
Communicating Over Extreme Distances

Some Preliminary Thoughts

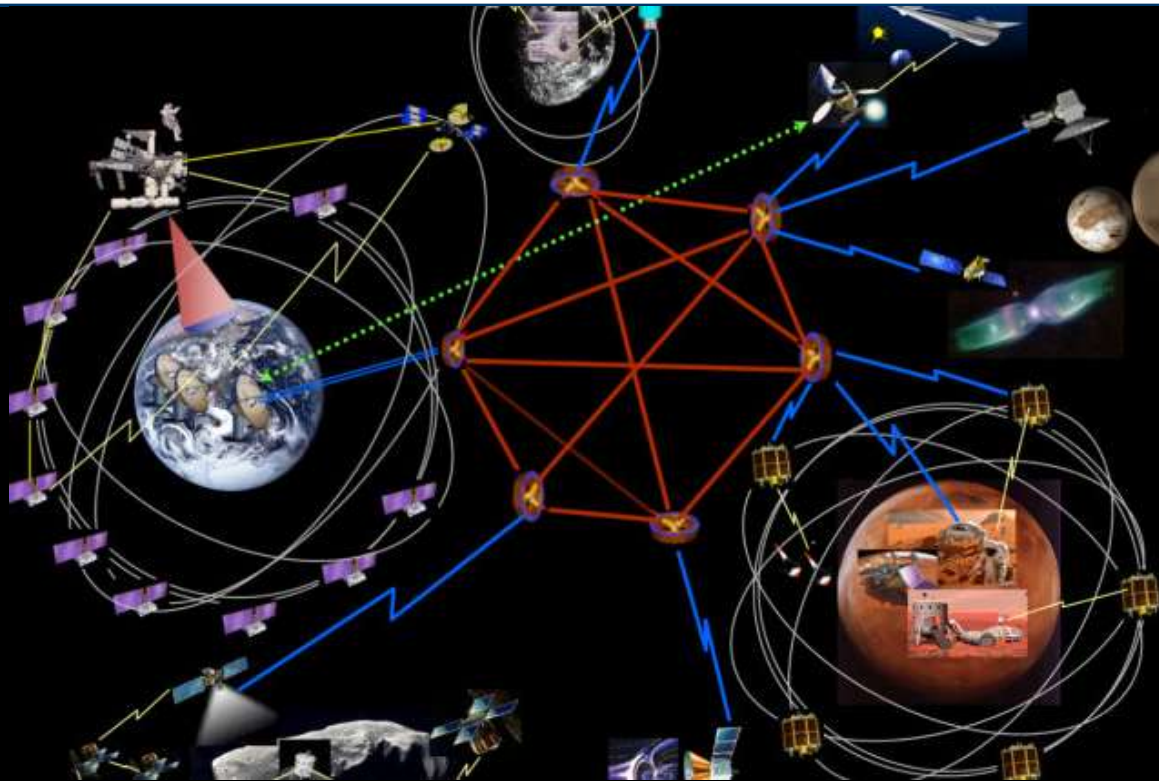
Don M Boroson

**Presented to
Interplanetary Networking Special Interest Group
June 2021**





Space-Based Networked Communications



I have nothing to add to this



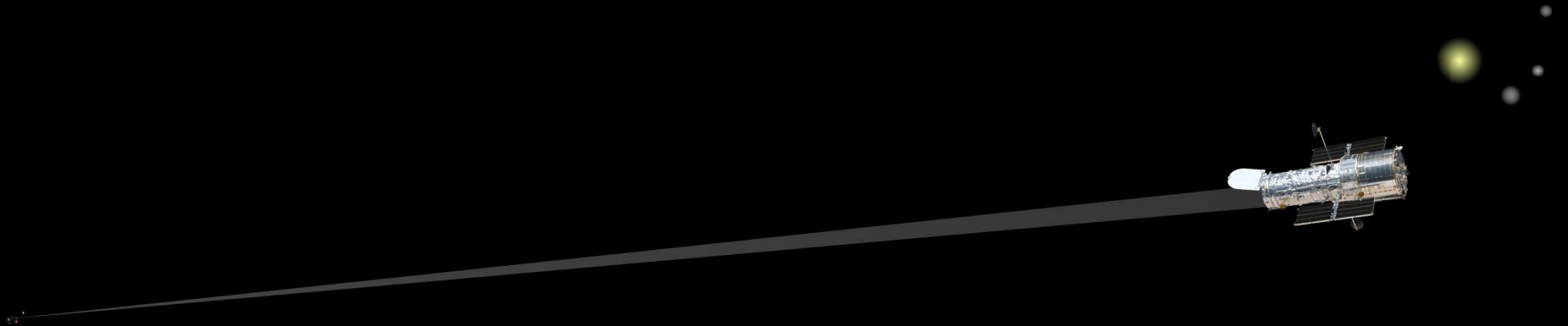
Space-Based Networked Communications



**Outer Solar System and just beyond
– already a different paradigm**



Space-Based Networked Communications



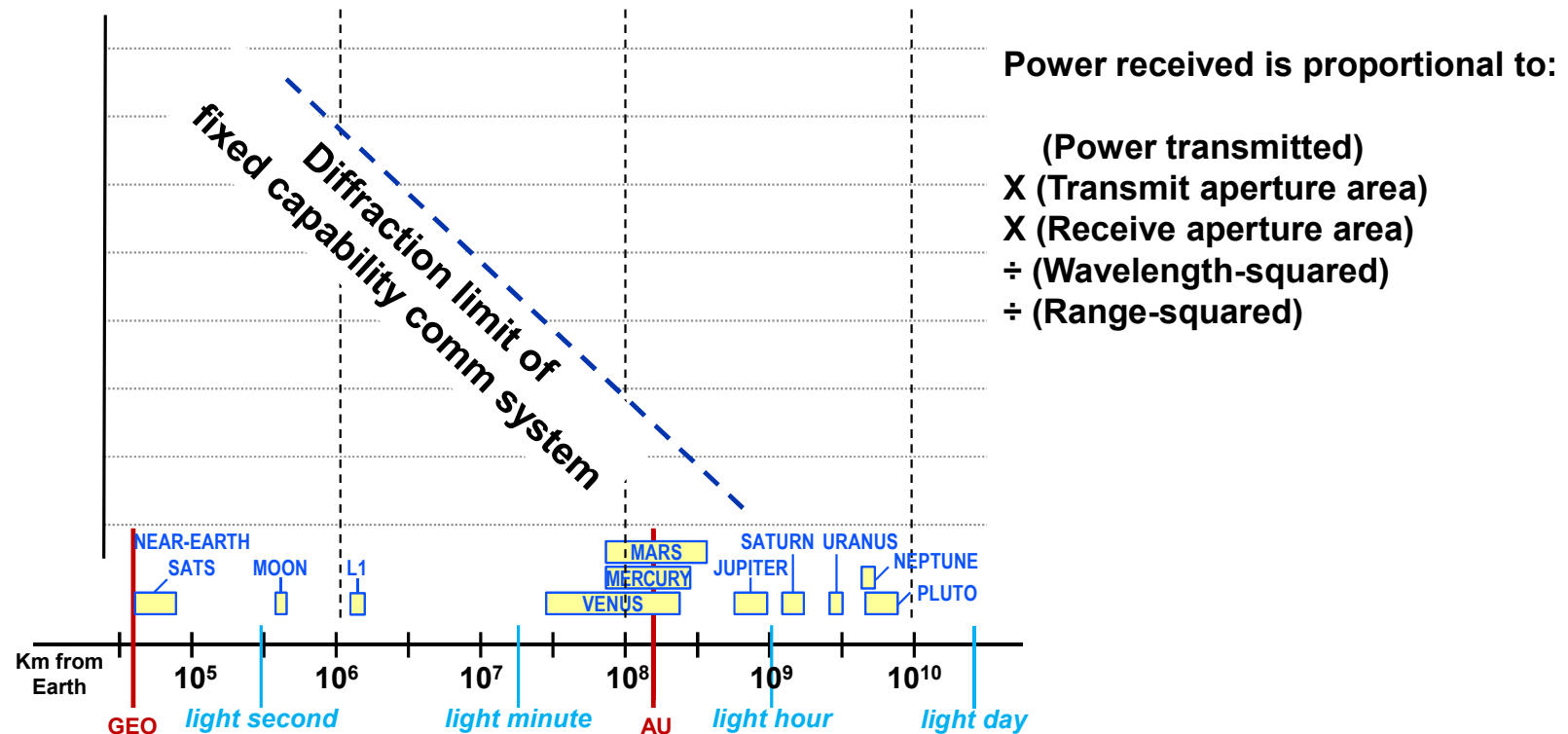
Goal: Communicate back from a star



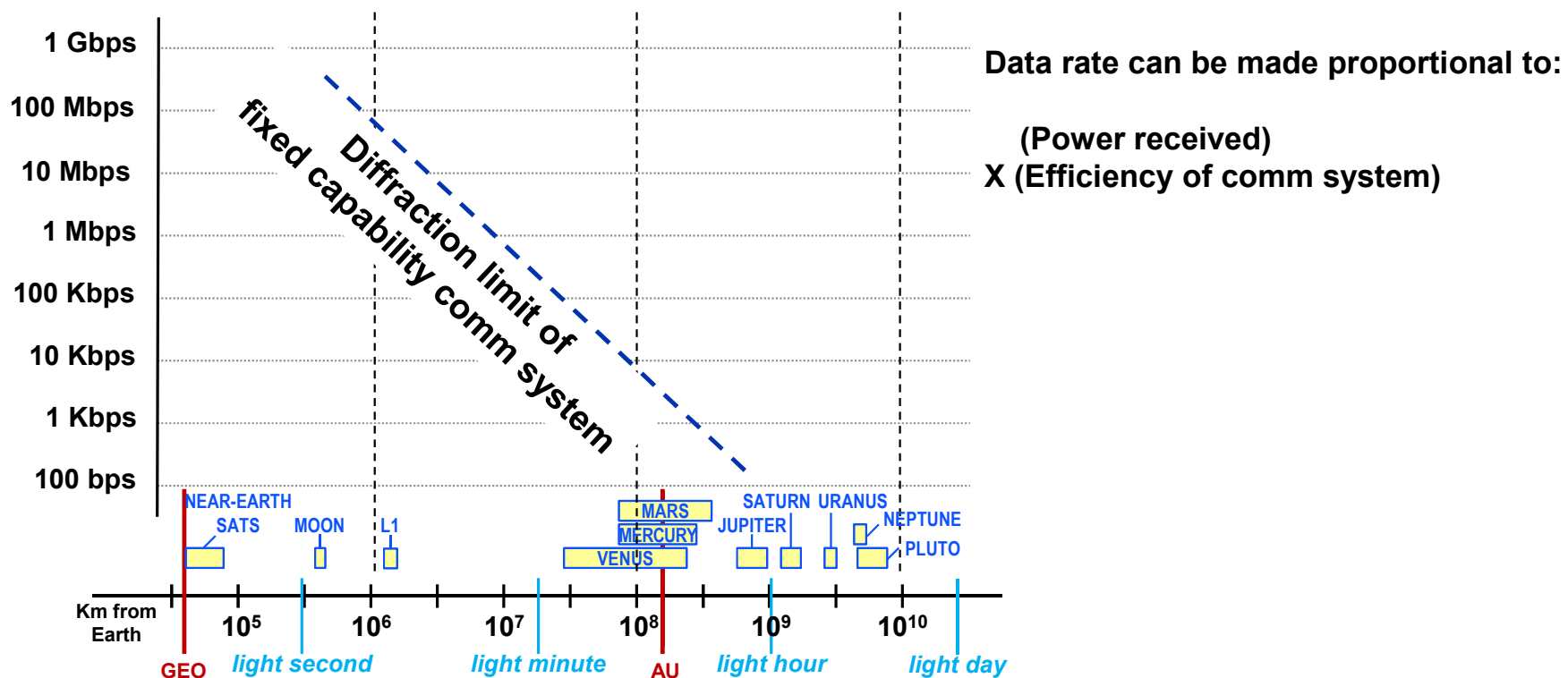
Outline

- **Links over extreme ranges**
- **Some observations about pointing**
- **Getting there**
- **Further observations**

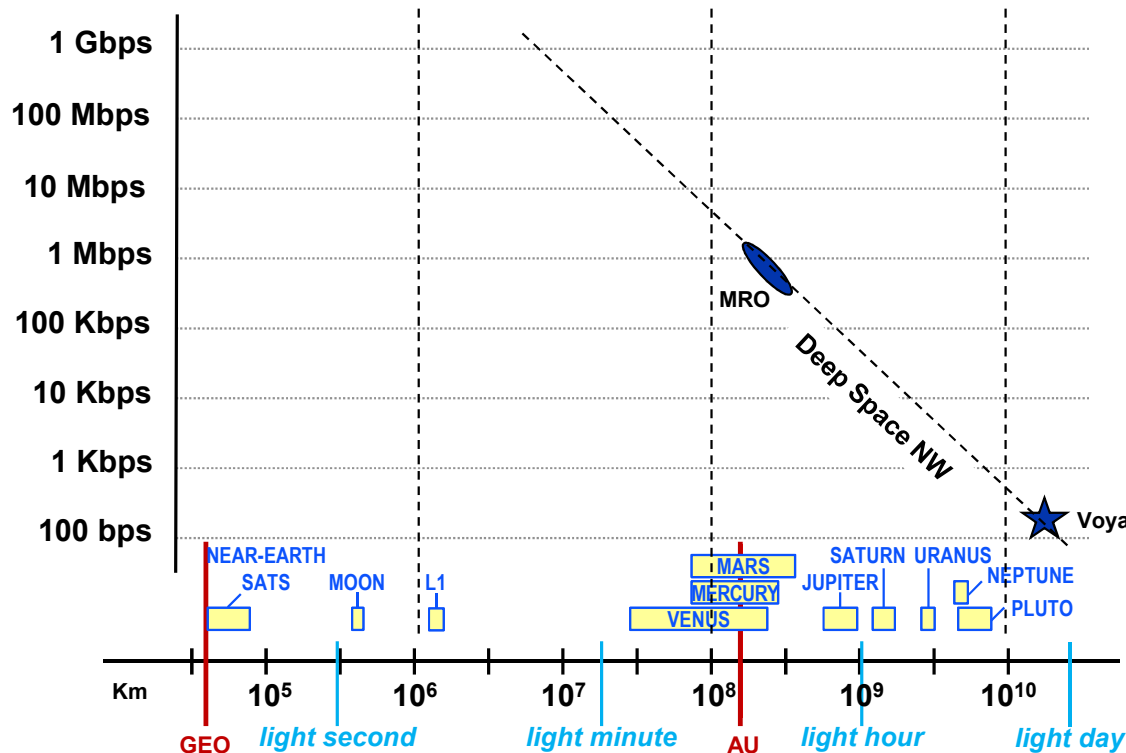
Present Ranges and Rates



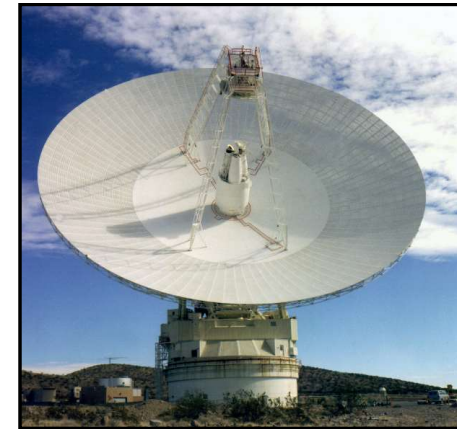
Present Ranges and Rates



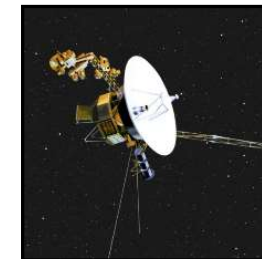
Present Ranges and Rates Radio Bands



**Mars Reconnaissance
Orbiter
(3-m dish)**

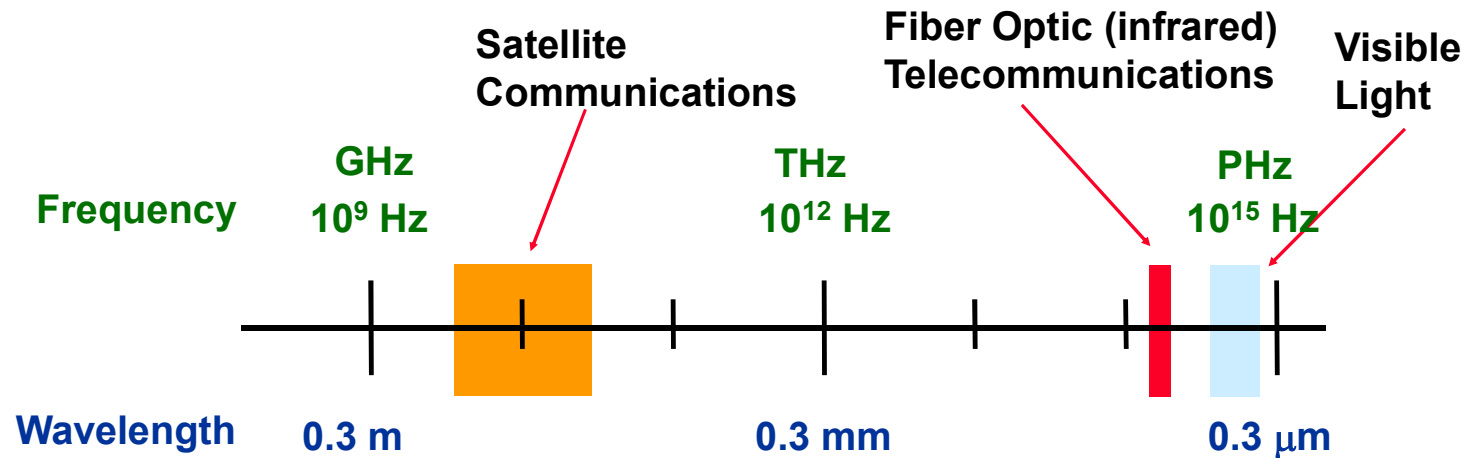


**DSN
(70-m)**



Voyager I

The Optical Bands



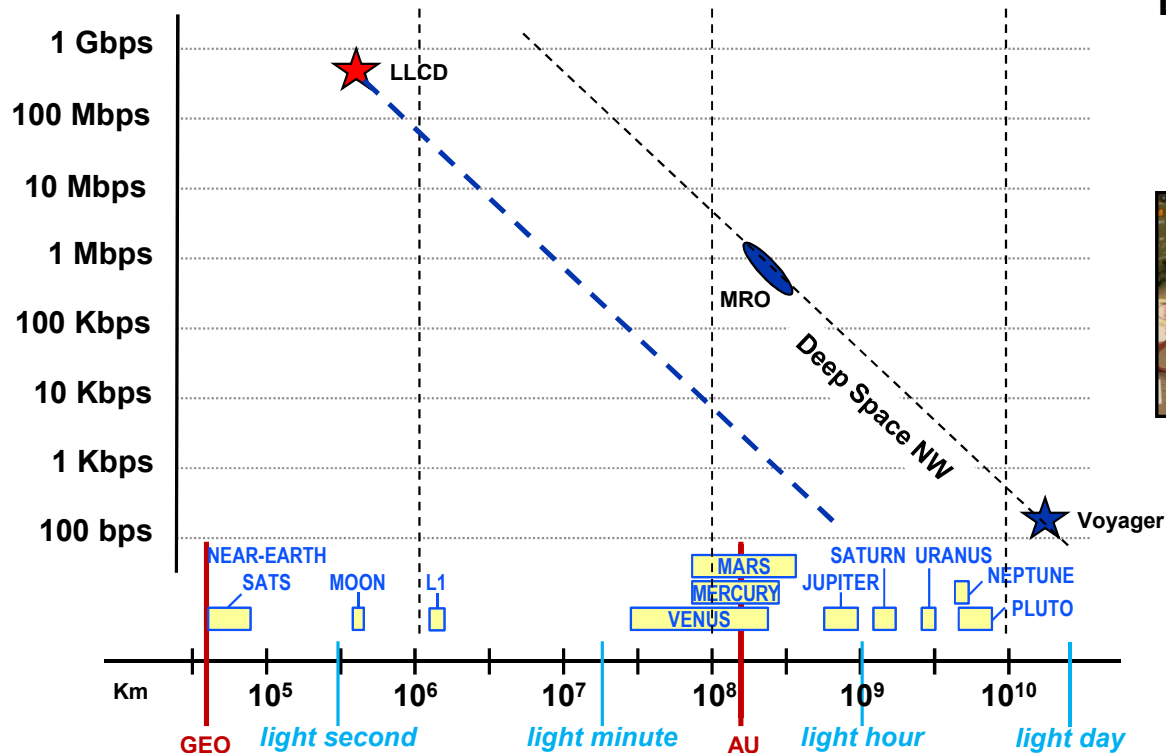
Approximately 10^4 shorter wavelength leads to:

10^8 times greater power transfer for fixed diameter apertures

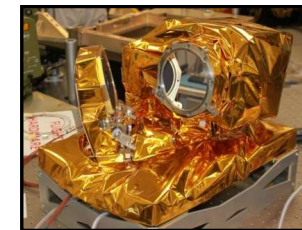
10^4 times more quantum noise

Resulting in 10^4 times higher SNR for fixed diameter apertures

Present Ranges and Rates Optical Bands



Lunar Laser Comm Demo (LLCD, 2013)
(NASA – MIT Lincoln Lab)
on Lunar Atmosphere and Dust Environment
Explorer (LADEE)



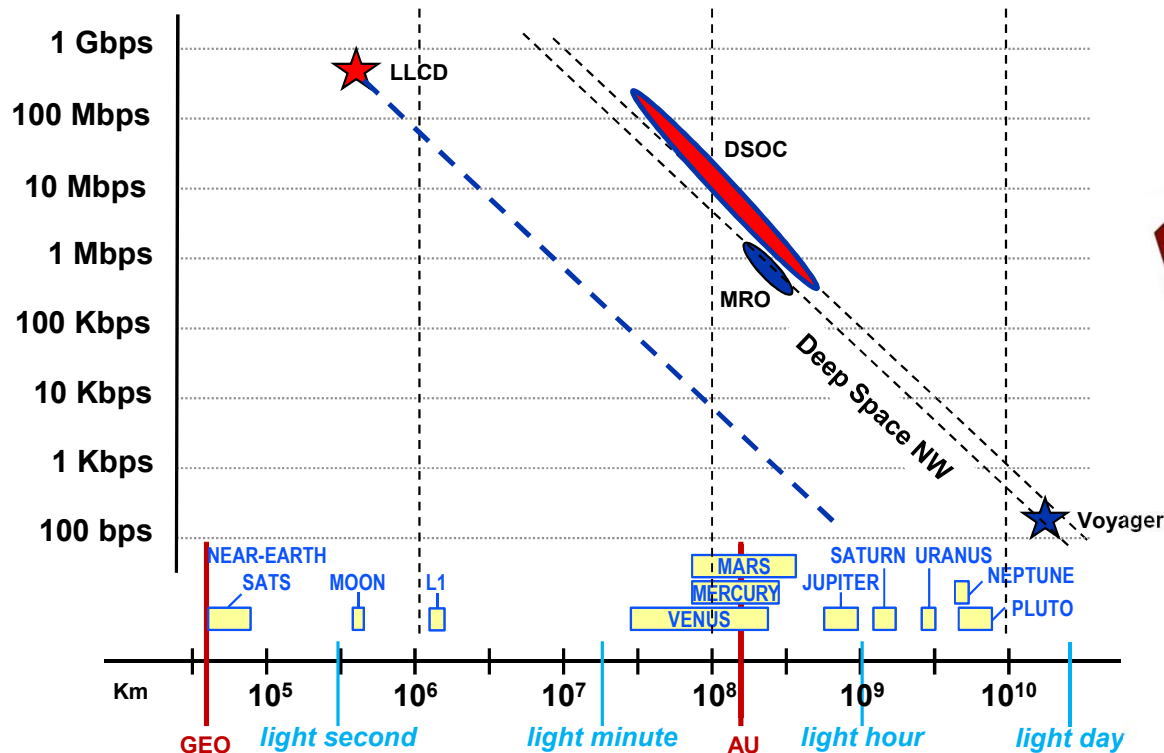
**10-cm aperture
0.5 W laser
622 Mbps**



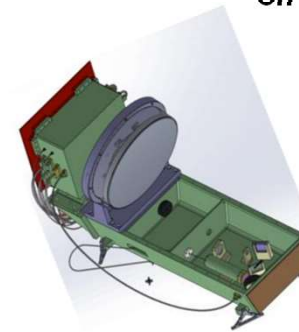
**0.8-m
equiv diam
aperture**

Longest laser comm link so far

Present Ranges and Rates Optical Bands



**Deep Space Optical Comm
(DSOC, 2022, NASA-JPL)
on Psyche Mission**

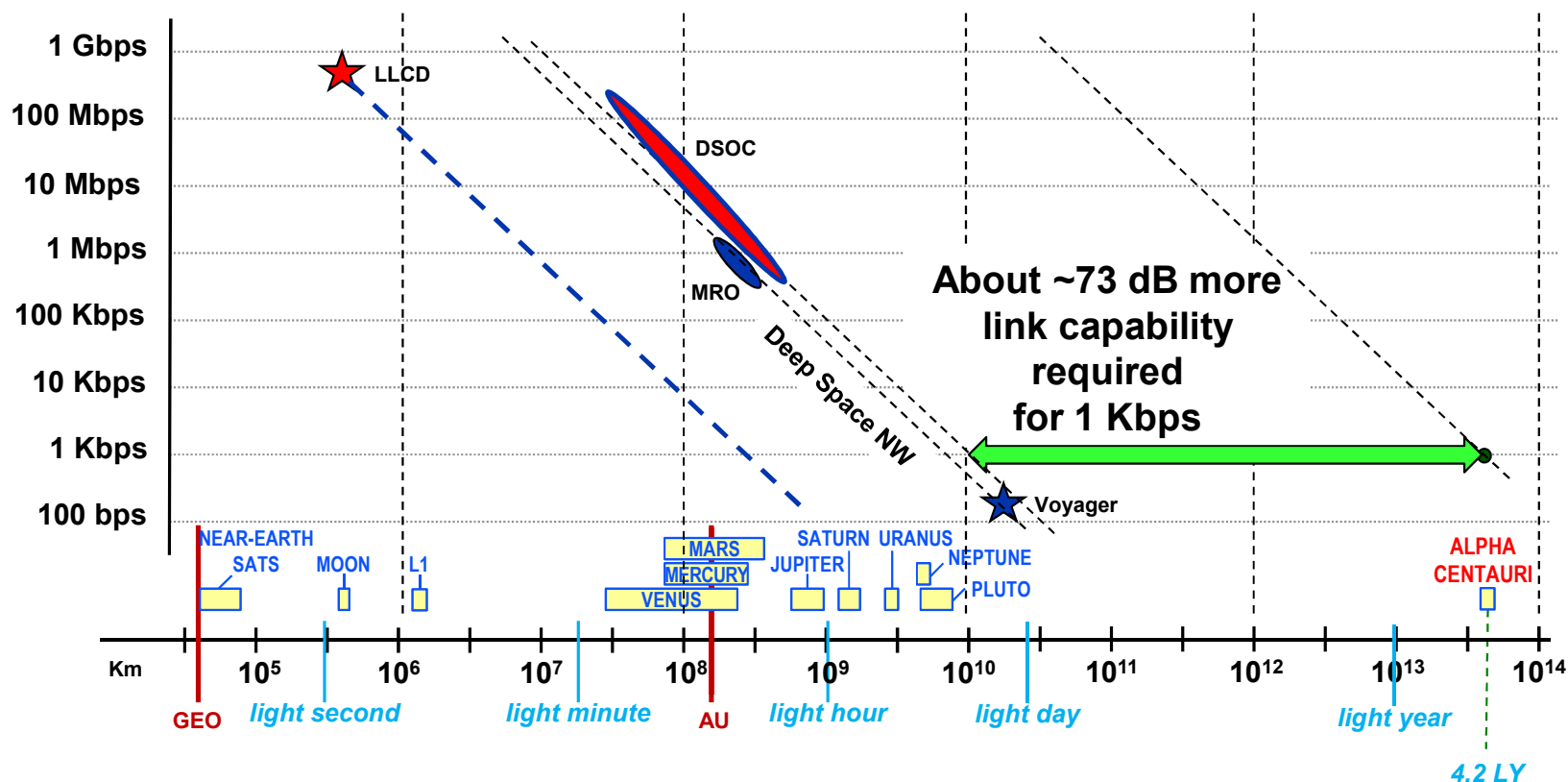


**22-cm aperture
4.0 W laser**

**Hale
Telescope
5-m**



How About from a Star?





On Communications Efficiency

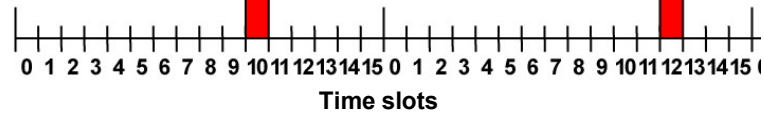
- **Most efficient signaling:**
 - Transmit one of $M=2^N$ orthogonal signals



On Communications Efficiency

- **Most efficient signaling:**
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Timed pulses – Pulse Position Modulation

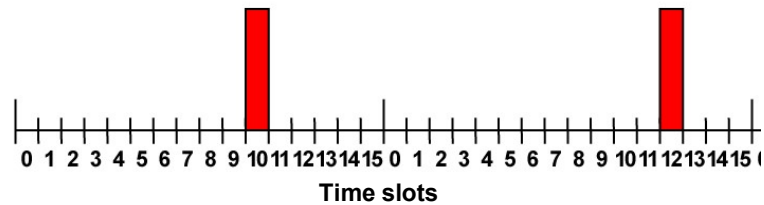
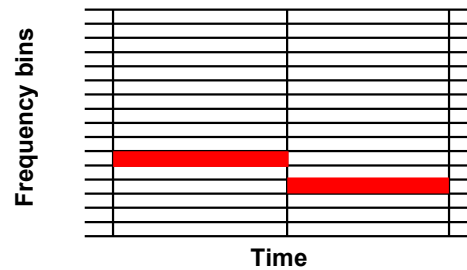




On Communications Efficiency

- **Most efficient signaling:**
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Timed pulses – Pulse Position Modulation



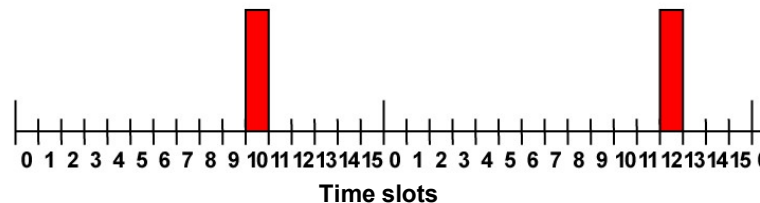
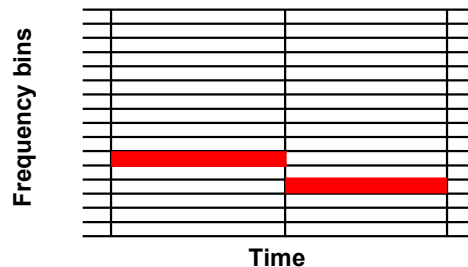
Frequencies – Frequency Shift Keying



On Communications Efficiency

- **Most efficient signaling:**
 - Transmit one of $M=2^N$ orthogonal signals

Timed pulses – Pulse Position Modulation



Frequencies – Frequency Shift Keying

- Measure all possible signals with noiseless photon counters
 - Detection of single photon demodulates N bit symbol
 - With coding, can achieve as high as N bits per average received photon!
- **LLCD and DSOC – PPM, $M=16$ and $M=16-128$**
 - **Alpha-Centauri link – possibly FSK, $M=1024$**



Example Alpha Centauri Link Design

(Many Details Omitted)

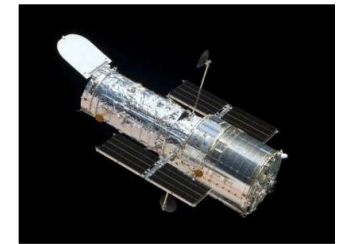
-	DSOC*	DSOC link (relative dB)
Space aperture (cm)	22	0
Optical power (W)	4	0
Earth aperture (m)	5	0
Comm efficiency (b/ph)	2	0
Total Gain		0



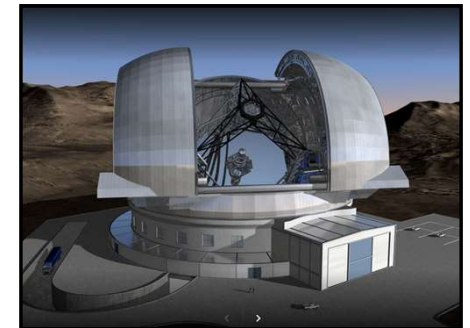
Example Alpha Centauri Link Design (Many Details Omitted)

One way to find ~72 dB

-	DSOC*	DSOC link (relative dB)	A-C Link (example solution)	A-C Link (relative dB)
Space aperture (cm)	22	0	350	24
Optical power (W)	4	0	1000	24
Earth aperture (m)	5	0	40	18.1
Comm efficiency (b/ph)	2	0	8	6
Total Gain		0		72.1



**Hubble Space Telescope
(3.5-m)**



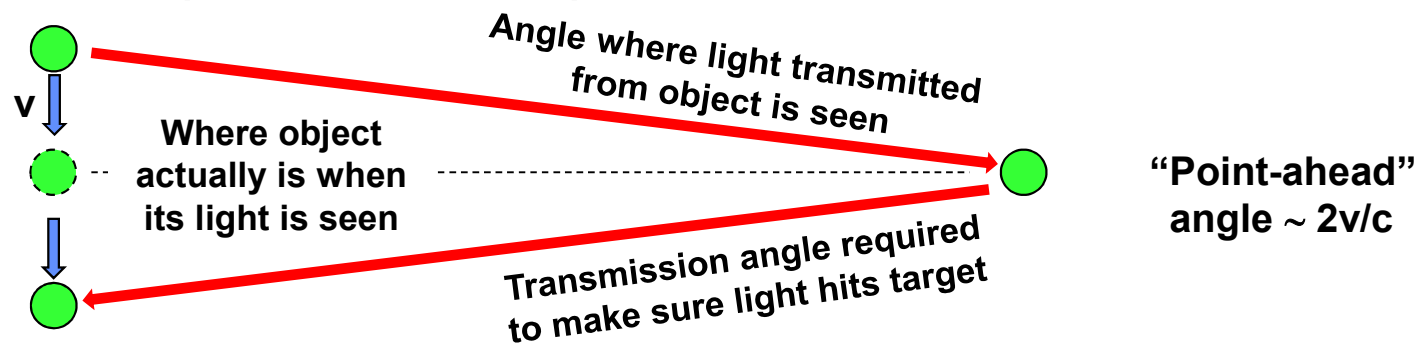
**European Extremely Large
Telescope in its enclosure
(artist's impression) (42-m)**

Credit: ESO

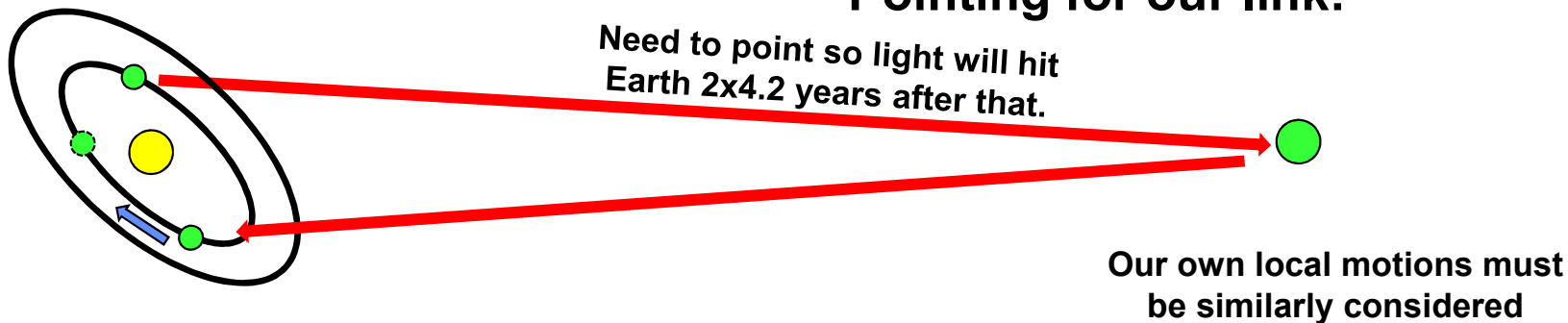
https://www.eso.org/public/images/e-elt-1_2008/

Interstellar Pointing

Linear (and near-linear) relative motions:



Pointing for our link:





Transmitting to the Earth from Far Away

Our example: 3.5-meter telescope at $1.55\ \mu\text{m}$:

Beamwidth is about $0.44\ \mu\text{rad}$

Spot at Earth is about 17.7 M km diameter (~12.5 sun diameters)

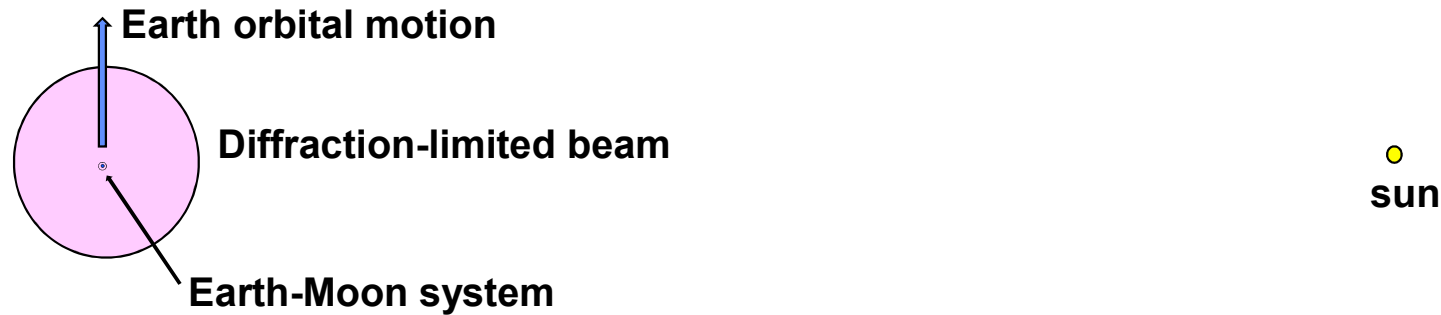
Earth velocity is about 29.8 km/sec (107 K km/hour)

Earth traverses spot in 7 days (depends on orbital position*)

ie, need to predict orbital location $\pm 3.5^\circ$

ie, need to know exact 4.2 light year distance to ~ 0.2%

If cannot see Earth, need to do entire pointing wrt sun and, say, Jupiter or Venus



Sizes & distances approximately to scale

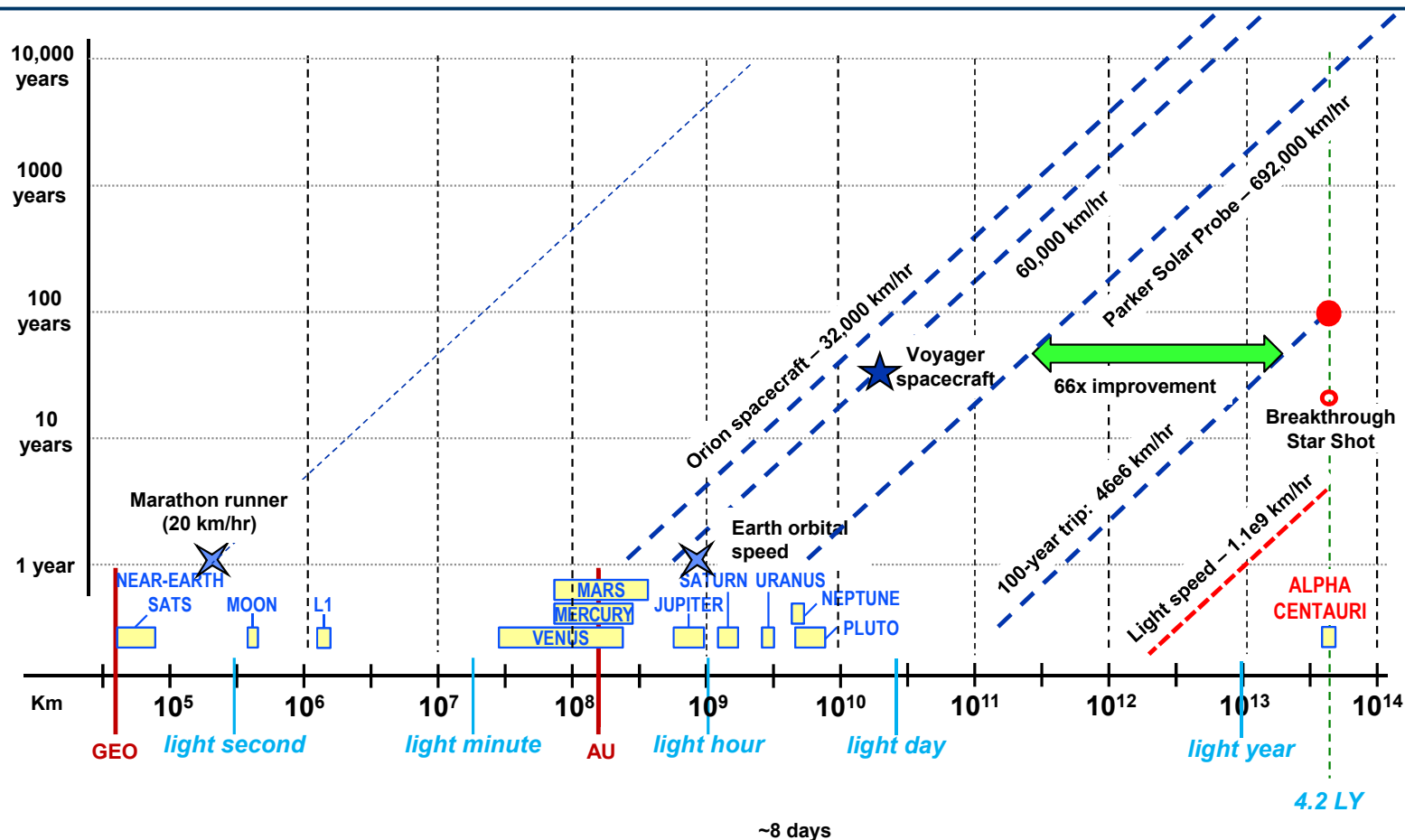


Whole Mission Needs to Be Considered

- **Comm link seems doable, although expensive**
- **However – the entire system would need to be built, flown, and work when it arrives**



How to Get There? And How Long a Trip?





Miscellaneous Link Design Considerations

	Star Link (ex)	Notes
Space aperture (cm)	350	Size/mass – Hubble Pointing – inertial/Sun/planets “Point ahead” to 1-yr orbit via 8-yr round-trip link
Optical power (W)	1000	Wall plug important, efficiency/thermal
Earth aperture (m)	40	Cost Daytime ops (not necessary)
Comm efficiency (b/ph)	8	Stresses on transmitter design (probably use FSK instead of PPM)
Total Gain		

- If power source is Alpha Centauri – need to slow down by a lot when arrive to make use of it for more than a few days.
- Need power during long cruise to keep electronics from freezing. (Or design to sleep and withstand.)
- No electronics have ever been designed to survive for 100 years, especially in space.



Perhaps Accept Only 1 bps Link

	Star Link (ex)	Link (relative dB)	
Space aperture (cm)	110	14	Smaller
Optical power (W)	10	4	Easier
Earth aperture (m)	40	18.1	Same
Comm efficiency (b/ph)	8	6	Same
Total Gain		42.1	43 required

- **Difficult to receive at extremely low flux/data rates – any background noise would be deleterious – Alpha Centauri itself would be in field of view**
 - If the 40-meter ground telescope could be made diffraction-limited (39 nrad at 1.55 μm) it would see 1.5 million km disc at Alpha Centauri
 - So if spacecraft is at Earth-radius-type distance, would be able to block out starlight at Earth
 - Perhaps space- or Moon- based receiver to reduce atmospheric scattering effects - \$\$



Notes on 10 bps *Uplink*

	Star Link (ex)	Link (relative dB)	
Space aperture (cm)	350	24	
Optical power (W)	1000	24*	
Earth aperture (m)	10	6*	Require diffraction-limited AO (or space-based)
Comm efficiency (b/ph)	8	6	
Total Gain		60	53 required

- **10-m uplink telescope creates 4.4e6 km diameter spot at Alpha Centauri**
- **Point-ahead must deal with local Earth motion, likely orbital motion at A-C, and 4-year light transit**



General Discussion

- **Sending HST to a star via a huge rocket – would be very expensive**
 - Complicated orbital dynamics to slow down at destination
- **Large mission almost certainly would want to do science monitoring en route and at A-C system**
 - Would require much power and thermal control
- **Even 100-year mission – hard to envision an Earth-based organization that would exist that long**
- **With all these considerations, should likely re-optimize design for best mass or power or whatever is the main driver**
 - Likely, *much* less capable terminal, *much* larger Earth receiver
 - Breakthrough Starshot considering large number of tiny downlink transmitters
- **Highly unlikely for this mission to happen.....**