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PERFORMANCE REQUIREMENTS FOR NEAR-TERM INTERPLANETARY SOLAR SAILCRAFT MISSIONS

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Solar sailcraft mission opportunities

Solar sailcraft . . .

- have unlimited Δv-capability
- provide a wide range of mission opportunities

Rendezvous missions (especially multiple rendezvous and sample return):

- Near Earth Objects (asteroids and short period comets)
- Inner planets (and eventually Jupiter)
- Asteroid belt

Fast fly-by missions ('solar photonic assist' trajectories):

- Outer planets
- Edgeworth-Kuiper belt
- Near interstellar space

Solar missions (very close to the sun and/or over the sun's poles)

Advanced solar sailcraft missions

Target body	Sailcraft performance		Transfer time	References
	a_c [mm/s^2]	σ [g/m^2]	[yr]	
Mercury	0.5	16.0	1.4	C. Sauer
Venus	1.0	8.0	0.6	C. Sauer
Mars	1.0	8.0	1.0	C. Sauer
Pluto (fly-by)	0.7	11.4	10.4	M. Leipold
(4) Vesta	0.75	10.7	3.3	M. Leipold
(433) Eros	1.0	8.0	1.2	C. Sauer
(1566) Icarus	1.25	6.4	1.2	J. Wright
2P/Encke	0.85	9.4	3.0	M. Leipold
21P/Giacobini-Zinner	1.0	8.0	6.8	J. Wright

*Rendezvous, if not stated otherwise

a_c: maximum acceleration at Earth distance

σ: specific mass (including payload)

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Presentation objectives

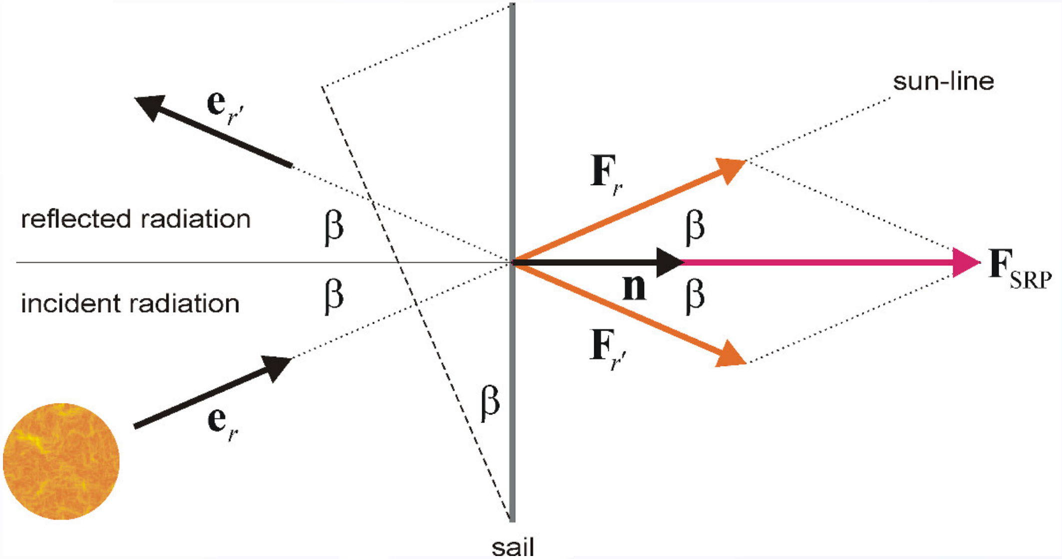
As a matter of fact . . .

- near-term solar sailcraft will be of moderate performance
- few ***near-term*** deep space missions have been proposed

We will . . .

- demonstrate that challenging scientific deep space missions are feasible
  - with solar sailcraft of moderate performance
  - at relatively low cost
- propose a sample return mission to a Near Earth Asteroid

Propulsion by solar radiation pressure



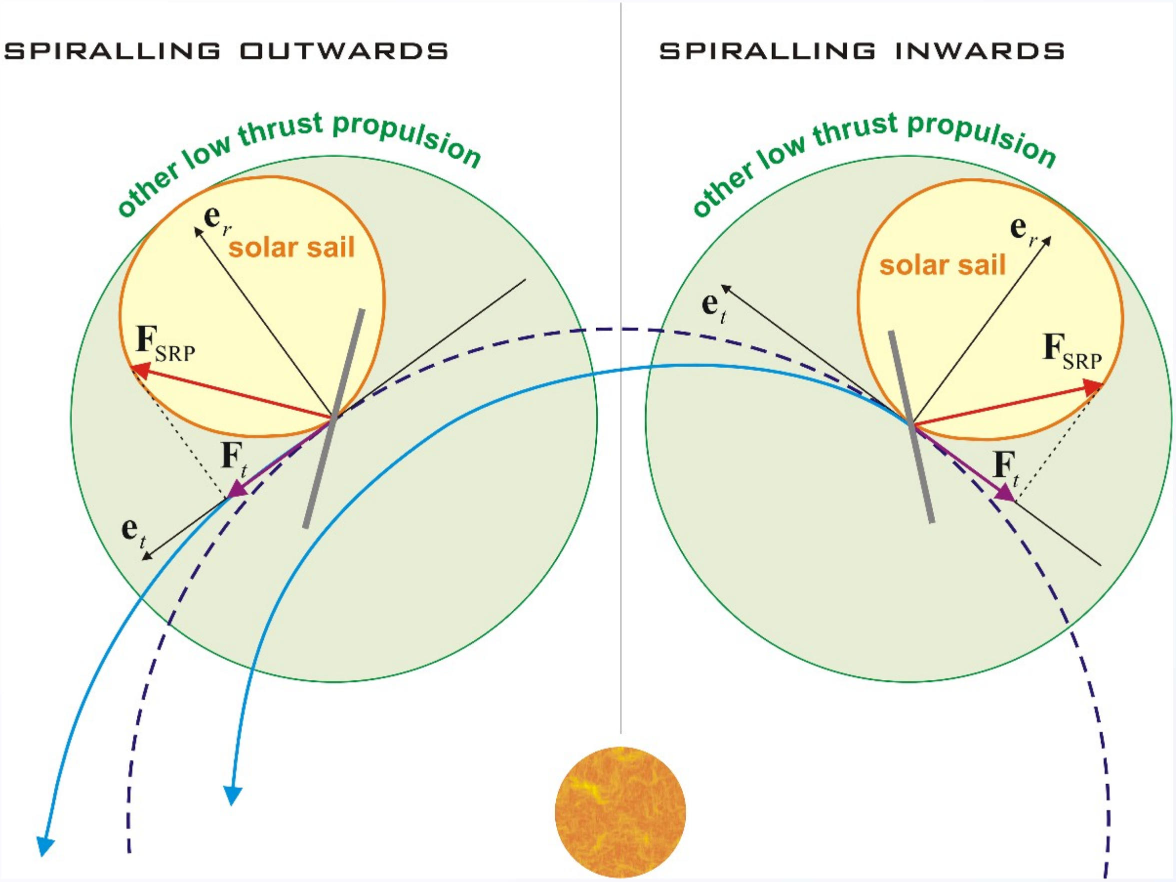
Solar radiation pressure (SRP) force on a perfectly reflecting surface:

$$\mathbf{F}_{\mathrm{SRP}} = \mathbf{F}_r + \mathbf{F}_{r'} = 2PA\cos^2\beta\,\mathbf{n}$$

A: sail area

P: solar radiation pressure ($\approx 4.65\,\mu\mathrm{N/m}^2$ at Earth distance)

Solar sailcraft orbital dynamics



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Solar sailcraft performance parameters

sail assembly loading:

$$\sigma_s = \frac{m_s}{A}$$

sailcraft loading:

$$\sigma = \frac{m}{A} = \frac{m_s + m_p}{A} = \sigma_s + \frac{m_p}{A}$$

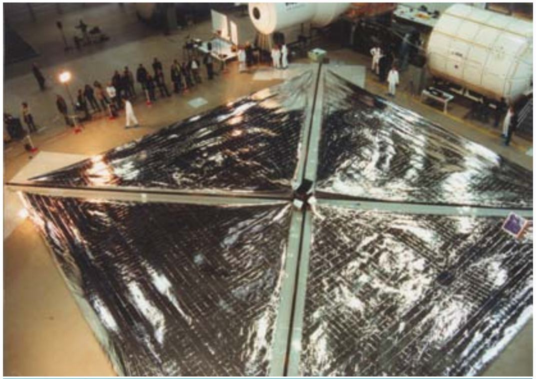
characteristic acceleration:

maximum acceleration at Earth distance

$$a_c = \frac{(P_{\text{eff}})_{1\text{AU}} A}{m} = \frac{(P_{\text{eff}})_{1\text{AU}}}{\sigma} = \frac{(P_{\text{eff}})_{1\text{AU}}}{\sigma_s + \frac{m_p}{A}}$$

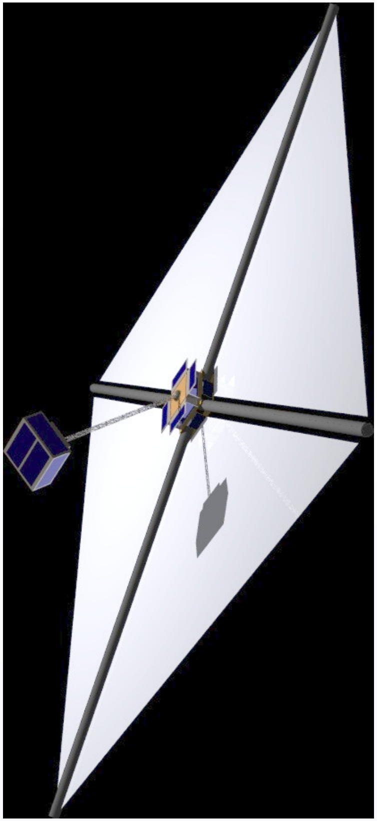
A:	sail area
m_s:	sail assembly mass (sail film + structure required for storing, deploying and tensioning the sail)
m_p:	payload mass (everything except the sail assembly)
m:	total solar sailcraft mass
$(P_{\text{eff}})_{1\text{AU}}$:	effective solar radiation pressure at Earth distance

DLR/ESA solar sail technology demonstration



- performed Dec 99 at DLR, Cologne
- $20\,\mathrm{m} \times 20\,\mathrm{m}$ solar sail
- 4 aluminum-coated sail segments
  - ▷ $12\,\mu\mathrm{m}$ Mylar®($18.9\,\mathrm{g/m^2}$)
  - ▷ $7.5\,\mu\mathrm{m}$ Kapton®($12.4\,\mathrm{g/m^2}$)
  - ▷ $4\,\mu\mathrm{m}$ PEN ($10.5\,\mathrm{g/m^2}$)
- 4 CFRP (carbon fiber reinforced plastics) booms ($101\,\mathrm{g/m}$)
- $60\,\mathrm{cm}\times 60\,\mathrm{cm}\times 65\,\mathrm{cm}$ deployment module
- Total mass: $34\,\mathrm{kg}$

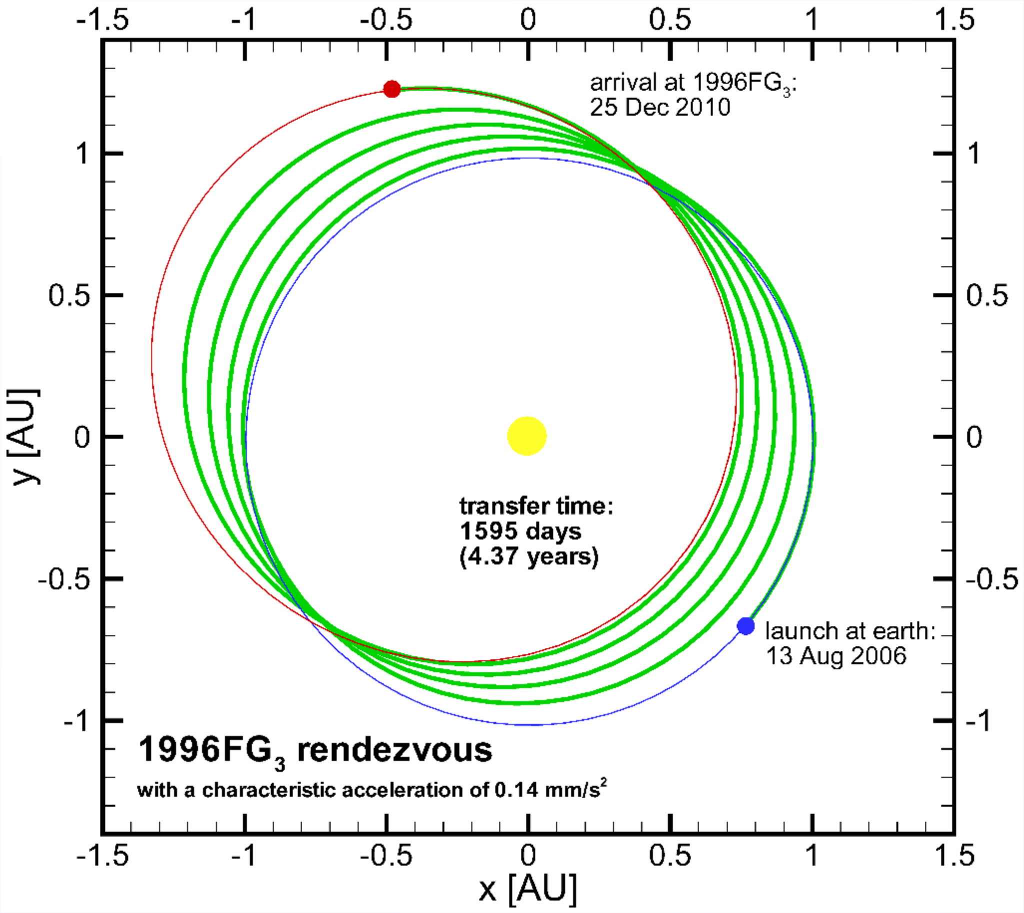
ENEAS: Exploration of Near Earth Asteroids with solar Sailcraft (proposal within the German small satellite program, 2000)



- Target body: Near Earth Asteroid $1996FG_3$
  - binary body
  - probably a 'rubble pile' ($\rho \approx 1.4\,\mathrm{g/cm^3}$)
- $5\,\mathrm{kg}$ scientific payload for remote sensing
  - CCD camera
  - IR spectrometer
  - magnetometer

Sail area	$(50\,\mathrm{m})^2$
Sail assembly loading	$29.2\,\mathrm{g/m^2}$
Sail assembly mass	$73\,\mathrm{kg}$
Payload mass	$65.5\,\mathrm{kg}$
Char. acceleration	$0.14\,\mathrm{mm/s^2}$
Char. SRP force	$19.5\,\mathrm{mN}$

Optimized ENEAS trajectory

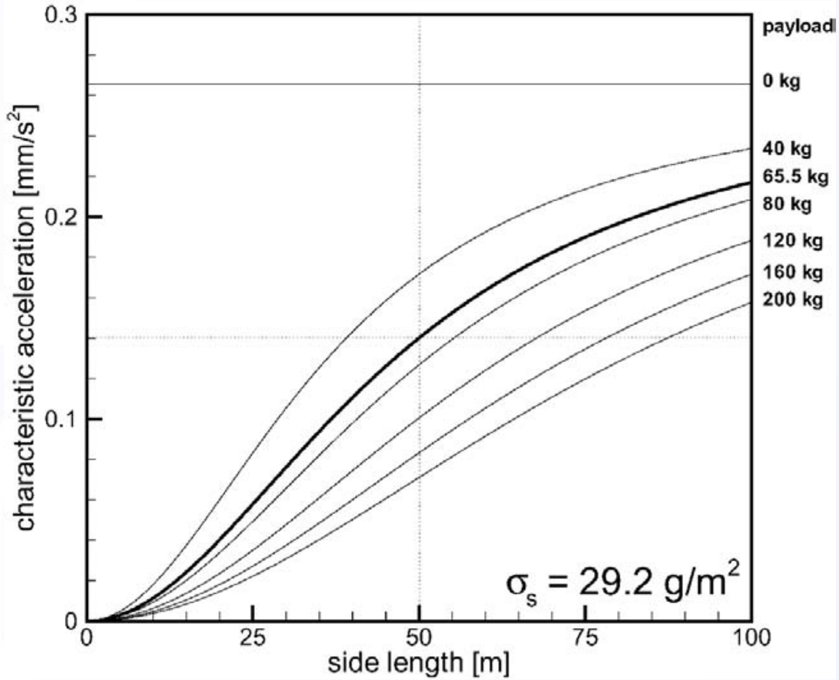


Solar sailcraft performance

$$a_c = \frac{(P_{\text{eff}})_{1\text{AU}}}{\sigma_s + m_p/s^2}$$

Performance depends on 3 design parameters:

- ▶ sail assembly loading σ_s
- ▶ payload mass m_p
- ▶ side length s (or area s^2)



Parametric section of the design space for a fixed $\sigma_s = 29.2\,\text{g}/\text{m}^2$ (ENEAS)

ENEAS with sample return (ENEAS-SR) scientific mission objectives

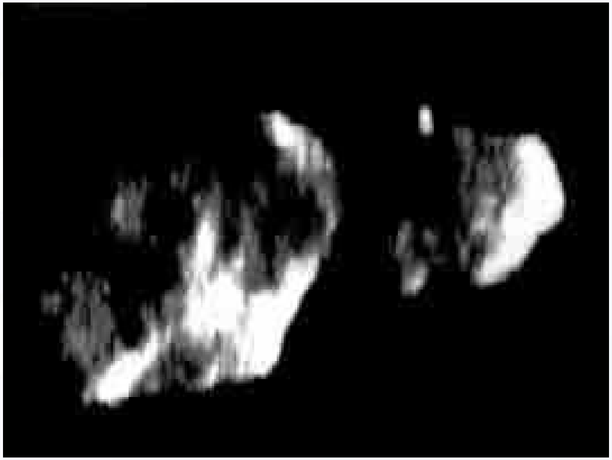
Remote sensing

- ▶ CCD camera
- ▶ IR spectrometer
- ▶ magnetometer

Sample return

- ▶ micro-structure analysis
- ▶ isotope analysis

⇒ determination of age and evolution of the $1996FG_3$ system



Radar picture of binary NEA (4179) Toutatis (NASA/JPL)

Key questions for the ENEAS-SR mission design

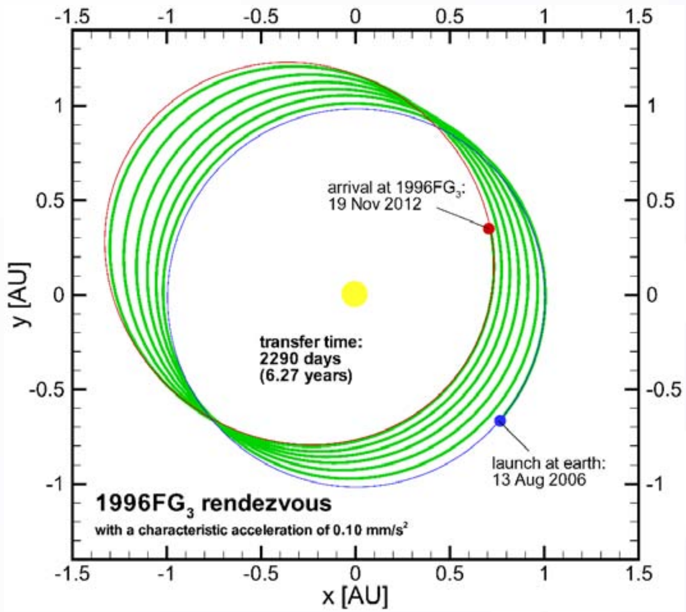
Question 1: What is the maximum acceptable mission duration $T_{\max}$?

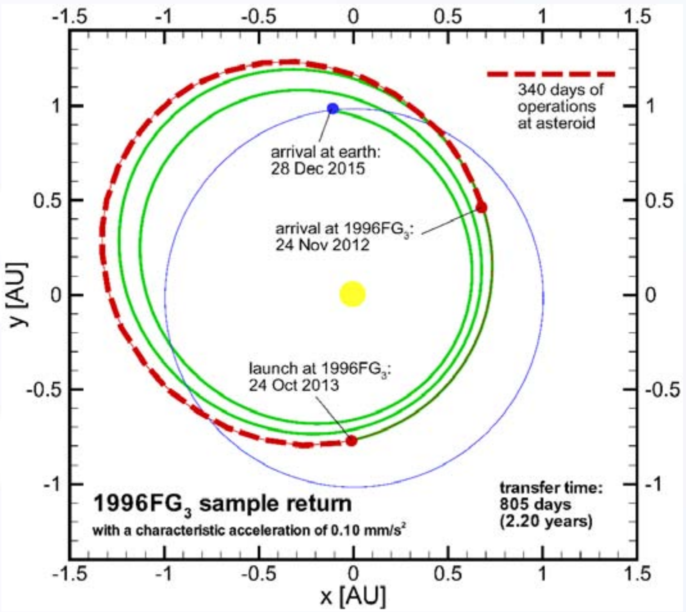
Question 2: What is the minimum characteristic acceleration $a_{c,\min}$ to perform the mission in $T_{\max}$?

Question 3: What is the expected sail assembly loading σ_s and sail dimension s for near-term solar sailcraft?

Question 4: What is the maximum payload mass to get $a_{c,\min}$ for the specified σ_s and s?

ENEAS-SR trajectories





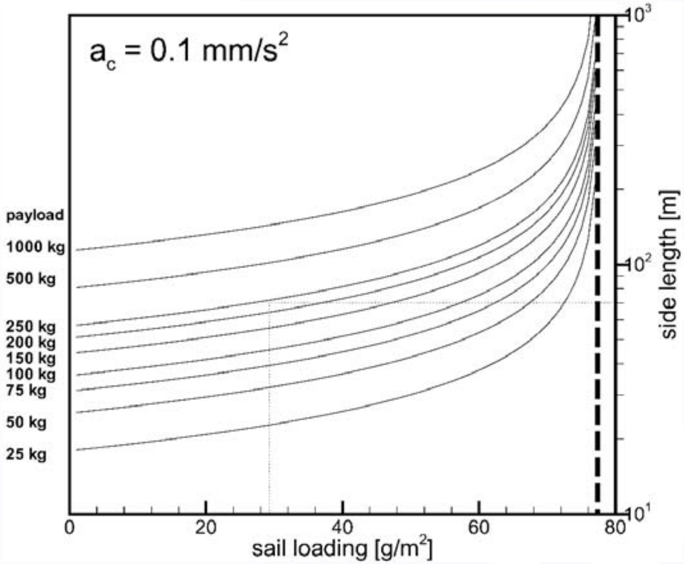
Hyperbolic excess velocity: $0\,\mathrm{km/s}$ at Earth and 1996FG$_3$

Hyperbolic excess velocity: $0\,\mathrm{km/s}$ at 1996FG$_3$

Hyperbolic excess velocity: $8.4\,\mathrm{km/s}$ at Earth

Earth re-entry velocity: $14.0\,\mathrm{km/s}$

ENEAS-SR performance



Required sail size for different sail assembly loadings and payload masses, to obtain a characteristic acceleration of $0.10\,\mathrm{mm/s^2}$.

ENEAS-SR parameters:

Sail area	$(70\,\mathrm{m})^2$
Sail assembly loading	$29.2\,\mathrm{g/m^2}$
Sail assembly mass	$143\,\mathrm{kg}$
Payload mass	$237\,\mathrm{kg}$
Total sailcraft mass	$380\,\mathrm{kg}$
Char. acceleration	$0.10\,\mathrm{mm/s^2}$
Char. SRP force	$38.0\,\mathrm{mN}$

Near-term solar sailcraft missions within the inner solar system

Target body	Transfer time [yr] for a_c [$\mathrm{mm/s^2}$]		
	0.10	0.15	0.20
Mercury	8.3	5.9	4.2
Venus	4.6	2.9	2.0
Mars	9.2	7.5	5.1

Summary

- Realistic near-term baseline: $70\,\mathrm{m} \times 70\,\mathrm{m}$ solar sail with a sail assembly loading of $29.2\,\mathrm{g/m^2}$
- With this solar sail, a characteristic thrust of $38\,\mathrm{mN}$ can be achieved
- The characteristic acceleration should be $a_c \geq 0.10\,\mathrm{mm/s^2}$ to avoid unacceptable long mission durations
- For $a_c = 0.10\,\mathrm{mm/s^2}$ a payload mass of $237\,\mathrm{kg}$ can be accommodated
- A near-term sample return mission to a NEA is feasible within a mission duration of ≈ 9.4 years

Questions?