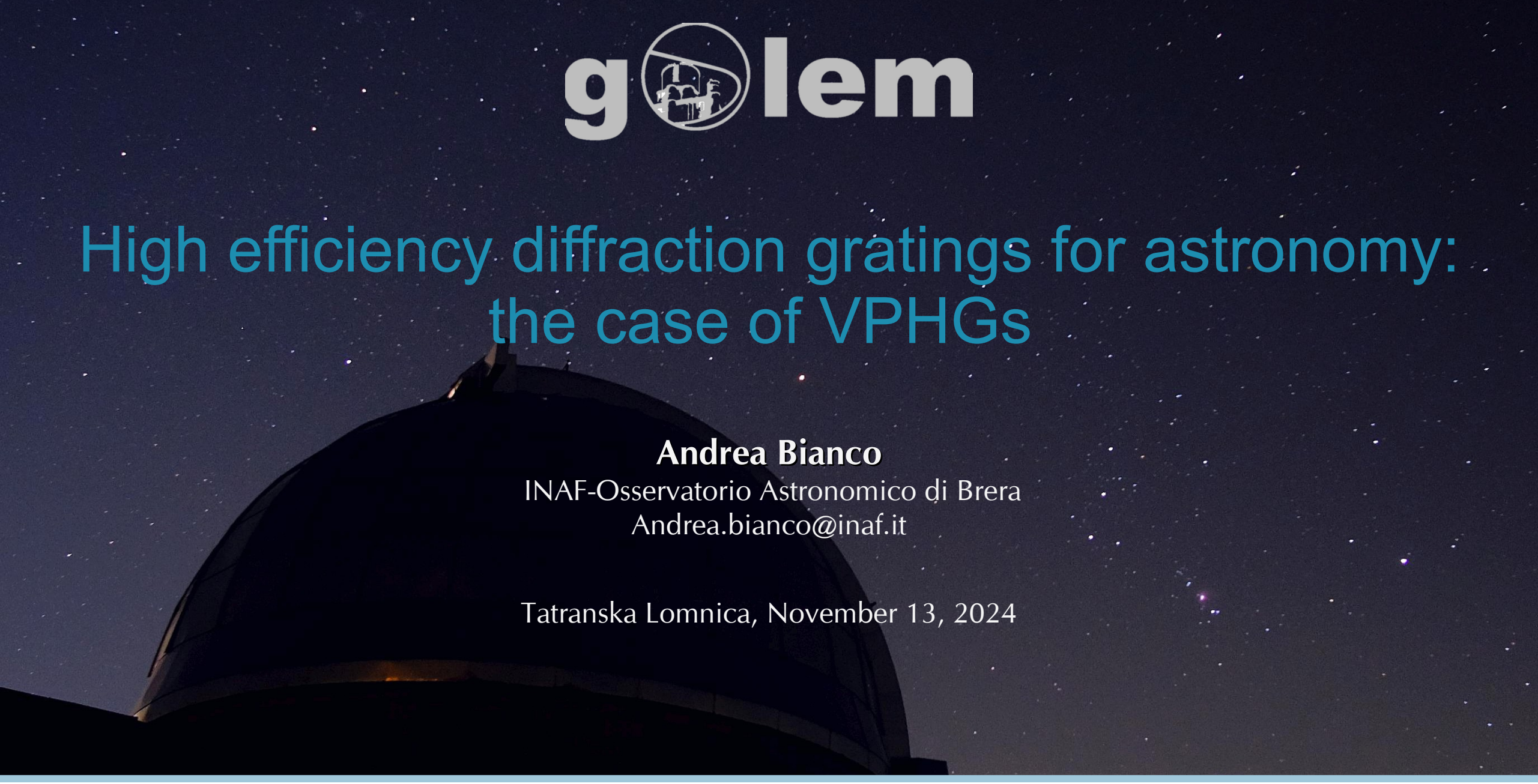

High efficiency diffraction gratings for astronomy: the case of VPHGs

Andrea Bianco
INAF-Osservatorio Astronomico di Brera
Andrea.bianco@inaf.it

Tatranska Lomnica, November 13, 2024

OPTICON RadioNet Pilot

INAF ISTITUTO NAZIONALE DI ASTROFISICA NATIONAL INSTITUTE FOR ASTROPHYSICS

INAF – OABr

INAF stands for "**Istituto Nazionale di Astrofisica**". It is the leading Italian research institute that deals with astronomy and astrophysics. INAF was founded in 1999 and currently finances and manages twenty separate research centers, which in turn employ scientists, engineers, and technical personnel.

More than 1700 people work in INAF, which provides important contribution to the main astronomical observing facilities both ground-based and space.

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More than 1700 people work in INAF, which provides important contribution to the main astronomical observing facilities both ground-based and space.

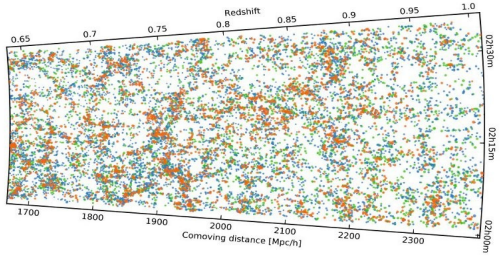
The **Astronomical Observatory of Brera** is part of INAF and it is the oldest scientific institution in Milan (1762).
Another site in Merate (LC) since 1923.

INAF – OABr

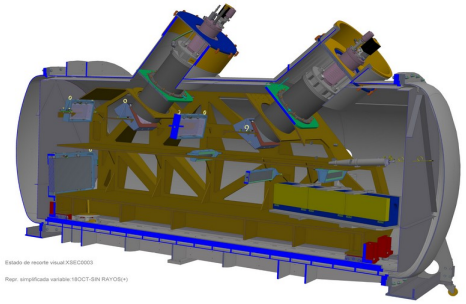
Merate since 1923

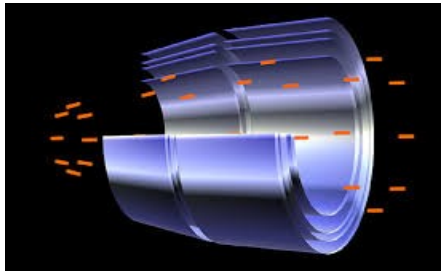
Milano since 1762

Science

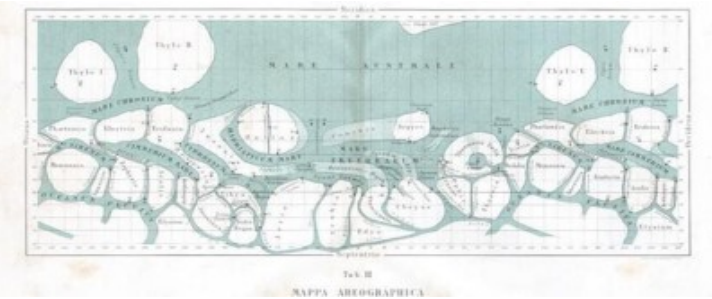


Technology

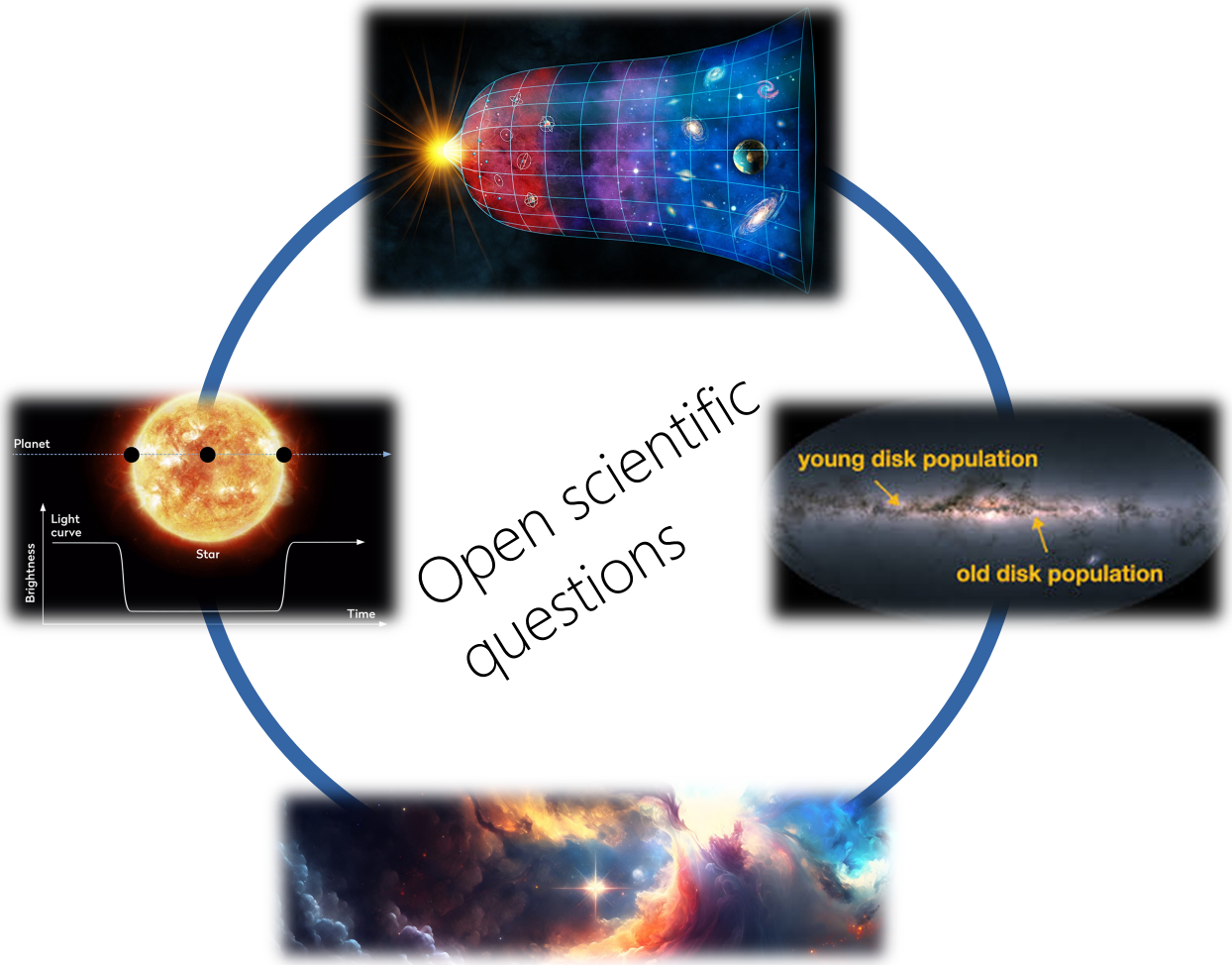




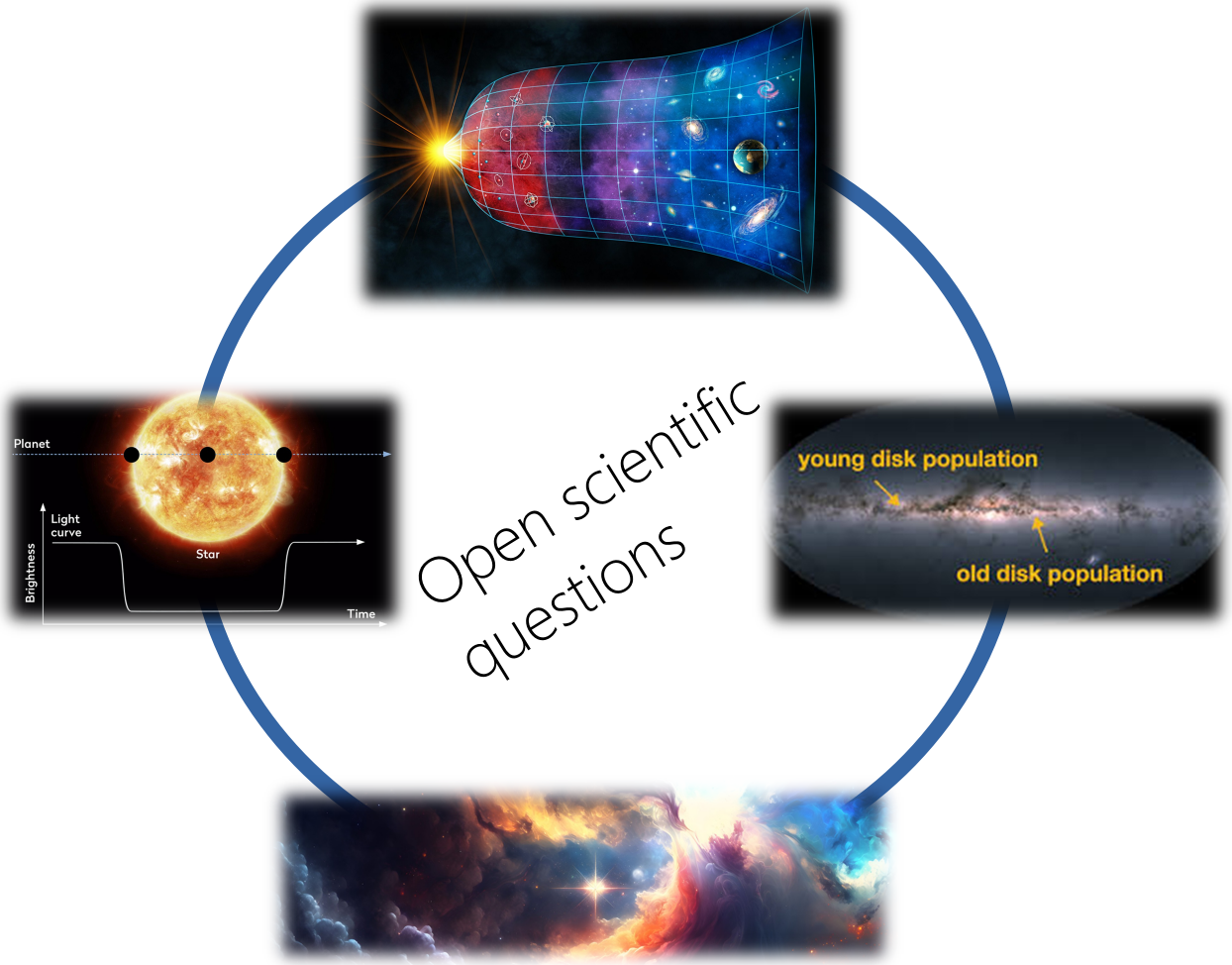
Museum, historical library



Astronomy and its tools



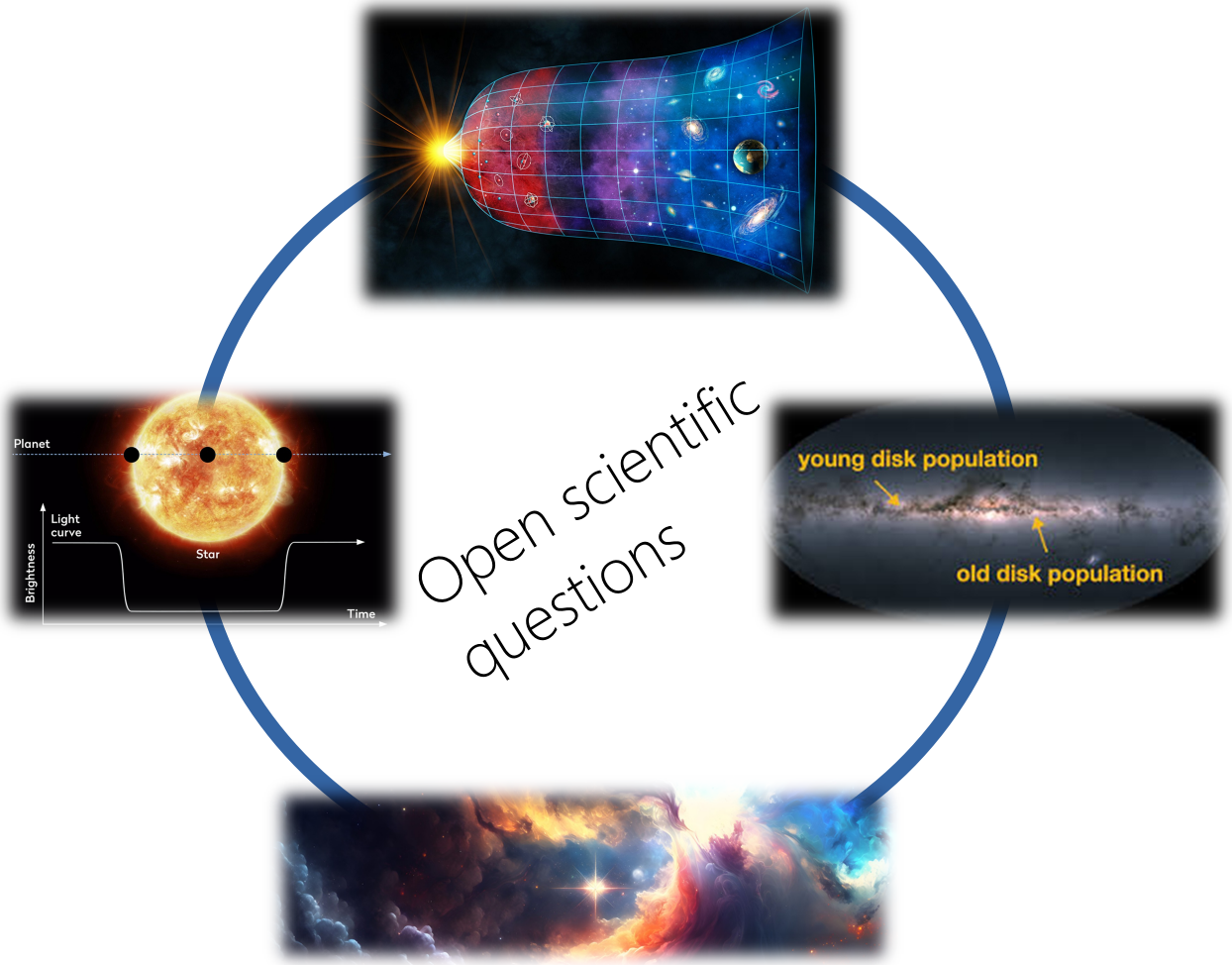
Astronomy and its tools



Observing facilities with suite of instruments

Astronomy and its tools

Observing facilities with suite of instruments



OPTICON RadioNet Pilot

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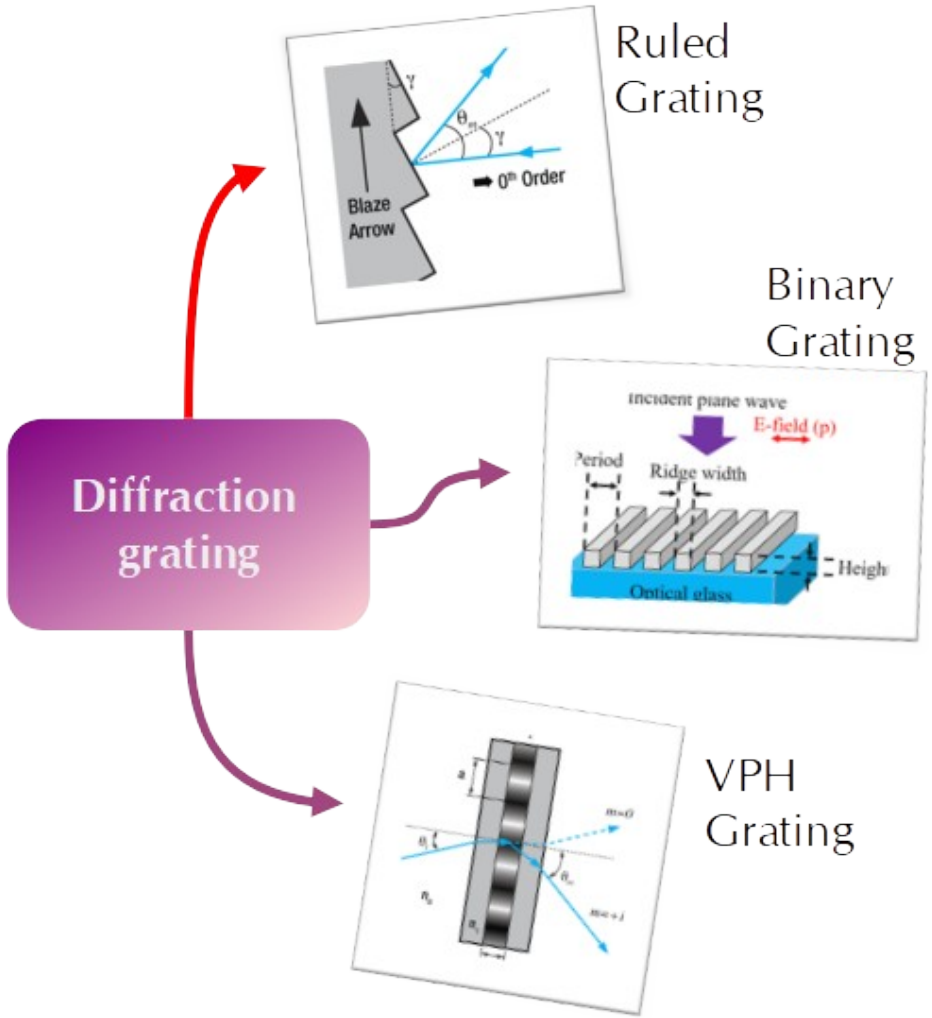
Diffraction gratings in astronomy

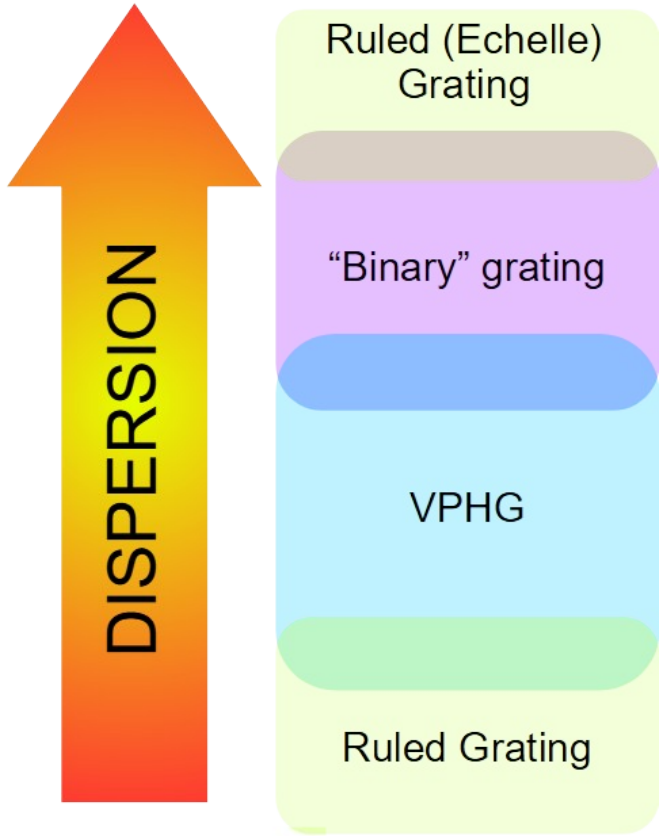
"Let in the sun's light, by a small hole to a darkened house, and at the hole place a feather (the more delicate and white the better for this purpose)...a number of small circles and ovals (appear), **one is somewhat white and all the rest severally coloured.**"

$$R = \frac{\lambda}{\Delta\lambda}$$

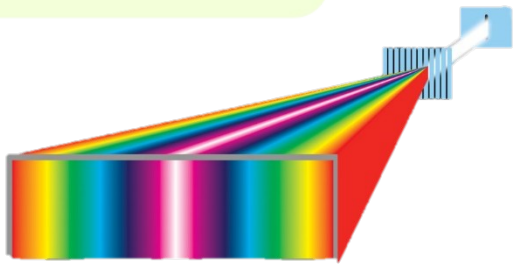
James Gregory
(1638-1675)

Diffraction gratings: possibilities

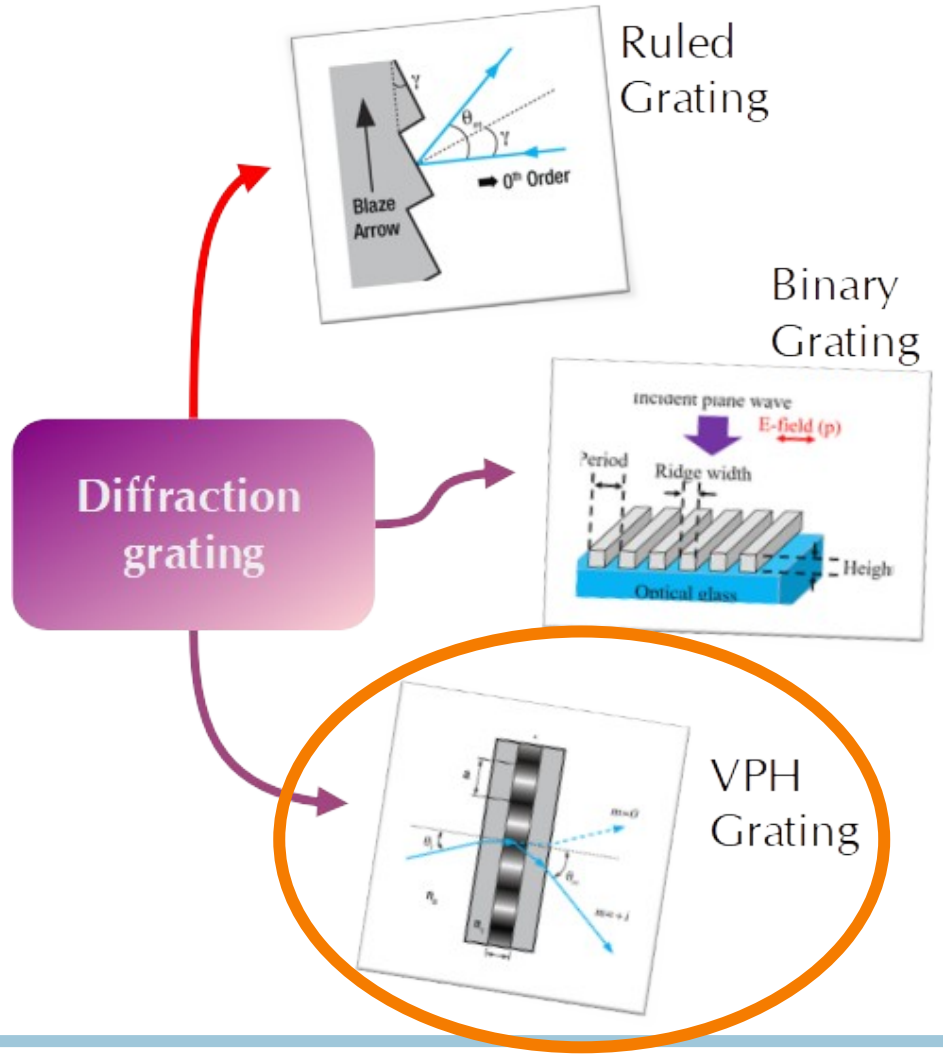


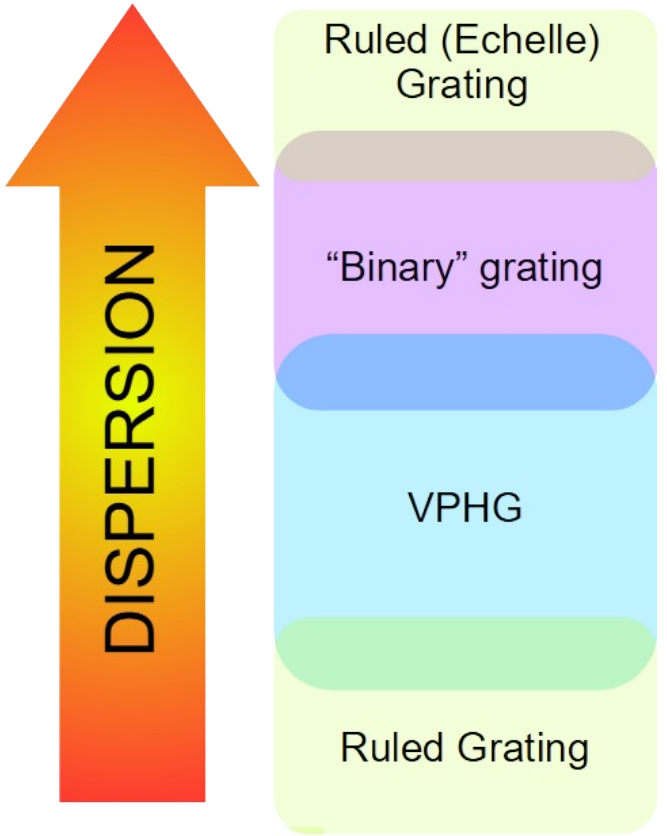


$$D = \frac{d\beta}{d\lambda} = \frac{mG}{\cos\beta}$$

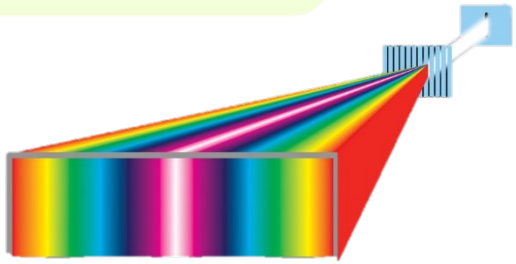


Diffraction gratings: possibilities

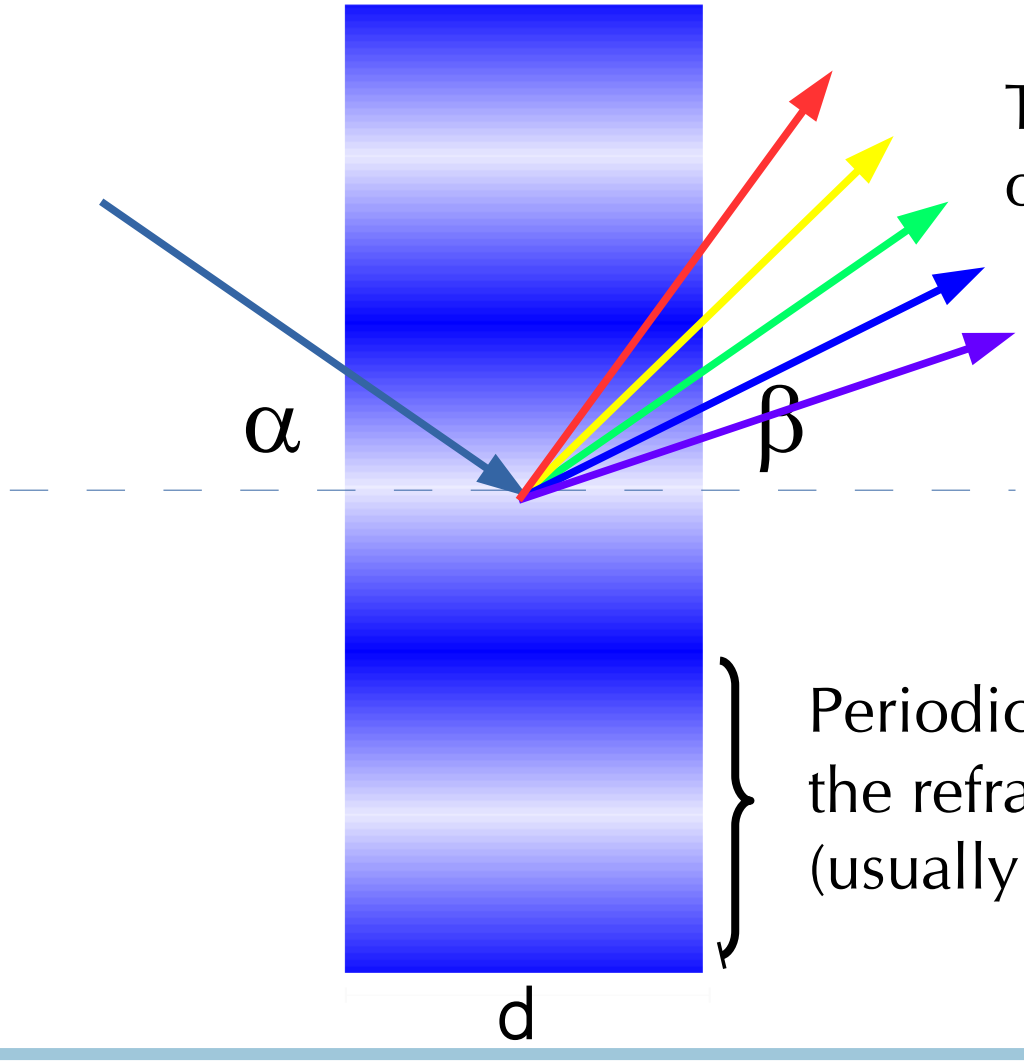




$$D = \frac{d\beta}{d\lambda} = \frac{mG}{\cos\beta}$$



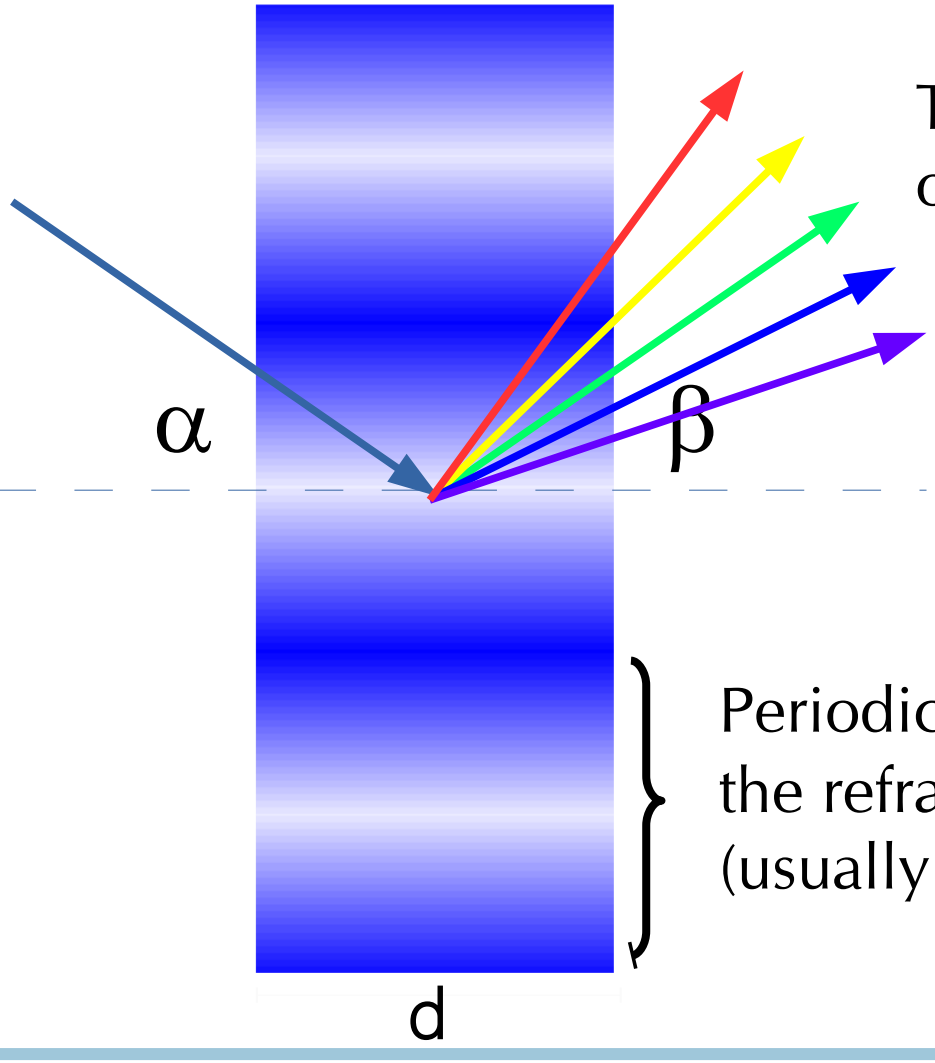
VPHG: principle of work



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).

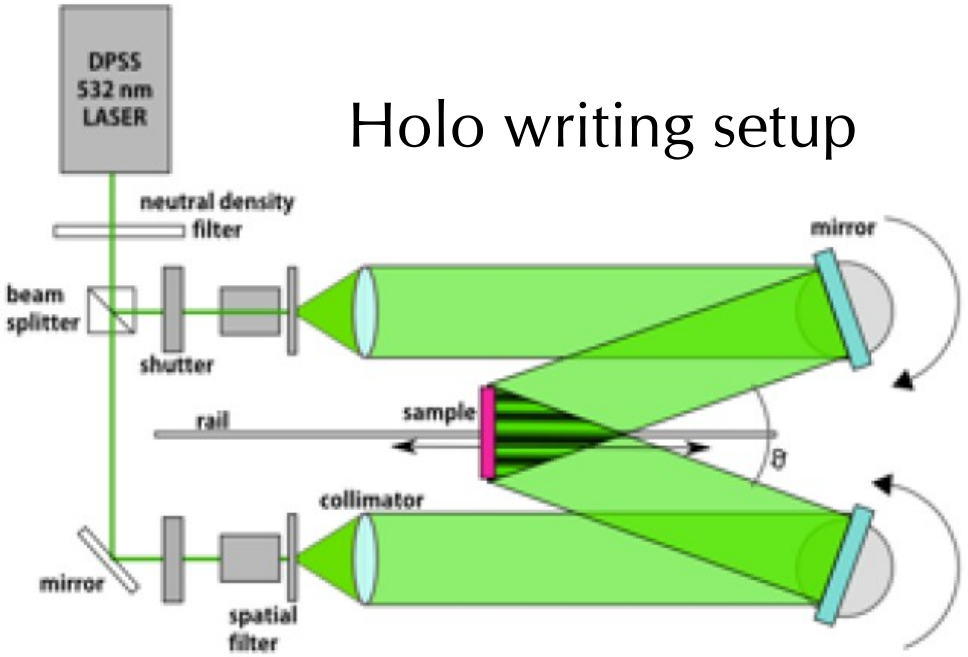
VPHG: principle of work



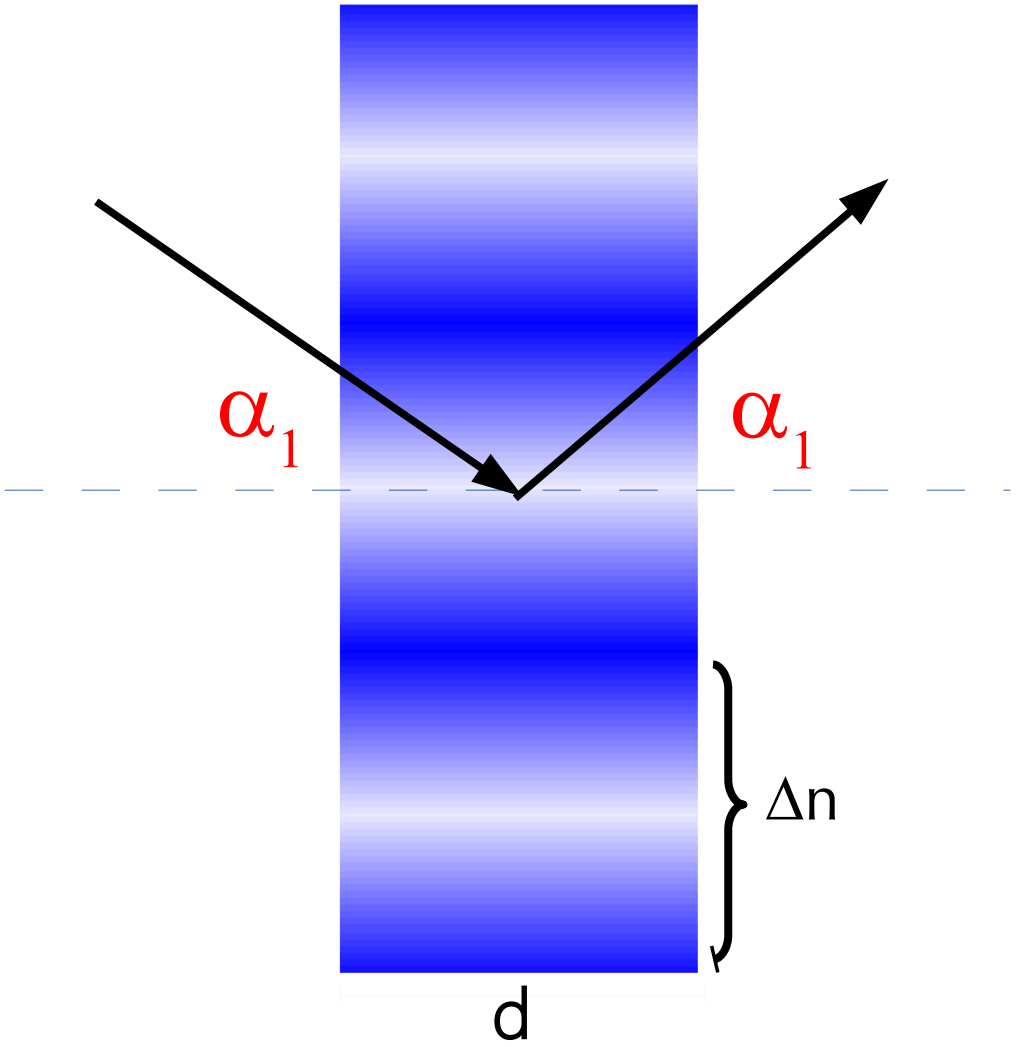
The diffraction occurs thanks to a periodic modulation of the refractive index in the volume of the material.

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

Holo writing setup



VPHG: principle of work

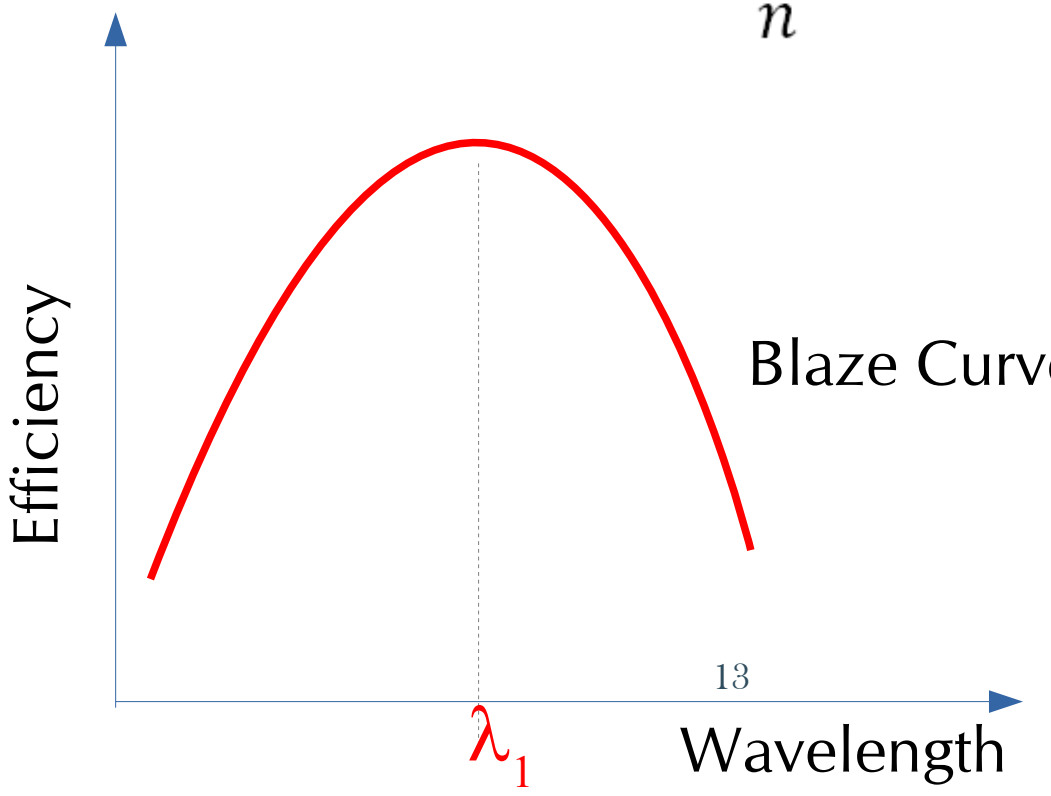


Bragg Condition:

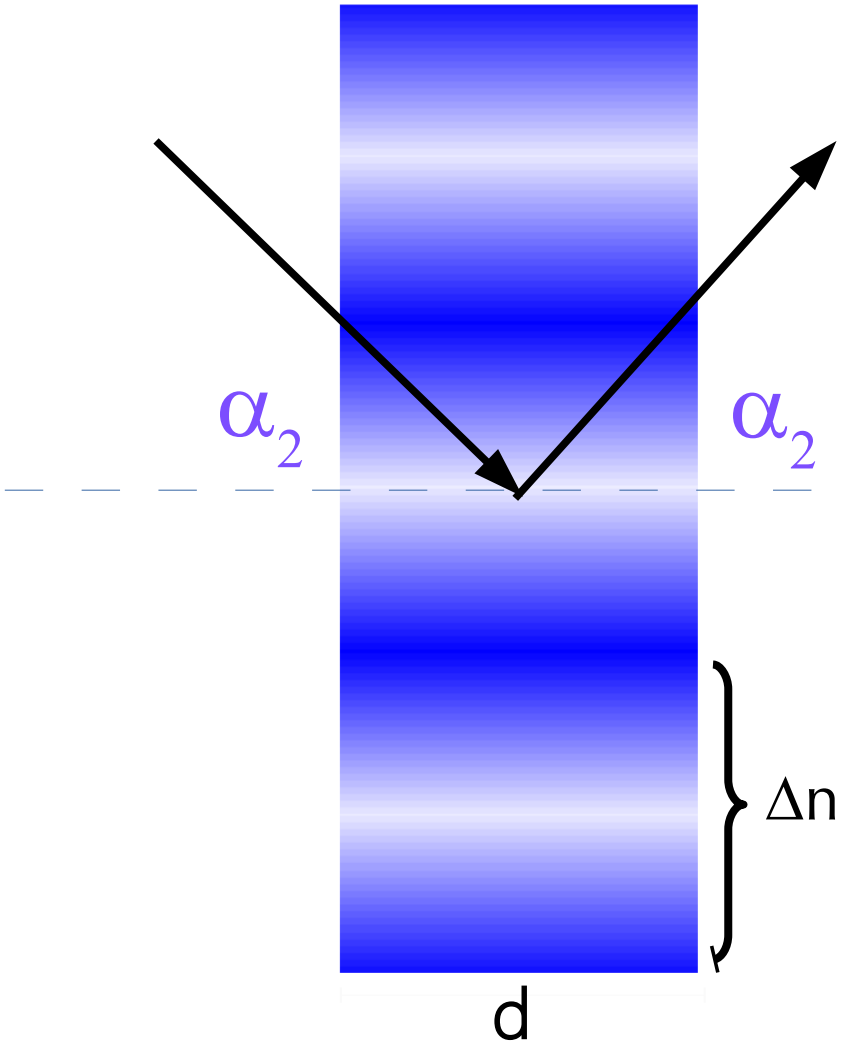
$$\alpha = \beta$$

High peak efficiency is achieved when...

$$\frac{mG\lambda_1}{n} = 2\sin\alpha_1$$



VPHG: principle of work

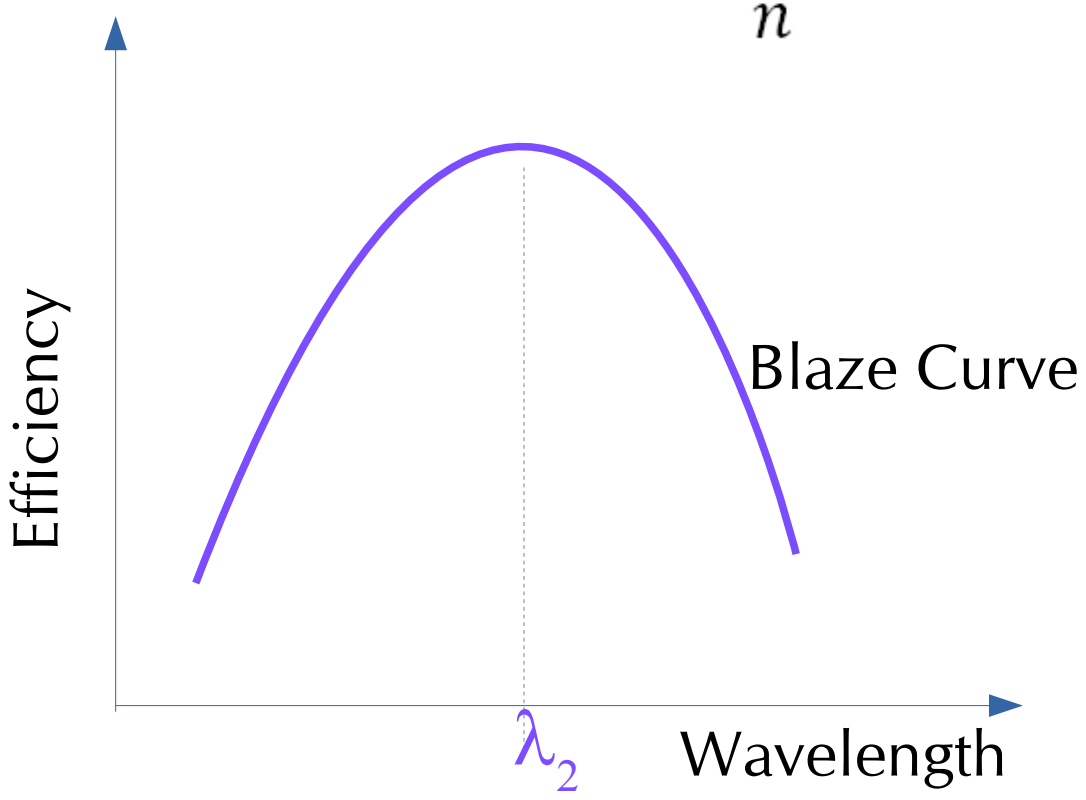


Bragg Condition:

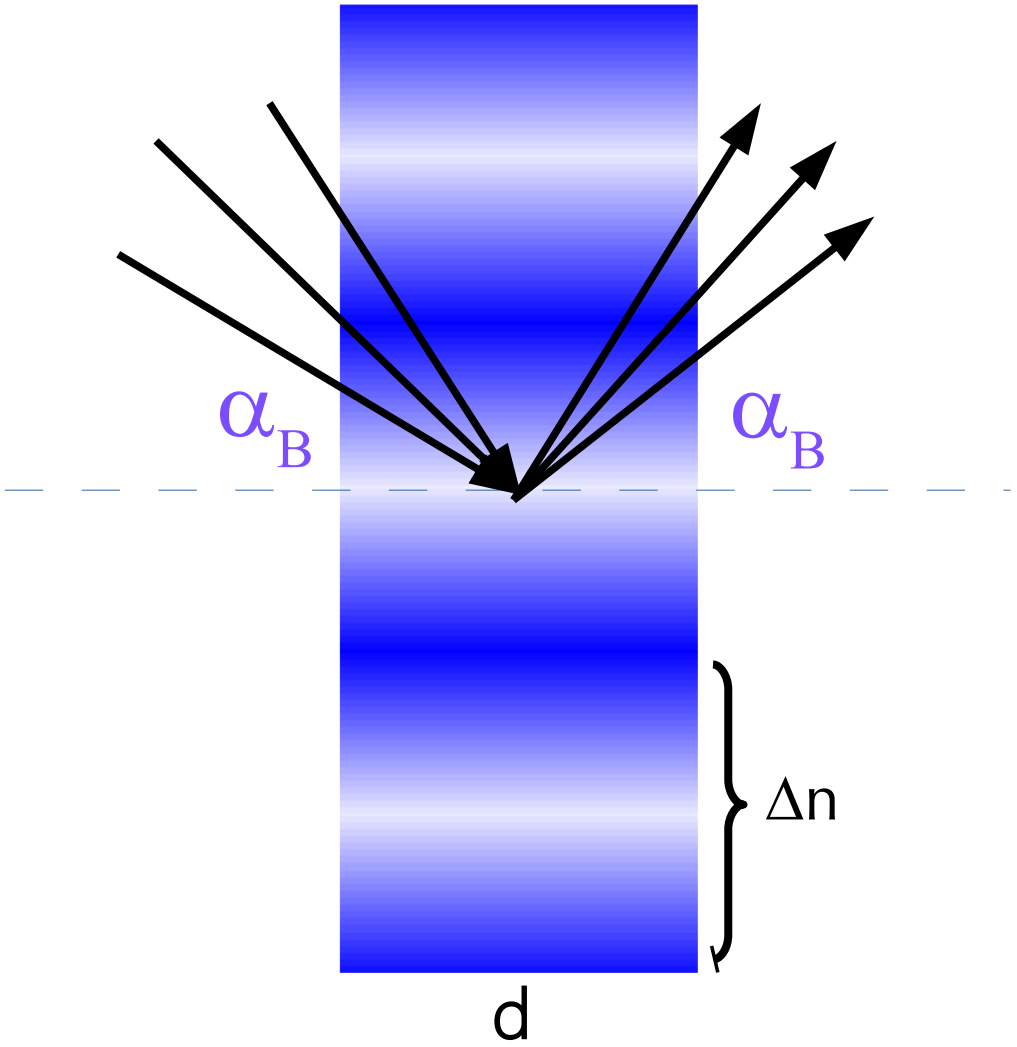
$$\alpha = \beta$$

High peak efficiency is achieved when...

$$\frac{mG\lambda_2}{n} = 2\sin\alpha_2$$



VPHG: principle of work

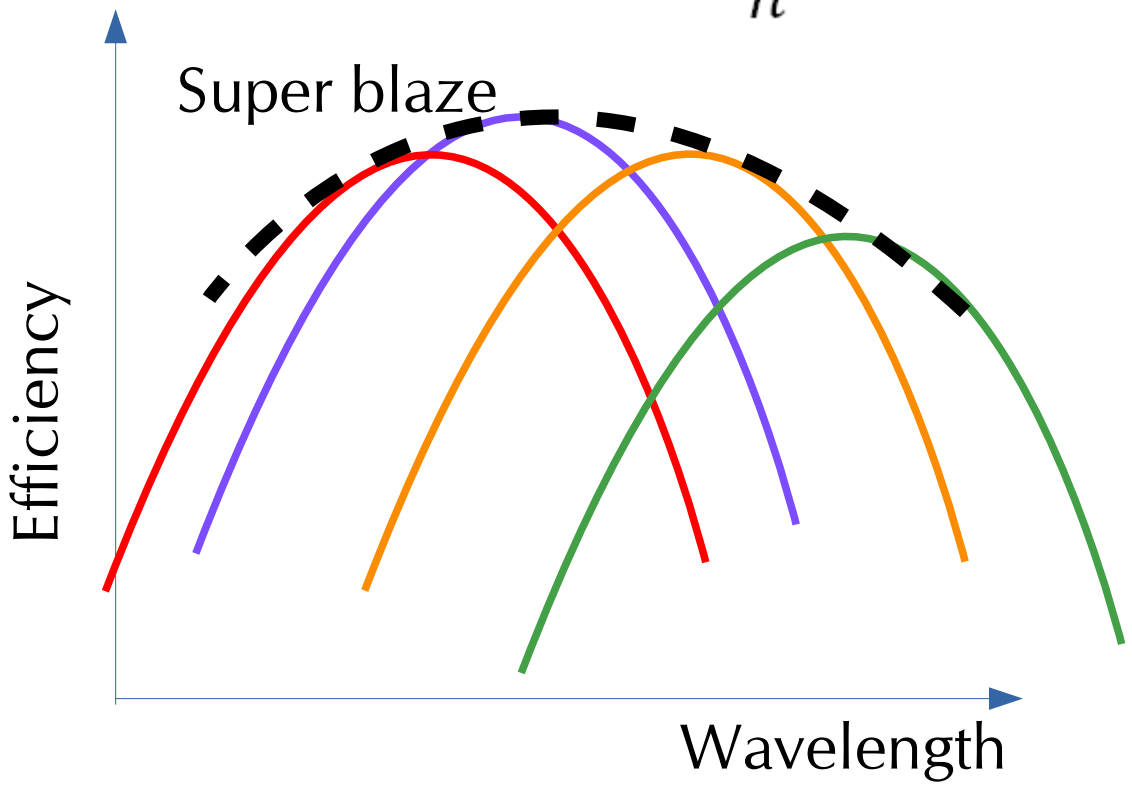


Bragg Condition:

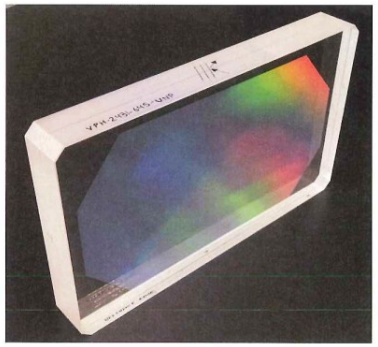
$$\alpha = \beta$$

High peak efficiency is achieved when...

$$\frac{mG\lambda}{n} = 2 \sin \alpha_B$$



VPHG: main features for astronomy



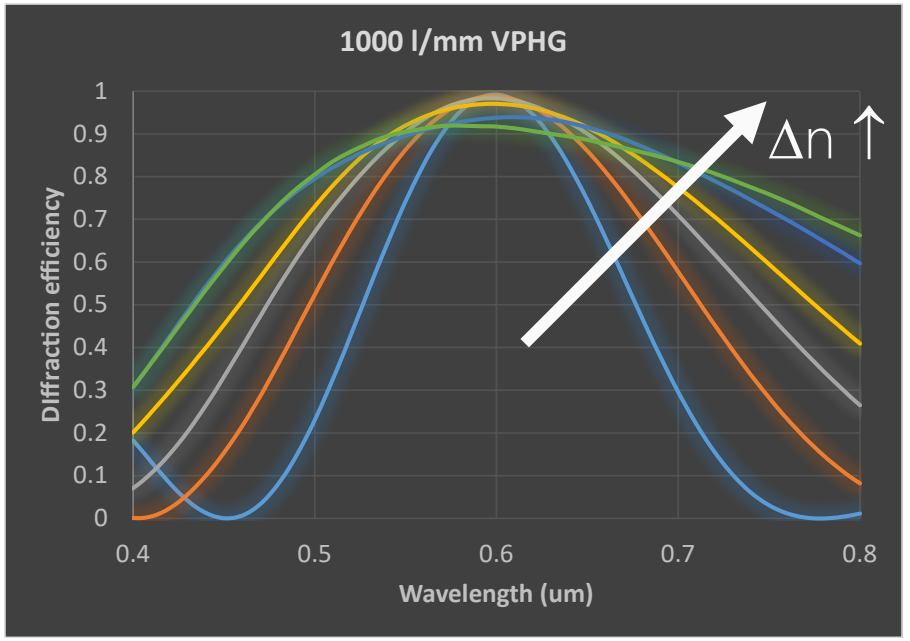
- The peak efficiency can be easily > 90%; **large bandwidth** if we can store a high Δn;

- The device is **easily customizable** from UV to NIR and multi-functional structures can be obtained (multi order, multiplexed);

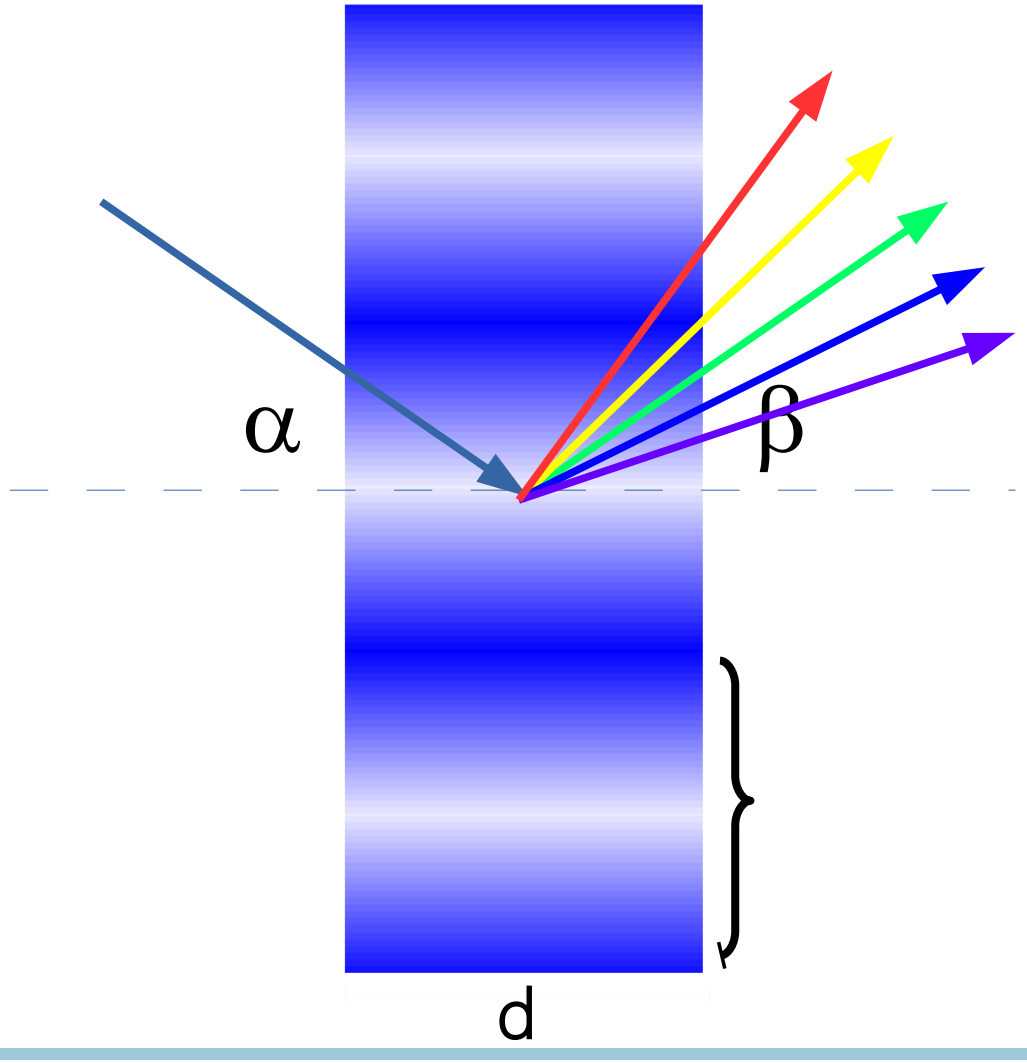
- Especially suitable for **low and medium dispersion** spectrographs;

- **Reliable and repeatable** design process;

- **Fast production and characterization process** suited for multi VPH copies.



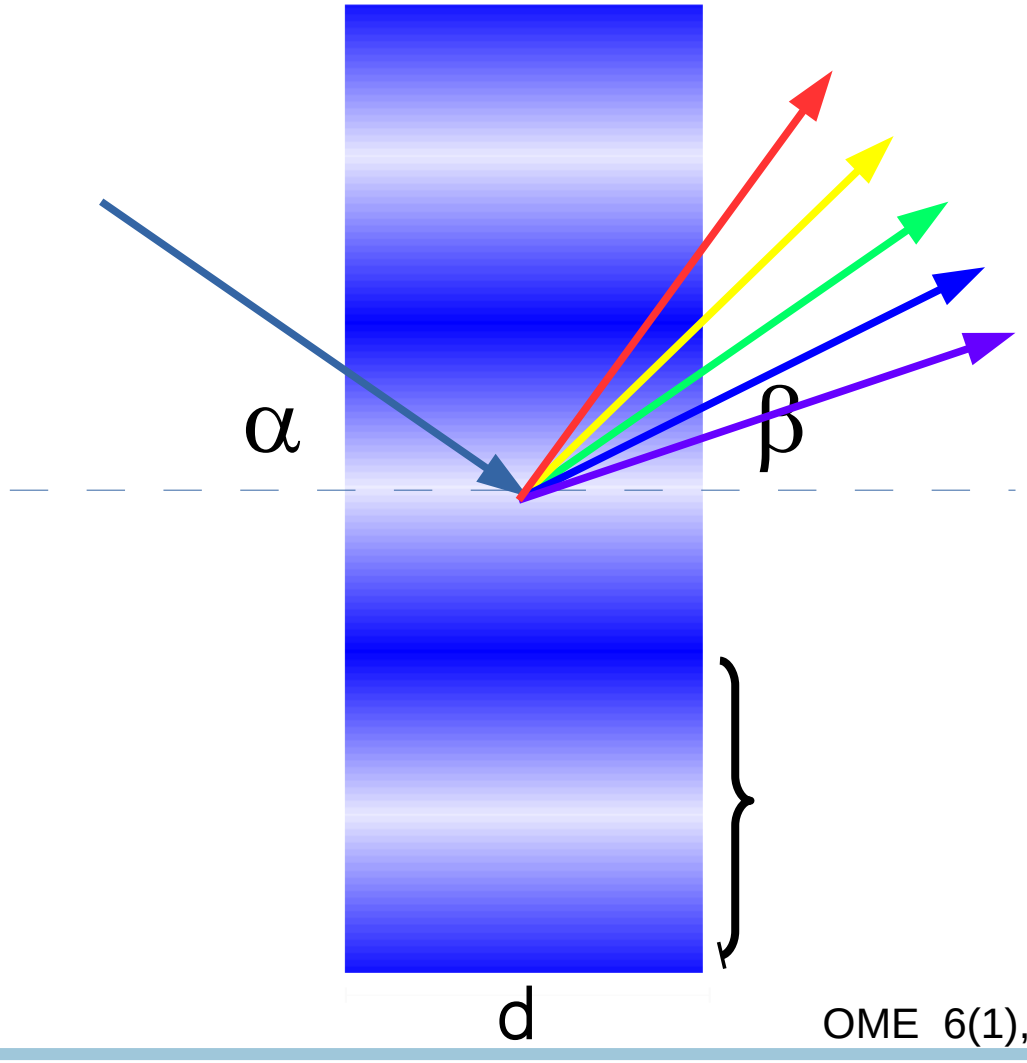
VPHG: Diffraction efficiency



The diffraction efficiency of a VPHG depends on:

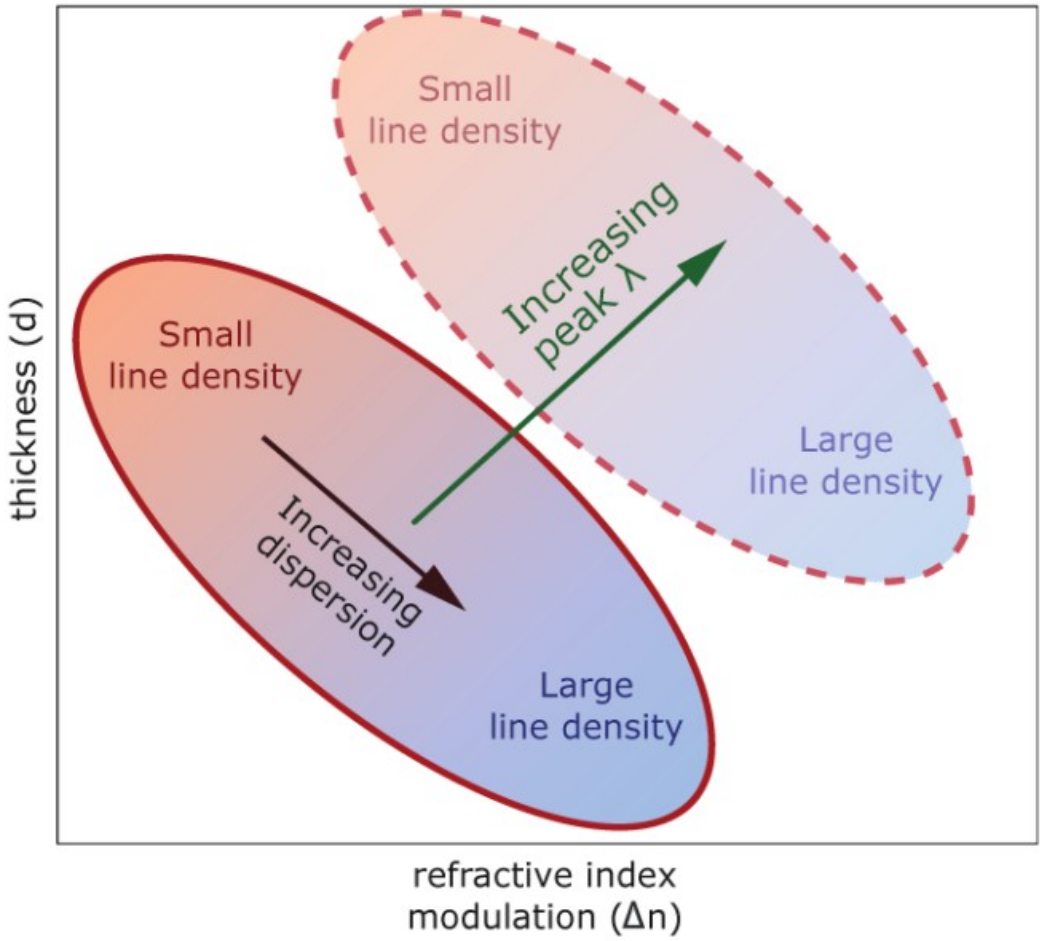
- Film thickness (d);
- Refractive index modulation (Δn);
- Profile of Δn;
- Average refractive index;
- Line density (G).

VPHG: design



OME 6(1), 252–263 (2016)

Grating Optimization



Low dispersion: thick films, small Δn

High dispersion: thin films, large Δn

Our VPHG Path

Instrument requirements

VPHG design

Production and test

Our VPHG Path

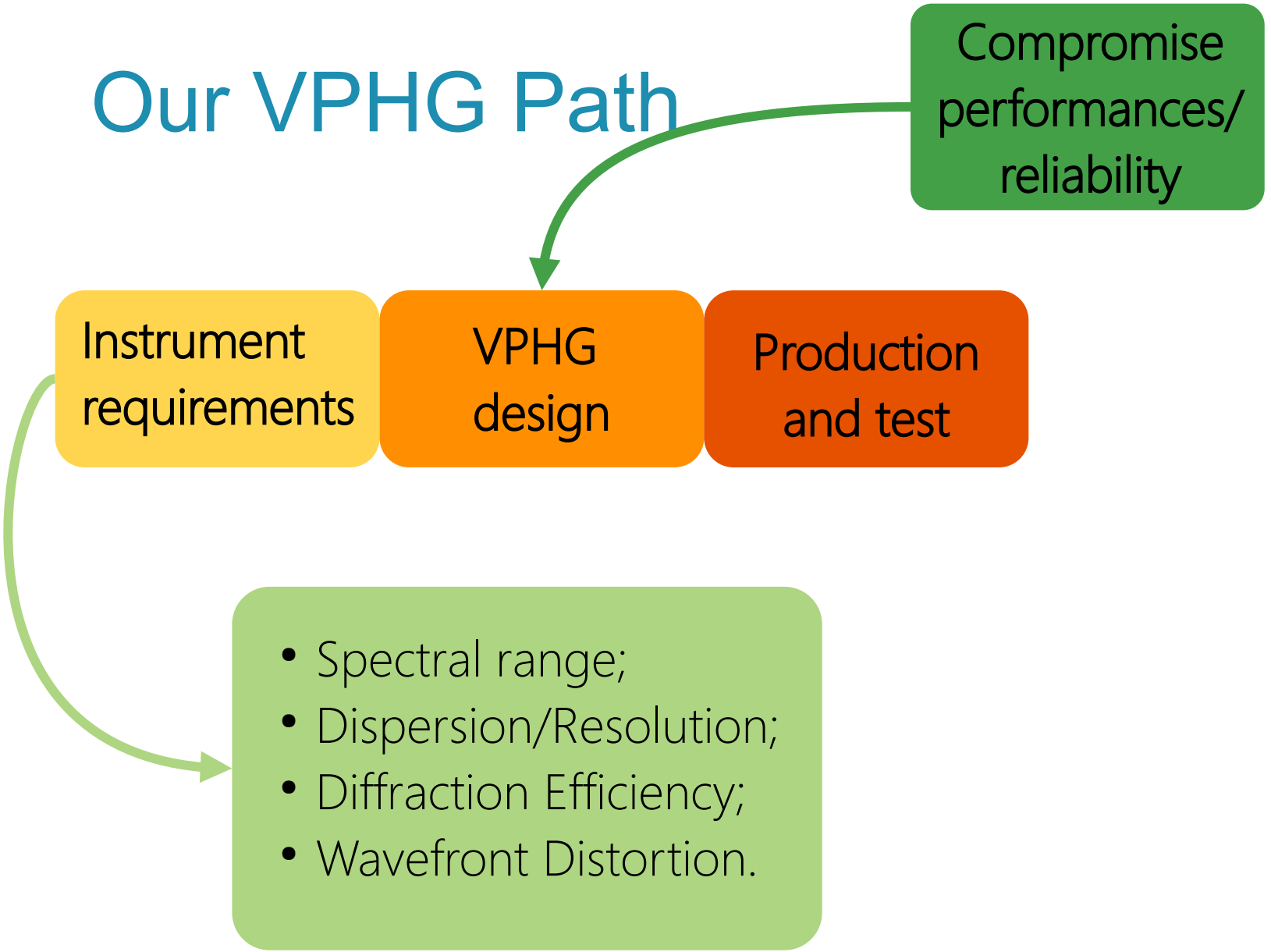
Instrument requirements

VPHG design

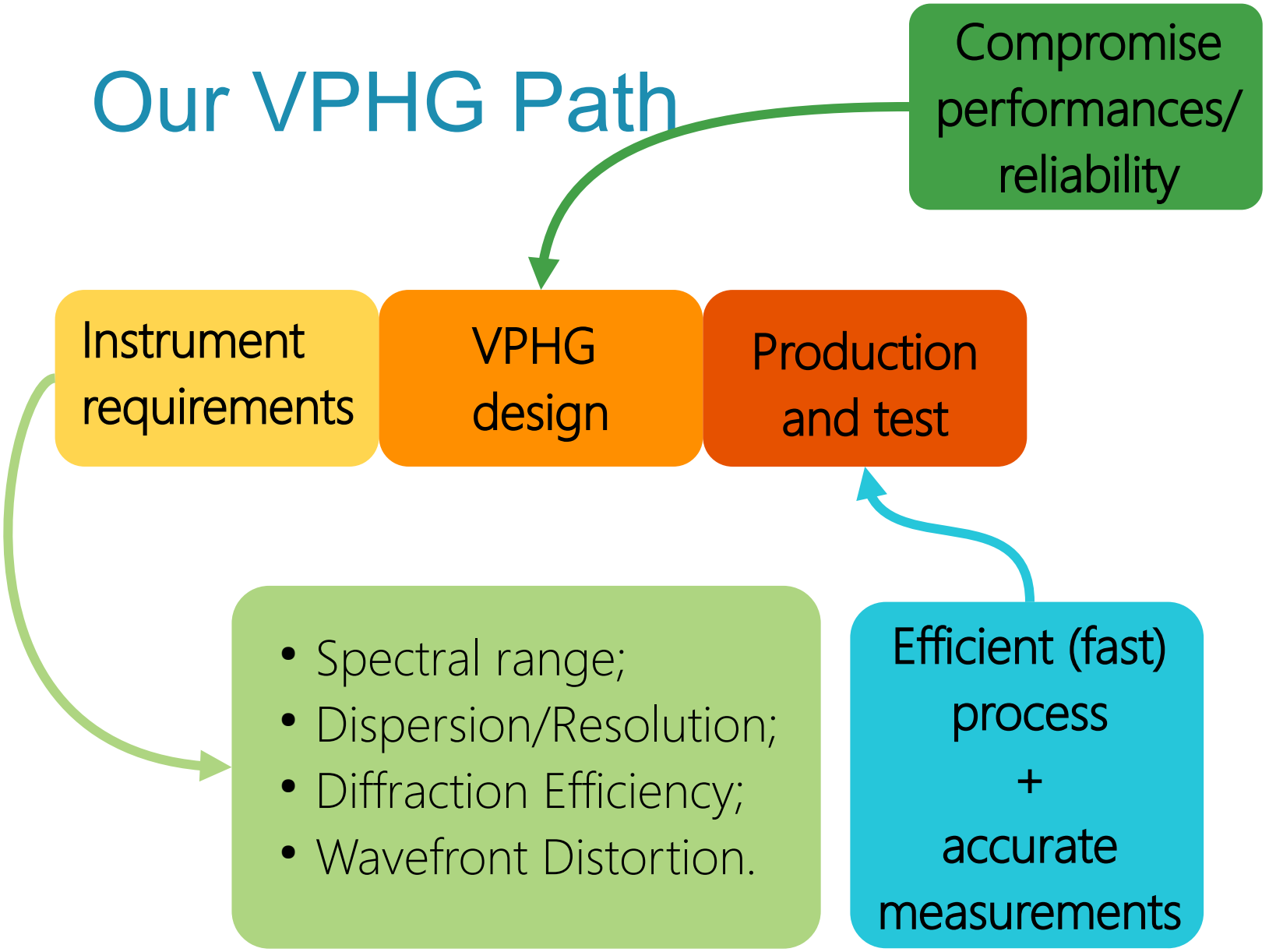
Production and test

- Spectral range;
- Dispersion/Resolution;
- Diffraction Efficiency;
- Wavefront Distortion.

Our VPHG Path



Our VPHG Path



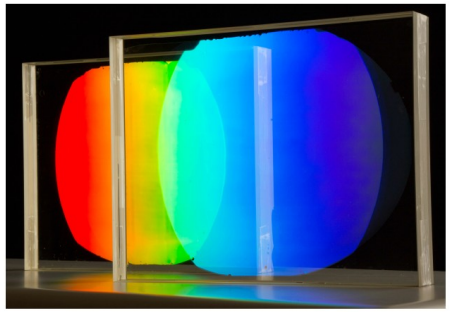
Our VPHG Path

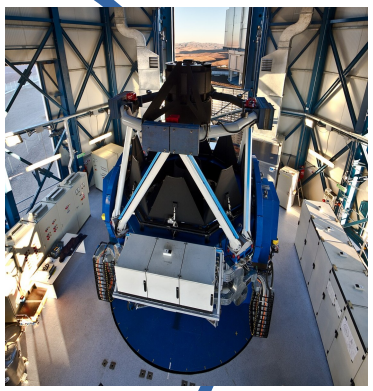
Compromise performances/ reliability

Instrument requirements

VPHG design

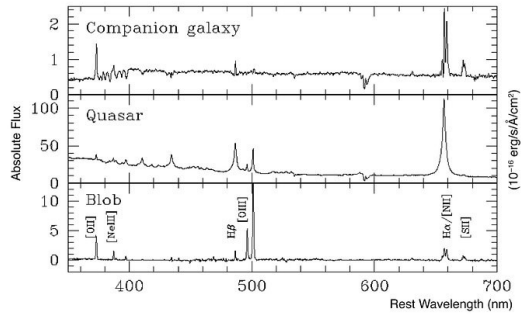
Production and test





- Spectral range;
- Dispersion/Resolution;
- Diffraction Efficiency;
- Wavefront Distortion.

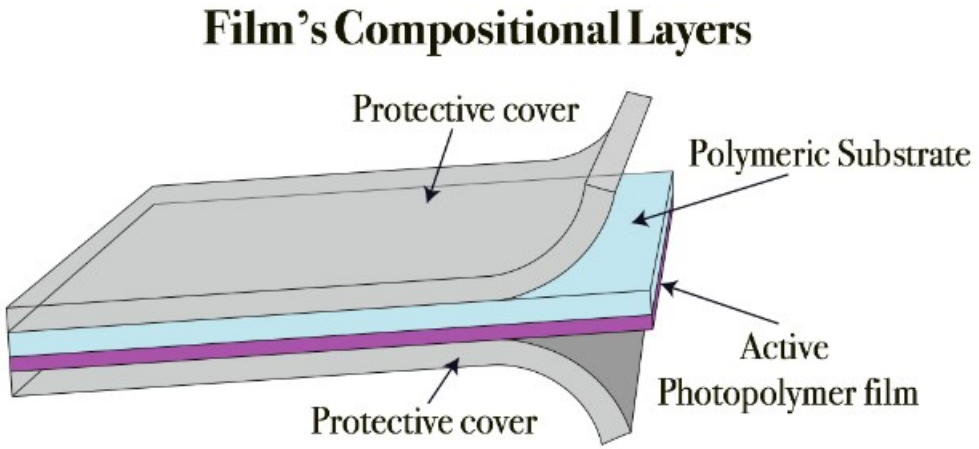
Efficient (fast) process + accurate measurements

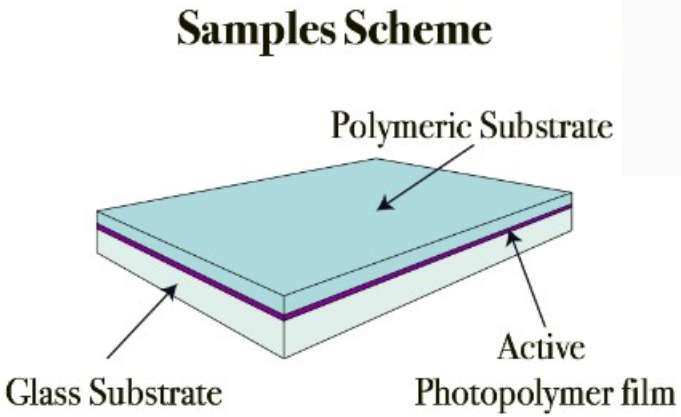


Spectrum of Quasar HE0450-2958, the Blob and the Companion Galaxy (FORS/VLT)

Photosensitive material: photopolymer

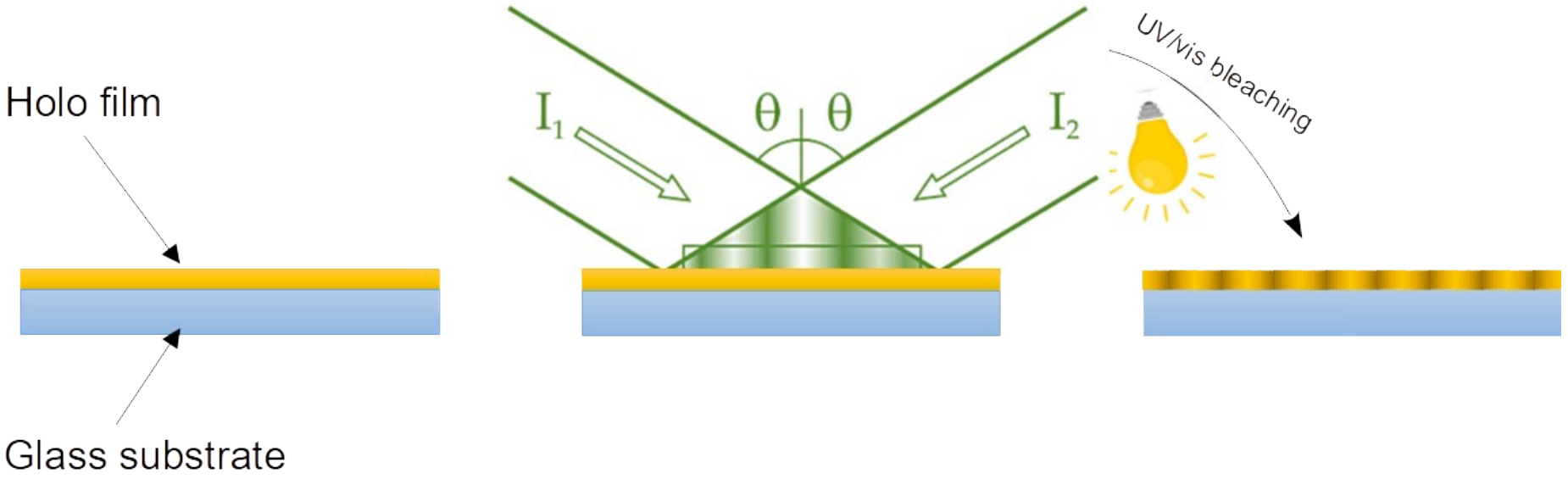
Photopolymers are available showing a very simple and “easy to use” structure:



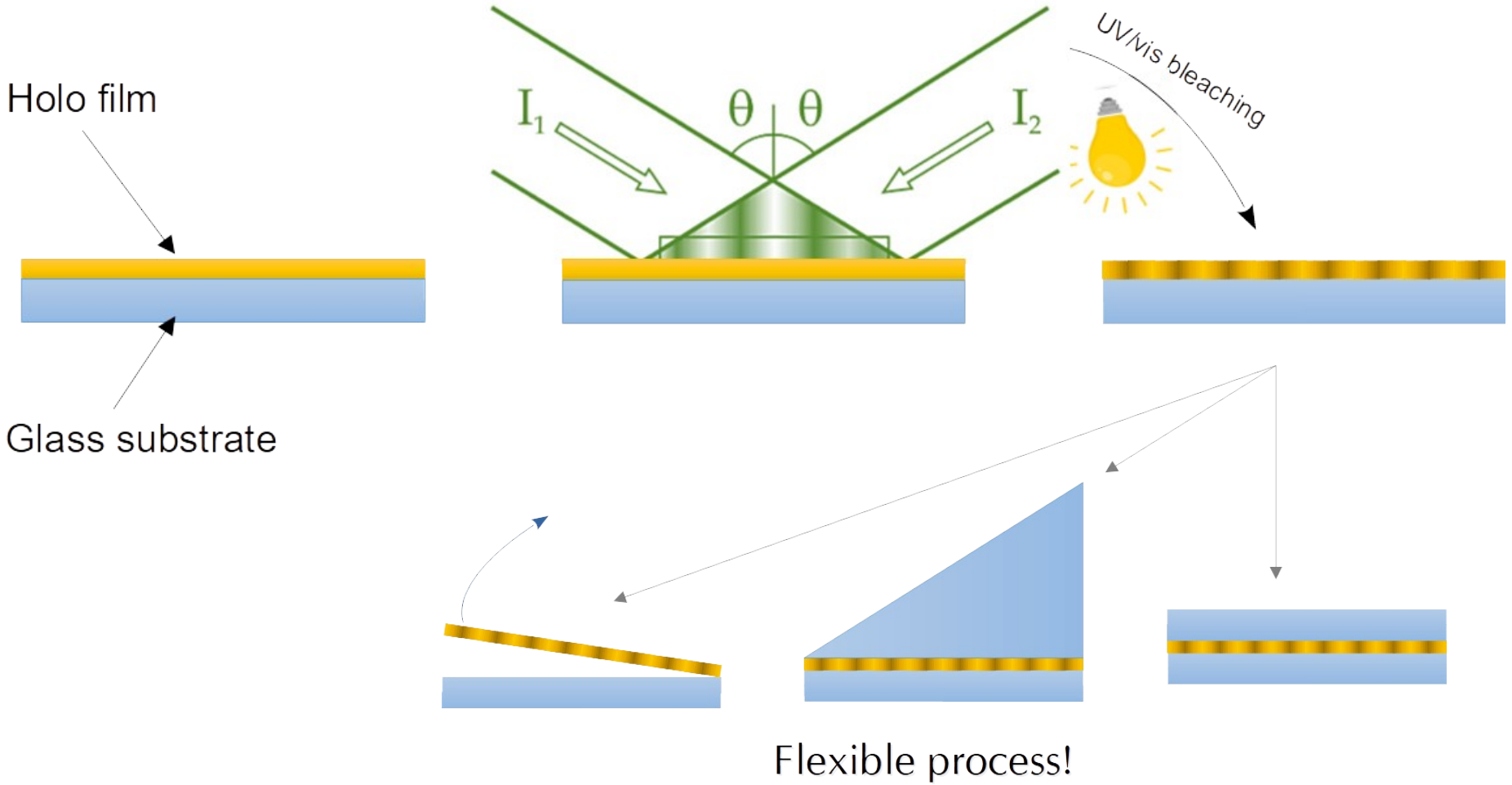


- The structure is like a protective layer of smartphone and tablet;
- They can show different thicknesses and size;
- The holograms can be removed and attached to different substrates like the protective layers.

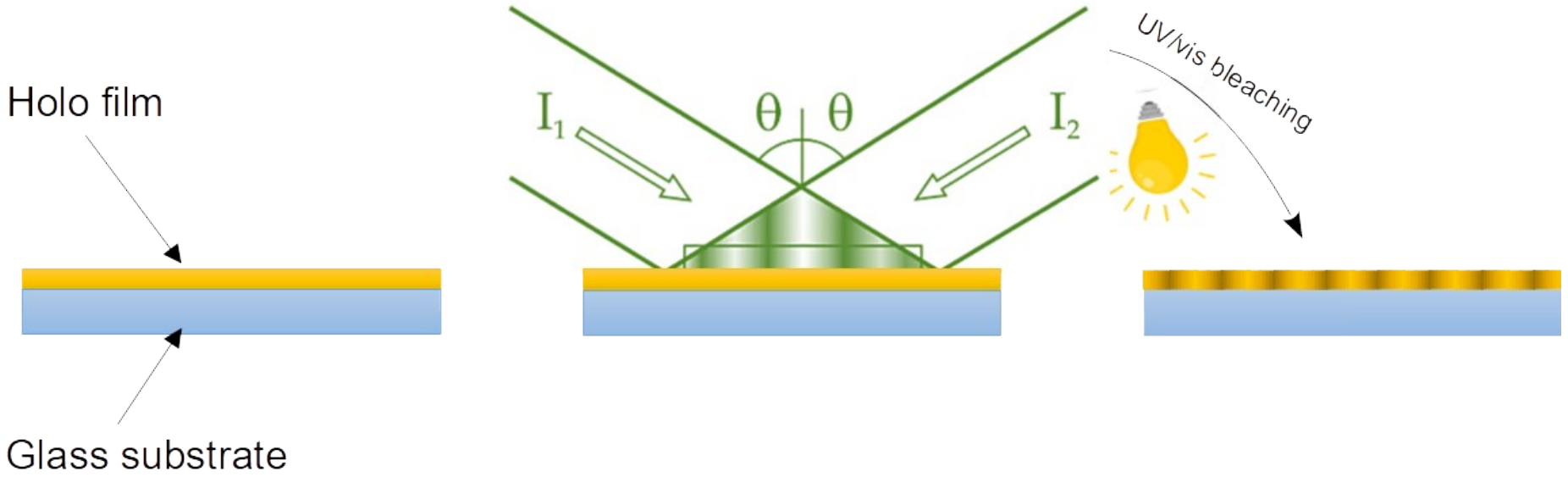
Photosensitive material: photopolymer

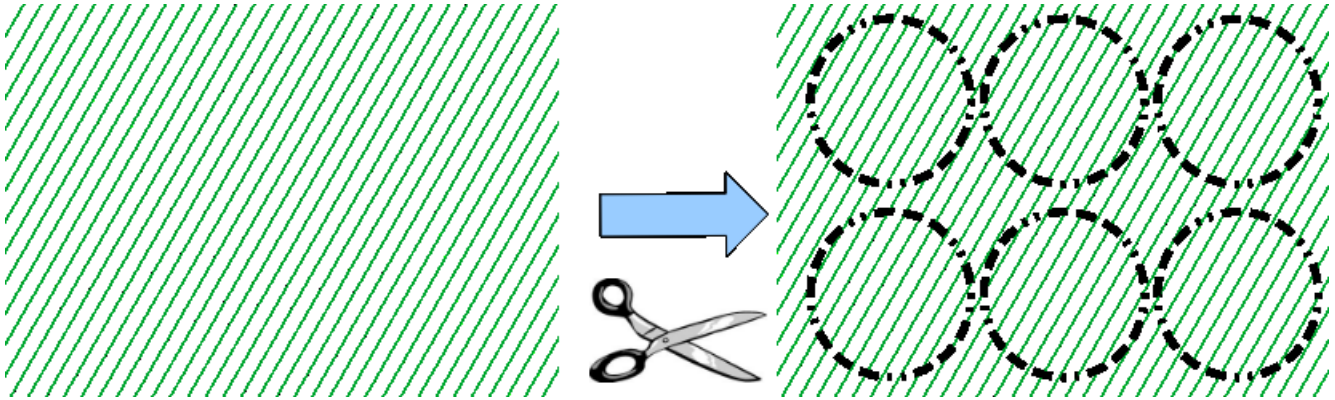


Photosensitive material: photopolymer



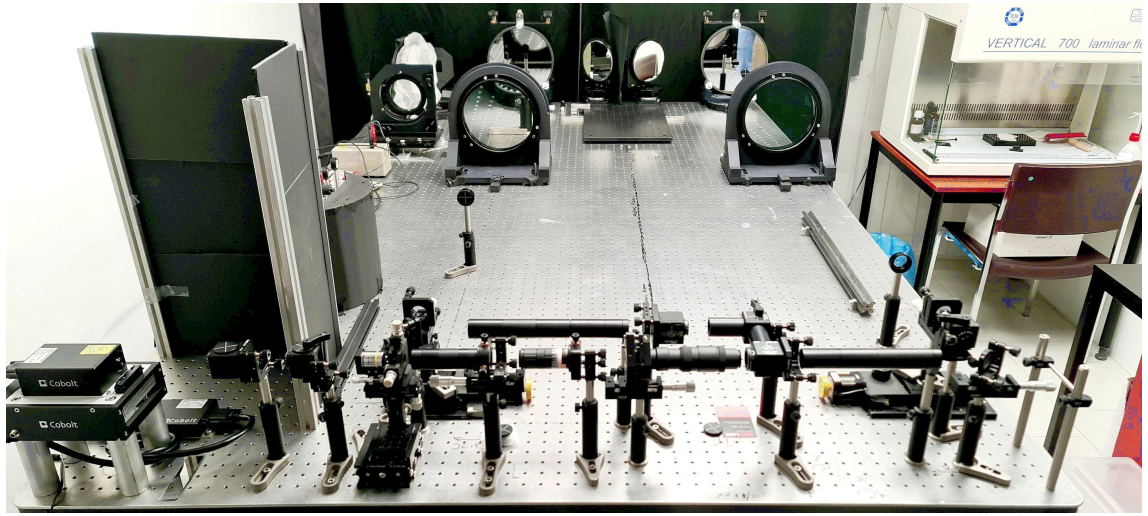
Photosensitive material: photopolymer





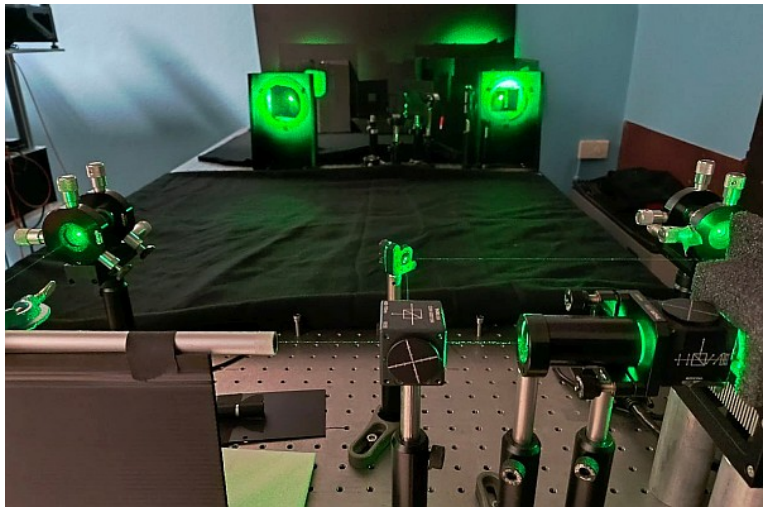
Cut identical copies of the same grating…useful in some cases.

Manufacturing capabilities @ INAF – OABr



Large setup

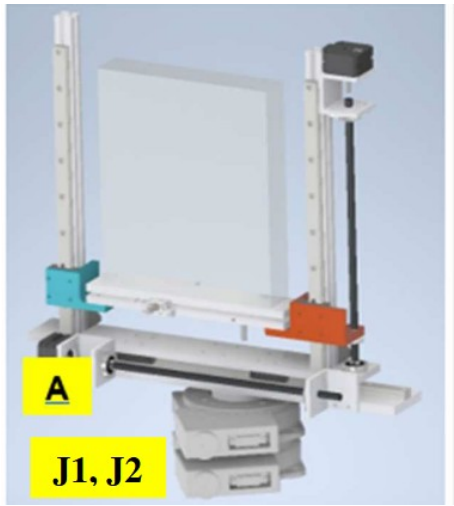
- Red laser system;
- Size up to 190 mm x 200 mm;
- Line density: 150 – 3000 l/mm;
- Spectral range: 0.33 – 2.5 um;

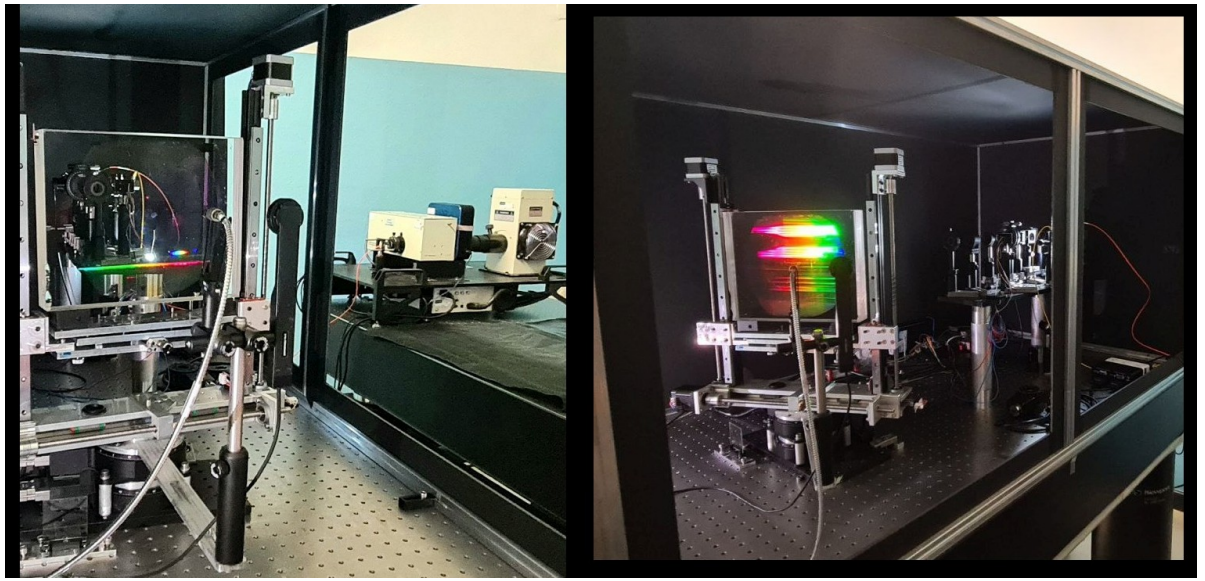


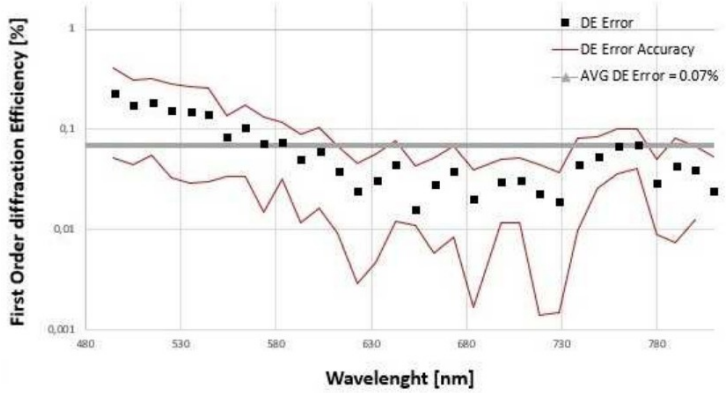
Small setup

- Green (red) laser system;
- Size up to 80 mm x 80 mm;
- Line density: 250 – 3000 l/mm;
- Spectral range: 0.33 – 2.5 um;

Characterization capabilities @ INAF – OABr

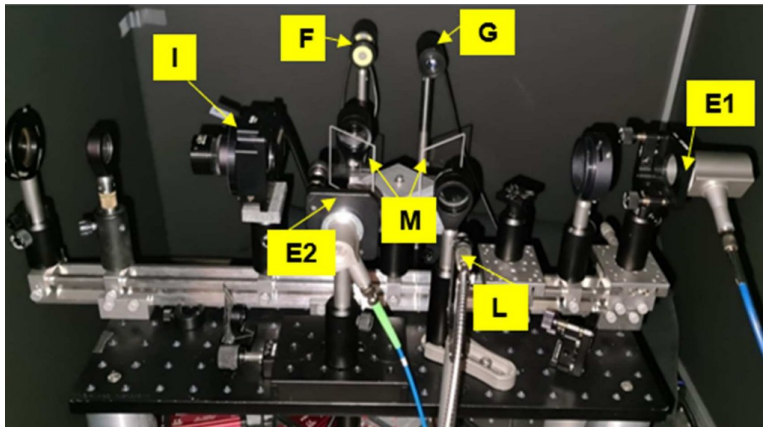


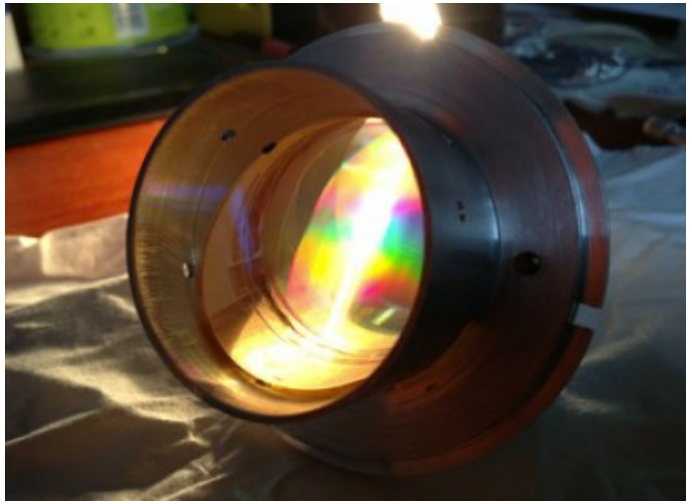


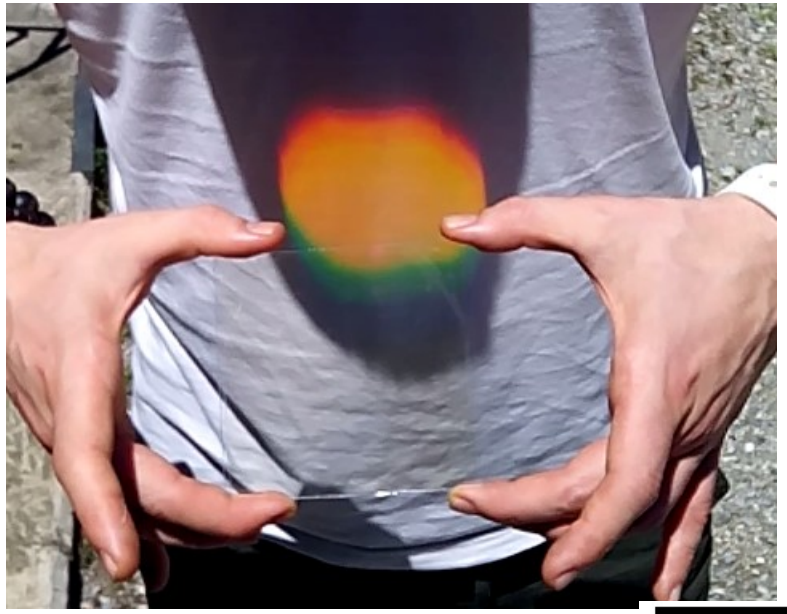


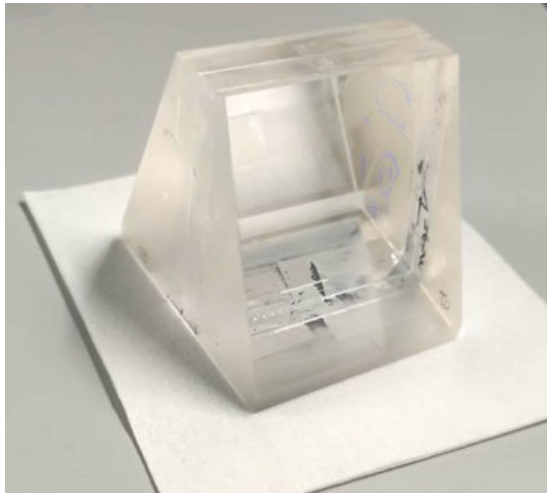
Characterization capabilities

- Fully automatic measurements;
- Diffraction efficiency from UV to NIR;
- Efficiency map (X – Y);
- Line density (< 0.5 l/mm) and orientation;
- WFE distortion.

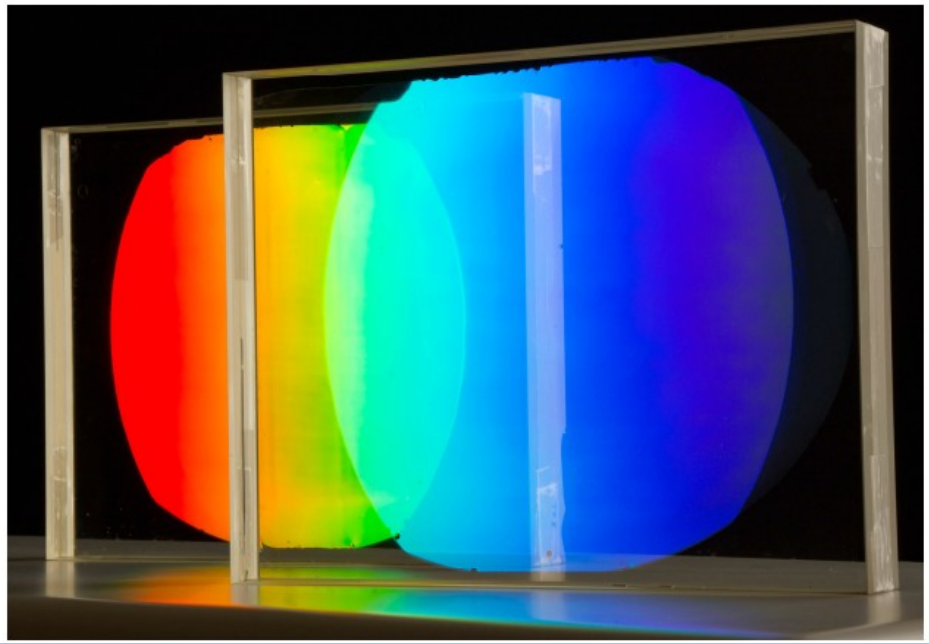




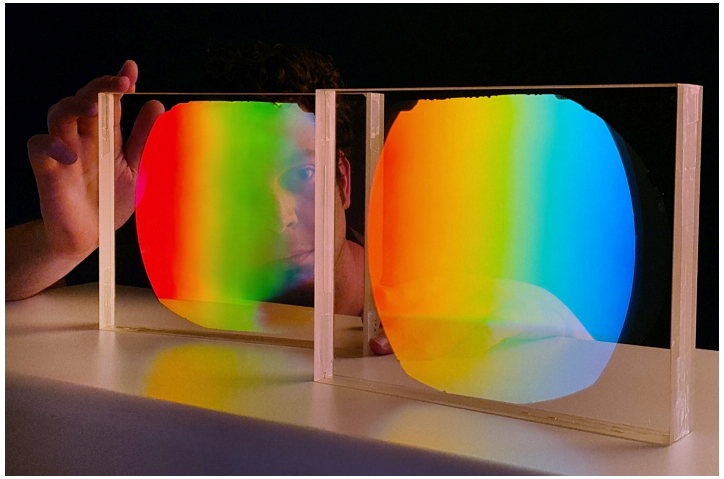




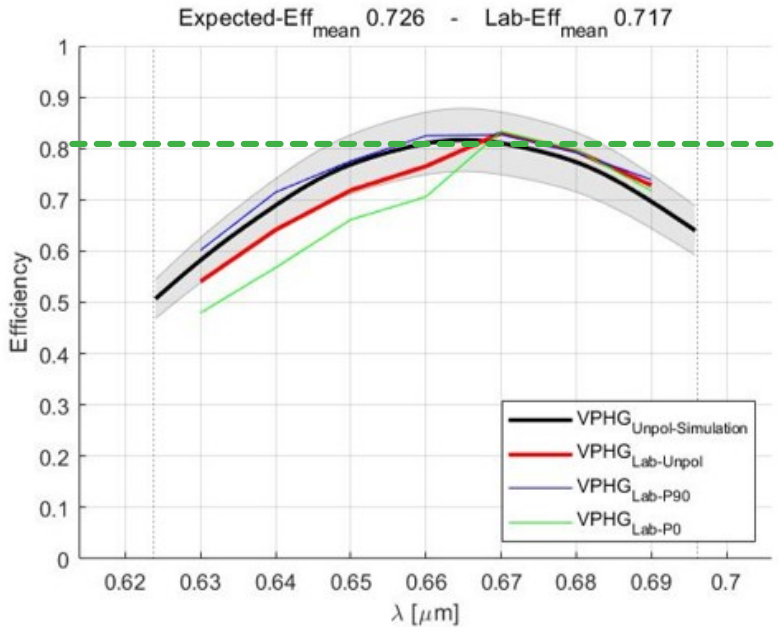

K
H
J
Y



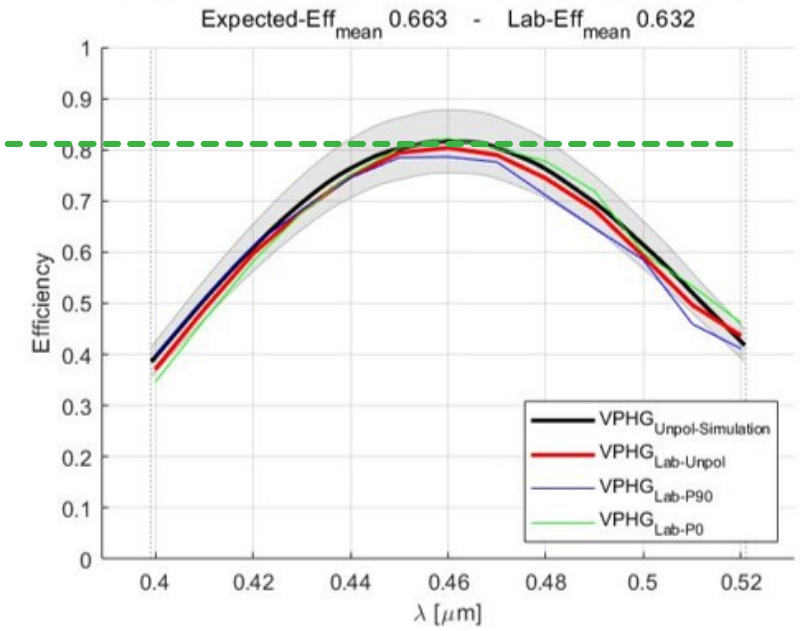
Example: large size VPHGs - Blue and Red



Parameter	Value	
	Red	Blue
Spectral range (nm)	624 – 696	400 – 500
Central wavelength (nm)	660	450
Line density (l/mm)	1720	1720
Incidence angle in air (degrees)	34.35	22.8
Clear Aperture VPHG	>170 mm in diameter	
Peak efficiency	>80%	
Minimum efficiency at the edges	>50%	
Substrate material	BK7	
Substrate size (L x H x T mm)	250 x 200 x 20	
Clear aperture (substrate)	>90%	
Surface quality	40/20	
WFE transmitted (PtV)	< 1 λ	
AR coating	R<1% 400 – 700 nm	



Average efficiency: 72%



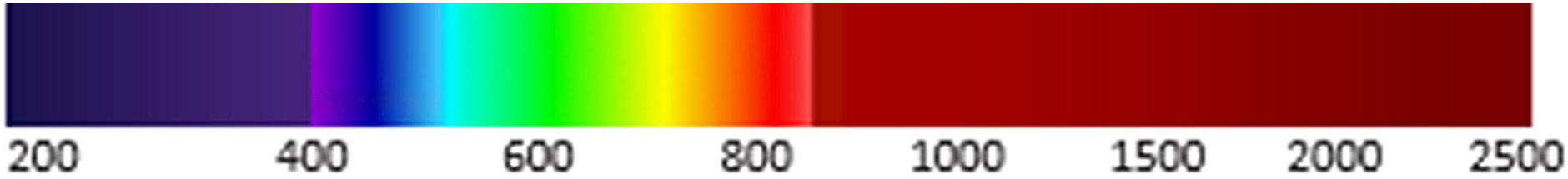
Average efficiency: 63%

BLUE and RED VPHGs:
Peak efficiency > 80%;

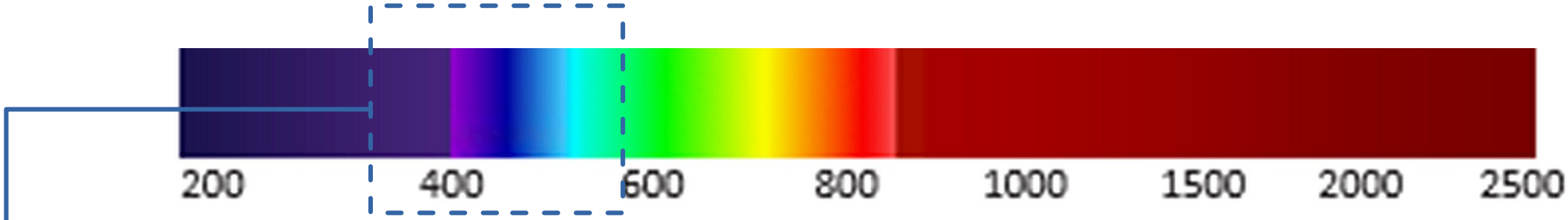
Very good homogeneity;
Good esthetic quality.

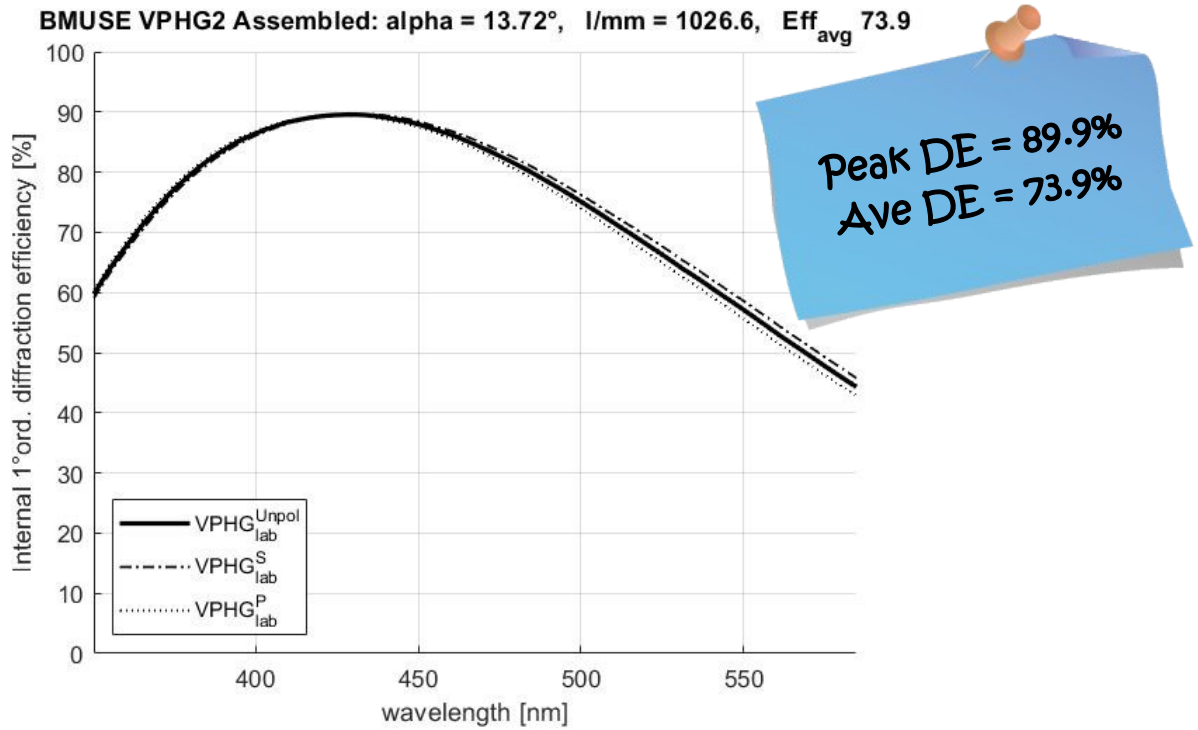
Proc. of SPIE Vol. 12188 1218823-1

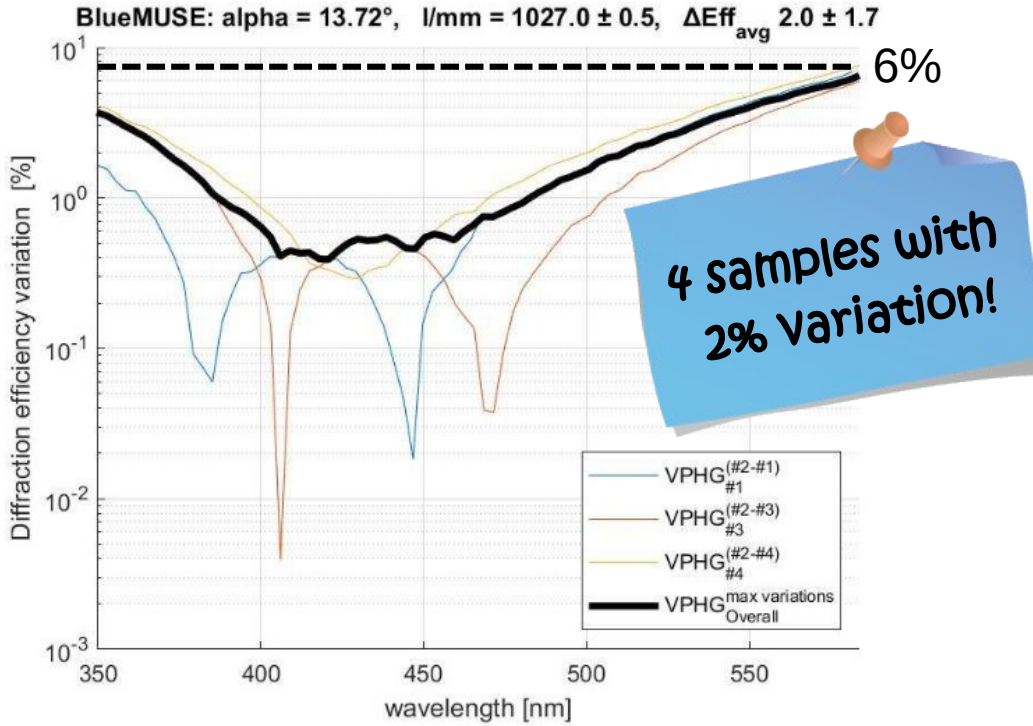
Diffraction efficiency: from UV to NIR (K band)



Diffraction efficiency: BlueMuse (samples)

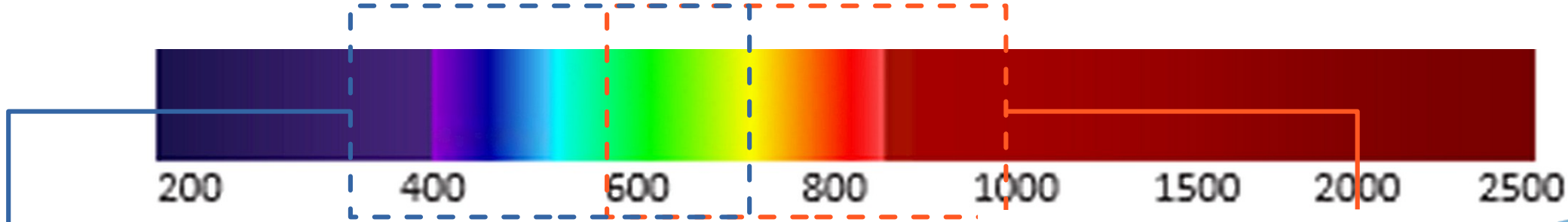


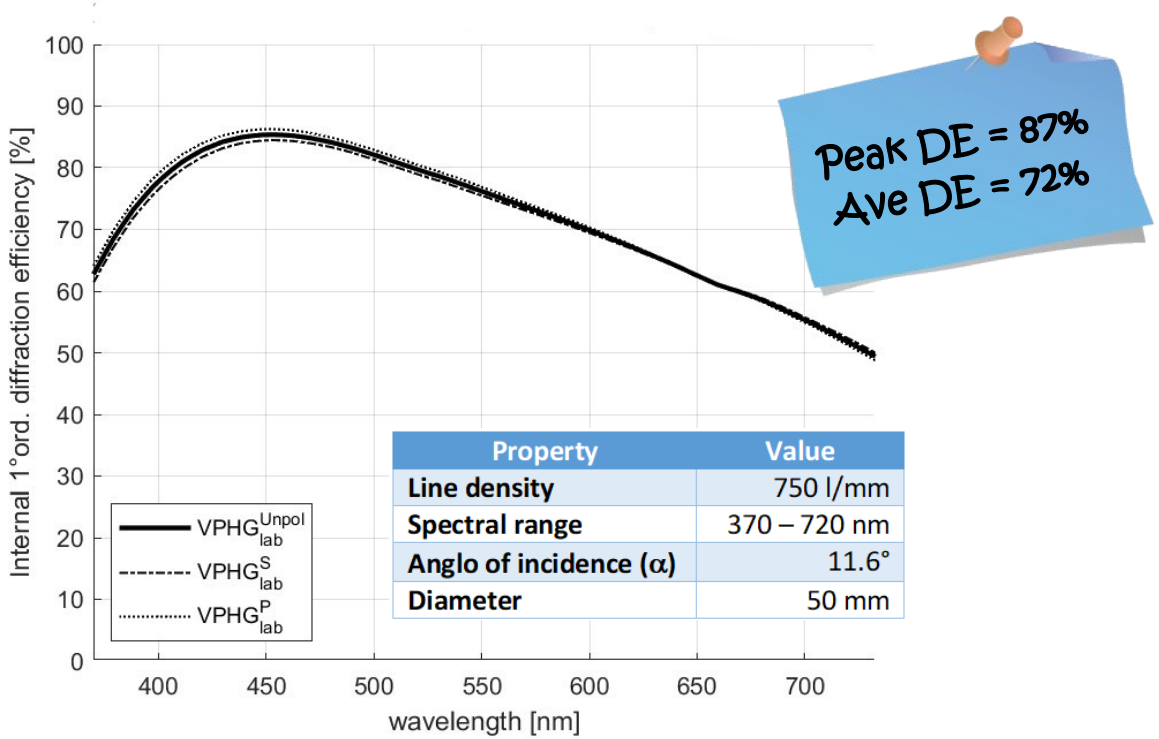




JATIS, Vol. 10, Issue 4, 040501, (2024)
https://doi.org/10.1117/1.JATIS.10.4.040501

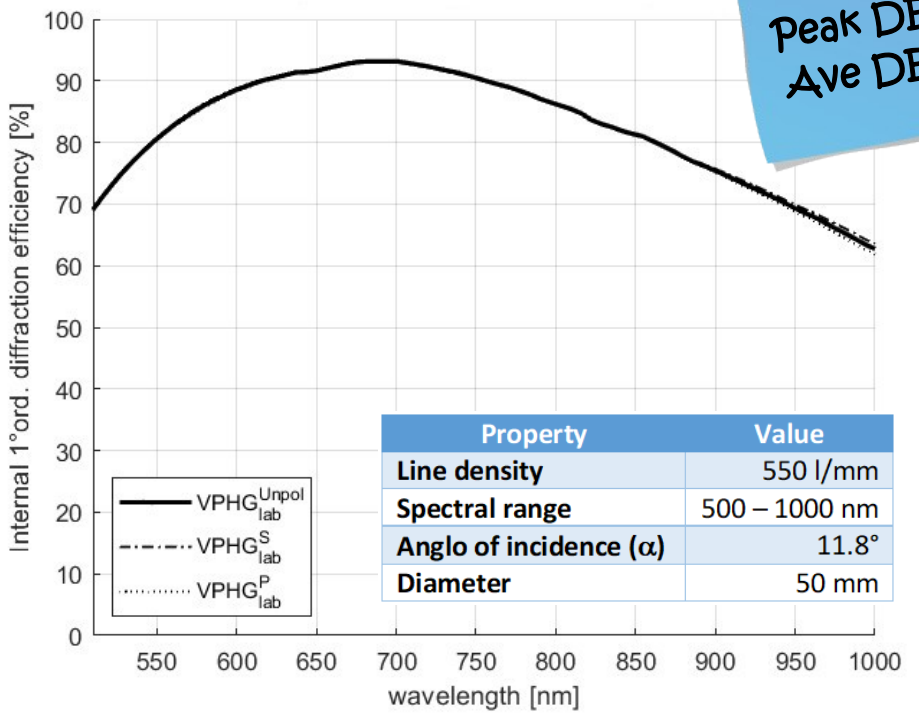
Diffraction efficiency: MAVIS (LR samples)





Peak DE = 87%
Ave DE = 72%

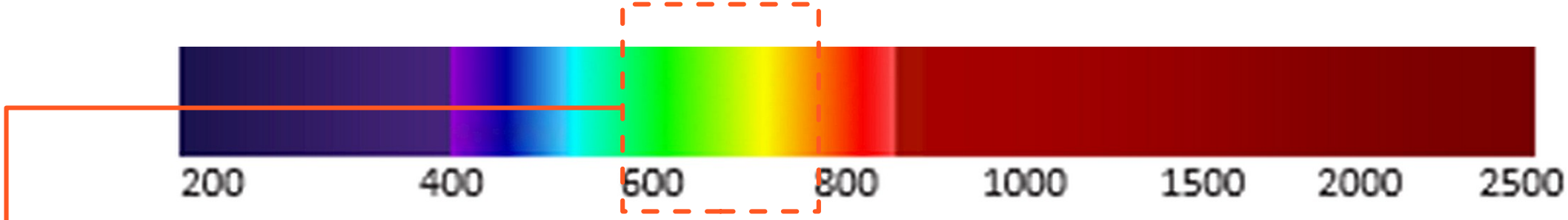
Property	Value
Line density	750 l/mm
Spectral range	370 – 720 nm
Anglo of incidence (α)	11.6°
Diameter	50 mm

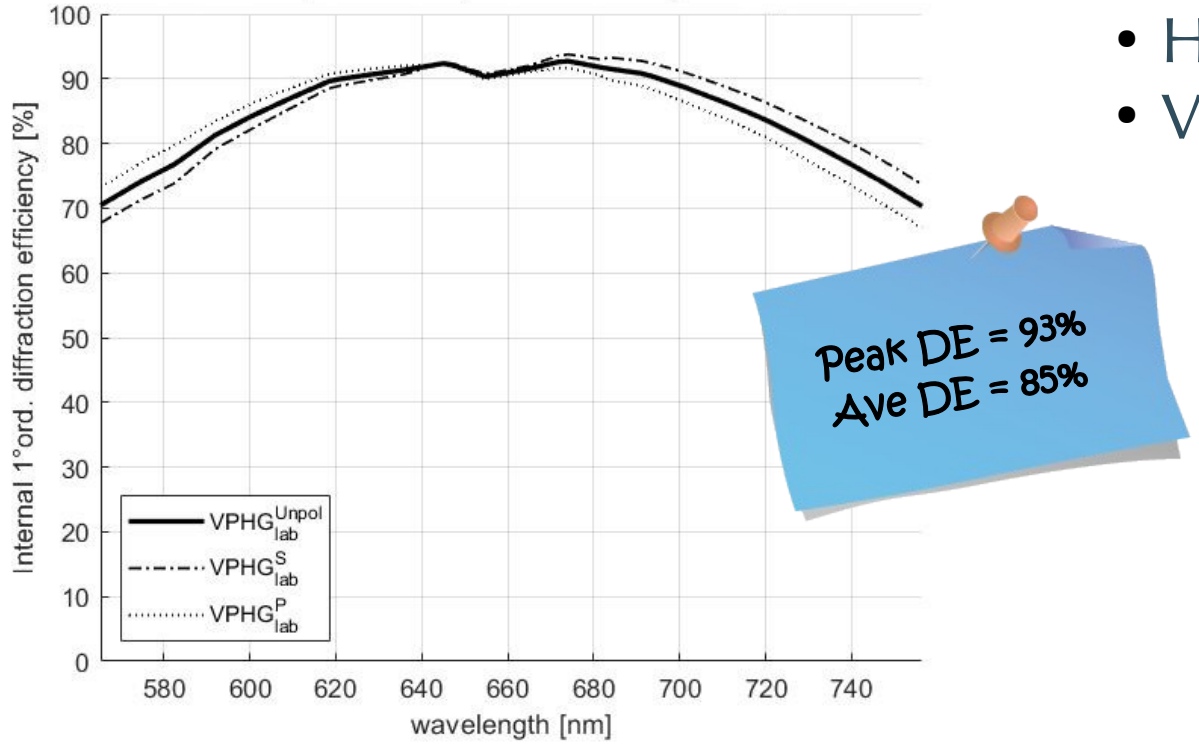


Peak DE = 93%
Ave DE = 85%

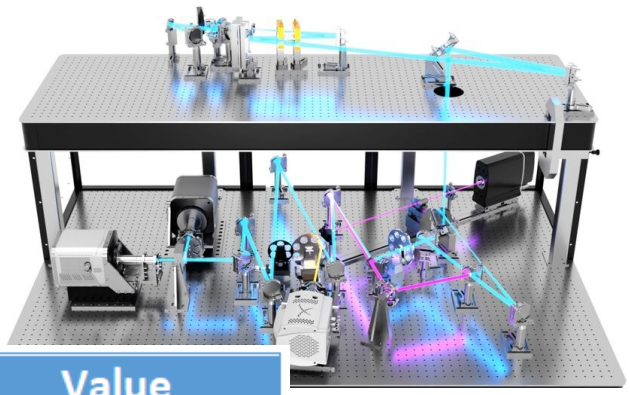
Property	Value
Line density	550 l/mm
Spectral range	500 – 1000 nm
Anglo of incidence (α)	11.8°
Diameter	50 mm

Hα VPHG (Vis-X@Magellan Telescope)



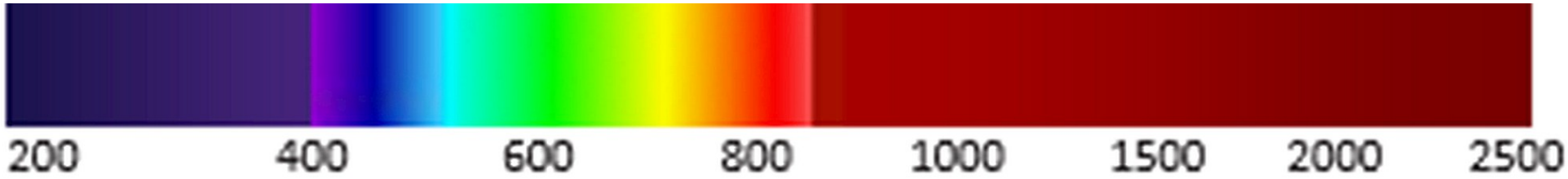


- High resolution thanks to AO.
- Very good efficiency!



Property	Value
Line density	341 l/mm
Spectral range	350 – 1000 nm
Angle of incidence (α)	15.1°
Diameter	40 mm

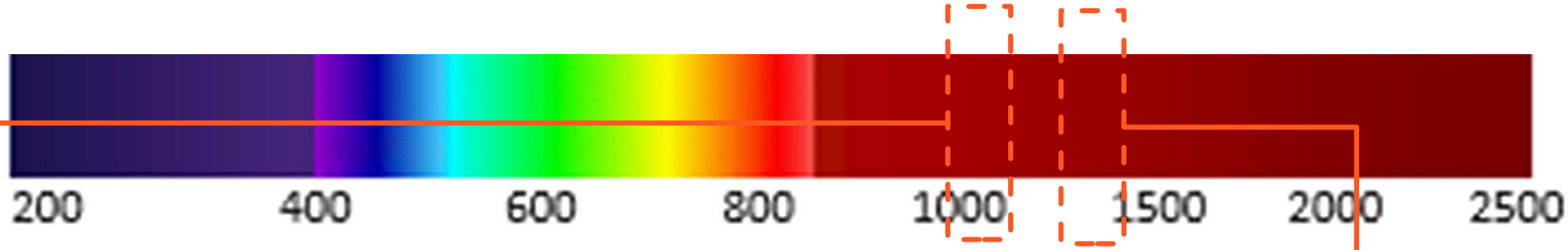
MIRC-X/MYSTIC at CHARA: going into IR!

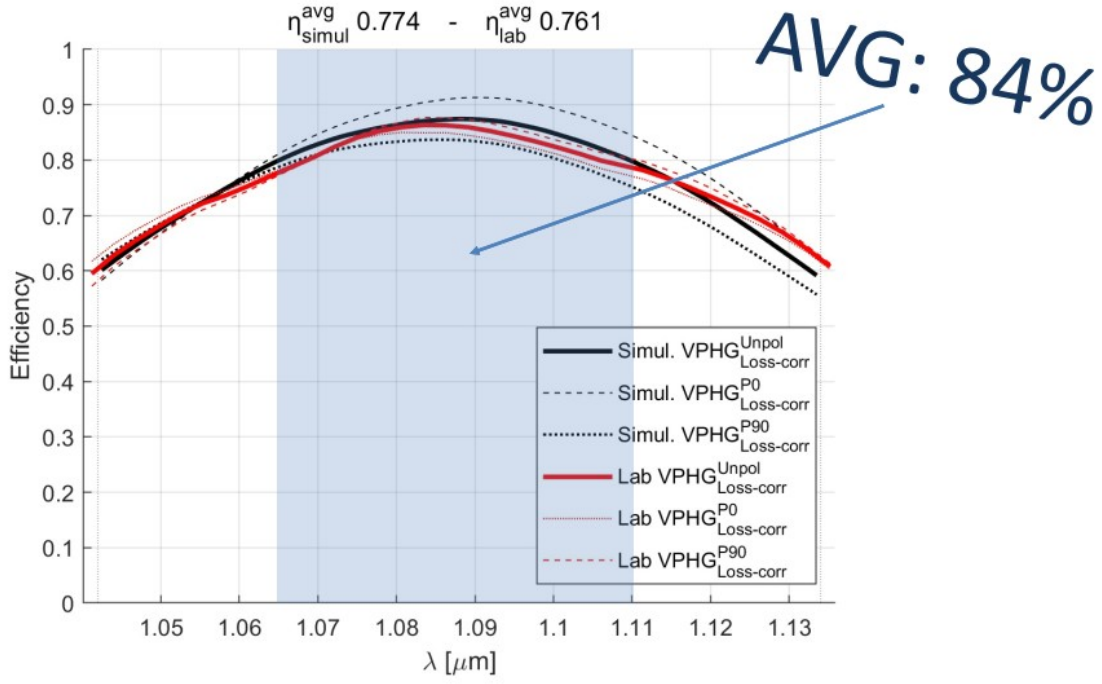


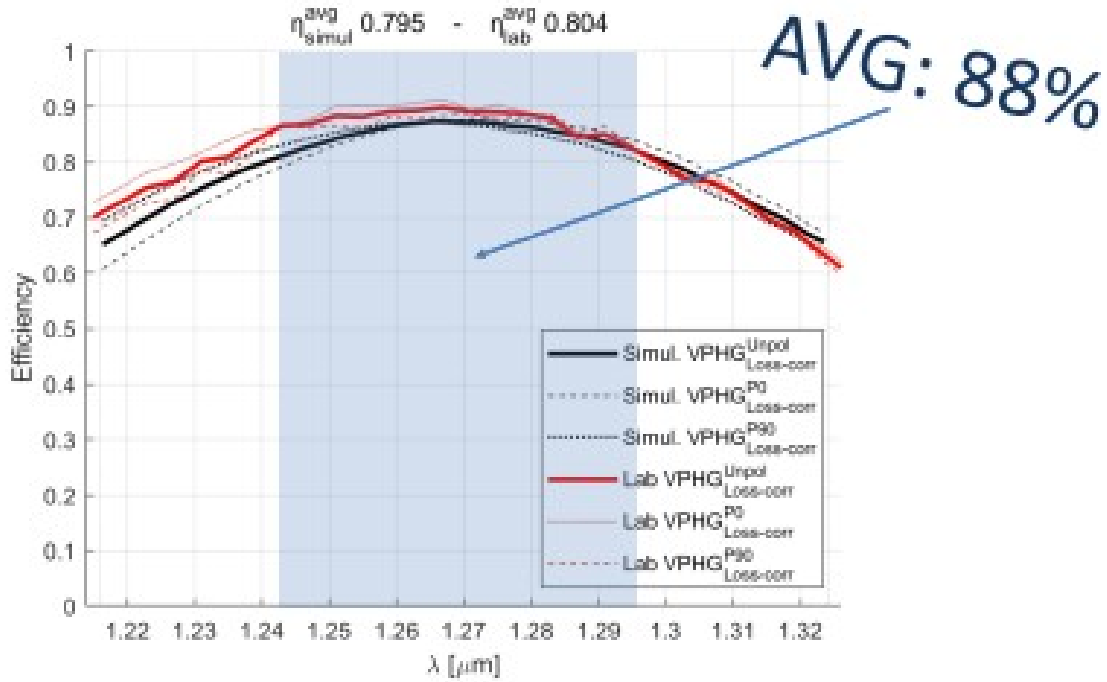
Name	J1	J2	K1	K2
Resolution [R]	6000	6000	4000	4000
Central Wavelenght [nm]	1088	1270	2170	2330
Bandwidth [nm]	1065-1111	1243-1297	2100-2239	2255-2404

- CHARA:optical interferometric array of six telescopes located on Mount Wilson;
- MIRC-X/MYSTIC beam combiners of six telescopes simultaneously;
- Medium resolution and K band, not yet covered;
- 2 J and 2 K band GRISMs;
- Ready for commissioning.

MIRC-X/MYSTIC at CHARA: going into IR!







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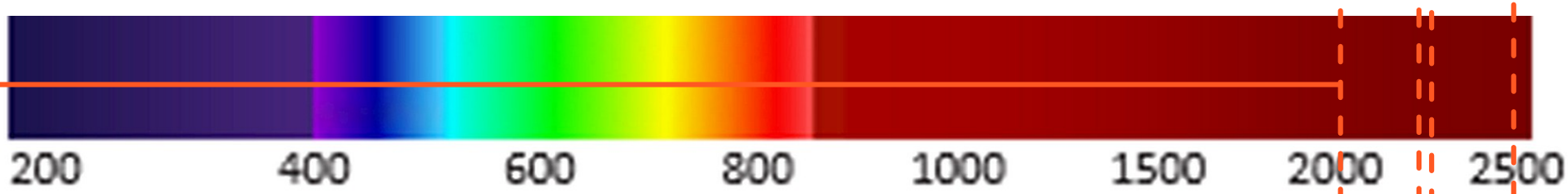
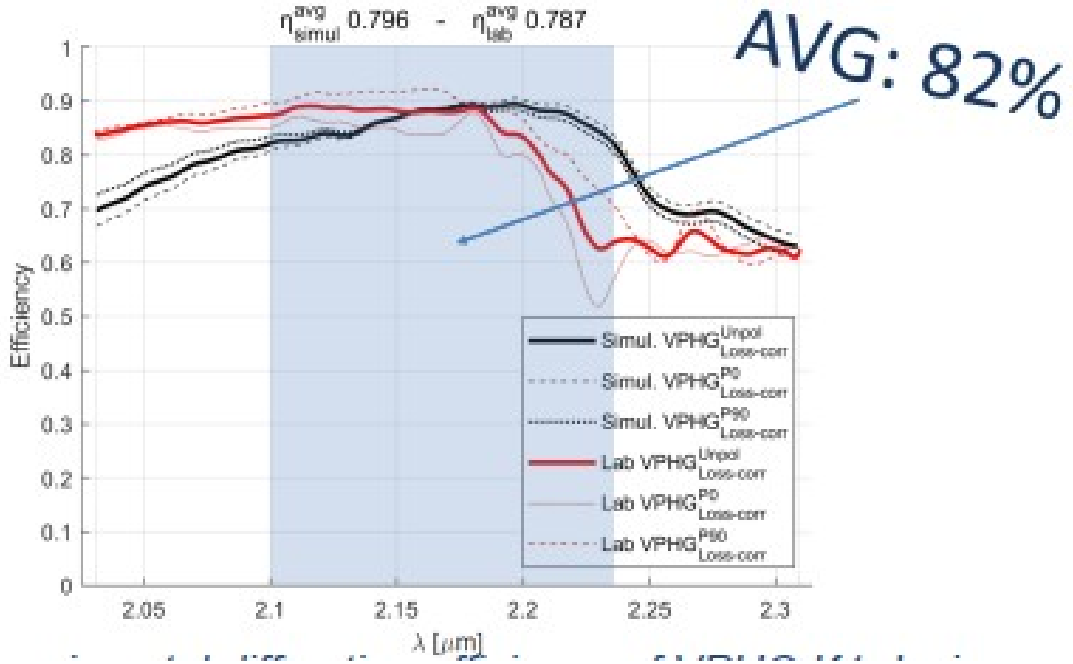
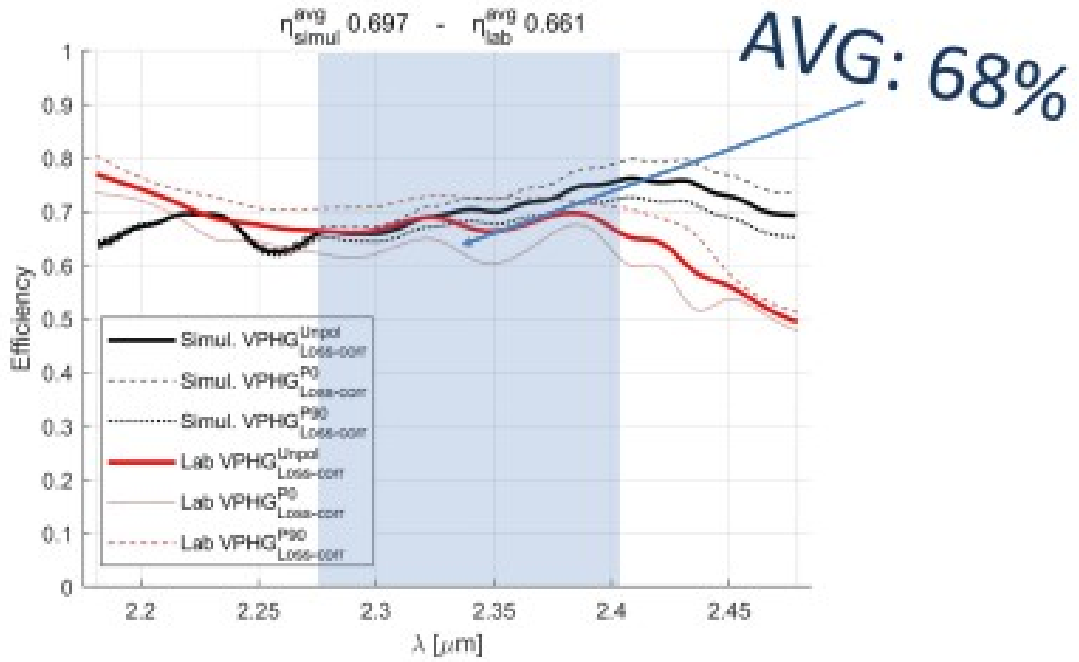
MIRC-X/MYSTIC at CHARA: going into IR!







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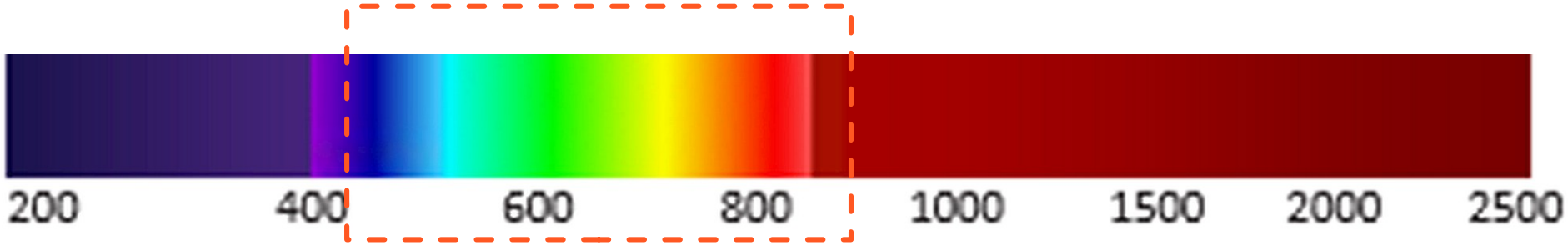
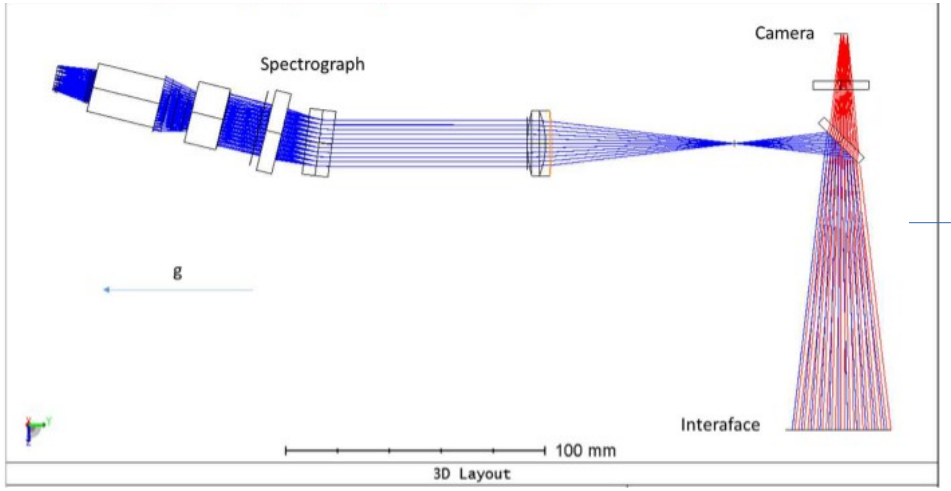
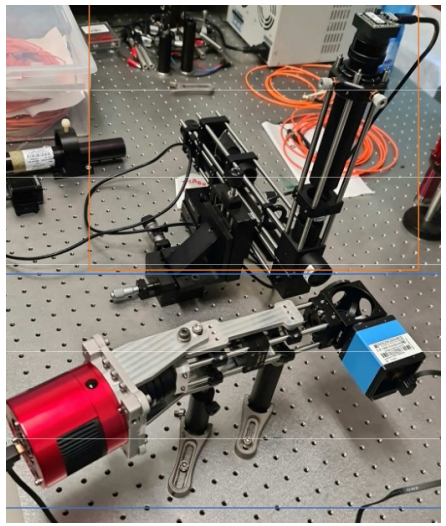
Small VPHG based spectrograph@AGO70

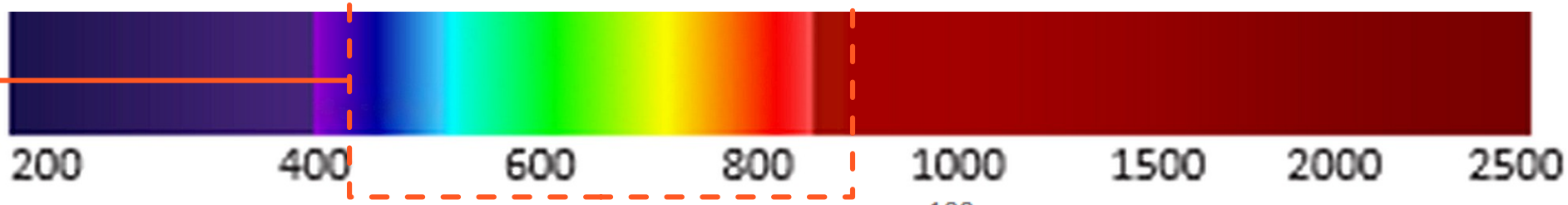


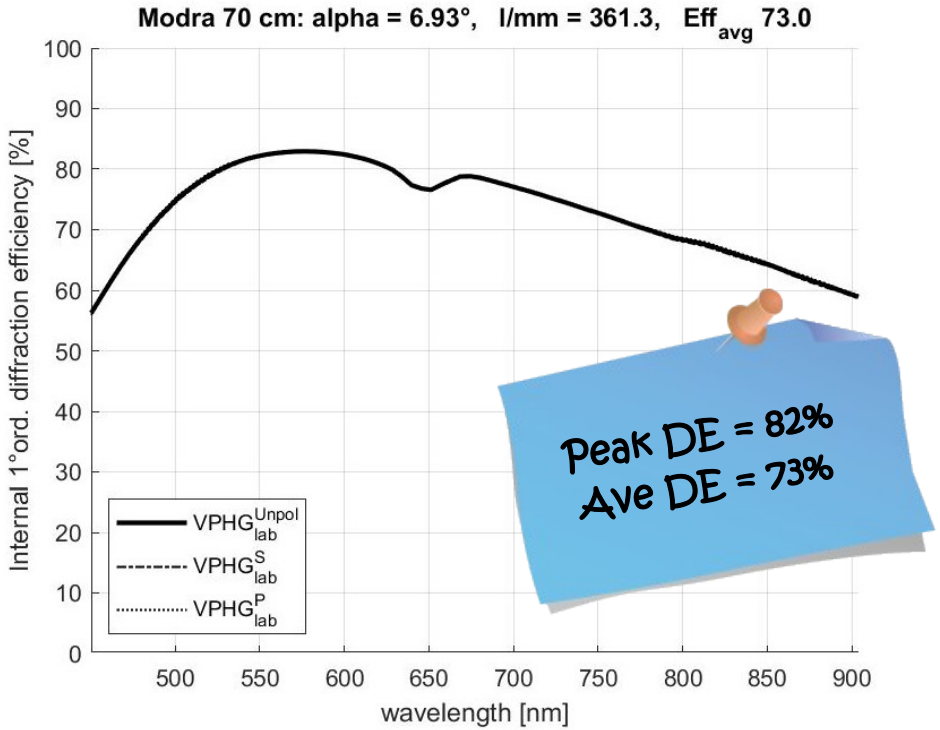
- Provide spectroscopic capabilities to AGO70 (Modra, Slovakia);
- **Develop compact and cheap high performance vis spectrograph** (0.45 – 0.9 um).

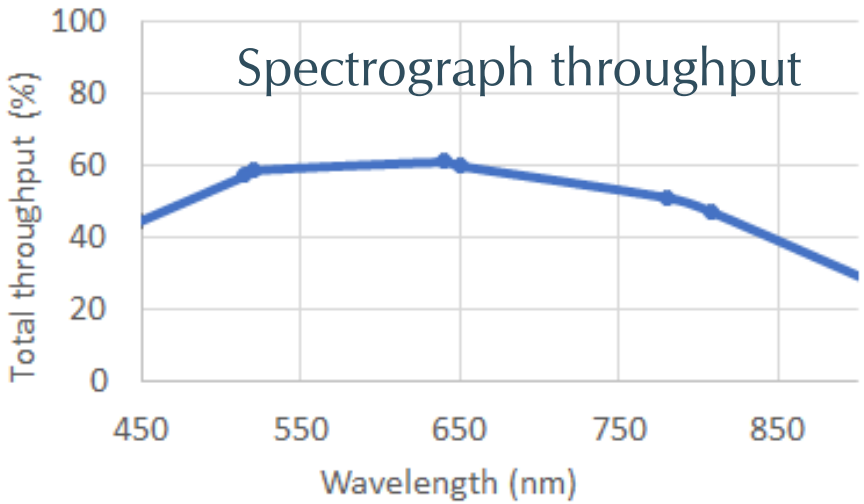


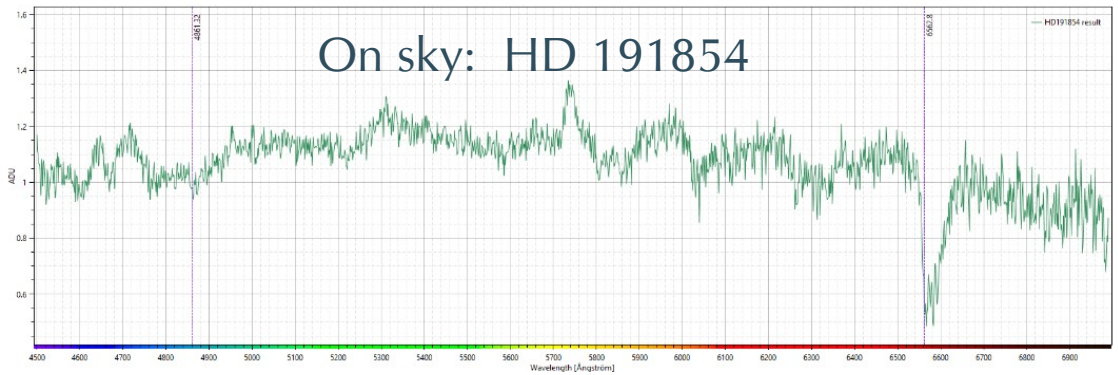


Small VPHG based spectrograph@AGO70









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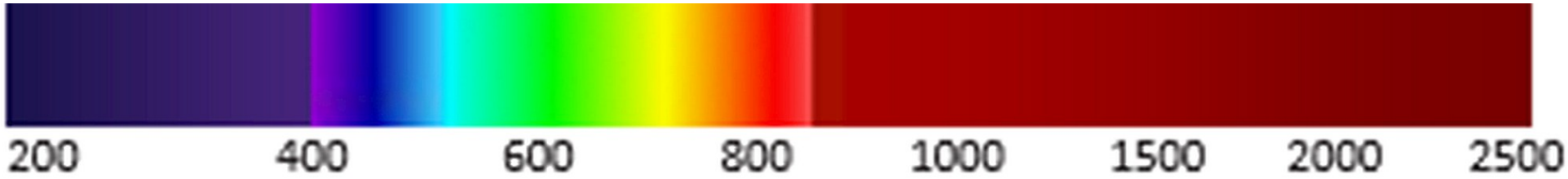
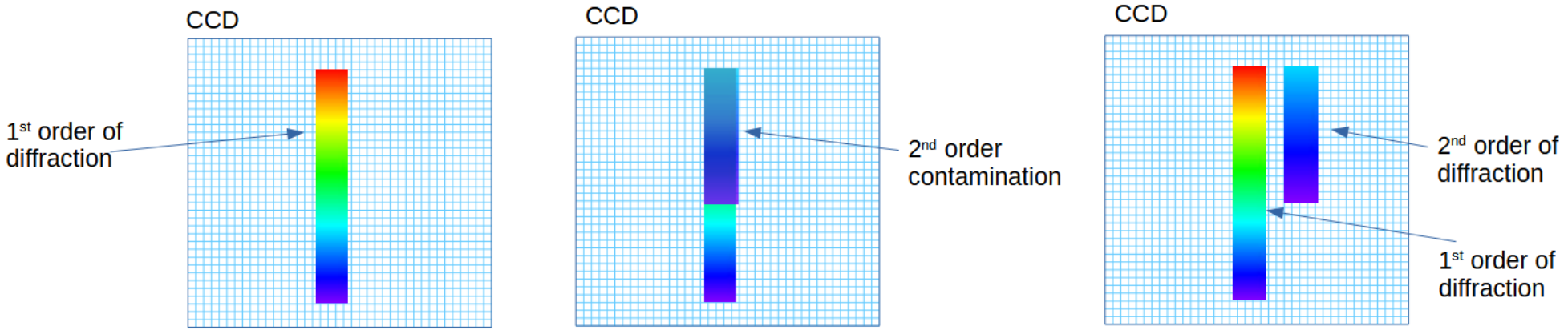
Dual order GRISM@Asiago 1.8m telescope

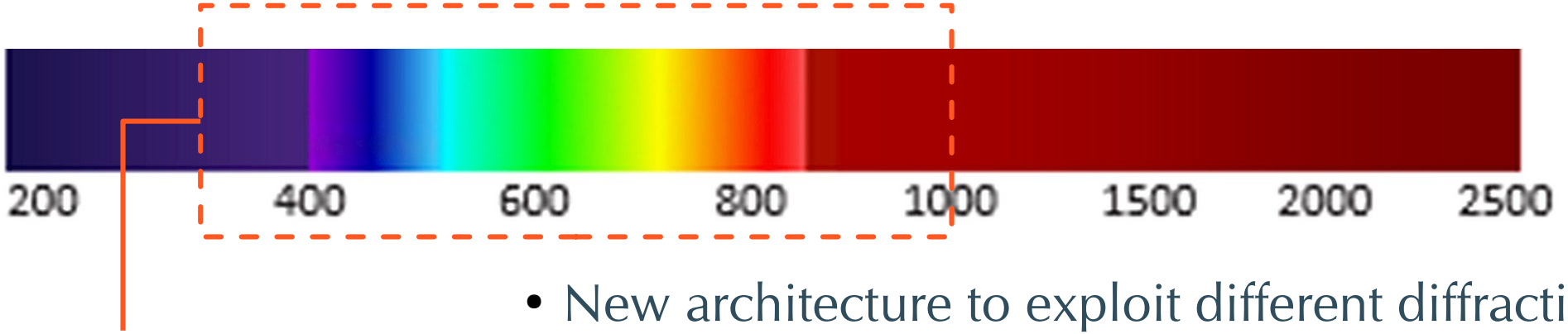


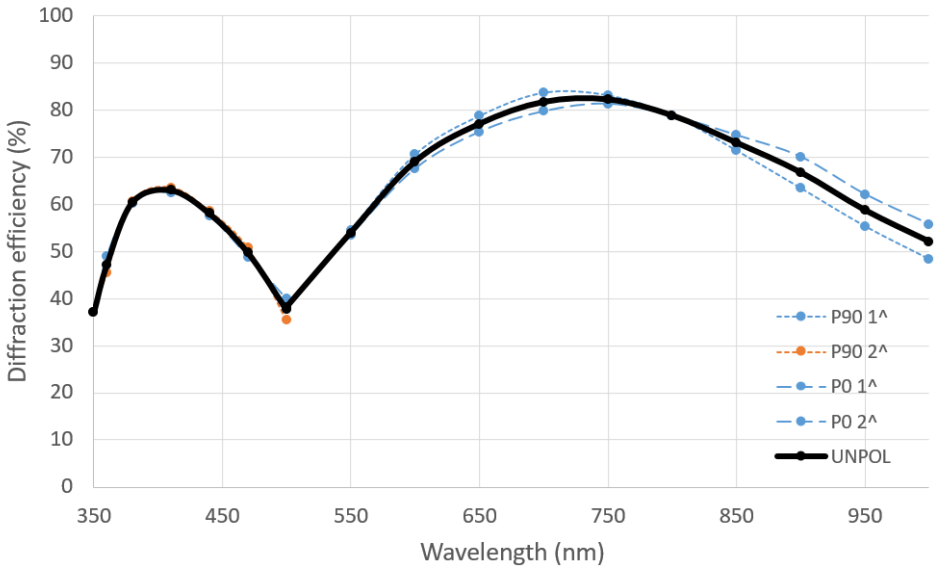
Property	Value
Line density	341 l/mm
Spectral range	350 – 1000 nm
Angle of incidence (α)	15.1°
Diameter	40 mm

- New architecture to exploit different diffraction orders;
- Avoid orders overlap;
- **Wide spectral range (0.35-1.0 um) in one exposure!**

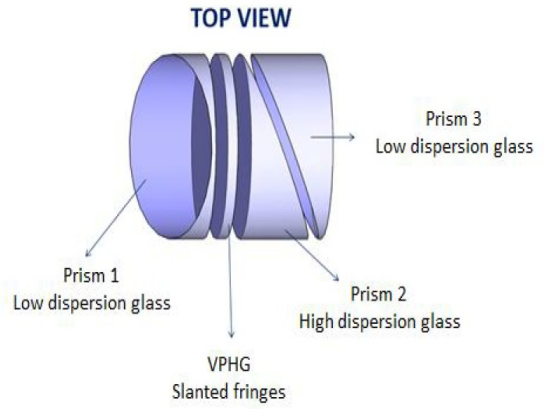


Dual order GRISM@Asiago 1.8m telescope

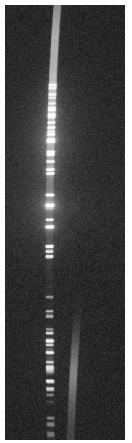




- New architecture to exploit different diffraction orders;
- Avoid orders overlap;
- **Wide spectral range (0.35-1.0 um) in one exposure!**



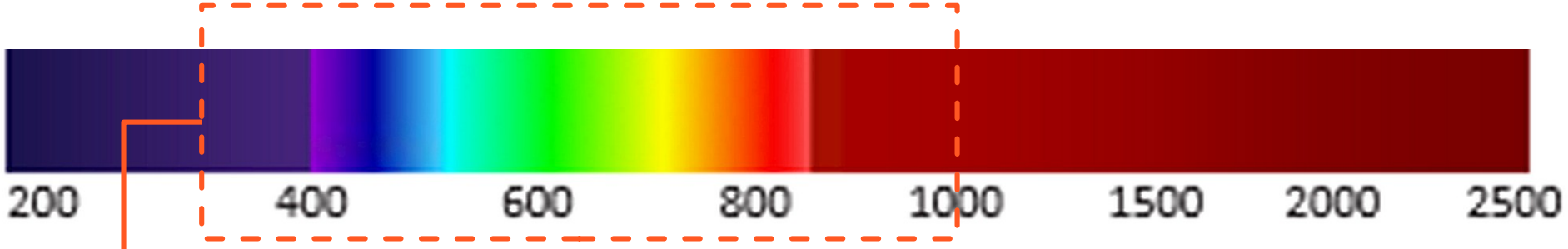
CCD image

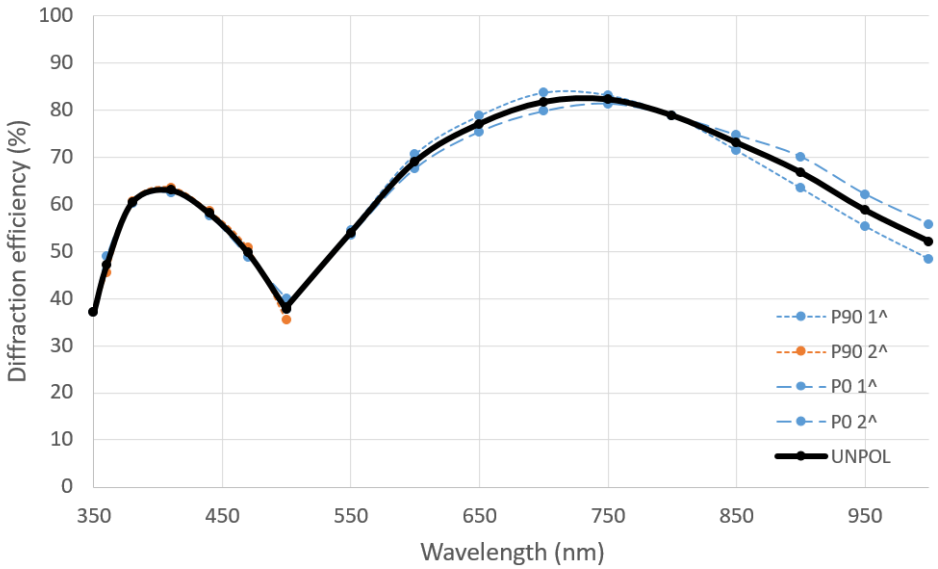


1st order

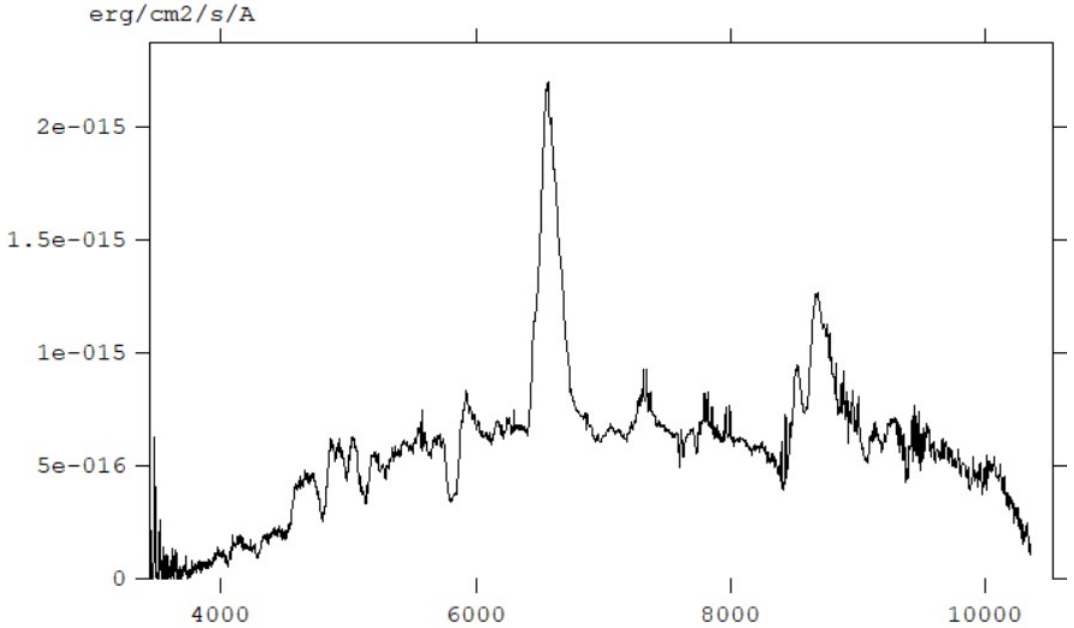
2nd order

Dual order GRISM@Asiago 1.8m telescope



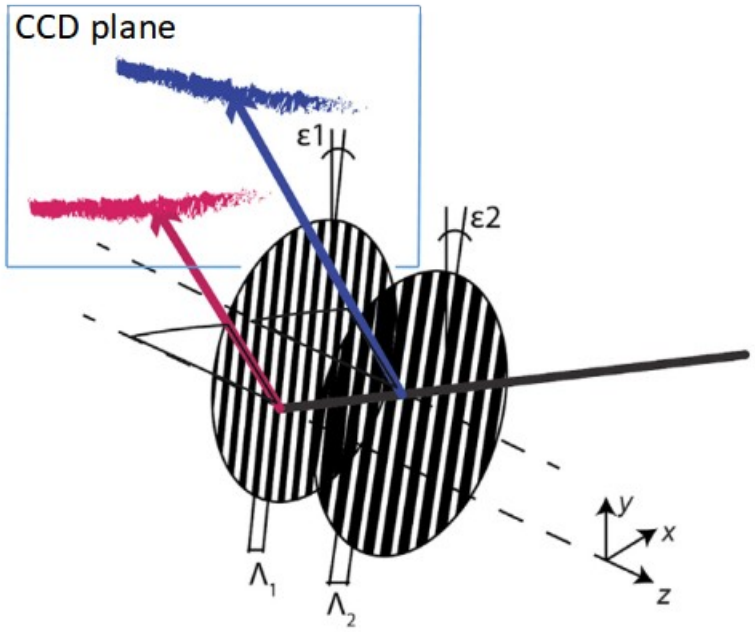


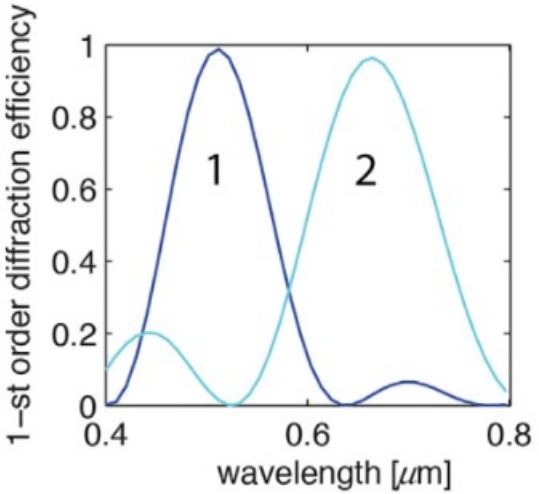
Used for supernovae classification:



New approaches: multiplexed VPHG

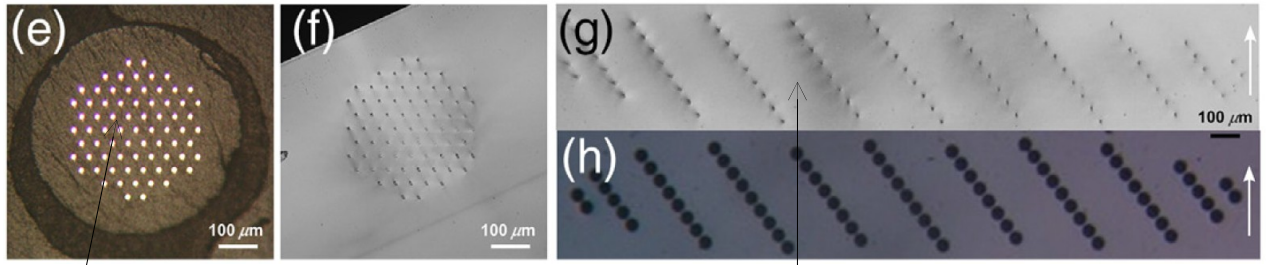
- ISSUE: the number of pixel is limited (especially in the infrared) and a tight tradeoff resolution-spectral range is mandatory.
- IDEA: Make a stack of VPHGs with a suitable clock that provide separated sub spectra like an echellette grating.





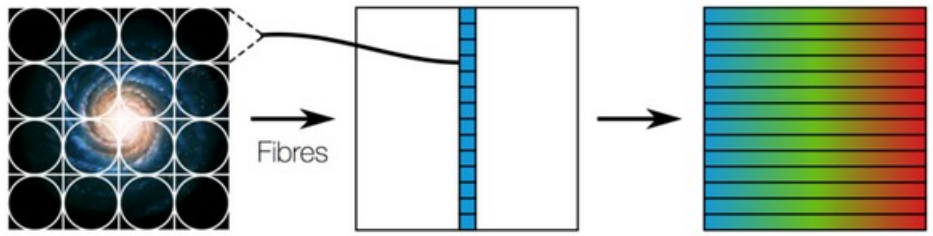
multiplexed VPHG: MCIFU

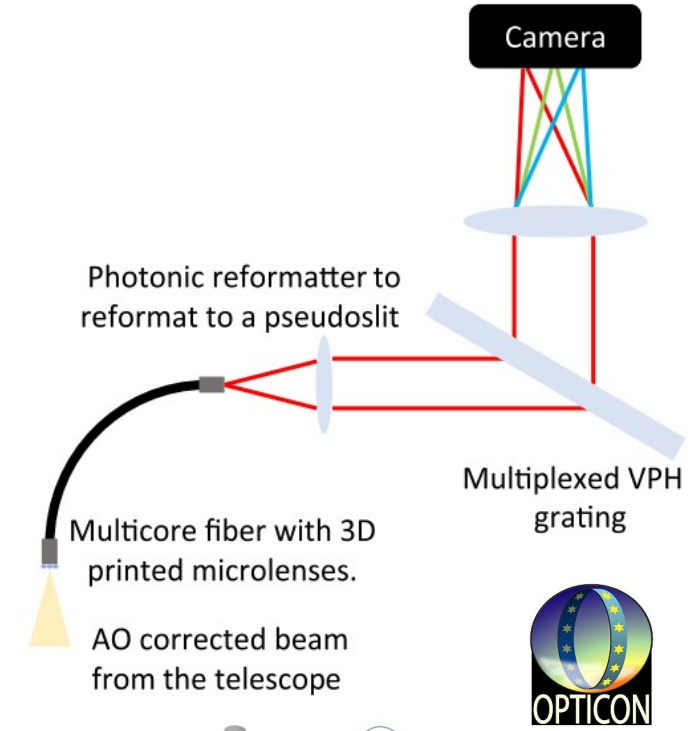
- A fiber fed AO IFS, 1.0 – 1.6 um @ R = 5000;
- Mounted at Canary@WHT;
- Astrophotonics for making multicore fibers;

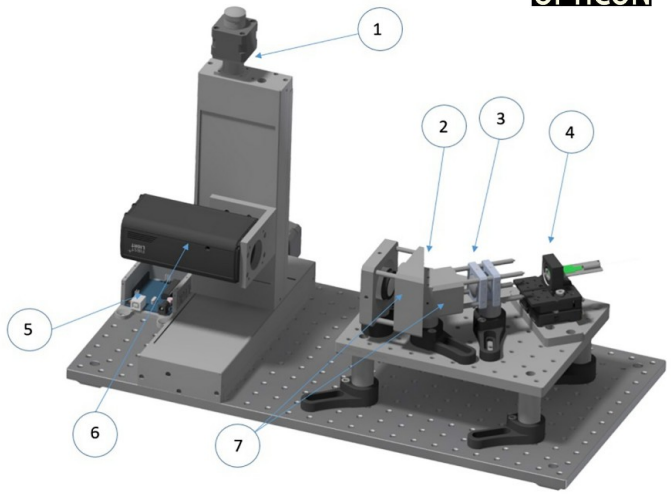


At the AO focal plane

Reformatted fiber as entrance slit

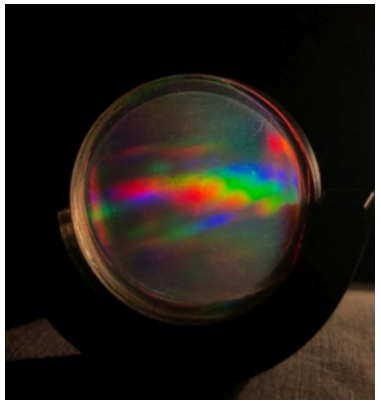


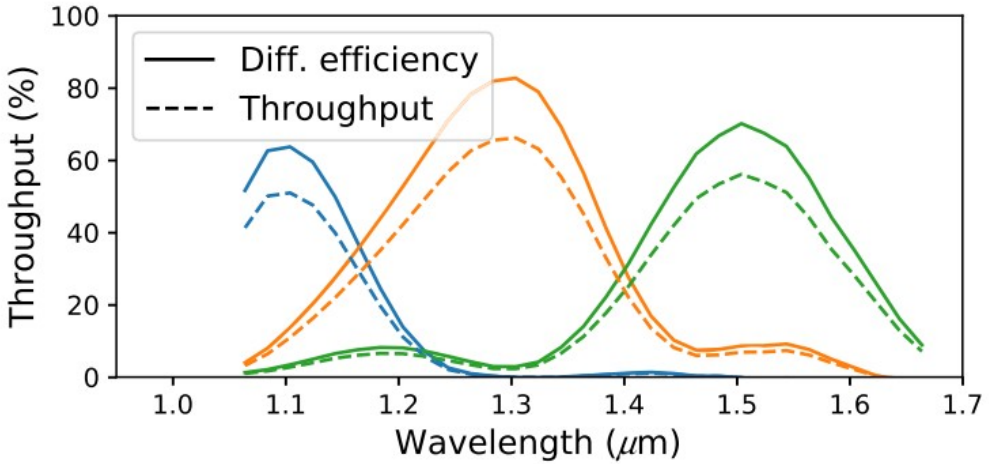


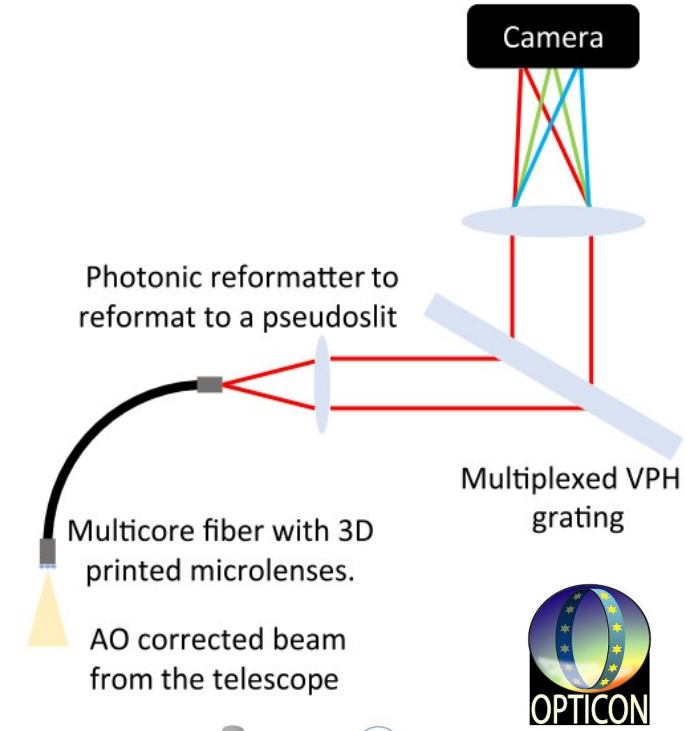


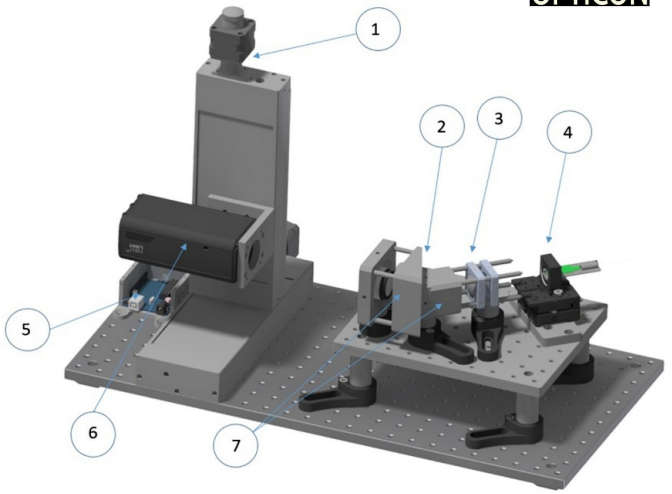
Multiplexed VPHG: MCIFU

- A fiber fed AO IFS, 1.0 – 1.6 um @ R = 5000;
- Mounted at Canary@WHT;
- Astrophotonics for making multicore fibers;
- **3 layers multiplexed VPHG.**



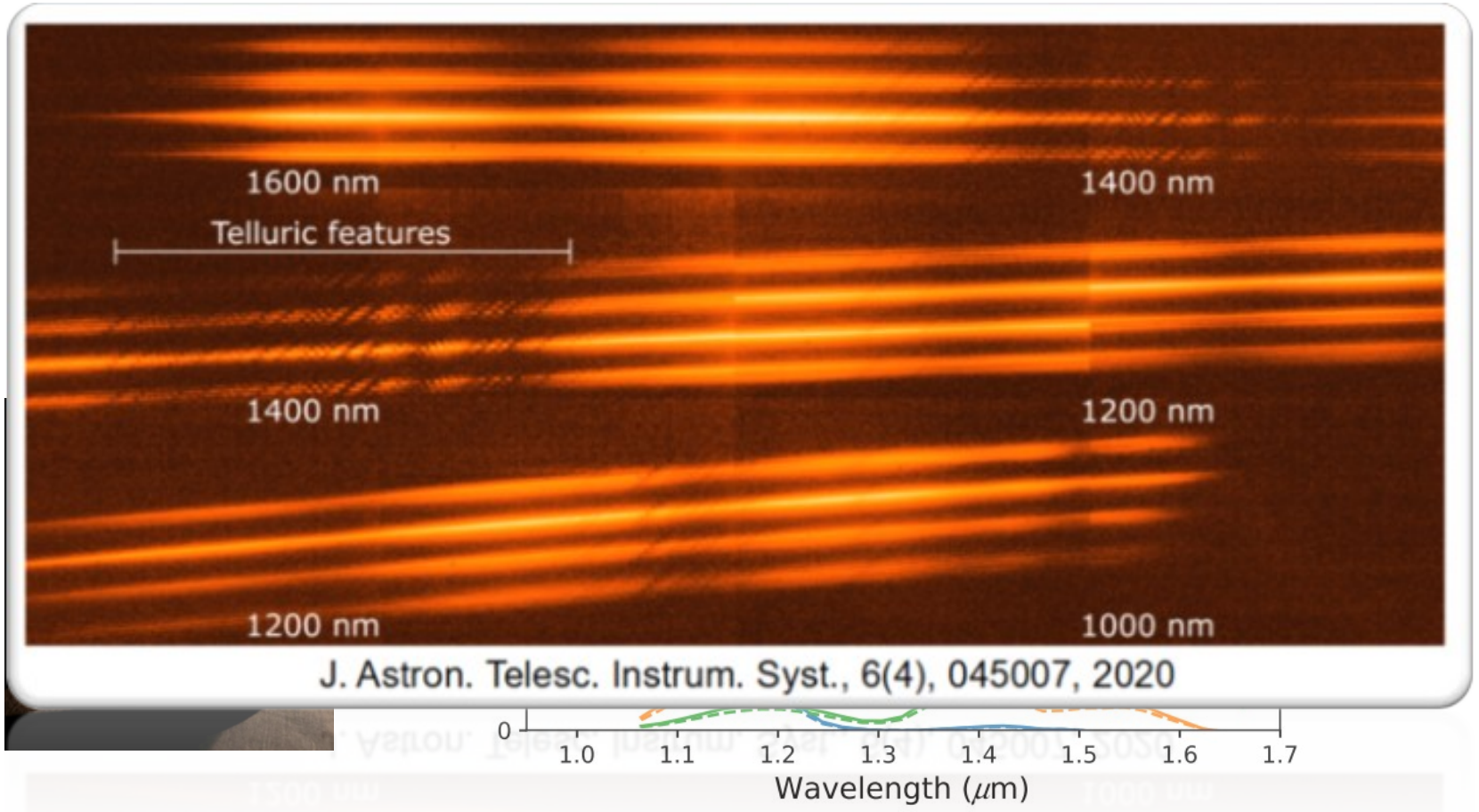


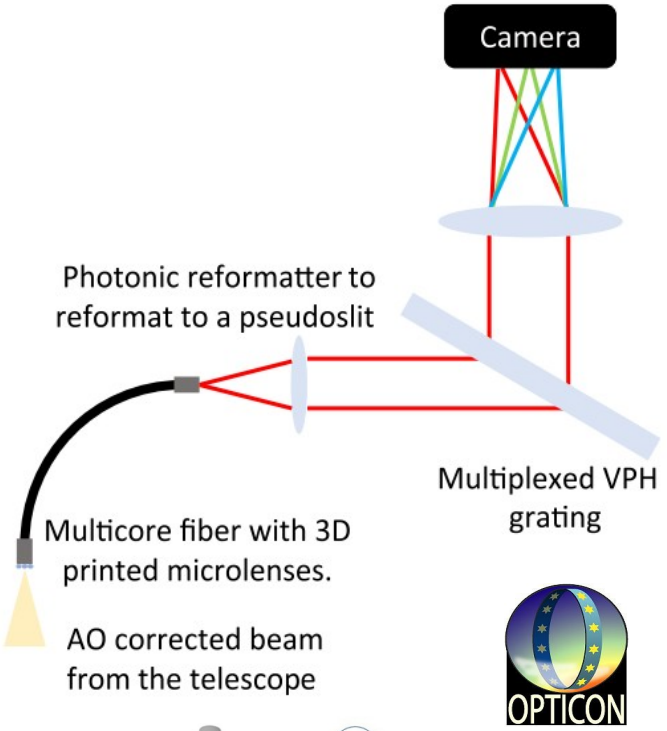


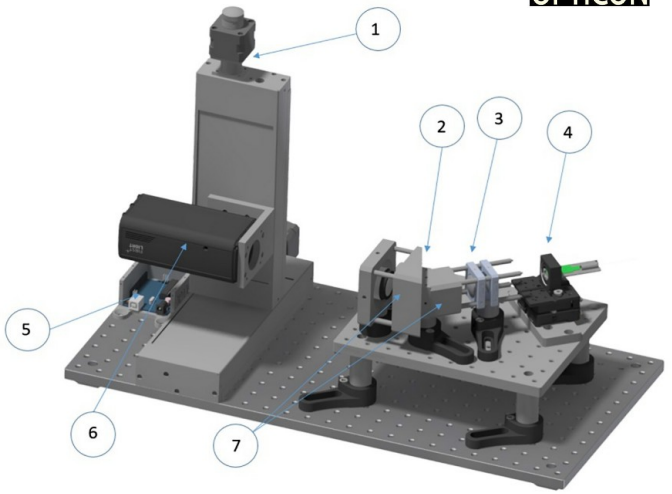


J. Astron. Telesc. Instrum. Syst., 6(4), 045007, 2020

Multiplexed VPHG: MCIFU

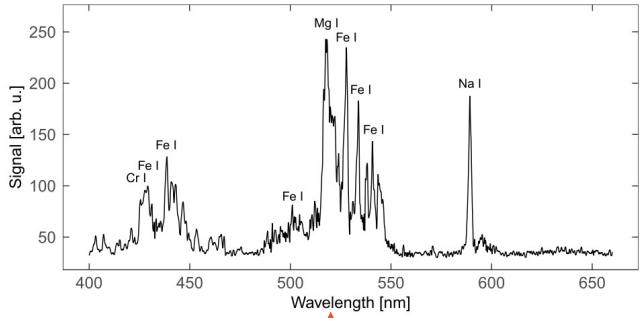


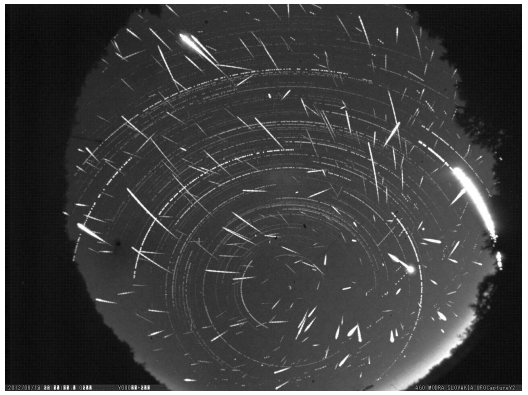


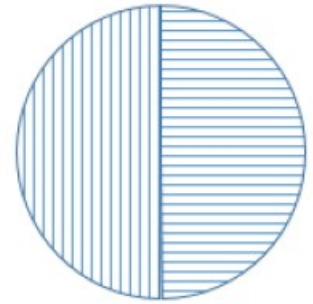


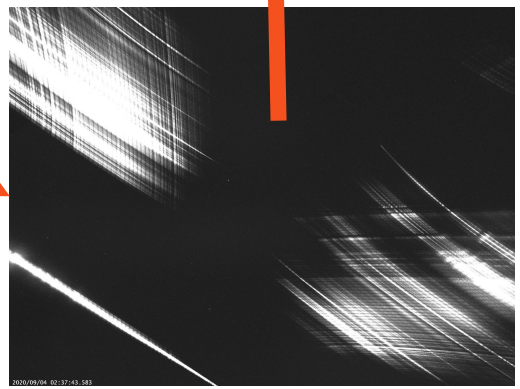
Criss-Cross grating for meteor detection

- Meteors are detected by wide field cameras (AMOS);
- Important to have the spectrum to determine the composition
- A VPHG with two halves to have spectra no matter the direction of the meteor on top of the camera.









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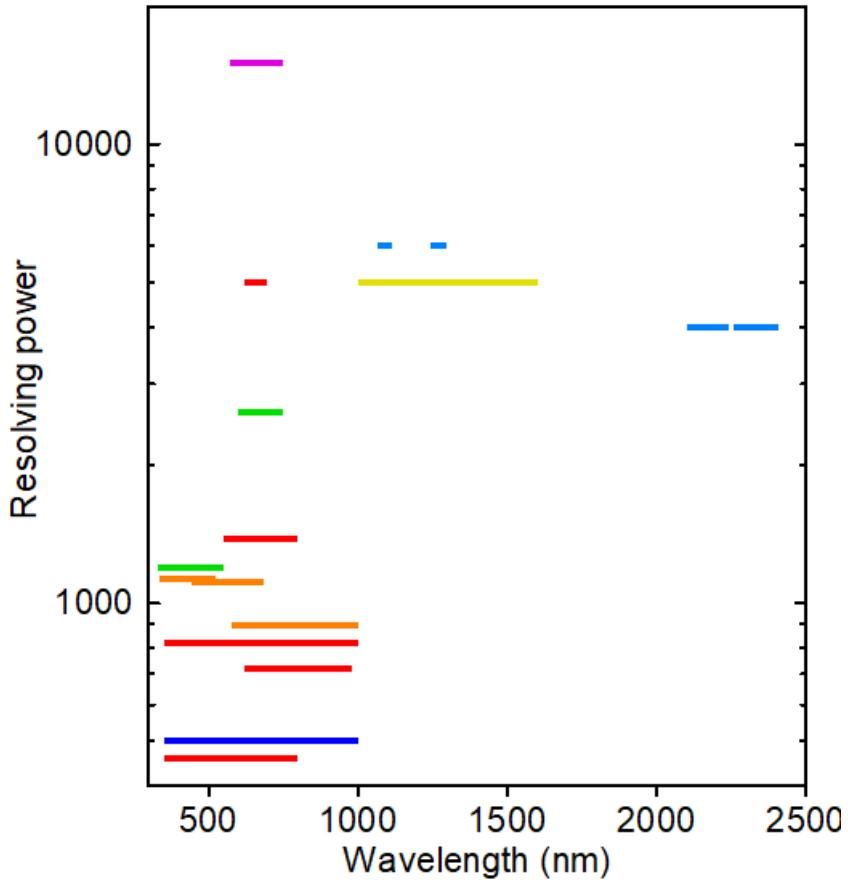
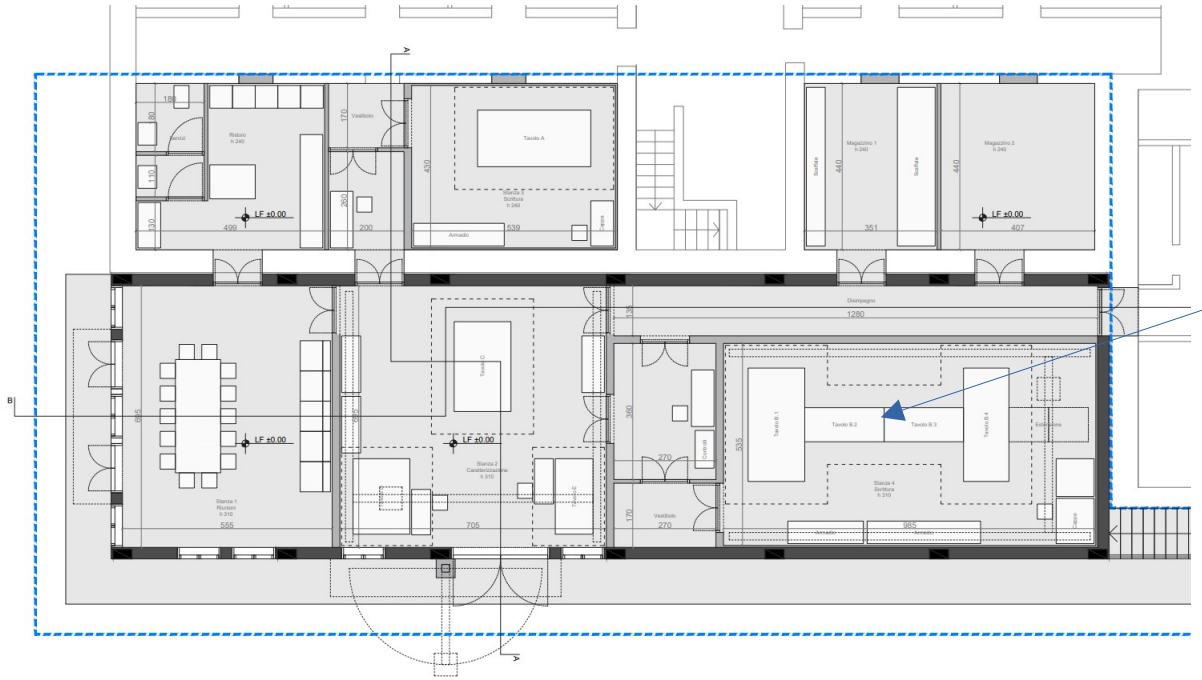
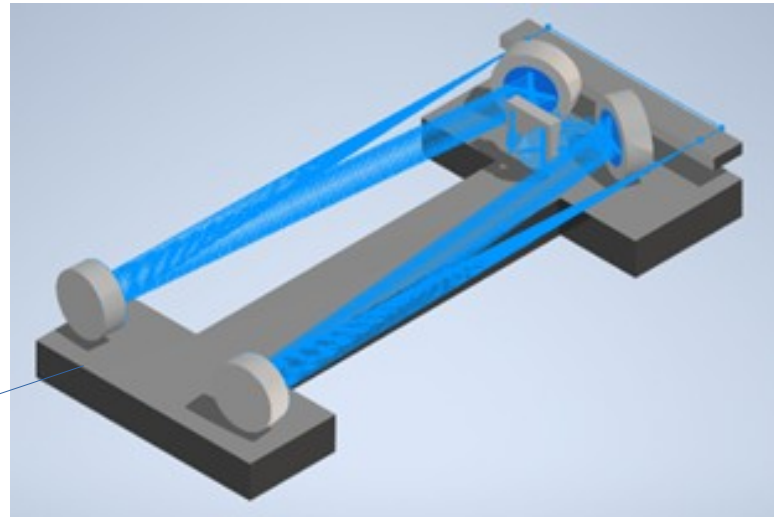
Some of our VPHGs installed in telescopes



We have more than 10 VPHGs working in astronomical spectrographs around the world

Next step: big facility (on going)





GOAL: Build a large size VPHG ecosystem

- Improve the reliability of the design/production;
- Improve the DE performances.

- **All optomech items ordered;**
- New building project accepted;
- Red laser > 3 W (Sep 2024);
- Fully automatic;
- **>400 mm holo setup**;
- 190 mm setup still there;
- 100 mm setup already available;
- **New characterization facility too;**
- First light in Q3/2025.

Conclusions

- VPHGs are useful dispersing elements for astronomical spectrographs;
- **We developed an efficient process:**
  - Reliable design in terms of DE from UV to K band;
  - Fast production and testing of VPHGs;
  - Possible to design and build cheap but high performance spectrographs;
- **Next steps:**
  - Increase the size of the VPHGs (up to 400 mm x 550 mm) in a new laboratory;
  - Improve the production process to increase the DE;
  - Work even more on the WFE control on both holo writing and post processes.

Thanks...

The gOlem galaxy...25 years of technologies for astronomy