UCSB DEEPSPACE GROUP
Experimental Cosmology at UCSB

NIAC
NASA Innovative Advanced Concepts

Directed Energy Propulsion

The Path Forward to Strategic Transformation

NASA Starlight Team
UCSB Breakthrough Starshot team
lubin@ucsb.edu

www.deepspace.ucsb.edu/starlight
→(online non and relativistic photon prop calculator)←
50 Technical papers to date – many more coming including Acta Futura Issue 12, 2019
"A Roadmap to Interstellar Flight" arxiv.org/abs/1604.01356 (JBIS) 2015
"Interstellar Communication" arxiv.org/abs/1801.07778 (Ap J) 2018
"Relativisitic Spacecraft Driven by DE" arxiv.org/abs/1710.10732 (Ap J) 2017
"Directed Energy Intercept of Satellites "arxiv.org/abs/1809.09196 (ASR) 2018
....

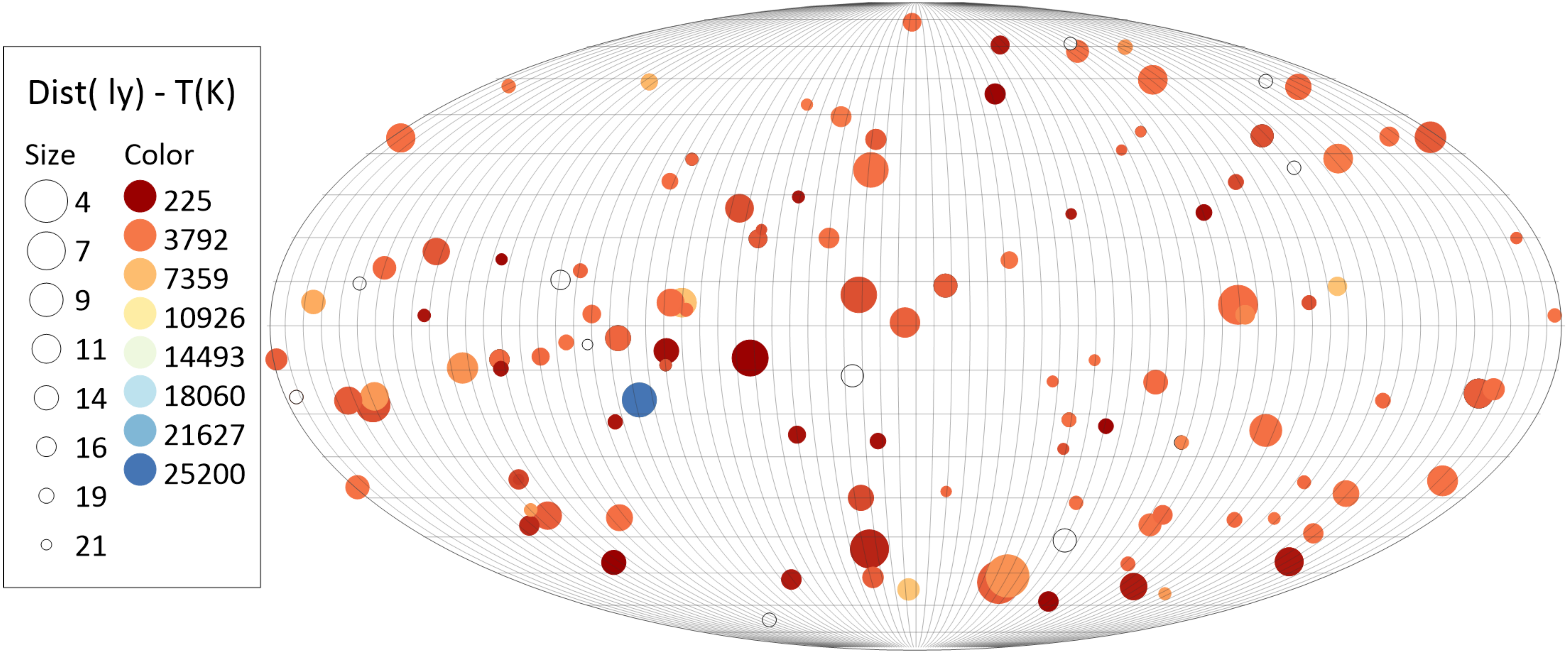
→Three NASA Phase I and II DE programs to date
Primary Funding Comes from Anonymous Private Donor

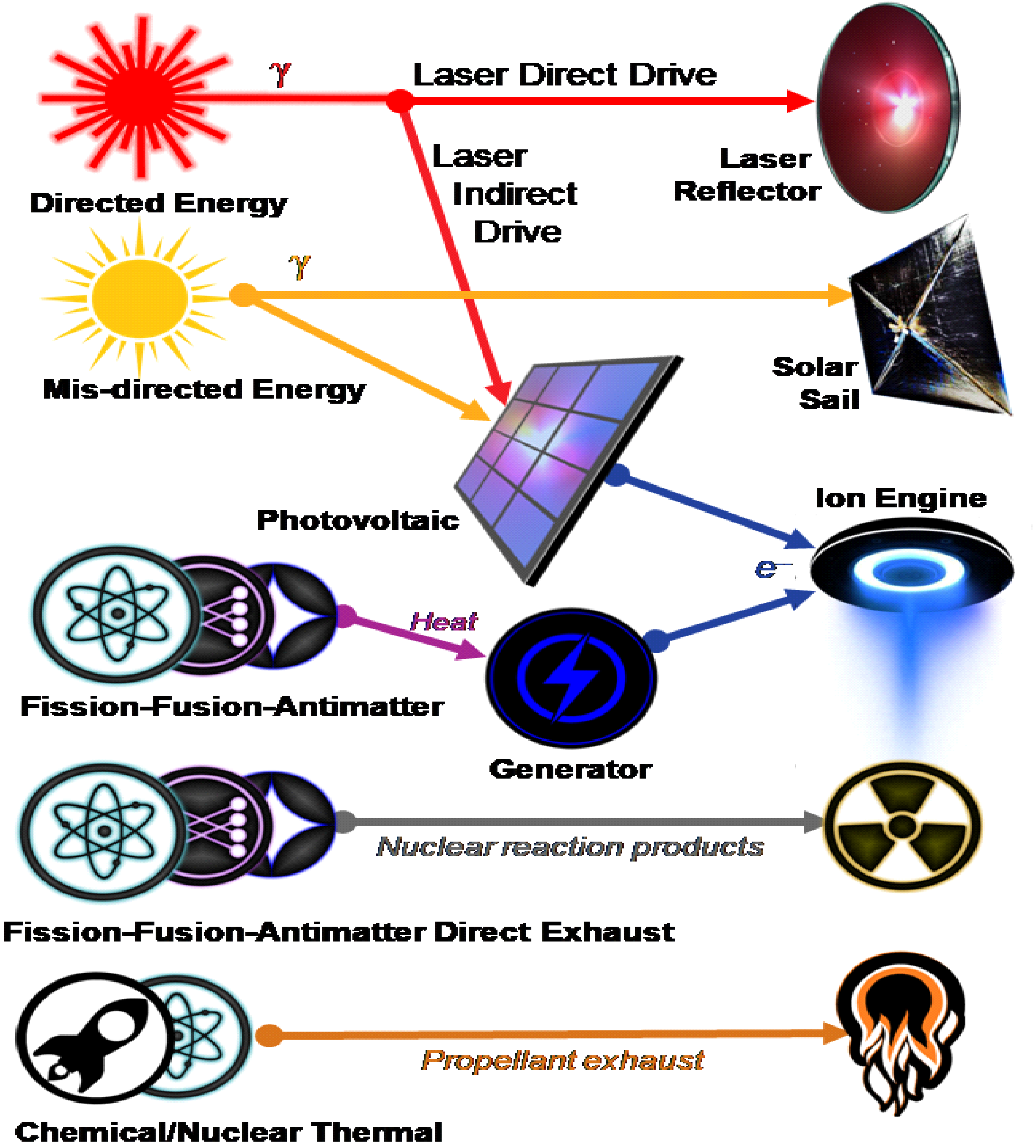
MIT Lincoln Laboratory
BREAKTHROUGH INITIATIVES
Emmett and Gladys W. Technology Fund

Why are you here?

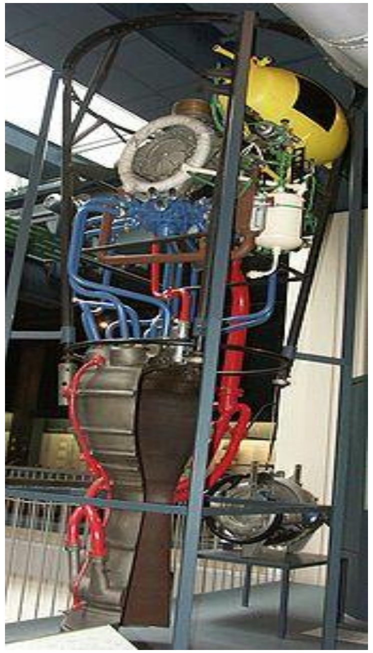
- We dream about something we see in the sky or read in book or see in movies
- **We desire the extraordinary but we are stuck in the ordinary**
- How do get “there”?
- We can continue to dream as we should but we should do more than dream
- We want to “do”
- To do requires us to understand the limits of our known Physical reality
- We all want the “warp button” to be real
- Perhaps it will be some day – but that day is not today
- If we want to go to the stars within our current understanding of Physics…
  - We have to face harsh realities until the “warp button” is found
  - Those harsh realities push us into a corner
  - A very tight corner…
  - There is a path forward now but it is not like the movies unfortunately
  - **Fortunately there is a roadmap that allows us to do incredible things but no “warp button” yet**

>150 Stellar Systems within 21 ly

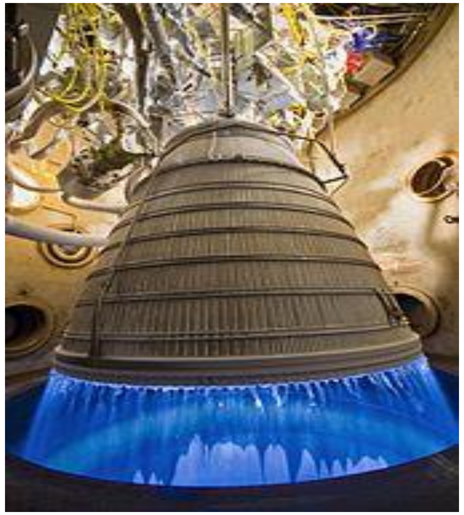


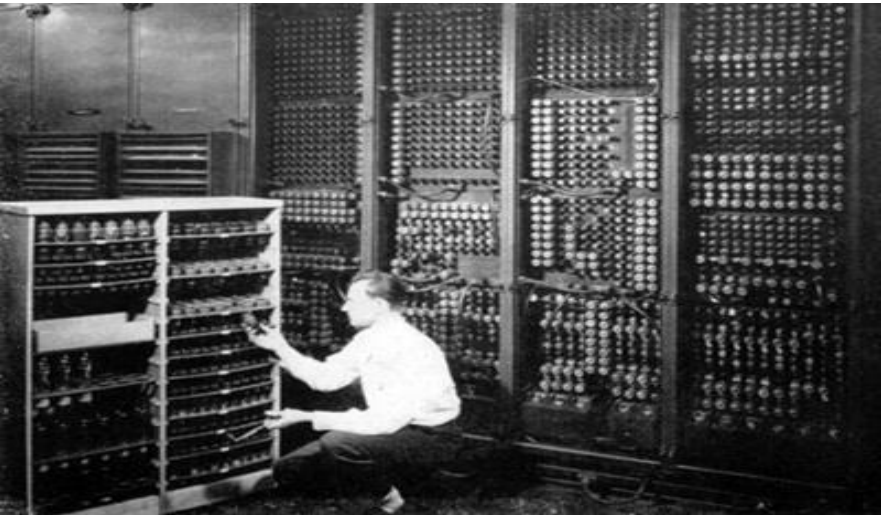

γ
Laser Direct Drive
Laser Indirect Drive
Laser Reflector
Directed Energy
γ
Mis-directed Energy
Solar Sail
Photovoltaic
Ion Engine
e⁻
Heat
Fission-Fusion-Antimatter
Generator
Nuclear reaction products
Fission-Fusion-Antimatter Direct Exhaust
Propellant exhaust
Chemical/Nuclear Thermal

75 years of Propulsion and Computing



V2 1943 – Isp ~215 →Falcon 9 – Isp~ 350 →SLS – 2018 – Isp~ 460
2x increase in performance metric (Isp) – actually NOT
Cost ~ flat





1943 EINIAC – 500 FLOPS
→2017 Intel i9 Teraflop
>1 billion x performance increase
>1 trillion times less power/FLOP
>1000 trillion x less mass/FLOP

Speed and Mass Ratios with Mass Ejection Propulsion

All the mass in the universe cannot get even one proton to rel speed with chemical propulsion

$$\frac{mv_{esc}^{\ 2}}{2} = \frac{GMm}{R}$$

$$\rightarrow v_{esc} = \left[\frac{2GM}{R}\right]^{1/2} = \sqrt{2}v_{orb}$$

$$\text{Note if } R = r_S = \frac{2GM}{c^2} \rightarrow v_{esc} = c$$

$$\mathbf{v_{esc} = c\left[\frac{r_S}{R}\right]^{1/2}} \qquad r_S(Earth) \sim 8.87mm$$

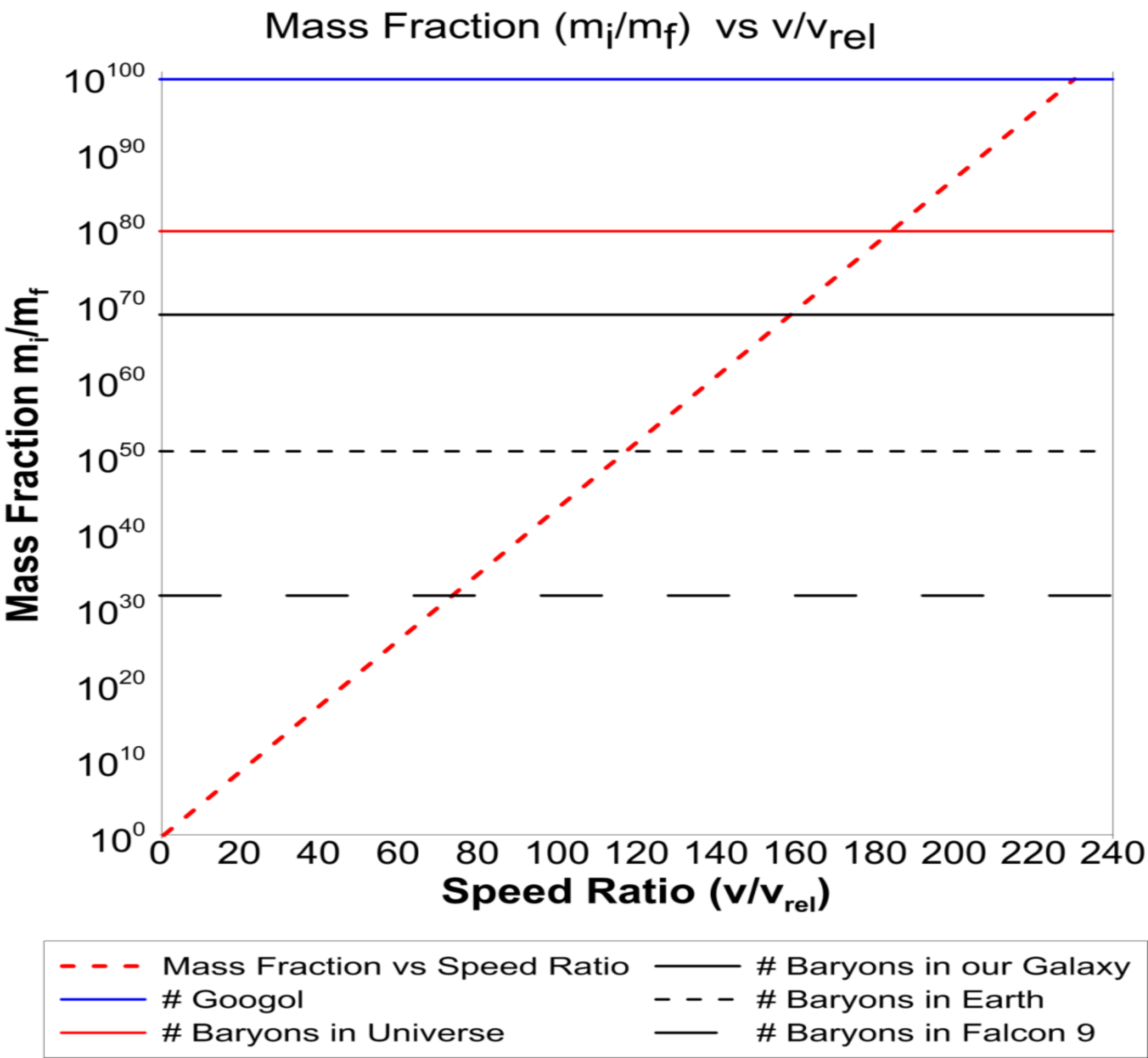
$$R(Earth) \sim 6.37x10^6 m$$

$$\rightarrow v_{esc} \sim 3.73x10^{-5}c \sim 11.2km/s$$

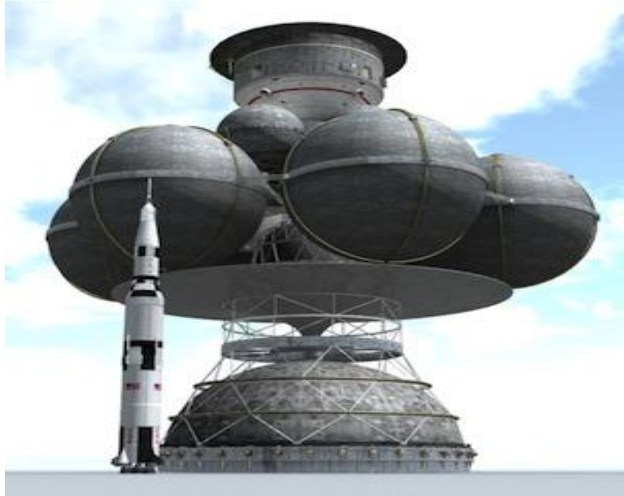
Chemical propellants

$$v_{rel} \sim 2-4km/s(Solid - H_2O_2)$$

We just barely escape the Earth ($e^3 \sim 20$)



What about Nuclear Engines?



$$E_{exh} = m_{exh}c^2(\gamma - 1) \sim 1/2 m_{exh} c^2 \beta_{rel}{}^2 \rightarrow \beta_{rel} = \left[2 \frac{E_{exh}}{m_{exh}c^2} \right]^{1/2}$$

Define ε_{exh} as the ratio of the exhaust kinetic energy to the exhaust rest mass energy as

$$\varepsilon_{exh} \equiv \frac{E_{exh}}{m_{exh}c^2} = (\gamma - 1) \sim 1/2 \beta_{rel}{}^2 = 1/2 (g_{Earth} I_{sp})^2 / c^2$$

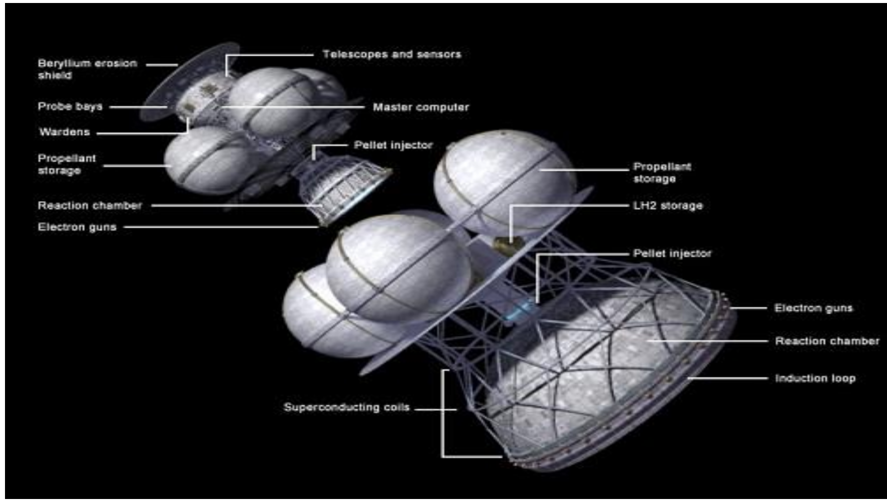
ε_{exh} is an upper limit on the engine conversion efficiency (compared to annihilation energy).

Here $\beta_{rel} = \sqrt{2\varepsilon_{exh}}$ and $I_{sp} = v_{rel} / g_{Earth} = \frac{c}{g_{Earth}} \sqrt{2\varepsilon_{exh}}$ For chemical engines $\varepsilon_{exh}(chem) < 10^{-9}$

Fission fragment engines ε_{exh} fission $\lesssim 10^{-4}$

For fusion engines ε_{exh} fusion $\lesssim 10^{-3}$

For nuclear thermal ε_{exh} nuclear thermal $\lesssim 10^{-9}$



$$\frac{m_f}{m_i} = e^{-\beta/\beta_{rel}} = e^{-\beta(2\varepsilon_{exh})^{-1/2}} = 10^{-0.43\beta(2\varepsilon_{exh})^{-1/2}} = 10^{-0.43\beta/\beta_{rel}} \text{ (this kills nuclear)}$$

As another example consider β=0.2 (20% c) and "realistic" fusion propellants with

ε_{exh} ~ 2x10^{-4} (5MT / T large scale thermonulcear weapon yield)

$$\frac{m_f}{m_i} = 10^{-0.43\beta(2\varepsilon_{exh})^{-1/2}} < 10^{-4.3} \sim 5x10^{-5}$$

Mass ratio is very sensitive to the final speed. If we use β=0.12 (12% c as in Project Daedalus) gives:

Daedalus Study

$$\frac{m_f}{m_i} = 10^{-2.58} \sim 2.6x10^{-3} \text{ (Daedalus } e^- \text{ ICF - 46Mkg D/He-3 - mine from Jupiter! - } v_{rel} \sim 10\text{Mm/s)}$$

Storage, confinement and reaction mass large ↑NOT feasible for v > 0.1c missions

DE - Two Modes of Operation – Direct and Indirect Drive

→One launch driver – Unlimited mission space and number←

- **Direct Drive (Photon Drive) – Use photon momentum exchange – Very High Power**
  - **→NASA Phase II**
  - Lowest system mass (no internal "fuel or engine")
  - **→Scalable to any payload mass**
  - **→Only known solution to relativistic flight – enables interstellar capability**
  - Requires higher power than indirect mode
  - 6.6 nN/w_{op} $I_{sp}=3x10^7$ (highest possible) - get 2x thrust increase from reflection
  - Can be used in ping-pong mode in solar system (eg Mars, Moon etc) if needed
    - This would require second unit or reflector at target (Mars, Moon etc)
- **Indirect Drive (reconvert to electrical power to drive ion engine) – Low Power**
  - **→NASA Phase II in collaboration with JPL**
  - **Use for larger mass slower mission – good in solar system**
  - **Can stop (orbital insertion) if needed at least out to Jupiter**
  - **→Scalable to ANY mass payload – grams to >100 tons**
  - **→NOT for relativistic flight – NOT for interstellar**
  - Use laser tuned PV – eff ~ 60% or more
  - Can drive any ion engine – choose engine to match mission requirements

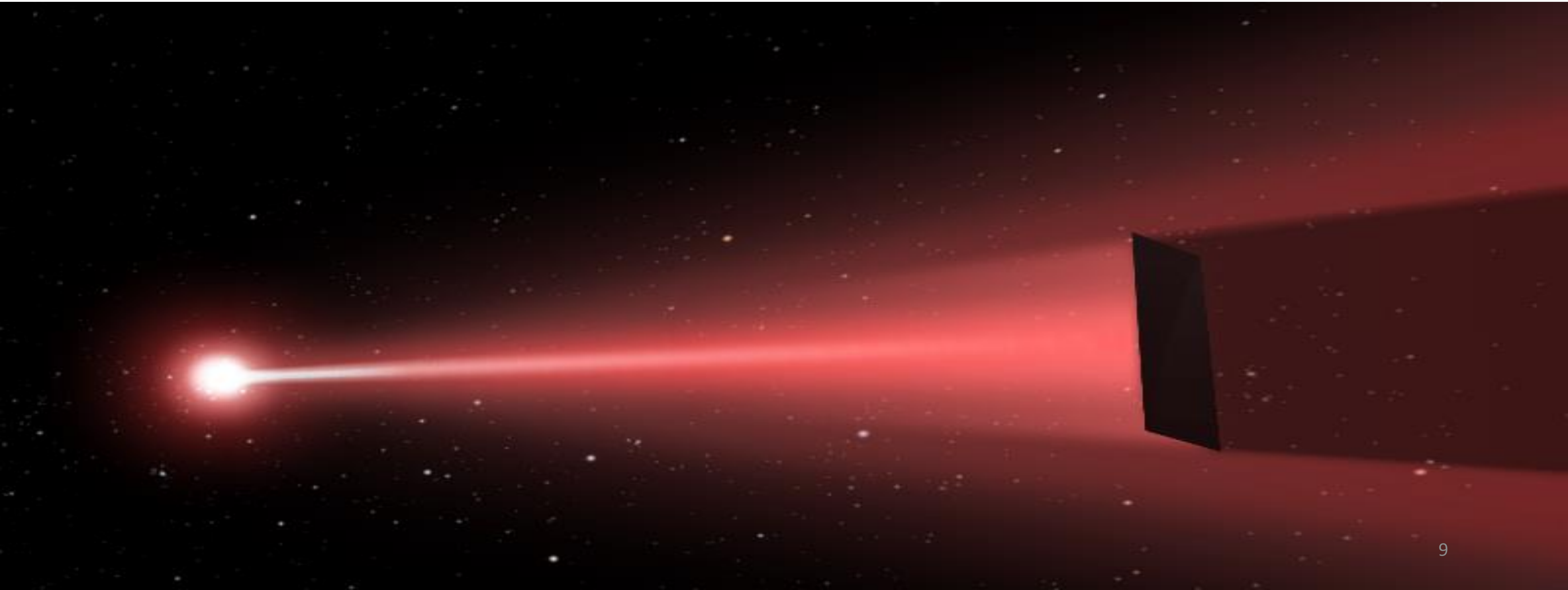
The First Interstellar Missions - On a beam of Light

Directed Energy is only "on" a few min per small mass mission

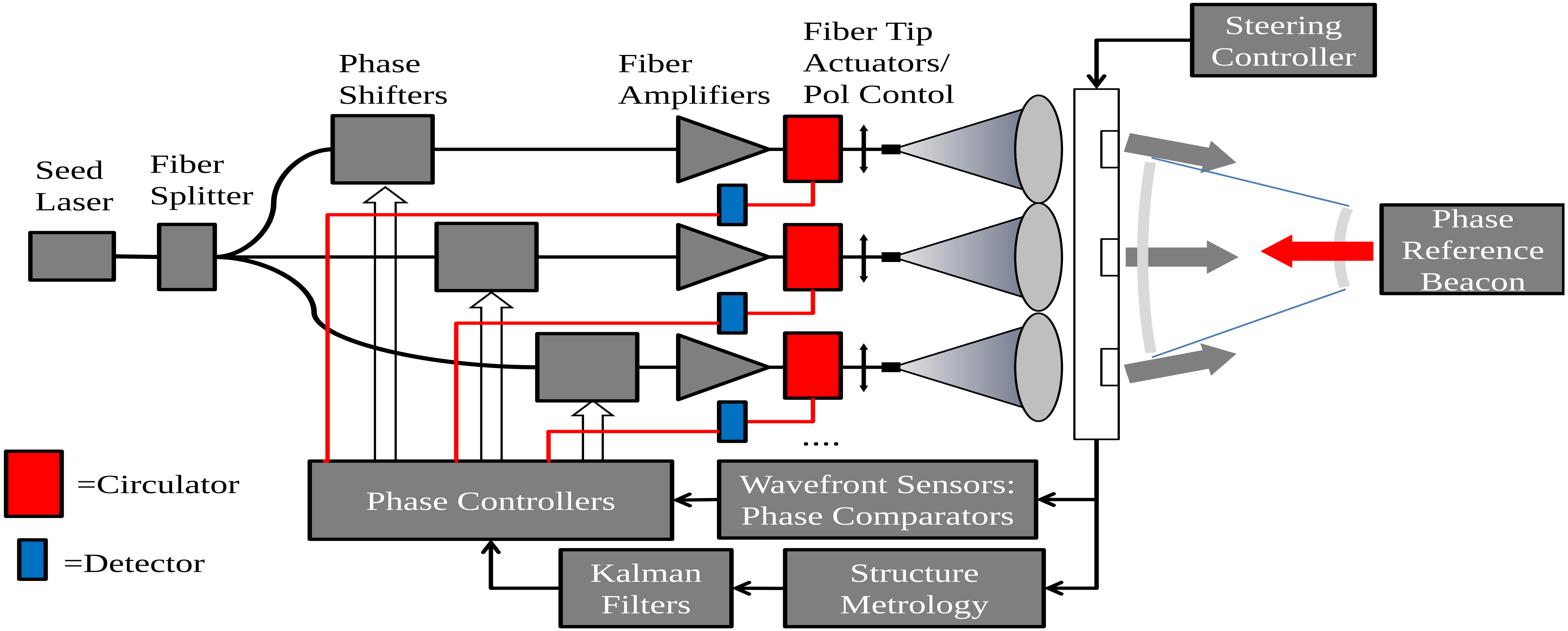
→ hundreds per day←

The nearest stars can be reached in 20 year flight time with small scouting missions

MANY other mission options become possible with this core technology



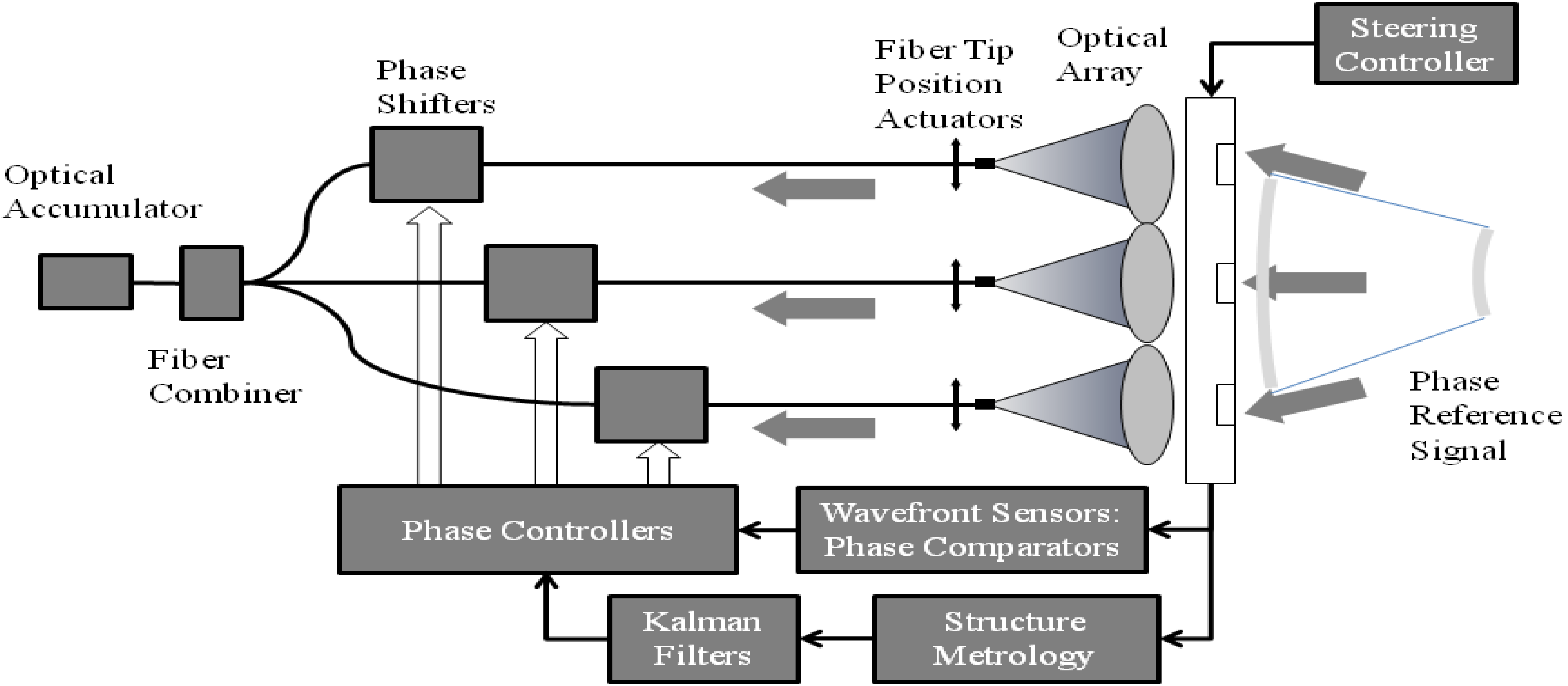
Phased Array Laser Driver Makes it Possible Analogous to Parallel Supercomputer →Power is NOT the problem – Parallelization IS



Phased Array Telescope

Critical for Interstellar Laser Communications

A path to astronomical km scale telescopes – space+ground

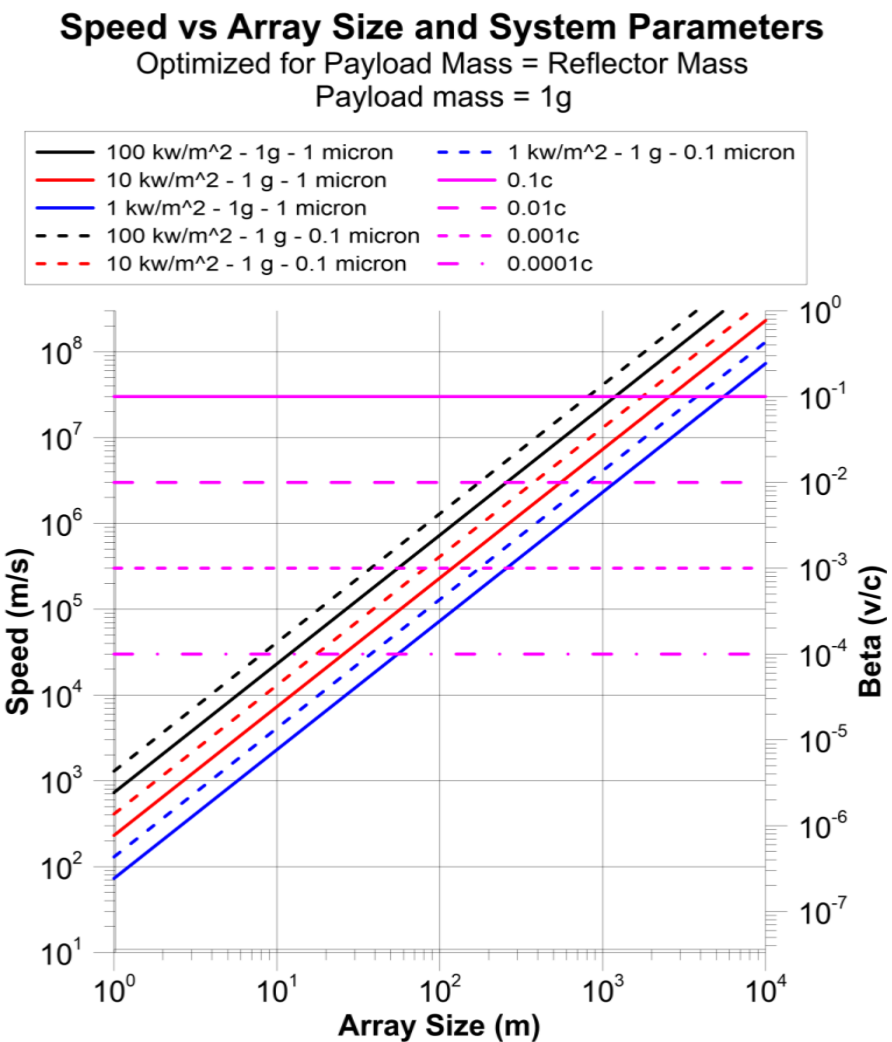


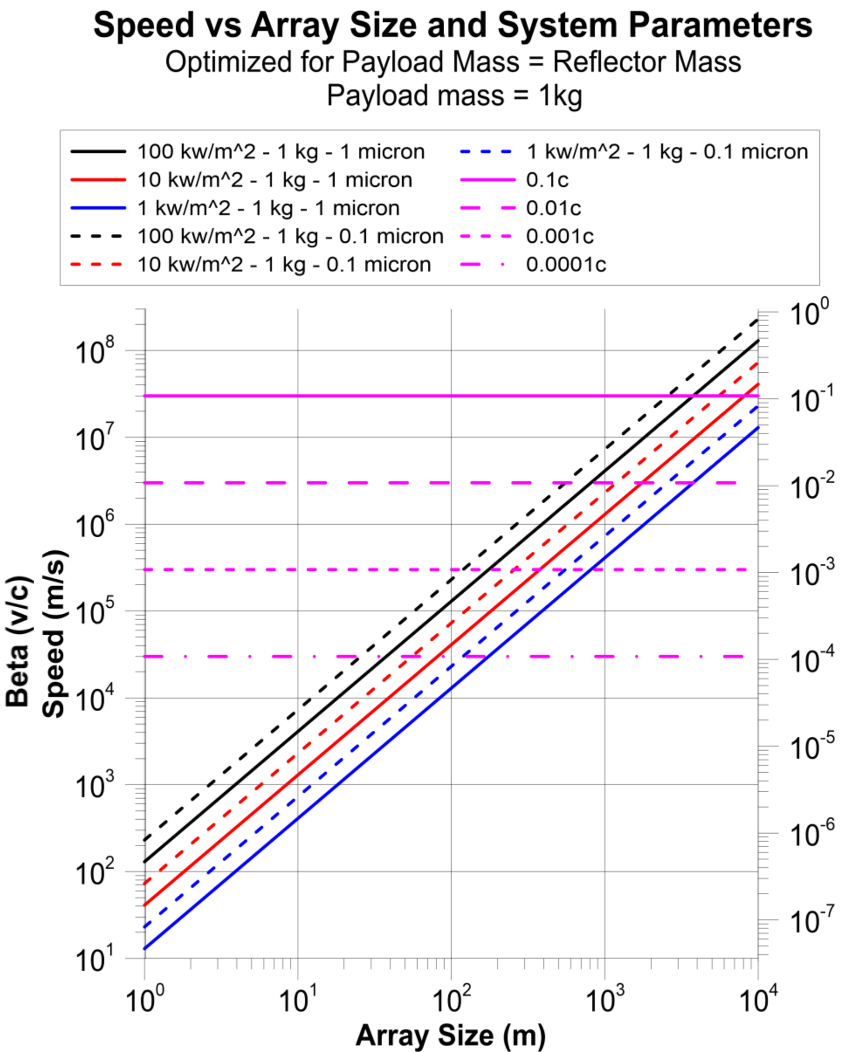
Direct Drive Photonic Driven Speed vs Array Size & Aperture Flux

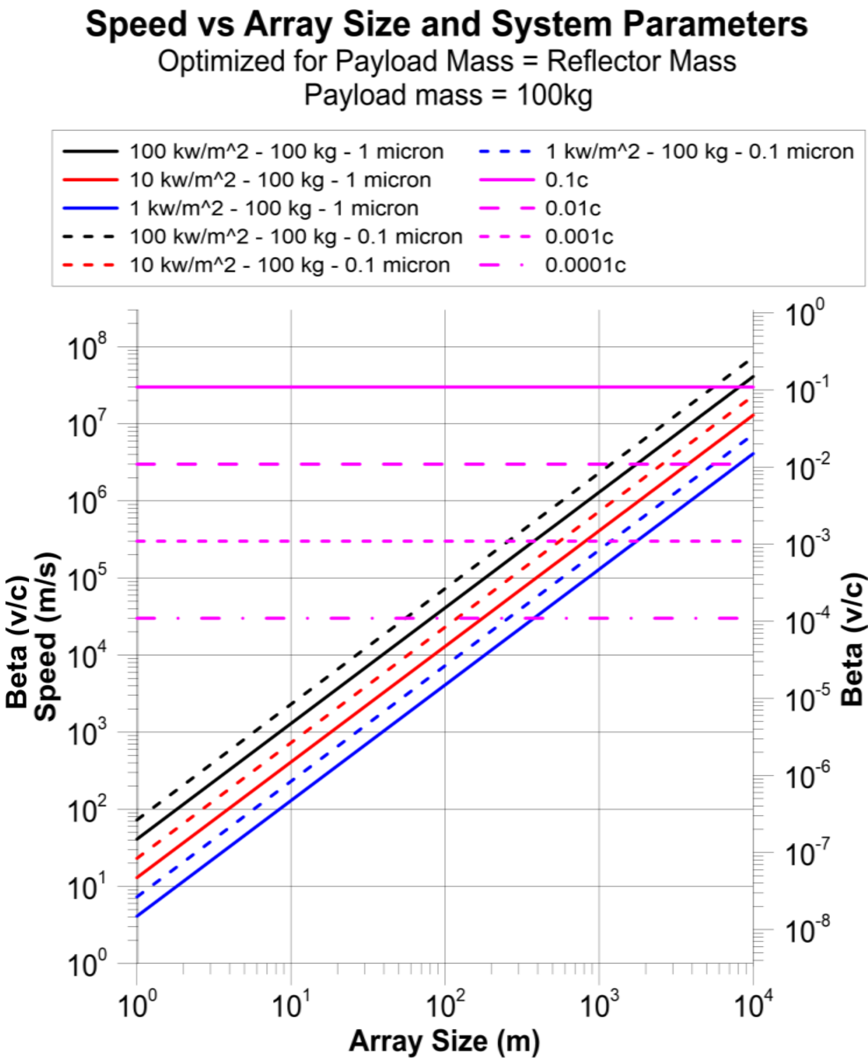
→Modular and Scalable – Large Mission Space←

1g, 1, 100 kg (Not Just for wafer scale) Speed~$(Pd/\lambda)^{1/2} m^{-1/4}$ (λ=1.06μ below)

→NOTE: Flux on sail ~ 1/mass – smaller is HARDER←





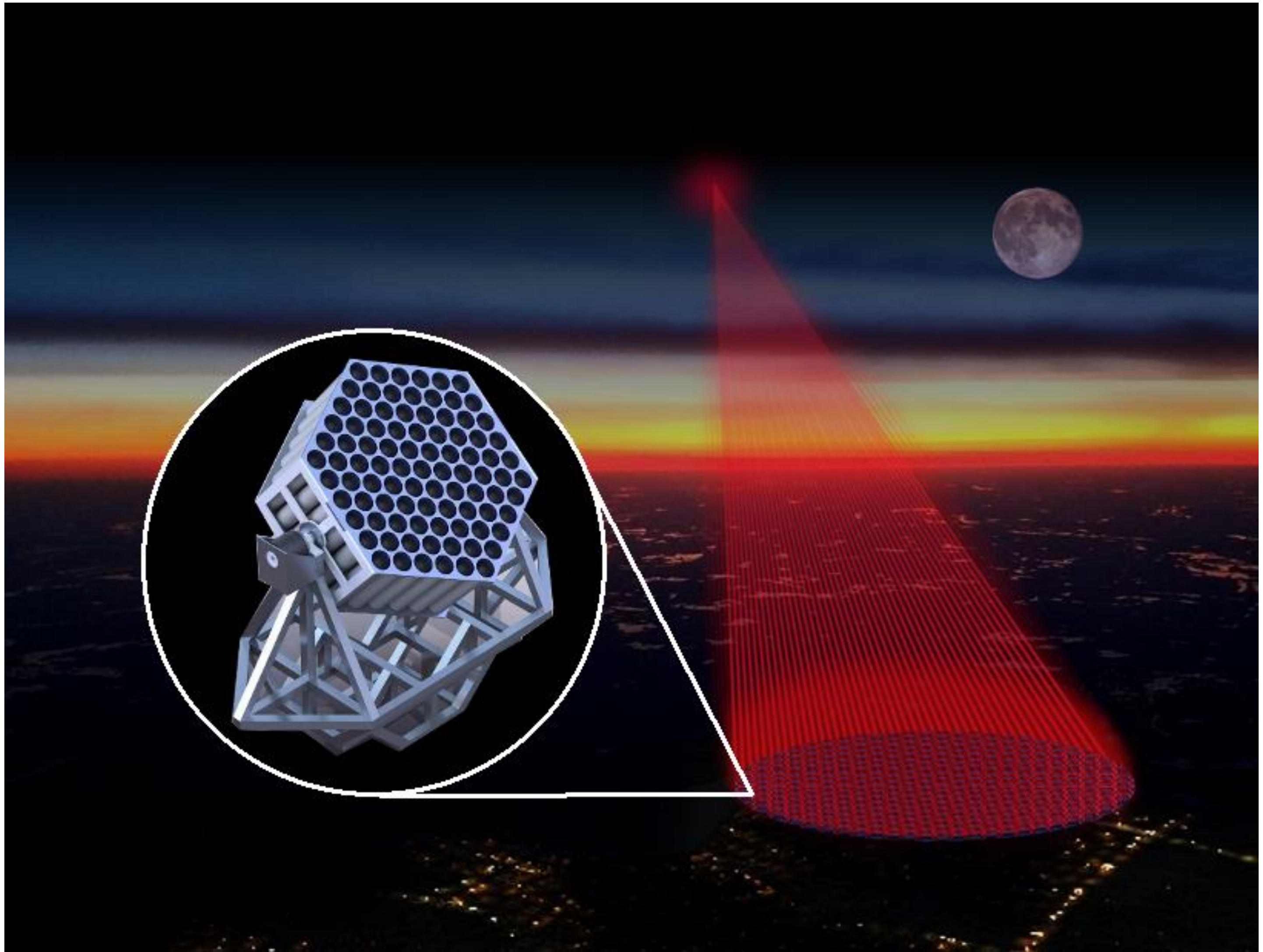


UC Santa Barbara One Meter Panel Demonstrator

91 element Hexagonal Close Packed Array with UCSB Yb Amplifiers

Sub element matched to be < isoplanatic patch (Fried length)

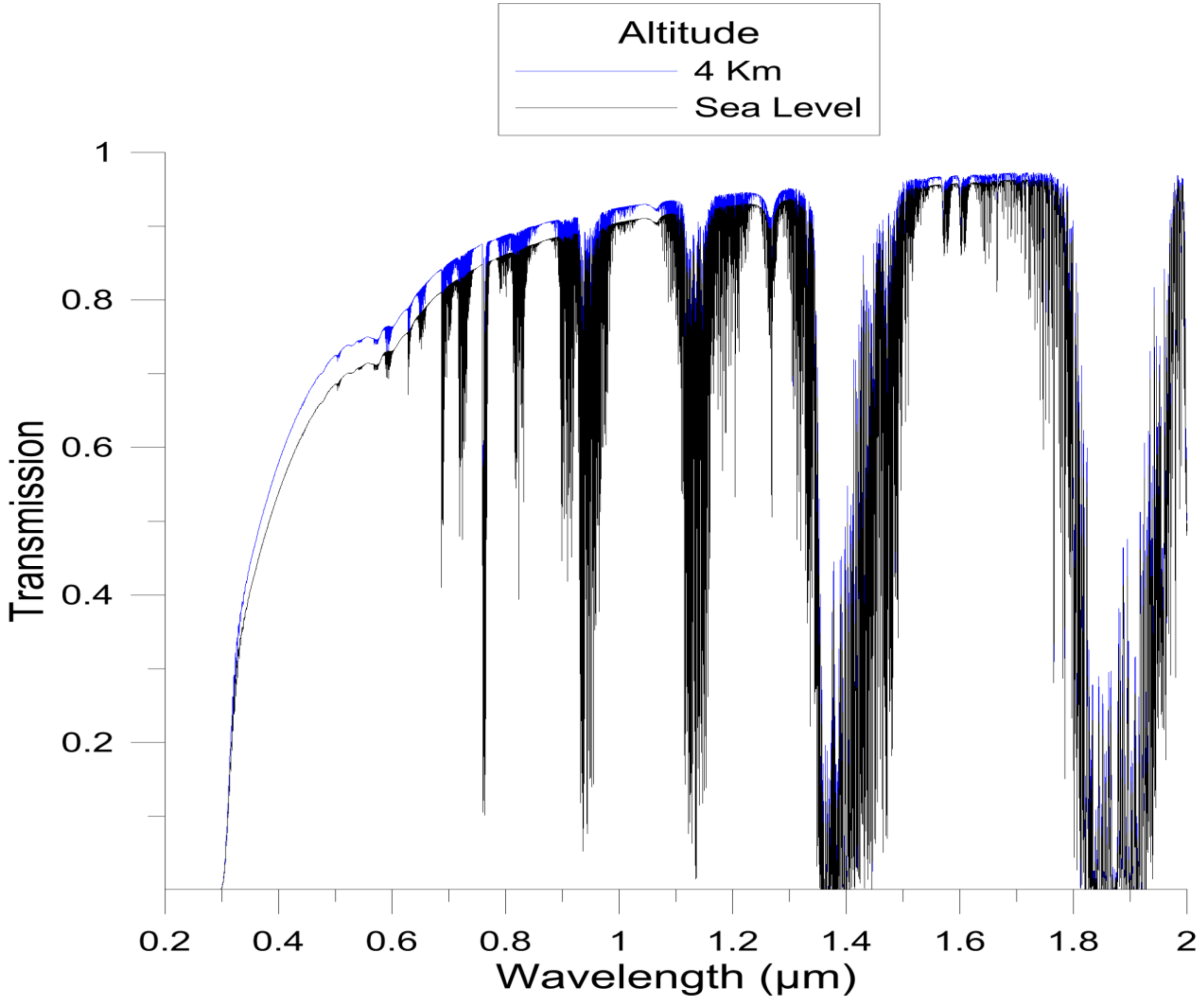
→Not an issue for space based array←

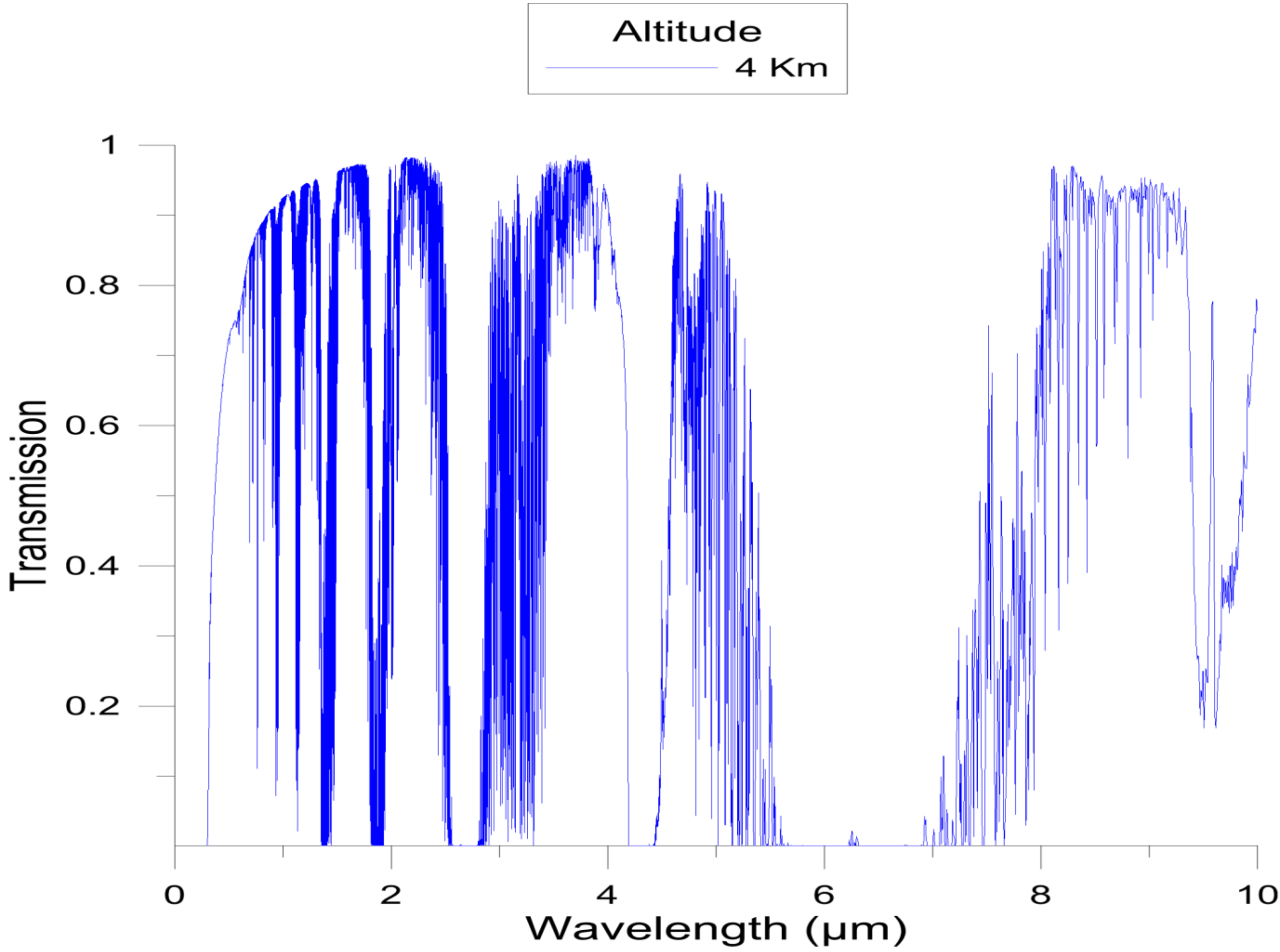


Ground based atmos transmission

Testing prototypes – 4 Km ~ 95% transmission @1.06 μm

UC Santa Barbara White Mountain Site

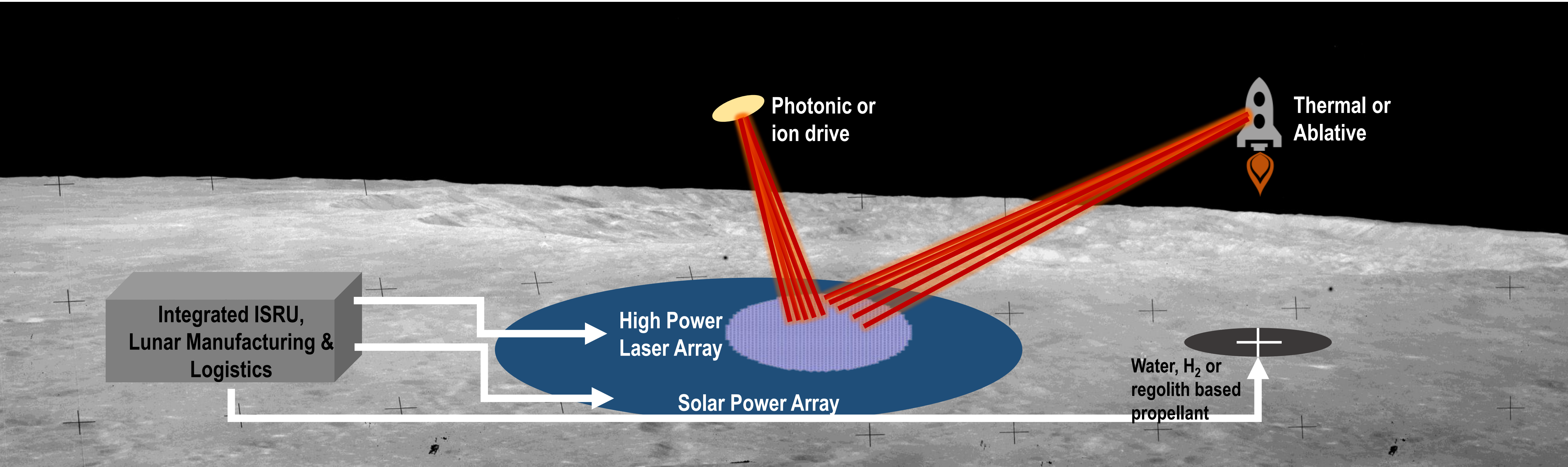




The Moon – A Better Place

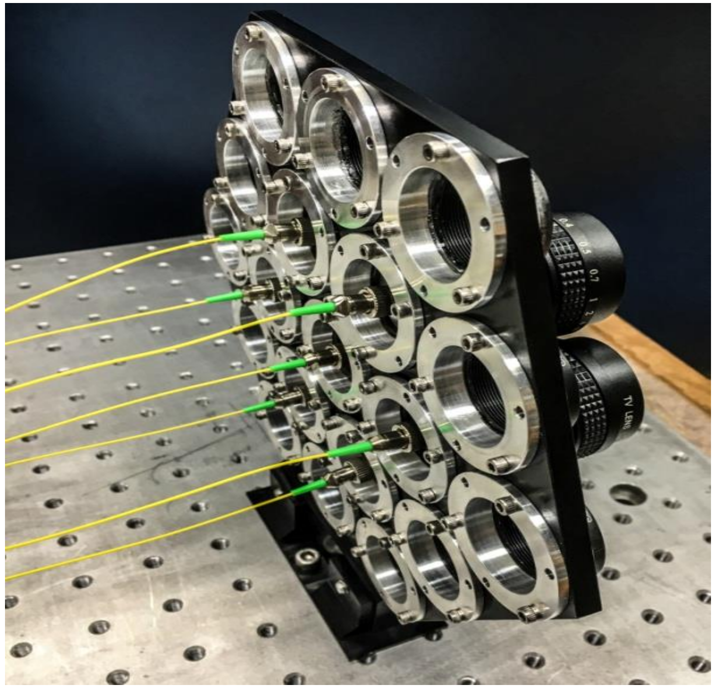
Photon, Ion, Ablative Launch or Hybrid
Back side for policy mitigation

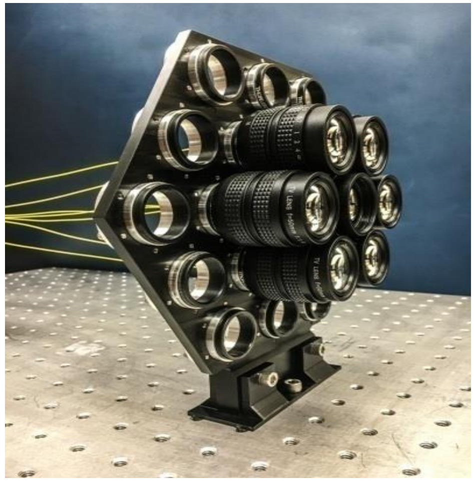
- Back side for policy mitigation
- Slow rotation advantageous - ~ 1 month
- Possible long term solution – g~1.6 m/s^2



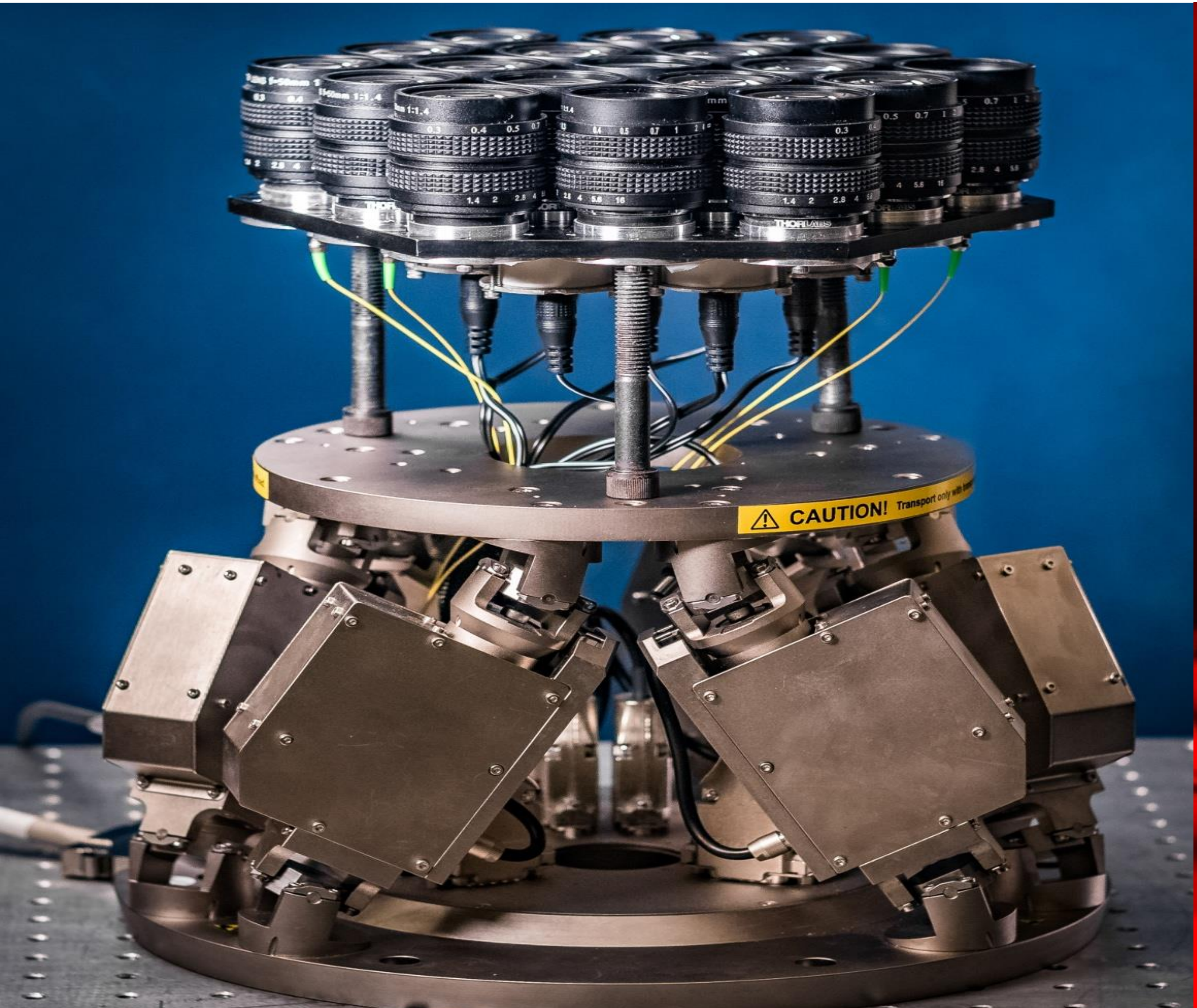
UCSB 19 Element Prototype Array – Xmit/Rcv

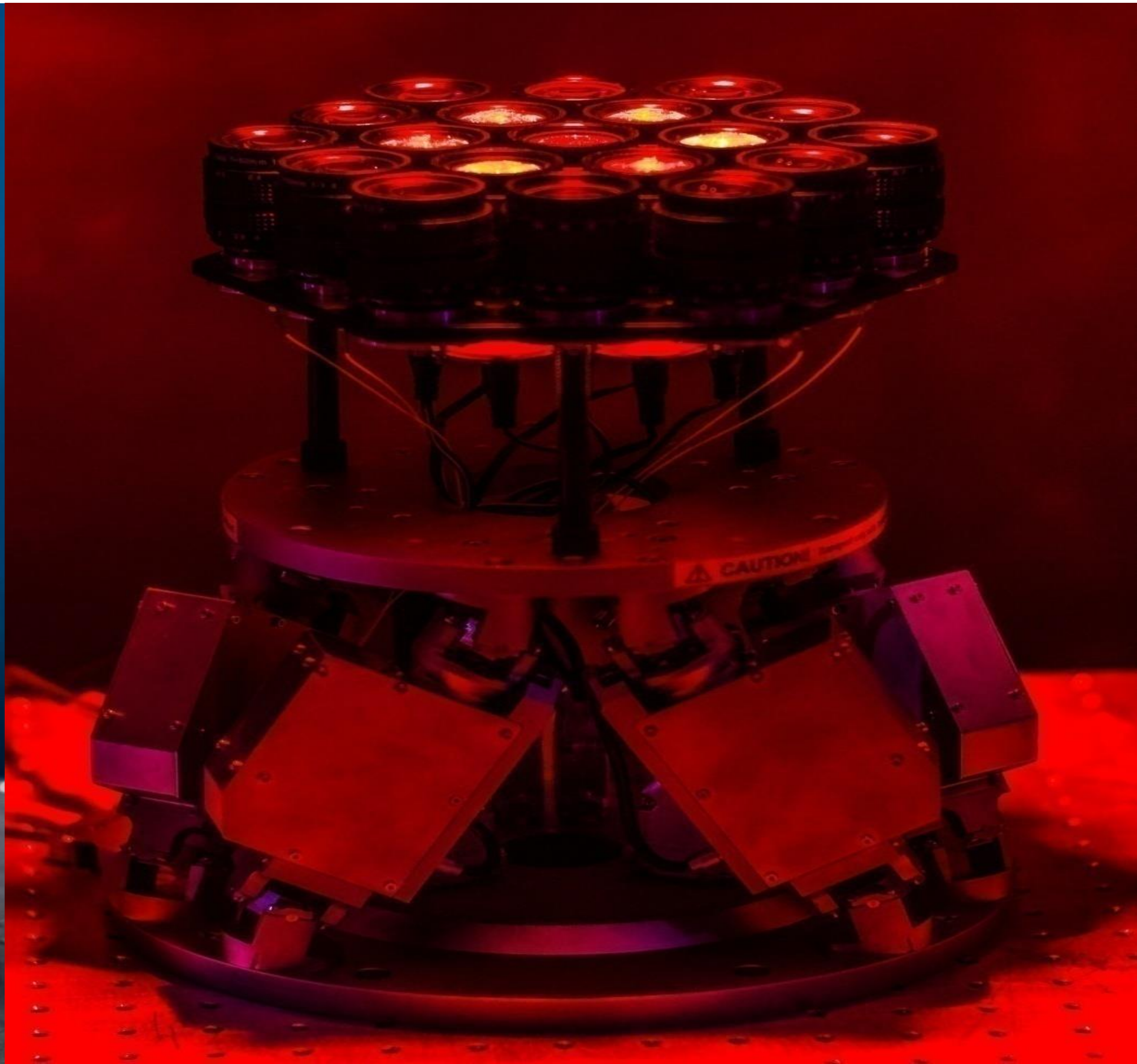
Single Mode Fiber Feed Optics - ~1/4 scale of ONE module





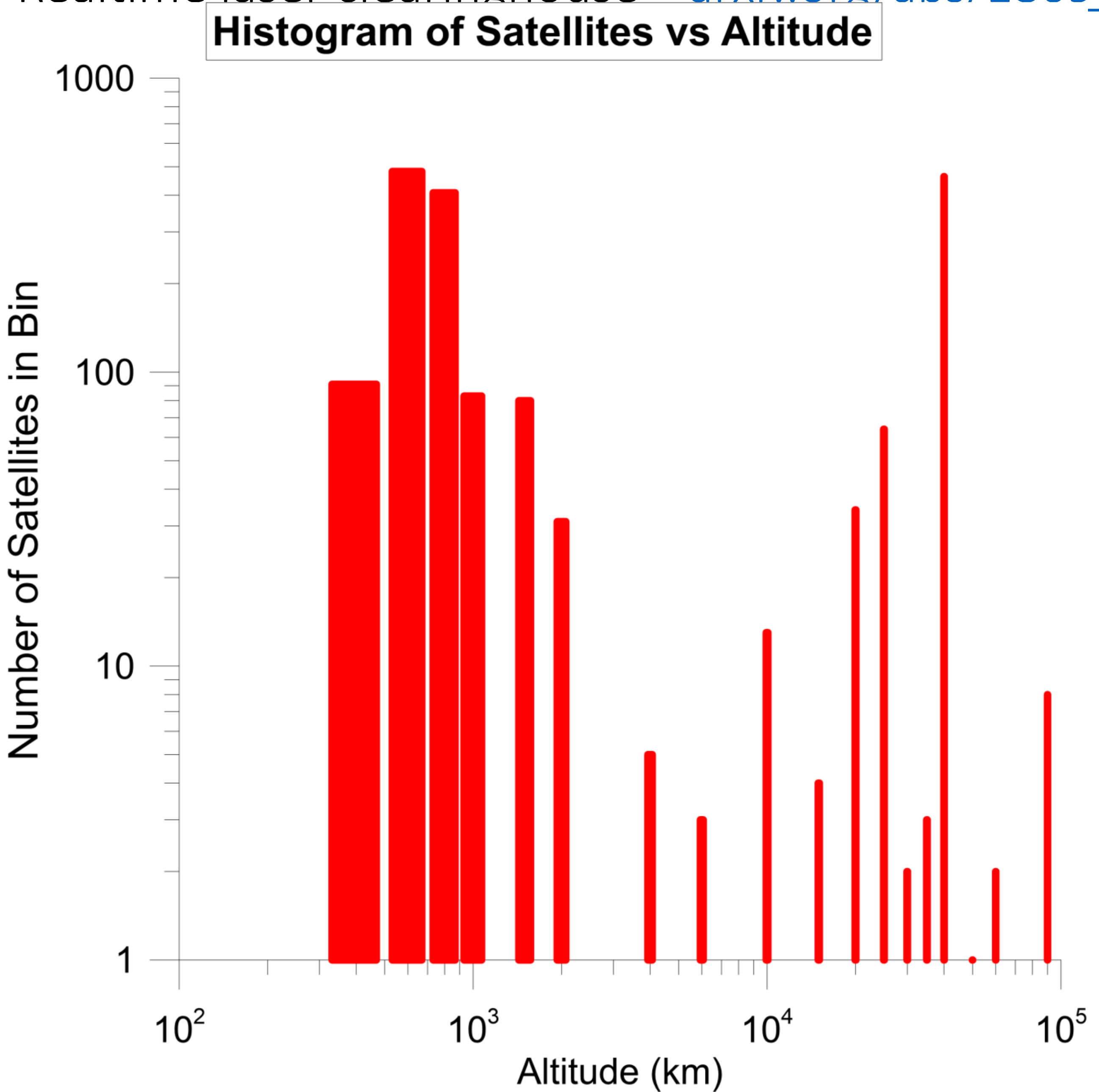
UCSB Array on Hexapod

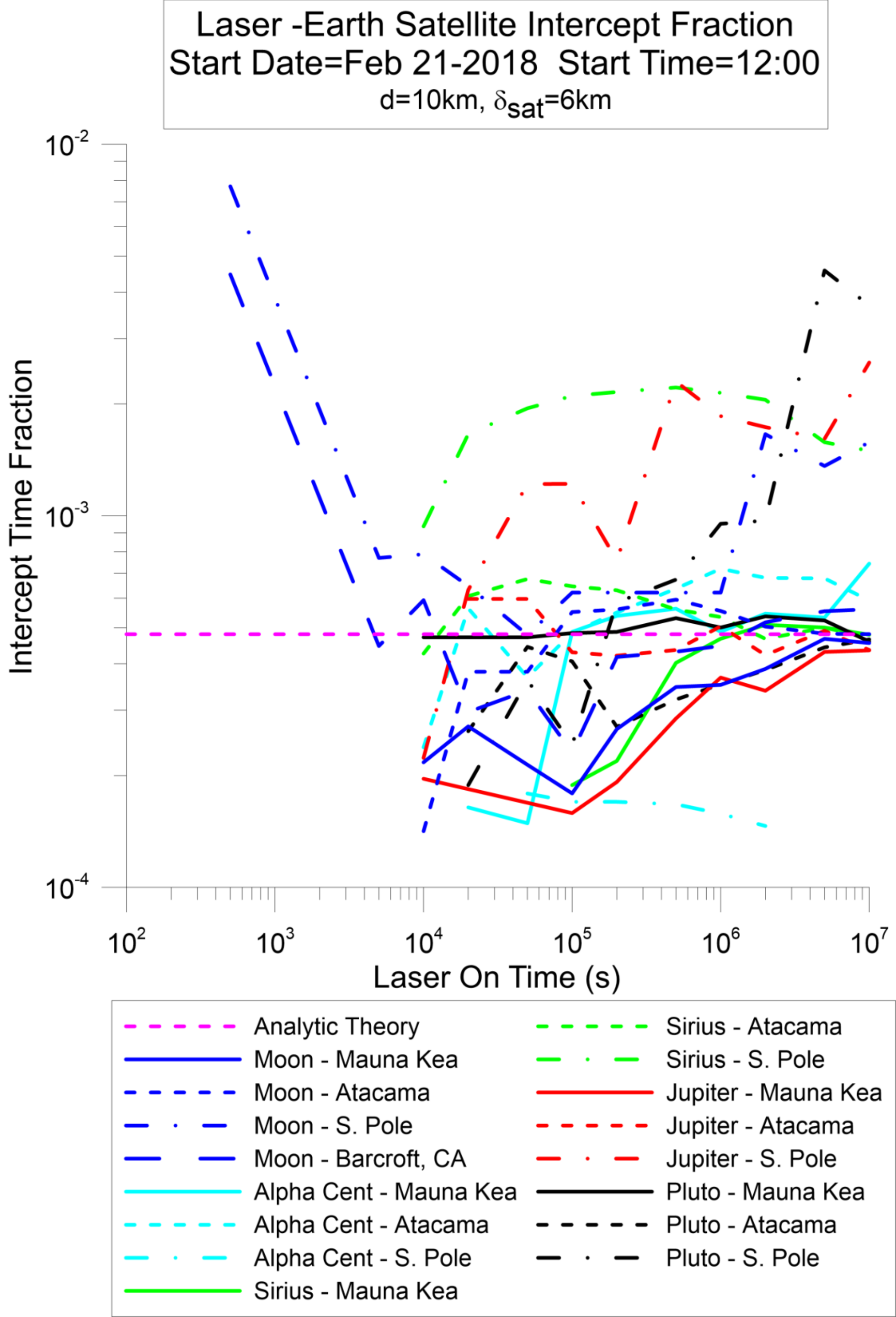




DE Intercept of Satellites – Aug 2018

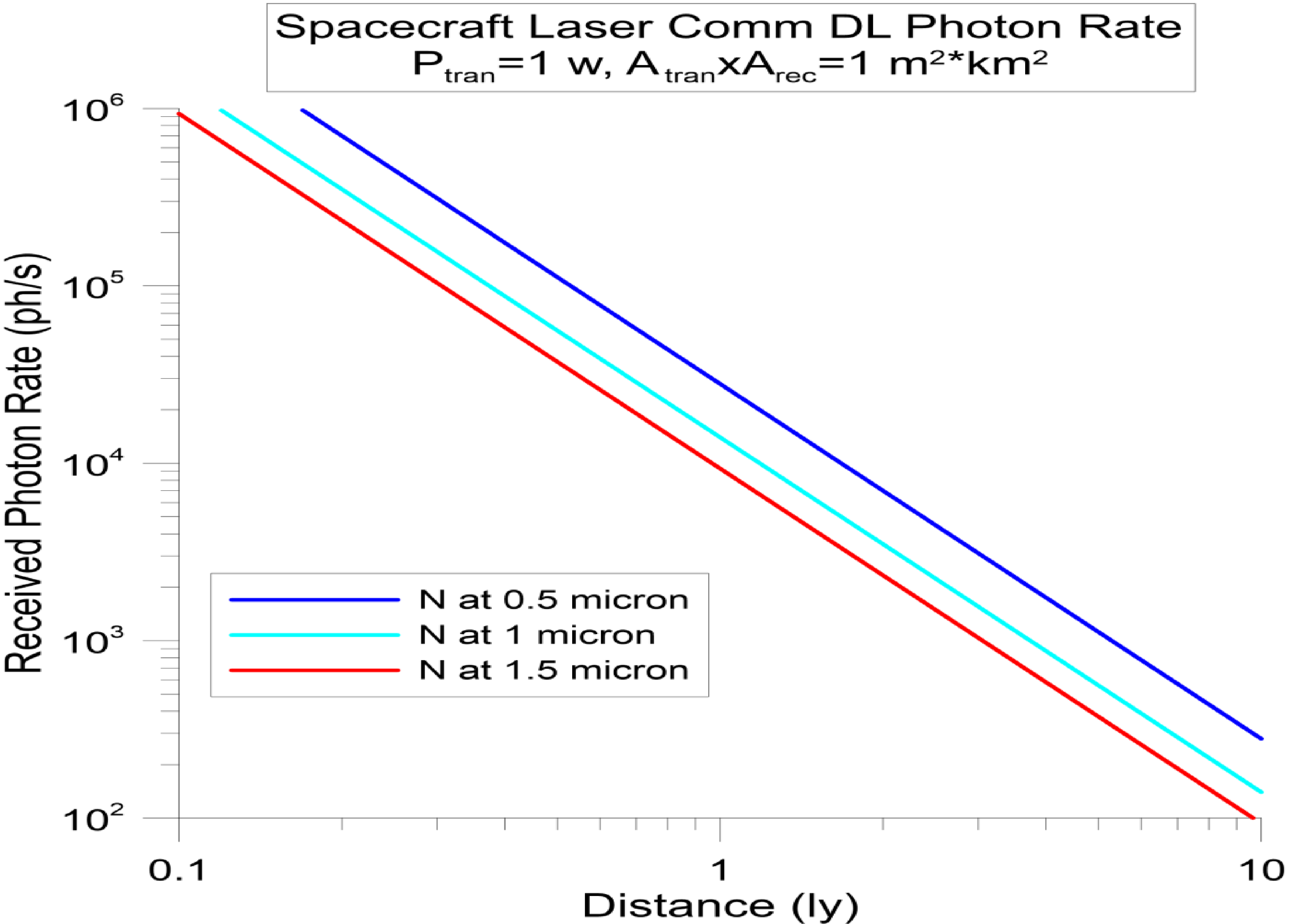
Realtime laser clearinghouse   arxiv.org/abs/1809.09196





Interstellar Communications a Challenge

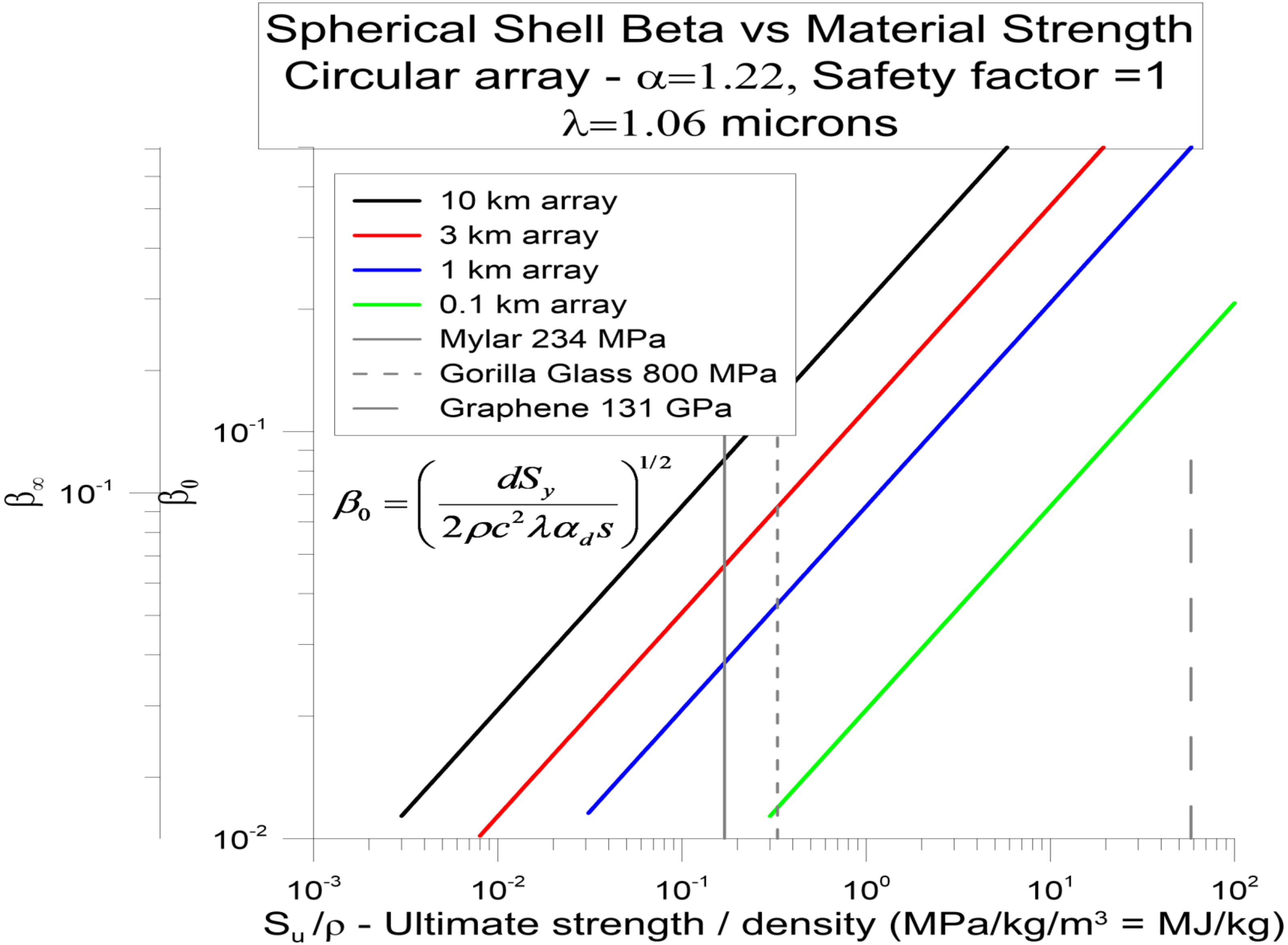
Interstellar Mission Communications – Low Background regime – http://arxiv.org/abs/1801.07778



Reflector Material Work

Theoretical and Experimental

→ Material Strength (indep of P) (d, ρ, λ) set a Fundamental Speed Limit – assumes $m_{ref} = m_0$

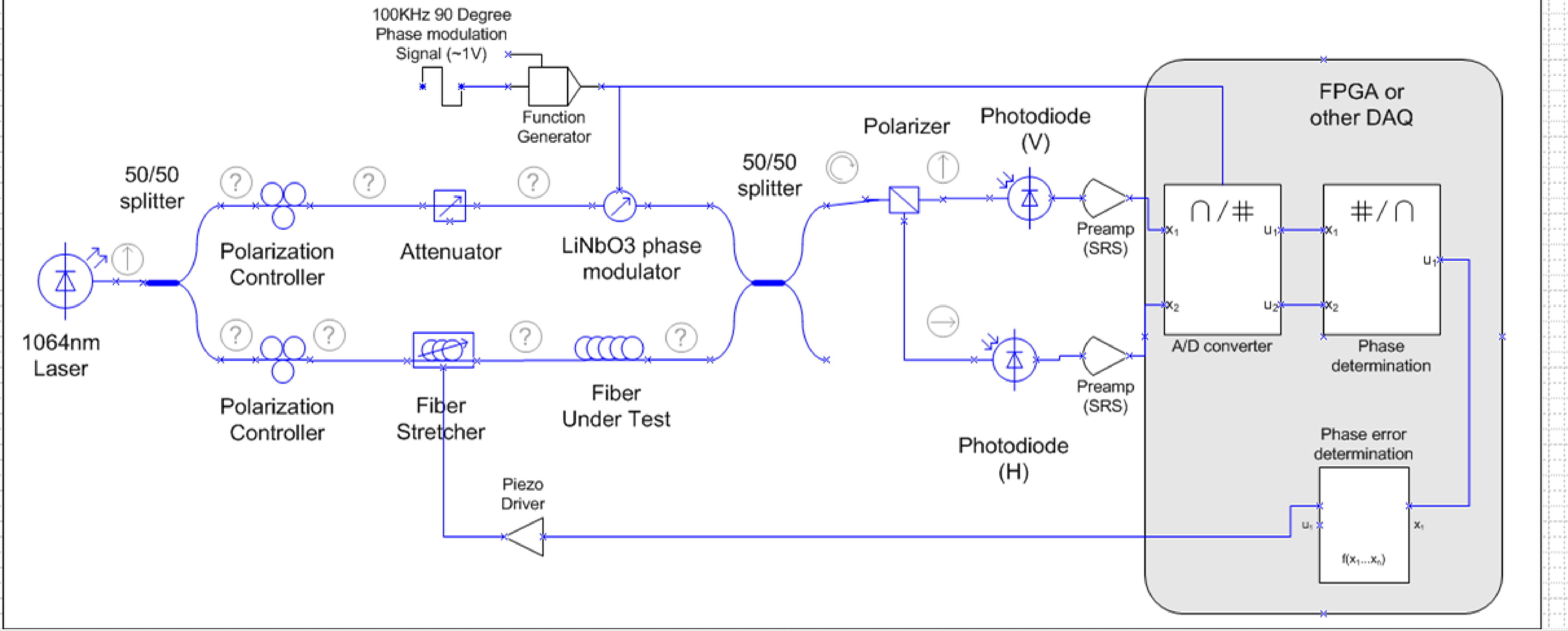


Test Chamber with 500 nm polymer film
S_u ~ 230 MPa

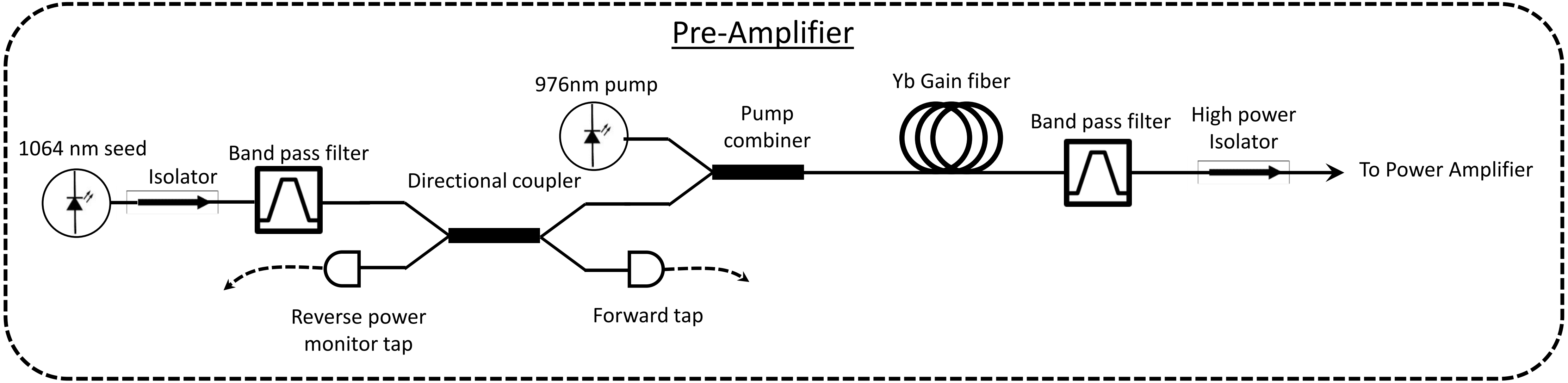
Laboratory Testbed
Long Coherence Length Amplifier Development

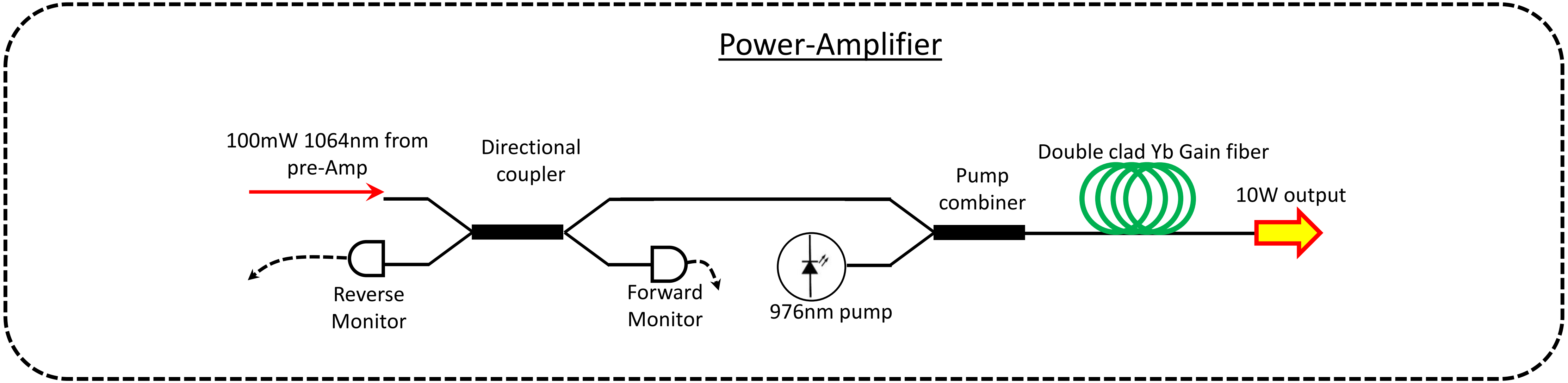
Long Baseline Experimental Setup

Mach Zehnder interferometer – 2 element array – 100 MS/S FPGA Data Acq I,Q

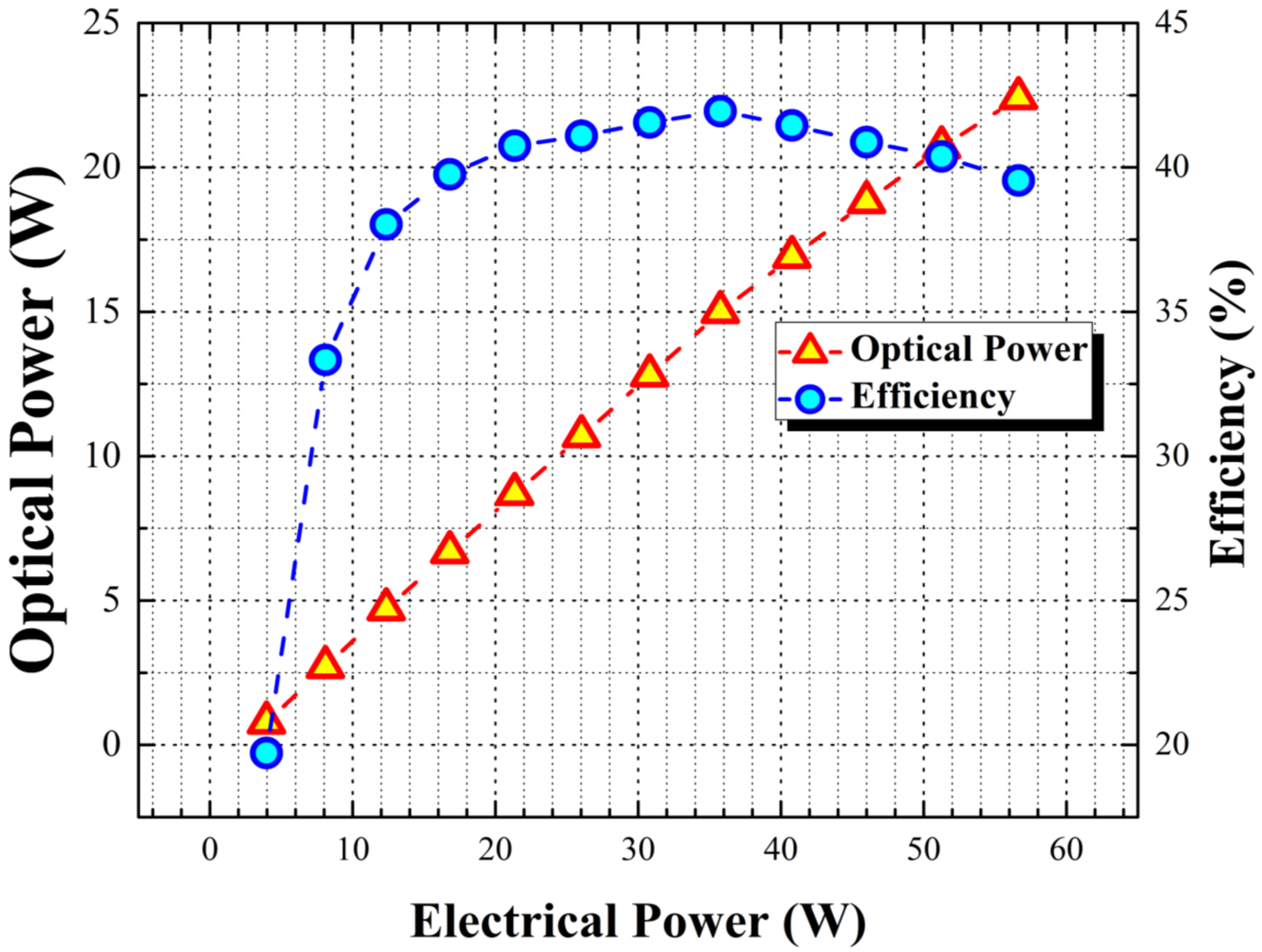


UCSB Long Coherence Length Fiber Amplifiers





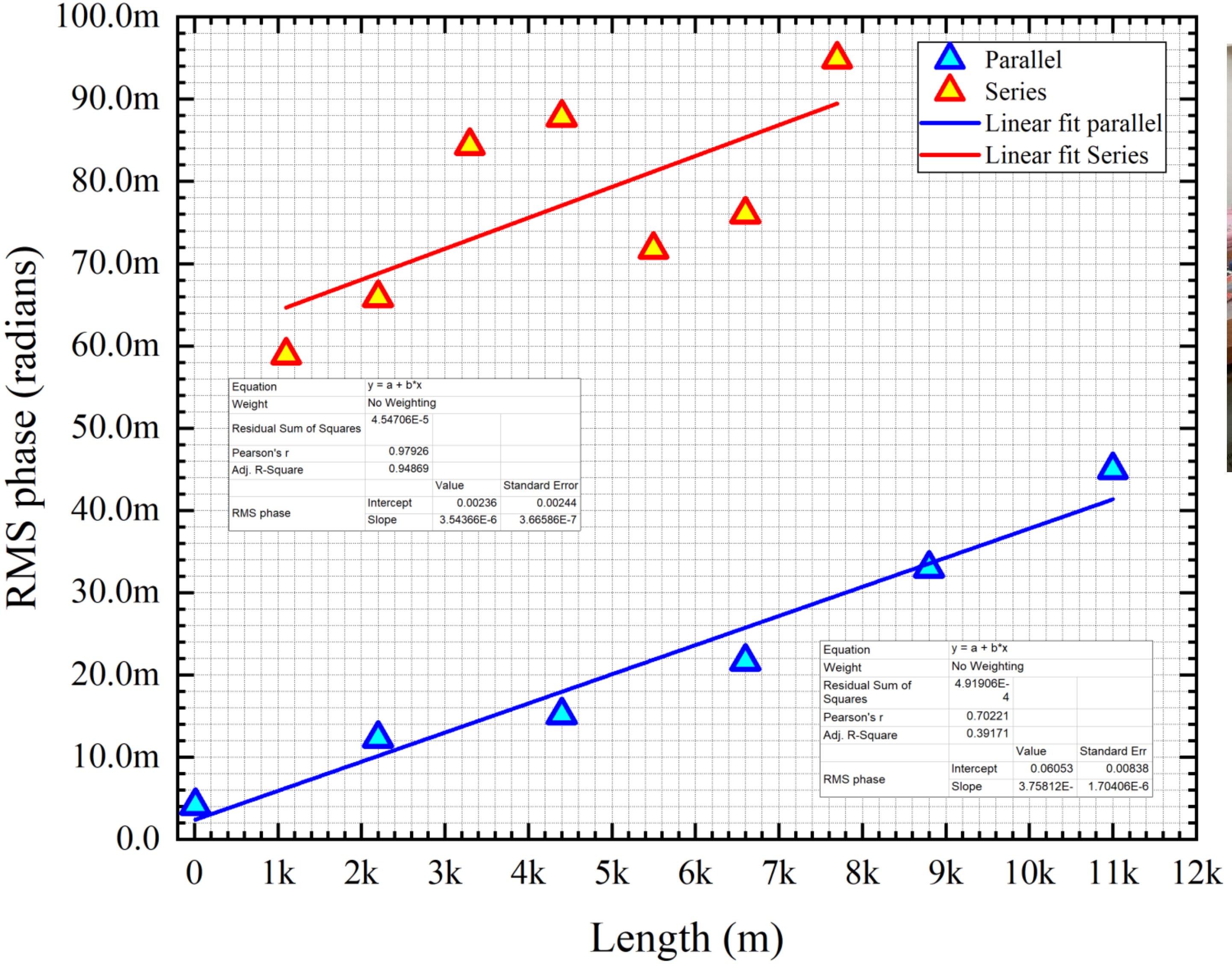
UCSB Yb High Eff Long Coherence Fiber Amplifier
42% wall plug efficiency - >30 km coherence length

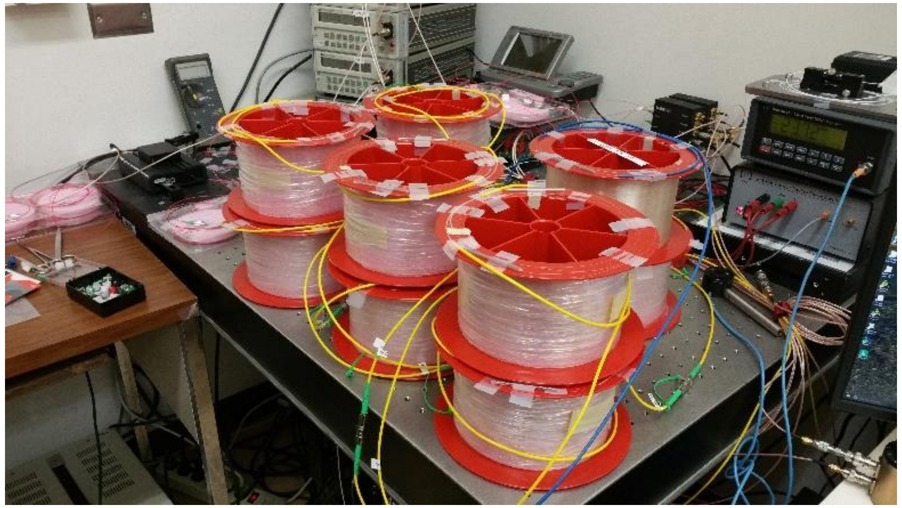


RMS Error vs Phased Array Diameter (Oct 2018 data)

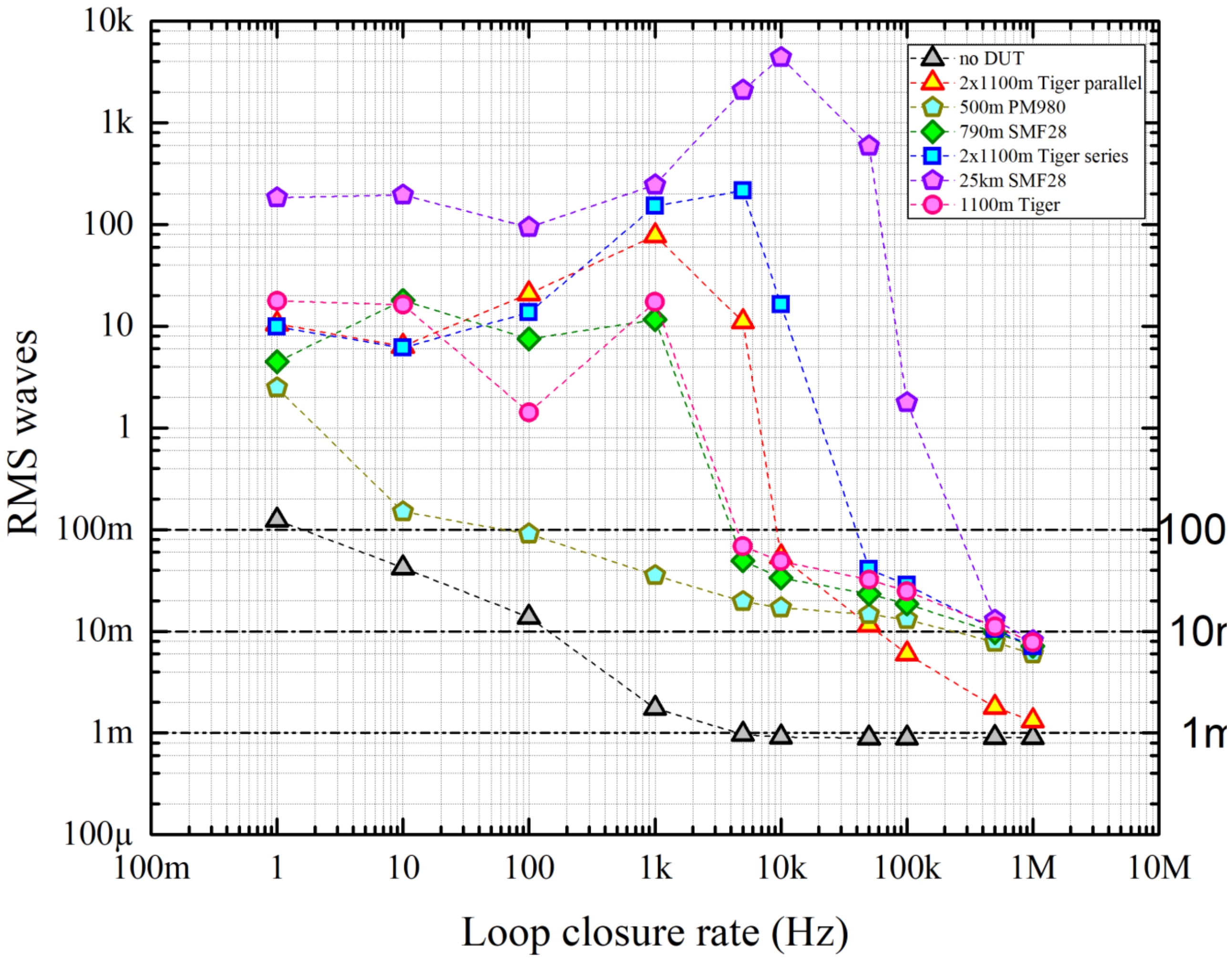
Divide RMS radians by 2 π to get RMS wave

Much better than we require (<λ/10) - achieved <λ/100 @ 11 km



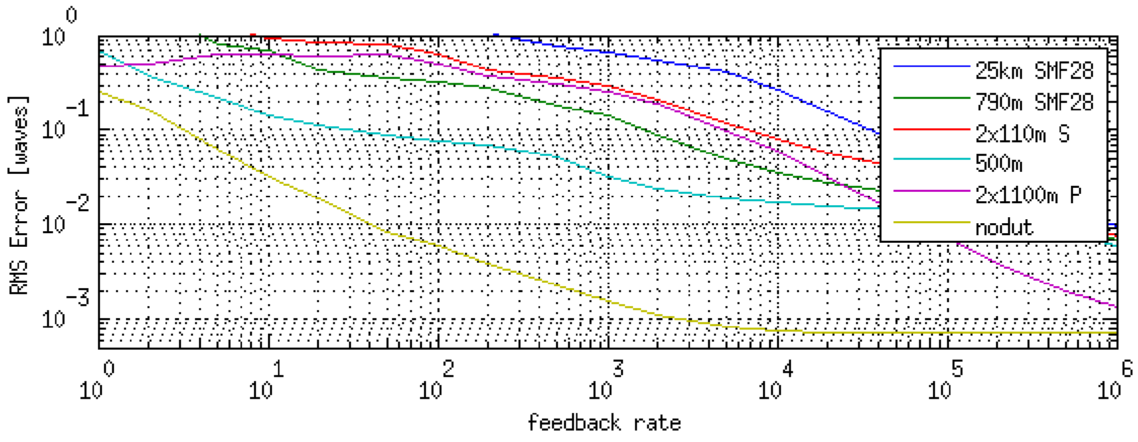


RMS vs Loop Closure Rate to 25 km Array - Data and Simulation Results –For multi km array need to lock >100 KHz for <1/10 wave



Simulation

- Start with measured unlocked phase vs time data
- Apply simulated hardware setup
    - Simple integral controller, with gain of 1 per tick, updating once per nth loop iteration
- Same plotting/analysis code



Long Term WORST CASE Outdoor Fiber Phase Noise Tests 2x 1.1 km

We would NEVER build a system like this - How well did we do?

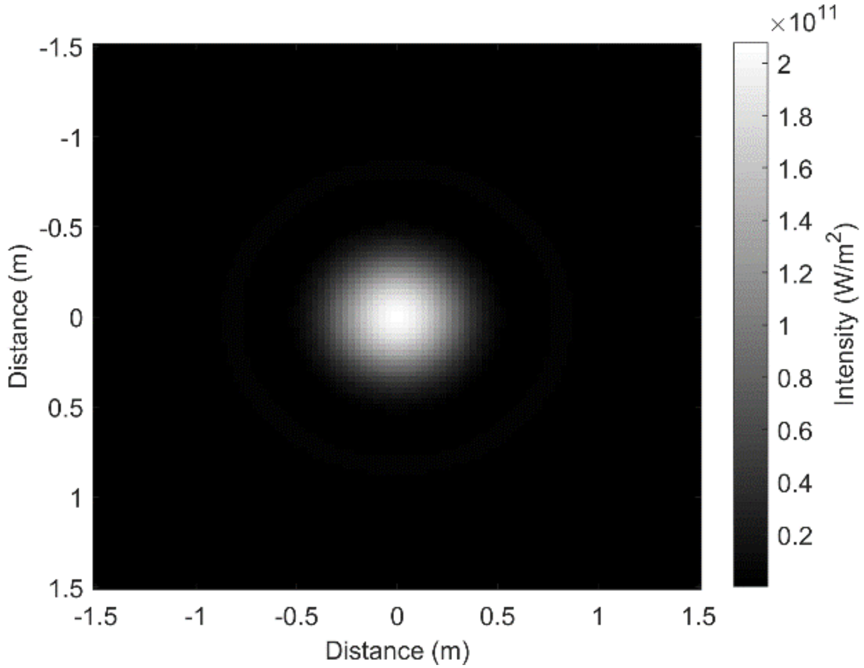
Answer : We did quite well ~ λ/100 - Except when it is raining hard/ high wind

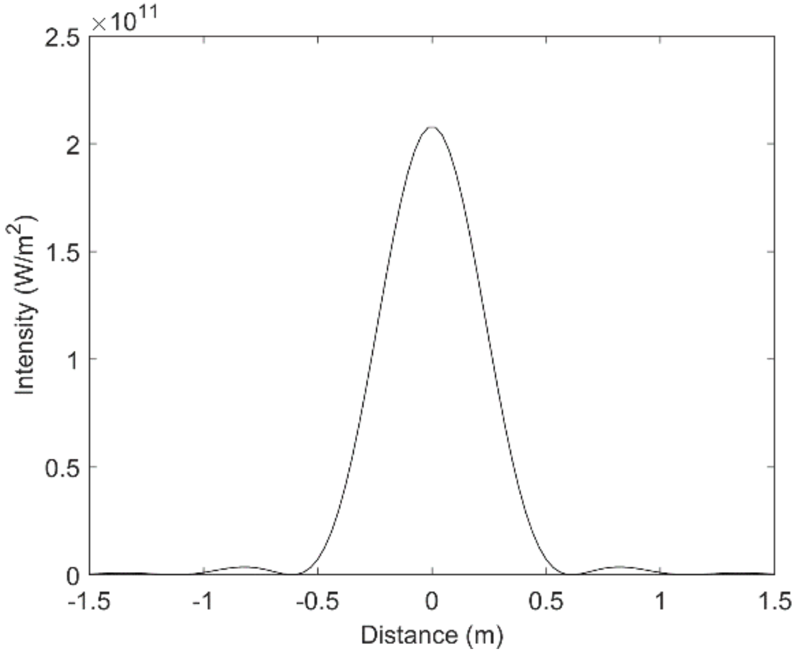
- Phase noise measured in various weather conditions. Day, night, light rain and thunderstorms.
- Main test questions:
  - What is the residual RMS phase noise when locked in the reverse direction (Beacon)?
  - Explore constraints when recording data at a lower sampling rate.
  - How bad can you be and still succeed?

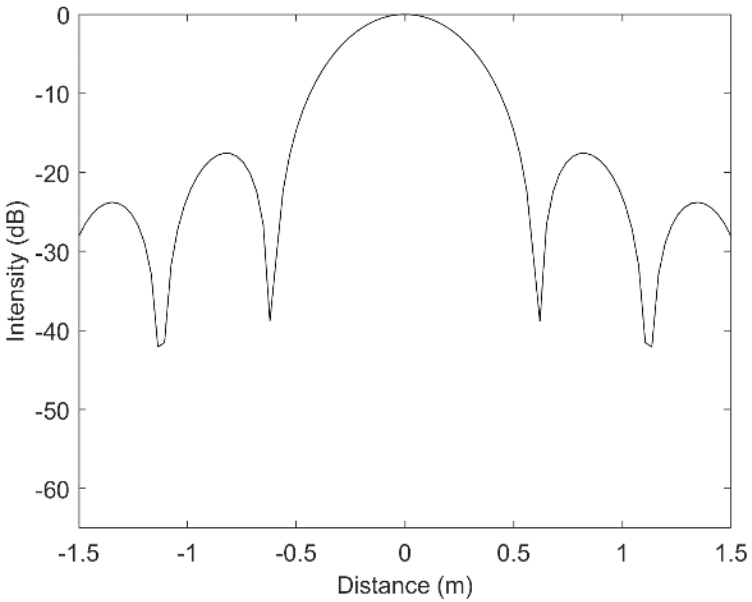
Beam Synthesis (GPU) Simulation – 10^{10} element array

UCSB

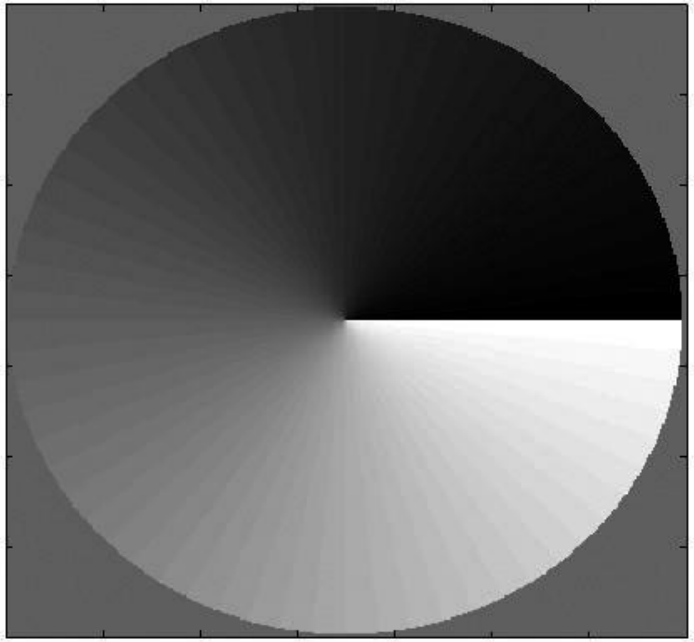
- Target: 5×10^9 m (~12 x lunar distance)
- 10 cm 10 w apertures hexagonally packed
- 10 km array at 100 GW – DDM interstellar case (1-10 km)
- Tranmit Aperture Flux = 1 KW/m^2
- Truncated Gaussian emitters
- Get ~ 60% encircled power in main beam – good enough



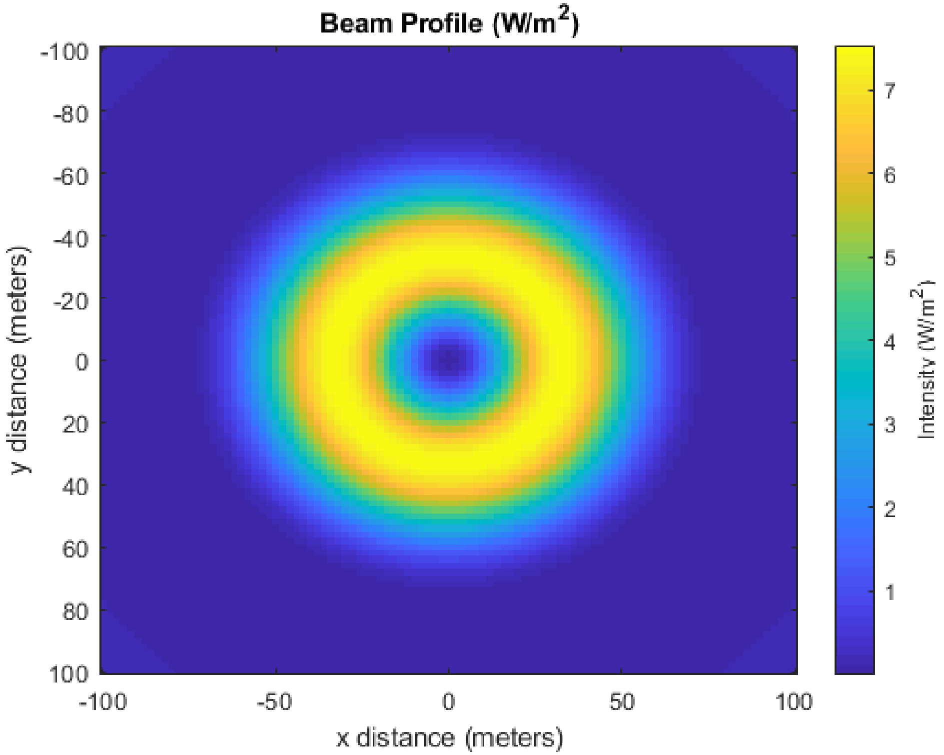


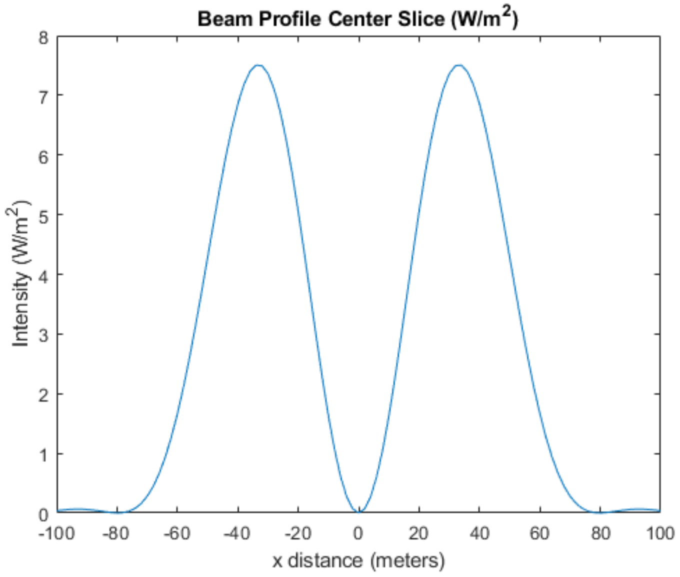


Beam Synthesis (GPU) Simulation – Example of Beam Shaping
Helical Phase to Passively Trap Spacecraft



Phase



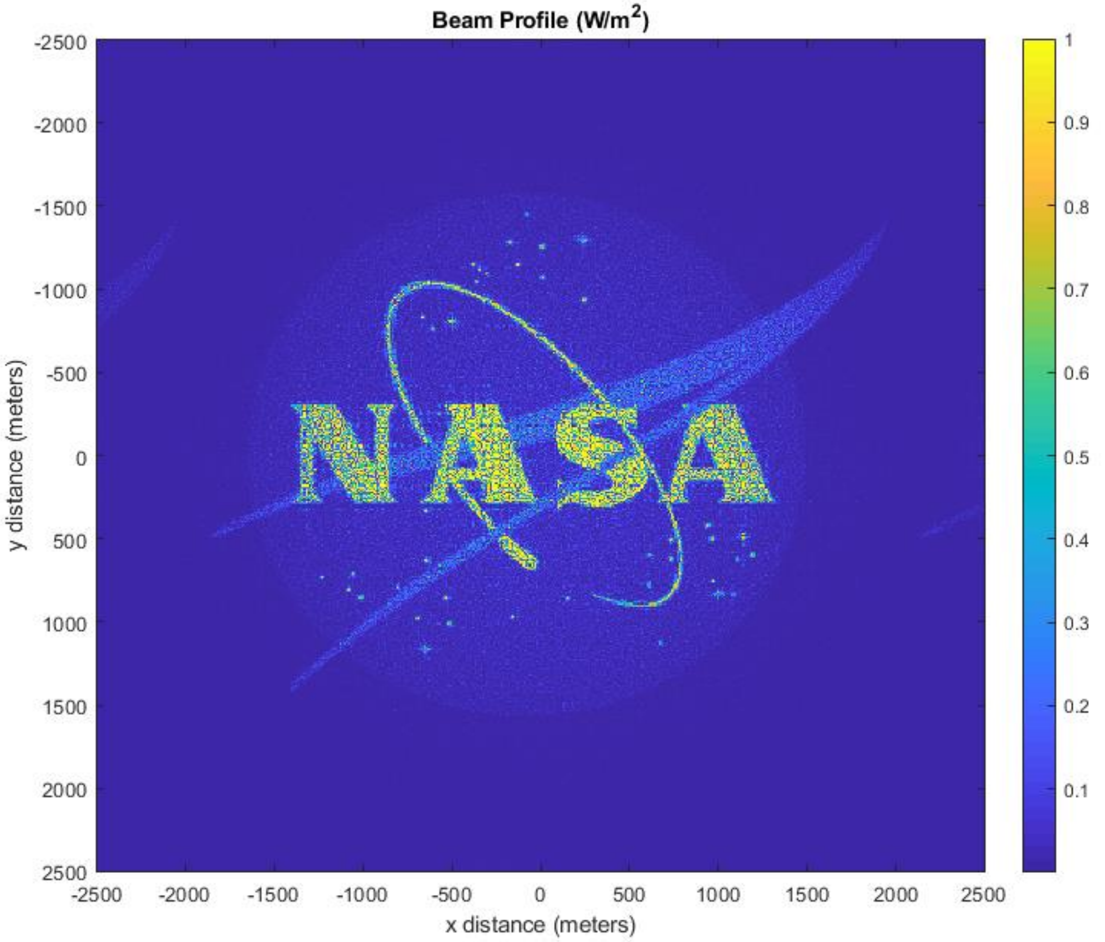


- **Target: $4x10^8$ m**
- **10 m diameter circular array – 10^4 Sub apertures – 100 KW**
- **10 cm 10 w sub-apertures hexagonally packed**
- **~ 60% of transmitted power is in main (donut) beam**
- **Flux scales linearly with power and quadratically with array diameter**
  - **Ex: 30m array with 500 KW would yield peak flux ~ 3 kw/m^2**

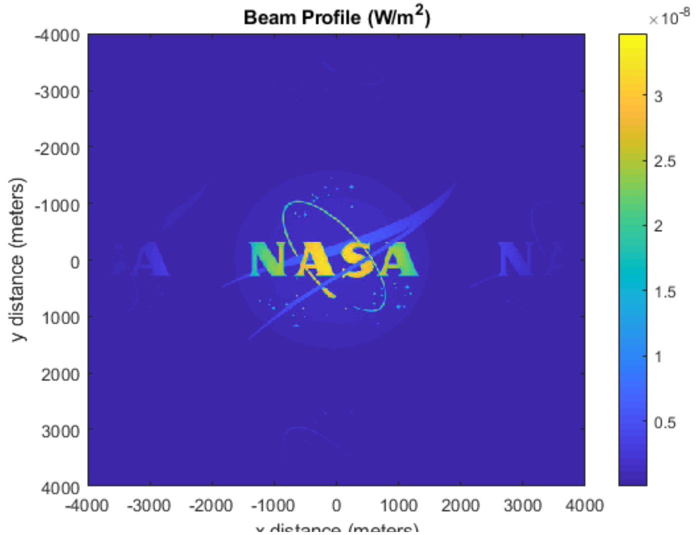
Beam Synthesis (GPU) Simulation – Beam Shaping

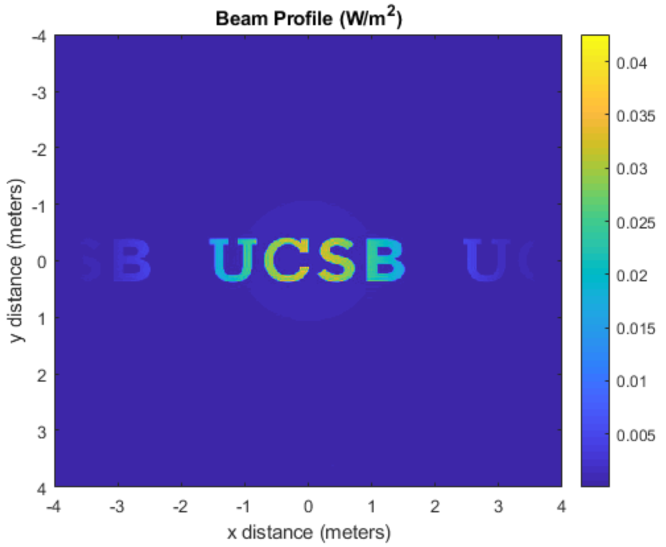
Fourier Optics for Any Desired Beam Profile

Phase Only Control



Amplitude and Phase Control

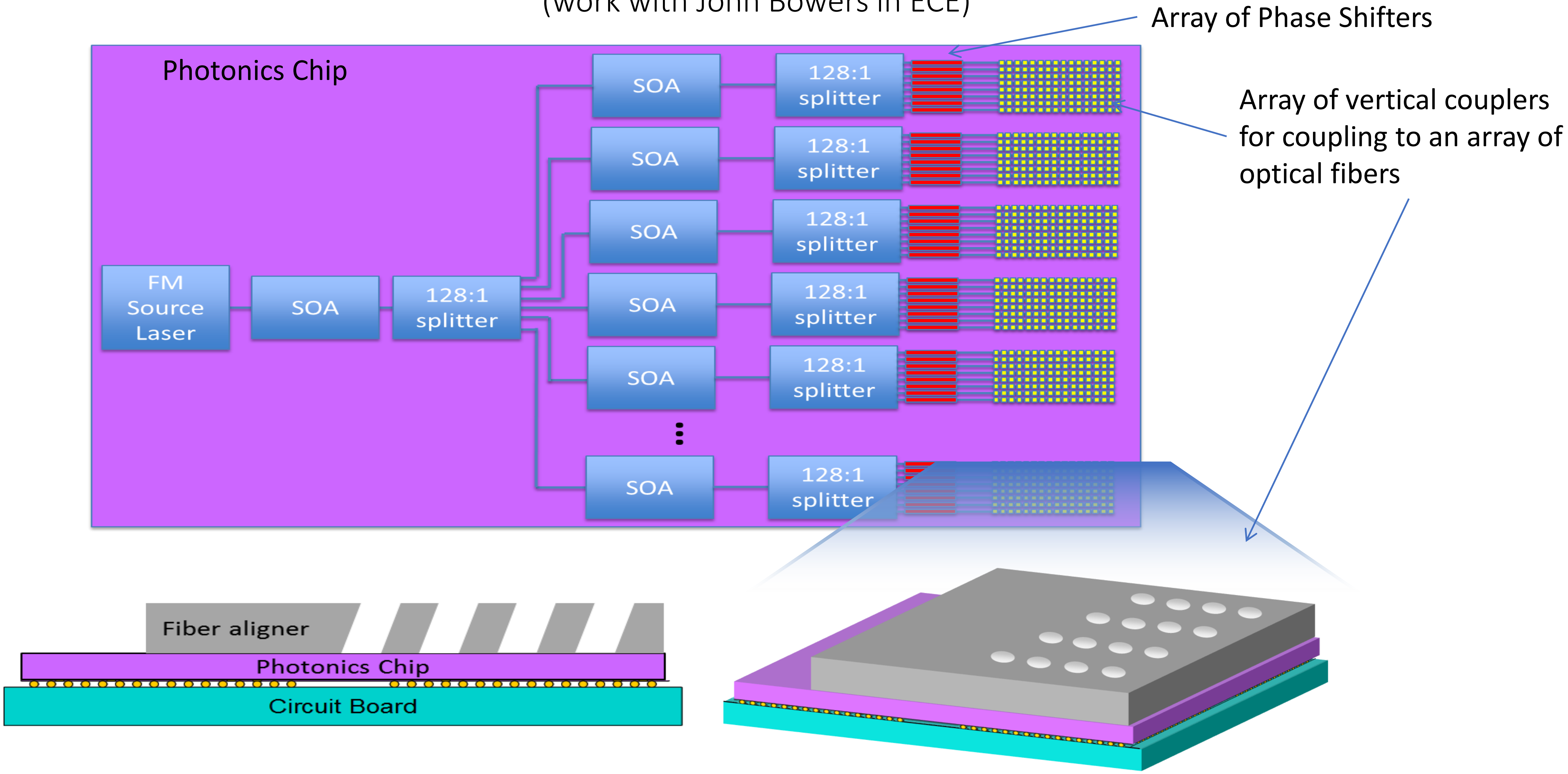




UCSB

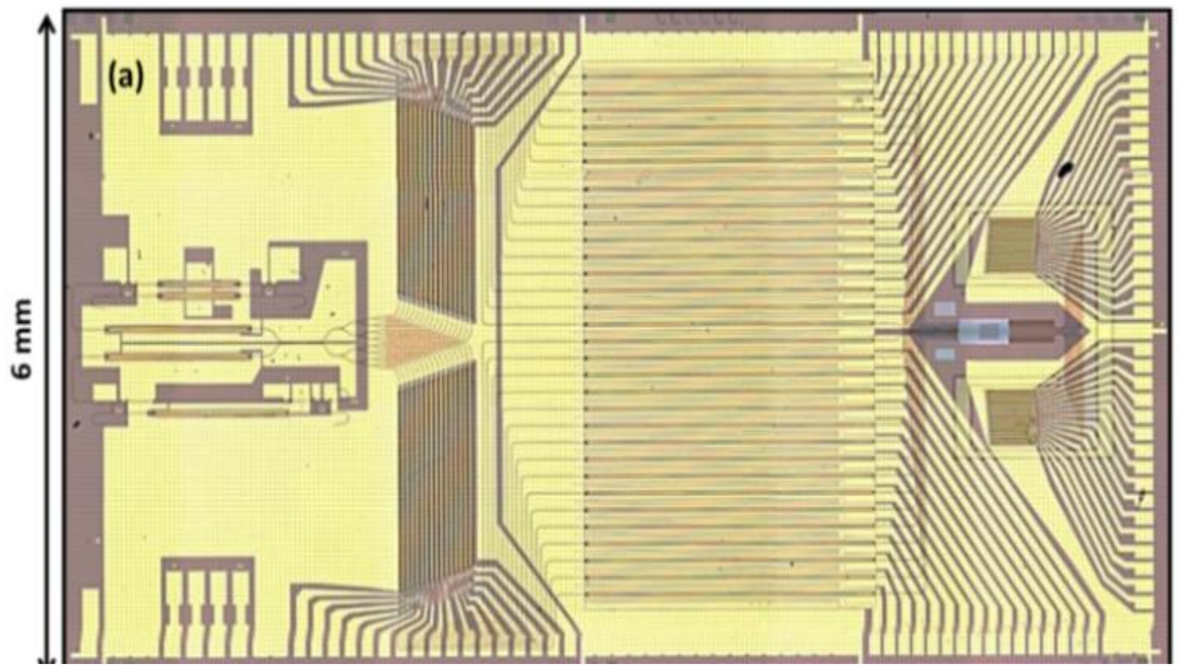
The path forward – Photonic Integration
Integrated Wafer Scale Photonics for DE Side

(work with John Bowers in ECE)



Integrated Photonics Wafer Example

Path to Low Cost Mass Production of DE Systems

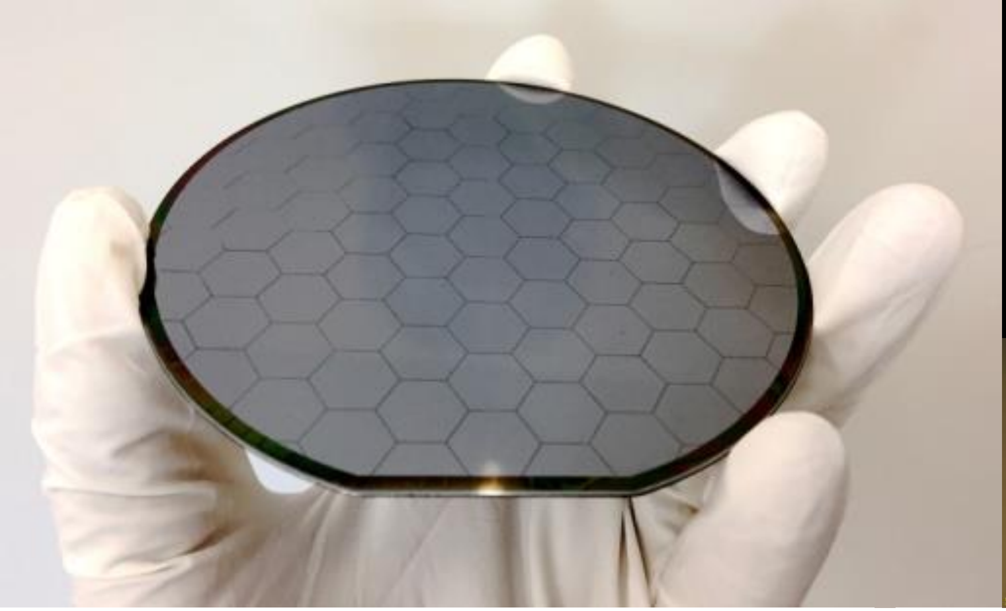


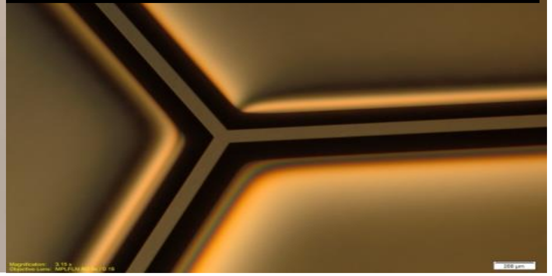
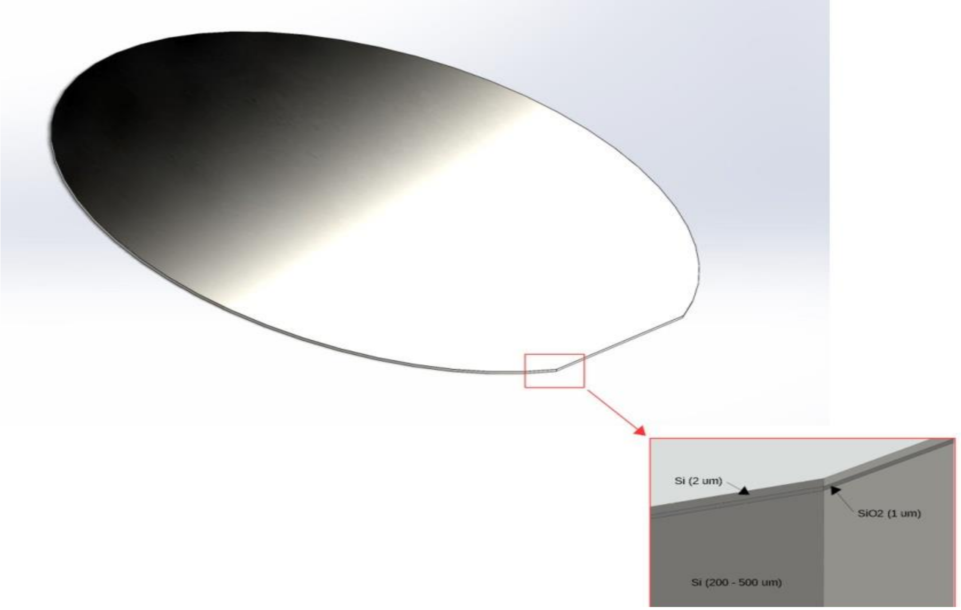
Integrated 32 channel beam steering incorporating 4 lasers, 32 amplifiers and 32 phase shifters operating at 1550nm, designed and fabricated at UCSB – ECE – Bowers - AIM.

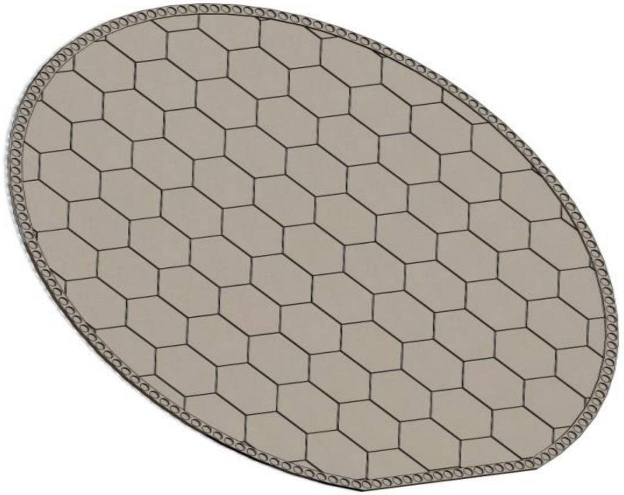
Current Wafer Scale Spacecraft (WSS)+CubeSat Launch

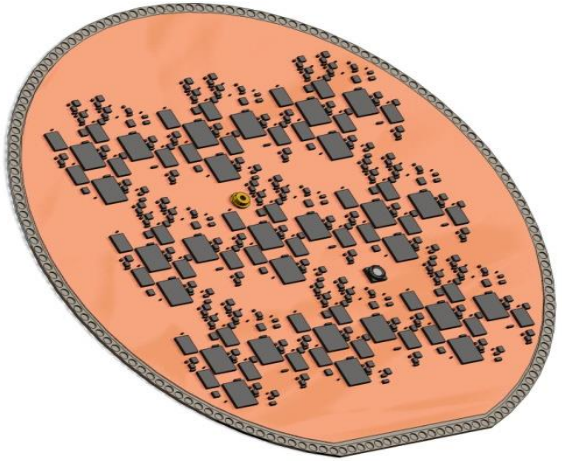
UCSB Nanofab DRIE Etching Si and Ti Wafers – 10^{12} transistors

SOI Etch stop – 2 micron membrane – hexcel back – 0.5g - 100 mm diam - hybridize



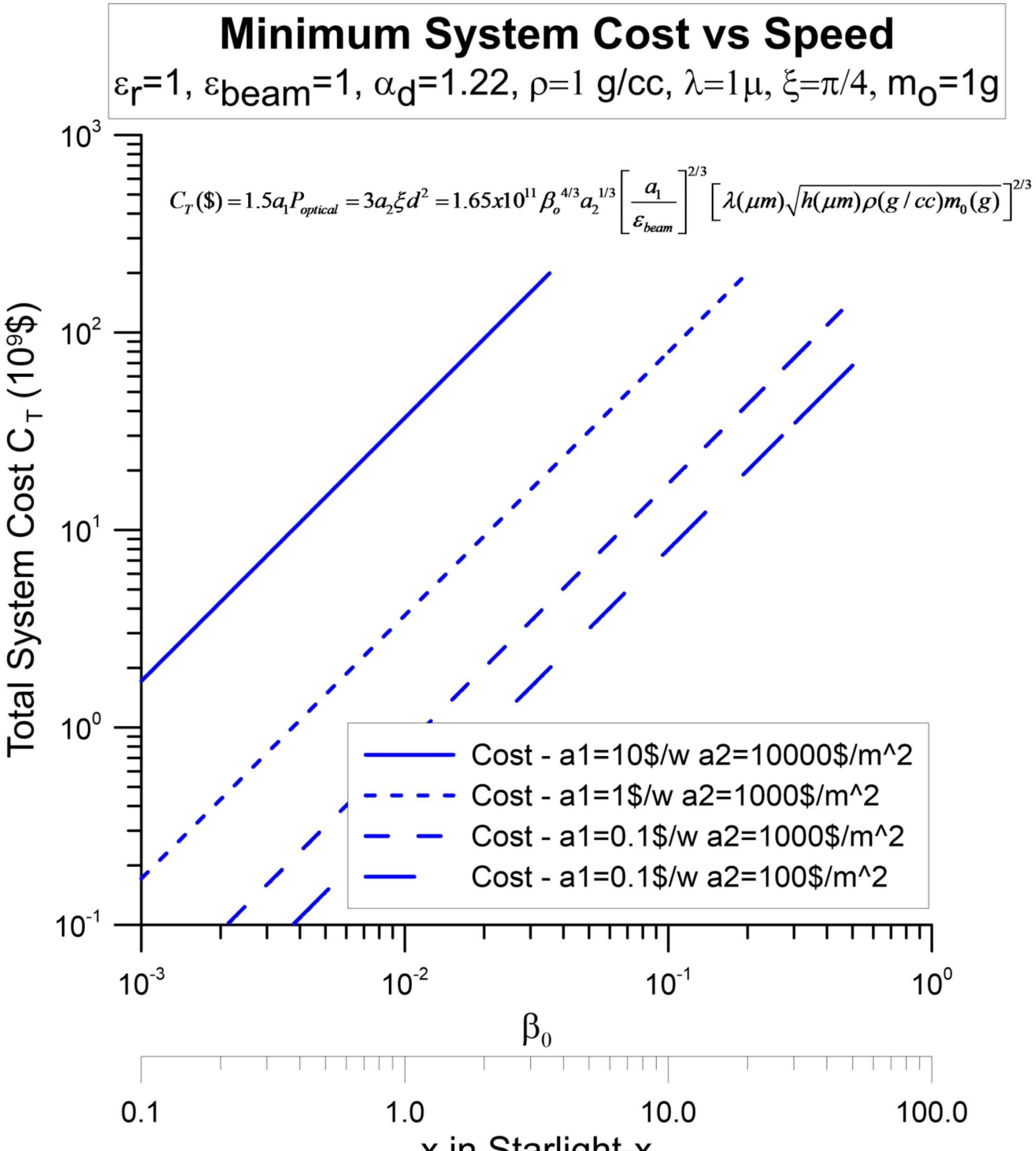



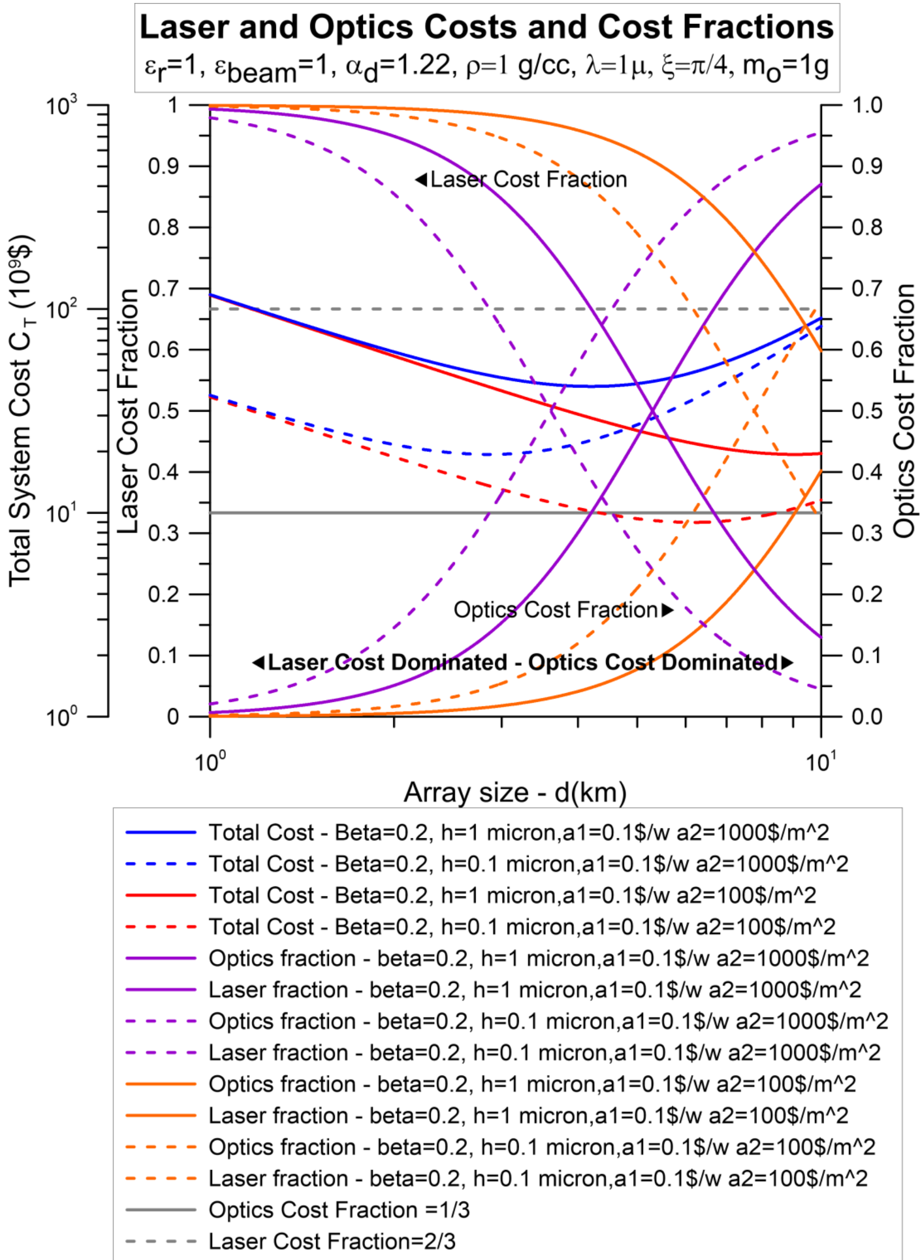




Fundamental Cost Analysis – Direct Drive – Optics and Photonics

For reference current terrestrial Si Solar PV is ~ $0.3/w and $60/m^2





Large Scale Solar is of Comparable Size
→30 years ago this was not deemed viable←

Topaz Solar – California – 0.55 GW – 5 km size

In Calif - 11 GW total installed – 2.5 GW last year

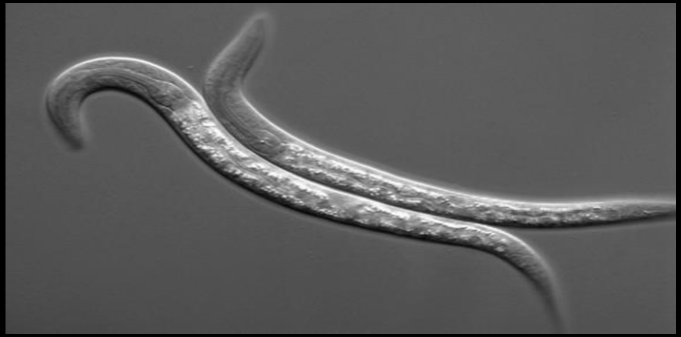
Kurnool Ultra Mega Solar Park, India – 1 GW

Propagation of Life

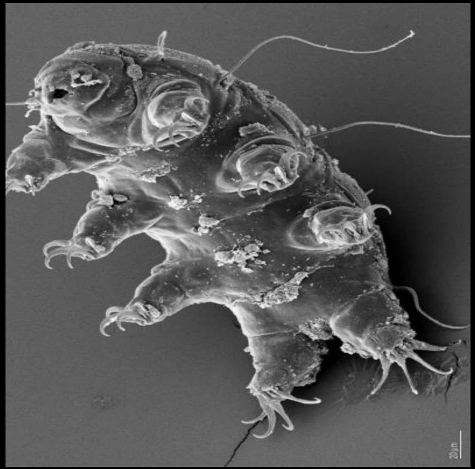
Humans are High Maintenance – Not Well Suited for Interstellar

The future of Interstellar Humanity?

We are developing the capability to test whether terrestrial life, as we know it, can exist in interstellar space by preparing small life forms – C. elegans and rad resistant Tardigrades - which are ideal candidates to be our first interstellar travellers. They will be asleep during the cruise phase and awakened at various points along the way. "Real Passengers"

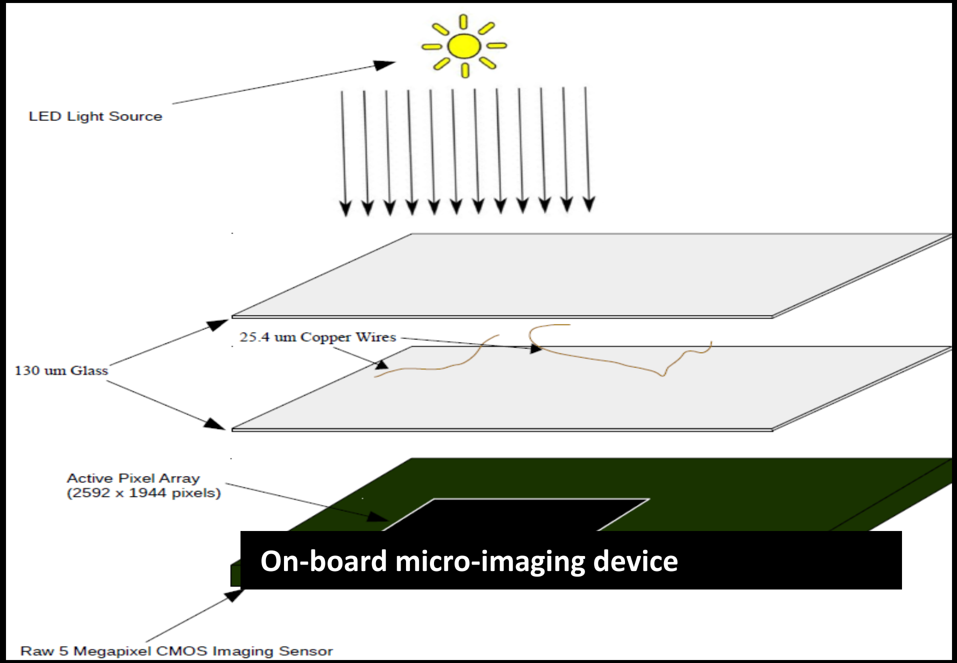


Nematode: C. elegans

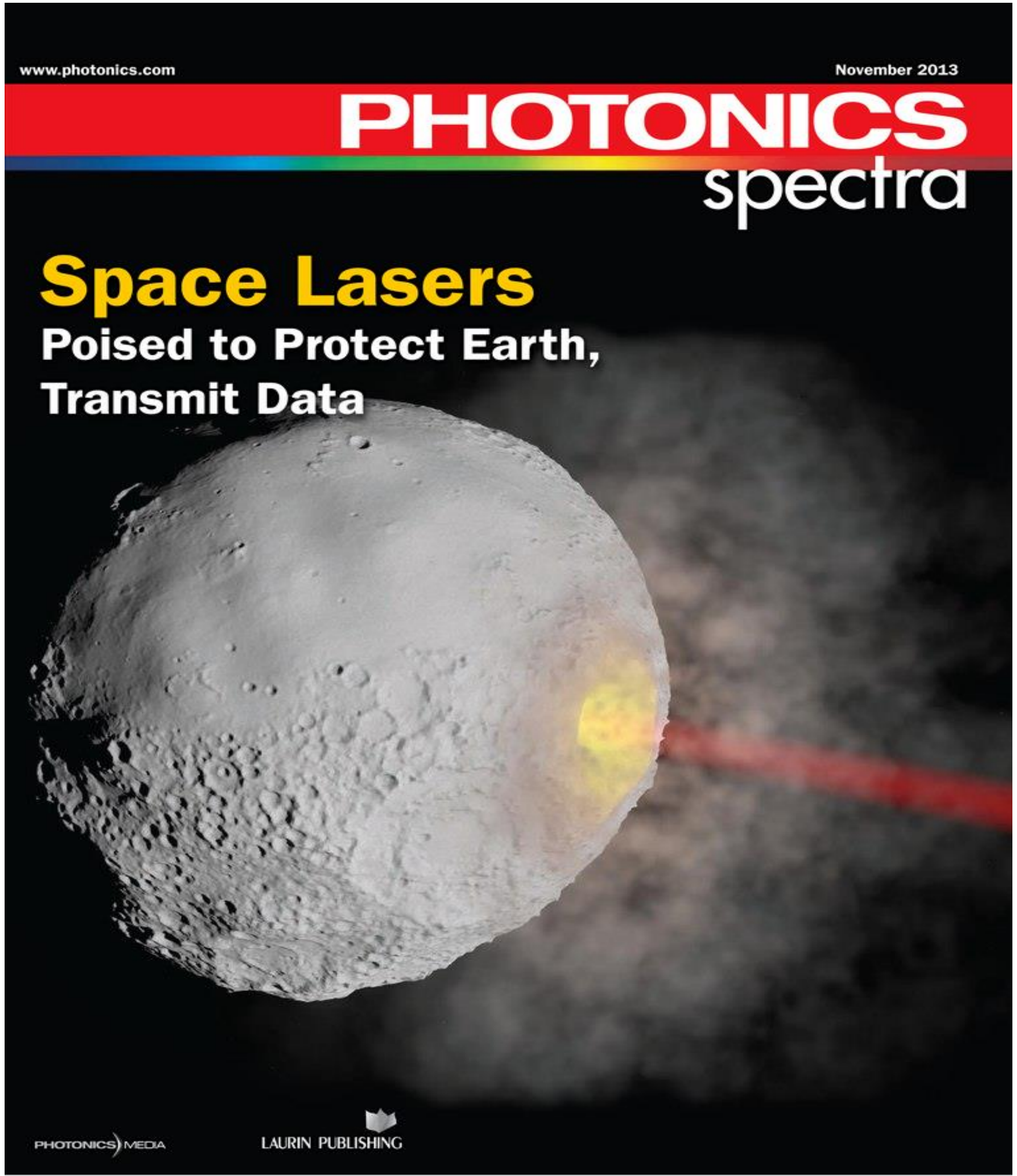


Tardigrade: H. dujardini

See www.deepspace.ucsb.edu/et



DE Planetary Defense and Space Debris Mitigation



Challenges – MANY!

- Phased array – phase coherence over km – looks good so far!
- If ground based – atmospheric perturbation
- Economic issues – need 100x reduction (<15 years)
- Material issues for sail and spacecraft
- Radiation damage – extreme front edge damage
- **Communications – laser comm for interstellar - see our papers**
- Policy issues – 10^6 x tactical DE power
- Not for the faint of heart
    - **→Long term commitment and R&D needed←**
    - **THIS IS THE BIGGEST PROBLEM**

Amortization – Over Multiple Missions and Capabilities

- **This is NOT like Apollo – been there - done that**
- **One DE driver enables radical transformation**
- Interstellar
    - Sub gram to kg level
- Rapid interplanetary travel – **any mass →more=slower – ion engine option**
    - Amazon "same day" to Mars
    - Mars Human Shuttle capability – ping pong ~ 30 days
- Full planetary defense
- Asteroid capture and mining
- Asteroid composition
- Power beaming to distant Spacecraft
- Scalable and modular → long term options for even larger systems

Conclusions

- **DE is the path forward to propulsion transformation**
- **Path ultra high speed spacecraft – IDM allows large mass in solar system**
- **Only known way to interstellar flight - DDM**
- **MANY applications – Mol Comp, PD, LIDAR, laser comm, space debris**
- **Long range power beaming applications including ultra high I_{sp} ion engines**
- **→Will heavily leverage photonics and electronics**
- **→Leverages exponential growth**
- **Logical progression - basic understanding of tall polls**
- **→Path to the full system requires photonic integration for economics**
- Many challenges both technical and economic
- **Requires a dedicated program over a long period**
- **We have begun – encourage collaboration in this long term effort**

UC Santa Barbara DE Team – 2016 and 2018

Inspiring the next generation to dream

→>100 students in DE lab over past 5 years

→DE is an excellent outreach program

→Engages the public imagination