

Holographic Optical Method for Exoplanet Spectroscopy



Thomas D. Ditto - NIAC Fellow

David Content - NASA GSFC

Stephen McGrew - NLI

Sergiy Lysenko - RUM





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 exo-
planet 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.



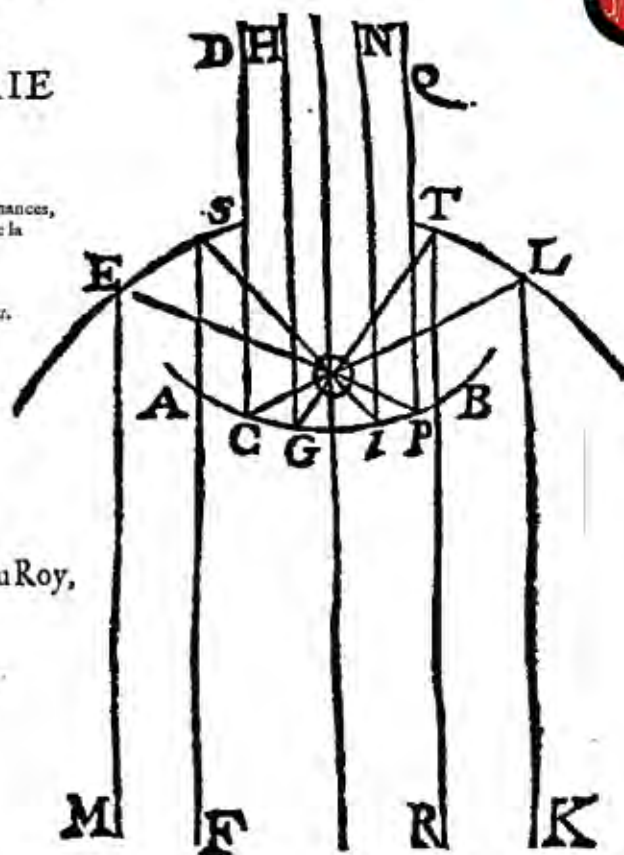
HARMONIE VNIVERSELLE, CONTENANT LA THEORIE ET LA PRATIQUE DE LA MVSIQUE.

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,
rue S. Jacques, aux Cicognes.

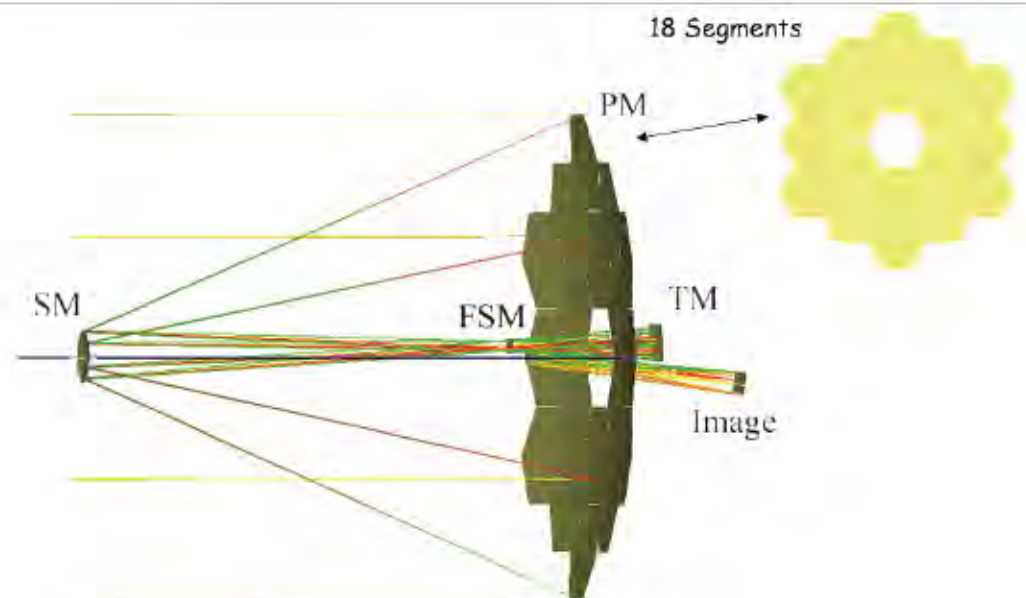
M. DC. XXXVI.
Avec Privilège du Roy, & Approbation des Docteurs.



1636



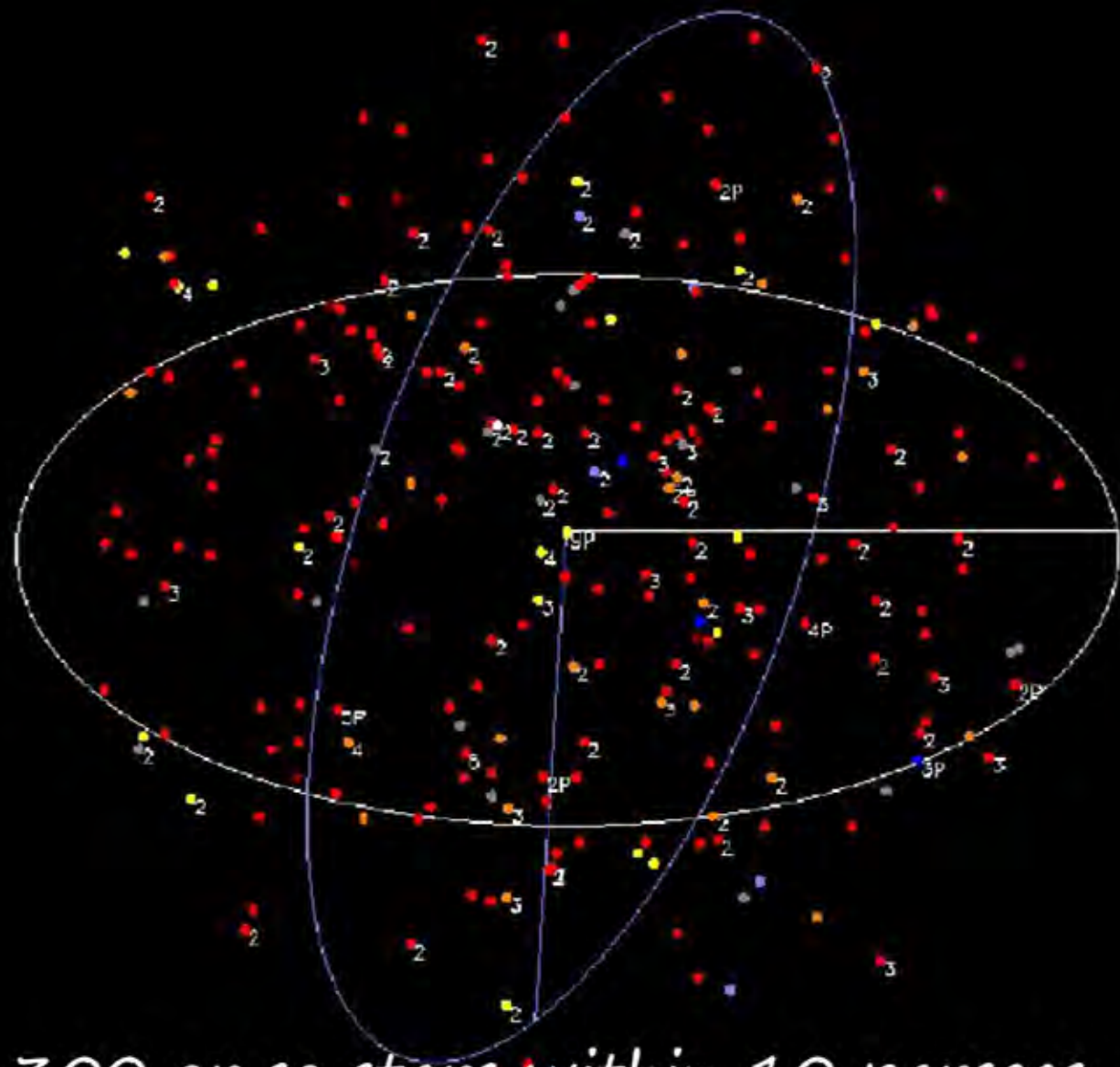
Optical Design of JWST



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

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.

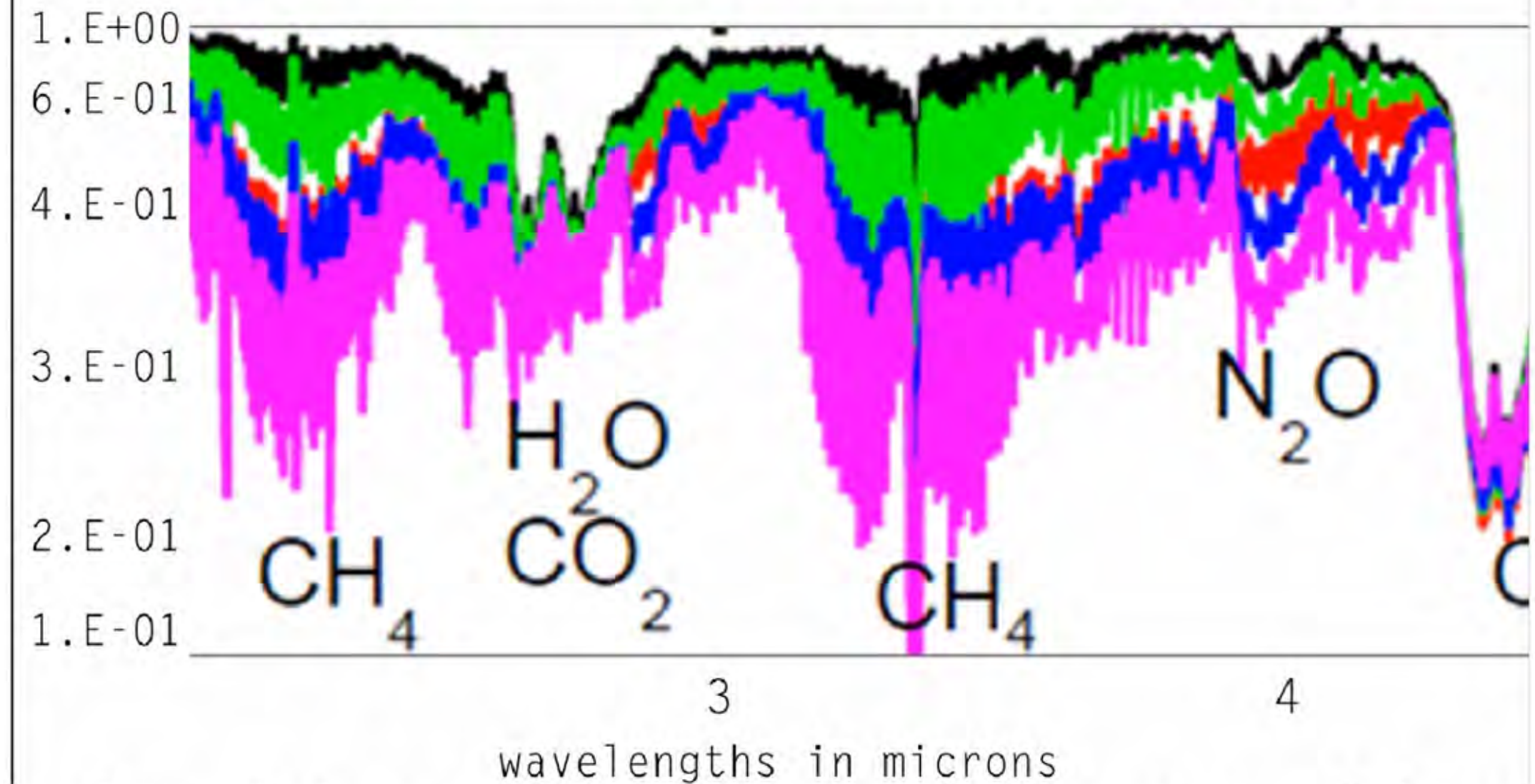




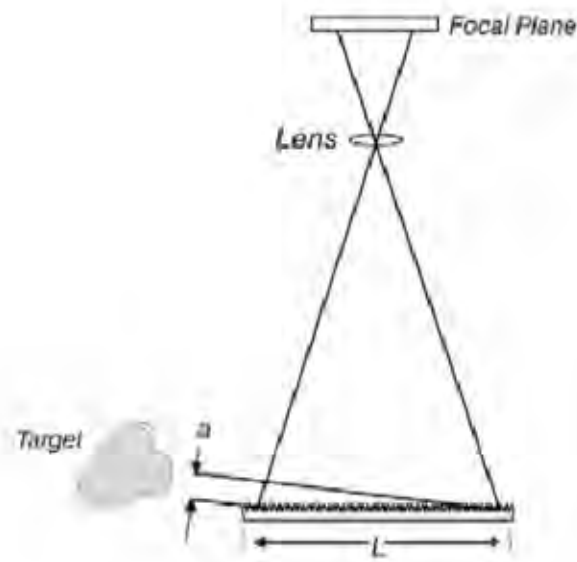
Exoplanets are as faint as the most distant objects ever detected. To make this image, the Hubble made 2000 observations over 556 hours pointed at an extremely dark field. Brighter objects in the field would have swamped the sensors.



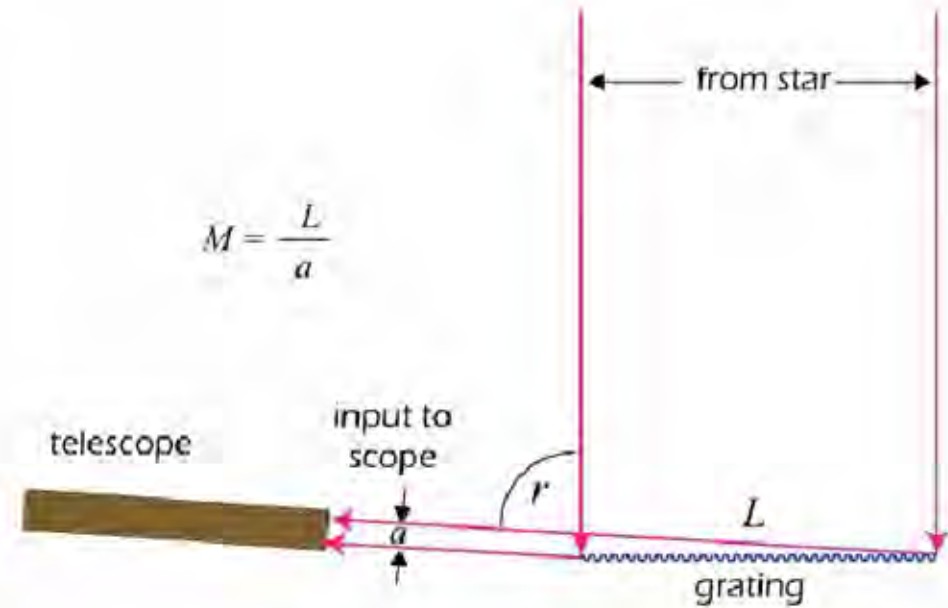
Synthetic Spectra of an Earth-like Planet



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 text-books 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 revolutionary telescope design based grazing exodus rather than grazing incidence would enjoy the same leverage as the microscope.

1. THE GENIUS IS IN THE GENERALITIES,
AND NOT THE DETAILS.

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

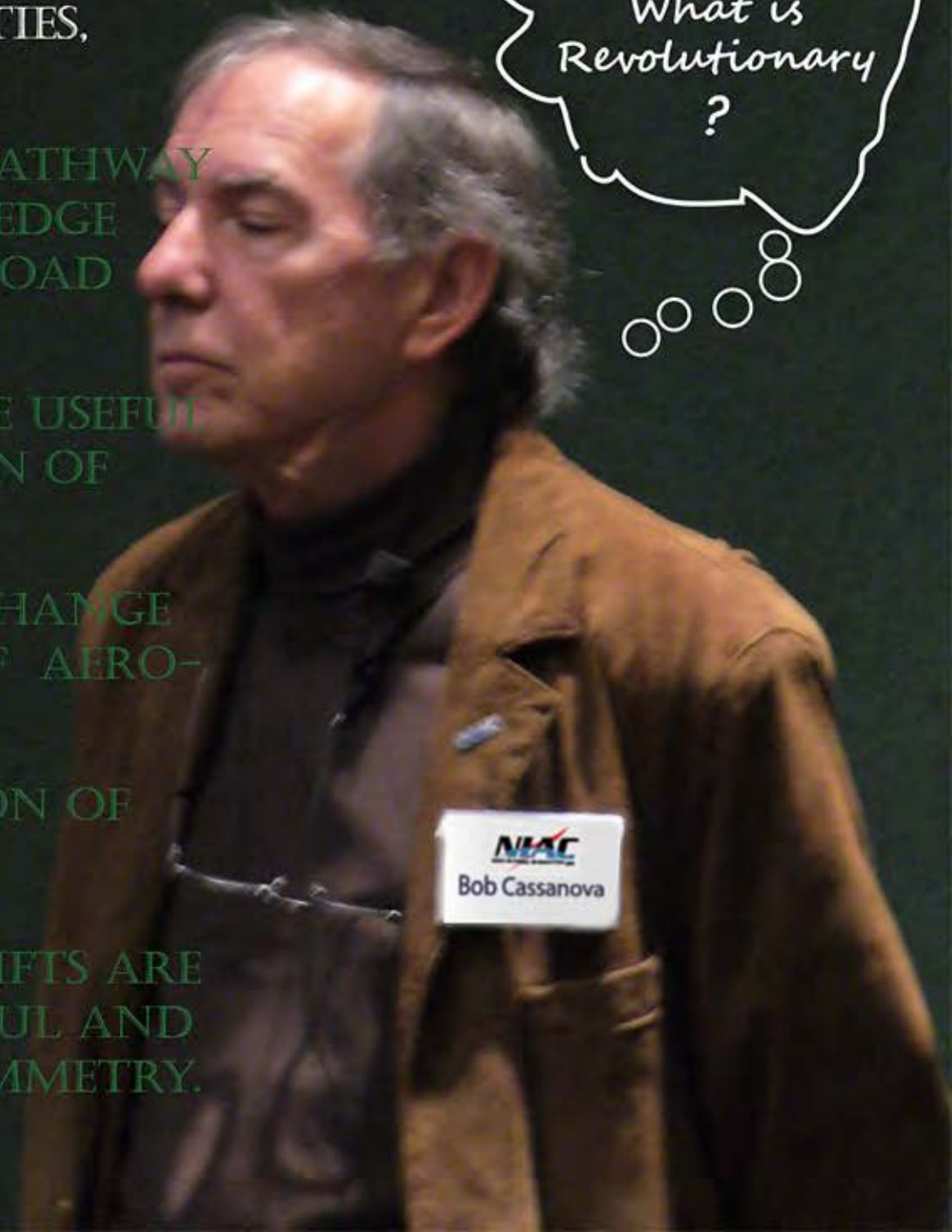
3. IT INSPIRES OTHERS TO PRODUCE USEFUL
SCIENCE AND FURTHER ELABORATION OF
THE FUNDAMENTAL IDEA.

4. IT CONTRIBUTES TO A MAJOR CHANGE
IN THE ESTABLISHED FRAMEWORK OF AERO-
SPACE POSSIBILITIES.

5. IT TRIGGERS A TRANSFORMATION OF
INTUITION.

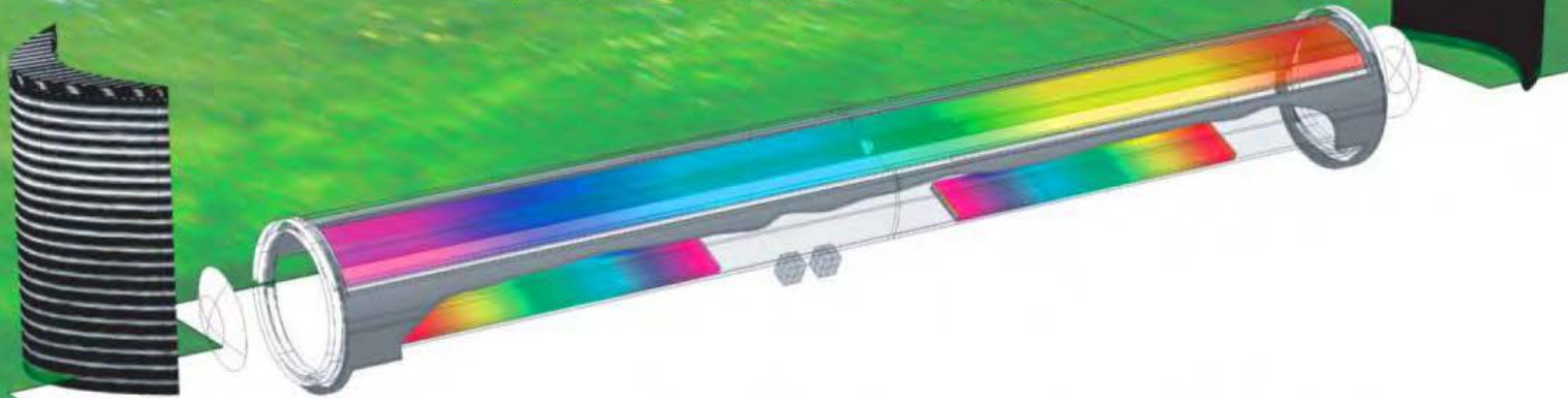
6. REVOLUTIONARY PARADIGM SHIFTS ARE
SIMPLE, ELEGANT, MAJESTIC, BEAUTIFUL AND
CHARACTERIZED BY ORDER AND SYMMETRY.

What is
Revolutionary
?

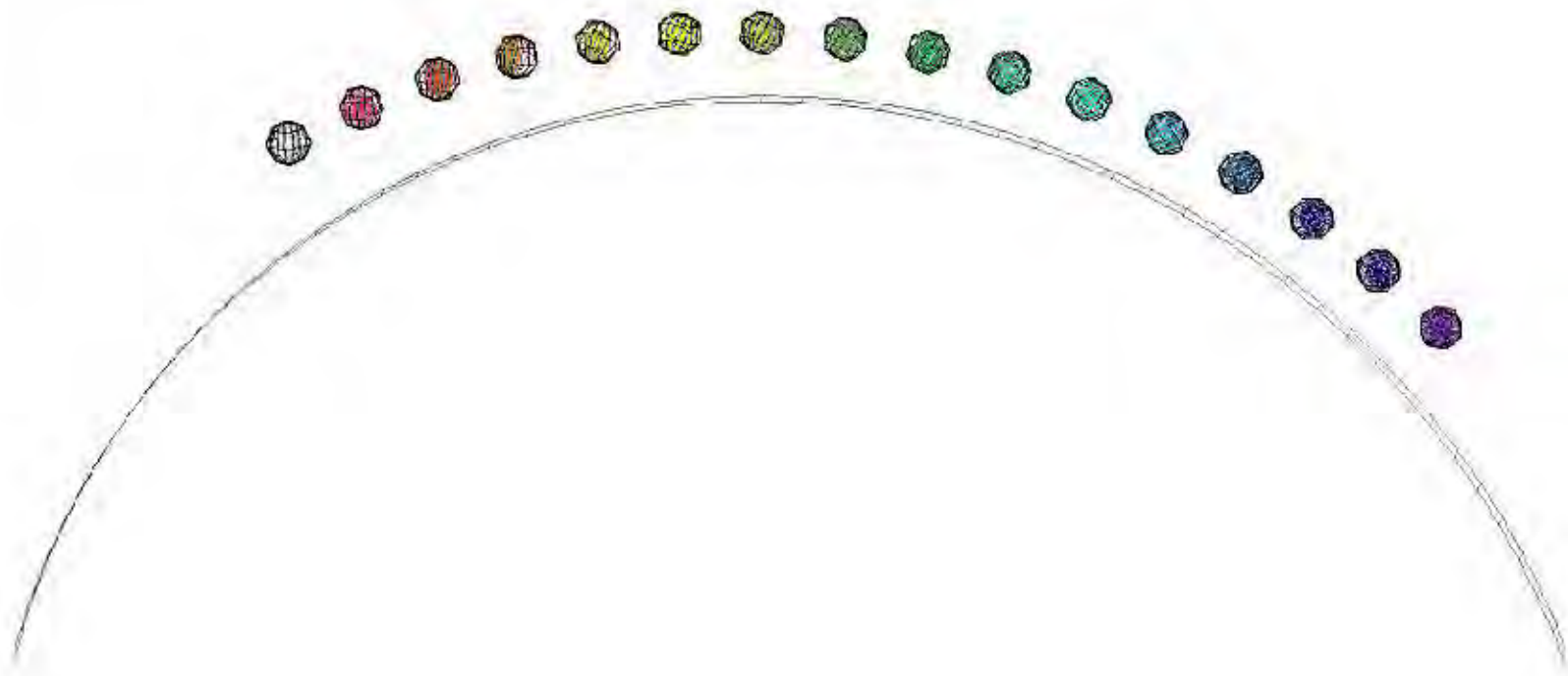


Multiple Object Spectrographic Telescope

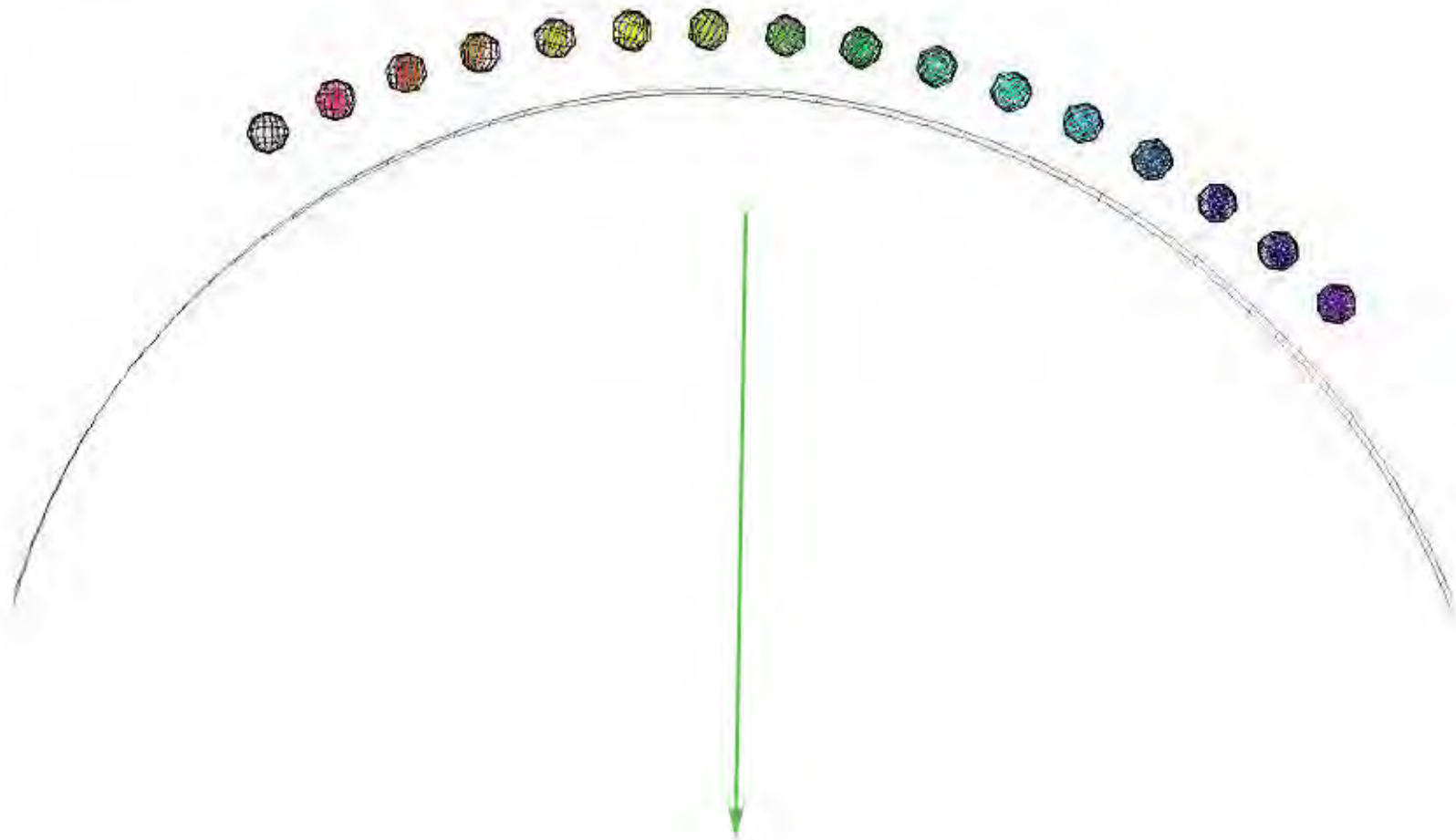
The MOST



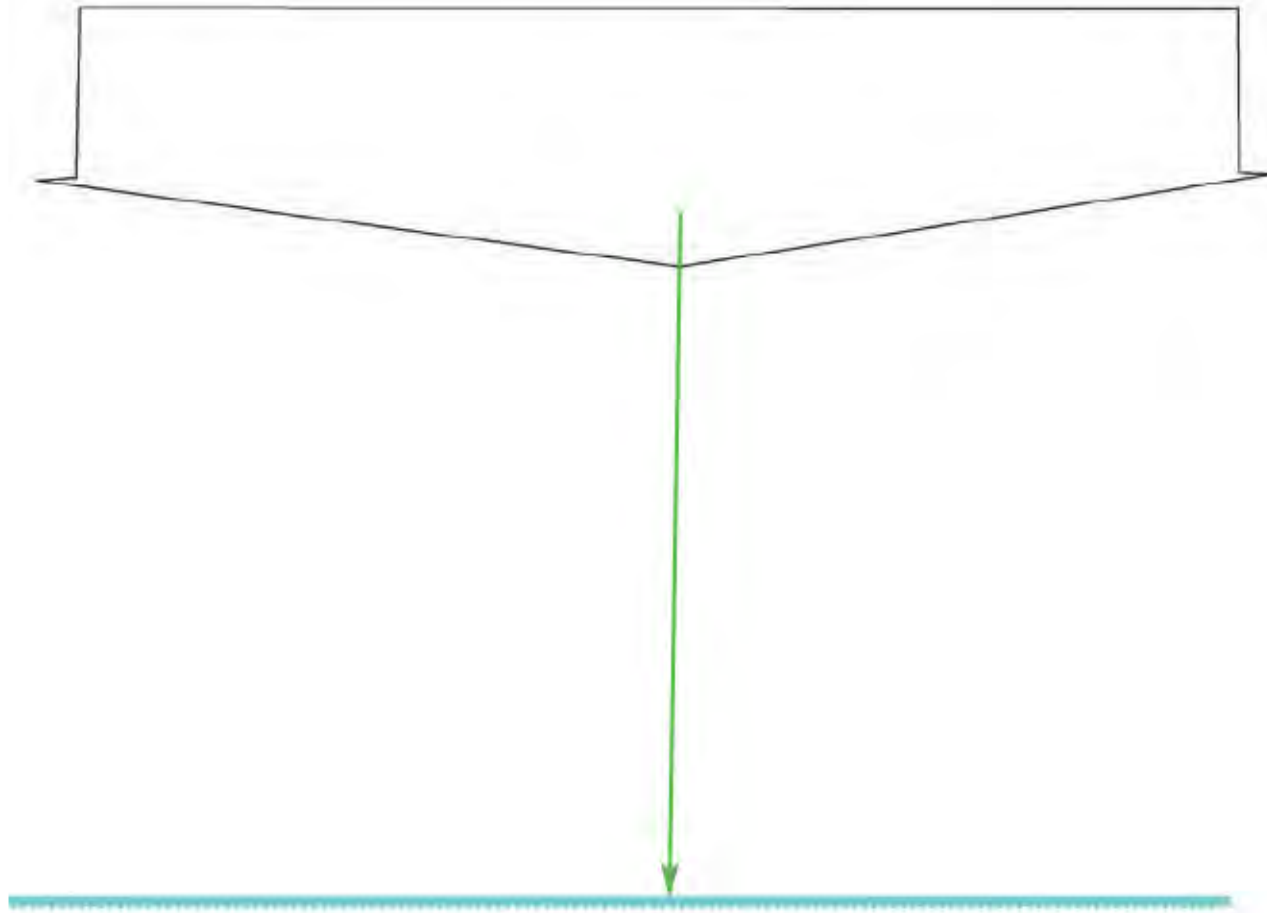
First Principles



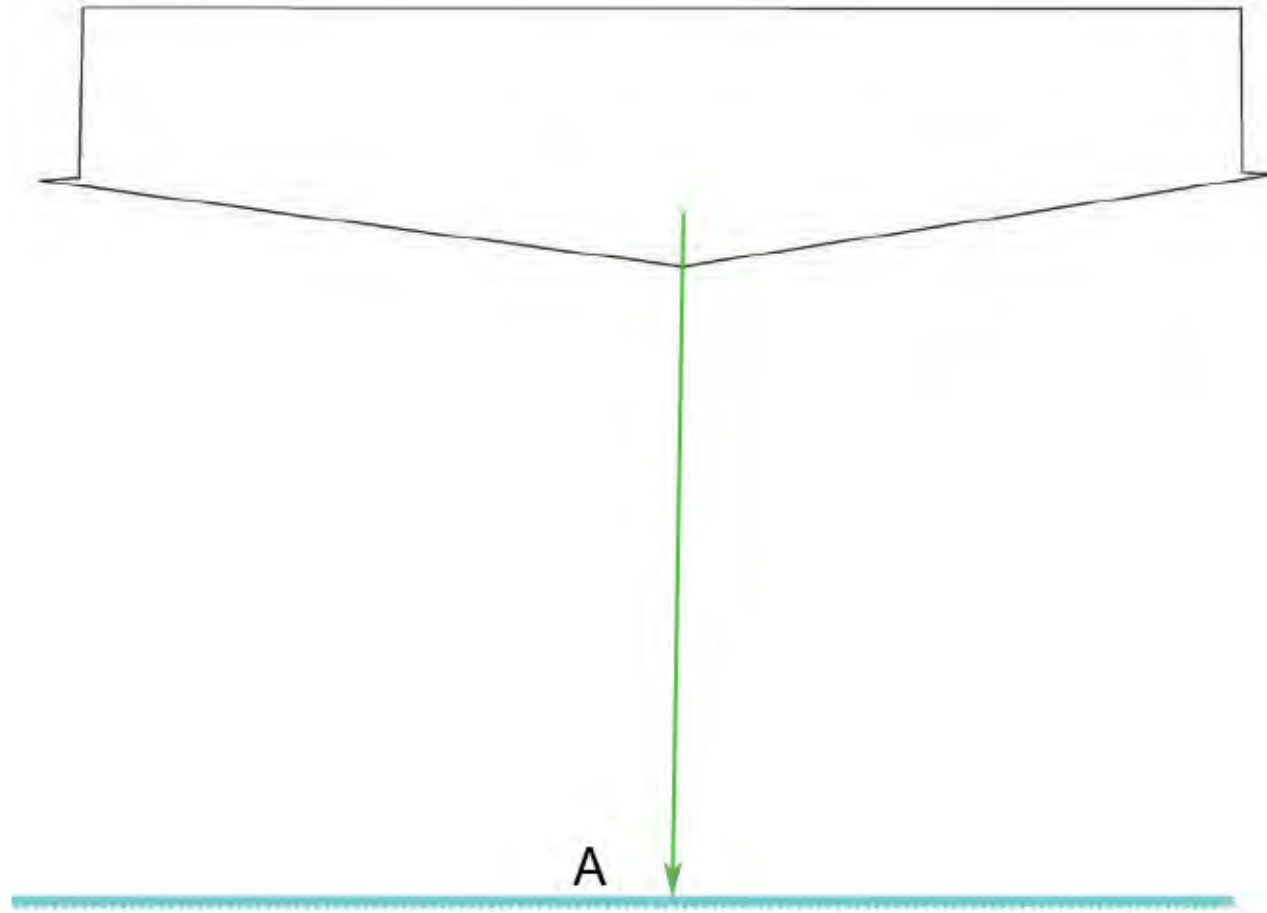
A source of distant illumination, say a star, precesses.
How can it be made to progress through its spectrum?



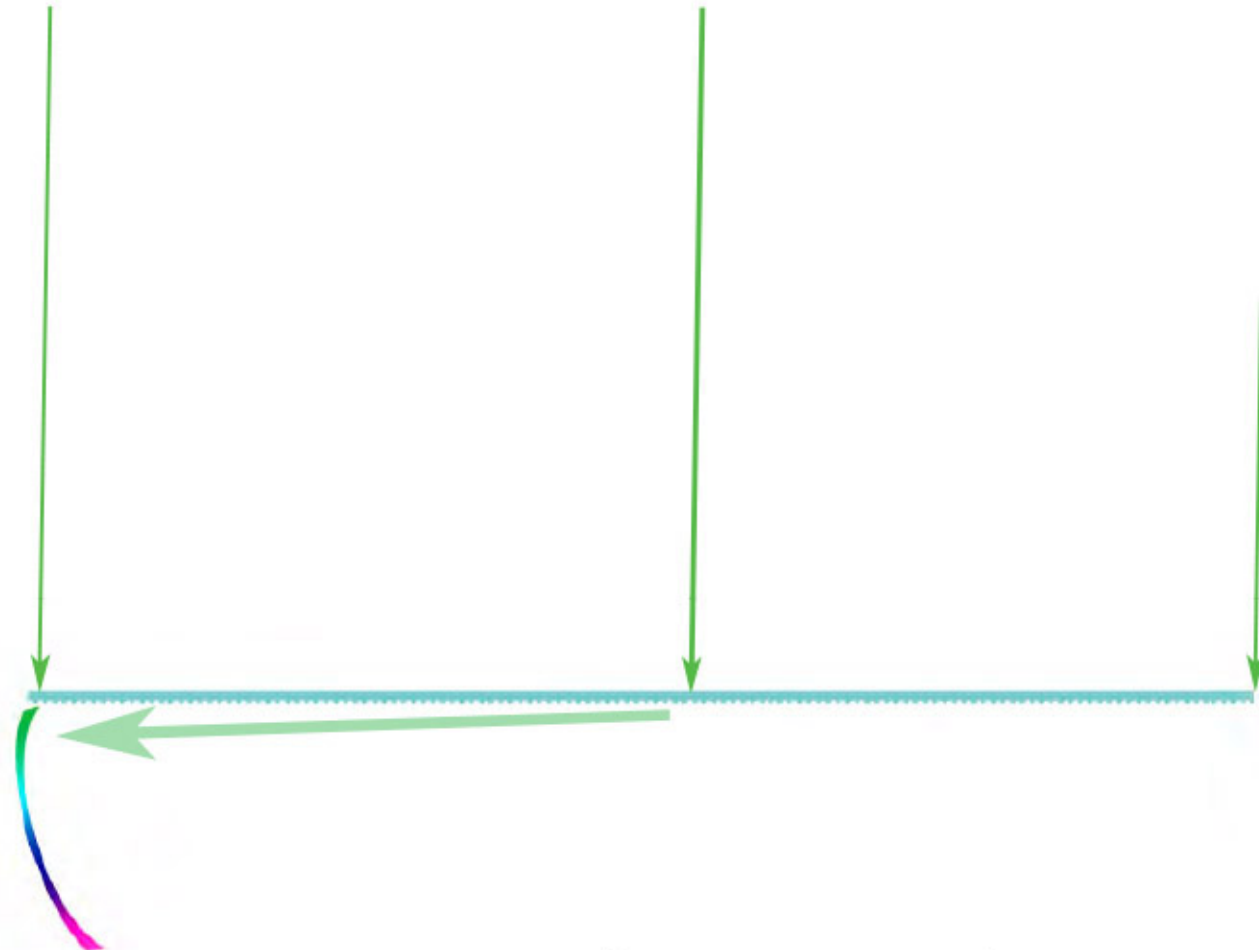
Consider an object at the zenith.



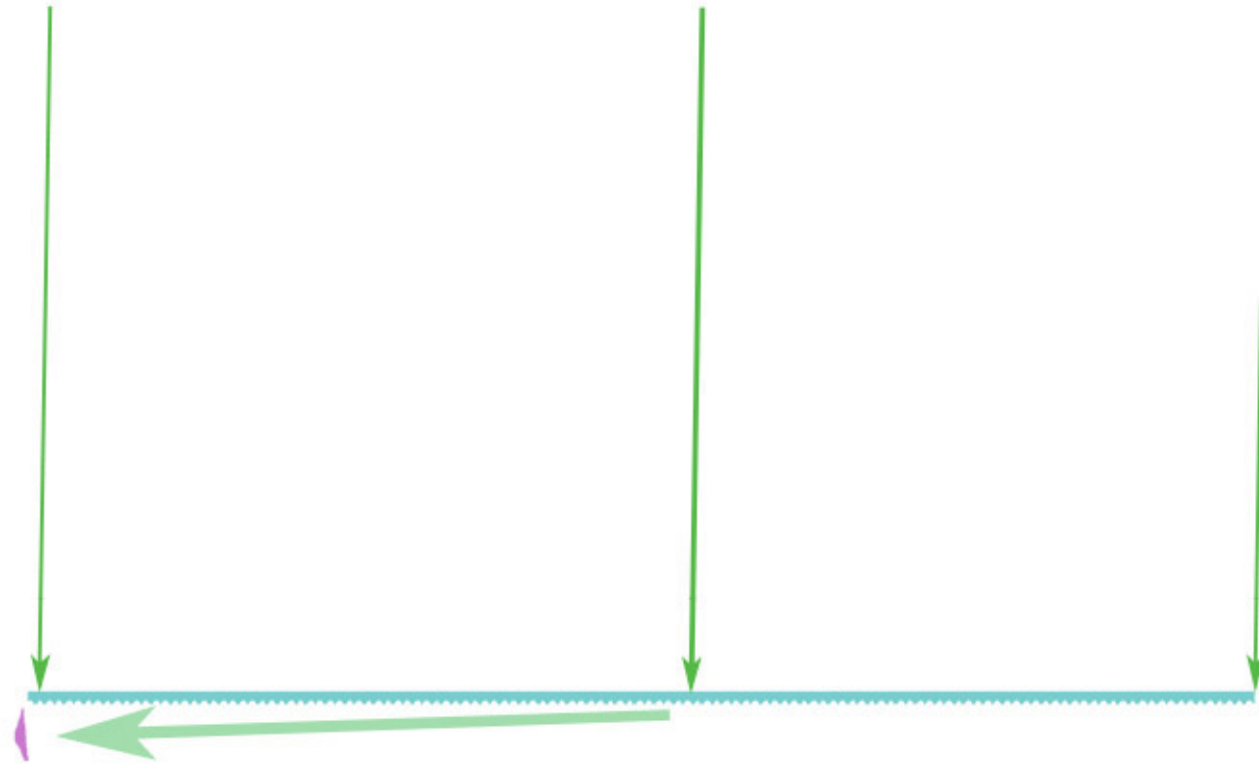
Light from the source arrives as plane wave.



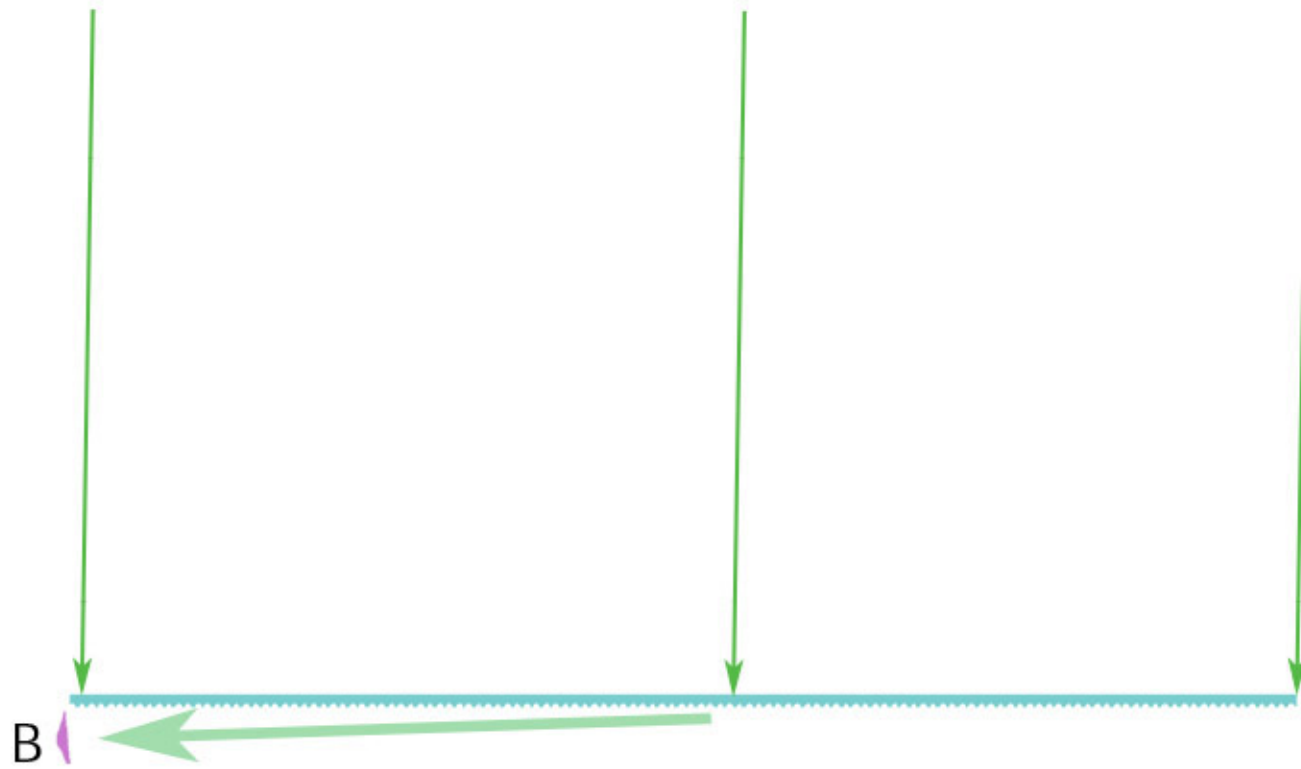
The plane wave strikes plane grating A.



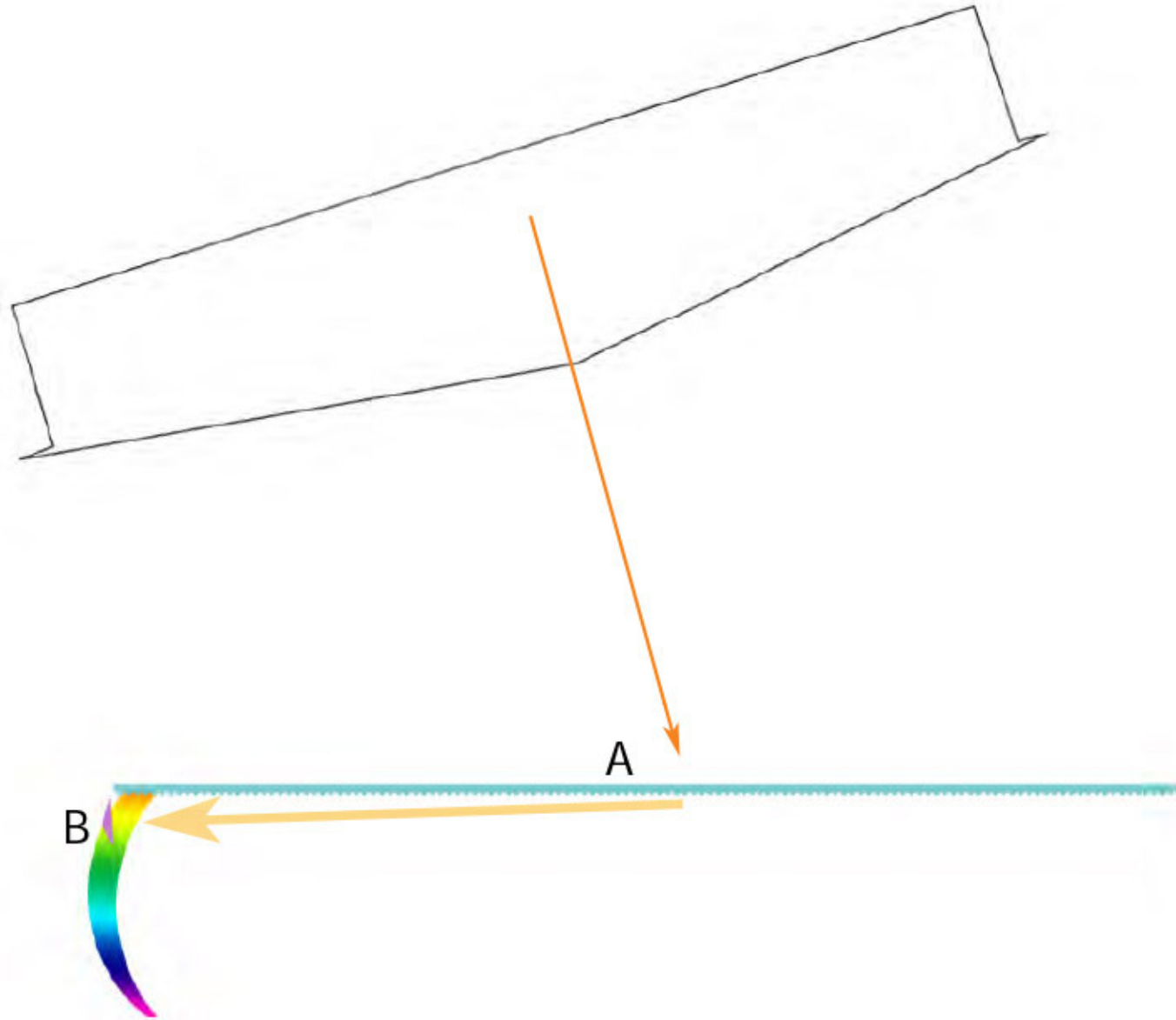
Light is dispersed from the plane grating at angles inversely proportional to wavelength.



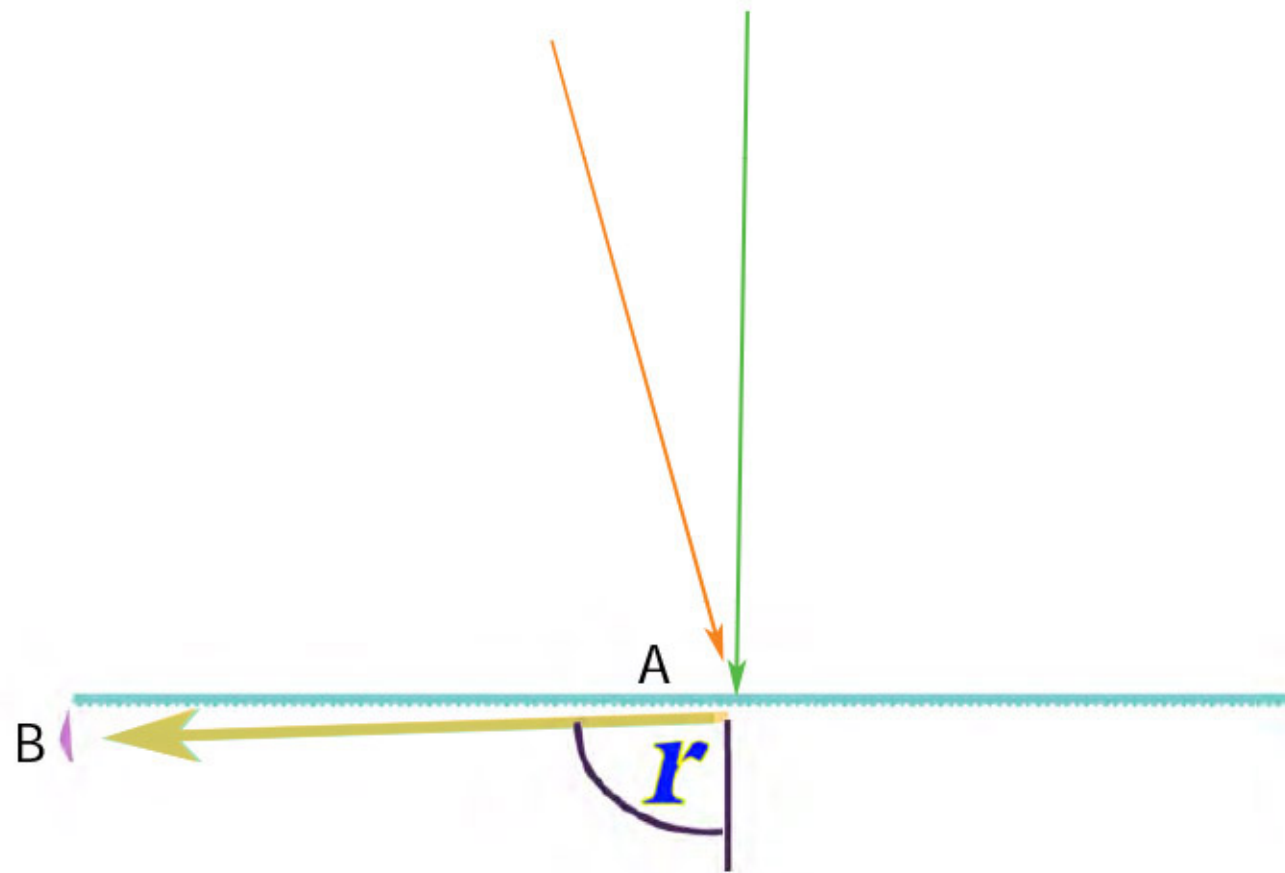
Diffraction gratings reconstruct the plane wave at a new angle where it can be collected .



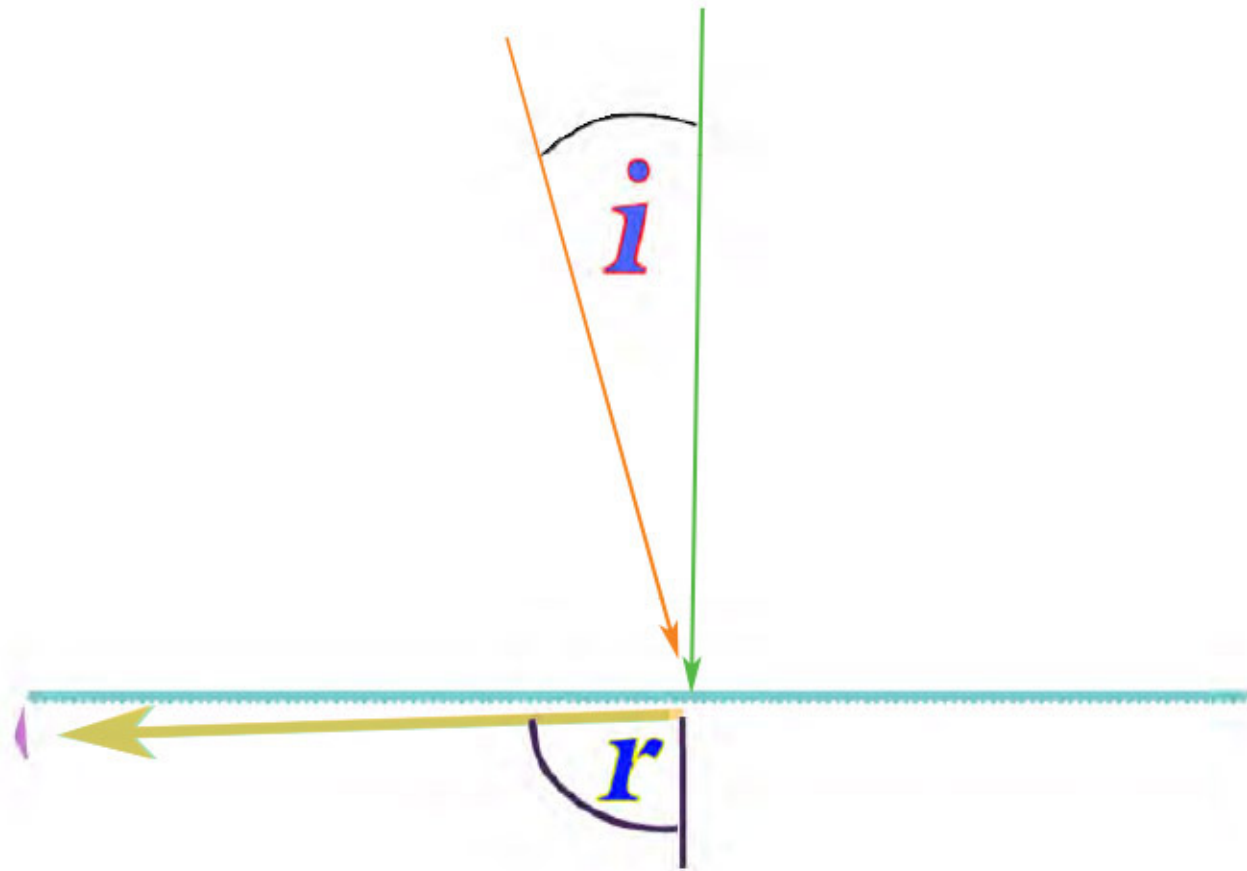
A specific wavelength is dispersed to parabolic mirror B.



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

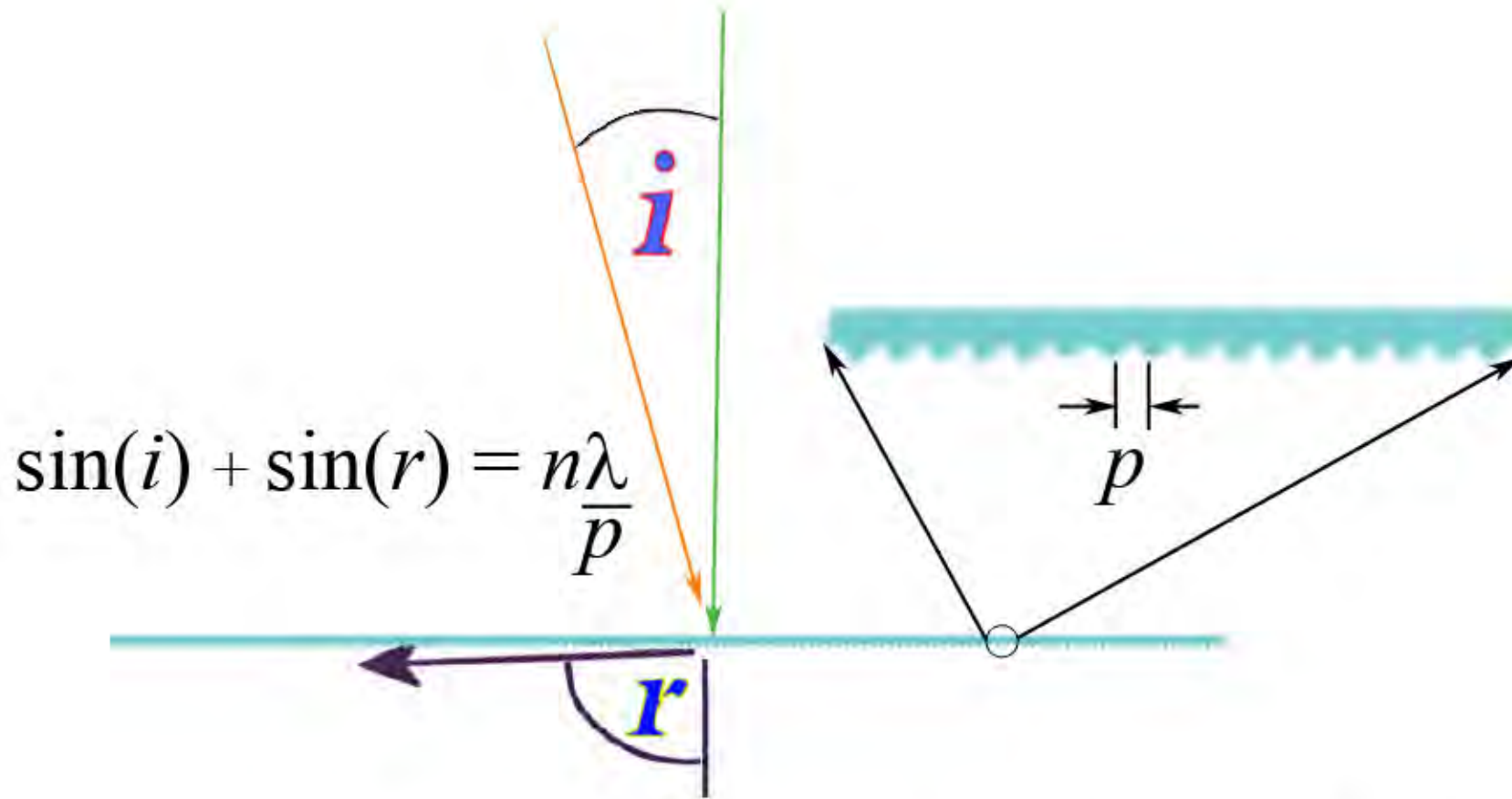


Varying angles of incidence upon grating A sharing a fixed and common angle of reconstruction r will disperse varying wavelengths to parabolic mirror B.

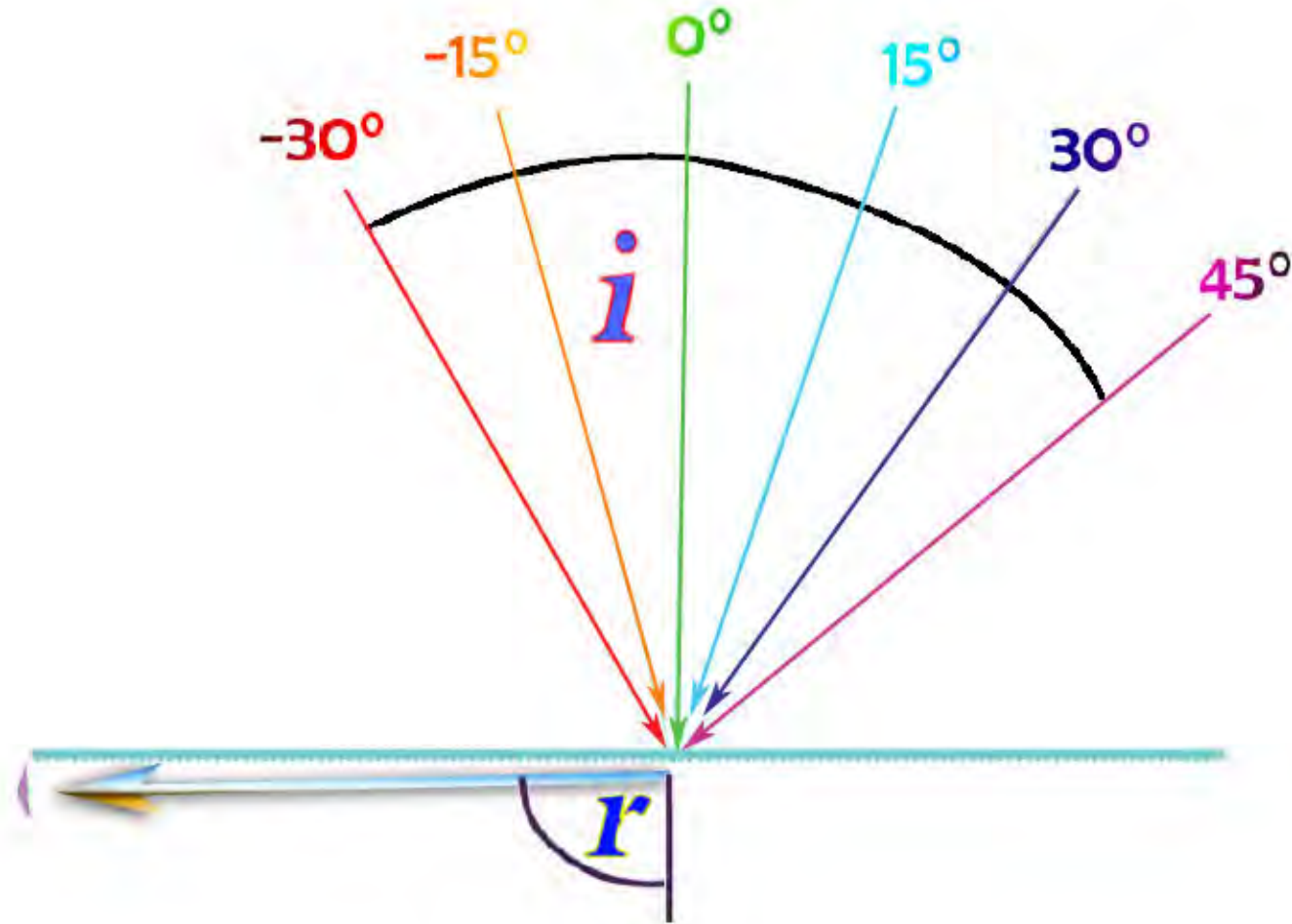


This configuration has angle of incidence i varying and a fixed grazing angle of wavefront reconstruction r .

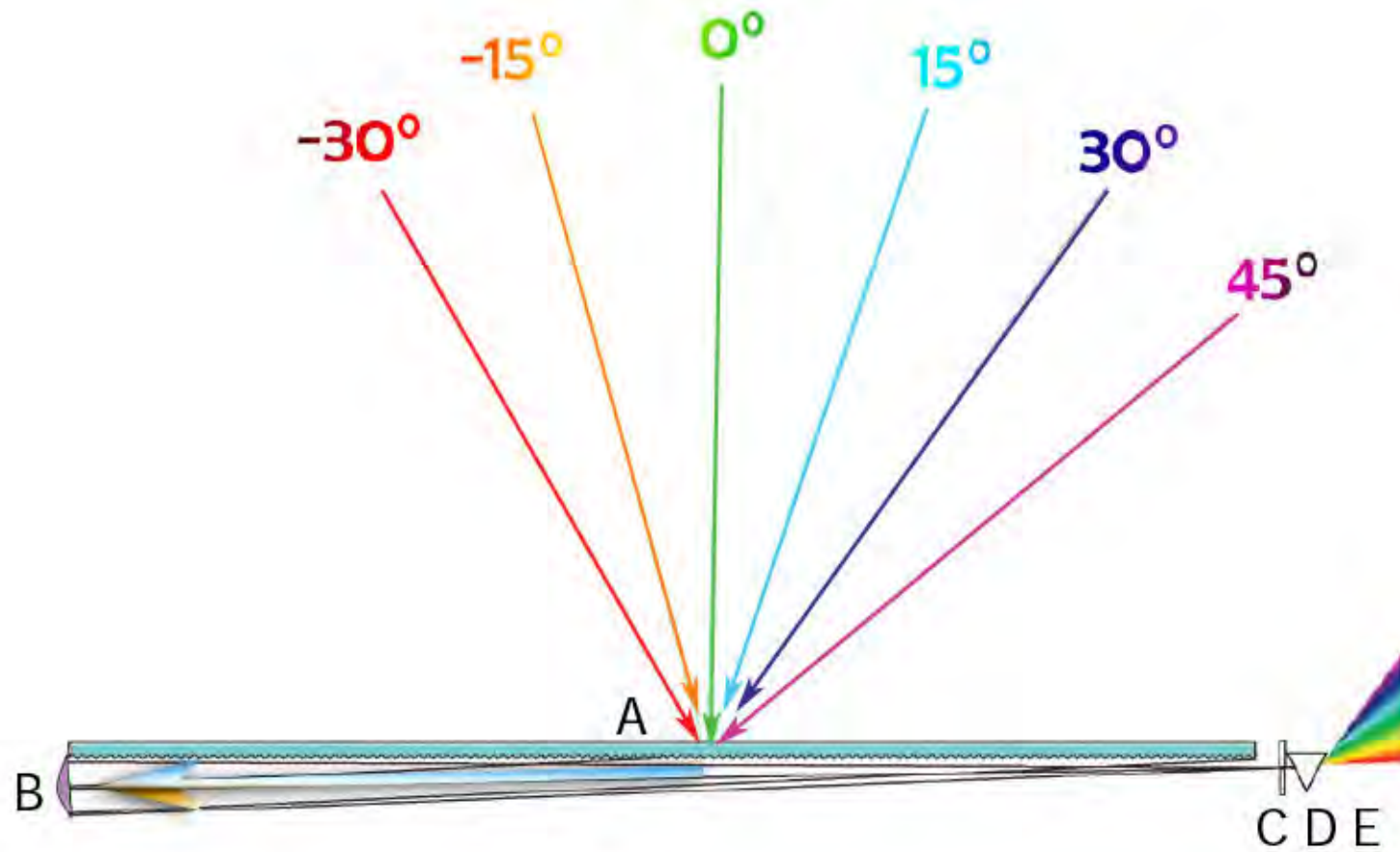
The Diffraction Equation



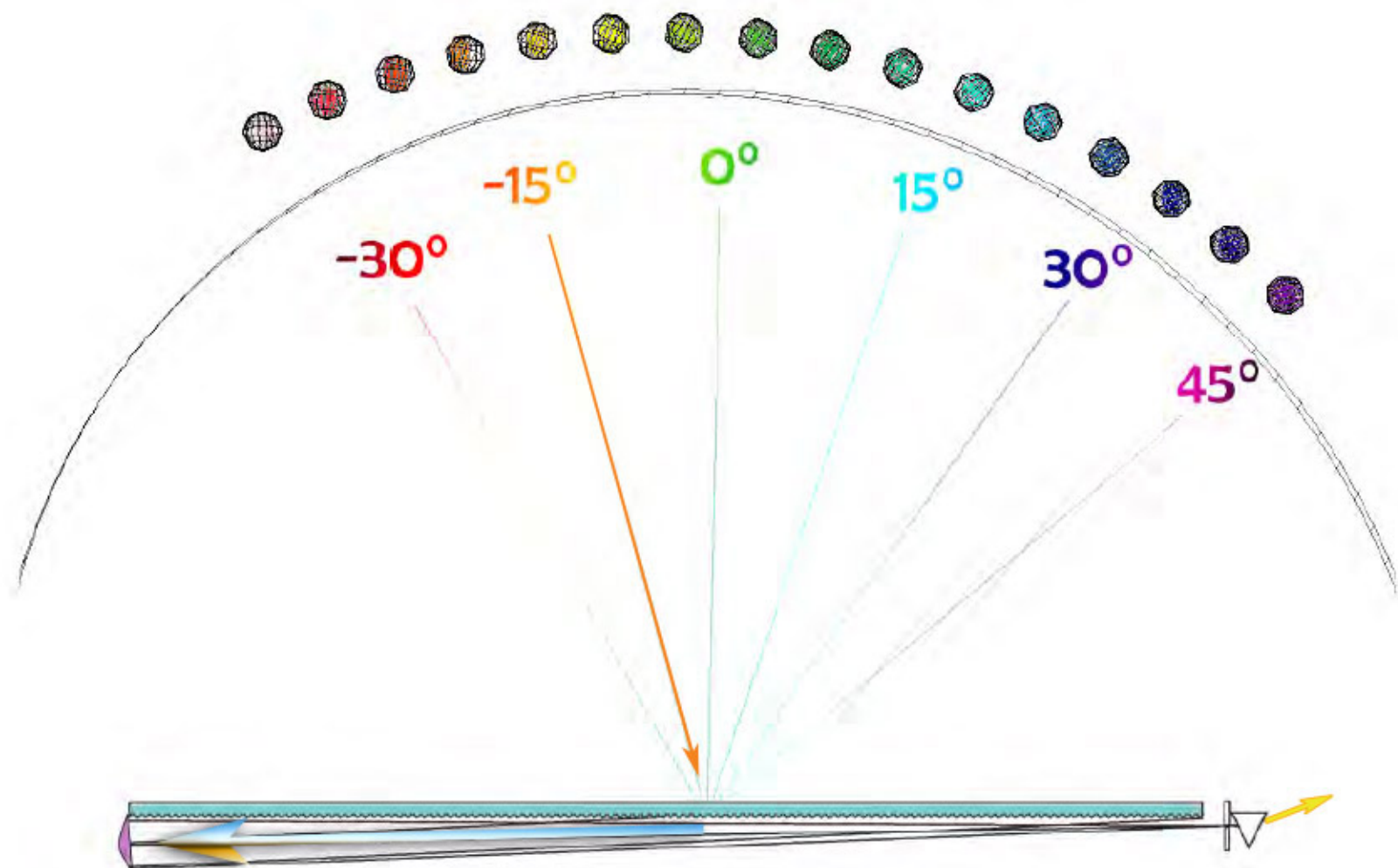
When the angle of reconstruction r , the pitch of the grating p , and the diffraction order n are fixed, the angle of incidence can be calculated by a measurement of wavelength λ .

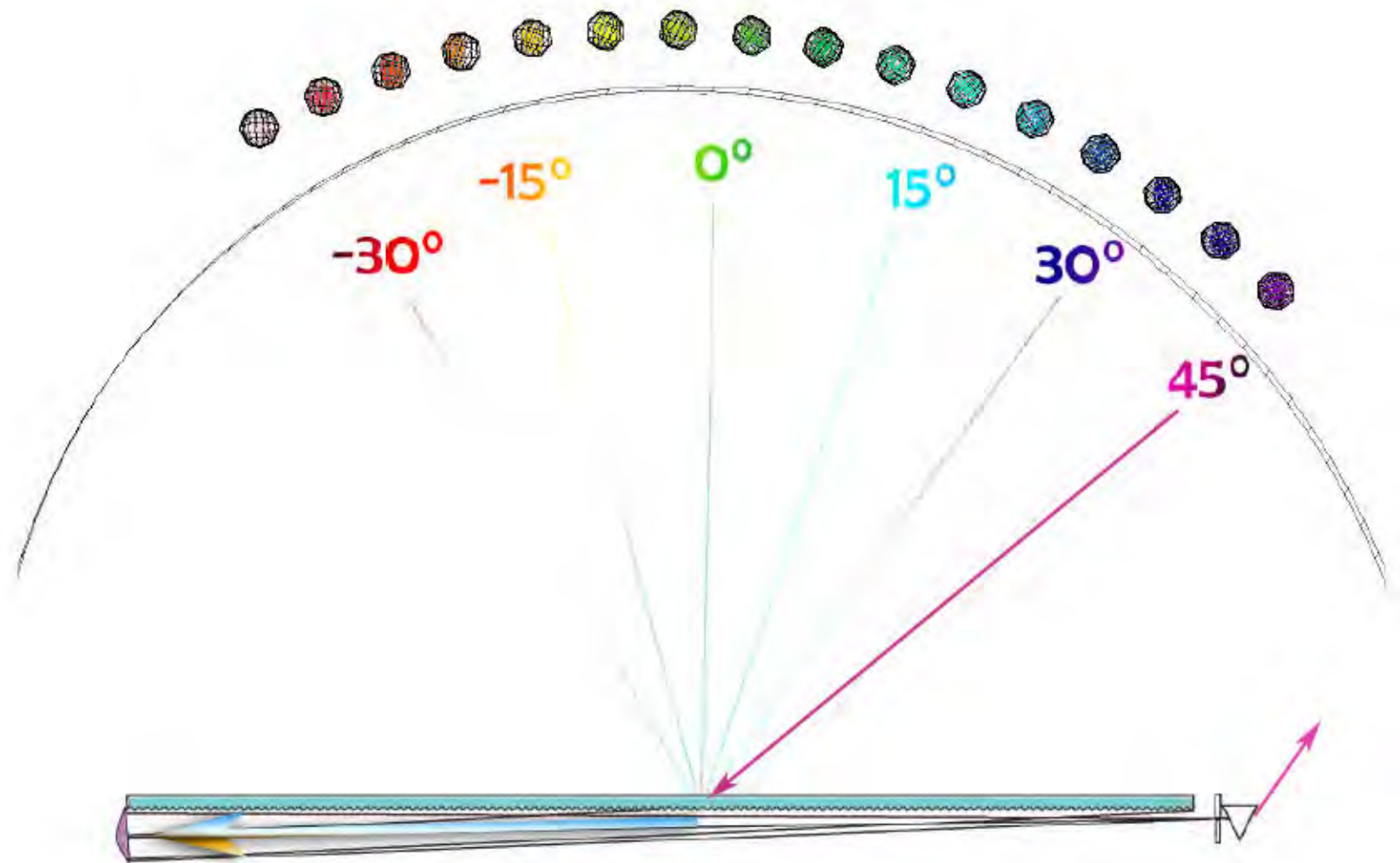


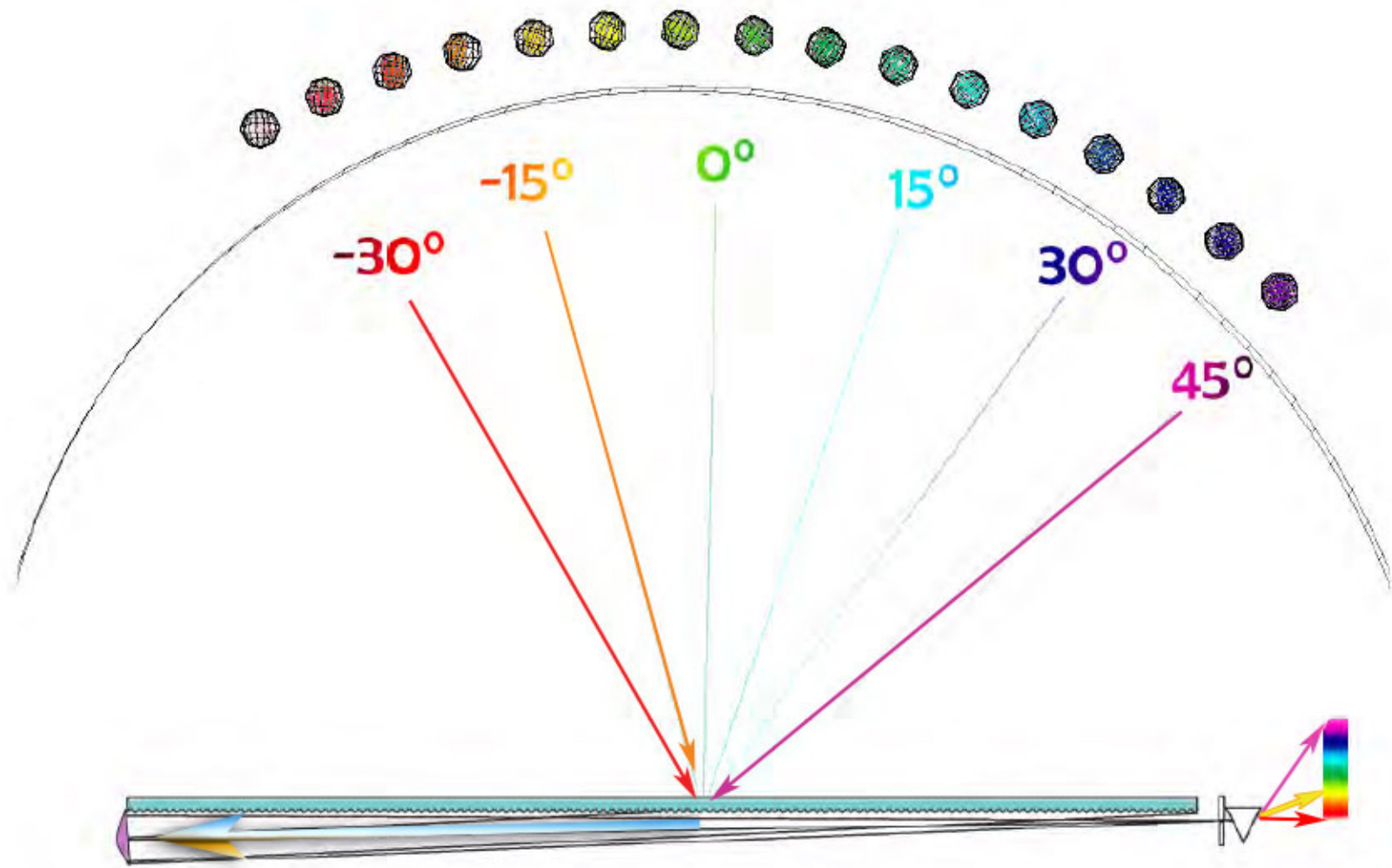
Variations in the angle of incidence over a fixed angle of reconstruction will disperse a spectrum of wavelengths.



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







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.



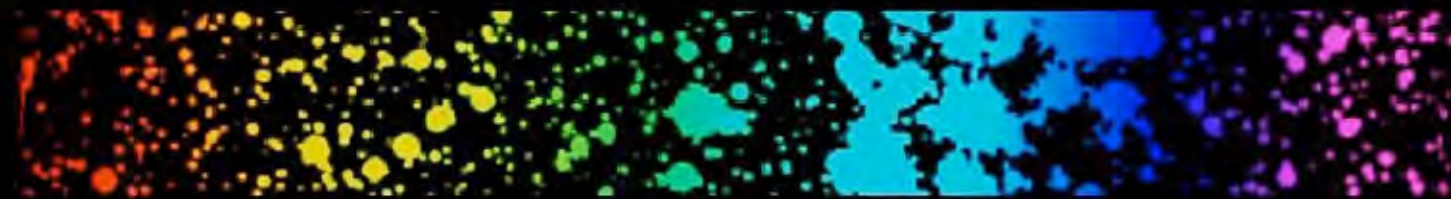
Look at the firmament through an ordinary telescope and see this.





Things look different through The Most.

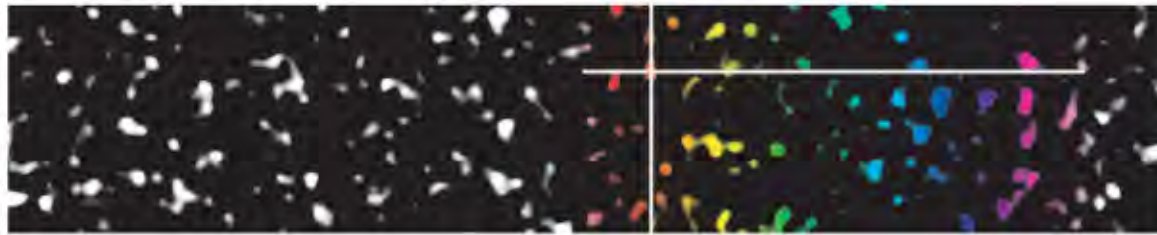
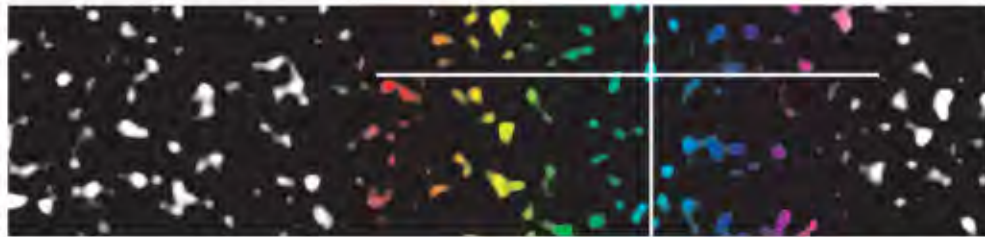
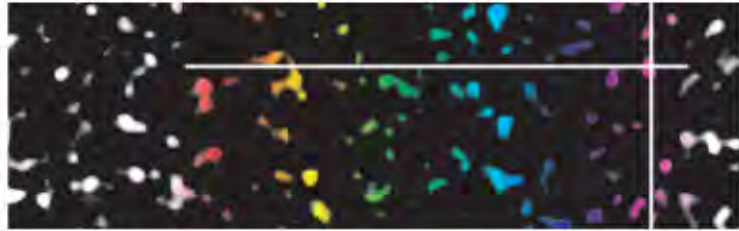




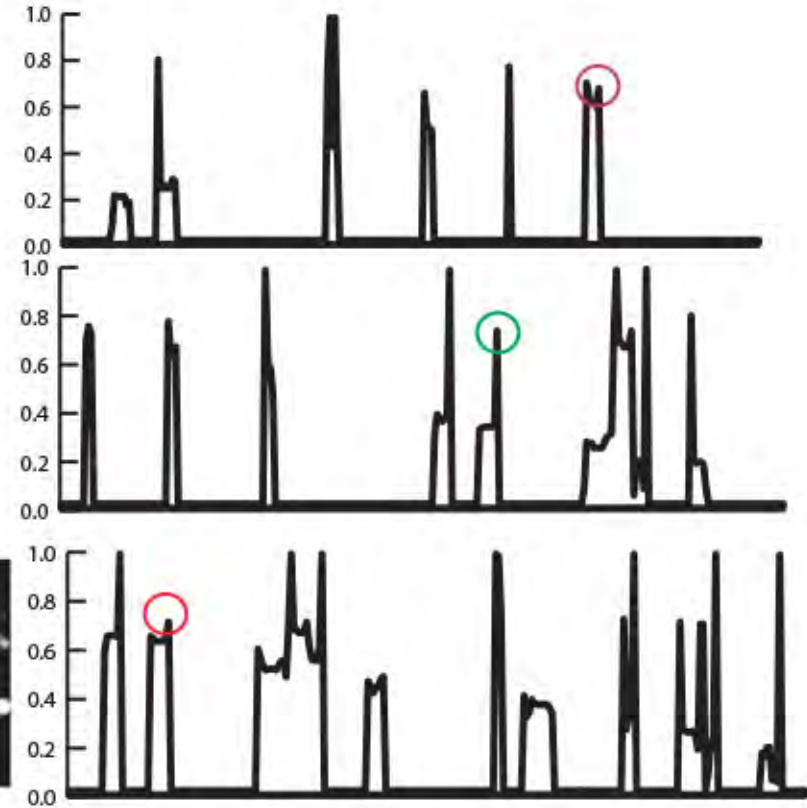
The focal plane array of The Most acquires an image like this.



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.

1. THE GENIUS IS IN THE GENERALITIES,
AND NOT THE DETAILS.

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.

4. IT CONTRIBUTES TO A MAJOR CHANGE
IN THE ESTABLISHED FRAMEWORK OF AERO-
SPACE POSSIBILITIES,

5. IT TRIGGERS A TRANSFORMATION OF
INTUITION.

6. REVOLUTIONARY PARADIGM SHIFTS ARE
SIMPLE, ELEGANT, MAJESTIC, BEAUTIFUL AND
CHARACTERIZED BY ORDER AND SYMMETRY.



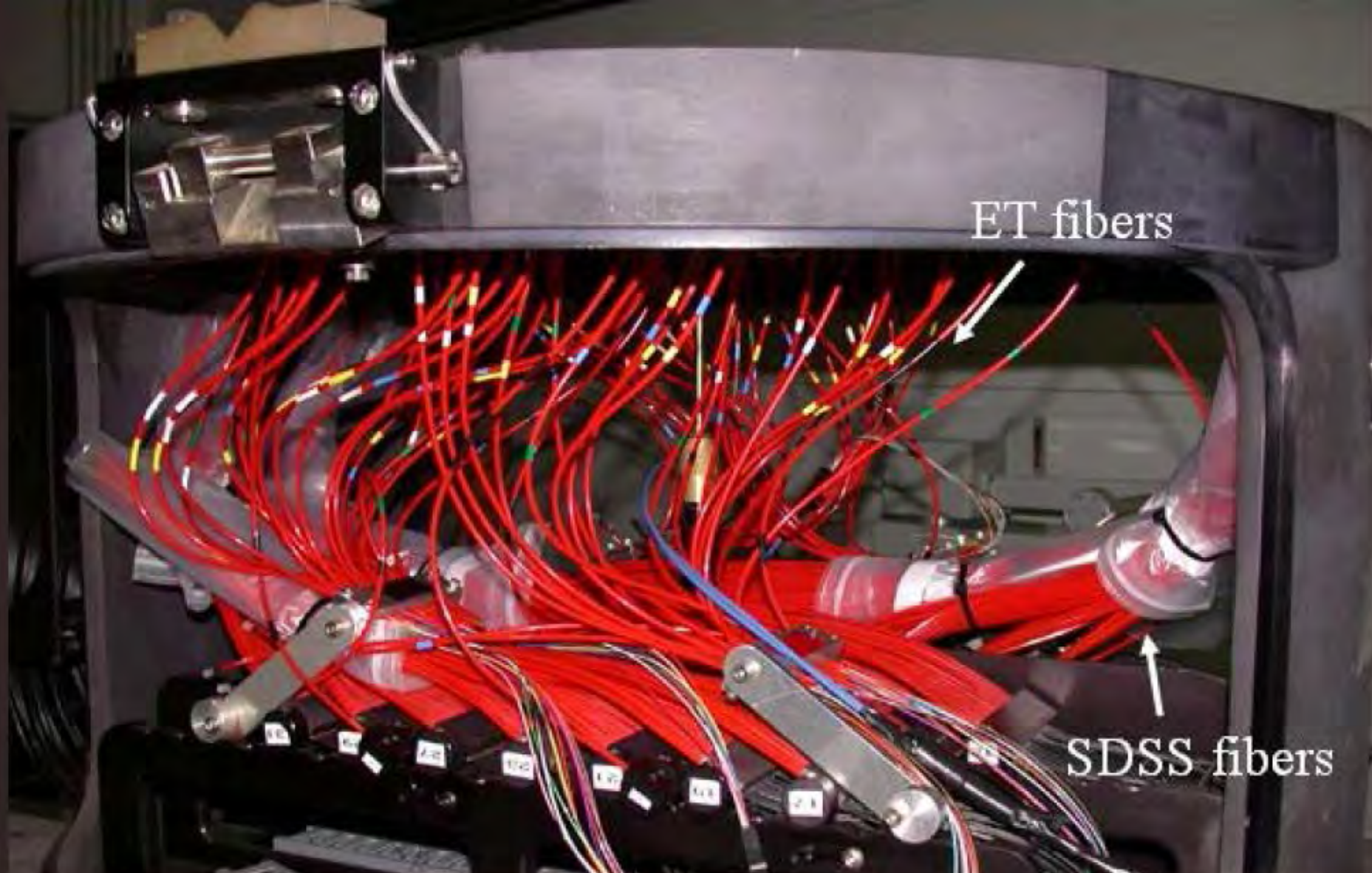
What is
Revolutionary
?



metamers

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

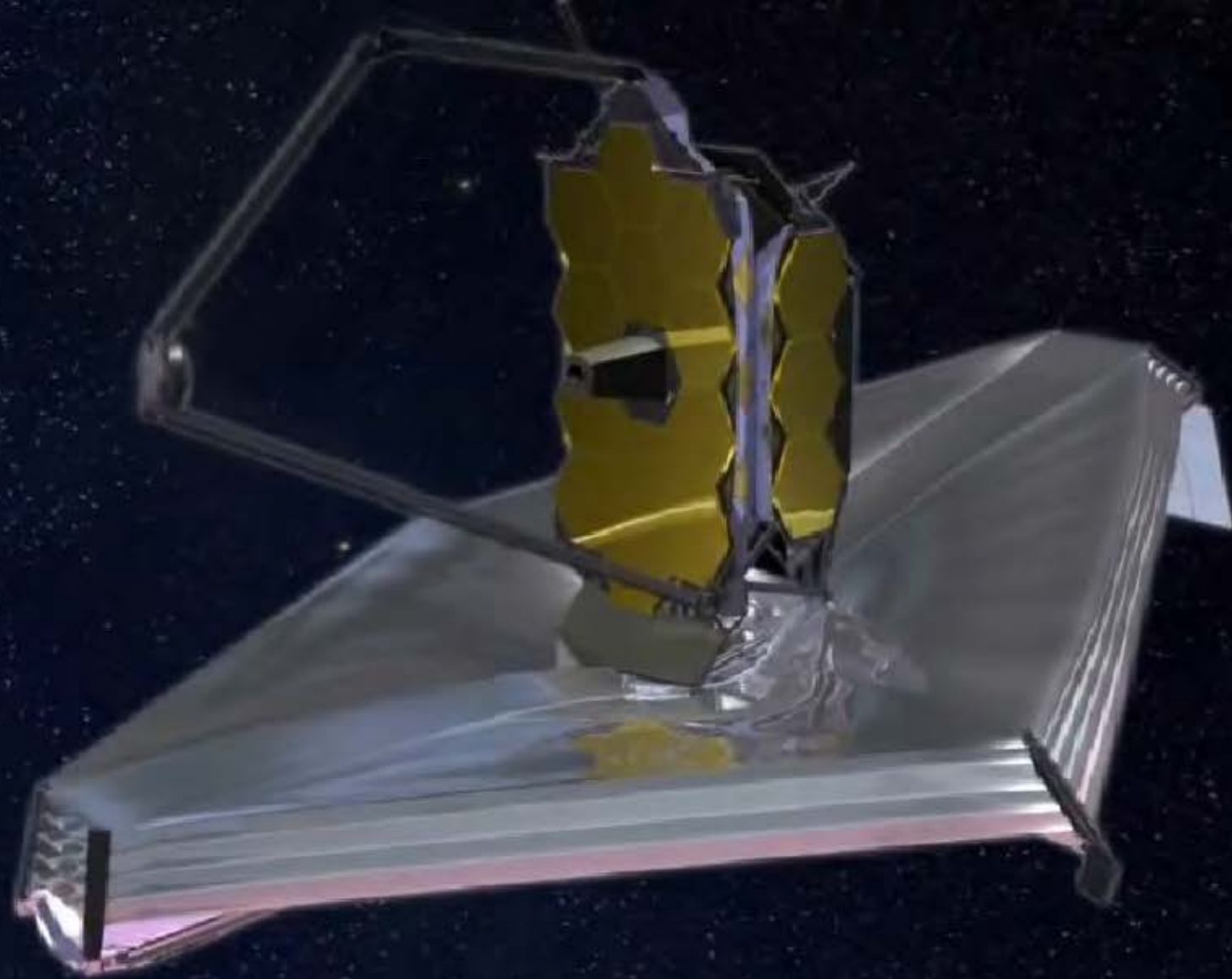
The **MOST** *multiple object spectroscopy*

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

Scaling up mirrors

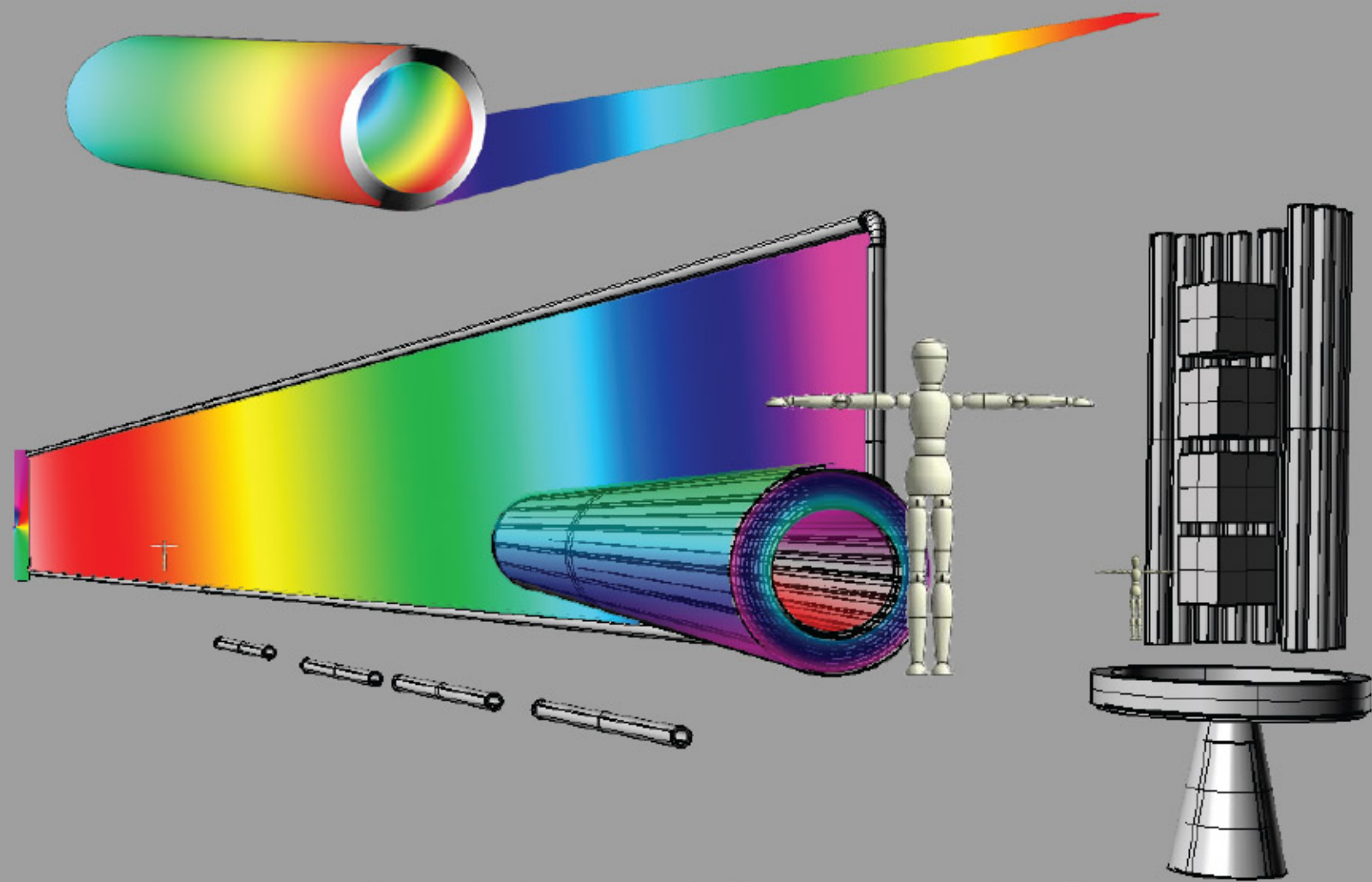


*Each doubling of mirror diameter has taken twice as long.
There are limits as to how large mirror primaries can grow.*



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.

1. THE GENIUS IS IN THE GENERALITIES,
AND NOT THE DETAILS.

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.

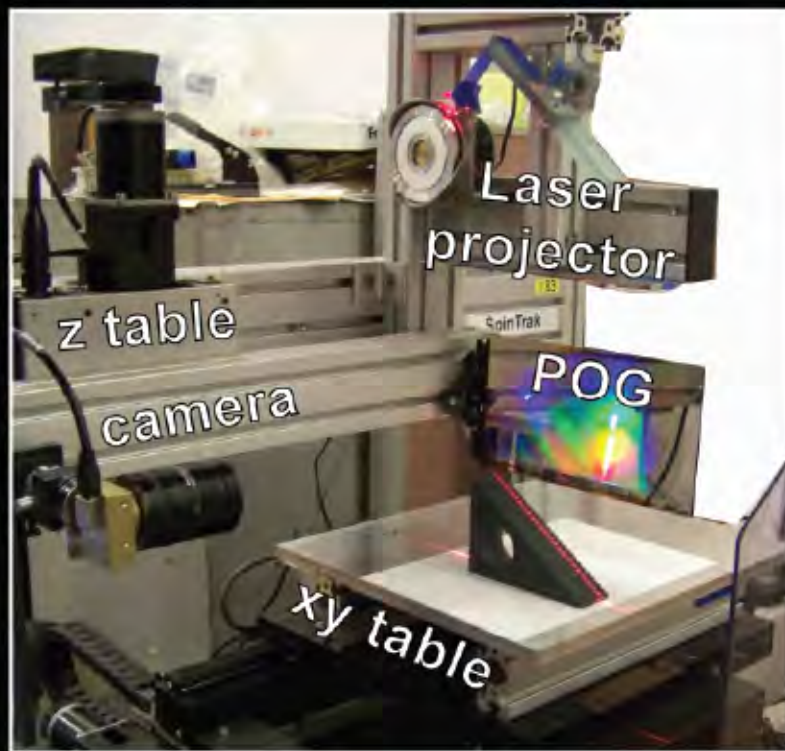
4. IT CONTRIBUTES TO A MAJOR CHANGE
IN THE ESTABLISHED FRAMEWORK OF AERO-
SPACE POSSIBILITIES,

5. IT TRIGGERS A TRANSFORMATION OF
INTUITION.

6. REVOLUTIONARY PARADIGM SHIFTS ARE
SIMPLE, ELEGANT, MAJESTIC, BEAUTIFUL AND
CHARACTERIZED BY ORDER AND SYMMETRY.



What is
Revolutionary
?



3D Microscope

Primary
Objective
Grating
Optical
Devices
made
by
3DeWitt



3D Ring

Research funded
by
The National
Science
Foundation



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



1. THE GENIUS IS IN THE GENERALITIES,
AND NOT THE DETAILS.

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.

4. IT CONTRIBUTES TO A MAJOR CHANGE
IN THE ESTABLISHED FRAMEWORK OF AERO-
SPACE POSSIBILITIES.

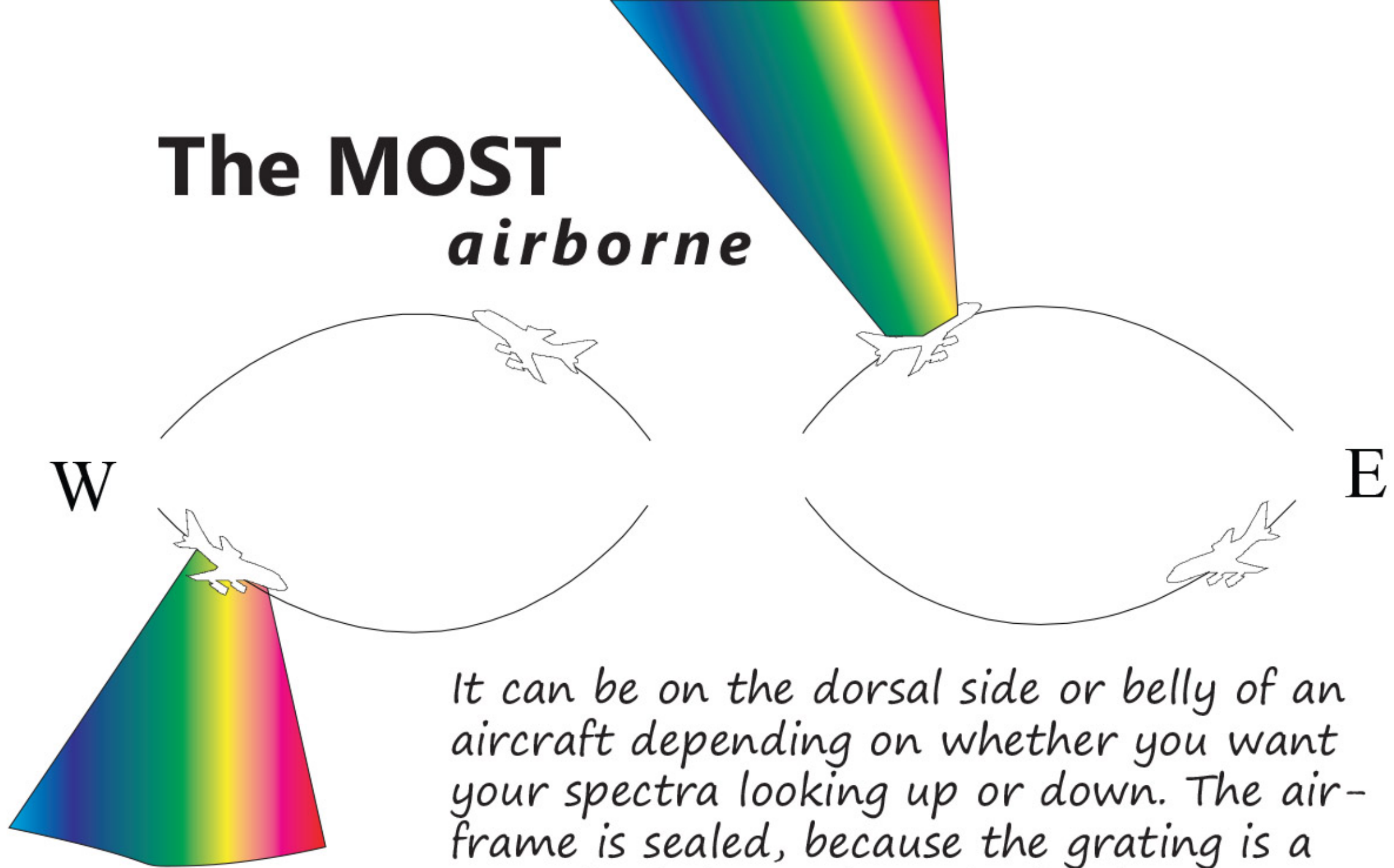
5. IT TRIGGERS A TRANSFORMATION OF
INTUITION.

6. REVOLUTIONARY PARADIGM SHIFTS ARE
SIMPLE, ELEGANT, MAJESTIC, BEAUTIFUL AND
CHARACTERIZED BY ORDER AND SYMMETRY.

*Here are a
couple of new
ways of doing
things...*



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 air-frame 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.



1. THE GENIUS IS IN THE GENERALITIES
AND NOT THE DETAILS.

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.

4. IT CONTRIBUTES TO A MAJOR CHANGE
IN THE ESTABLISHED FRAMEWORK OF AERO-
SPACE POSSIBILITIES.

5. IT TRIGGERS A TRANSFORMATION OF
INTUITION.

6. REVOLUTIONARY PARADIGM SHIFTS ARE
SIMPLE, ELEGANT, MAJESTIC, BEAUTIFUL AND
CHARACTERIZED BY ORDER AND SYMMETRY.

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



1. THE GENIUS IS IN THE GENERALITIES,
AND NOT THE DETAILS.

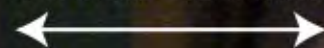
2. THE NEW IDEA ILLUMINATES A PATHWAY
TOWARD AN EXPANSION OF KNOWLEDGE
AND MAY ADDRESS A SIGNIFICANT ROAD
BLOCK.

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

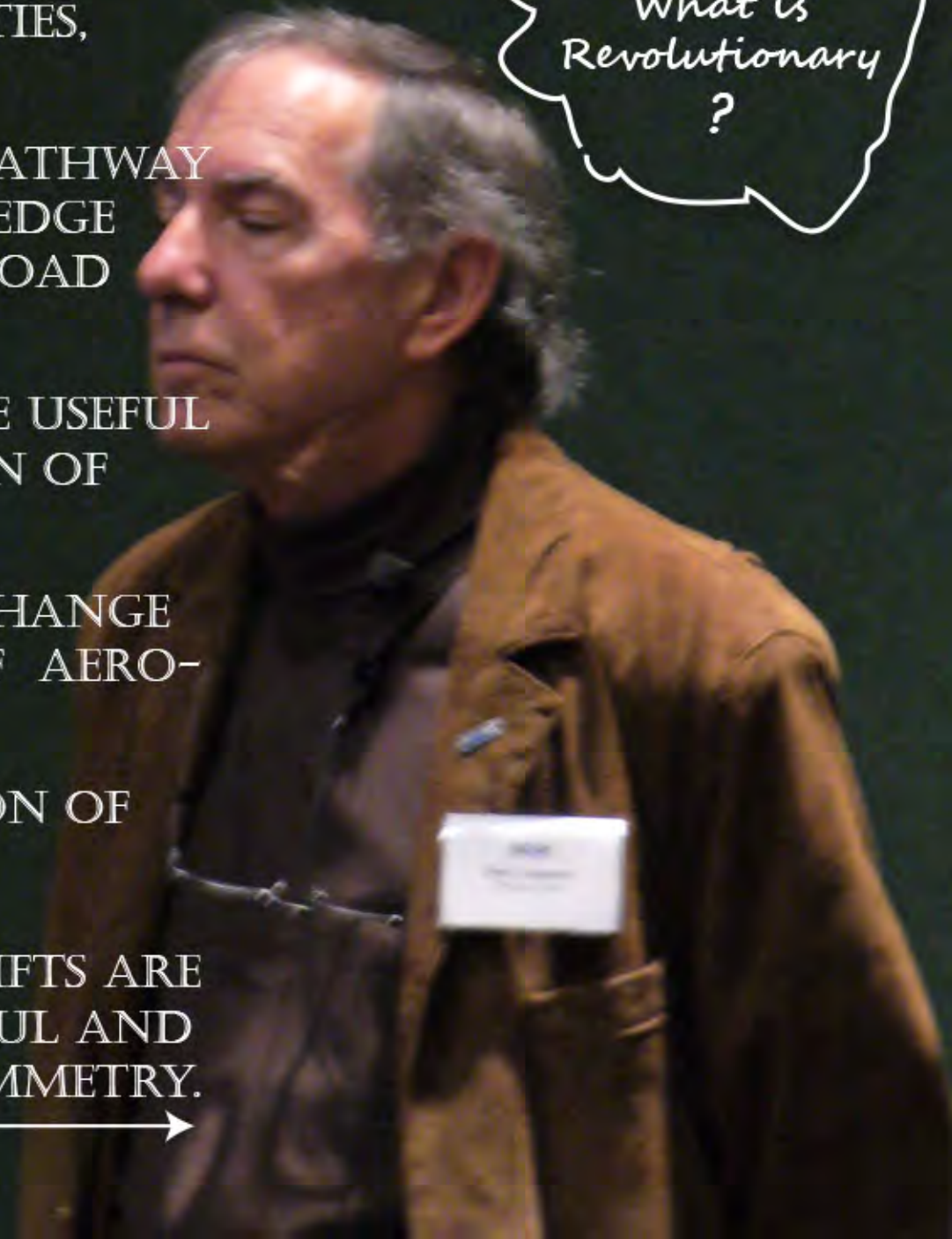
4. IT CONTRIBUTES TO A MAJOR CHANGE
IN THE ESTABLISHED FRAMEWORK OF AERO-
SPACE POSSIBILITIES,

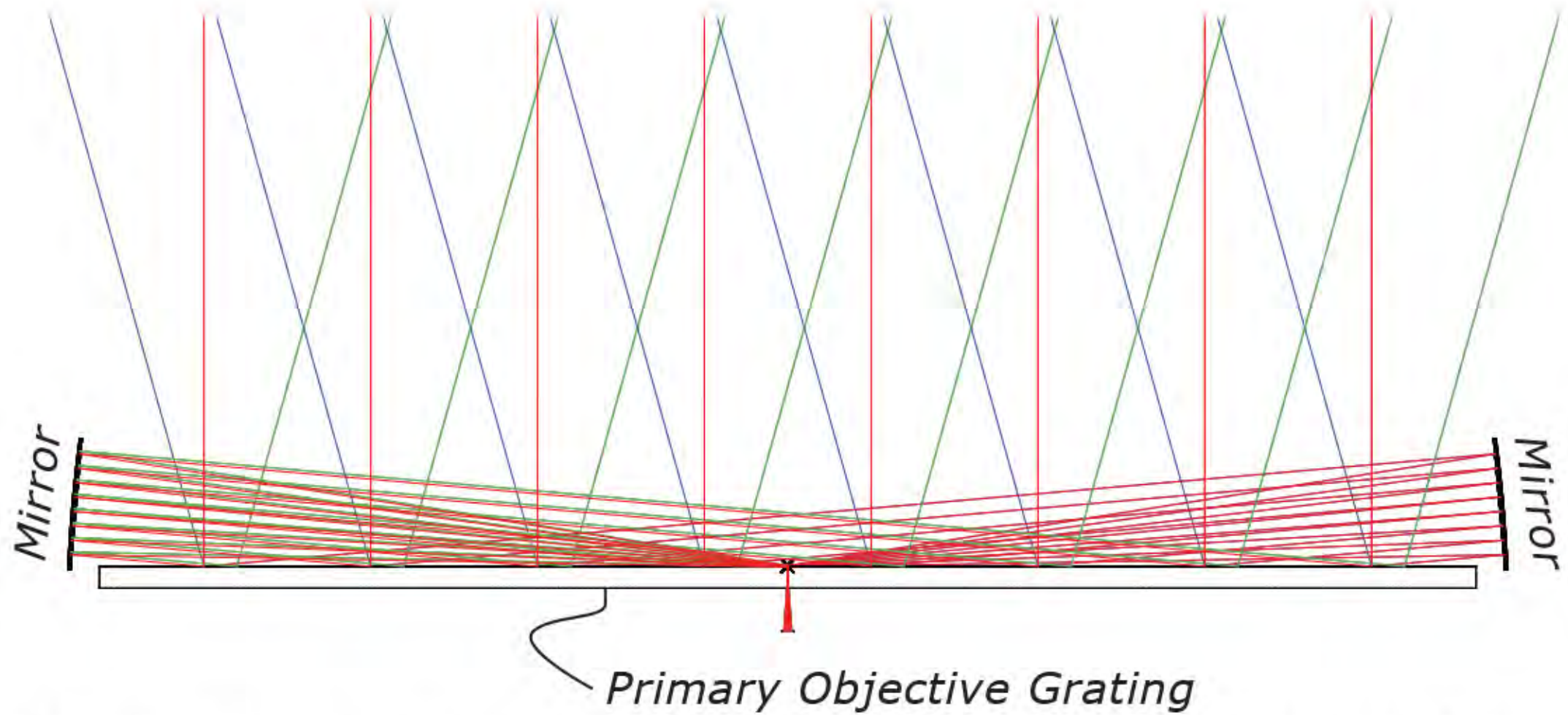
5. IT TRIGGERS A TRANSFORMATION OF
INTUITION.

6. REVOLUTIONARY PARADIGM SHIFTS ARE
SIMPLE, ELEGANT, MAJESTIC, BEAUTIFUL AND
CHARACTERIZED BY ORDER AND SYMMETRY.

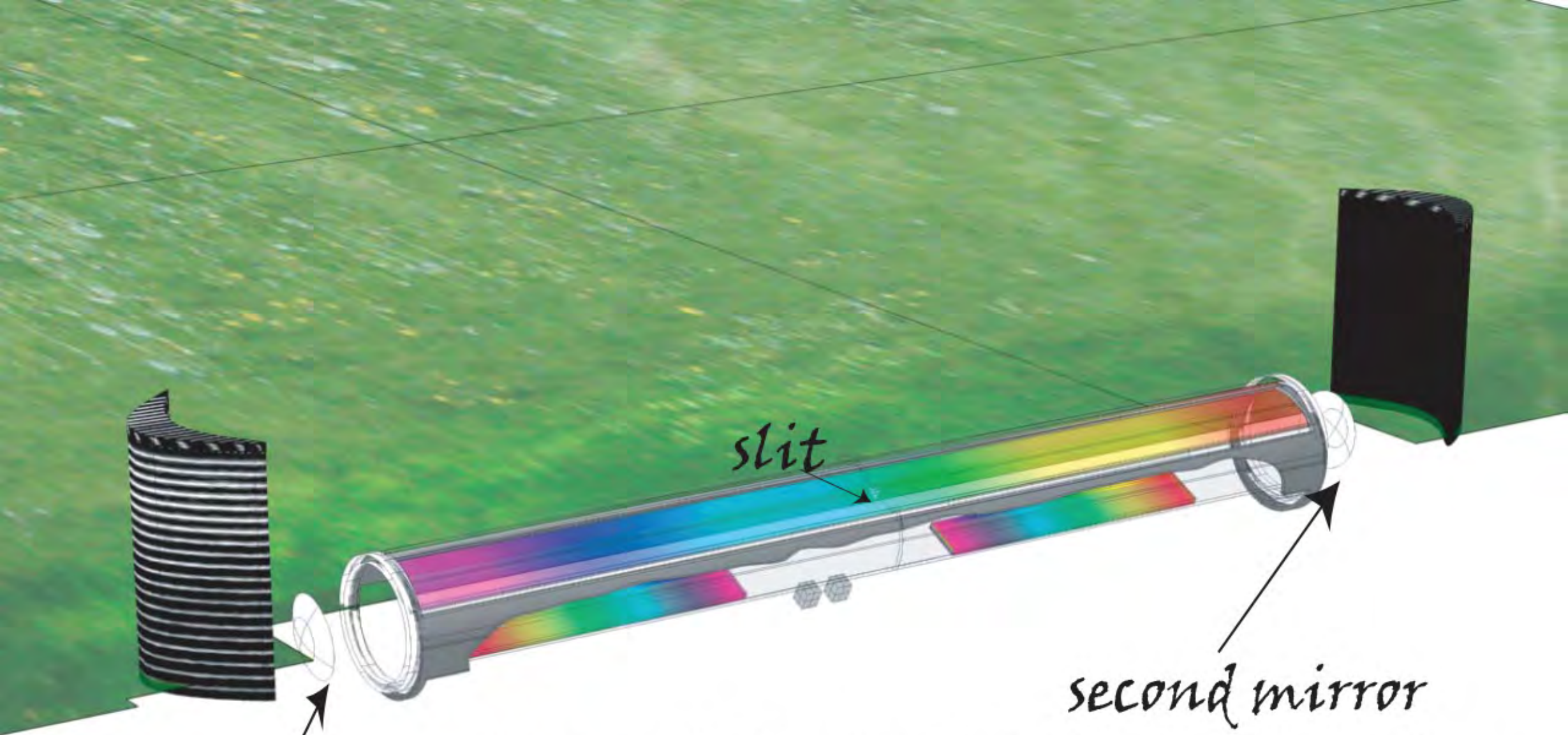


What is
Revolutionary
?





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.



First Mirror

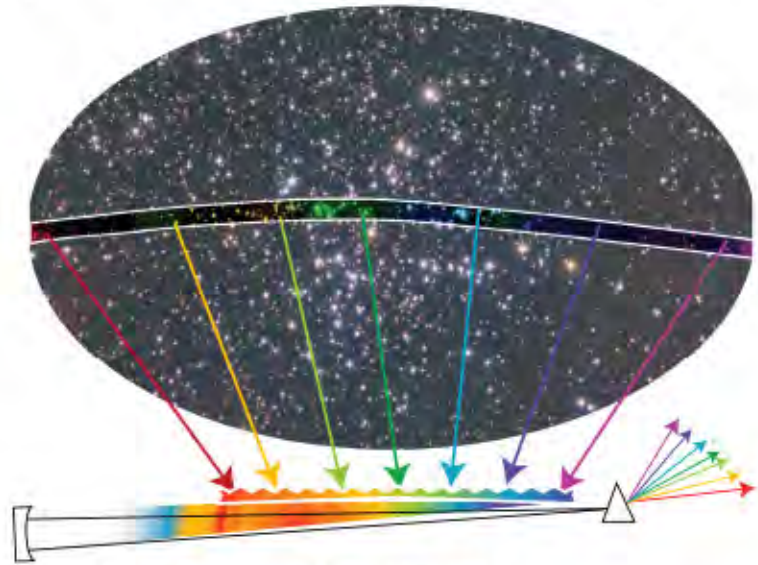
second mirror

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.

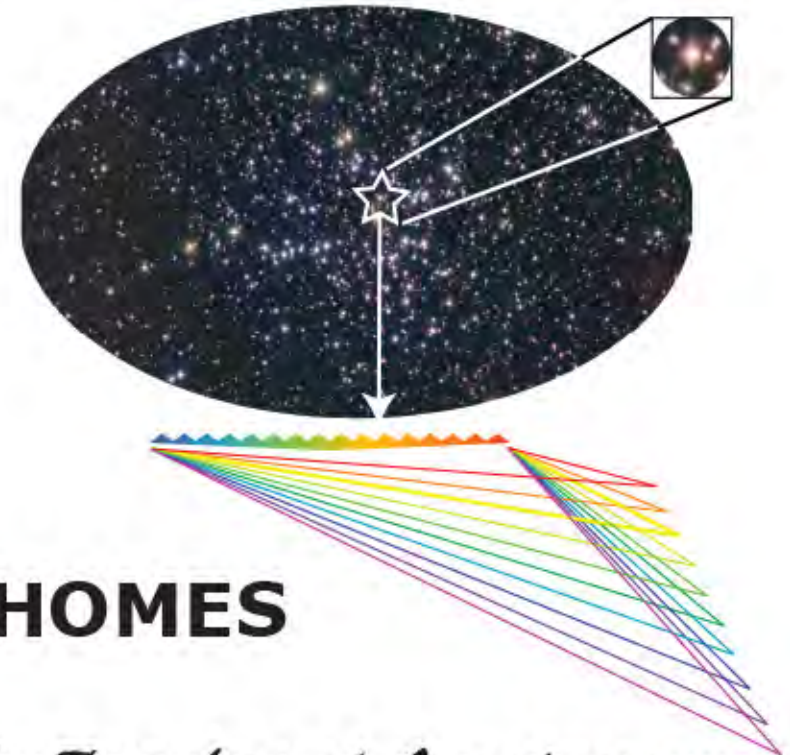


A telescope that can be buried below ground with no dome, no wind shear and works essentially with no moving parts during observation cycles

The Multiple Object Spectrographic Telescope



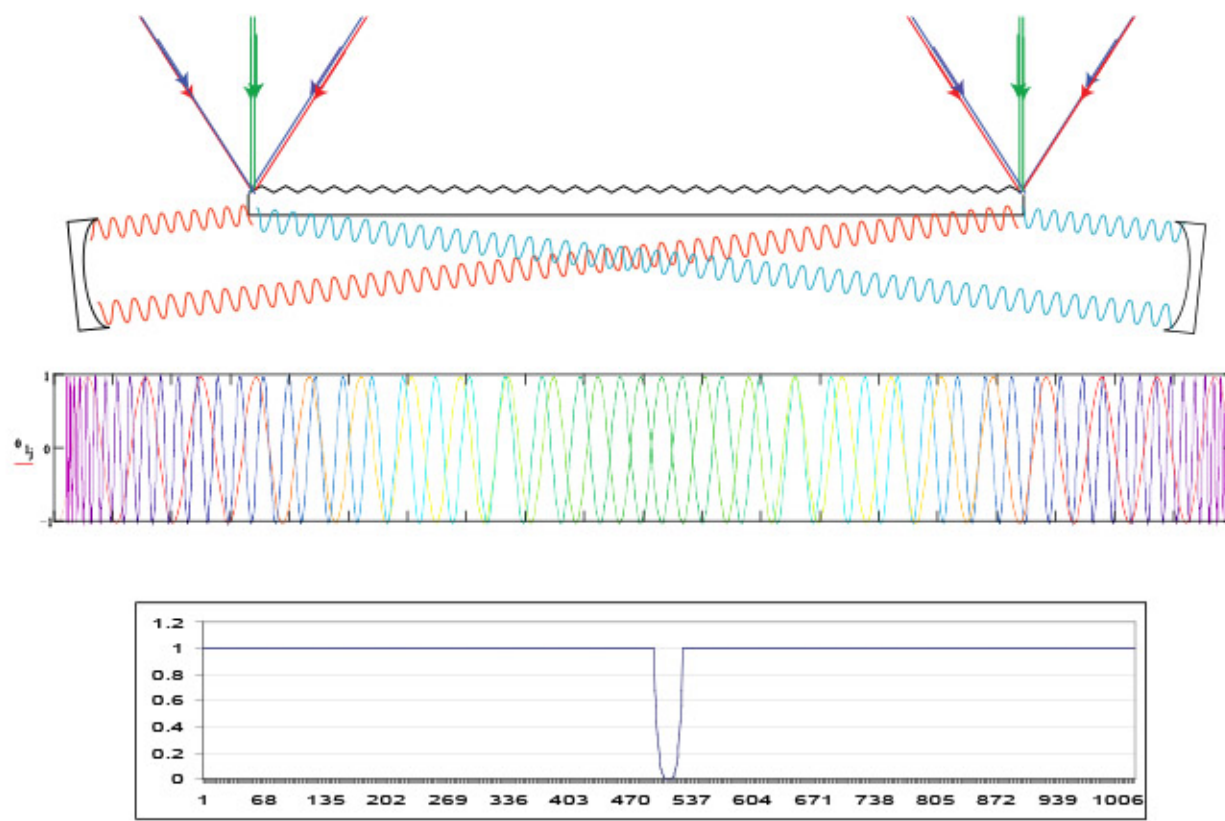
The MOST



HOMES

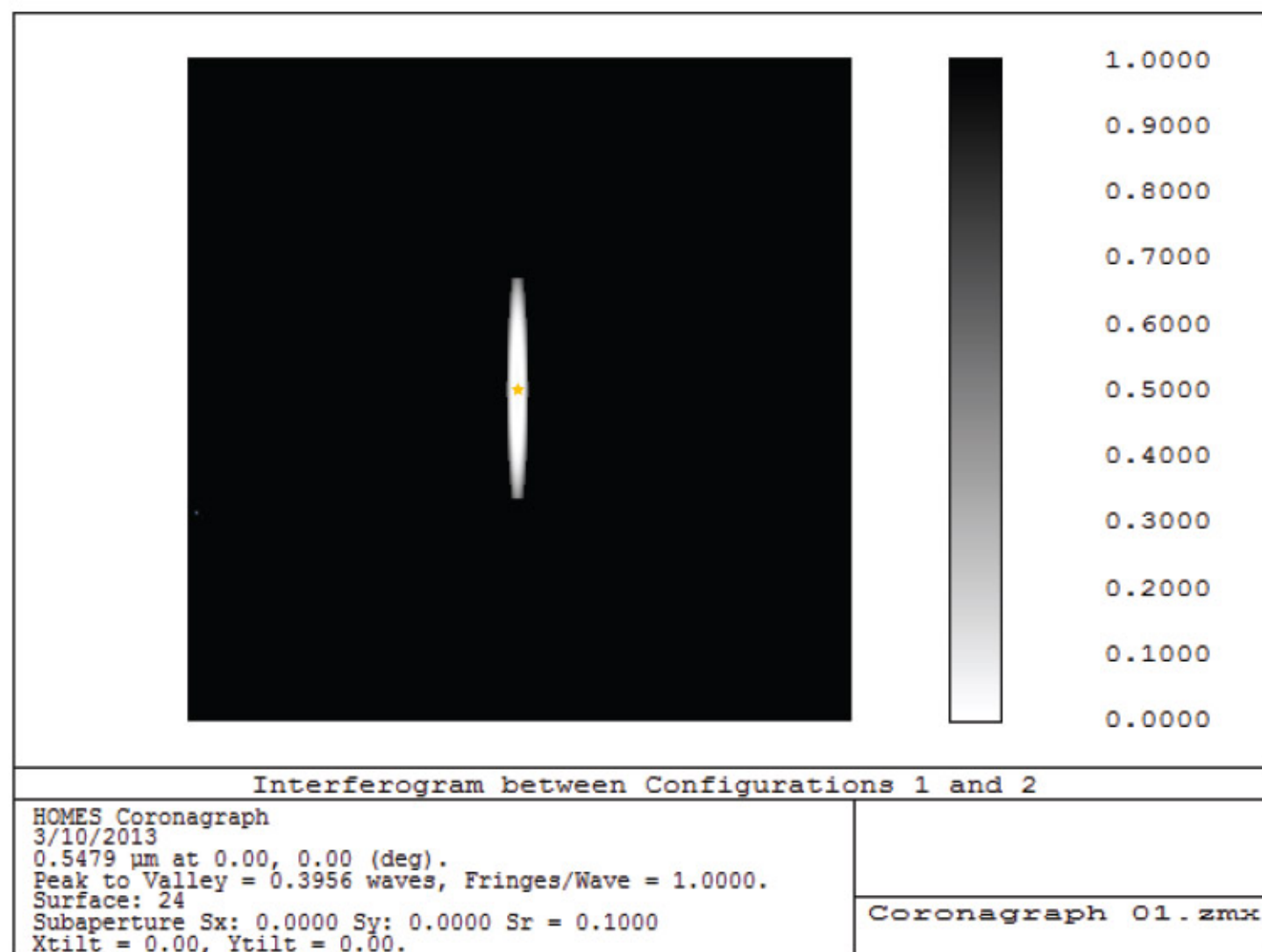
Holographic Optical Method for Exoplanet Spectroscopy

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.



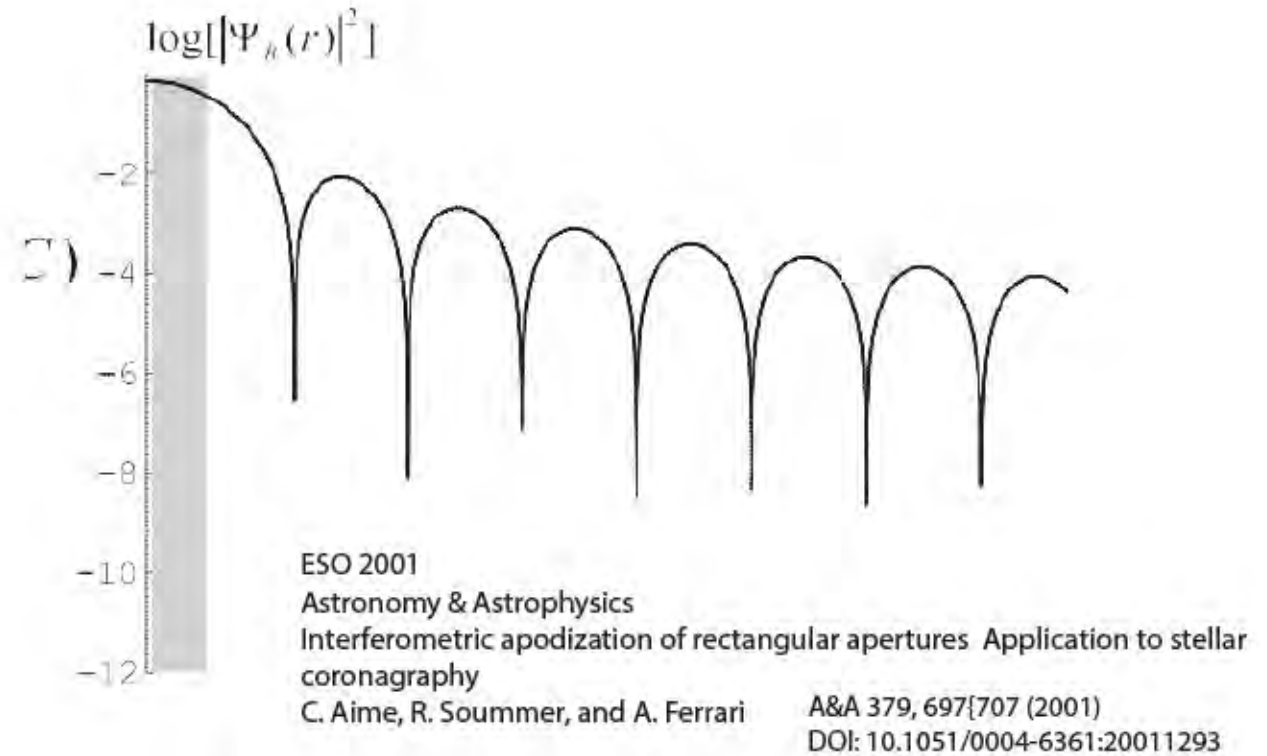
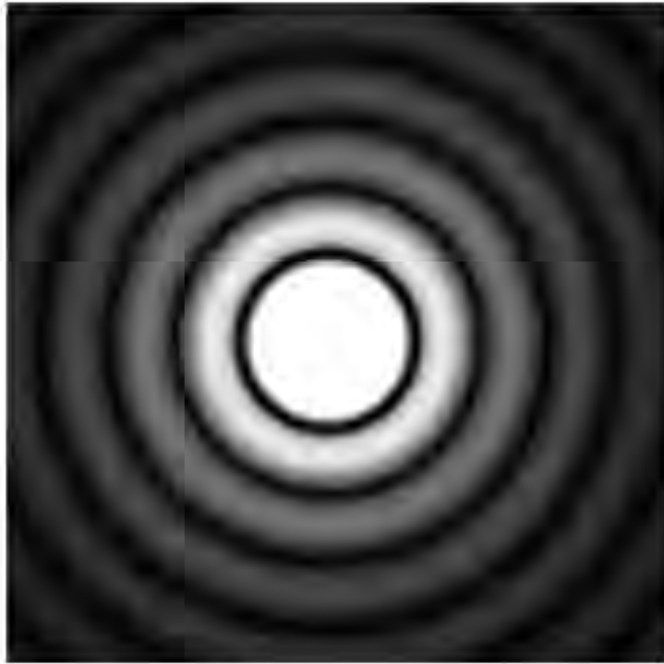
06:	0.00539	0.00381	0.00207	0.00060	0.00000	0.0
07:	1.00000	1.00000	1.00000	1.00000	1.00000	1.0
08:	0.00548	0.00389	0.00212	0.00063	0.00000	0.0
09:	1.00000	1.00000	1.00000	1.00000	1.00000	1.0
10:	0.00557	0.00397	0.00218	0.00066	0.00000	0.0
11:	1.00000	1.00000	1.00000	1.00000	1.00000	1.0
12:	0.00566	0.00404	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.

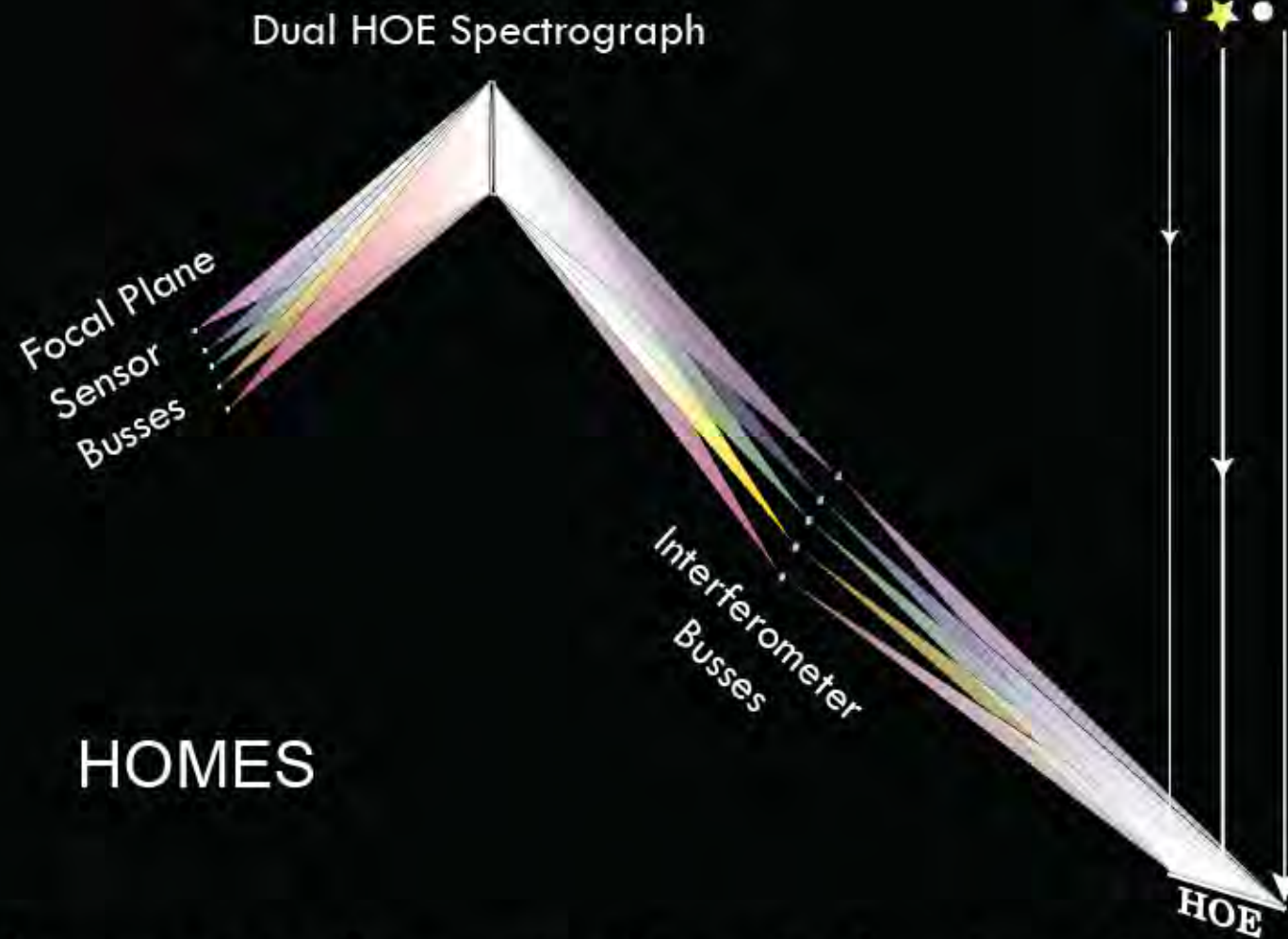


We see that null in this interferogram. The interferometer is a coronagraph because its null is on a single central wavelength band leaving the rest of the field for acquisition of the planetary system. A tiny "star" is marked in yellow at the null.

Nulling interferometer for coronagraphy



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

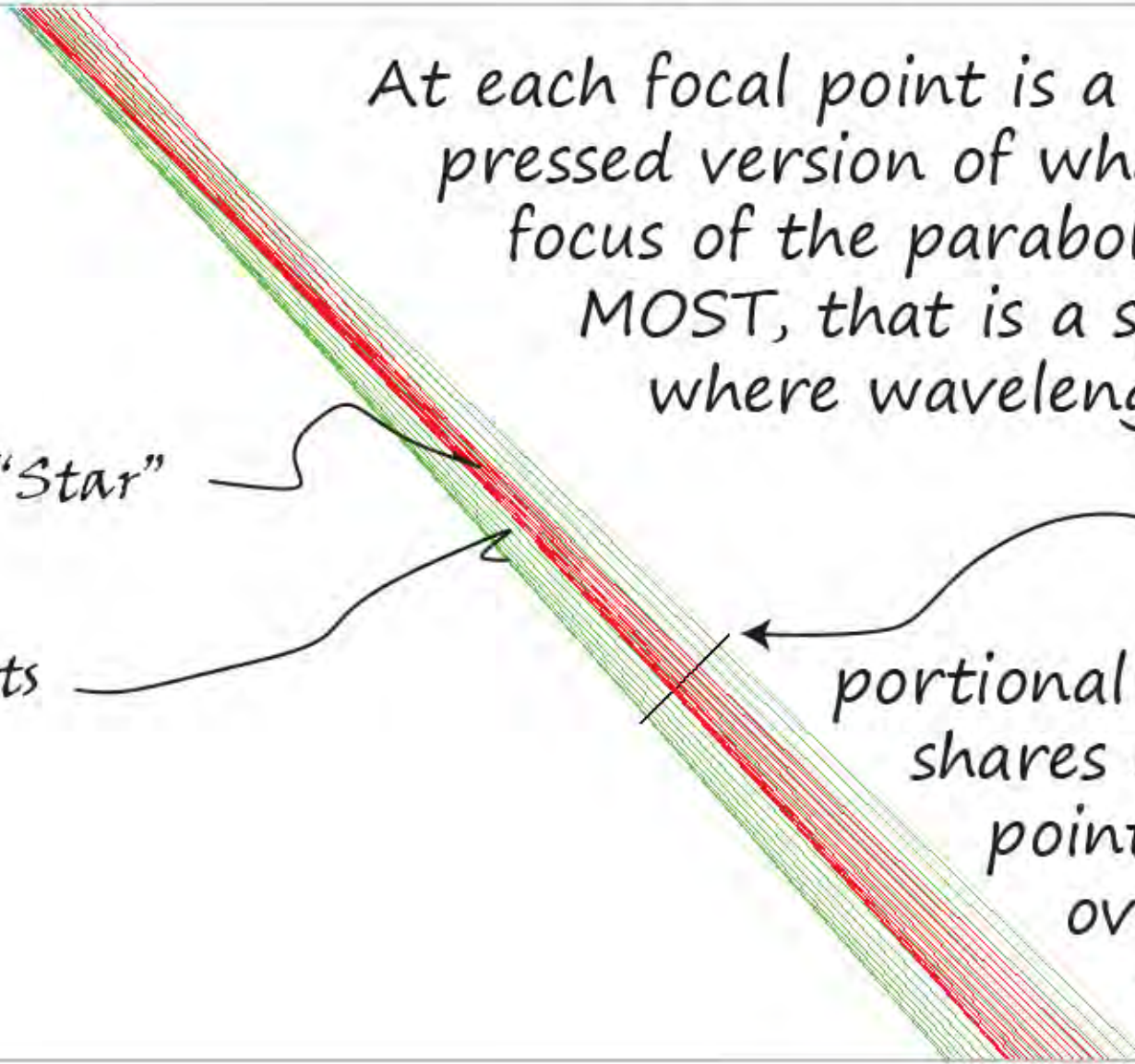
At each focal point is a highly compressed version of what is seen at the focus of the parabolic mirror of The MOST, that is a spectral spread where wavelength is propor-

"Star"

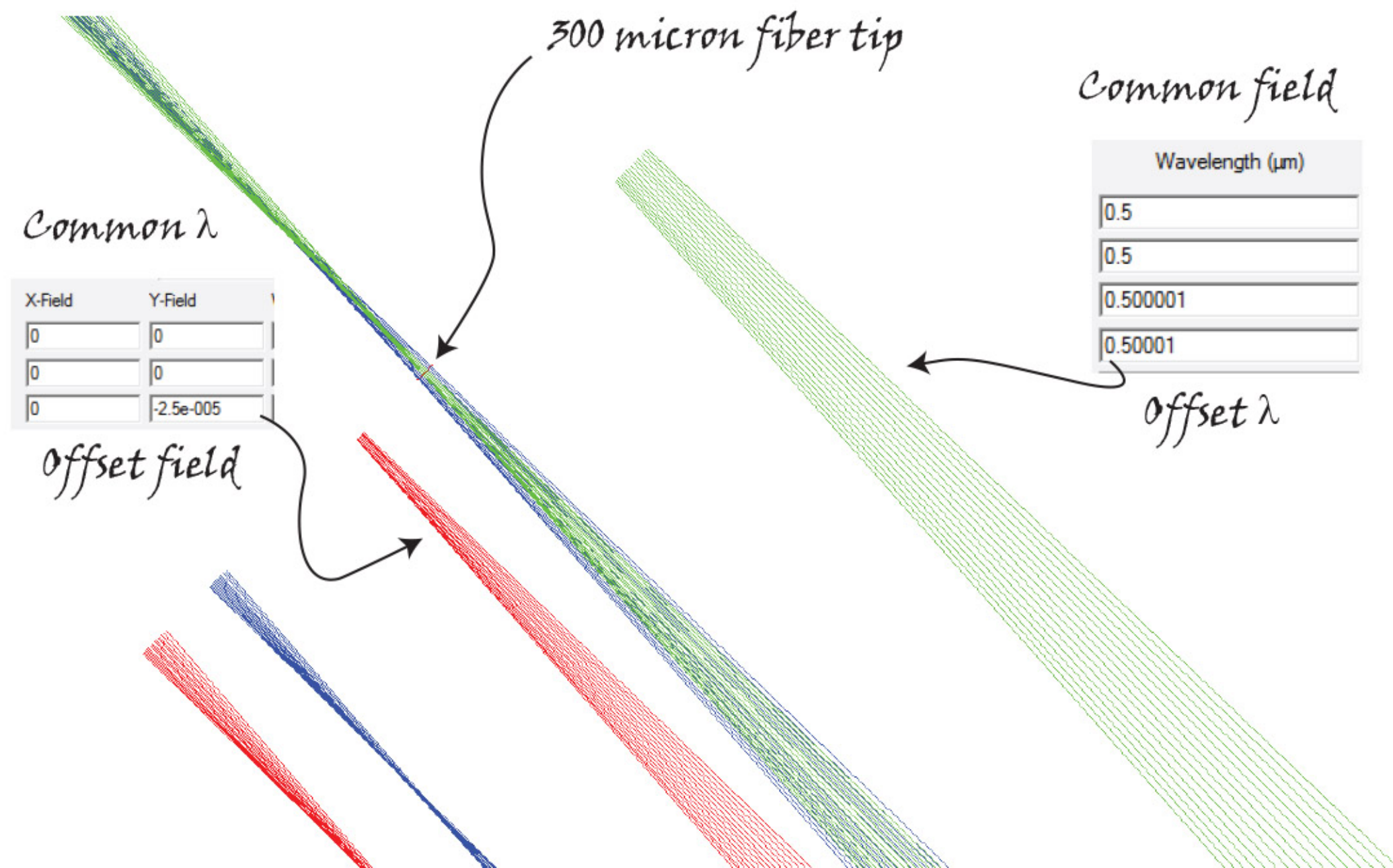
300 micron fiber tip

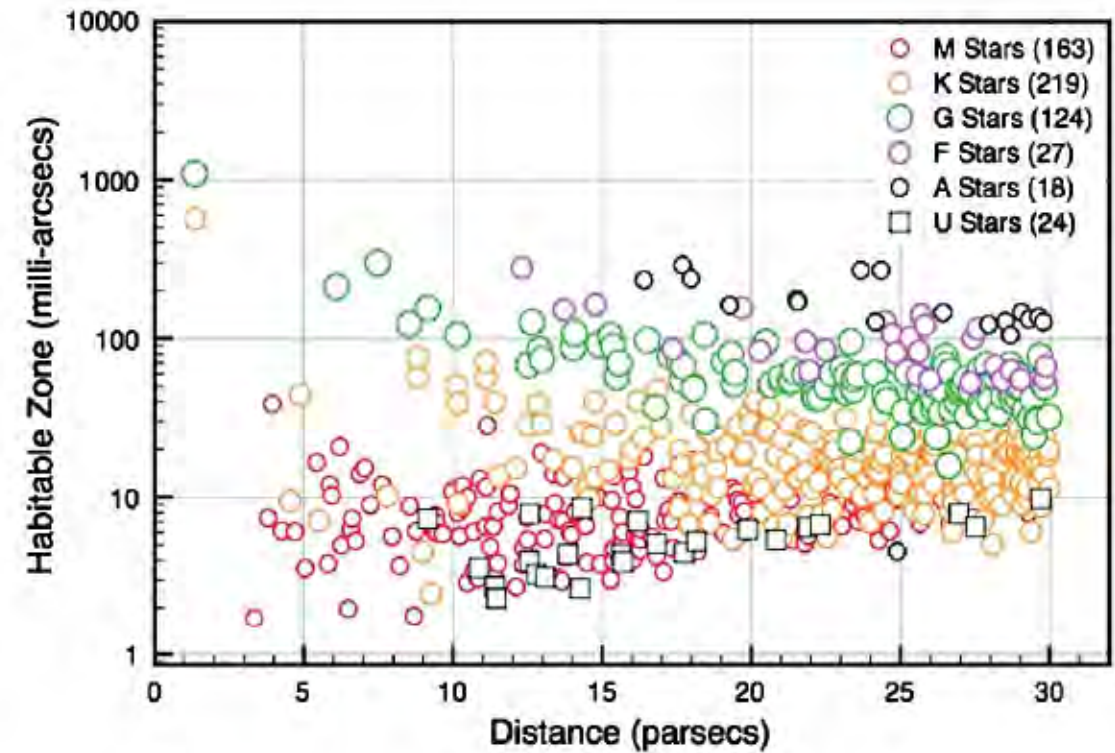
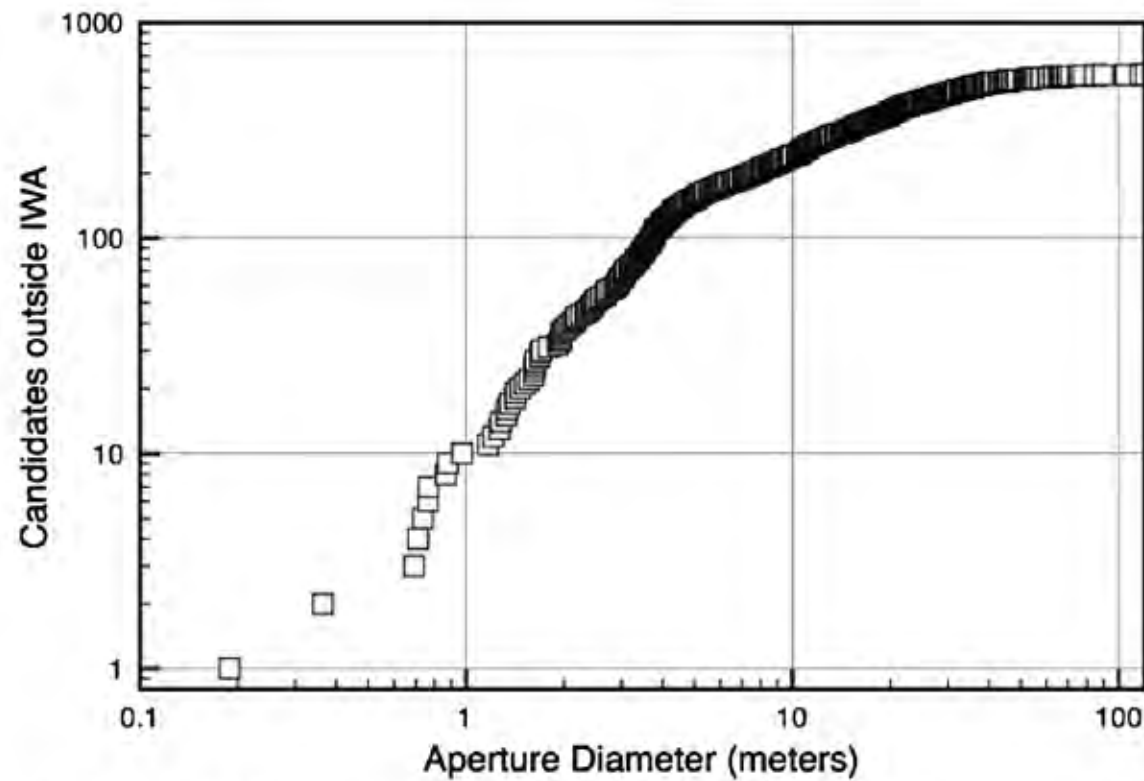
Exoplanets

portional 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.





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.

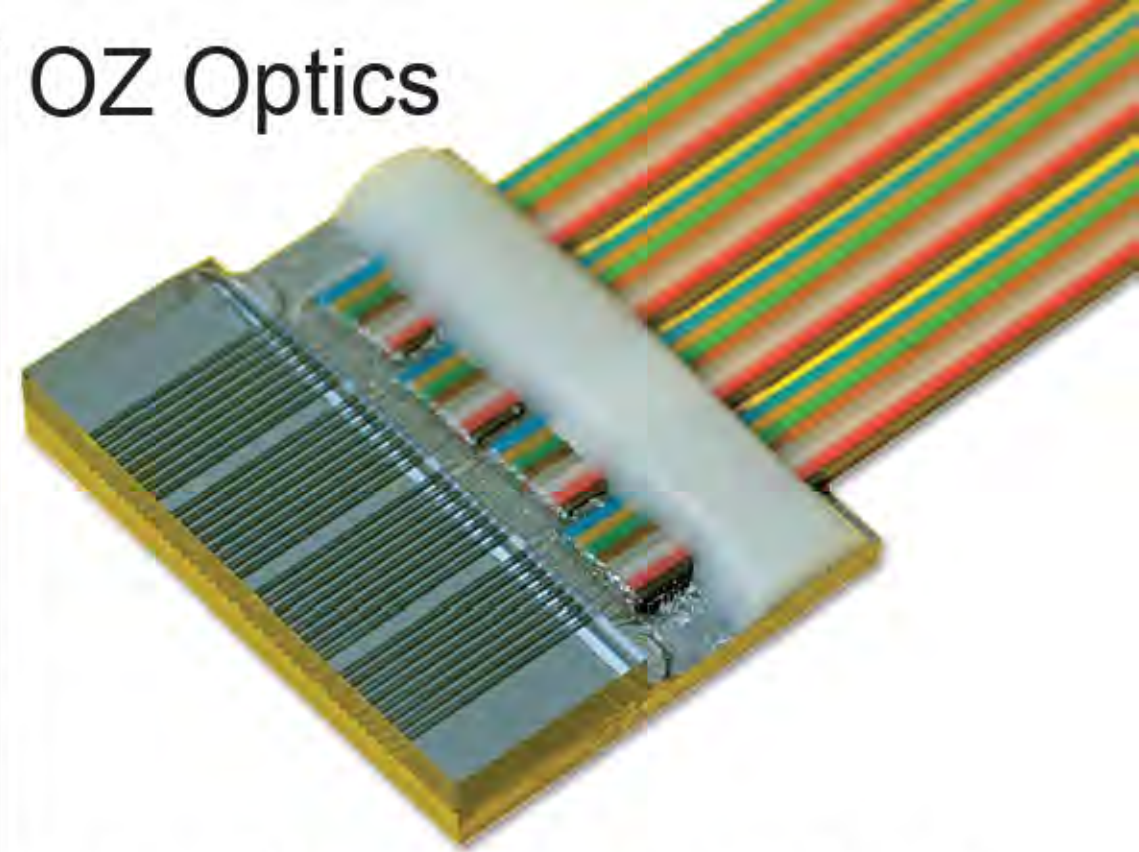
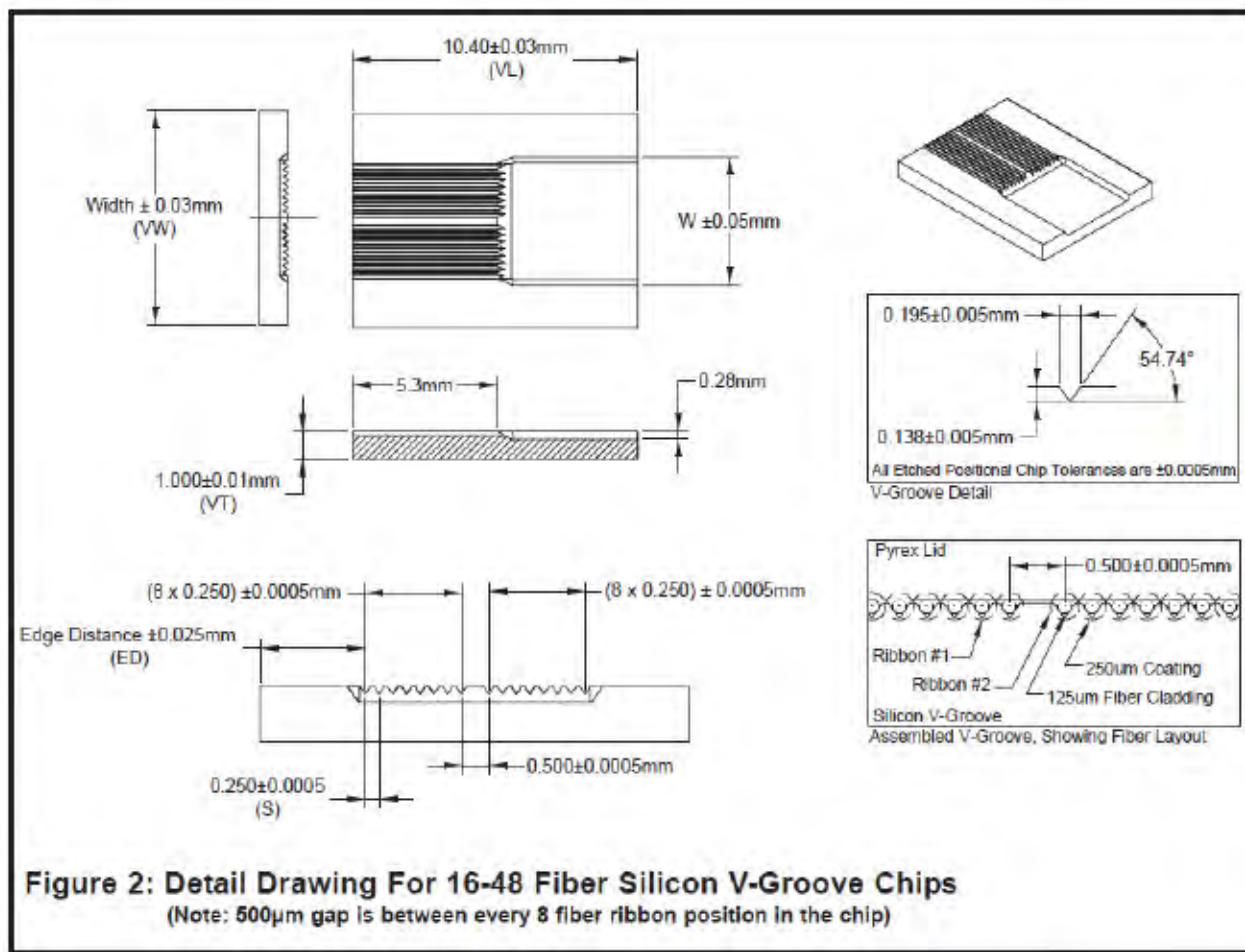
Table 1 Candidate stars versus aperture.

Diameter (meters)	IWA (mas)	Number of stars at or outside IWA						Total (575)	Δt in days Δt to SNR = 5
		A (18)	F (27)	G (124)	K (219)	M (163)	U (24)		
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.*

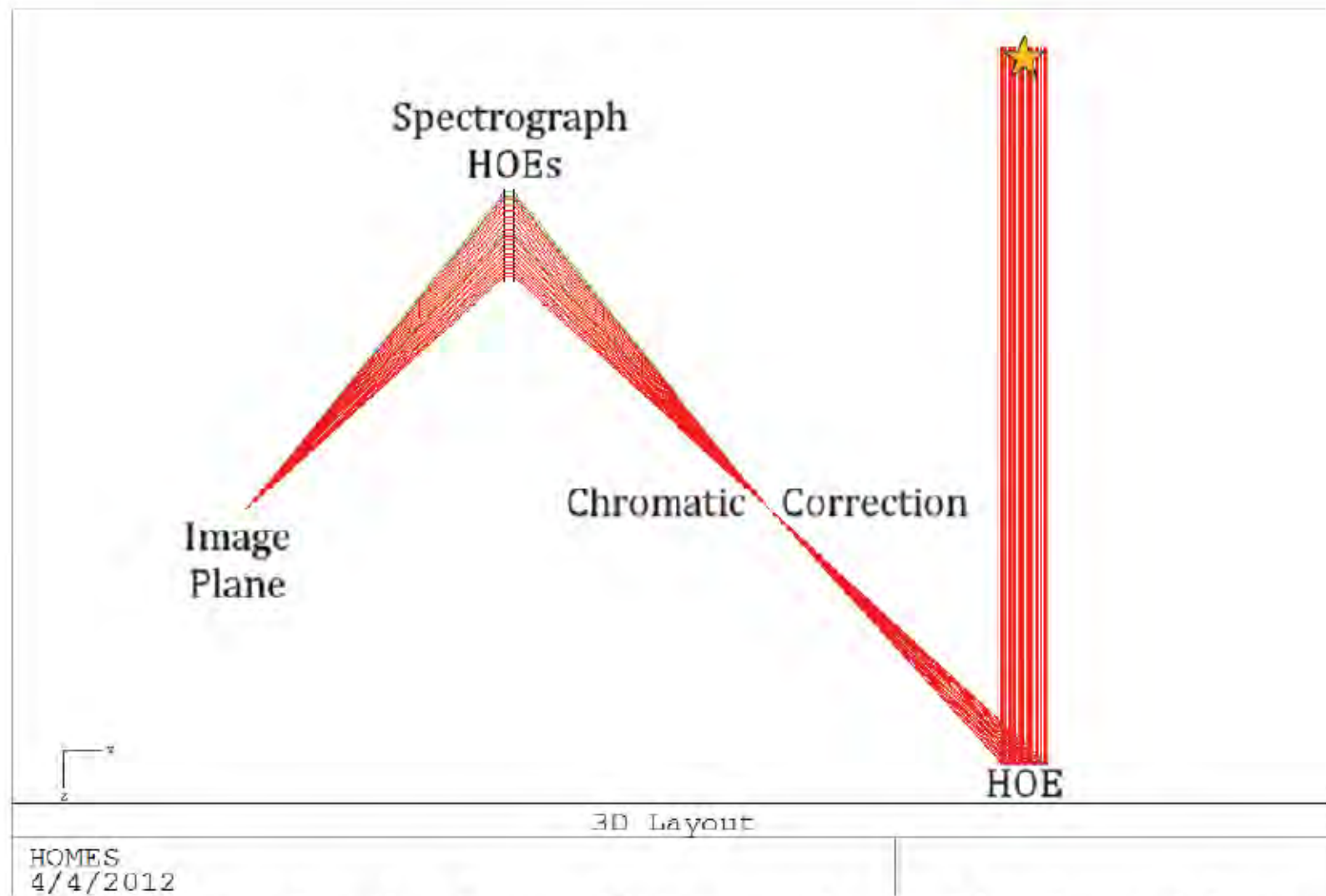
The problem is the flux, because each highly resolved HOMES bandpass sees few photons. Let's say an exoplanet at 10 parsecs produces 10 photons per square meter per minute. That means with a HOMES 500 square meter primary about 500 photons per minute at 100% efficiency or 50 photons per minute with 10%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

OZ Optics

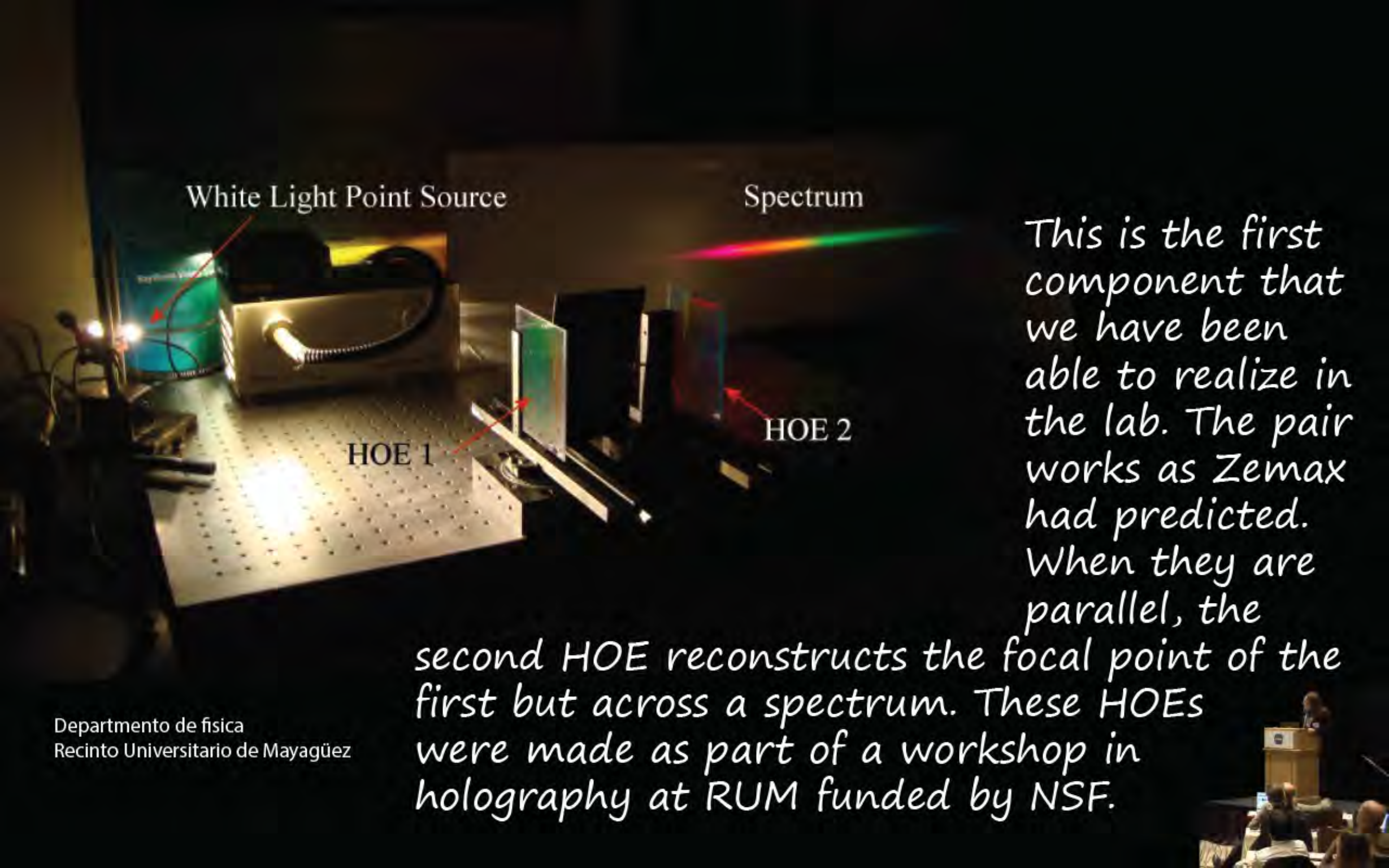


standard optical
connector with
500 micron
spacers.

We will need thousands of
fibers spanning many meters.
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.



White Light Point Source

Spectrum

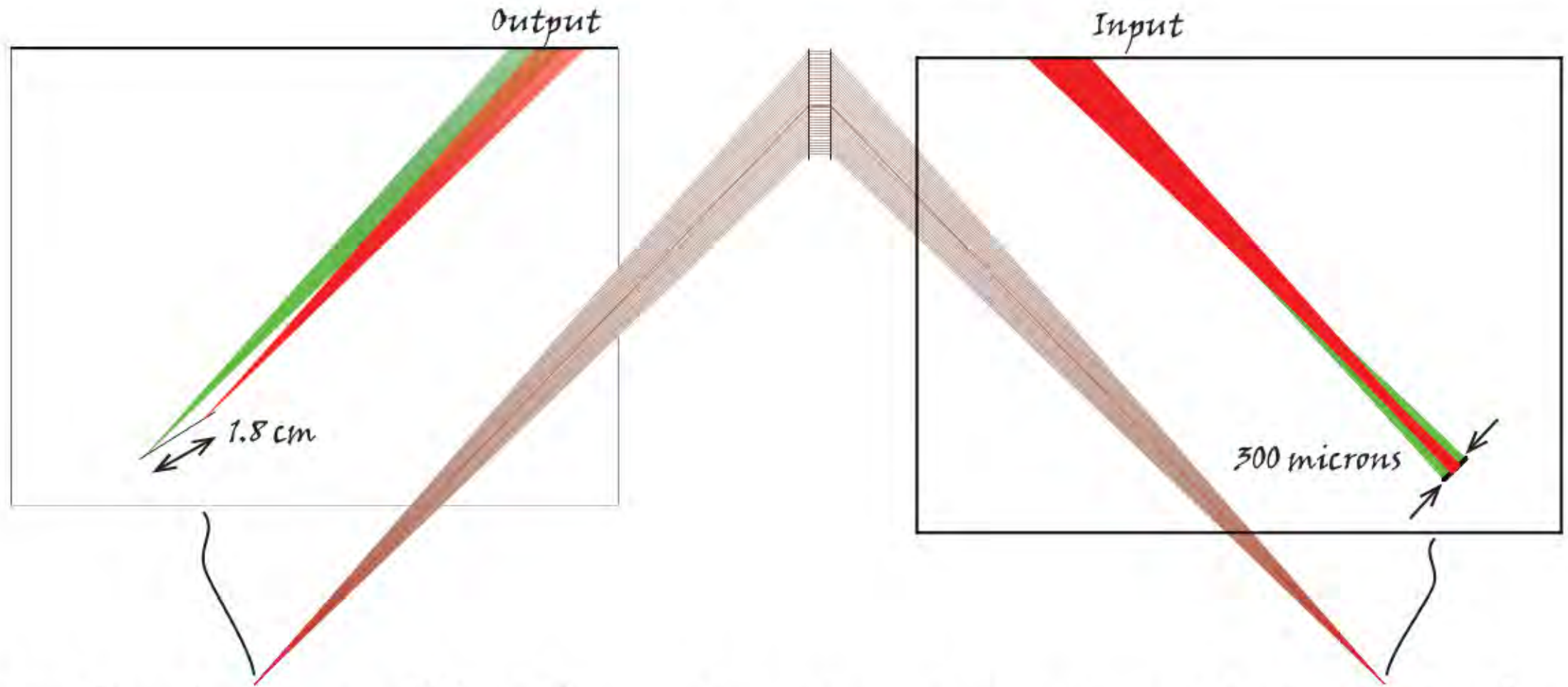
HOE 1

HOE 2

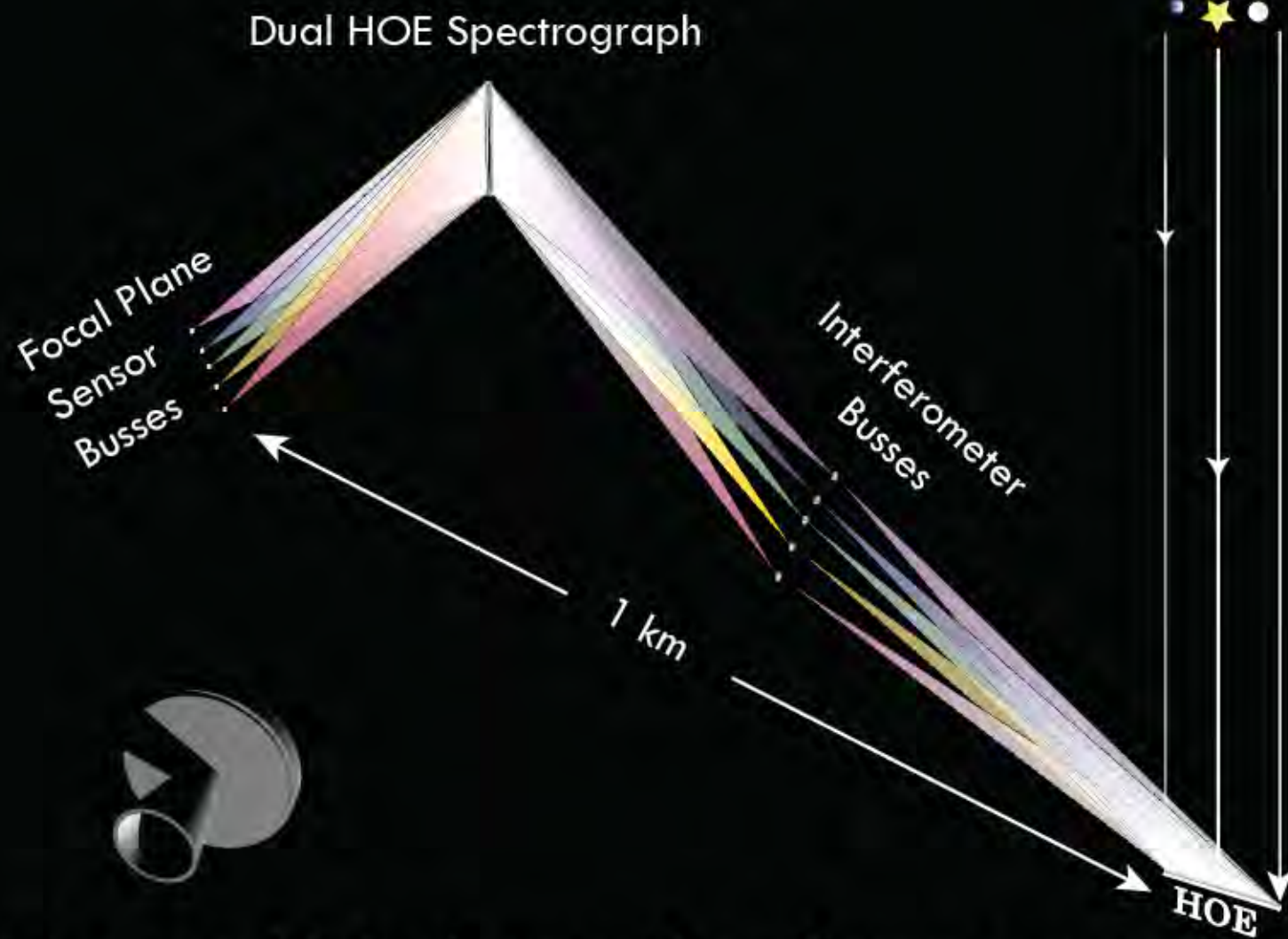
This is the first component that we have been able to realize in the lab. The pair works as Zemax had predicted. When they are parallel, the

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.

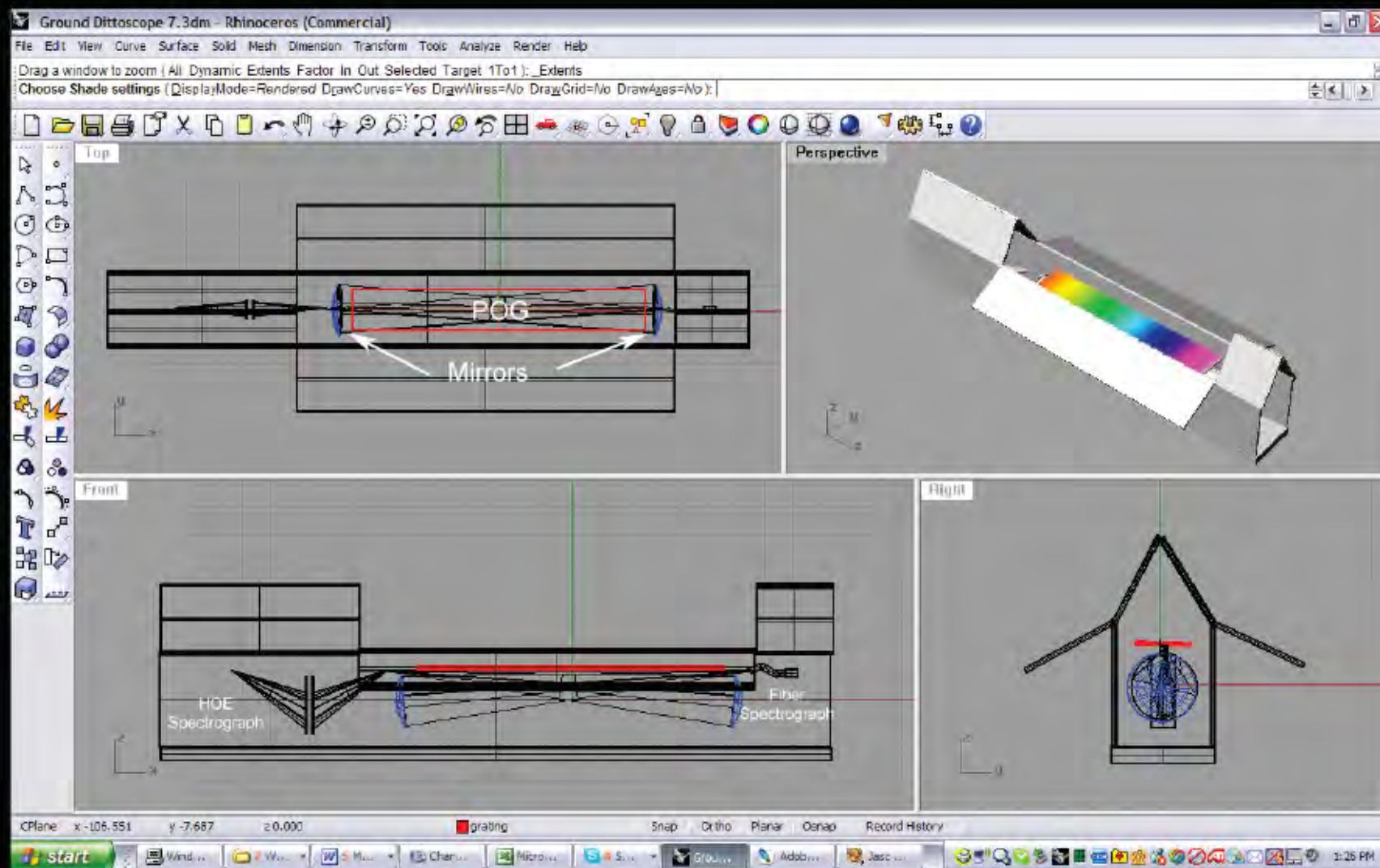
2 sources separated by 100 mas



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.



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													
Bench Optics	Mirror Mount							grazing exodus	phase error			Astigmatism	Niekamp 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					Mightex 6 Fiber	Driver Software					Monkhouse
Data Reduction		Fab UPR		Star Map	Star Map III	Star Map IV				Integration Time			Warren
Observation			Star Map I II										
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	Prepare	SPIC	Prepare	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 sequestered, we do have our Phase II plans ready.

Holographic Optical Method for Exoplanet Spectroscopy



HOMES

Questions?

www.3dewitt.com/tele.html

