The Brijuni Conference
Deep Space Communication, Navigation and Propulsion
August 29-31, 2022

Big Science in Small Packages:
The Sundiver Concept: A New Paradigm

NASA Innovative Advanced Concepts

Direct Multipixel Imaging and Spectroscopy of Exoplanets
with a Mission to the Focal Region of the Solar Gravitational Lens

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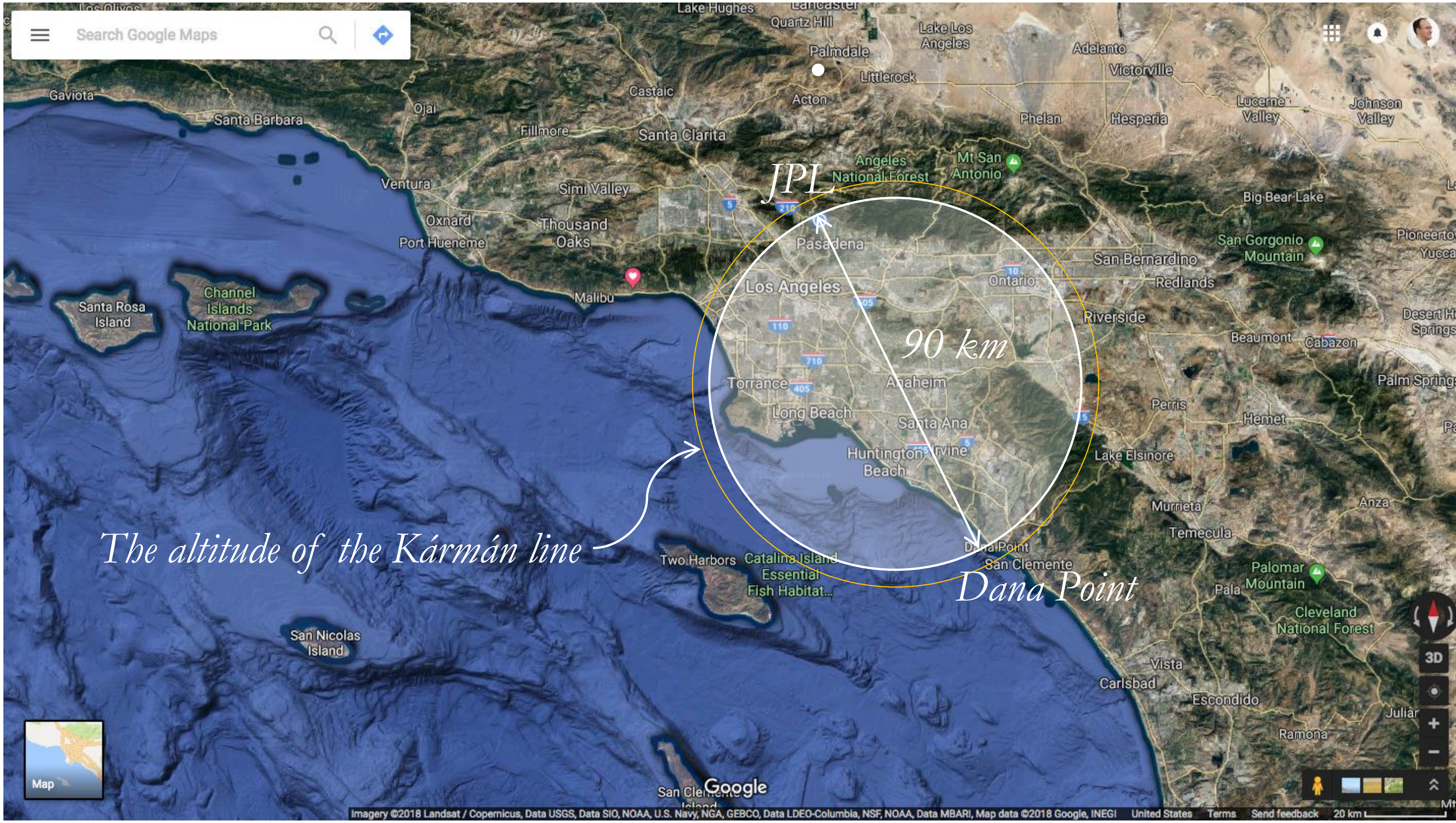
A (10k×10k)-pixels image of our Earth

This 2002 Blue Marble image features land surfaces, clouds, topography, and city lights at a maximal resolution of 1 km per pixel.

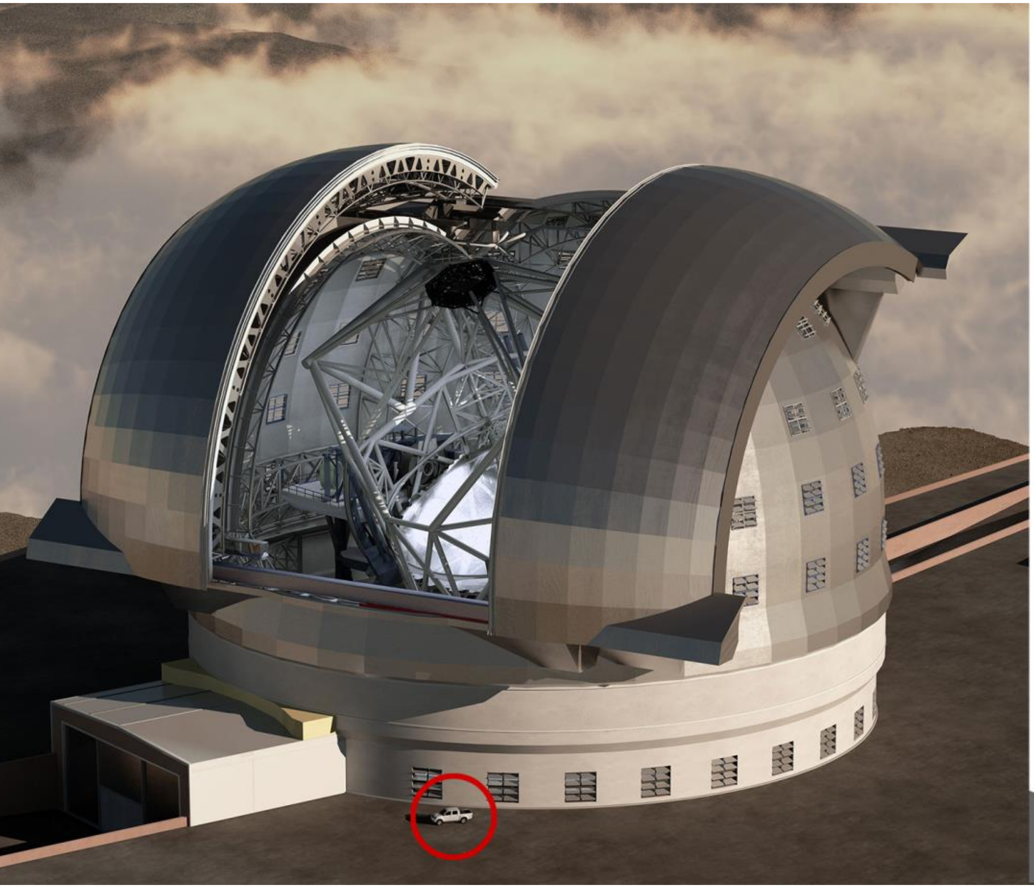
Composed from 4 months data from NASA's Terra satellite by R.Simmon, R.Stöckli.

Imaging of an exo-Earth with just 1-pixel…

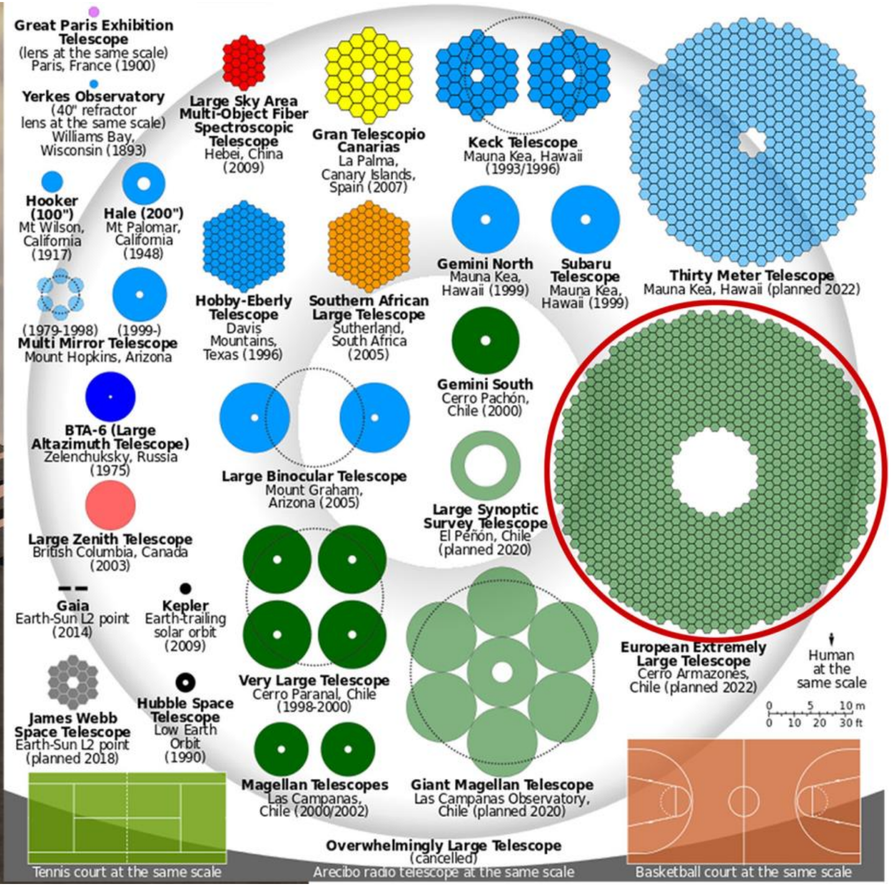
The tyranny of the diffraction limit: To make a 1-pixel image of an exo-Earth at 30 parsec (~100 ly), one needs a telescope with a diameter of ~90 km…



Largest telescopes to date…

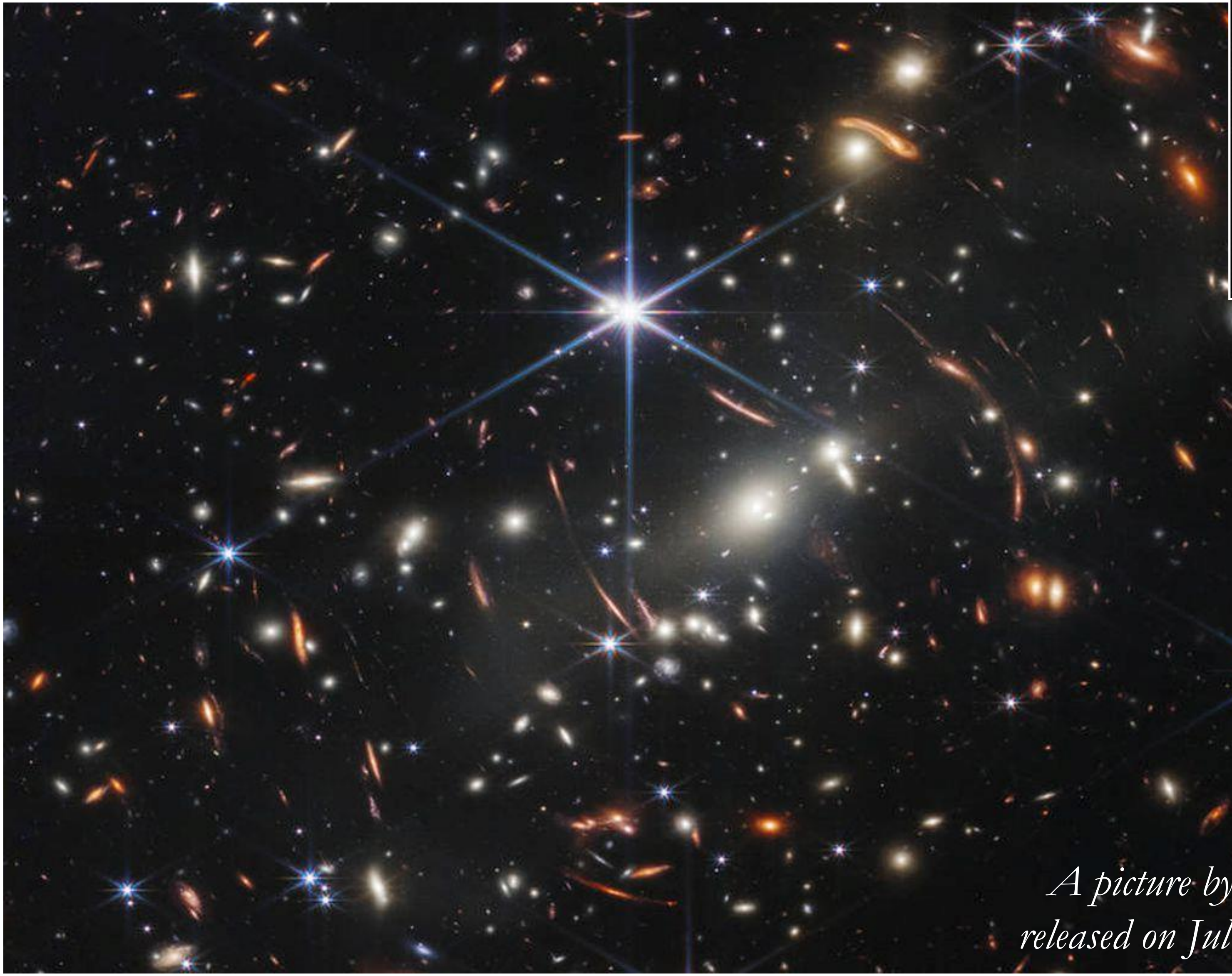


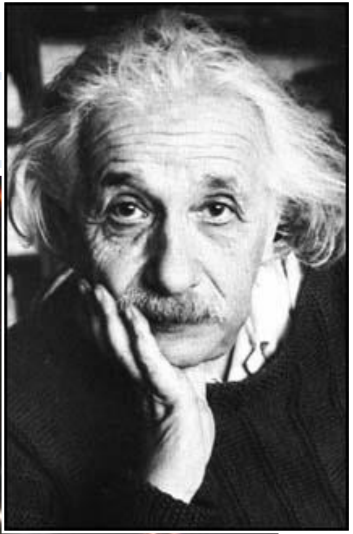
European Extremely Large Telescope
39 meters, Chile (est. 2022)



The largest telescopes for the last 125 years
to date, both on the ground and in space

Gravitational lensing is well-known

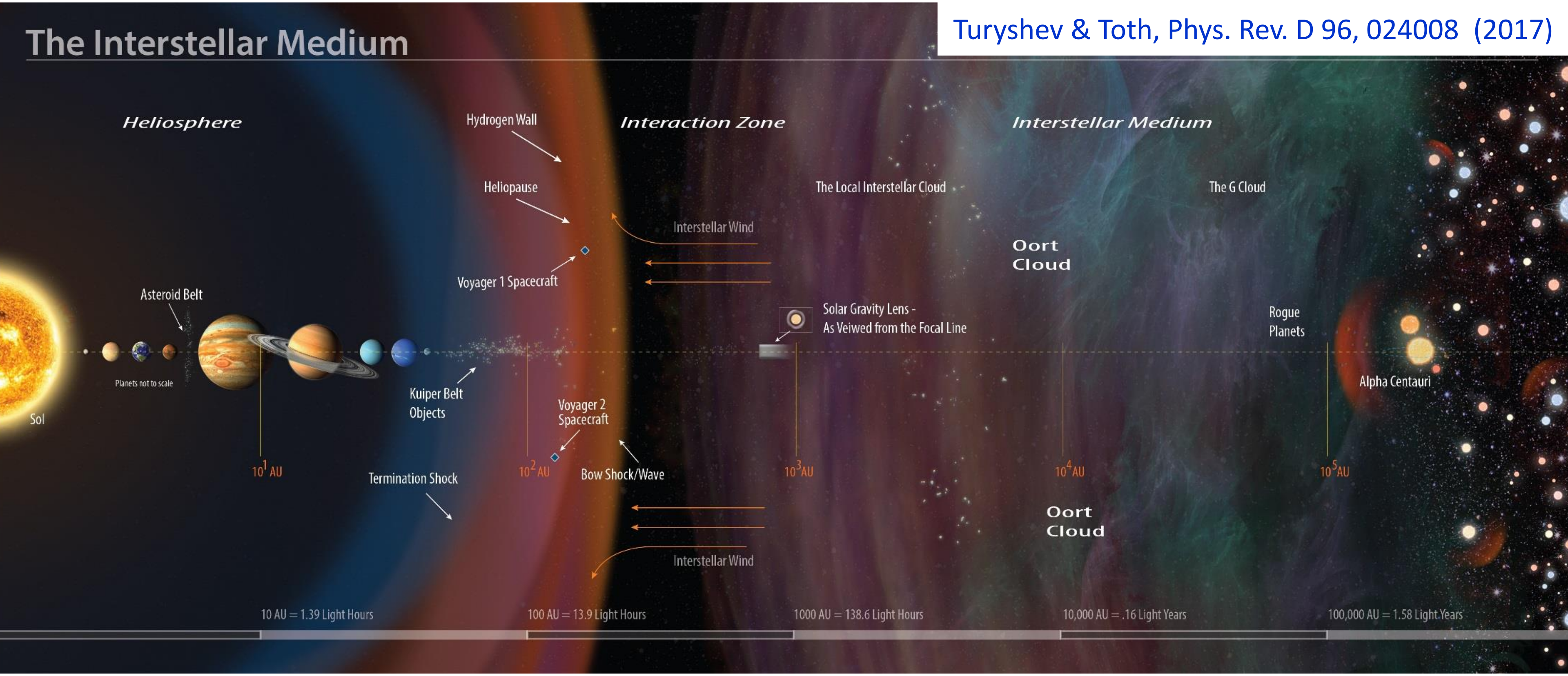




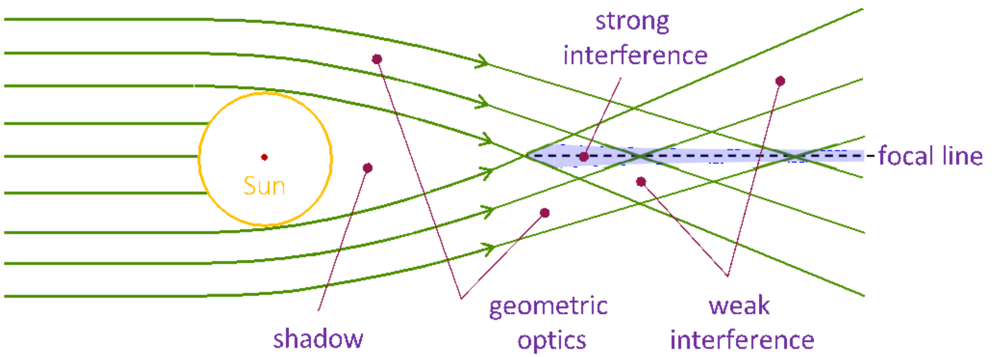
SUNDIVER MISSION CONCEPT

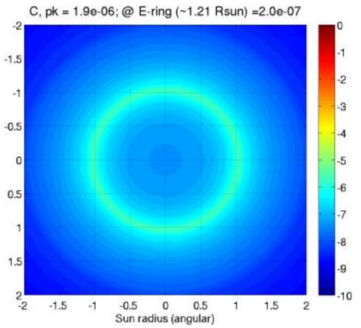
The Solar Gravitational Lens (KISS study, 2015)

Turyshev & Toth, Phys. Rev. D 96, 024008 (2017)



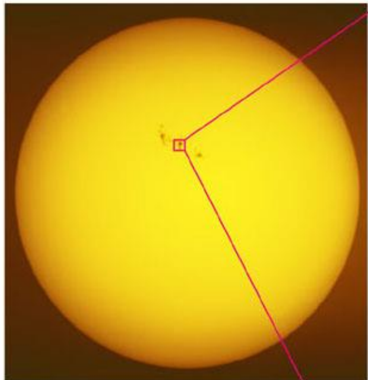
Earth-like exoplanet

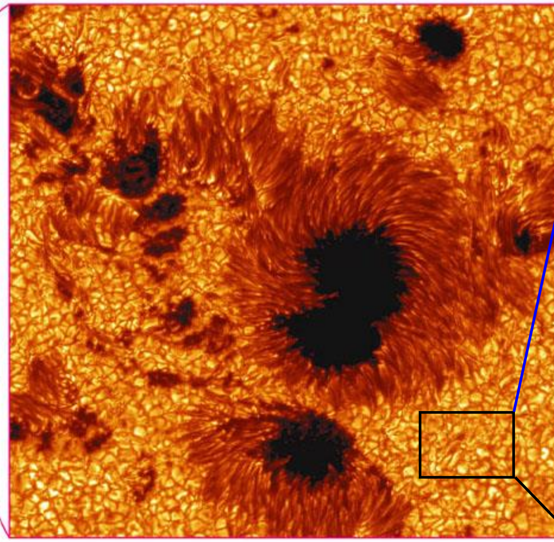




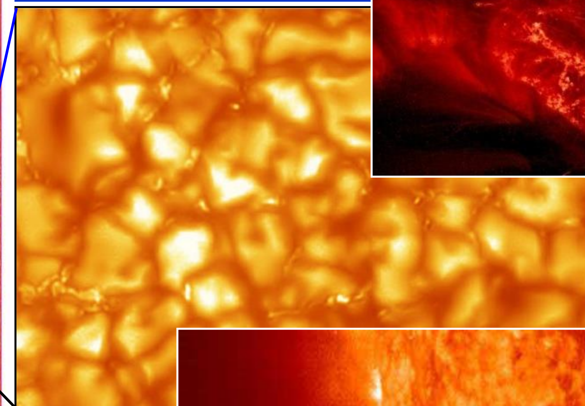
Image

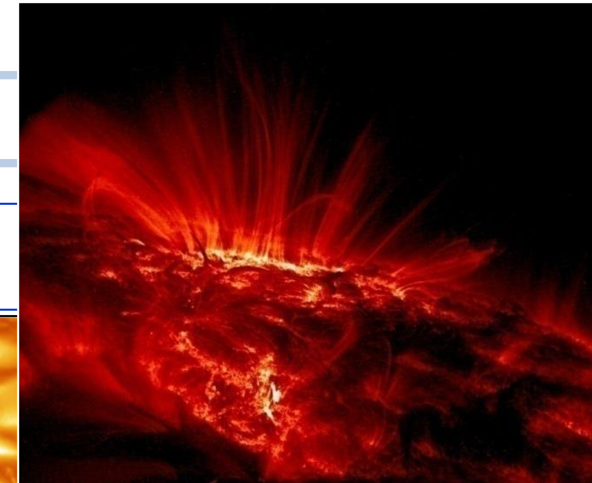
Do not point at the Sun!!!!





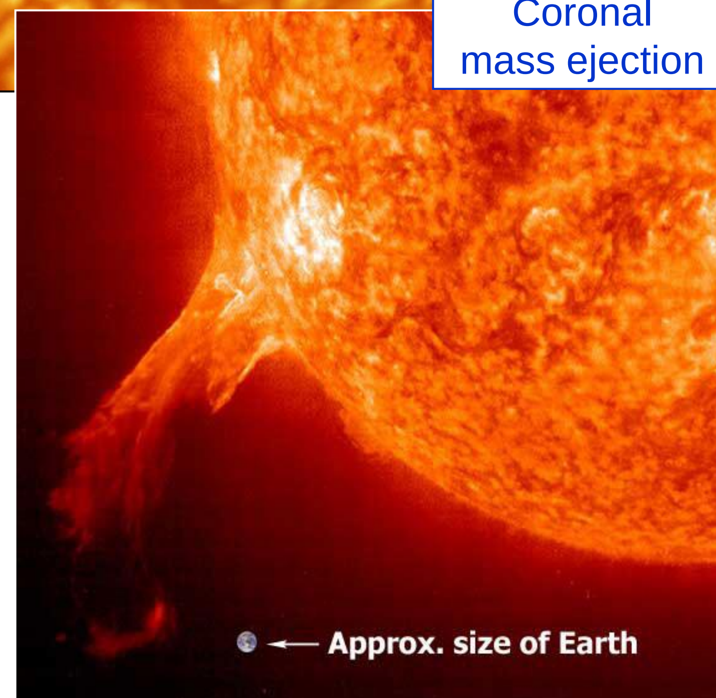
Granulation
of solar surface

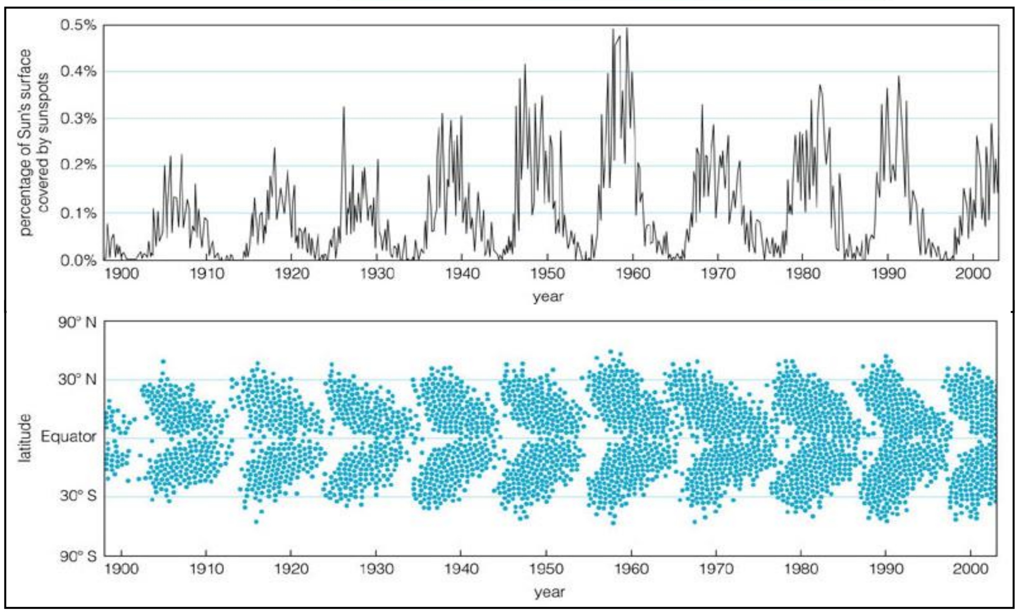




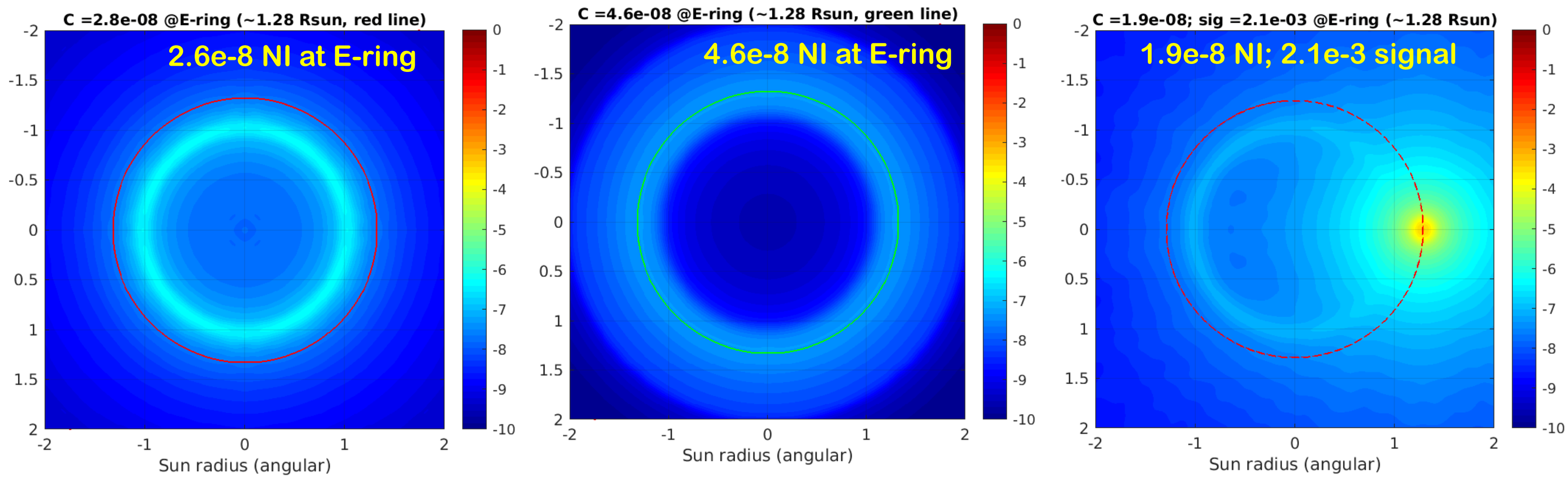
A solar flare

Coronal
mass ejection





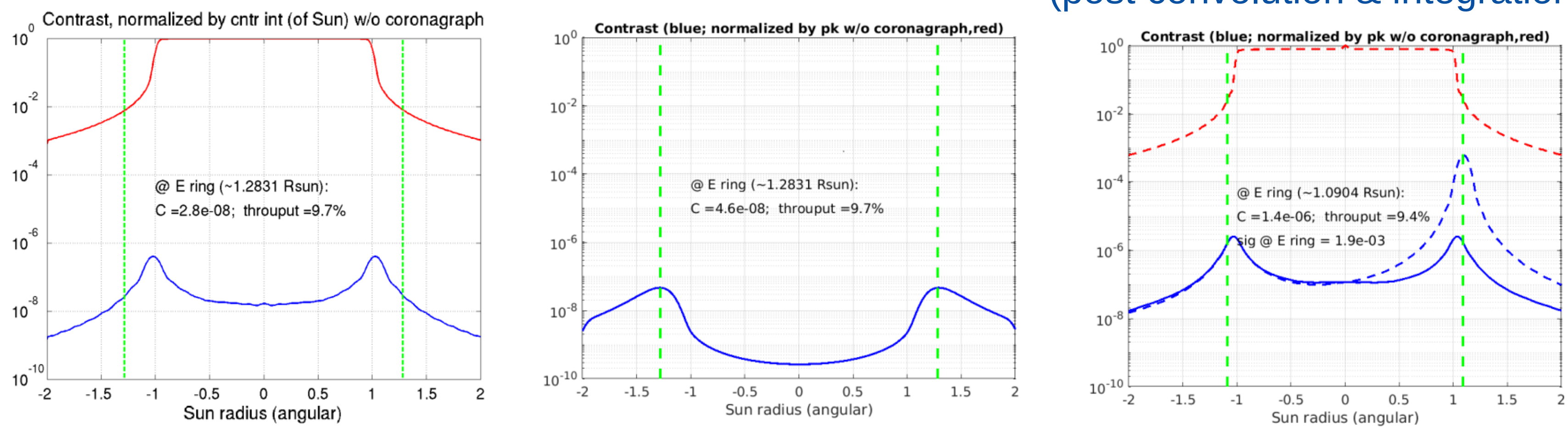
Sun, Corona, a point source at the E-ring



Sun only

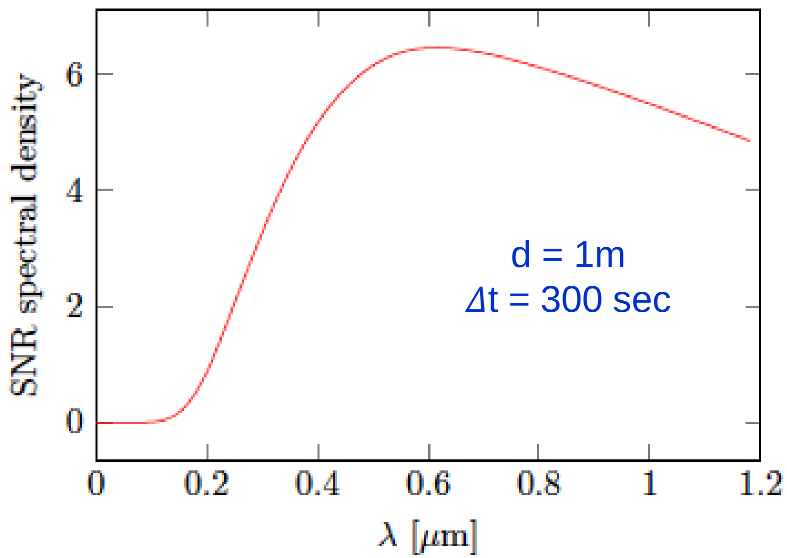
Corona only

Sun + corona + pnt src @E-ring
(post convolution & integration)

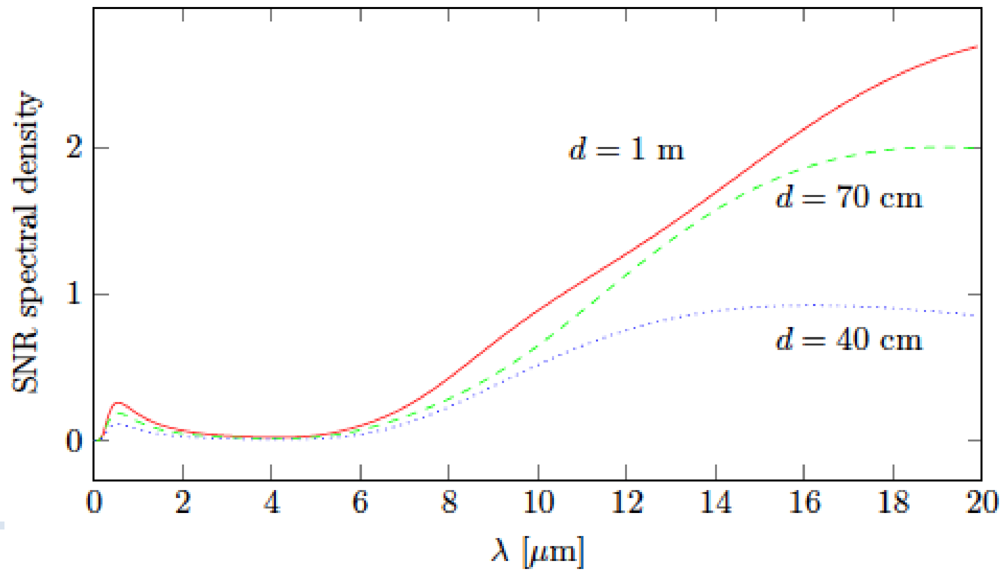


Current design for SGL solar coronagraph satisfy mission requitements

Relevant SNRs

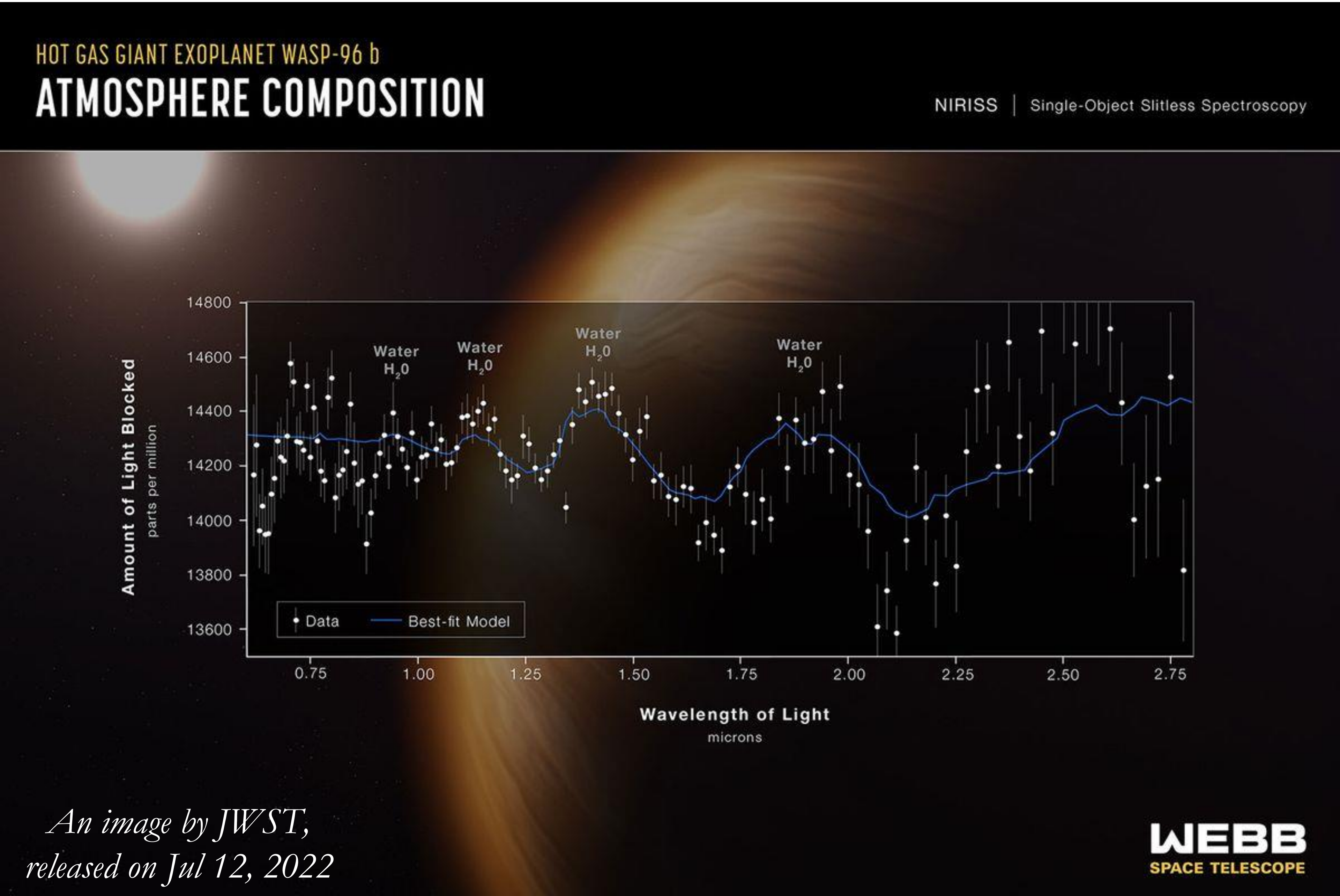


The SNR integrated over the Einstein ring in the visible part of the spectrum.



Depicted is the broadband spectral SNR density in mid-IR band

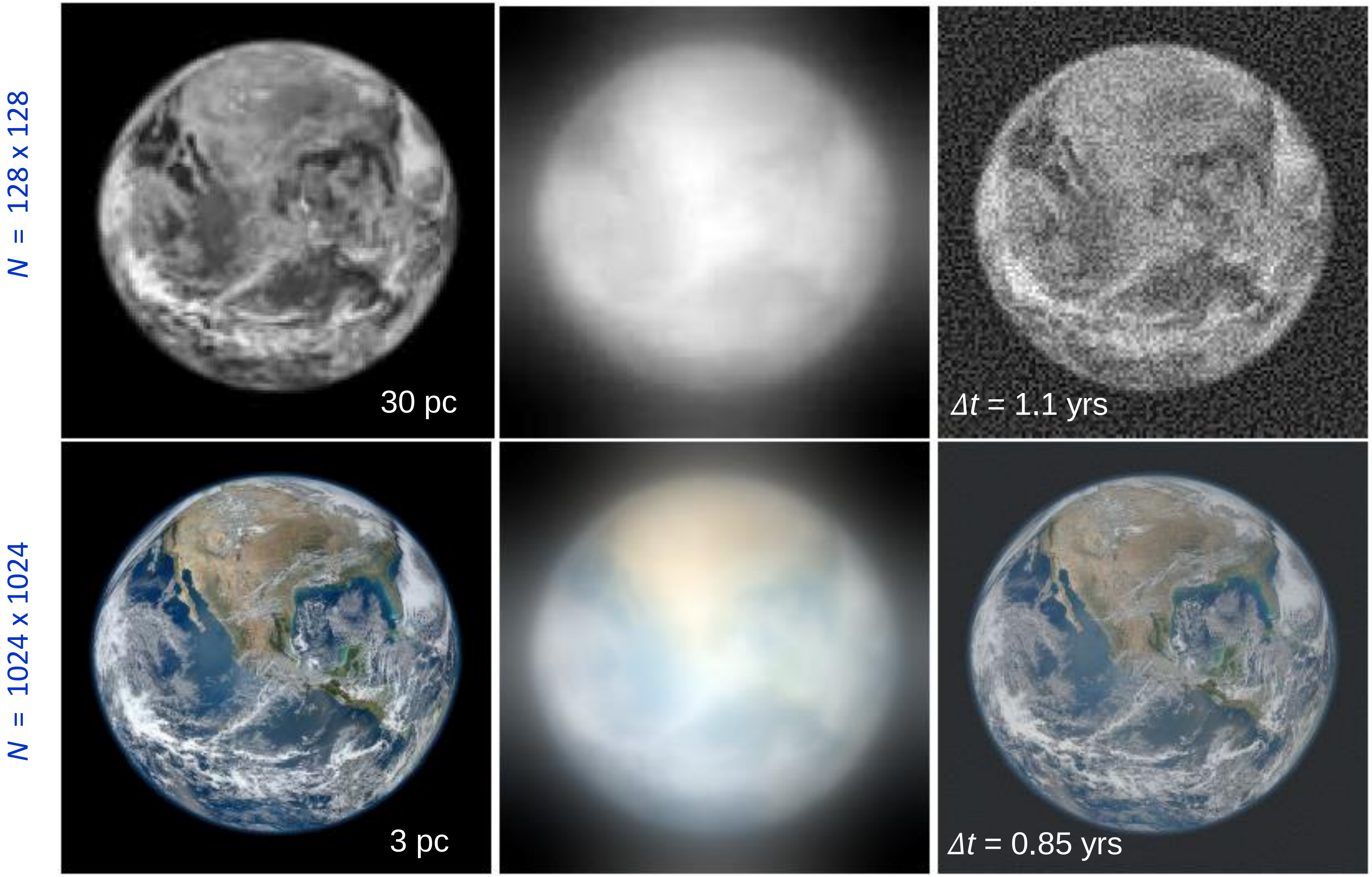
Exoplanetary spectra



An image by JWST, released on Jul 12, 2022

High-resolution Imaging with the SGL

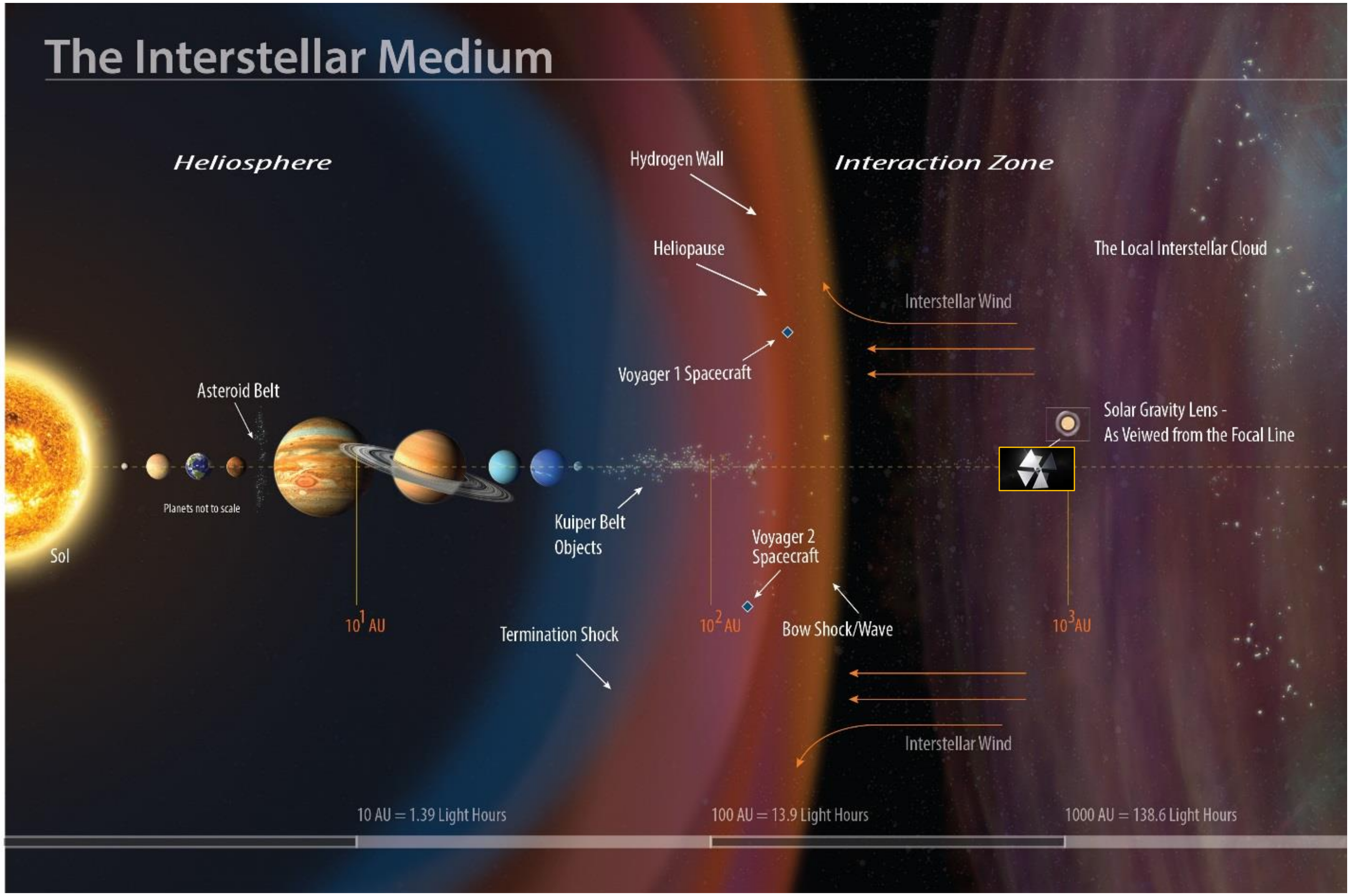
Phys. Rev. D 102, 024038 (2020)



Simulated convolution of an Earth-like exoplanet image with the SGL PSF and sub-sequent deconvolution.

Addressing SGL's primary challenge – distance

Reaching SGL's focal region in decades, not centuries, we need to move fast! Speeds > 20 AU/yr are needed.



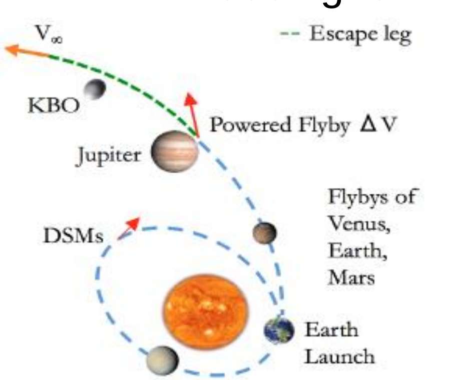
- Solar sailing allows for solar system exit velocities of ~20-30 AU/yr
    - Potential targets may be outside the ecliptic plane

Achieving High Solar System Exit Velocity

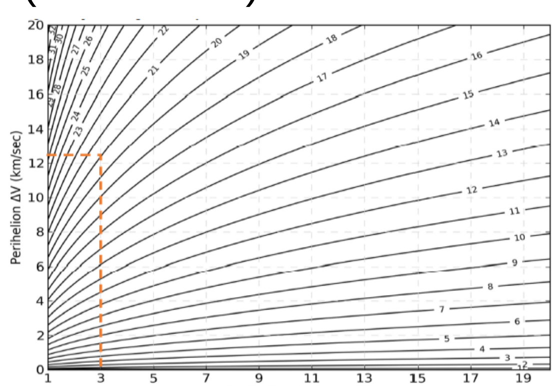
Propulsion Options Considered:

- Chemical: < 15 AU/year
  - Requires large ΔV close to the Sun, and larger SV
- Solar Thermal: 22 AU/year
  - Needs 2-3$R_\odot$ flyby requiring a heat shield of >1,000 kg;
  - JPL/MSFC point design was 500 kg spacecraft with 8,000 kg (dry) propulsion stage;
- Nuclear Electric: 20 AU/year
  - 2-stage 30kW SEP/20 kW reaches 20 AU/yr, but maximum 40-year trip time;
- Electric Sail: 12-23 AU/year
  - 20 tethers, each 10 km length ⇒ 23 AU/yr (P. Januhen)
  - 500 kg to ~12 AU/yr (L. Johnson)

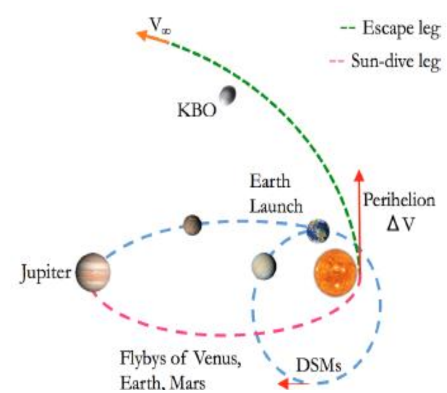
All have features that have high risk, too costly and do not meet desired approach (e.g., share-rides, etc.)



Arora, N., et. al., "Trajectories for a Near Term Mission to the Interstellar Medium"

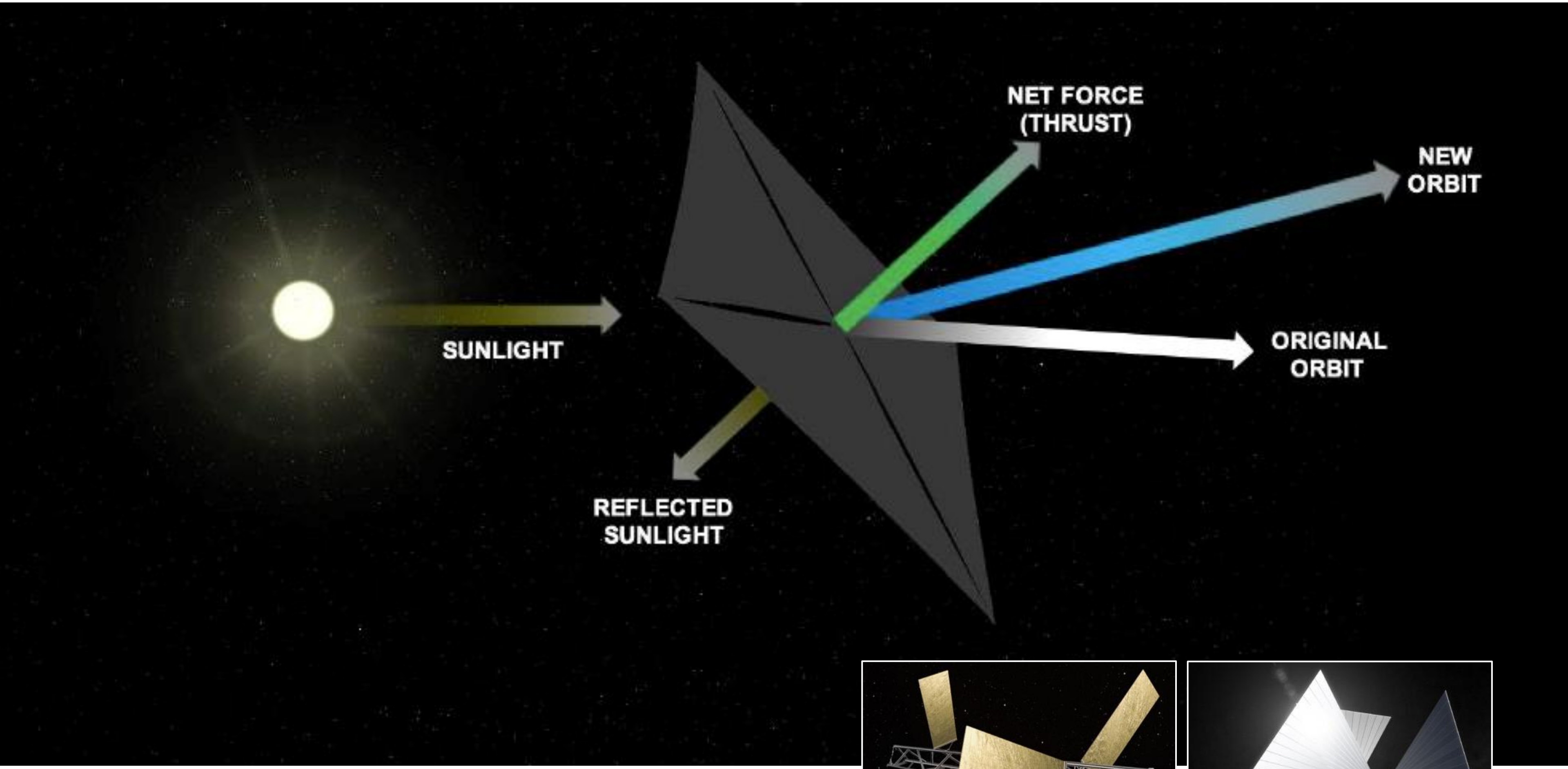


Alkalai, L., et. al., "A Vision for Planetary and Exoplanets Science: Exploration of the Interstellar Medium – The Space Between Stars", 2017

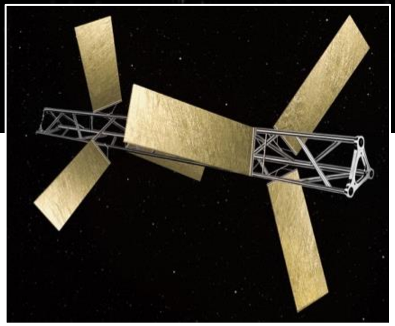


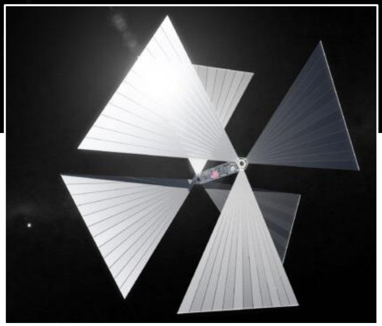
Arora, N., et. al., "Trajectories for a Near Term Mission to the Interstellar Medium"

Sail Dynamics and Design Parameters



Vane technology allows for precision sailcraft navigation & attitude control

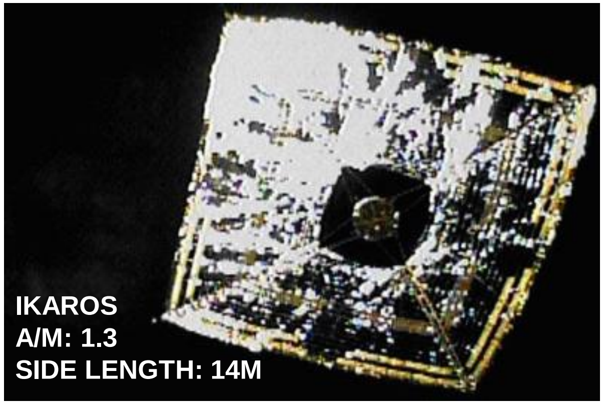


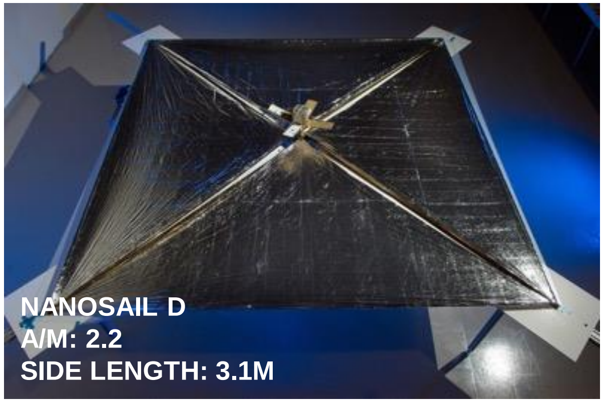


Key Enabling Technologies

- Interplanetary Smallsats (<50 kg):
  - Small mass: 1) is required to gain fast hyperbolic speeds (>5-20 AU/yr) at modest cost, 2) it allows for low energy launch velocity (rideshare).
  - MarCO and NEA Scout are first examples.
- Solar Sail – high velocity with zero propellant:
  - Now flown: IKAROS (JAXA), LightSail (Planetary Society), many in development;
- Small Nuclear Power:
  - with electric micro-thrusters for maneuvers in the SGL focal region.

Current Sails



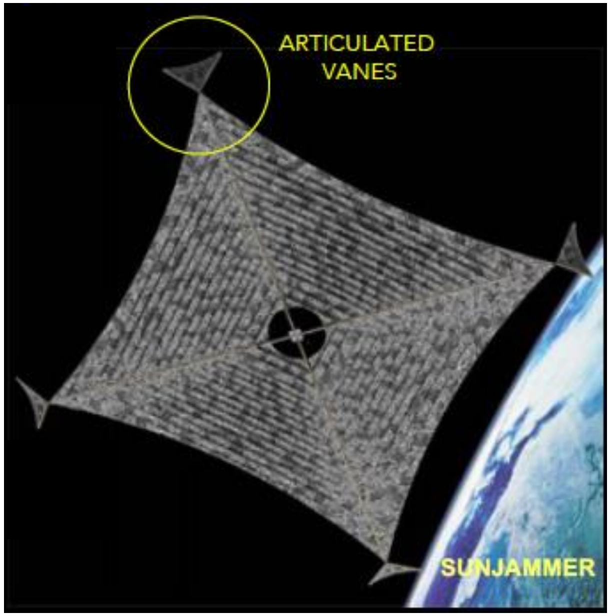


Task 3: Technology Demonstration Mission

- Towards a Low-cost Technology Demonstration Mission (TDM):
  - Develop a TDM capable of achieving a high solar system transit velocity (5-7 AU/yr), while maintaining sail control, precision navigation;
  - Develop a TDM development plan including cost estimate;
  - Conduct a PDR for the TDM and validate it readiness;
  - Develop public-private mission proposals, and implementation plan.

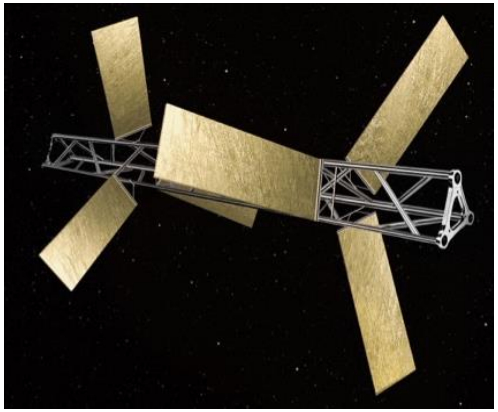
- Public-Private Partnership (PPP) for a post-Phase III Transition:
  - Science advocacy to broaden the SGLF mission support;
  - Engage philanthropic organizations, private industry, and academic partners including Breakthrough, Xplore, L'Garde, Blue Origin, Cornell Tech, Caltech, MIT, UCLA, and others;
  - Work with NASA leadership and the ongoing NAS Decadal surveys to include SGLF mission in their science strategy;
  - Engage NASA STMD and other key players for potential TDM flight(s).

Challenges of Planar Sails



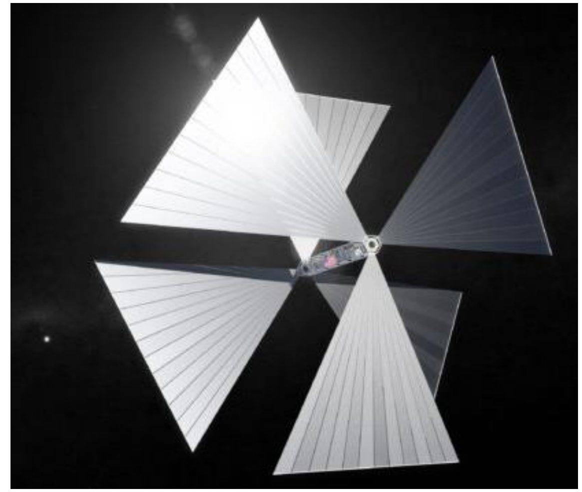
- Planar sail fabrication and operational challenges:
  - Significant infrastructure requirements
    - Large clean rooms for manufacture
  - Complex packaging and deployment
    - Deployable booms and mechanisms
    - Parasitic mass of support structure
    - Sail material is not under tension
  - Limited Control
    - Inefficient attitude control with sail
    - Dynamic stability of Center of Pressure vs Center of Mass
    - Constrained & conflicting pointing requirements
    - Power vs Comm vs Trajectory vs Payload
    - Attitude and trajectory are coupled
- Sunvane: A new design for advanced sailcraft
  - Internal review of Sunjammer program identified the corner control vanes as enabling technology to advance sailcraft performance & utility

Innovative Approach to Sailcraft Architecture



SunVane (L'Garde, 2010)

Design heritage for higher TRL

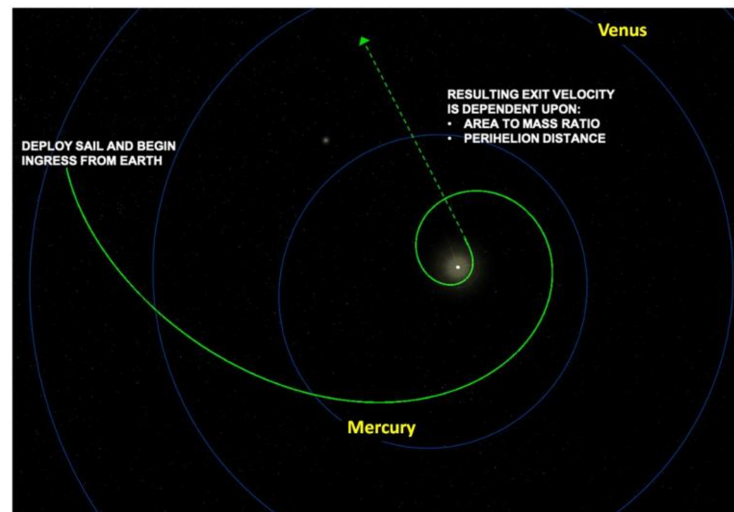


Advanced solar sailcraft design for the SGLF mission

(Xplore, 2020)

Innovative sailcraft design allows:

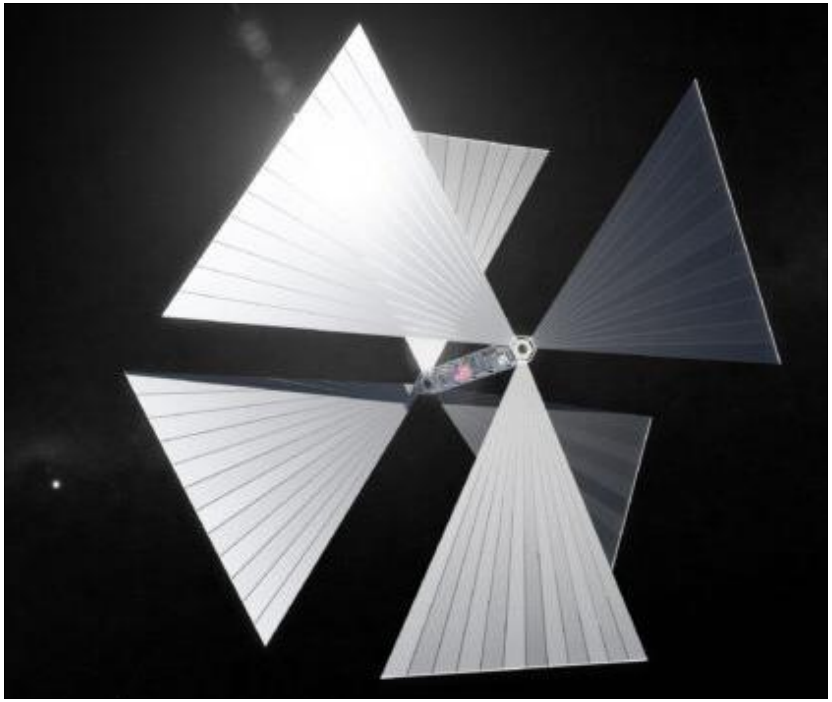
- Simplified deployment;
- Articulated vanes enable control;
- Significant power generation;
- Scalable to 400+ A/m ratio with current technology;
- Leverages truss advances (<10 g/m);
- Vanes with multifunctional capabilities: COMM and power generation.



New design enables fast transit through the solar system at ~20-30 AU/yr

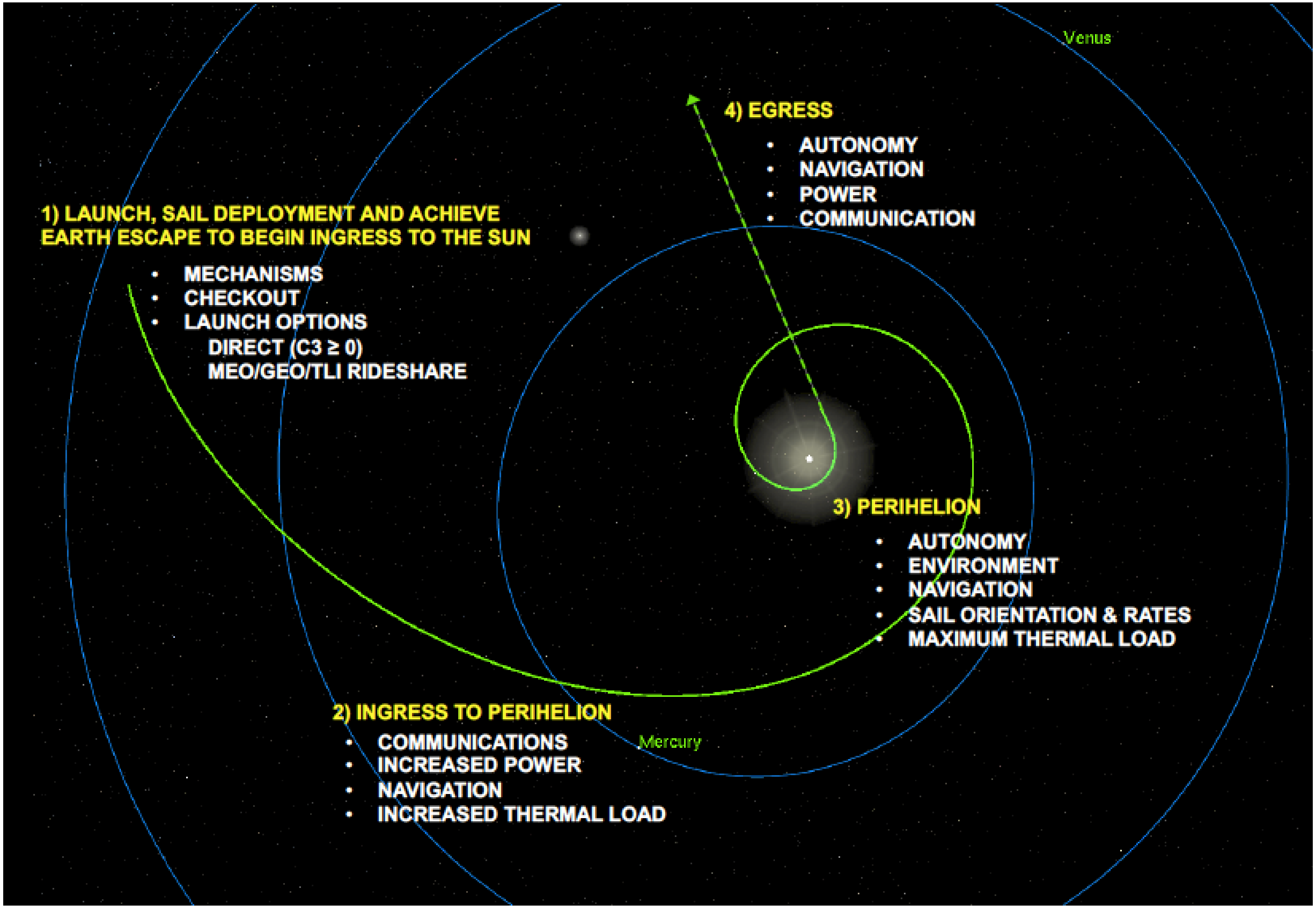
Technology Demonstration Mission (PDR: July 2022)

- TDM Objectives:
  - A/m ratio: > 50 m^2/kg;
  - Achieve 6-8 AU/yr exit velocity;
  - Survive perihelion of 0.2 AU;
  - Low Cost & Manufacturable;
  - Capabilities-based, no development;
  - Rideshare compatible.
- TDM design features:
  - A/m: 22.3 m^2/kg (3x NEA Scout);
  - Six 20-m^2 vanes: (775 g per vane, 5-μm Kapton);
  - Carbon fiber truss (120g).
- Avionics & GNC leverages MARCO
  - 500 g for UHF SDR, 3 wheels, 2 star-trackers, battery;
  - 100 g for shape memory motors.
- Total mass: 5.37 kg
  - 86% of mass is in vanes.



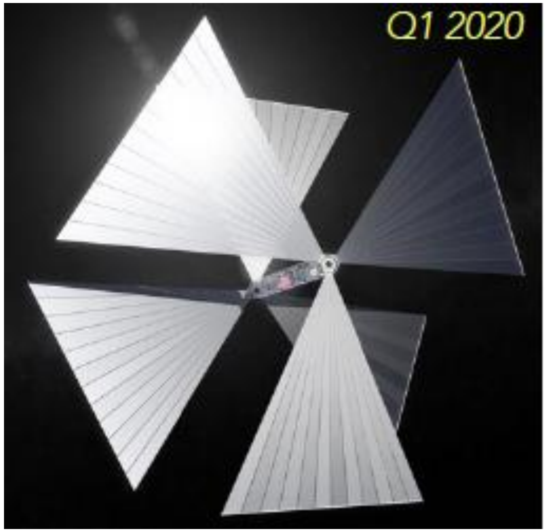
Our effort increases the current A/m ratios by at least a factor of 2

Common SGLF/TDM Phases & Systems Engineering

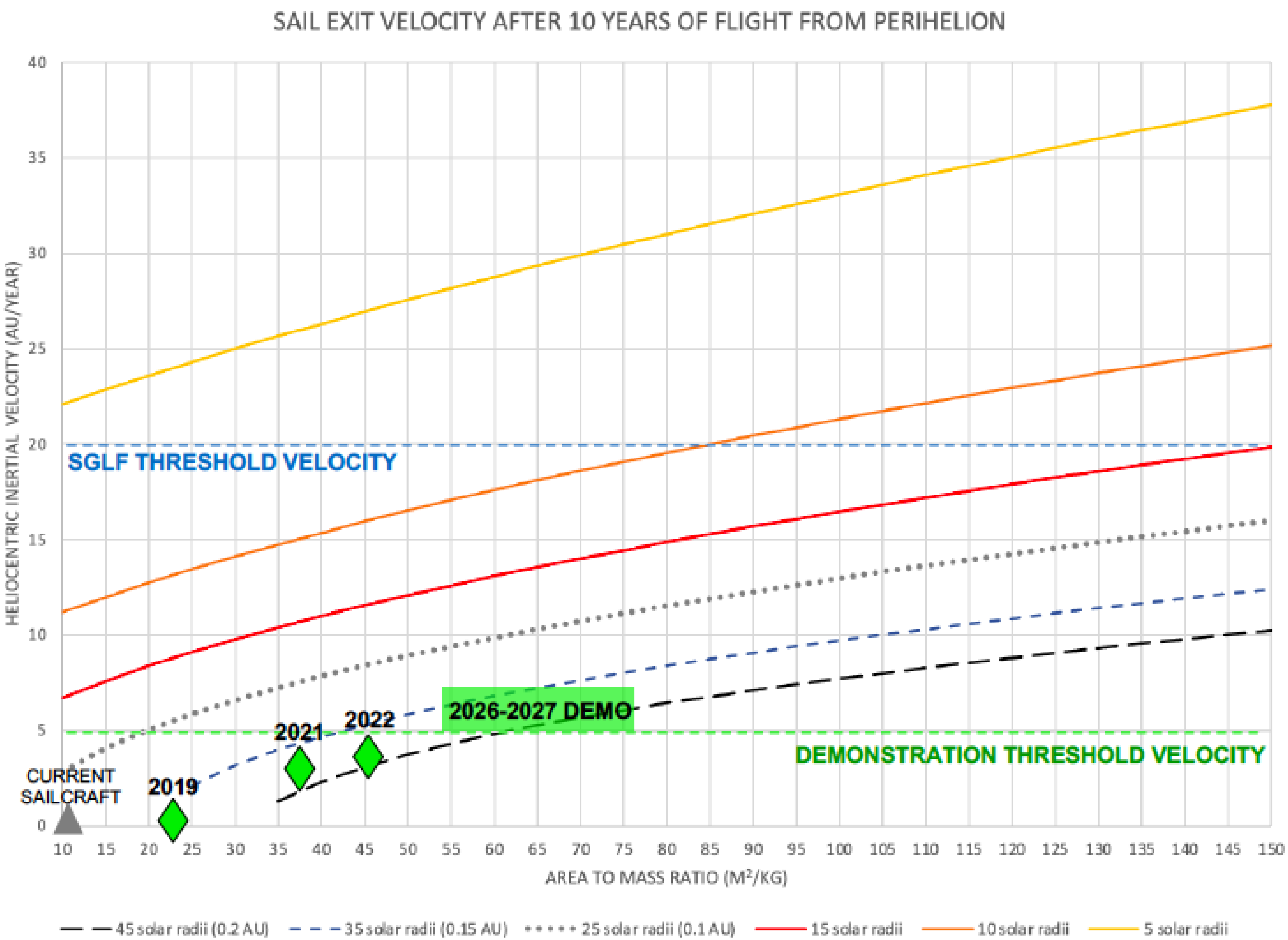


TDM Objectives and Tasks

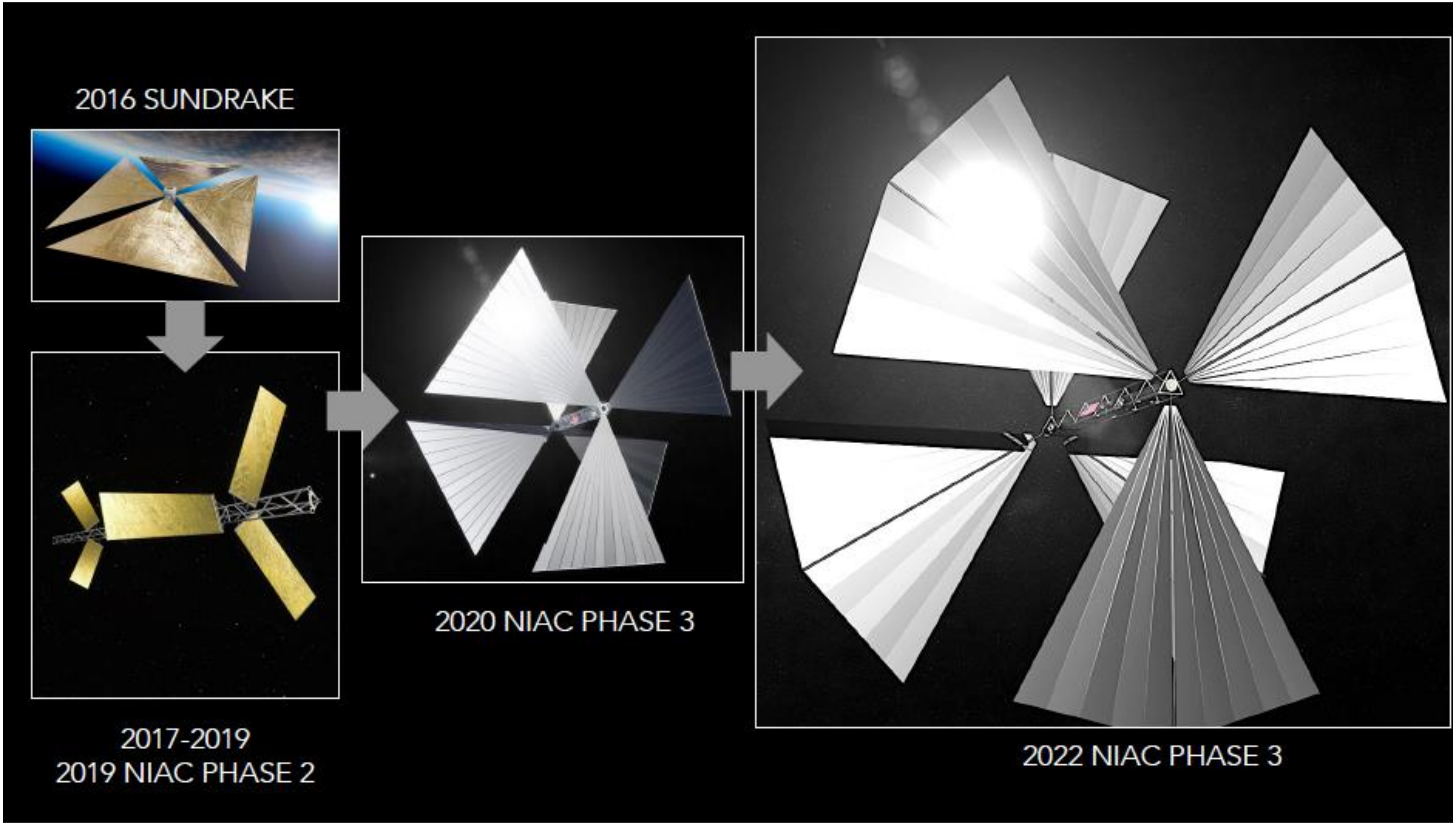
- TDM Objective:
  - Achieve a heliocentric velocity of 5 AU/year
  - The objective velocity is achieved as a function of the vehicle's A/m ratio and perihelion distance
- Current design goals:
  - Minimum Perihelion Distance: 0.2 AU
  - Minimum Area to Mass Ratio: 50 m^2/kg
- TDM Objective Demonstration Goals
  1. Navigate from GEO to perihelion
  2. Quantify egress vector knowledge/ability to correct
  3. Quantify pointing control, knowledge and stability
  4. Direct characterization of perihelion environment
  5. Autonomous ground
  6. FFP cost and maintain schedule
- Design Goals to constrain mission trade space:
  - Capabilities based, minimal development
  - Low Cost (single millions per unit)
  - Manufacturable & Rideshare compatible



TDM Development Plan



TDM Vehicle Design Evolution



Our path: TDM → Sundivers → SGL

TDM VEHICLE CONFIGURATION

TDM objective: > 5AU/year

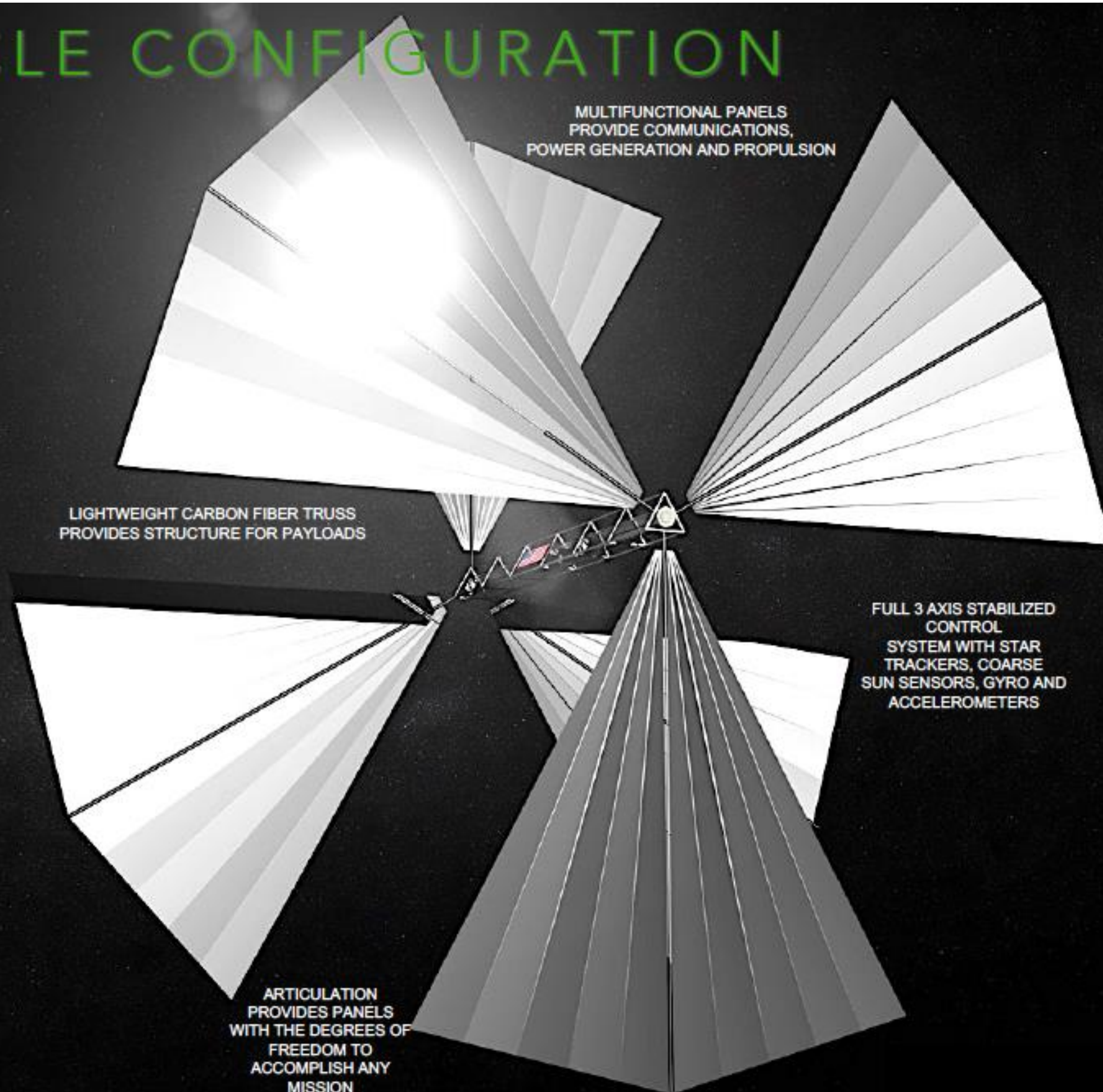
Implementation of the LGarde Sunvane design

Six multifunctional vanes
- Shape memory motors
- Embedded photovoltaics
- Thin film phased array elements

Carbon fiber truss

Avionics integrates TRL 9 components
- Dual use SDR & flight computer
- Triad of RCS wheels
- Star tracker
- Battery

Full 3-axis stability and control via wheels not vanes



Vane Mass Estimates

- 20 sqm 3 strut vane – maintains tension (15 PSI)
  - 2.5 micron Kapton
  - 0.135 kg – includes shape memory motors
- Alternate lighter materials
  - Nexolve improved thermal properties and lighter materials from advanced projects
  - 2 and 0.9 micron Mylar
- Alternate lighter truss
  - Current truss is 0.4 kg/m
  - Options for 0.2 and 0.15 kg/m

LIGHTSAIL NOT UNDER TENSION

3 STRUT VANE ENSURES TENSION

TDM Master Equipment LIst

- Structure:
  - 6.3 m carbon fiber truss
- Sail and structure
  - Six 20 sqm vanes
  - 2.5 micron Kapton
  - 3 strut format
  - 0.135 kg per vane per L'Garde
- Total mass: 4.07 kg
  - Vanes: 6 x 0.135 kg = 0.81 kg
  - Truss: 2.52 kg (0.4 kg/m)
  - Avionics: 0.74 kg
  - Add 20% for margin
  - Margined mass: 4.81 kg
- Baseline A/m: 25 m^2/kg (margin)
  - Unmargined: 30 m^2/kg
  - Lighter Sail Option: 33 m^2/kg
  - Lighter Truss Option: 42 m^2/kg
  - Combined Option: 50 m^2/kg

OEM	Component	Description	Unit Mass (g)	Number	Total Mass (kg)	
Miga Motors	NM70R-6P	Rotary SMA (shape memory actuator), 60 degree throw	5.5	6	0.033	
Miga Motors	MADv5	Mosfet driver for SMA actuator	15	6	0.090	
Helical	Custom Beam flexure	Ti helical beam flexure for deployment of sail, actuator coupler	3	6	0.018	
Sinclair	RW-.01	picosatellite reaction wheel	50	3	0.150	
Sinclair	ST-16RT2	2nd generation star tracker	158	1	0.158	
Gomspace	Nanocom AX100	UHF Radio	24	1	0.024	
Gomspace	Nanomind A3200	Flight computer	24	1	0.024	
Gomspace	Battery	Battery	240	1	0.240	
					0.737	kg

LightCraft 1:3 prototype (Sep 21, 2021)

LightCraft 1:3 model at Xplore, Inc

Thermal analysis of the TDM vehicle

Component	Surface Coating/ Color	Emissivity (ε)	Absorptivity (α)	Source
Sail	White (Barium Sulphate with Polyvinyl Alcohol)	0.88	0.06	NASA Ref Pub 1121
Sail	Black	0.82	0.90	Sheldahl Redbook
Sail	Metalized	0.05	0.22	Sheldahl Redbook
Sail Structural Elements	White (Barium Sulphate with Polyvinyl Alcohol)	0.88	0.06	NASA Ref Pub 1121
Truss Rods	White (Barium Sulphate with Polyvinyl Alcohol)	0.88	0.06	NASA Ref Pub 1121
Truss/Vane Interface	Clear Anodized Aluminum	0.76	0.27	NASA Ref Pub 1121
Reaction Wheels	White (Barium Sulphate with Polyvinyl Alcohol)	0.88	0.06	NASA Ref Pub 1121
Star Tracker	White (Barium Sulphate with Polyvinyl Alcohol)	0.88	0.06	NASA Ref Pub 1121
Spacecraft	Clear Anodized Aluminum	0.76	0.27	NASA Ref Pub 1121

Component	Surface Coating/ Color
Sail	White/Metalized
Sail Structural Elements	White
Truss Rods	White
Truss/Vane Interface	Clear Anodized Aluminum
Reaction Wheels	White
Star Tracker	White
Spacecraft	Clear Anodized Aluminum

Orbits	Truss Rods	Spacecraft	Sail Structural Elements	Truss/Vane Interface	Star Trackers	RCS Wheels
LEO	-15.2	-1.3	-22.4	-14.2	-33.0	-28.1
Cislunar	6.5	6.5	-19.8	-31.9	-72.5	-22.8
Venus	24.1	38.3	25.7	39.8	24.2	19.3
Mercury	59.8	126.2	116.3	104.7	49.4	50.0
0.25 AU from Sun	130.6	234.9	238.5	243.2	130.6	130.6

Thermal treatments reduced the thermal load on the vehicle’s components in all orbit regimes. The remaining thermal limit violations can be mitigated by adding thermal tape and MLI for the star tracker and reaction wheels. (Complete by PDR in September 2022).

Thermal analysis: LEO to 0.25 AU

- Untreated:

Orbits	Truss Rods	Spacecraft	Sail Structural Elements	Truss/Vane Interface	Star Trackers	RCS Wheels
LEO	35.0	133.9	86.3	120.1	54.4	108.1
Cislunar	50.7	168.4	32.2	108.3	2.2	71.9
Venus	120.9	286.0	128.8	243.9	121.6	147.1
Mercury	173.9	488.1	321.7	418.6	148.4	413.8
0.25 AU from Sun	313.3	638.0	347.1	487.9	413.7	414.1

Component	Surface Coating/ Color
Sail	White/Metalized
Sail Structural Elements	Plain Carbon Fiber
Truss Rods	Plain Carbon Fiber
Truss/Vane Interface	Polished Aluminum
Reaction Wheels	Polished Aluminum
Star Tracker	Black
Spacecraft	Polished Aluminum

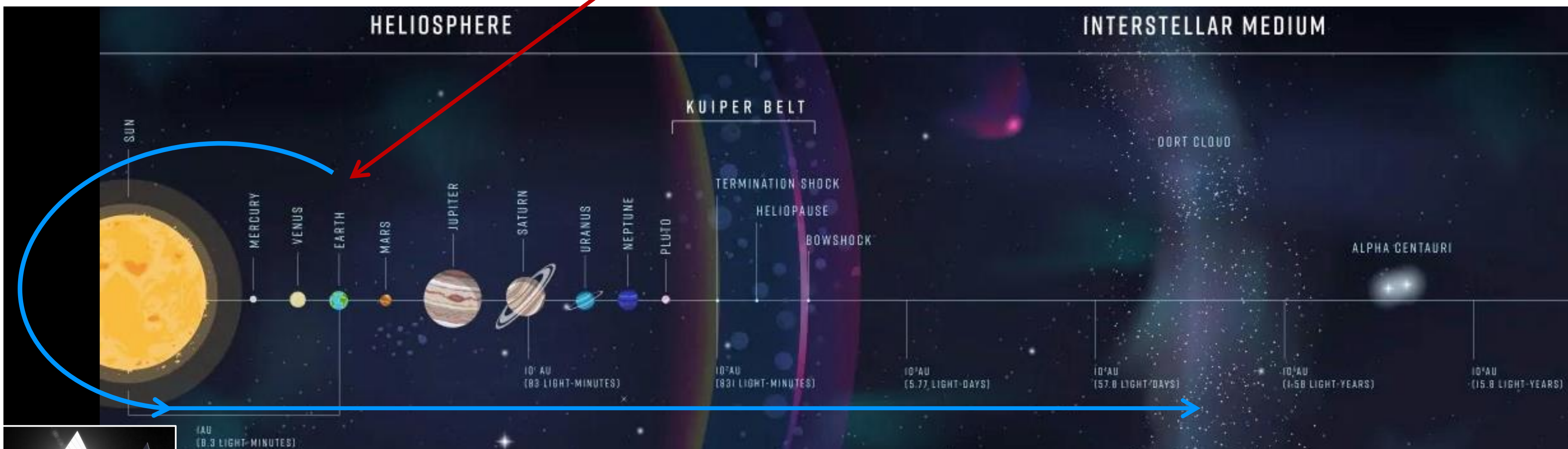
- Treated:

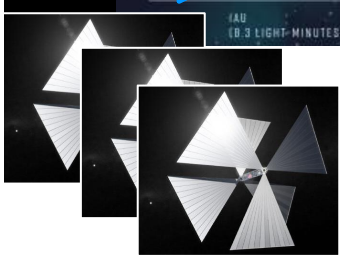
Orbits	Truss Rods	Spacecraft	Sail Structural Elements	Truss/Vane Interface	Star Trackers	RCS Wheels
LEO	-15.2	-1.3	-22.4	-14.2	-33.0	-28.1
Cislunar	6.5	6.5	-19.8	-31.9	-72.5	-22.8
Venus	24.1	38.3	25.7	39.8	24.2	19.3
Mercury	59.8	126.2	116.3	104.7	49.4	50.0
0.25 AU from Sun	130.6	234.9	238.5	243.2	130.6	130.6
MLI 0.25 AU from Sun	130.6	234.9	238.5	243.2	53	53

Component	Surface Coating/ Color
Sail	White/Metalized
Sail Structural Elements	White
Truss Rods	White
Truss/Vane Interface	Clear Anodized Aluminum
Reaction Wheels	White
Star Tracker	White
Spacecraft	Clear Anodized Aluminum

New Paradigm – Fast, Low-cost, Interplanetary Sailcraft

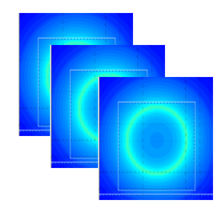
Low energy launch from High Earth Orbit – spiral into low perihelion flyby of Sun





Smallsat – solar sail spacecraft

TDM	ISOs, Enceladus	Ura, Nep, KBOs	SGL focal region
5-6	7-9	9-14	20-30 AU/yr



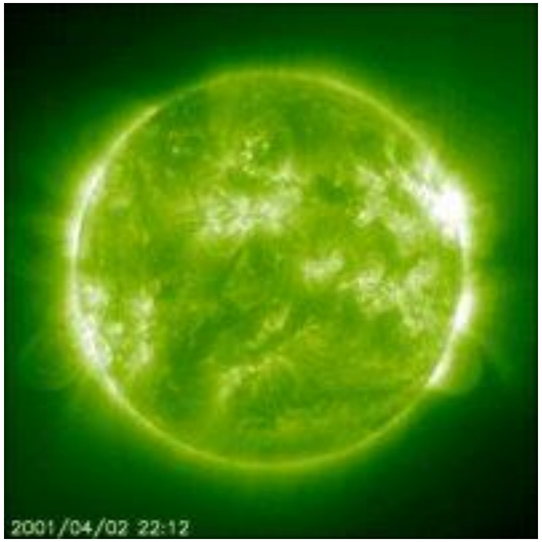
- Larger deployable sails & smaller mass spacecraft
- Higher temperature and thinner sails

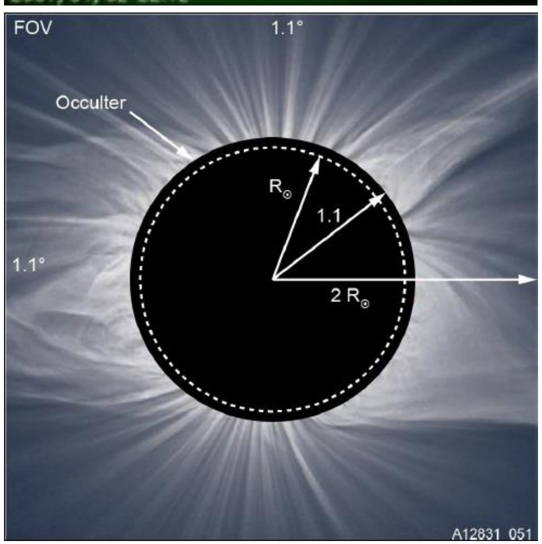
Big Science in Small Packages

- Heliophysics
  - Solar polar regions (out ecliptic plane)
  - Shape & structure of the Heliosphere
  - Pristine ISM
  - Interstellar Turbulence
- Planetary
  - Asteroids (MBA, NEA), ISO, comets
  - Planetary satellites: i) Titan's atmosphere, ii) plumes of Europa/Enceladus, etc.
  - Kuiper Belt and Oort Cloud
  - Probing Planet 9
- Astrophysics
  - Extragalactic Background Light (EBL)
  - Zodiacal Background,
  - Interplanetary Dust
  - Parallax science
  - Gravitational inverse square law

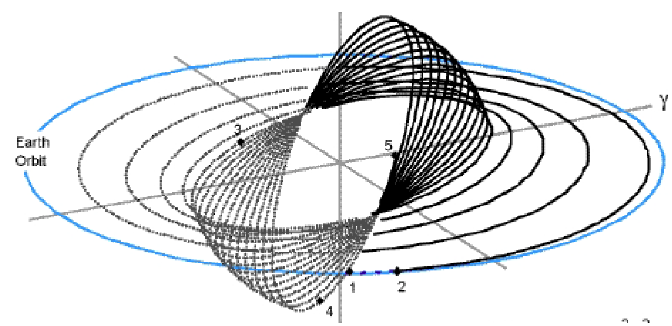
- Spacecraft bus:
  - Multipurpose (PV-power, RF-comm)
  - In-flight aggregation
- Mission types:
  - Fast flybys
  - Impactors
  - Swarms
  - (no orbiters)
- Instruments:
  - Small wight
  - Low power
  - Small size

Solar Polar Imager

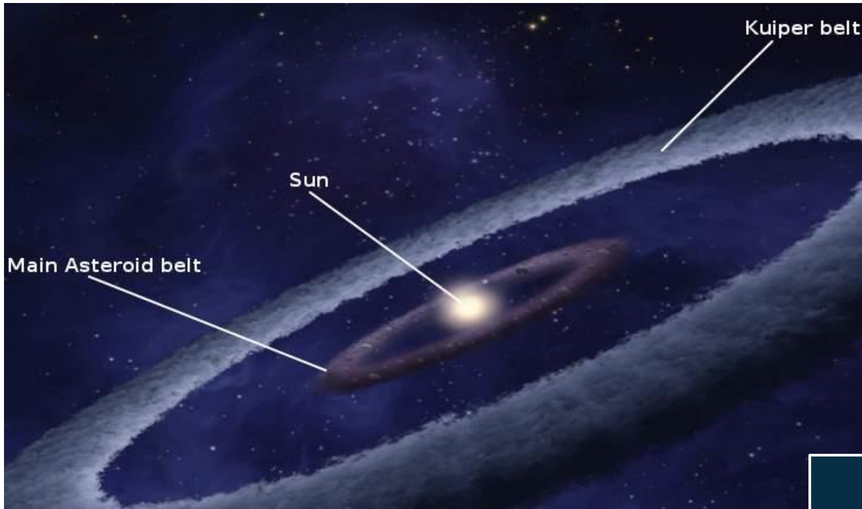


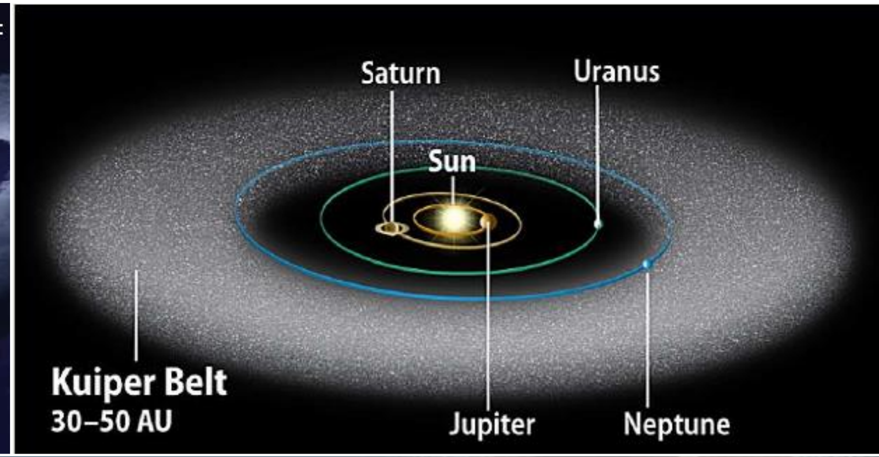


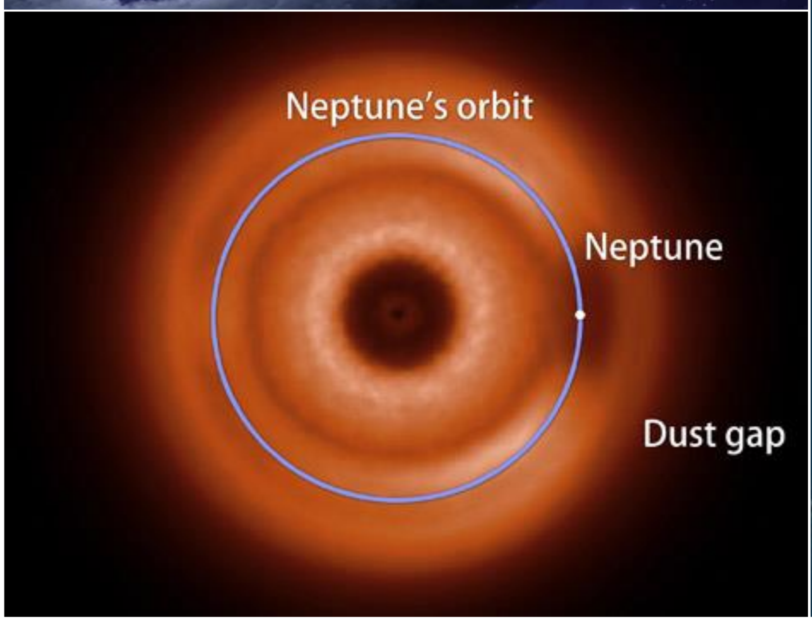
- Exciting scientific objectives:
  - image the global extent and dynamic effects of coronal mass ejections
  - discover the sources, longitudinal structure, rotational curvature and time variability of coronal features
  - link particle and field observations to images of the Sun, corona, and heliosphere at all latitudes
  - determine magnetic structures and convection patterns in polar regions
  - follow the evolution of solar structures over a full solar rotation

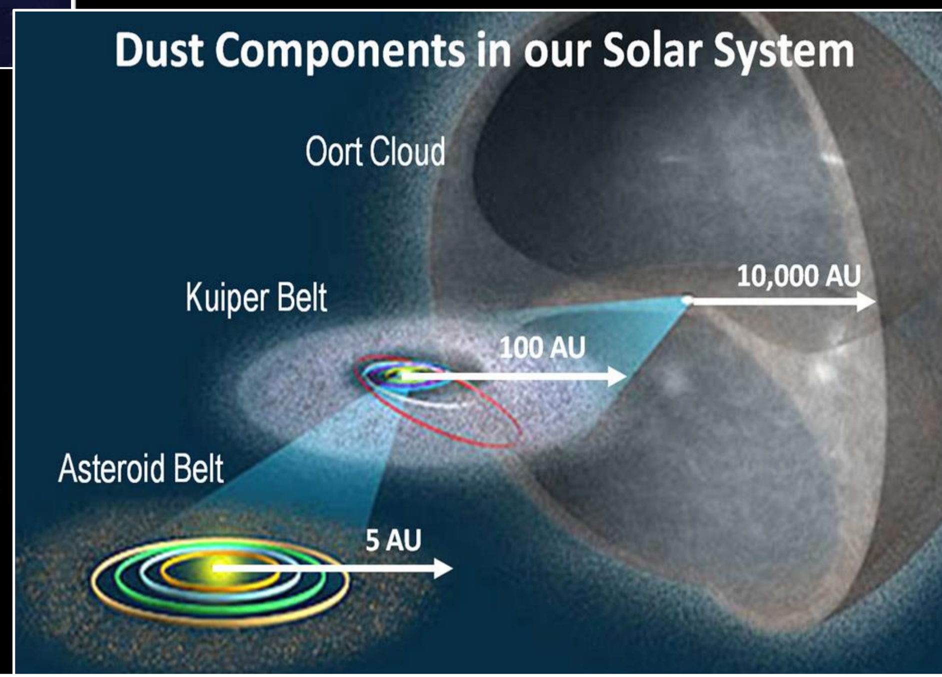


Dusty background in the solar system



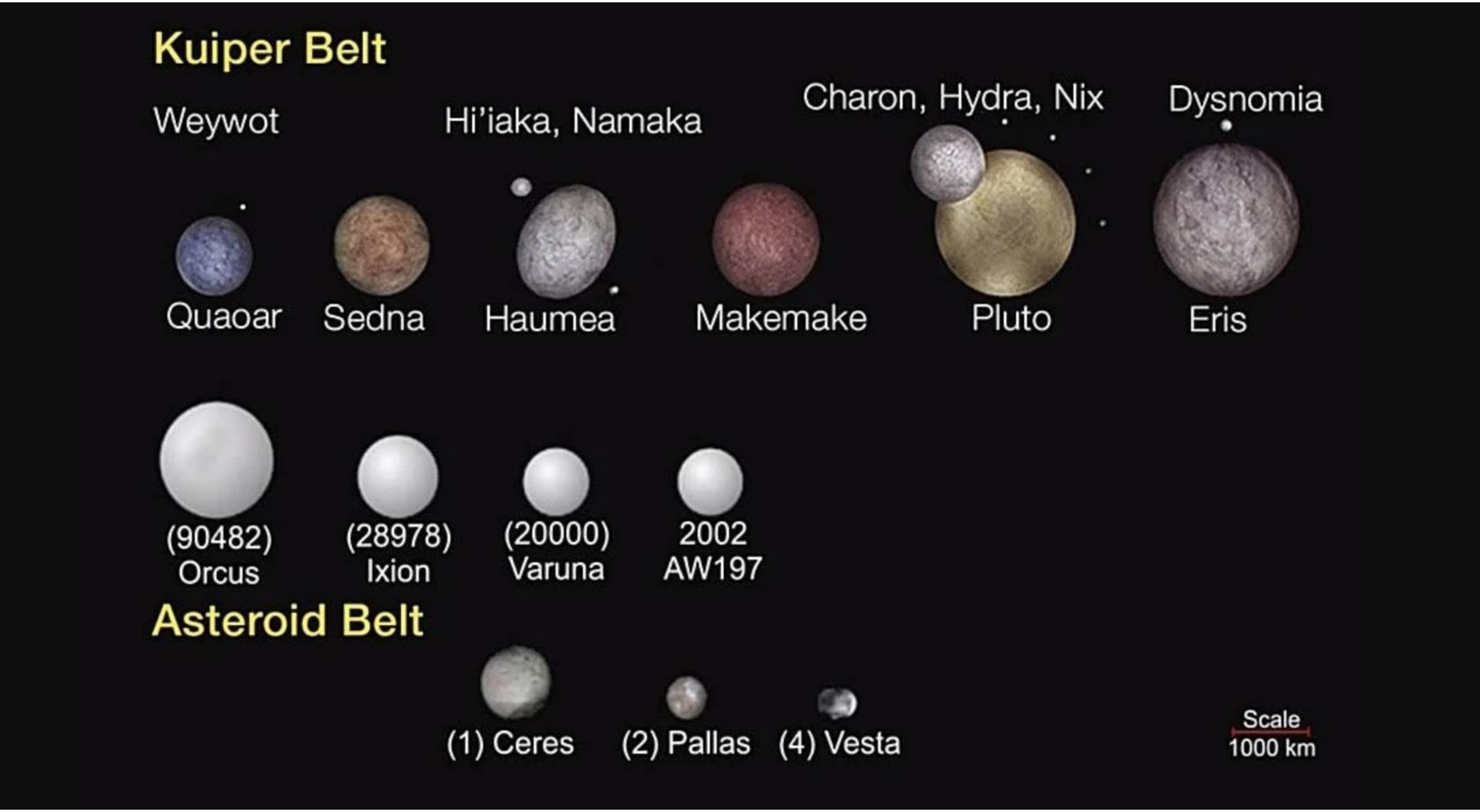






The outer solar system: dwarf planets . . .

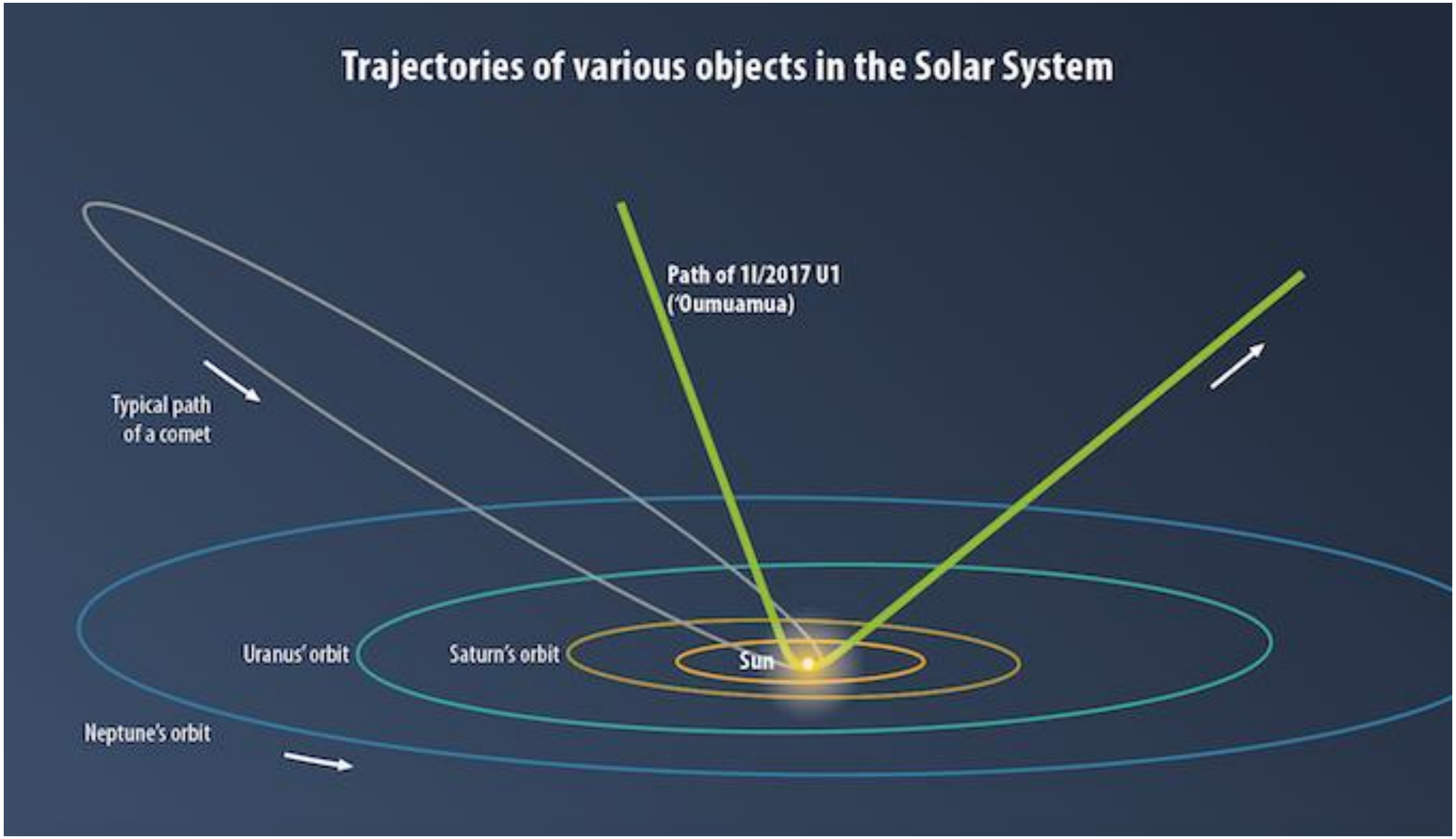
- The outer solar system contains many fascinating dwarf planets . . .



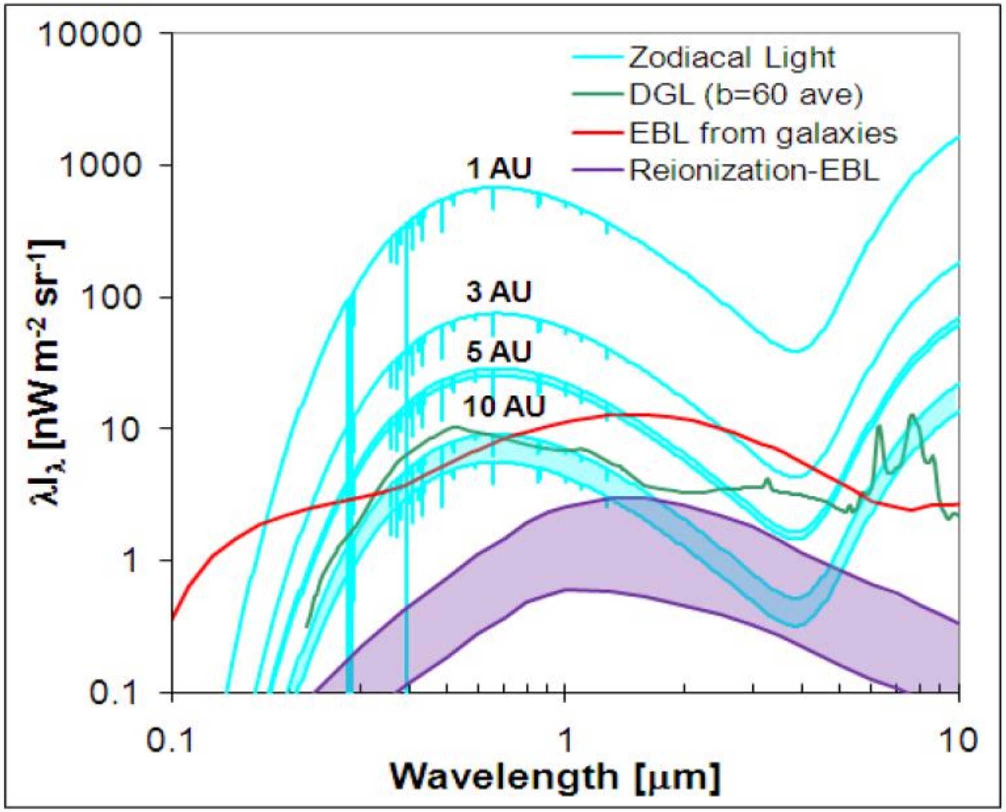
Types of missions to interstellar objects

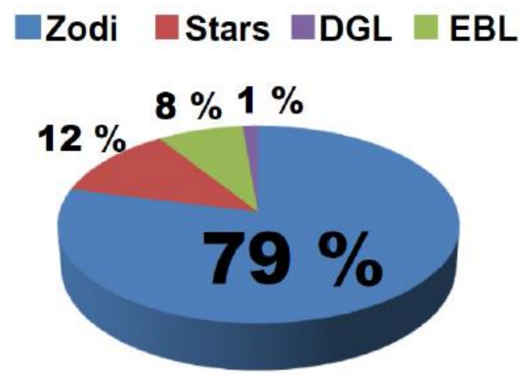
Types of missions to InterStellar Objects.

Target	Mission Type	Exploration Type	Notes
ISOs Entering the Solar System	Loiter Missions	Sample Return	Requires Prepositioning of Spacecraft
ISOs Leaving the Solar System	Chase Missions	Flyby	High ΔV, Long Duration
Captured ISOs	Preplanned Missions	Orbiters, Landers	Similar to other asteroid/comet missions.

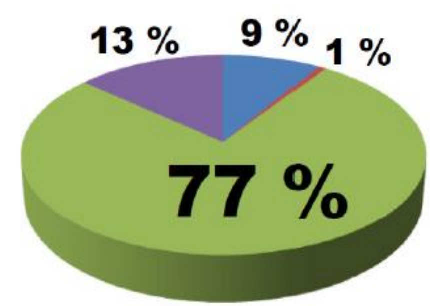


Surveying the Sky at 10AU





DIRBE Sky at 1 AU



ZEBRA Sky at 10 AU