SCENARIOS FOR DEALING WITH APOPHIS

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2007 Planetary Defense Conference
Washington, DC
March 5-8, 2007

Brief History of Apophis

June 19, 2004: Asteroid discovered, designated 2004 MN4, subsequently lost.

Dec. 18. 2004: Rediscovered.

Dec. 23, 2004: Possible Earth impact on April 13, 2029, probability = 0.0043,
Torino scale = 2, Palermo Scale = 0.39.

Dec. 25, 2004: 2029 impact probability = 0.024.

Dec. 27, 2004: 2029 impact probability = 0.027,
Torino Scale = 4, Palermo Scale = 1.1.

Dec. 27, 2004: Prediscovery images found from March 15, 2004;
impact in 2029 ruled out. However, very close pass
makes future impacts possible.

Brief History of Apophis (Continued)

April 2005: Impact probability for April 13, 2036, = 6.8×10^{-5},
Torino Scale = 1, Palermo Scale = –1.76.
Four other dates with probability > 10^{-6}.

June 2005: Number 99942 assigned.

July 2005: Name Apophis assigned.

Recent: 2036 impact probability = 2.2×10^{-5},
Torino Scale = 0, Palermo Scale = –2.52.
All other dates have probability < 10^{-6}.

Estimated Properties of Apophis

Diameter = 250 m.

Mass = 2.1×10^{10} kg.

Approach speed = 5.87 km/s.

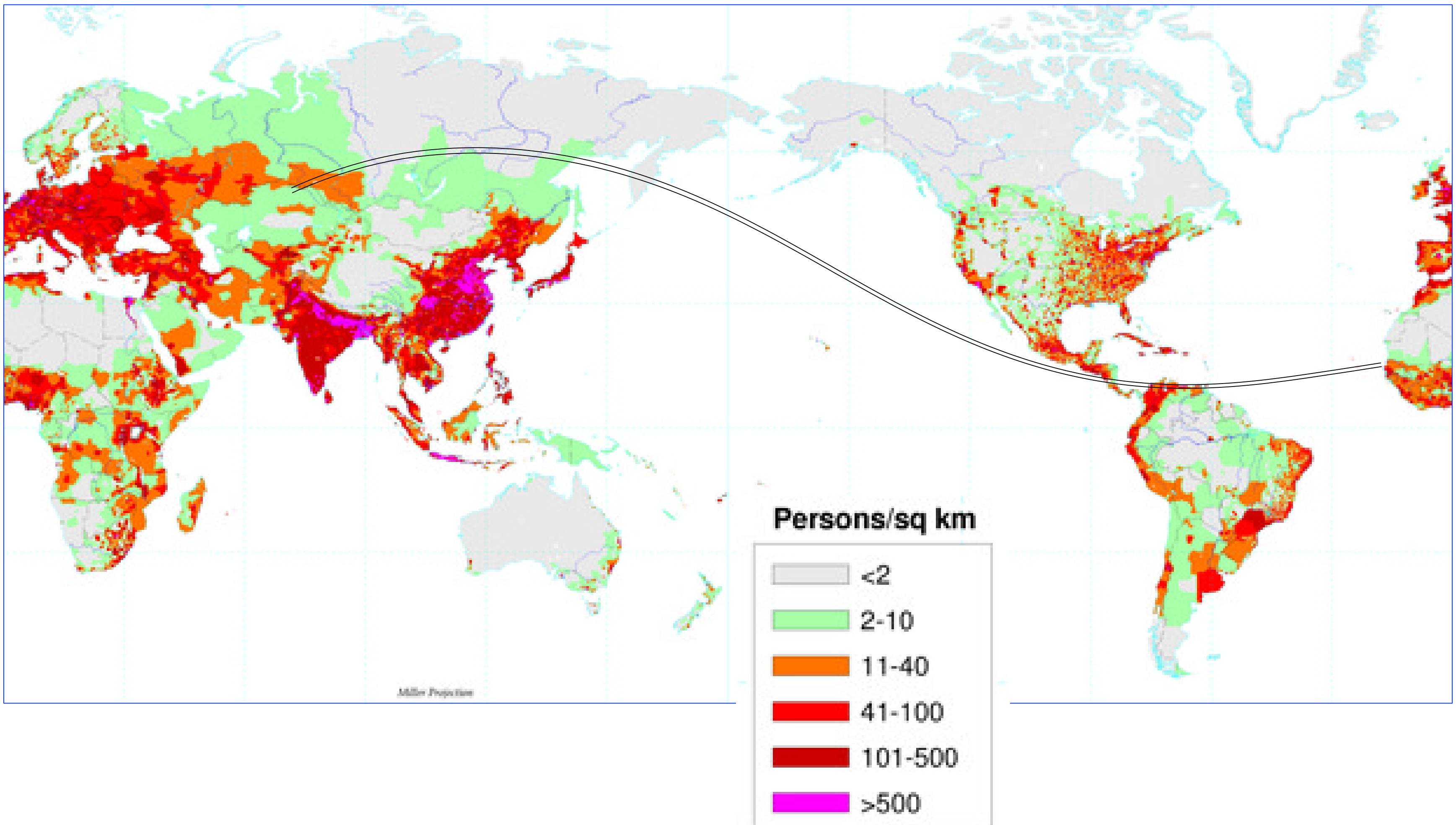
Impact speed = 12.6 km/s.

Impact energy = 400 MtTNT.

Diameter of destruction on land $\approx$ 100 km.

Possible tsunami from ocean impact.

Range of Possible Impact Points on April 13, 2036



Map adapted from Global Population Density - 1994, at http://soils.usda.gov/use/worldsoils/mapindex/popden.html, Natural Resources Conservation Service, United States Department of Agriculture.

Encounter with Earth on April 13, 2029

Closest approach:

38,200 km from center (σ = 600 km).

Visual magnitude:

3.3 near western tip of Africa,
3.5 in most of Europe and Africa,
about 4 in most of Asia,
> 6 in most of North America.

Keyhole:

Width = 0.61 km.
If Apophis passes through it on April 13, 2029,
it will hit Earth on April 13, 2036.

Gain due to Earth's Gravity

Change in position in 2036 relative to change before close approach in 2029:
about 40,000.

Useful gain because of uncertainty in the orbit:
less than 100 to more than 10,000.

These large gains make practical the use of kinetic impact or a gravitational tractor.

Conservative Assumptions Used in Deflection Computation

Mass of Apophis: 4.2×10^{10} kg (twice the current estimate).

Deflection needed in the 2029 b plane: $\Delta b = 5\sigma_b + w/2$,
where σ_b is the standard deviation in the b plane
and w is the width of the keyhole (0.61 km).

Minimum mass of hardware delivered to Apophis: 700 kg.

Only the momentum of the vehicle is considered in the kinetic impact method.

Assumptions about Propulsion

Method	Effective exhaust velocity	Specific impulse	Maximum thrust
Chemical rockets (kinetic or tractor)	3.1 km/s	316 s	high
Solar-electric propulsion (tractor only)	31 km/s	3160 s	0.1 or 1 N

For towing by a gravitational tractor, the engines are angled out, so that only 58% of each above value is effective then.

Main Scenarios before 2029

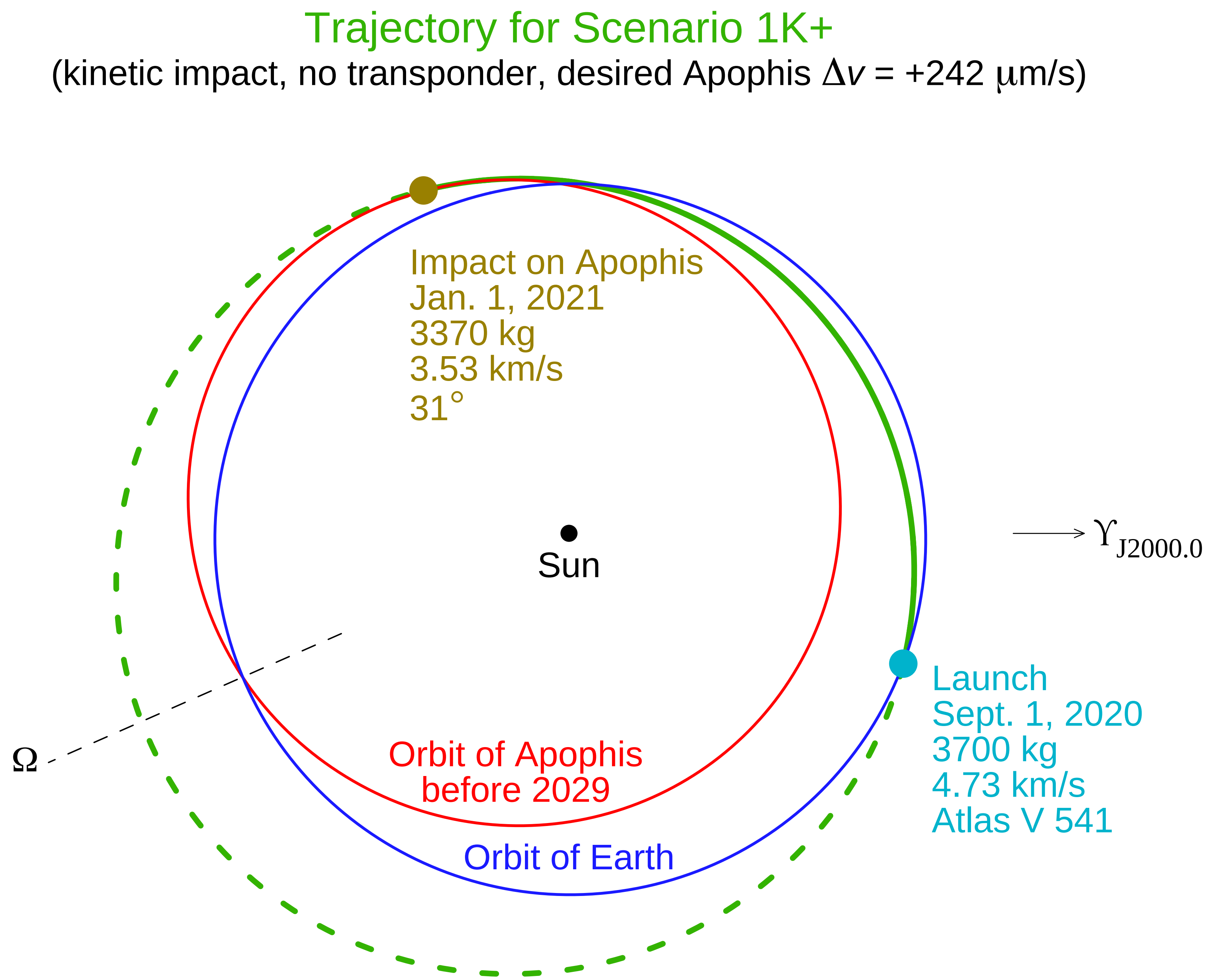
Scenario	Rationale	Launch	Arrival	σ_b without transponder	Δb without transponder
1	Early deflection	2020-2021	2021	30 km	150 km
2	Late launch	2023	2027	1.1 km	5.8 km
3	Low relative arrival speed	2020-2022	2023-2024		
				σ_b with transponder	Δb with transponder
All				0.13 km	0.96 km

Key to Information about Trajectories on the Following Pages

For launch:
- Date
- Mass escaping from Earth
- Hyperbolic excess velocity
- Appropriate launch vehicle

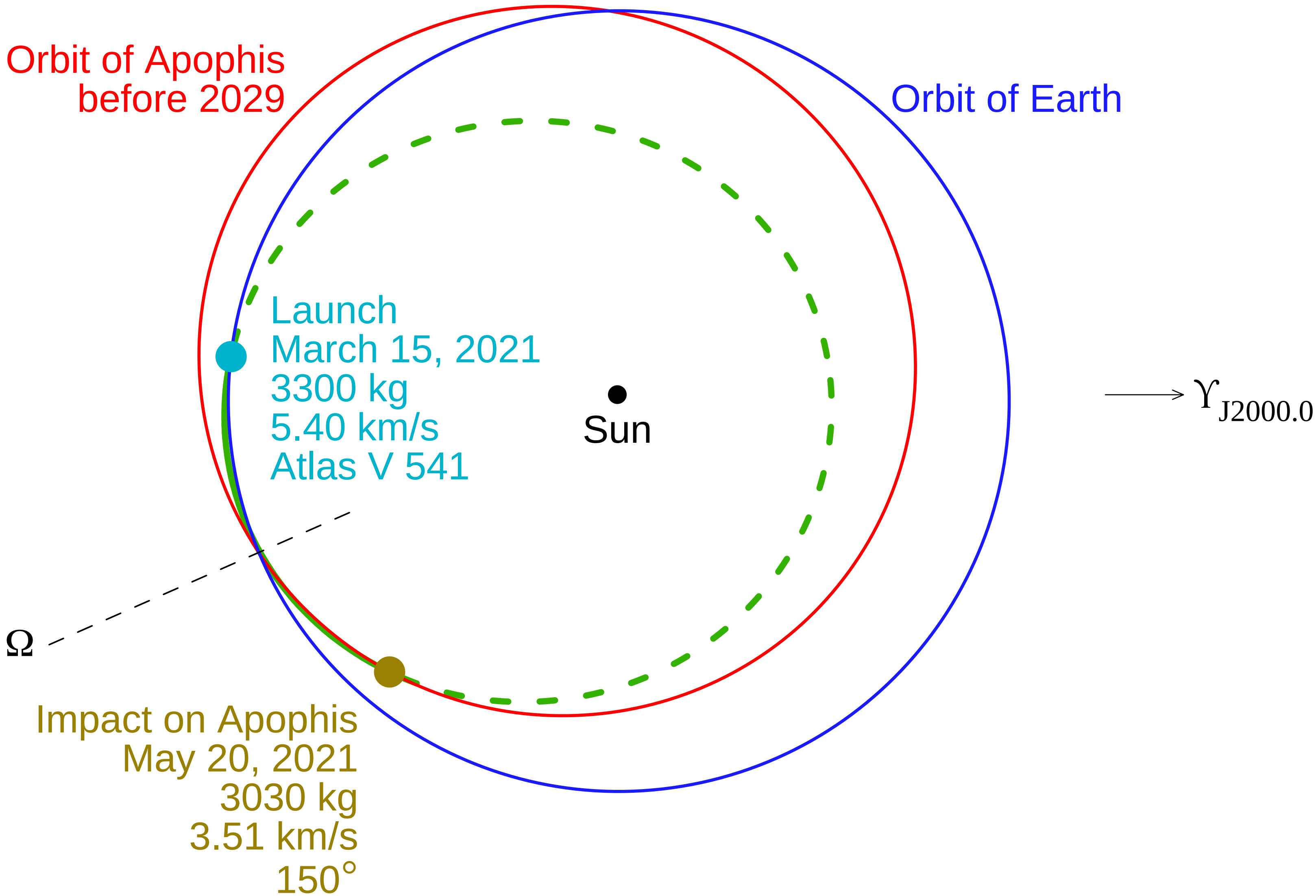
For arrival at Apophis (impact or rendezvous):
- Date (middle of rendezvous acceleration for gravitational tractor)
- Mass arriving at Apophis (impacting or after rendezvous)
- Relative approach velocity
- Angle between above velocity and orbital velocity of Apophis

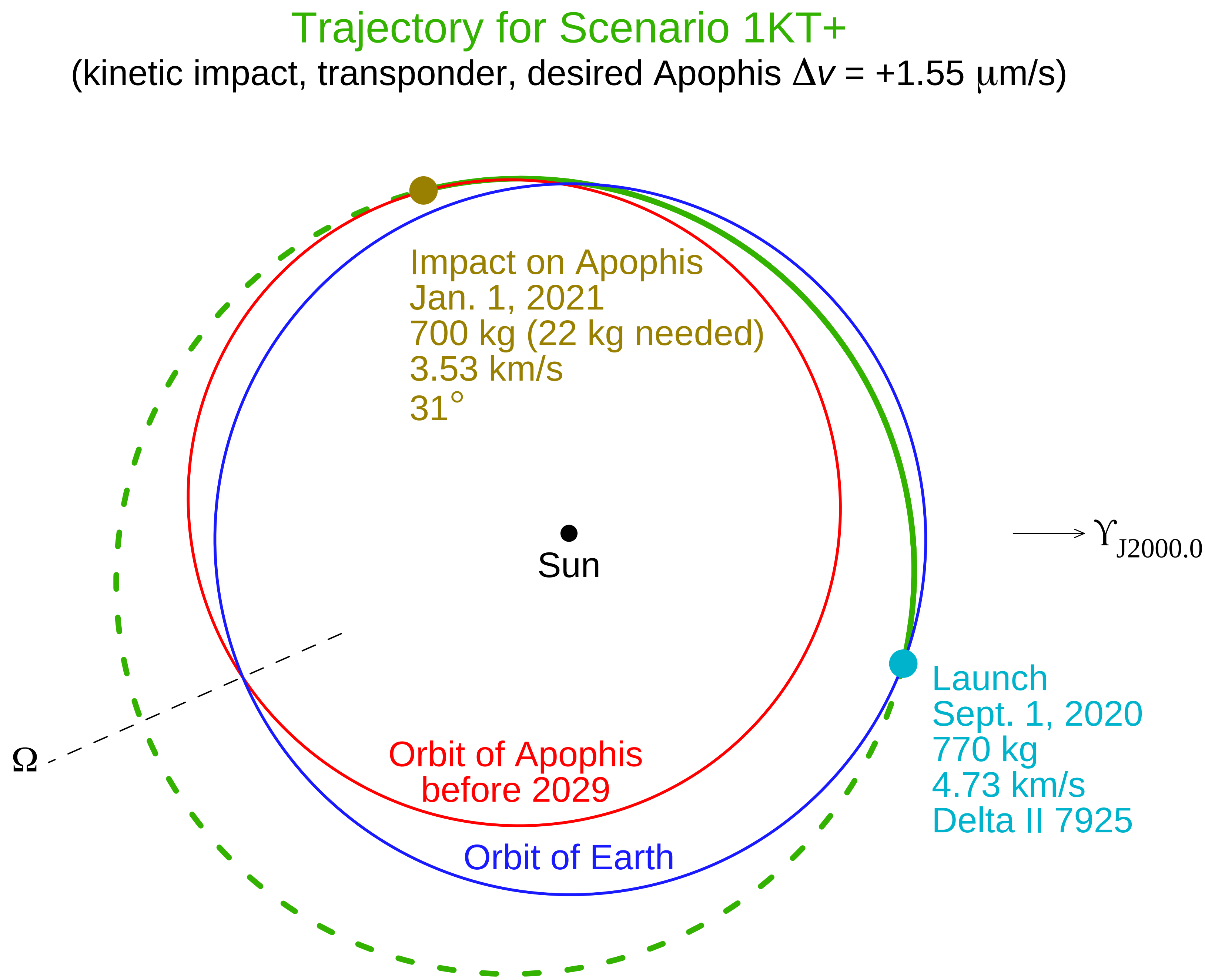
The trajectory of the spacecraft is shown as a solid green line, and the unused portion (if any) of its elliptical orbit is shown as a dashed green line.


Trajectory for Scenario 1K+
(kinetic impact, no transponder, desired Apophis Δv = +242 μm/s)
Impact on Apophis
Jan. 1, 2021
3370 kg
3.53 km/s
31°
Sun
ϒ J2000.0
Ω
Launch
Sept. 1, 2020
3700 kg
4.73 km/s
Atlas V 541
Orbit of Apophis
before 2029
Orbit of Earth

Trajectory for Scenario 1K–

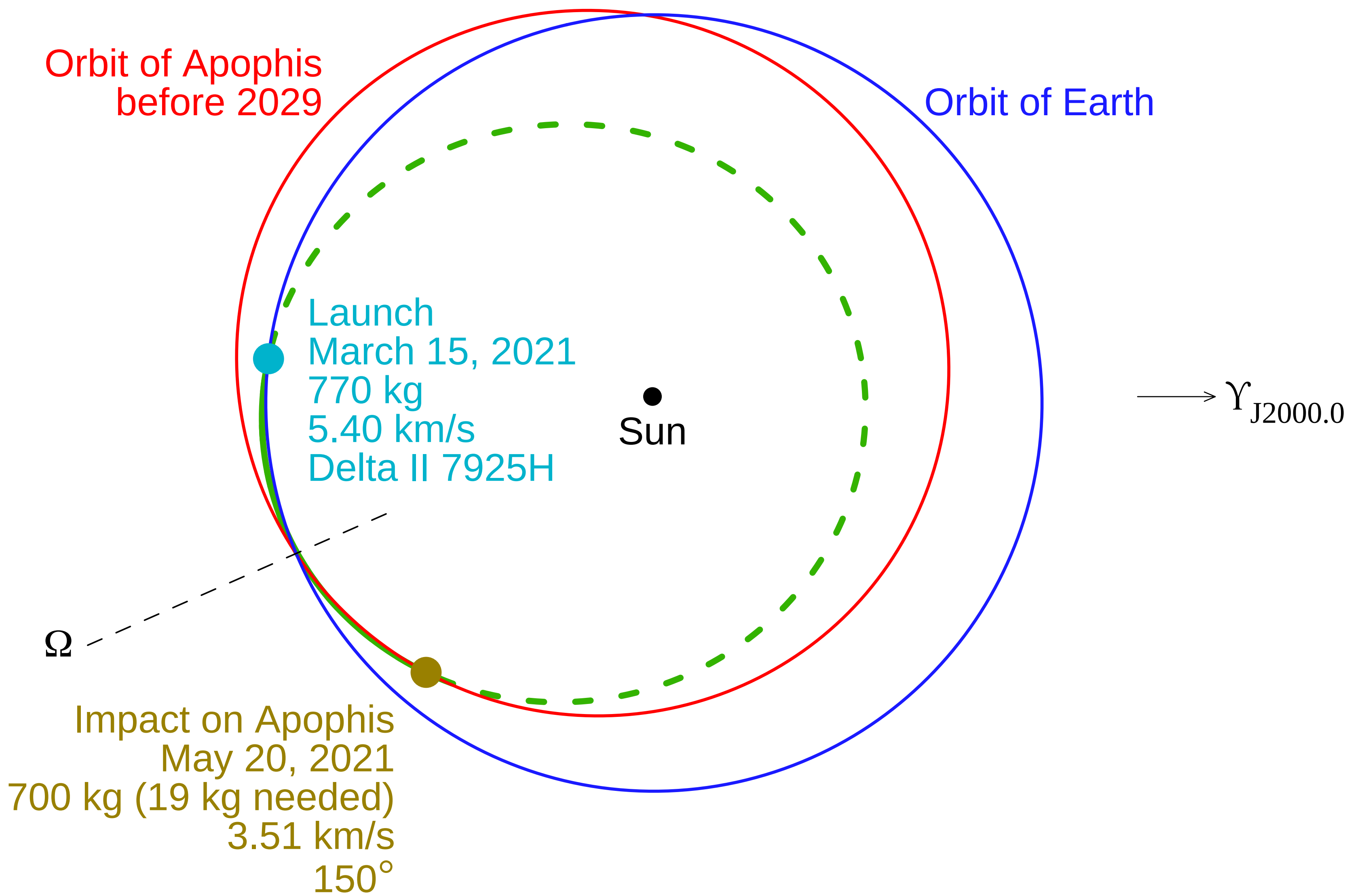
(kinetic impact, no transponder, desired Apophis Δv = –220 μm/s)




Trajectory for Scenario 1KT+
(kinetic impact, transponder, desired Apophis Δv = +1.55 μm/s)
Impact on Apophis
Jan. 1, 2021
700 kg (22 kg needed)
3.53 km/s
31°
Sun
Υ J2000.0
Ω
Launch
Sept. 1, 2020
770 kg
4.73 km/s
Delta II 7925
Orbit of Apophis
before 2029
Orbit of Earth

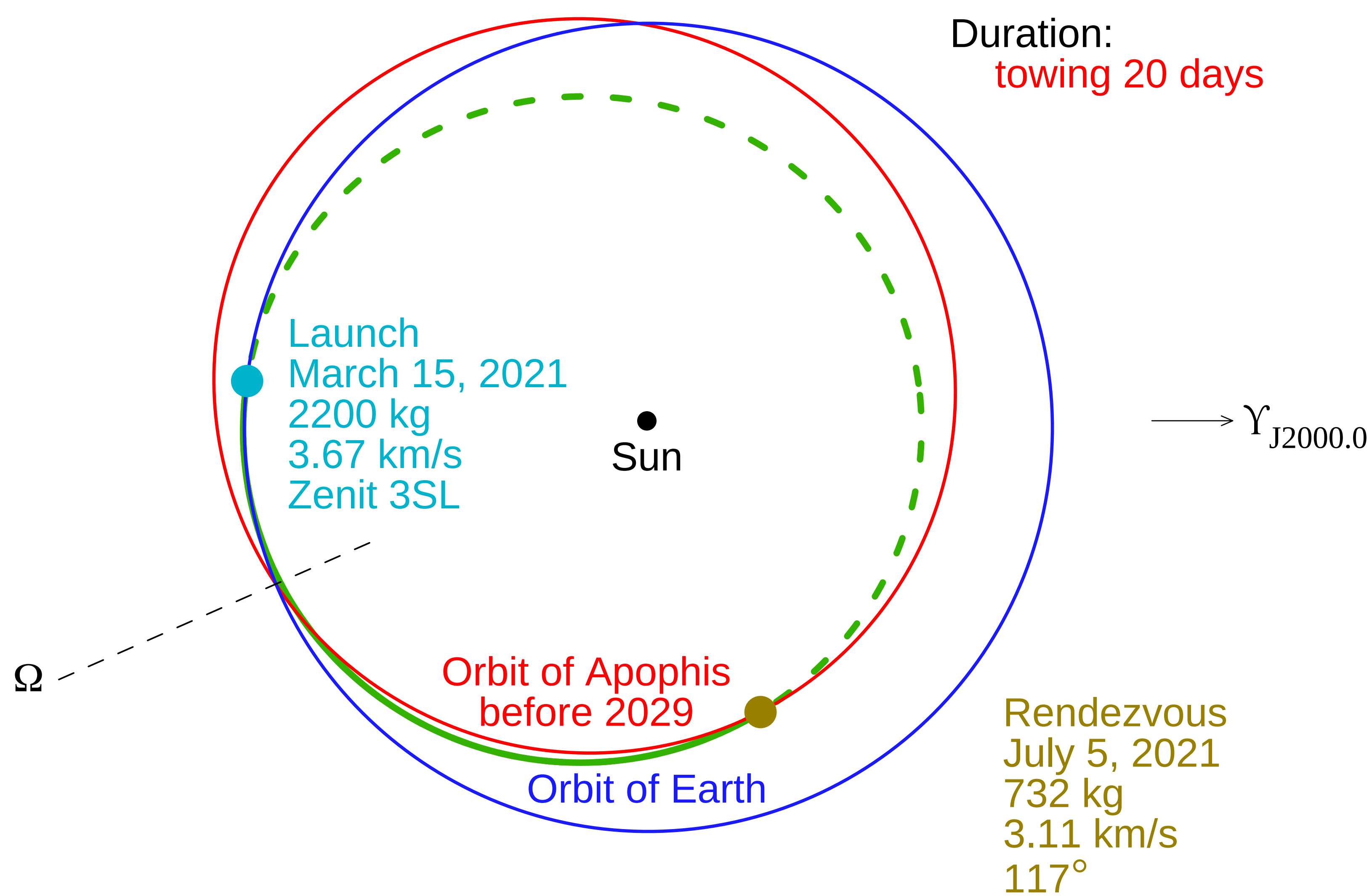
Trajectory for Scenario 1KT–

(kinetic impact, transponder, desired Apophis $\Delta v = -1.41\ \mu\text{m/s}$)



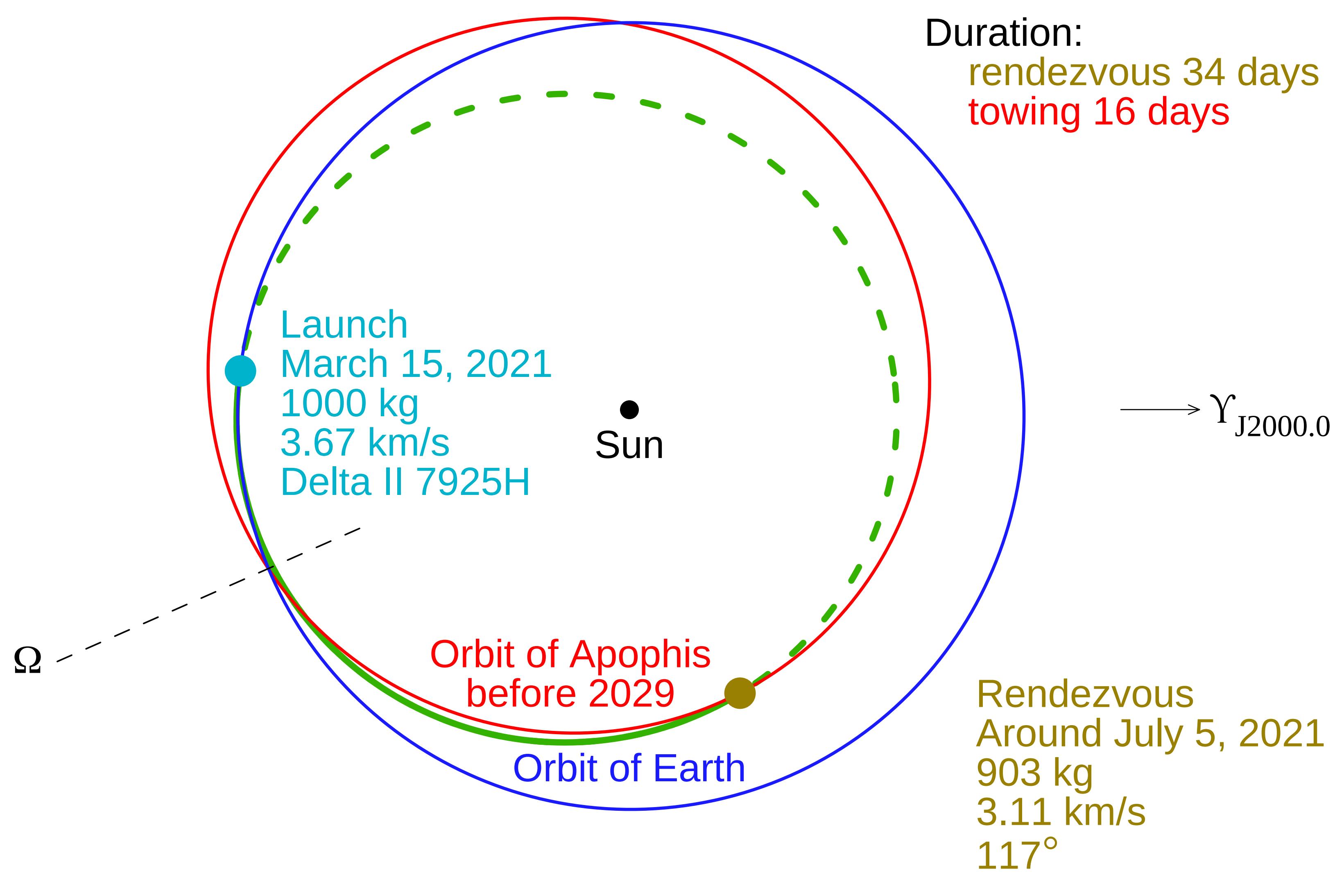
Trajectory for Scenario 1GC

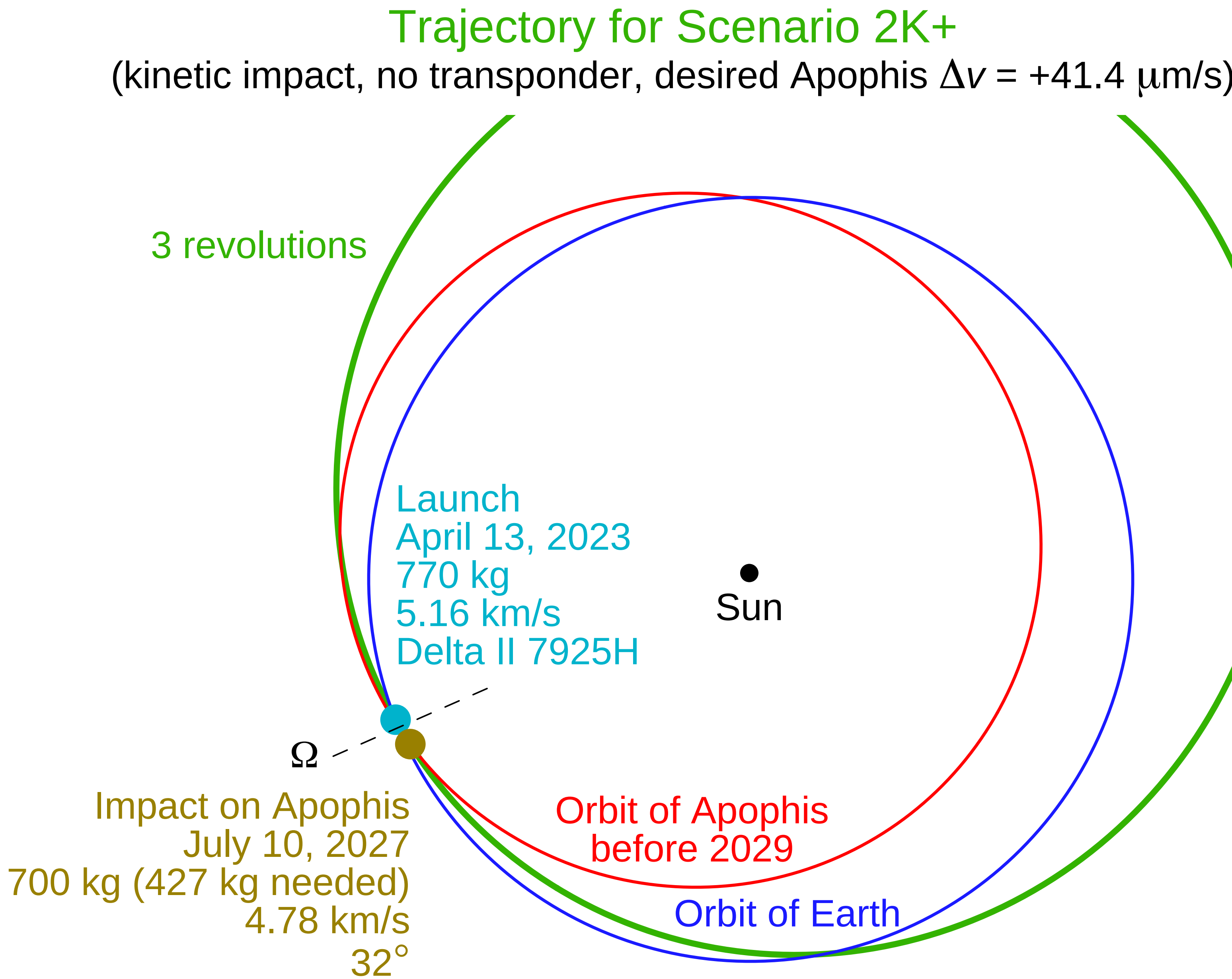
(gravitational tractor, chemical propulsion, desired Apophis Δv = 1.35 μm/s)

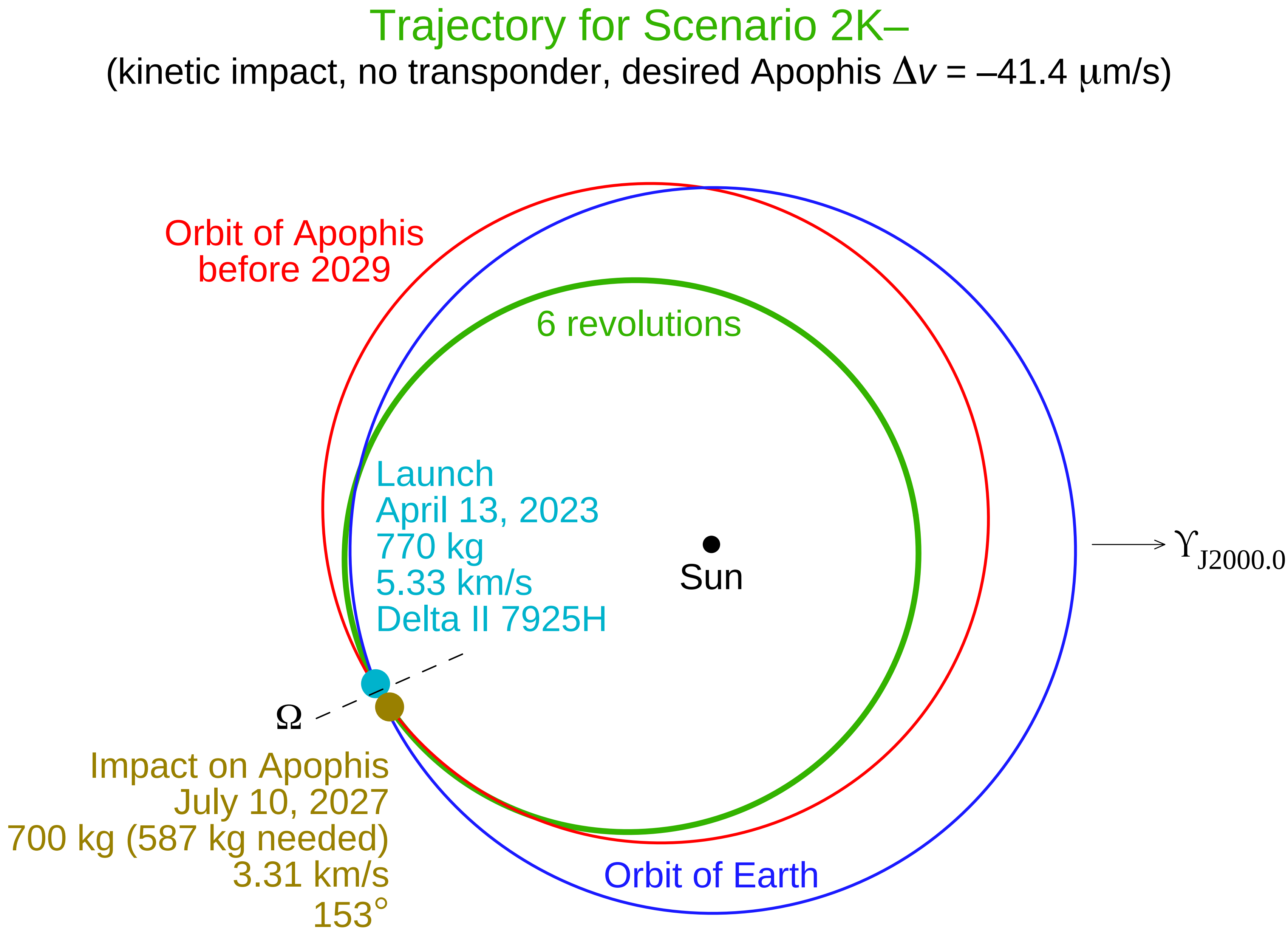


Trajectory for Scenario 1GE

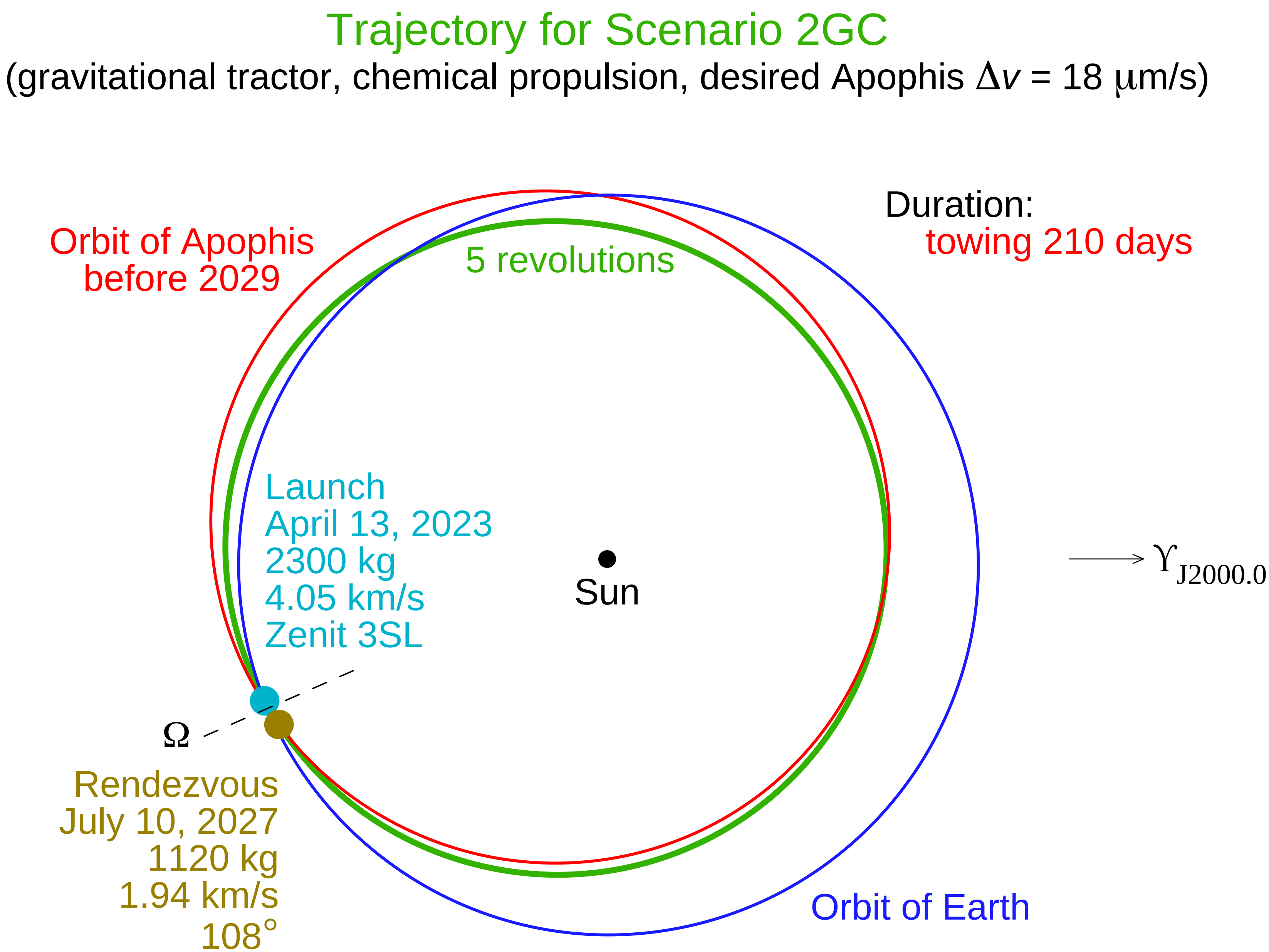
(gravitational tractor, 1-N electric propulsion, desired Apophis Δv = 1.35 μm/s)




Trajectory for Scenario 2K+
(kinetic impact, no transponder, desired Apophis Δv = +41.4 μm/s)
3 revolutions
Launch
April 13, 2023
770 kg
5.16 km/s
Delta II 7925H
Sun
Ω
Impact on Apophis
July 10, 2027
700 kg (427 kg needed)
4.78 km/s
32°
Orbit of Apophis
before 2029
Orbit of Earth



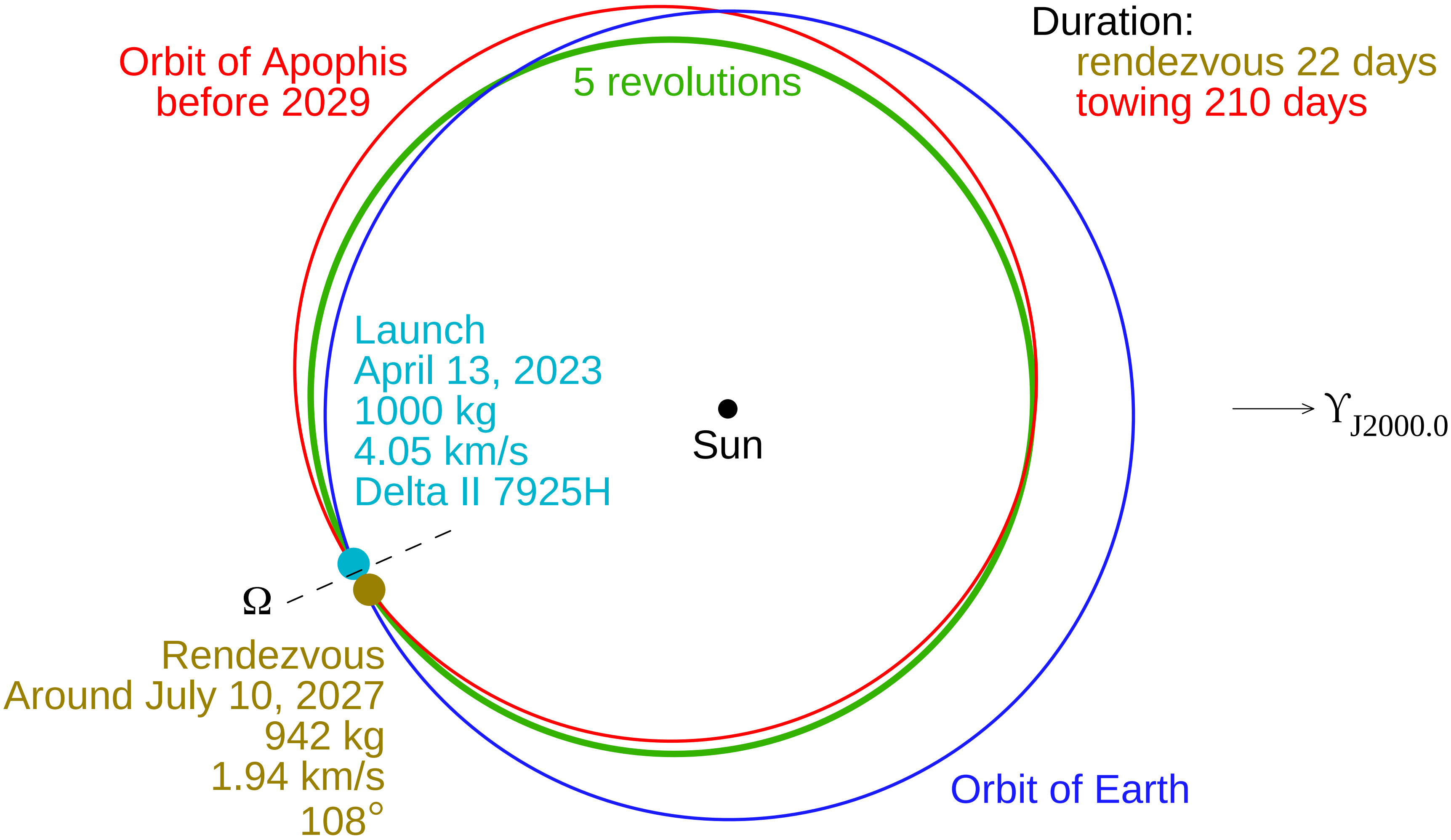
Trajectory for Scenario 2K–
(kinetic impact, no transponder, desired Apophis Δv = –41.4 μm/s)
Orbit of Apophis
before 2029
6 revolutions
Launch
April 13, 2023
770 kg
5.33 km/s
Delta II 7925H
Sun
ϒJ2000.0
Ω
Impact on Apophis
July 10, 2027
700 kg (587 kg needed)
3.31 km/s
153°
Orbit of Earth



Trajectory for Scenario 2GC
(gravitational tractor, chemical propulsion, desired Apophis Δv = 18 μm/s)
Orbit of Apophis before 2029
5 revolutions
Duration: towing 210 days
Launch
April 13, 2023
2300 kg
4.05 km/s
Zenit 3SL
Sun
ϒJ2000.0
Ω
Rendezvous
July 10, 2027
1120 kg
1.94 km/s
108°
Orbit of Earth

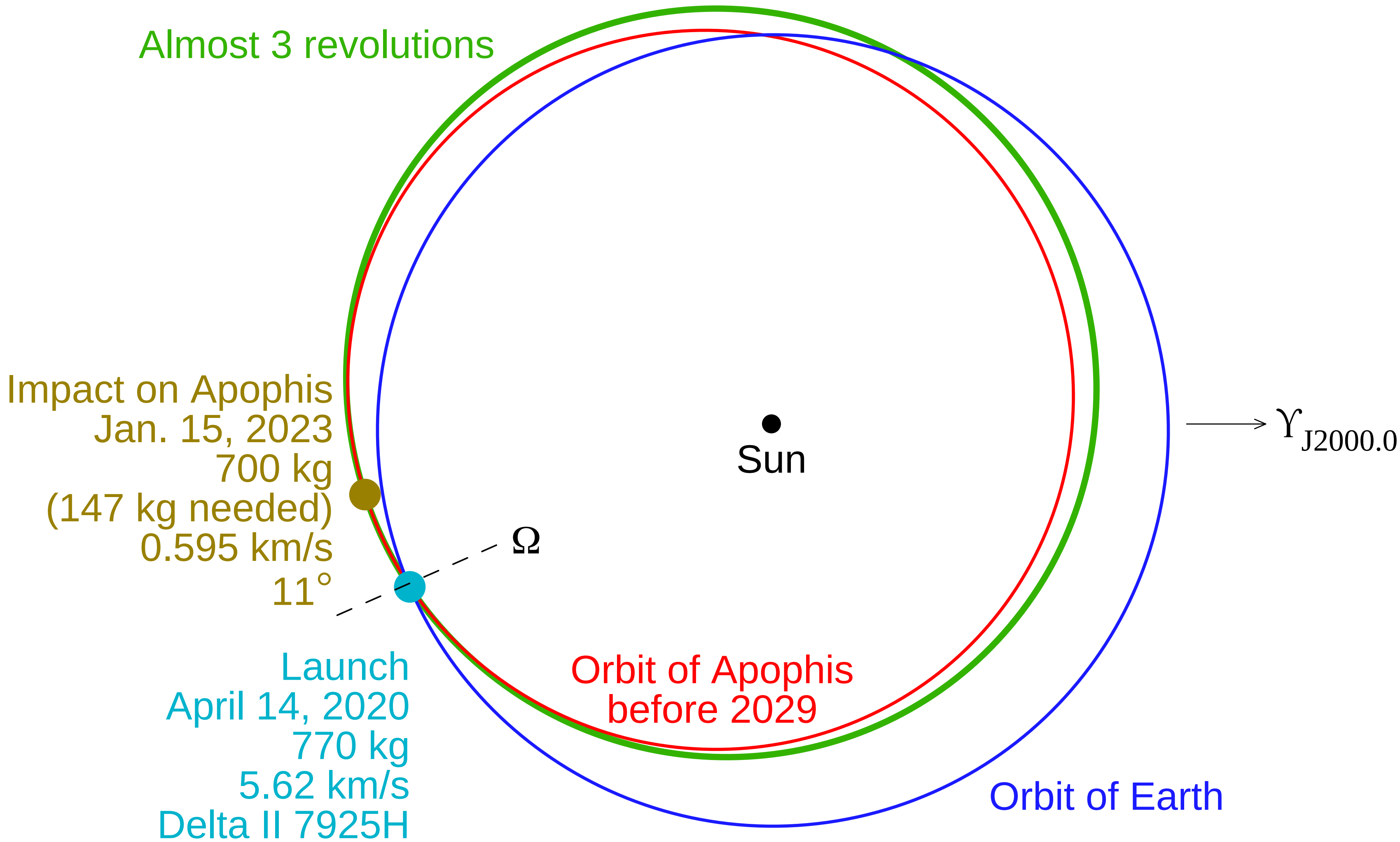
Trajectory for Scenario 2GE

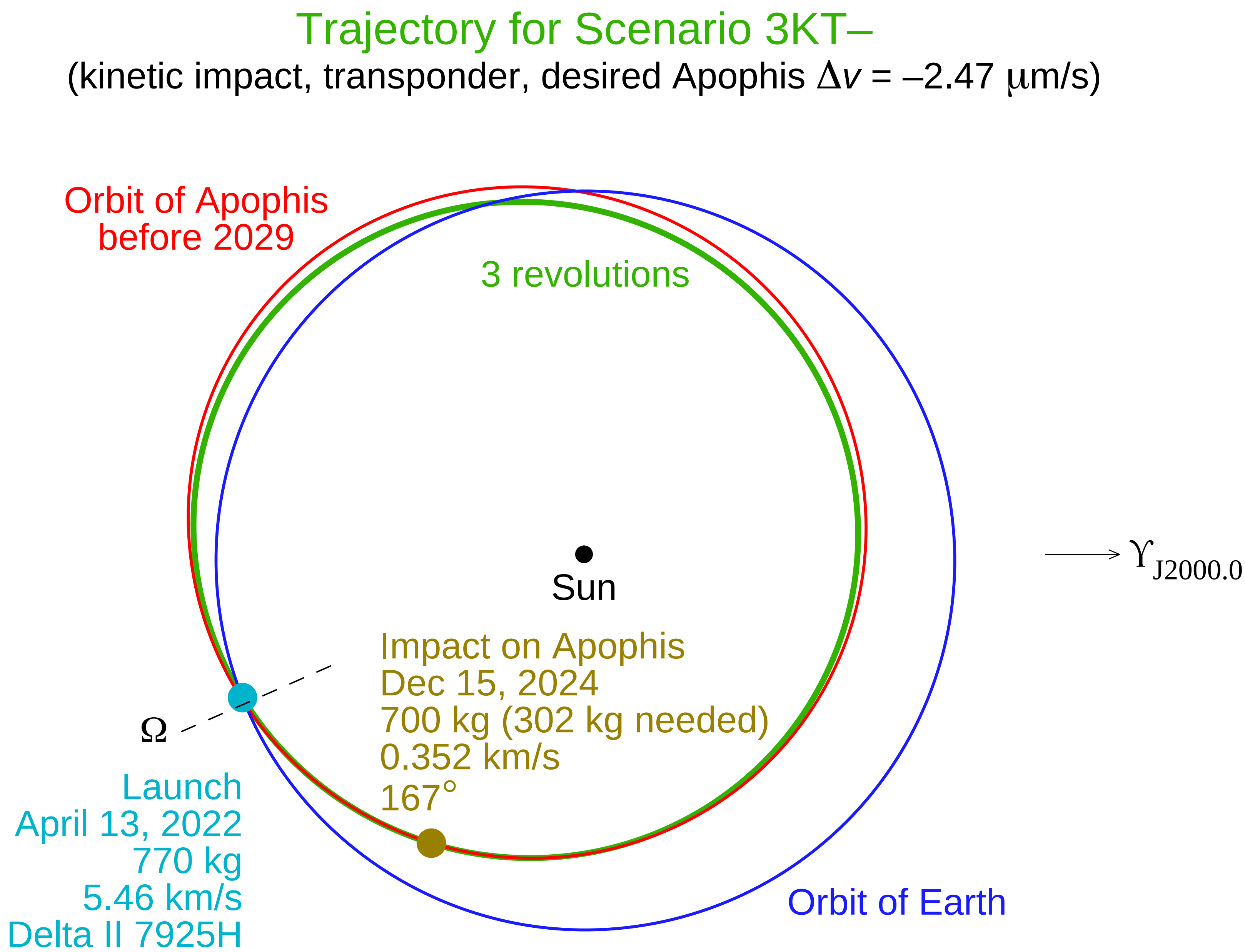
(gravitational tractor, 1-N electric propulsion, desired Apophis Δv = 18 μm/s)



Trajectory for Scenario 3KT+

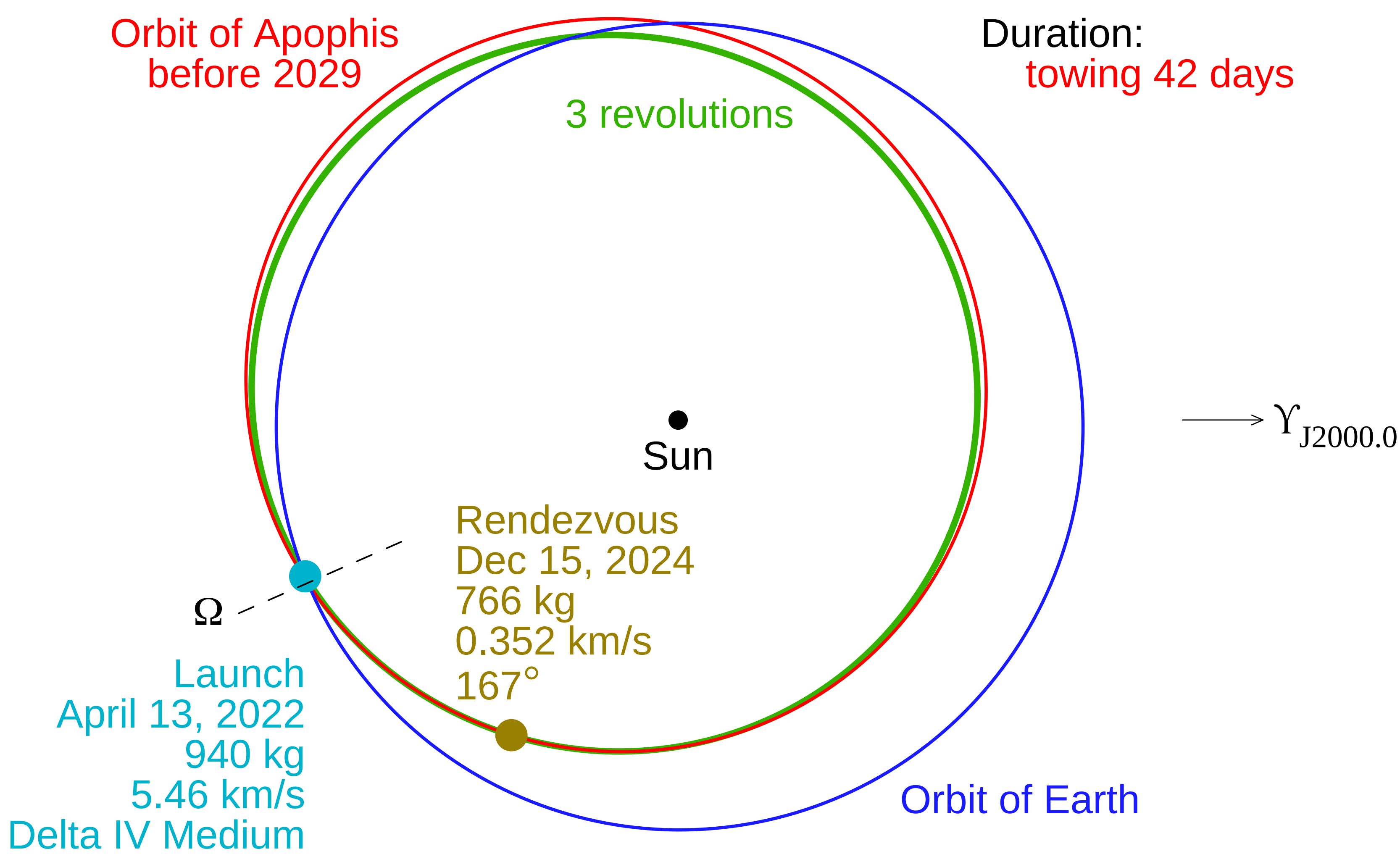
(kinetic impact, transponder, desired Apophis Δv = +2.04 μm/s)

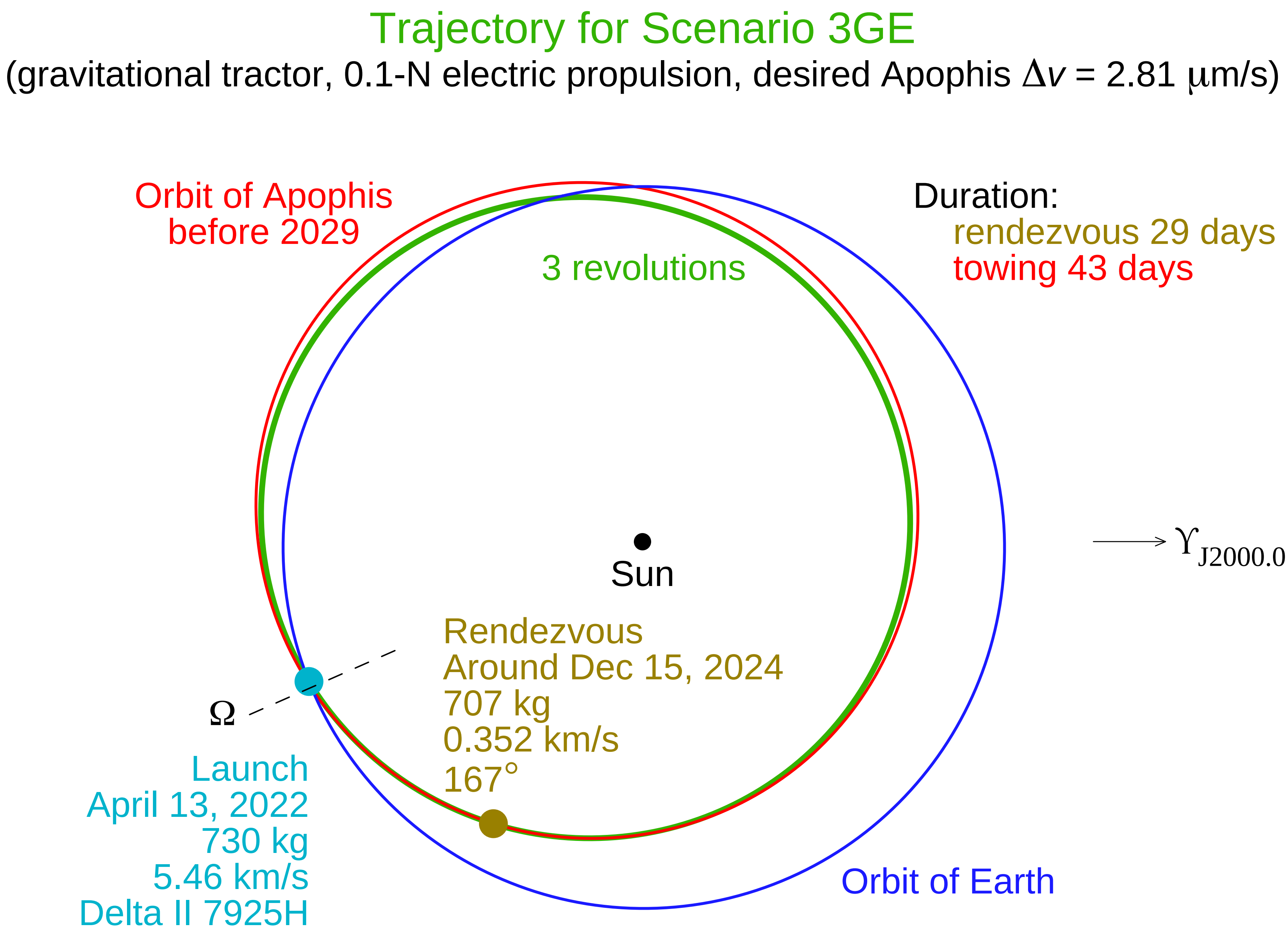



Trajectory for Scenario 3KT–
(kinetic impact, transponder, desired Apophis Δv = –2.47 μm/s)
Orbit of Apophis
before 2029
3 revolutions
Sun
ϒJ2000.0
Impact on Apophis
Dec 15, 2024
700 kg (302 kg needed)
0.352 km/s
167°
Ω
Launch
April 13, 2022
770 kg
5.46 km/s
Delta II 7925H
Orbit of Earth

Trajectory for Scenario 3GC

(gravitational tractor, chemical propulsion, desired Apophis Δv = 2.81 μm/s)




Trajectory for Scenario 3GE
(gravitational tractor, 0.1-N electric propulsion, desired Apophis Δv = 2.81 μm/s)
Orbit of Apophis before 2029
Duration:
rendezvous 29 days
towing 43 days
3 revolutions
Sun
ϒJ2000.0
Rendezvous
Around Dec 15, 2024
707 kg
0.352 km/s
167°
Ω
Launch
April 13, 2022
730 kg
5.46 km/s
Delta II 7925H
Orbit of Earth

Aiming a Kinetic Impactor

$$\text{Difficulty} \propto \frac{v^2}{D}$$

Deep Impact	$\dfrac{(10.3\ \text{km/s})^2}{6\ \text{km}} = 18\ \text{km/s}^2$
Don Quijote	$\dfrac{(10\ \text{km/s})^2}{0.5\ \text{km}} = 200\ \text{km/s}^2$
Scenario 2K+	$\dfrac{(4.78\ \text{km/s})^2}{0.25\ \text{km}} = 92\ \text{km/s}^2$
Scenario 3KT–	$\dfrac{(0.352\ \text{km/s})^2}{0.25\ \text{km}} = 0.50\ \text{km/s}^2$

The Possibility of Dispersal

Apophis:	Gravitational binding energy	Escape velocity
	0.14 GJ	150 mm/s

Scenario	Kinetic energy of impact	Δv given to Apophis
1K+	21 GJ	0.57 mm/s
1KT+	4.4 GJ	0.12 mm/s
1KT+ detached 22 kg	0.14 GJ	0.0037 mm/s
2K+	8.0 GJ	0.16 mm/s
3KT+	0.12 GJ	0.019 mm/s

Deflection after 2029 Using Buried Nuclear Explosions

Some examples, using existing bombs, approximately:

2 ktTNT in 2031

10 ktTNT in 2035

150 ktTNT in 2036, one month before impact

Deflection after 2029 Using Standoff Nuclear Explosions

Some examples:

One B53 bomb (9 MtTNT) in 2031

Six B83 bombs (1.2 MtTNT each) in 2031

One custom 10-MtTNT high-neutron-yield bomb in 2035

Conclusions

Deflection of Apophis is easy before 2029, using either kinetic impact or a gravitational tractor.

Deflection of Apophis after 2029 is difficult, but it can be done by means of nuclear explosions.

Each scenario presented here requires the use of only one existing launch vehicle, except:

Some of the kinetic scenarios use a separate transponder mission.
One of the nuclear scenarios uses several separately launched bombs.

The danger from fragments due to dispersing Apophis is:

nonexistent with a gravitational tractor,
very small to nonexistent in the kinetic-impact method,
generally small in the nuclear method, depending on the particular scenario.