Efficient Direct Conversion of Sunlight to Coherent Light at High Average Power in Space

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Outline

Goal: Optical Power Infrastructure in Earth-moon space

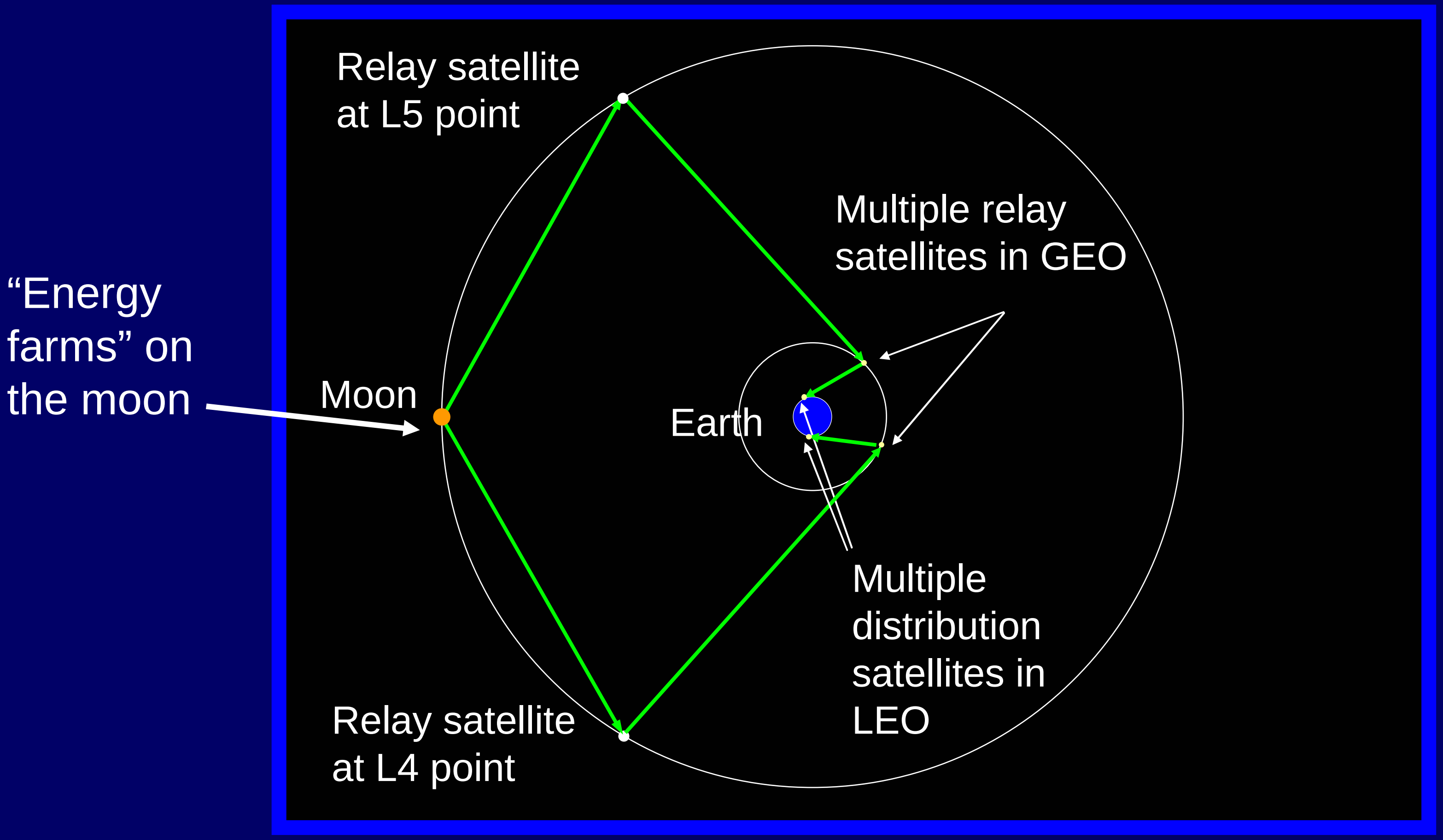
Methodology: Solar pumped solid state laser power oscillators most likely located primarily on the lunar surface combined with relay mirrors at L4 and L5 LaGrangian points

Results: Find an Optical Power Infrastructure providing needed power virtually anywhere virtually anytime is allowed by fundamental physical laws

Conclusions: Direct attention to maturation of four technical advances for transforming sunlight to coherent light that are required. Could be accomplished in time frame of exploration program.

<u>Goal:</u> Optical Power Infrastructure in Earth-moon space

> 100 kW power virtually <u>anywhere</u> and virtually <u>anytime</u> in Earth-moon space

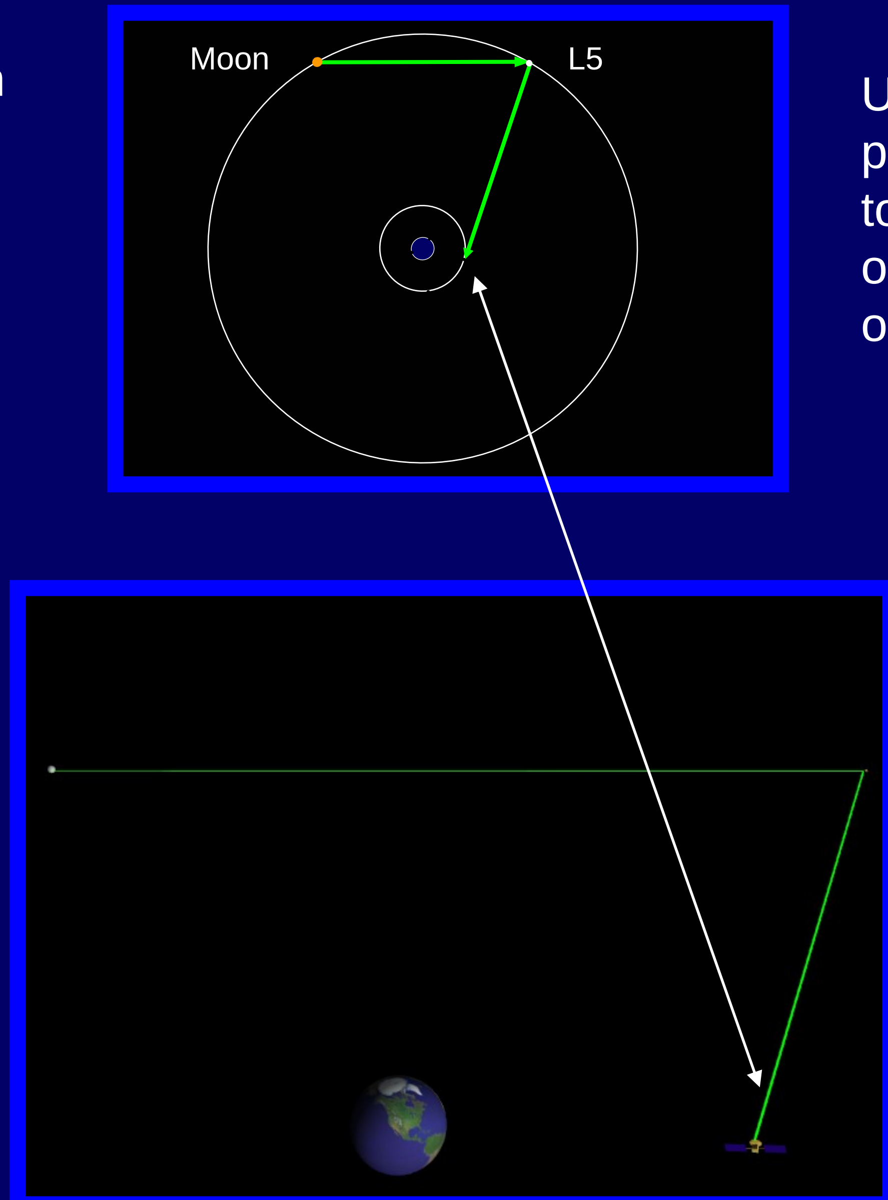


Require high average power high coherence power laser oscillators

Schematic and image of optical power delivery

Supply power from lunar surface to spacecraft near Earth

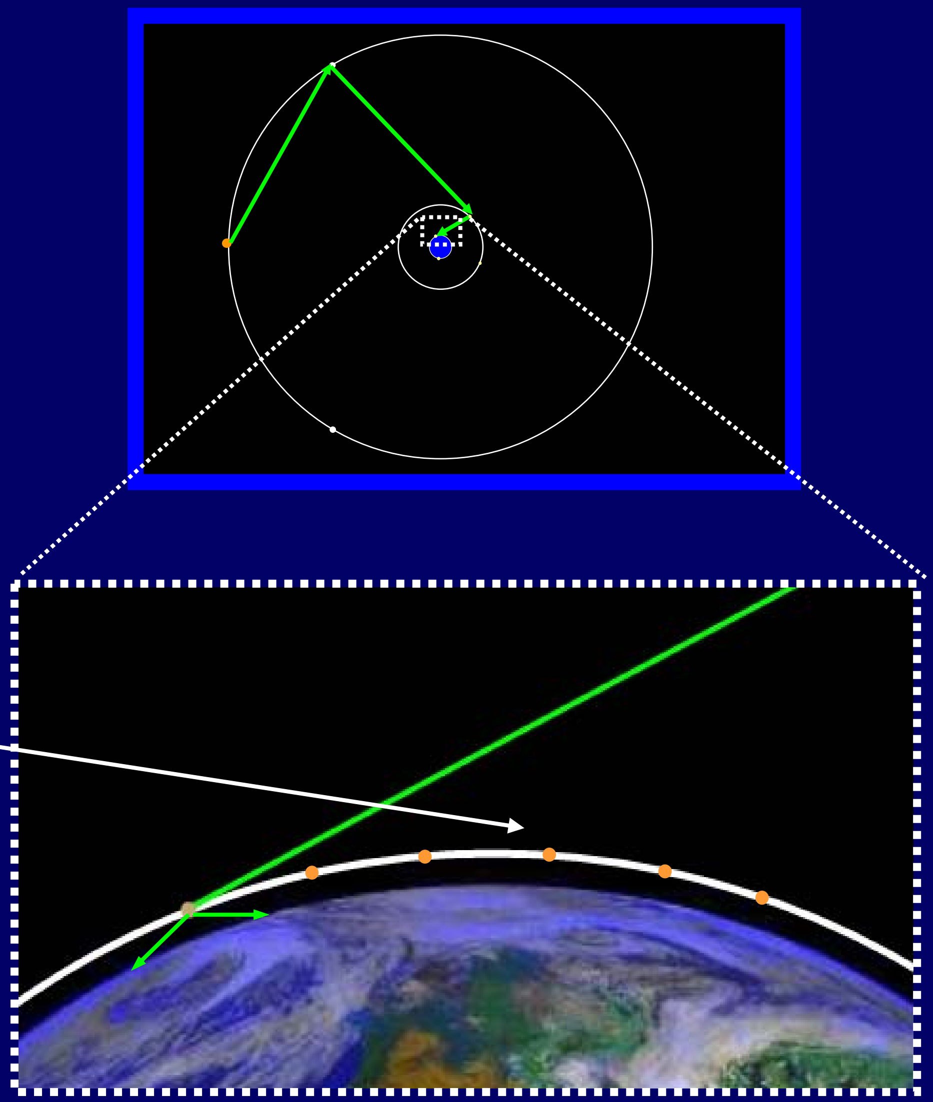
Use of LaGrangian points provides access to regions that might otherwise be obstructed by Earth



Optical beams would normally not be visible in space

Image of optical power being beamed to spacecraft near Earth

Schematic and image of distribution of optical power to satellites in low Earth orbit and then to Earth’s atmosphere

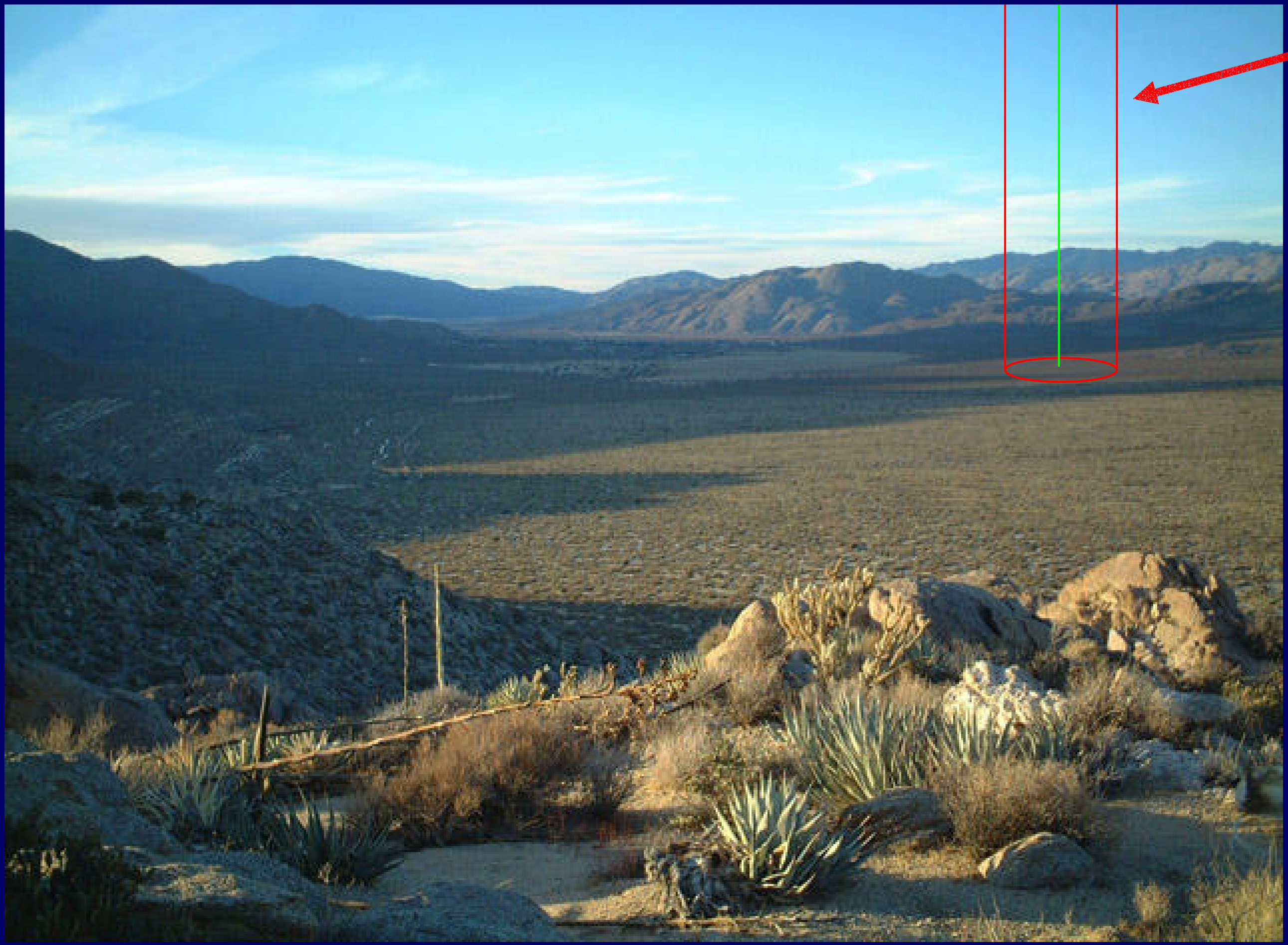


Non-military
vs. military use

Array of
remotely
powered
economical
small satellites
in LEO

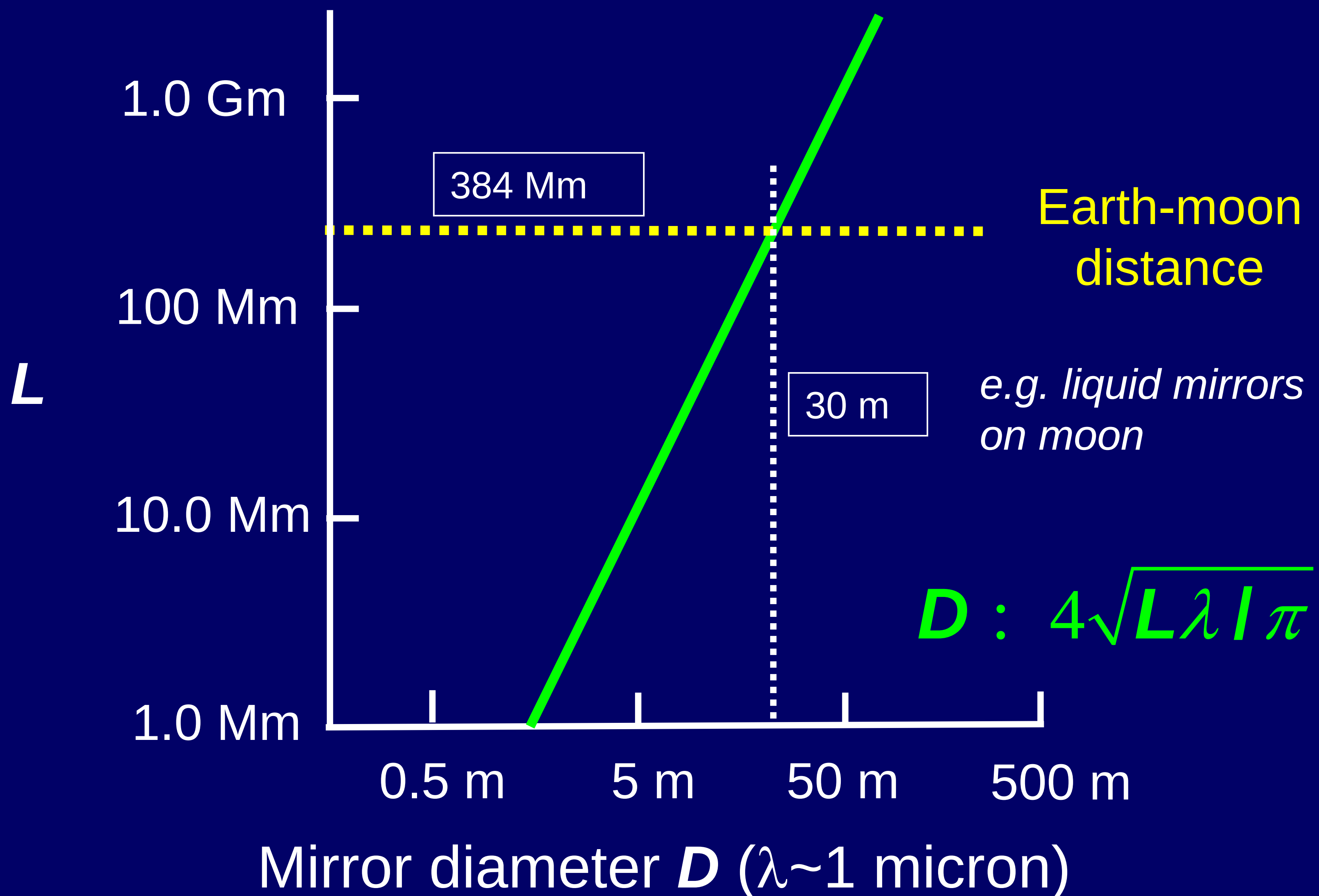
e.g.,
atmospheric
monitoring

Delivery of coherent power safely to Earth from space



Safety beam at low intensity surrounds power beam

Propagation distance vs. beam radius



Initial Findings

- Billions of terawatts of continuously renewed clean solar power are available in Earth-moon space as sunlight

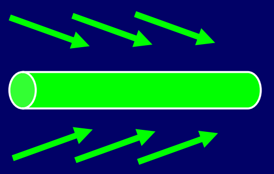
- Sunlight cannot be usefully redistributed by linear optical systems

- Optical power in the form of coherent light (as lowest order Gaussian modes of free space) can be distributed virtually anytime virtually anywhere in Earth-moon space

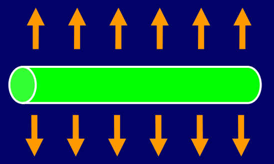
The principal need is to transform sunlight into coherent light at high average power at reasonable efficiency in space

Transforming sunlight into coherent light at high average power in space requires four technical advances

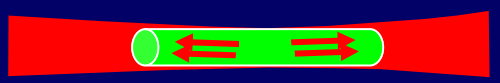
1. Concentrate solar pump power to the saturation intensity of a useful laser transition in a gain volume approximating the lowest order Gaussian mode of a near confocal resonator



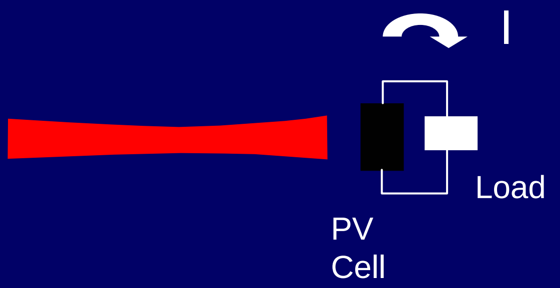
2. Remove waste heat from the gain volume in a manner that avoids unacceptable thermally induced optical distortion and stress



3. Transfer the solar pump power efficiently and selectively into the lowest order Gaussian mode of a near confocal resonator

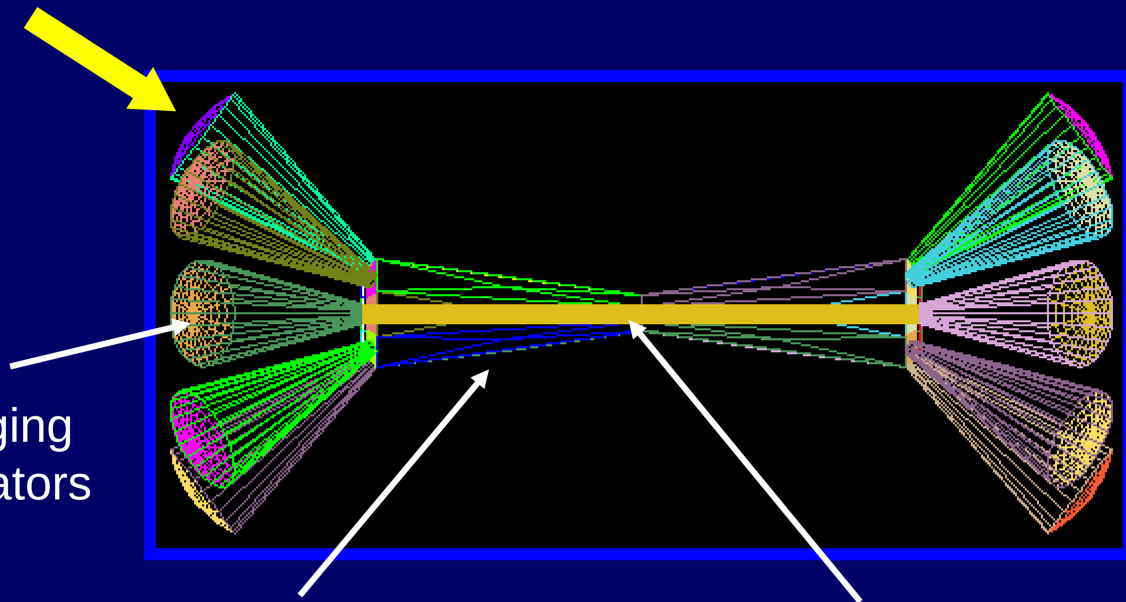


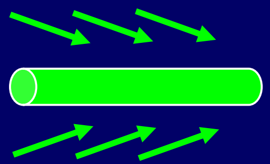
4. Transform temporally and spatially coherent light beamed of Earth-moon distances at high efficiency, e.g. > 90%, into alternative, e.g. electrical power



#1: Concentrate needed solar pump power in required volume at ~ saturation intensity of laser transition, e.g. 10 kW/cm^2

Spectrally filtered sunlight





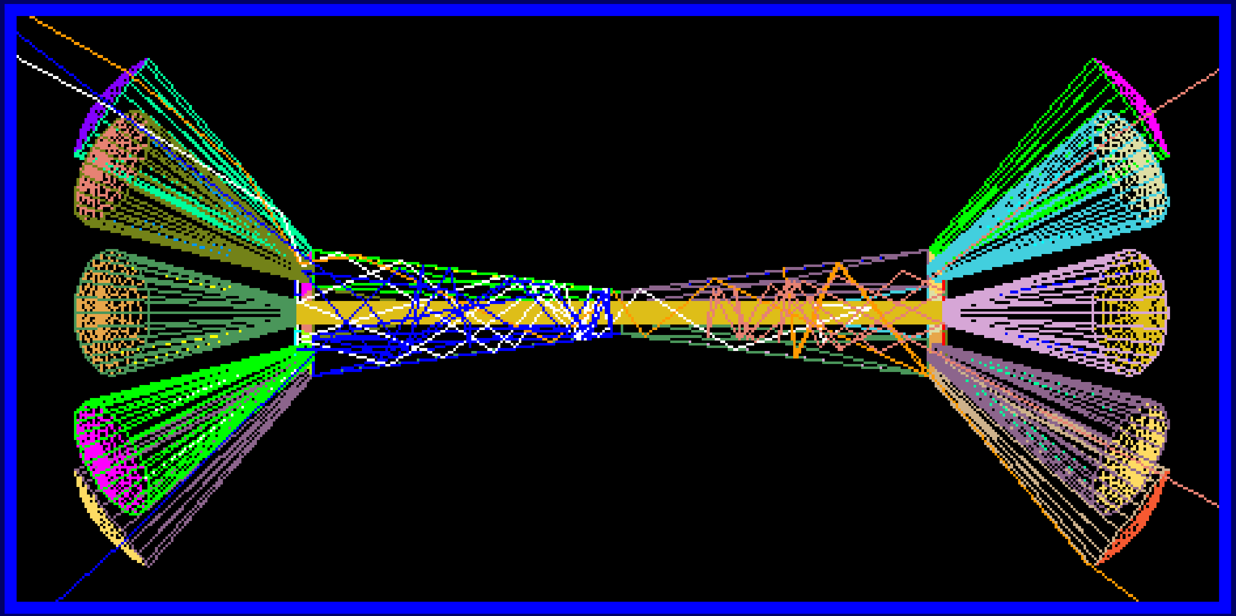
Non-imaging concentrators

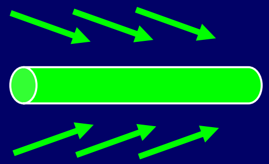
Tapered duct

Core doped with laser material

Design determined by optimizing concentration of pump power in most favorable geometry and dimensions using Advanced Systems Analysis Program (ASAP) (Hubble)

Selective absorption in central gain material doped region



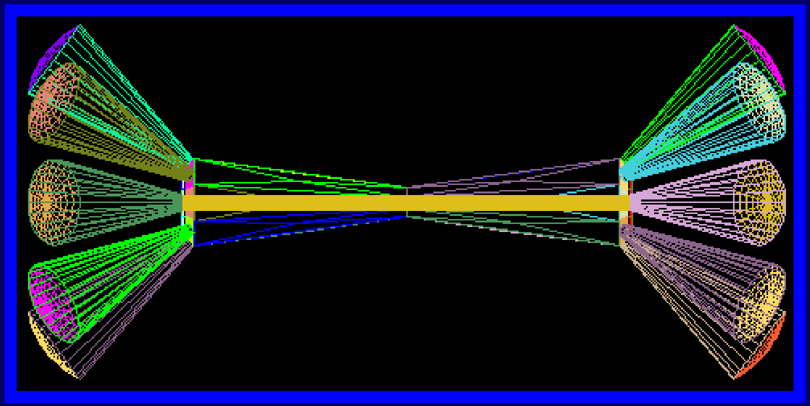


Rays "bounce" in zigzag pattern, but are eventually absorbed with high probability in the gain material

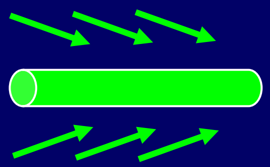
Achieve <u>integrated</u> pump intensity <u>substantially larger</u> than intensity at the surface of the Sun

“Multiple suns” point of view

16 non-imaging concentrators each concentrate sunlight to maximum intensity at a plane

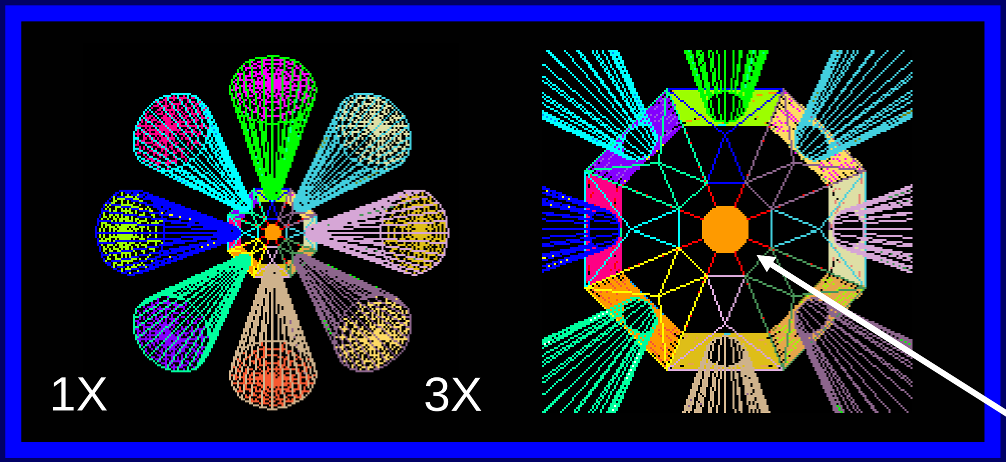


Each concentrator contributes power to gain medium comparable to conventional concentrator



3m length yields ~ 100 kW

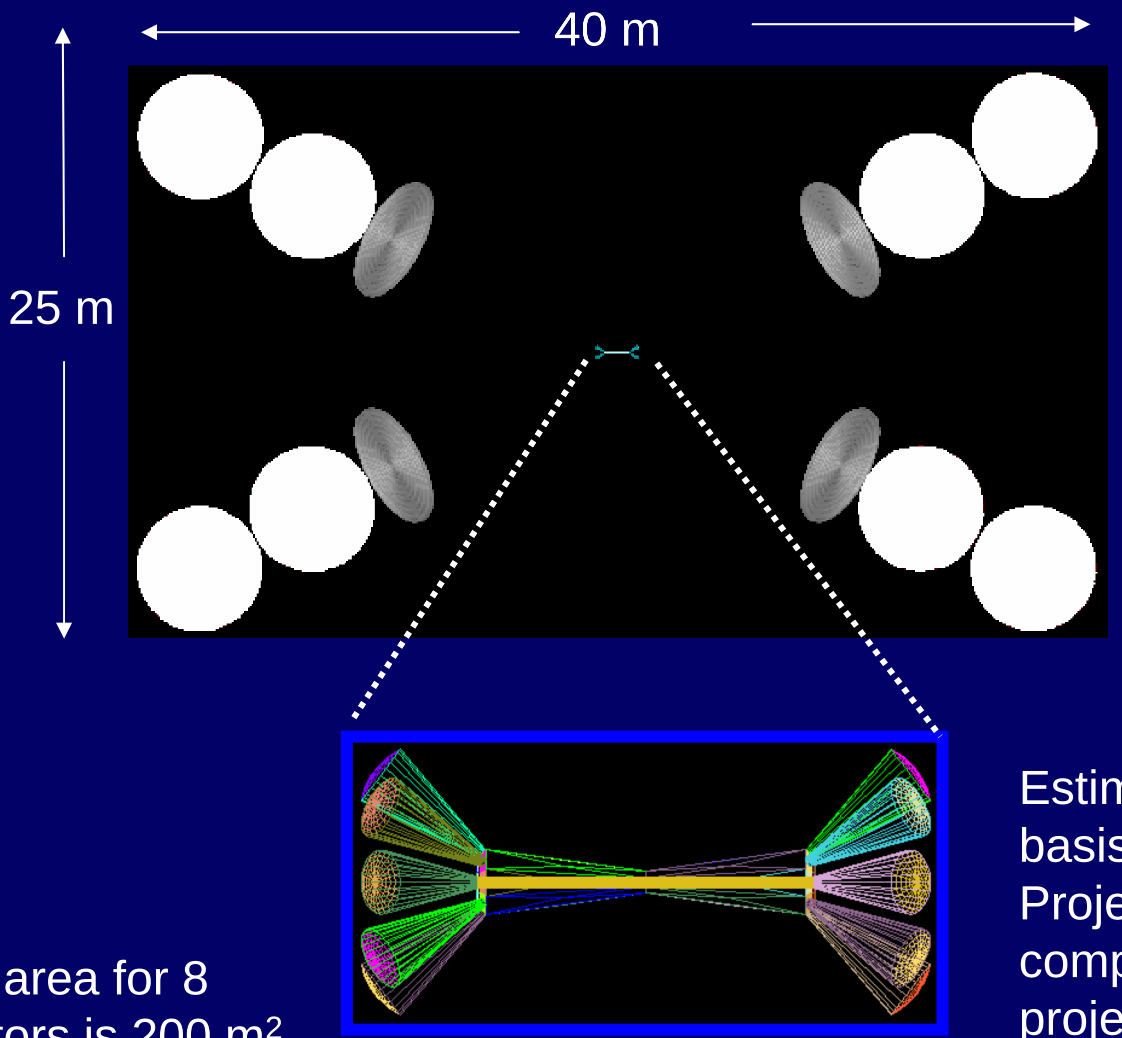
End view

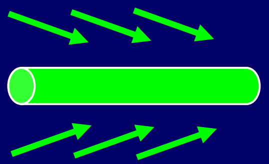


> 80% of solar pump power is ~uniformly absorbed in the core region

Sixteen times the effective intensity of one concentrator

Conventional optics for 8 collector concentrator





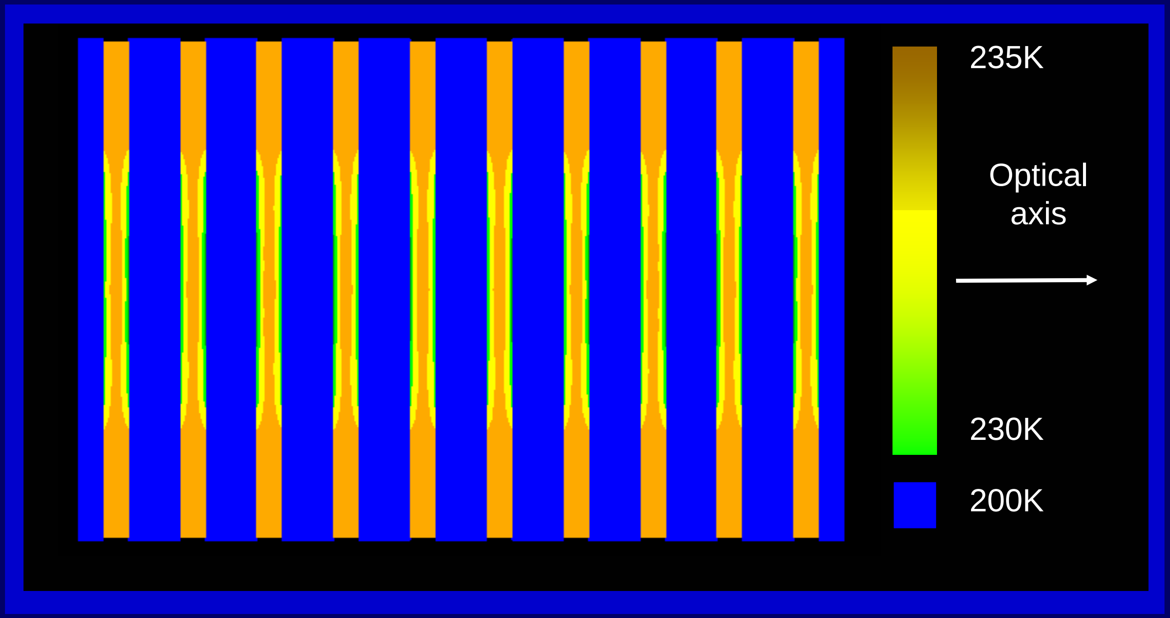
Collecting area for 8 concentrators is 200 m^2

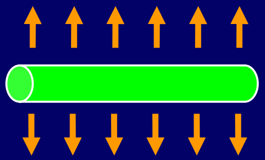
At 1 kg/m^2 mass is 200 kg

Estimate 4 kg/kW on basis of NASA optics Projections- comparable to nuclear projections

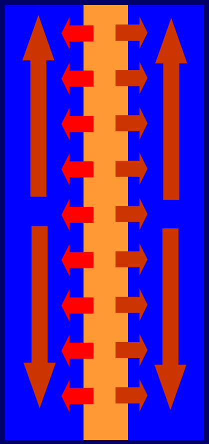
<1 metric ton for 200 kW output

#2: Remove heat from gain medium while avoiding thermally induced lensing and distortion





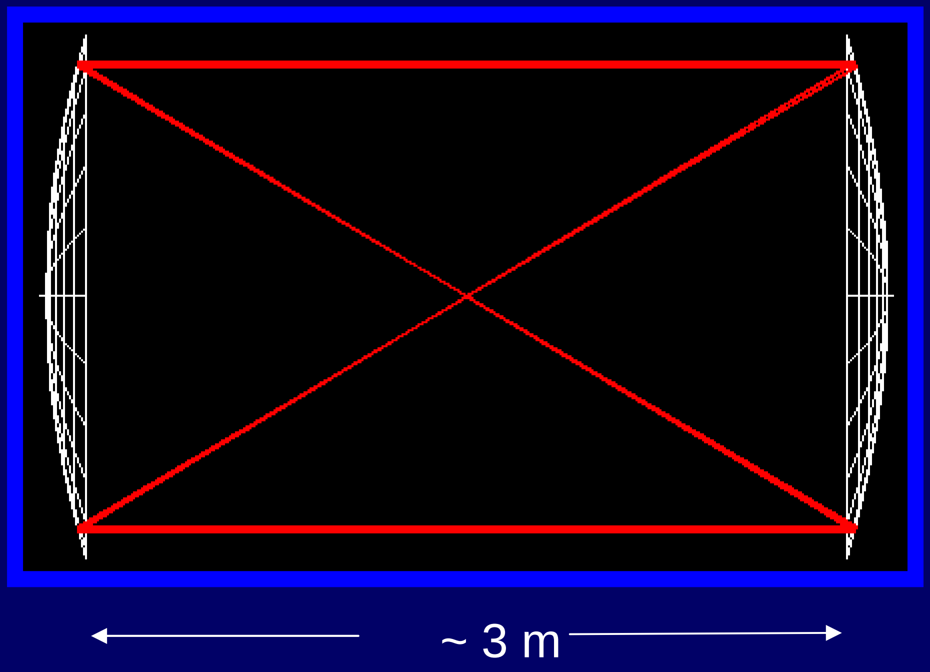
Heat removed radially using material having small thermo-optic coefficient and large thermal conductivity, e.g. diamond or undoped sapphire

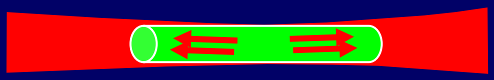


Heat removed axially from gain material having large thermo optic coefficient, e.g. YAG

Positive thermally induced lens is compensated by negative thermally induced lens

#3: Need large cross sectional area, e.g., 1.5 cm radius, lowest order Gaussian mode of a near confocal resonator of practical dimensions

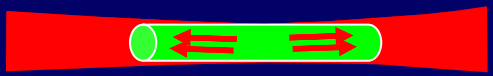


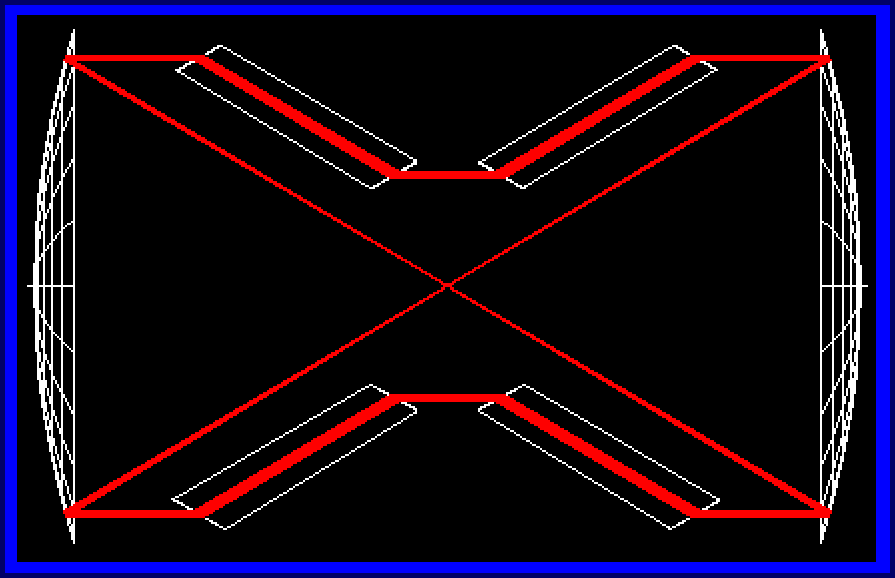


Double confocal paraboloidal resonator

Conventional lowest order Gaussian mode resonators would be <u>kilometers</u> long

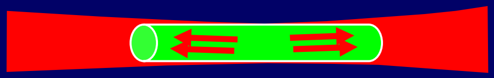
#3. Double confocal paraboloidal resonator using Brewster angle gain elements

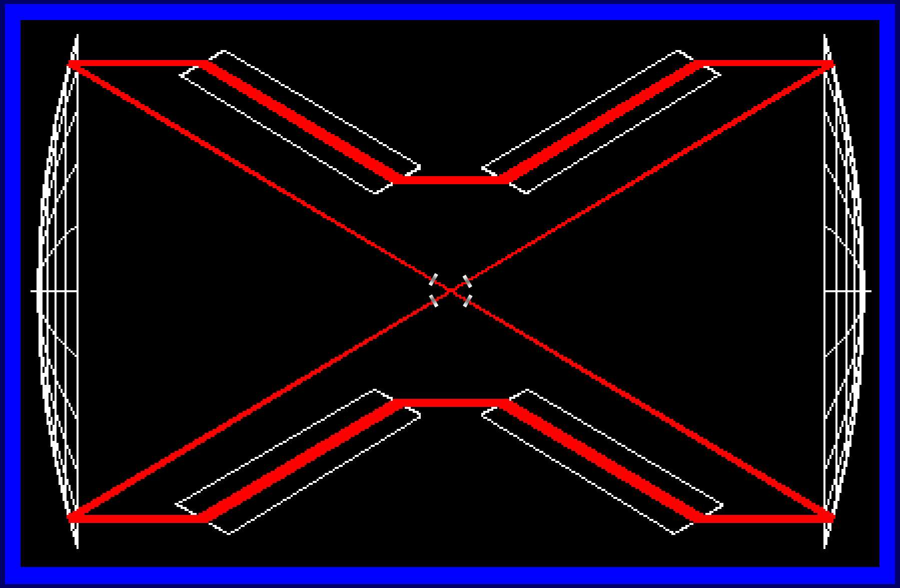




Provides low loss gain elements

#3 Double confocal paraboloidal resonator using Brewster angle gain elements

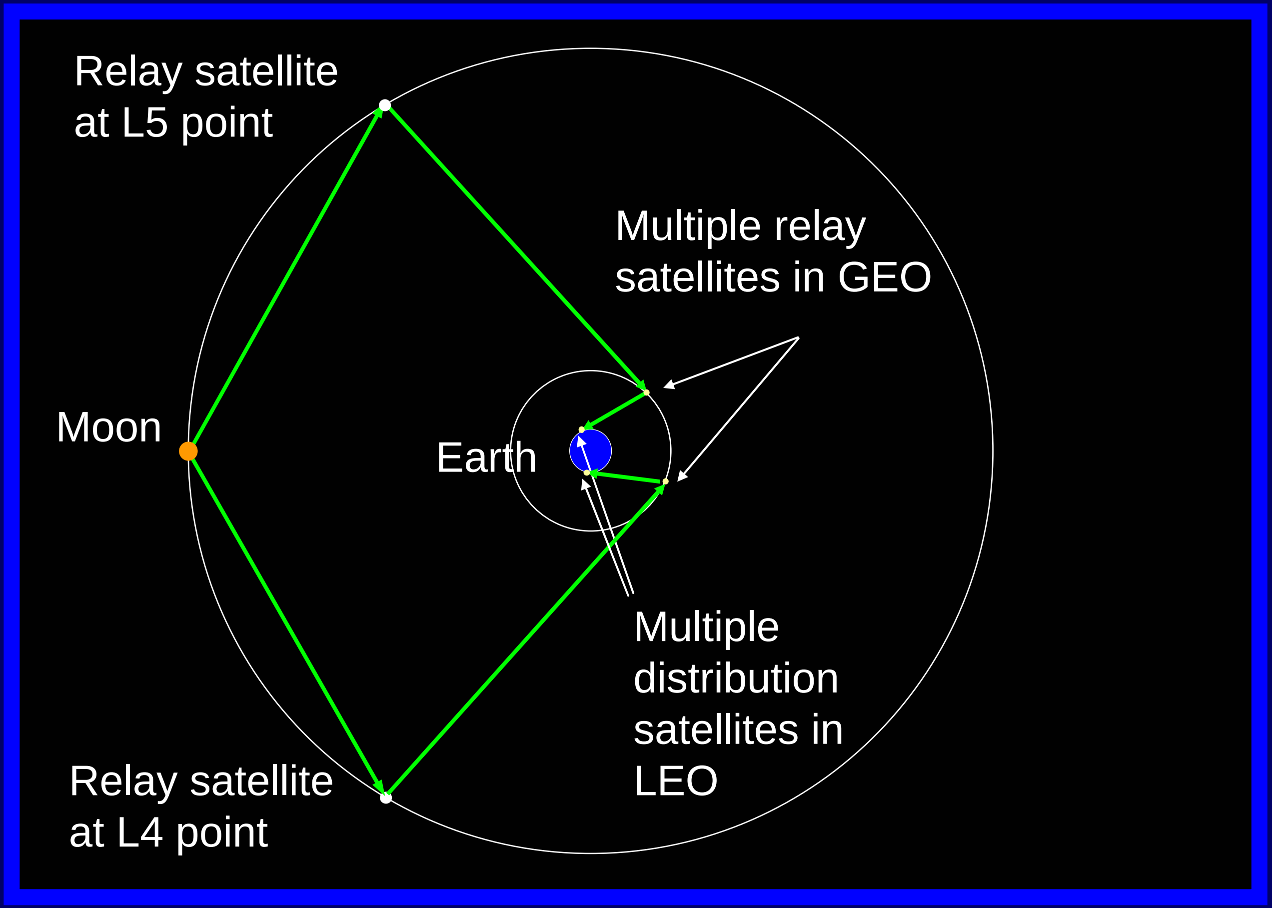




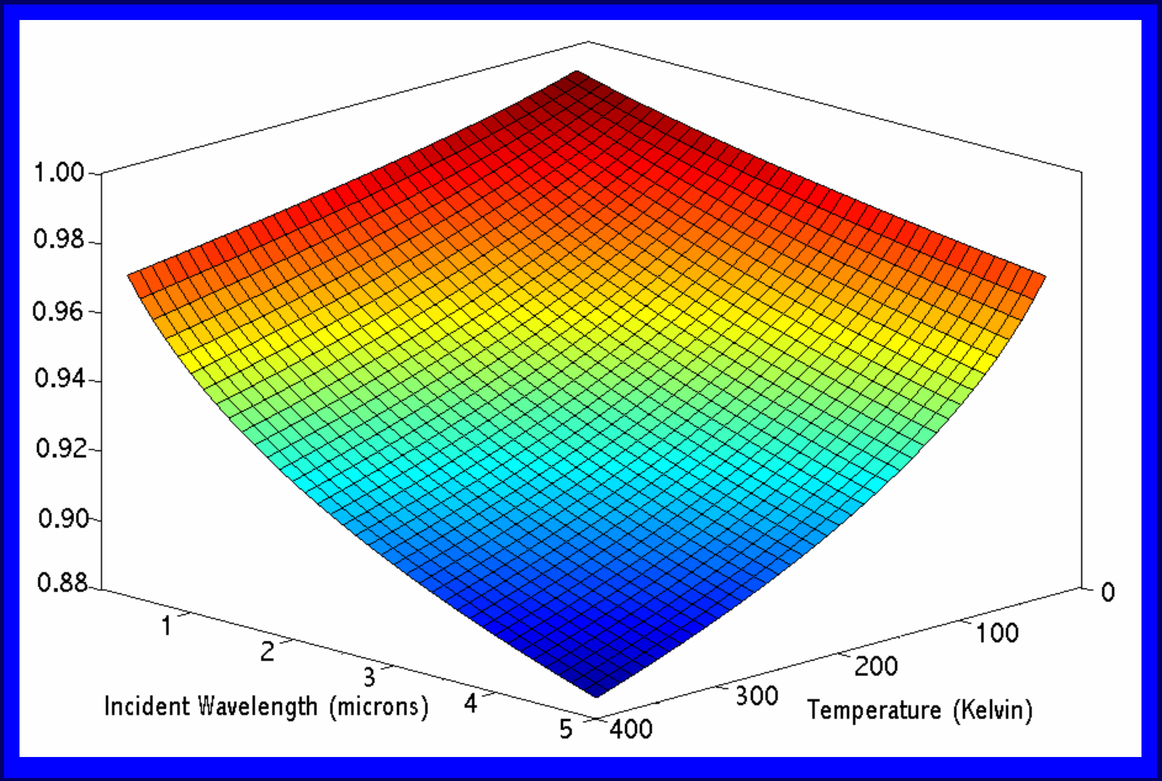
Energy brought in by solar pump photons must be transferred with high probability to <u>lowest order Gaussian mode</u>

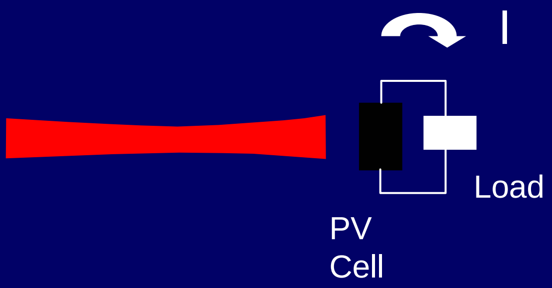
Selective transfer to the lowest order Gaussian mode requires <u>selective loss</u> introduced in the resonator

Technical advances 1,2,and 3 provide means of delivering optical power throughout Earth-moon space



#4: Transform received optical power to alternative form, e.g., electrical, at high efficiency at receiving site



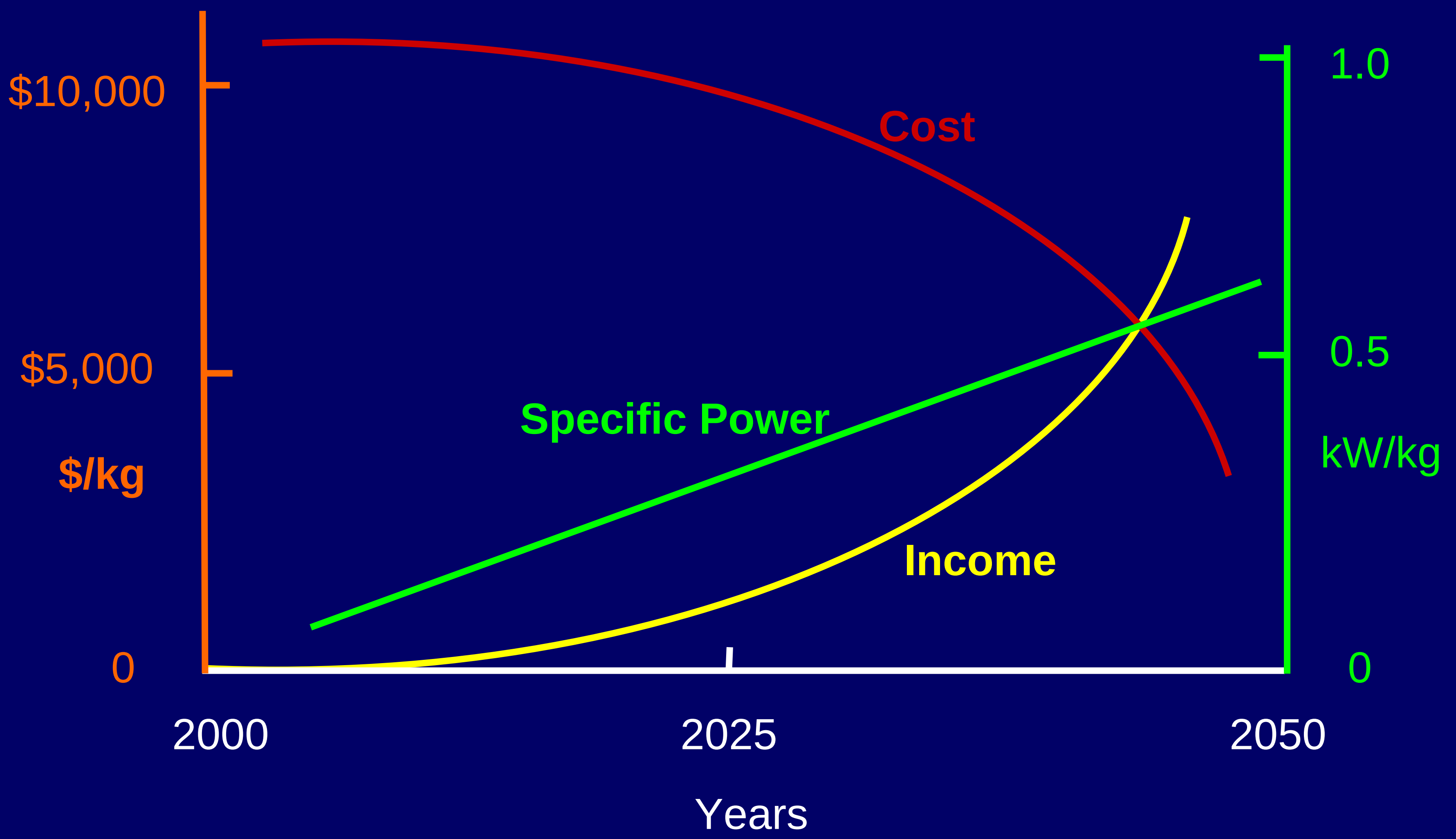


Requires matched coherent light

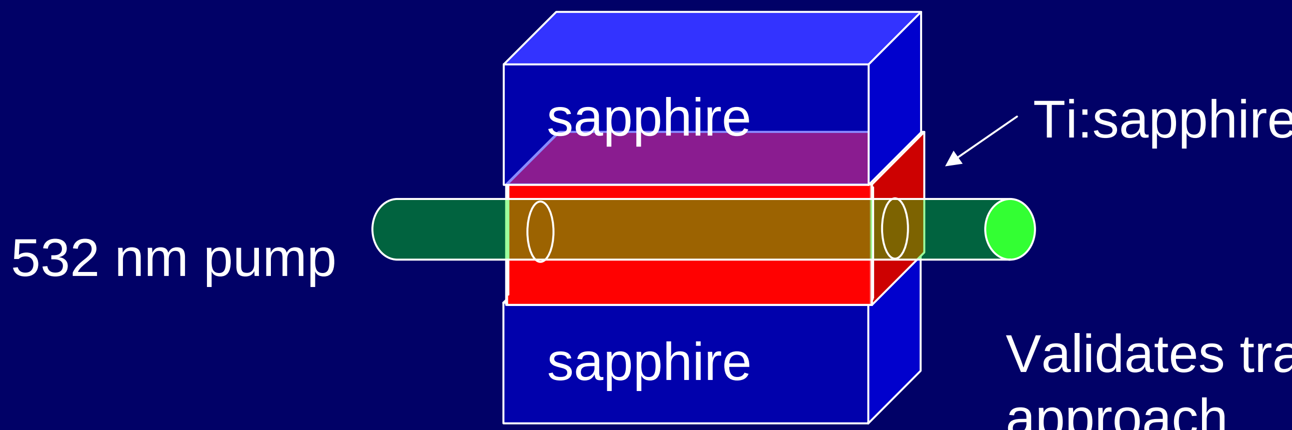
$$\eta \cong (1-\xi)[1+\xi \ln \xi] \qquad \xi = kT/h\nu = 1$$

Have neglected all sources of inefficiency except for thermal mechanisms

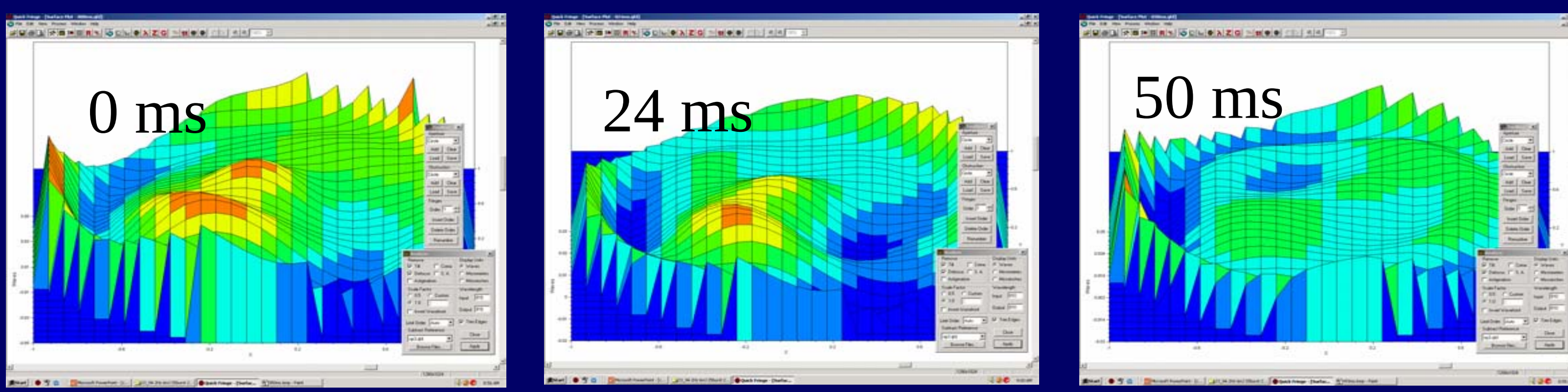
Cost, income, specific power vs. year



Current Experimental Results



Validates transient approach



Experimentally measured temperature profile in Ti:sapphire as a function of time

Plan of work

TASK	Experiment	Technical development	Analysis	Partner
1. Concentration of solar pump power	Laser for transient, heliostat for cw	Build concentrator elements	Measure power concentration	?
2. Removal of heat with no distortion	Transient pump probe experiment	Nanostructured interfaces	Compare results and simulation	NRL, ANL
3. Large area resonator with selective excitation	Build scaled down resonator in our laser lab	Paraboloidal reflectors	Compare results and predictions	?
4.High efficiency optical to electrical	Perform experiments on NASA diodes	Sample diodes to be built	Compare results and theory	Entech, Inc

Issues:

1. Can transient measurements provide data adequate to evaluate high cw power?

Ans. Longest relevant time constants are ~10 ms, so approach has scientific validity. Only way to perform meaningful experiments within current budget.

2. What is the case for scaling to high total power at reasonable cost?

Ans. The physical phenomena allow construction of small scale system that illustrates the key mechanisms.

Build small scale system and project the cost. The answers will be found in the maturing of the technologies.

No obvious reason cost will be a show stopper.

3. What would be the cost of robotic assembly in space?

Ans. We can make the system elements modular. The technology is similar to that of Project Lasso now being explored.

4. Sounds to good to be true.

Ans. Coherent light is different from conventional light. One may discover capabilities that were not fully anticipated.

Conclusions

1. An optical Power Infrastructure in Earth-moon space is allowed by fundamental physical laws

2. There are four areas of technology maturation that are required to make such an infrastructure a possible

3. The advances that are required are difficult, but are likely to yield to determined efforts.

4. The cost benefit analysis strongly recommends making the effort.

Special thanks to this years UAH laser and optics classes!

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