Holographic Optical Method for Exoplanet Spectroscopy

HOMES

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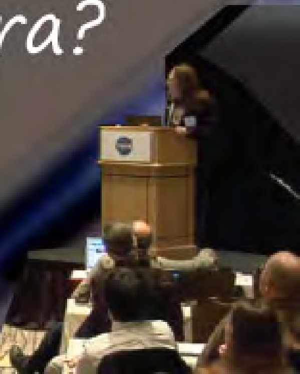
3DeWitt llc

NIAC
NASA Innovative Advanced Concepts

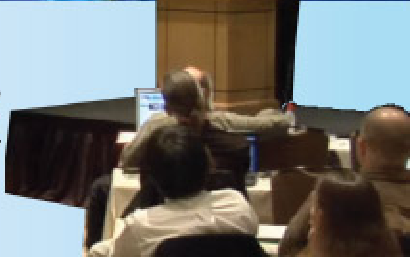
We're looking for a pale blue marble, not too hot, not too cold but just right for the three phases of water. We're looking for exoplanets in the Goldilocks zone.

But we're not looking simply for water.
We're looking for some porridge, some key organics....

How can we do that if the exoplanet occupies little more than one pixel in our science camera?



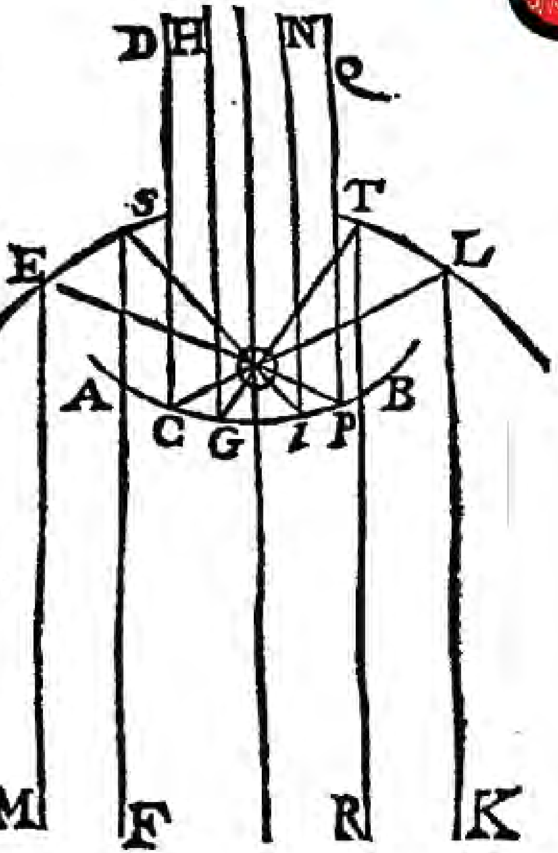
The problem of imaging exoplanets is daunting. Resolving earth at a distance of 10 light years is like seeing my hand at a distance from San Francisco to New York City.

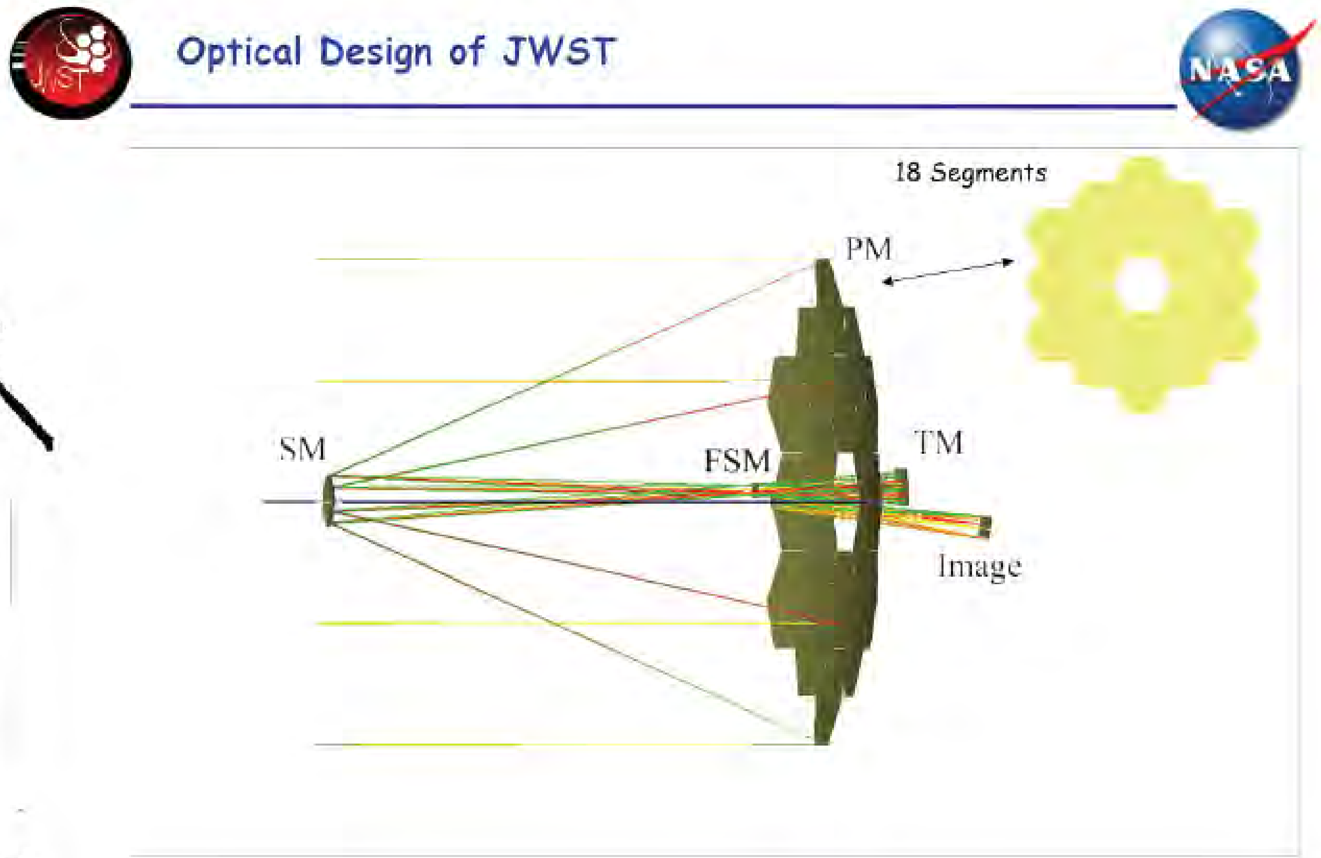


HARMONIE
VNIVERSELLE,
CONTENANT LA THEORIE
ET LA PRATIQVE
DE LA MVSIQVE.
Où il eſt traité de la Nature des Sons, & des Mouuemens, des Conſonances, des Diſſonances, des Genres, des Modes, de la Compoſition, de la Voix, des Chants, & de toutes ſortes d'Inſtrumens Harmoniques.

Par F. MARIN MERSENNE de l'Ordre des Minimes.

A PARIS,
Chez Sebastien Cramoisy, Imprimeur ordinaire du Roy,
ruë S. Iacques, aux Cicognes.
M. DC. XXXVI.
Auec Priuilege du Roy, & Approbation des Docteurs.





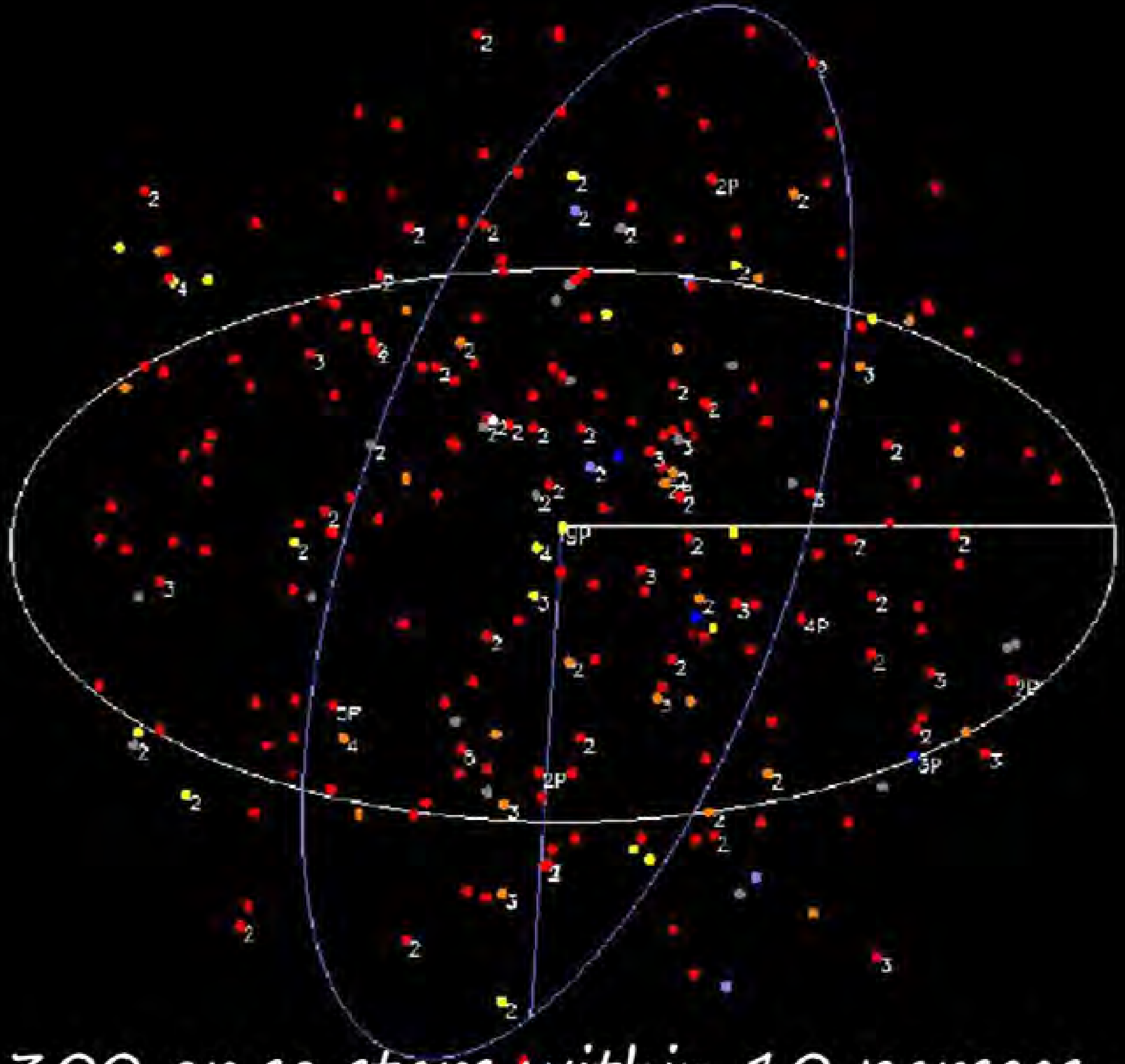
Optical Design of JWST

Three-Mirror-Anastigmat (TMA) wide-field telescope design

1636

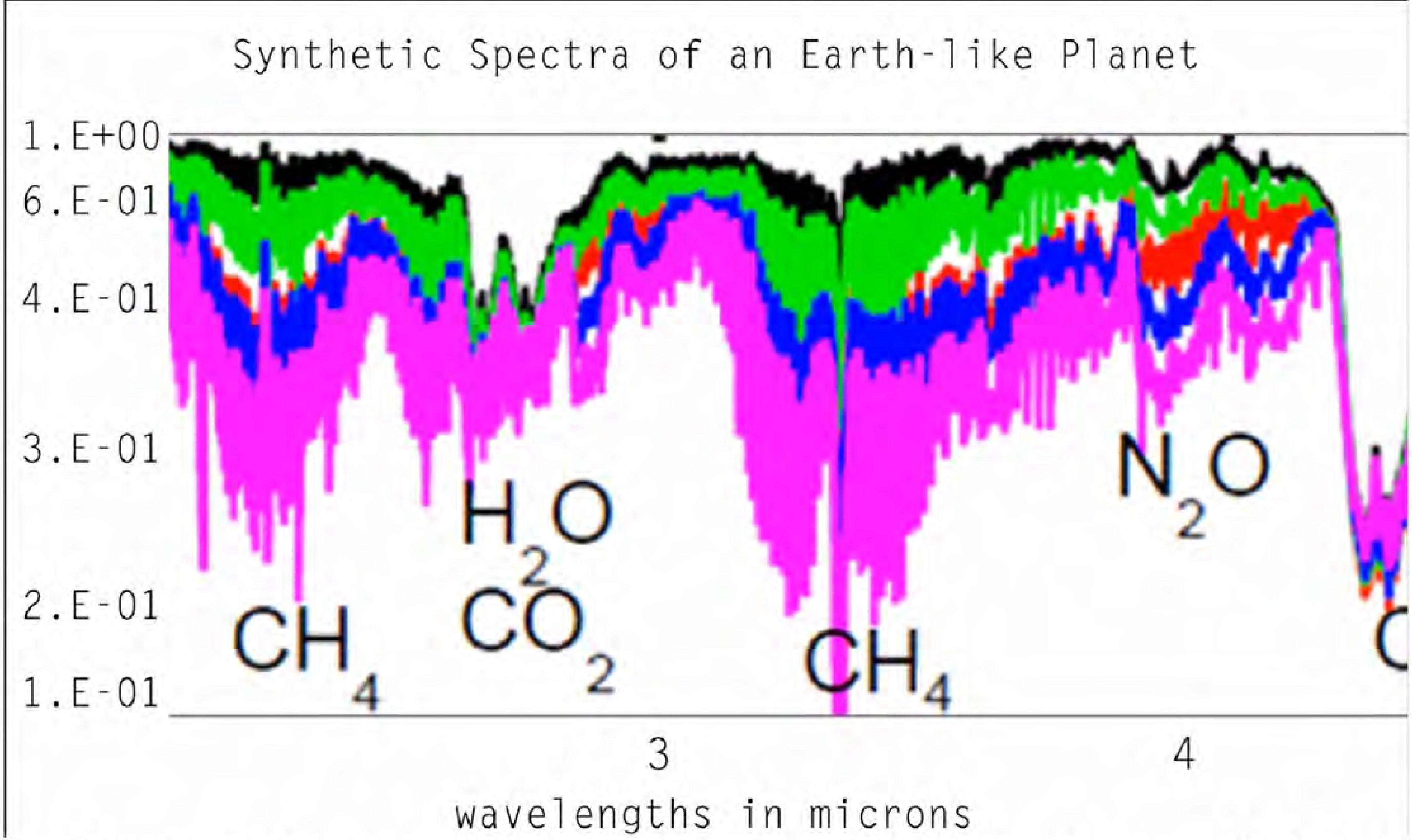
2018

We're looking through telescopes that haven't changed in basic concept in over 350 years. Mirror telescopes are too small, too rigid and suffer from excessive aerial mass.

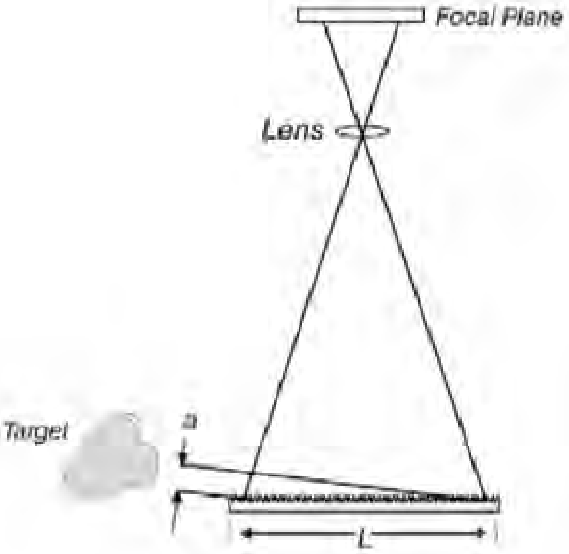


Here are the 300 or so stars within 10 parsecs – our stellar neighborhood. We can see them. However, there is no way to see their planets, because stars are 1 billion times brighter and a mere 100 milliarcseconds separate from their planets.

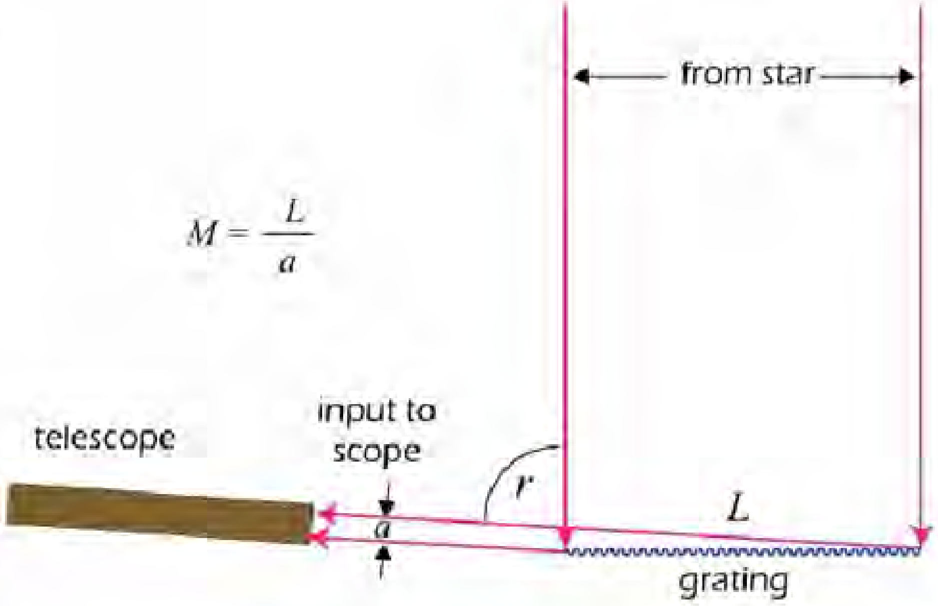
Exoplanets are as faint as the most distant objects ever detected. To make this image, the Hubble made 2000 observations over 556 hours pointed at an extremely dark field. Brighter objects in the field would have swamped the sensors.



Even if we do image an exoplanet on a pixel or two and determine it exists in the habitable zone of its solar system, we cannot declare it habitable without taking its spectrum to find signatures.



microscope



telescope

To take a spectrum we need a powerful diffraction grating. The textbooks do not teach using a diffraction grating as a primary objective, but we built a microscope with a diffraction grating primary. The microscope works on grazing Incidence where magnification is in proportion to the length of a grating L to a, the incidence aperture. A revolutinary telescope design based grazing exodus rather than grazing incidence would enjoy the same leverage as the microscope.

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2. THE NEW IDEA ILLUMINATES A PATHWAY TOWARD AN EXPANSION OF KNOWLEDGE AND MAY ADDRESS A SIGNIFICANT ROAD BLOCK.

3. IT INSPIRES OTHERS TO PRODUCE USEFUL SCIENCE AND FURTHER ELABORATION OF THE FUNDAMENTAL IDEA.

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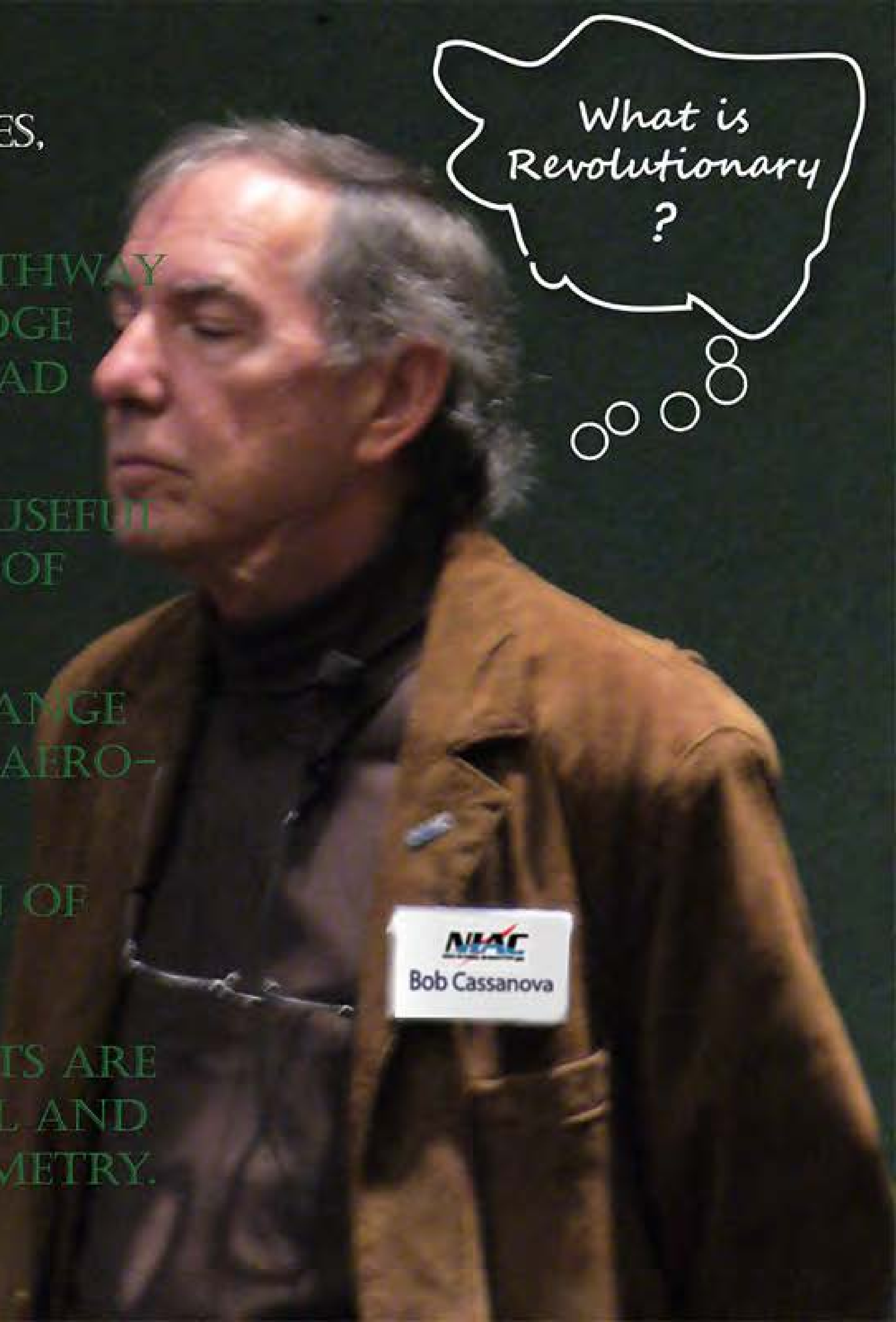
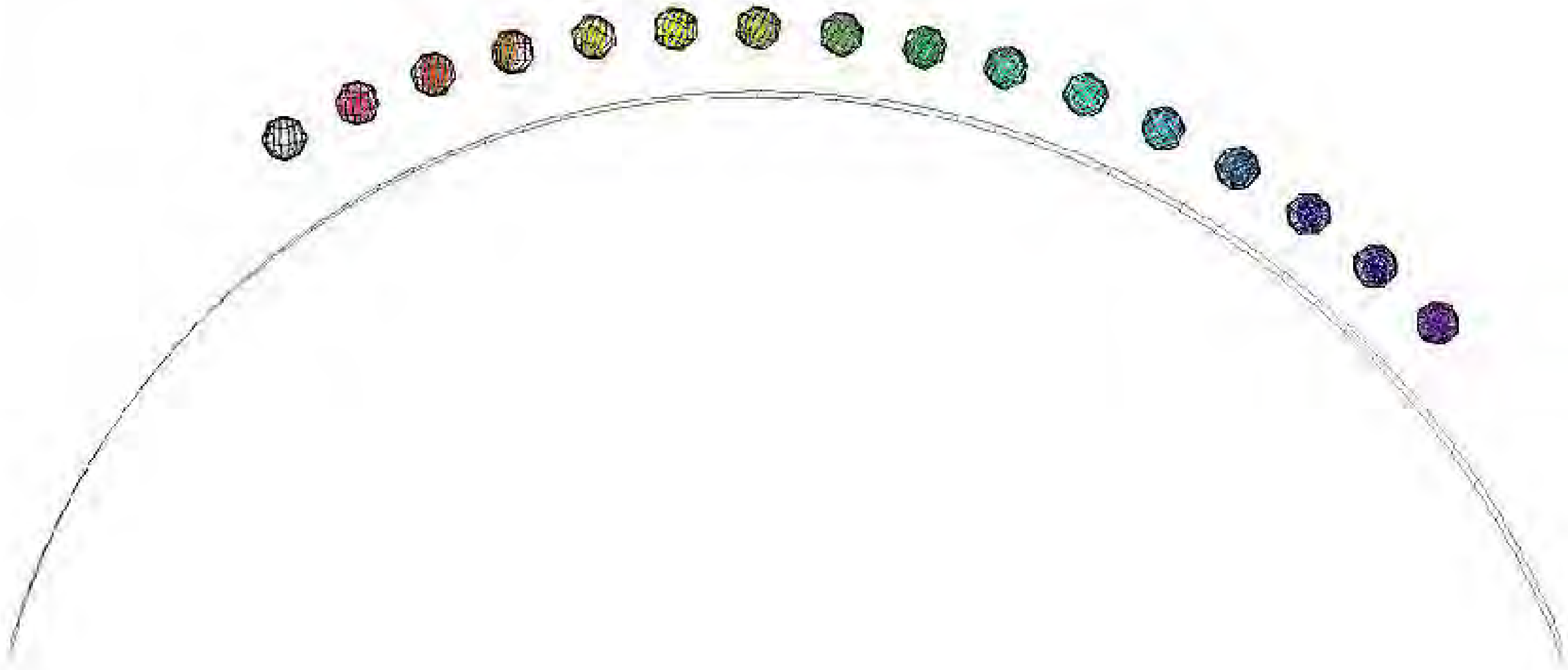


Multiple Object Spectrographic Telescope

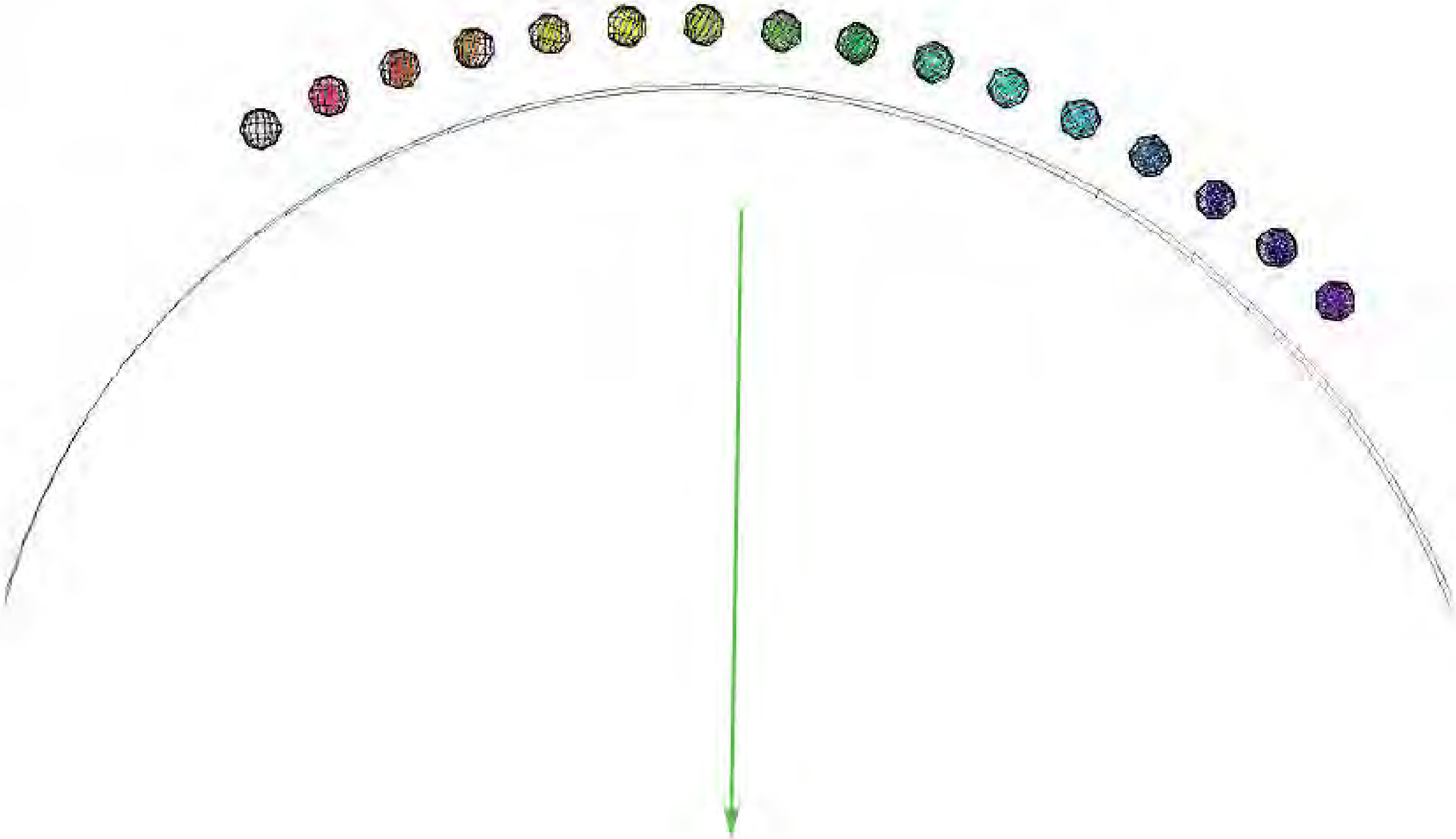
The MOST

First Principles

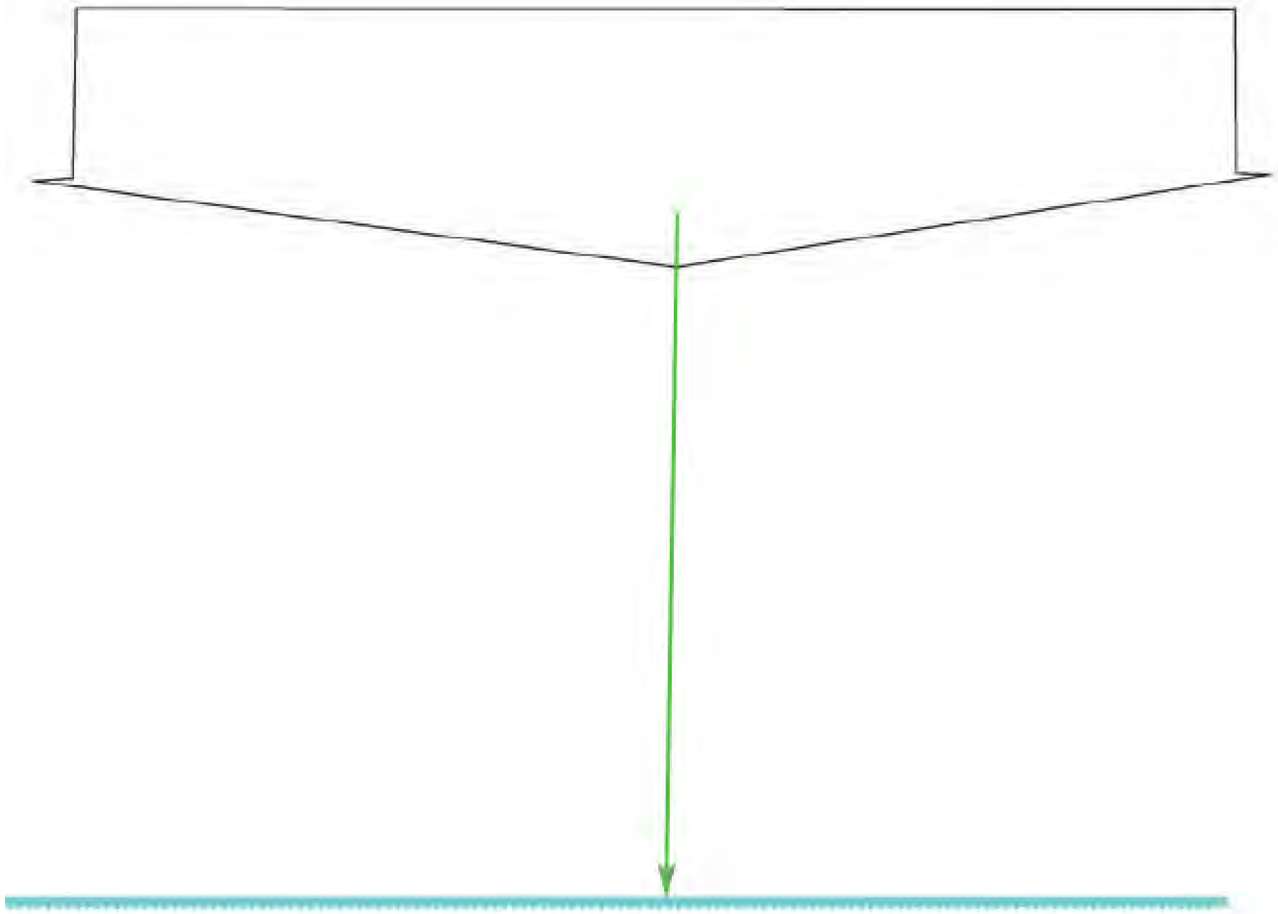


A source of distant illumination, say a star, precesses.

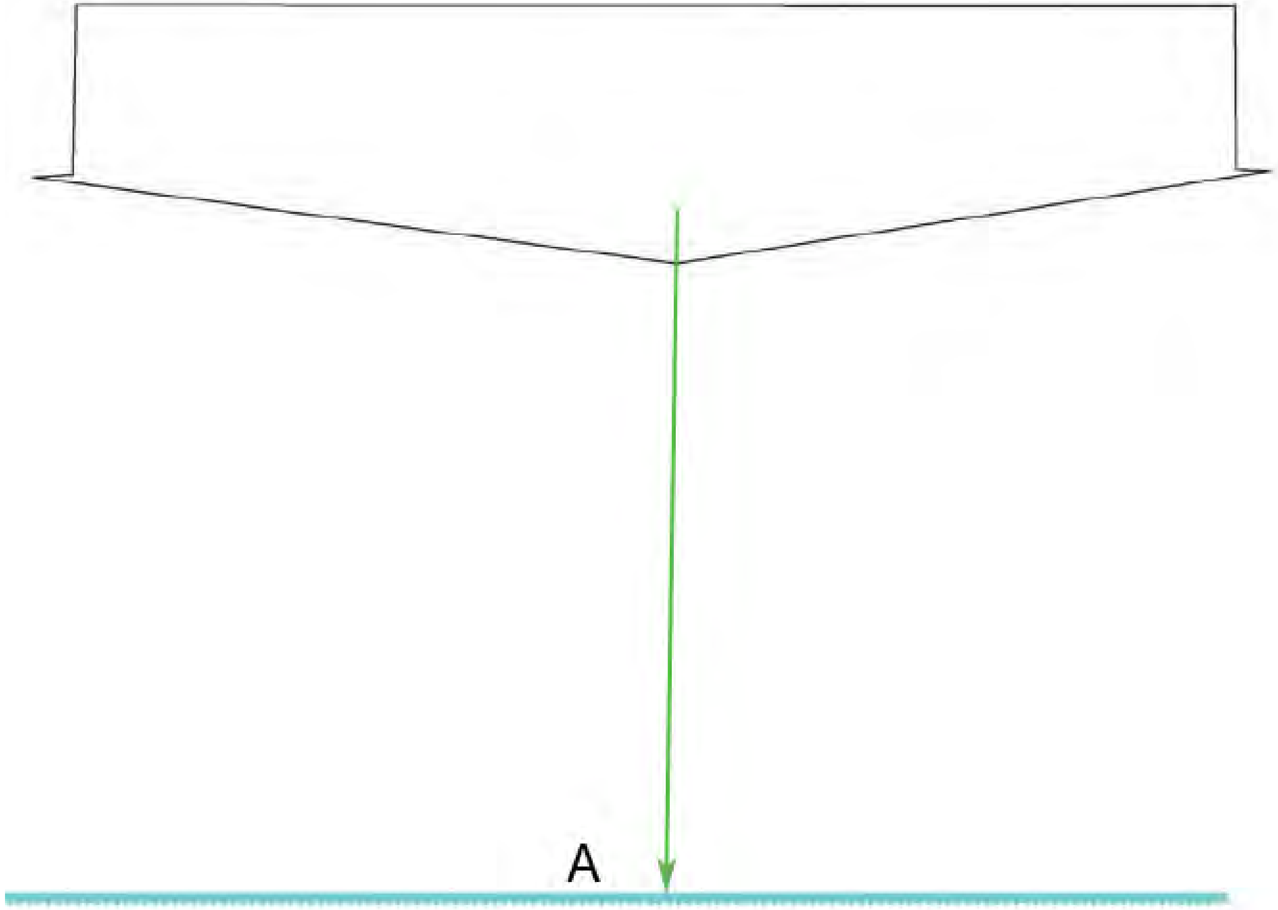
How can it be made to progress through its spectrum?



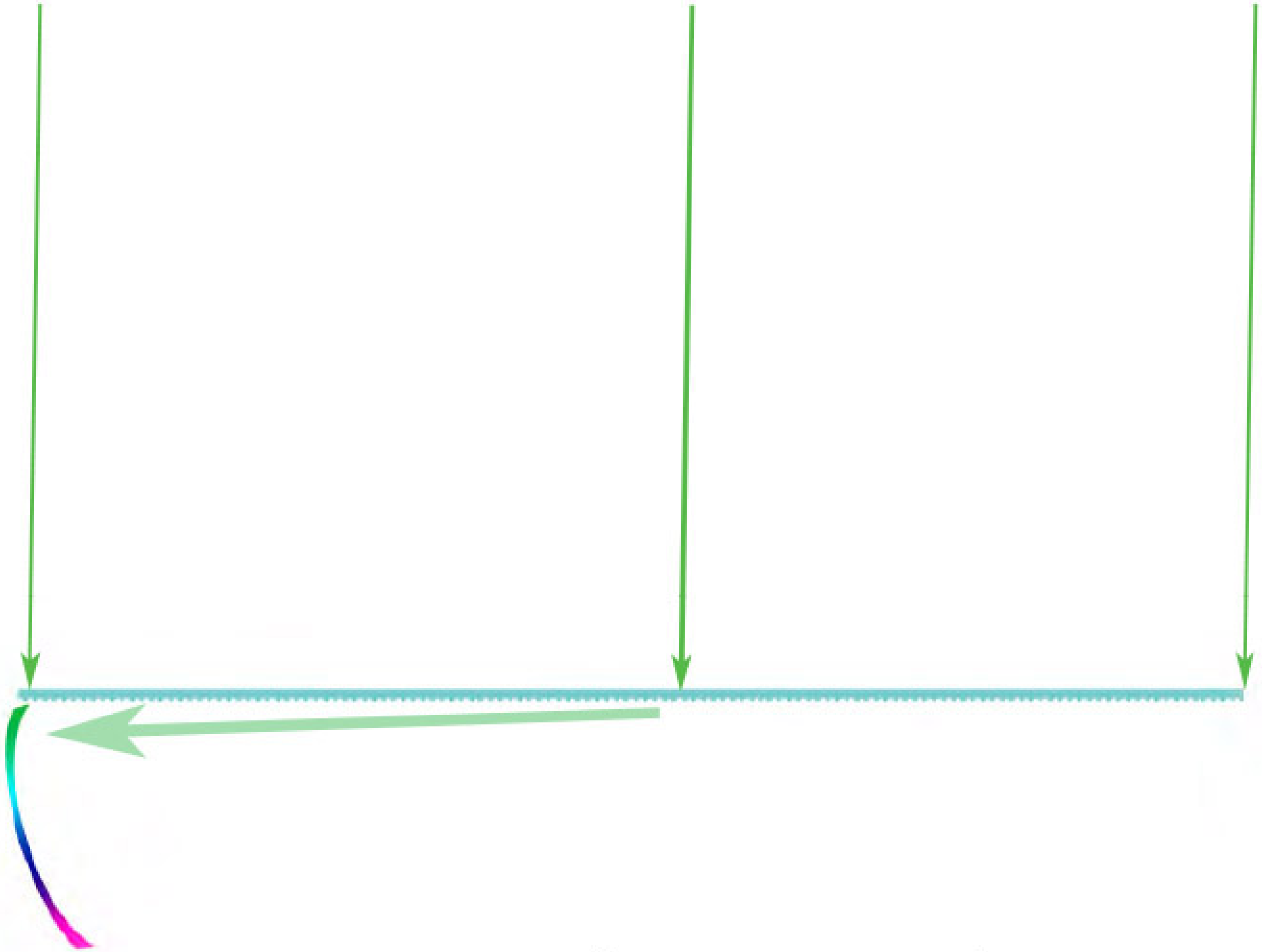
Consider an object at the zenith.



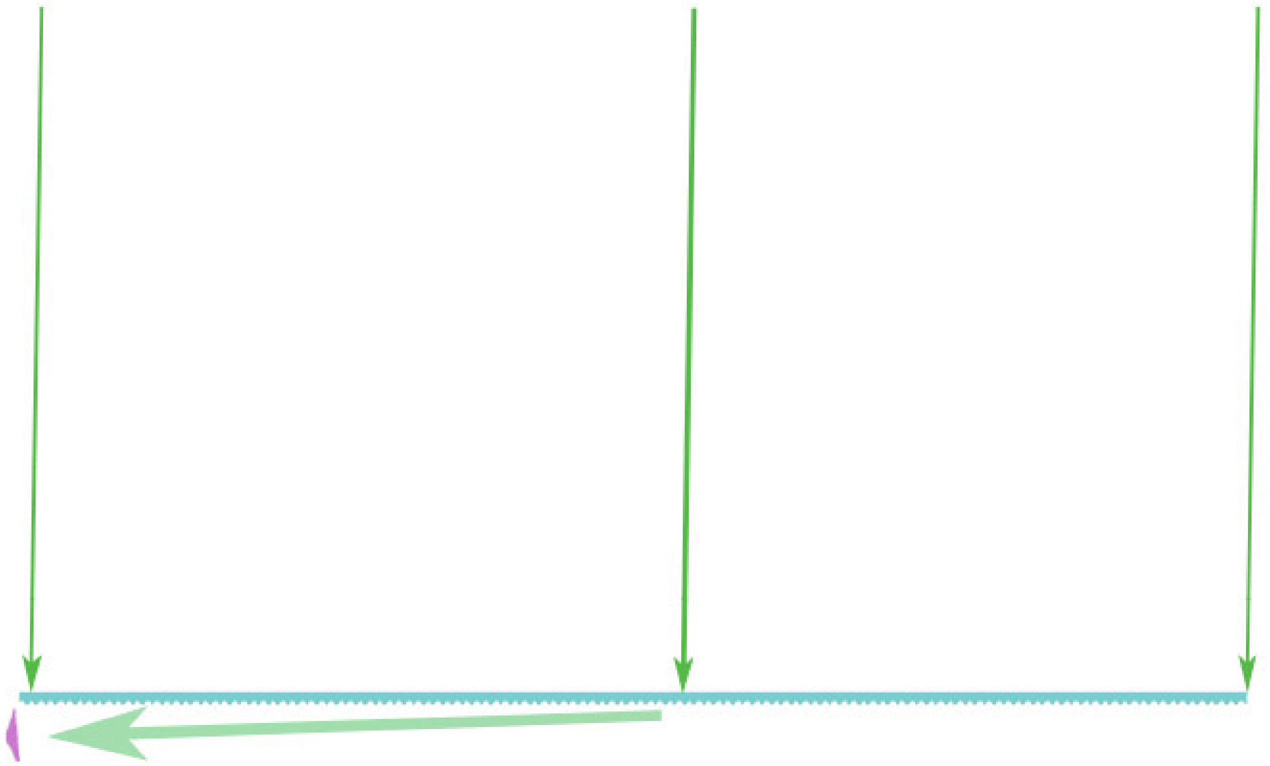
Light from the source arrives as plane wave.



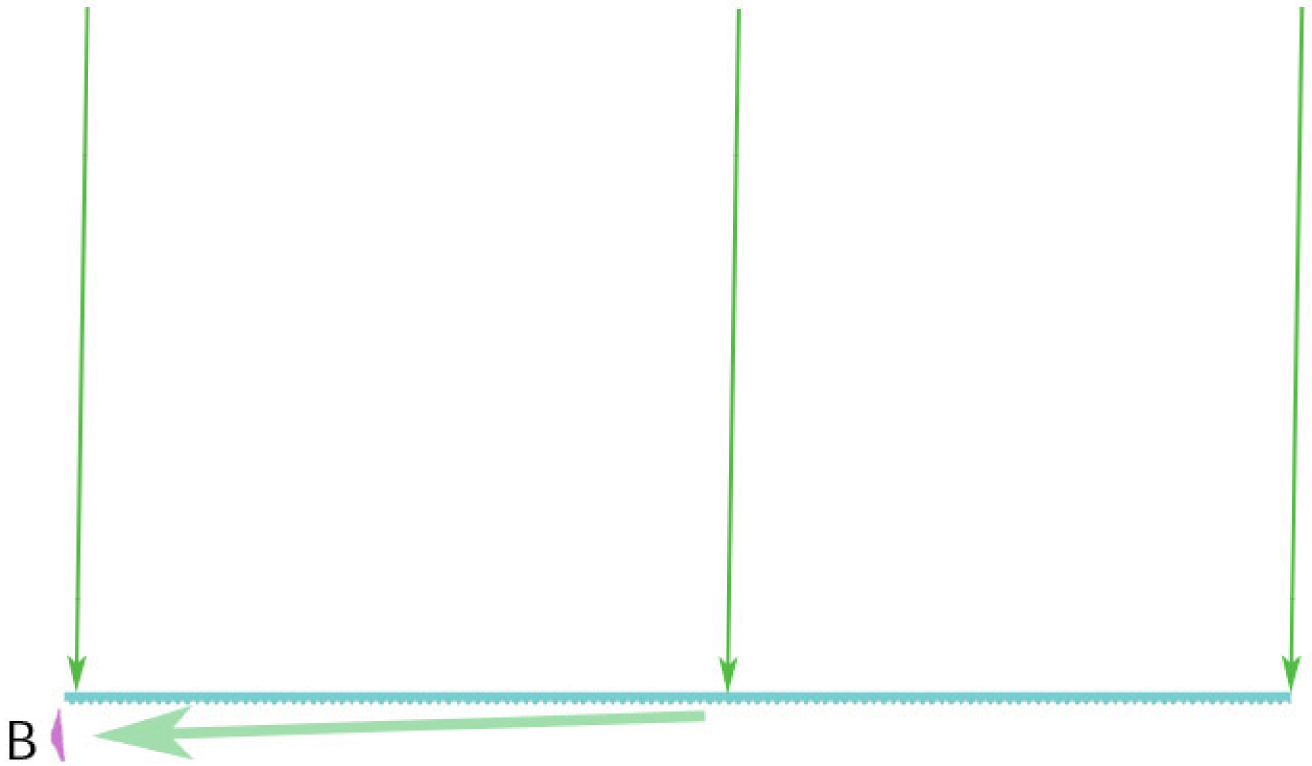
The plane wave strikes plane grating A.



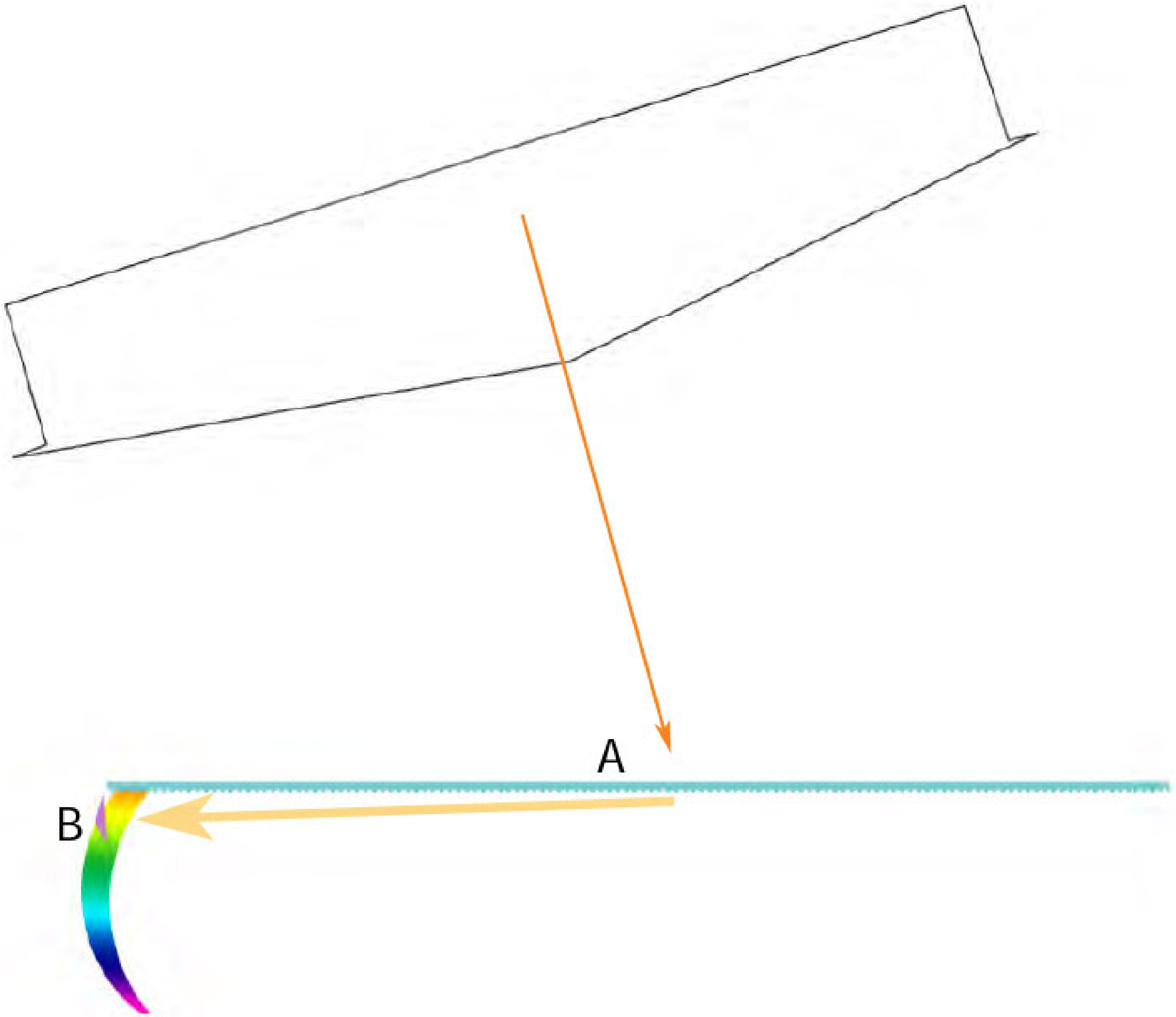
Light is dispersed from the plane grating at angles inversely proportional to wavelength.



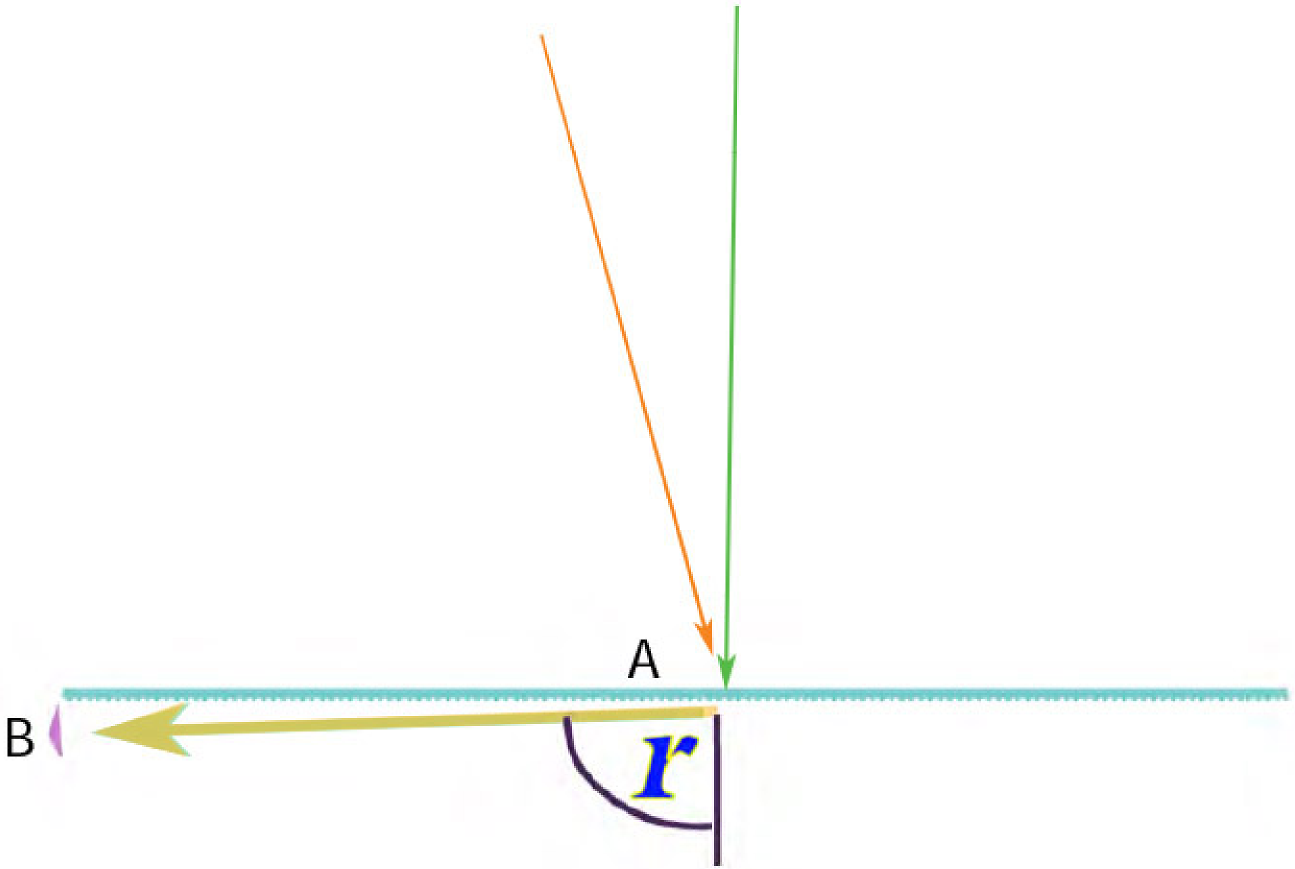
Diffraction gratings reconstruct the plane wave at a new angle where it can be collected .



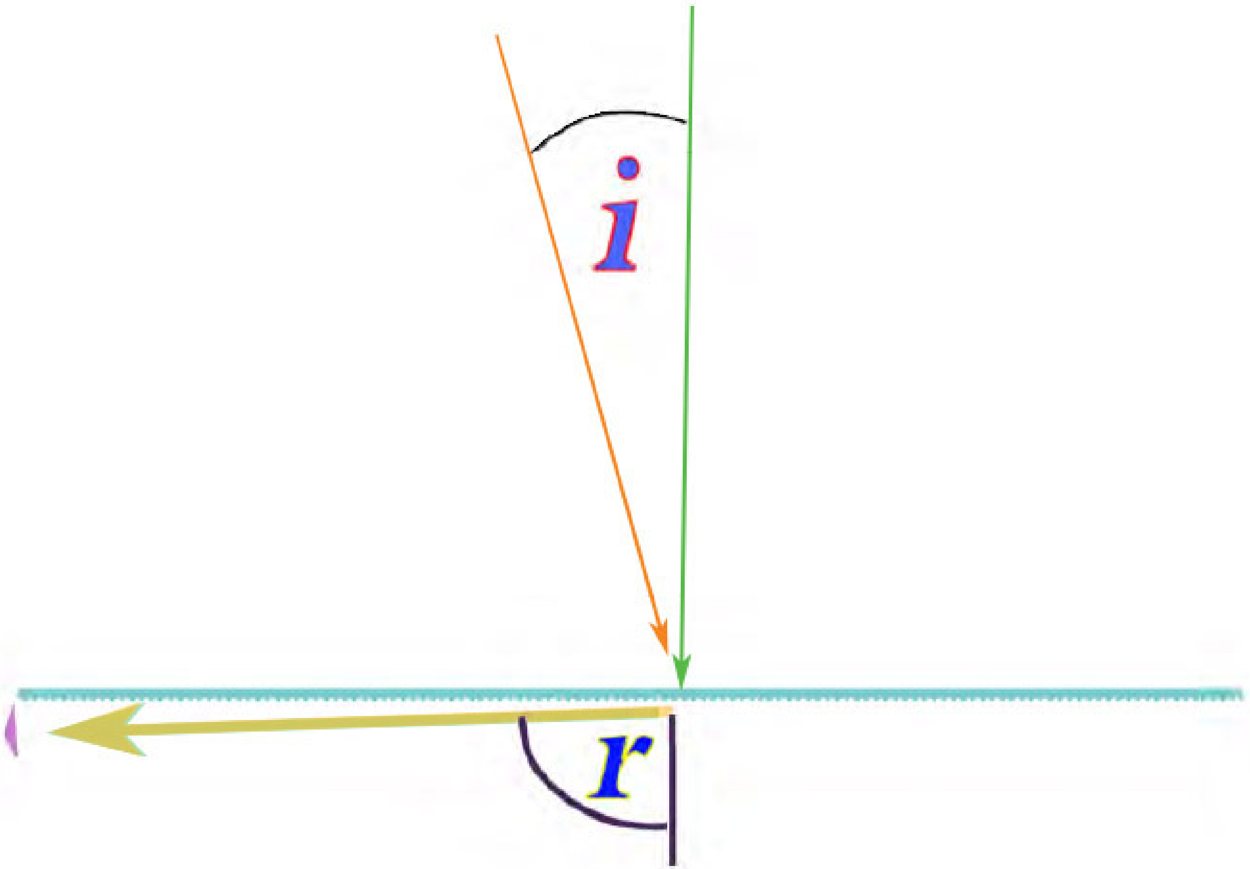
A specific wavelength is dispersed to parabolic mirror B.



For another angle of incidence upon grating A parabolic mirror B will collect another wavelength.

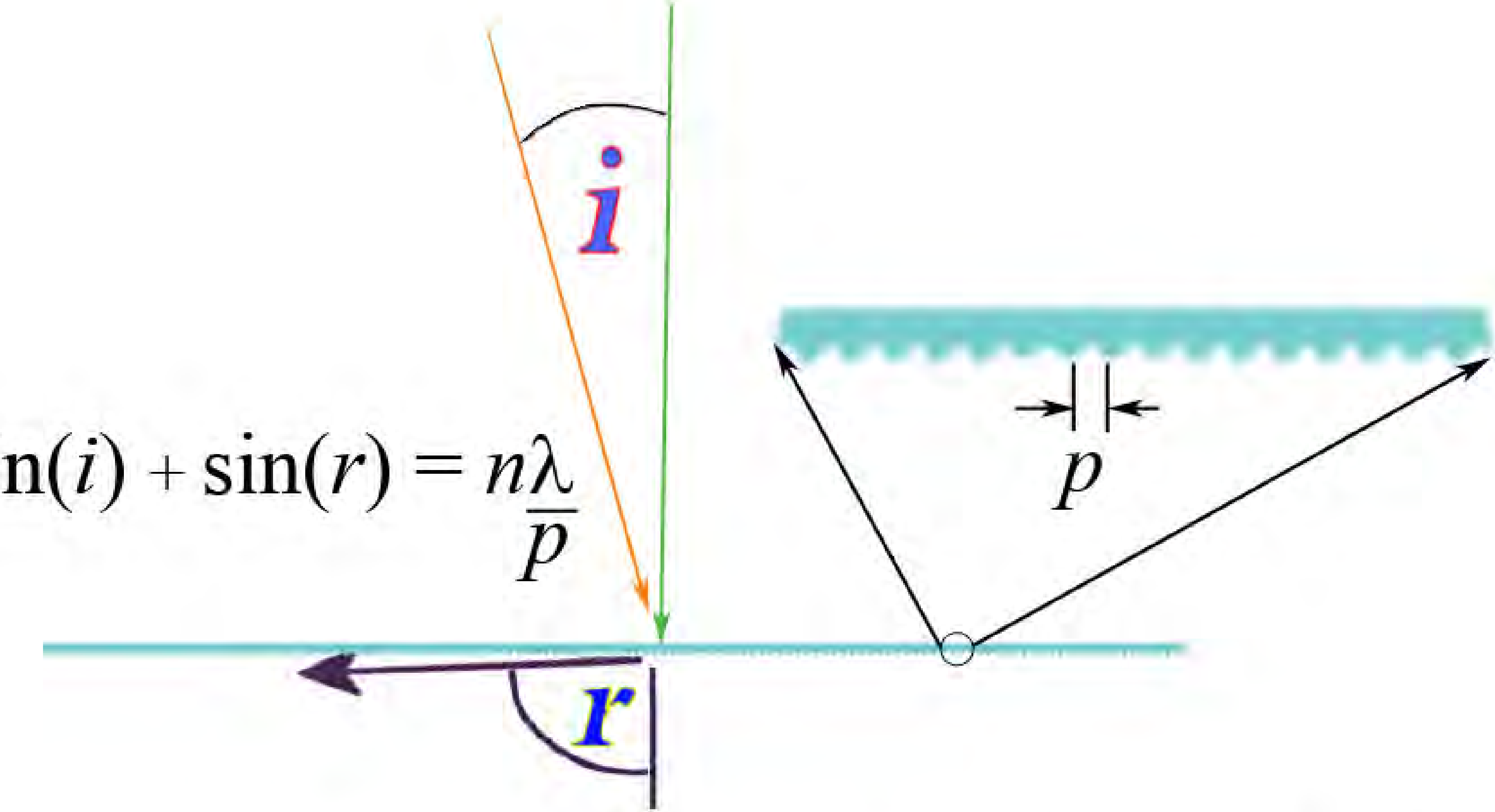


Varying angles of incidence upon grating A sharing a fixed and common angle of reconstruction r will disperse varying wavelengths to parabolic mirror B.



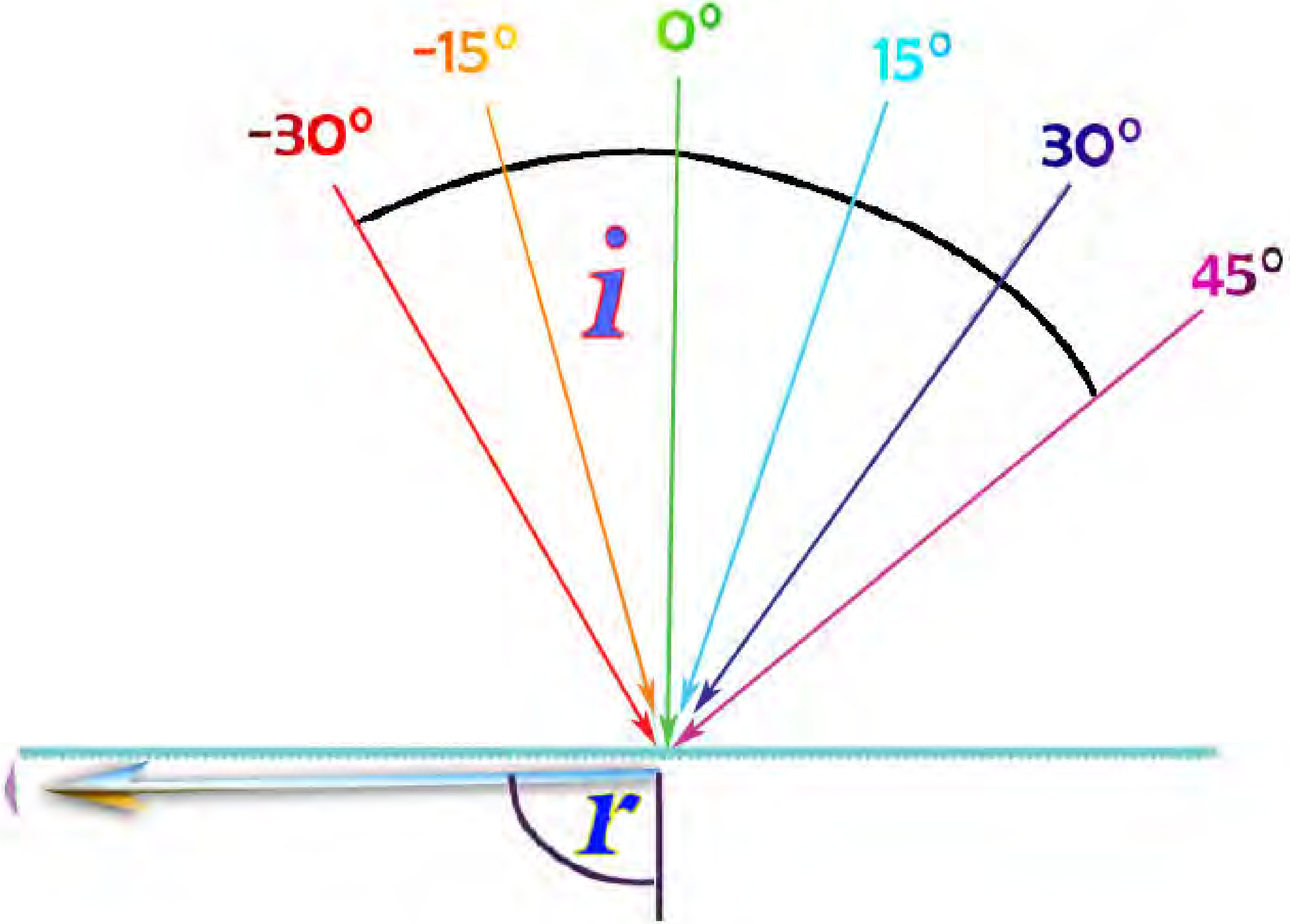
This configuration has angle of incidence i varying and a fixed grazing angle of wavefront reconstruction r.

The Diffraction Equation

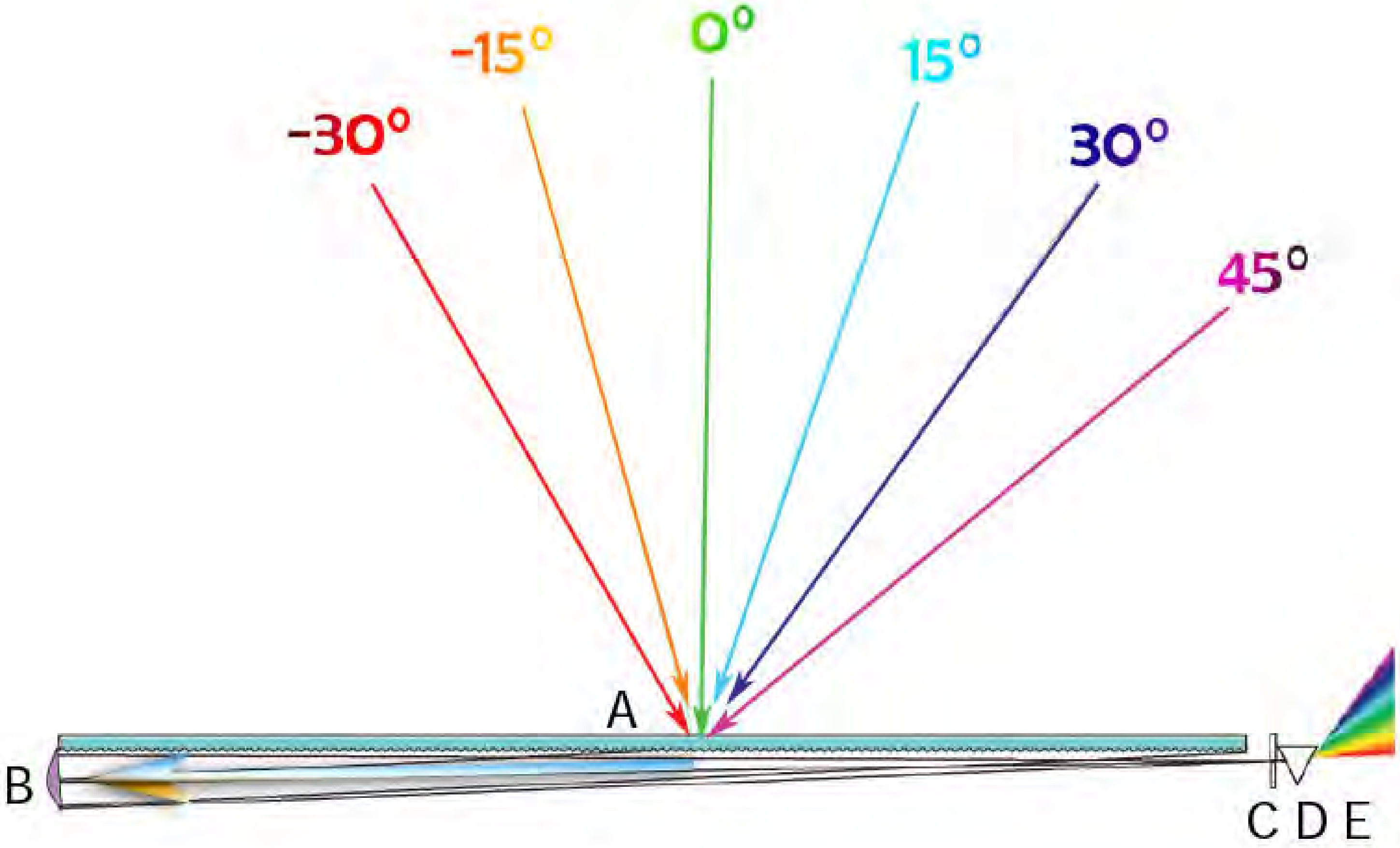


$$\sin(i) + \sin(r) = \frac{n\lambda}{p}$$

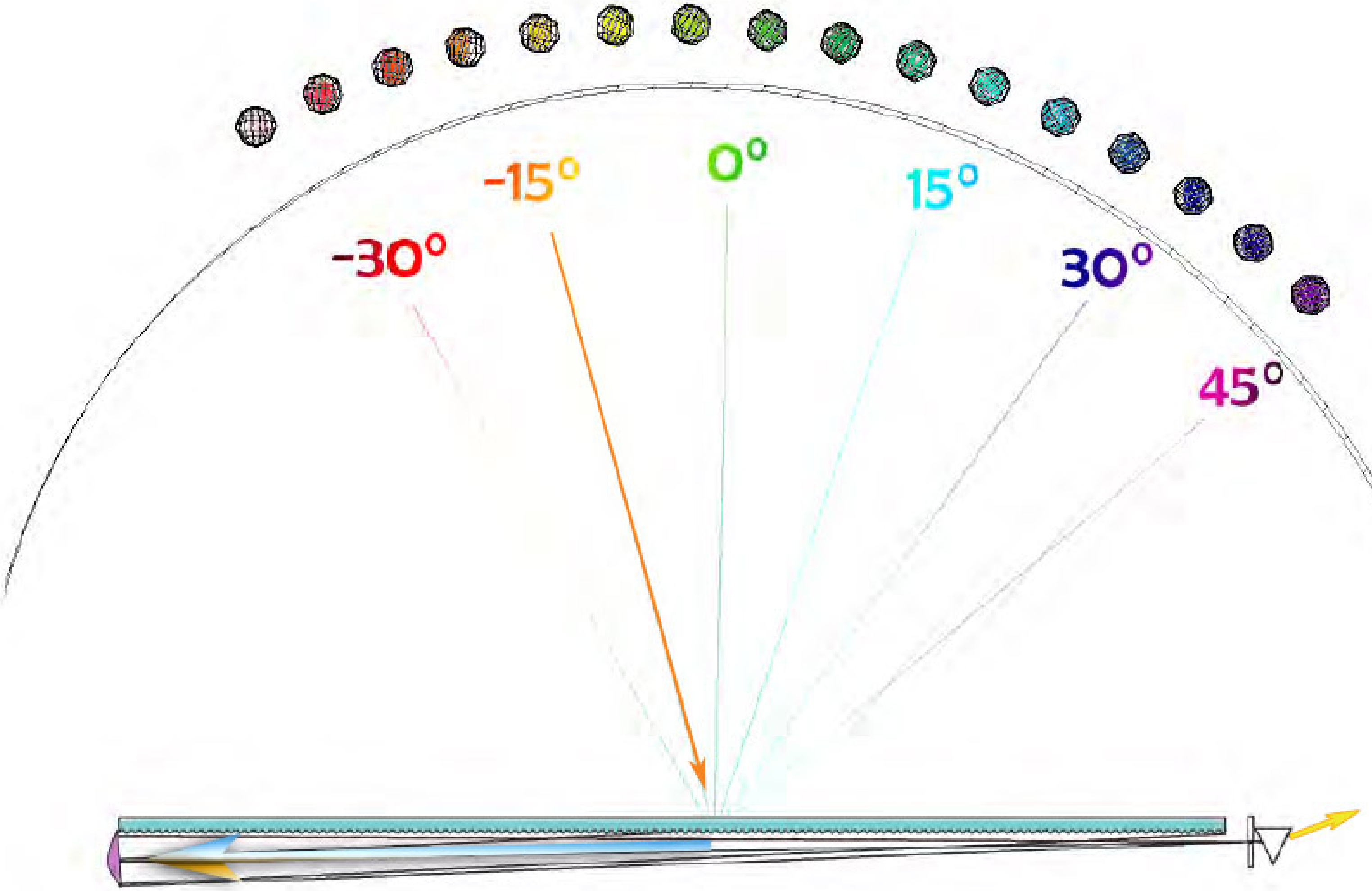
When the angle of reconstruction r, the pitch of the grating p, and the diffraction order n are fixed, the angle of incidence can be calculated by a measurement of wavelength λ.



Variations in the angle of incidence over a fixed angle of reconstruction will disperse a spectrum of wavelengths.



For grating A dispersing to parabolic mirror B there will be a common focal point C that can be a spectraph slit. A secondary disperser D can then produce spectrum E.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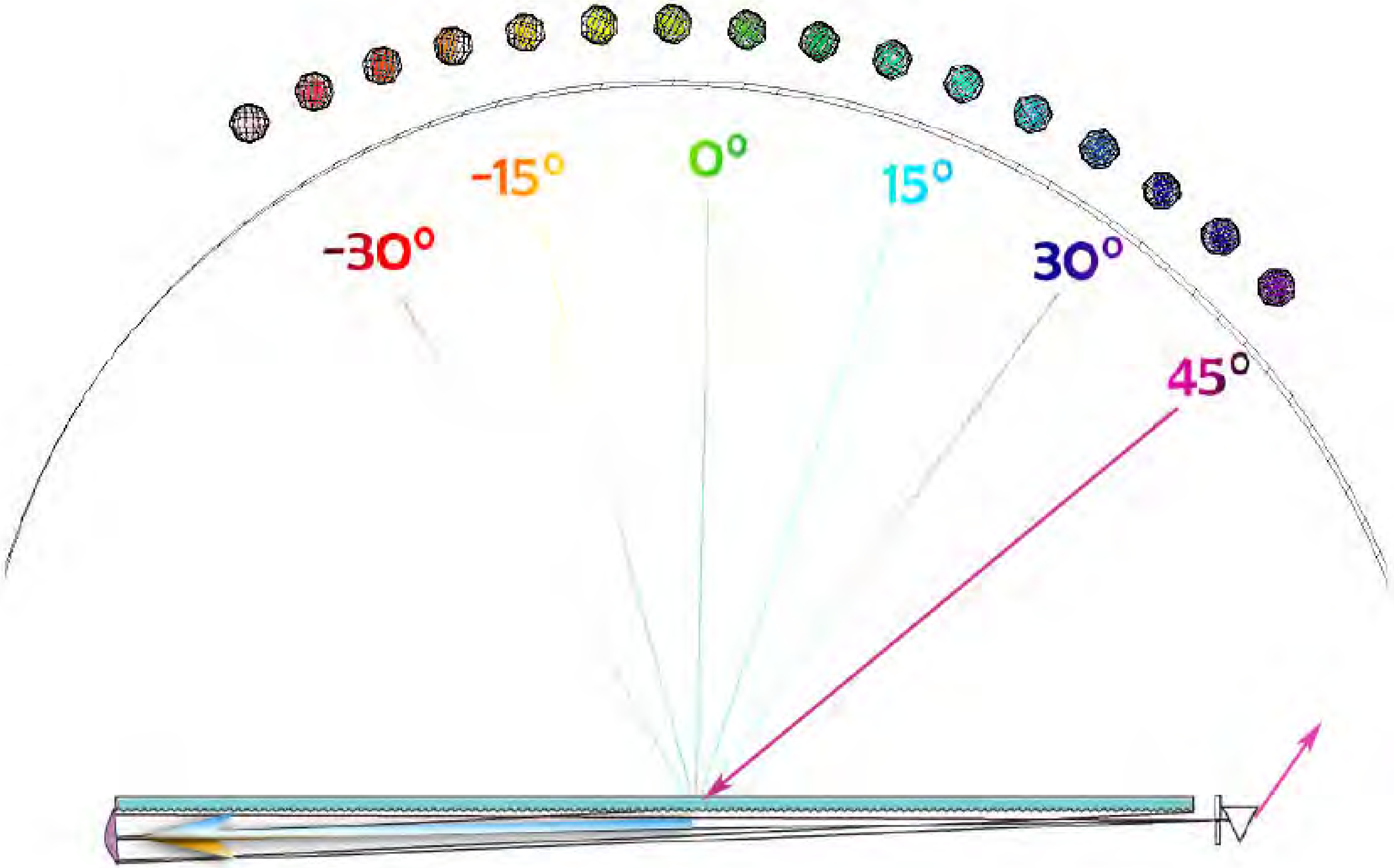
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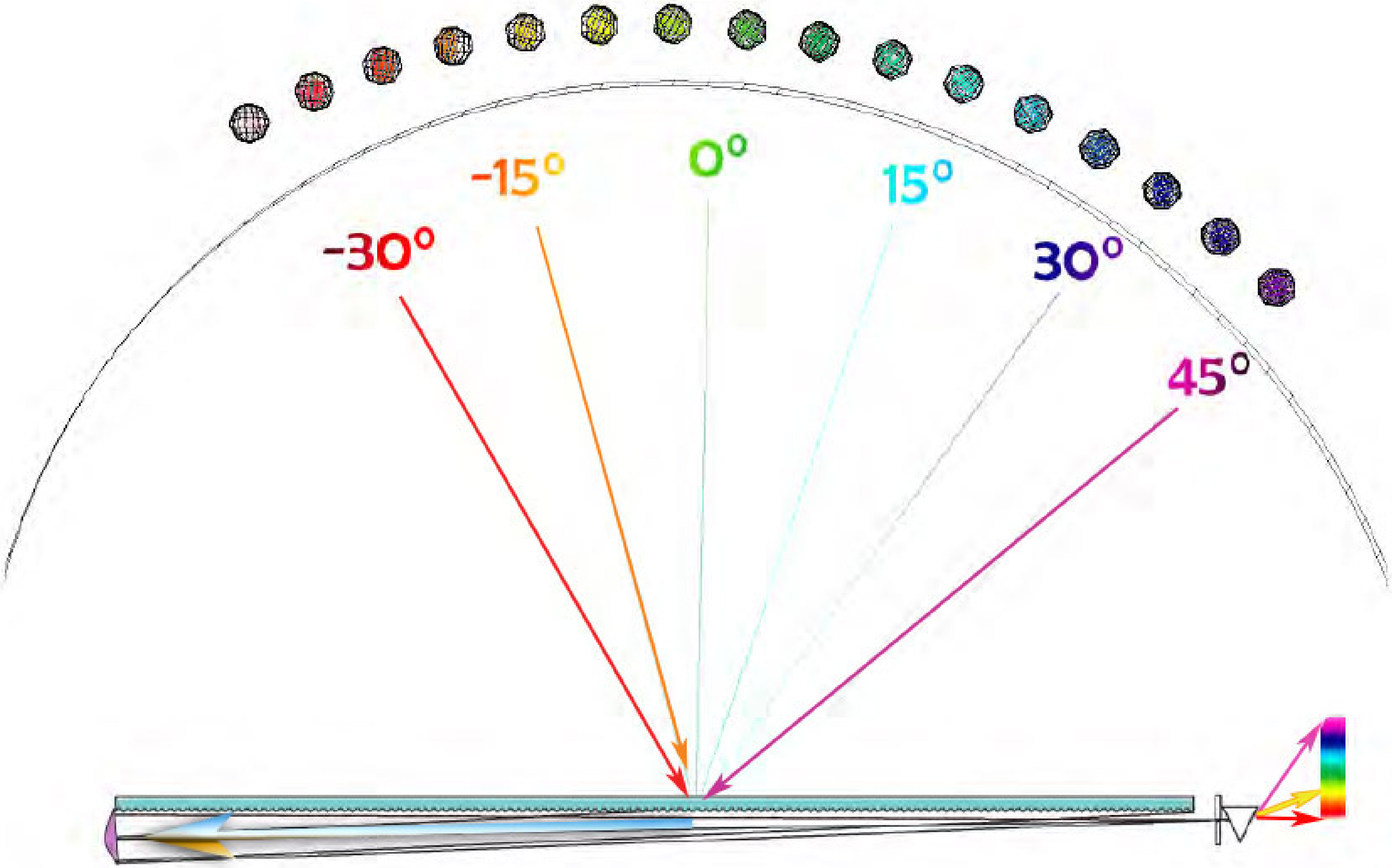
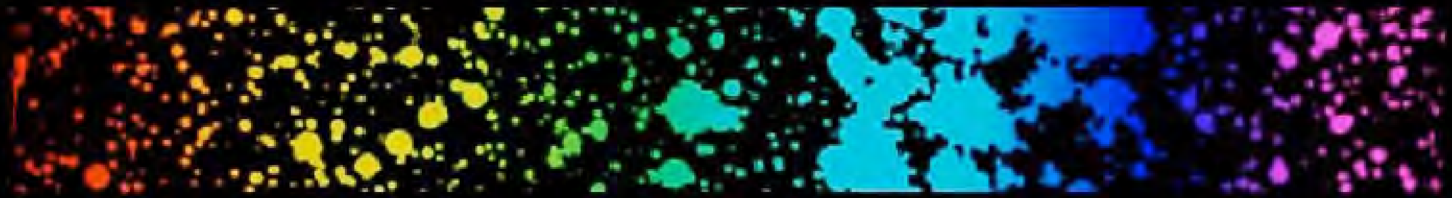


As an object precesses, its spectrum can be taken, and all objects can be seen – one wavelength at a time – over the course of an observation cycle.

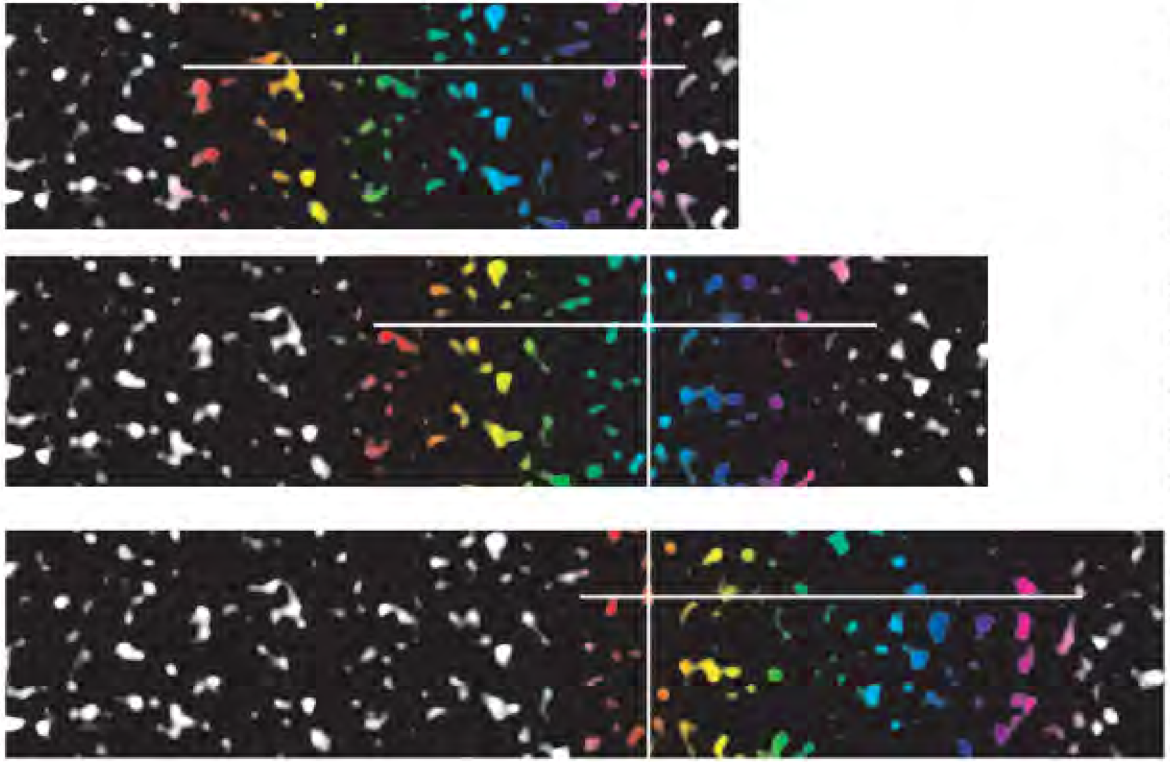
Look at the firmament through an ordinary telescope and see this.

Things look different through The Most.

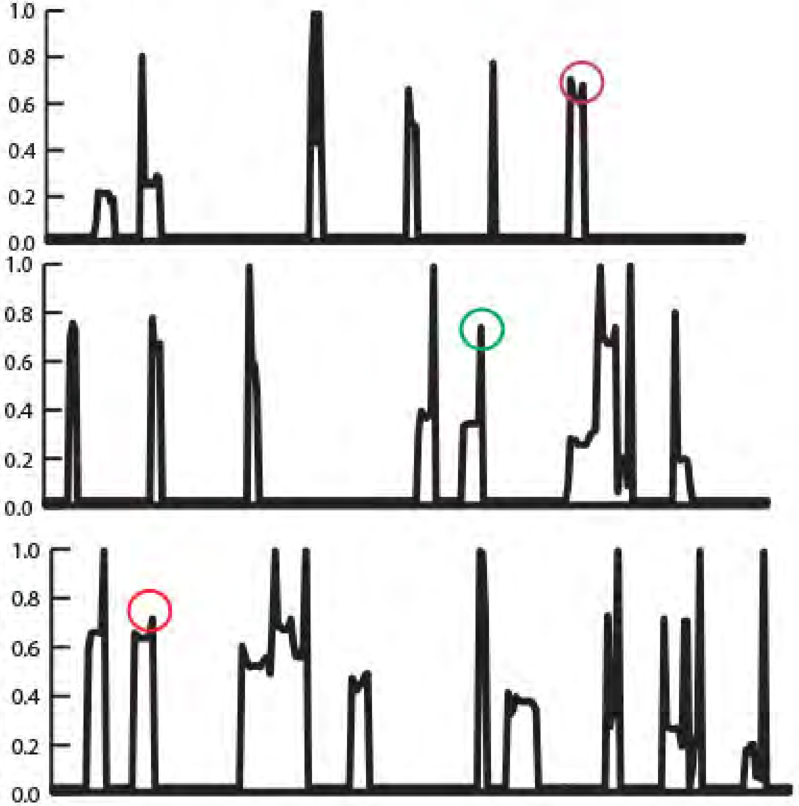


The focal plane array of The Most acquires an image like this.

Data Reduction



Three samples of one star



Three frames in the data parade

A sequence of frames taken at short integration periods results in a spectrum for each object and for all objects.

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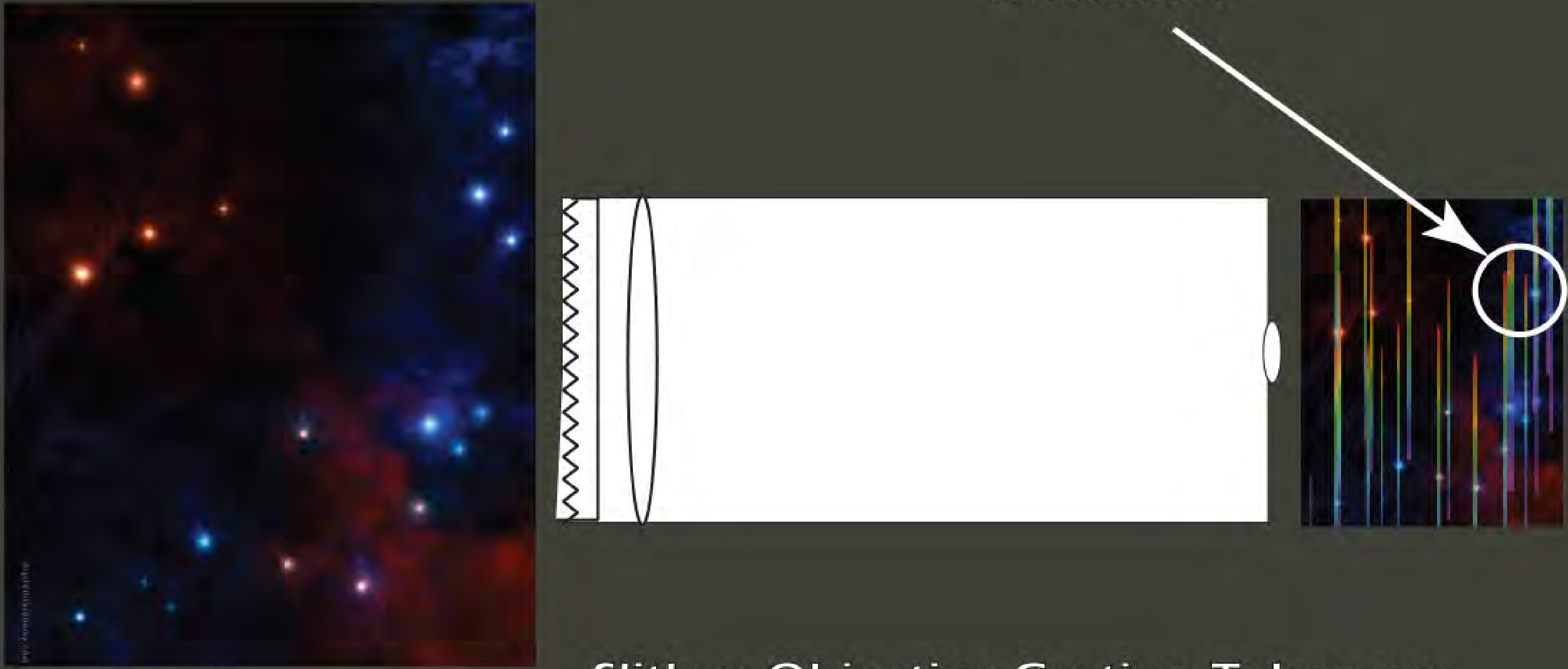
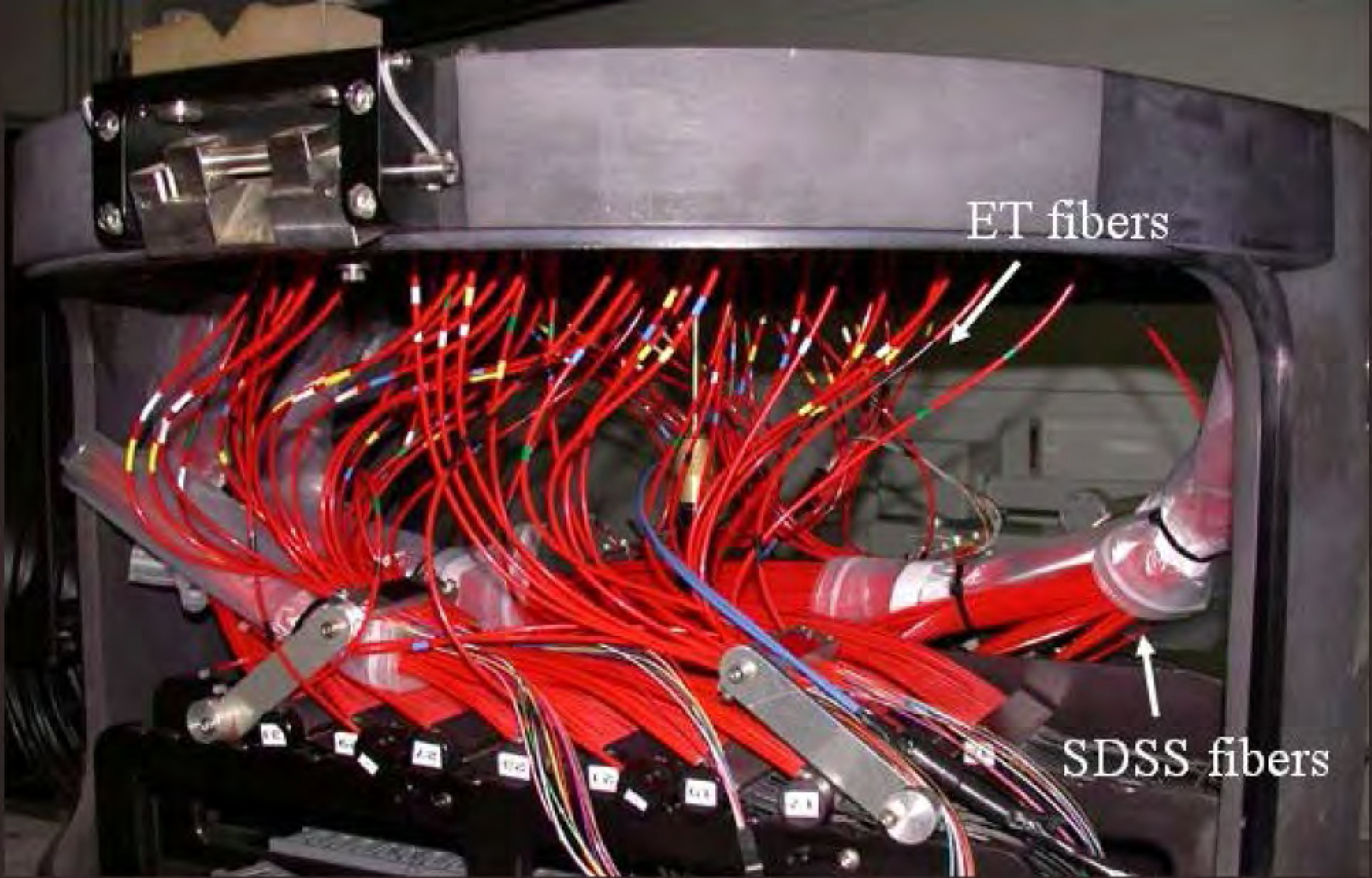


Slitless Objective Grating Telescope

Originally, to take multiple object spectrograms, astronomers put a disperser in front of a telescope. This didn't work because of overlapping spectra cause ambiguities called metamers.



Disambiguating methods do exist. A brute force method has a fiber positioned at each star. The most advanced are capable of taking a few thousand spectra in a single observation cycle.

Luminosity Function

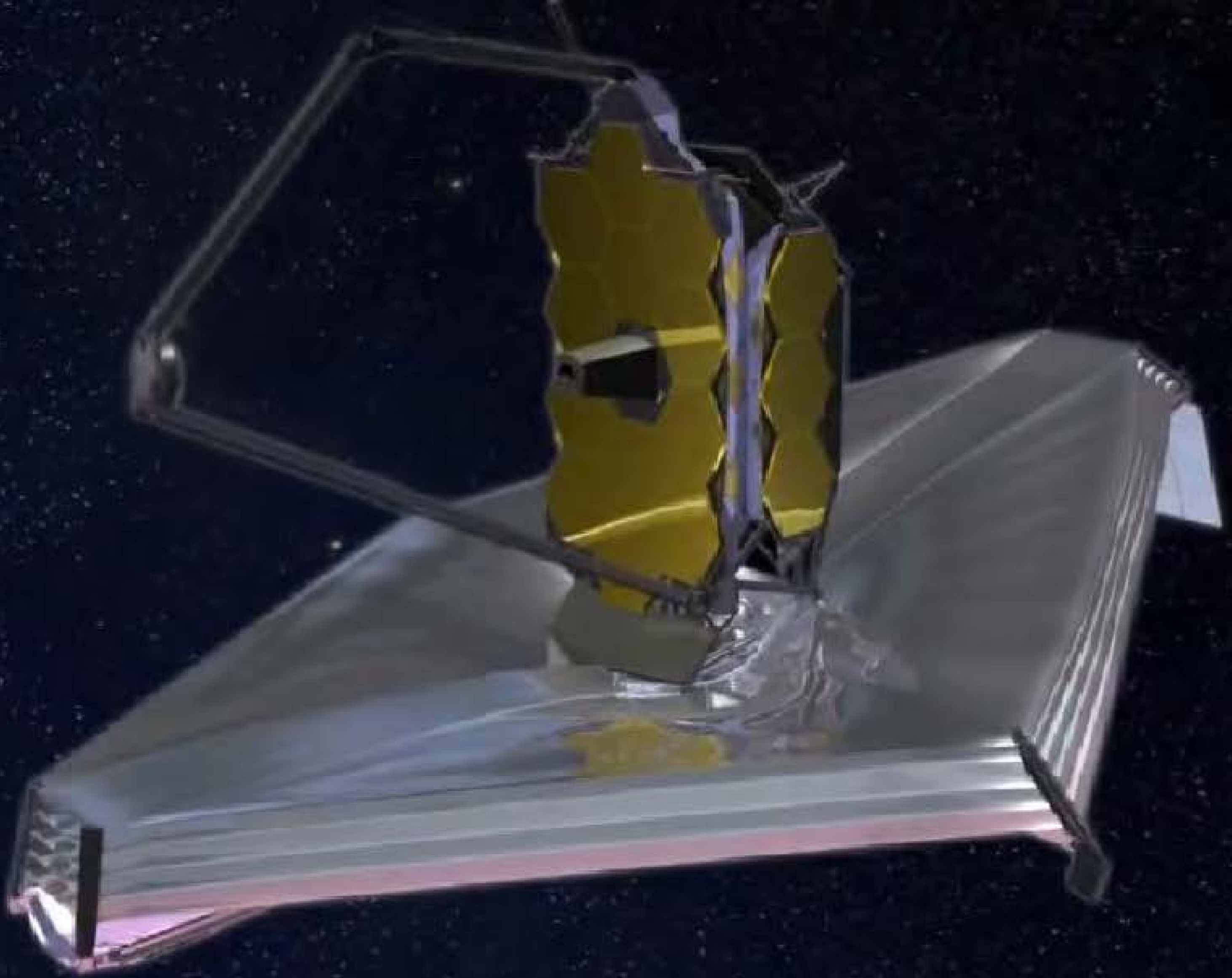
Magnitude	Example	Stars / degree^2	1° x 90°	Stars to this magnitude
-1.42	Sirius			1
6.5	Yale catalog			6,500
10.5	Hipparchus cat.	3	270	110,000
12	3" scope	12	1,080	500,000
13	6" scope	25	2,250	1,000,000
14	10" scope	60	5,400	2,500,000
15.5		300	27,000	10,000,000
20.5		30,000	**2,700,000**	1,000,000,000
23	Best scope	300,000	**27,000,000**	10,000,000,000

The MOST *multiple object spectroscopy*

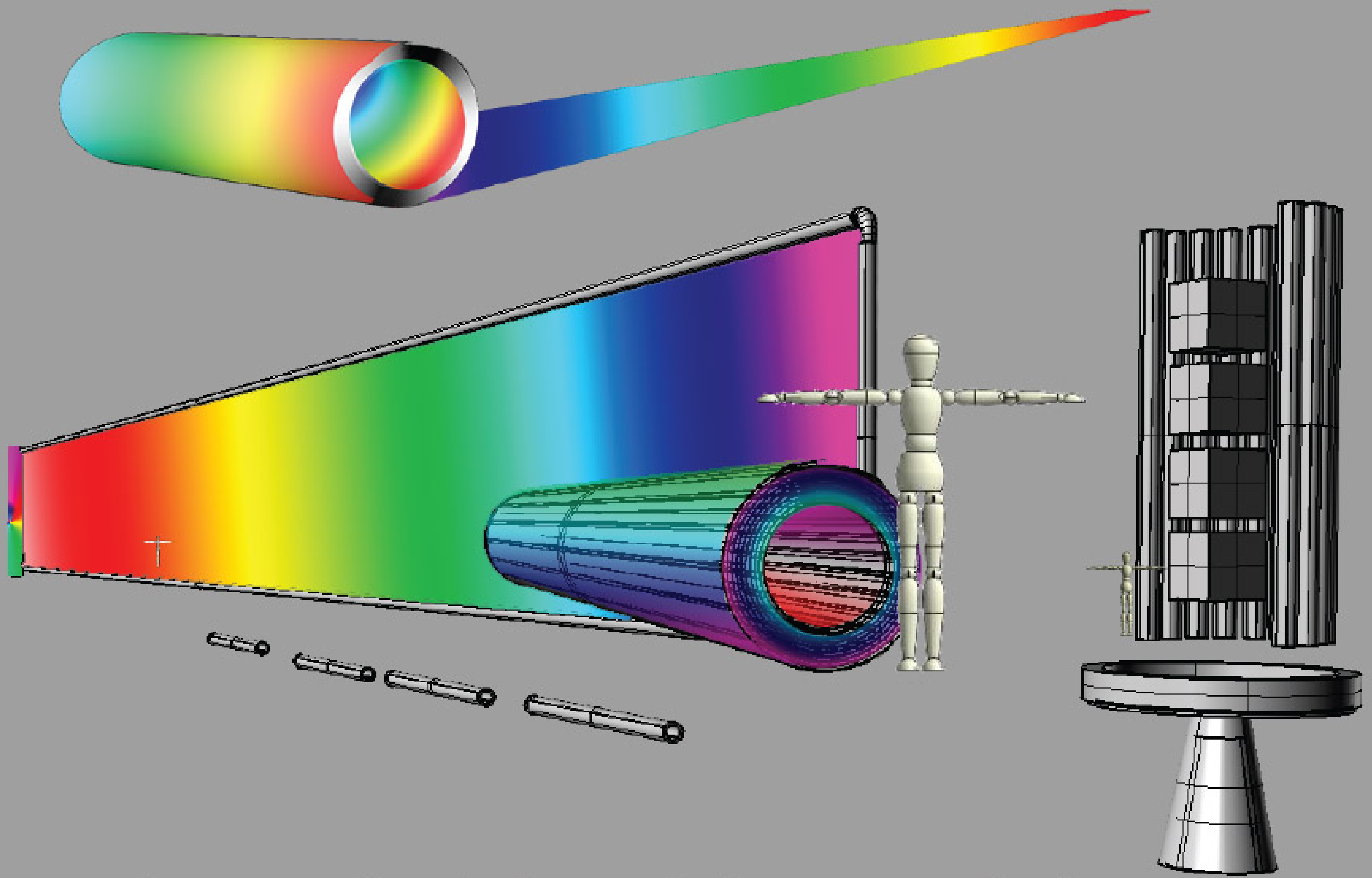
A three order magnitude increase in the number of simultaneous spectra per oberservation cycle over any competing technology at a 10 x increase in resolution.

Scaling up mirrors

Each doubling of mirror diameter has taken twice as long.
There are limits as to how large mirror primaries can grow.



Deliverability is another roadblock. The facets of the JWST fold up into a delivery vehicle rigidly and provide a mere 25 sq meters of collector.



A diffraction grating can be delivered from a cylinder roll as a gossamer membrane of any length and 10 meters height. How long do you want the aperture? How big do you want the collector? 100 sq. meters? 500 sq meters? Once deployed, gratings are flat, light weight, conceivably capable of kilometer scale in the optical regime.

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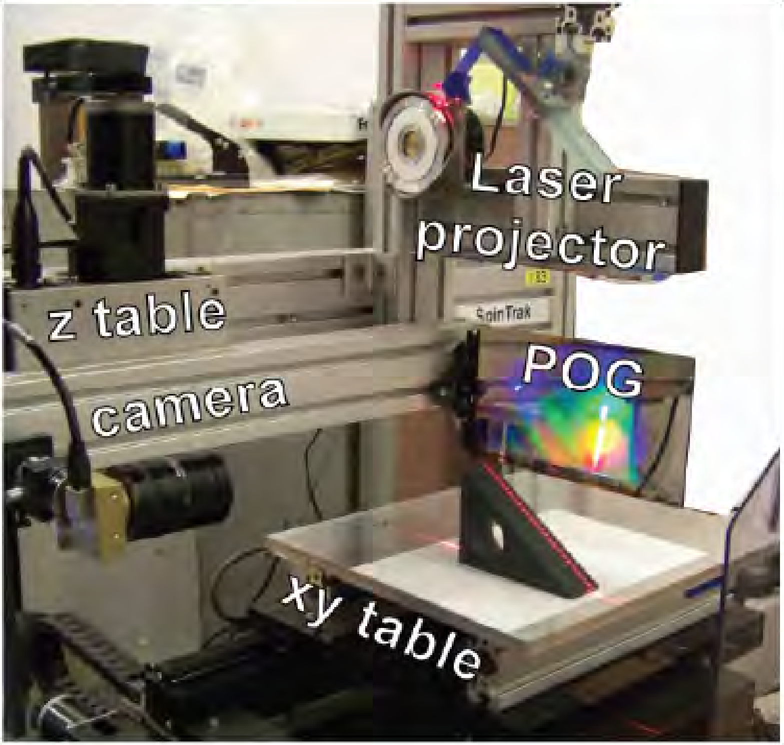
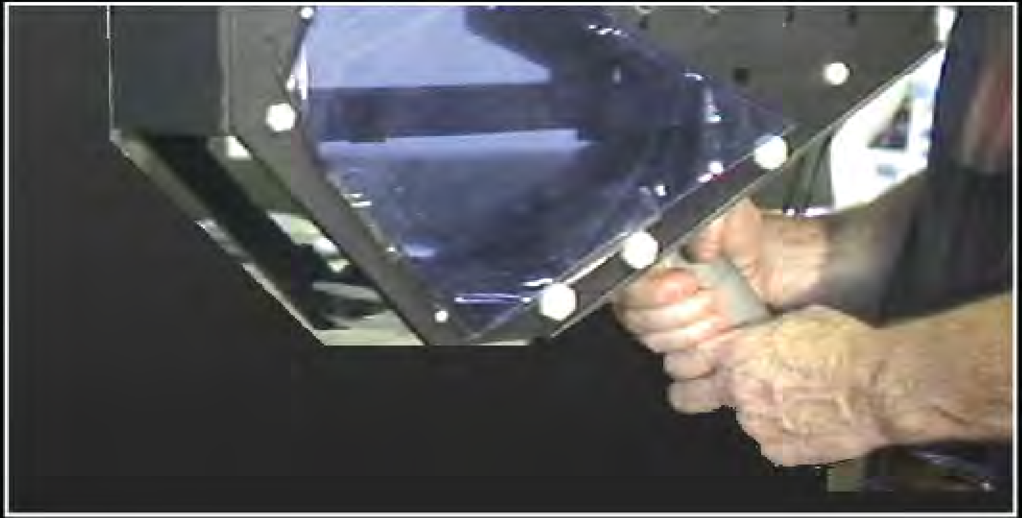
Primary Objective Grating Optical Devices made by 3DeWitt



3D Microscope

3D Ring



3D Scanner

Research funded by The National Science Foundation

We're just the first. So much more to come.

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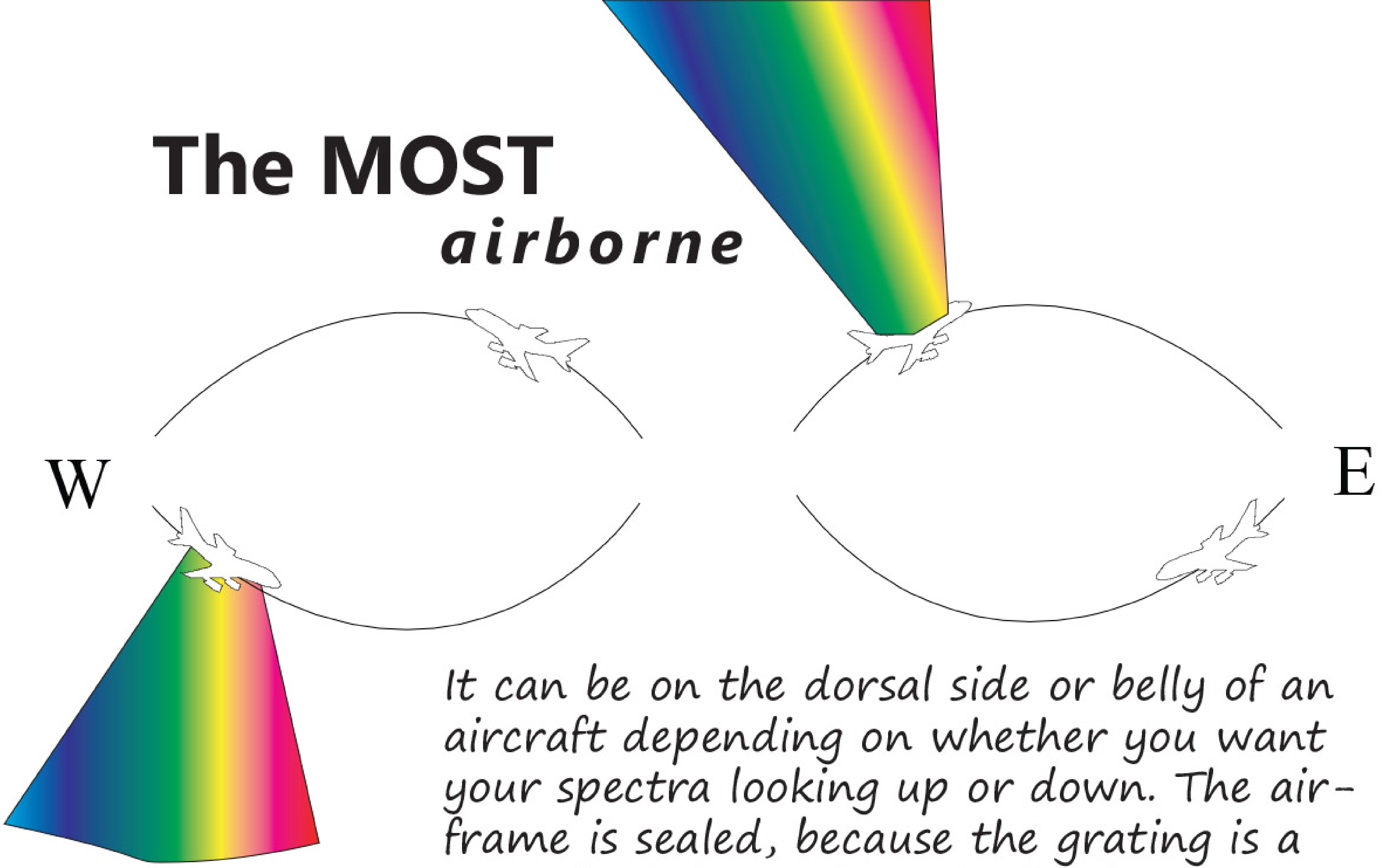
The MOST *airborne*



It can be on the dorsal side or belly of an aircraft depending on whether you want your spectra looking up or down. The airframe is sealed, because the grating is a row of windows along the fuselage.

100 Meter Aperture
geostationary

The
telescope can be in
geostationary. Given a long
aperture it will acquire detailed
spectra on the ground. Rob Hoyt
might send his spiderfab 'bot to
build the support trusses.

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Everything you know is wrong.
The primary objective is a disperser.

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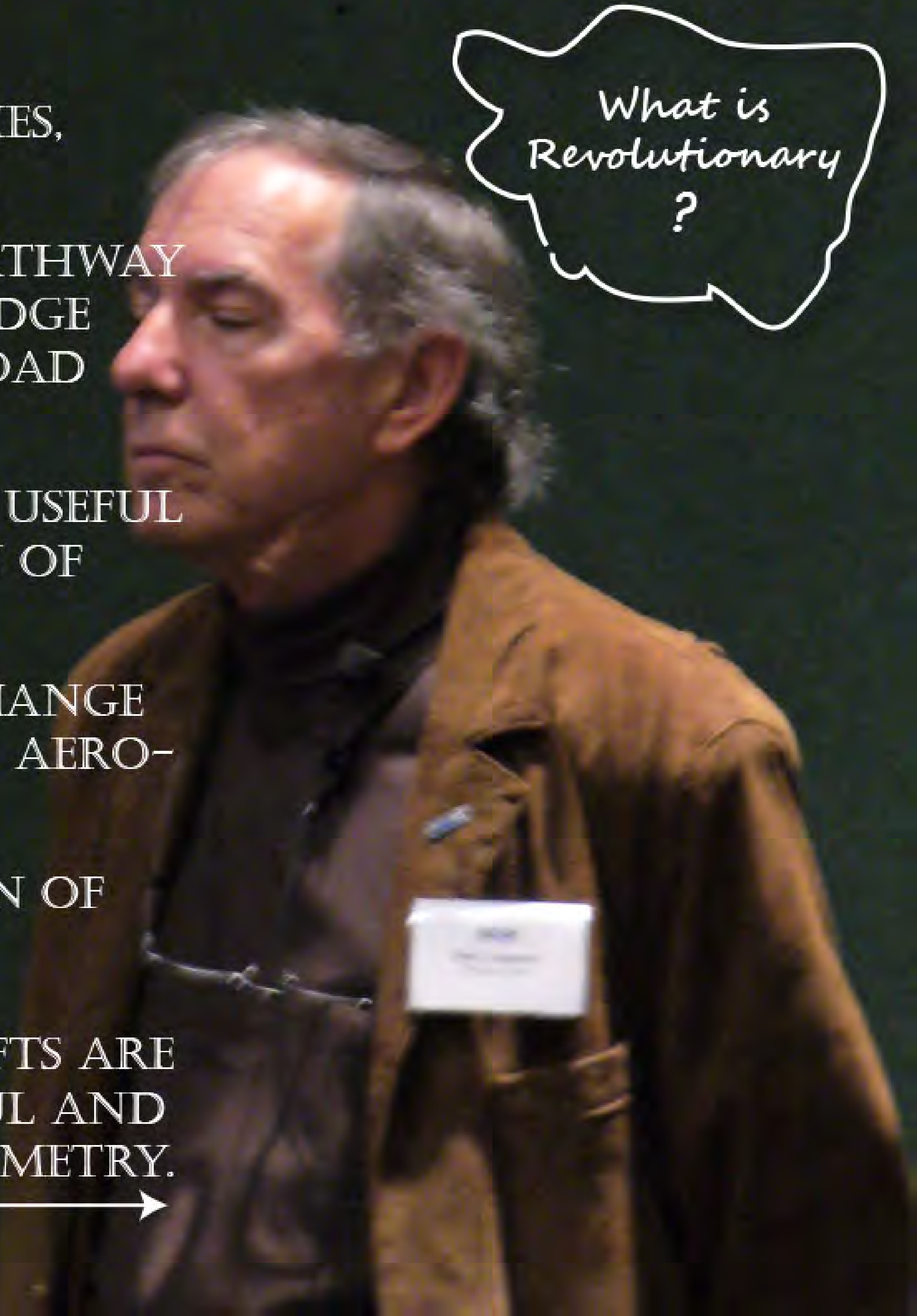
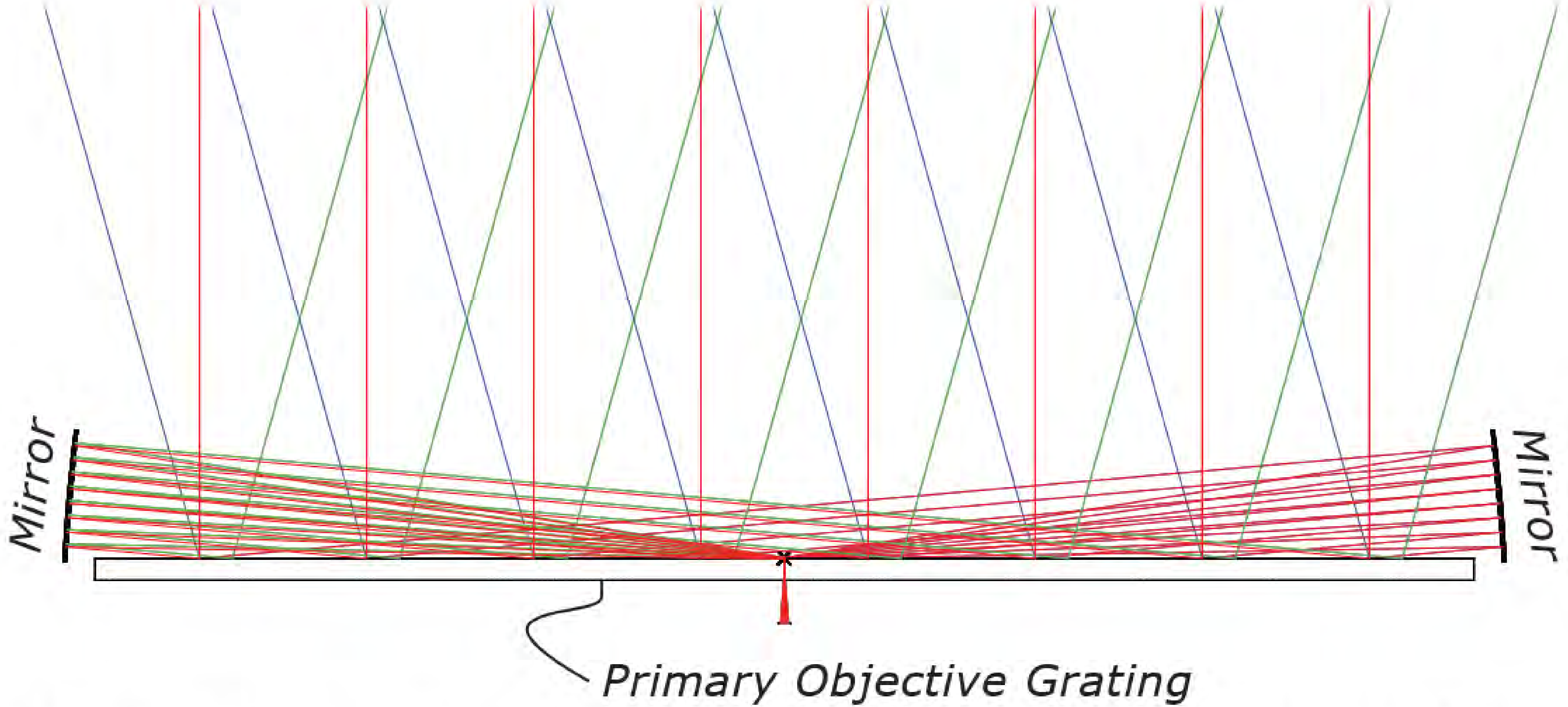
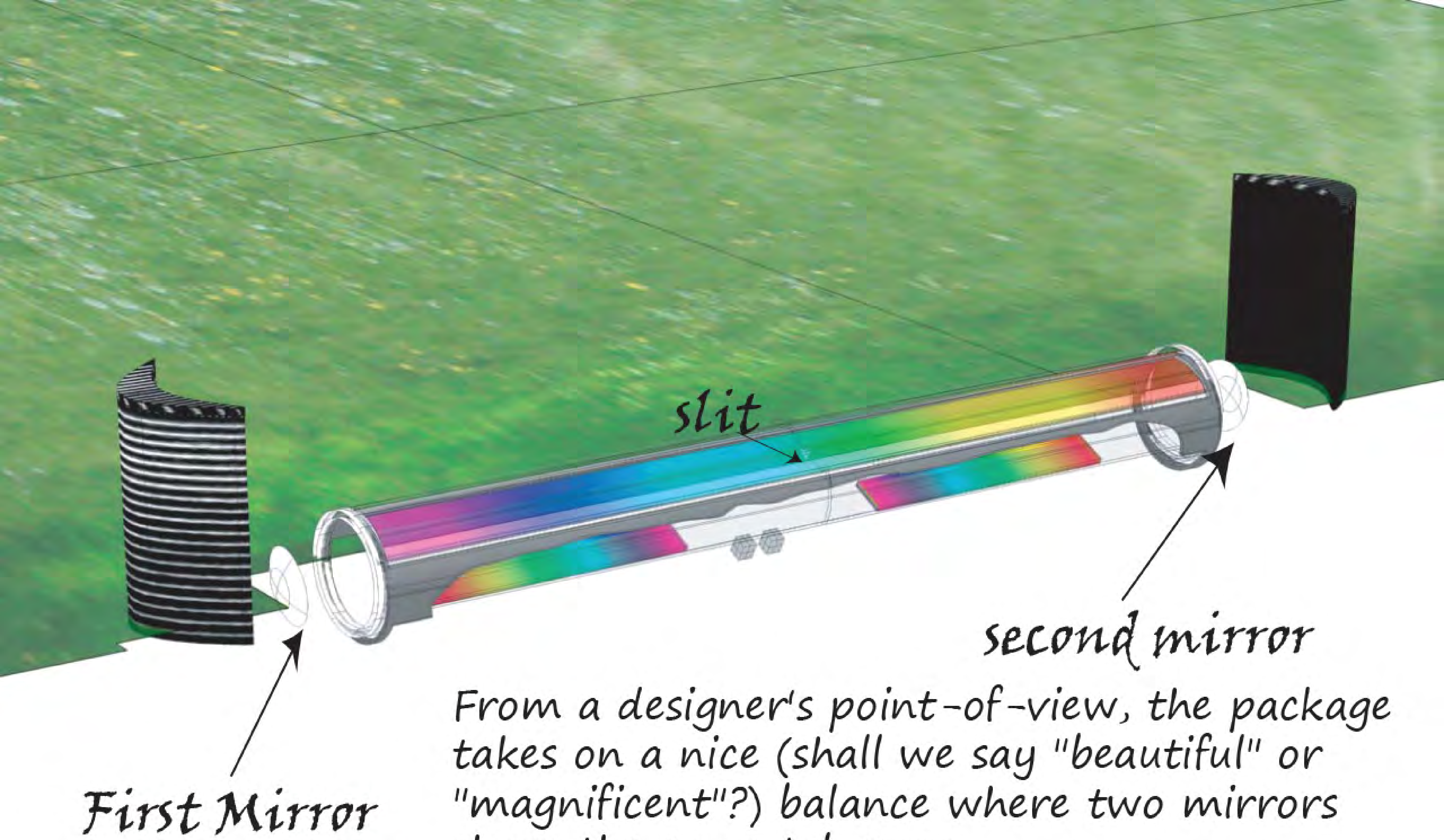
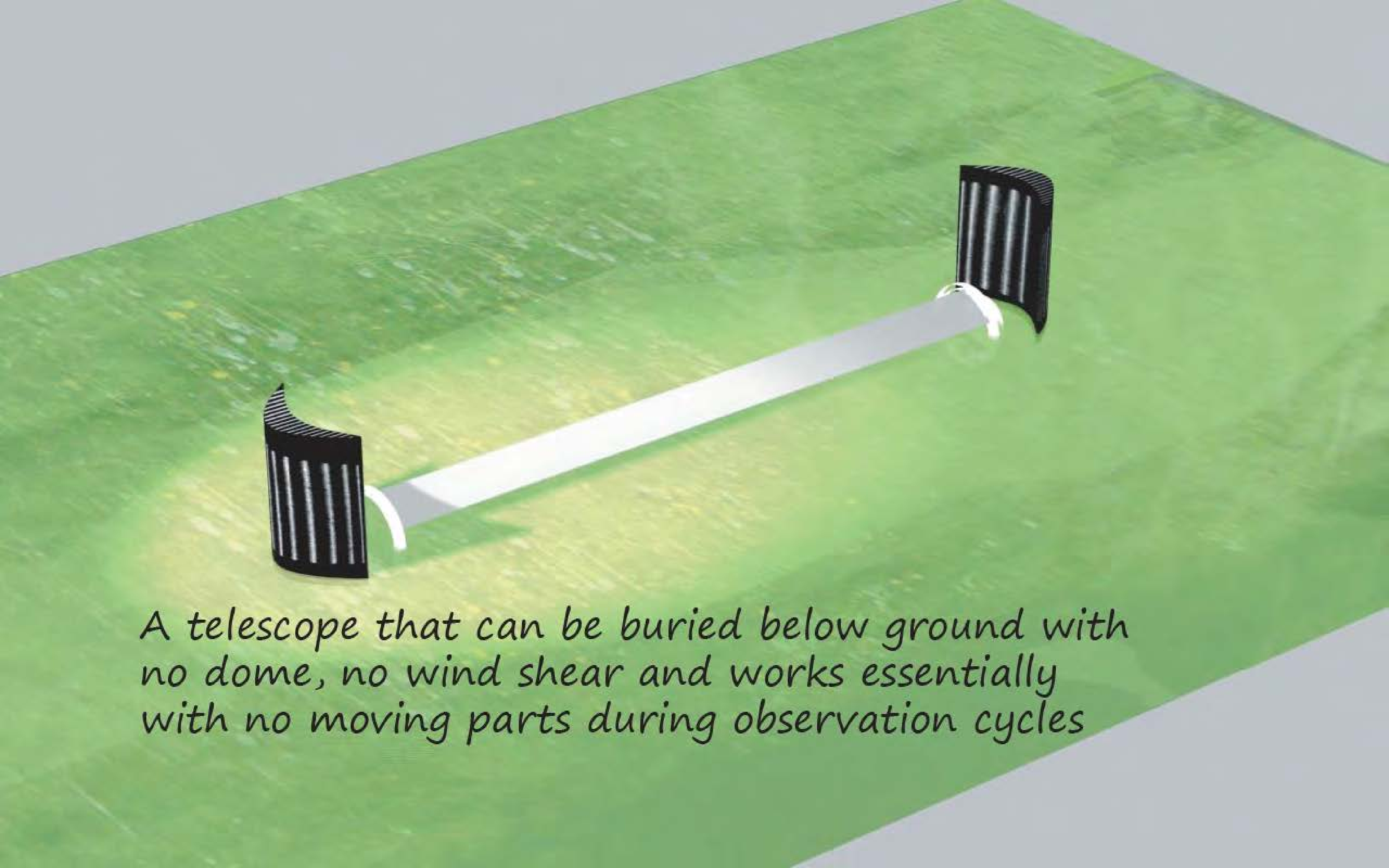




What happens when the secondary mirror is symmetrically opposed by a second mirror?. Flux collection is doubled. The free spectral range doubles from 90 degrees to 180 degrees. Third, calibration can be achieved by cross-correlation between two readings of the same object at different moments in time.

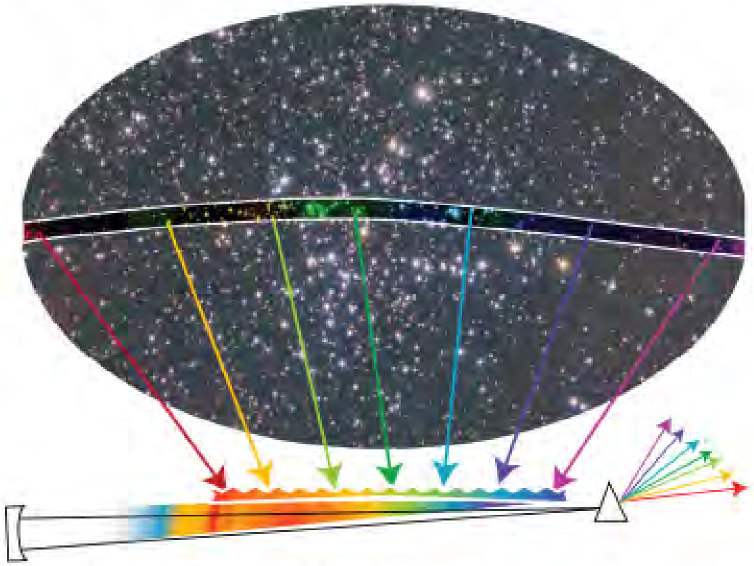


From a designer's point-of-view, the package takes on a nice (shall we say "beautiful" or "magnificent"?) balance where two mirrors share the same telescope.



A telescope that can be buried below ground with no dome, no wind shear and works essentially with no moving parts during observation cycles

The Multiple Object Spectrographic Telescope



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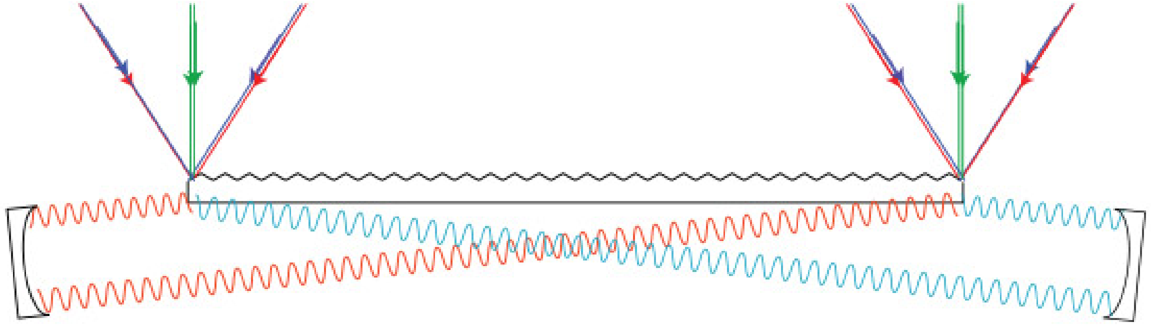
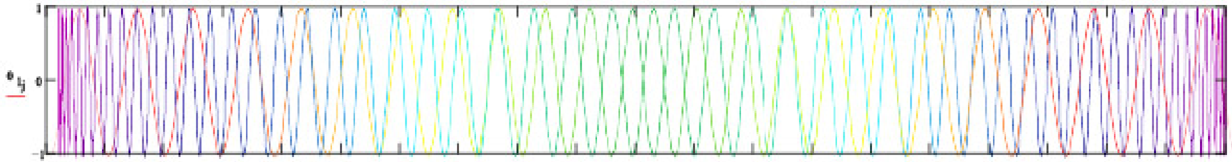
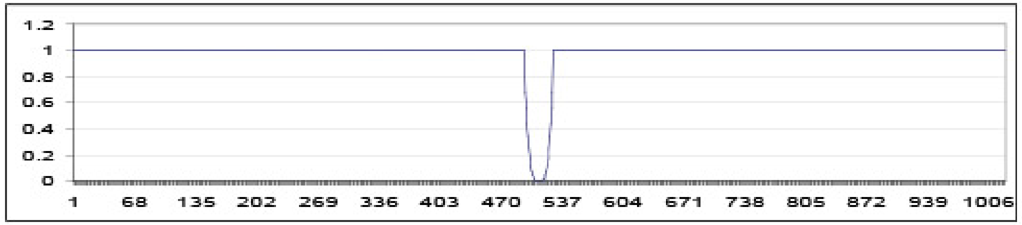
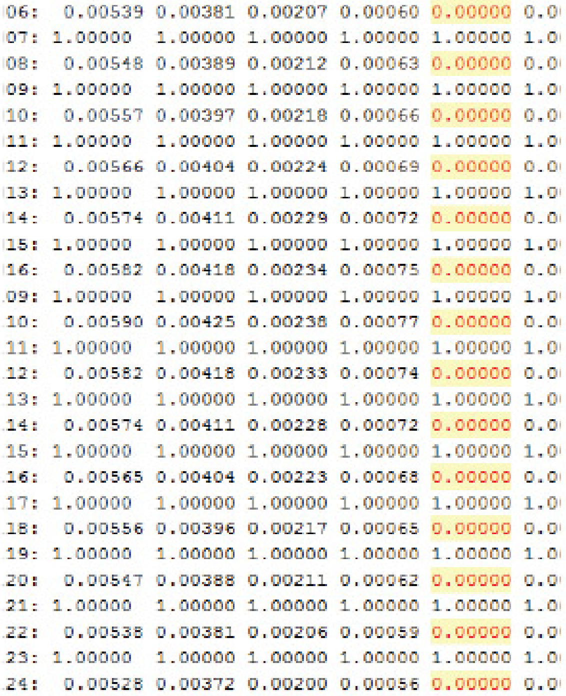
Holographic Optical Method for Exoplanet Spectroscopy

The dual mirror symmetry now leads us from The MOST The Multiple Object Spectrographic Telescope to HOMES, the Holographic Optical Method of Exoplanet Spectroscopy. The MOST sees all stars one wavelength at a time. HOMES sees the planets of one star in all wavelengths all the time.









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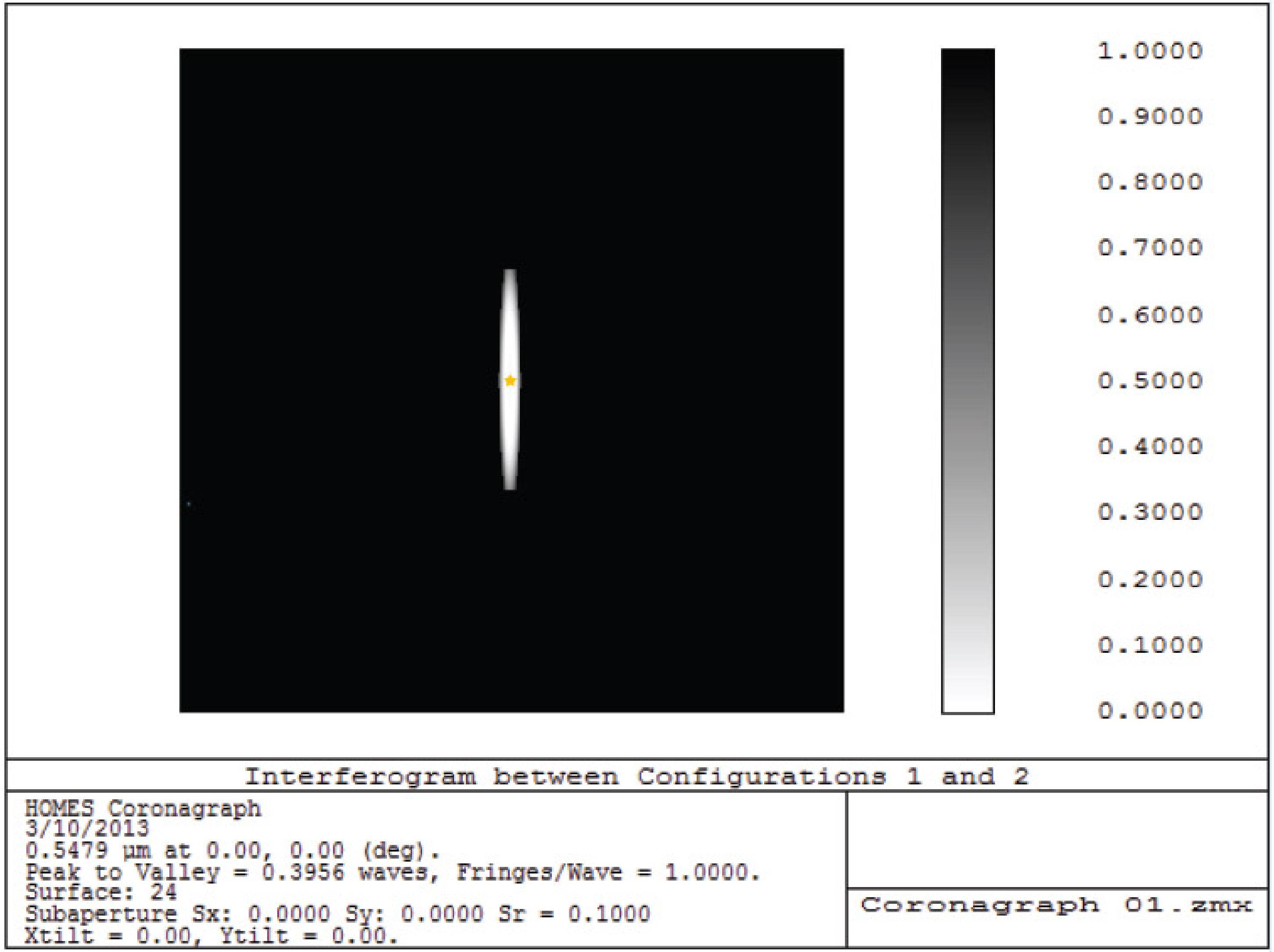
07: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
08:  0.00548 0.00389 0.00212 0.00063 0.00000 0.0
09: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
10:  0.00557 0.00397 0.00218 0.00066 0.00000 0.0
11: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
12:  0.00566 0.00404 0.00224 0.00069 0.00000 0.0
13: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
14:  0.00574 0.00411 0.00229 0.00072 0.00000 0.0
15: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
16:  0.00582 0.00418 0.00234 0.00075 0.00000 0.0
09: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
10:  0.00590 0.00425 0.00238 0.00077 0.00000 0.0
11: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
12:  0.00582 0.00418 0.00233 0.00074 0.00000 0.0
13: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
14:  0.00574 0.00411 0.00228 0.00072 0.00000 0.0
15: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
16:  0.00565 0.00404 0.00223 0.00068 0.00000 0.0
17: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
18:  0.00556 0.00396 0.00217 0.00065 0.00000 0.0
19: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
20:  0.00547 0.00388 0.00211 0.00062 0.00000 0.0
21: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
22:  0.00538 0.00381 0.00206 0.00059 0.00000 0.0
23: 1.00000  1.00000 1.00000 1.00000 1.00000 1.0
24:  0.00528 0.00372 0.00200 0.00056 0.00000 0.0
```

We start with the dual mirror configuration and design a coronagraph. An exoplanet cannot be seen if its host star is not extinguished. When two mirrors are opposed facing a single diffraction grating, and their beams combined, then two equal and opposite spectra share one spectral line where destructive interference creates a single extremely sharp subtraction to zero. The interference at the line where the beams share a single wavelength is a singularity, an absolute null.



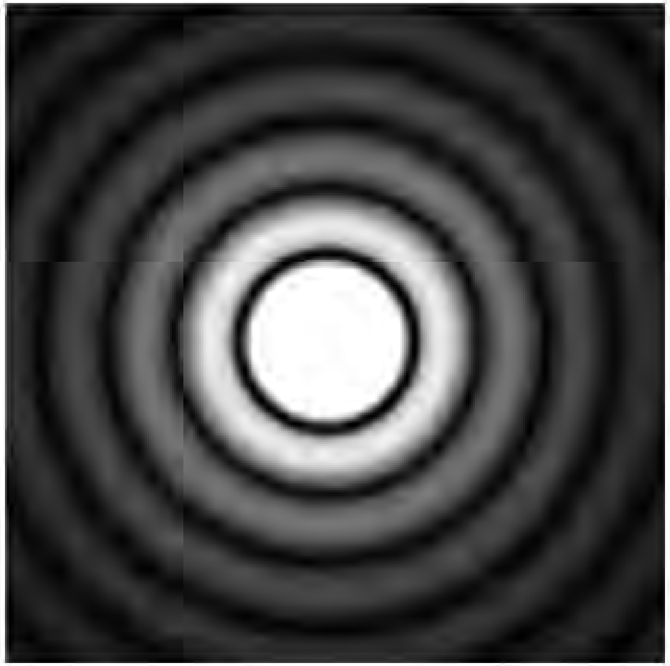
Interferogram between Configurations 1 and 2

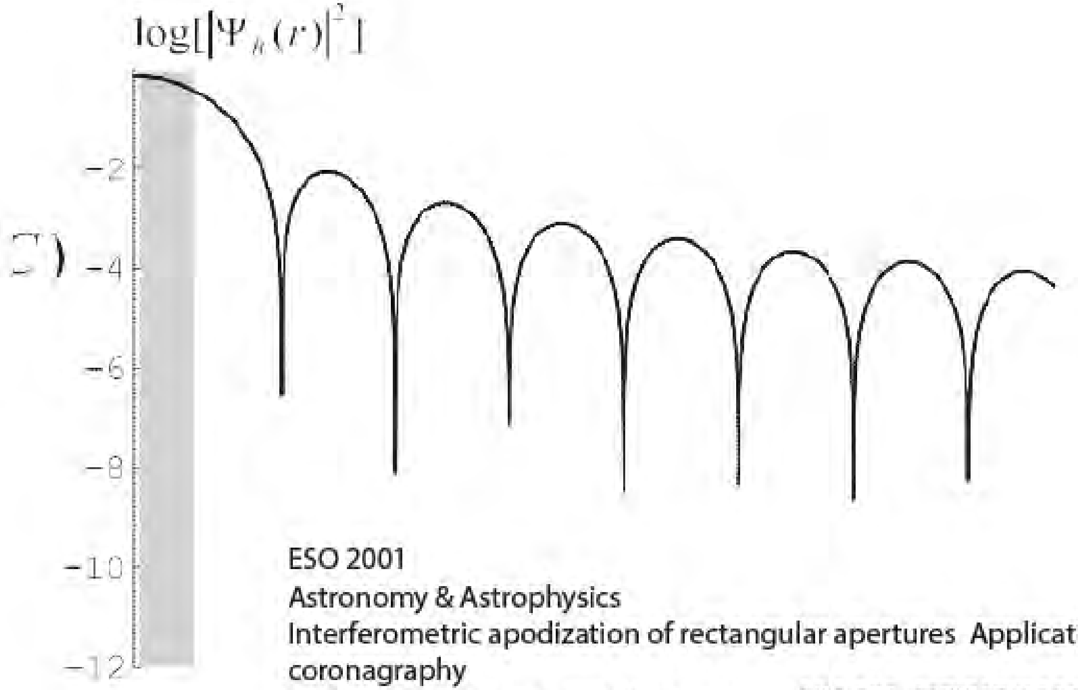
```
HOMES Coronagraph
3/10/2013
0.5479 µm at 0.00, 0.00 (deg).
Peak to Valley = 0.3956 waves, Fringes/Wave = 1.0000.
Surface: 24
Subaperture Sx: 0.0000 Sy: 0.0000 Sr = 0.1000
Xtilt = 0.00, Ytilt = 0.00.
```

```
Coronagraph 01.zmx
```

We see that null in this interferogram. .The interferometer is a coronagraph because its null is on a single central wavelength band leaving the rest of the field for acquisition of the planetary system. A tiny “star” is marked in yellow at the null.

Nulling interferometer for coronagraphy

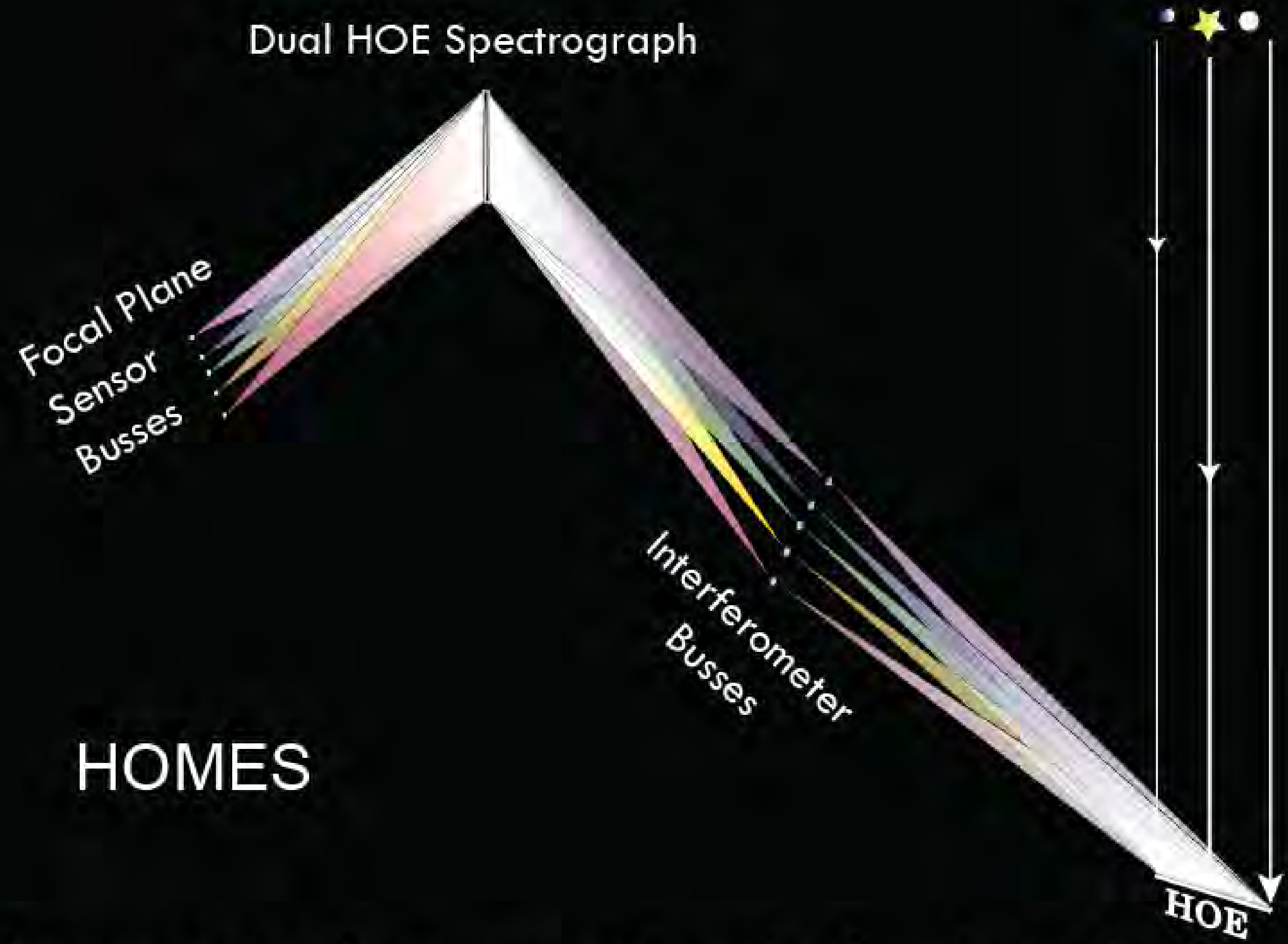




ESO 2001
Astronomy & Astrophysics
Interferometric apodization of rectangular apertures Application to stellar coronagraphy
C. Aime, R. Soummer, and A. Ferrari

A&A 379, 697{707 (2001)
DOI: 10.1051/0004-6361:20011293

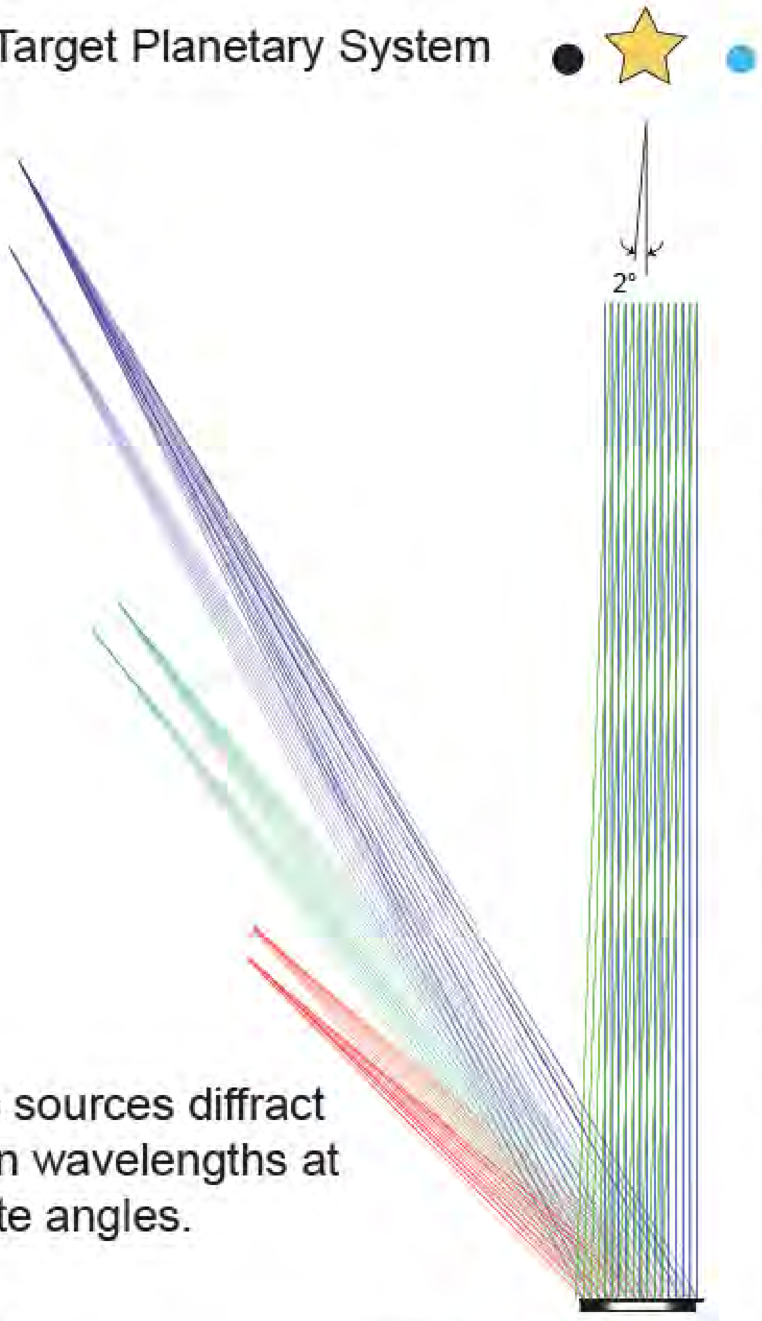
Contrast this with conventional nulling interferometry and you can see the advantage. Conventional nulling interferometry has multiple rings which in a coronagraph will null in the planetary region and can extinguish flux from very planets we are looking for.



The interferometer is part of a chain that forms a whole: HOMES, a formation-flown telescope parked at the second Lagrange Point. It has a holographic reflective primary, a nulling interferometer coronagraph which relays the images to a secondary spectrograph and on to the science cameras that collect the dispersed planetary spectra.

Target Planetary System

Example - Second source off-axis by 2°

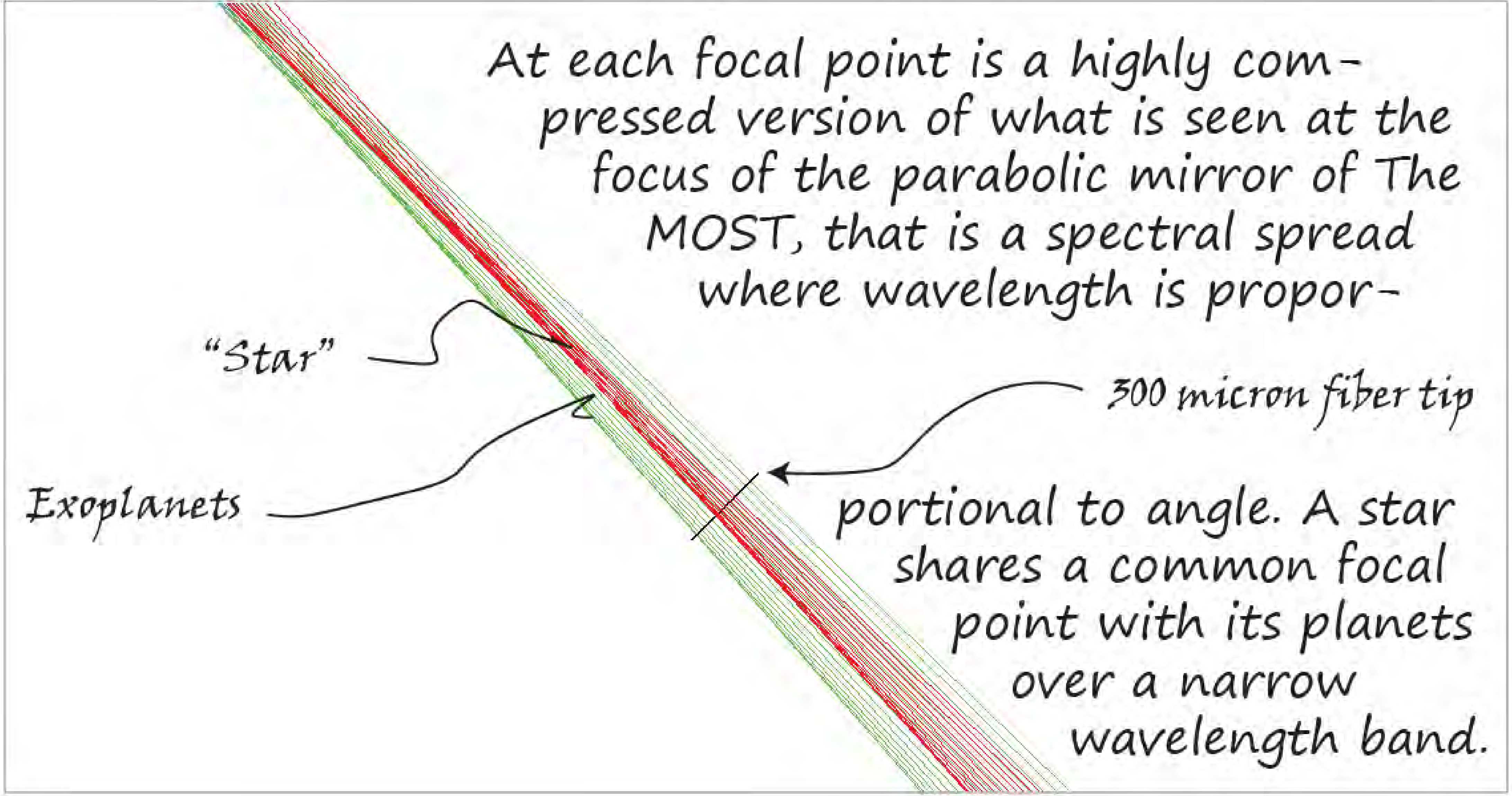


HOMES uses a hologram as a primary objective. When the star and its planetary system at infinity play back the hologram, they focus as an infinite number of images of themselves, each image at different wavelength. Here we compare the focii for a target star and its planets as compared with a other source off-axis by 2 degrees

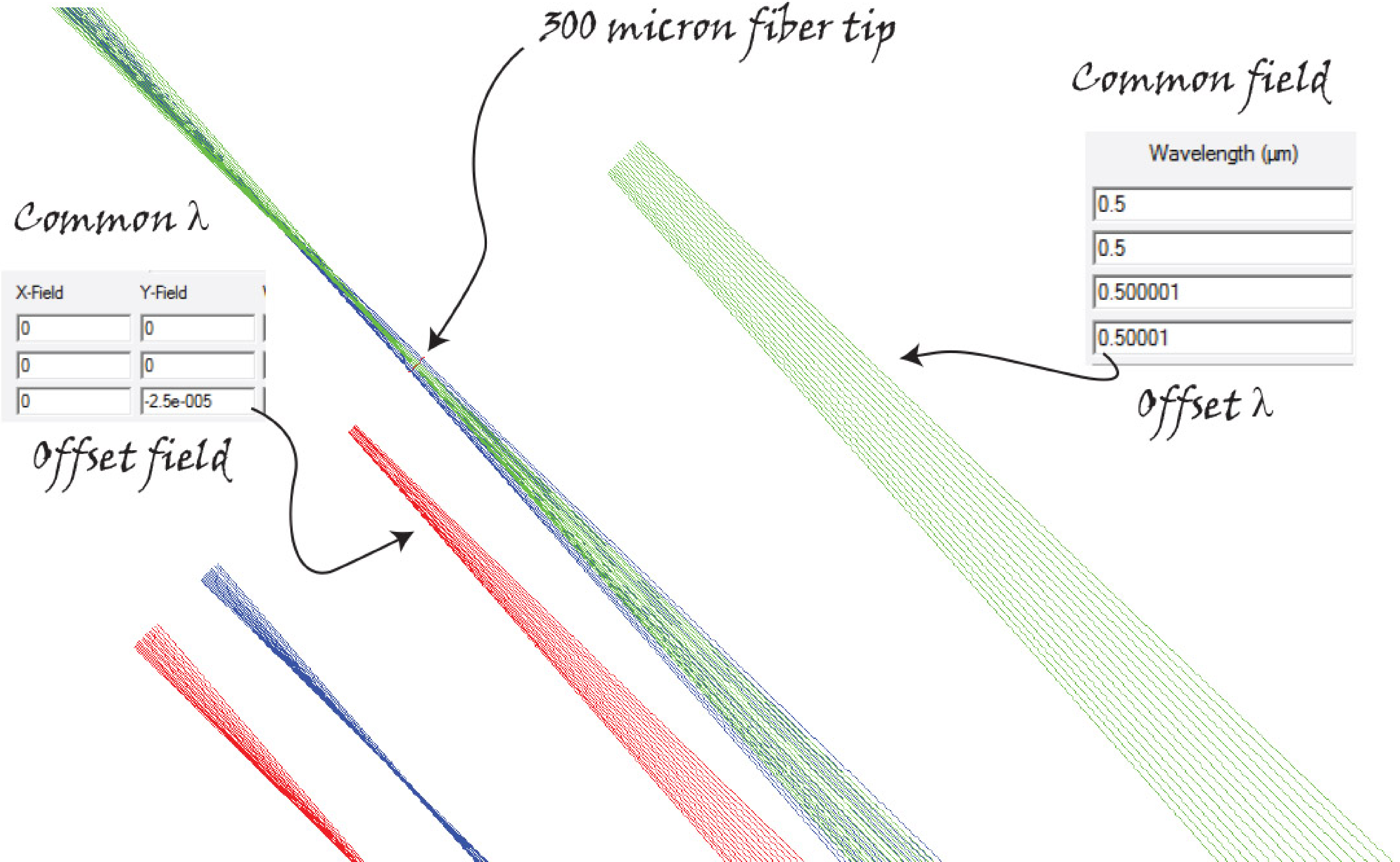
Off-axis sources diffract common wavelengths at disparate angles.

Holographic Optical Element Primary

At each focal point is a highly compressed version of what is seen at the focus of the parabolic mirror of The MOST, that is a spectral spread where wavelength is proportional to angle. A star shares a common focal point with its planets over a narrow wavelength band.



Only one narrow band focuses on each fiber tip.



300 micron fiber tip

Common λ

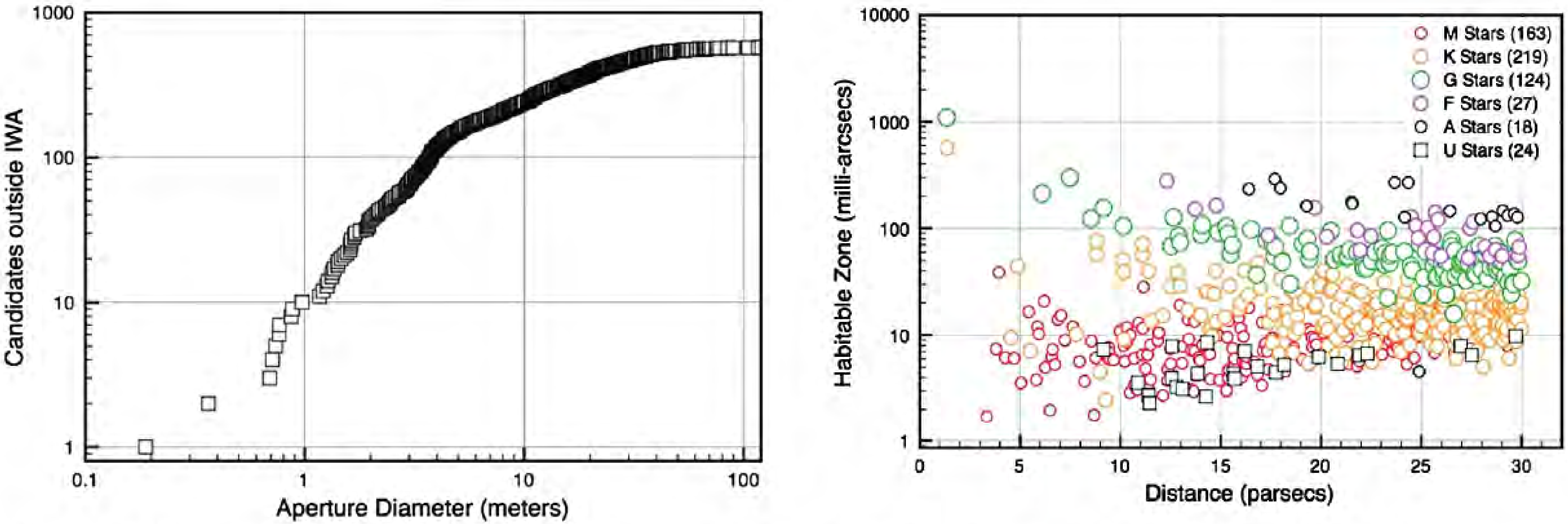
X-Field	Y-Field
0	0
0	0
0	-2.5e-005

Offset field

Common field

Wavelength (µm)
0.5
0.5
0.500001
0.50001

Offset λ



Richard G. Lyon & Mark Clampin, "Space telescope sensitivity and controls for exoplanet imaging" *Optical Engineering* 51(1), 011002 (January 2012)

The problem is not resolution. A 50 to 100 m primary objective hologram has the requisite angular and spectral resolution to see exoplanets within 10 parsecs. Indeed, according to Lyon & Clampin a 100 meter primary could resolve habitable exoplanets out to 30 parsecs.

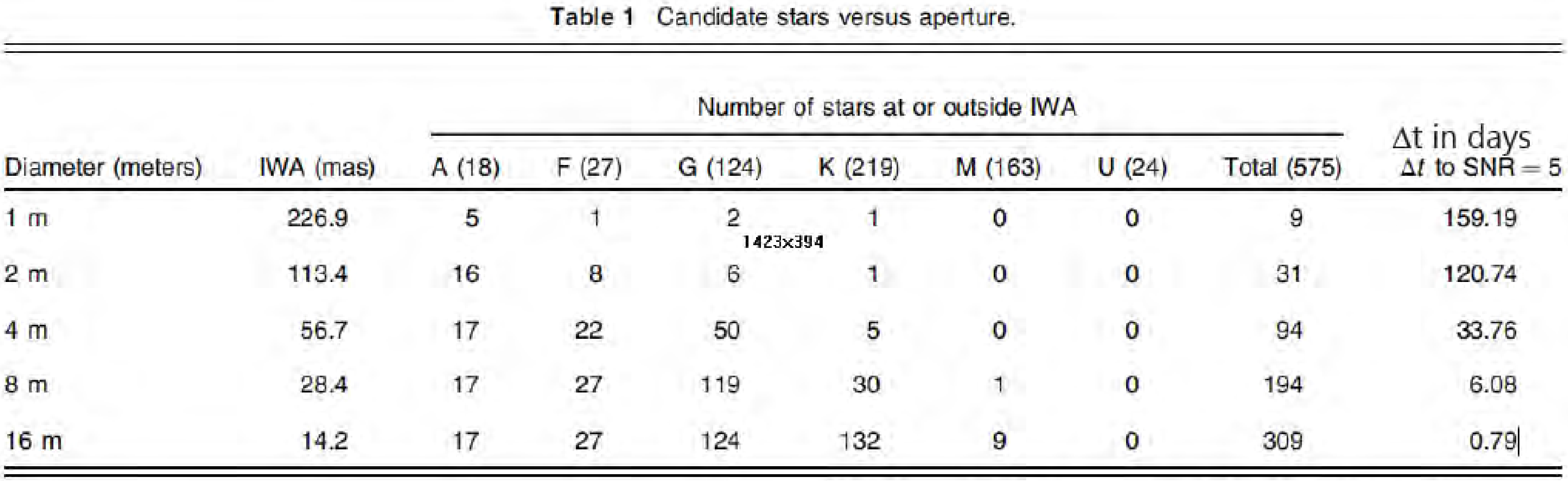


Table 1 Candidate stars versus aperture.

		Number of stars at or outside IWA							Δt in days
Diameter (meters)	IWA (mas)	A (18)	F (27)	G (124)	K (219)	M (163)	U (24)	Total (575)	Δt to SNR = 5
1 m	226.9	5	1	2	1	0	0	9	159.19
2 m	113.4	16	8	6	1	0	0	31	120.74
4 m	56.7	17	22	50	5	0	0	94	33.76
8 m	28.4	17	27	119	30	1	0	194	6.08
16 m	14.2	17	27	124	132	9	0	309	0.79

Richard G. Lyon & Mark Clampin, *op. cit.*

The problem is the flux, because each highly resolved HOMES bandpass sees few photons. Let's say an exoplanet at 10 parsecs produces 10 photons per square meter per minute. That means with a HOMES 500 square meter primary about 500 photons per minute at 100% efficiency or 50 photons per minute with 10% throughput. Dividing these into spectra means picking broad bands to achieve integration times of days rather than weeks or months.

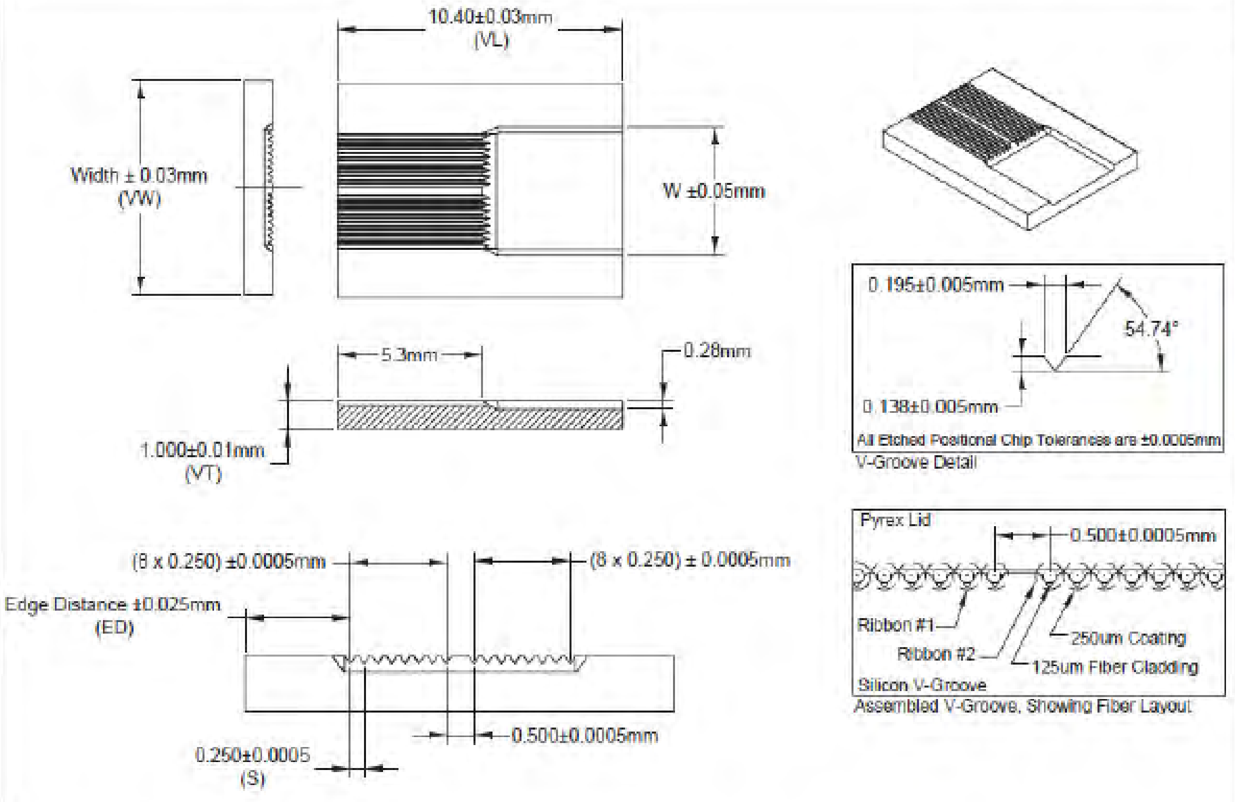
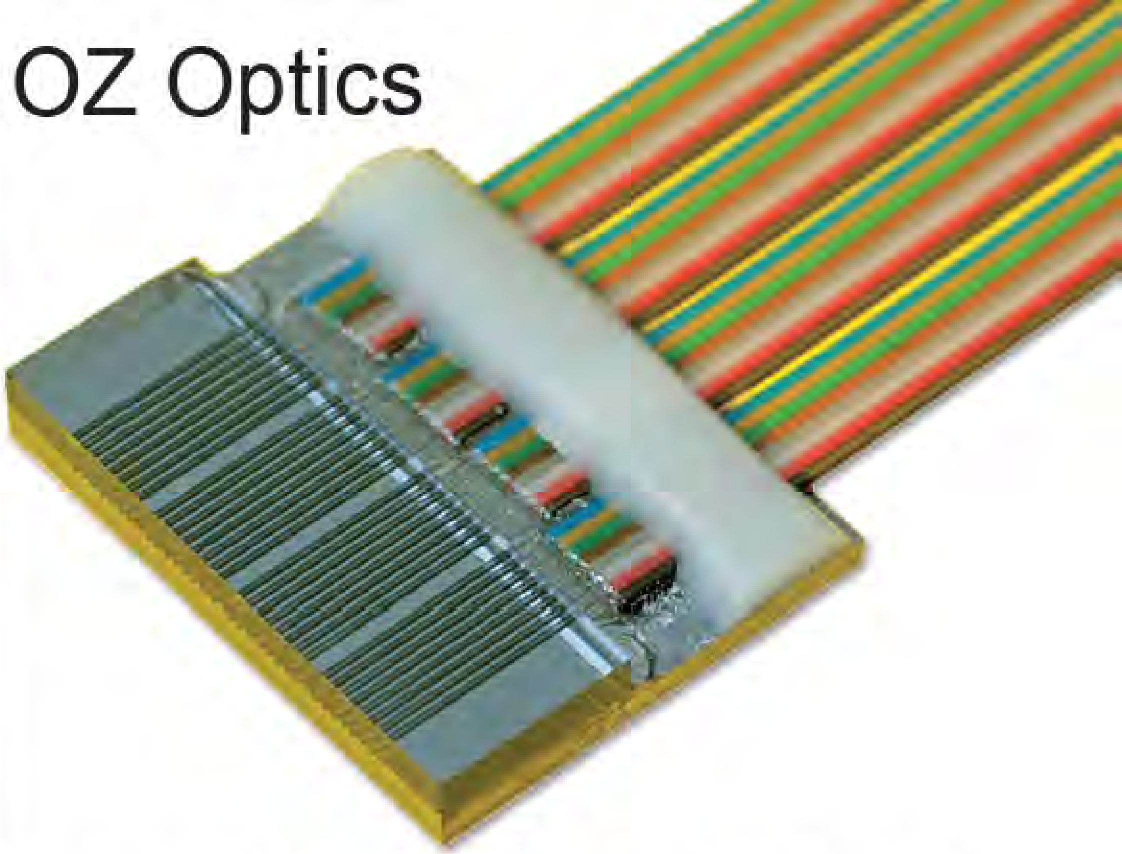


Figure 2: Detail Drawing For 16-48 Fiber Silicon V-Groove Chips
(Note: 500µm gap is between every 8 fiber ribbon position in the chip)

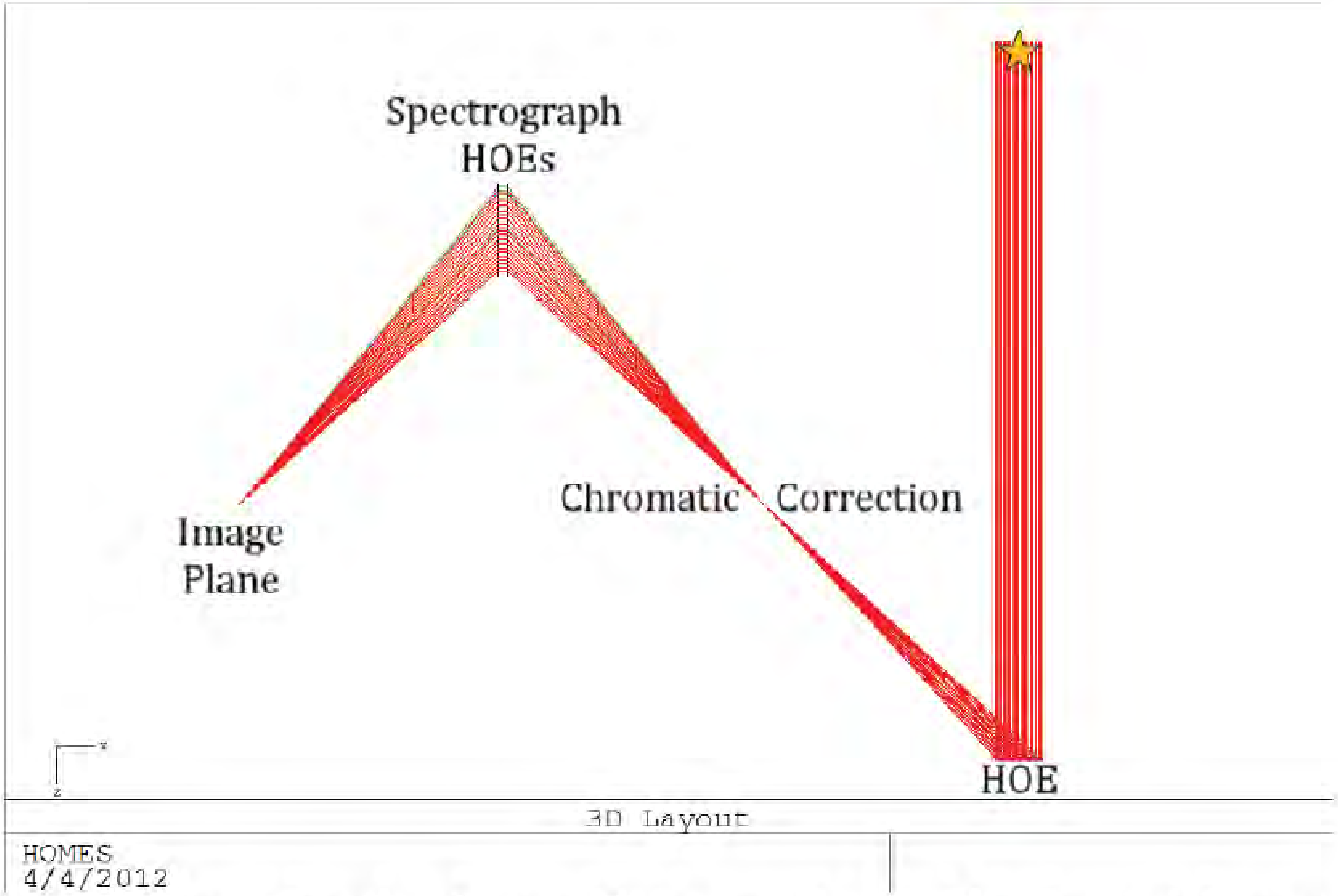
OZ Optics



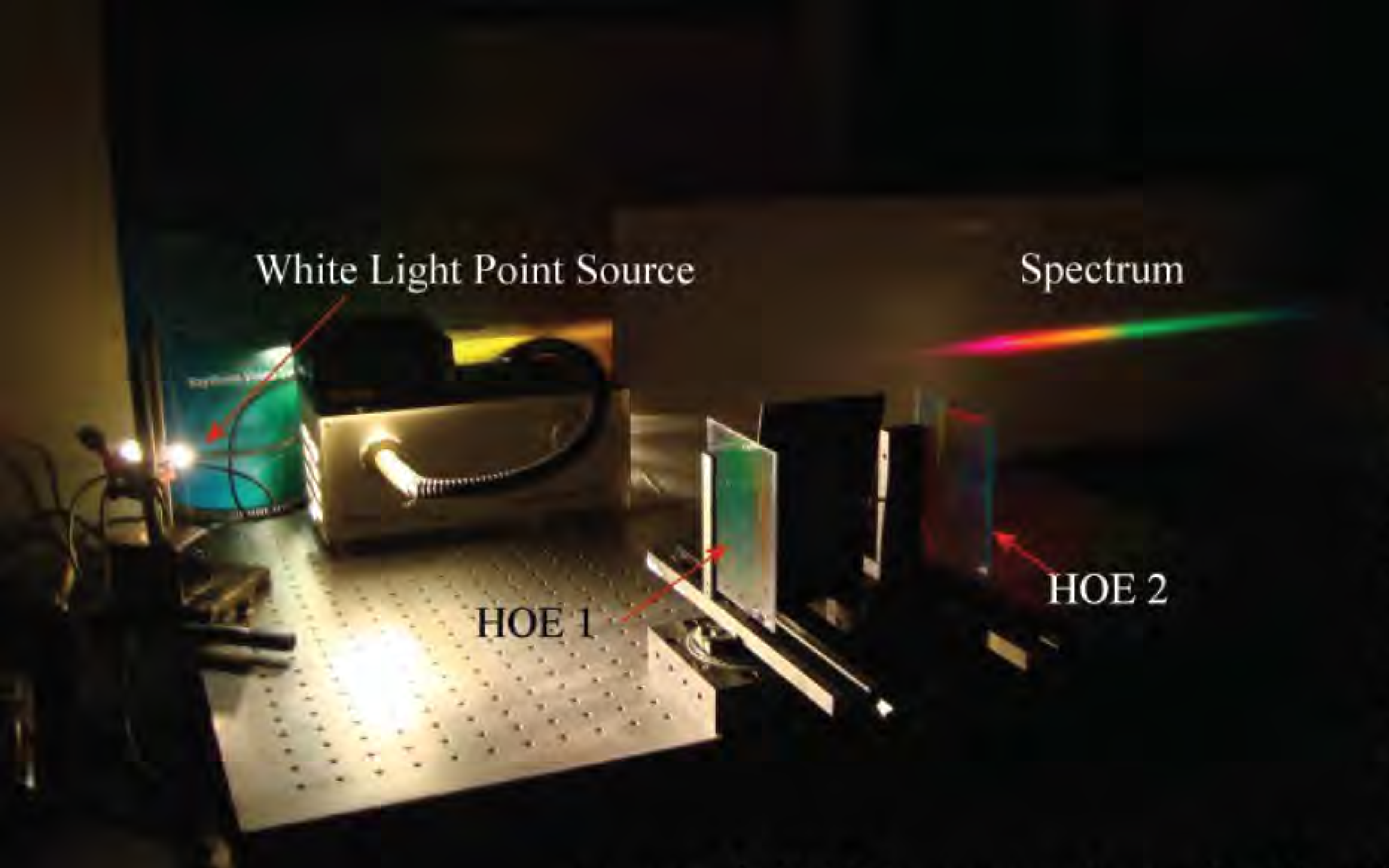
We will need thousands of fibers spanning many meters.

standard optical connector with 500 micron spacers.

These bars derive from a commodity product used today for communication fibers. A one meter bar of fibers will acquire 1 nm of spectrum. One hundred bars would acquire a 100 nm enough bandwidth to see organics, Goldilocks' porridge.



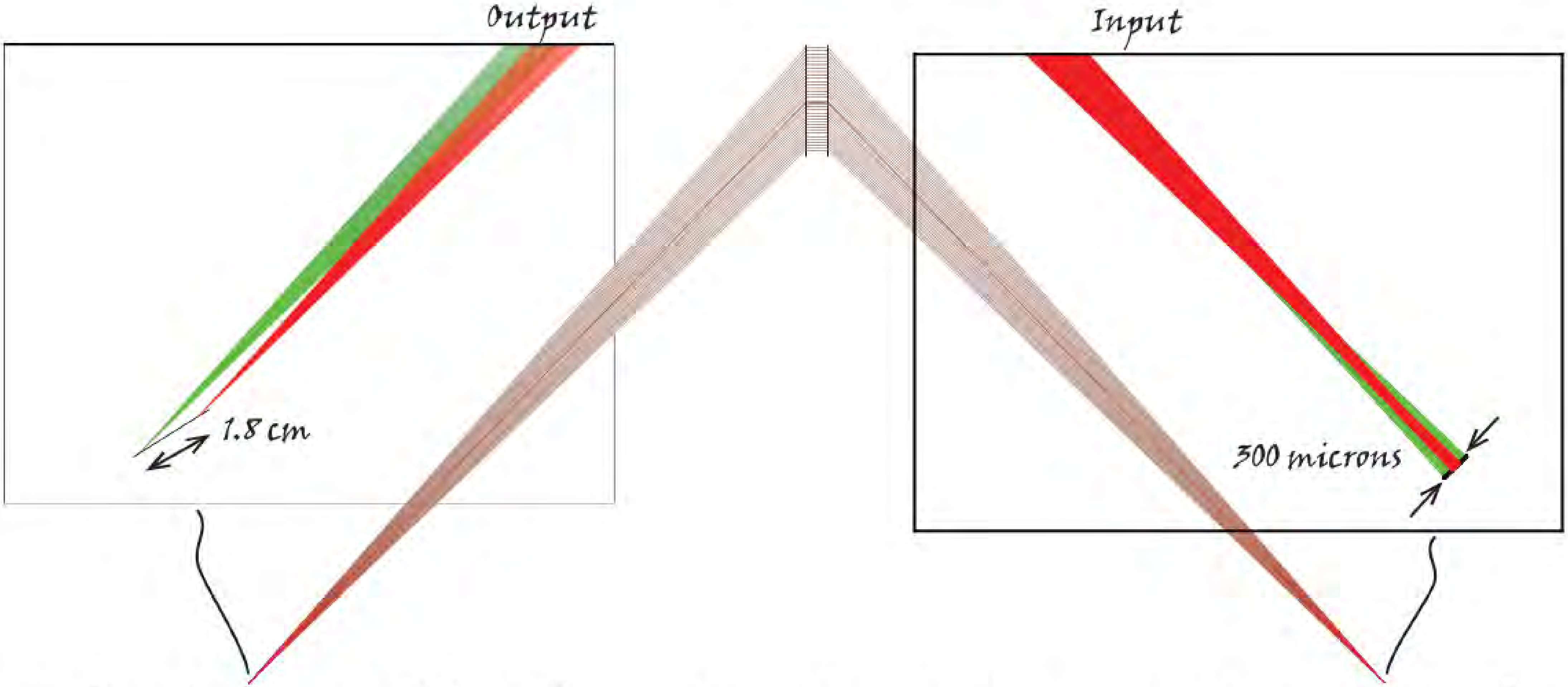
I knew when we started on this project that we'd need a very high resolution secondary spectrograph and considered membrane optics. Zemax predicted that we could use two copies of the primary HOE but in transmission rather than reflection.



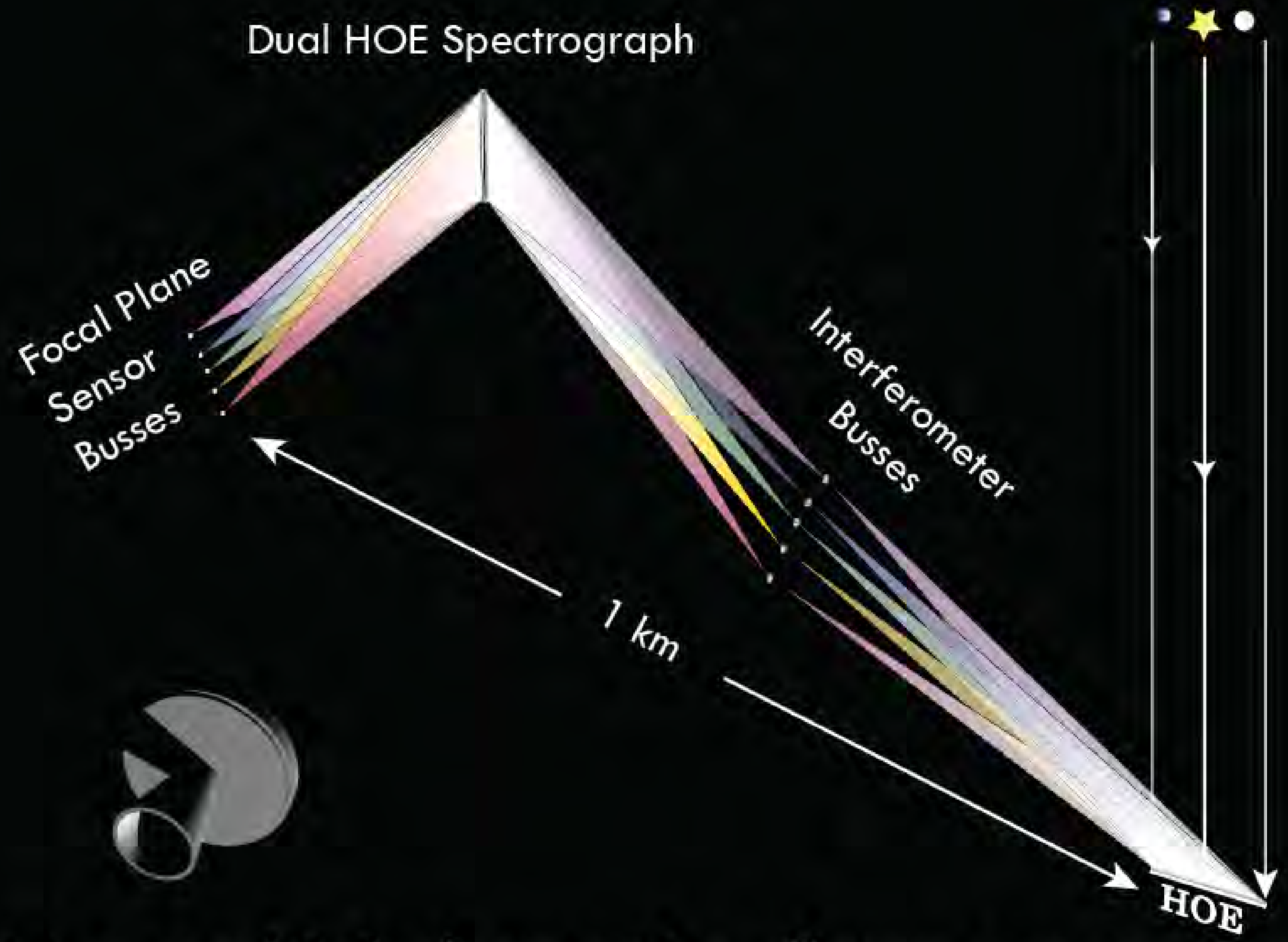
This is the first component that we have been able to realize in the lab. The pair works as Zemax had predicted. When they are parallel, the second HOE reconstructs the focal point of the first but across a spectrum. These HOEs were made as part of a workshop in holography at RUM funded by NSF.

Departmento de fisica
Recinto Universitario de Mayagüez

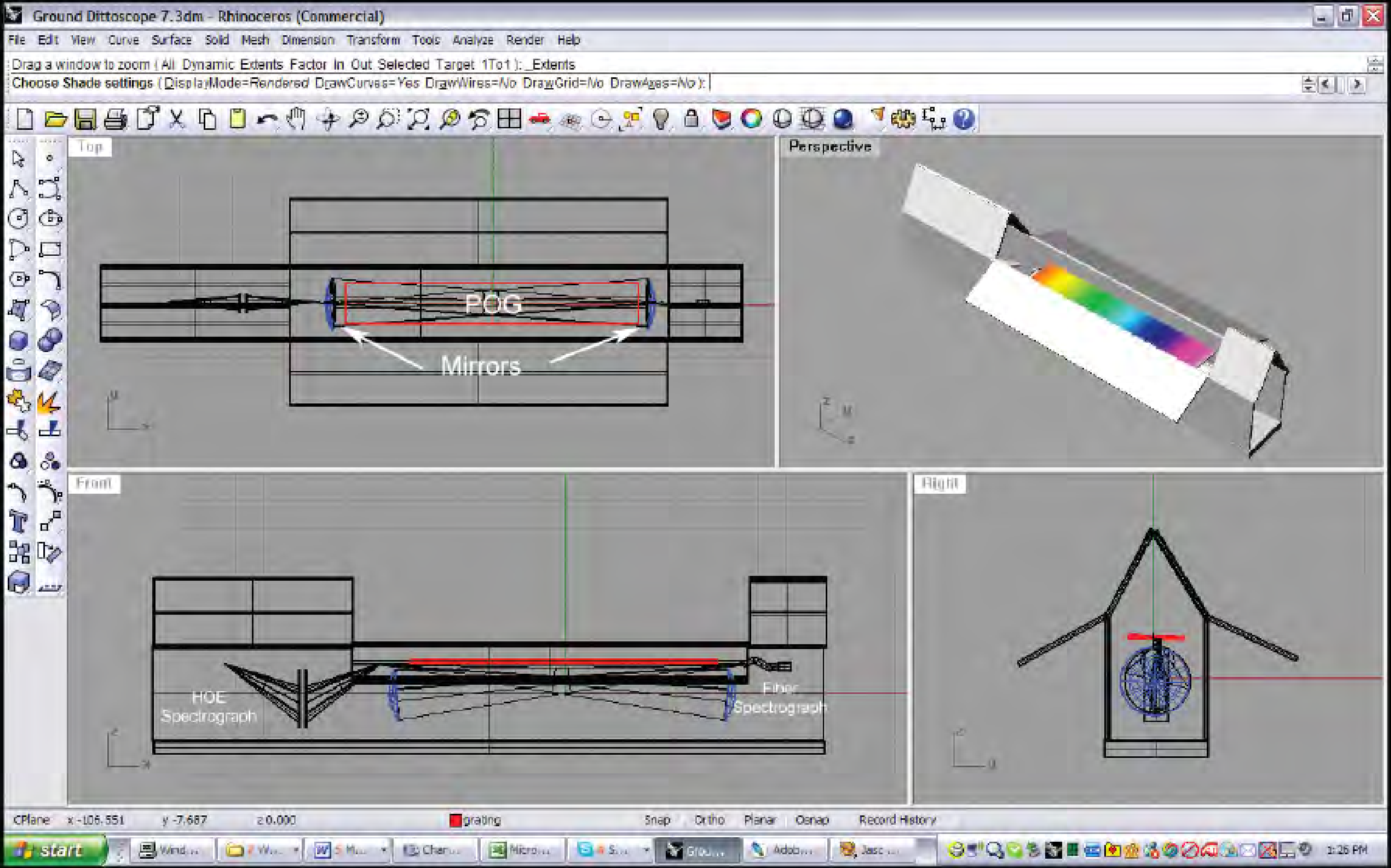
2 sources separated by 100 mas



The focal plane differs from the source image in that at the focus what was a co-axial input containing the wavelength-encoded images of the planets are now spatially separated by dispersion. In this example 100 milliarcseconds angular separation translates into 1.8 cm separation on the focal plane array.



HOMES has multiple formation-flown components that would span a kilometer. The primary objective and secondary spectrographic HOEs could be ribbons of 10 x 50 or 10 x 100 meters. It would be parked at the second Lagrange Point.


Ground Dittoscope 7.3dm - Rhinoceros (Commercial)

```
Drag a window to zoom ( All Dynamic Extents Factor In Out Selected Target 1To1 ): _Extents
Choose Shade settings ( DisplayMode=Rendered DrawCurves=Yes DrawWires=No DrawGrid=No DrawAxes=No ):
```

```
CPlane  x -106.551  y -7.687  z 0.000  grating  Snap  Ortho  Planar  Osnap  Record History
```

In Phase II, the project would be to build a ground-based version of The MOST scaled down to a 3 meter length primary objective. The goal is to map 1000 spectra in one observation at 12th Mag.

	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14	Feb-14	Mar-14	Apr-14	May-14	Jun-14	Jul-14	Aug-14	
Theory													
Math	Hologram design				grazing exodus		phase error		Astigmatism		Integration Time		Ditto
Zemax		Hologram design				grazing exodus				Astigmatism			Friedman
PCGrate			Hologram design				grazing exodus				phase error		RPI DSK
Prototype													Niekamp
Bench Optics	Mirror Mount							grazing exodus	phase error			Astigmatism	Mozurkewich
POG				Plane Grating I	SEM	Emboss	SEM	Plane Grating II	SEM	Emboss	Emboss		Baker
Stretcher									Drawing	Drawing	Parts	Parts	McGrew
Spectrograph	Computer	Dual HOE Fab UPR					Mightex 6 Fiber	Driver Software					Monkhouse
Data Reduction			Star Map I	Star Map II	Star Map III	Star Map IV				Integration Time			Warren
Observation													
Report													
	NIAC					Prepare	NIAC					Prepare	

	Sep-14	Oct-14	Nov-14	Dec-14	Jan-15	Feb-15	Mar-15	Apr-15	May-15	Jun-15	Jul-15	Aug-15	Sep-15
Theory													
Math	Free Spectra												
Zemax		Free Spectra											
PCGrate													
Prototype													
Bench Optics													
POG													
Stretcher	Assemble	Assemble			Change Declination			Second Mirror					
Spectrograph													
Data Reduction			Free Spectra										
Observation			First Light	Observe	Observe	Observe	Observe	Observe	Observe				
Report													
	NIAC					Prepare	NIAC		Prepare	Pre-	SPIE	Pre-	NIAC

When the NASA Chief Administrator wrote a letter that described NIAC as being "de-scoped," the choice of language registered with this telescope maker, but if not sequestrated, we do have our Phase II plans ready.

Holographic Optical Method for Exoplanet Spectroscopy

HOMES

Questions?

www.3dewitt.com/tele.html

3DeWitt llc

NIAC
NASA Innovative Advanced Concepts