3 Observable systems

1. Effects of a perturbing planet on the transit timings

1.1 Descriptions and assumptions



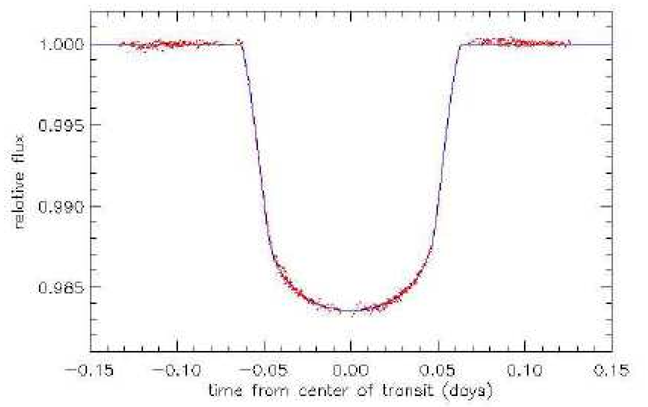
Transit interval: $\Delta t(t) = t_{n+1} - t_n = T_1 + \delta t(t)$

- Direct effect (interactions with the perturbing planet)
- Indirect effect (motion of the star)

1.1 Descriptions and assumptions

Main assumptions:

1. Edge-on system and coplanar orbits.
2. General relativity and tidal effects neglected
3. Gaussian noise ($\sigma = 5$ sec)
4. The transiting planet is a HD209458b-type planet ($T_1 = 3.52$ days, $a_1 = 4.5\ 10^{-2}$ AU, $e_1 = 0.025$)
5. 2-year observations (170 transits)



A HD209458b transit observed with the HST. Charbonneau et al (2005)

1.2 Parameters dependencies

M. Holman, N. Murray:

$$\Delta(t) \sim \frac{45\pi}{16}\left(\frac{m_2}{M_\odot}\right) T_1 \alpha_e^3 \left(1 - \sqrt{2}\alpha_e^{3/2}\right)^{-2}$$

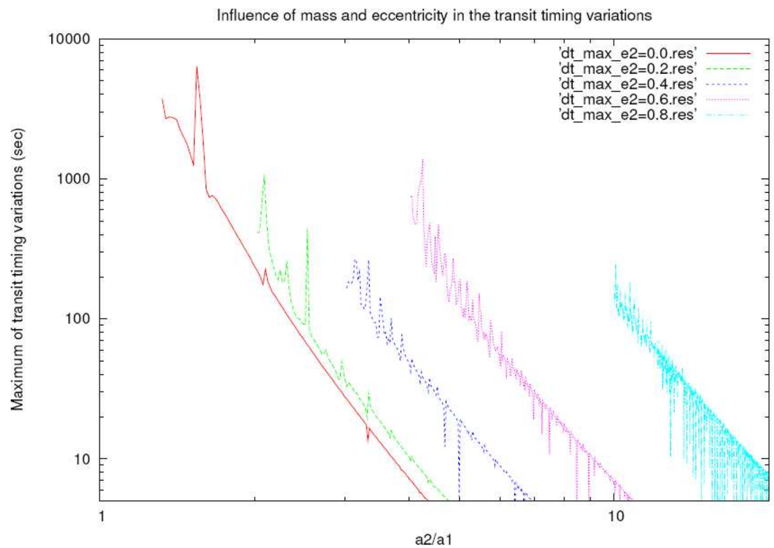
$$\alpha_e = \frac{a_1}{a_2(1 - e_2)}$$

Mass, m_2: amplitude of variations is a linear function of the mass.

Eccentricity, e_2: amplitude is a monotone increasing function.

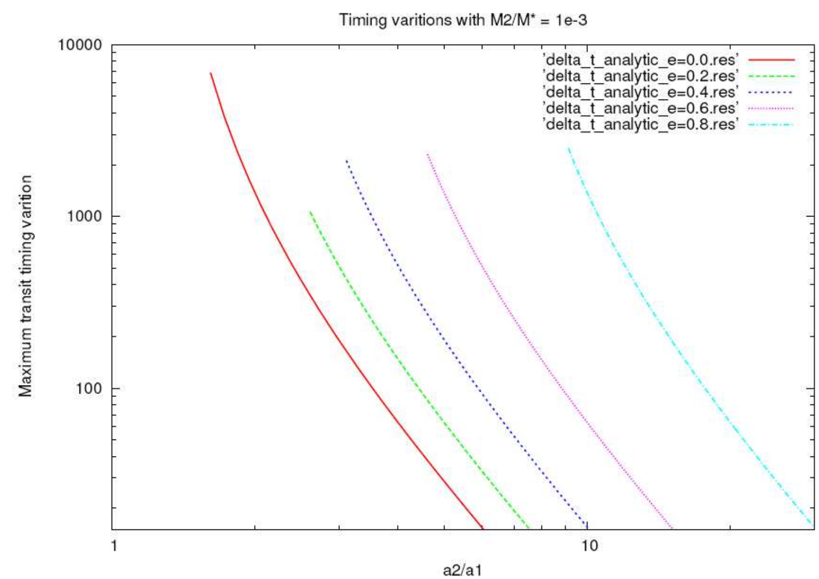
Semi-major axis, a_2: amplitude is a monotone decreasing function (except for resonances).

1.2 Parameters dependencies



← Numerical computation of the maximum of the variations

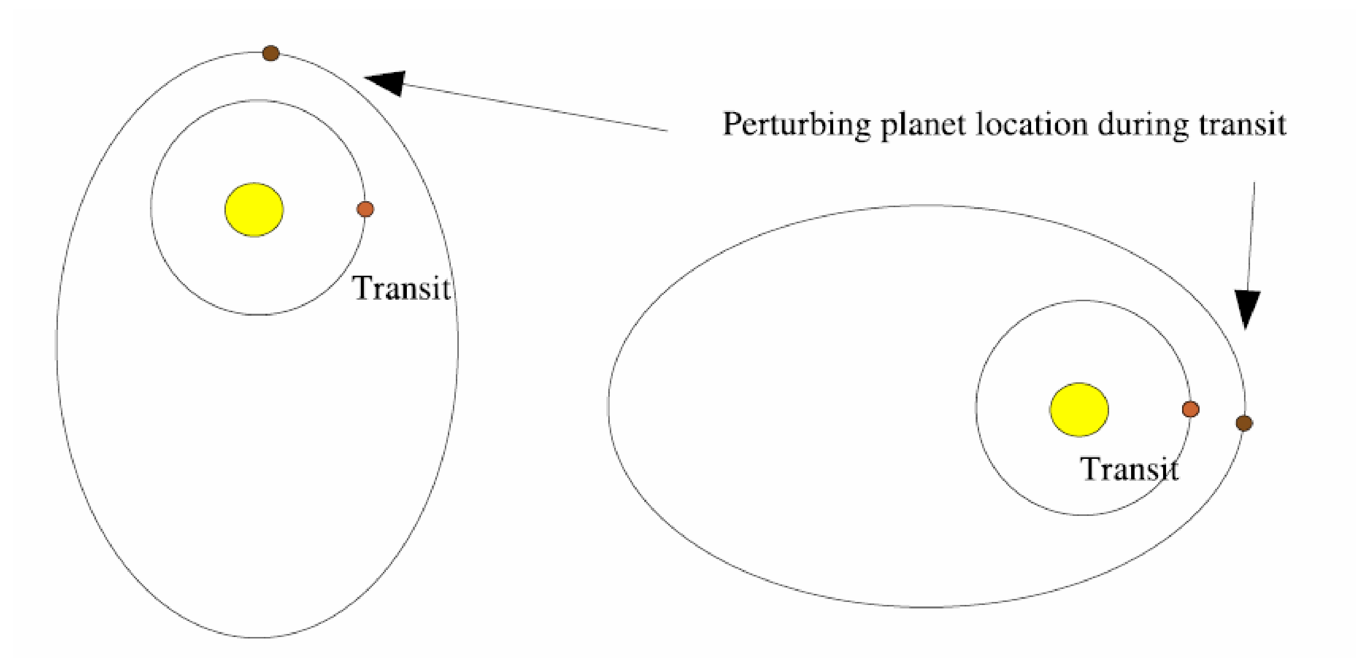
Analytical expression →



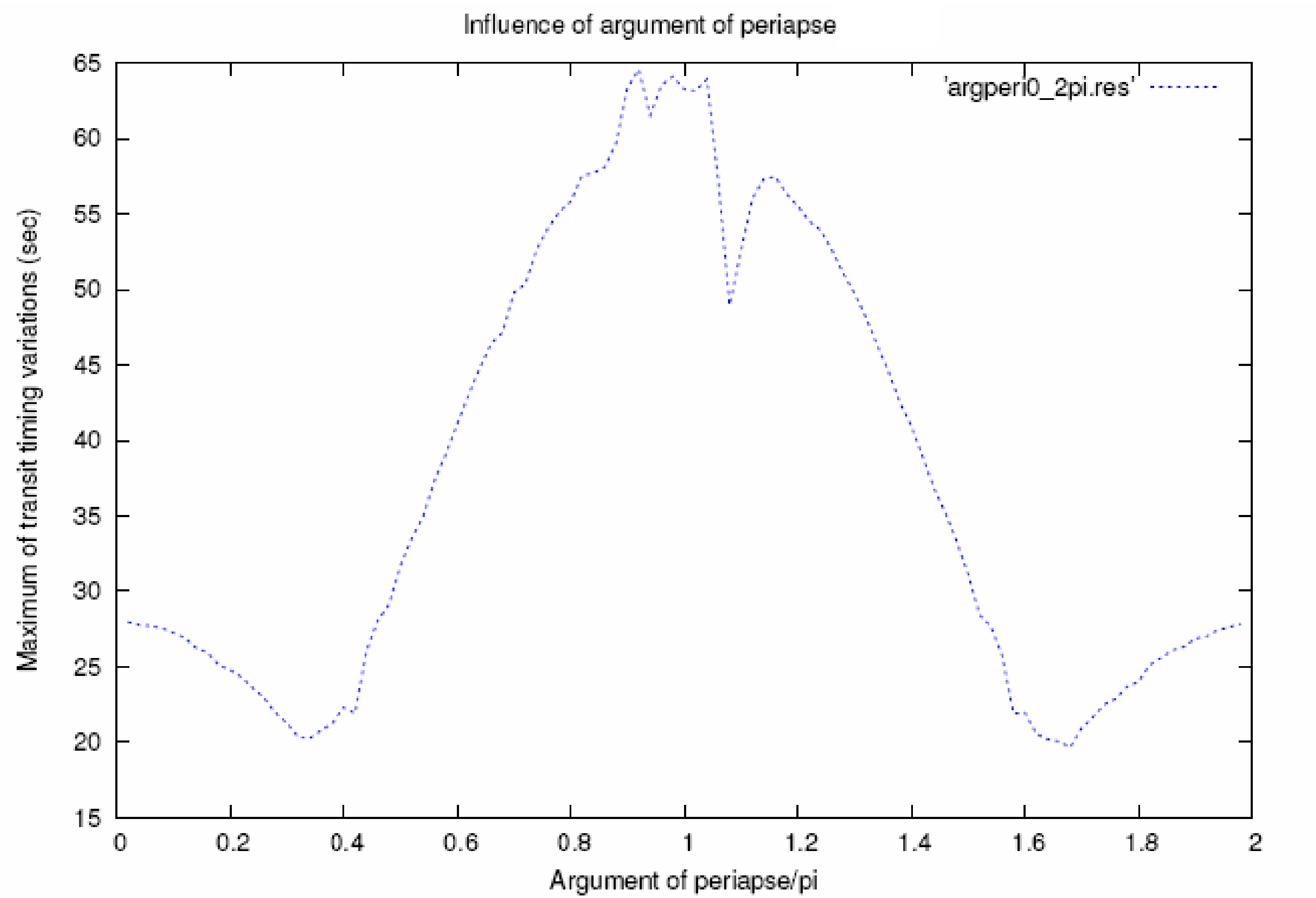
1.2 Parameters dependencies

Mean-anomaly (at t = 0), M_2: the changes in this parameter don't modify the amplitude but can affect the pattern of the transit timings data set.

Argument of periapse, ω_2: when $\omega_1 = \omega_2$, amplitude is minimum because the direct effect tends to oppose the indirect effect.

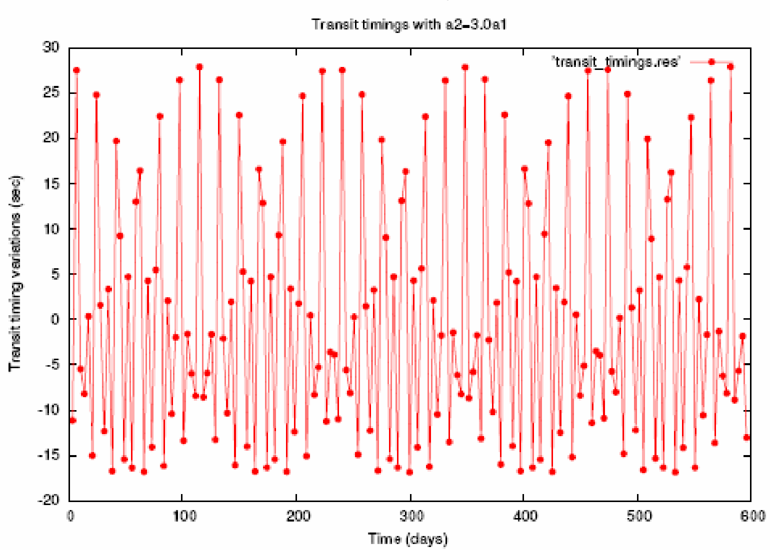


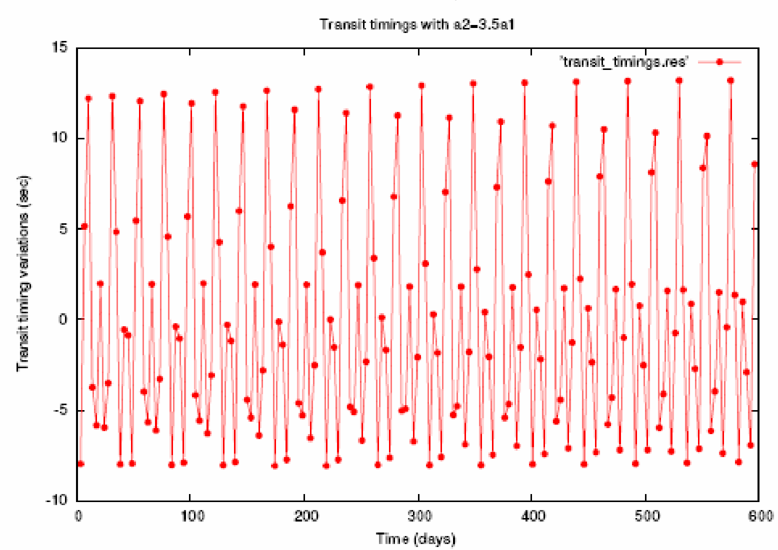
1.2 Parameters dependencies



1.3 Numerical results

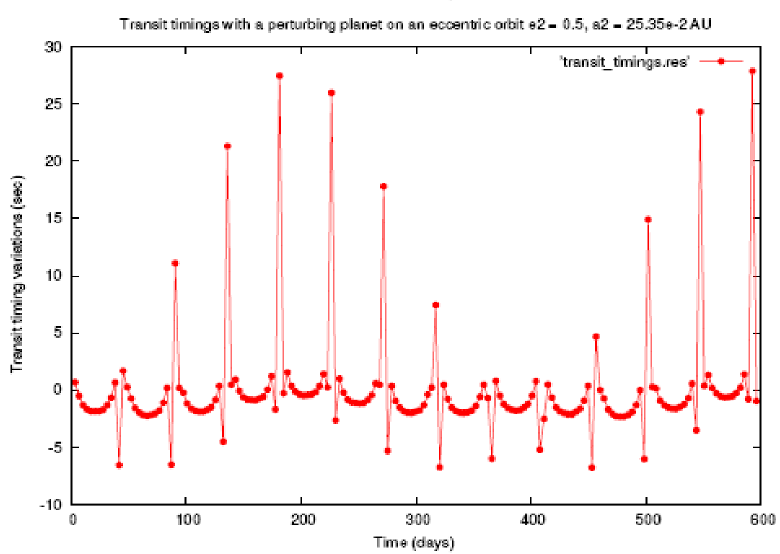
Planets on circular orbits

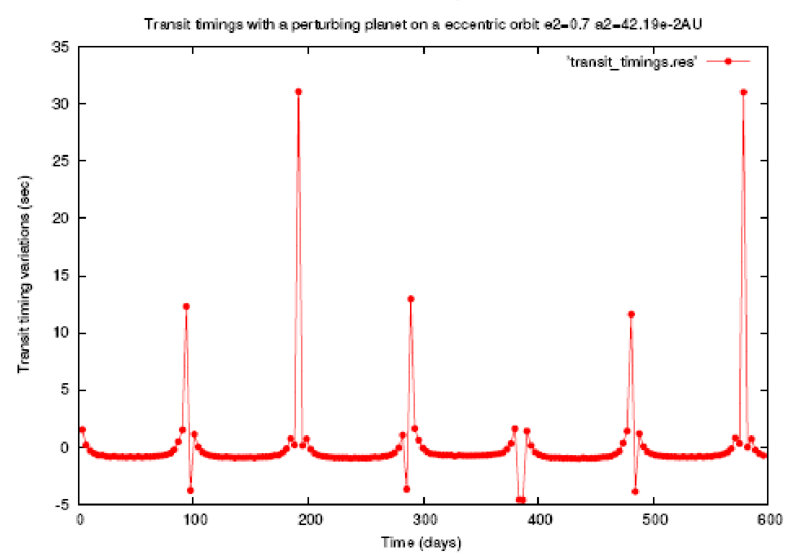




1.3 Numerical results

Perturbing planet on an eccentric orbit





2. Estimation of the parameters of the perturbing planet

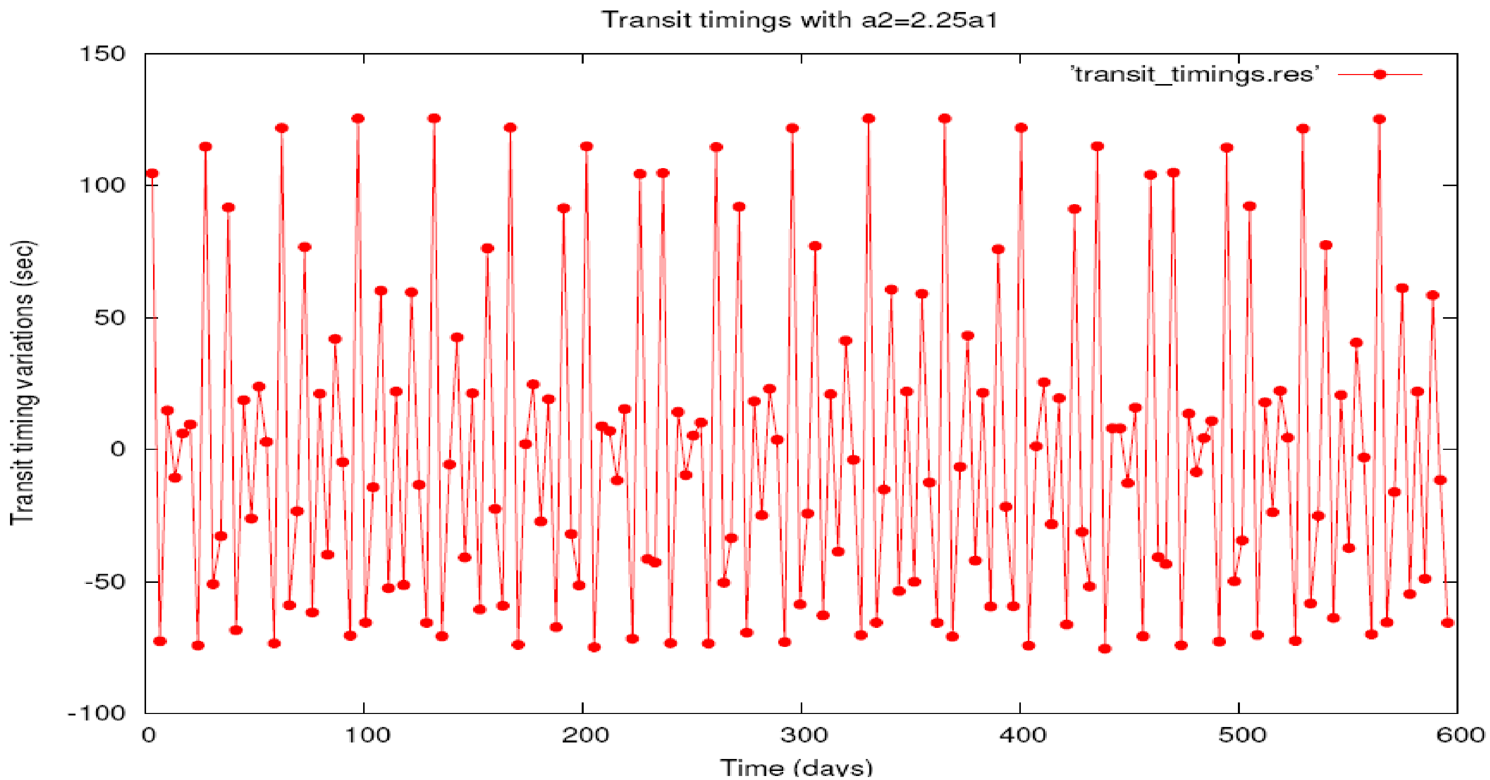
2.1 Method

Extract the maximum of information from the transit timing set of data.

Put some *a priori* information on the system.

Invert the problem by a χ^2 minimization.

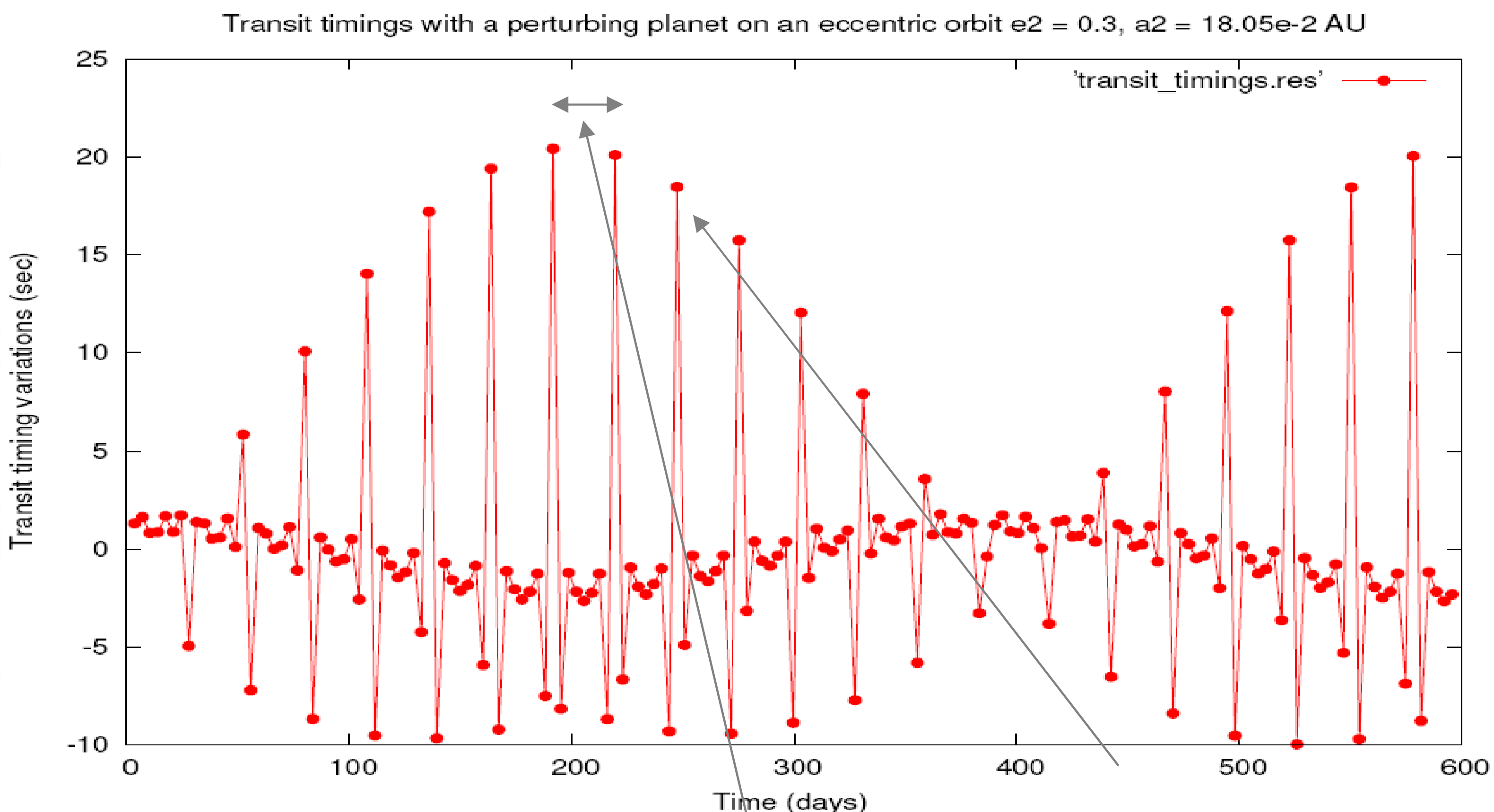
2.2 Planets on circular orbits



We cannot distinguish the period of the transiting planet ⟹ e_2 must be small.

Variations are big enough to see the pattern of the transit timings.

2.3 Perturbing planet on an eccentric orbit



⇨ Large eccentric orbit

Periapse time passage

Period of the transiting planet

3. Terrestrial planet in mean-motion resonance

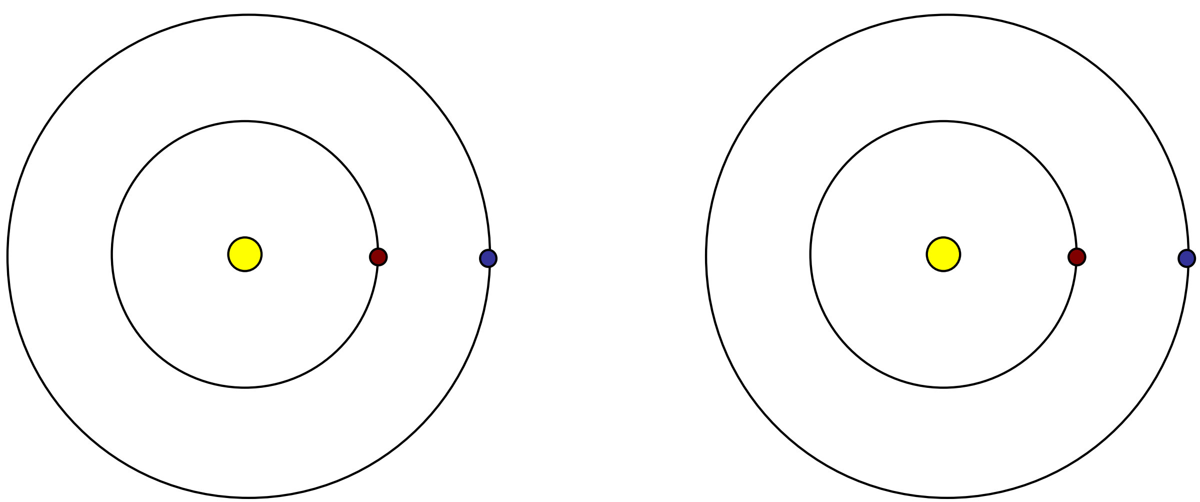
3.1 New assumptions

The previous analytic expression doesn't work anymore

We must take into account the variations on the **perturbing** planet, because perturbations are amplified at each conjunction

Example: 2:1 resonance

$t = T_1$ $t = 2T_1$



3.1 New assumptions

The resonant argument φ, will depend on:

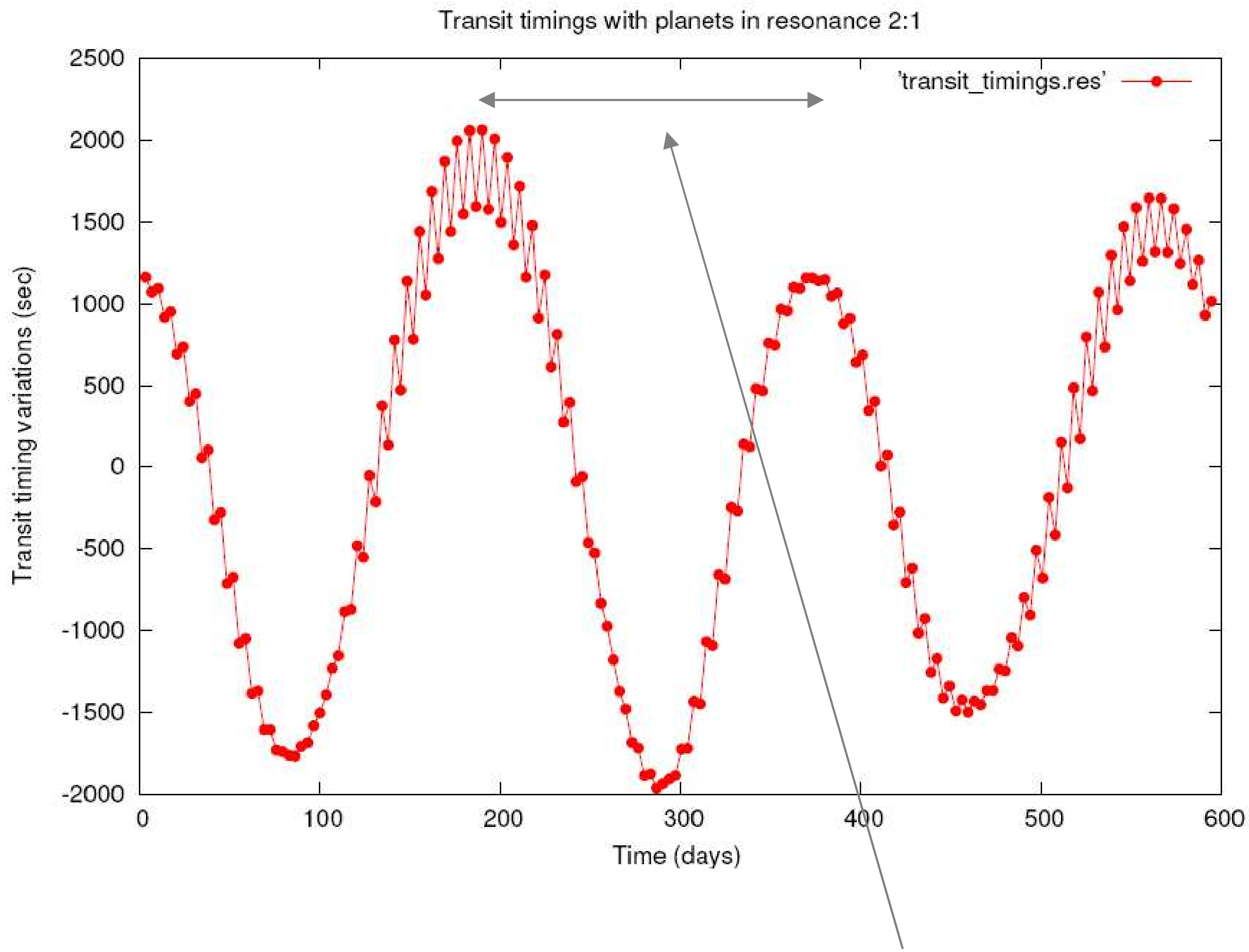
•Masses of both planets

•Orbital elements of both planets

dφ/dt leads to the libration frequency

We will see the libration period.

3.2 Numerical results



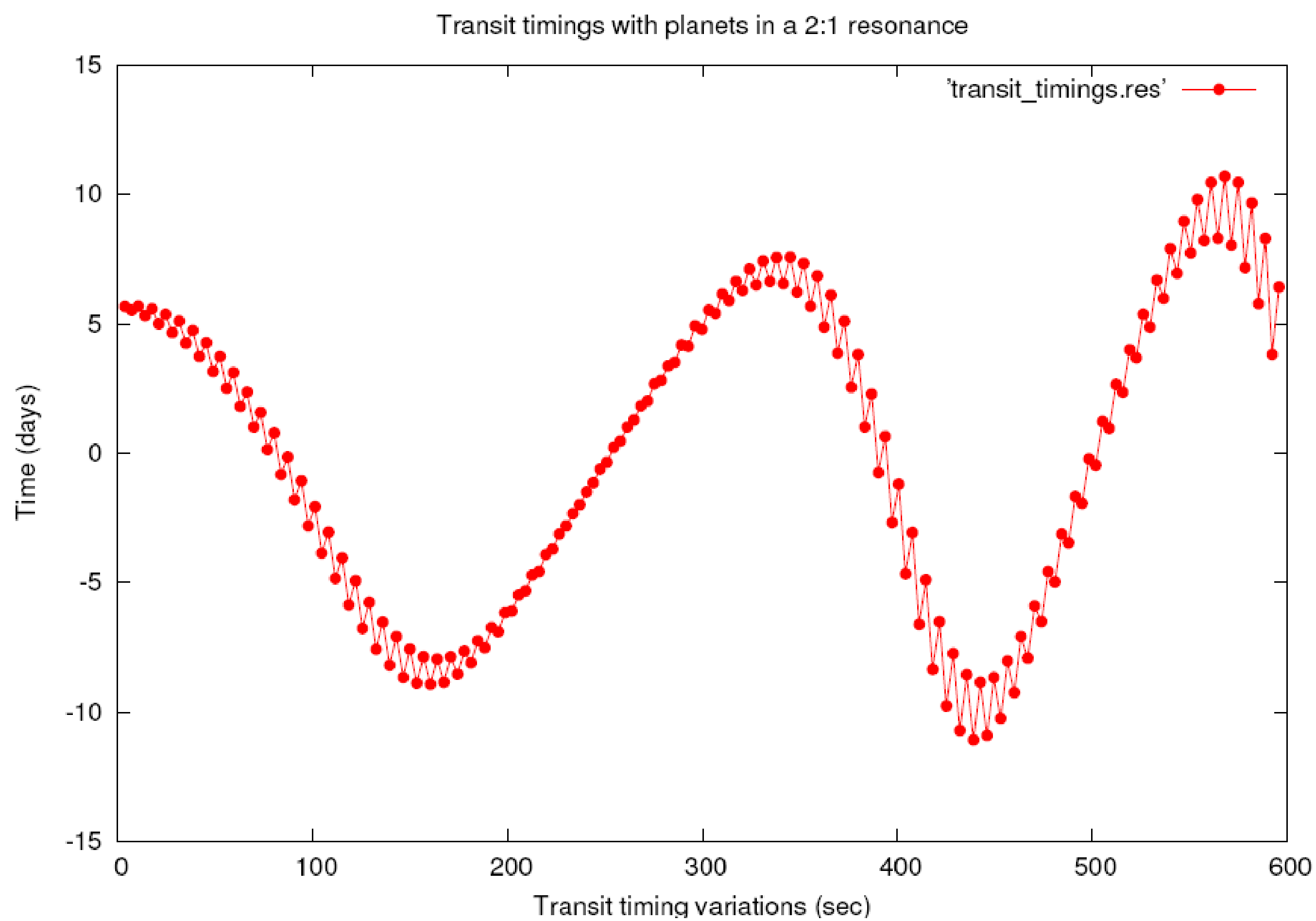
$m_2 = 10^{-3} M_\odot$

Libration period

3.2 Observable systems

Numerical computations give $m_{2,\,min} = 5.10^{-6} M_\odot$

Maximum timing deviation = 25 sec ⟹ detectable !!!



Conclusion

A new method to detect extrasolar planets:

Efficient method for most of the systems.

However one must have a good accuracy for the measurements.

Leads to a lot of information on the parameters of the perturbing planet.

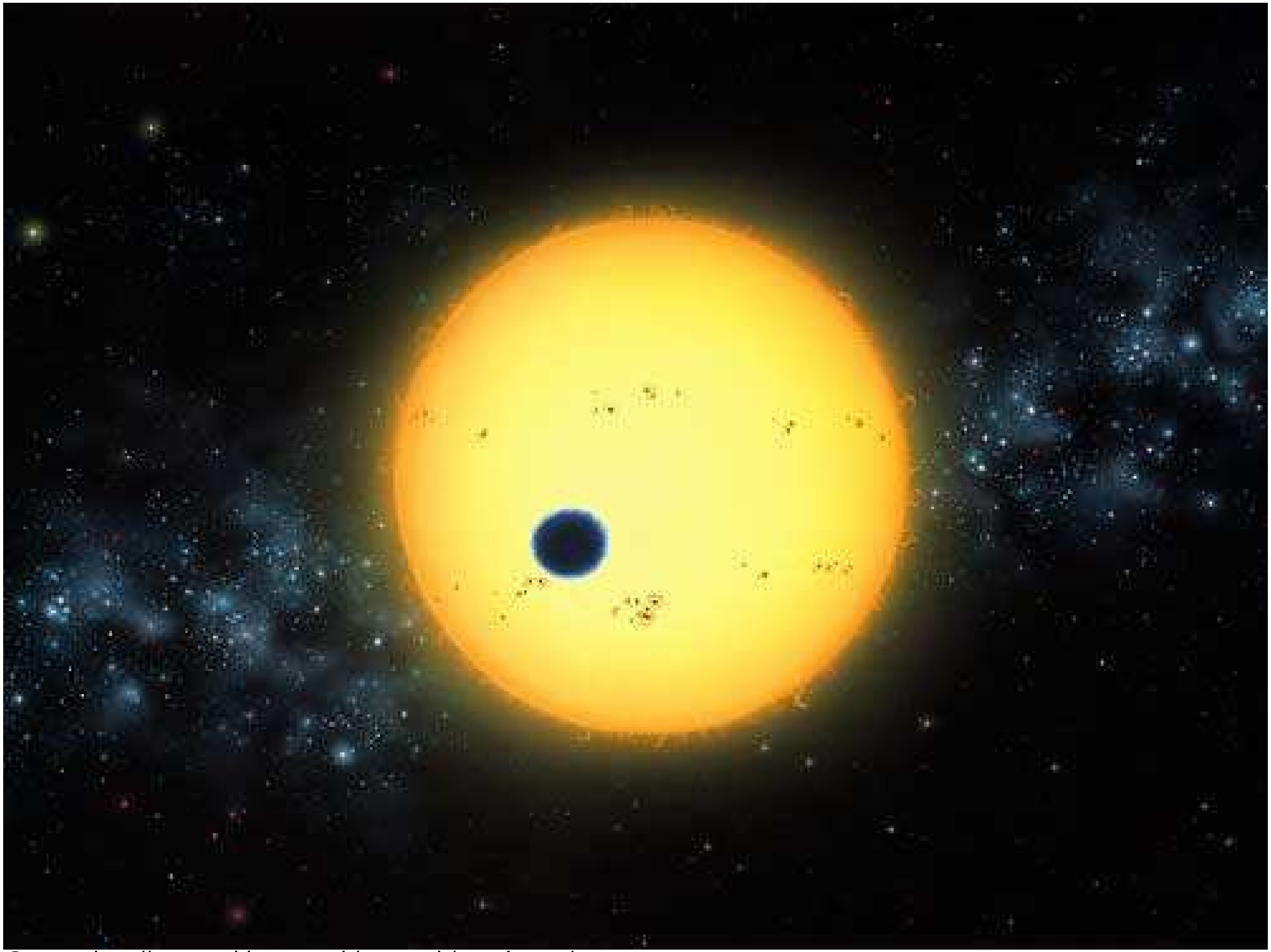
Conclusion

A way to discover small planets:

The resonant perturbations are degenerated and are special cases…

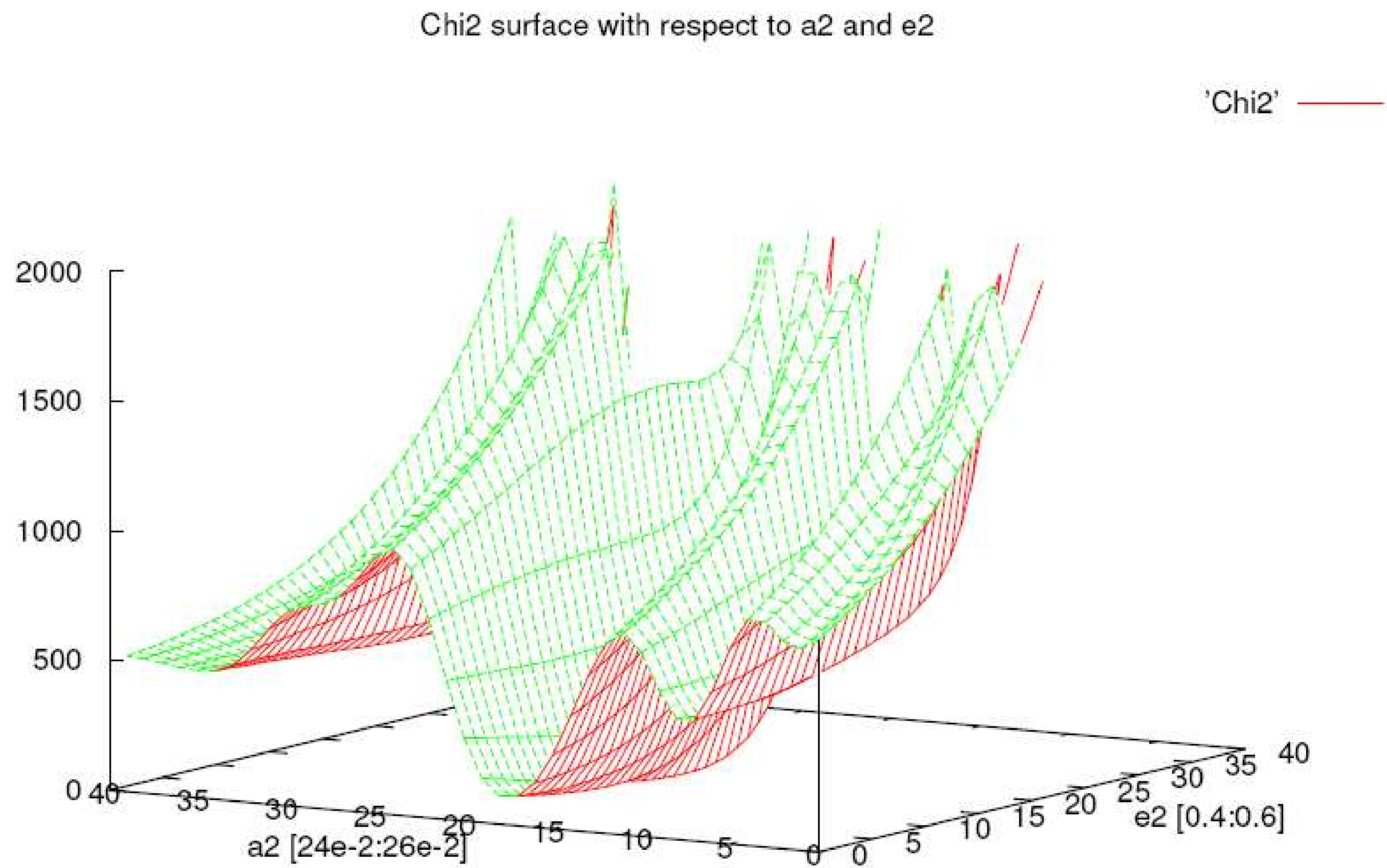
…but Earth-mass planets can be detected by this method!!

The end

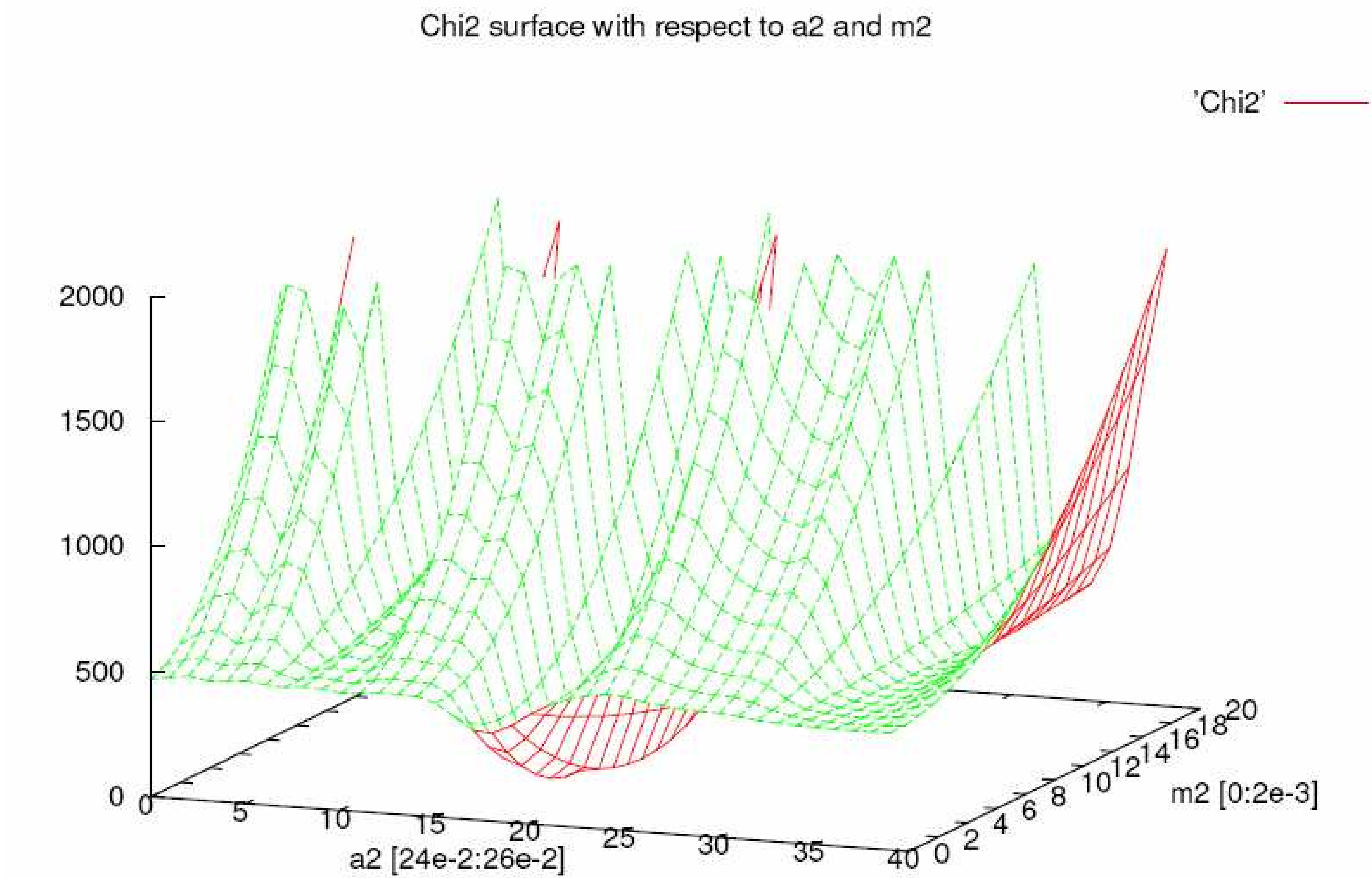


Source: http://www.sr.bham.ac.uk/research/exoplanets/

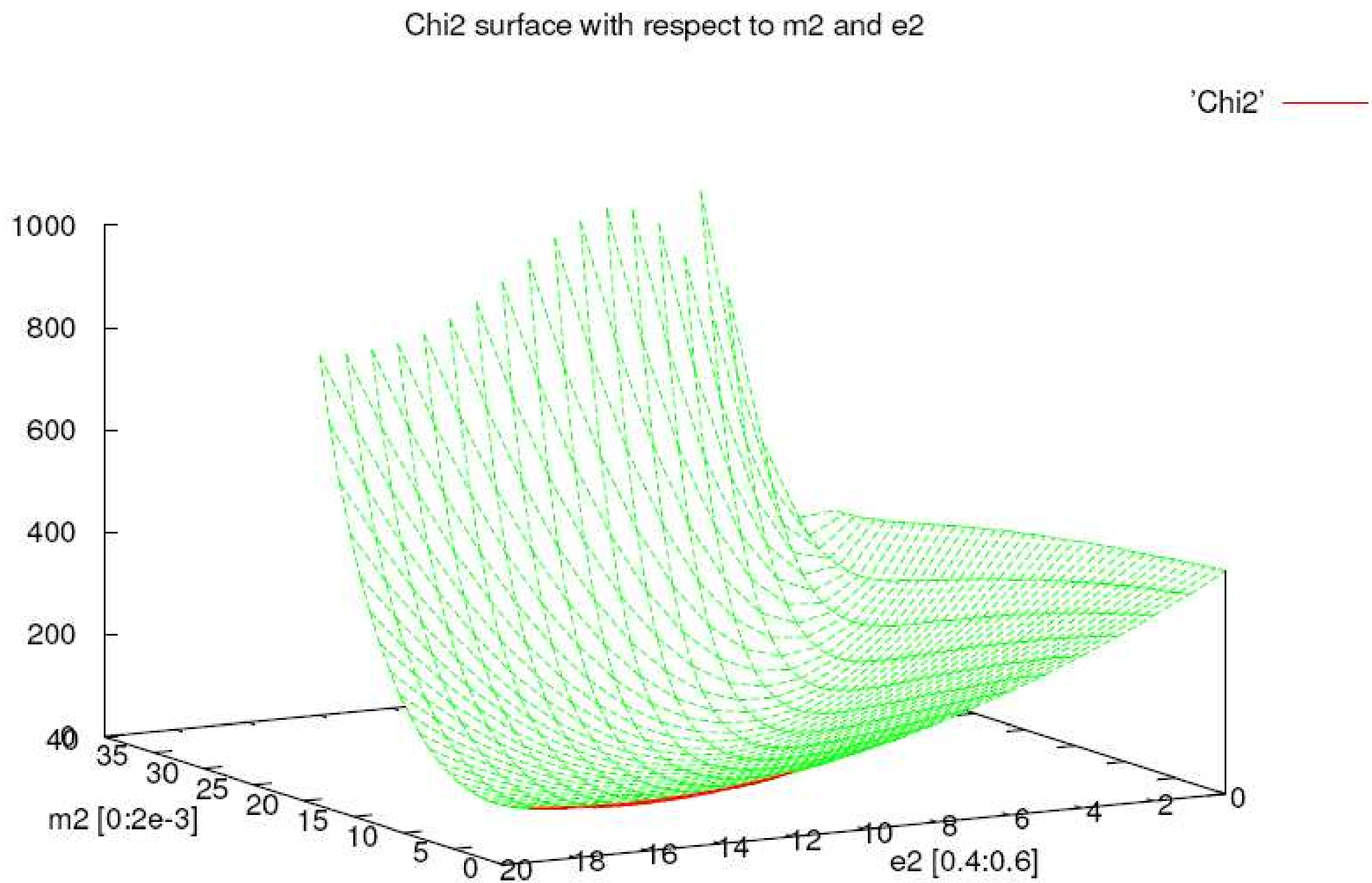
χ^2 surfaces



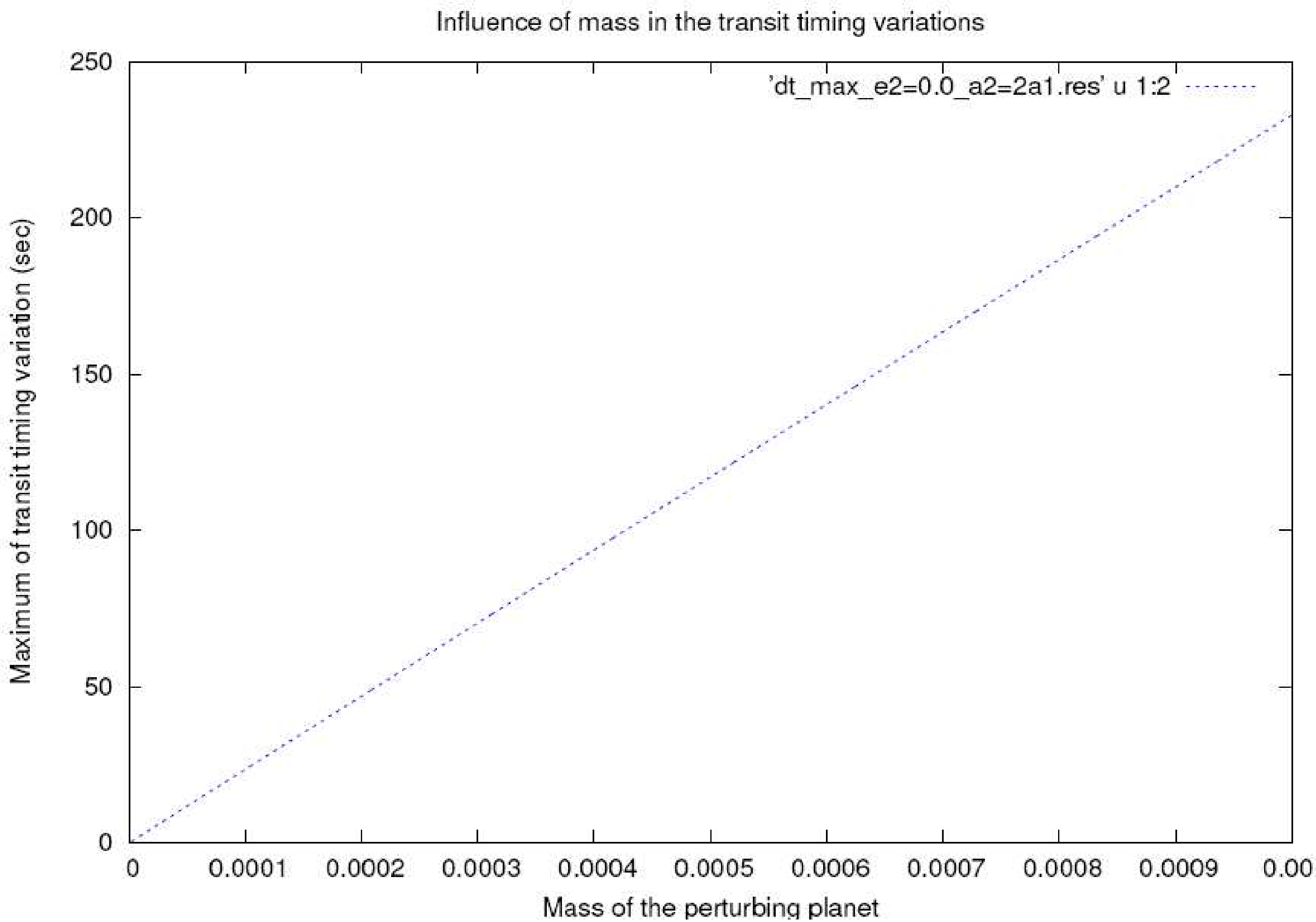
χ^2 surfaces



χ^2 surfaces



Mass



Influence of mass in the transit timing variations
'dt_max_e2=0.0_a2=2a1.res' u 1:2
Maximum of transit timing variation (sec)
250
200
150
100
50
0
0
0.0001
0.0002
0.0003
0.0004
0.0005
0.0006
0.0007
0.0008
0.0009
0.001
Mass of the perturbing planet

Mass. Resonance 2:1