Detecting additional planets from the transits of known extrasolar planets

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Fermilab Astrophysics Seminar

February 23, 2009

Fermilab Exoplanets Team

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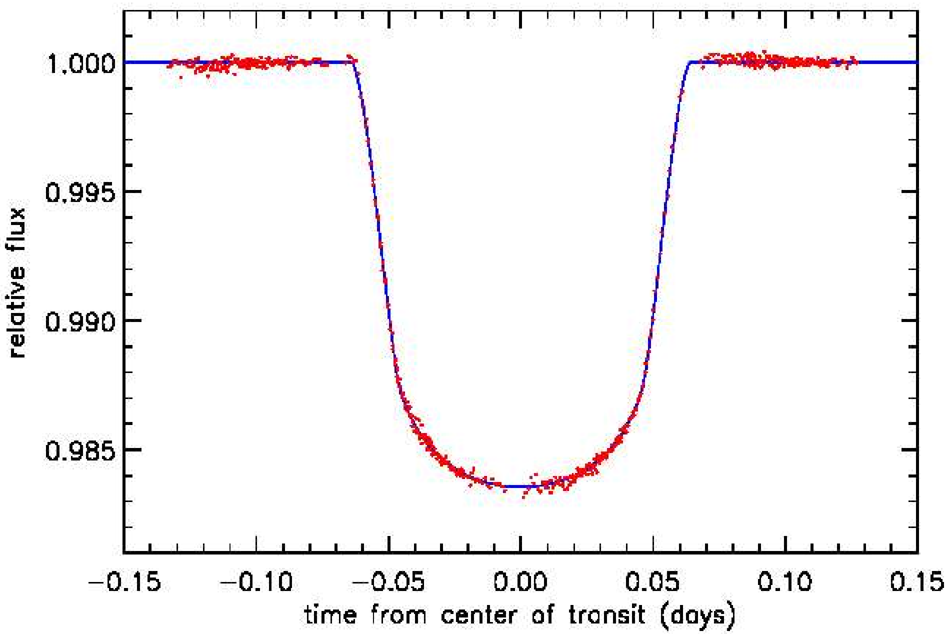
Outline

- Transiting planets primer
- Introduction to Transit Timing Variations
  - Non-interacting planets
  - Perturbation theory
  - Tidal weirdness
  - Resonance
- Theoretical prospects for meaningful TTV application
- Analysis of real data: TrES-1 and HD209458
- The Kepler Mission
- Outstanding issues
- Conclusions

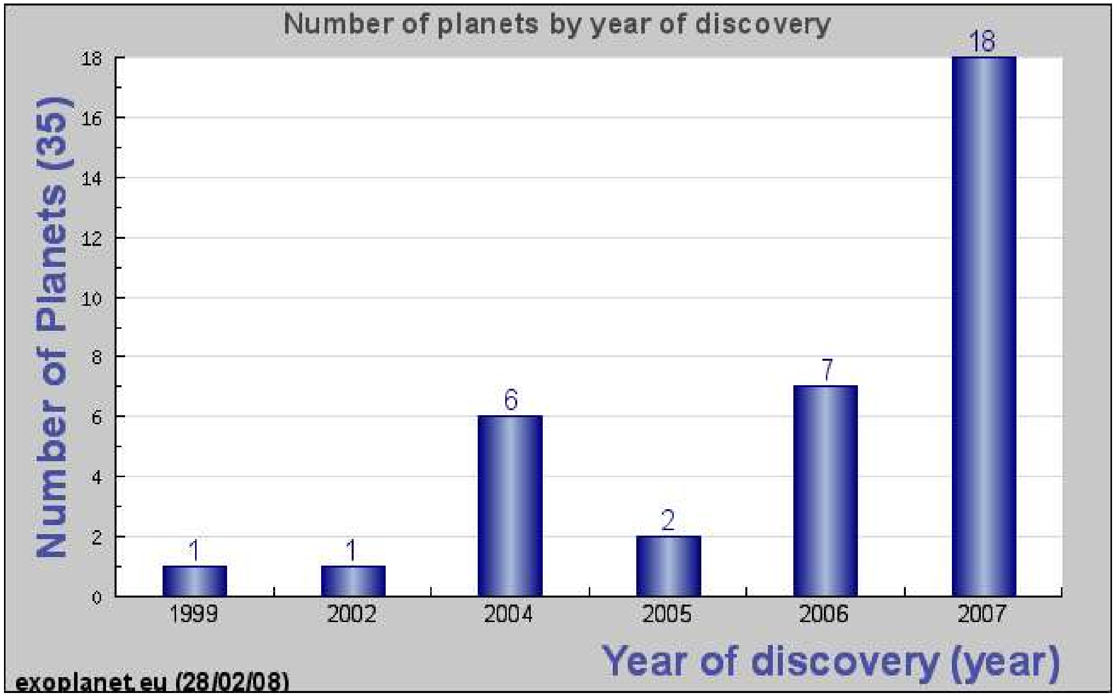
Transiting Planets

Discoveries



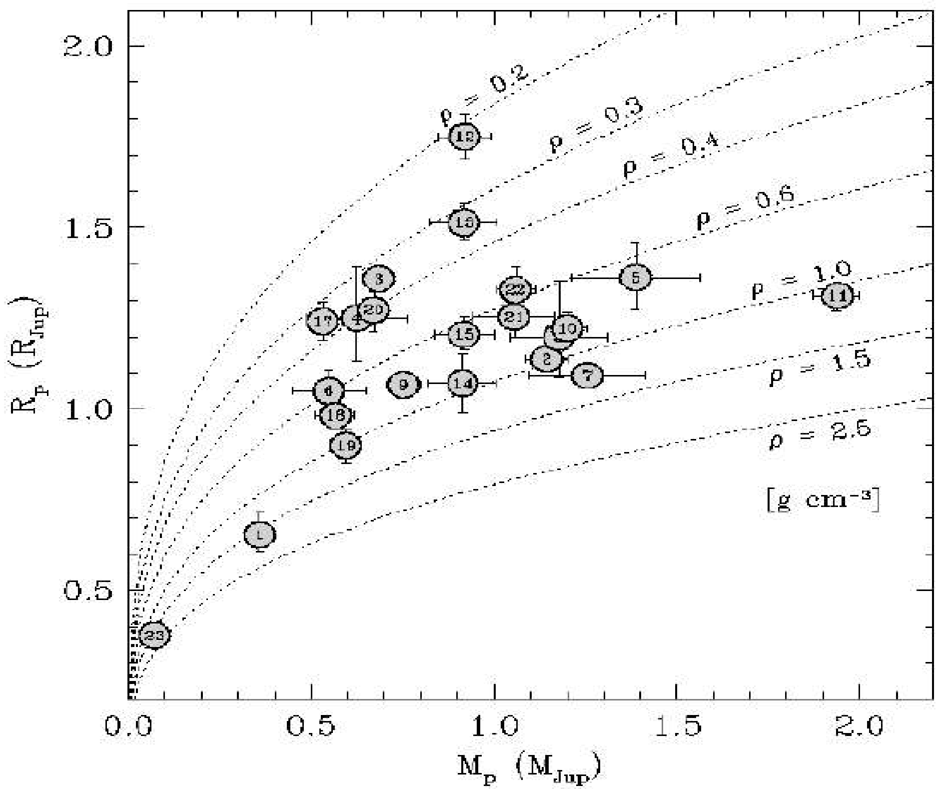
New planets are announced ~monthly, most are now discovered via transits and confirmed with RV.

HD 209458 was the first exoplanet seen to transit. It was discovered via RV measurements.



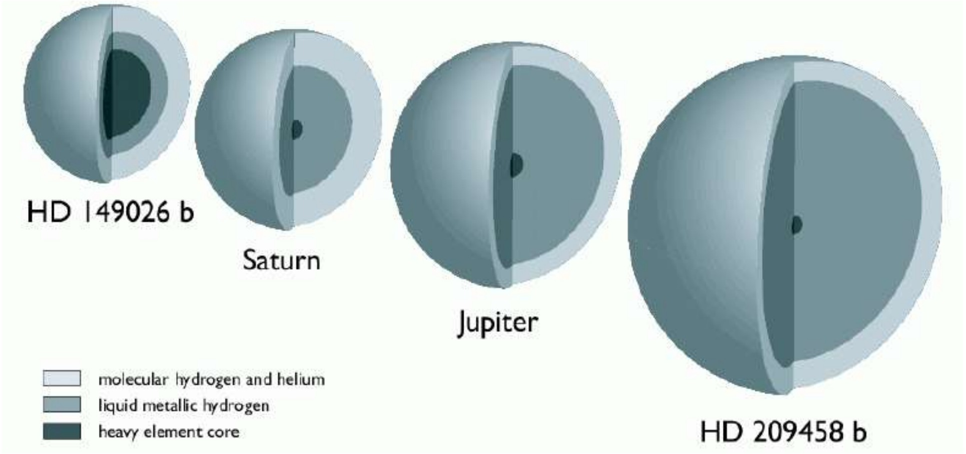
Transiting Planets

Mass, Radius, and Density



Torres et al 2008

- Transit depth gives the ratio of the planet and stellar radii
- Radial Velocity (RV) measurements give the planet mass
- These combined with stellar models give the bulk density

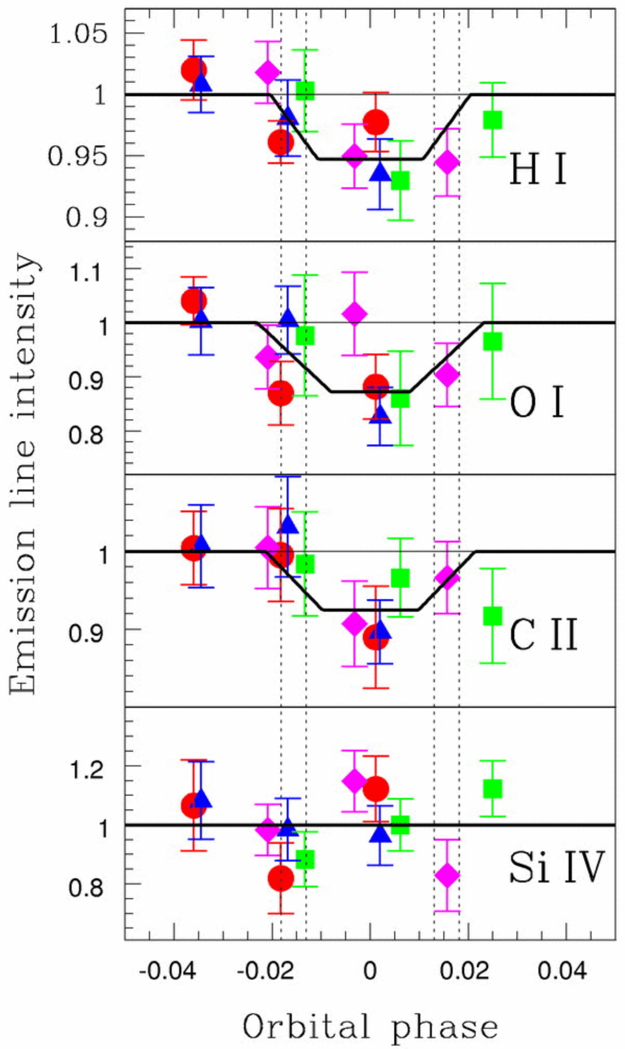


Charbonneau et al 2007

Transiting Planets

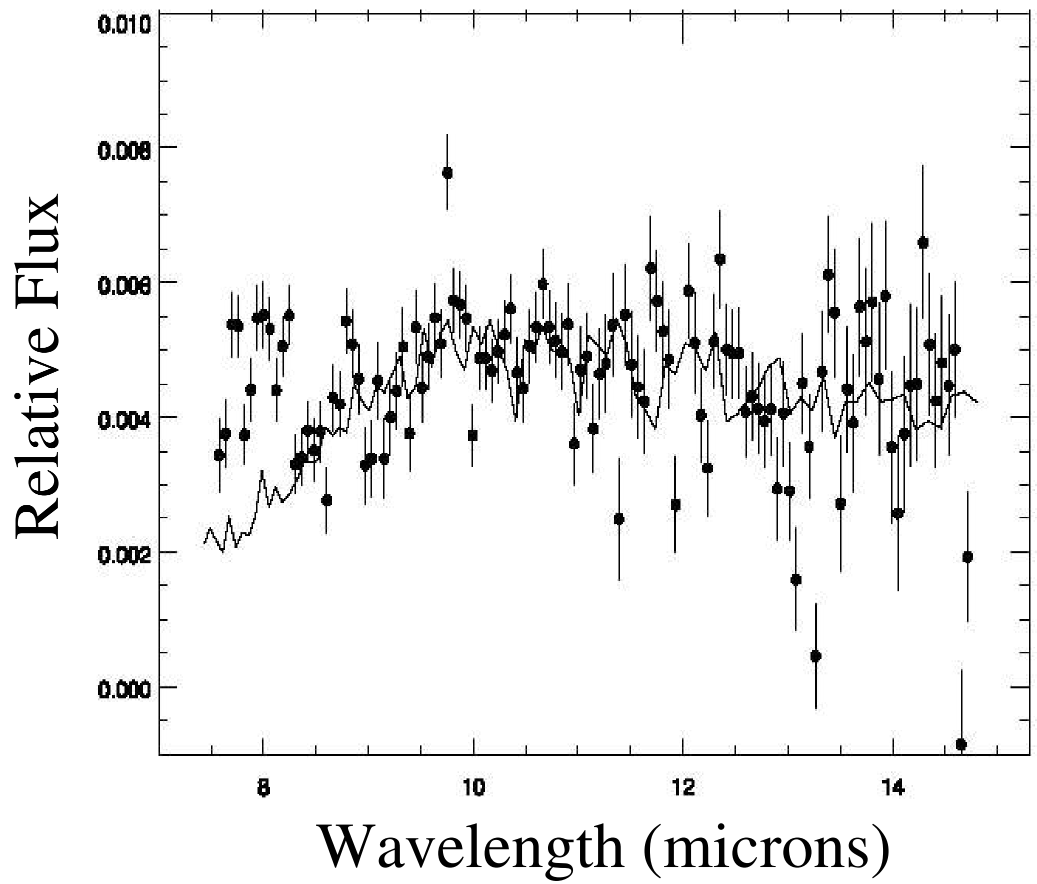
Atmospheres

HD 209458



Vidal-Madjar et al (2004)

HD 189733

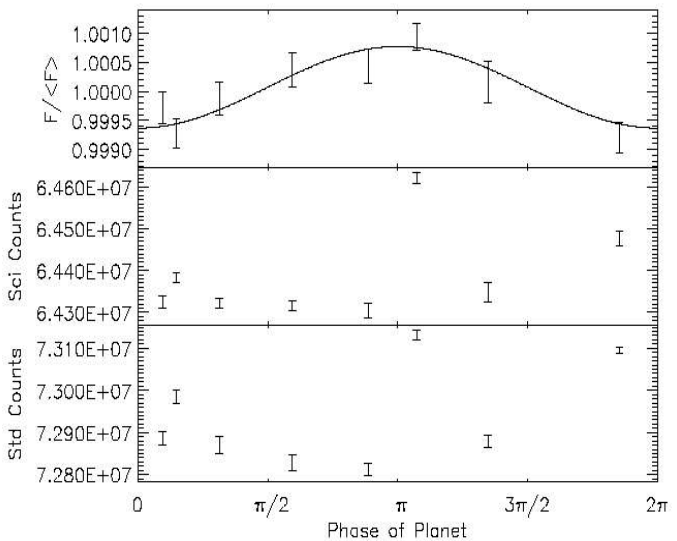


Grillmair et al (2007)

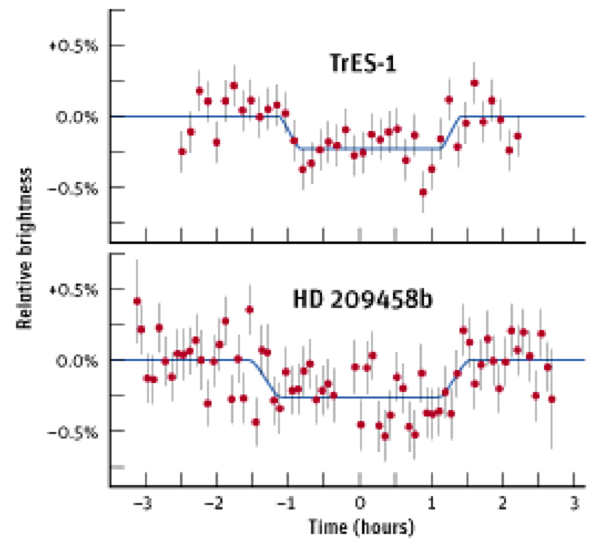
Transiting Planets

Emission, reflection, and temperatures

HD 179949

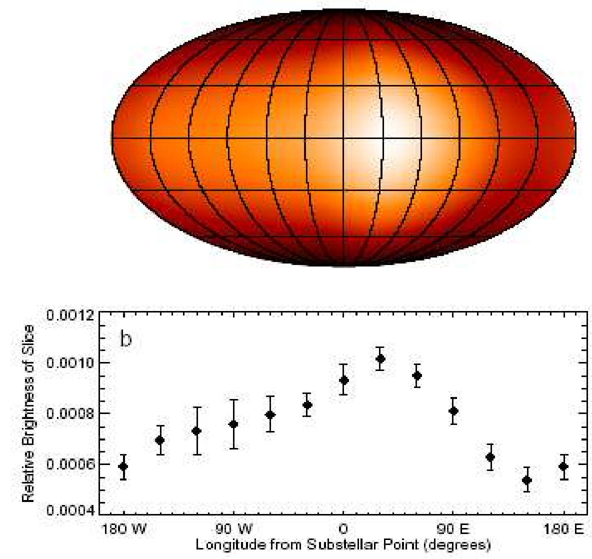


Phase Variations



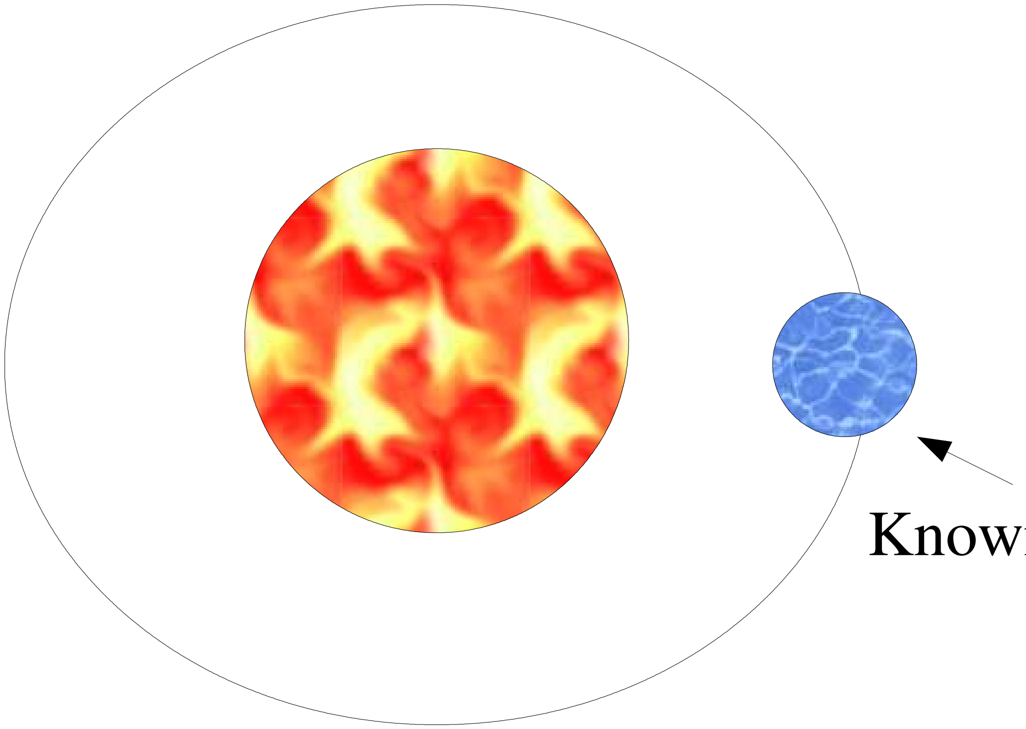
Secondary Eclipse

HD 189733



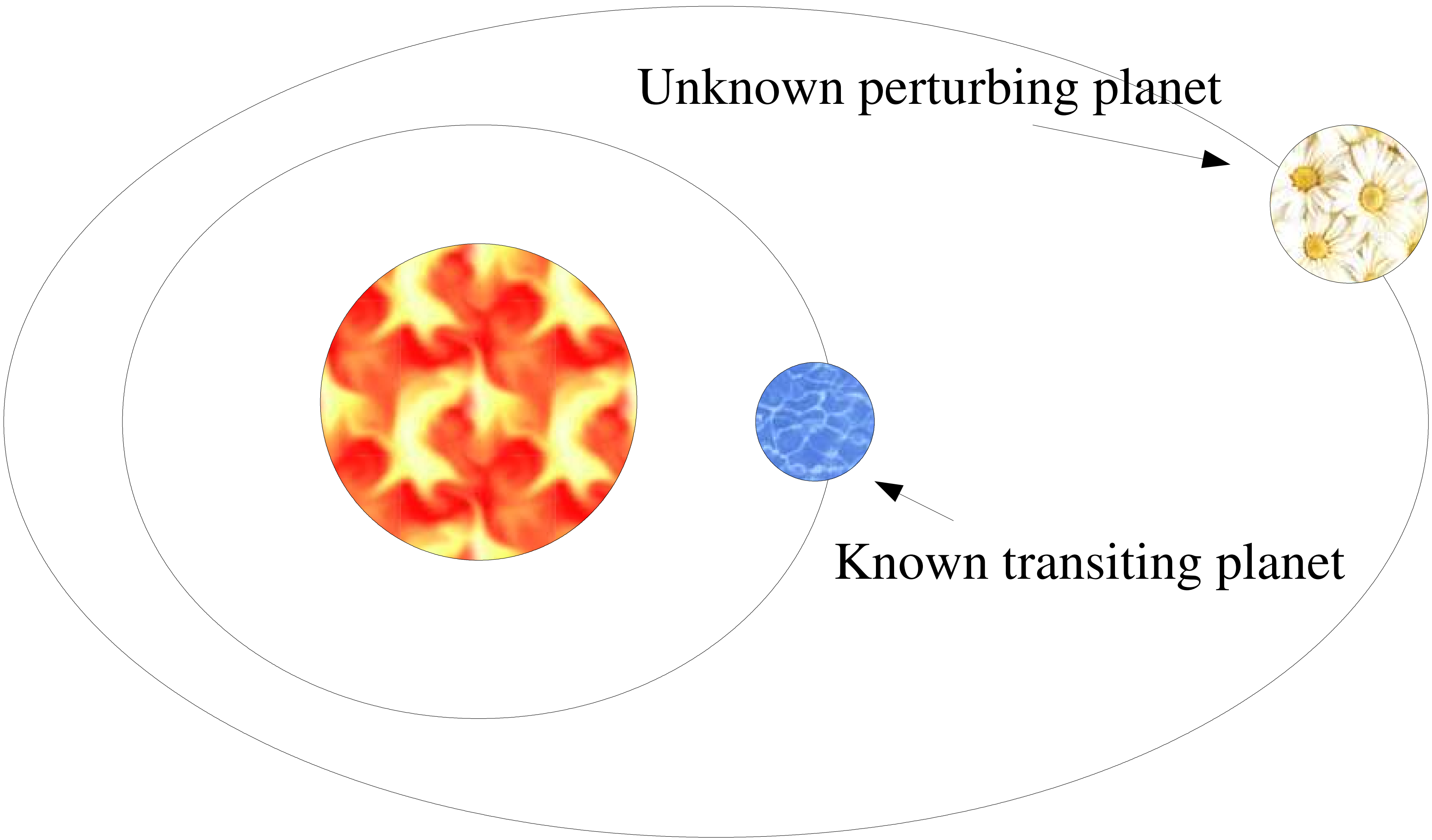
Temperature Variations

Transit Timing Variations



Transit times are equally spaced.

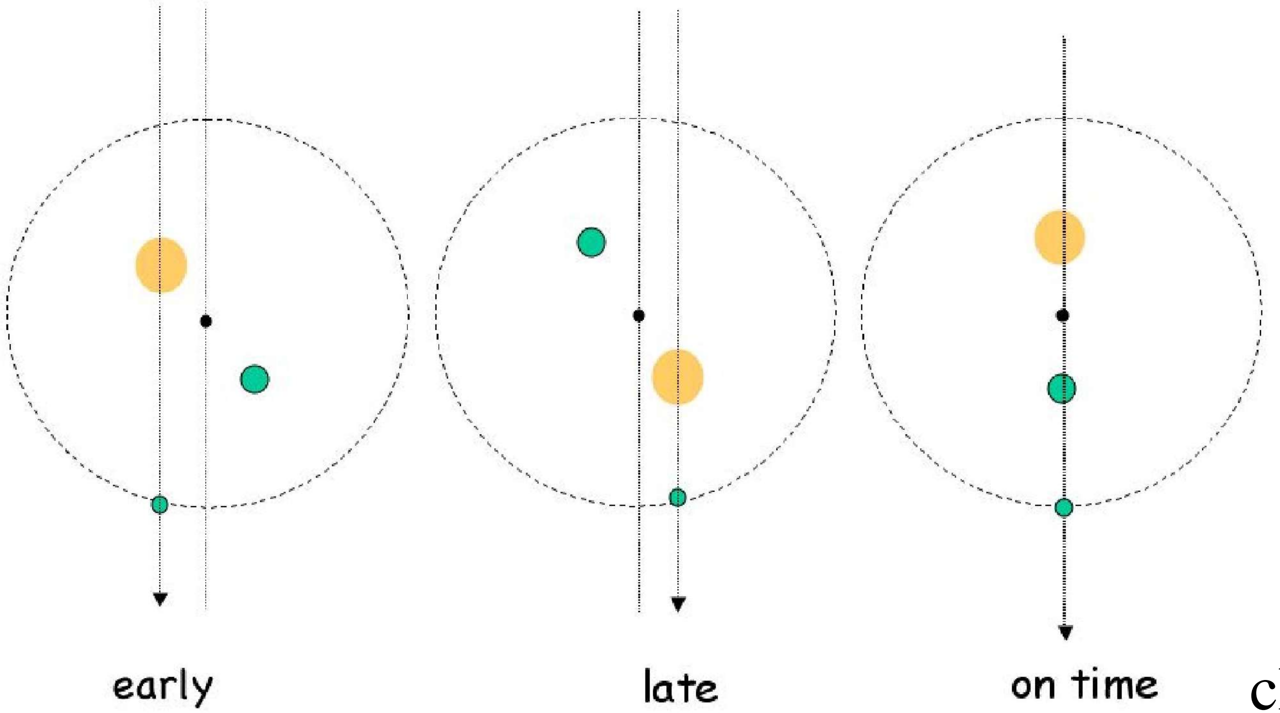
Transit Timing Variations



Transit times are NOT equally spaced.

TTV – Noninteracting Planets

The TTV Poster Child

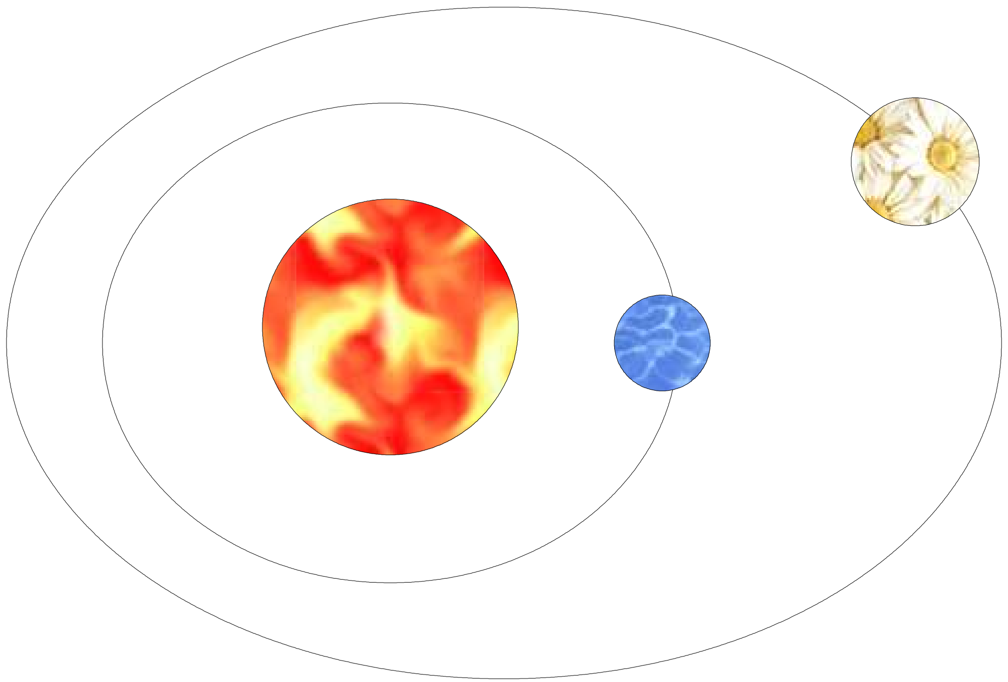


characteristic velocity

$$\sigma_t \sim \left(\frac{P_2}{a_2}\right)\left(\frac{m_1 a_1}{m_0}\right)$$

characteristic displacement

TTV – Perturbation Theory



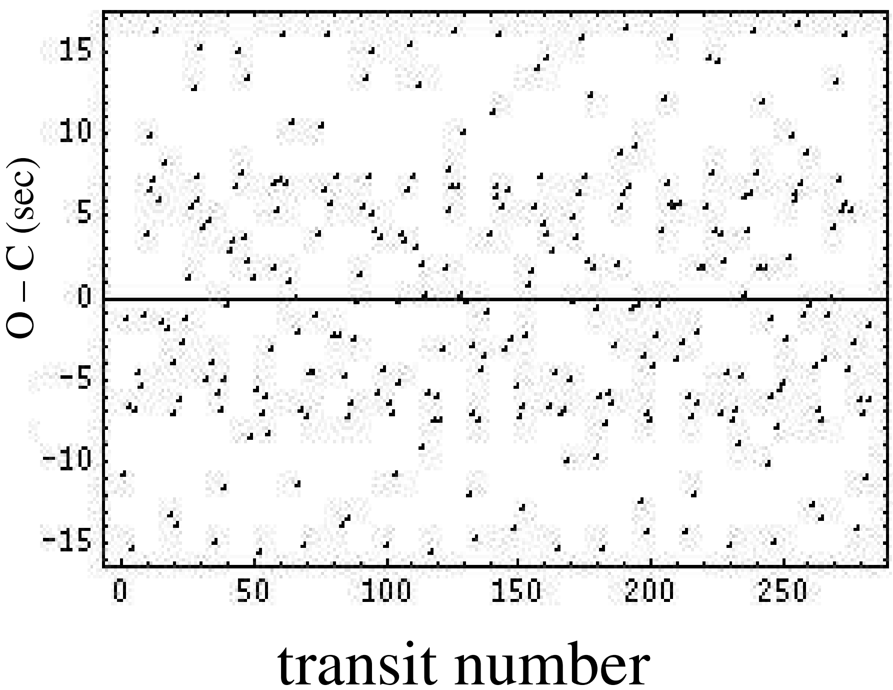
Non-resonant interactions excite multiple oscillatory modes with various resonance arguments (e.g. $\sin[n_1 - 2n_2]$).

$$\sigma_t \sim P_{trans} \left(\frac{m_{pert}}{m_0} \right) \left(\text{Big Messy Expression} \right)$$

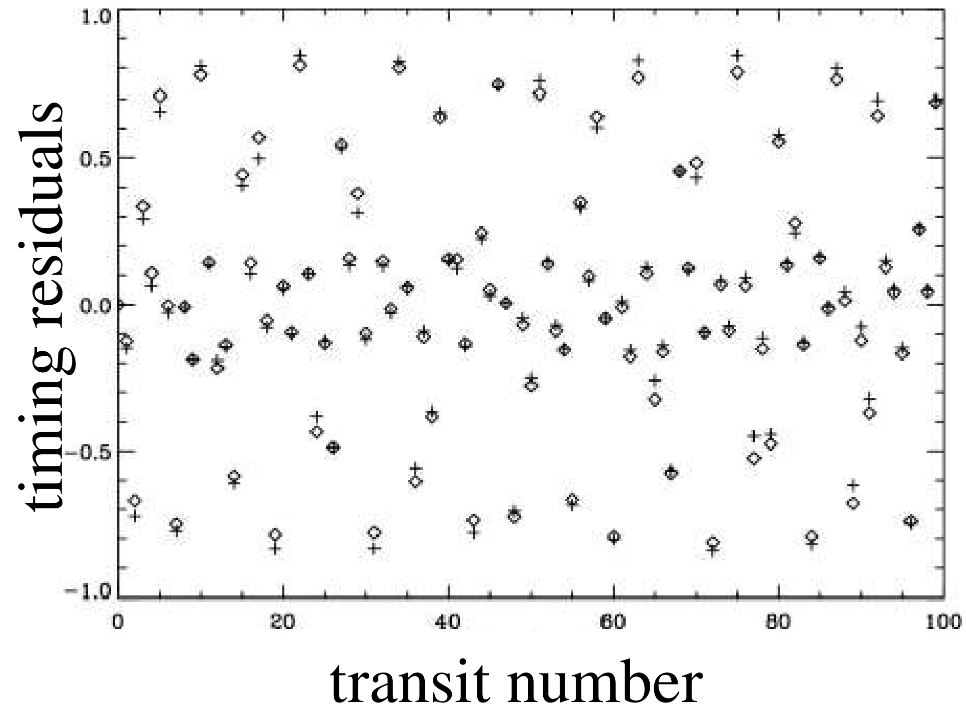
TTV – Perturbation Theory

Sample signal for a non-resonant, 0.1 Jupiter-mass planet perturbing a Jupiter-mass planet that is on a 3-day orbit.

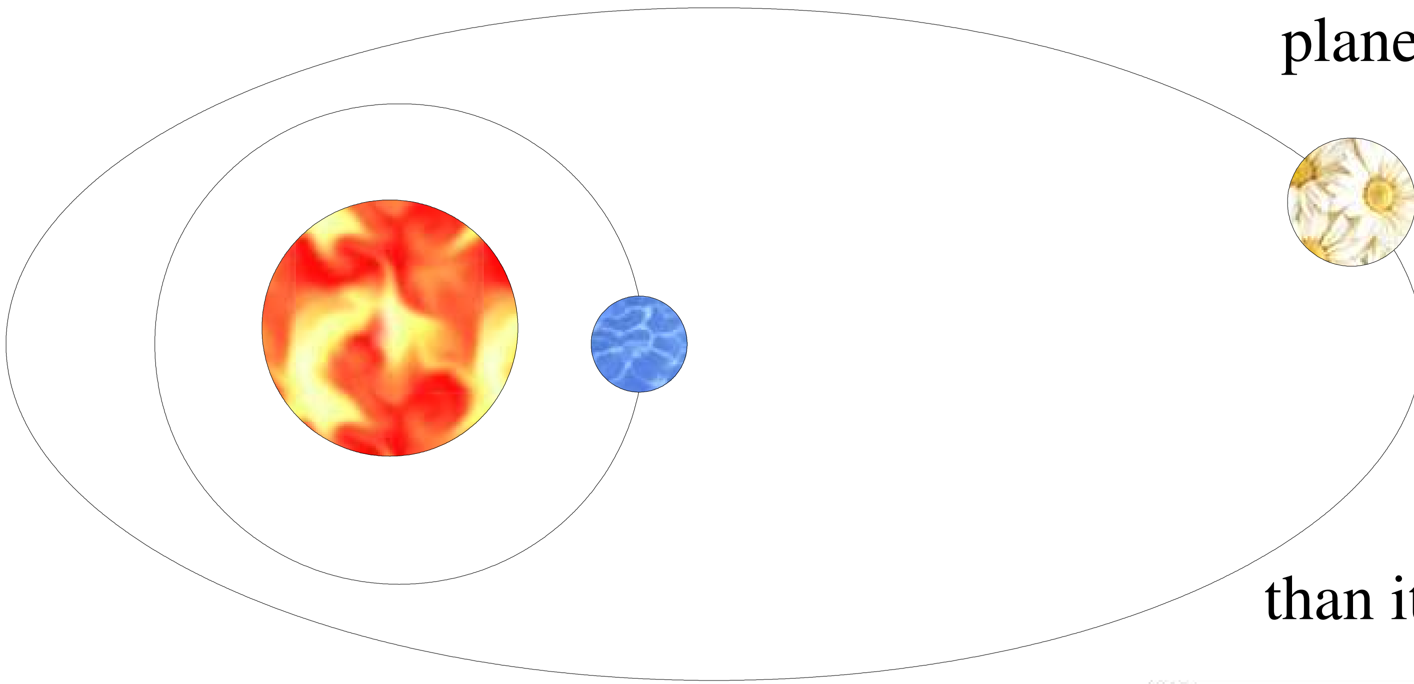
2:1 – semi-major axis ratio



Comparison with analytic model

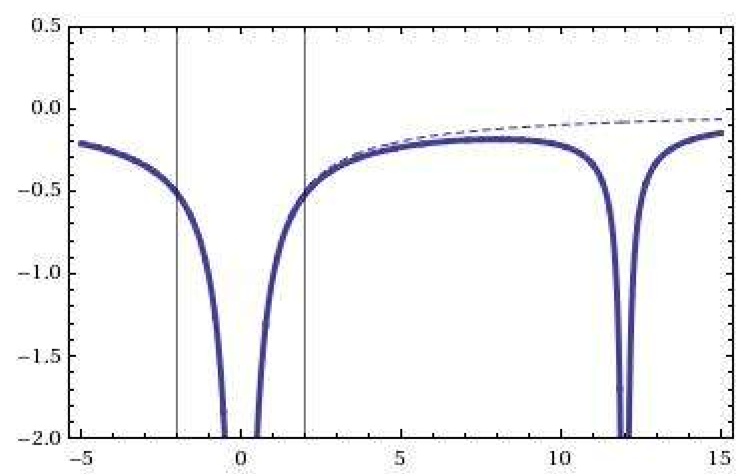


TTV – Weird Tidal Effect



Way out here the perturbing planet has little effect.

In fact, it is less than its average effect.



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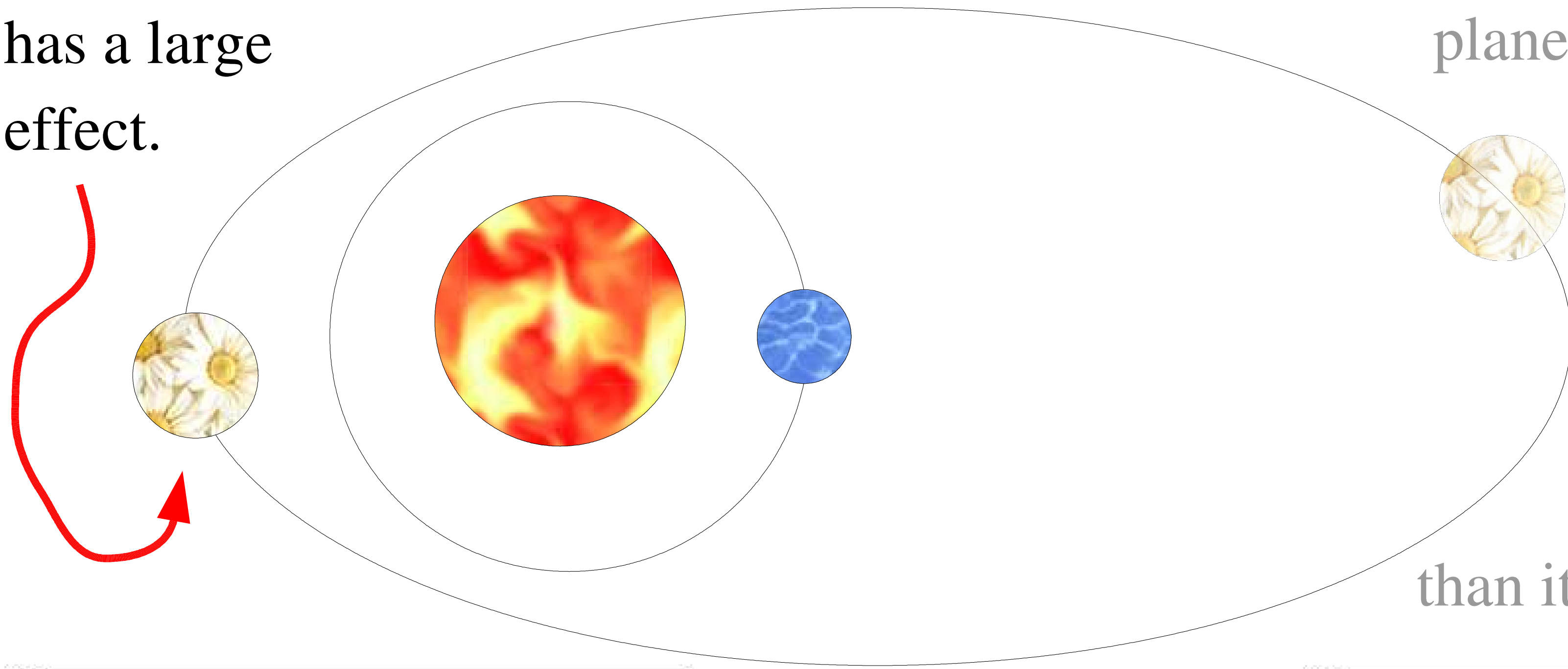

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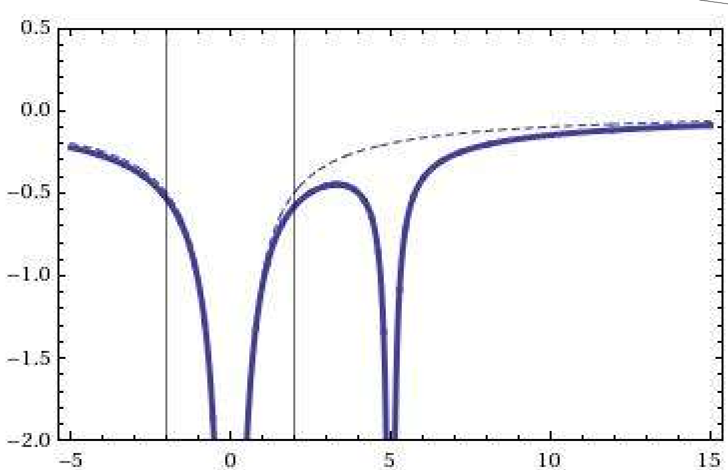

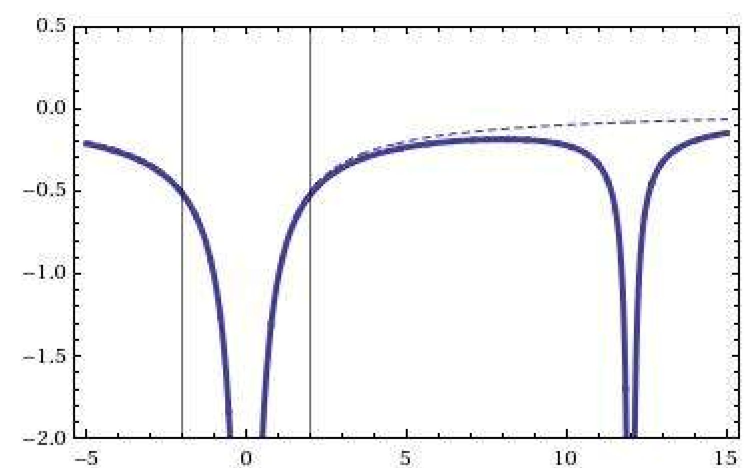

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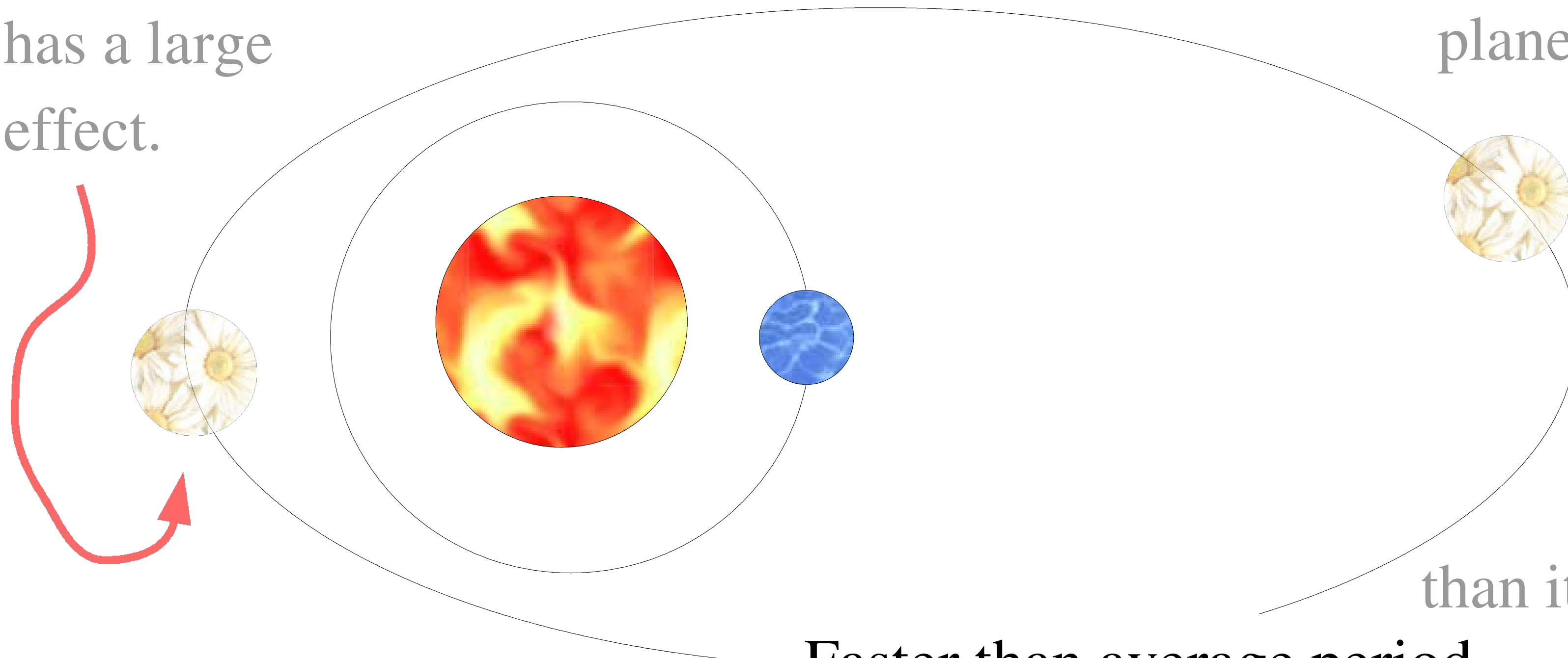

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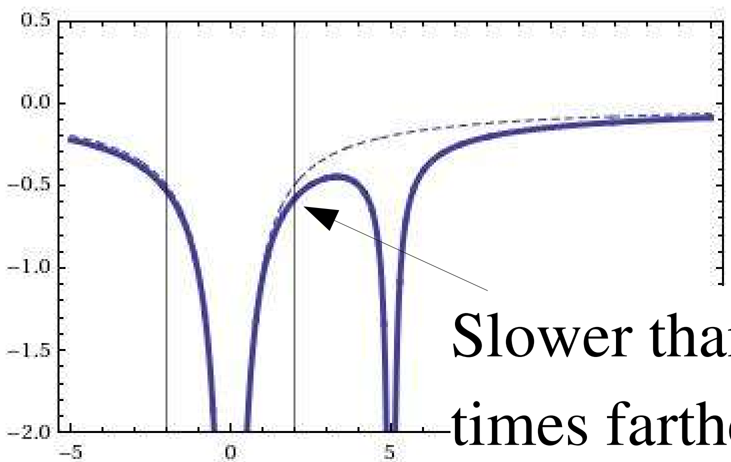
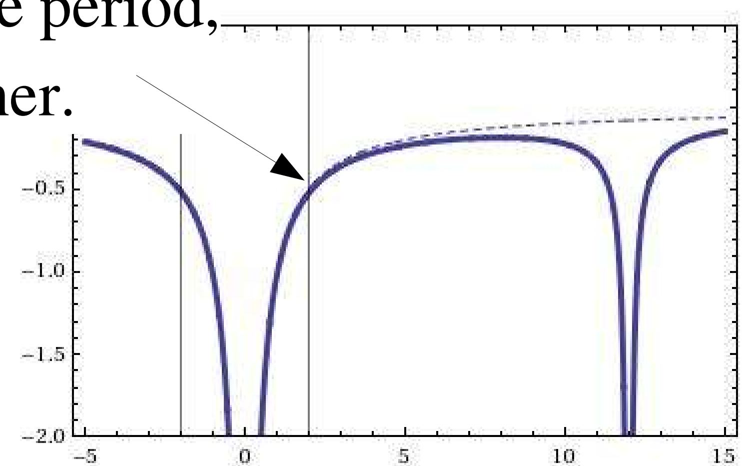
Faster than average period, times closer together.



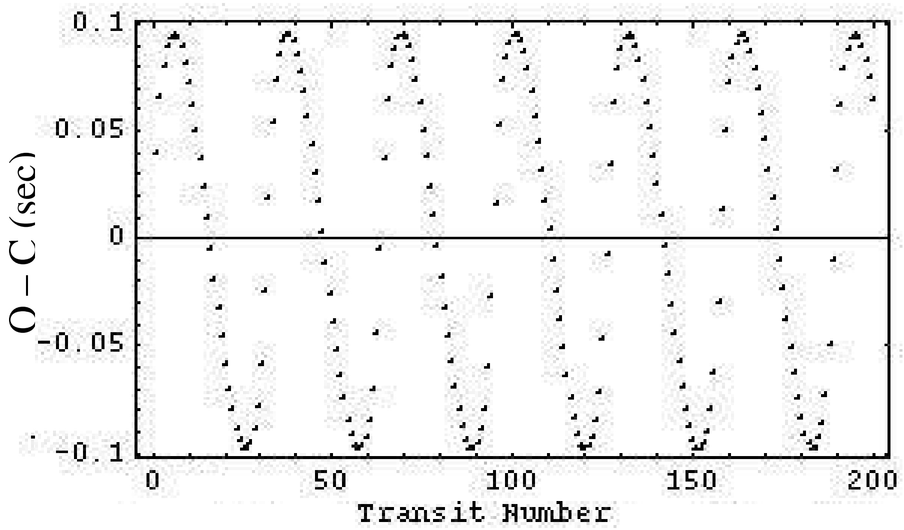
Slower than average period, times farther apart.



TTV – Weird Tidal Effect

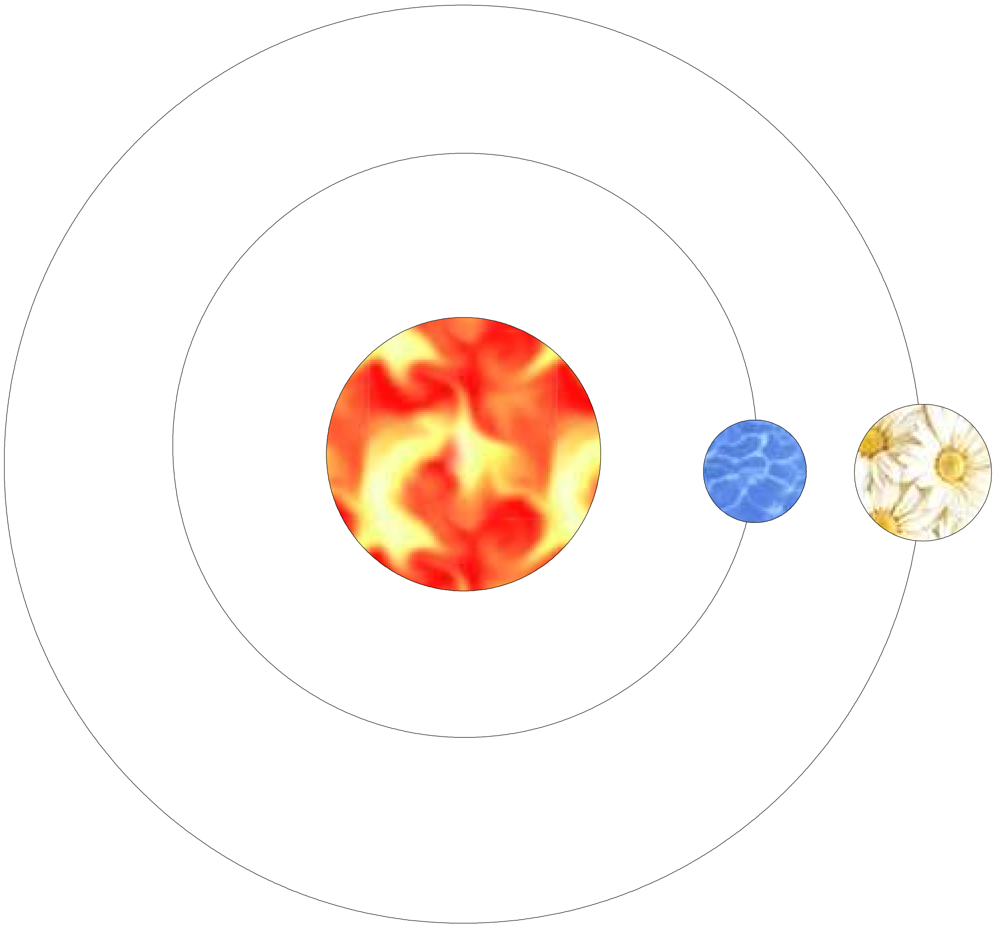
Sample signal for a non-resonant, 0.1 Jupiter-mass planet perturbing a Jupiter-mass planet that is on a 3-day orbit.

10:1 axis ratio, high eccentricity



$$\sigma_1 \sim e_2 P_2 \left(\frac{m_2}{m_0}\right) \left(\frac{a_1}{a_2}\right)^3$$

TTV – Resonant Planets



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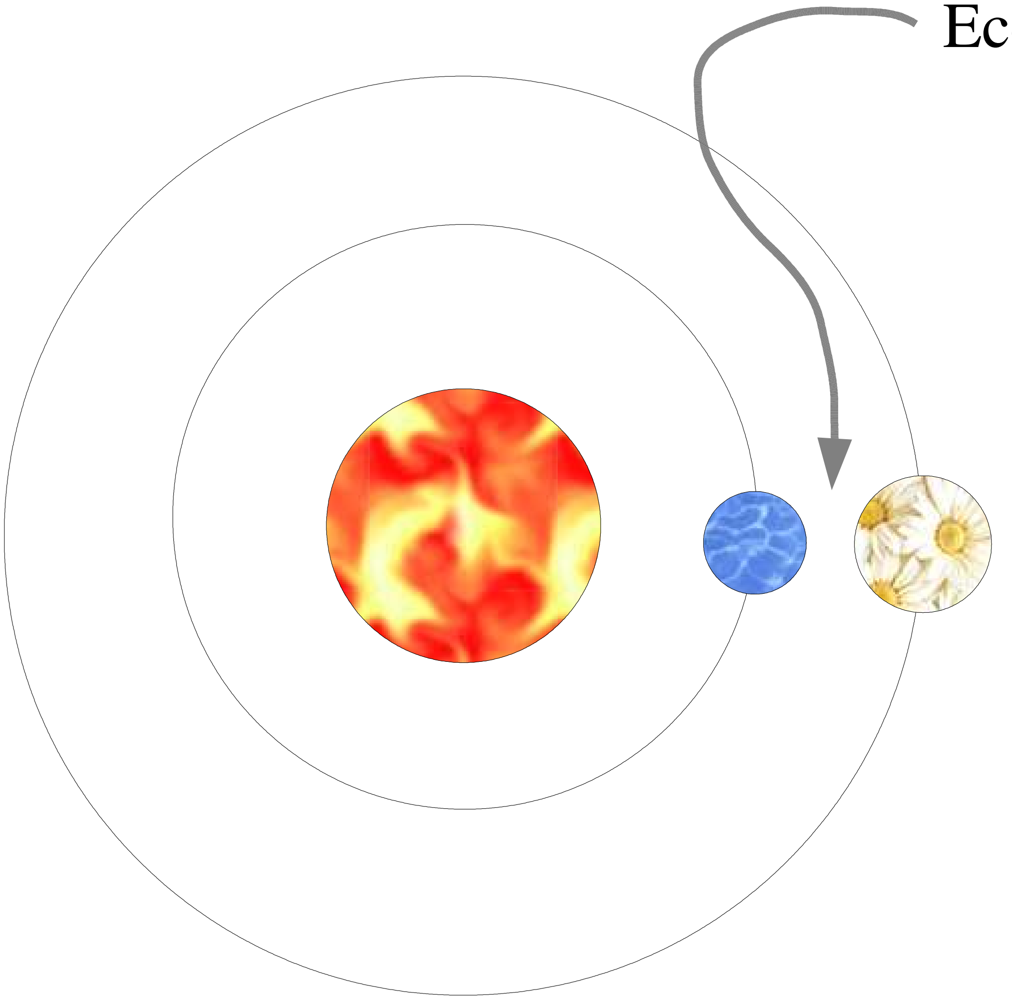
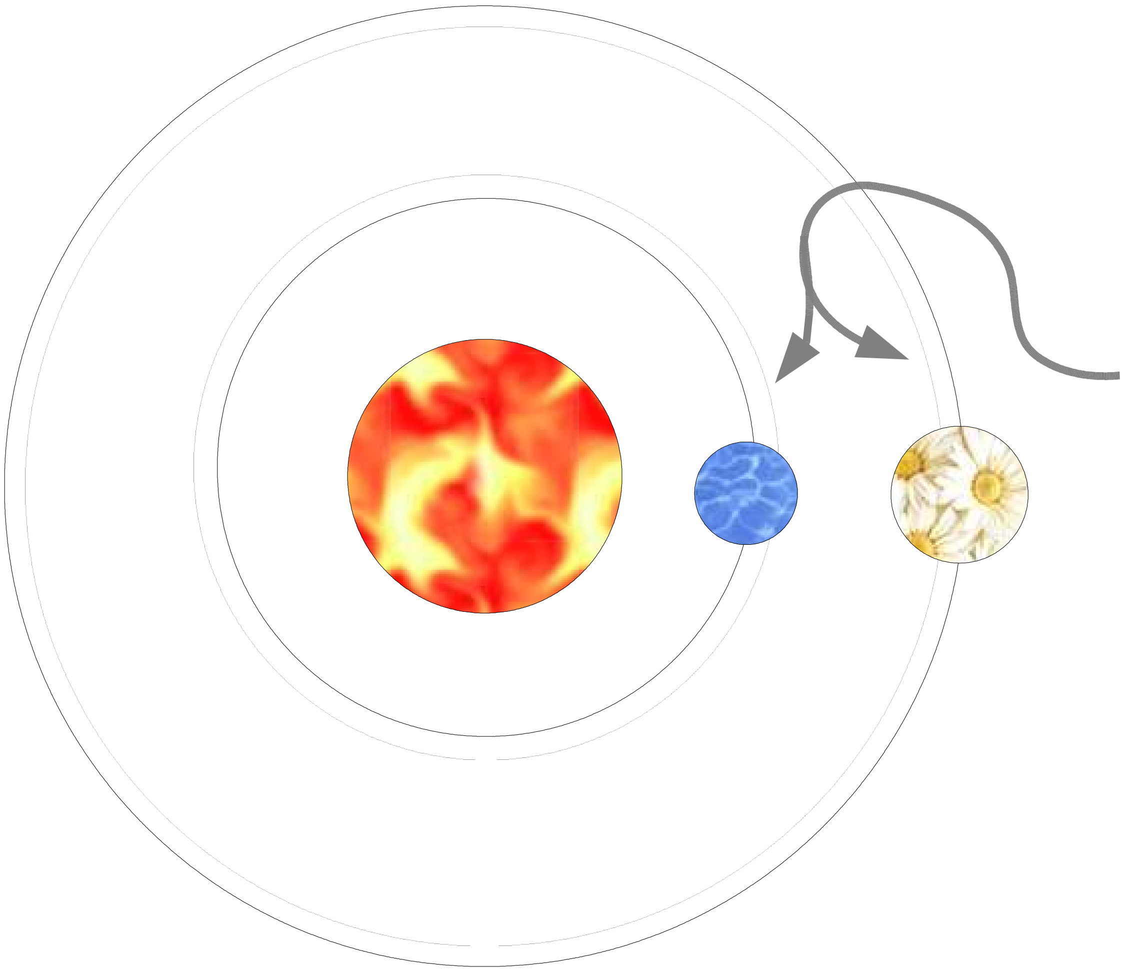


Eccentricity is induced at conjunction

TTV – Resonant Planets



Eccentricity is induced at conjunction

Eccentricity change causes period of each planet to change such that energy is conserved.

TTV – Resonant Planets

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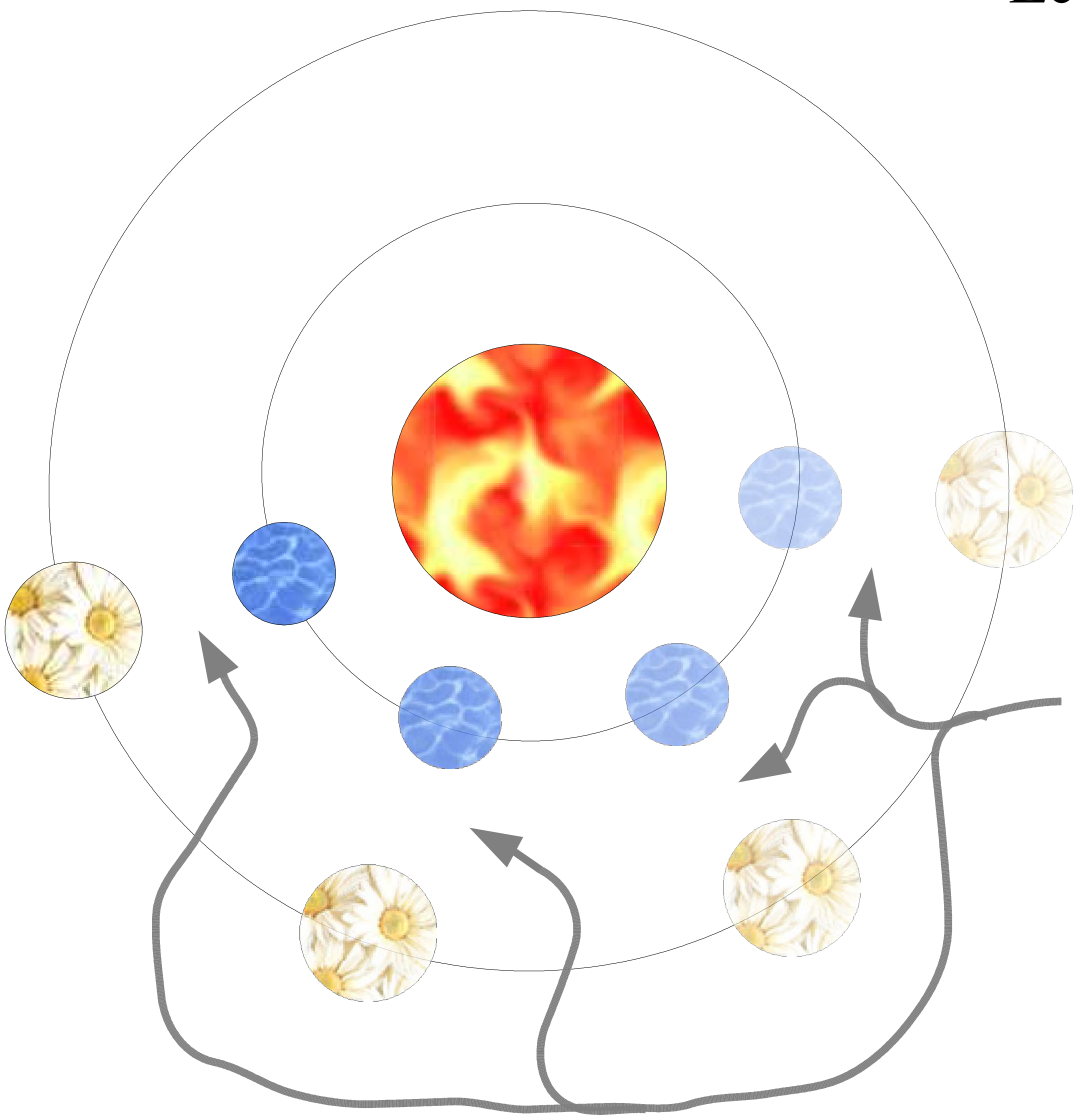
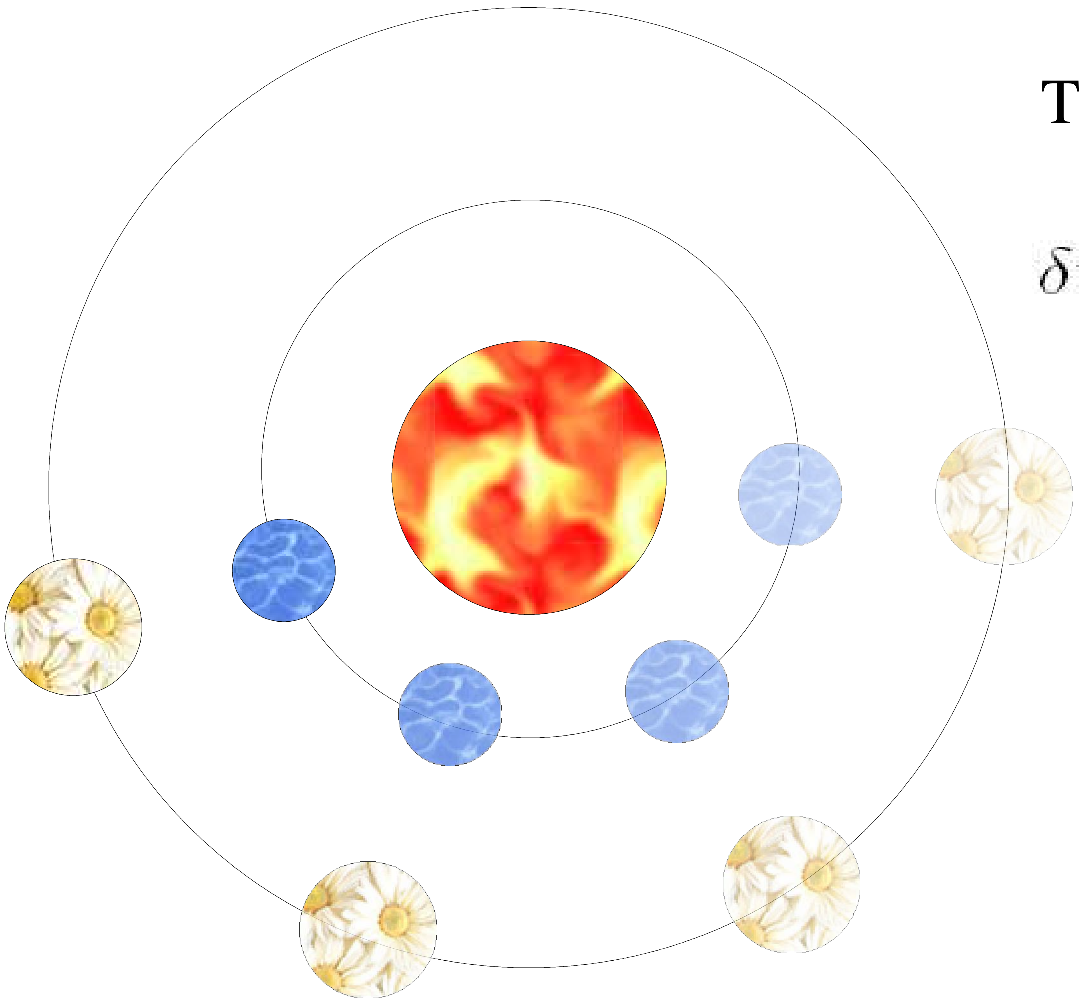


Eccentricity change causes period of each planet to change such that energy is conserved.

The longitude of the conjunction drifts until it reaches π relative to its initial longitude. Then it reverses.

TTV – Resonant Planets



The resulting libration causes TTV.

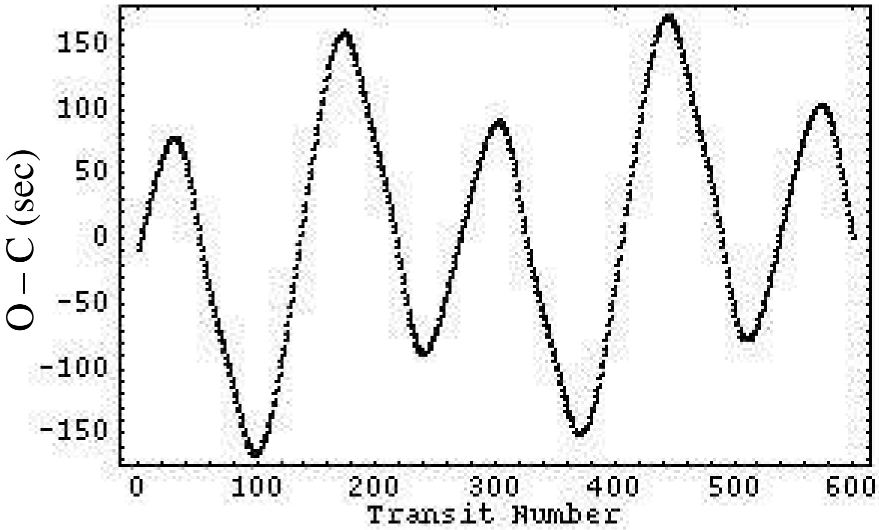
$$\delta t_{max} \sim \frac{P}{4.5j} \frac{m_{pert}}{m_{pert} + m_{trans}}$$

Mass dependence corresponds to large increase in the size of the signal compared to non-resonant case.

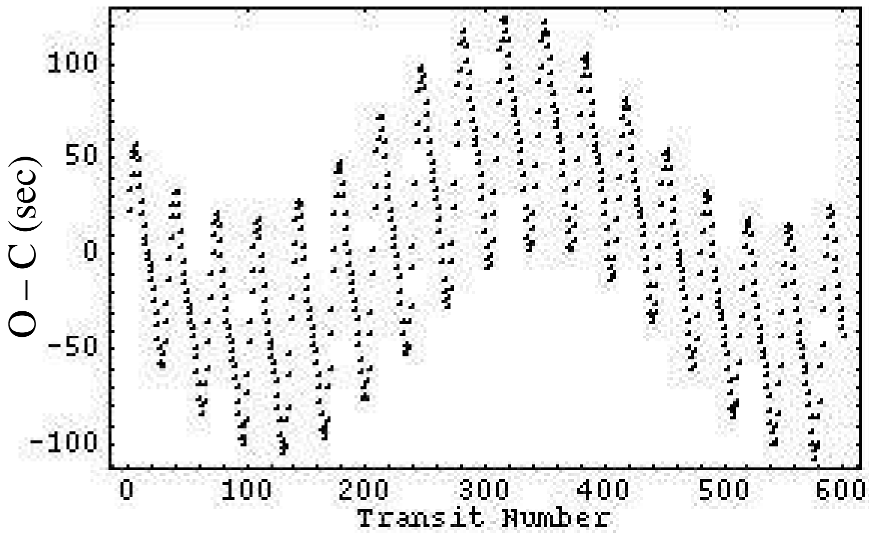
TTV – Resonant Planets

Sample signal for a resonant, Earth-mass planet perturbing a Jupiter-mass planet that is on a 3-day orbit.

2:1 – low eccentricity

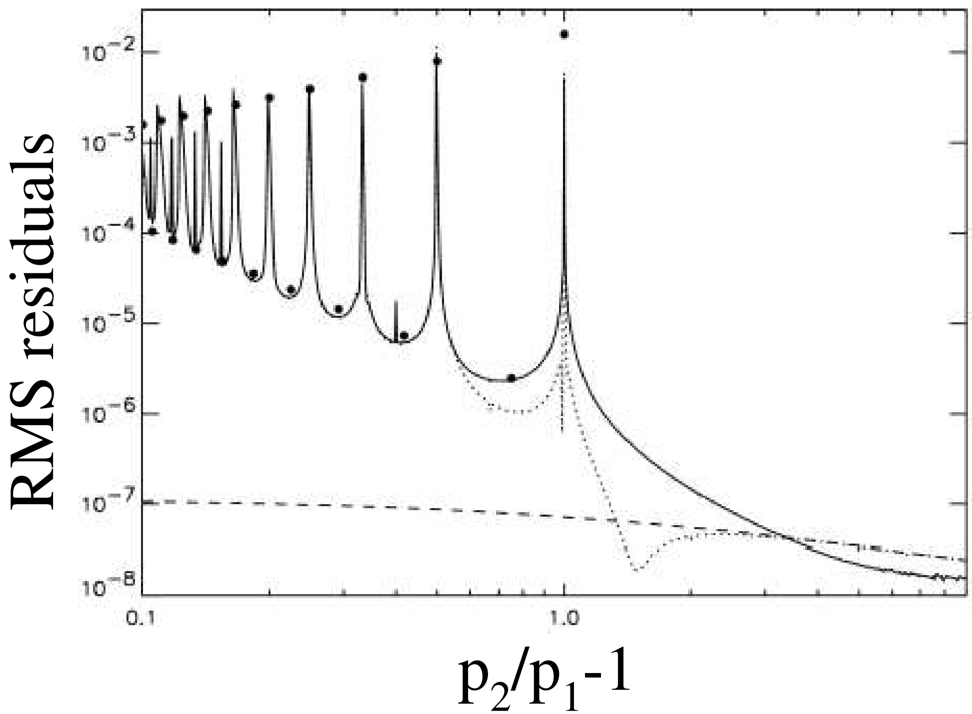


2:1 – high eccentricity

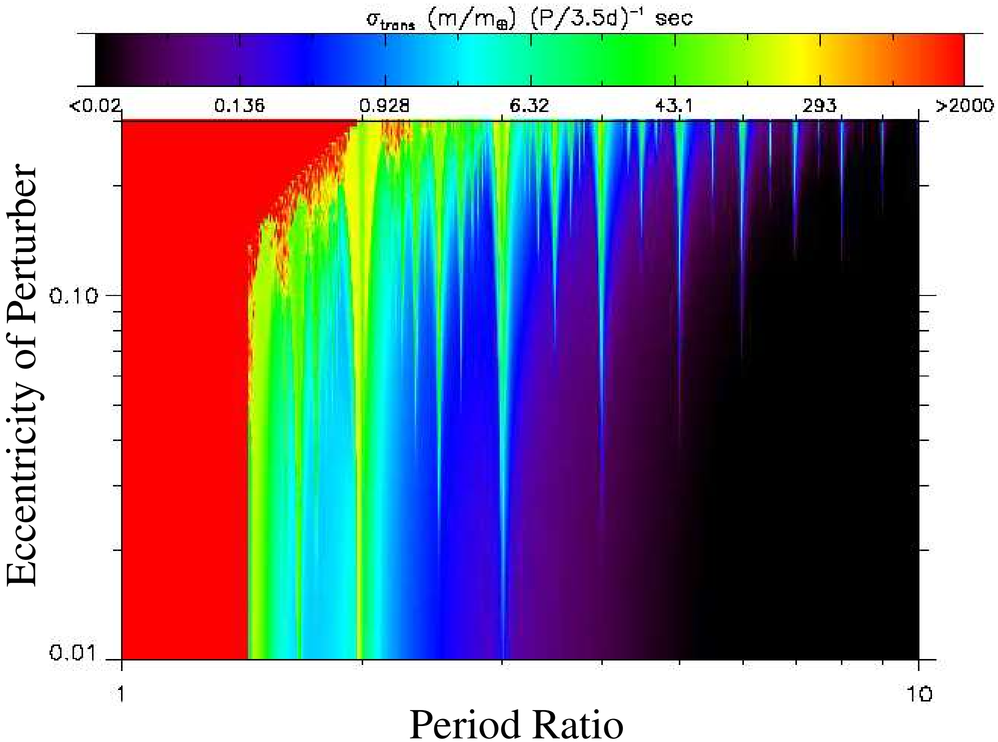


Transit Timing Variations

Comparison of Analytic and Numerical Results



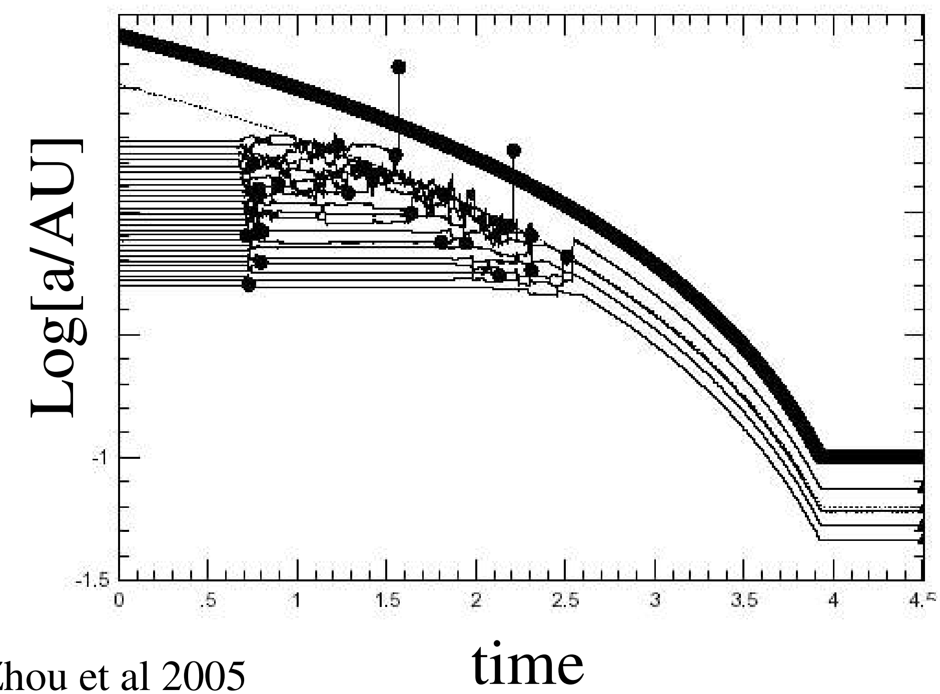
TTV with Eccentricity



Signal increases with period of the transiting planet, the mass of the perturber, and the proximity to mean-motion resonance.

Image from Agol et al 2005

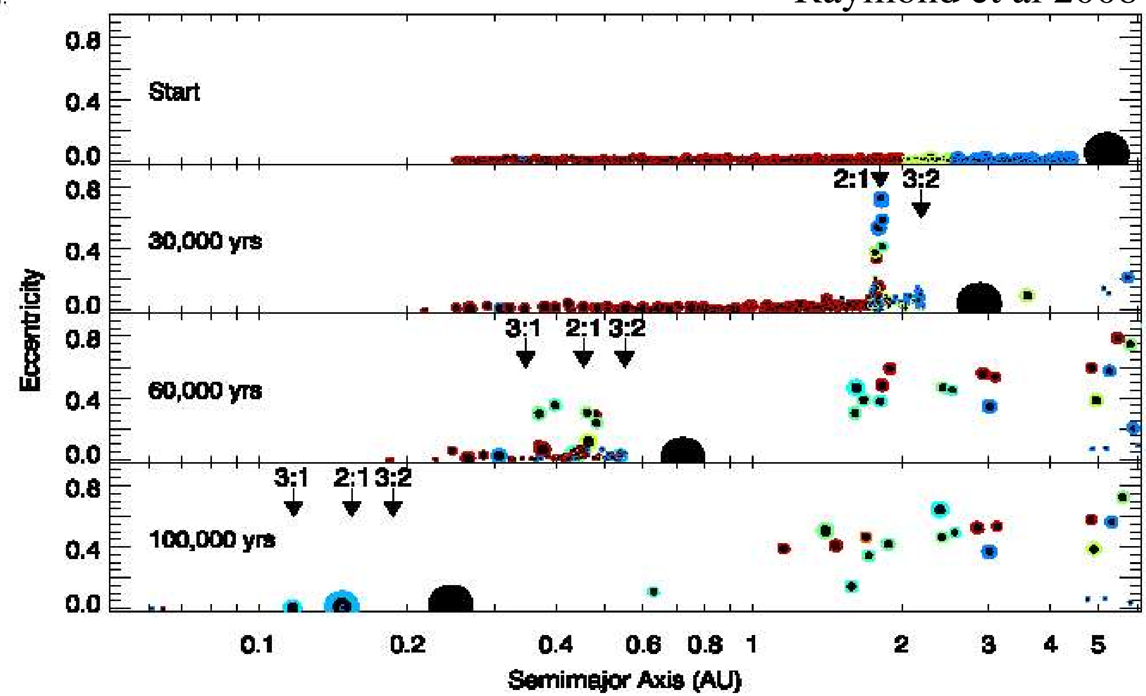
Prospects for Resonant Systems



Zhou et al 2005

As a giant planet migrates inwards it can shepherd planetesimals into resonant orbits.

Raymond et al 2008



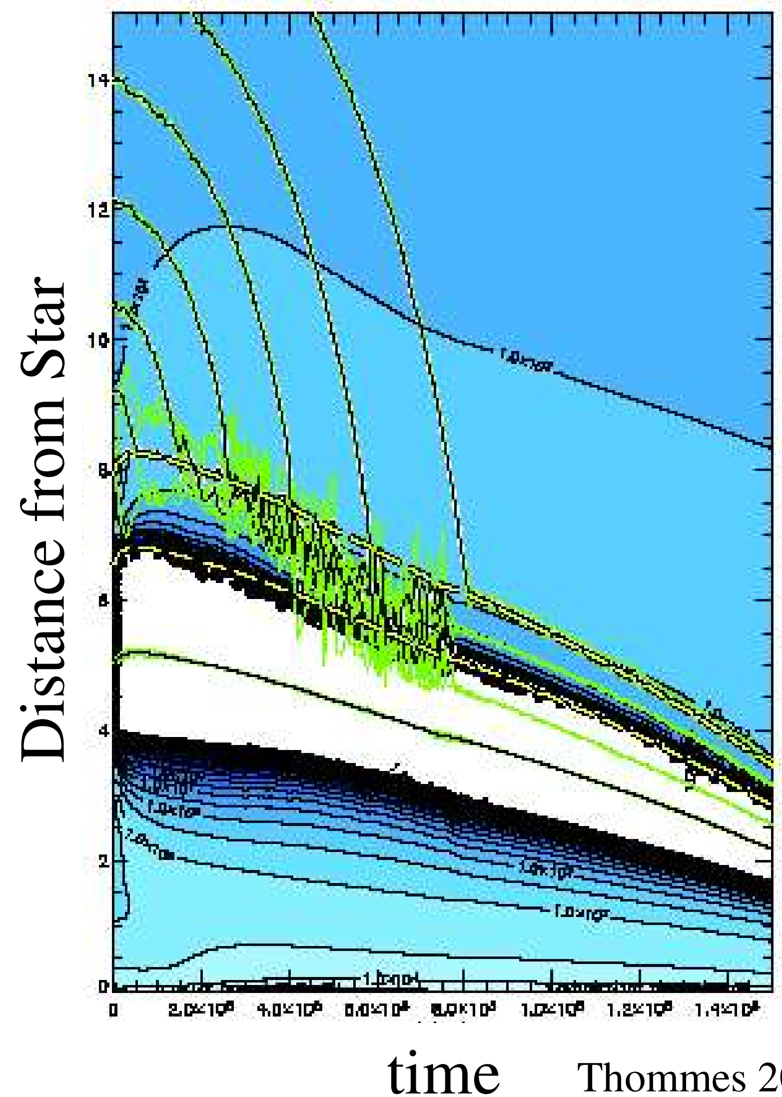
This is precisely the regime where TTV is best suited to probe.

Prospects for Resonant Systems

- Planetesimals that are exterior to the giant planet may interact with the gas disk and fall inwards.

- These planetesimals become trapped in exterior mean-motion resonances.

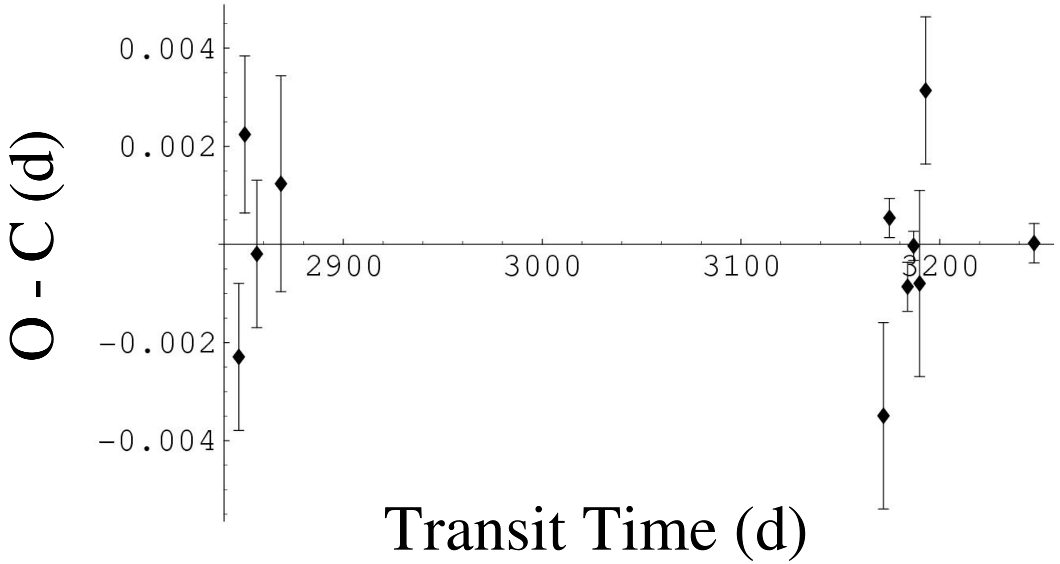
- Their final resting place is determined by the lifetime of the gas disk.



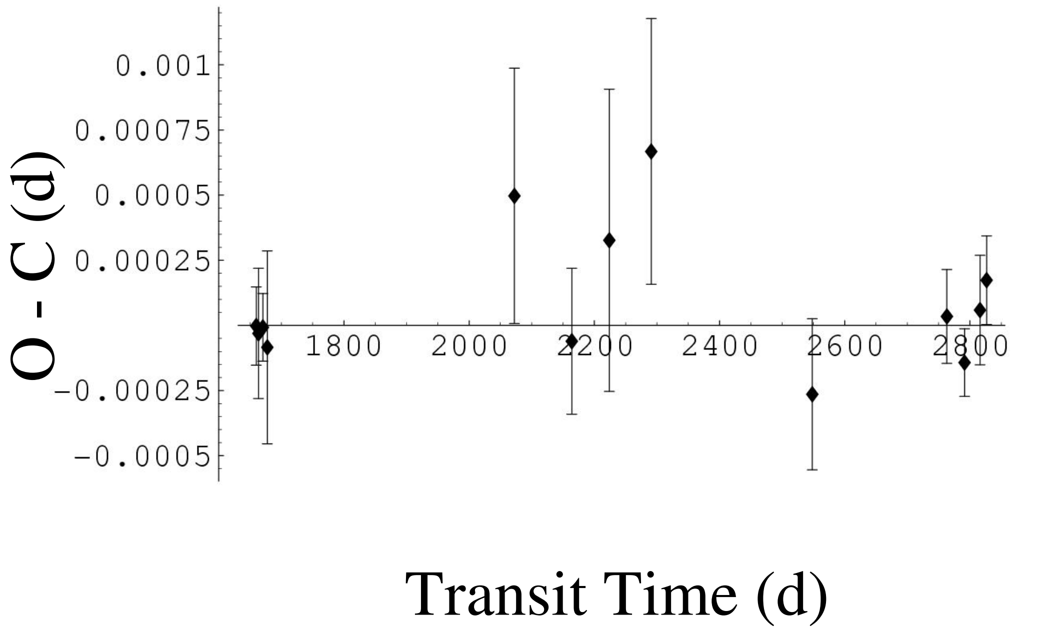
Thommes 2005

Analyzing Real Data, Part 1

TrES-1 system
(Ground Based)

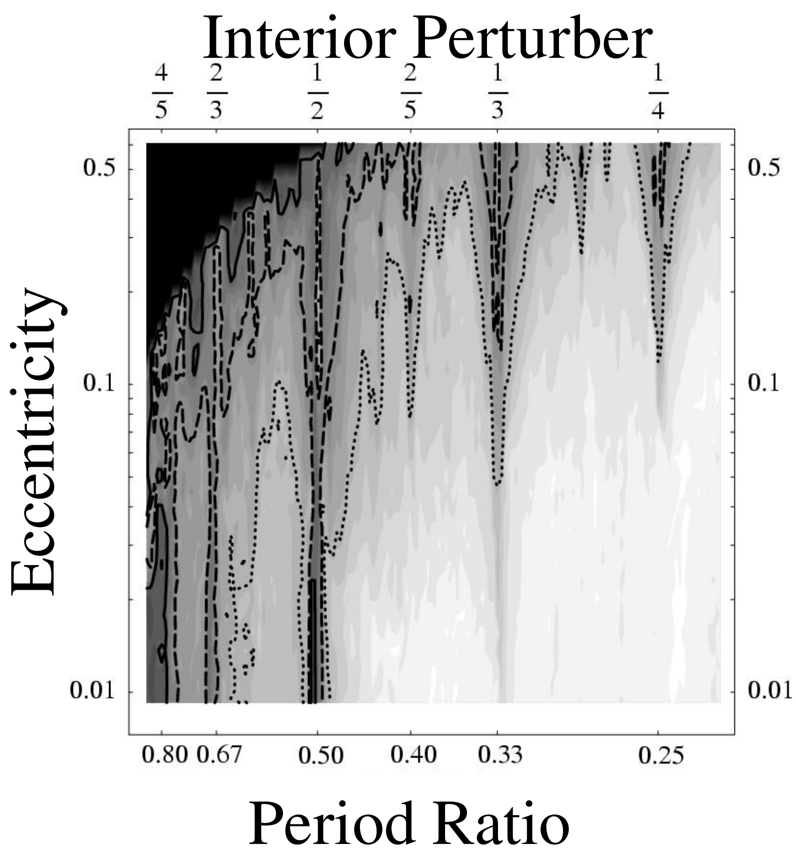


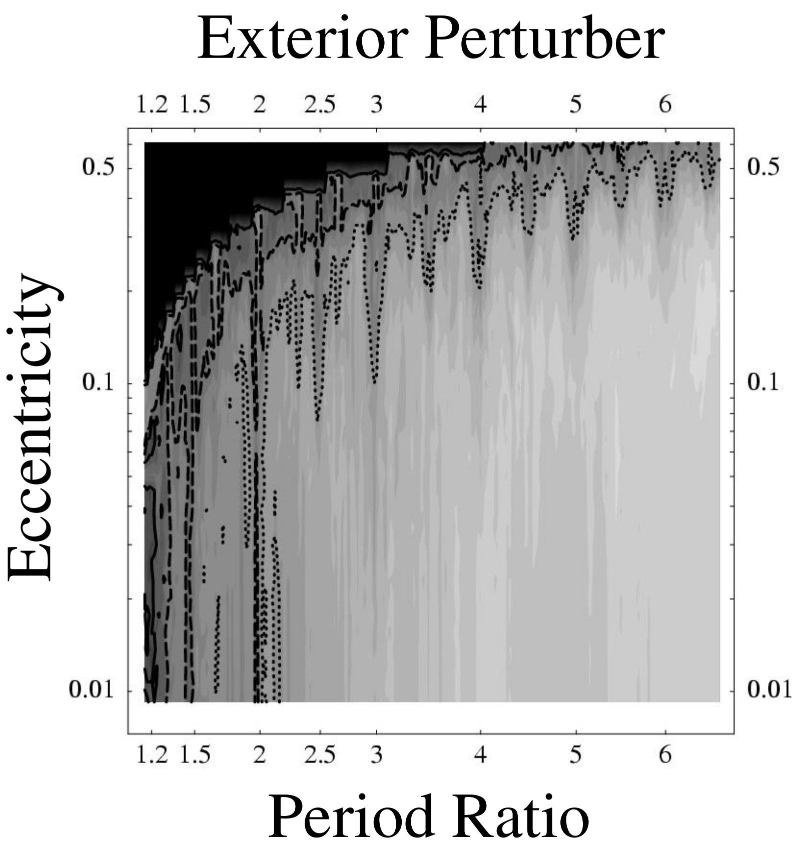
HD 209458 system
(HST)



The TrES-1 System

Constraints on the Mass of a Secondary Planet





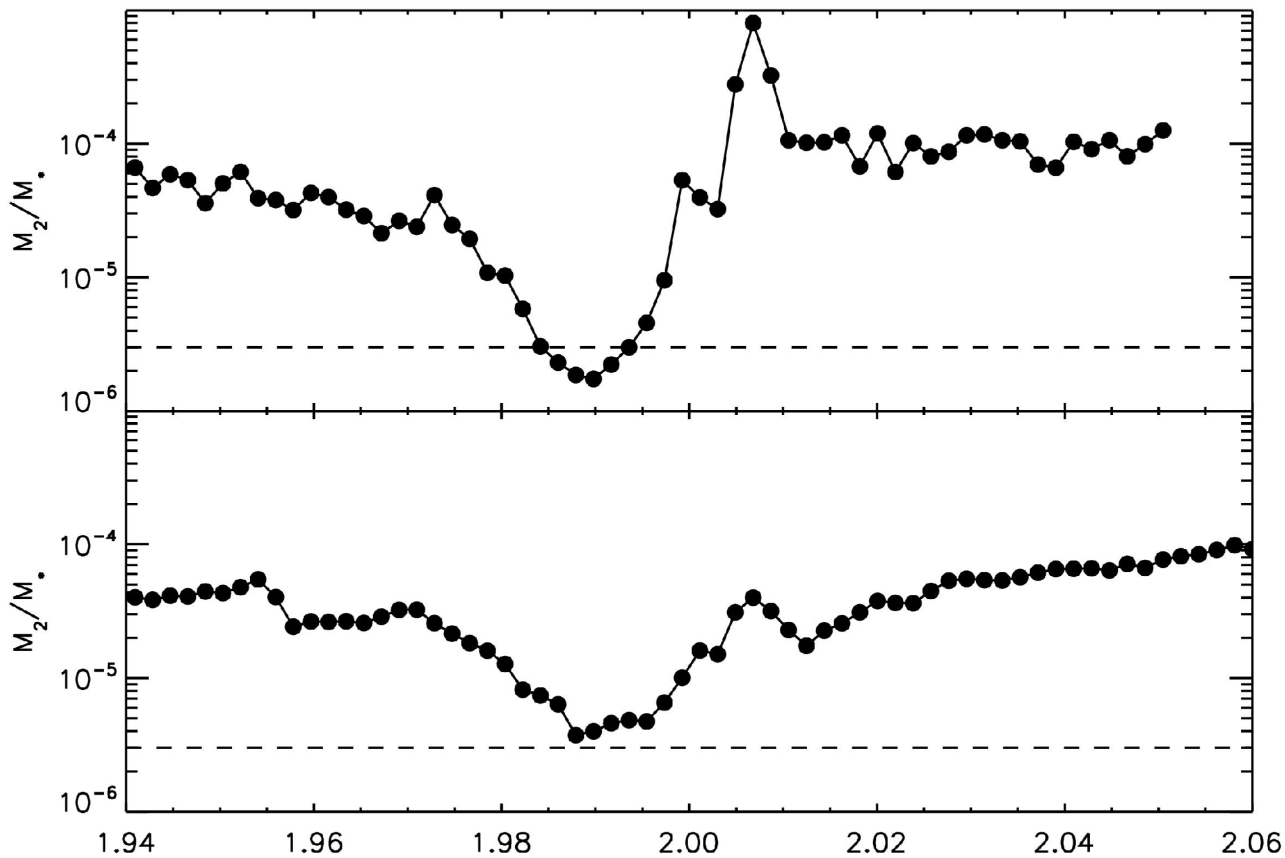
Contours: 100, 10, and 1 Earth mass

The HD 209458 System

Maximum allowed mass of companion
in 2:1 resonance with any eccentricity

Interior Perturber

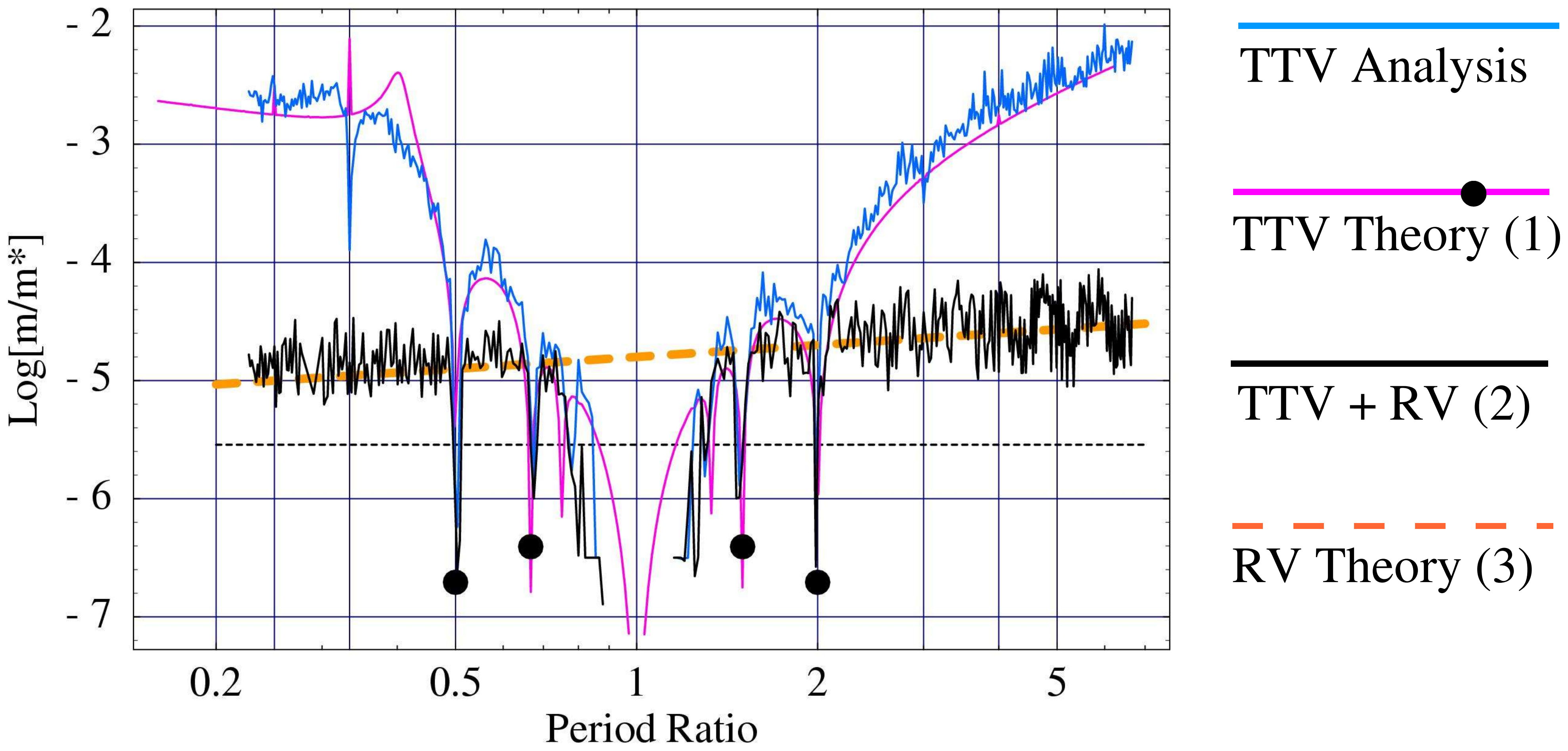
Exterior Perturber



Period Ratio

The HD 209458 System

Maximum allowed mass for companion in initially circular orbit



(1) Eqns. (A7-8) & (33) from Agol, Steffen, Sari, & Clarkson MNRAS 359, 567 (2005)

(2) RV measurements from Laughlin et al. ApJ 629, L121 (2005)

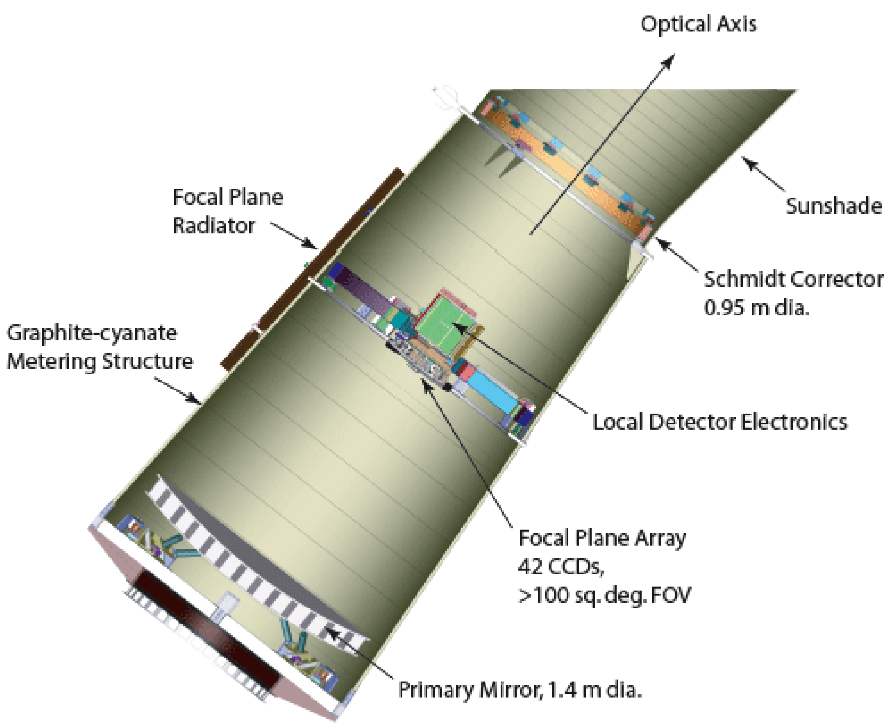
(3) Eqn. (2) from Steffen & Agol MNRAS 364, L96 (2005)

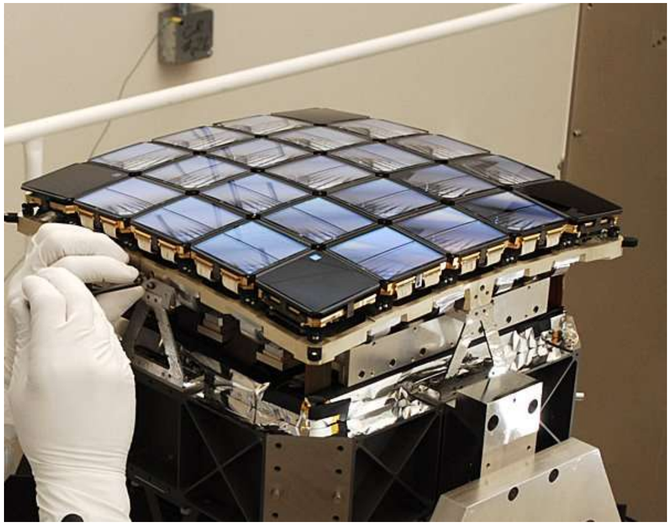
The Future of TTV

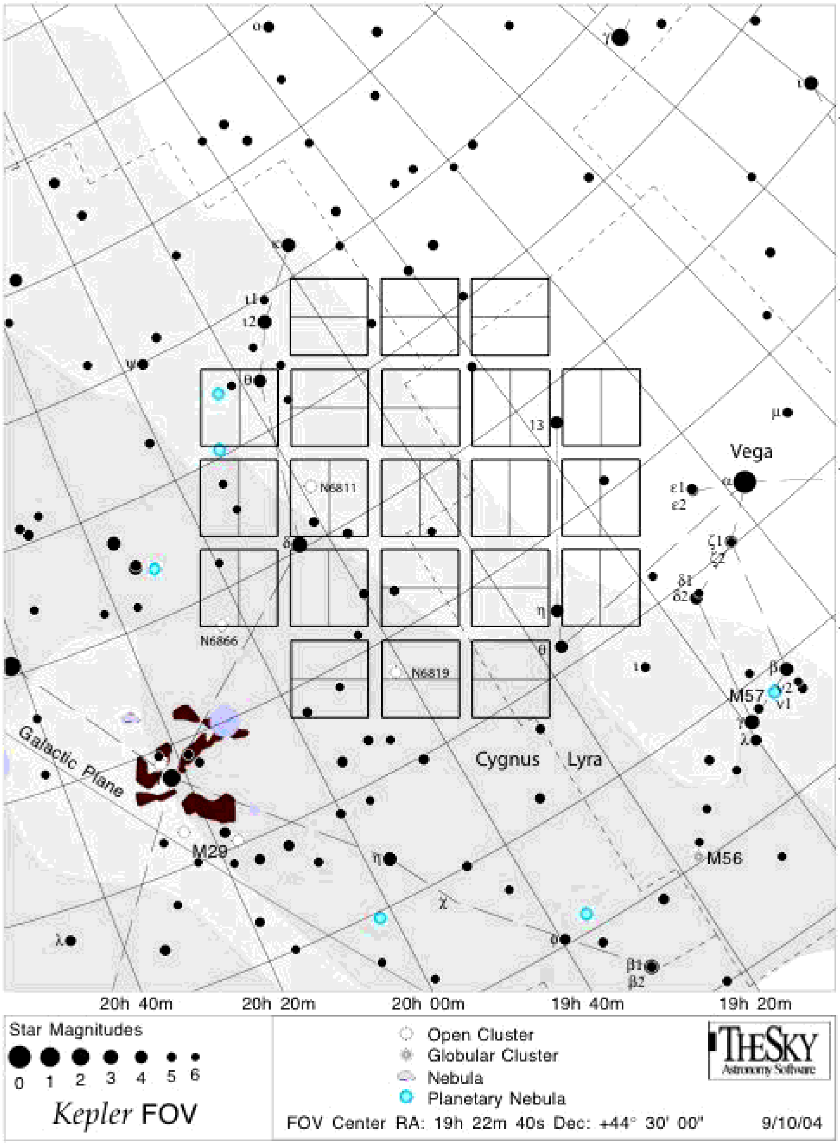
NASA's
Kepler
Mission

Launch
Scheduled
March 5
2009

The Future of TTV







The Future of TTV

Some Kepler Particulars

- Continuously* monitor ~120,000 stars for 3.5 years.
- Expect to detect ~ (few)x100 planets in various orbits.
- Timing precision as good as 2-3 seconds.
- No gaps in coverage.

Advantages of TTV Analysis

- Detect planets with masses smaller than the moon
- Detect non-transiting planets that orbit in the habitable zone
- Determine mass of stars without using stellar models
- Study tidal evolution models for short-period systems
- Constrain planet formation and evolution models

Inferring Orbital Elements

Some “Opportunities” Exist

- Large parameter space (at least 14 parameters)
- Highly nonlinear optimization problem
- Multiple local minima
  - Very narrow near resonances
  - Widely separated
- Each iteration requires high-accuracy integration of the 3-body problem
- Even small changes in initial condition can cause large differences in dynamics
- Confusion from systematic effects

Opportunity 1: Godzillaflops

- Need to calculate transit times for millions of systems to high accuracy (1e-13 or better)
- Requires single processors but minimal interface with the file system
- Algorithm has frequent “checkpoints” where existing work can be saved

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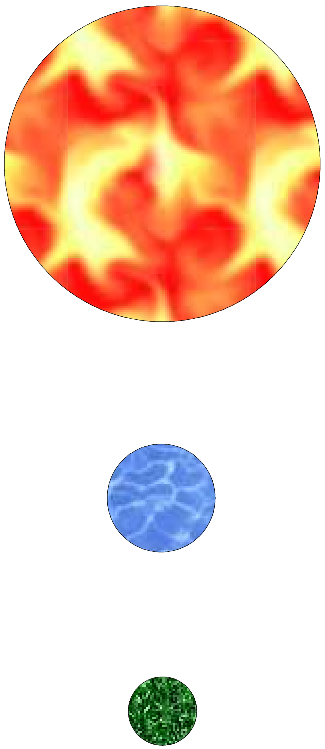
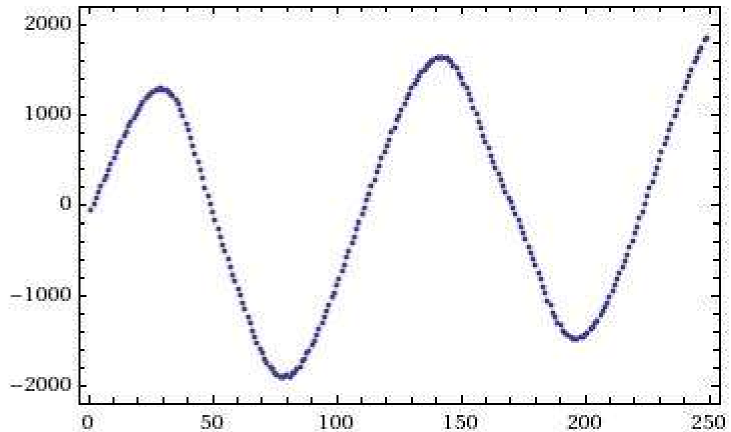
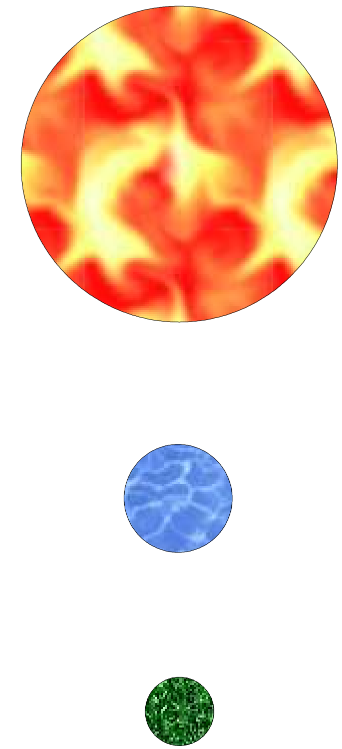
- Requires single processors but minimal interface with the file system
- Algorithm has frequent “checkpoints” where existing work can be saved
- Really could use a network of processors where I could submit lots of individual jobs...

Opportunity 2: Bonus Planets

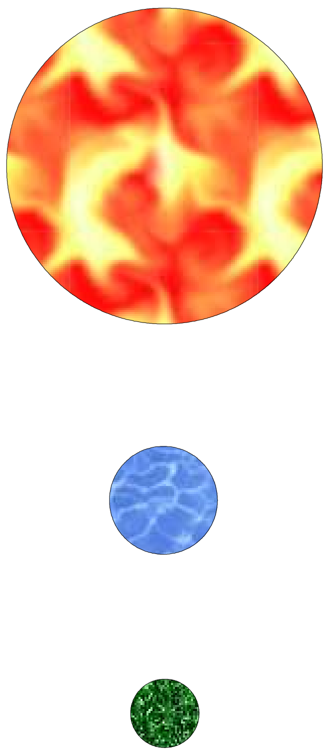


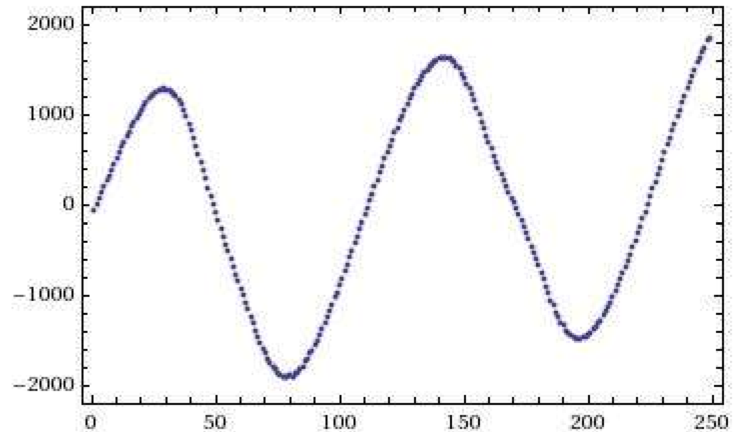


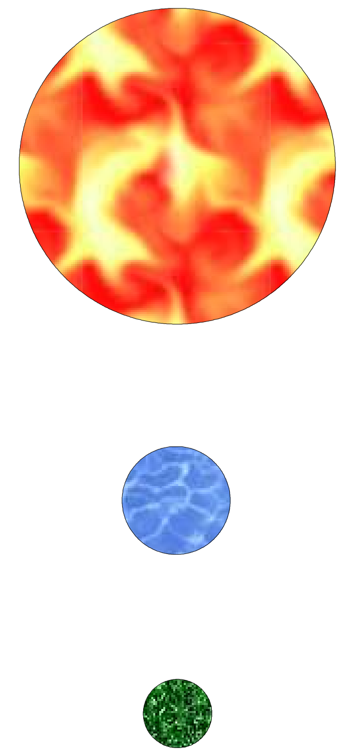


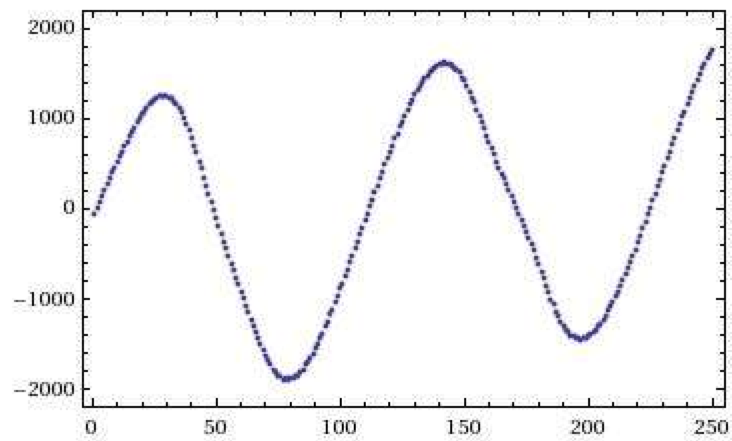
No bonus planet, no complications.

Opportunity 2: Bonus Planets



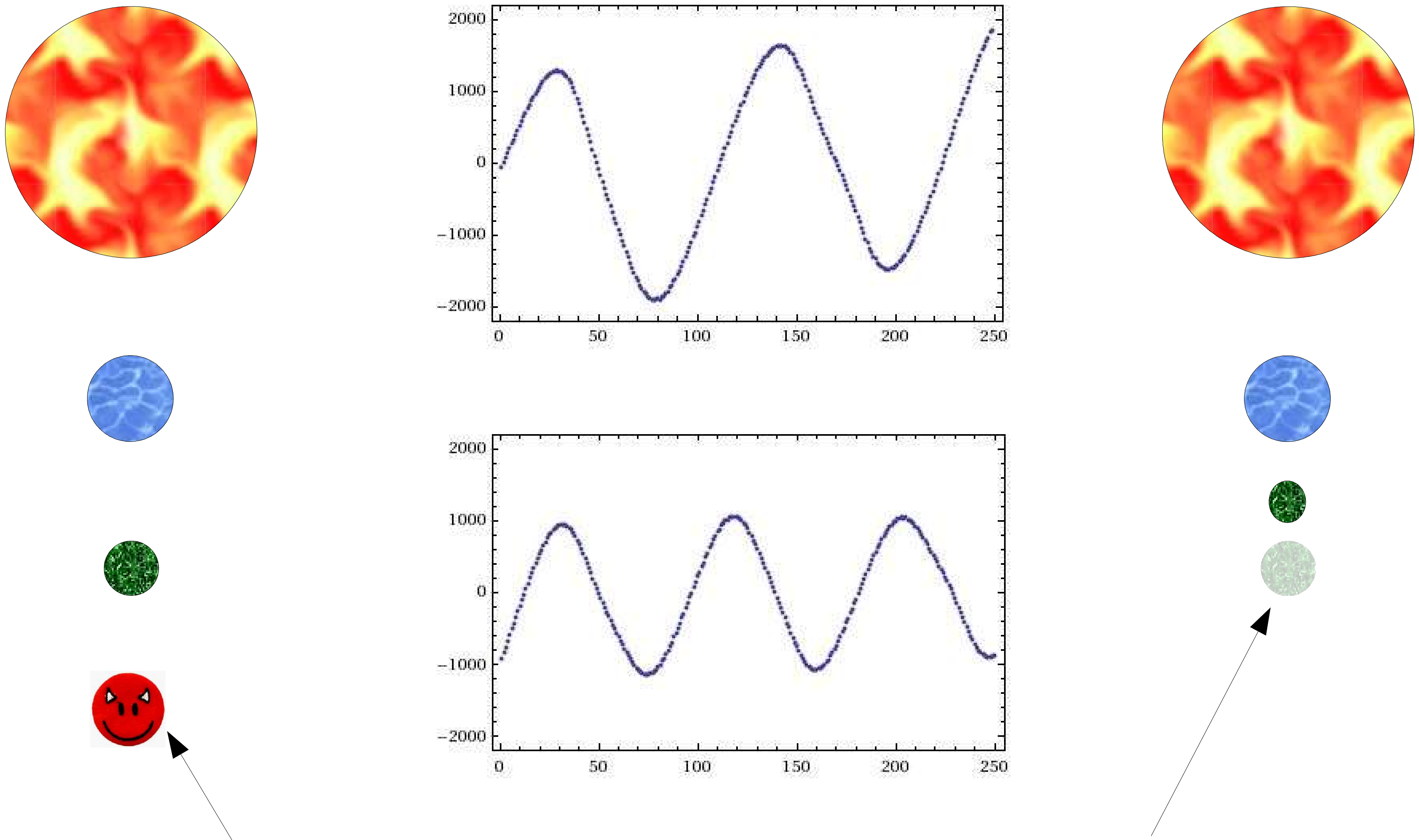






Friendly bonus planet, no complications.

Opportunity 2: Bonus Planets



Unfriendly bonus planet, big complications.

Opportunity 2: Bonus Planets

It appears as though this is only a problem when:

- The TTV signals from the two individual planets are comparable

- There are strong (i.e. resonant) interactions among all of the planets.

Other signatures, particularly Radial Velocity measurements, can help disentangle the effects of bonus planets.

Opportunity 3: Many Parameters

Coming to grips with a large, unruly parameter space...

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Things to Ignore

Opportunity 3: Many Parameters

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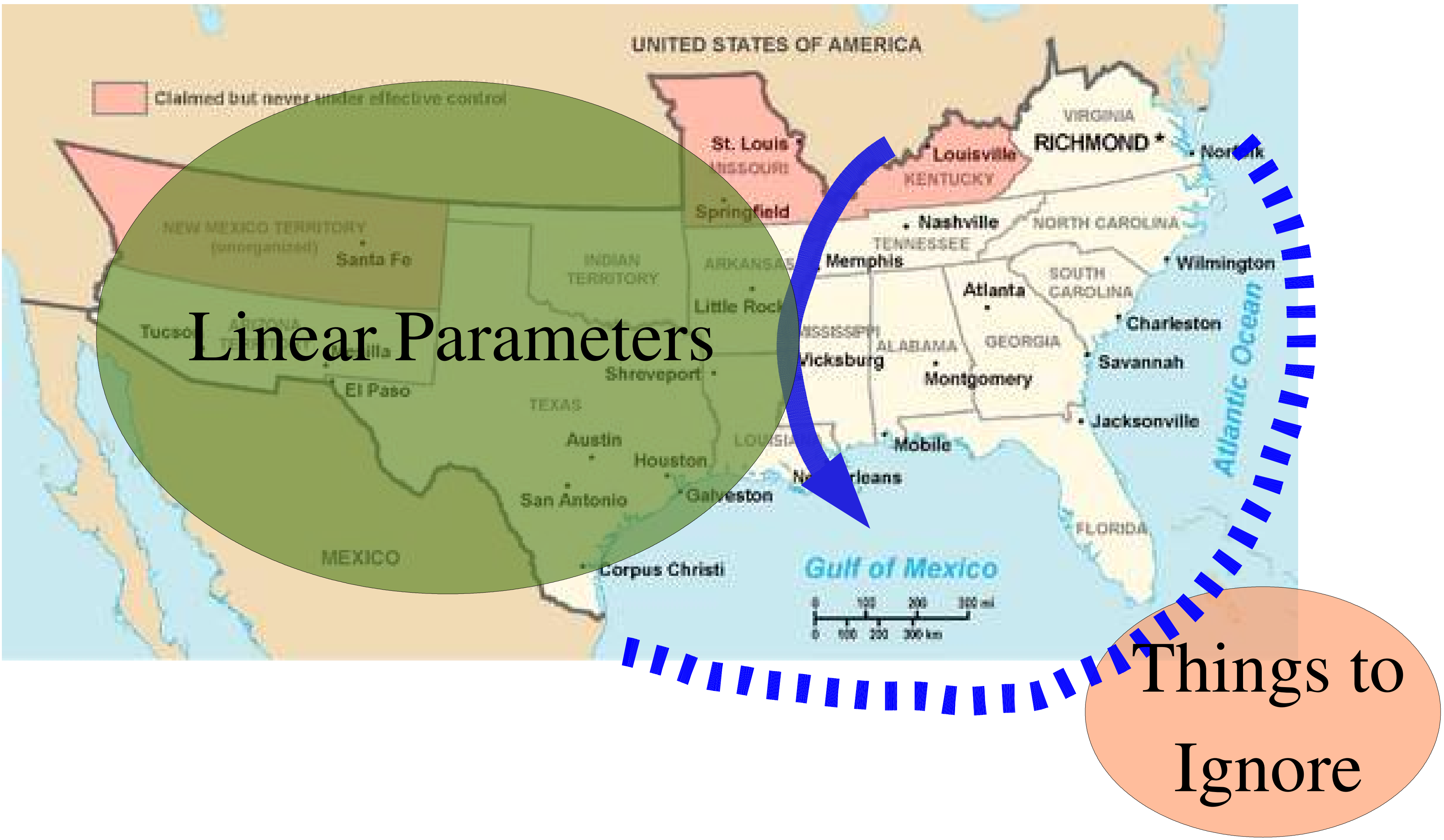

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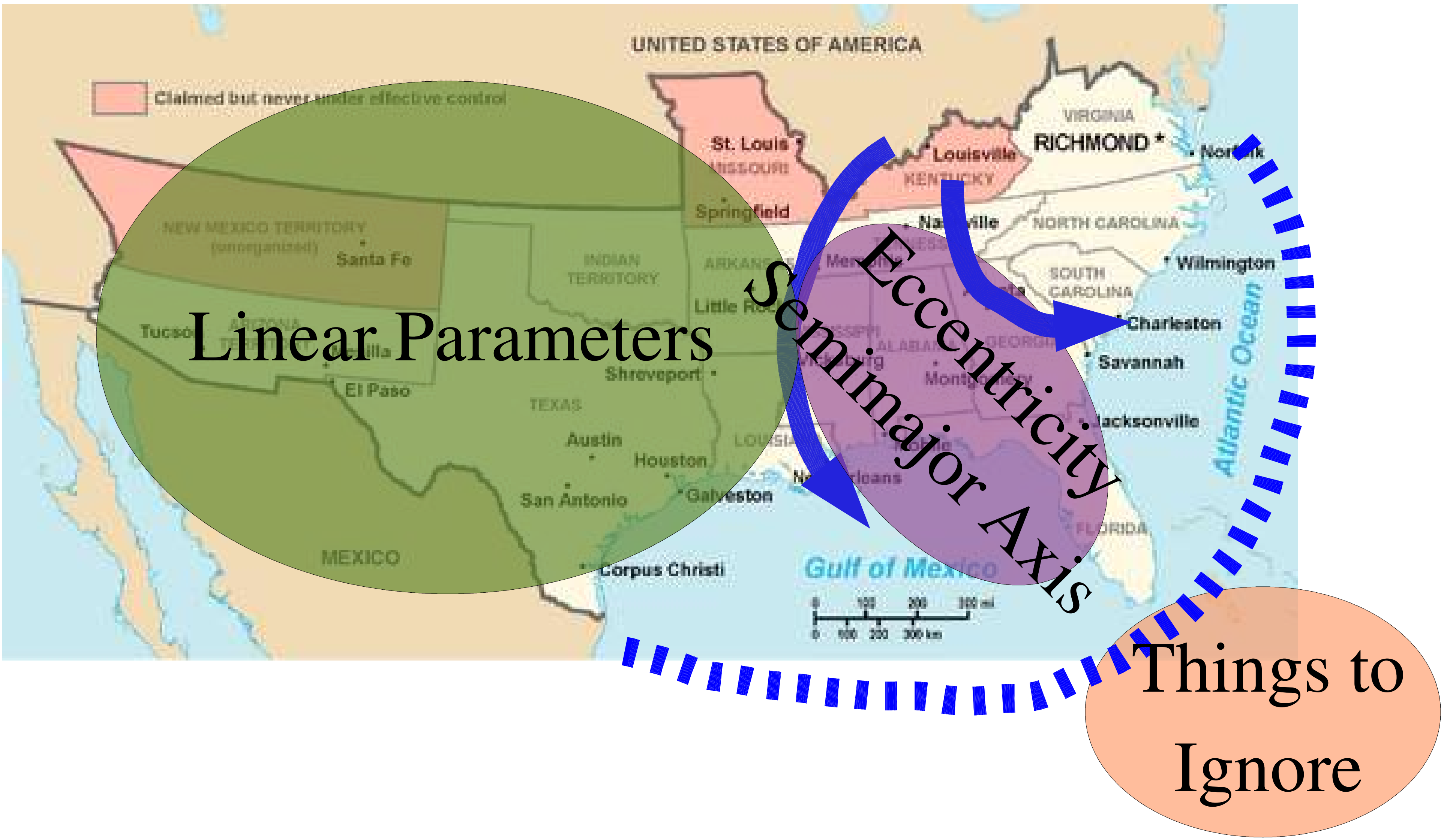

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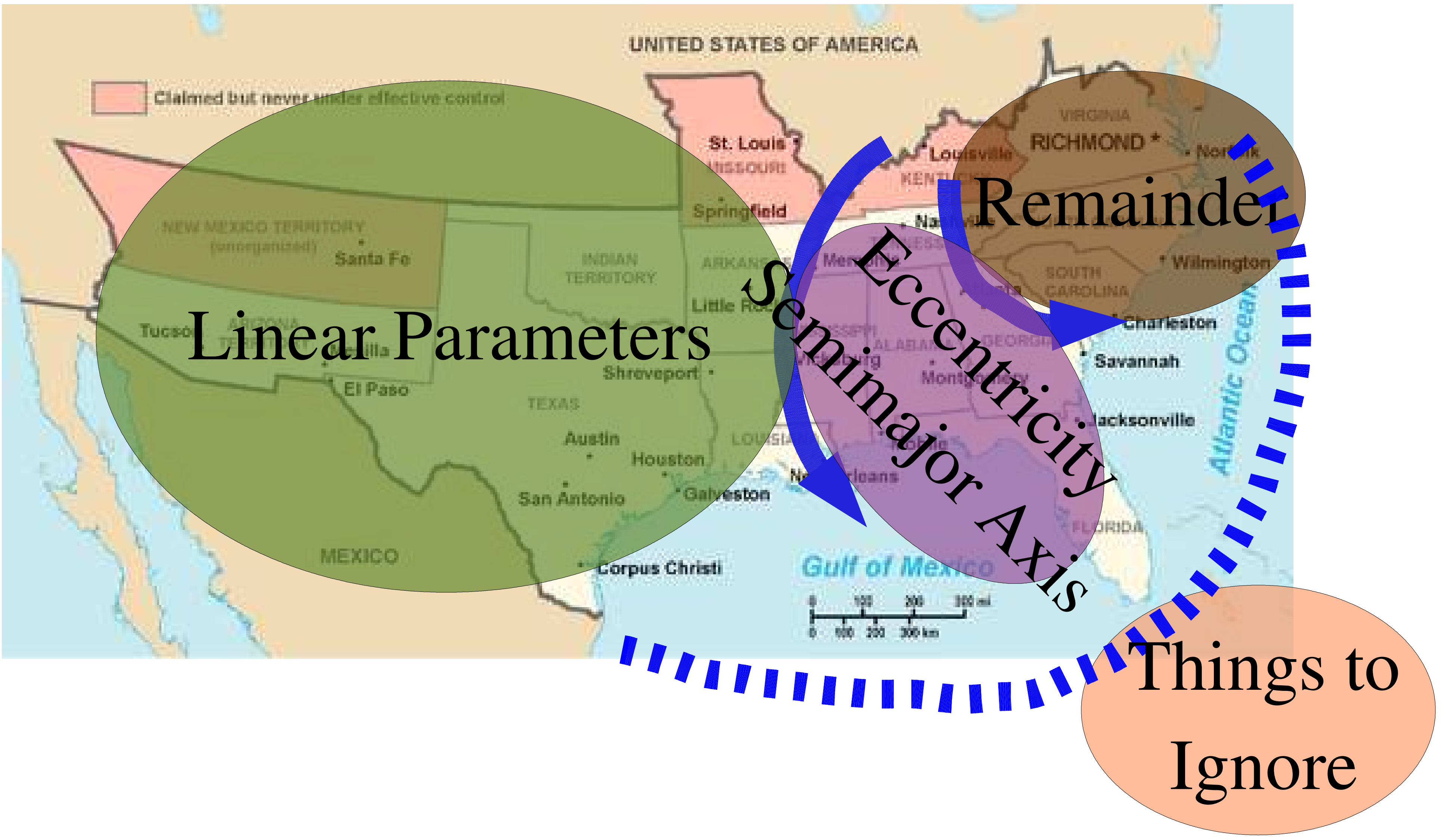


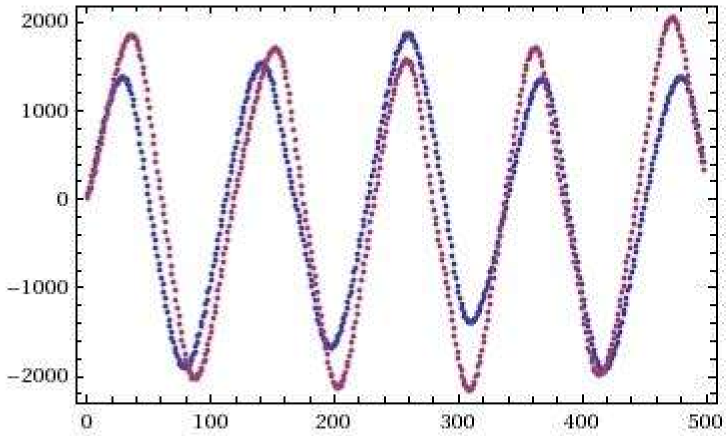
Opportunity 3: Many Parameters

Things to Ignore

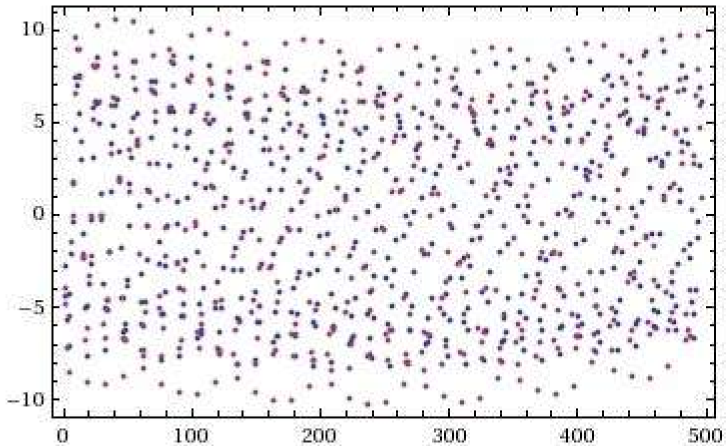
- If the effect of mutually inclined orbits is small then you eliminate 5 parameters.
- This appears to work for mutual inclinations less than about 6 degrees (0.1 radians).
- Need better statistics to see where the actual limits are

Better Statistics

Inclination causes disagreement.



10^o resonant



18^o nonresonant

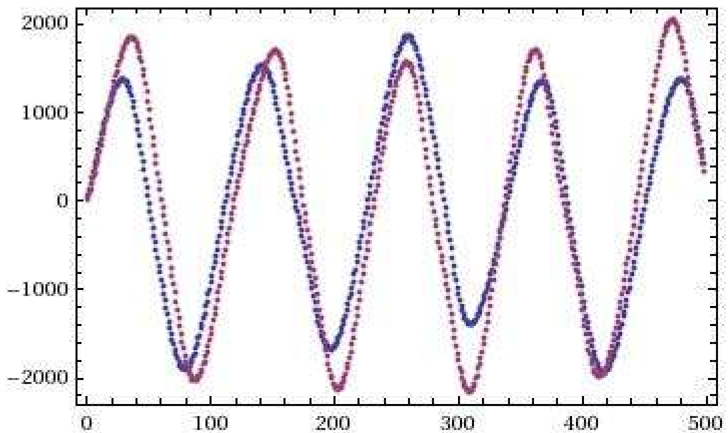
We need to know:

- Given these changes to the signal, is there still a co-planar solution?
- How much error is introduced in the orbital parameters if you ignore the inclination?

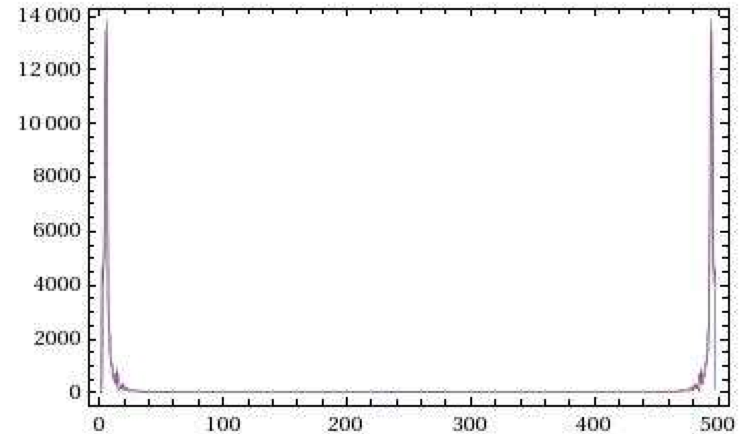
Better Statistics

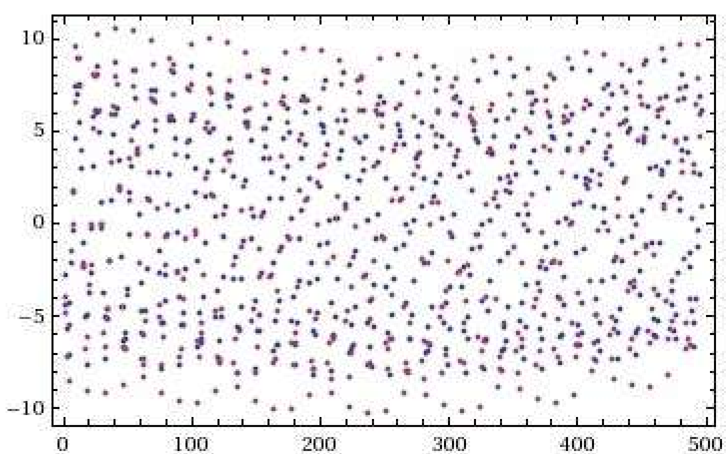
Inclination causes disagreement.

Fourier representation appears better.

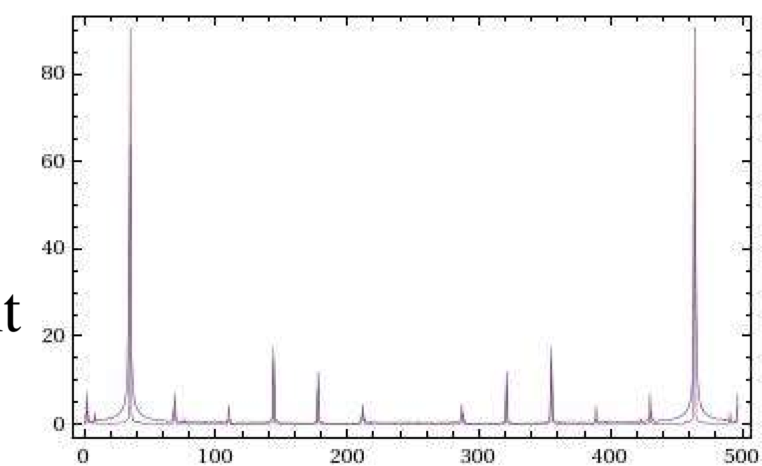


10^{o}
resonant



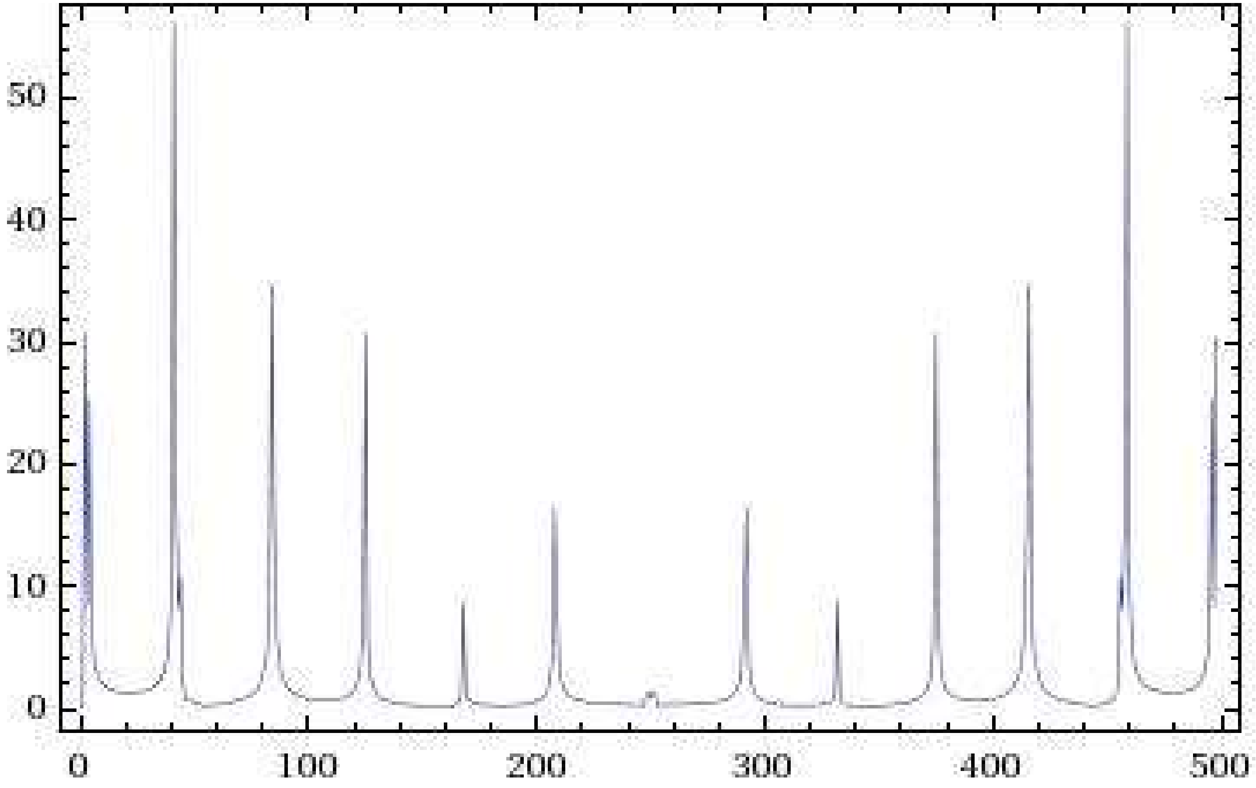


18^{o}
nonresonant



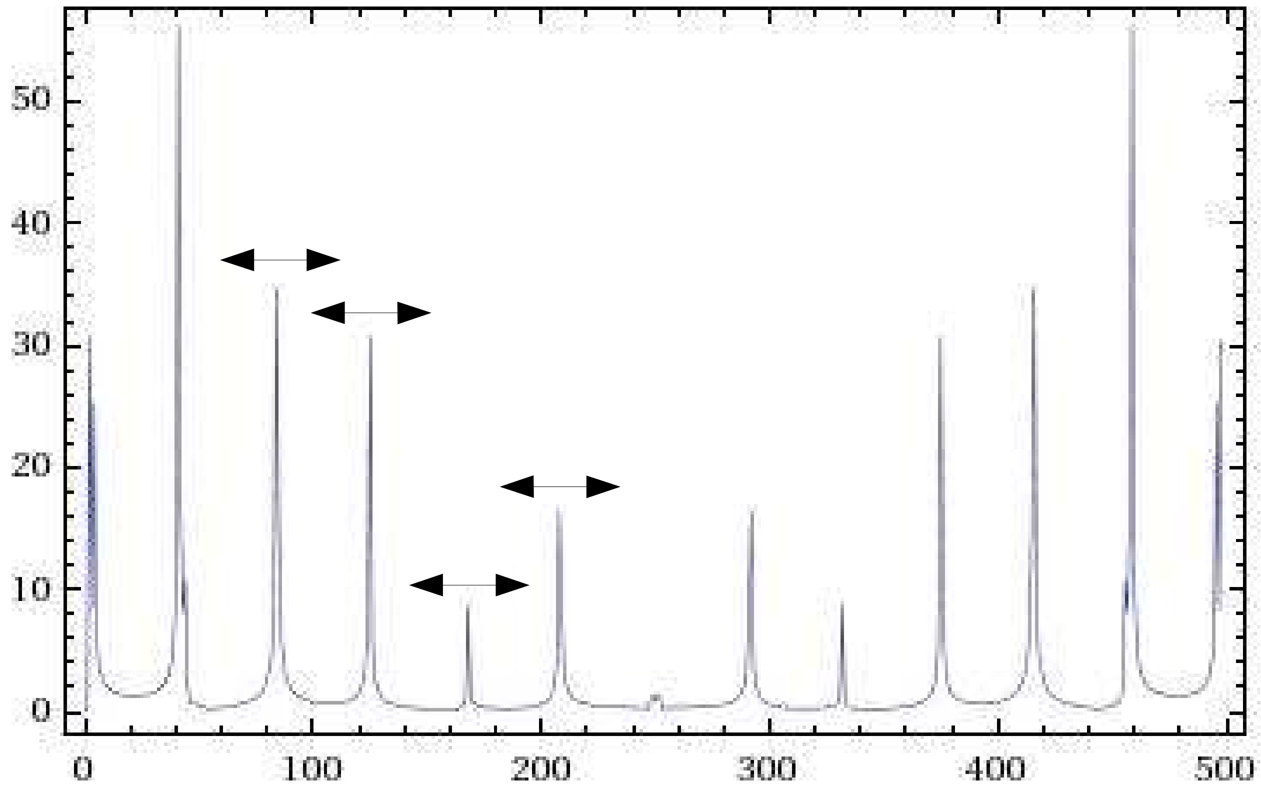
Better Statistics

Important frequencies look like $e^{|i-j|}\sin(in_1 - jn_2)$.



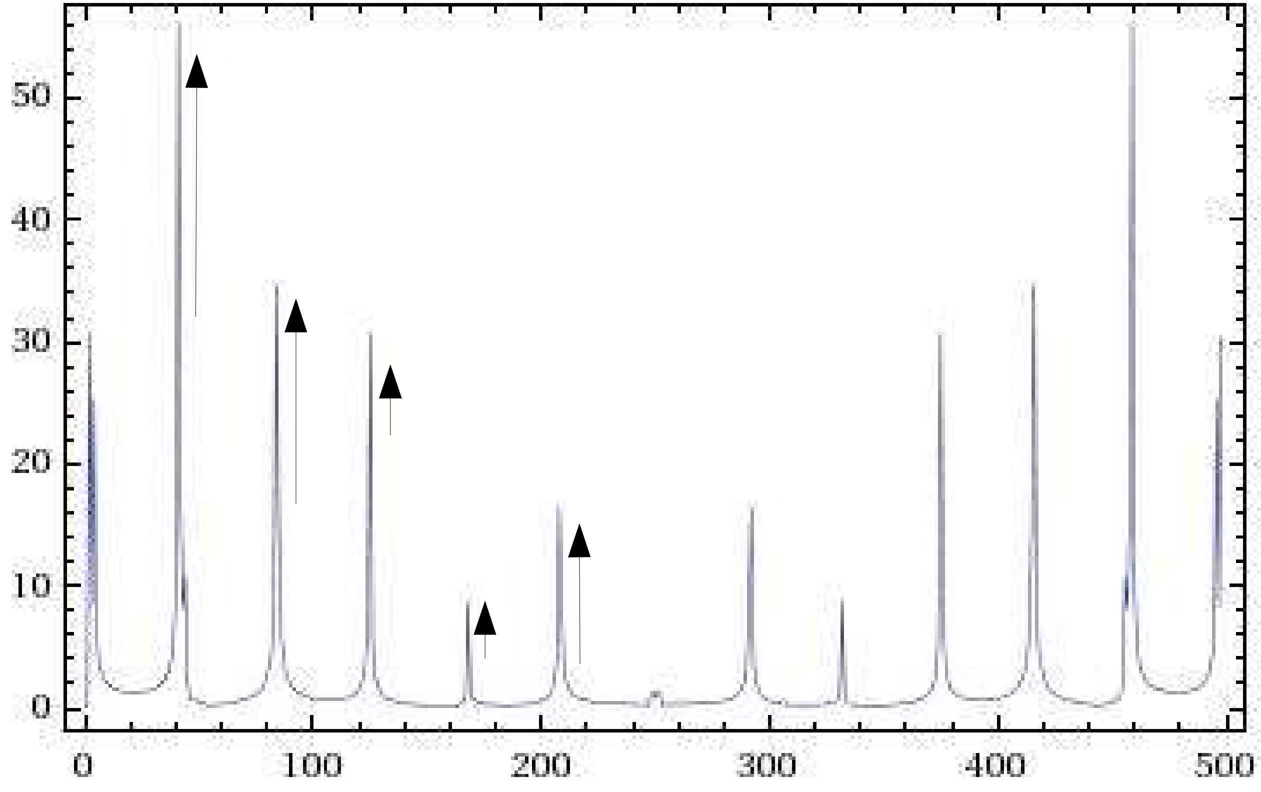
Better Statistics

change to *a* shifts frequencies



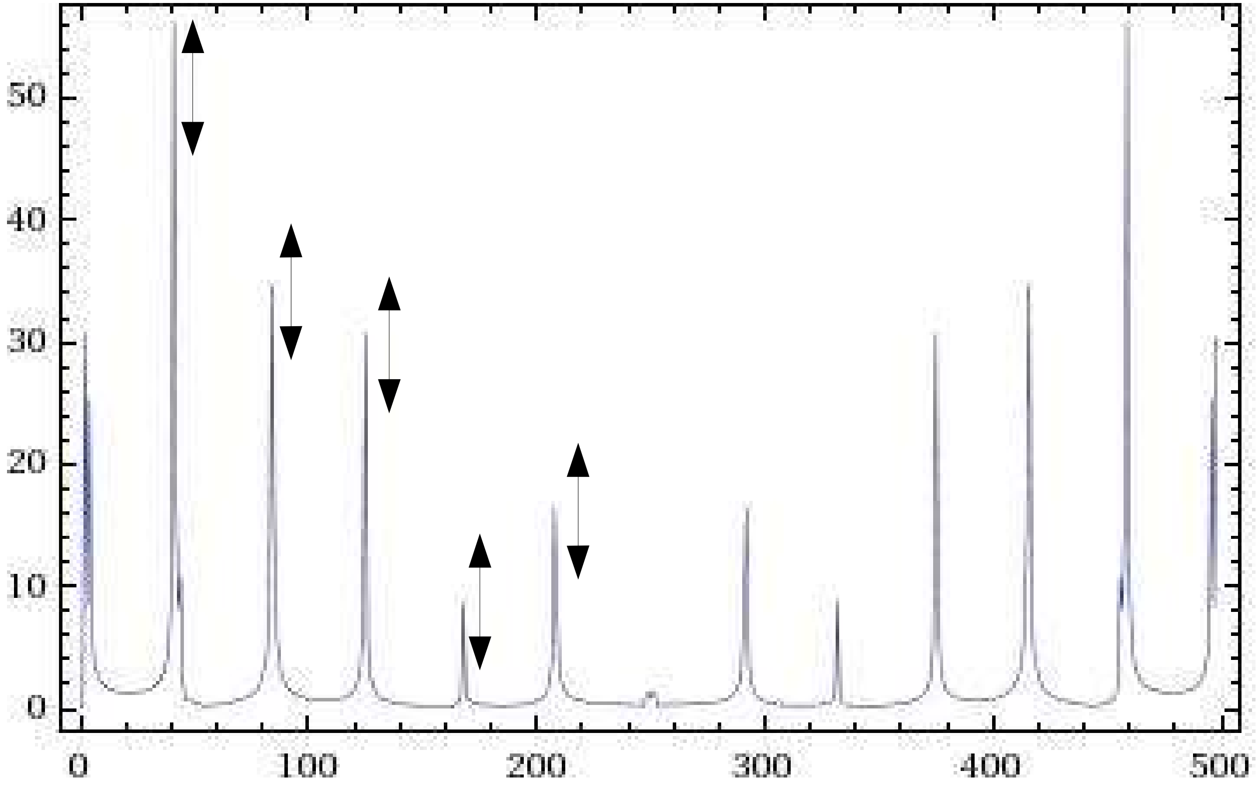
Better Statistics

change to *e* amplifies modes

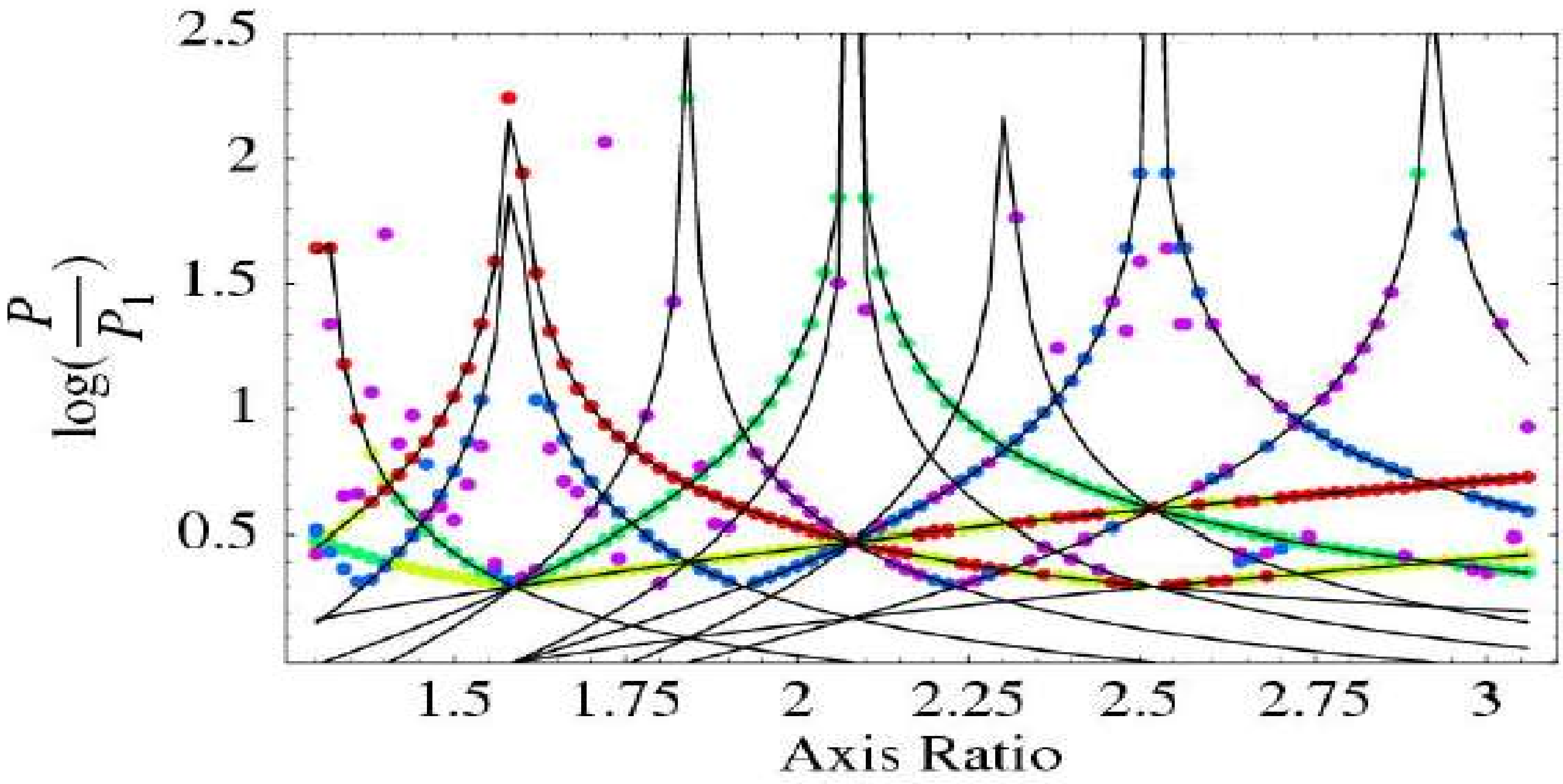


Better Statistics

change to *w* or *M* adjusts relative heights



Better Statistics



$$\frac{P_{\mathrm{peak}}}{P_{\mathrm{trans}}} = \frac{P_{\mathrm{pert}}}{iP_{\mathrm{trans}} - jP_{\mathrm{pert}}}$$

Better Statistics

Studying the effects of both mutual inclination and a fourth body in the Fourier representation looks like a promising avenue to:

- Determine when the 3-body and/or coplanar approximations are valid
- Identify the systematic errors that might appear in the inferred orbital elements
- Perhaps find a more efficient parameter-fitting algorithm

Conclusions

1) Transit Timing is a very sensitive probe for extrasolar planets.

2) No low-order resonant ~Earth-mass planets in HD 209458 or TrES-1
   - Sensitivity to 0.2 Earth-masses in low-eccentricity orbits for HD 209458 and 0.7 Earth-masses in TrES-1

3) Many transit surveys are running and planned.
   - Kepler will soon launch and will be a significant source of high quality data

4) There remains some work in identifying limitations imposed upon TTV from simplified models (3-bodies and/or coplanar orbits).
   - The effects of these uncertainties appear to be "well behaved".