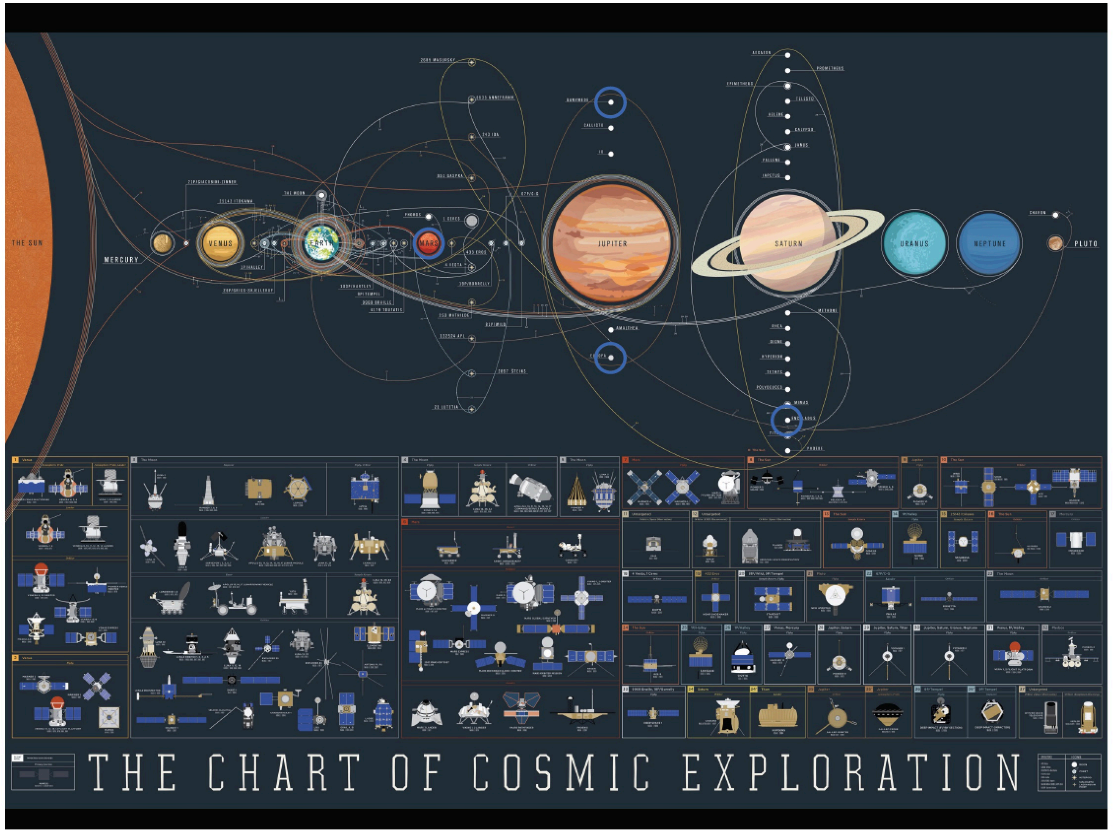
The Search for Habitable Planets via the Solar Gravity Lens

Shaping the Future - A “Big Idea” for Space Exploration and Technology Development



Been There – Done That →

THE SOLAR GRAVITATIONAL LENS

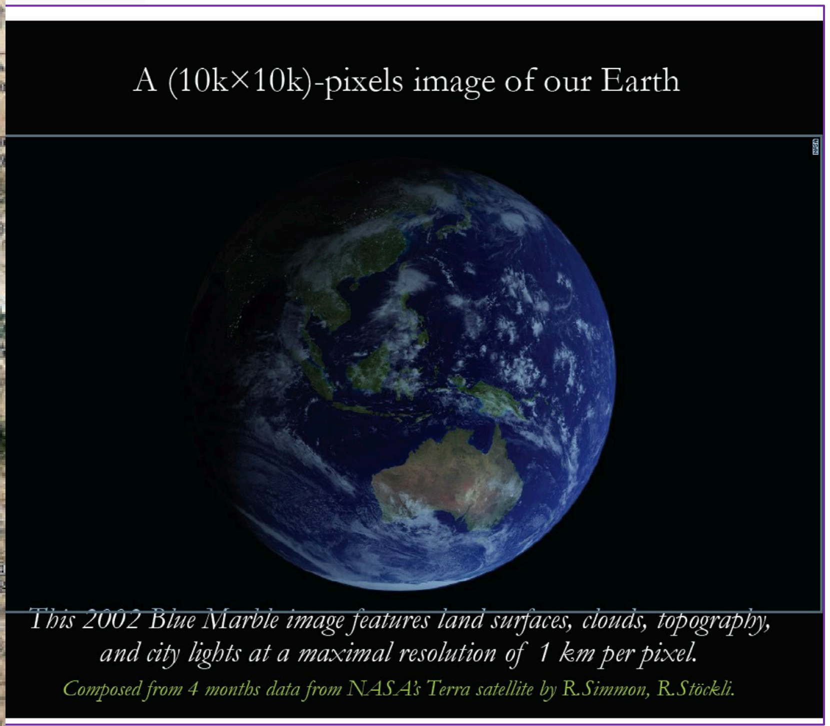
The image in a form of the Einstein ring

Credit: ESA, Hubble & NASA Wikimedia

Exploit Einstein’s Rings to Explore Distant Solar Systems

Solar Gravity Lens (SGL) is Being funded by NASA

DIRECT MULTIPIXEL IMAGING AND SPECTROSCOPY OF AN EXOPLANET WITH A SOLAR GRAVITY LENS MISSION



We have just completed the mid-term review NASA Innovative Advanced Concepts (NIAC) phase II Effort.
" This is three NIAC projects worth of work, very impressive, mission design fantastic"

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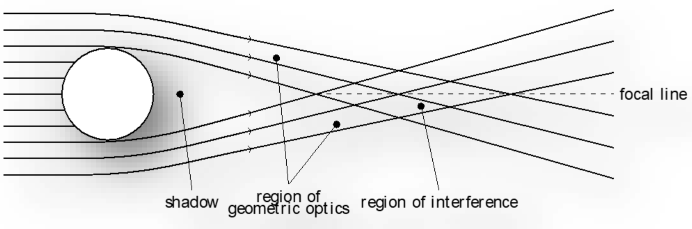

Direct Multipixel Imaging and Spectroscopy of an Exoplanet with a Solar Gravity Lens Focus (SGLF) Mission

An imaging mission to SGLF appears to be feasible, but needs further study

Concept

- SGLF provides a major gain (~10^{11} at 1um), resolution of 10^{-9} arcsec in a narrow FOV;
- A 1-m telescope at ~750AU has a collecting area equivalent ~80 km aperture in space;
- A mission to the SGLF could image Earth 2.0 up to 30pc away with resolution to ~10km to see surface features;
- A small s/c with electric propulsion (or solar sails) can reach the SGLF in <35-40 yrs.

Proposed Study and Approach

- Define baseline design, sub-syst components;
- Define mission science goals & requirements;
- Develop system and subsystem requirements;
- Study mission architecture and con-ops;
- Assessment of feasibility (cluster) small-sats;
- Identify technology development needs;
- Study instruments & systems: power, comm, pointing, s/c, autonomy, coronagraph, nav, propulsion, raster scan in the image plane, etc.

Benefits

- A breakthrough mission concept to resolve a habitable exoplanet at modest cost/time;
- Could find seasonal changes, oceans, continents, life signatures on an exo-Earth;
- Small-sat & fast exit from the solar system;
- Electric propulsion for raster-scanning the image using tethered s/c (or cluster);
- SLGF is valuable for other astrophysics and cosmology targets.

Earth with resolution of (1000 × 1000) pixels.

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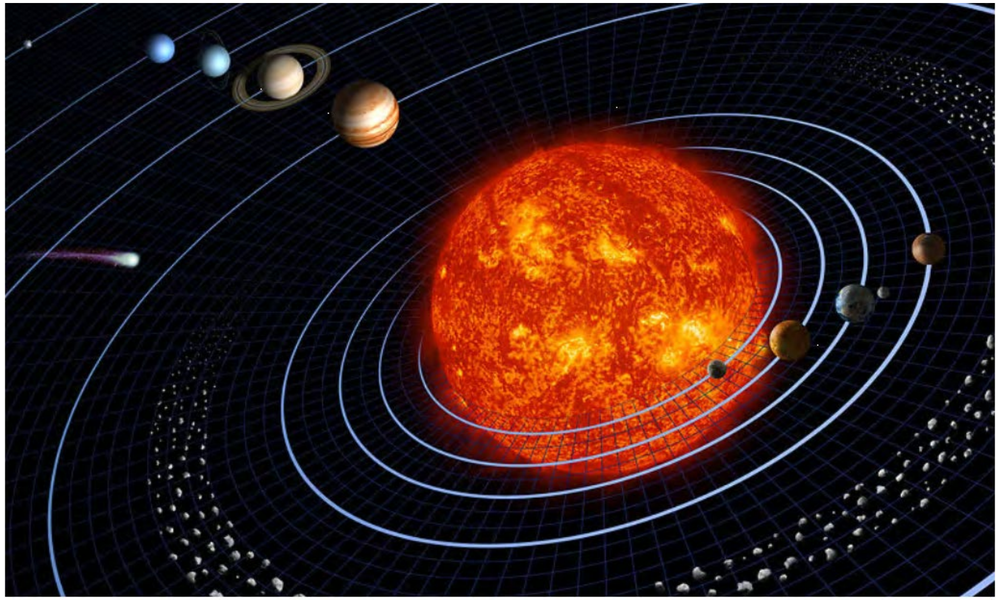
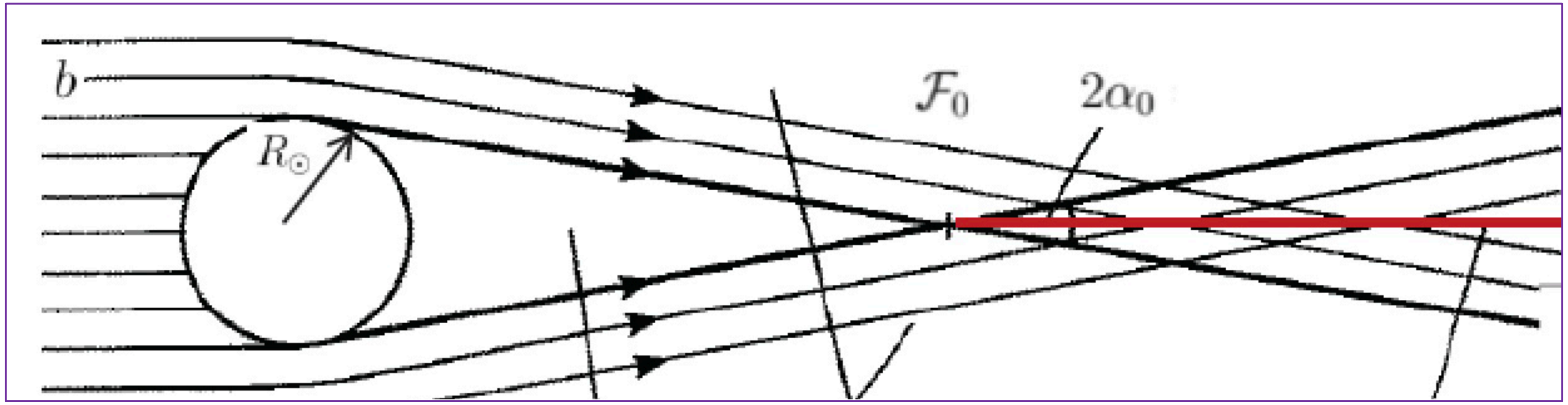
The Power of 10^4 – SGL Shrinks the Exo-Solar System by the Ratio of Star to Focal Point (FP) Distances

This distance compression means that a mission can be designed to survey an entire exo-solar system



Star is ~100 light Years Distant



FP is 4 light days (0.01 LY) Distant

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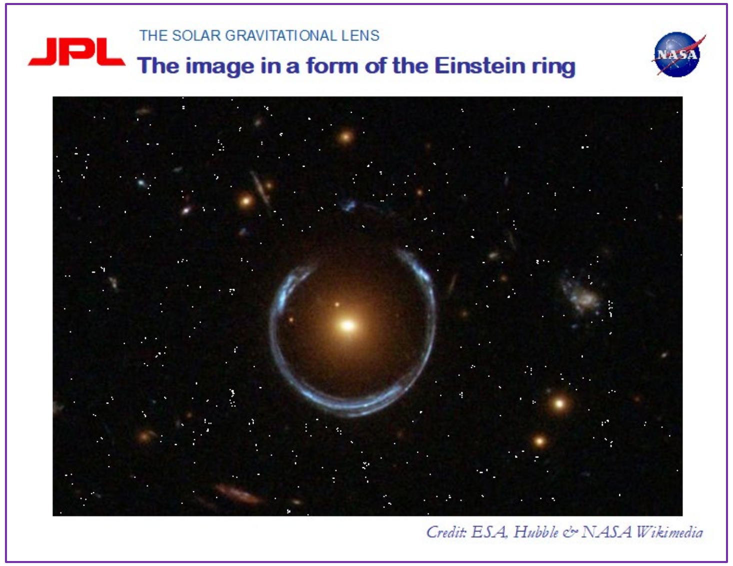
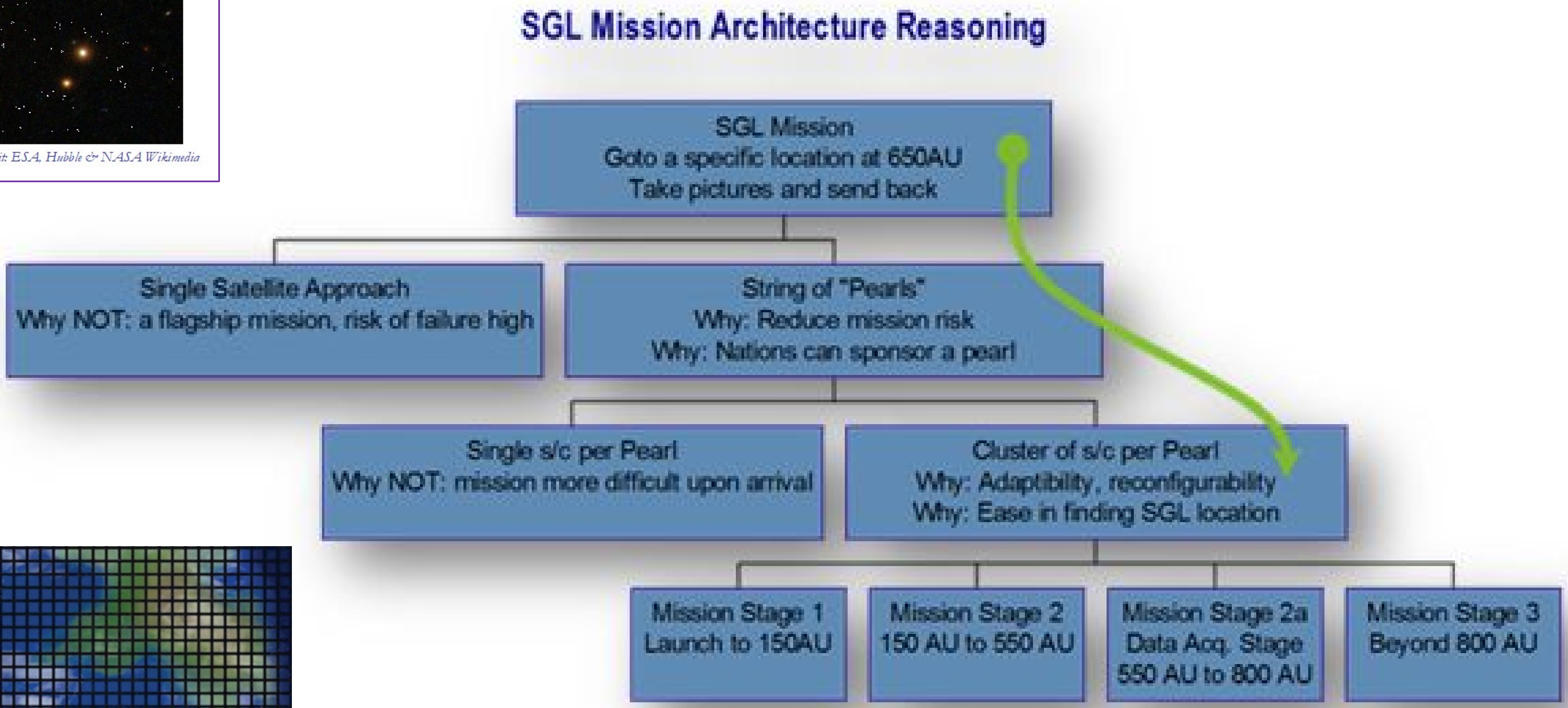
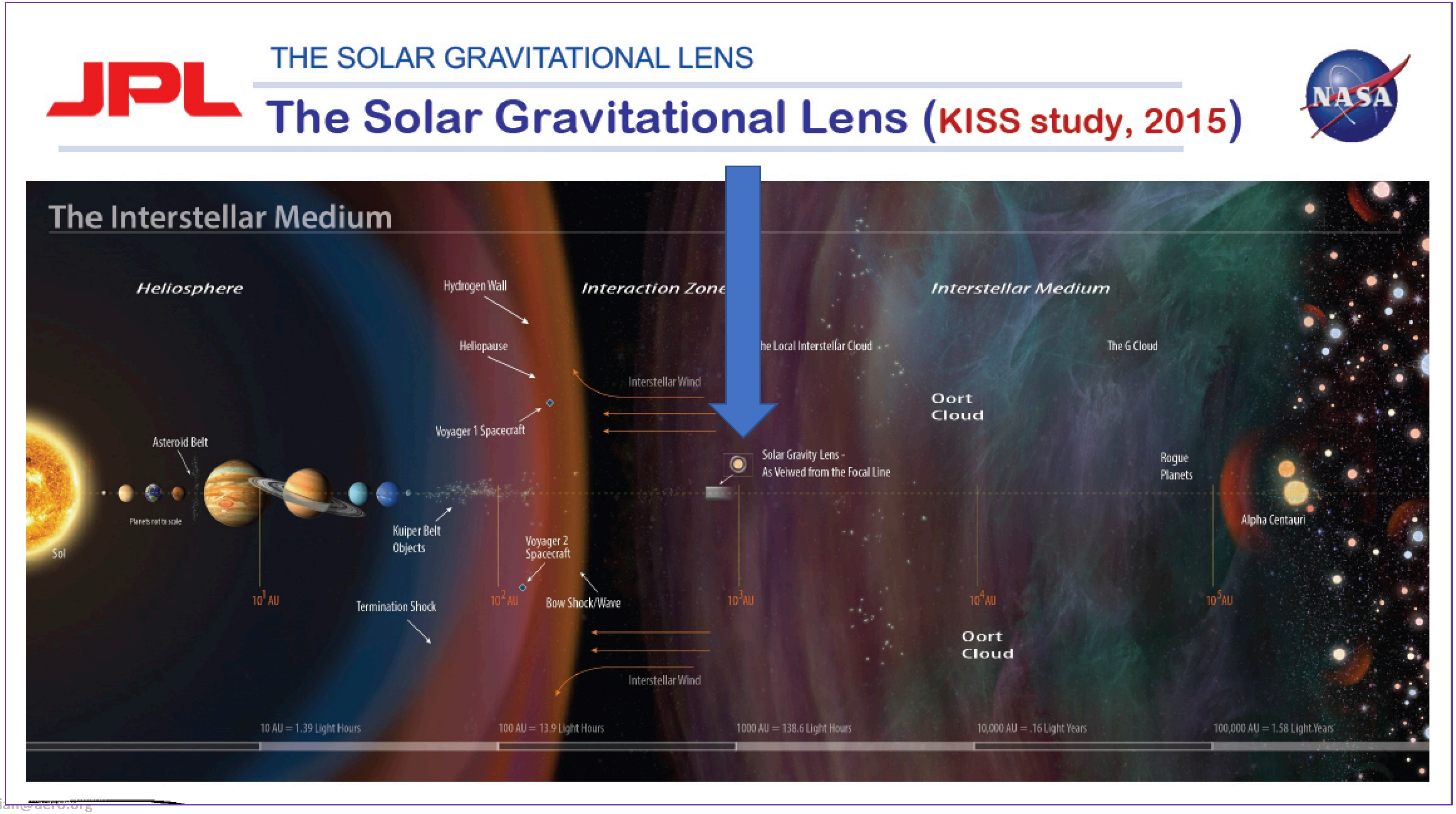
Multiple Spacecraft Architecture to the Einstein Ring Solar Gravity Lens (SGL) Mission





Where We Want to Go



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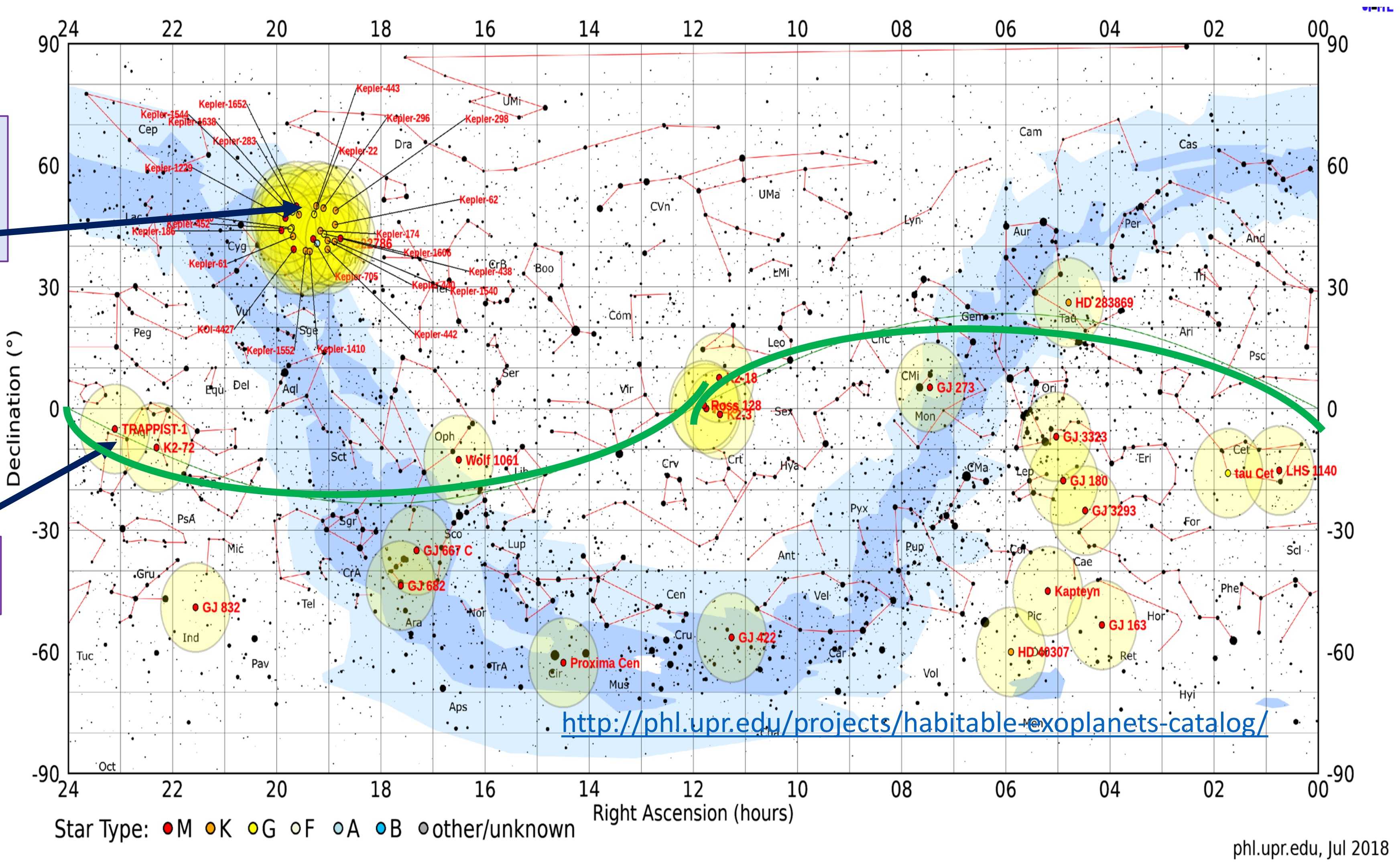
Possible Location of Candidate Stars

A candidate-rich cluster lies some 70 degrees north of the ecliptic plane

Trappist is a likely candidate



What we might want to look at

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Why investigate this mission?

- It is challenging and delivers a tool to future generations that could possibly answer the age-old question, “are we alone”.
- It explores the development of satellite architectures that are
    - “self-reliant”,
    - adaptable,
    - and long lived.
- Attributes that will be expected in future space systems

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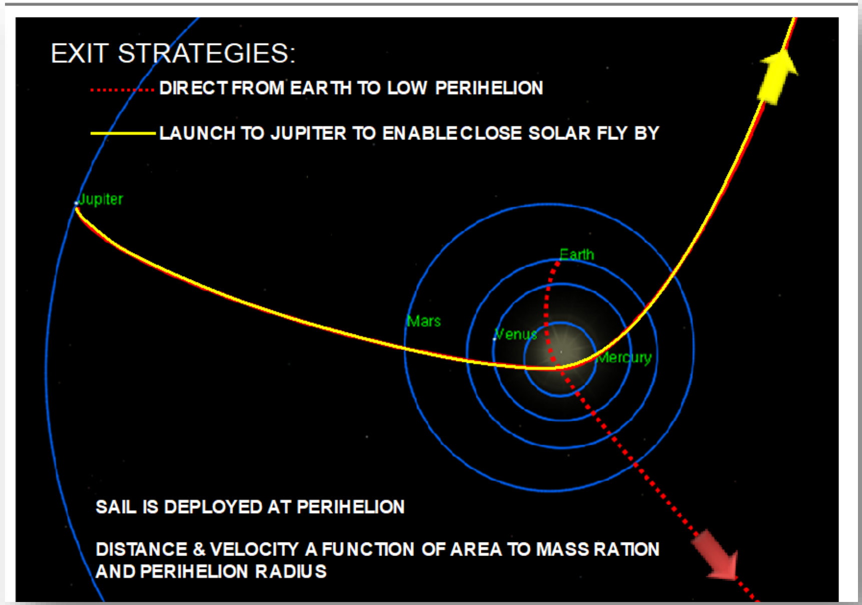
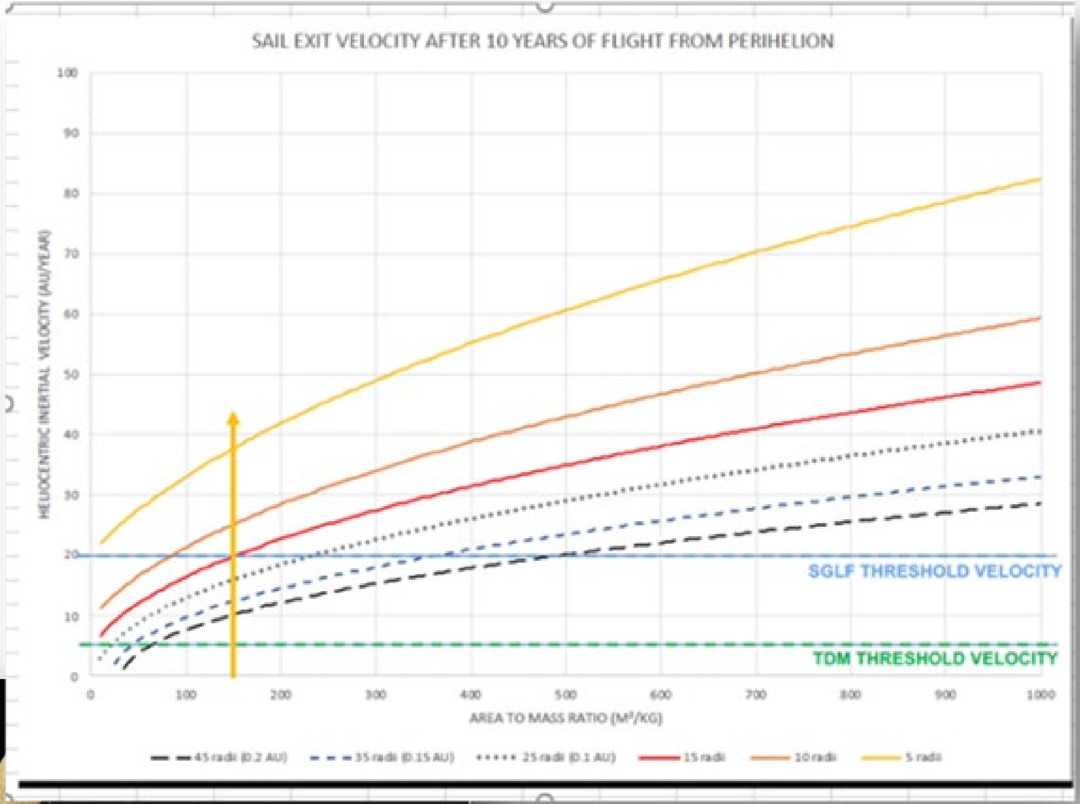
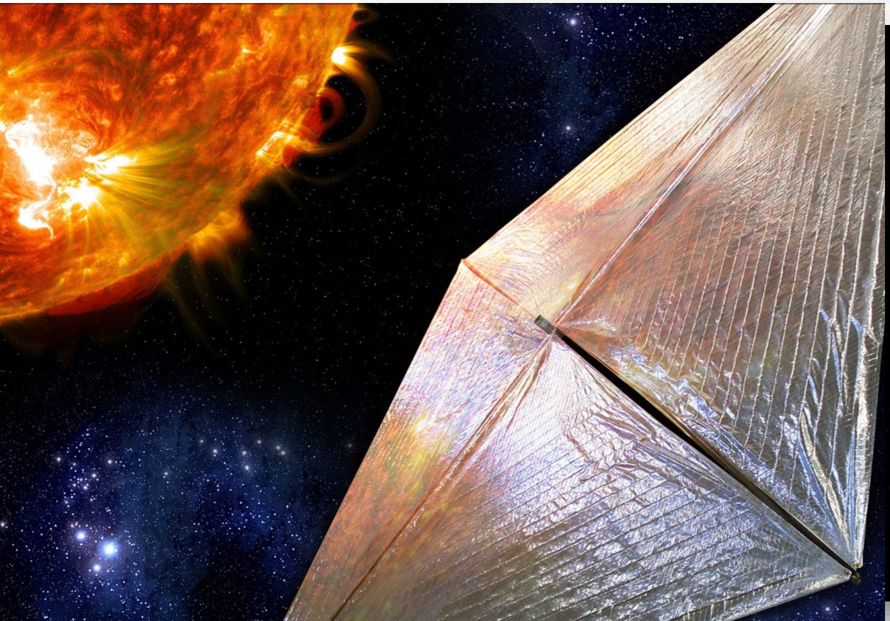
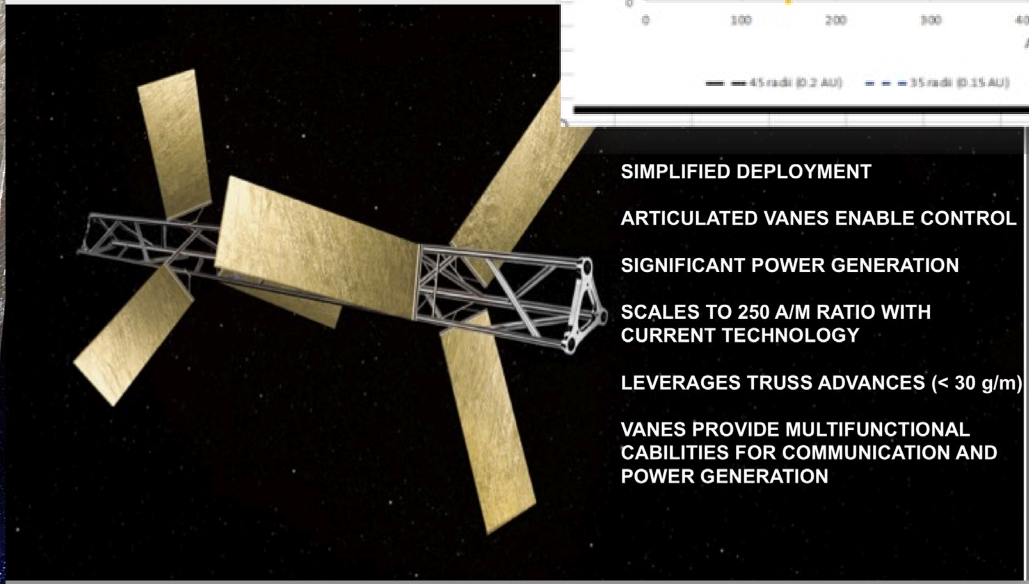
The first problem is exiting the solar system at >25 AU/year with extreme precision





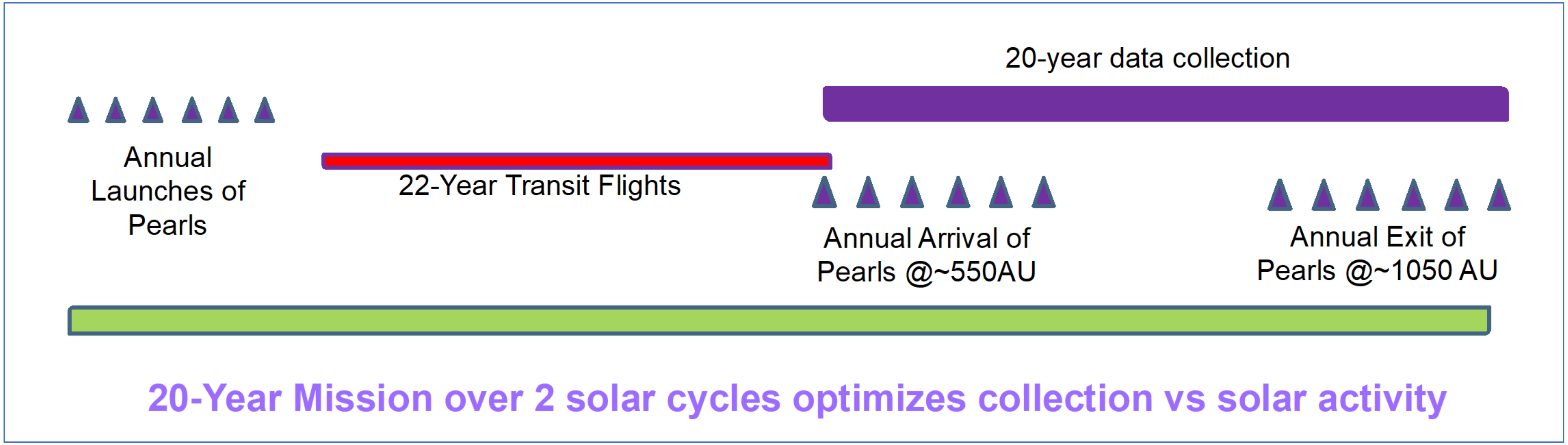




This drives the weight of each s/c to < 10 kg.

SGL String of Pearls Architecture

Missions Can be Concurrently Flown to One or Several ExoSolar Systems



- Architecture is ~10 “pearls” each composed of 10-20 small “sailcraft” (payload + solar sail) launched by cost-effective shared or dedicated launches.
- The pearls “learn as the fly”, to optimize science return.
  - Designs based on concurrent developments in spacecraft miniaturization, AI flight management, swarm CONOPS, and long-term reliability.
  - Successive pearls benefit from technology advancements to improve cost-effectiveness.

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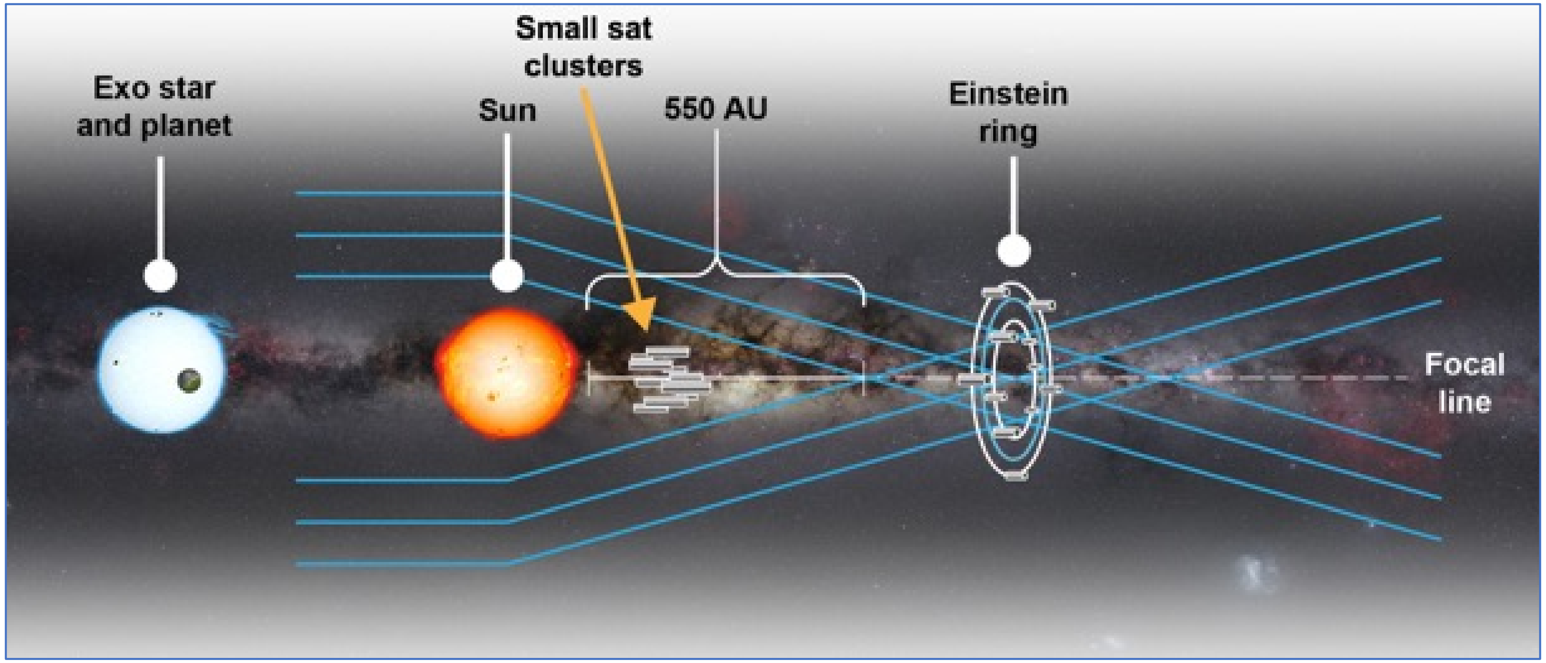
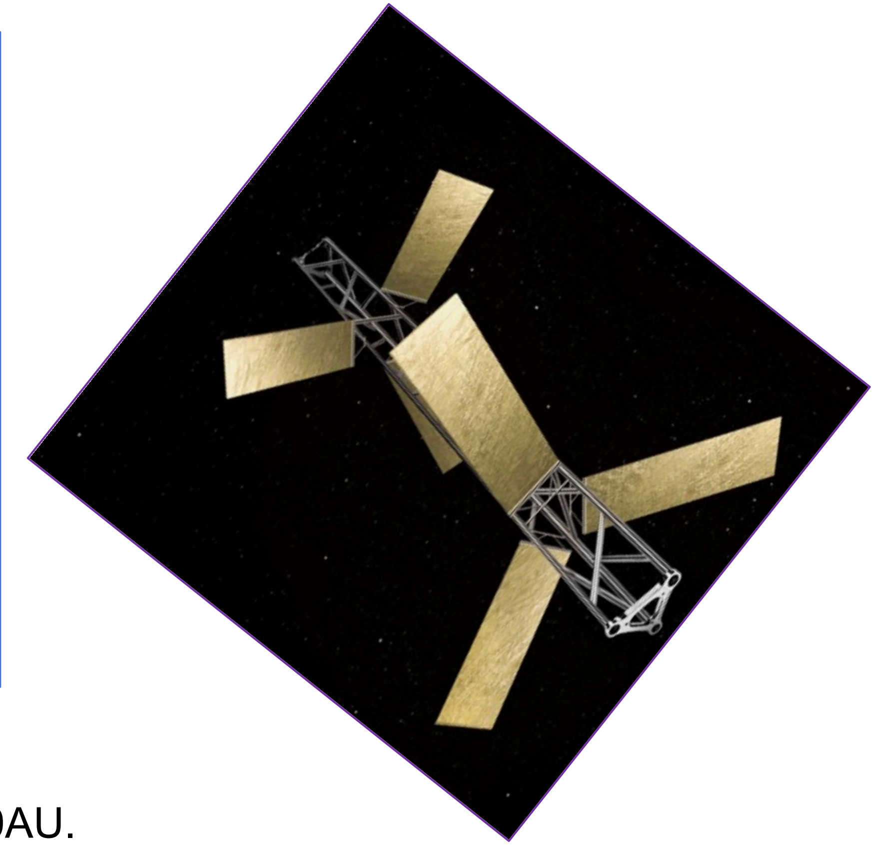
String of Pearls Architecture Overview





- Navigation uses existing and planned resources
  - DSN support during flight to solar perihelion and then outward to ~ 200AU.
  - From 200 AU to 900 AU, optical imaging –parallax using planets and occultation astrometry.
- Multi-vane solar sails control flight trajectories to perihelion and to self-assembly point.
  - E-propulsion used for midcourse corrections and flight along the SGL
- Flying many s/c on the mission ensures reliability and science return.

Spread the risk, spread the cost, minimize launch costs to maximize science return.

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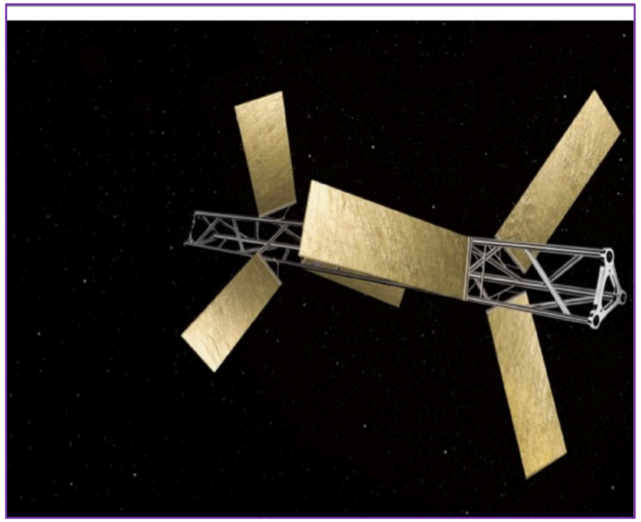
Propulsion Uses Solar Sails and e-Propulsion

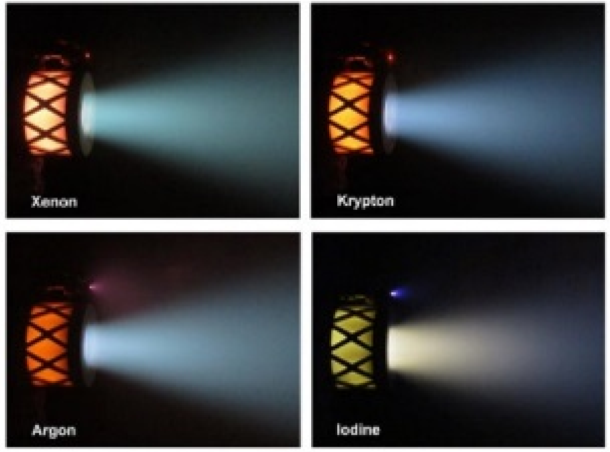
Solar Sail Phases of the Flight

- Group each swarm of s/c into a “pearl” having interactive links and nodes.
- Spiral down to the perihelion while setting the orbital inclination.
- Accelerate at perihelion to ~160 km/sec for escape velocity of 20 AU/year.
- Adjust trajectory from hyperbolic to linear to align with SGL with precise aim at SGL.
- Use DSN and solar sails to minimize residual trajectory error.



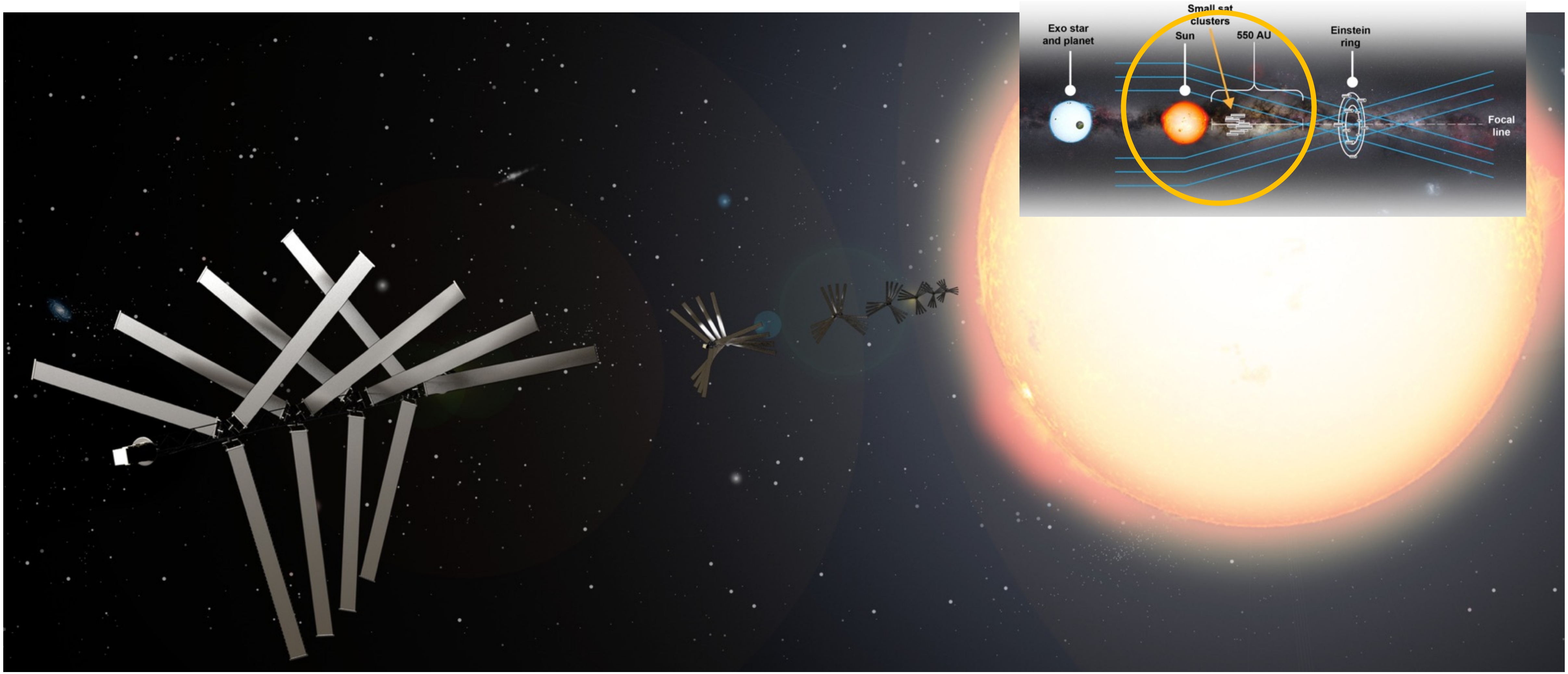
E-Propulsion Phases of the Flight

- Multiple sailcraft, drop sails and re-assemble to form the mission capable spacecraft. Transition to e-propulsion to acquire and fly along the SGL



Solar sail propulsion does large delta v in our solar system, then there is a transition to e-propulsion for small delta v for the cruise and SGL mission

Each spacecraft passes perihelion to achieve >100 km/sec escape velocity



Solar sail propulsion accelerates the s/c without need for propulsive fuel

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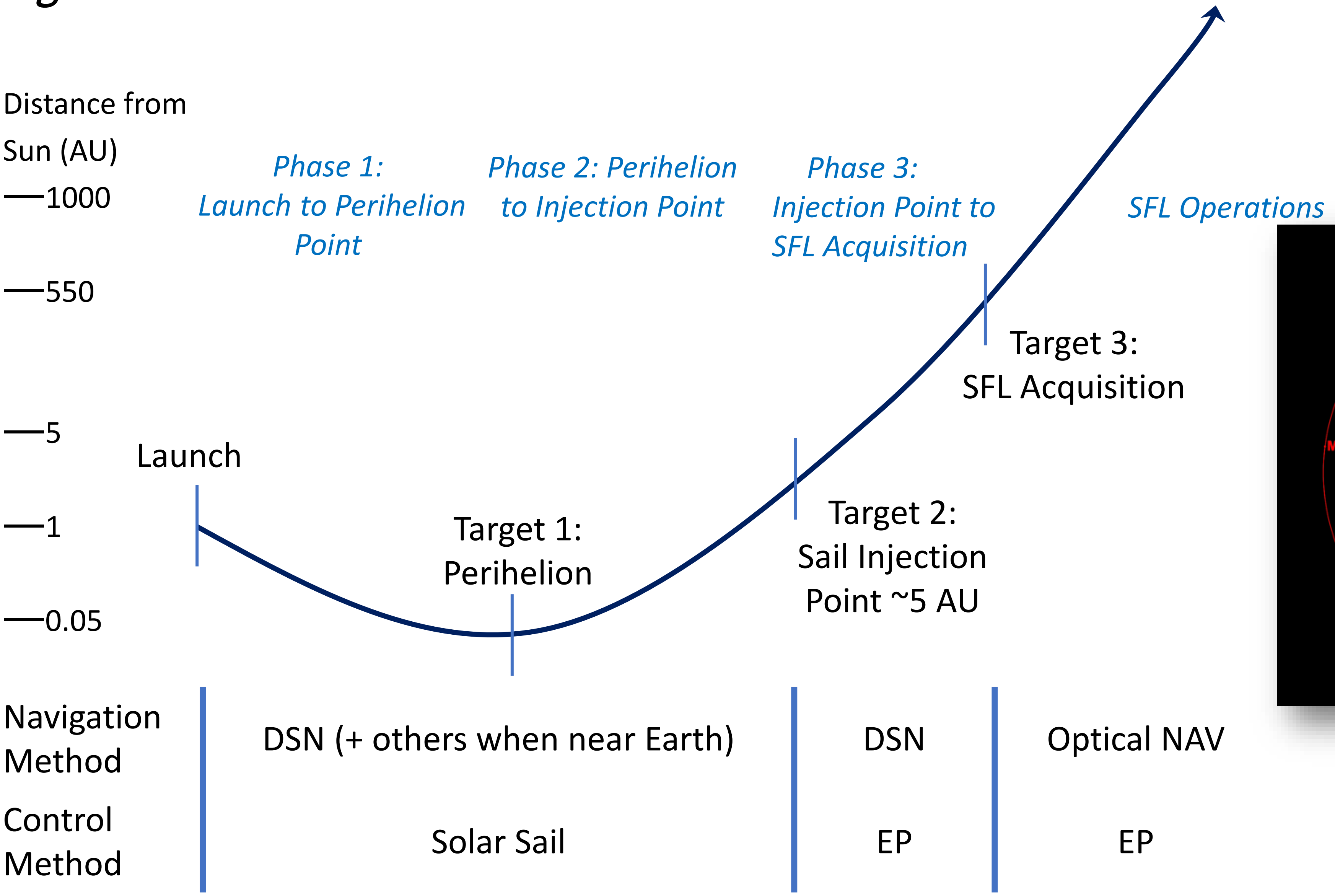
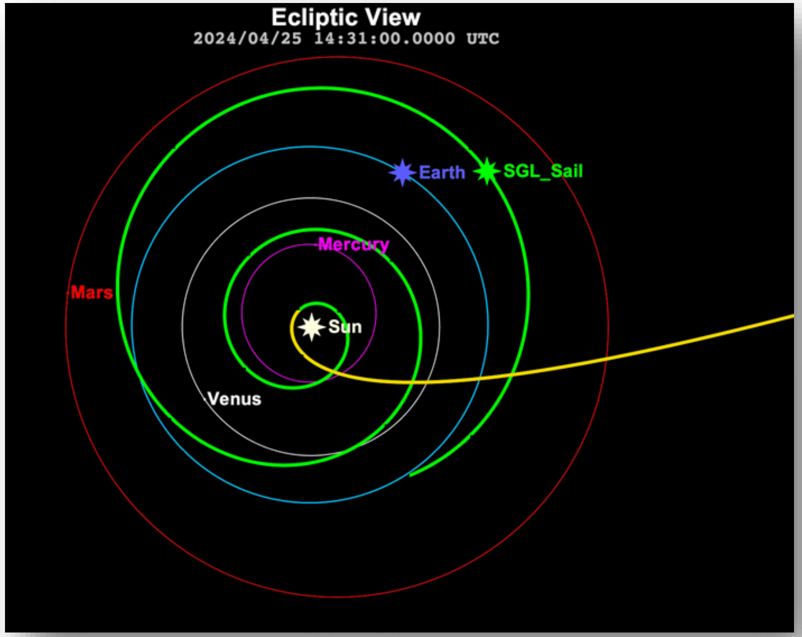
Navigation Phases Timeline





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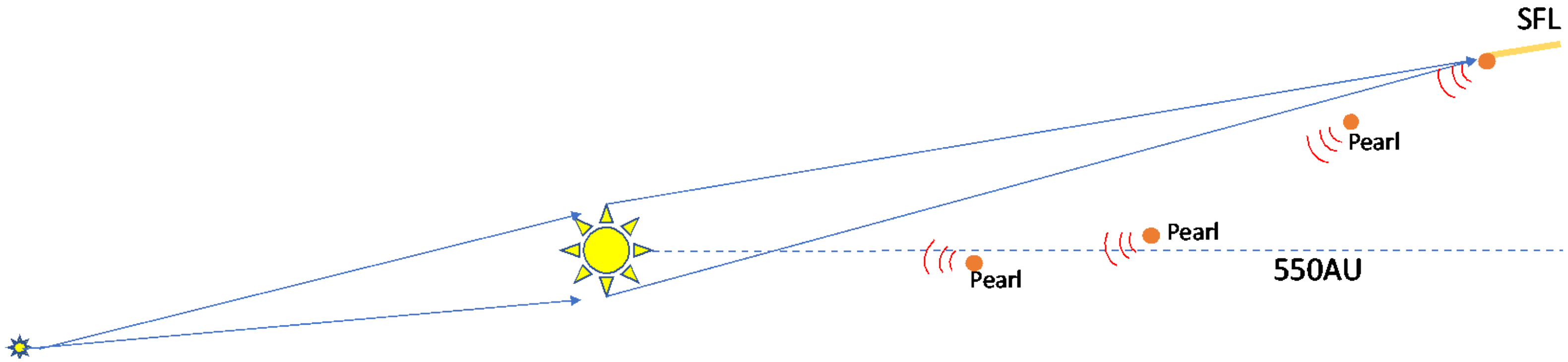
Navigation from Injection Point to SFL Acquisition

- From self-assembly orbit outward toward the SFL, precise tracking and monitoring will continue on a weekly basis to maintain the low position uncertainty limits.

- Autonomous navigation will be employed for the pearl cluster of satellites
  - Navigation status sent back with health and safety report schedules.
  - EP system is available for small maneuver adjustments if needed

- SFL acquisition is NOT similar to a New Horizon's Pluto/Charon approach
  - We won't be able see the SFL upon approach and will have to detect it when we are within exo-star SFL.
  - Use the exo-star SGL line (which will be orders of magnitude brighter) as guide.

- Once SFL acquisition is confirmed, a hand over to intra-cluster ranging relative to the exo-star focal line will be used to determine relative positioning of spacecraft (establish a local coordinate system based on the exo-star SGL focal line.



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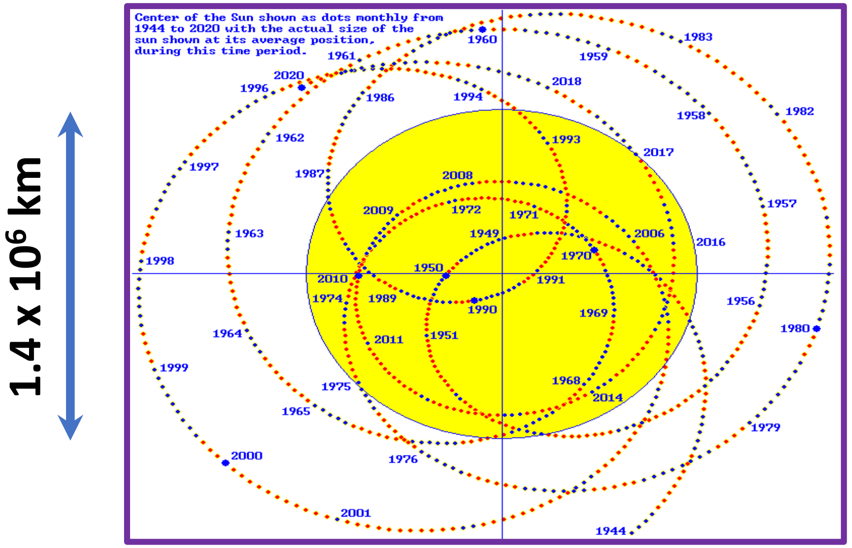
Focal Region CONOPS

Science Operations and CONOPS

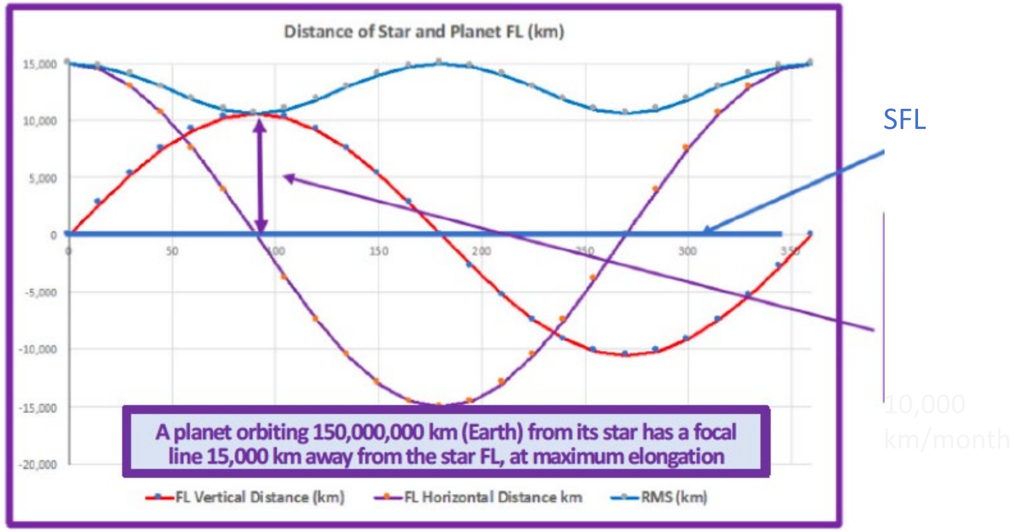
- An acquisition strategy that looks for the thin and dim exo-planet focal line (FL) is difficult, but a strategy that acquires the exo-star's FL first, and then moves to the planet's FL is much easier.
- Electric Propulsion (EP) will be required to maintain the path along the exo-star line as our Sun wobbles and also to maneuver to other planet FLs.
- The science environment between ~500 – 1000 AU expected to be benign with no significant perturbations to flight in terms of satellite performance.
- Strategies for moving from Star FL to Planet FL are illustrated in the right-hand figure below
  - Factor in the geometry of the planet's orbital plane with respect to the s/c line of sight

Solar Wobble Geometry over 76 years



KISS Symposium Briefing, 2018

Star-Planet FL Geometries
Planet's Orbit Inclined 45° Vertically



KISS Symposium Briefing, 2018

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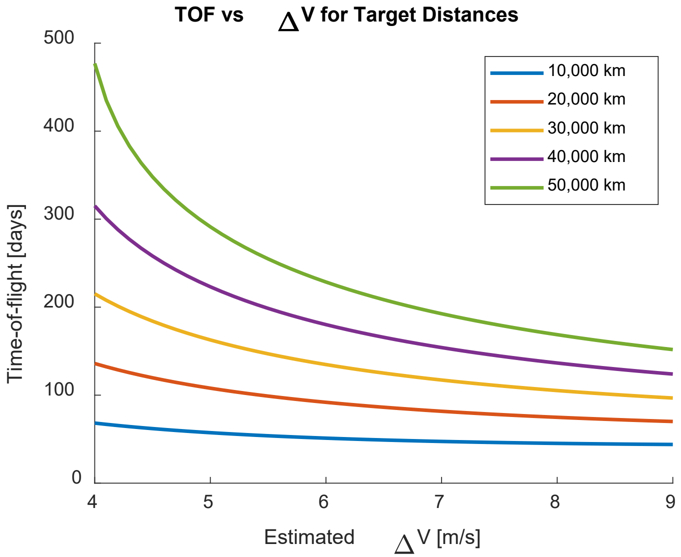
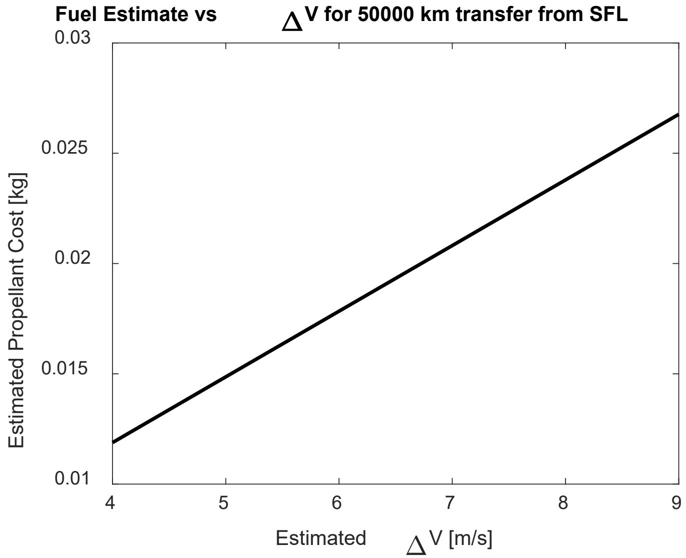
ΔV Estimates for Focal Line Maneuvering

- Using a rectilinear model to estimate the delta-v as a first order approximation
  - Not accounting for station keeping due to Solar wobble
- Assuming the following EP engine:
  - Electrospray thruster: Isp (s)/ Thrust (mN) = 1200/0.1
- Model assumptions:
  - Constant gravity from Sun at 550 AU
  - Constant thrust from engine at 0.1 mN
  - Started at zero initial velocity
  - Burn in direction against Sun for a time, then immediately turn around and burn in the opposite direction such that vehicle is at zero velocity again at desired distance





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Technology Hardware and Software

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Timing & Synchronization with Earth Clocks

How to maintain synchronization of on-board clocks given length of SGL mission

Microsemi Spec sheet: 900-00744-007. A. 4/19

- **<120 mW, 35 g, < 17cm^3**
- **Rad Tolerant 20krad,**
- **SEL, SEU tested to 64 MeV*cm^2/mg (LET$_{th}$ for Cosmic Ray 10-100 MeV*cm^2/mg)**

Design to maintain on-board clocks to < 1 ppm for duration of mission					
	Current TRL	**Approach**	**Synchronization period**	**Improvement in 10 years (aggressive)**	**Key technology barrier**
Baseline	7-8	10 MHz CSAC (Microsemi) on s/c, Laser in Earth orbit. (100W, 10 MHz, 1 micron wavelength, 5 m output beam telescope	CSAC clock every 4 months (Allan Deviation ~ 1E-11 @ 1000s),	100X, so 33 years synchronization period (10MHz clock)	Controlling thermal drift
Eventual	2-3	Optical frequency comb on s/c	~ 1300 years for 10 MHz clock, 32 years for 500 MHz clock (Allan Deviation 2E-15, Y. Hisai et al. Optics Exp. 27(5) 2019,pg 6404.)	10X, so 53 years, for (3 GHz clock).	Support equipment very large (tabletop)

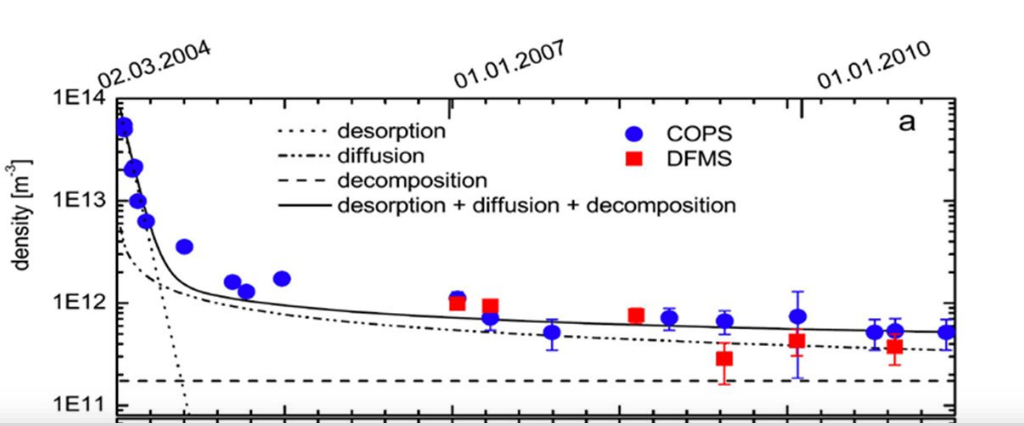
NIST physicists Scott Diddams (left) and Scott Papp with a prototype atomic clock based on a chip-scale frequency comb. Diddams is holding the silicon chip, which fits into the clock apparatus on the table.

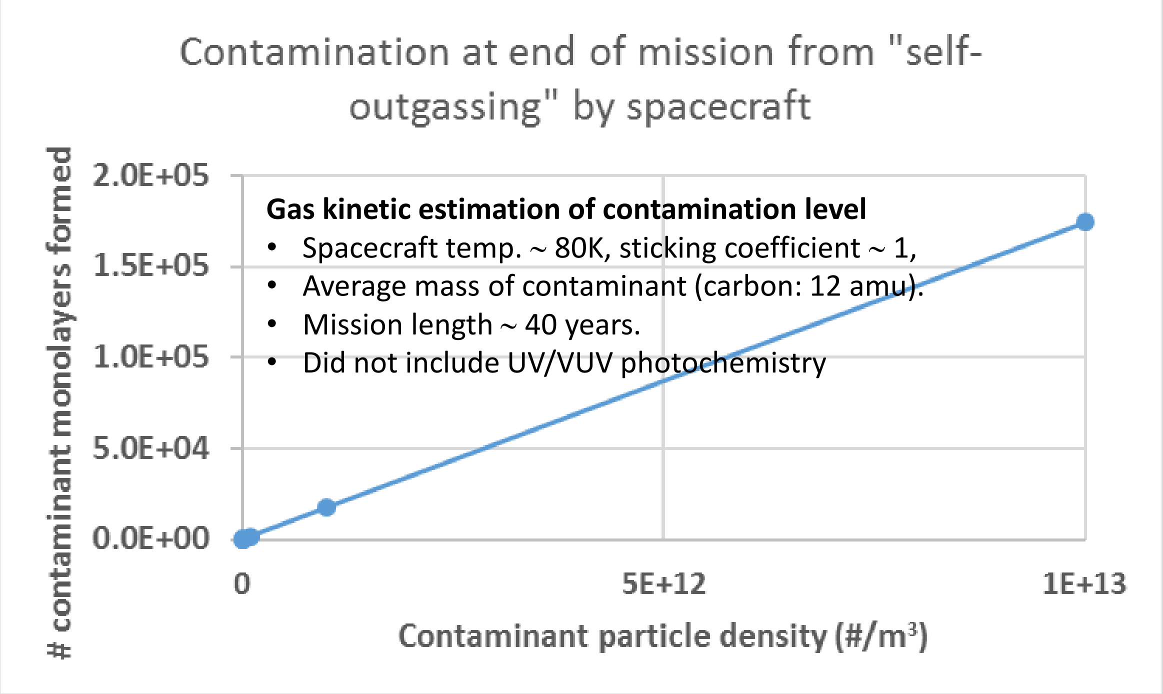
Length of Mission and Sensor Contamination

Self-produced outgassing contaminating sensors and reflectors during the SGL journey

	Contamination requirements (End of life – Beginning of life)	Contaminant particle density around spacecraft m^{-3}	Expected number of contaminant monolayers forming from "self outgassing" during SGL mission (40 years)
Rosetta Mission		**6E11 (measured 6.9 yrs)**	**16500 (~9μm)**
NASA LADEE Mission	**~ 20 Angstroms (160 days)**	**1.8E10 (Calculated value from requirement)**	**495 (~0.3μm)**

Data from Rosetta Mission





- **Baseline solution** (TRL 8-9):
  - Heating sensors, proper spacecraft venting design.
  - Open spacecraft structure.
- **Possible eventual solution** (TRL 2):
  - Ultrasonic excitation for enhanced diffusion on critical surfaces.
    - Enhancement of surface diffusion of atomic/molecular adsorbates by ultrasonic surface excitation.
      - 19-fold measured, 4500-fold estimated. M. V. Shugaev et al. PRB 91, 235450 (2015).
      - A 4500-fold enhancement in surface diffusion corresponds to an equivalent temperature increase of 1000 K.

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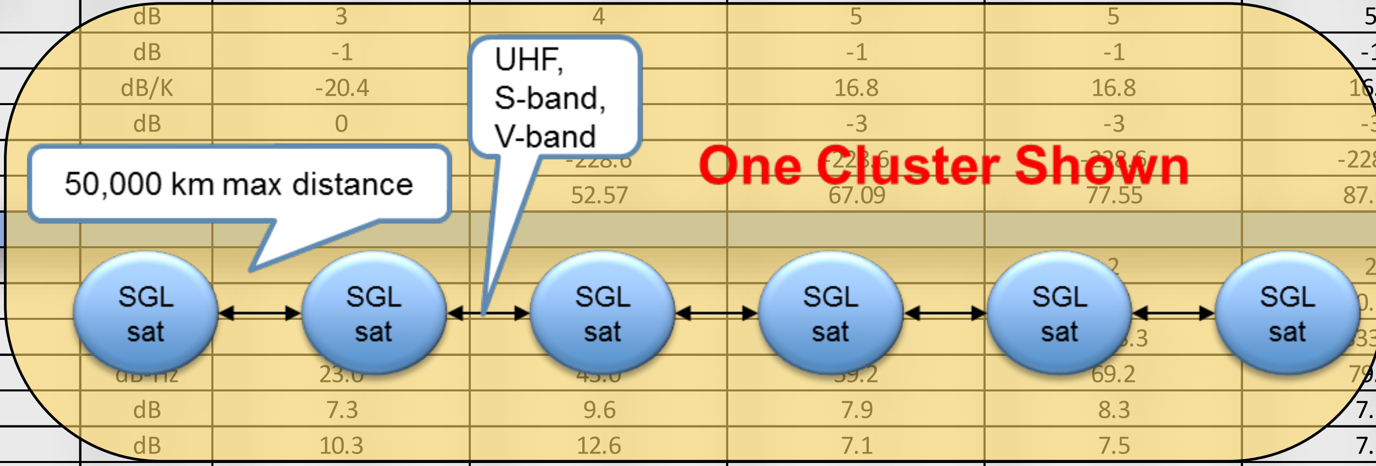
Crosslink COMM

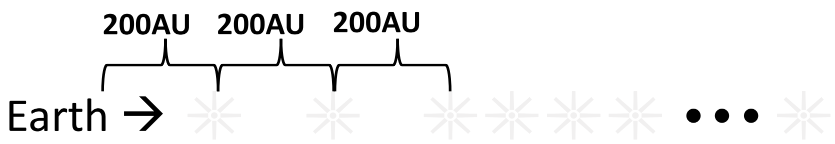
Parameter	Units	Intra Pearl (UHF)	Intra Pearl (Ka-band)	Intra Pearl (V-band)	Intra Pearl (V-band)	Intra Pearl (V-band)
Data Rate	kbps	0.1	10	1000	10000	100000
Frequency	MHz	401	28000	80000	80000	80000
Distance	km	50000	50000	20000	6000	2000
Transmit Station Parameters						
Antenna Diameter	m		0.20	0.20	0.20	0.20
Antenna efficiency	%		65%	65%	65%	65%
Wave length	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.004
Antenna Gain	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	42.61
Transmit Power	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	1
Line Loss	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-1
Transmit EIRP	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	41.61
Propagation Parameters						
Free Space Loss	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-196.5
Atmospheric Loss	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
Polarization Loss	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-0.4
Tx Pointing Loss	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0
Isotrapic Signal Level at Rx Station	dB	-177.88	-183.27	-175.31	-164.85	-155.31
Receiving Station Parameters						
Antenna Diameter	m		0.20	0.20	0.20	0.20
Antenna efficiency	%		65%	65%	65%	65%
Antenna Gain	dBi	2	33.5	42.6	42.6	42.6
System Noise Temperature	K	140	140	140	140	140
Noise Figure	dB	3	4	5	5	5
Receiver Loss	dB	-1	[illegible]	-1	-1	-1
Receiver G/T	dB/K	-20.4	[illegible]	16.8	16.8	16.8
Rx Pointing Loss	dB	0	[illegible]	-3	-3	-3
Boltzman constant	[illegible]	[illegible]	-228.6	-228.6	-228.6	-228.6
Received C/No	[illegible]	[illegible]	52.57	67.09	77.55	87.09
Carrier Parameters						
Modulation order	[illegible]	[illegible]	[illegible]	[illegible]	2	2
Code Rate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.6
Symbol Rate	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	333.3
Noise Bandwidth	dB-Hz	23.0	45.0	59.2	69.2	79.2
Received Es/No	dB	7.3	9.6	7.9	8.3	7.9
Received Eb/No	dB	10.3	12.6	7.1	7.5	7.1
Implementation Loss	dB	-2	-2	-2	-2	-2
Received Eb/No	dB	8.3	10.6	5.1	5.5	5.1
Required Eb/No at BER=10^-7	dB	8	8	2	2	2
Margin	dB	0.3	2.6	3.1	3.5	3.1

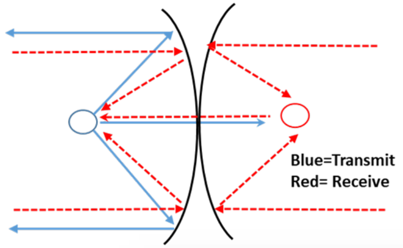
Intra-Pearl Distance (km)	Data Rate (Mbps) ~ 3dB link margin	Frequency (MHz) (V-Band)
2000	100	8000
6000	10	8000
20000	1	8000



- Assumptions into analysis
  - Establish a Local Area Network,
  - SGL spacecraft flying in formation,
  - Low gain or omni directional antenna on each of the SGL sat,
  - Low pointing accuracy required,
  - Frequency division among the cross links to avoid interference,
- Link budgets worked for Intra Pearl or Cluster
  - UHF, Ka, and V-band
  - Really should use V-band

Downlink COMM: Pearl-to-Pearl





Laser COMM

	Cross-Link Parameters	Variable	20 AU Value	Units	dB	Units	40 AU Value	Units	dB	Units	100 AU Value	Units	dB	Units	200 AU Value	Units	dB	Units	500 AU Value	Units	dB	Units
Satellite Transmitter	Transmission Rate	R_T	4000.0	bps	36.0	dB	1000.0	bps	30.0	dB	160.0	bps	22.0	dB	40.0	bps	16.0	dB	6.3	bps	8.0	dB
	Code Rate	r	0.5				0.5				0.5				0.5				0.5			
	Information Rate	R_I	8000.0	bps			2000.0	bps			[illegible]	[illegible]			80.0	bps			12.5	bps		
	Modulation Format	M	4				4				4				4				4			
	Transmit Wavelength	λ	1.55	μm			1.55	μm			1.55	μm			1.55	μm			1.55	μm		
	Tx Power																					
	Tx WDM Loss																					
	Tx Fiber Coupling Los																					
	Output Backoff																					
	Telescope Diameter																					
	Rx Telescope Efficien																					
	Tx Angular Beamwid																					
	Tx Telescope Gain																					
	Tx Pointing Loss																					
	Transmit EIRP																					
Channel	Elevation Angle																					
	Slant Range (max)																					
	Path Loss																					
	Total Atmospheric Lo																					
	Net Path Loss																					
Satellite Receiver	Rx Footprint Diamete																					
	Rx Telescope Diamet																					
	Rx Telescope Efficien																					
	Rx Telescope Gain	G_{Rx}			131.1	dBi			131.1	dBi			131.1	dBi			131.1	dBi			131.1	dBi
	Polarization Mismatch Loss	L_{pol}			0.0	dB			0.0	dB			0.0	dB			0.0	dB			0.0	dB
	Receiver Pointing Loss	$L_{Rxpoint}$	0.2	arcsec	0.7	dB	0.2	arcsec	0.7	dB	0.2	arcsec	0.7	dB	0.2	arcsec	0.7	dB	0.2	arcsec	0.7	dB
	Rx Fiber Coupling Loss	$L_{Rxfiber}$			0.5	dB			0.5	dB			0.5	dB			0.5	dB			0.5	dB
	Rx WDM Loss	L_{RxWDM}	100.0%	%	0.0	dB	100.0%	%	0.0	dB	100.0%	%	0.0	dB	100.0%	%	0.0	dB	100.0%	%	0.0	dB

System	Range (AU)	Link (5 dB margin)	Suggestions
5W (1.55 μm) laser, 40 cm Tx telescope, 2.5 m Rx dish,	**20**	**80 kbps**	Could get 10-15X increase in Tx rate: Increasing laser power 3X, Tx telescope to 1m dia.
use PPM over DPSK	**200**	**80 bps** (~ 6 hrs to transmit S&HS data for a 3U CubeSat ca 2019)	The caboose should be a sequence of 3 s/c with higher power lasers (@ 200, 400 and 600 AU).
	500	**12.5 bps**	

DPSK Summary | 20 AU PPM | 40 AU PPM | 100 AU PPM | 200 AU PPM | 500 AU PPM | **PPM Summary**

RF COMM

Parameter	Units	Pearl to Pearl (V-band)
Data Rate	kbps	0.1
Frequency	MHz	80000
Distance	km	2992000000
Transmit Station Parameters		
Antenna Diameter	m	4.00
Antenna efficiency	%	65%
Wave length	m	0.004
Antenna Gain	dBi	68.63
Transmit Power	W	10
Line Loss	dB	-1
Transmit EIRP	dBW	77.63
Propagation Parameters		
Free Space Loss	dB	-320.0
Atmospheric Loss	dB	[illegible]
Polarization	dB	[illegible]
Tx Pointing Loss	dB	0
Isotrapic Signal Level at Rx Station	dB	-242.79
Receiving		
Antenna		
Antenna		
Antenna		
System N		
Noise Fig		
Receiver Loss	dB	-1
Receiver G/T	dB/K	42.8
Rx Pointing Loss	dB	-3
Boltzman constant	dBW/Hz/K	-228.6
Received C/No	dB-Hz	25.63
Carrier Parameters		
Modulation order		2
Code Rate		0.2500
Symbol Rate	ksps	0.2
Noise Bandwidth	dB-Hz	23.0
Received Es/No	dB	2.6
Received Eb/No	dB	5.6
Implementation Loss	dB	-2
Received Eb/No	dB	3.6
Required Eb/No at BER=10^-7	dB	1.5
Margin	dB	2.1

Range	Link
20 AU (4m antenna)	**100bps (2.1 dB margin)**

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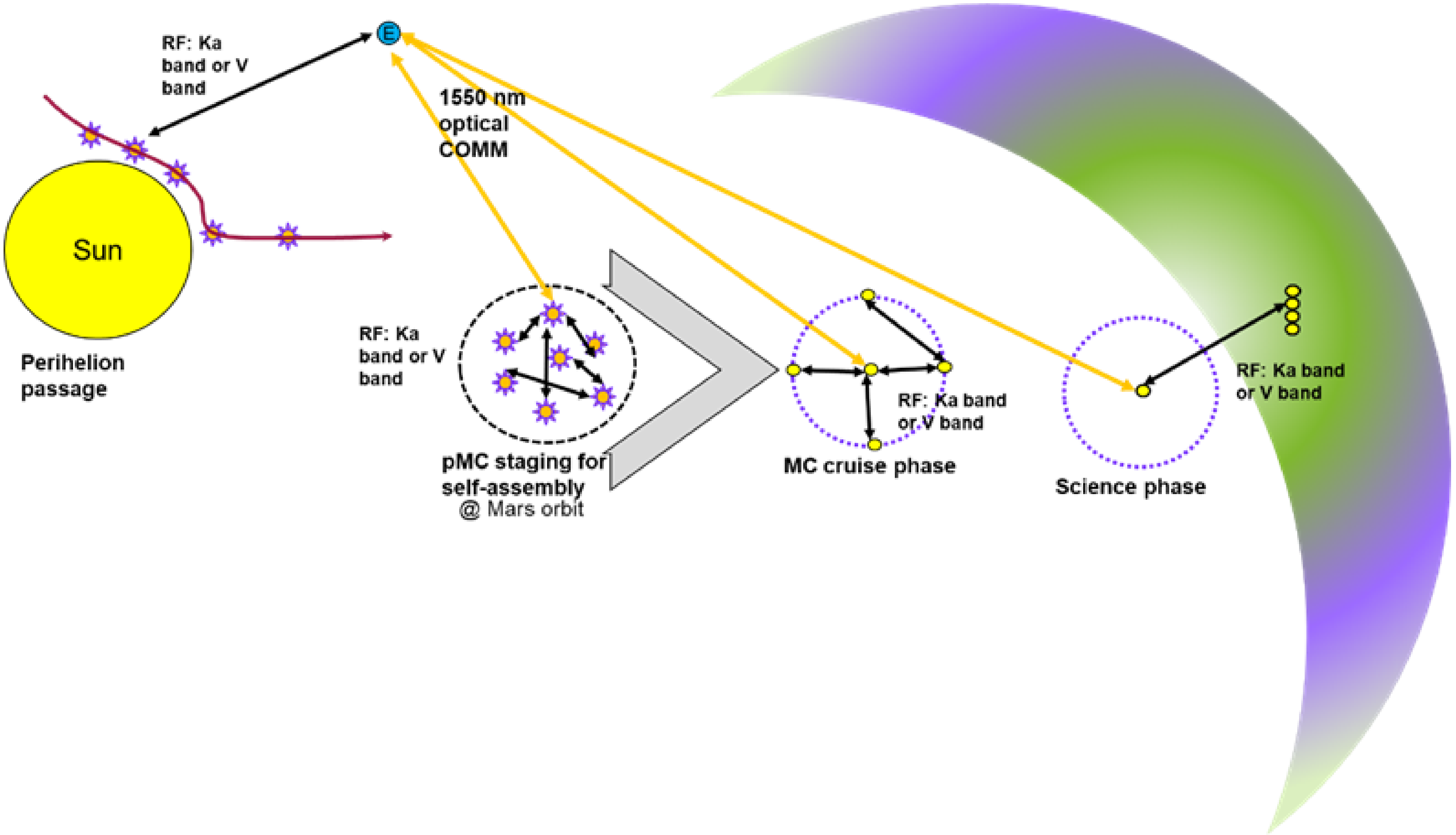
Overview of current COMM architecture



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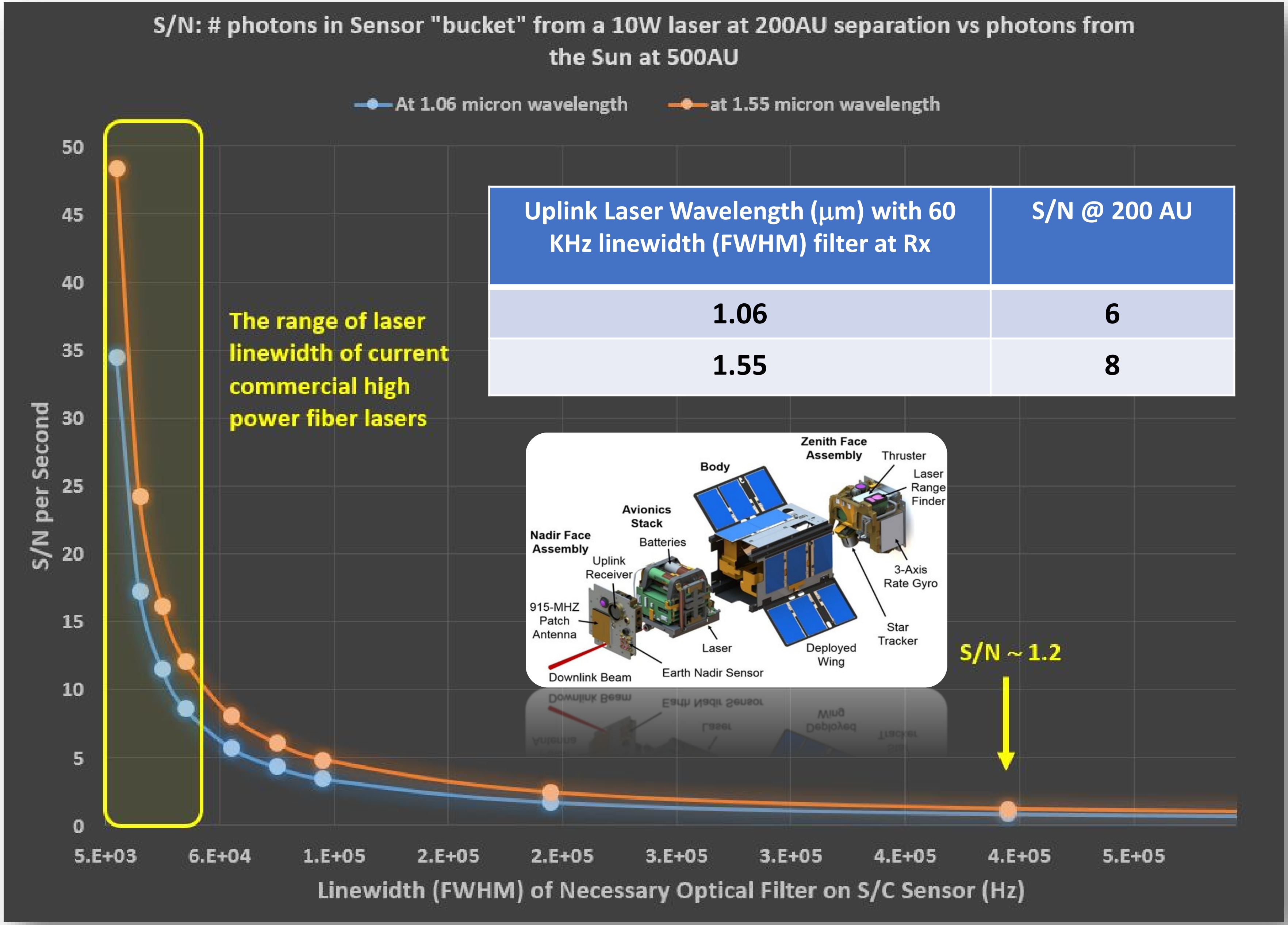
Laser Comm While "Staring at the Sun"



Uplink Laser Wavelength (μm) with 60 KHz linewidth (FWHM) filter at Rx	S/N @ 200 AU
1.06	6
1.55	8

- NASA to install Deep space optical Comm
  - Data rates of 200 Gbs at 1 AU have been claimed
    - then at 500AU and 800AU 800 kbs and 300 kbs can be expected.
- For SGL, constraints of emission from sun limit S/N
  - Situation critical for receiving s/c sensor
  - For Comm to 550AU need ~100W laser in LEO
  - Or ~10W repeater" s/c at 200 AU distances.
- Advantages of formation flying a cluster of s/c and laser COMM.
  - Not every s/c needs laser downlink capability.

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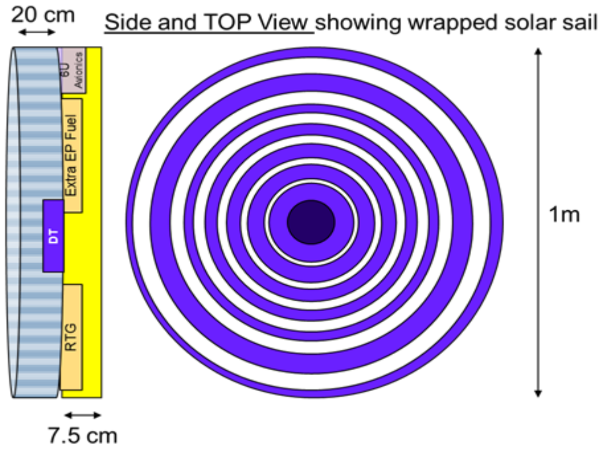
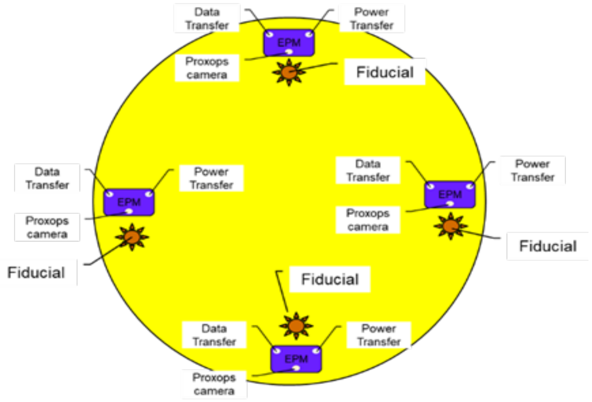
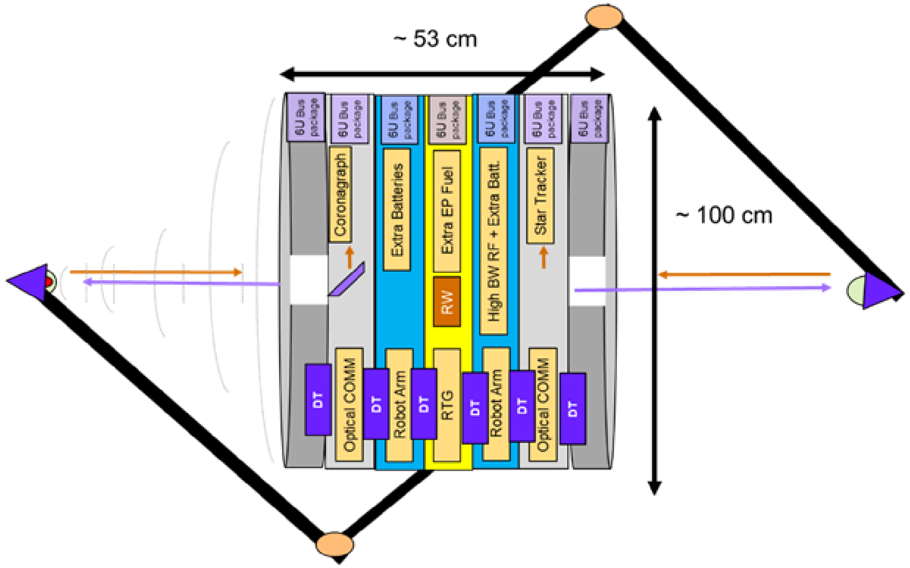
SGL spacecraft design

Current Space Craft Design

- Parse mission functions into functional *units* trying to reduce each unit to ~10 kg mass.
- Give each *unit* the capabilities of a 6U Cubesat (avionics, ACS, batteries, EP, …), operates alone for limited time.
- Each unit can “take care of itself”, self powered but also carries a critical function or capability for the SGL mission (e.g.; primary telescope mirror, RTG, extra batteries, coronagraph, optical COMM, …)
- Fly each *unit* on a solar sail to high velocities.
- Deploy the *units* between Earth and Mars orbits.
- Conduct in-orbit self-assembly using 6U CubeSat propulsion and ACS
- The assembled vehicle then conducts the SGL mission.







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Component	pMC-1	pMC-2	pMC-3	pMC-4	pMC-5	pMC-6	pMC-7
3U CubeSat Bus	x	x	x	x	x	x	x
Solar Sail	x	x	x	x	x	x	x
Primary Mirror	x						x
Optical Comm		x				x	
Coronagraph		x					
High Res Star Tracker		x				x	
Robotic Arm (boom) + Secondary Mirror			x		x		
Extra Battery			x		x		
RPS				X			
Larger RW (100 kg mass)				x			
Extra EP				x			

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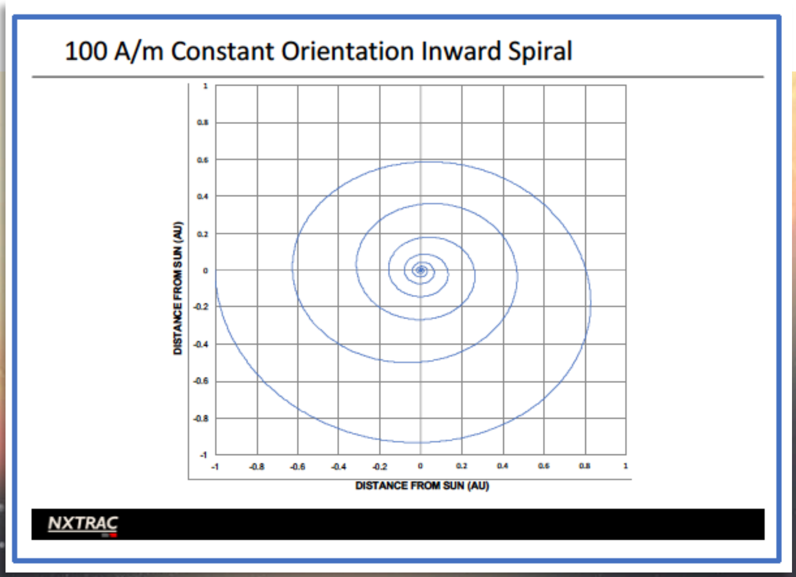
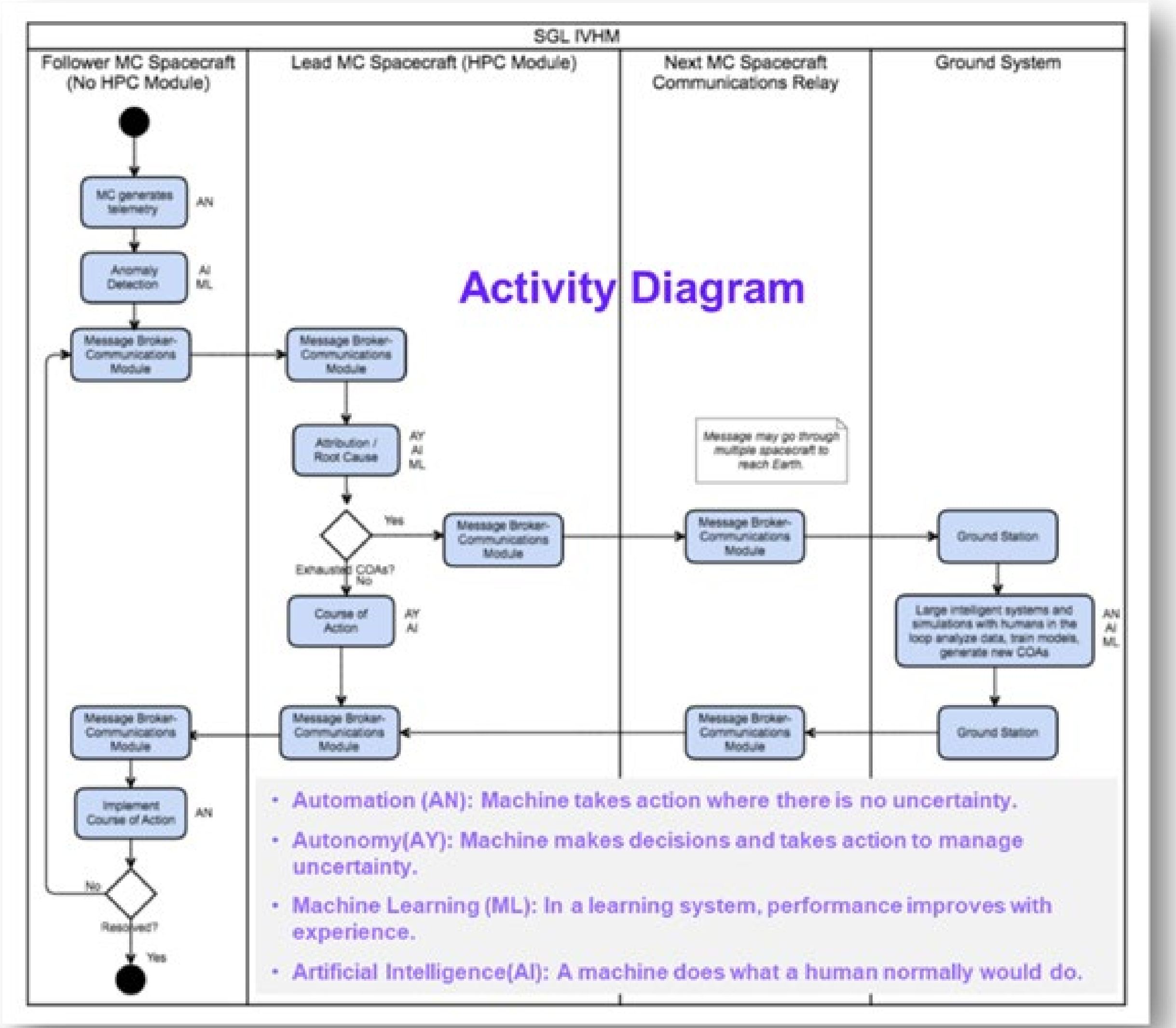
Intelligent Autonomy Drivers

- Months-long period of blackout, where comms link will be blocked by the sun
- Perihelion passage for the gravity assist, when the AI will need to manage GNC
- 4+ light day distance to the SGLF, where optimal operations will require intelligent autonomy
- Optimize power usage on smallsats, given limited power for extensive mission requirements



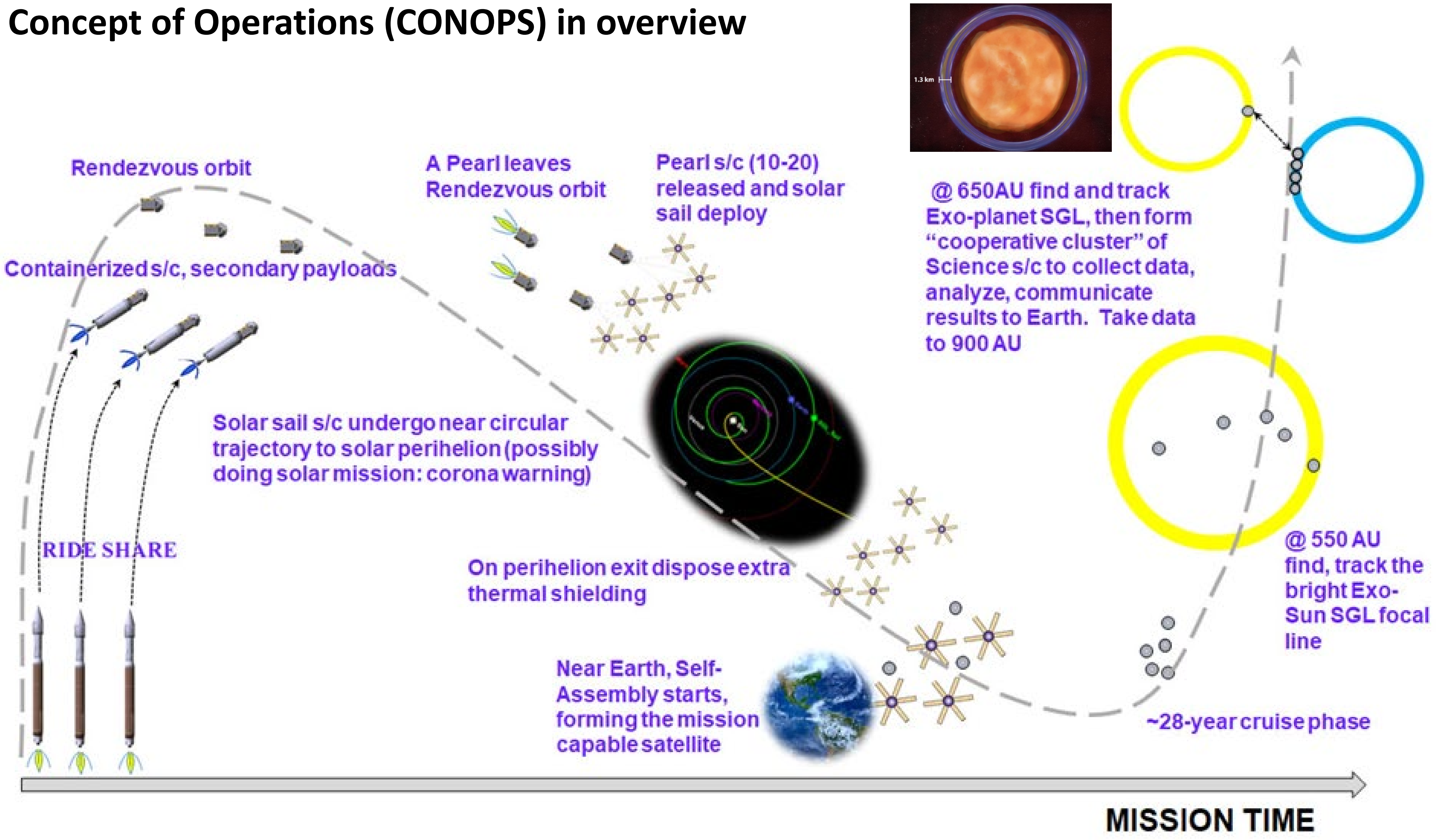
AI Algorithm Design

- AI Executive functionality with Intelligent Autonomous Agents (AI Subsystem concept)
- Deep Convolutional Neural Networks (CNNs) for pattern recognition
- Recurrent Neural Networks (RNNs) for Anomalous Signal Processing
- Reinforcement Learning to learn from new data then find and drive optimal solutions
- General Adversarial Network (GANs) and/or Hierarchical Temporal Memory (HTM) to find "imaginative" optimal solutions to unknown data coming available throughout the mission



USE Case understudy: Integrated Vehicle Health Management (IVHM) system

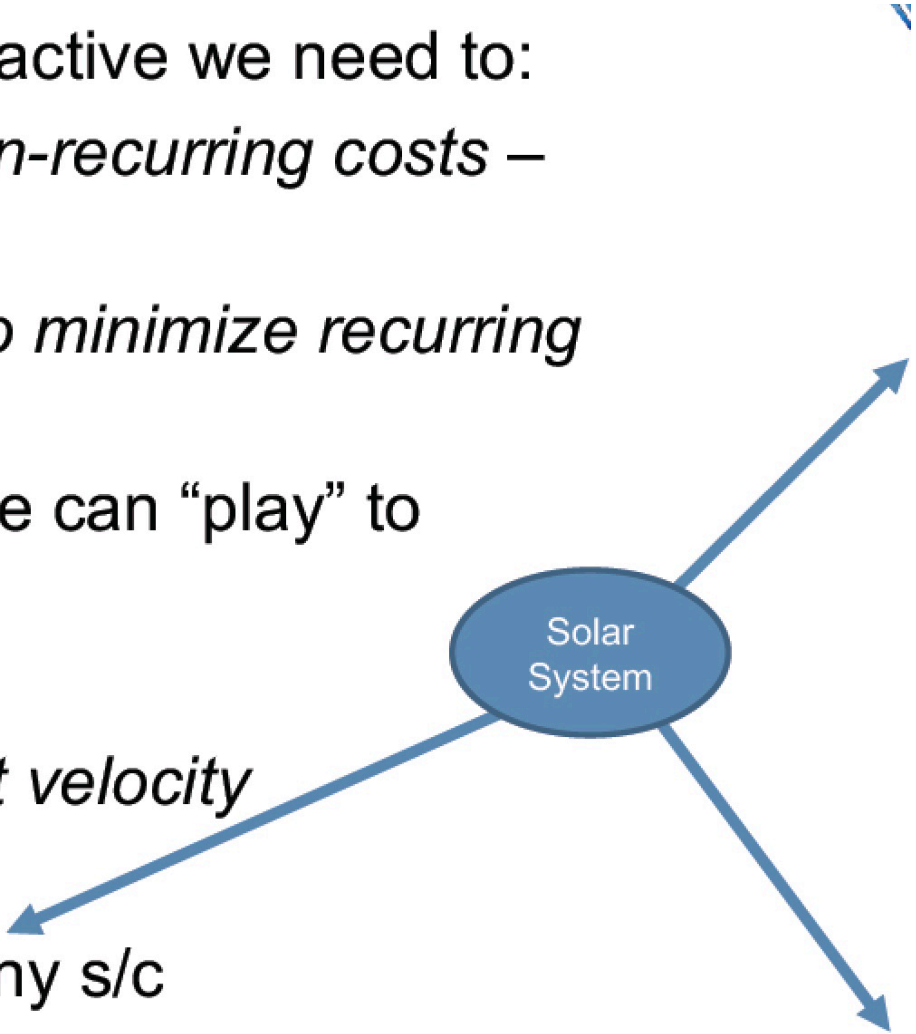
The Concept of Operations (CONOPS) in overview



Henry.H

The Keys to Mission Executability

- To make the SGL mission attractive we need to:
  - *Drive down and spread non-recurring costs – lots of players*
  - *Gain economies of scale to minimize recurring costs – lots of spacecraft*
- Open architecture so everyone can “play” to spread costs
  - *Small s/c (<10 kg)*
  - *Affordable methods for exit velocity*
  - *Lean ground-based TT&C*
- Then we can build and fly many s/c
  - *To a single exo solar system, or*
  - *To multiple exo solar systems*



Come Join Us

https://aerospace.org/article/solar-gravity-lens-looks-exoplanets

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