An Architectural Framework for the design of missions to explore the ISM

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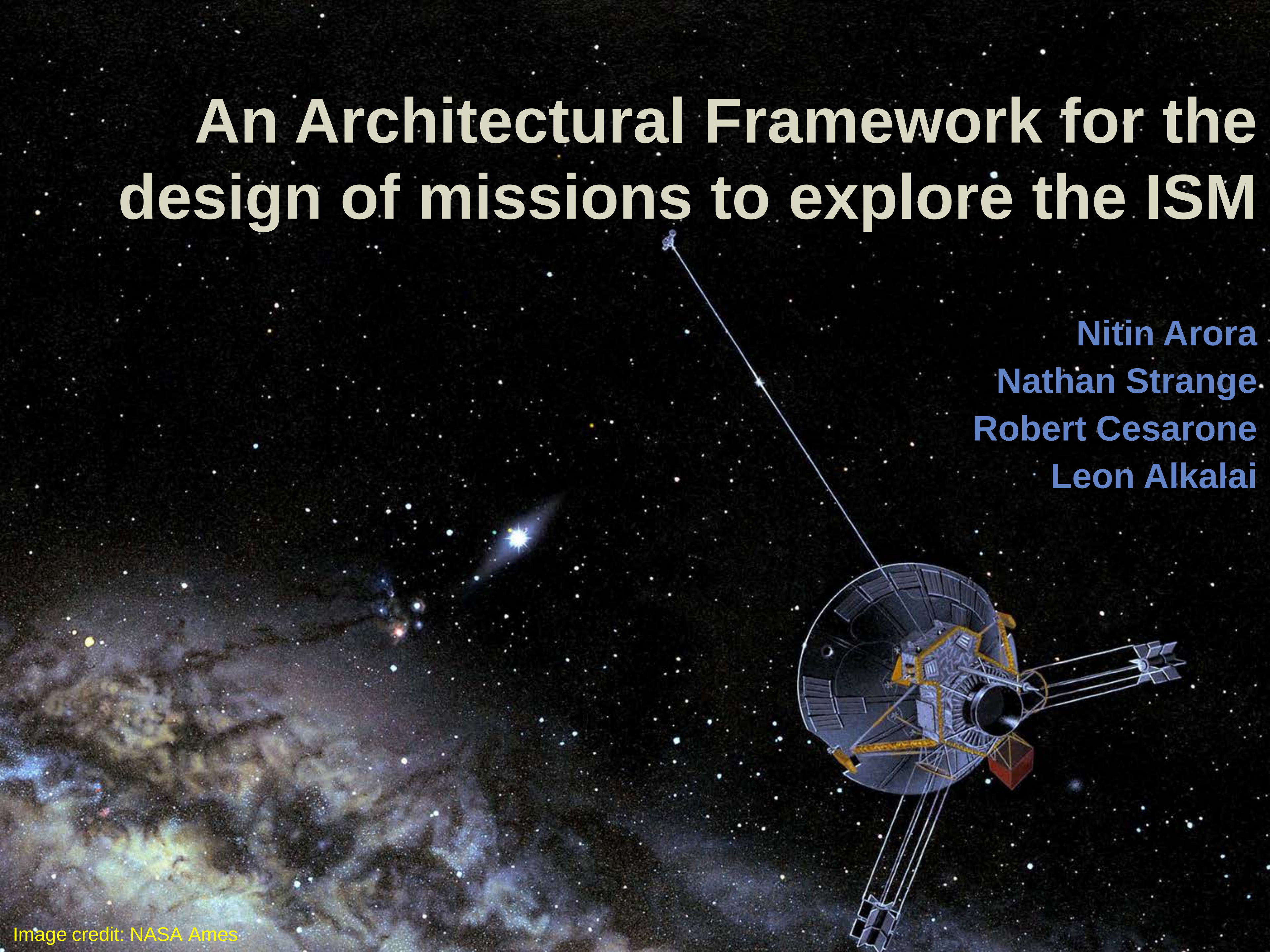
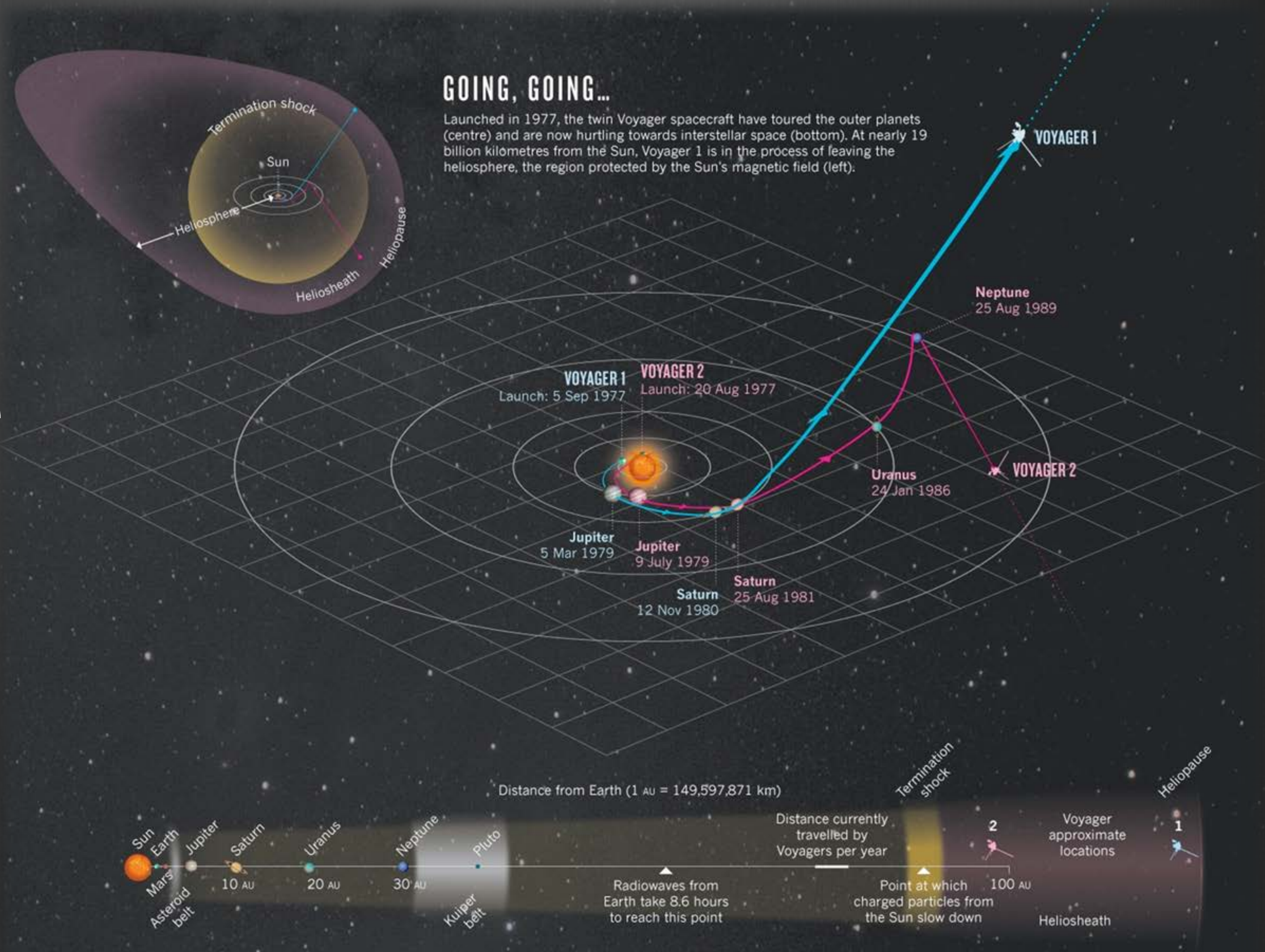


Image credit: NASA Ames

First steps taken by Voyager …

What are the next steps?



(ALEXANDRA WITZE) Nature 497, 424–427 (23 May 2013); doi:10.1038/497424a

Voyager

- Took 36 years to reach the ISM
- Escape velocity (V_∞) is 3.6 (AU/year)
  - using gravity assists: Jupiter, Saturn, Uranus, Neptune
- 37 years old and going

Mission Capability Goals

1. Get there sooner : 100+ AU in 10 years
2. Travel faster : 5x – 10x Voyager speed
3. Survivability : 50-100 years

In Principle

- It is not possible to achieve required V_∞ using direct launch

  → We need gravity assists, carry propulsion, etc.

- It is better to burn (propellant) when going fast:

  → ΔV more efficient when moving faster (e.g. near Sun): Oberth Effect

- High launch energy needed to get close to the Sun

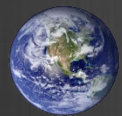
  → use Jupiter to get to the Sun

- Lower spacecraft mass means higher V_∞

  → The less massive the ISM probe, the faster it will go

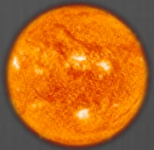
3 Mission Phases

Launch Phase (1)



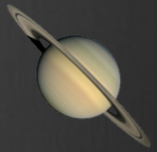
- SLS performance launch from Earth with high energy
- Solid rocket kick stage to further increase launch energy
    - Solar probe plus
    - Voyager 1, 2

Speedup Phase (2)

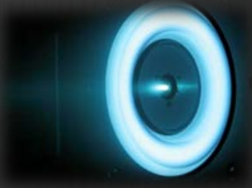


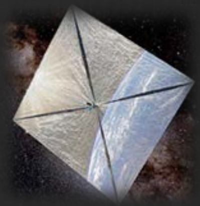
- Plunge towards the Sun to increase s/c speed
- Use Jupiter to achieve low solar perihelion
- Utilize inner solar system to gain speed (gravity assists)

Escape Phase (3)



- Increase speed
- Gravity assist
- Probe propulsion
    - Electric Propulsion
    - Solar Sails





3 Mission Scenarios to illustrate the architectural framework

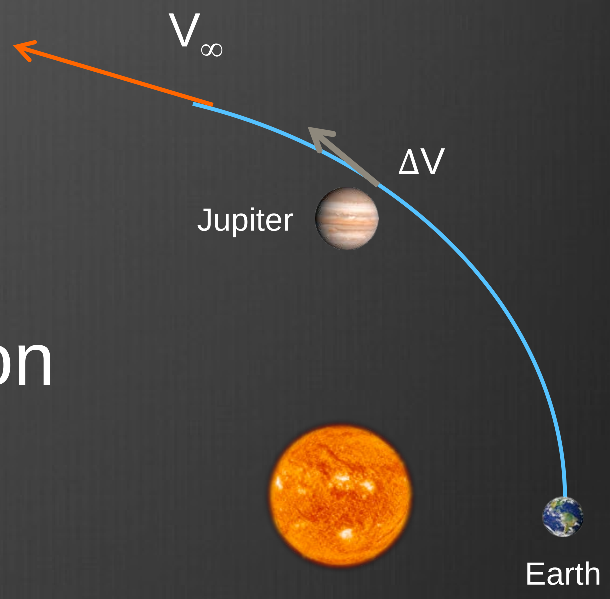
A. Simple approach

B. More complex

C. Ambitious and challenging

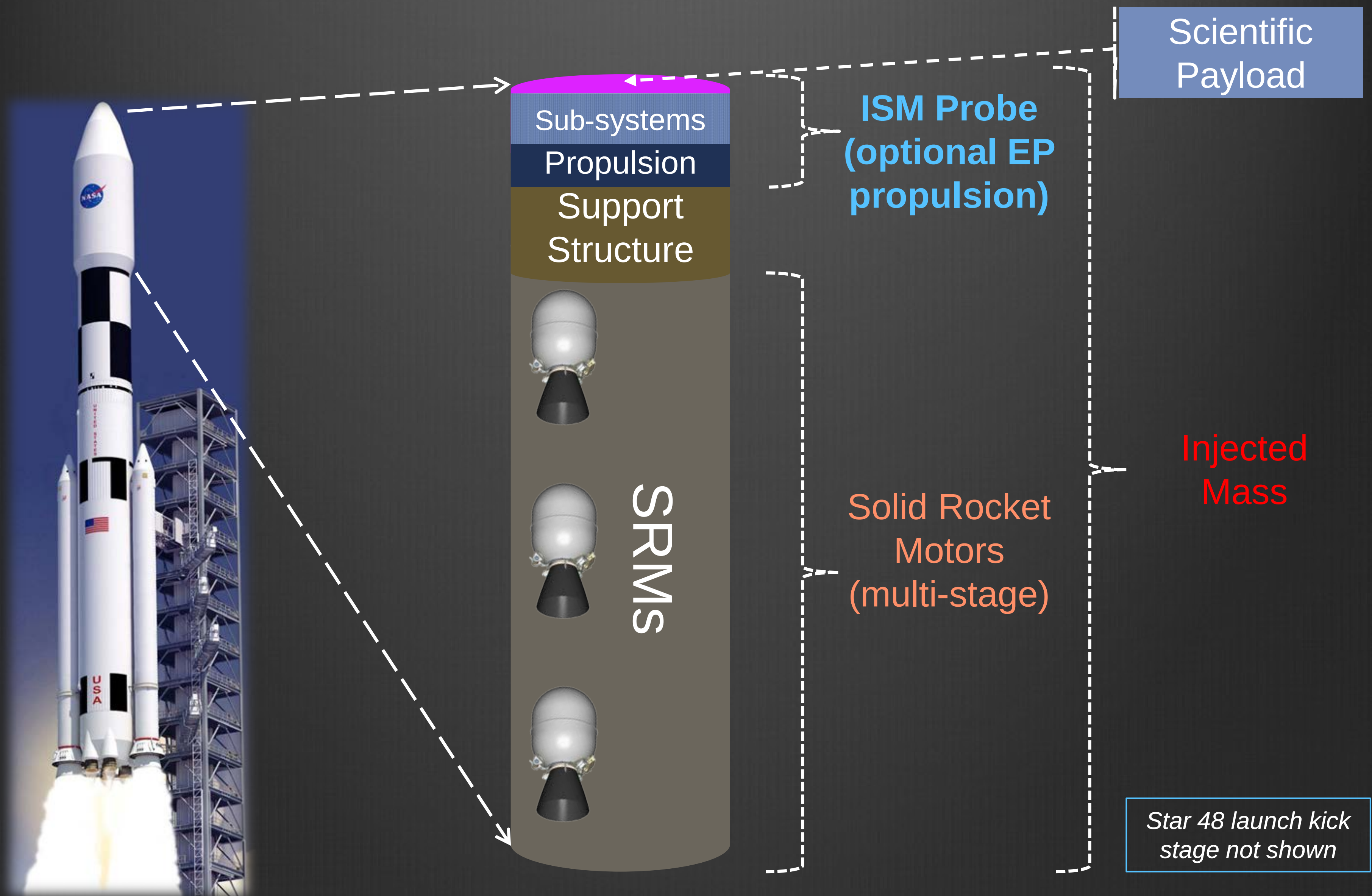
Mission Scenario - A

1. SLS performance launch from Earth to Jupiter
2. ΔV at close approach to Jupiter
3. Separate, optional propulsion escape after Jupiter flyby



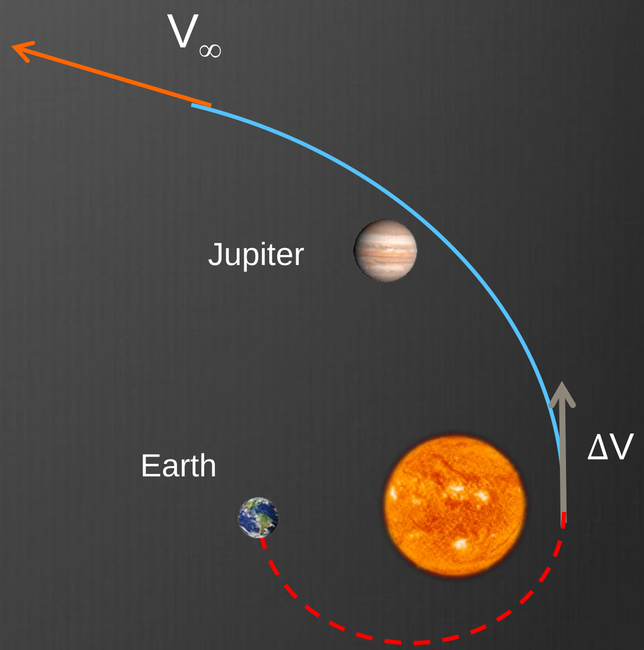
Option	Launch energy ($C3$, km^2/s^2)	Injected mass (Ton)	Gravity assist bodies	ISM Probe propulsion options	Closest approach to the Sun (AU)	Max V_∞ for 75 kg science payload (AU/Year)	Max Distance in 10 years (AU)
A	95	10.3	Jupiter	Optional EP	1	10	65

Flight System Model - A



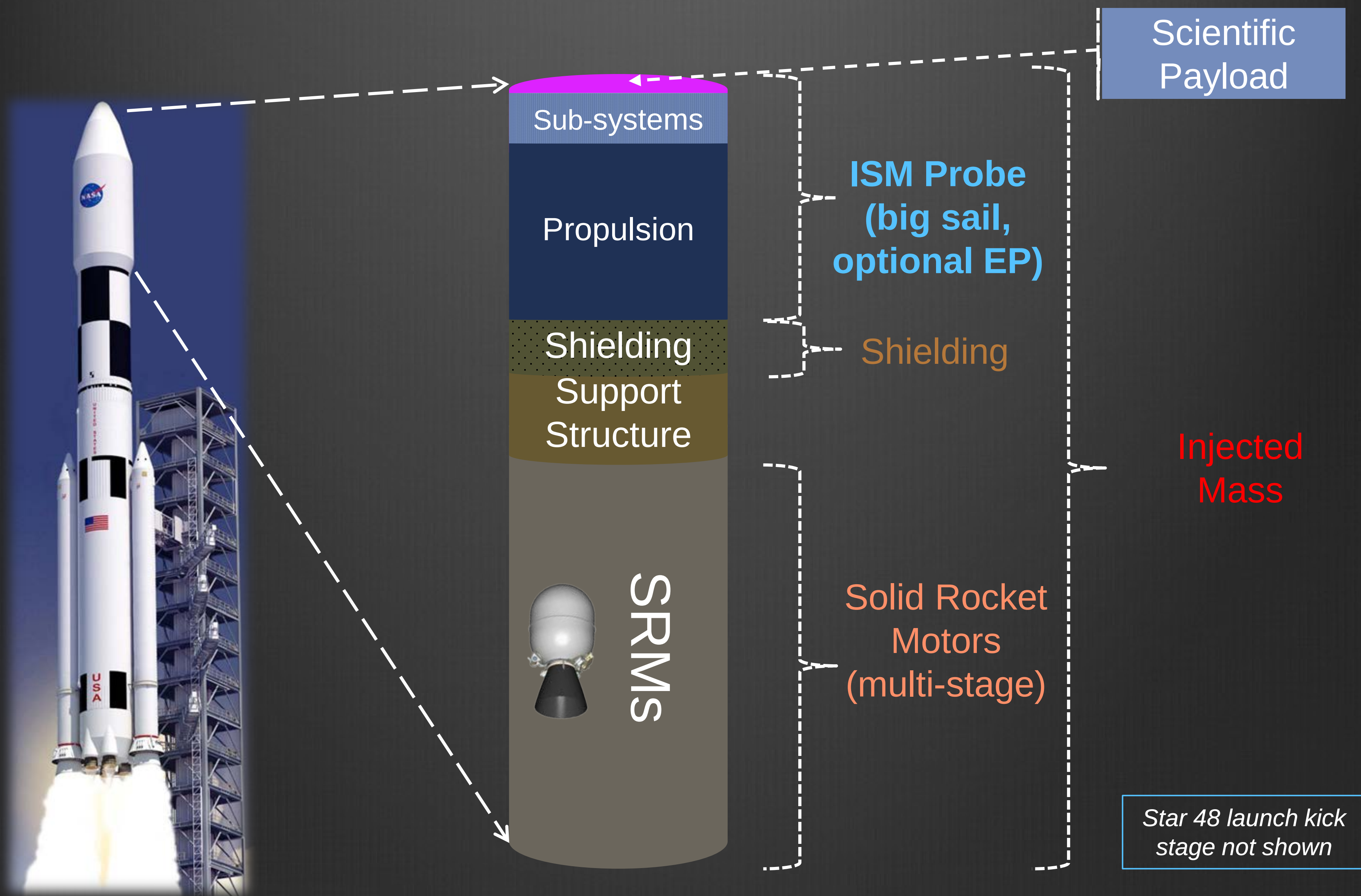
Mission Scenario - B

1. SLS performance launch from Earth to Venus
2. ΔV at close approach to Sun ~ 32-70 solar radii
3. Separate, optional propulsive escape with Jupiter flyby



Option	Launch energy ($C3$, km^2/s^2)	Injected mass (Ton)	Gravity assist bodies	ISM Probe propulsion options	Closest approach to the Sun (AU)	Max V_∞ for 75 kg science payload (AU/Year)	Max Distance in 10 years (AU)
B	240-90	0.9 – 10.7 (optimized)	Jupiter	Solar Sail, EP + Solar sail	0.14-0.35	11	92

Flight System Model - B



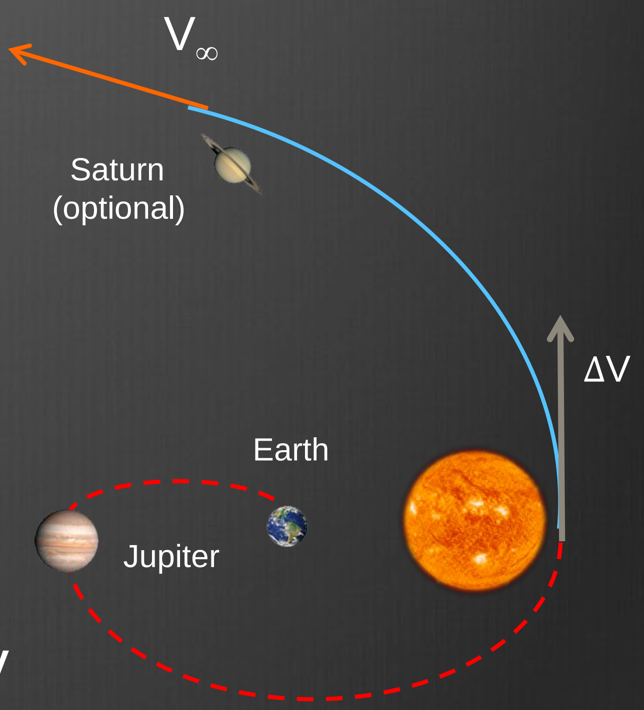
Mission Scenario - C

1. SLS performance launch from Earth to Jupiter

2.a Jupiter gravity assist to bend spacecraft towards the Sun

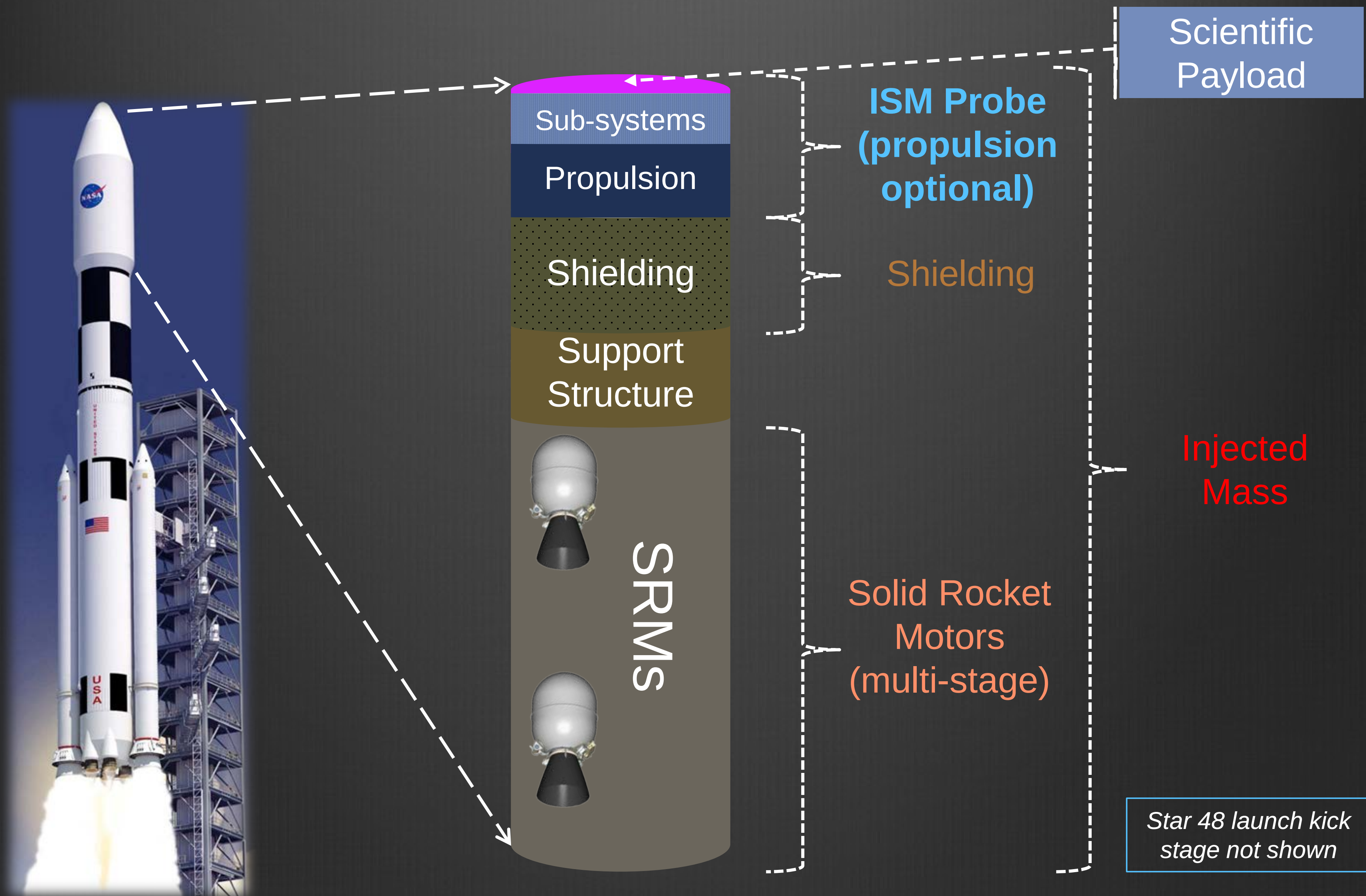
2.b ΔV at close approach to the Sun ~ 3-20 solar radii

3. Separate, optional propulsive escape with optional Saturn flyby



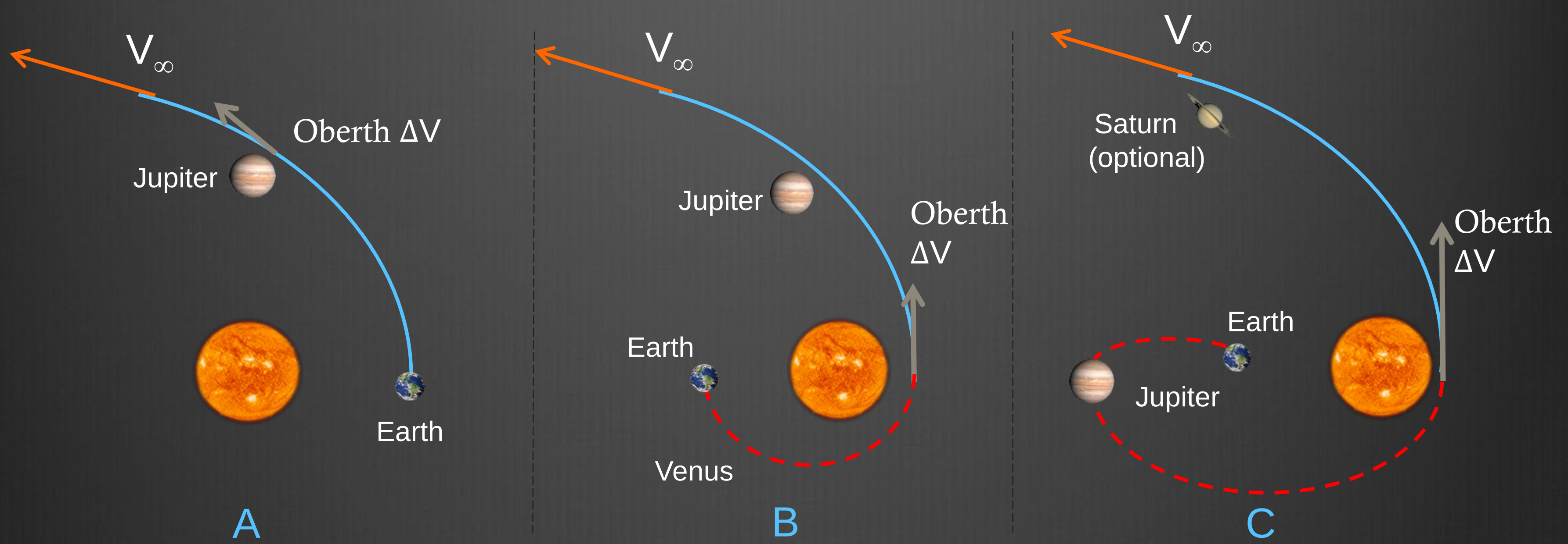
Option	Launch energy (C3, km^2/s^2)	Injected mass (Ton)	Gravity assist bodies	ISM Probe propulsion options	Closest approach to the Sun (AU)	Max V_∞ for 75 kg science payload (AU/Year)	Max Distance in 10 years (AU)
C	116	7.3	Jupiter, Saturn	Solid, EP, Solar sail	0.015 -0.1	16	108

Flight System Model - C



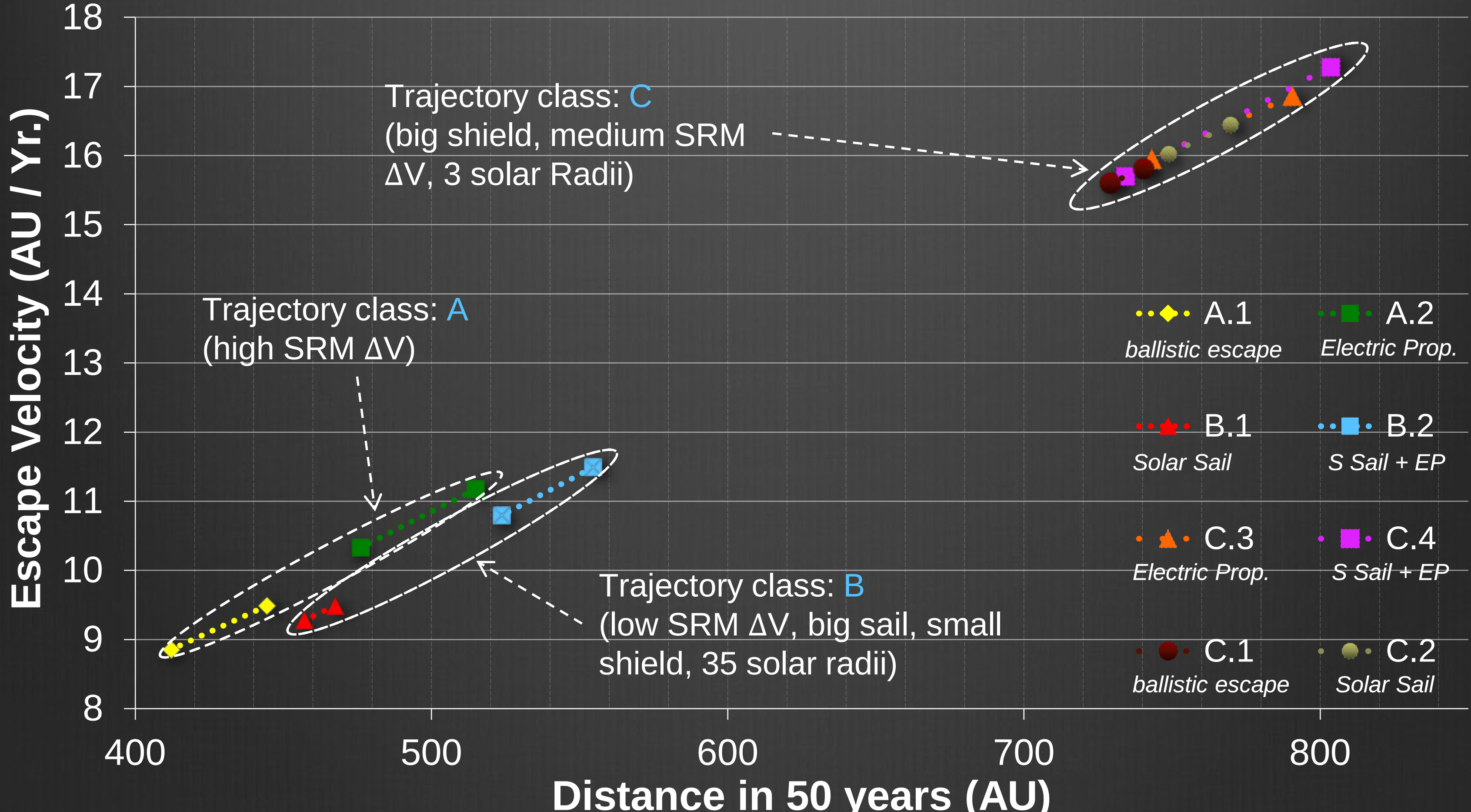
Star 48 launch kick stage not shown

Preliminary Results



Option	Launch energy (C3, km²/s²)	Injected mass (Ton)	Gravity assist bodies	ISM Probe propulsion options	Closest approach to the Sun (AU, [Solar Radii])	Max V_∞ for 75 kg science payload (AU/Year, [km/s])	Max Distance in 10 years (AU)
A	95	10.3	Jupiter	None, EP	1, [215]	10, [47]	65
B	240-90	0.9 – 10.7 (optimized)	Jupiter	Sail, EP + sail	0.15-0.33, [32-70]	11, [52]	92
C	116	7.3	Jupiter, Saturn	None, EP, Sail, EP + Sail	0.014 -0.1 [3-20]	16, [76]	108

Summary Trajectory Performance
75 – 30 kg Science Payload



Lower marker on a line = 75 kg science payload
Upper marker on a line = 30 kg science payload

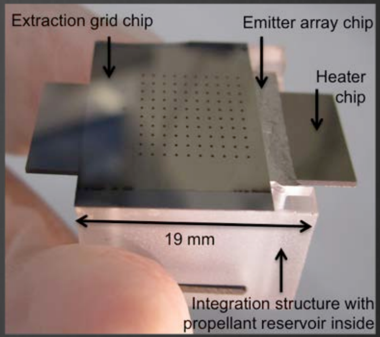
In Summary

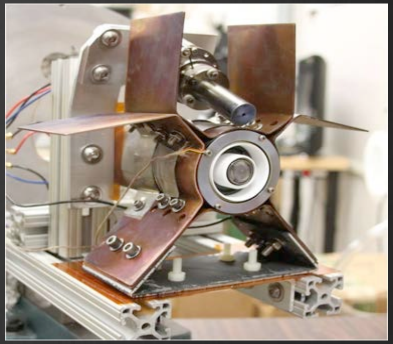
Whereas it is technologically challenging, it is conceivable that a mission in the next 10-20 years, can be designed and launched using the SLS to carry a science payload of at least 75 kg to:

- Reach the ISM in 10 years
- Travel at 15 AU/year into the ISM
- Last over 50 years to reach 700 – 800 AU

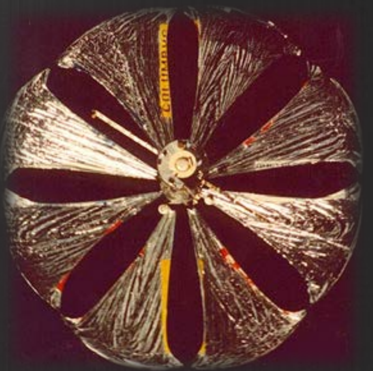
Probe Propulsion Assumptions

- Electric Propulsion
  - Large ΔV's over long flight times
  - Two options:
  - **MEP**
    - Very high ISP (~6000s), very low thrust > 1 mN
    - Low power per unit ~ 7w
    - Very light weight > 100 grams (per unit + PPU)
    - Very short life ~ 6 months (optimistic), low TRL
  - **MaSMi**
    - Magnetically shielded → very long lifetime
    - ISP ~ 1870s, anode efficiency ~ 56%
    - Light weight ~ 20 kg (complete system with PPU)
    - ~390w system input power





- Solar Sails
  - Spin stabilized, disc shaped, e.g. Znamya sail, HelioGyro
  - Assume 5 g/m^2 sail specific weight of sail + support structure (applied on CBE) → used for sizing the sail
  - Spacecraft sail loading (A/M) = 40 - 110 (m^2/g) → used for computing sail acceleration
  - 30 % cont. for solar sail mass; no additional system margin



Previous Work

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2. R. F. Wimmer-Scweingruber, R. McNutt, N. A. Schwadron, R. C. Frisch, M. Gruntman, P. Wurz, E. Valtonen, and the IHP/HEX Team., "*Interstellar Heliospheric Probe/Heliospheric Boundary Explorer Mission–a Mission to the Outermost Boundaries of the Solar System*", Experimental Astronomy, Vol. 24, Issue 1-3, May 2009.

3. R.L. McNutt Jr., G.B. Andrews, J. McAdams, R.E. Gold, A. Santo, D. Oursler, K. Heeres, M. Fraeman, B. Williams, "*Low-cost interstellar probe*", Acta Astronautica, Volume 52, Issues 2–6, January–March 2003.

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5. R.A. Mewaldt, J. Kangas, S.J. Kerridge, M. Neugebauer, "*A small interstellar probe to the heliospheric boundary and interstellar space*", Acta Astronautica, Volume 35, Supplement 1, 1995.