Rømer Revisited Reprised

OASI's Measurement of the Speed of Light, Part IV

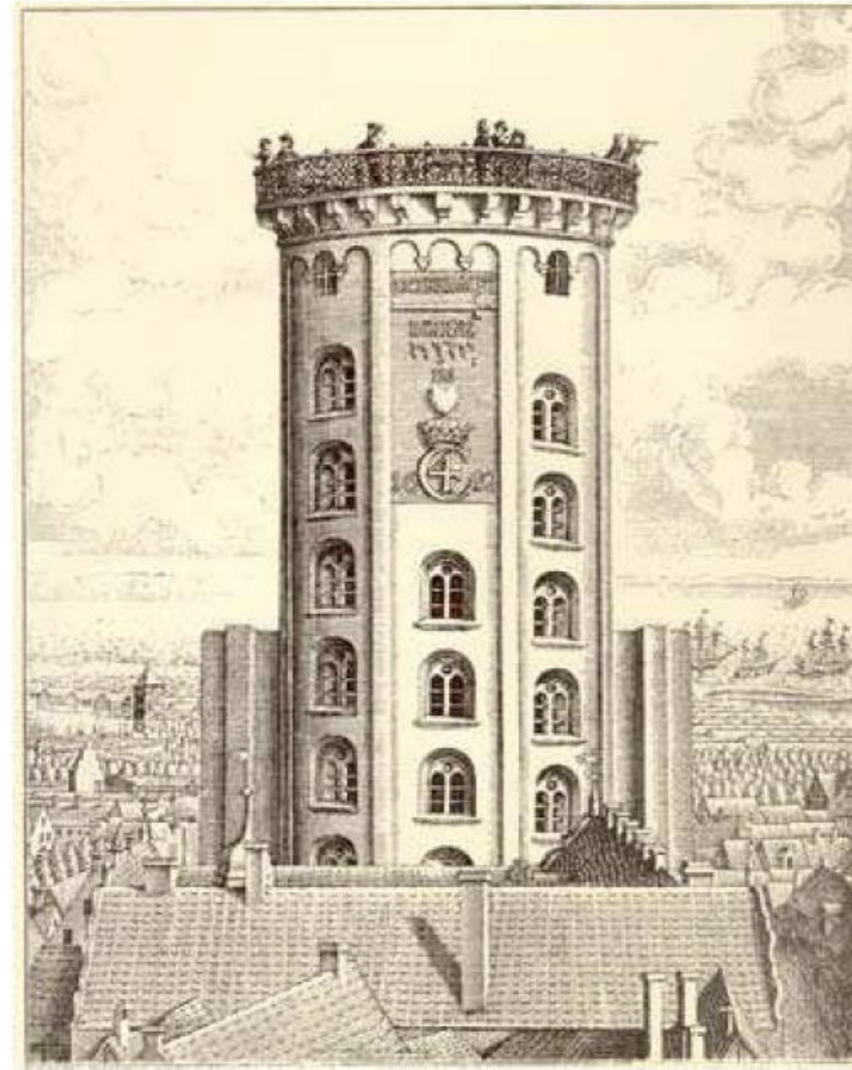
James Appleton

10 December 2014

Agenda

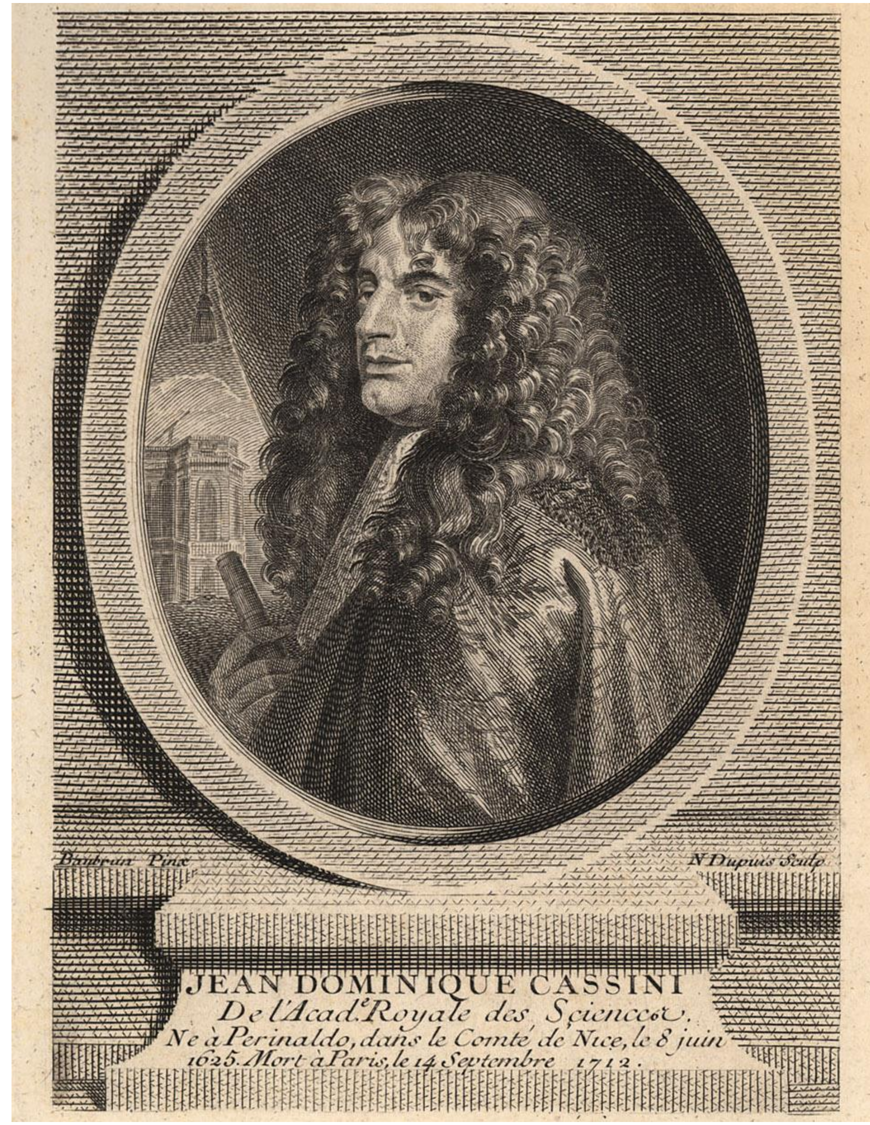
1. Historical background
2. Phenomena of the Galilean satellites
3. Analysis of OASI & HAG observations
4. Detailed examination of “Rømer’s method”
5. Apply the method to observations by Rømer & Picard
6. Tea break
7. Q & A

Ole Rømer (1644-1710) by Jacob Coning, *circa* 1700.



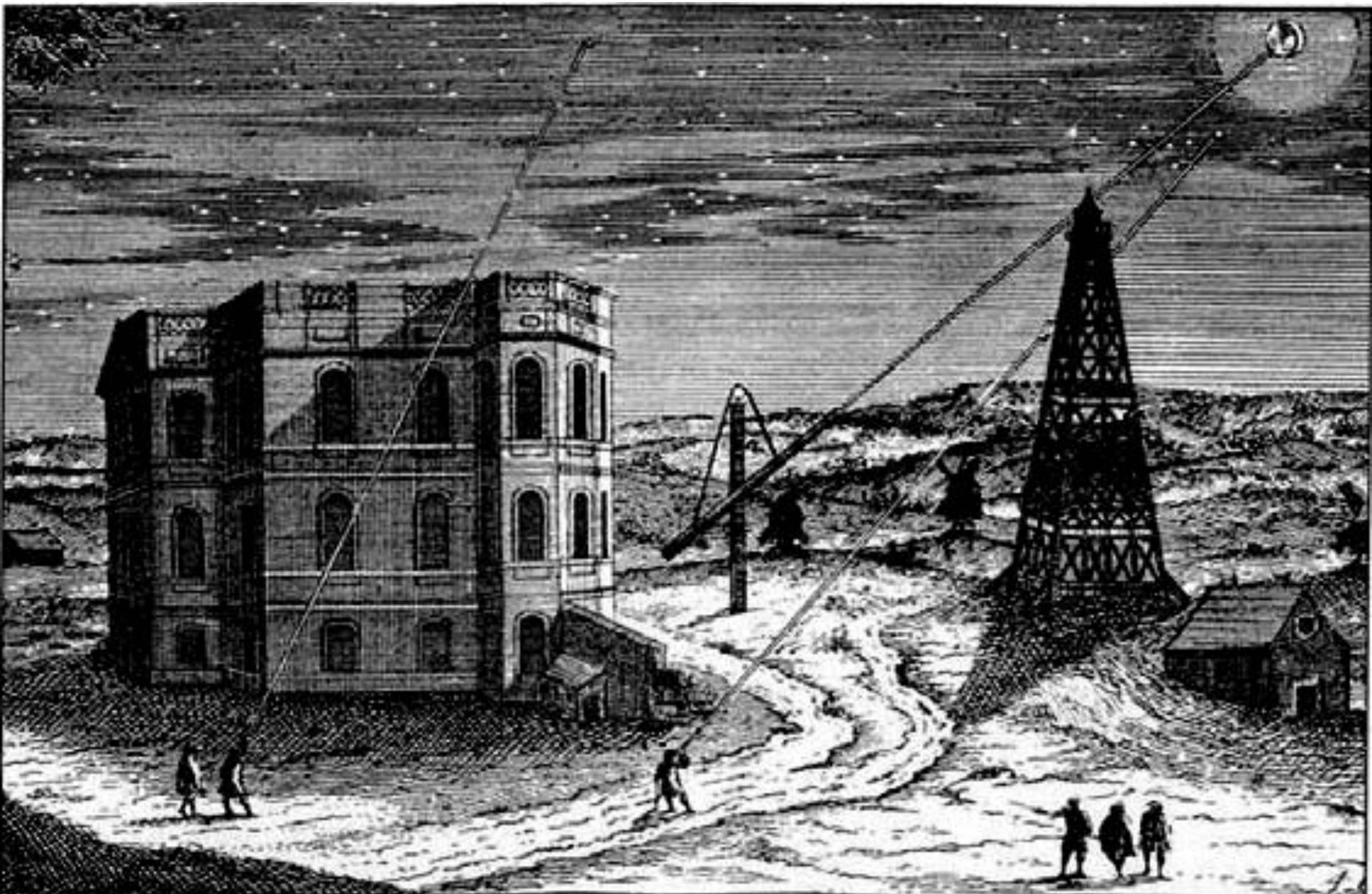
Copenhagen Rundetårn Observatory in 1657.

Jean Picard
(1620-82).



Giovanni Domenico
Cassini (1625-1712).

Observatoire de Paris, Early 18th C



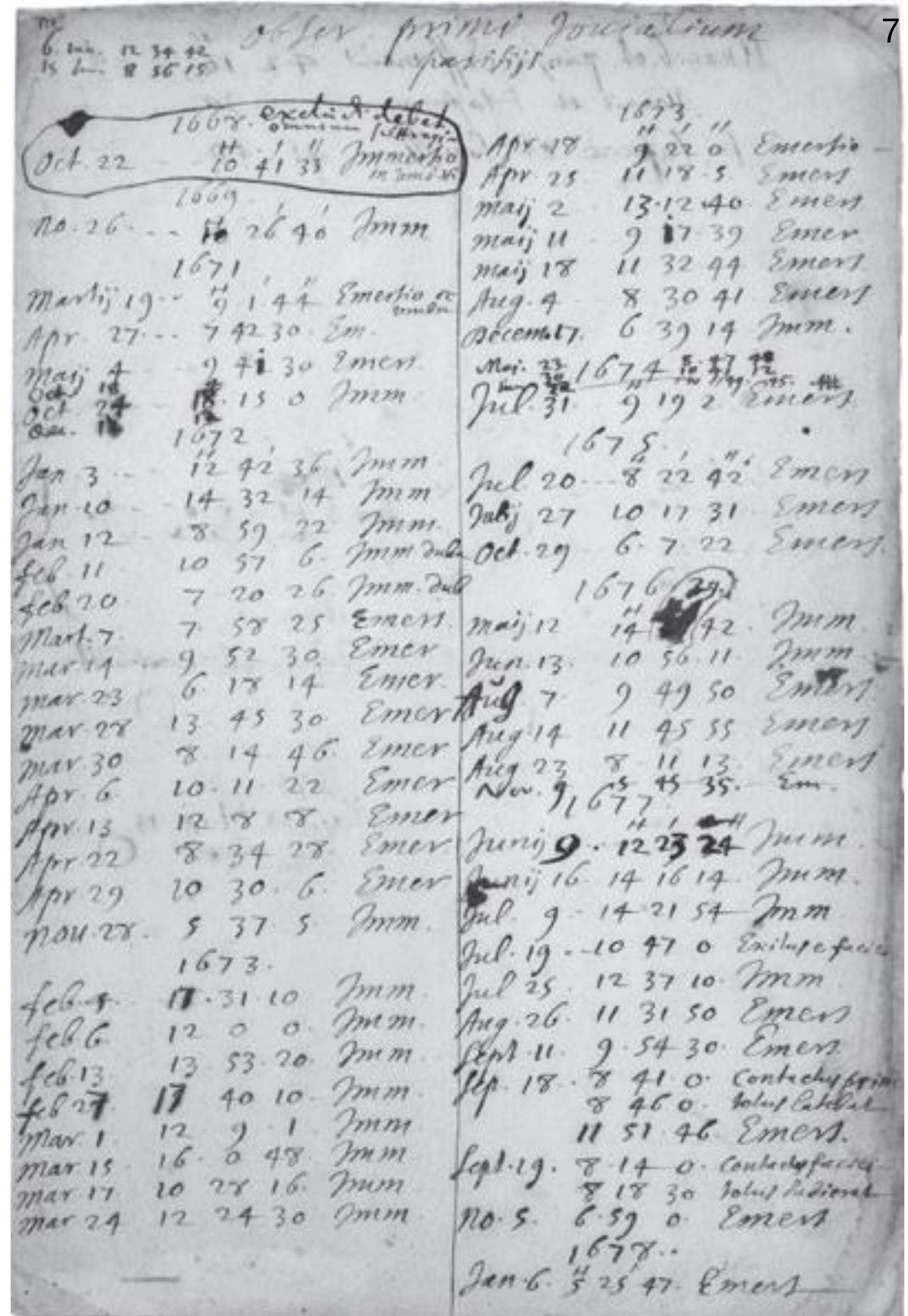
Journal des Sçavans, 1676

DEMONSTRATION TOUCHANT LE mouvement de la lumiere trouvé par M. Römer de l'Academie Royale des Sciences.

IL y a long-temps que les Philoſophes ſont en peine de decider par quelque experience, ſi l'action de la lumiere ſe porte dans un inſtant à quelque diſtance que ce ſoit, ou ſi elle demande du temps. Mr Römer de l'academie Royale des Sciences s'eſt aviſé d'un moyen tiré des obſervations du premier ſatellite de Jupiter, par lequel il démontre que pour une diſtance d'environ 3000 lieuës, telle qu'eſt à peu prés la grandeur du diametre de la terre, la lumiere n'a pas beſoin d'u-

A Brief History of the Observations by Rømer & Picard

- Recorded 1668 onwards.
- Subsequently lost.
- Rediscovered in 1913, attributed to Rømer.
- Analysed in the late 20th Century and re-attributed jointly to Rømer & Picard.
- Now available over the Internet.



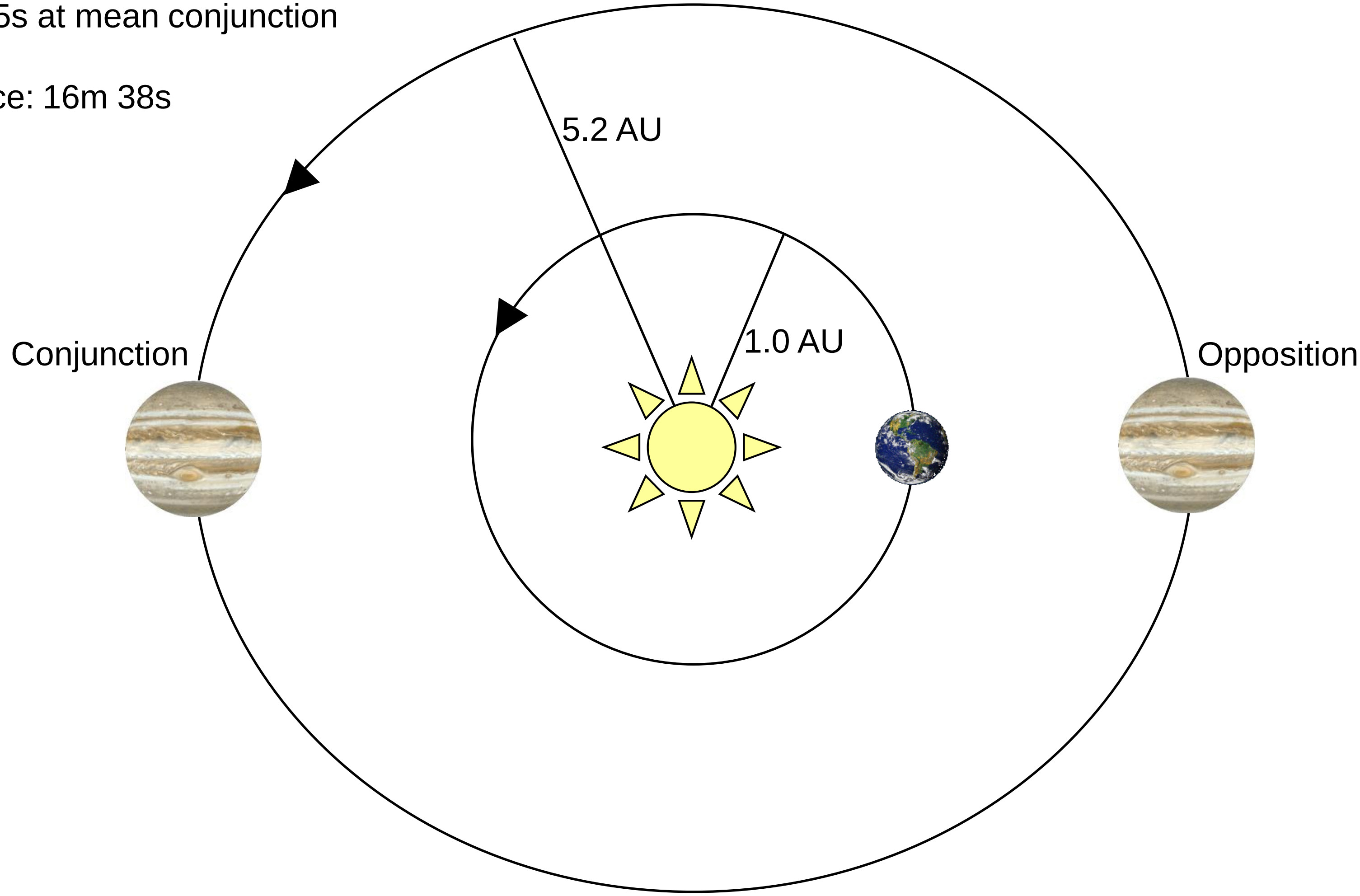
Orbital Dimensions

Light travel time of 299,792 km/s equates to 8 min 19 sec per AU

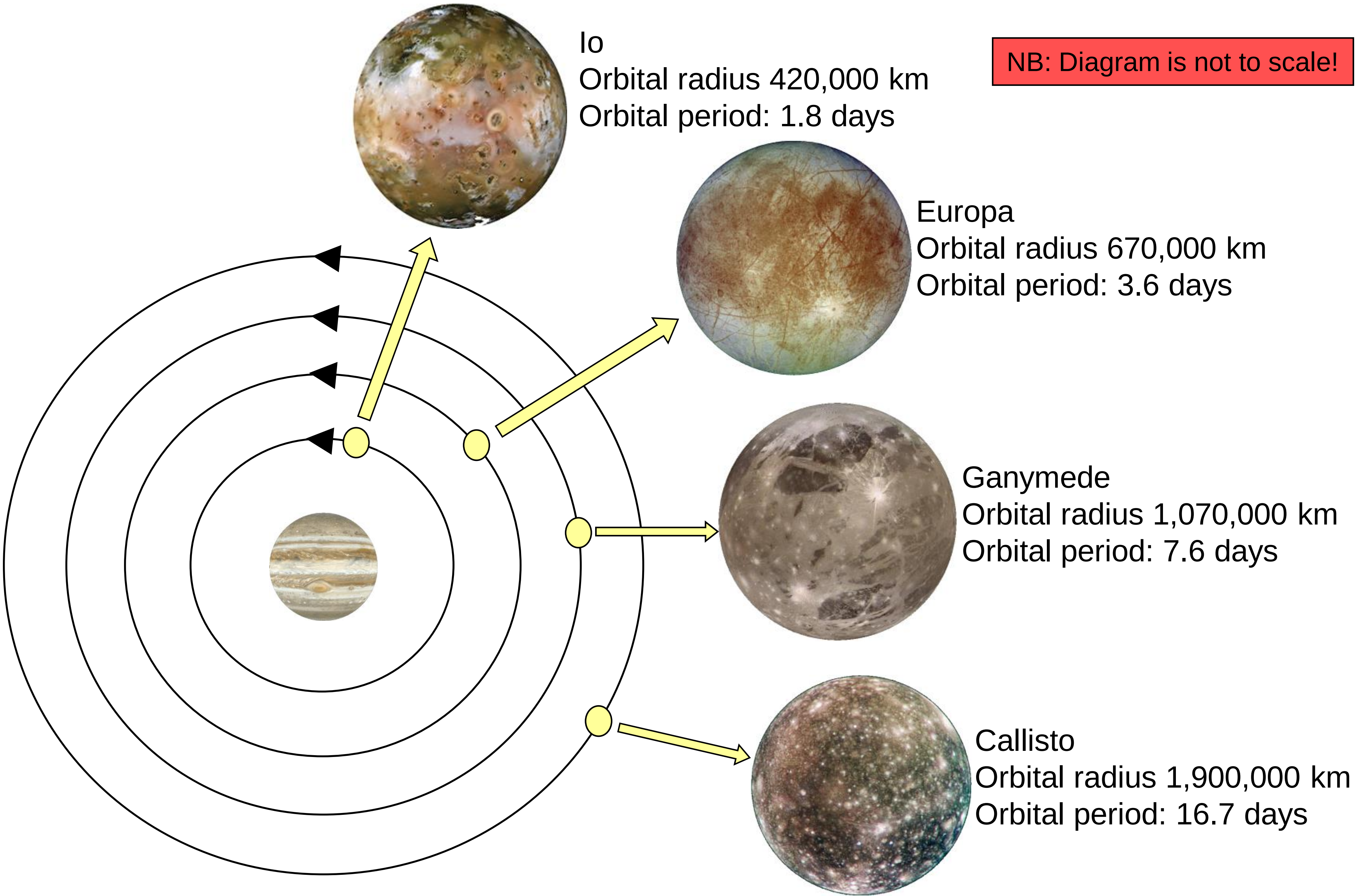
NB: Diagram is not to scale!

Light travel time Jupiter → Earth:
  34m 57s at mean opposition
  51m 35s at mean conjunction

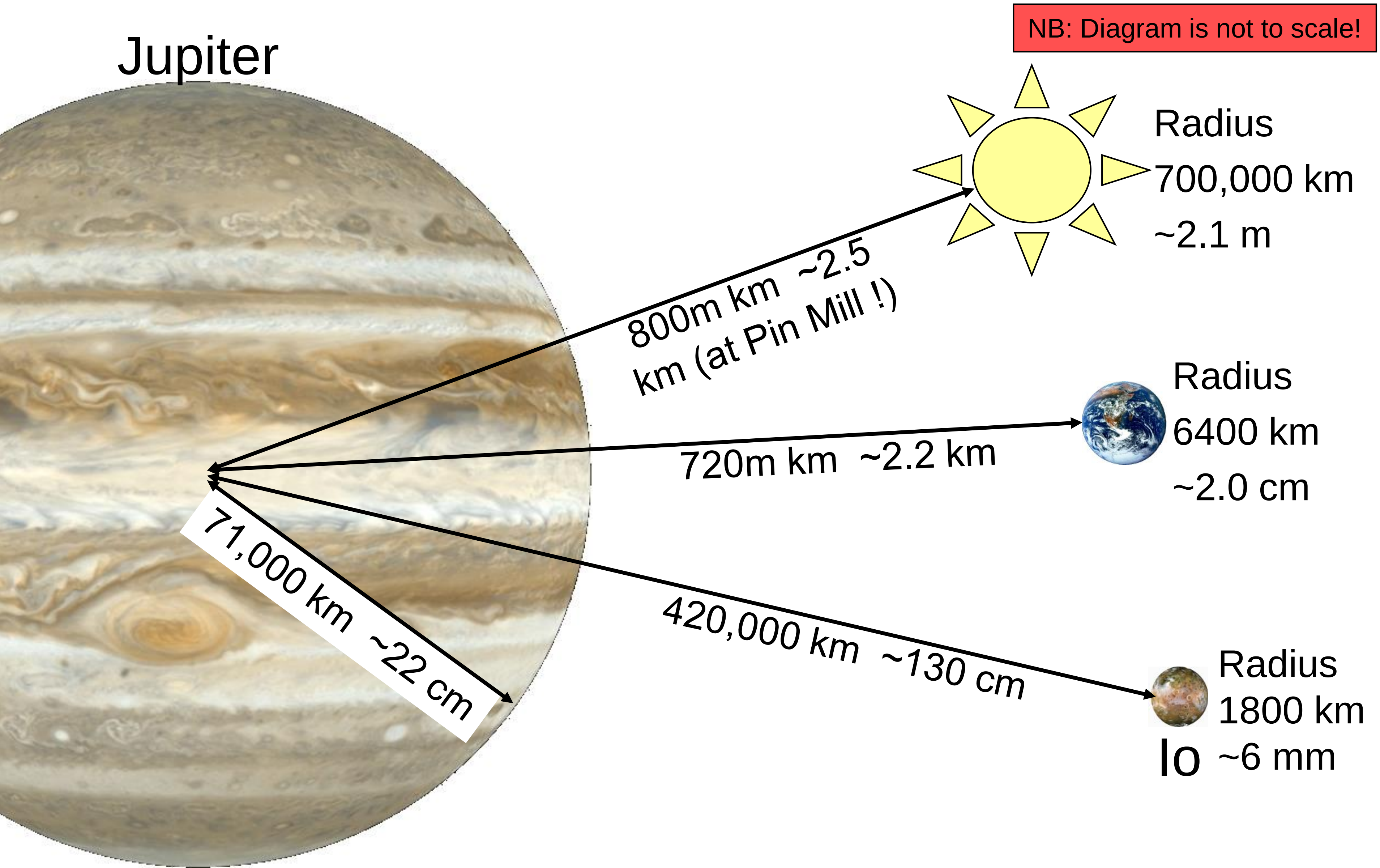
Difference: 16m 38s



Jupiter & The Galilean Satellites



Model Scale 1:325,000,000



Model Checklist

- Galilean phenomena:
  - Transit
  - Shadow transit
  - Occultation
  - Eclipse
- Eclipse most suitable timekeeper for Rømer’s method
- Effect of Jupiter’s axial tilt
- Difficulties in timing eclipses

Sidereal and Synodic Periods

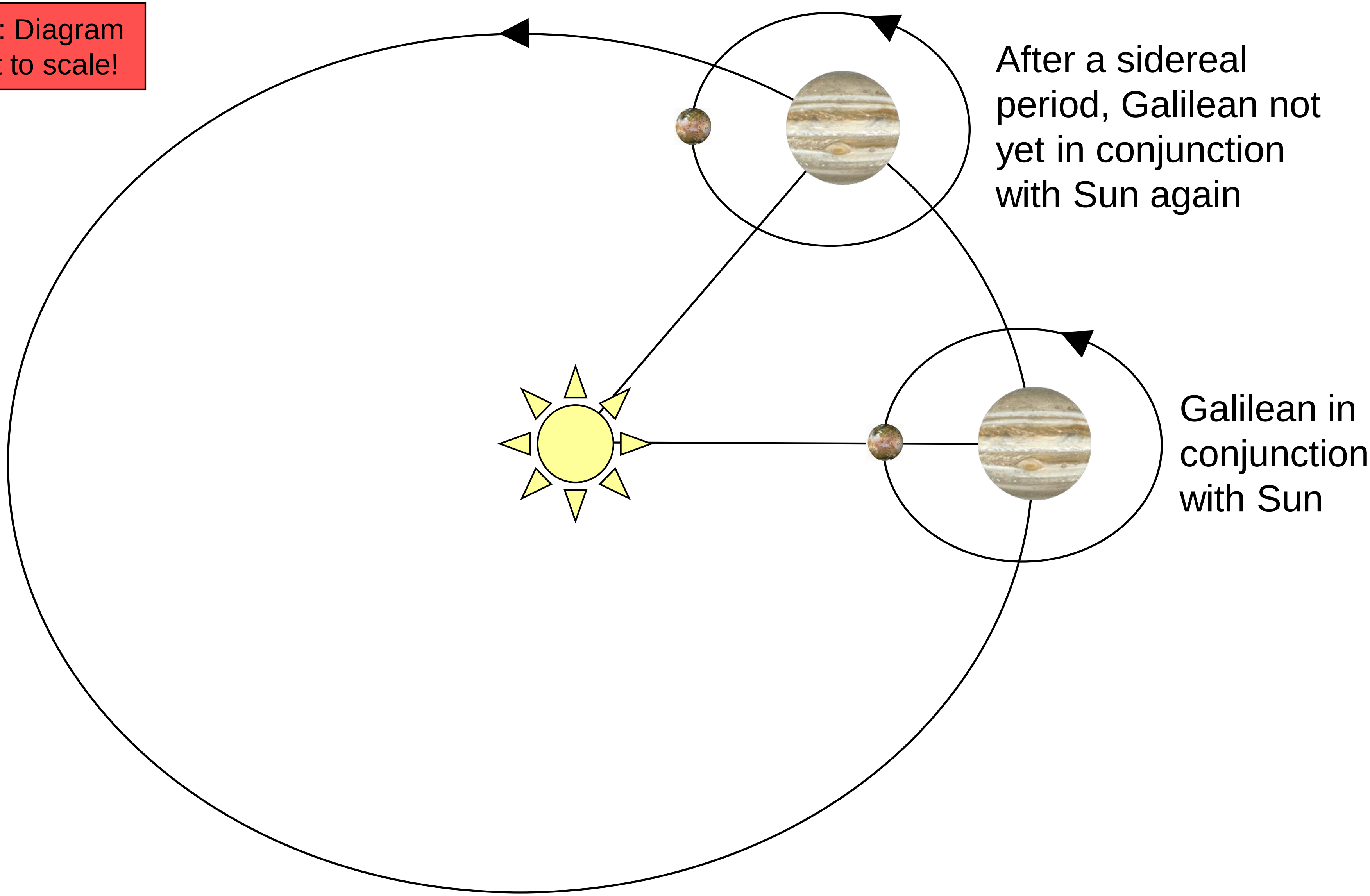
Definition, for a Galilean satellite

- *Sidereal period*: average time to complete a revolution of Jupiter, measured with reference to the stars
- *Synodic period*: average time between successive conjunctions with the Sun, as seen from Jupiter

The two differ due to Jupiter's orbital motion

Sidereal and Synodic Periods

NB: Diagram not to scale!



Europa Disappearance Observation

Mike Whybray, 114mm Helios reflector, F/8, 9mm e/p, 100x mag.
Eyepiece projection to compact digital camera.
Image wobble due to gusty wind!

Disappearance 20:32:44 on 29 November 2013

Starts approx. two minutes before disappearance

Starts approx. 25 seconds before disappearance

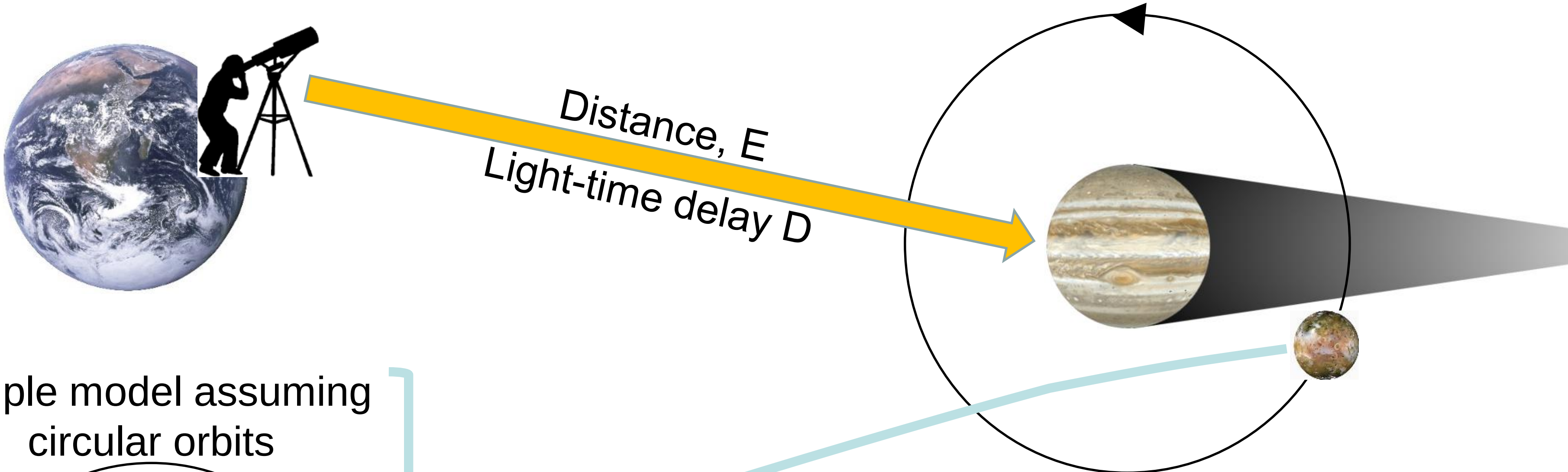
Eclipse Observations

D=disappearance
R=reappearance

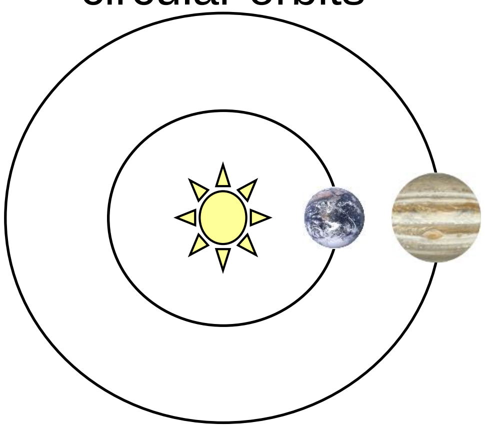
	Io		Europa	Ganymede		Callisto
	D	R	R	D	R	D
James Appleton	1	1	2	3	3	
Martin Cook	3	8	2	2		
Andy Gibbs		2				
Roy Gooding	1					
HAG	10	7				
Mike O'Mahoney		5	1		1	
Neil Morley		2	1			
Gerry Pilling		4	1			1
Robin Scagell		1 (v)				
Alan Smith	4	10	3	3	2	
Joe Startin	2	6	1		2	
Chris Stevens	1					
Mike Whybray	1 (v)	2	1			

Total 32 D, 68 R during observation period 14 January 2012 – 18 May 2014.
Observations also submitted of 16 occultations and two transits.

"Rømer's Method"



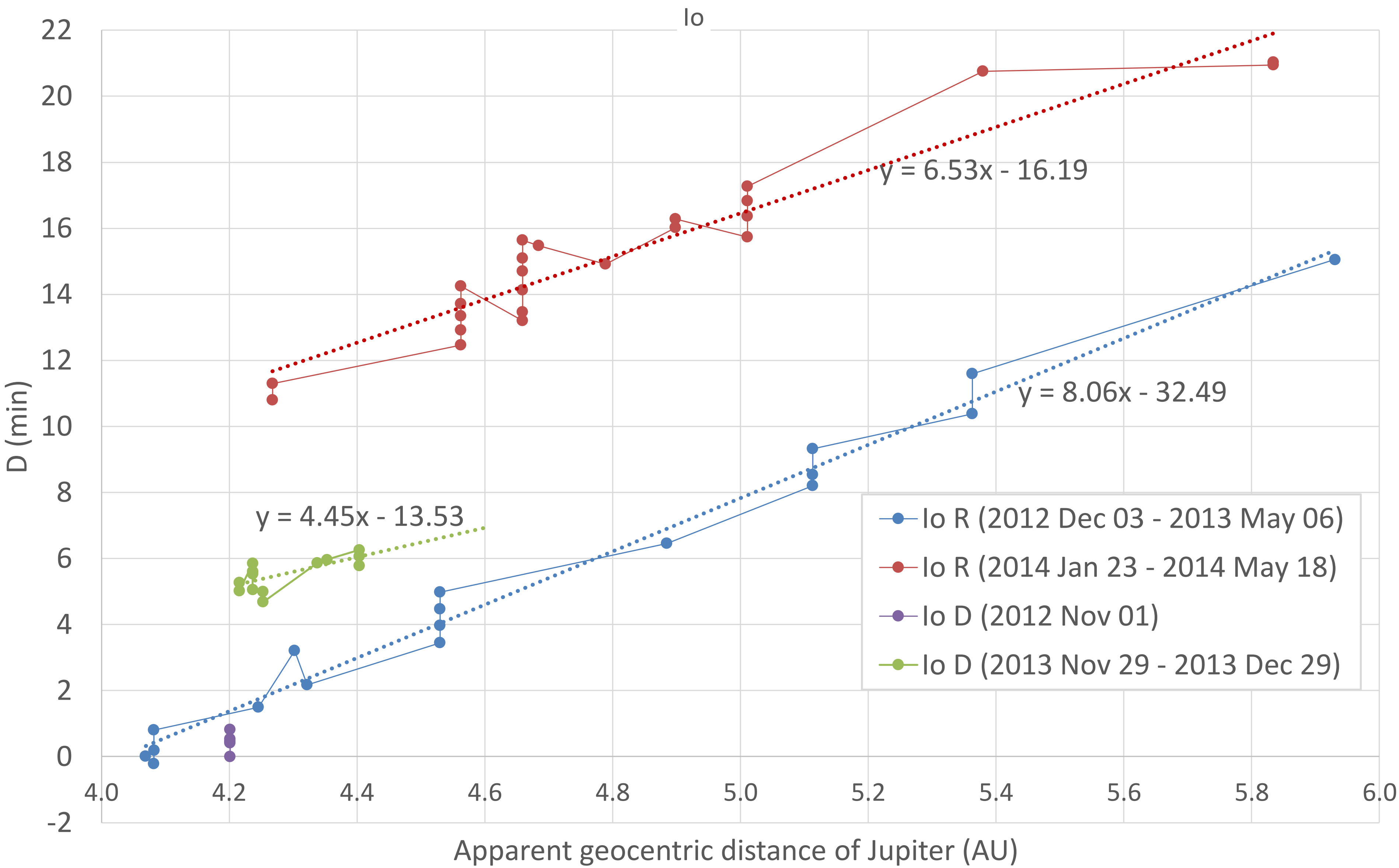
Simple model assuming circular orbits



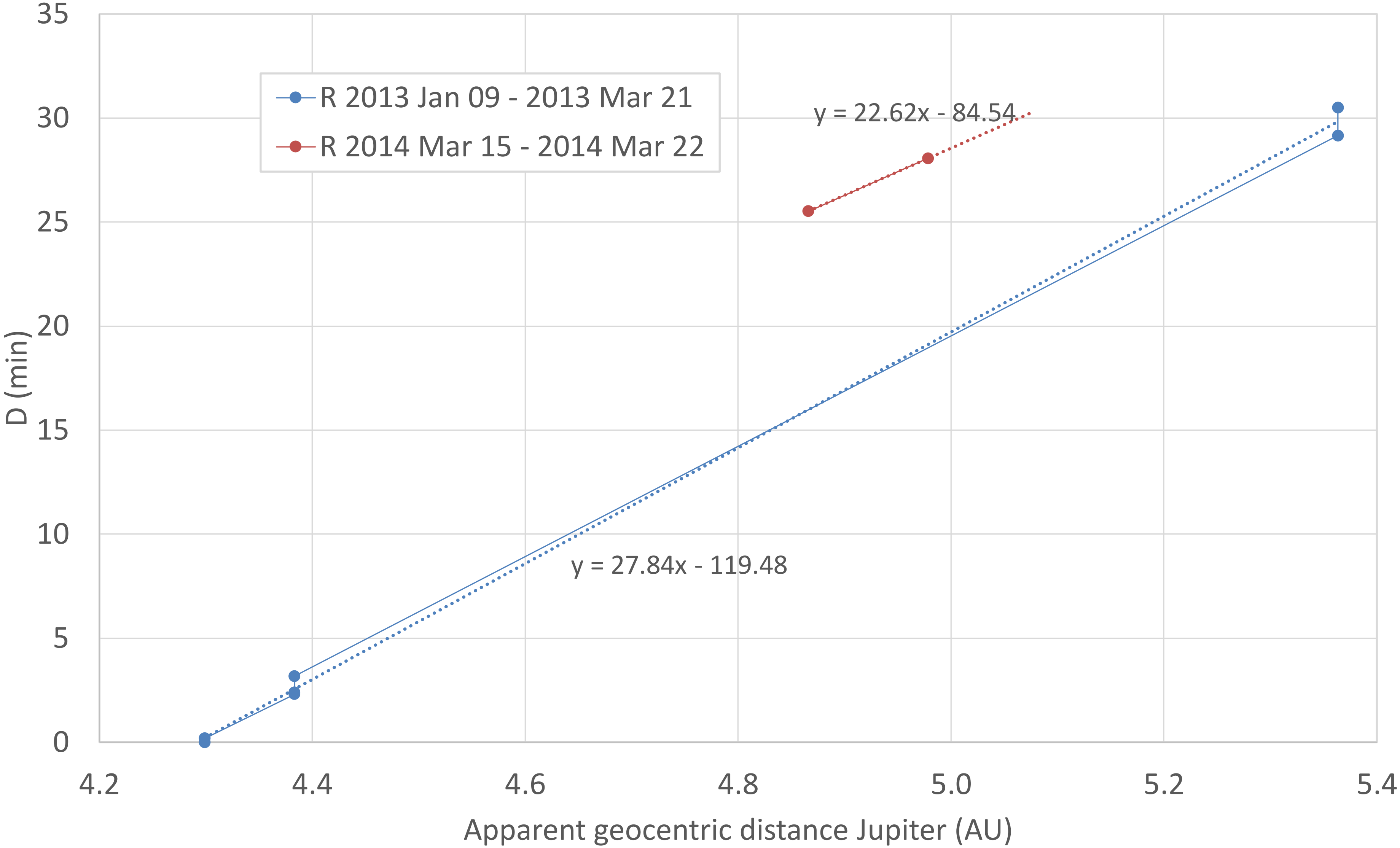
Or high-precision ephemeris, e.g. NASA JPL DE-405

1. Analyse separately each Galilean, and D and R events.
2. Observe eclipse event times O_1, O_2,...
3. Calculate Jupiter-Earth distances E_1, E_2,…
4. Predict eclipse times P_i as multiples of synodic period after first eclipse, O_1.
5. Calculate light time delay $D_i=O_i-P_i$
6. Plot delay vs. distance, D_i vs E_i.
7. Fit a simple linear regression line.
8. The slope of the line is an estimate of 1/c.

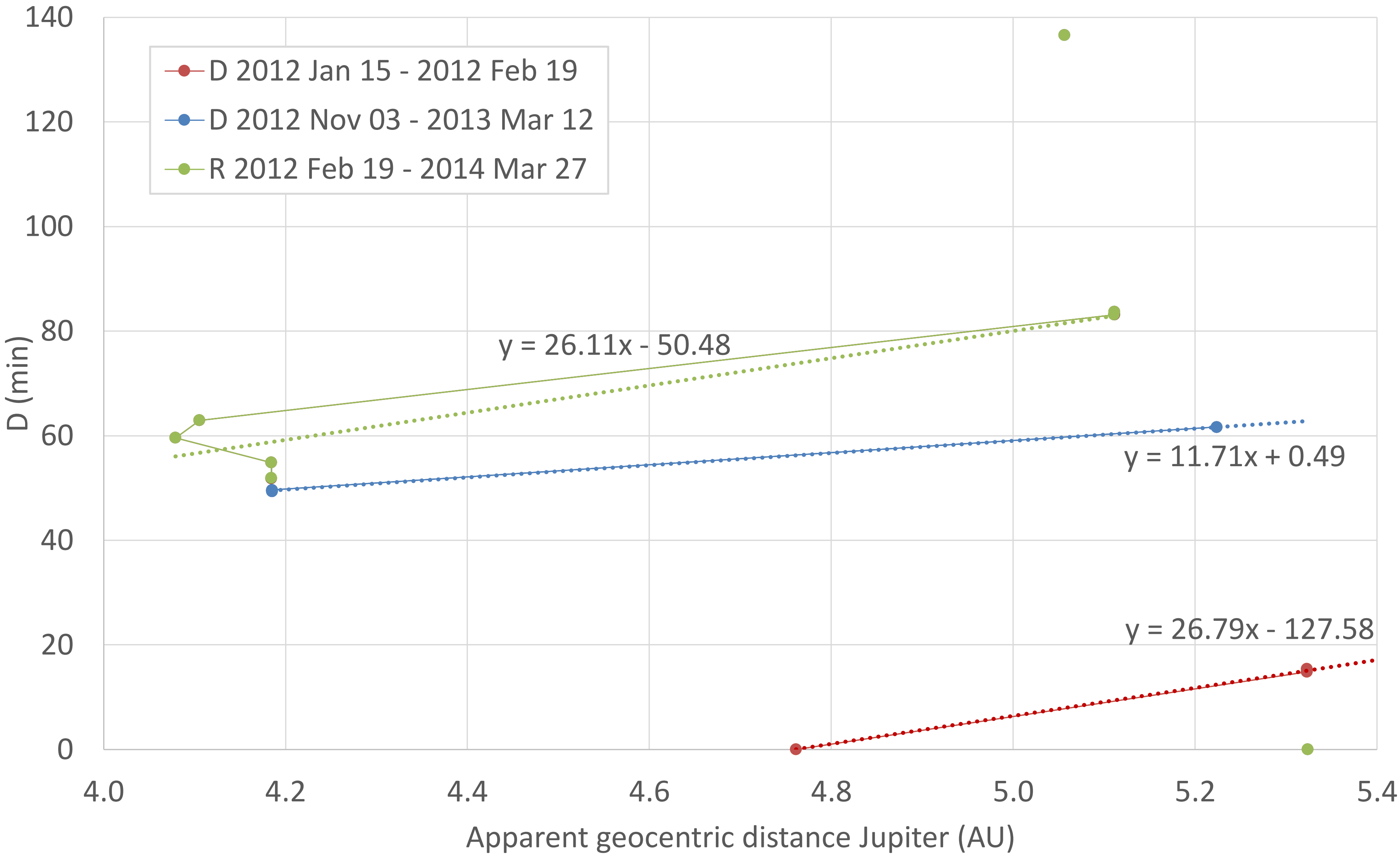
Results, Io


Io
y = 6.53x - 16.19
y = 8.06x - 32.49
y = 4.45x - 13.53
Io R (2012 Dec 03 - 2013 May 06)
Io R (2014 Jan 23 - 2014 May 18)
Io D (2012 Nov 01)
Io D (2013 Nov 29 - 2013 Dec 29)
D (min)
Apparent geocentric distance of Jupiter (AU)
22
20
18
16
14
12
10
8
6
4
2
0
-2
4.0
4.2
4.4
4.6
4.8
5.0
5.2
5.4
5.6
5.8
6.0

Results, Europa



Results, Ganymede



Results, Summary

Satellite	D / R	Observations	1/c (min/AU)	c (km/sec)
Io	R	2012 December 3 – 2013 May 6	8.06	309,000
		2014 January 23 – 2014 May 18	6.53	382,000
Io	D	2013 November 29 – 2013 December 29	4.45	560,000
Europa	R	2013 January 9 – 2013 March 21	27.8	90,000
		2014 March 15 – 2014 March 22	22.6	110,000
Ganymede	R	2012 November 3 – 2013 March 5	26.1	95,000
Ganymede	D	2012 January 15 – 2012 February 19	26.8	95,000
		2012 November 3 – 2013 March 12	11.7	213,000
Compound				319,000

Synodic Periods

Galilean	Accepted Value	Empirical Estimate
Io	$1^d\ 18^h\ 28^m\ 35.97^s$	$+2.4^s$
Europa	$3^d\ 13^h\ 17^m\ 53.85^s$	$+10.8^s$
Ganymede	$7^d\ 3^h\ 59^m\ 36.3$[illegible]^s	$+1^m\ 07.7^s$

Historical footnote: in 1693, Cassini adopted the value $1^d\ 18^h\ 28^m\ 36^s$

Working Hypothesis

- The synodic period is a critical factor in Rømer’s method
- The synodic period varies, primarily due to the following factors:
  - Jupiter’s orbital eccentricity
  - Inclination of Galilean orbit
  - Gravitational resonances and perturbations
- Variation in the synodic period occurs primarily on the timescale of the sidereal period of Jupiter
- Within one apparition, the synodic period is relatively constant
- Conclusion:
  - Rømer’s method “works”
  - But it often gives the wrong answer…

ALPO Observations

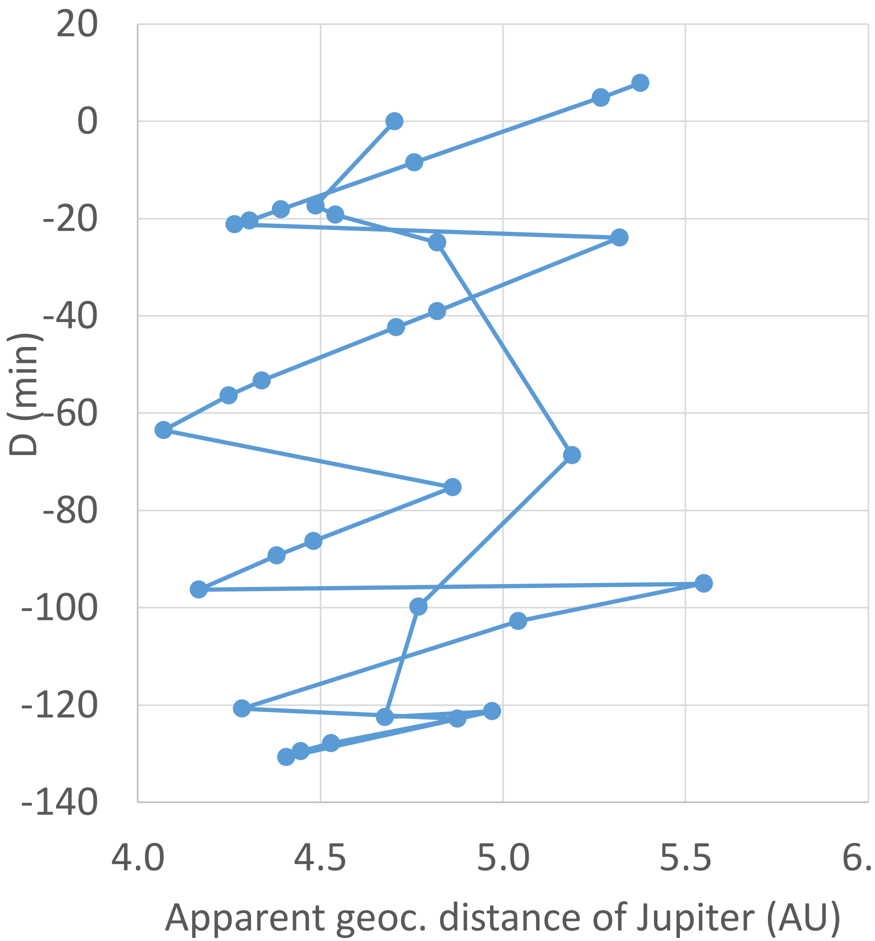
- Association of Lunar & Planetary Observers
- 548 eclipse timings, to professional standards, 1990-2009

Emergence of Jupiter's satellite Ganymede from the planet's shadow

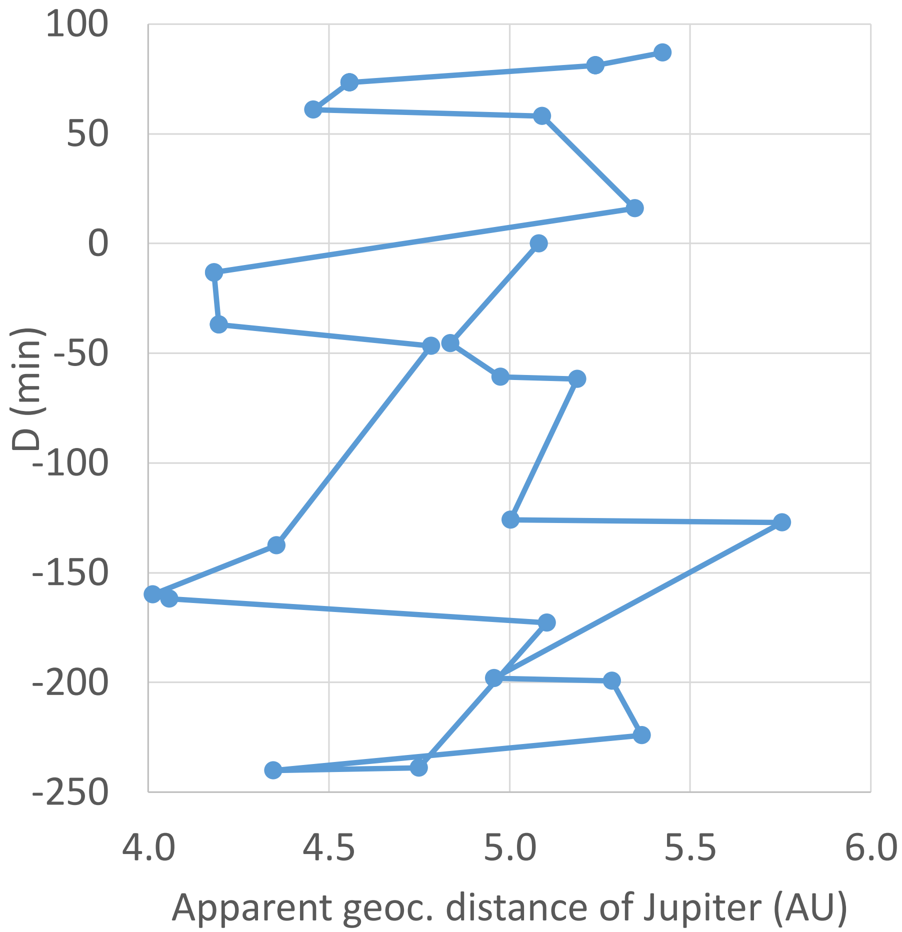
May 4, 1992

Anthony Mallama

Plotting The ALPO Data



Europa, 22 Mar 1991 – 19 Mar 2001



Ganymede, 11 May 1992 – 12 Sep 2001

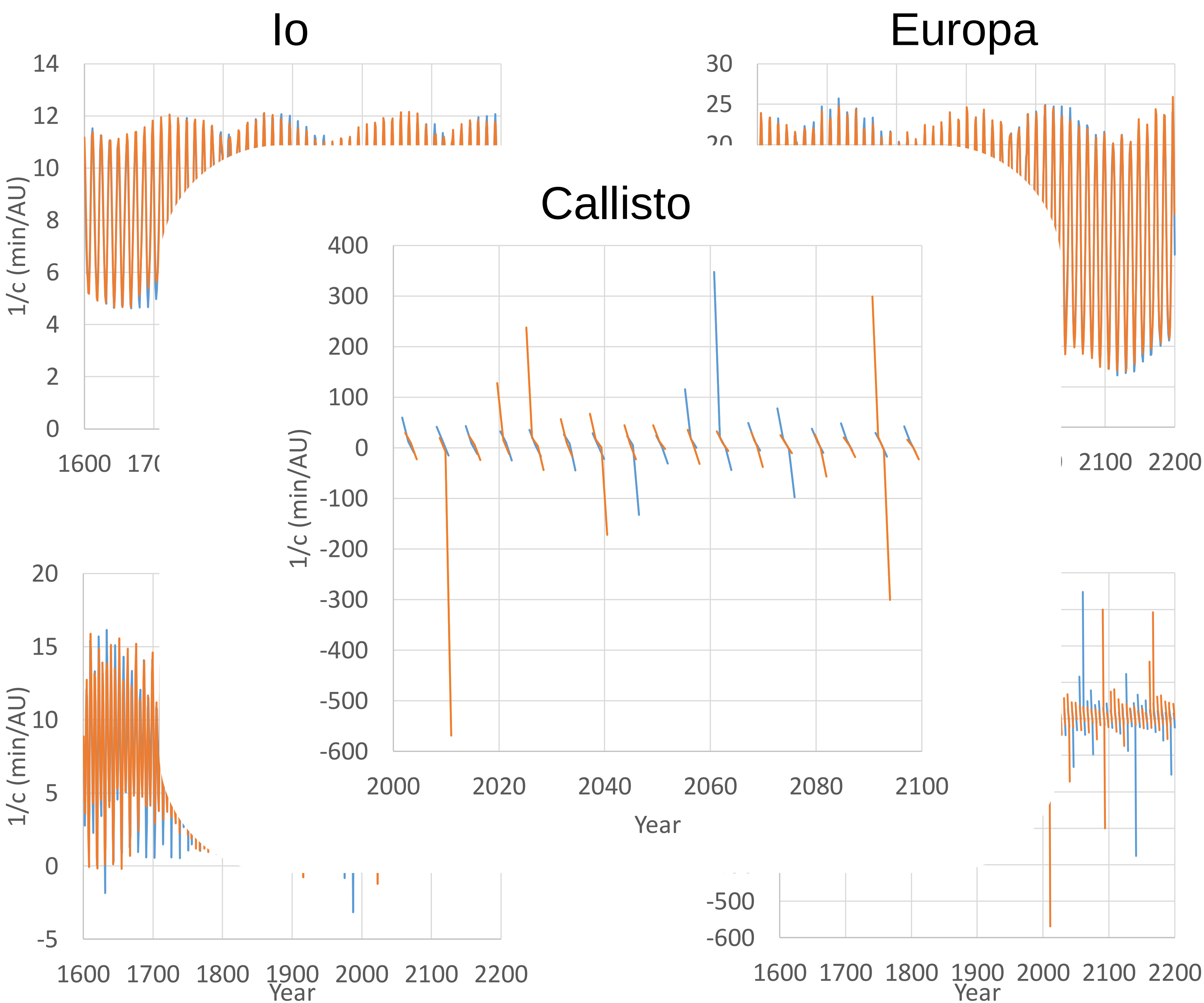
Variations in Eclipse Times

Variation (±minutes) in eclipse times by factor

Galilean	Eccentricity of Jupiter's Orbit	Longitude Perturbation*	Inclination of Galilean Orbit
Io	40	3.8	2.1
Europa	80	17	7.1
Ganymede	160	11	29
Callisto	373	62	71

* Estimated over the 601 year period 1600 – 2200.

c.f. 16m 38s, the difference in Jupiter → Earth light-travel time exploited by Rømer's method.


Io
Europa
Callisto
1/c (min/AU)
Year
400
300
200
100
0
-100
-200
-300
-400
-500
-600
2000
2020
2040
2060
2080
2100
14
12
10
8
6
4
2
30
25
20
15
5
-5
1600
1700
1800
1900
2200

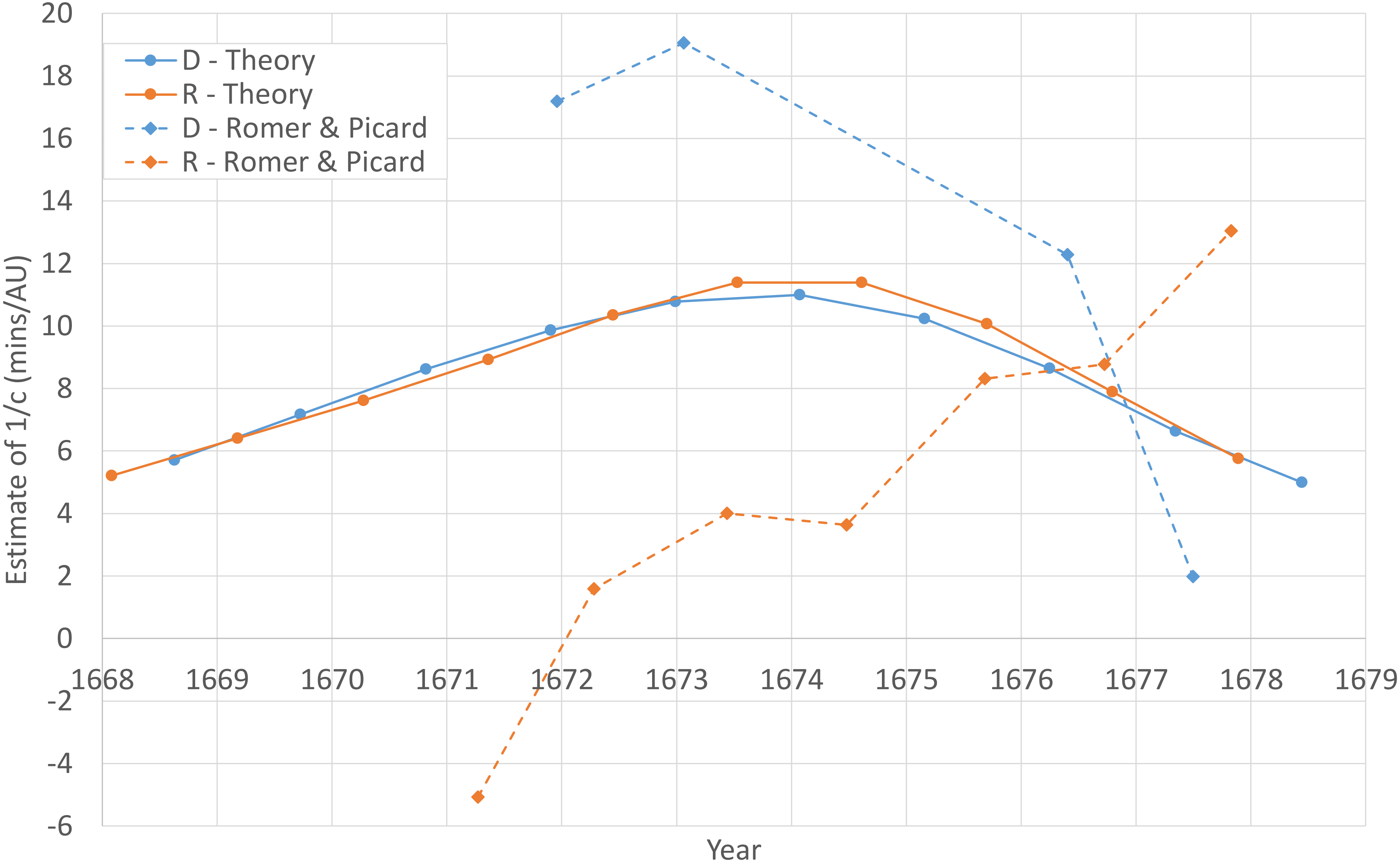
Critique of Rømer's Method

Galilean		Applicability of Rømer's Method
Io	√	Need to apply within one apparition of Jupiter. Synodic period relatively stable within this timescale, so method will generally work well.
Europa Ganymede Callisto	X	Too much variation in synodic period for method to be used reliably.

Application of the method beyond the above constraints requires either:

- pooling results over an extended period, or
- using compensation factors based on a detailed understanding of orbital dynamics.

Observations by Rømer & Picard



Conclusions

- The project to apply Rømer's method to estimate c was a great success!
- The method can work in limited circumstances, specifically for Io, within a single apparition of Jupiter
- Orbital dynamics prevent the method working more generally
- The project is highly accessible to amateur astronomers…
- But few have reported tackling it
- A paper on the subject, going into greater detail than we've covered tonight, will appear in *JBAA*

Tea Break…

Followed by Q & A


ANY
QUESTIONS
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