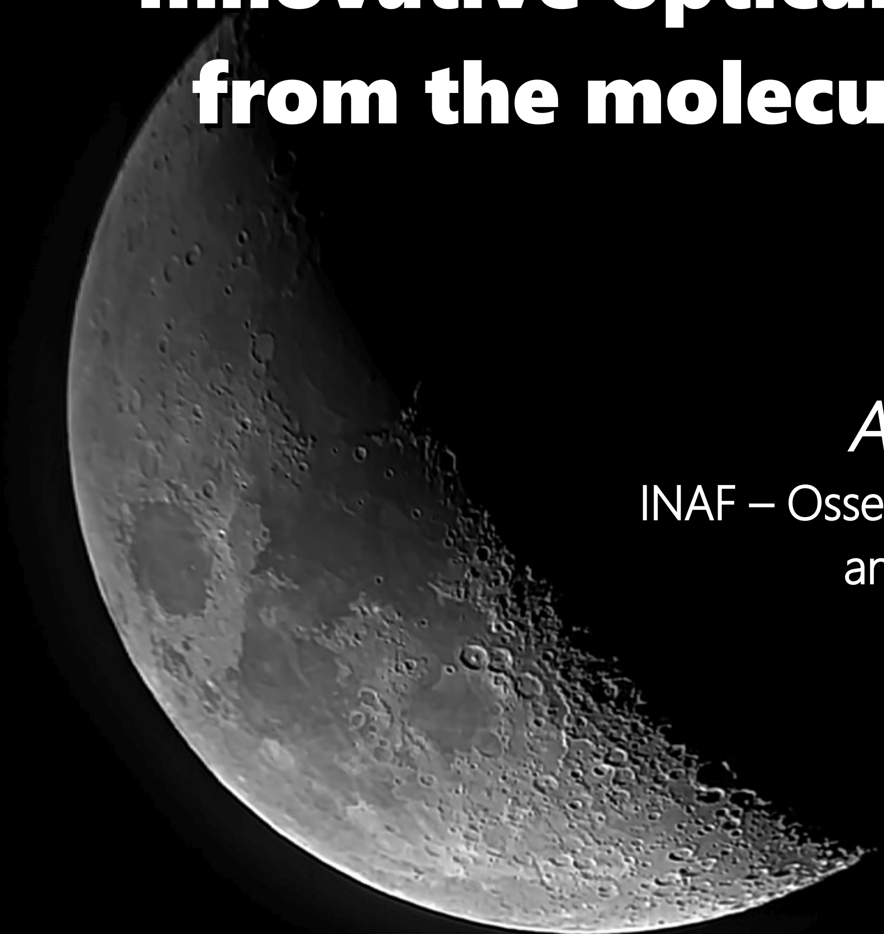
Innovative optical elements for astronomy: from the molecule to the "on sky" device



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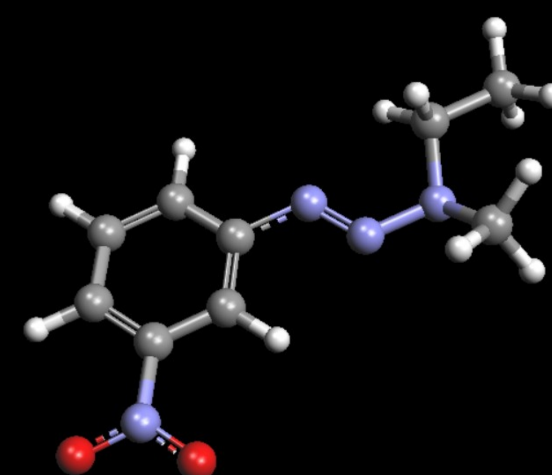


INAF – Astronomical Observatory of Abruzzo, Colloquia

April 13, 2023

The beginning…more than 400 years ago

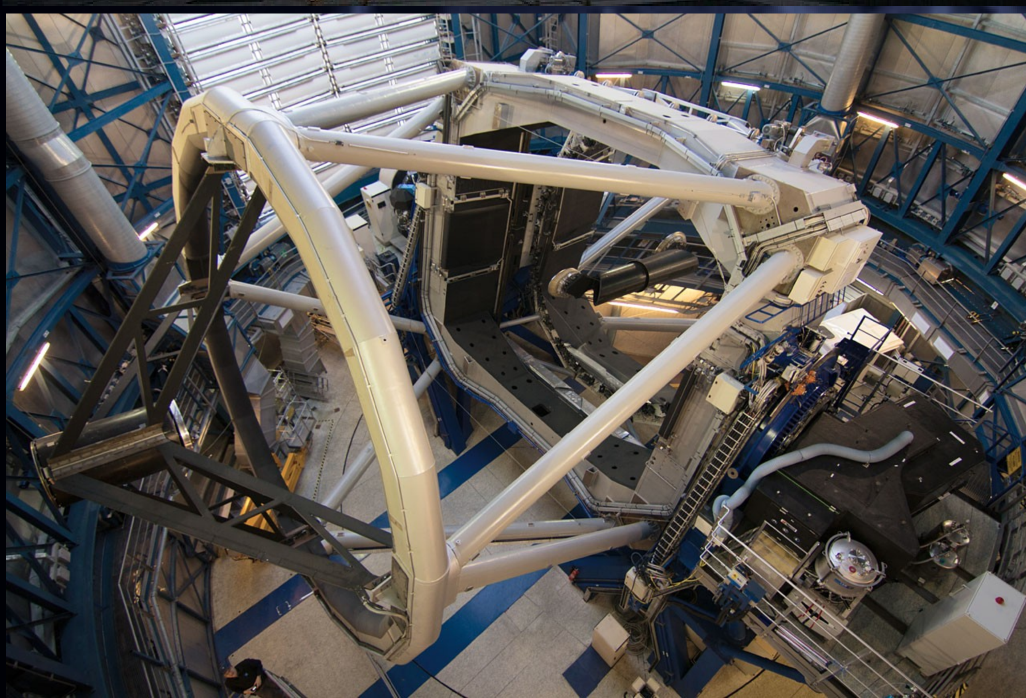
August 1609

Galileo Galilei showing the Doge of Venice how to use the **telescope**

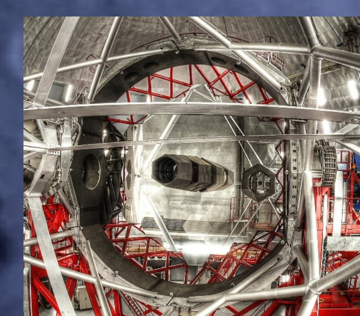
Ground based Telescopes: present

VLT: four Unit Telescopes main mirrors of 8.2m diameter

Since 2000

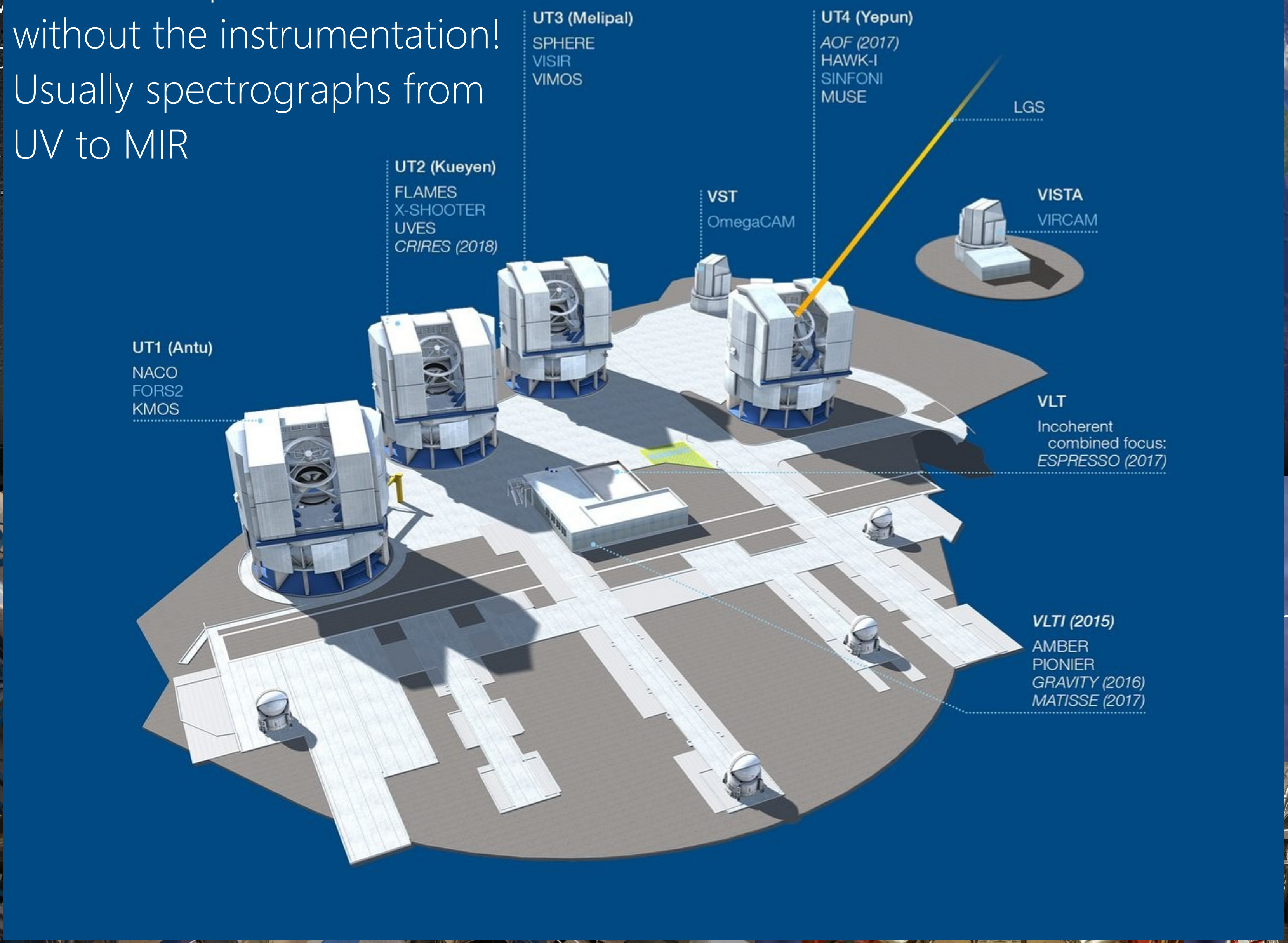


Nowadays, there are many 8-10 meter class telescopes both with monolithic and segmented mirrors.



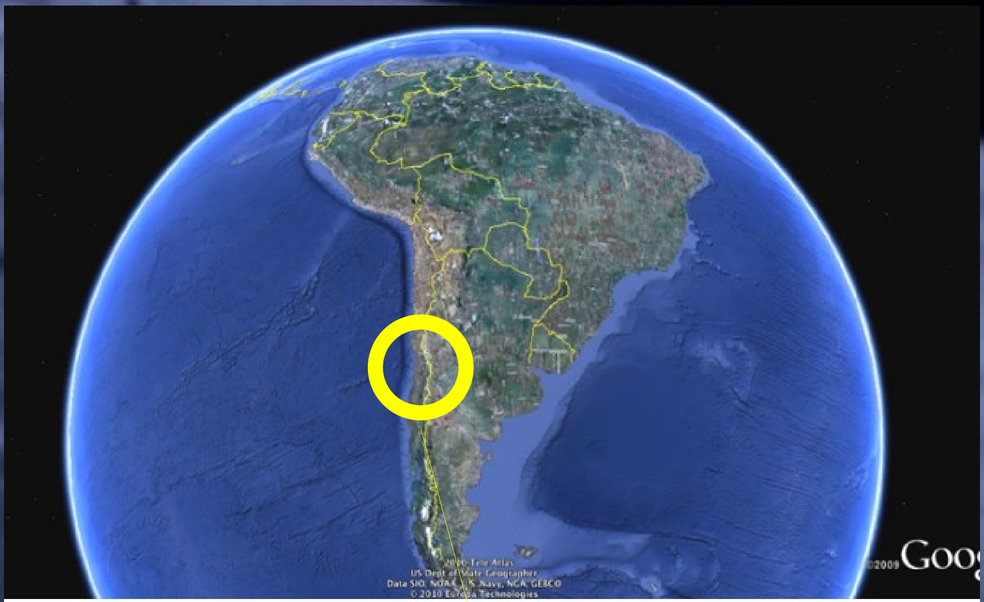
Ground based Telescopes: present

The telescope is useless without the instrumentation!
Usually spectrographs from UV to MIR



8-10 meter
monolithic

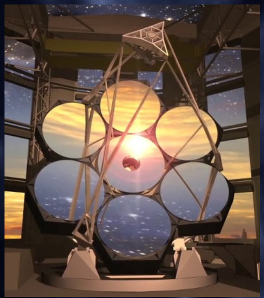
Ground based Telescope: future



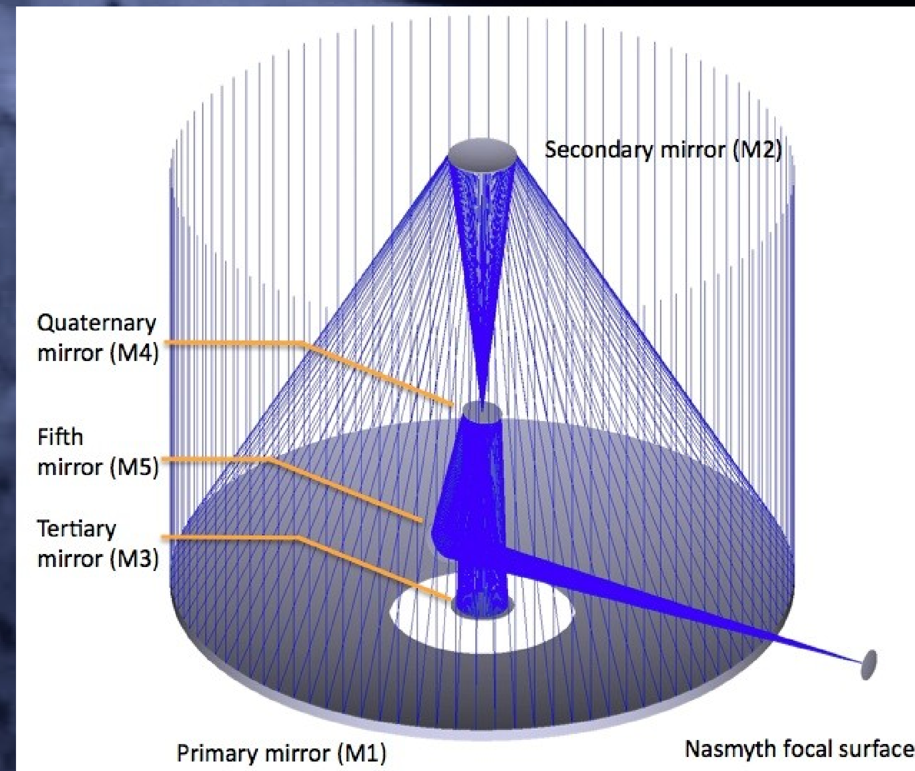
ELT: 39 m diameter primary mirror consisting of 798 segments, each 1.4 m wide, but only 50 mm thick.

Cerro Armazones in Chile

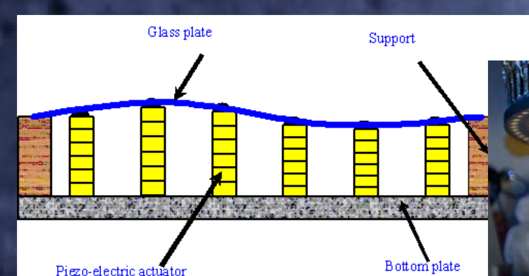
Similar ELTs in the US (GMT, TMT).



Ground based Telescope: future

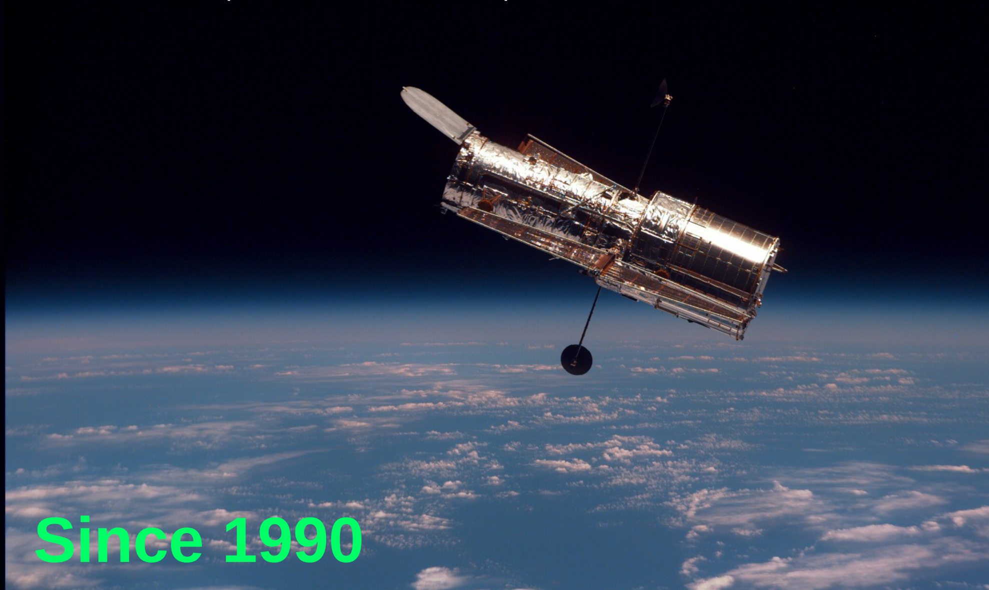


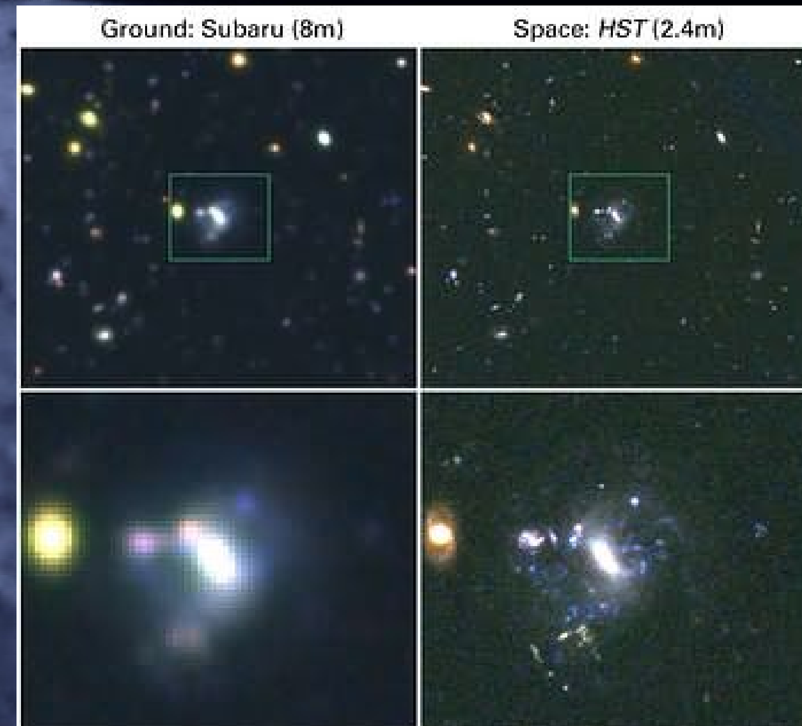
5 mirrors, two are adaptive, M4 and M5



Space Telescopes: past

Hubble space telescope: 2.4 m in diameter





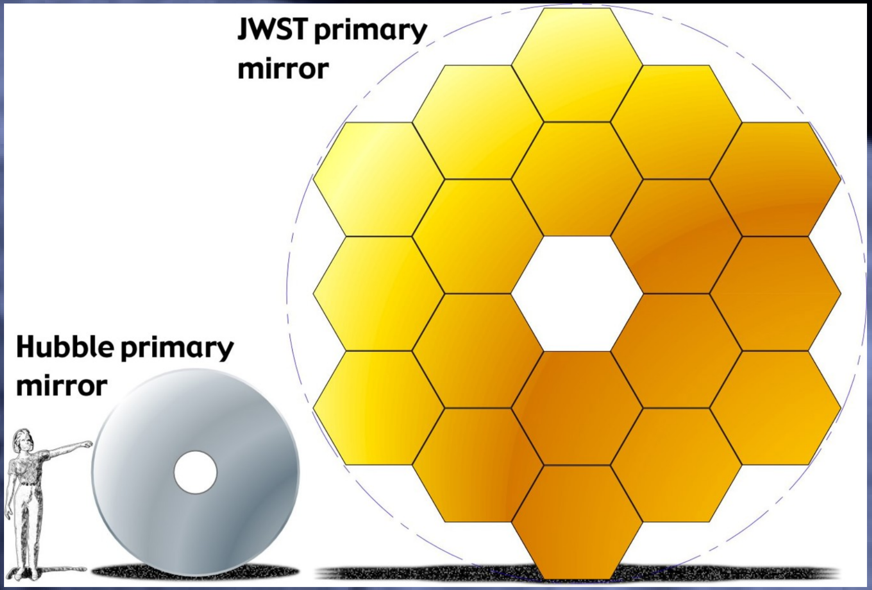
Space telescopes are not affected by the atmosphere, both turbolences and absorptions.

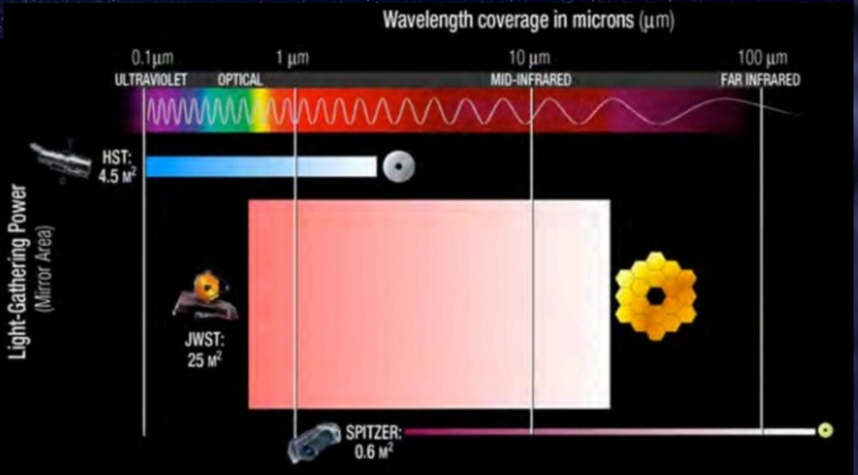
Hubble has four main instruments to observe in the near ultraviolet, visible, and near infrared spectra.

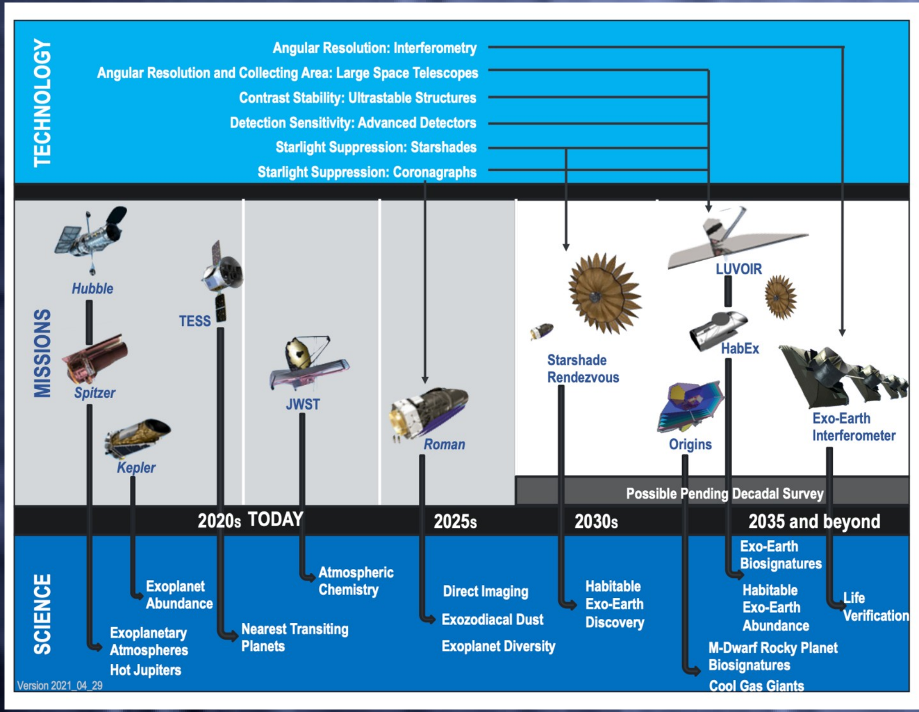
Space Telescopes: present

Launched Christmas 2021

James Webb Space Telescope:
6.5 m mirror, L2 orbit







https://youtu.be/RzGLKQ7_KZQ

Try to make stuff simpler…

- Both telescopes and the instrumentation are featuring a strong increase in their complexity, due to: i) the larger sizes; ii) the demanding performances and accuracy required by the new exciting scientific cases to be faced.
- The development of innovative materials and processes is a key strategy to reduce the complexity while keeping or improving the performances.

In other words…

The device complexity is "simplified" by the material.

Try to make stuff simpler...

- Both telescopes and the instrumentation are featuring a strong increase in their complexity, due to: i) the larger sizes; ii) the demanding performances and accuracy required by the new exciting scientific cases to be faced.
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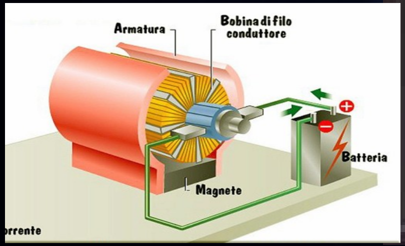
From the requirements to the devices
through the developing of suitable (smart) materials
=
Multidisciplinary approach

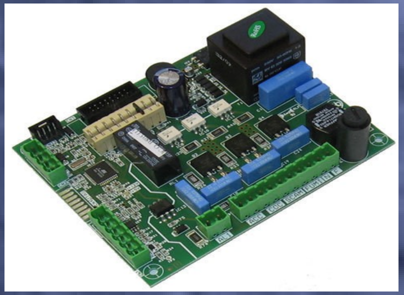
Complexity example…automatic blinds

- IDEA: implement an automatic electric blind

Complexity example…automatic blinds

- IDEA: implement an automatic electric blind





Complexity example…automatic blinds

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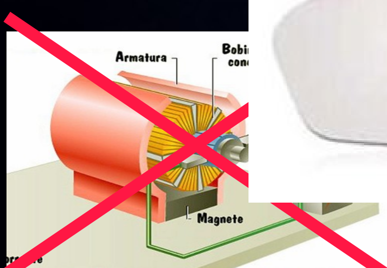
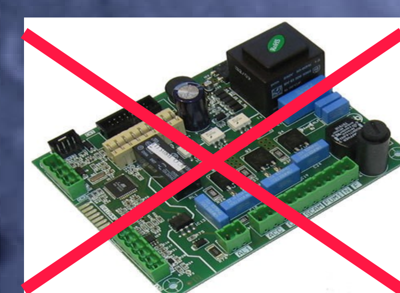
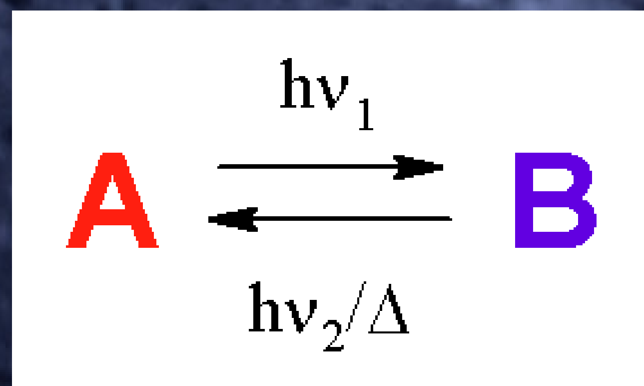


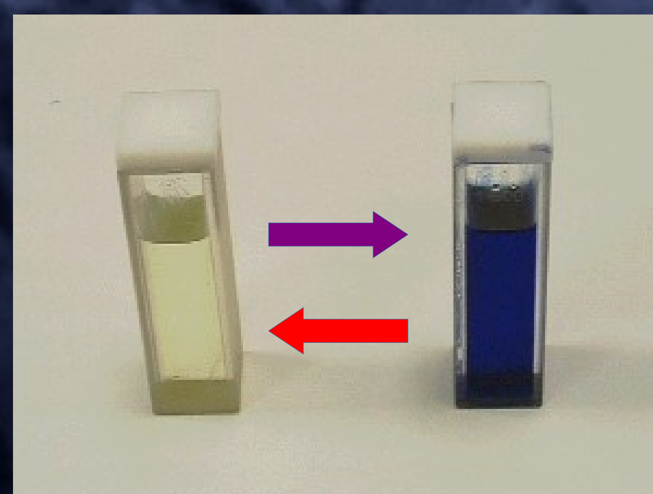


Photochromic materials

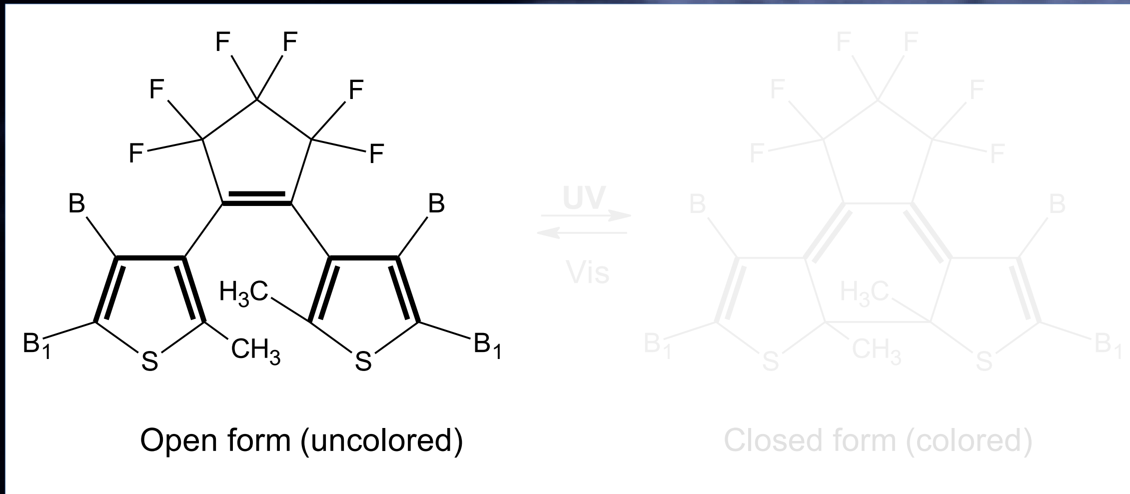
IUPAC definition:

*"**Photochromism** is a <u>reversible transformation</u> of a chemical species induced in one or both directions by absorption of electromagnetic radiation between two forms, A and B, having different absorption spectra"*

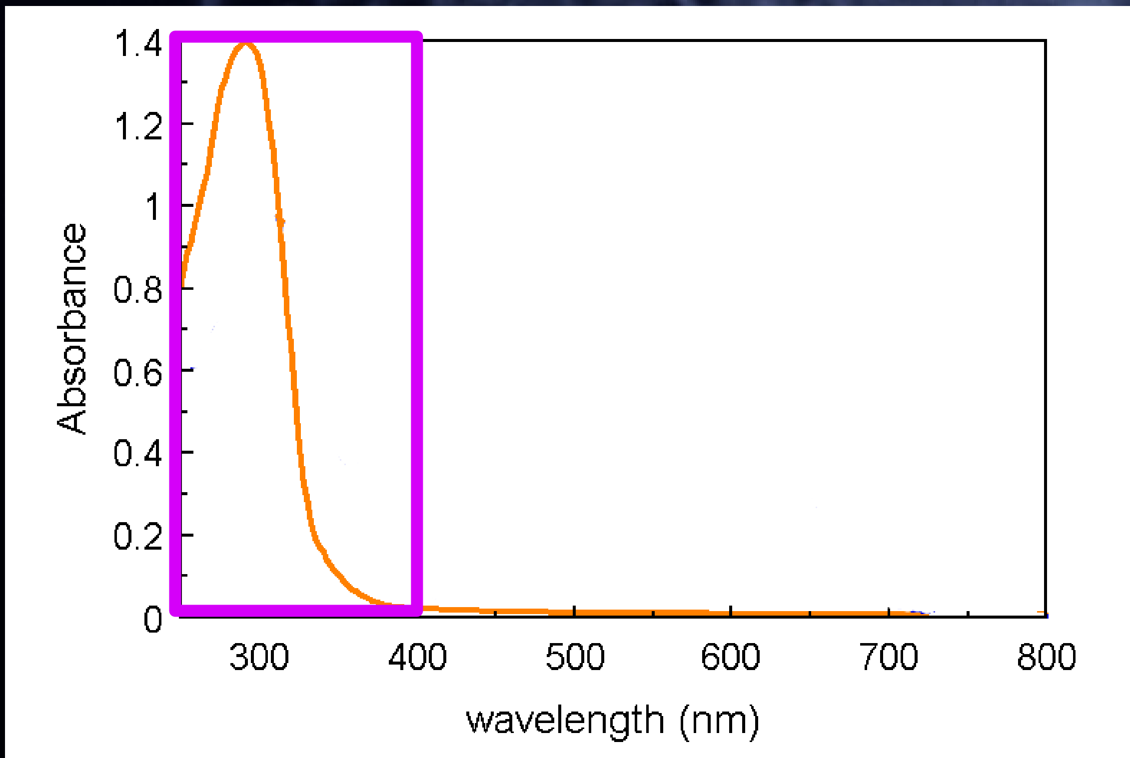




Diarylethenes



In this form, the absorption is only in the visible: uncolored material



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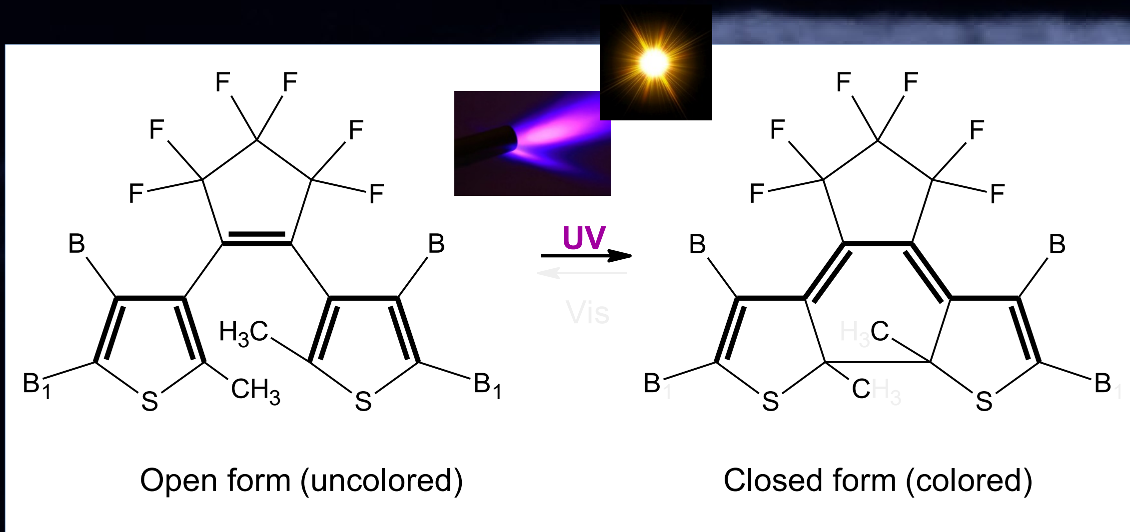
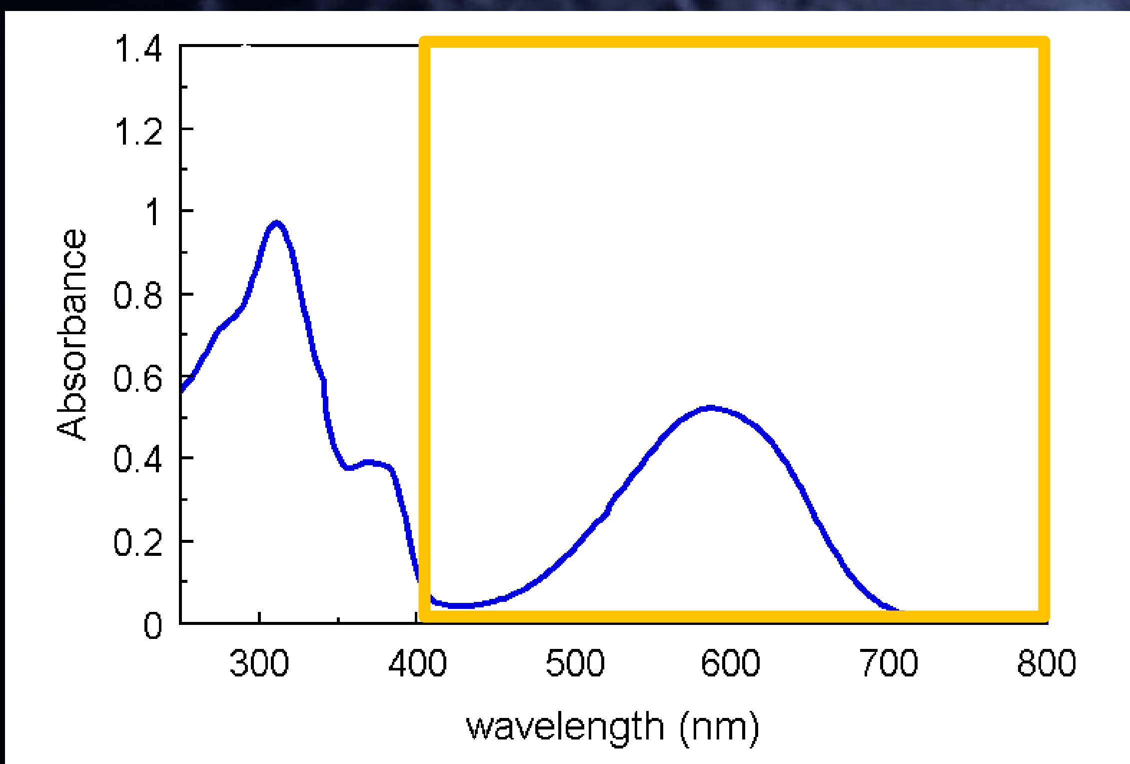


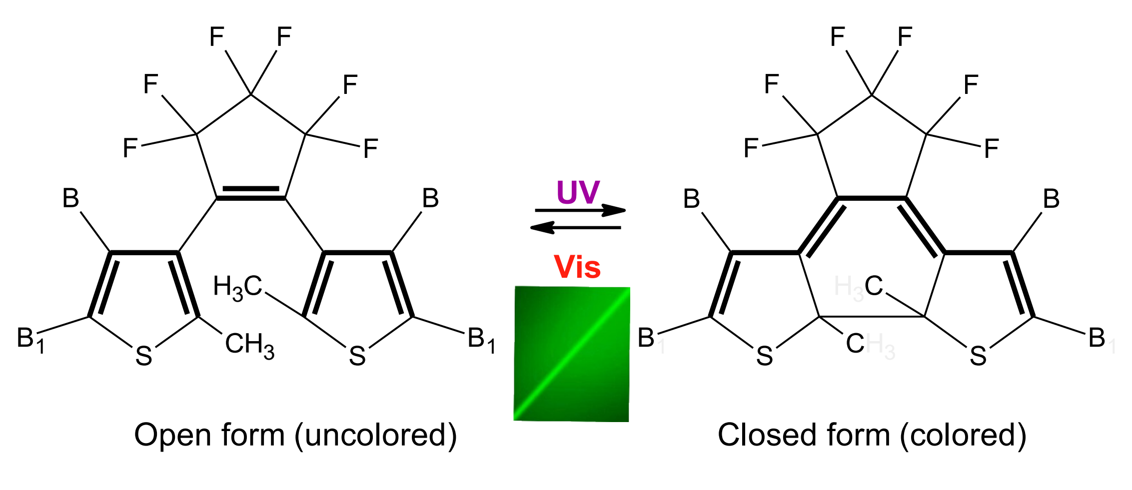
UV light

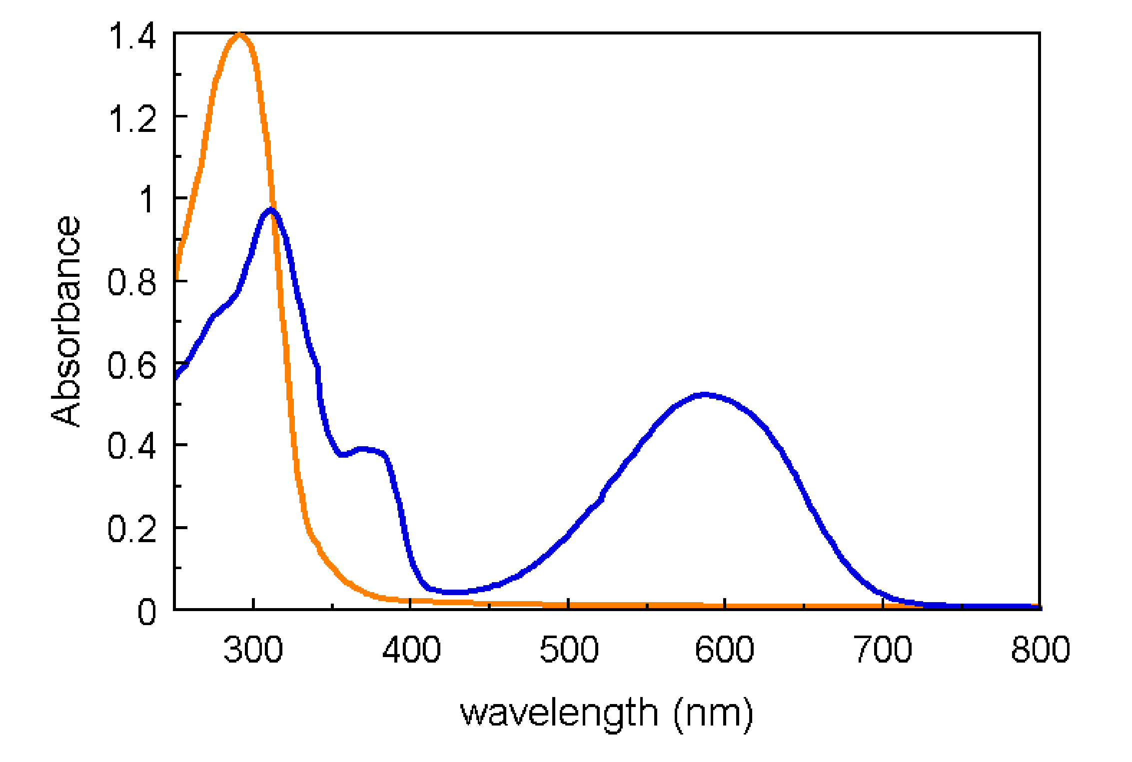
Cyclization reaction

Increase of π conjugation



Diarylethenes



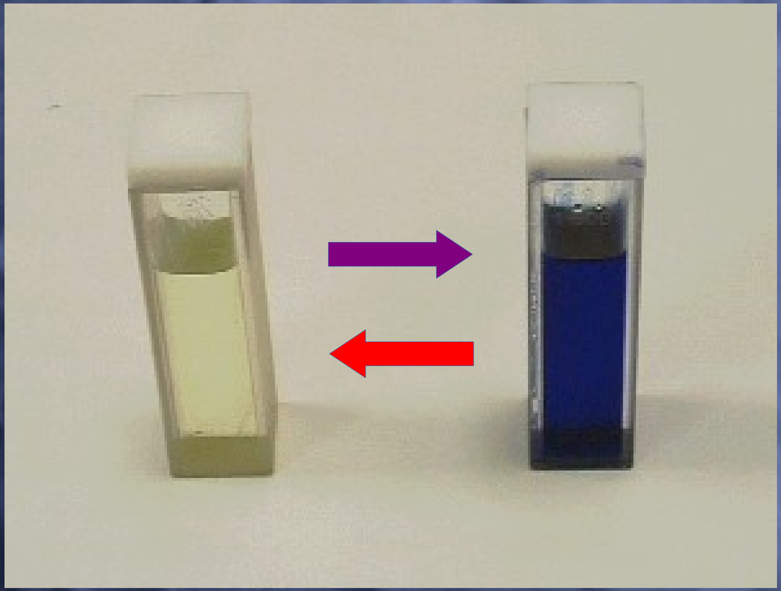


Visible light

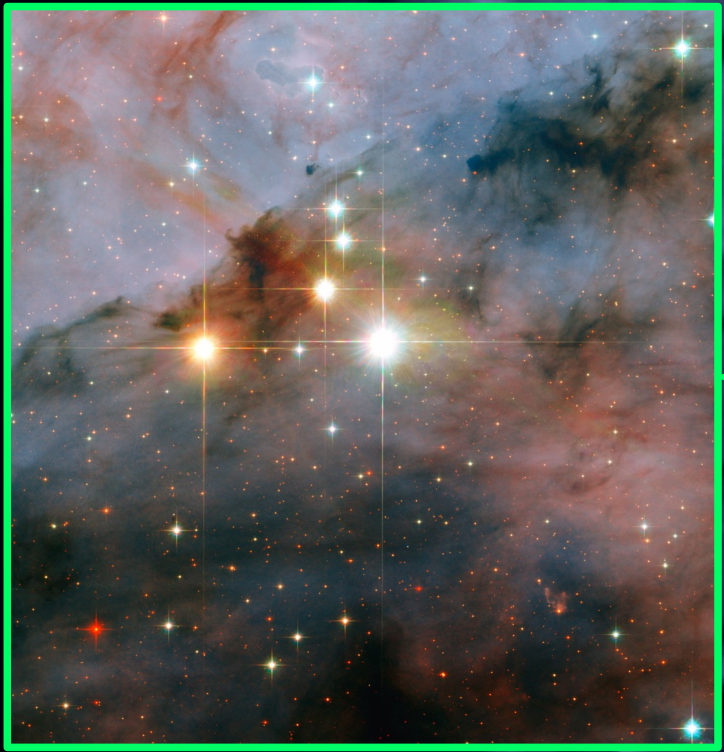
Restoring the uncolored form

The isomer is **termally stable.**

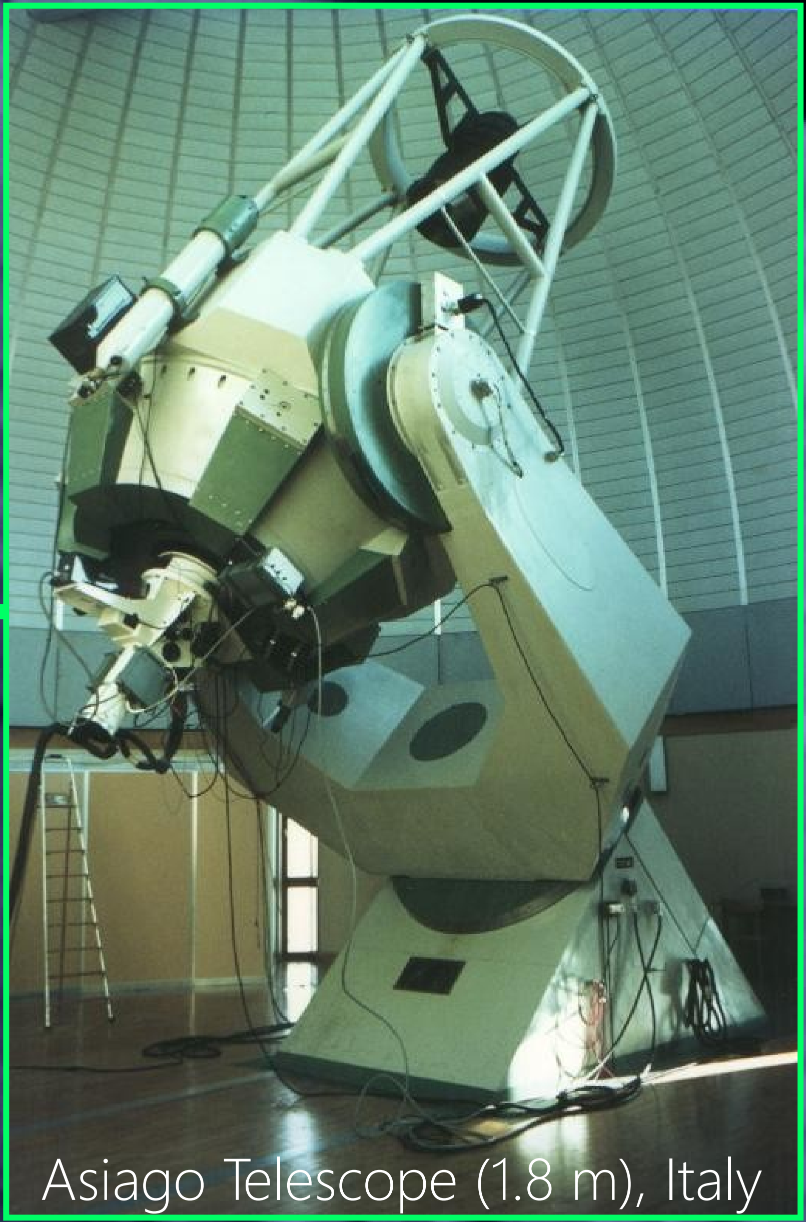
This is reversible!



Rewritable Focal Plane Mask



Target sky objects must be selected to record their spectra avoiding the sky contamination. (Multi Object Spectroscopy, MOS)



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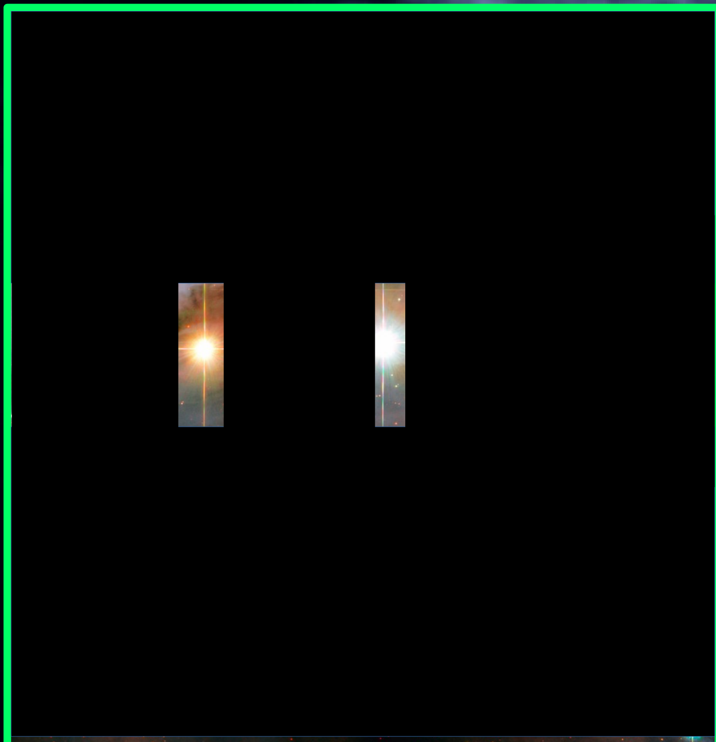

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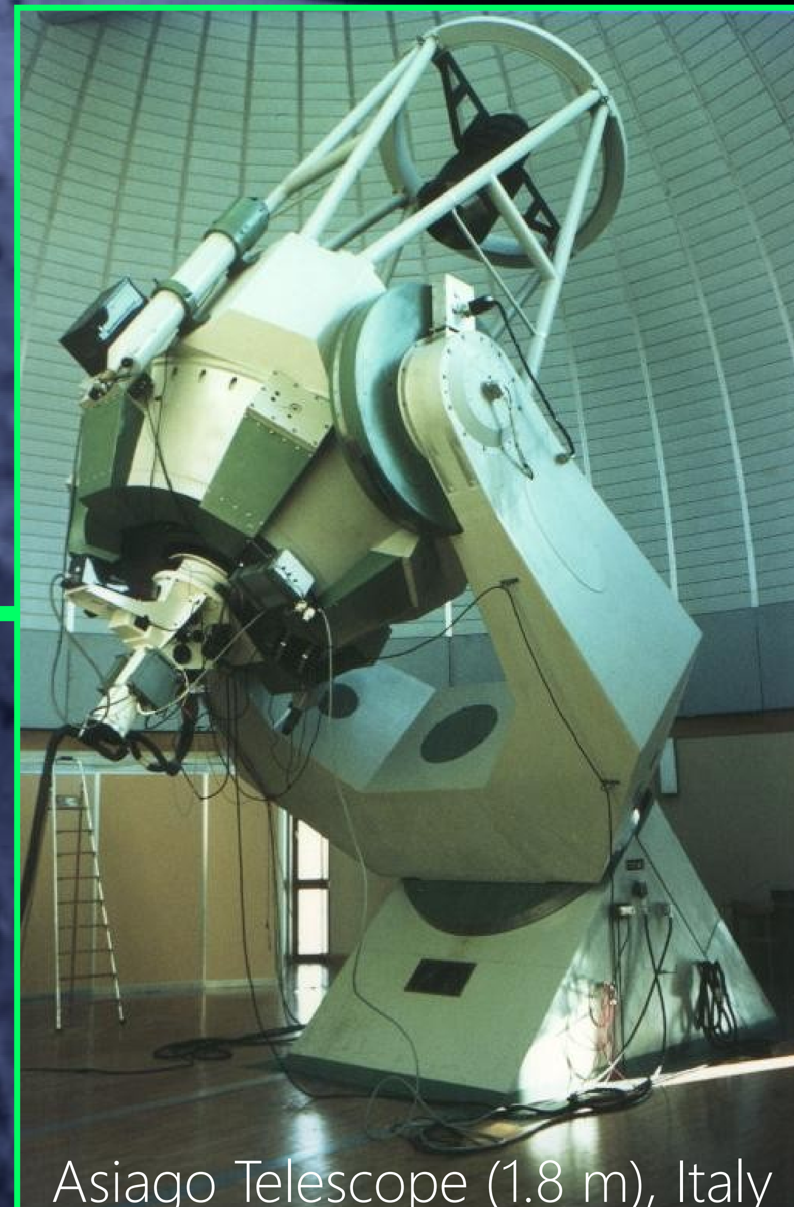
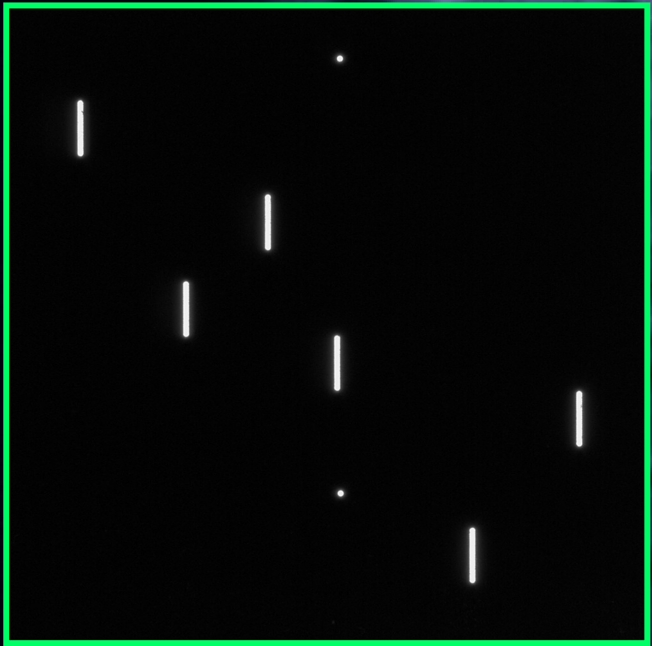
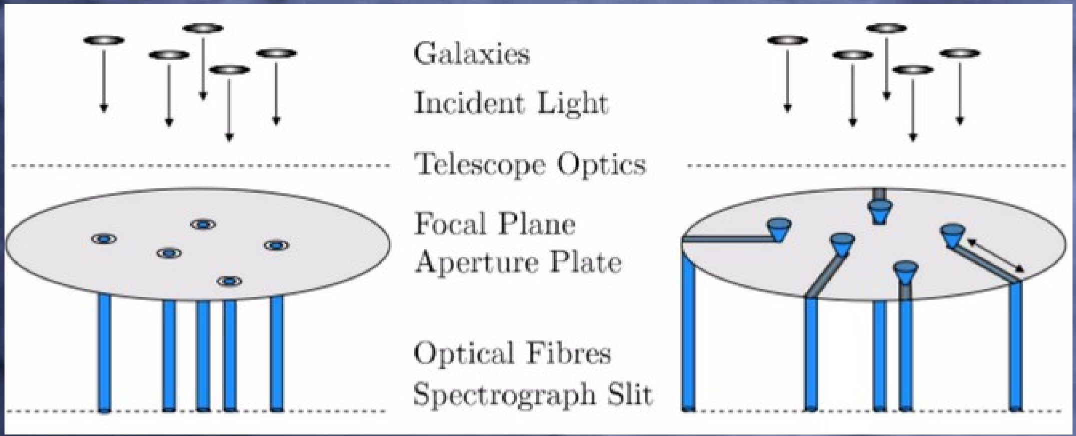
FOCAL PLANE MASKS



Asiago Telescope (1.8 m), Italy

Rewritable Focal Plane Mask





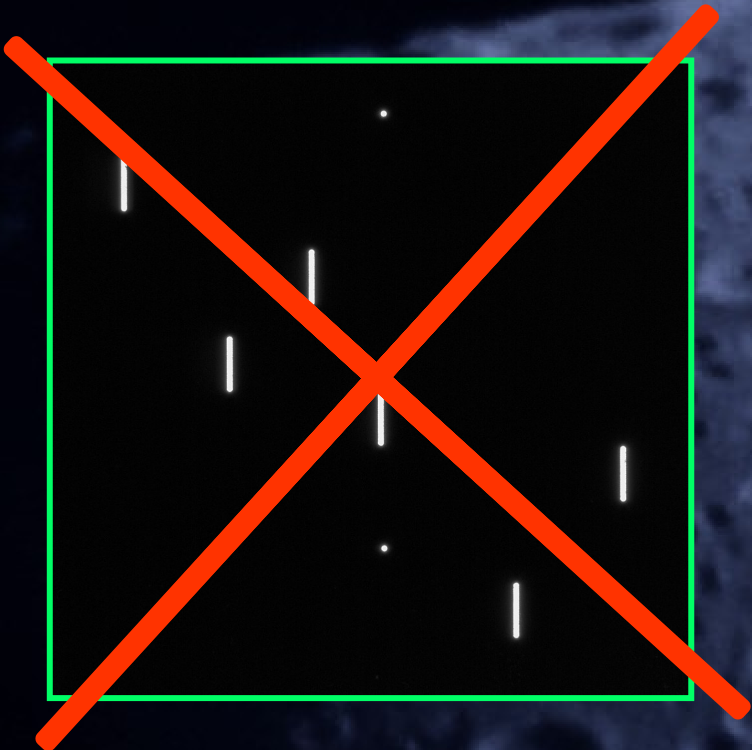
Optical fibers

- Different aproach, a huge modification of the instrument;
- Decouple the focal plane and the spectrograph;
- More complex approach.

Traditional focal plane mask:

- Metal sheet with cut slits
- well established technology
- highest contrast
- disposable

Rewritable Focal Plane Mask



Traditional focal plane mask:

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- well established technology
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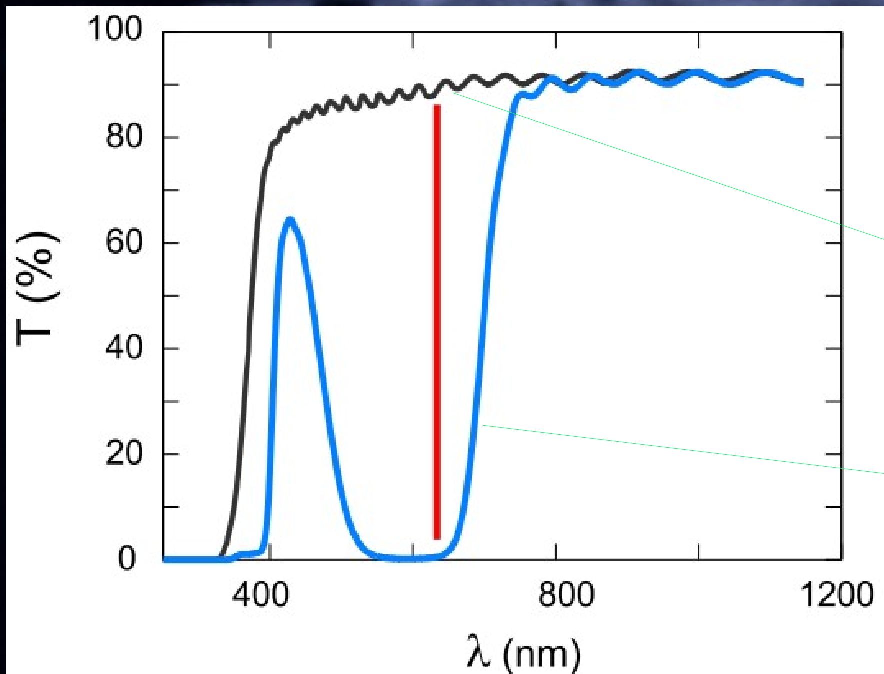
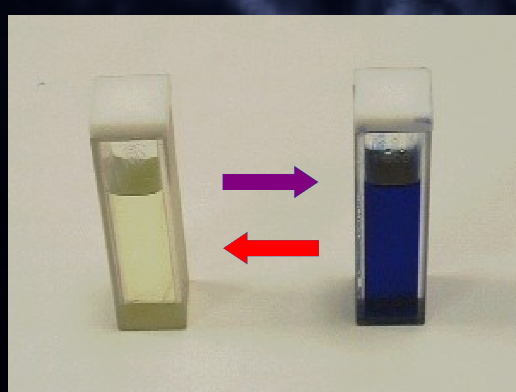
- disposable

Photochromic focal plane mask:

- Reusable
- Easy to use also for complex slits

Rewritable Focal Plane Mask

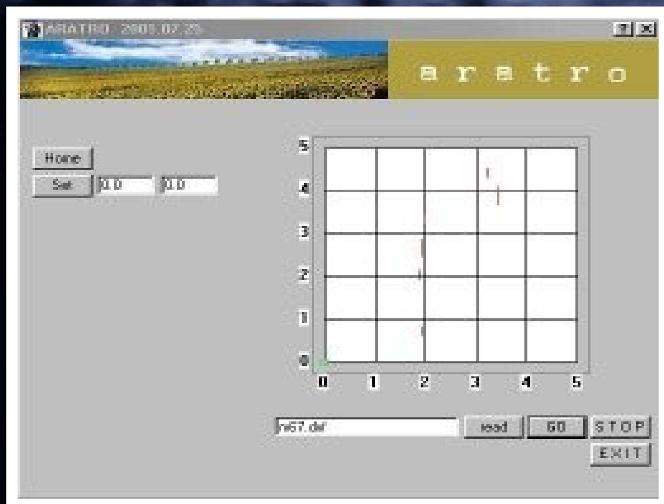


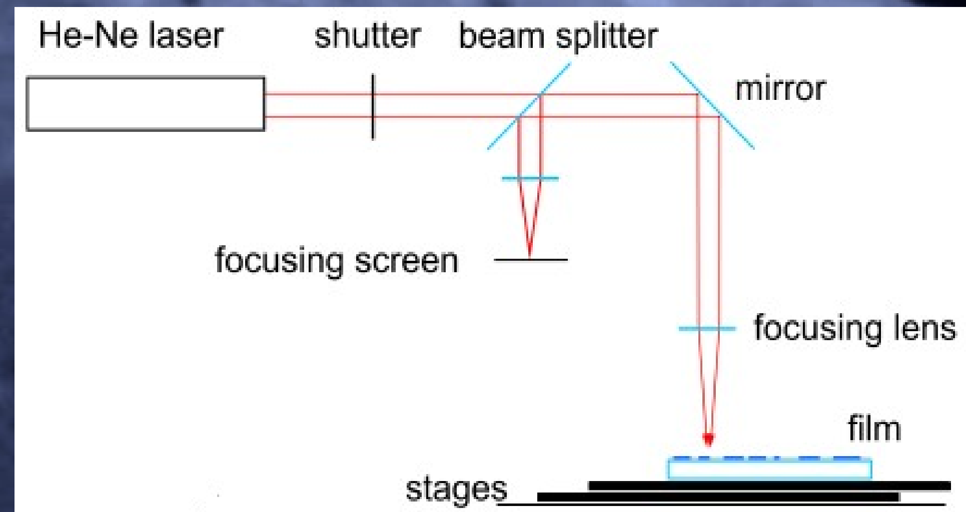


The colored form mimicks the metal and the uncolored form mimicks the slits.

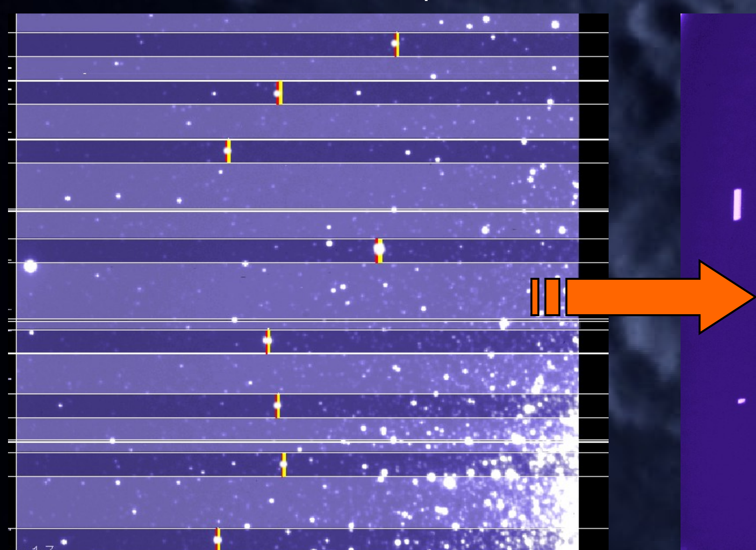
Rewritable Focal Plane Mask

ARATRO (Plow): Writing software and hardware

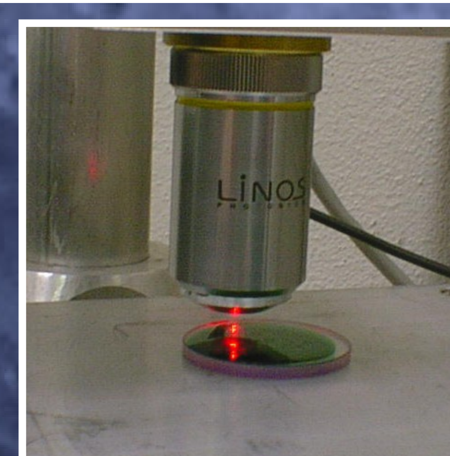


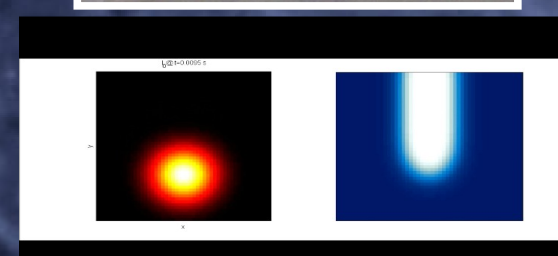


from the telescope...

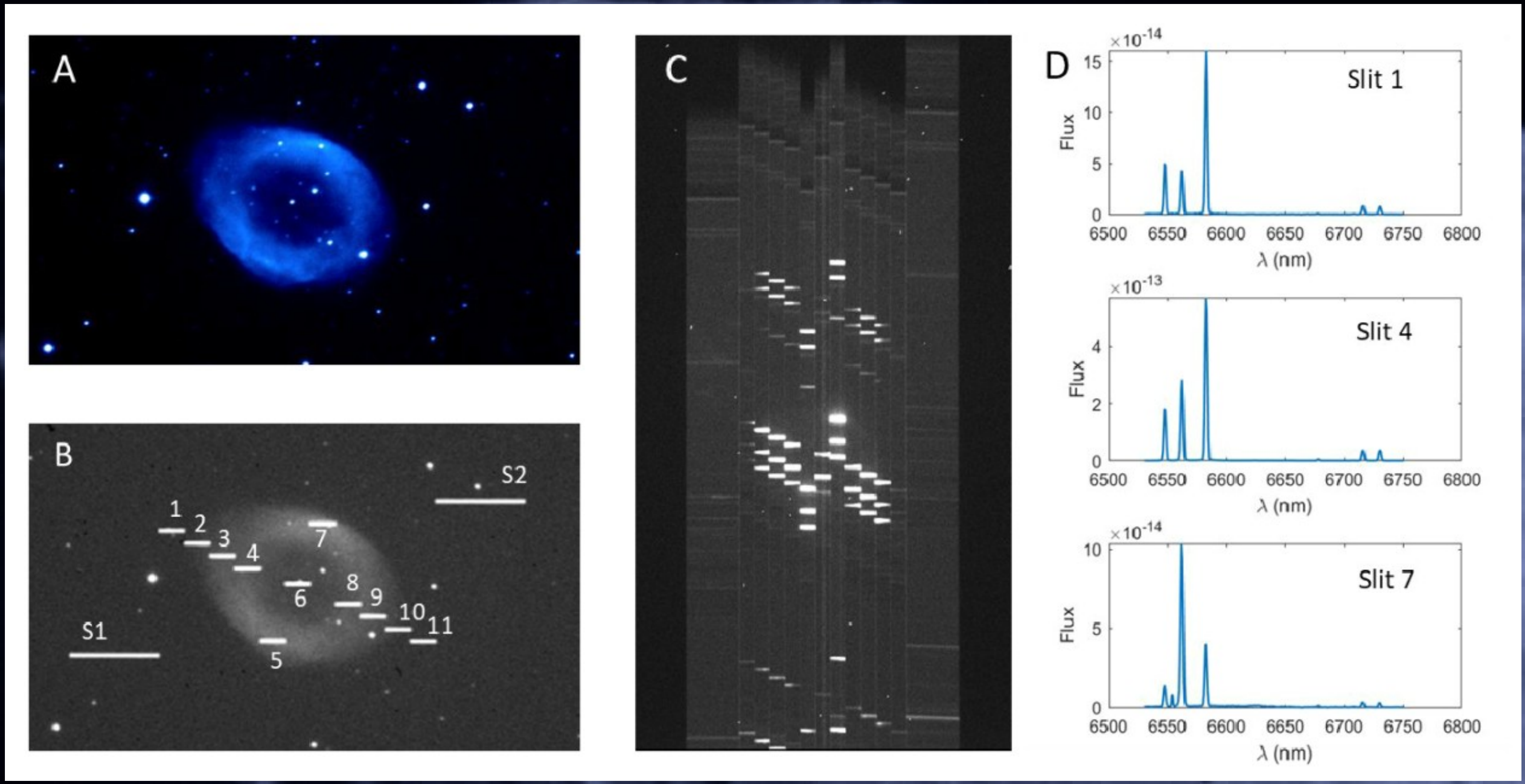


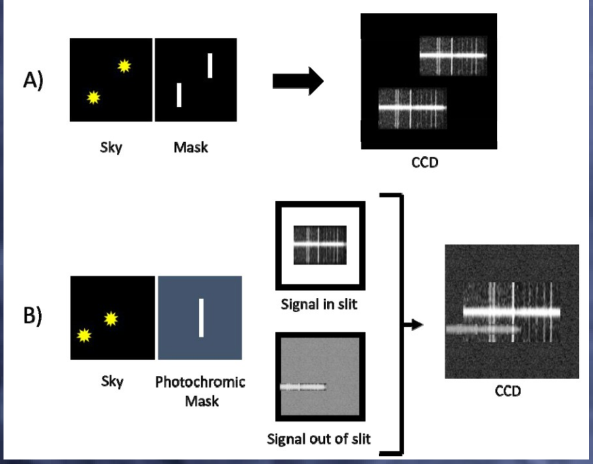
... to the mask





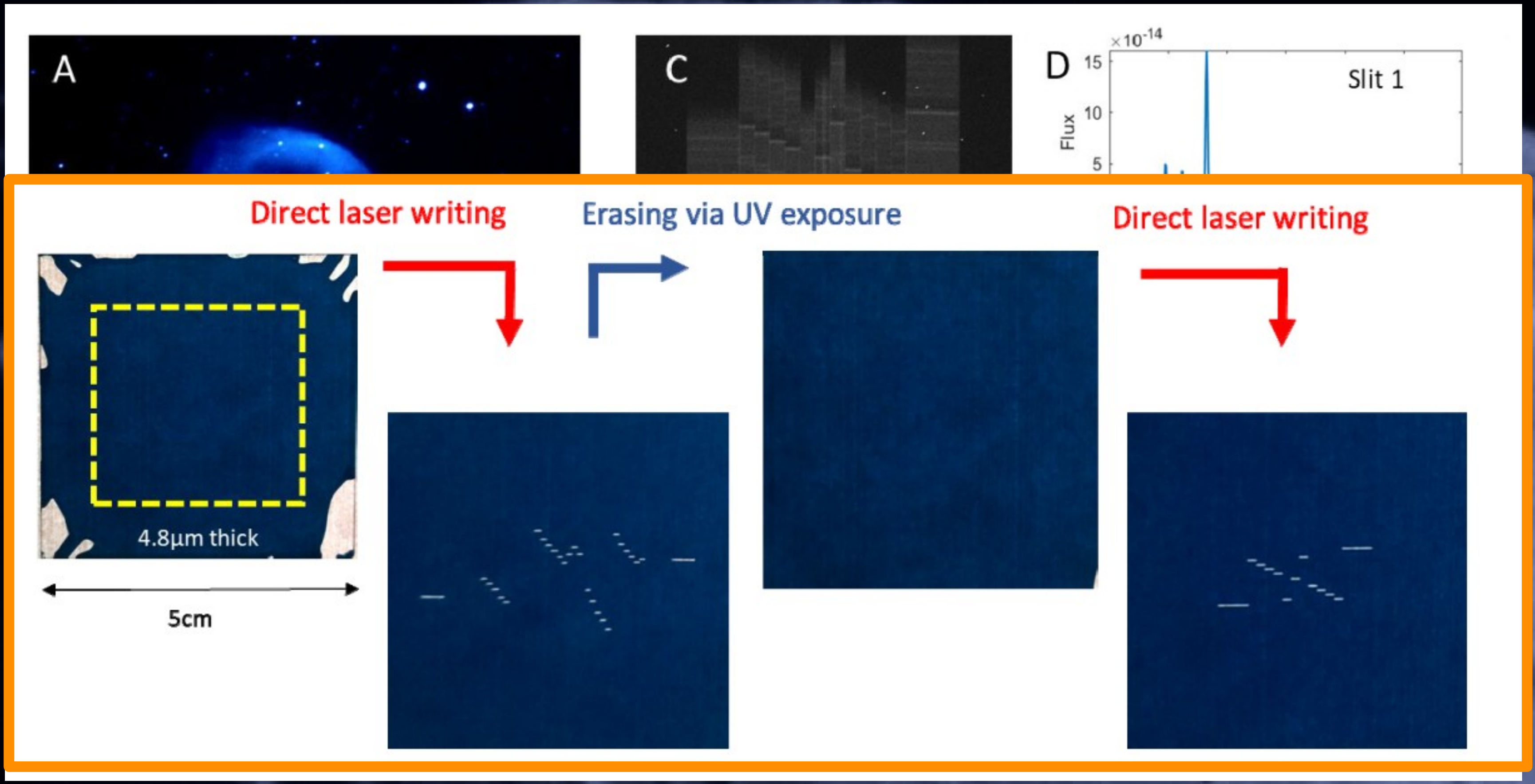
Rewritable Focal Plane Mask on sky

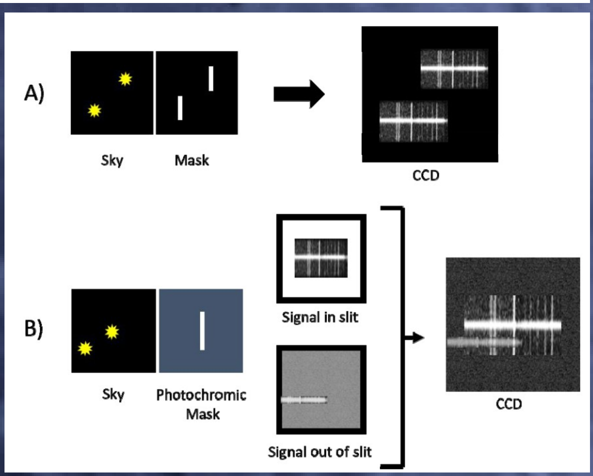




Luca Oggioni, et al., Proc. SPIE 10706, 1070636 (2018)

Rewritable Focal Plane Mask on sky





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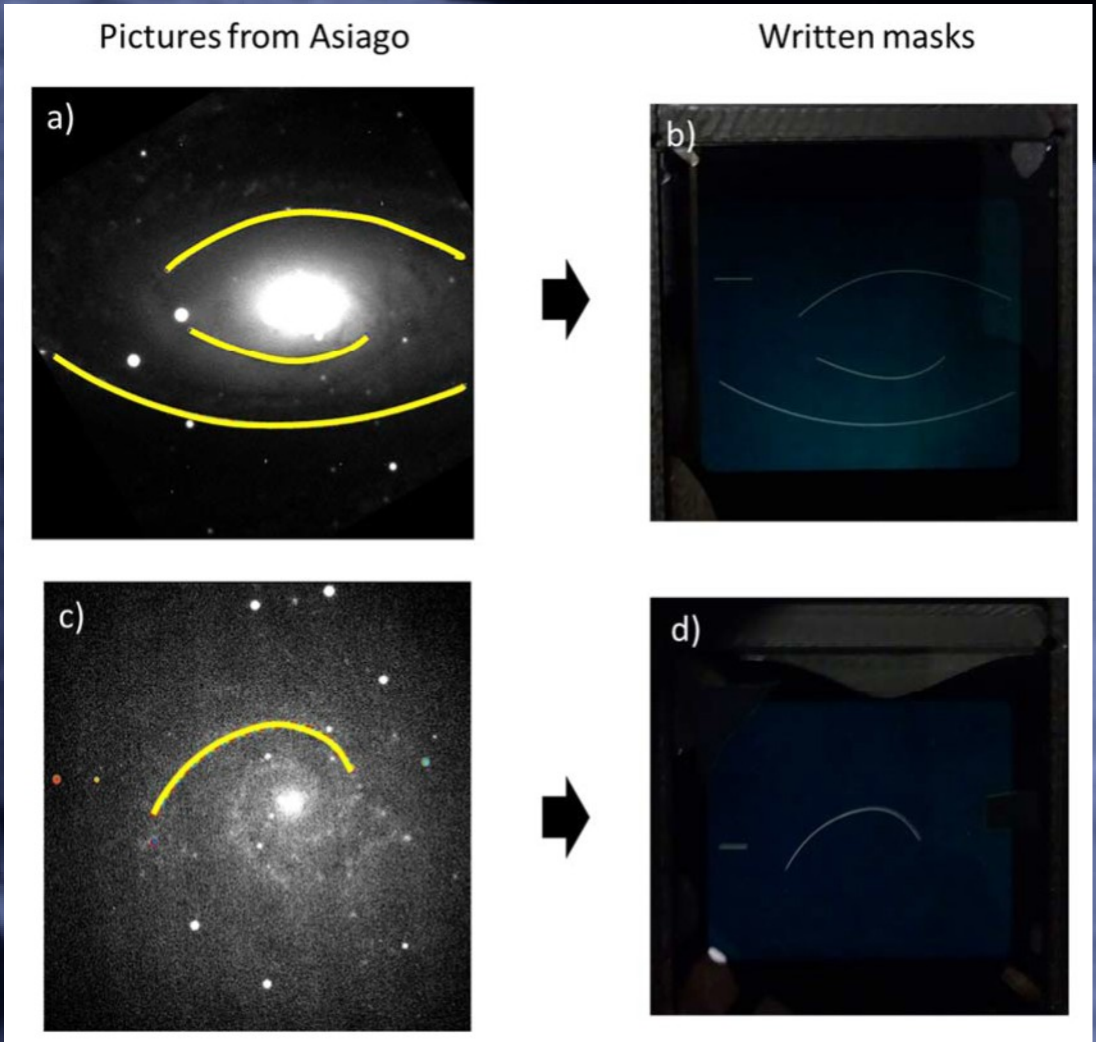

We can make the slit with the shape we want.

Curved slits "following" the galaxy arms.

Key Parameters

The key parameters for having an efficient device are:

- Wavelength range;
- Contrast value;

Key Parameters: Wavelength range

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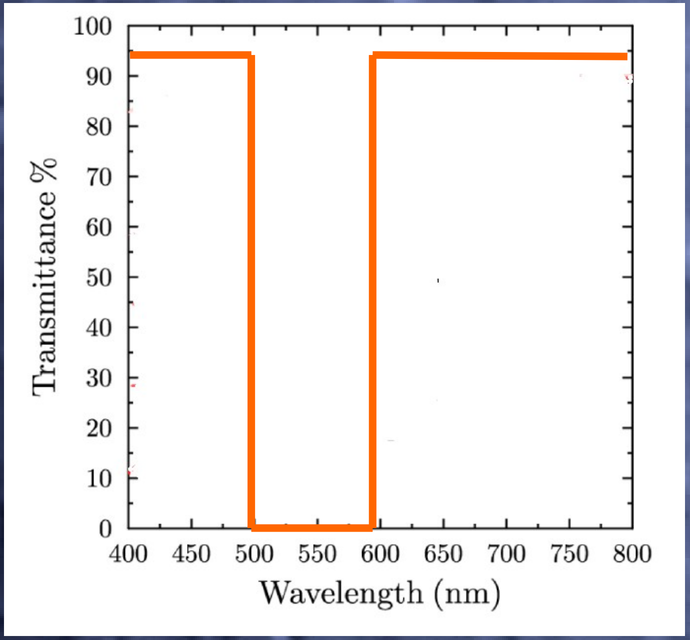

The wavelength range and position where the change in transparency occurs is important especially for the masks.

It means the possibility to collect spectra in a wider band.

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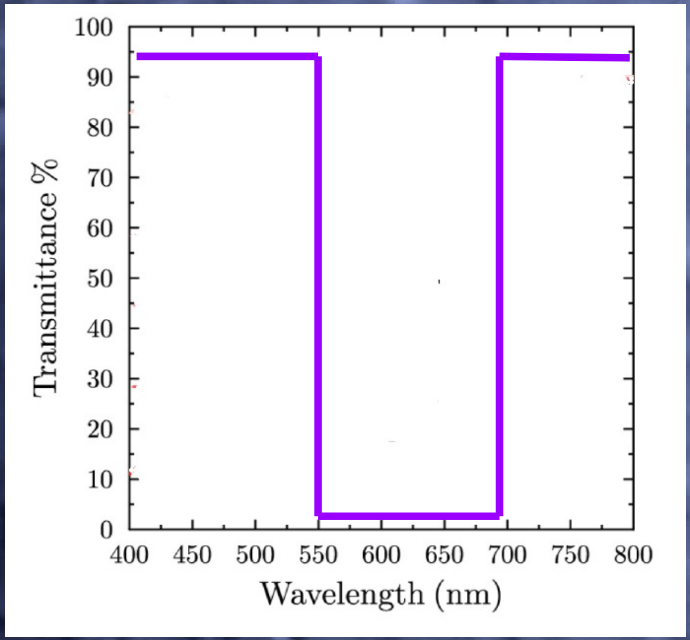

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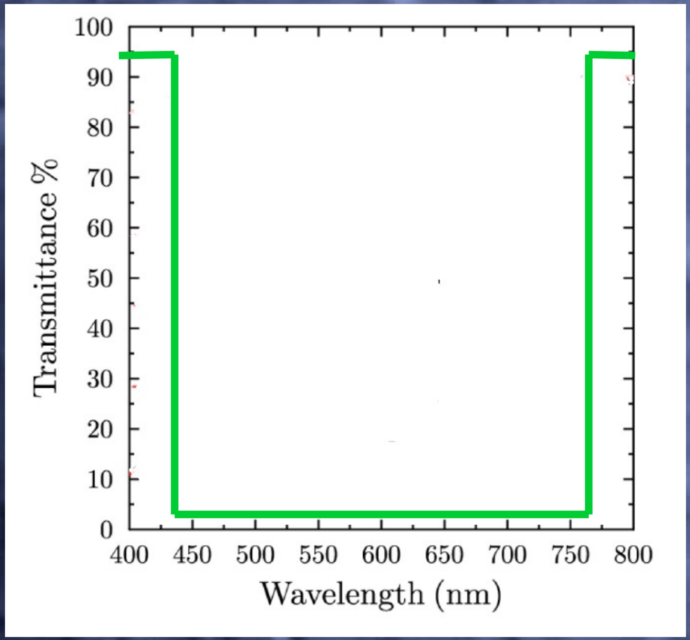

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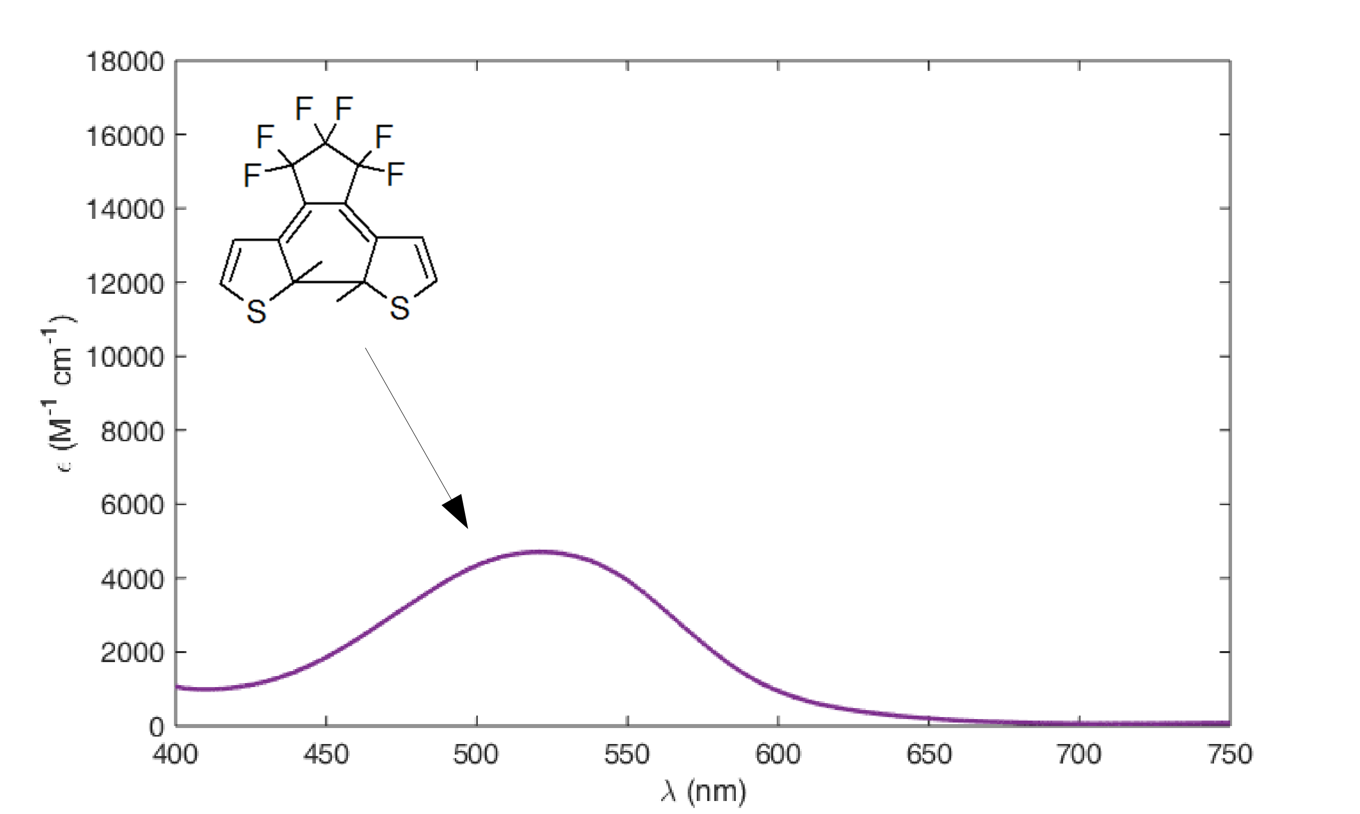
Key Parameters: Wavelength range

We can play with the chemical structure of the diarylethene:

- Extension of π conjugation;
- Electroactive substituents (electron donor and acceptor)



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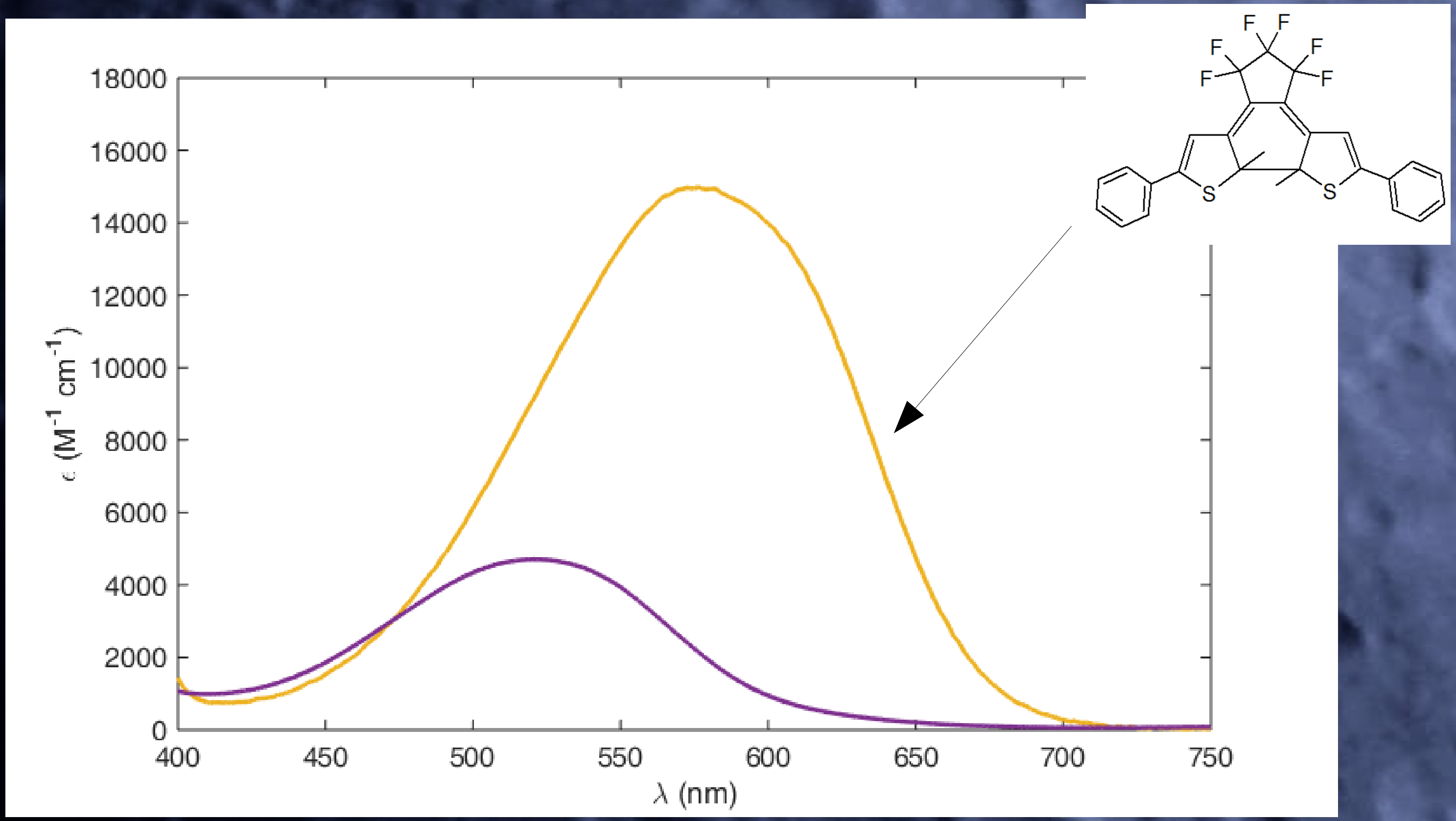

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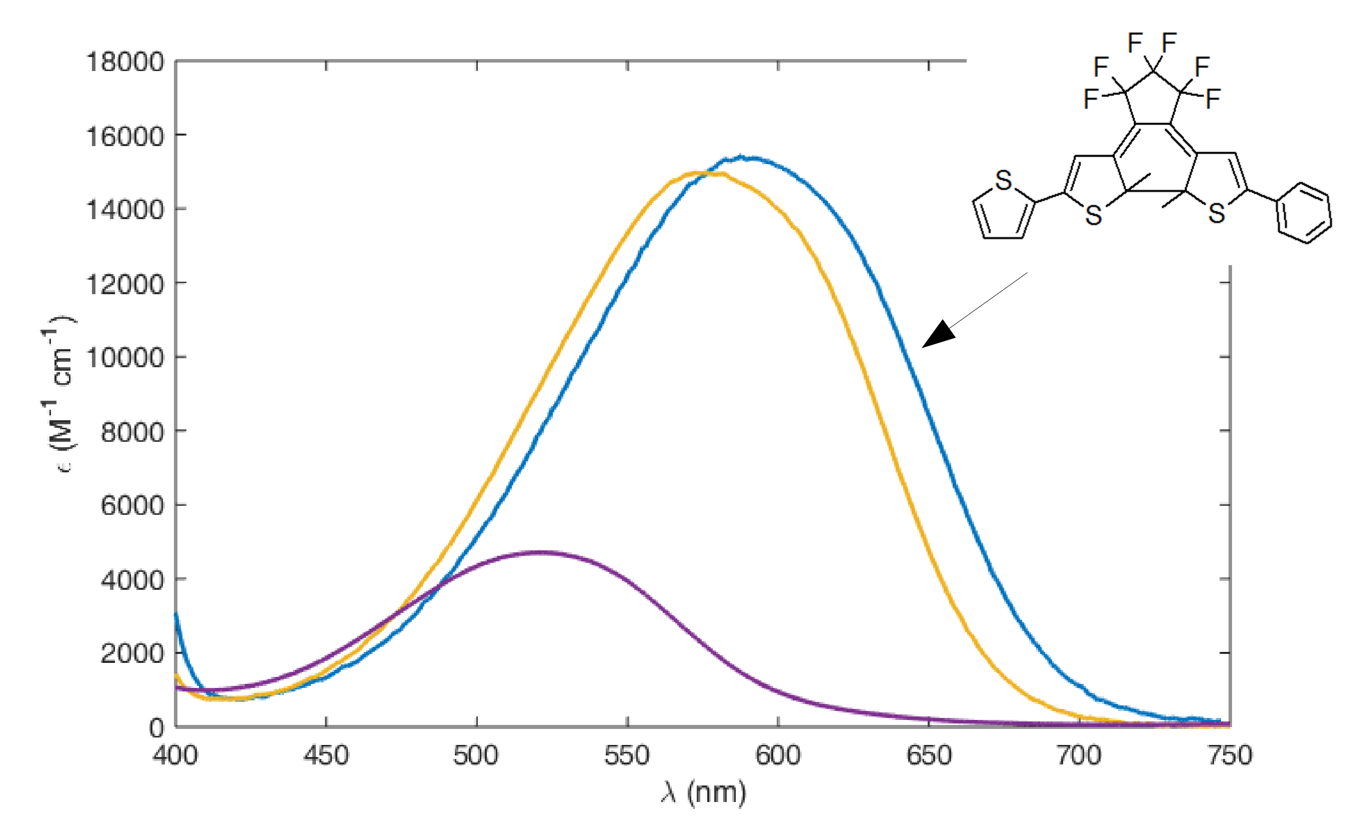

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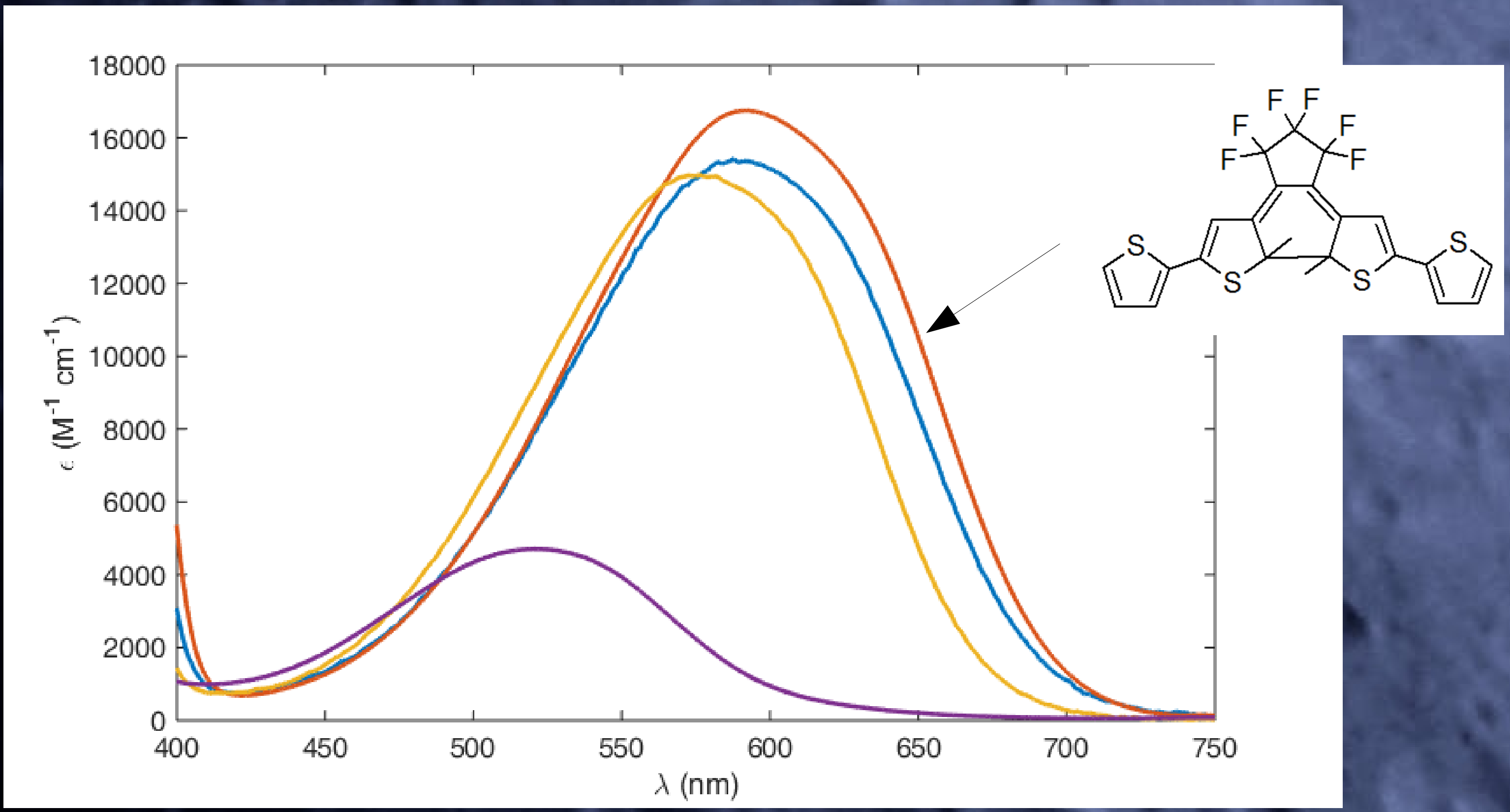

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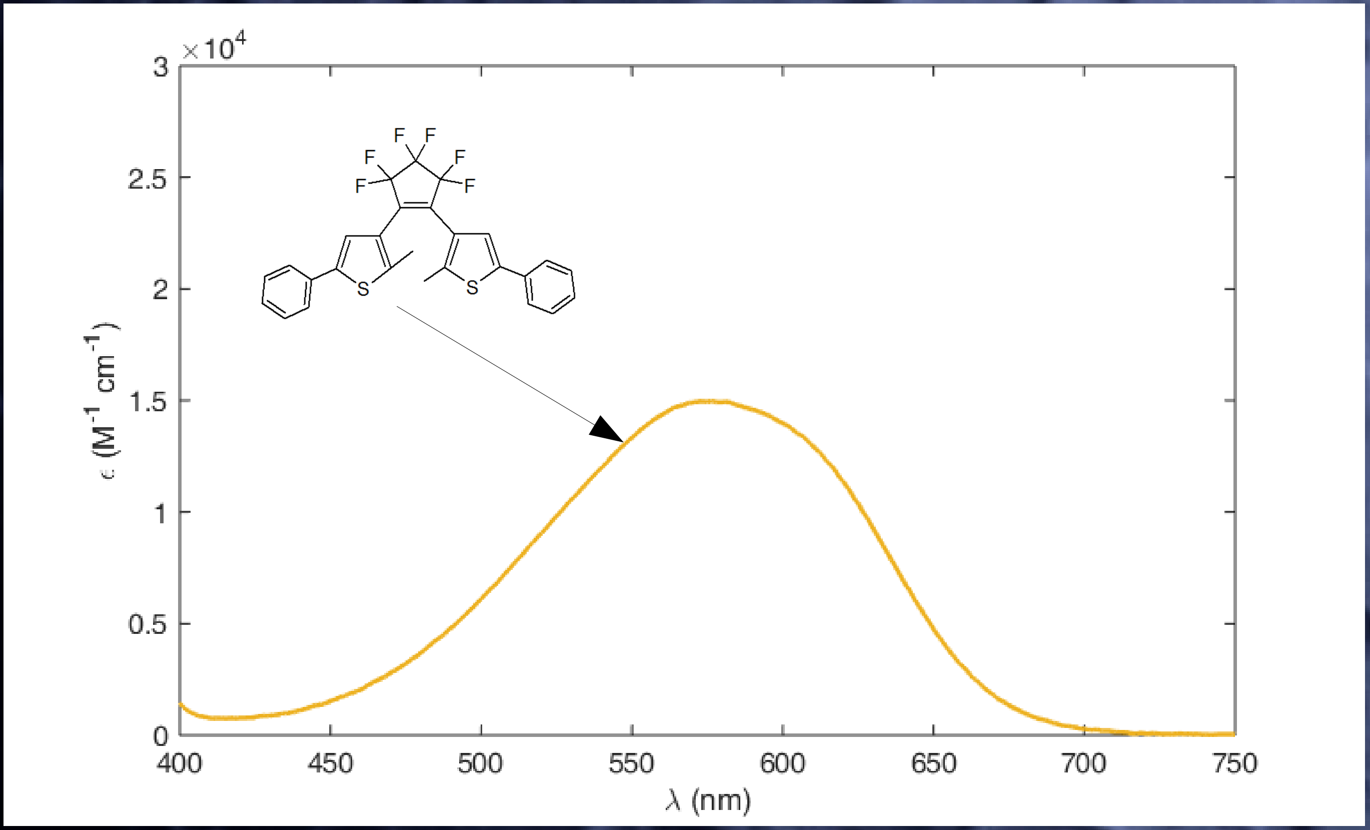

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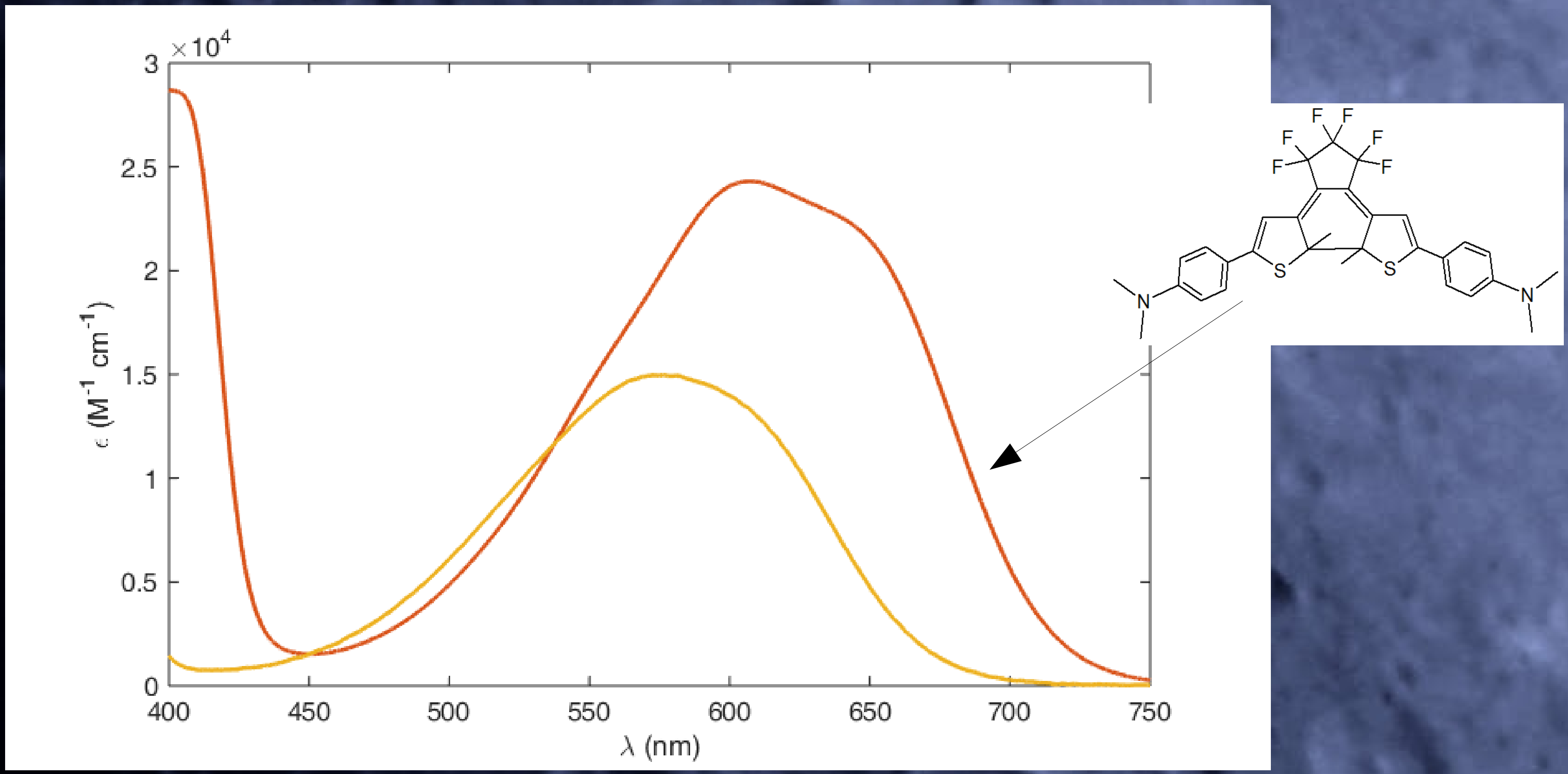

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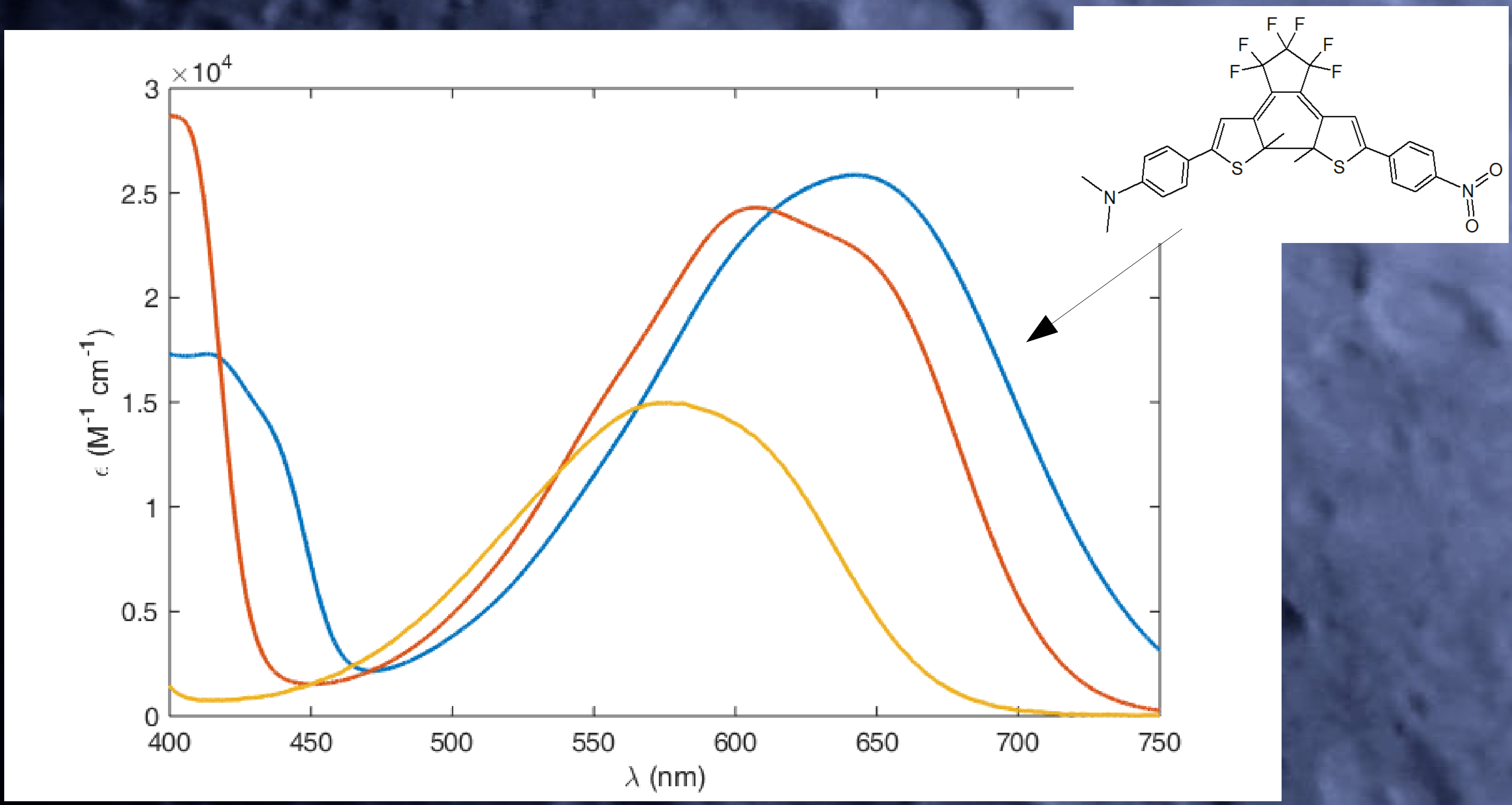
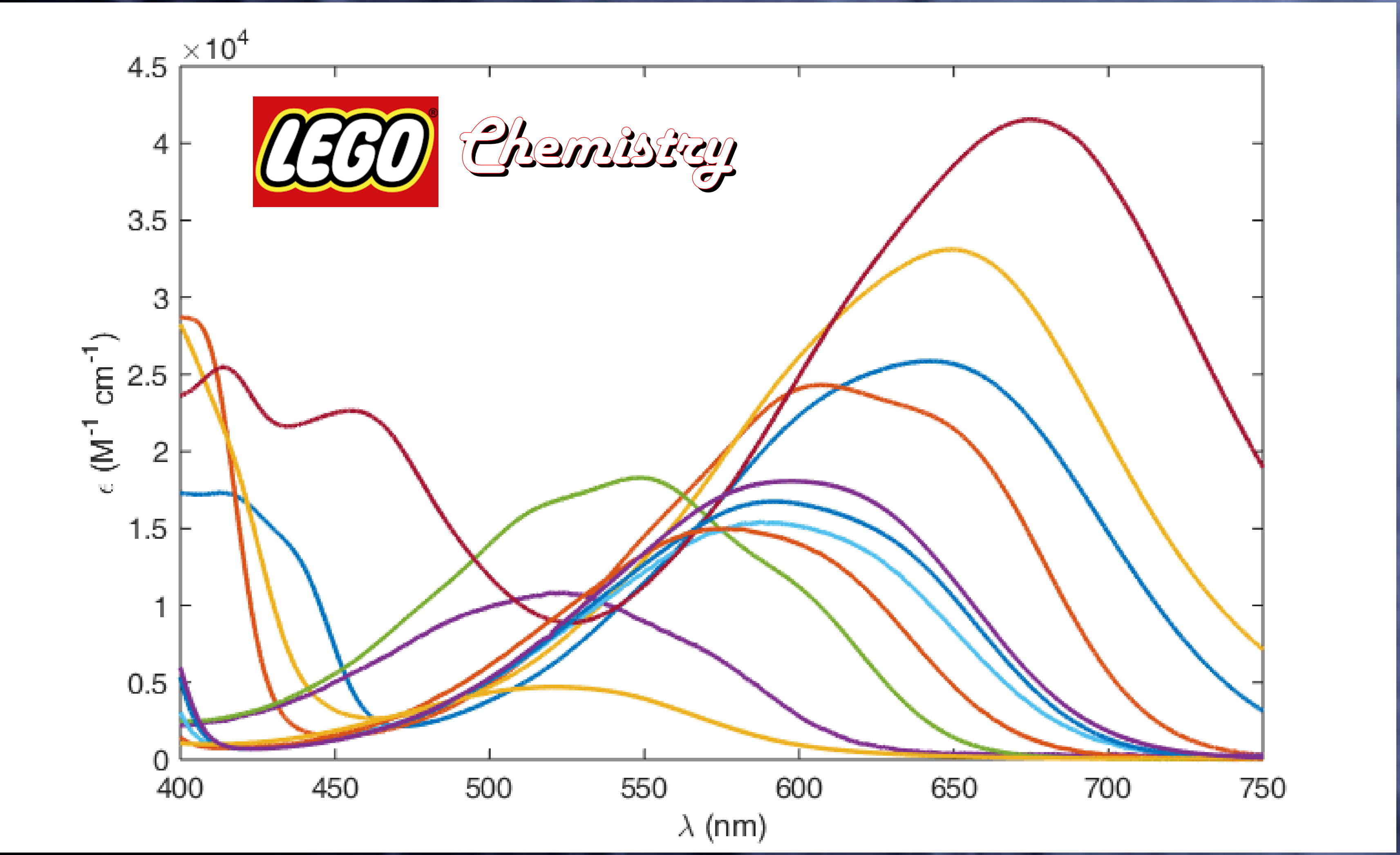


Key Parameters: Wavelength range

With the help of good chemists, we can cover the whole visible spectrum combining different diarylethenes

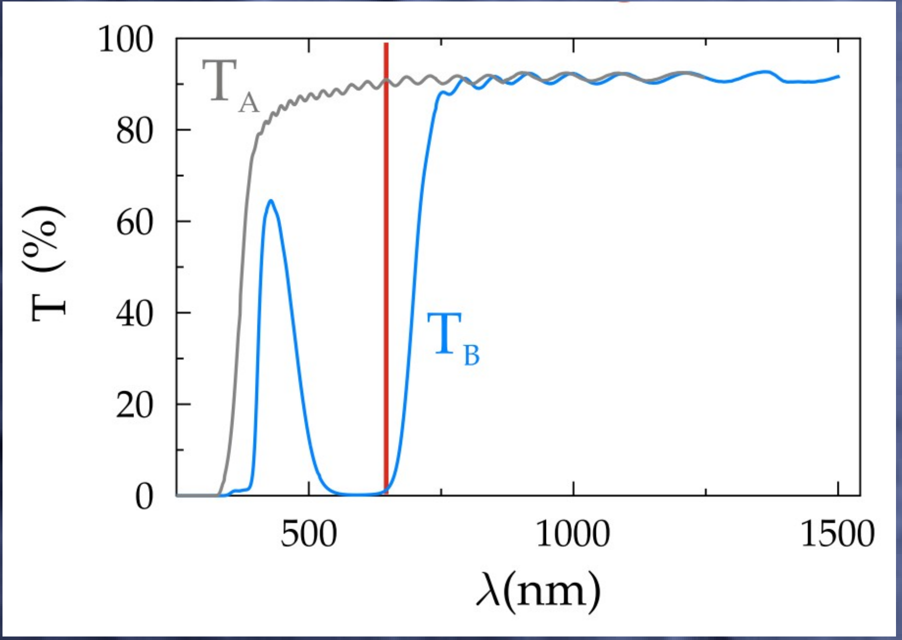


Key Parameters: Contrast

The key parameters for having an efficient device are:

- Wavelength range;
- Contrast value;

$$CT(\lambda) = \frac{T_A}{T_B}$$



The contrast **CT** is defined as the ratio of the transmittance in the uncolored form and the colored one

Key Parameters: Contrast

The key parameters for having an efficient device are:

- Wavelength range;
- Contrast value;

$$CT(\lambda) = \frac{T_A}{T_B}$$

In the case of focal plane masks, the higher the **CT**, the lower the sky contamination (S/N). The high contrast is required over a wide wavelength range.

Key Parameters: Contrast

The key parameters for having an efficient device are:

- Wavelength range;
- Contrast value;

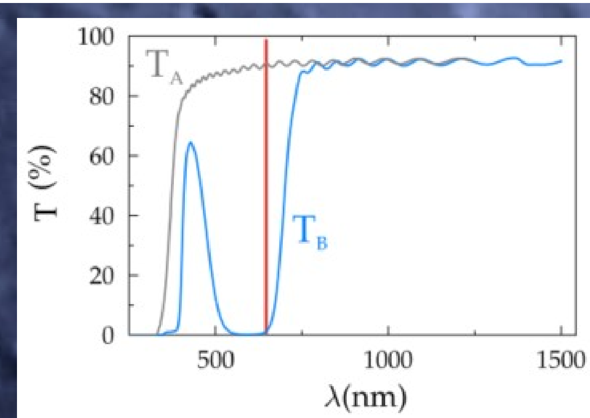
$$T_B = 10^{-\varepsilon_B C D}$$

Ext. Coeff.

Concentration

Thickness

$$CT(\lambda) = \frac{T_A}{T_B}$$

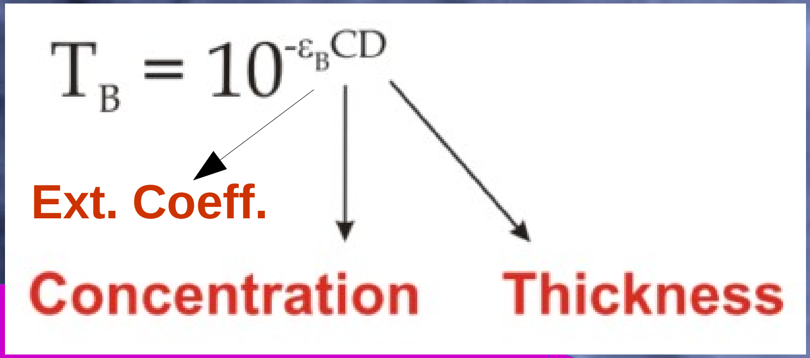


The contrast is driven by the <u>transmittance of the colored T_B form</u> through the Lambert-Beer law.

Moving from molecule to material…

The key parameters for having an efficient device are:

- Wavelength range;
- Contrast value;



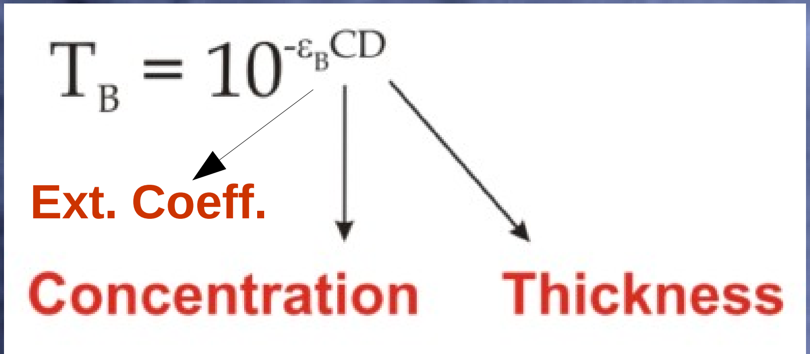
Make thick film with a large content of photochormic molecule!

Easy!

Moving from molecule to material…

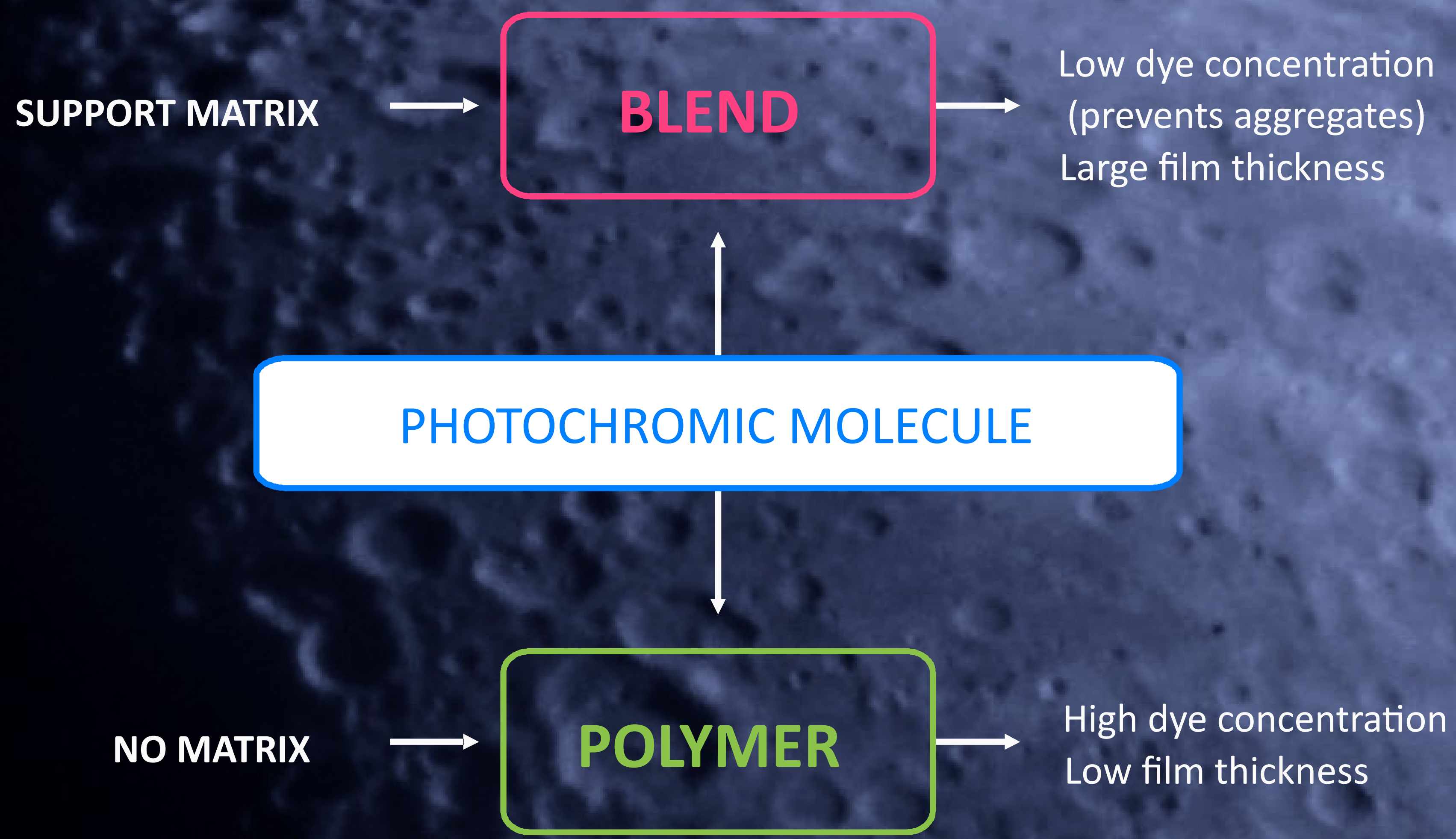
The key parameters for having an efficient device are:

- Wavelength range;
- Contrast value;



Yes, but how?
We have just the molecules
at the moment…

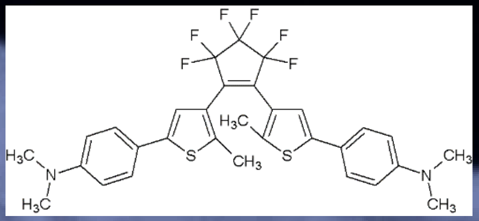
Strategies



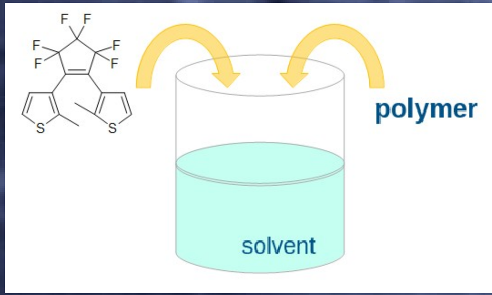
SUPPORT MATRIX
BLEND
Low dye concentration
(prevents aggregates)
Large film thickness
PHOTOCHROMIC MOLECULE
NO MATRIX
POLYMER
High dye concentration
Low film thickness

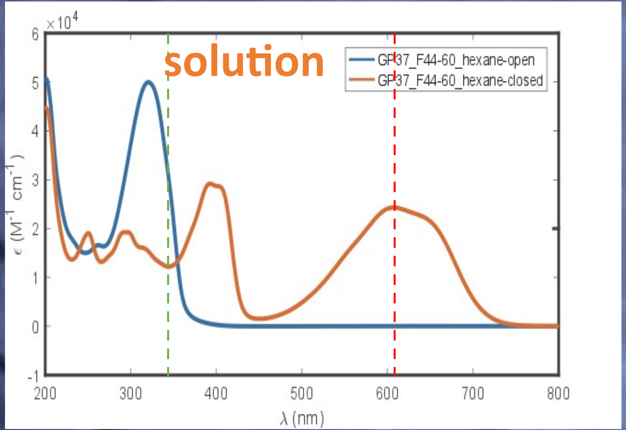
Blend

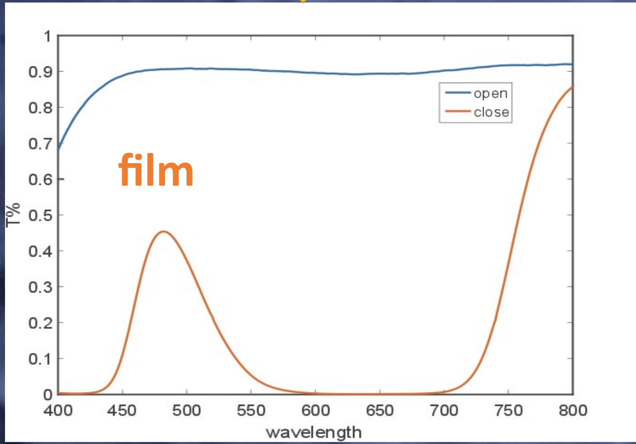
- Very simple film production
- Limited dye concentration to prevent segregation
- Strong property modulation is required in the diarylethene moiety
- Check the solubility of the molecule in the binder!



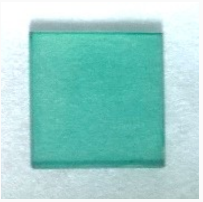
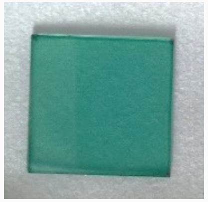
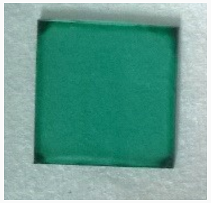
Polymer matrices (binders):
- Polystyrene
- PMMA
- Zeonex
- CAB (Cellulose Acetate Butyrate)



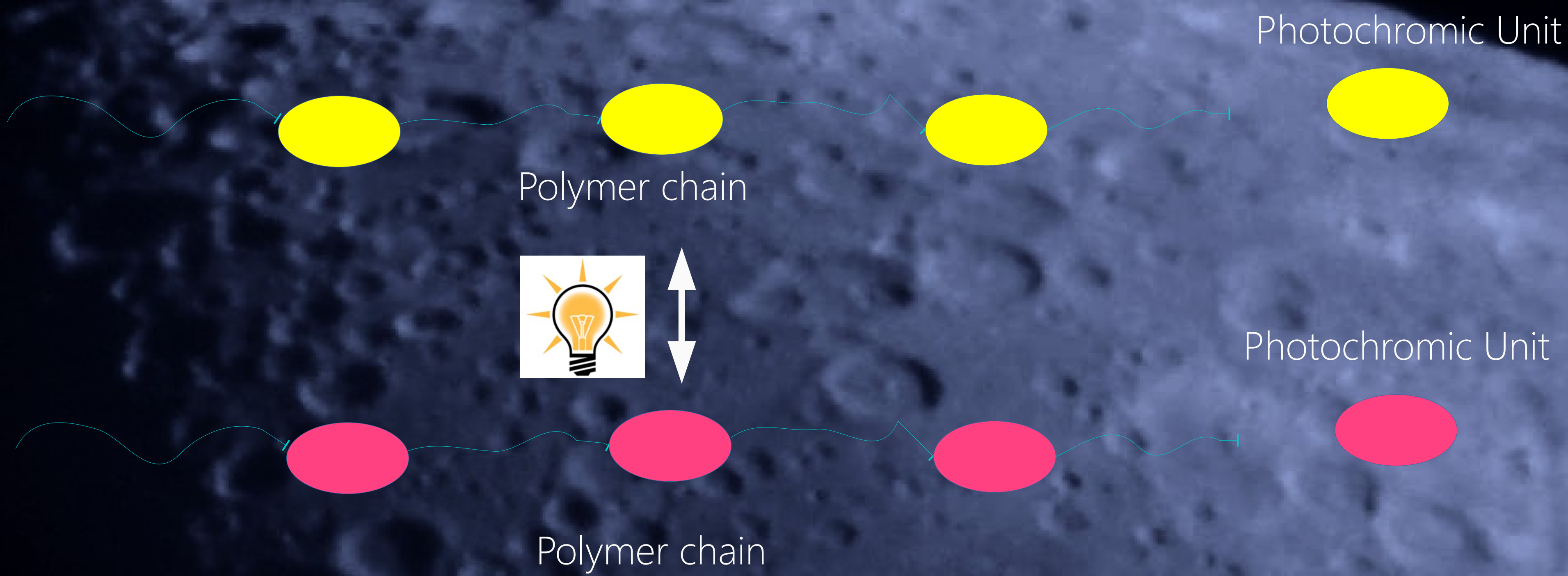




The molecule must be carefully chosen!

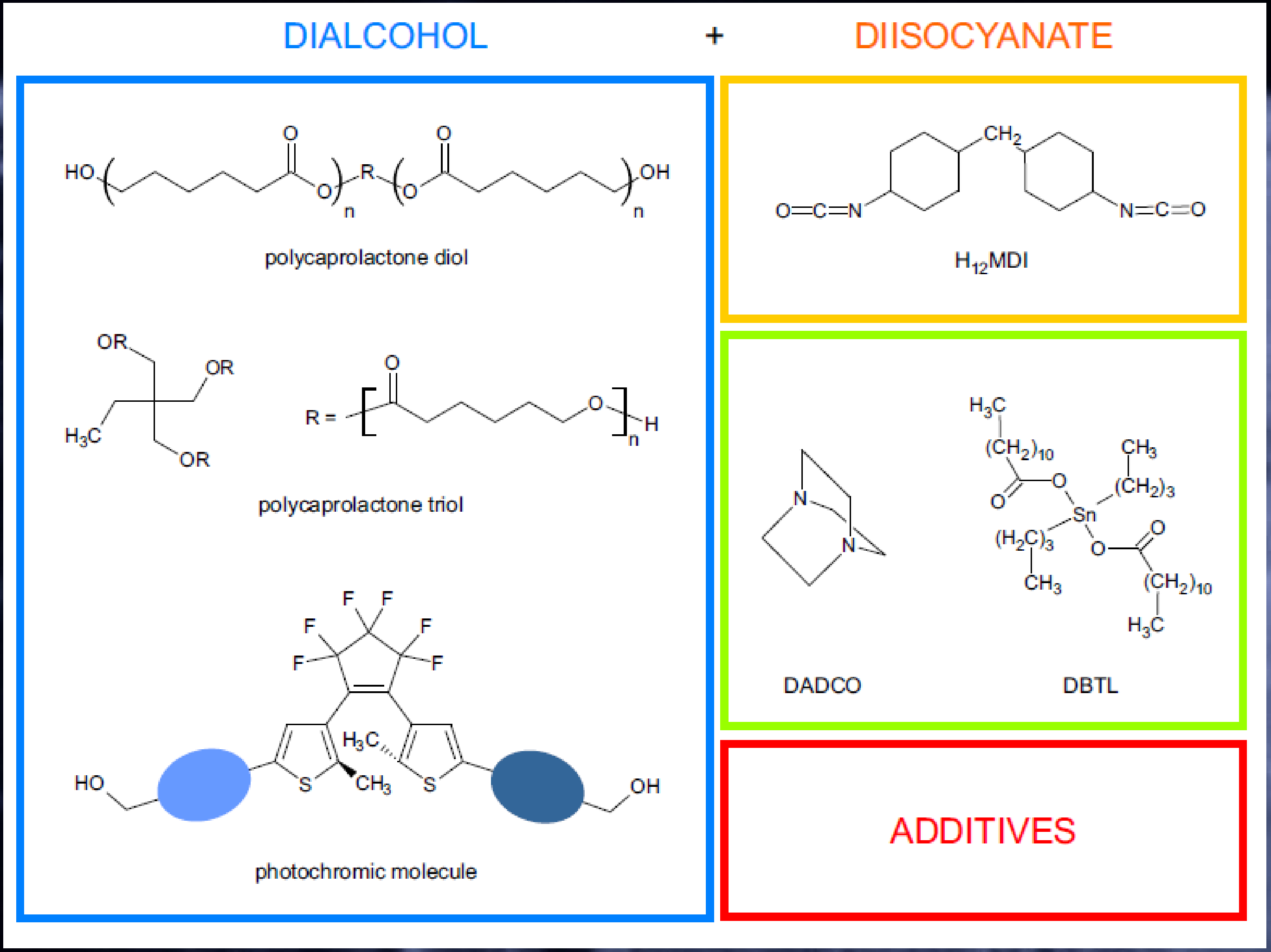
				
d (µm)	2.0	3.0	4.0	3.5
C (%wt.)	5	5	5	20
Abs@633nm	0.5	0.7	1.0	3.2

Backbone photochromic polymers

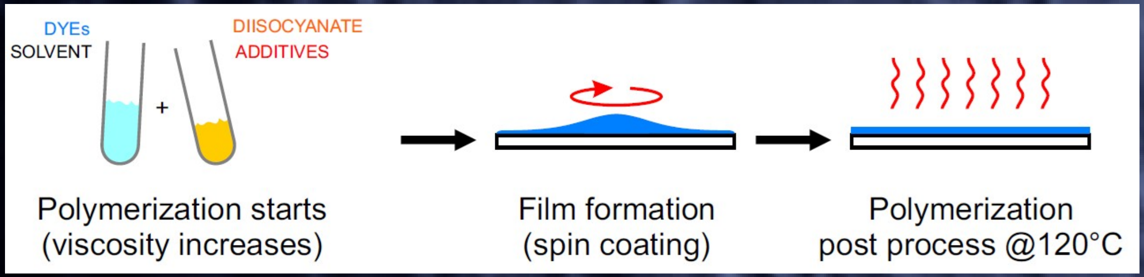


- The monomer is photochromic, therefore it need reactive groups;
- The optimization of the chemical structure is more difficult;
- It is **easy to have high content photochromic films** without segregation.

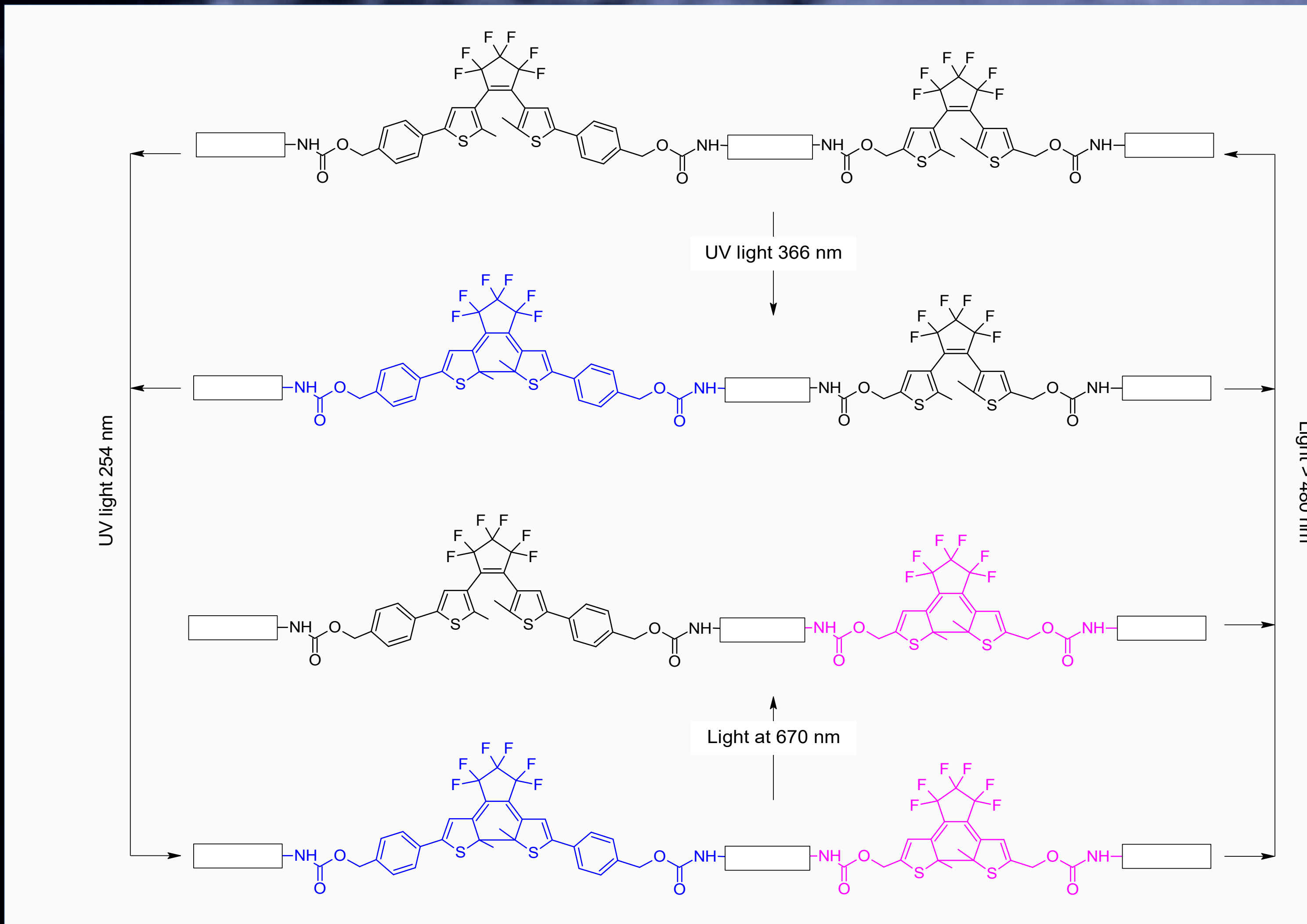
Photochromic polyurethane



Processing (*in situ* polymerization)

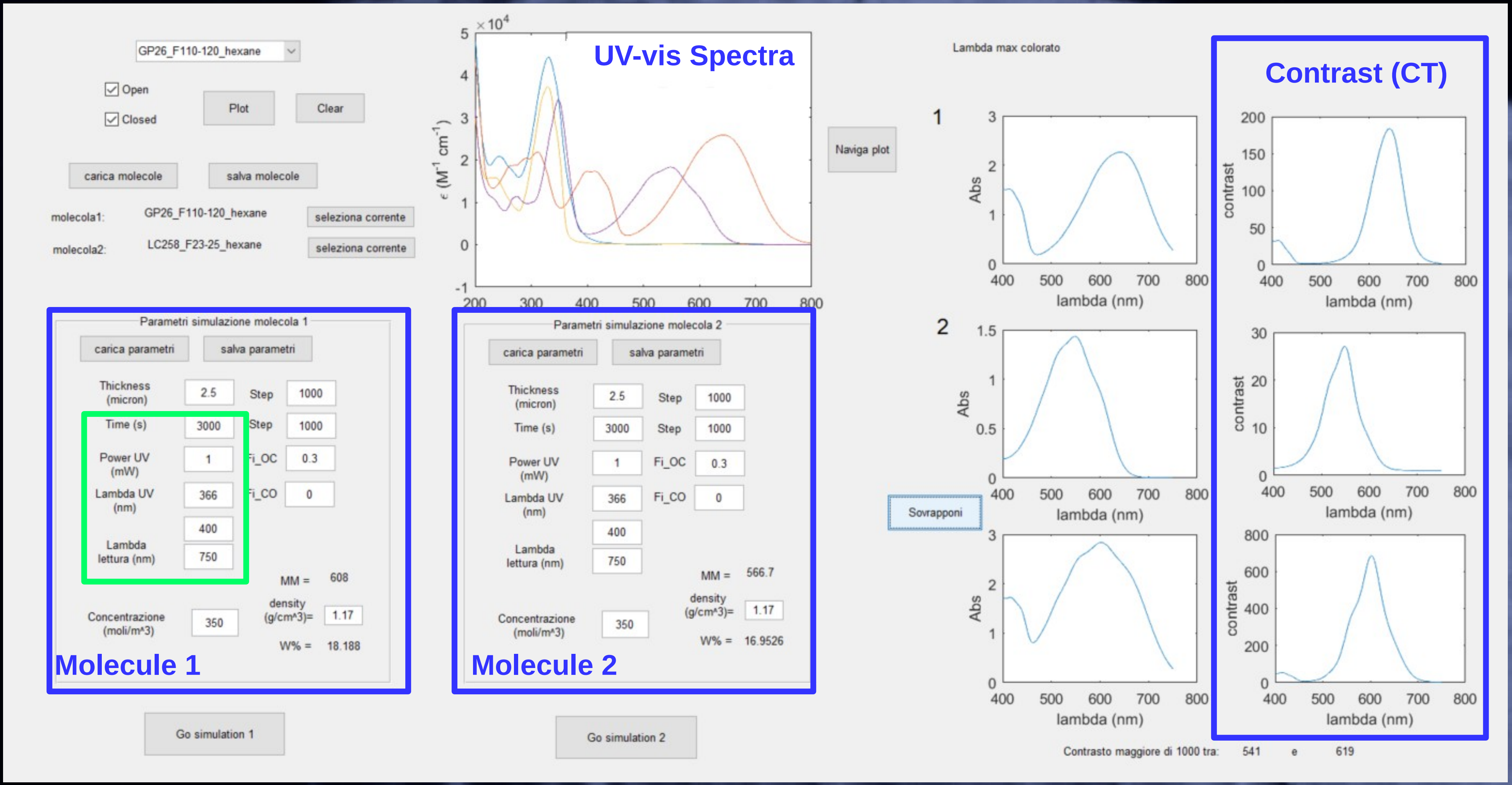


Photochromic polyurethane



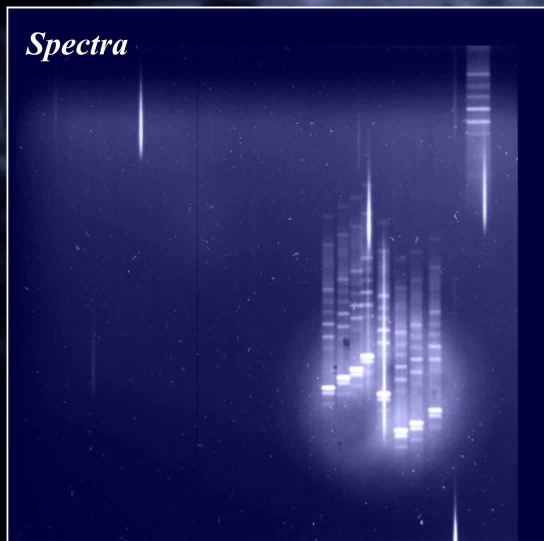
G. Pariani, R. Castagna, G. Dassa, S. Hermes, C. Vailati, A. Bianco and C. Bertarelli, *J. Mater. Chem.* **21**, 2011

A designing tools for photochromic films



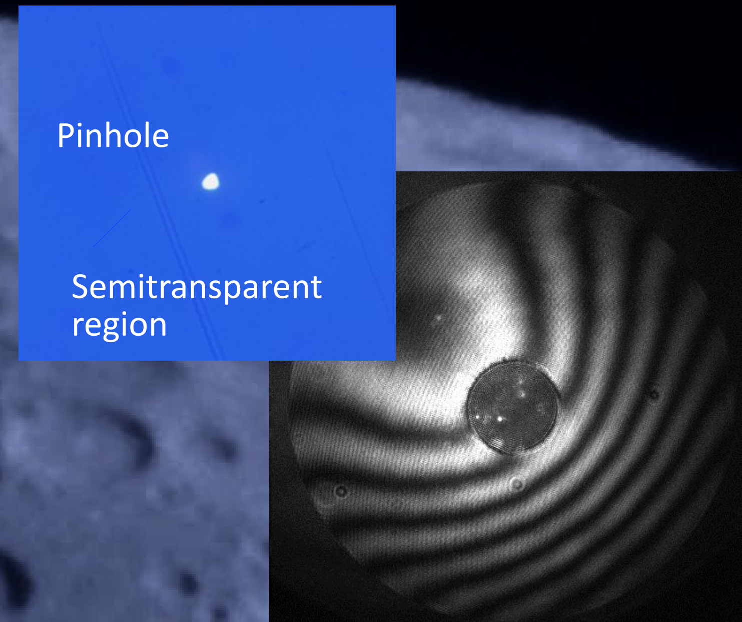
We developed a tool for the design of films with a target value of contrast as function of the "chemistry".

What we did with photochromic materials



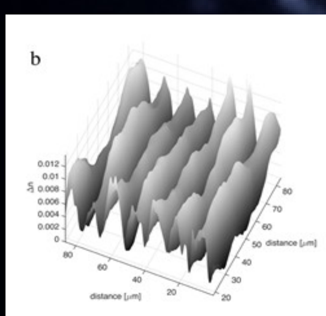
Focal Plane Masks

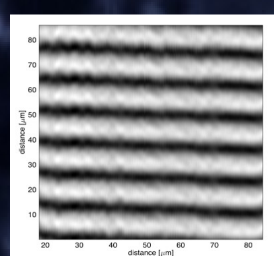
Bianco A., *Astron. Nachr.*, **326 (5)** pp. 370–374, 2005
Luca Oggioni, et al., Proc. SPIE 10706, 1070636 (2018)



Point Diffraction Interferometer

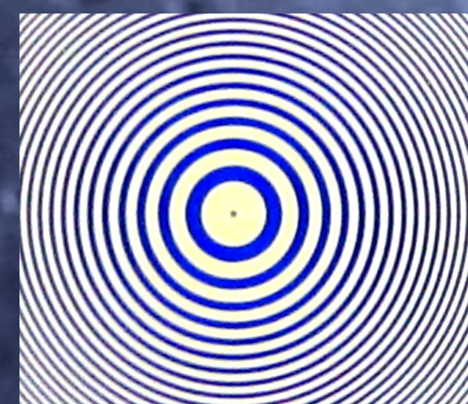
Quintavalla, M.; et al *Optics and Lasers in Engineering* **2014**, *56*, 134.





Mask for optical lithography

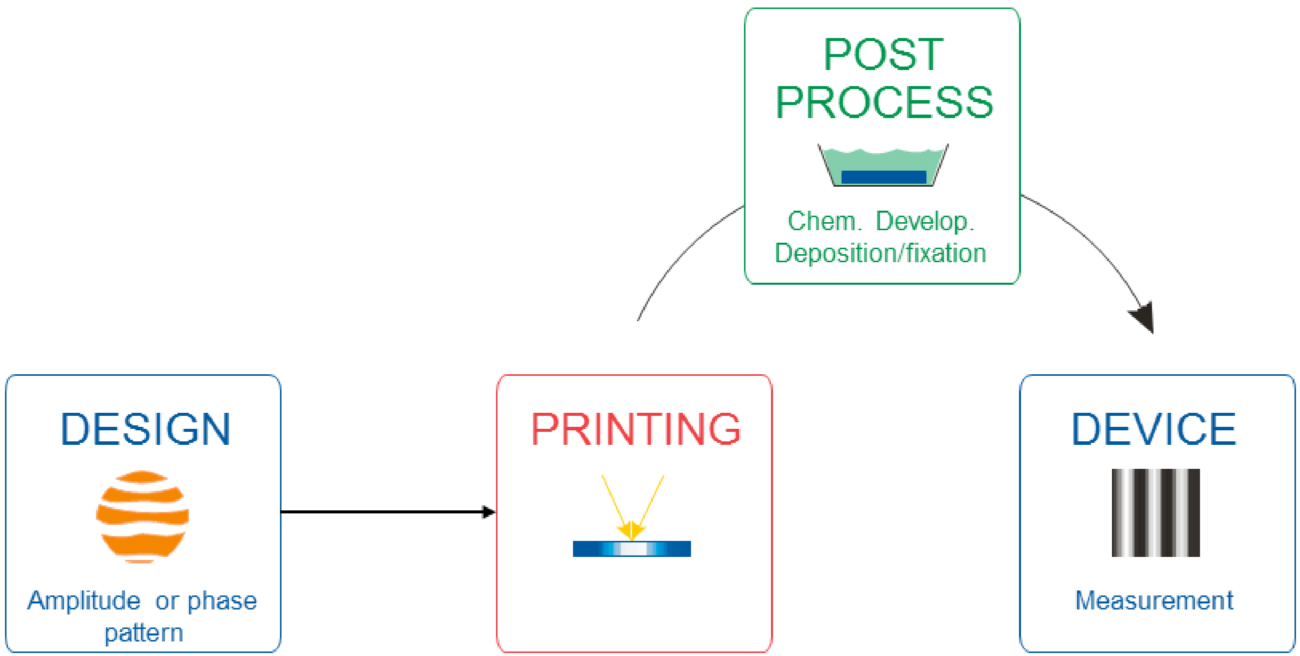
Pariani, G.; et al *Opt. Lett.* 38, 3024 (2013).
G. Pariani, et al. *Adv. Mater. Tech.* 3(3),1700325 (2018)



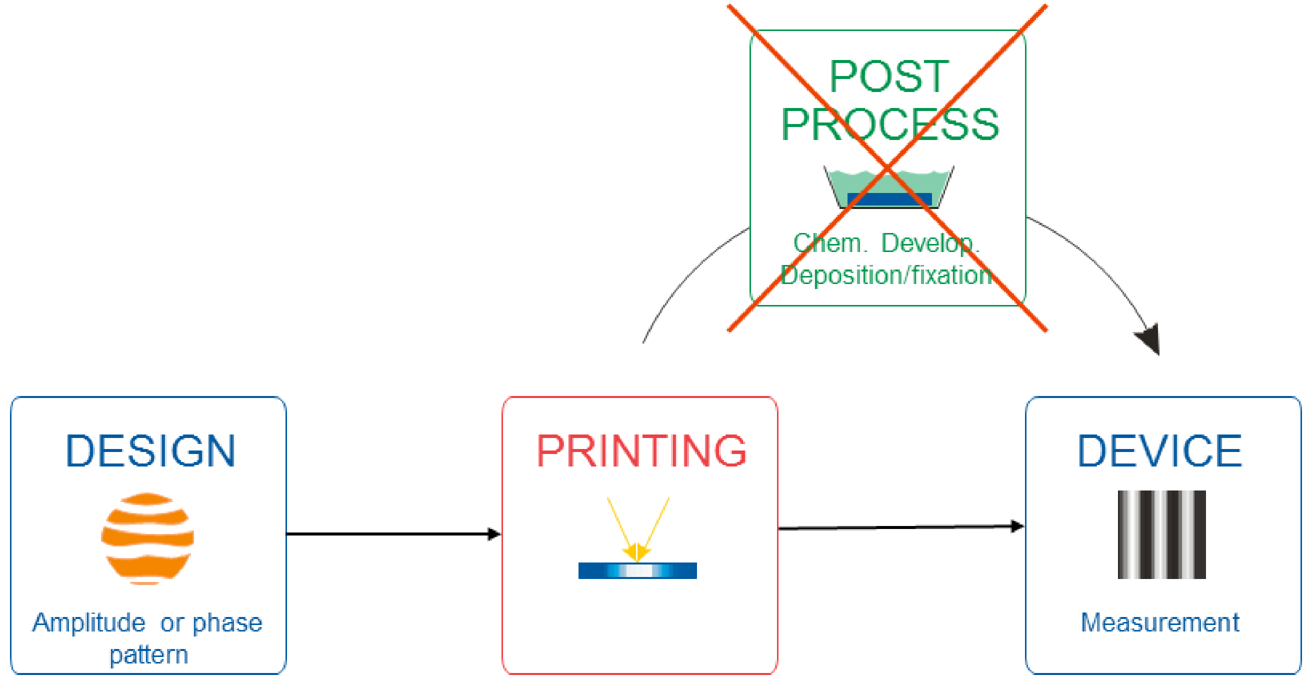
CGH for optical testing

Pariani, G.; et al *Opt. Express 19*, 4536 (2011)
Alata, R. et al, Proc. SPIE. 9912, 991234 (2016)
F. Zamkotsian, et al. *Opt. Express* 27(19), 26446 (2019).
L. Oggioni, et al. *Materials*, 12(7), 2810 (2019)

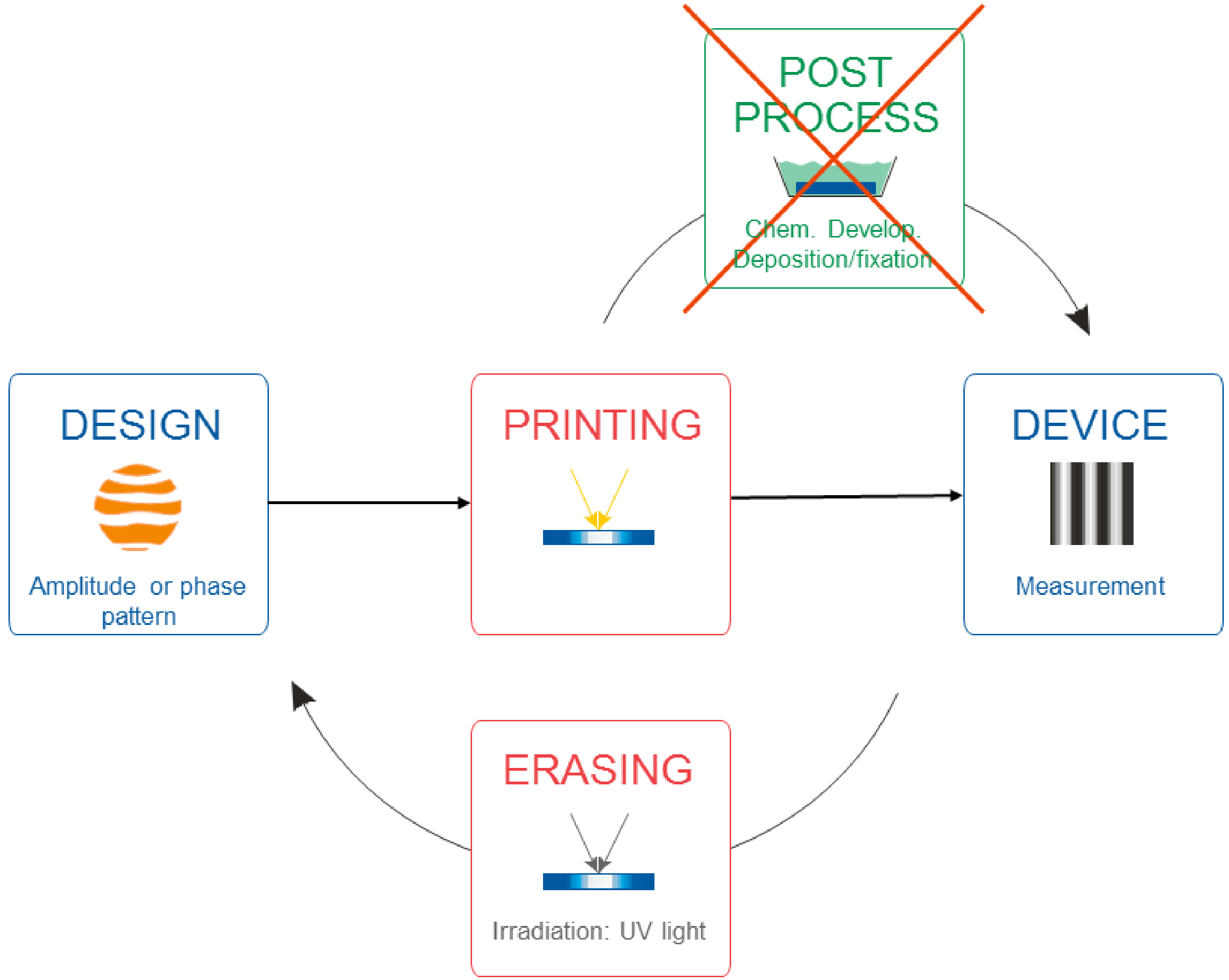
Simplify the process...



Simplify the process…



Simplify the process…



We developed a simple and reconfigurable platform for masks, waveguides, holograms,…

Dispersing elements

Spectral Resolution

Low Resolution (100 – 2000);

Medium Resolution (2000 – 5000);

High Resolution (5000 – 50000);

Very High Resolution (50000 – 200000).

Spatial Resolution

Single Object;

Multi Object Spectroscopy (MOS);

Spectral imaging.

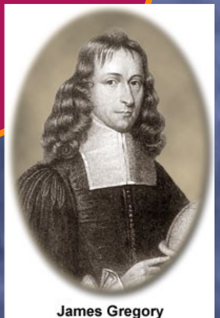
Spectral range

UV-Vis (0.3 – 1.0 μm)

NIR (0.9 – 2.5 μm)

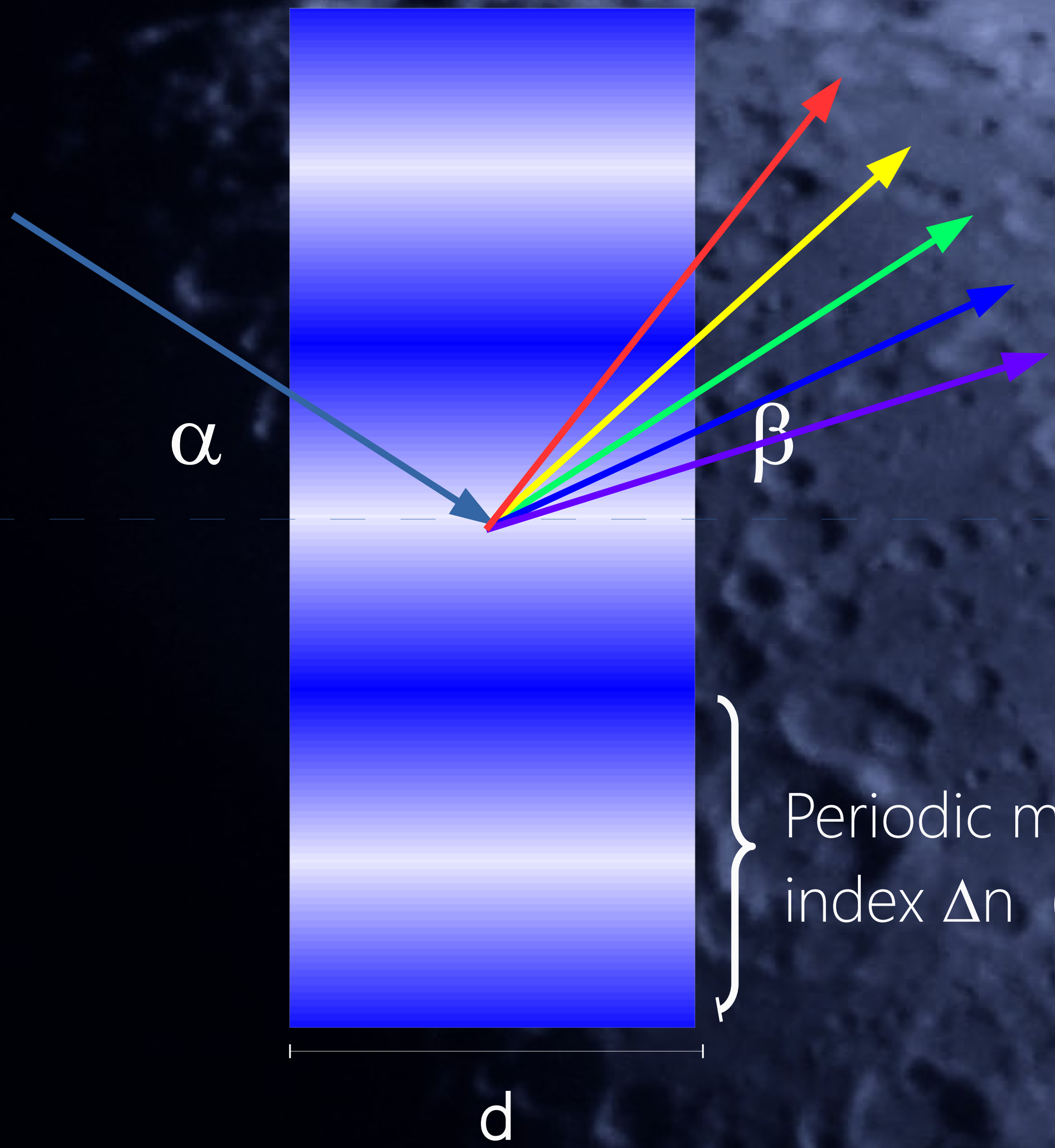
MIR (2.5 – 25 μm)

Dispersing element (grating) is a key element



James Gregory (1638-1675)

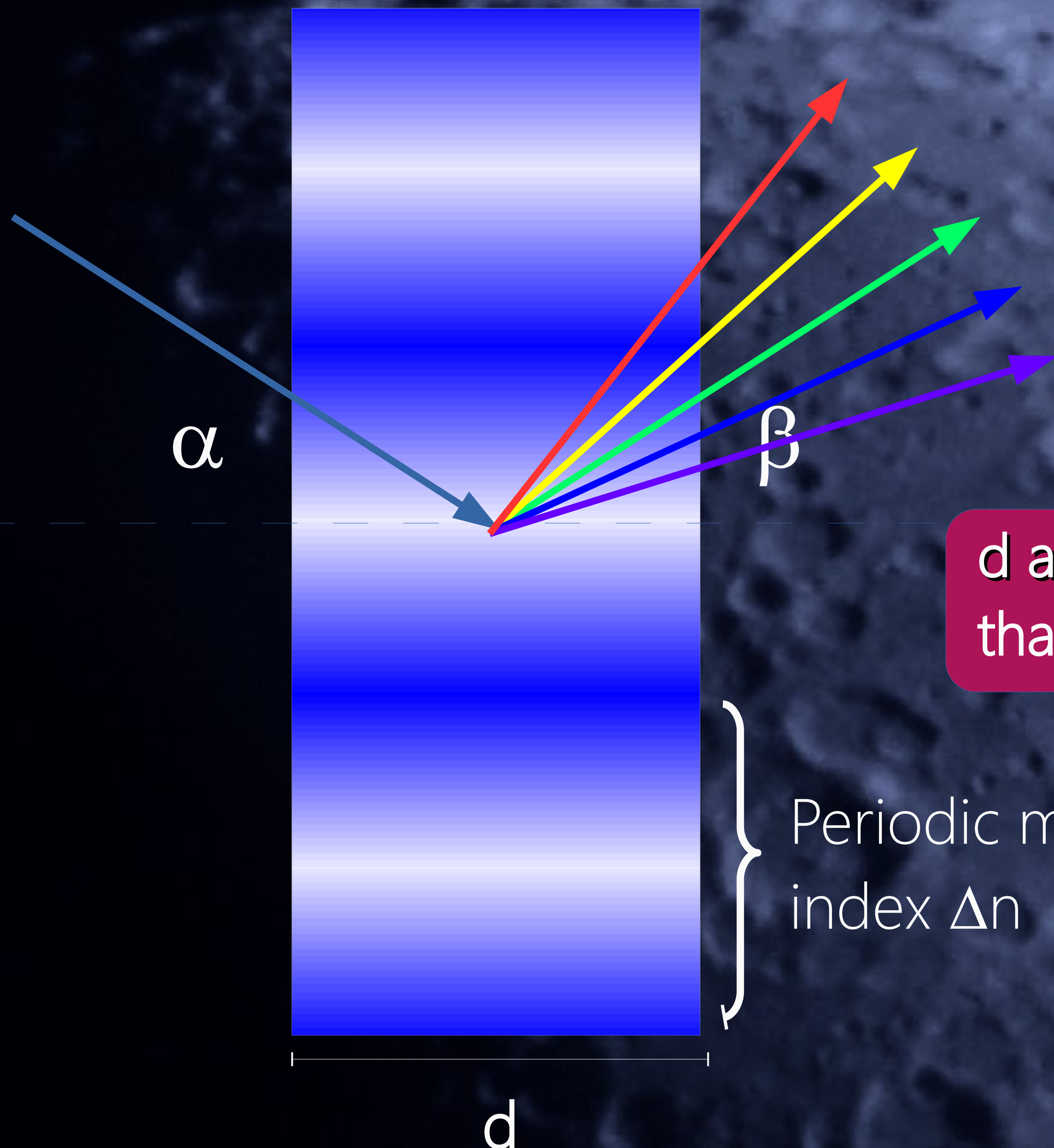
Dispersing elements: VPHG



The diffraction occurs thanks to a periodic modulation of the refractive index in the volume of the material.

Periodic modulation of the refractive index Δn (usually sinusoidal).

Dispersing elements: VPHG



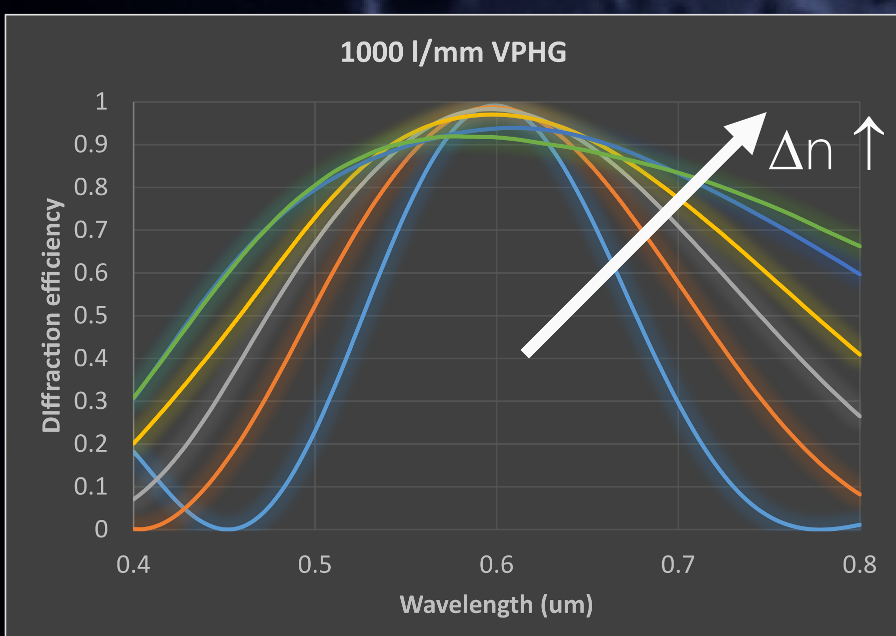
The diffraction occurs thanks to a periodic modulation of the refractive index in the volume of the material.

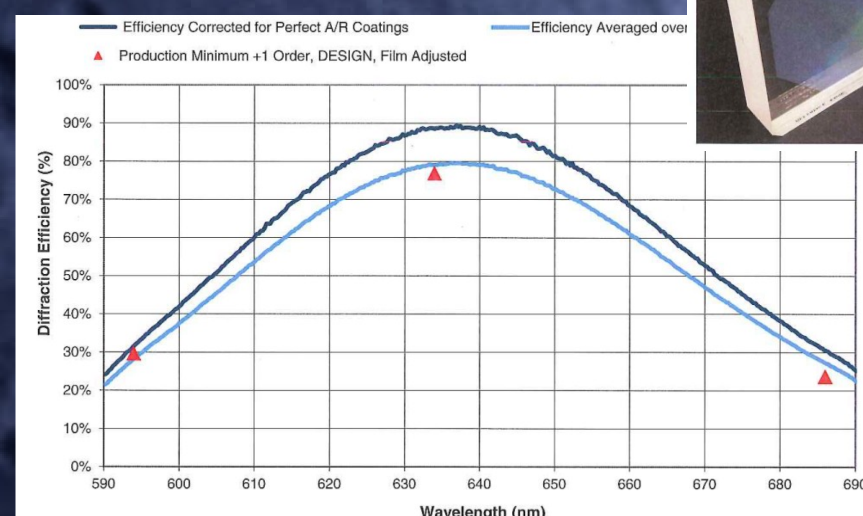
d and Δn are the key parameters that drive the diffraction efficiency

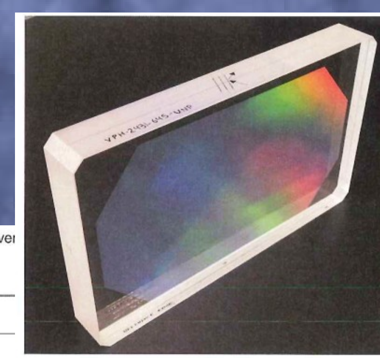
Periodic modulation of the refractive index Δn (usually sinusoidal).

Dispersing elements: VPHG

- The peak efficiency can be theoretically 100%. Easily, values of 90% are obtained;
- The devices are robust since the active material is usually embedded in between two glass windows and multilayer coatings can be applied;
- Large VPHGs can be produced if a big holographic setup is available;
- Large dispersion gratings with line density up to 6000 l/mm can be obtained;
- The device is easily customizable.







VPHG materials: DCG

- Dichromated gelatin (DCG) has been studied for making phase holograms for more than 40 years. It contains Cr (toxic);
- It is surely **the best** material for holography: reference material for VPHG in astronomy;
- Modulation of the refractive index very large => Δn up to 0.15!
- Low sensitivity (high laser power);
- Transparent up to 2.5 μm;
- Good homogeneity => very low scattering => high S/N.

T.A. Shankoff, Applied Optics 7(10), 1968

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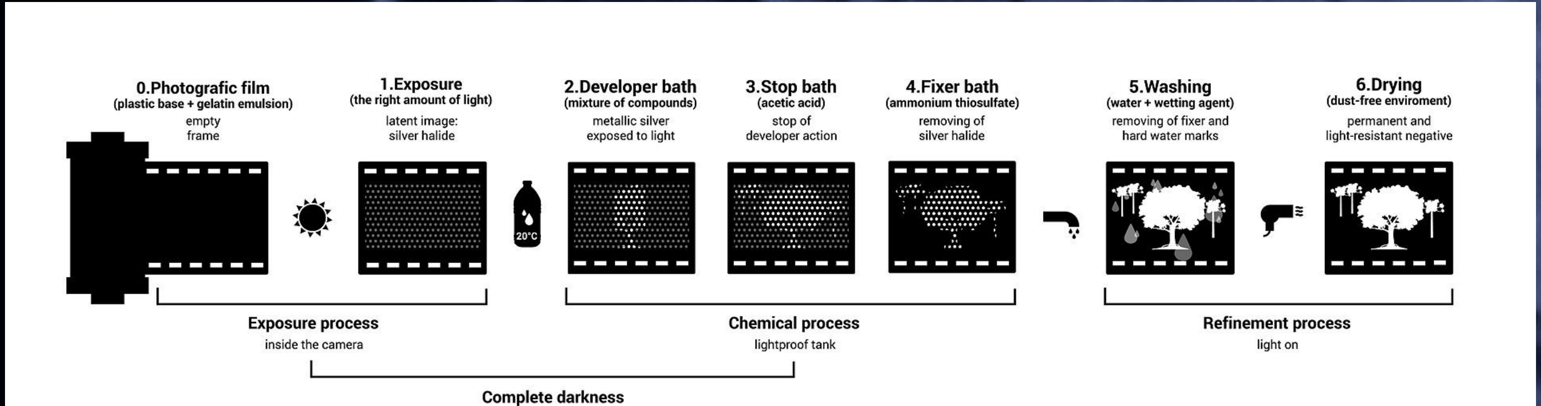
BUT…

A chemical development process is required (old camera films)



Microvoids are formed in the material

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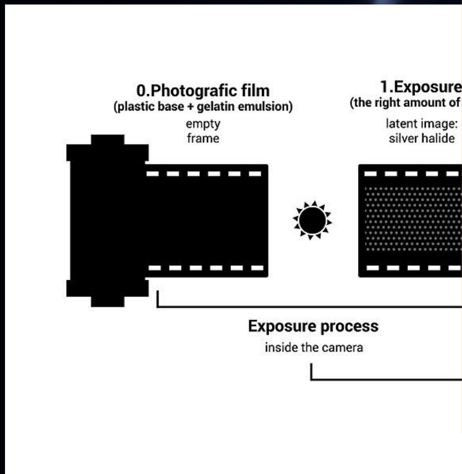
- Transparent up to 2.
- Good homogeneity

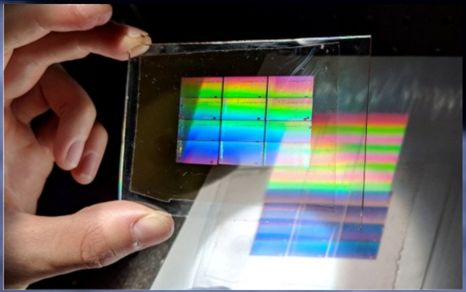
BUT...

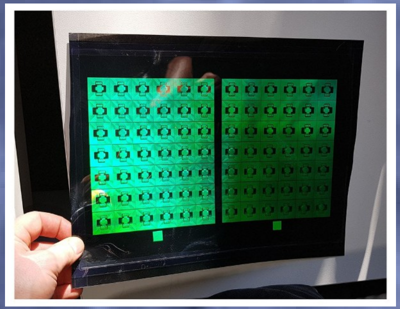
A chemical developme



VPHG materials: Photopolymers

- High sensitivity (low laser intensity required);
- Easy control of the film thickness;
- Limited modulation ($\Delta n < 0.05$);
- Flexible, self-standing films;
- Self-developing (no chemical post exposure process)!





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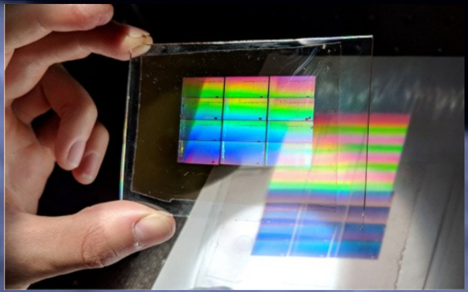
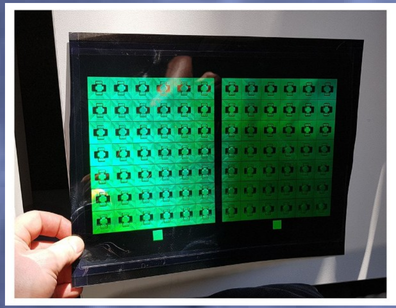
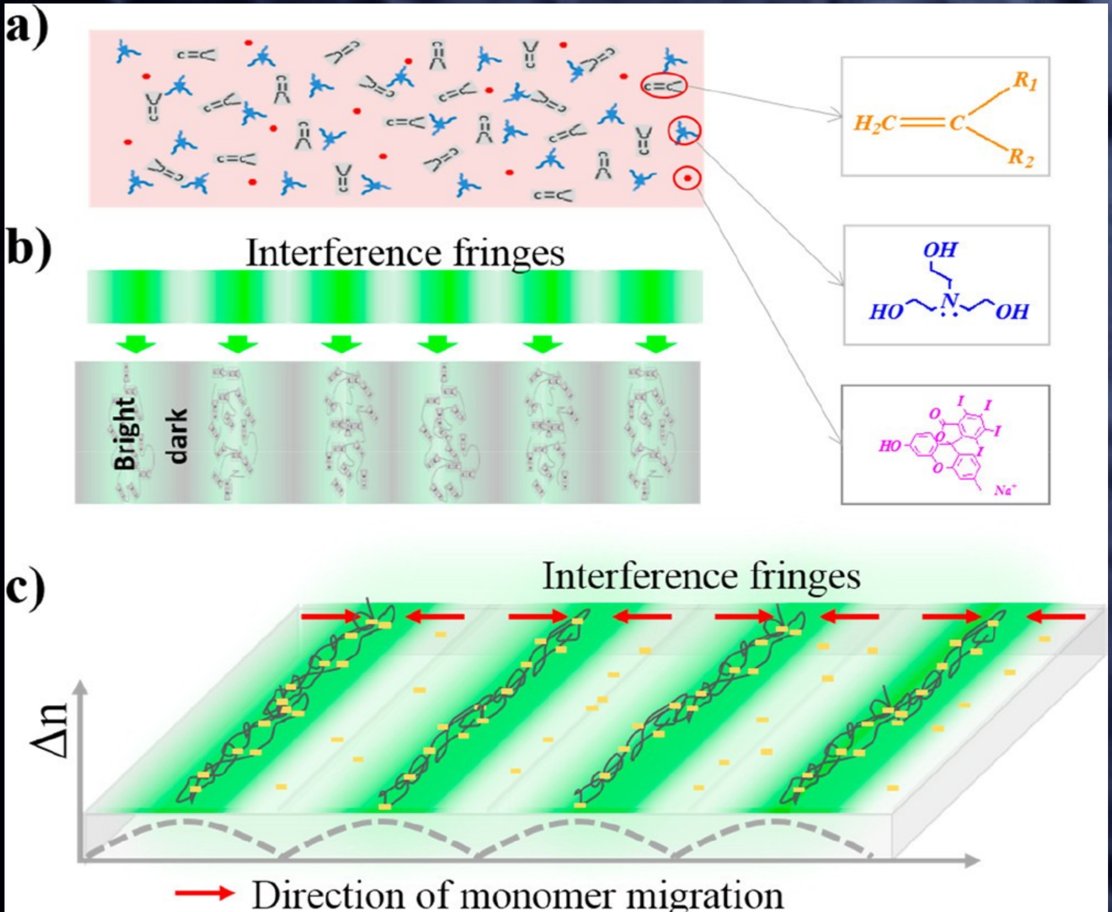






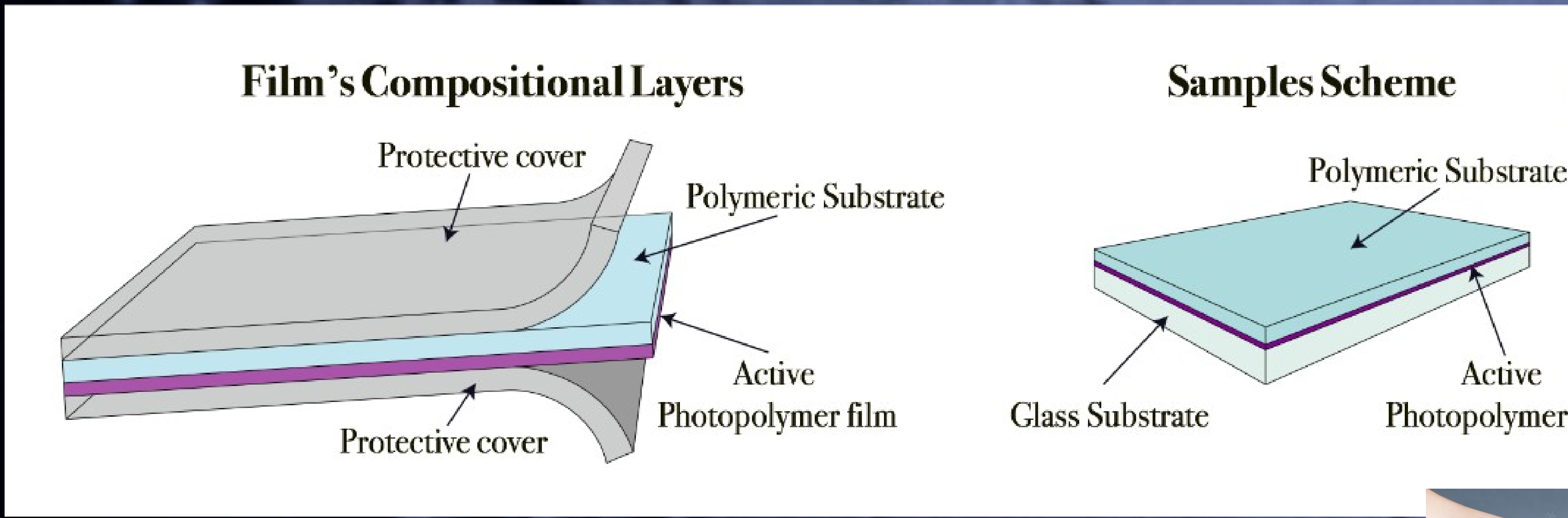
We start from a mixture of monomer, photoinitiator, dispersed in a binder (a polymer)

Migration of monomers from the dark to the bright areas;

Change in density = change in refractive index!

VPHG materials: Bayfol HX by Covestro

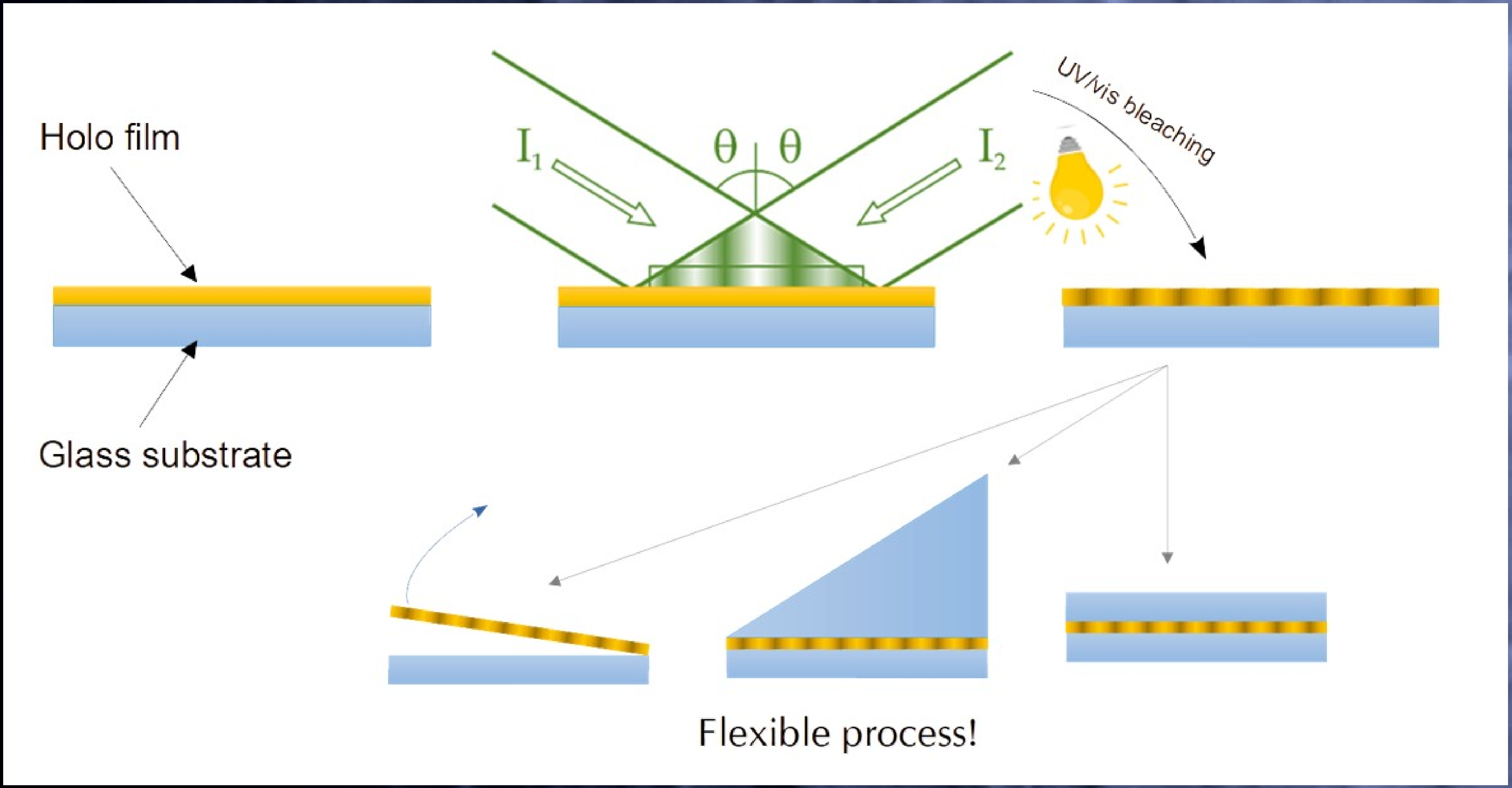
Bayfol® HX photopolymers by Covestro show a very simple and **"easy to use"** structure:



- The structure is like a protective layer of smartphone and tablet;
- Bayfol® HX photopolymers are available in different thicknesses and size (up to meter!).

VPHG materials: Bayfol HX by Covestro

The process is highly flexible, allowing for a better optimization of the device.
Once the element is written can be removed, coupled with prism, substrates,..



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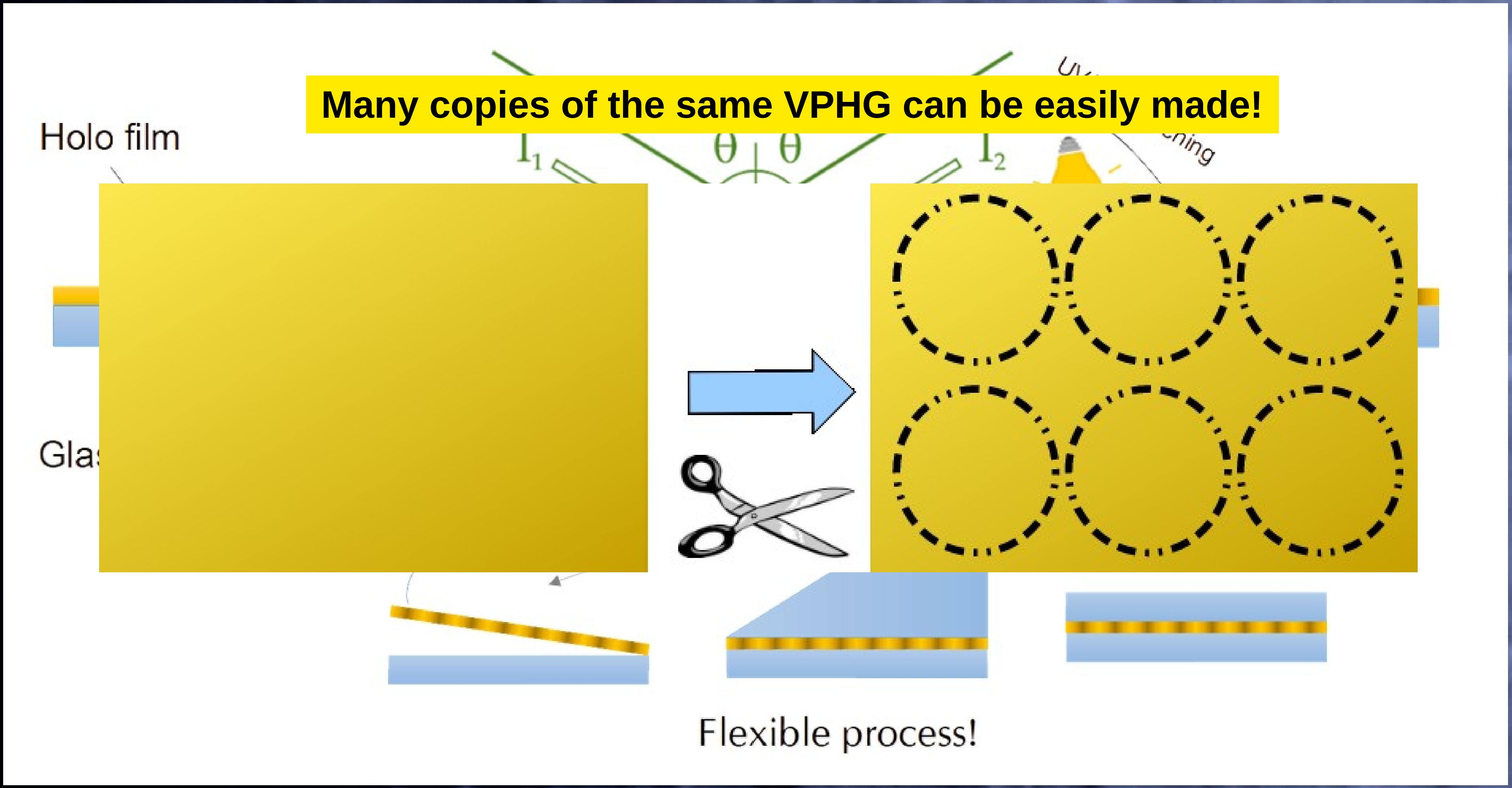
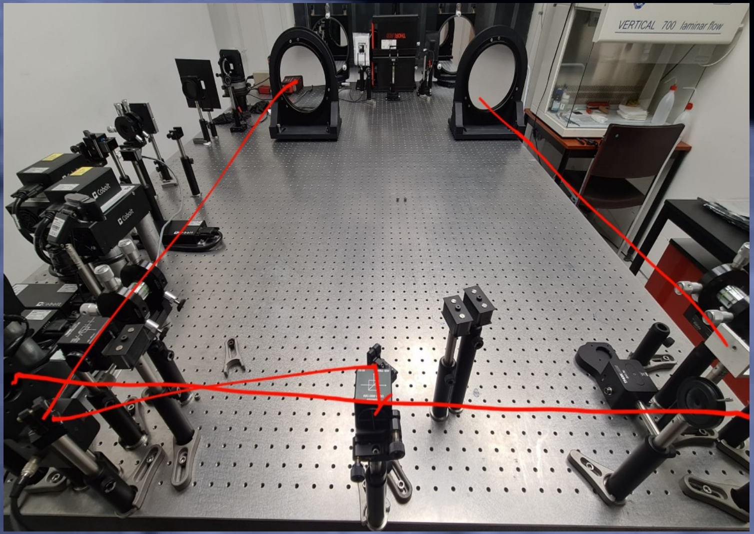


VPHG: what we can do…

- Holographic set-up with RGB lasers;
- VPHGs up to <u>190 mm in diameter</u> working in the VIS and NIR also at high dispersion;
- <u>Non conventional VPHGs (multiplexed, multiorders)</u> to increase spectral range and resolution;
- More than 10 VPHG *made in OABr* available on observing facilities.




covestro Solution Center

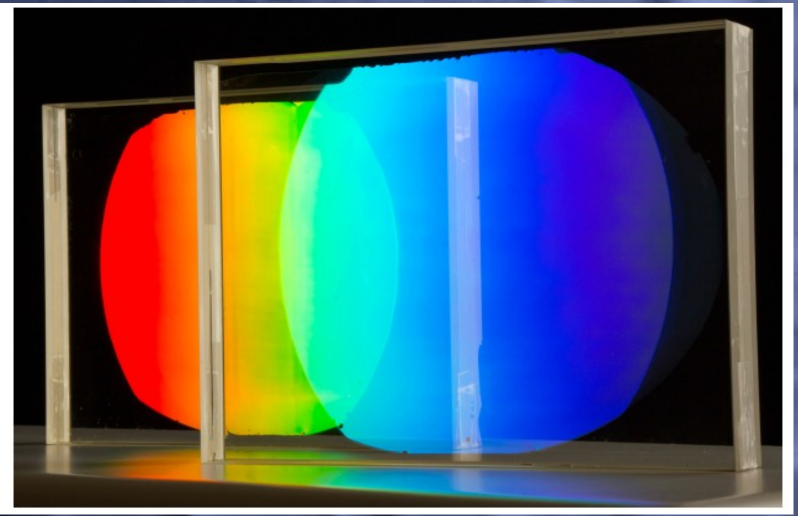
Covestro Websites EN

Industries Materials Products Highlights

CASE STUDY

Bayfol® HX holographic films star in INAF telescope application

The Italian National Institute for Astrophysics (INAF) needed a highly efficient, diffractive light-guiding material to improve the performance of its specialized telescopes. Bayfol® HX holographic films won the starring role. These films are versatile, easily processed and offer great optical quality.

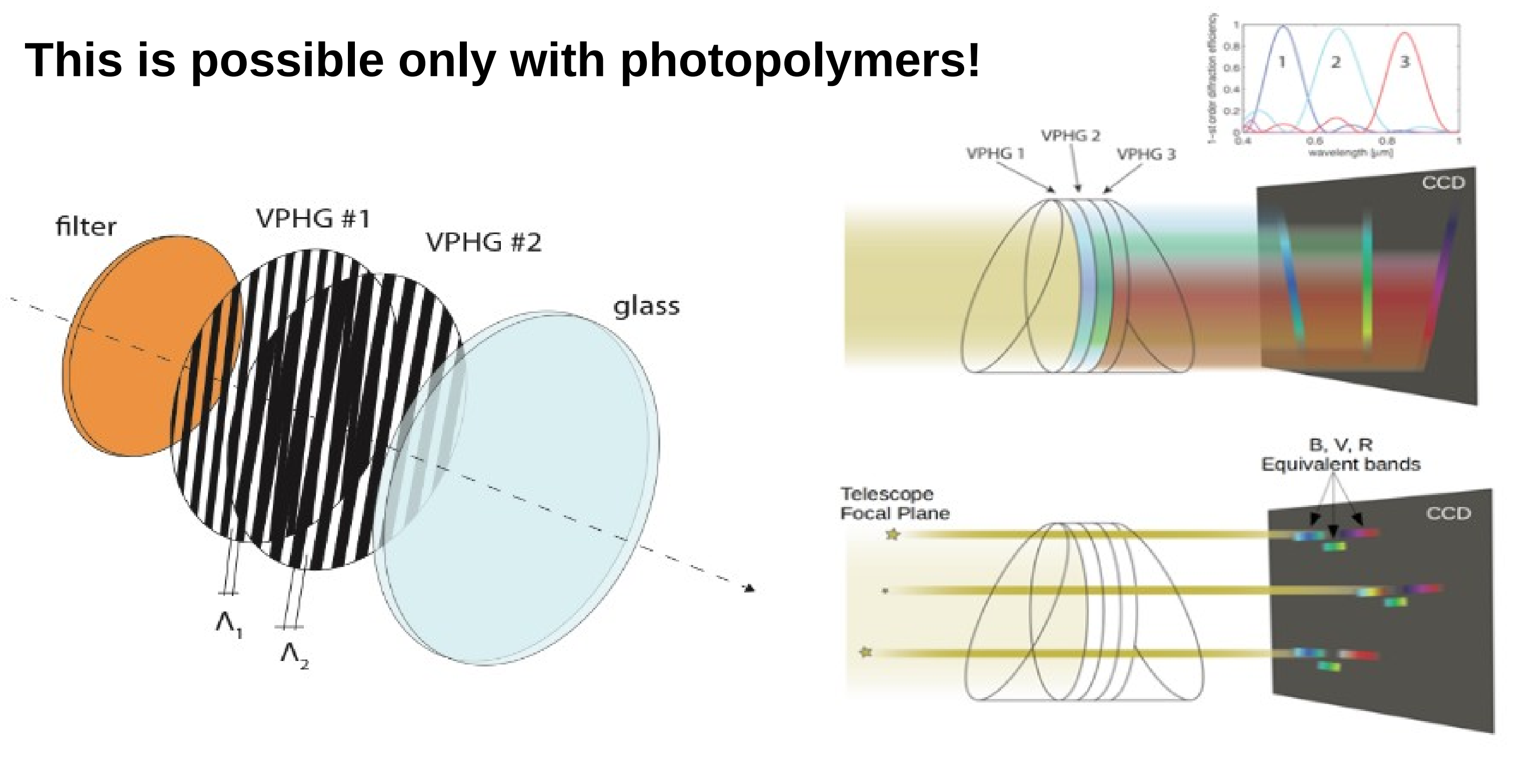


Example: Multiplexed VPHGs

ISSUE: increasing the resolution, the spectral range decreases due to the limited size of the detector. Multi exposures are necessary to cover a wide spectral range with the desired R.

IDEA: **Combine more than one VPHGs with suitable clock angle in the same device** to fill the detector in a similar fashion of an echelle. Target R = 3000 – 5000. Provide "high" res spectra only of some target features.

This is possible only with photopolymers!



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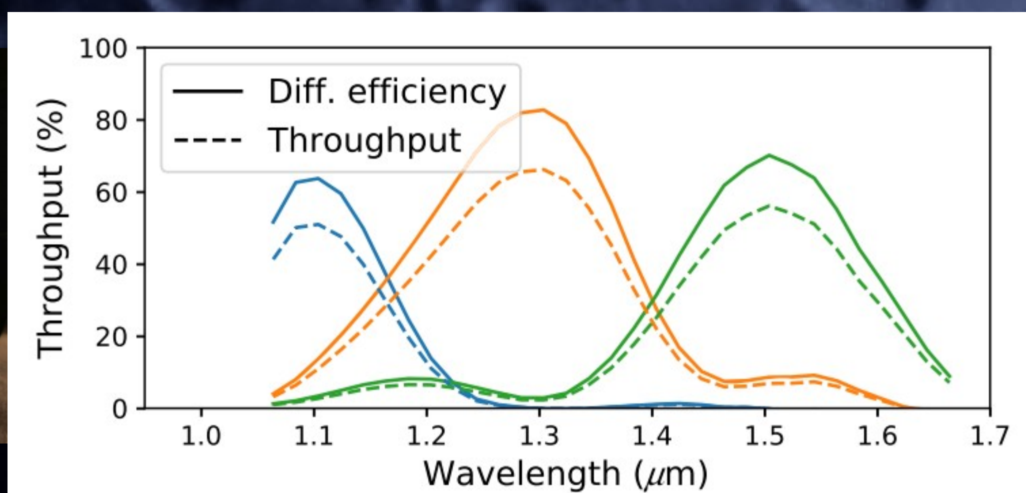

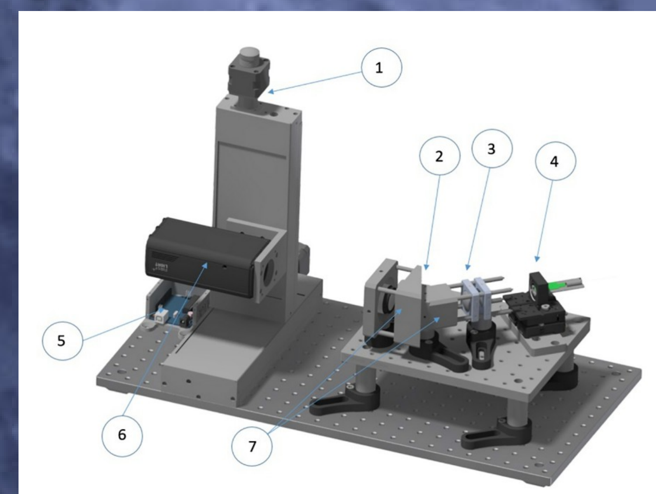

J. Astron. Telesc. Instrum. Syst., 6(4), 045007, 2020

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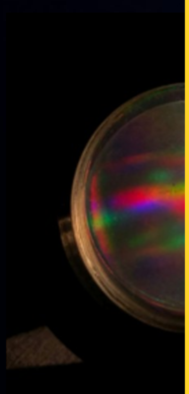

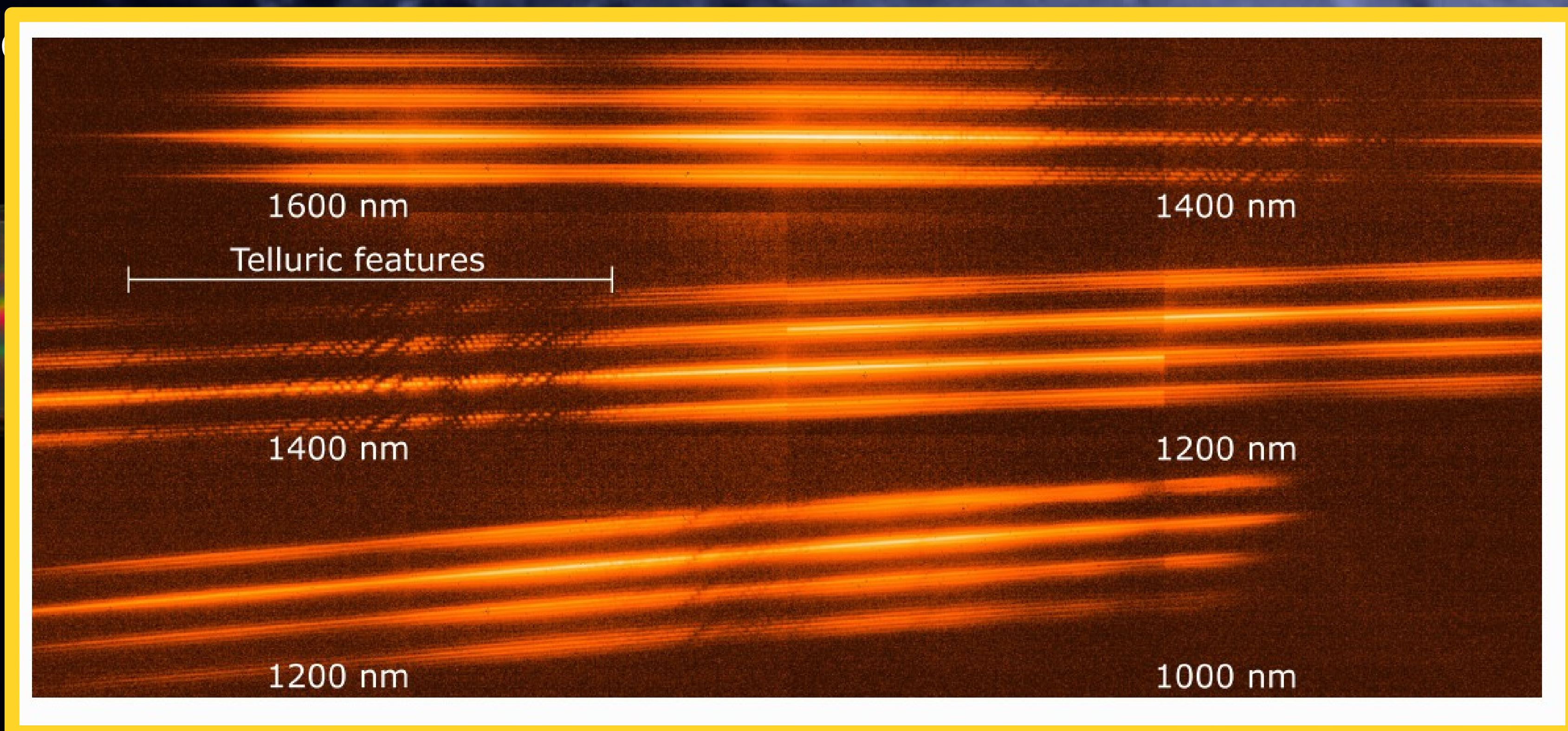

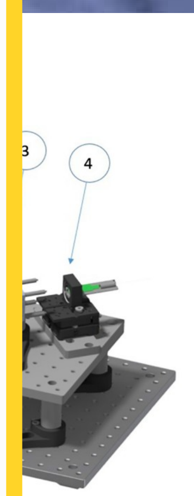

Conclusions

We will experience an increase in the complexity, of both telescopes and their instrumentation;

New materials and processes can have a key role in this task;

The context and approach is multidisciplinar…not always easy;

Photochromic materials are a good example in this sense;

The optimization of the device requires the understanding of the materials at different levels;

Understand when to start such activities and how to support them.