Project Lyra: What SpaceX could do

The Way to Go and the Launcher to Get There

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The Initiative & Institute for Interstellar Studies (i4is.org) recognised the significance of the first discovery of an Interstellar object (ISO), 1I/'Oumuamua, within days of the announcement from the Pan-STARRS system at Haleakalā Observatory, Hawaii, on 19 October 2017. i4is initiated Project Lyra and published the first study of a mission to 1I within three weeks of the announcement [1]. Since then our team have been the most active organisation in both studying missions to ISOs and advocating missions to them.

Here our primary mission planner, Adam Hibberd, addresses the question of which of the larger SpaceX launch vehicles might be best suited to the purpose. This prefigures a journal paper which Adam is preparing covering all the heavy launchers which might be considered for such a mission [2].

1I remains enigmatic, with a number of possible explanations for its properties and behaviour battling in the court of scientific opinion. Only by a mission to this strange object can we definitely determine its nature.

1 Introduction

Project Lyra is the feasibility study of missions to the first interstellar object to be discovered, 1I/'Oumuamua.

The Lyra papers have addressed various possible trajectory options ('the way to go' in the title) but have largely skirted the issue of which launcher should carry the Lyra spacecraft payload by assuming one or two select launchers. The NASA Space Launch System Block 2 is the outstanding candidate for such a mission due to its 'super-heavy lift' credentials.

Broadly speaking there are three possible trajectory options available to a putative craft destined for 'Oumuamua:

1. The Solar Oberth Manoeuvre (SOM)
2. The Jupiter Oberth Manoeuvre (JOM)
3 The Passive Jupiter Gravitational Assist (PJGA)

Since 'Oumuamua is on a hyperbolic orbit (by definition), has passed perihelion, and is now heading away in excess of 26 km/s (equivalent to 5.5 au/year), an intercept mission must seek ways to rapidly escape the Solar System with a heliocentric excess speed of at least this value, in order to stand any chance of catching it up.

It so happens that theoretically the SOM above is optimal for achieving this requirement, that is if one ignores practicalities such as the necessity for a heat shield to protect the craft from the powerful solar flux associated with the close slingshot of the Sun. The early Lyra papers naturally adopted the SOM as the optimal strategy for travelling to 'Oumuamua, and so therefore factored in a carbon-carbon composite heat shield (scaled up from the Parker Solar Probe's). The results using this option were relatively rapid intercept of the target (~22 years) but also have a rather lower technological maturity level (TRL) due to the innovative SOM requirement, a manoeuvre never so far implemented in any mission, and would require some technological advancement in the field.

In this document the SOM is excluded from the analysis, largely because reasonably effective missions using either the JOM or the PJGA can be realised by the powerful launchers to be considered here. Furthermore the PJGA and the JOM are, in that order, the priorities defined in the Interstellar Probe Project as is stated in the definition file produced by JHU APL.

[1] arxiv.org/abs/1711.03155 and subsequently in the journal Acta Astronautica, *Project Lyra: Sending a spacecraft to 1I/'Oumuamua (former A/2017 U1), the interstellar asteroid*, www.sciencedirect.com/science/article/abs/pii/S0094576518317004
[2] *Project Lyra: The Way to Go and the Launcher to Get There*, Hibberd, 4 May 2023 arxiv.org/abs/2305.03065

▶

As far as the selection of a launcher is concerned, the reason for the narrow line of enquiry so far, is the abundance of information on the SLS made available by NASA. Moreover, in specific regard to escape missions – ie missions which escape the gravitational influence of our home world in order to travel to distant destinations in our Solar System - many launch vehicle user guides, especially future ones, give only a broad estimate of the capability of the vehicle in question.

In this article I shall attempt to redress this bias by investigating two SpaceX launch vehicles, Falcon Heavy and the Super-Heavy + Starship, for the purpose of a mission to 'Oumuamua. The latter has yet to accomplish a maiden flight-to-orbit but will likely be available in the Project Lyra launch timeline (ie 2026,2028-2033). There are of course various non-SpaceX launch options, and so I shall cover these in a more comprehensive science paper I am currently preparing on the subject.

For information, the main candidate launchers for Project Lyra, including the SpaceX ones, are outlined in Table 1. Grey shaded rows correspond to launcher capabilities which will expire in the near future and so will not be treated in the following analysis. Pink shaded launch vehicles will, in principle, be available by the time of Project Lyra.

Table 1 Current and Forthcoming Launch Vehicles		LEO	GTO	Lunar	Mars	Jupiter
		C3 (km^2s^{-2}) [1]				
		-60	-16.3	0	12	84
Payload (mt)						
Heavy Lift Launch Vehicles						
Ariane 5[a]	Heavy Lift	20	9.2	6.6[b]	4.1	N/A
Ariane 6 4[c]	Heavy Lift	21.65	11.5	8.6	6.9	N/A
Delta IV Heavy	Heavy Lift	28.79[d]	14.22[d]	10[d]	8[e]	N/A
Falcon Heavy Exp.[f]	Heavy Lift	?	?	15.01	11.88	1.875
Near-Future Super-Heavy Launch Vehicles						
SH + Starship[g]	Super-Heavy Lift	150	21	?	?	?
Long March 9[h]	Super-Heavy Lift	150	?	54	44	?
SLS Block 2[i]	Super-Heavy Lift	130	58	46	37	8

a = Ariane 5 User's Manual Issue 5 Rev 1. www.arianespace.com/wp-content/uploads/2015/09/Ariane5_users_manual_Issue5_July2011.pdf

b = Sun/Earth Lagrange Point 2

c = Data from Ariane 6 User's Manual Issue 2 Rev 1. www.arianespace.com/wp-content/uploads/2021/03/Mua-6_Issue-2_Revision-0_March-2021.pdf

d = Delta IV Heavy User Guide 2013. www.ulalaunch.com/docs/default-source/rockets/delta-iv-user's-guide.pdf

e = Spaceflight Now, Justin Ray, "The Heavy: Triple-sized Delta 4 rocket to debut" www.spaceflightnow.com/delta/d310/041207preview.html

f = NASA Launcher Query Service. elvperf.ksc.nasa.gov/Pages/Default.aspx

g = SpaceX Starship User Guide Revision 1.0. www.spacex.com/media/starship_users_guide_v1.pdf

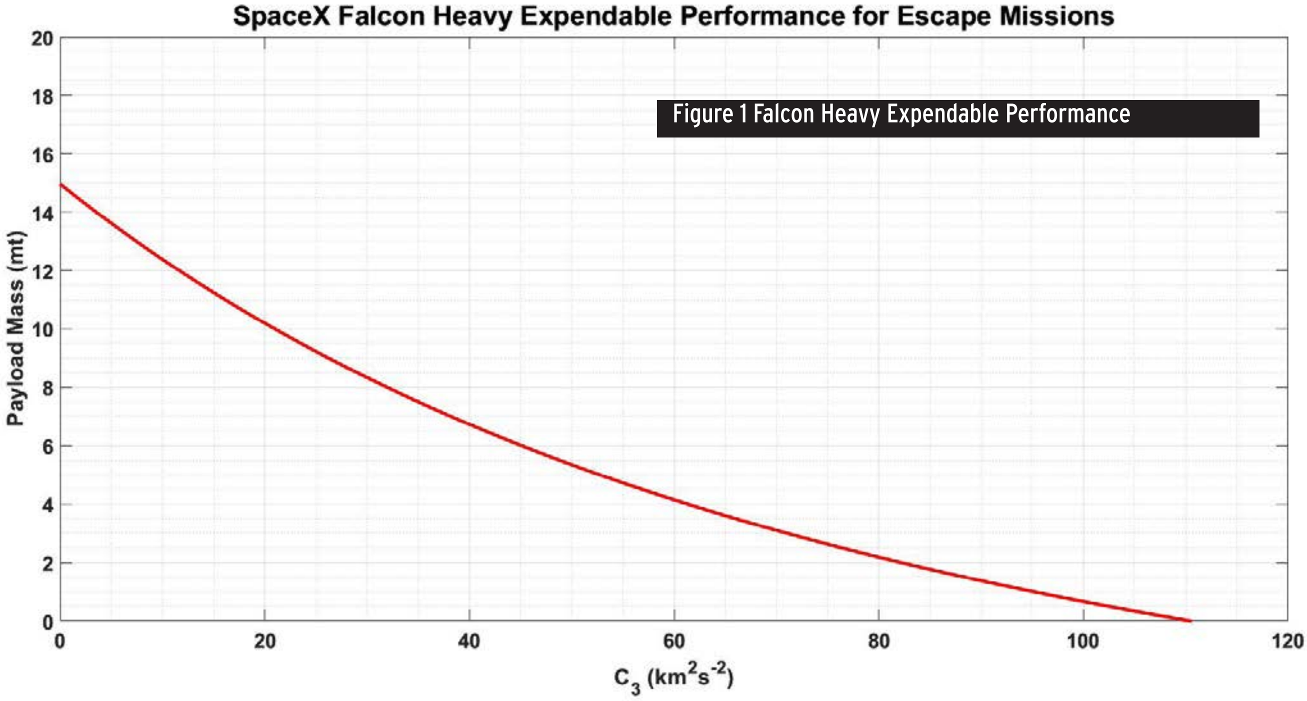
h = www.yangtse.com/zncontent/2767741.html (Translation: translate.goog/zncontent/2767741.html?_x_tr_sl=zh-CN&_x_tr_tl=en&_x_tr_hl=en&_x_tr_pto=sc

i = NASA's Space Launch System: Capabilities for Ultra-High C3 Missions, Robert W Stough. assets.pubpub.org/luea28iw/11617915904169.pdf

Grey Shading indicate to be phased out in near future

Pink Shading indicate near-future launch capabilities.

[1] C3 is the 'characteristic energy' and a measure of the energy of the target orbit in question.
$C_3 = V_\infty^2$ for a hyperbolic orbit where V∞ is the hyperbolic excess relative to Earth, ie. the speed at which the payload exits Earth's Sphere-of-influence
$C_3 = -\mu/a$ for an elliptical orbit where μ is the gravitational mass of the Earth and a is the semi-major axis of the elliptical orbit in question.



2 Falcon Heavy Expendable

The SpaceX Falcon Heavy is a super-heavy launch vehicle which, at the time of writing, has executed five successful launches. The fourth most powerful launcher of all time, that is until the SpaceX Super-Heavy + Starship achieves its maiden flight to orbit, this launch vehicle has two configuration options: either partially reusable or expendable, the latter more capable version is investigated here.

From Figure 1, a direct mission to Jupiter is feasible using this SpaceX rocket (the corresponding minimum energy Hohmann Transfer from Earth to Jupiter would require a C3 $\approx$ 77 km^2s^{-2}). The drawback is however that a payload mass of only around 2500 kg as indicated.

If we select a JOM (see Section 1) as our trajectory profile, then we must have attached to our spacecraft, a rocket booster less than this mass to fire at perijove. Table 2 provides a list of the candidates. Most of these are taken from the report on the Interstellar Probe project currently being pursued by JHU APL. We find that only the STAR 48B is light enough to deliver this kick, and it turns out that the overall flight time is rather too large to be practicable.

Table 2 Chemical Propellant Stages

Booster Stage	Exhaust Velocity (km/s)	Total Mass (kg)	Dry Mass (kg)	Propellant Mass (kg)	Height (m)
STAR 75	2.8225	8068	565	7503	2.59
STAR 63F	2.9106	4590	326	4264	1.78
STAR 48B	2.8028	2137	124	2013	2.03
ORION 50XL	2.8647	4306	367	3939	3.07
CASTOR 30B	2.9649	13971	1000	12971	3.5
CASTOR 30XL	2.8866	26406	1392	25014	6.0

Furthermore from Figure 1, we find that a C3 value of 100 km^2s^{-2}, which gets to Jupiter and more, can deliver a mass of 750 kg to the escape orbit from Earth. Is this sufficient to allow a mission to ‘Oumuamua within a realistic timeframe? The answer is also a definite no. So what are we to do?

Rescue is at hand: there is an alternative way which requires lower C3 values and might enable some sort of feasible mission for this heavy lift launcher, and that is the V-infinity Leveraging Manoeuvre (VILM).

For a VILM, the spacecraft (s/c) embarks on an Earth-return heliocentric elliptical arc, with a time-period of n multiples of Earth’s year (365 days), where n is a whole number, usually 1, 2 or 3. A VILM is a useful mechanism by which the speed of the s/c relative to the Sun can be augmented via exploiting the Earth’s mass with a gravitational assist (GA) of the planet. Table 3 spells out the three options n=1, 2 & 3, and provides not only the respective C3 values for each of these options, but also the Falcon Heavy payload lift capability to the escape orbits.

Table 3 Falcon Heavy payload performance to a range of VILM orbits.

n	Time Period (days)	Aphelion (au)	V∞ (km/s)	C3 (km2s-2)	FH Mass (mt)
1	365	1.0	0	0	15
2	730	2.2	5.140	26.42	10
3	1095	3.2	6.982	48.75	6

Table 4 highlights the results of this analysis, addressing each of the scenarios n=1, 2 & 3 in turn. As can be observed, the option n=2, hits the 'sweet-spot' for this Falcon Heavy launcher, with an overall flight duration of 28 years, and with the n=1 & 3 lagging quite significantly behind, at 54 years and 43 years respectively.

The n=2 scenario supposes that a STAR 63F and a STAR 48B are fired at the Earth return, and then a second STAR 48B is fired at perijove. Further an additional 0.5 km/s is applied at the DSM, the reason for adopting this value is so that a low-thrust, high specific impulse propulsion option, such as electric, would be able to deliver this ΔV velocity increment slowly over the course of the n-year Earth resonant orbit, if so desired.

Table 4 Results of missions to 'Oumuamua using Falcon Heavy and VILMs

n	Mass available (mt)	Stages	Mass used + Payload 100kg (kg)	ΔV at Earth Return (km/s)	ΔV at Earth Jupiter (km/s)	Flight Duration (years)	Launch Date
1	15	STAR 75 + STAR 48B	10,305	10.126	0	54	2029 DEC 19
2	10	STAR 63F + STAR 48B x2	9,857	3.6074	6.4499	28	2029 APR 08
3	6	STAR 48B x2	4,374	1.7282	6.4499	43	2027 FEB 25

Maiden launch of the Falcon Heavy, February 6, 2018 (including Musk's Tesla Roadster) Credit: SpaceX

3) Super-Heavy Starship

The SpaceX Starship will be a hugely capable launch vehicle, and as of the time of writing, has not yet achieved a maiden flight to orbit. The data on the internet is scant, but there is the User Guide.
With a good deal of reference to source documents on the internet, this has allowed me to construct the Table 5. The grey shaded areas are data that I have garnered from the internet. The mustard shaded areas are data which I have derived from the grey shaded parameters through appropriate calculations.
In Table 5, we are comparing the Starship with an SLS Block 1, as it is instructive, enabling us to make inferences from the comparison in order to have some idea as to the performance characteristics of the Starship.
We find that for an LEO, the SLS Block 1 and the Starship both have around the same calculated total ΔV, to around 0.05%.
For a Trans-Lunar Orbit (TLO) , however, where the C3 is around 0 km^2s^{-2}, the Starship is found significantly wanting, even with a supposed zero payload mass. And this would translate to an even larger degree of inadequacy for interplanetary missions.
Conclusion: Given the data we have at hand, the Super Heavy Starship is incapable of delivering a spacecraft directly to an Earth escape orbit. In fact this is not so surprising in that it is spelt out in so many words in the SpaceX Starship User Guide.
Let us instead look at the payload it can deliver to LEO, that amounts to an enormous 150 mt. However, the whole context of the Starship design is to allow the potential for in-space refuelling. Would this important asset permit missions to 'Oumuamua with much lower flight durations? We find that to entirely refuel a Starship in LEO, would need 8 launches of SH + Starship, each one carrying 150 mt of fuel.
Given that we have a fully refuelled Starship in LEO, what can we do to leverage this asset for a mission to 'Oumuamua via Jupiter? Figure 2 provides the necessary parameters for a Starship to exit LEO and carry a payload to Jupiter. The horizontal blue-dashed line is the minimum hyperbolic excess speed, V_∞, from Earth to travel along a Hohmann Transfer to Jupiter (ie the theoretical minimum 'energy' route to Jupiter). From this line we see that a fuelled Starship in LEO can send any mass up to around 170 mt to Jupiter.
This single important fact opens a wealth of options from which to choose in terms, for instance, of leveraging some combination of Booster Stages given in Table 2, to burn at perijove and arriving at 'Oumuamua extremely rapidly.
Let us address two such combination as example cases, Scenario 1 is a 2 stage option, and Scenario 2 is a 3 stage option (where in both cases the stages are fired at perijove).
Scenario 1 (2 stages):
We shall assume a payload mass of 860 kg (the same as the proposed Interstellar Probe). Together with a CASTOR 30XL and a STAR 75, this gives a total mass of 35.3 mt, and referring to Figure 3, this leads to a V_∞ of around 12 km/s. Not only that we have at Jupiter a ΔV for perijove of 8.632 km/s.
Results: Payload 860kg. Launch on 2031 MAR 01, Mission Duration = 23 years.
Scenario 2 (3 stages):
We shall again assume a payload mass of 860 kg. The three stages fired at perijove, in sequence are CASTOR 30XL, CASTOR 30B and then finally a STAR 48B. The total payload mass of all these stages corresponds to a V_∞ of about 11.8 km/s. The total ΔV at Jupiter is 9.829 km/s.
Results: Payload 860kg. Launch on 2031 FEB 28, Mission Duration = 20 years.

Table 5 Comparison of SLS and SH + Starship Performance

		SLS Block 1	SH + Starship	Notes
First Stage	Ve (km/s)	4.0479	3.2046 [g]	
	Mass Propellant (kg)	987471.0000 [b]	3600000.0000 [g]	
	Dry Mass (kg)	85275.0000 [b]	160000.0000 [g]	
	Burn time (s)	500.0000 [b]		
	Mass Flow Rate (kg/s)	1974.9420		
Strap-on Boosters	Ve (km/s)	2.6360 [c]		
	Mass Propellant (kg)	1451496 [c]		
	Dry Mass (kg)	200778.0000 [c]		
	Burn Time (s)	126.0000 [c]		
	Mass Flow Rate (kg/s)	11519.8095		
Second Stage	Ve (km/s)	4.5090 [d]	3.4300 [g]	
	Mass Propellant (kg)	29000.0000 [d]	1200000.0000 [g]	
	Dry Mass (kg)	3700.0000 [d]	100000.0000 [g]	
LEO	Payload Mass (kg)	95000.0000 [a]	150000.0000f	
	DeltaV Boosters On (km/s)	2.5745		
	DeltaV Boosters Ej (km/s)	6.0376		
	DeltaV First Stage (km/)	8.6120	3.7633	
	DeltaV Second Stage (km/s)	1.2238	6.0295	
	DeltaV Total (km/s)	9.7978	9.7928	Difference ~ 0.05%
Trans-Lunar	Payload Mass (kg)	27000.0000 [e]	*0.0000*	*Assuming NO MASS
	DeltaV Boosters On (km/s)	2.6786		To The Moon for
	DeltaV Boosters Ej (km/s)	7.2816		Starship*
	DeltaV First Stage (km/s)	9.9602	*3.9831*	
	DeltaV Second Stage (km/s)	3.1416	*8.7978*	
	DeltaV Total (km/s)	13.1018	*12.7809*	Difference ~ 2.5%

Yellow shaded data are calculated from grey shaded data
Grey shaded data are taken from various sources on the internet
*Asterisked data assume the SH + Starship has no payload mass to Trans-Lunar Orbit and demonstrates its lack of capability in this regard *

a= "The Great Escape: SLS Provides Power for Missions to the Moon" NASA, Aug 25, 2022, Jennifer Harbaugh, Brian Dunbar
b= "Space Launch System Core Stage", NASA, Oct 27, 2021, Jennifer Harbaugh, Brian Dunbar
c= "Space Launch System Solid Rocket Booster", NASA, Feb 11, 2022, Jennifer Harbaugh, Brian Dunbar
d="SLS Reference Guide 2022 V5 508", NASA
e= "America's Rocket for Deep Space Exploration", NASA, Jul 19 2022, Jennifer Harbaugh, Brian Dunbar
f= "SpaceX Starship User Guide Revision 1.0"
g= "Starbase Tour and Interview with Elon Musk", Everyday Astronaut, 11 Aug 2021, Trevor Sesnic

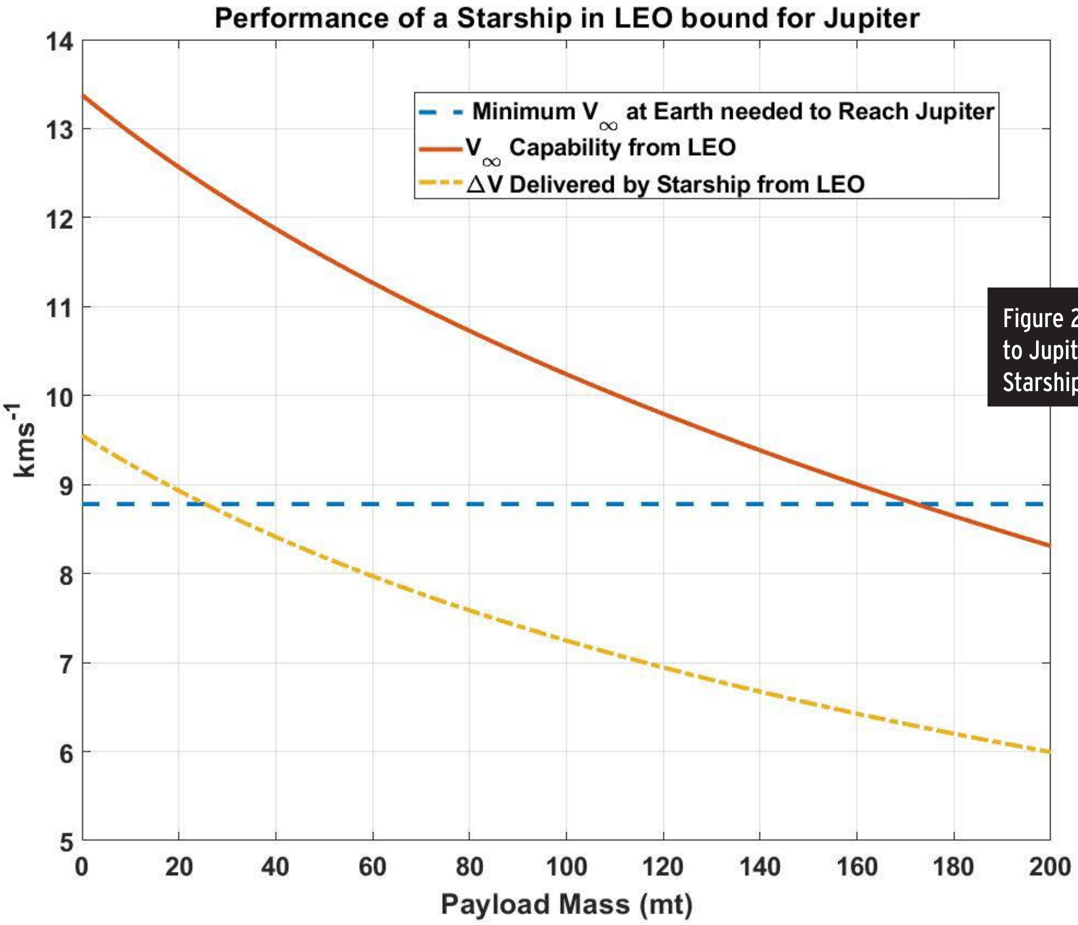


Figure 2 Performance to Jupiter for a Starship in LEO

4) Conclusions

Launch Vehicle	Additional Booster Stages	Payload Mass (kg)	Launch Date	Flight Duration (Years)	Cost/kg
Falcon Heavy*	STAR 63F + 2xSTAR 48B	100	2029 APR 08	28	$1500
Super Heavy + Starship	CASTOR 30XL + CASTOR 30B + STAR 48B	860	2031 FEB 28	20	$150

*With VILM

We have analysed two different launcher options which will be available for a mission to ‘Oumuamua, ‘Project Lyra’. Both trajectories exploited a Jupiter encounter with a powered Jupiter Oberth Manoeuvre, though with the Falcon Heavy, a *Vinfinity Leveraging Manoeuvre* was required to leverage sufficient hyperbolic excess at Earth to get to Jupiter.

We found by far the most powerful performance is provided by a refuelled Starship in LEO, the refuelling entails the launch of eight additional Starships with a propellant payload.

Currently a SpaceX launch on a Falcon Heavy is around $1500 per kg ($95M per launch), and the projected cost of a Starship launch is as low as $150 per kg ($22M per launch). Note however that SpaceX owner Elon Musk has big plans to reduce launch costs to $1M per launch, giving for the scenarios mentioned here, with 9 Starship launches, a total launch cost of $9M, also by far the cheaper launch option.

Falcon Heavy is a surprise because the combination of trajectory and solid booster stages considered hits a ‘sweet spot’ in terms of reaching ‘Oumuamua particularly propitiously, faring well in comparison to the much more powerful Starship.