PLANETS AND MOONS AS PROBES OF PHYSICS BEYOND THE STANDARD MODEL

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How things fall

On earth …

Galileo's alleged experiment at Pisa (c. 1600)

… on the Moon

Astronaut Dave Scott (Apollo 15, July 30 – Aug. 7, 1971)

Mass can be defined two ways!

Inertial:

$$a = \frac{F}{\boxed{m_i}}$$

Inertia- resistance to *any* force

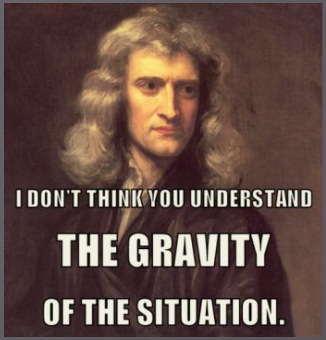
… vs. *gravitational*:

$$F = \frac{GM\boxed{m_g}}{r^2}$$

Gravitational “charge”

$$a = \frac{GM}{r^2}\frac{m_g}{m_i} = \mathrm{g}\cancelto{1}{\left(\frac{m_g}{m_i}\right)}$$

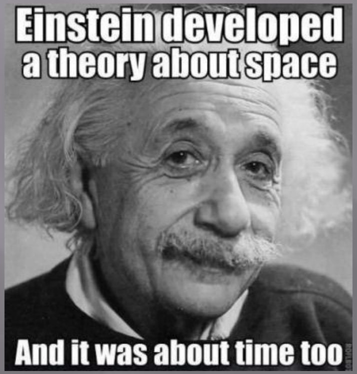
Why does $m_i = m_g$?



Newton did not try to answer this question

Einstein elevated it to a postulate: they <u>are</u> the same

Equivalence Principle



1. Gravity treats *all* matter/energy the same
2. Gravity must be a property of spacetime (not matter/energy)
3. What is this property?

Curvature $\rightarrow$ General Relativity

The problem

GR is almost certainly wrong- or at least incomplete!

This is because it can't be quantized or combined with the rest of physics (Standard Model of Particle Physics).

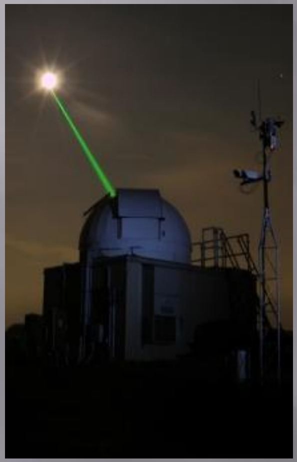
Those who try (e.g., string theorists) typically find $\frac{m_i}{m_g} \neq 1$

(Ultimately this is due to the presence of new fields that don't couple the same way to all forms of matter and energy, as the gravitational field does.)

How to test the EP

Just suppose! $\dfrac{m_i}{m_g} = 1 + \Delta$

Two bodies with different values of Δ will accelerate at different rates in the same gravitational field.

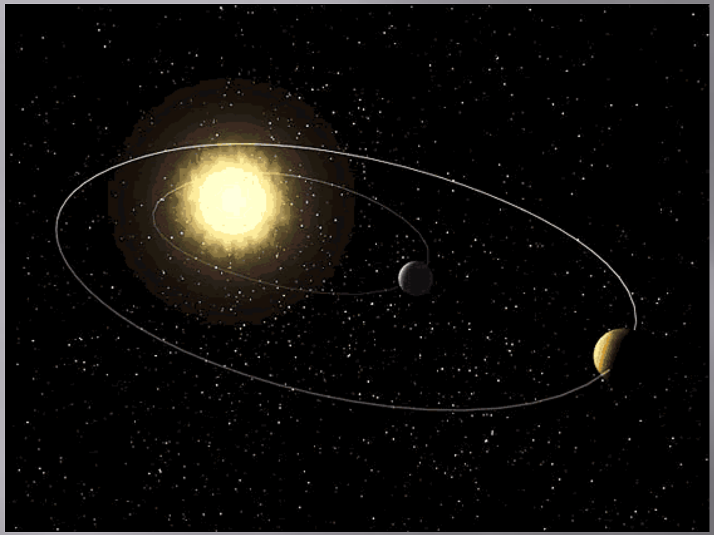


Lunar laser ranging implies that $\Delta \leq 10^{-13}$ for the Earth (iron) and Moon (silicates) in the field of the Sun.

Experiments using torsion balances give similar results for lead and copper.

We test with a combination of three methods:
Kepler's 3rd Law, Lagrange Points, and the Nordtvedt effect

1. Kepler's 3rd law



$$G(m_1 + m_2) = \omega^2 a^3$$

If $\Delta \neq 0$ for both bodies:

$$G(m_1 + m_2 + m_2\Delta_1 + m_1\Delta_2) = \omega^2 a^3$$

$$\left(\frac{m_\odot}{m_1}\right)\left(\frac{\omega}{k}\right)^2\left(\frac{a}{A}\right)^3 - \left(1 + \frac{1}{m_1/m_2}\right) = \left(\frac{\Delta_1}{m_1/m_2}\right) + \Delta_2$$

where $Gm_\odot = k^2 A^3$

We express ϵ_1 as the observational uncertainty in the left side, where $\left|\left(\frac{\Delta_1}{m_1/m_2}\right) + \Delta_2\right| \leq \epsilon_1$

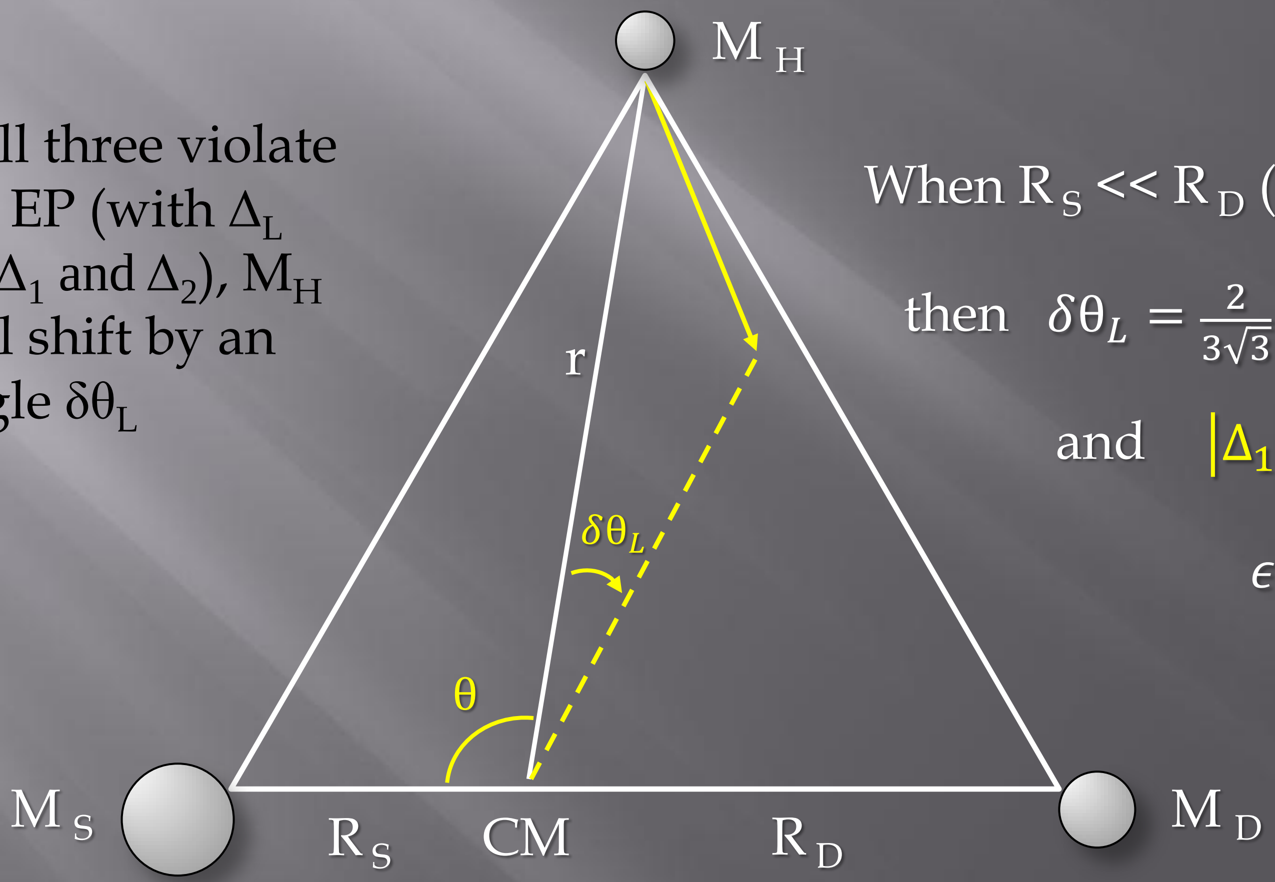
Limits using Kepler

Table 1. Kepler Limits				
Pair (m_1, m_2)	δa (km)	$\delta\omega$ ("/cty)	$\delta(m_1/m_2)$	ϵ_1
Sun, Mercury	2	0.002	300	1×10^{-7}
Sun, Venus	0.4	0.002	8×10^{-3}	1×10^{-8}
Sun, Earth	0.006	0.002	7×10^{-4}	1×10^{-10}
Sun, Mars	0.6	0.002	2×10^{-2}	8×10^{-9}
Sun, Jupiter	20	0.2	2×10^{-5}	9×10^{-8}
Sun, Saturn	0.6	0.2	1×10^{-4}	9×10^{-8}
Sun, Uranus	400	0.2	3×10^{-2}	5×10^{-7}
Sun, Neptune	2000	0.5	3×10^{-2}	2×10^{-6}
Earth, Moon	**0.0012**	**0.01**	$\mathbf{3\times10^{-6}}$	$\mathbf{1\times10^{-8}}$
		(°/day)		
Saturn, Tethys	0.02	4×10^{-7}	140	2×10^{-7}
Saturn, Dione	0.03	3×10^{-7}	18	2×10^{-7}

2. Lagrange Points

Consider Saturn, Dione, and their Lagrange point at L_4, Helene:

If all three violate the EP (with $\Delta_L << \Delta_1$ and Δ_2), M_H will shift by an angle $\delta\theta_L$



When $R_S << R_D$ (CM is in M_S)

then $\delta\theta_L = \frac{2}{3\sqrt{3}}\left(\Delta_1 - \frac{1}{2}\Delta_2\right)$

and $\left|\Delta_1 - \frac{1}{2}\Delta_2\right| \leq \epsilon_2$

$$\epsilon_2 = \frac{3\sqrt{3}}{2}\delta\theta_L$$

Limits from Lagrange

Table 2. Lagrange Limits

Pair (m_1, m_2)	n	T_{lib} (yrs)	T_{obs} (yrs)	δθ (“)	ϵ_2
Sun, Earth	1	400	2.5	2	8×10^{-1}
Sun, Mars	3	1400	17	0.05	2×10^{-3}
Sun, Jupiter	12	150	92	0.08	8×10^{-7}
Sun, Neptune	9	9400	7	20	2×10^{2}
Saturn, Tethys	2	1.9	33	20	2×10^{-4}
Saturn, Dione	**2**	2.1	**21**	**10**	$\mathbf{9\times10^{-5}}$

Helene, Polydeuces

[Spitale et al. 2006]

(discovered 1980, 2004)

[Jacobson 2012, priv. comm.]

3. Nordtvedt Effect

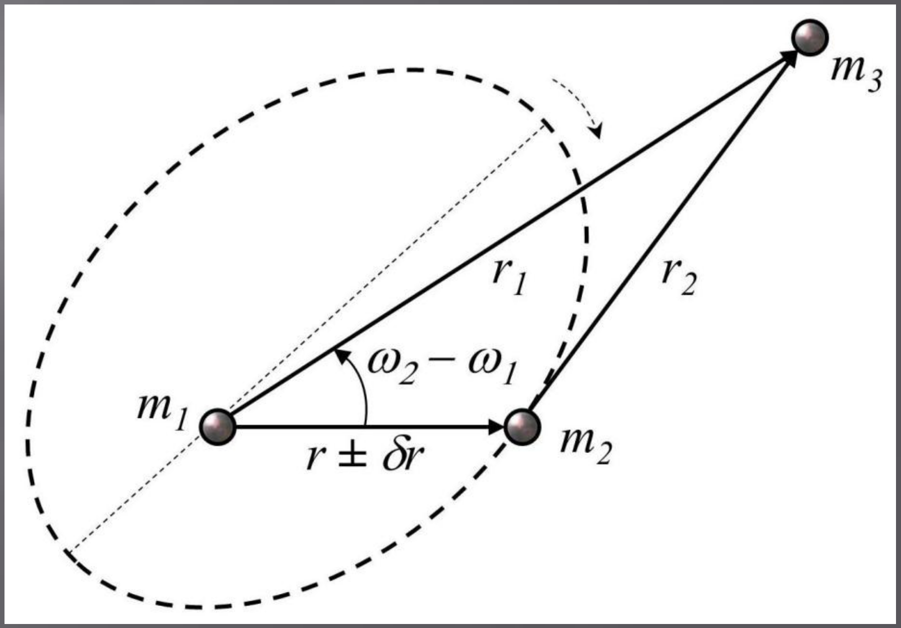
Consider m_1, m_2, falling towards m_3:

If all three violate the EP, their separation oscillates with frequency ω_2-ω_1 and amplitude:

$$\frac{\delta r}{r_1} = \left[\frac{1+2\omega_2/\omega_2-\omega_1}{2(\omega_2/\omega_1)-1}\right](\Delta_1-\Delta_2)$$

$$|\Delta_1 - \Delta_2| \le \epsilon_2$$

$$\varepsilon_2 = \frac{\delta r}{r_1}\left|\frac{(P_1-P_2)(2P_1-P_2)}{P_2(3P_1-P_2)}\right|$$



Limits with Nordtvedt

[Folkner 2011]

Table 3. Nordtvedt Limits

m_1	m_2	Best m_3	δr (km)	ε_2
Sun	Mercury	Venus	5	4×10^{-8}
Sun	Venus	Earth	1	2×10^{-9}
Sun	Earth	Venus	0.015	2×10^{-11}
Sun	Mars	Earth	1.5	5×10^{-10}
Sun	Jupiter	Saturn	50	3×10^{-8}
Sun	Saturn	Uranus	1.5	6×10^{-10}
Sun	Uranus	Neptune	1000	1×10^{-7}
Sun	Neptune	Uranus	5000	4×10^{-8}
Earth	Moon	Sun	6.7 mm	2×10^{-13}
Saturn	Tethys	Sun	0.10	7×10^{-11}
Saturn	Dione	Sun	0.15	7×10^{-11}

[Williams & Dickey 2003] [Antreasian et al. 2006]

Δ's for bodies

$$\left|\left(\frac{\Delta_1}{m_1/m_2}\right) + \Delta_2\right| \leq \epsilon_1$$

$$\left|\Delta_1 - \tfrac{1}{2}\Delta_2\right| \leq \epsilon_2$$

$$|\Delta_1 - \Delta_2| \leq \epsilon_2$$

$$\Delta_1 \approx c_2\epsilon_1 + \epsilon_2$$

$$\Delta_2 \approx \epsilon_1 + c_1\epsilon_2$$

Where $c_1 = m_2/m_1$
and $c_2 = 1$ or ½

Table 3. Best limits for individual bodies

Body	Δ
Sun	2×10^{-10}
Mercury	1×10^{-7}
Venus	1×10^{-8}
Earth	1×10^{-10}
Moon	9×10^{-9}
Mars	8×10^{-9}
Jupiter	9×10^{-8}
Saturn	9×10^{-8}
Tethys	2×10^{-7}
Dione	2×10^{-7}
Uranus	5×10^{-7}
Neptune	2×10^{-6}

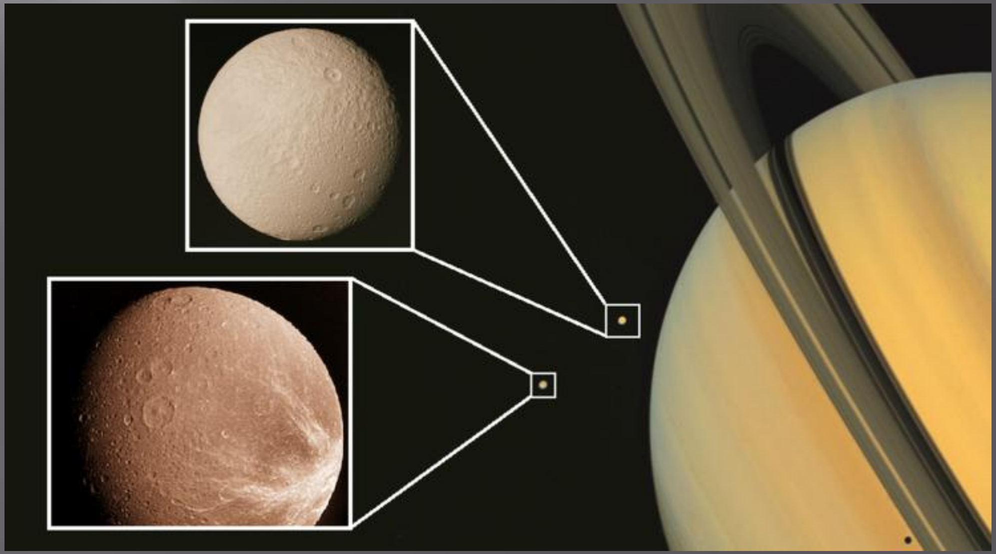
Limits on individual elements

If we consider the Δ in our body to be due to one element, we can limit constraints on individual elements.

Limits for Δ on certain elements:

Element	Δ
H	2×10^{-10}
He	6×10^{-10}
O	5×10^{-10}
Fe	5×10^{-10}
Si	8×10^{-10}
Mg	9×10^{-10}

Tethys (pure ice, ~ O_2)



Dione (rock/ice, ~ Si)

Questions?

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