Narrowband filters for far UV imaging

Paloma López-Reyes[1*],
Nuria Gutiérrez Luna[1],
Carlos Honrado-Benítez[1], Luis V. Rodríguez-de Marcos[2], and Juan I. Larruquert[1]

*paloma.lopez@csic.es

[1]Grupo de Óptica de Láminas Delgadas
Thin Film Optics Group

[2]Catholic University of America and NASA GSFC (CRESST II), Greenbelt, MD, USA

Outline

- **Our group**
- **Motivation:**
  - FUV and EUV astronomy
  - Future observatories
- **Experimental and facilities**
- **Results**
  - Tunable narrow bands in the FUV
  - Spectral line selection
  - Narrow bands in the LUV
  - Other coatings
- **Conclusions**

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- Coating deposition for the FUV-EUV
- Coating metrology FUV-EUV

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GOLD

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- **Coating deposition for the FUV-EUV**
- **Coating metrology FUV-EUV**
- Measurement of (n,k) of materials for the FUV-EUV
- Calculations and designs for specific targets in the FUV-EUV

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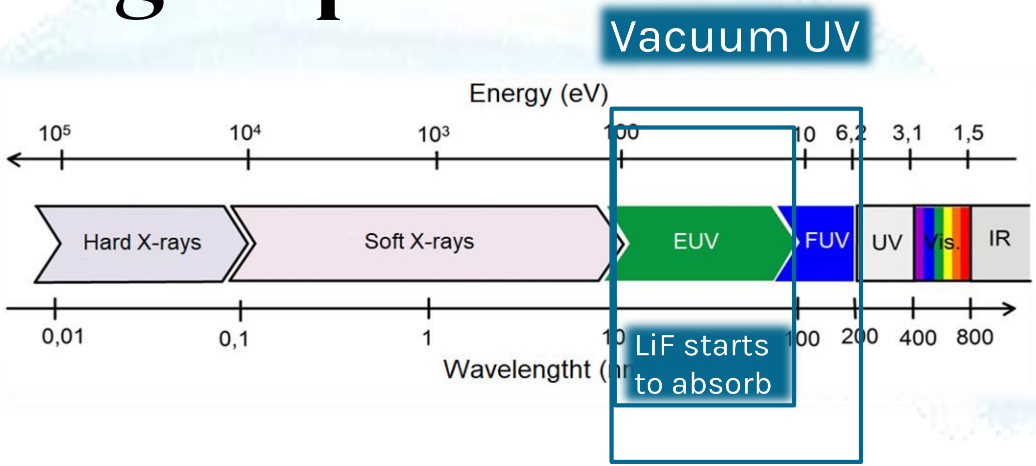

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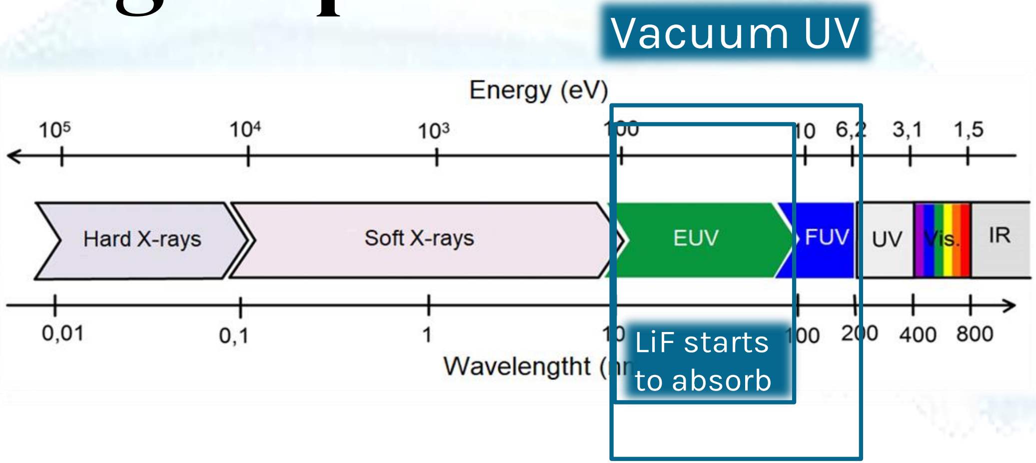

Main difficulties:

- Absorption of air → work in vacuum
- Absorption of materials → complex designs
- (n,k) not well known → uncertain designs

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Long-time and expensive

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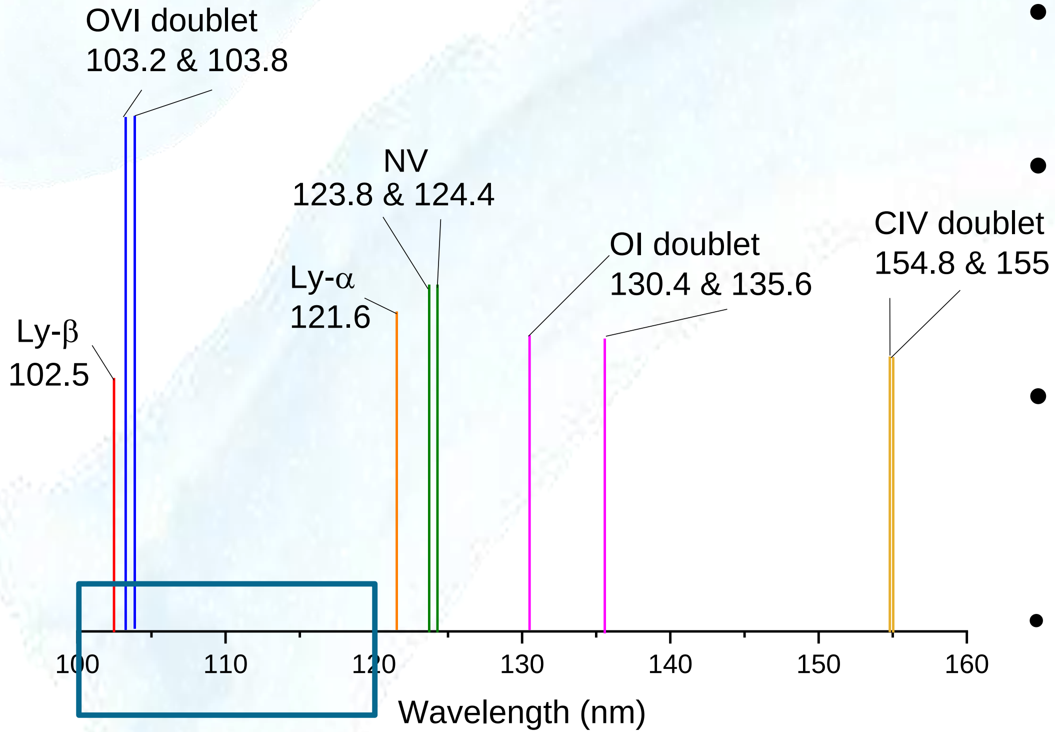

- Solar and atmosphere physics
- Exoplanet habitability
  - O_2, O_3, CH_4, and CO_2 depend strongly on the UV spectrum of the host star
  - Strong atmospherical mass losses due to the host-star EUV flux
- Tracers of gas at few hundred thousand kelvins
- Nearby galaxies have never been measured in 100-120 nm

Motivation: future observatories

2020 Astronomy and Astrophysics Decadal Survey

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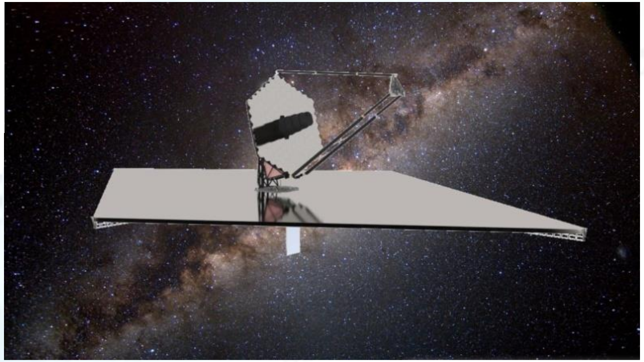

Next priority flagship space mission:

Infrared (IR)/Optical (O)/Ultraviolet (UV) Large Telescope

LUVOIR/LUVEX

- Habitable exoplanets
- General astrophysics

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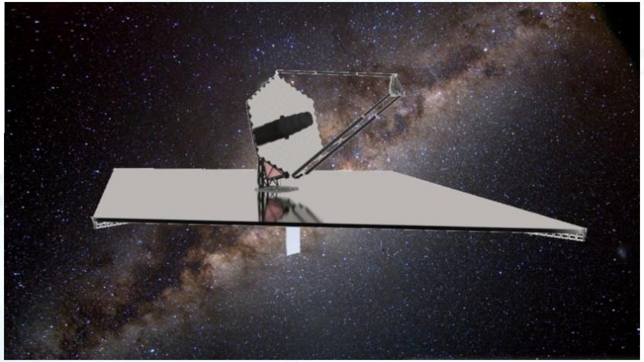

LUMOS

Multiobject spectrograph: FUV-Vis

France et al. 2017

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Motivation: future observatories

FLUID: Far and Lyman Ultraviolet Imaging Demonstrator

Motivation: future observatories

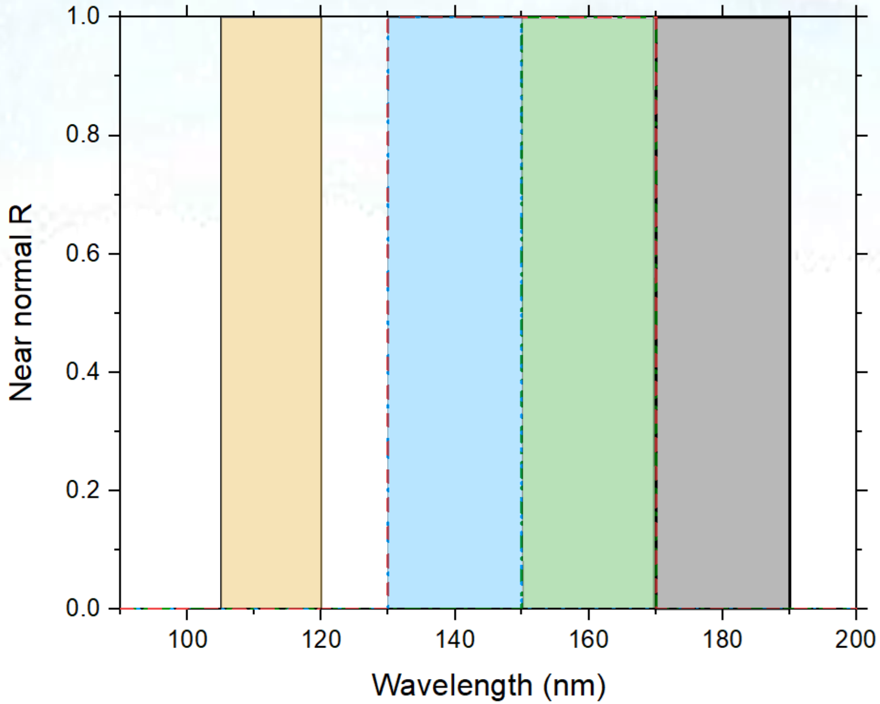
FLUID: Far and Lyman Ultraviolet Imaging Demonstrator

narrow- and medium-band interference filters for the LUVOIR/LUMOS imaging channel covering 100 – 180 nm

Motivation: future observatories

LUMOS

Spectral Bandpass:
100-400 nm
Narrowband filters for the FUV and NUV:
Δλ ~ 15 nm



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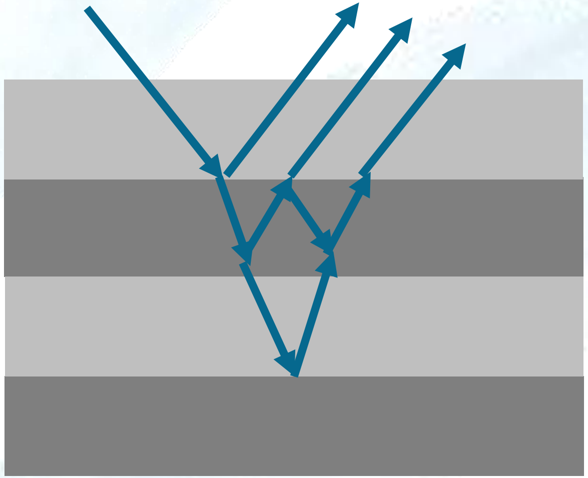
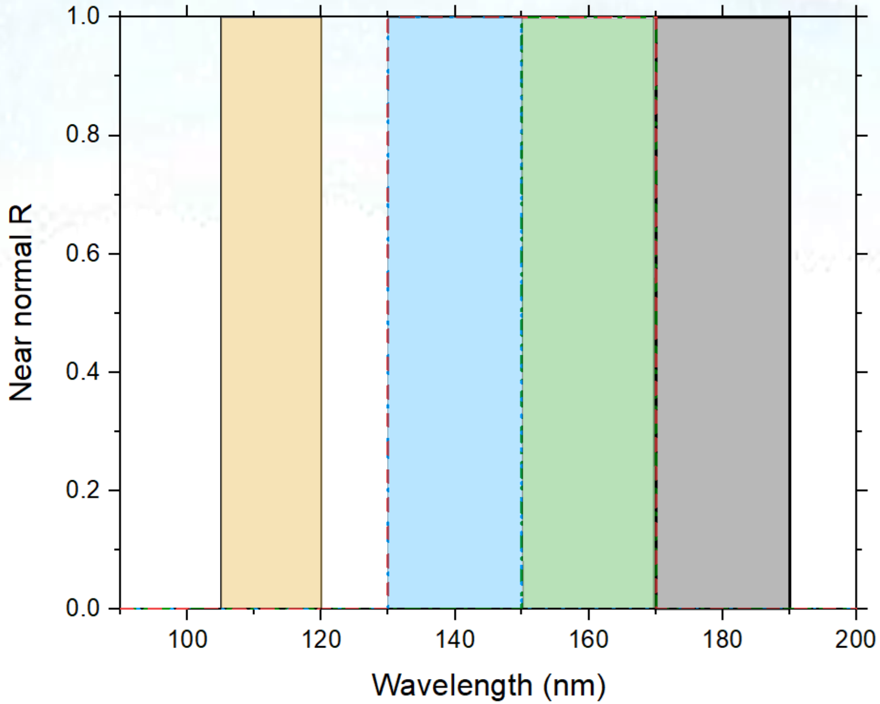


Best approach: Multilayers in Bragg configuration



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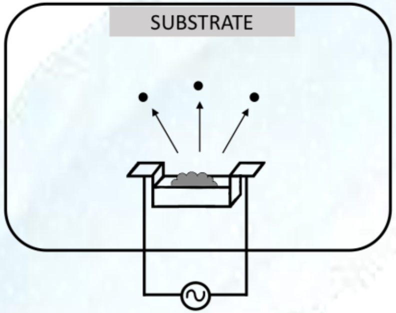
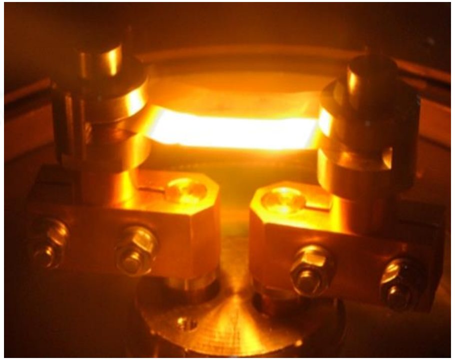
Thermal evaporation





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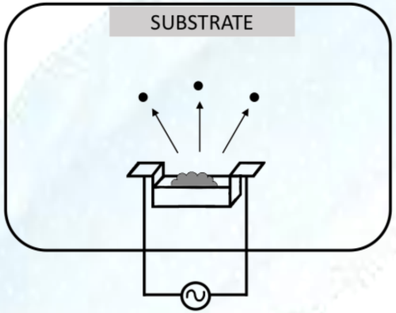

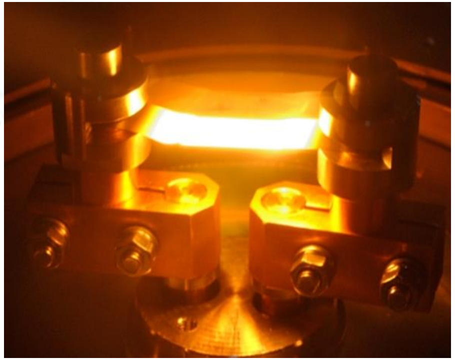

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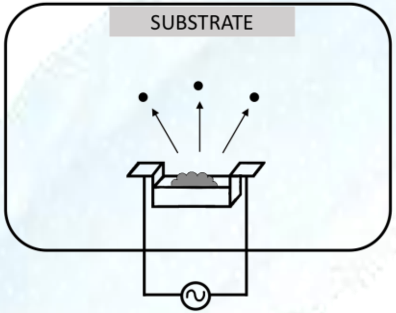

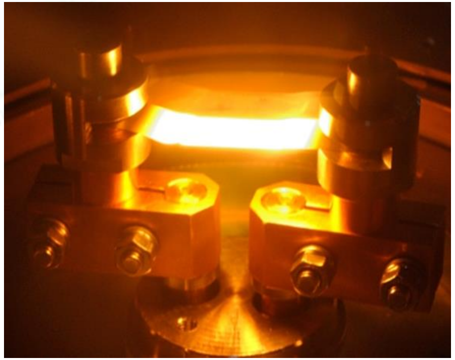

ISO-6

Evaporation + sputtering

70 cm Ø

Rotator heater 15 cm Ø

P~10^{-8} mbar

Experimental: characterization

Reflectometry in the FUV-EUV

ISO-8
40-200 nm
+ deposition system
insitu

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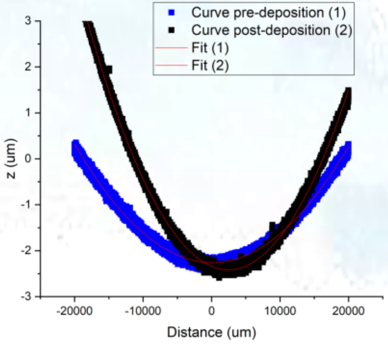
Stress



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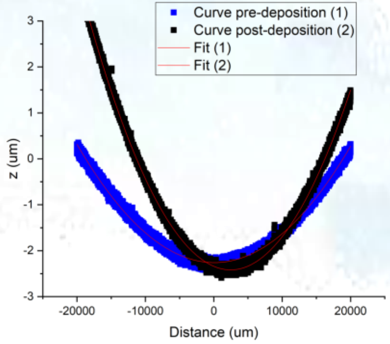
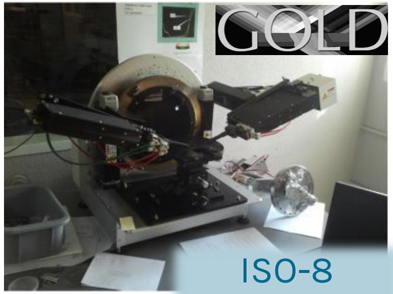


Ellipsometry



ISO-8
190-900 nm

Experimental: characterization

Reflectometry in the FUV-EUV

ISO-8
40-200 nm
+ deposition system
insitu

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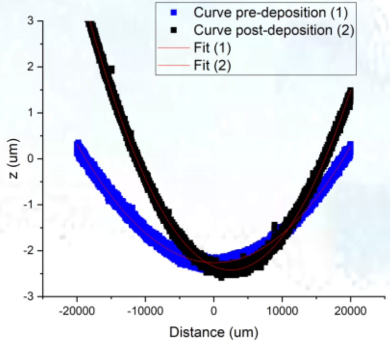
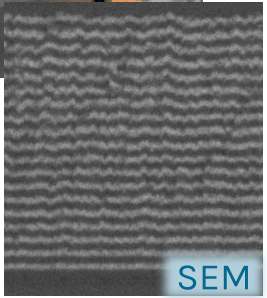
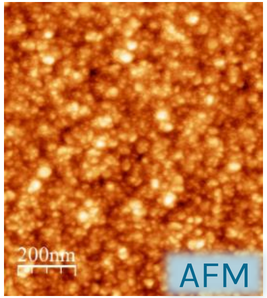


Other

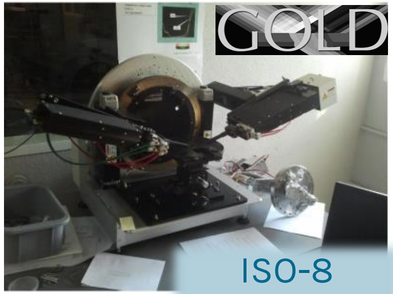


SEM



AFM

Ellipsometry



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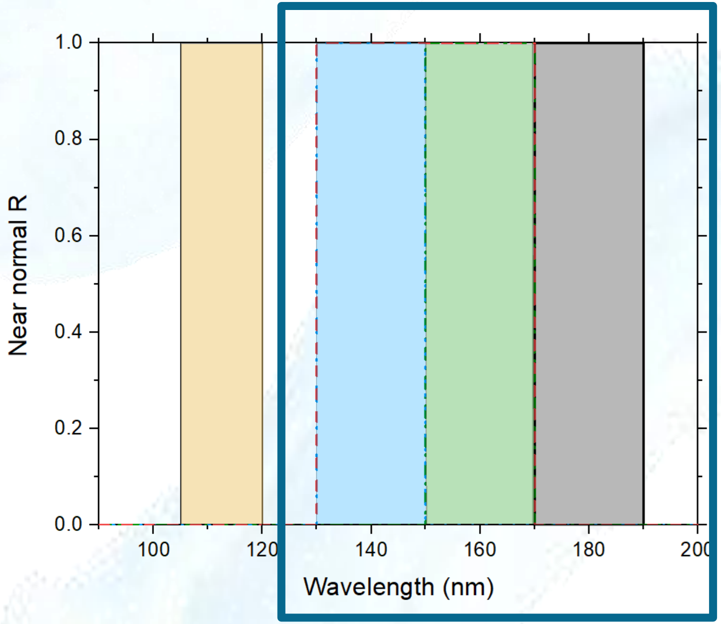

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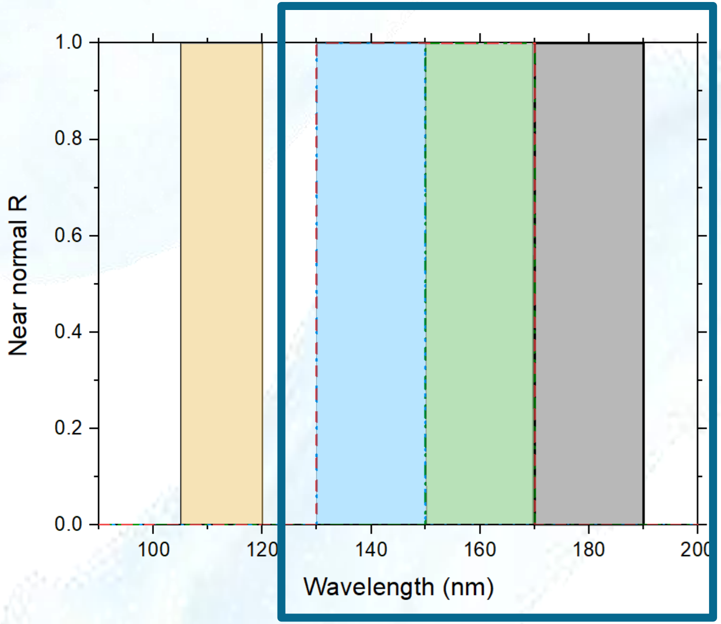
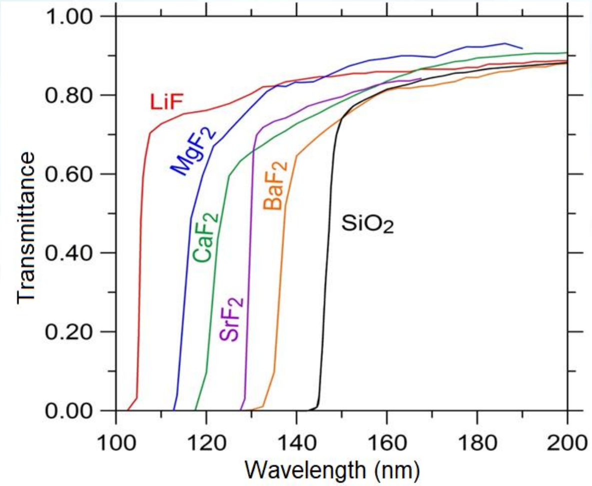


Fluorides: shortest cutoff



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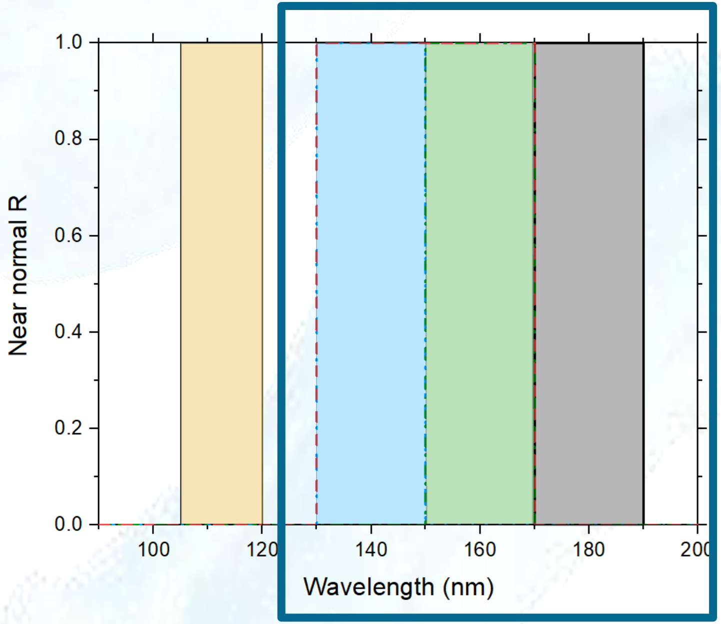

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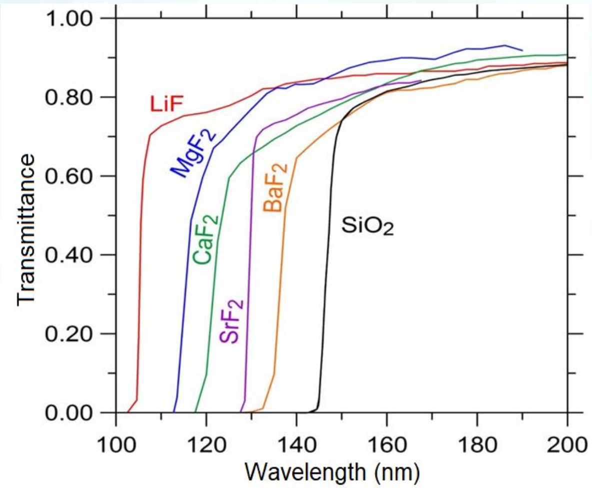

Low Index	High index
MgF_2, AlF_3, LiF…	LaF_3, GdF_3, LuF_3…

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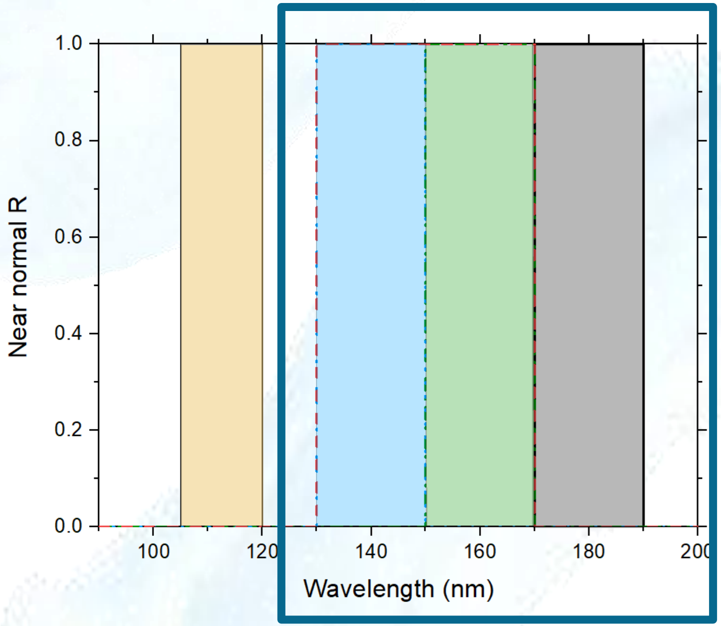

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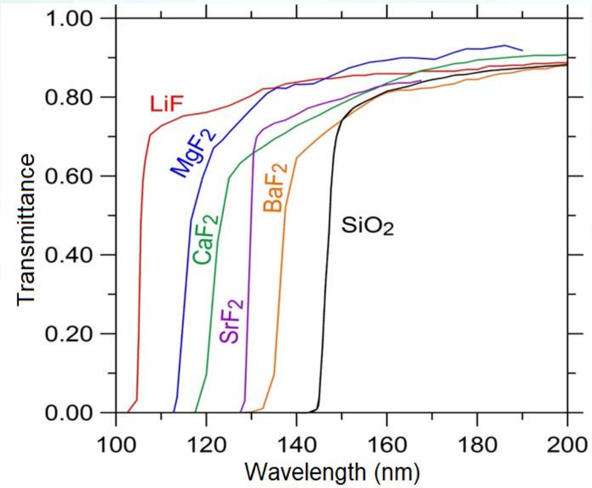

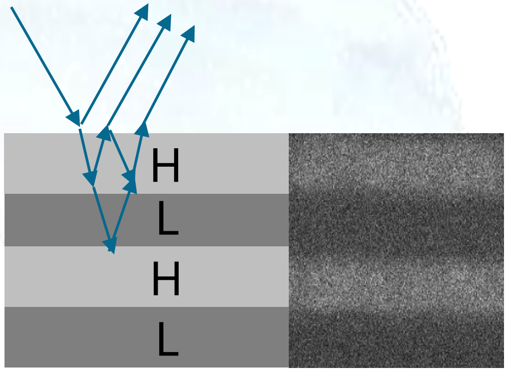

Contribution of many interfaces:
Multilayer

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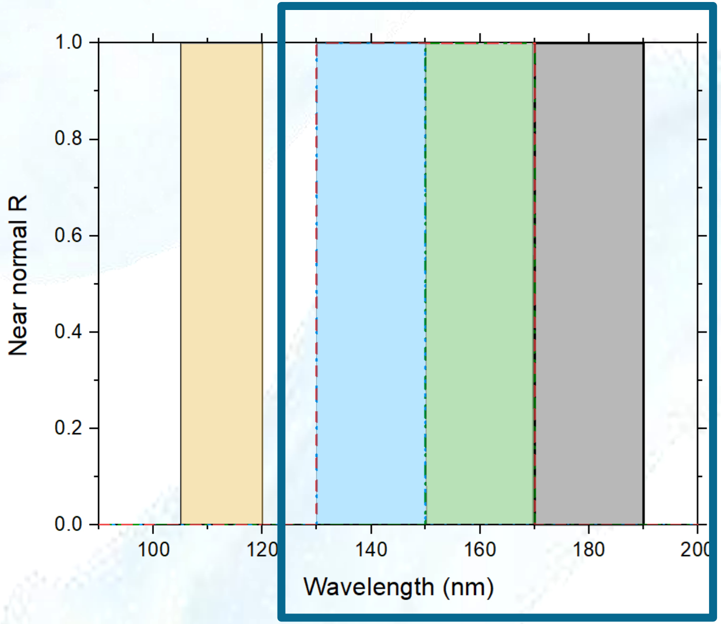

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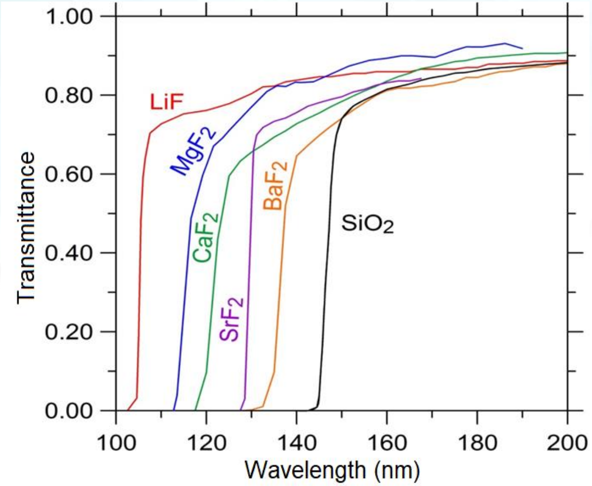

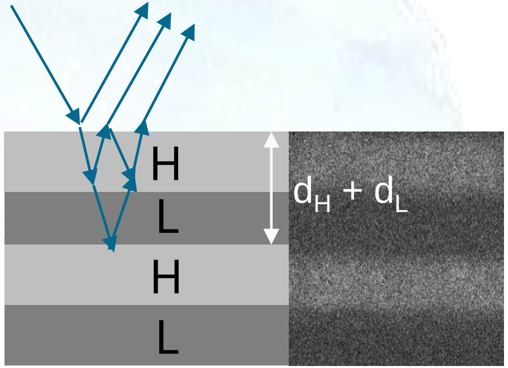

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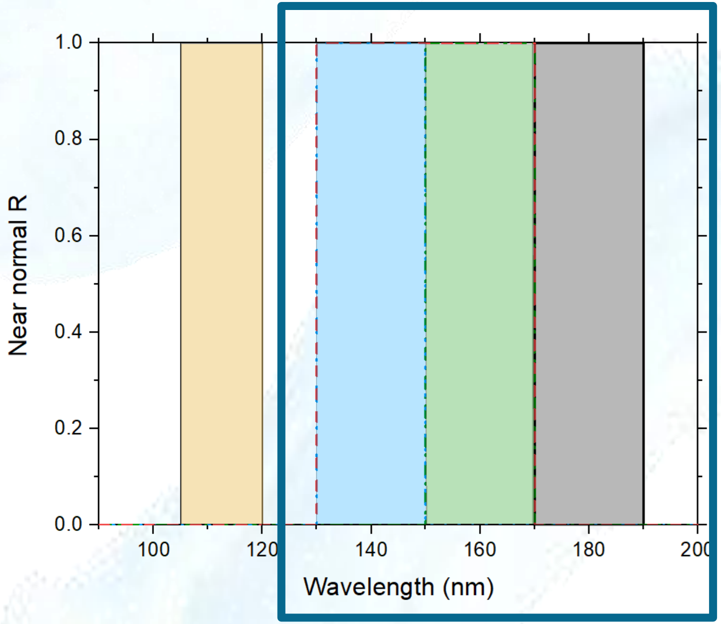
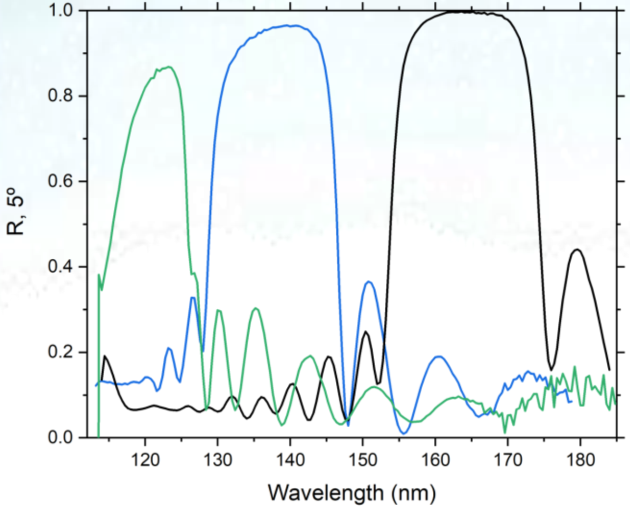
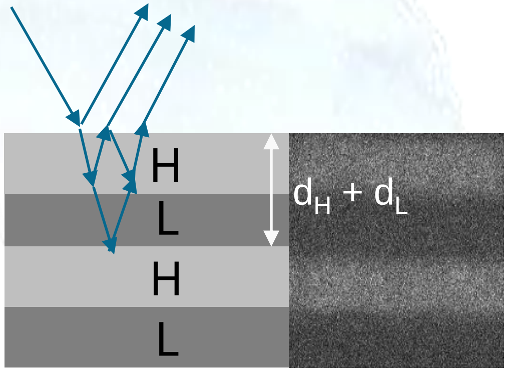
$$d_L * n_H = d_H * n_H = \frac{\lambda}{4}$$

Quarterwave design $(H/L)^m$

Results: tunable bands in the FUV @ λ≥120 nm







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Objectives:

- High throughput
- Optically stable
- Mechanically stable

Results: tunable bands in the FUV @ $\lambda \geq 120$ nm

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Challenges:

- Stress-related problems
- Material's stability

Results: tunable bands in the FUV @ λ≥120 nm

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Fluorides are more transparent:
✓Thermal evaporation
✓**Hot deposited**

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Typical fluoride CTE ~8-15 x10^{-6} /°C

Substrate	CTE α (10^{-6}/°C)
Fused Silica (FS)	0.55
BK7	7.1
Silicon	2.8

Challenges:

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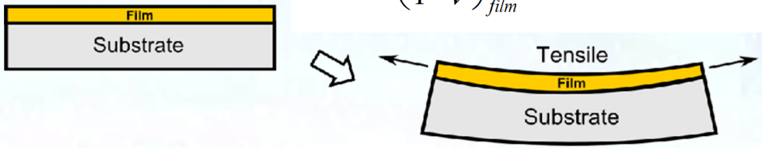
$$\sigma_{therm} = \left(\frac{E}{1-\nu}\right)_{film} \left(\alpha_{sub} - \alpha_{film}\right)\left(T - T_d\right)$$



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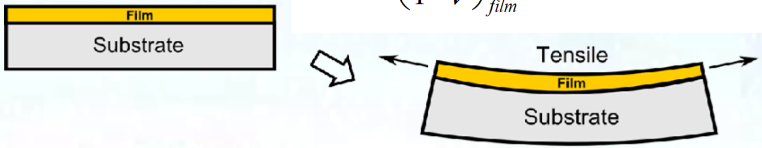
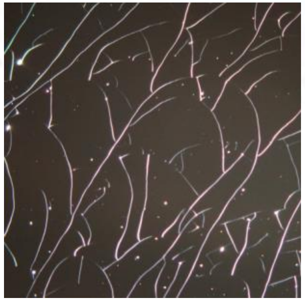


large stress + high thickness

↓

Cracks & delamination



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Challenges:

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- Material's stability

Results: tunable bands in the FUV @ $\lambda \geq 120$ nm

Technology needs to be optimized

Reflectance and mechanical stability will depend on:

1. Design (number of bilayers)
2. Deposition temperature
3. Substrate
4. Coating materials

$$\sigma_{therm} = \left(\frac{E}{1-\nu}\right)_{film} \left(\alpha_{sub} - \alpha_{film}\right)\left(T - T_d\right)$$

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~R increases up to 13-15 bilayers at ~250ºC while stress, cracks, and scattering are acceptable

López-Reyes, P., et al. *Optical Materials Express*, *11*(6), 2021

López-Reyes, P., et al. *Optical Materials Express*, *12*(2), 2022

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CaF_2	18.85

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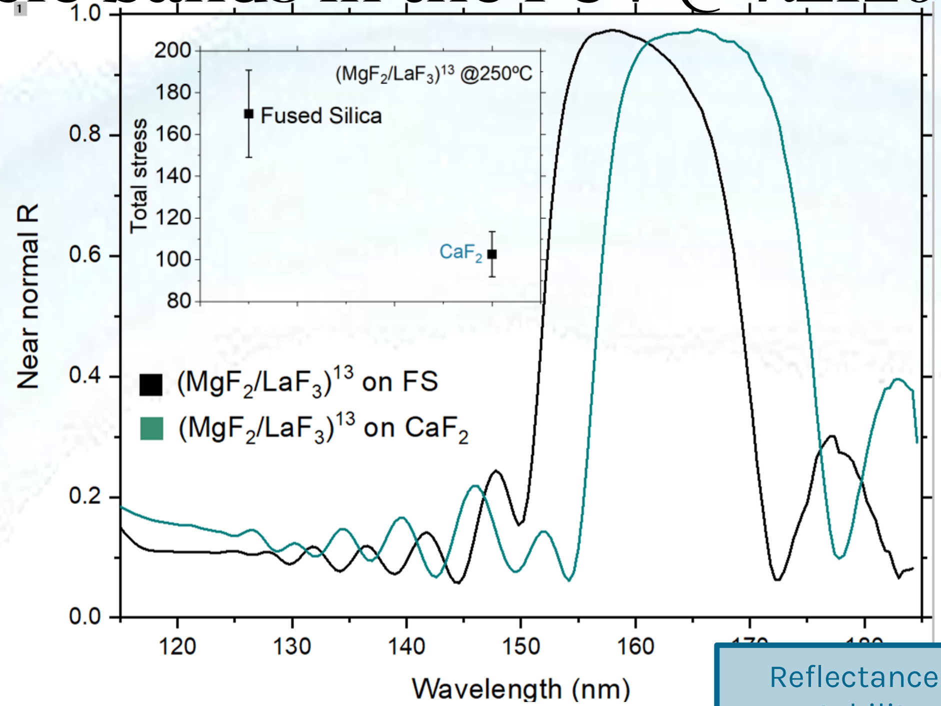

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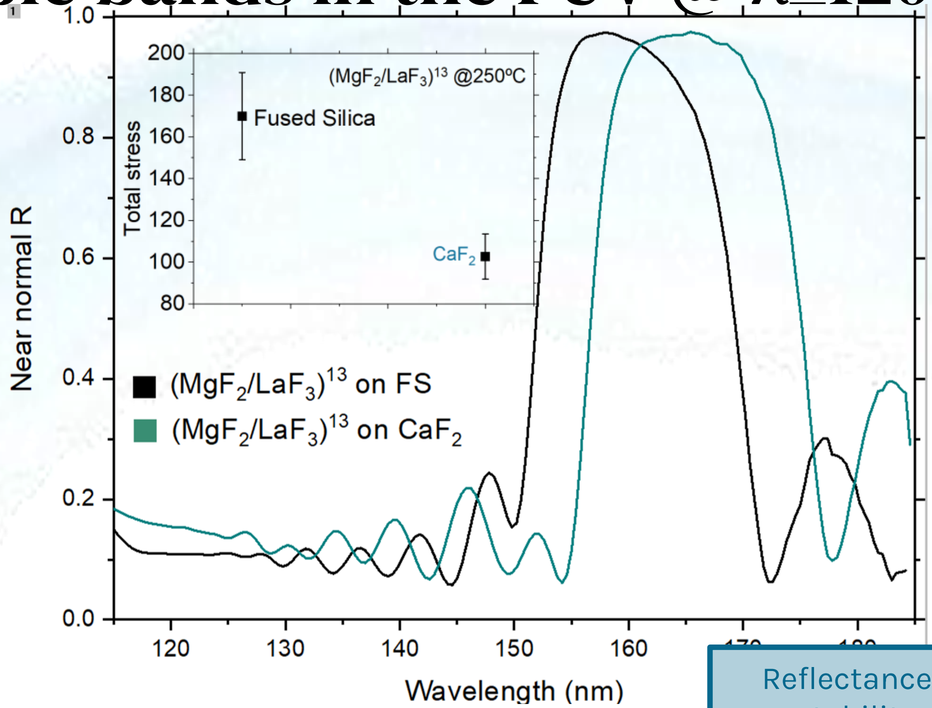

….but you can't always choose the substrate
Other parameters: manageability, price, tolerance to thermal changes, polish, shape….

Reflectance and mechanical stability will depend on:
1. Design (number of bilayers)
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3. **Substrate**
4. Coating materials

Results: tunable bands in the FUV @ λ≥120 nm

4. Coating materials

Low Index	High index
LiF, MgF_2, AlF_3...	LaF_3, GdF_3, LuF_3...

Typical combination

Reflectance and mechanical stability will depend on:

1. Design (number of bilayers)
2. Deposition temperature
3. Substrate
4. **Coating materials**

Results: tunable bands in the FUV @ λ≥120 nm

4. Coating materials

Low Index	High index
~~LiF~~, MgF_2, AlF_3...	LaF_3, ~~GdF_3~~, LuF_3...

Typical combination

Reflectance and mechanical stability will depend on:

1. Design (number of bilayers)
2. Deposition temperature
3. Substrate
4. **Coating materials**

Results: tunable bands in the FUV @ λ≥120 nm

4. Coating materials

Low Index	High index
~~LiF~~, MgF_2, AlF_3...	LaF_3, ~~GdF_3, LuF_3~~...

Typical combination

Promising new combination

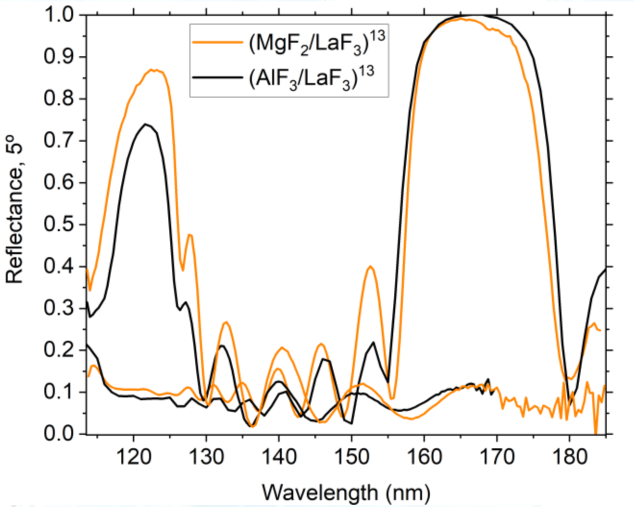
$AlF_3 + LaF_3$

Reflectance and mechanical stability will depend on:

1. Design (number of bilayers)
2. Deposition temperature
3. Substrate
4. **Coating materials**

Results: tunable bands in the FUV @ λ≥120 nm

4. Coating materials



$(AlF_3/LaF_3)^m$:

✓ higher reflectance

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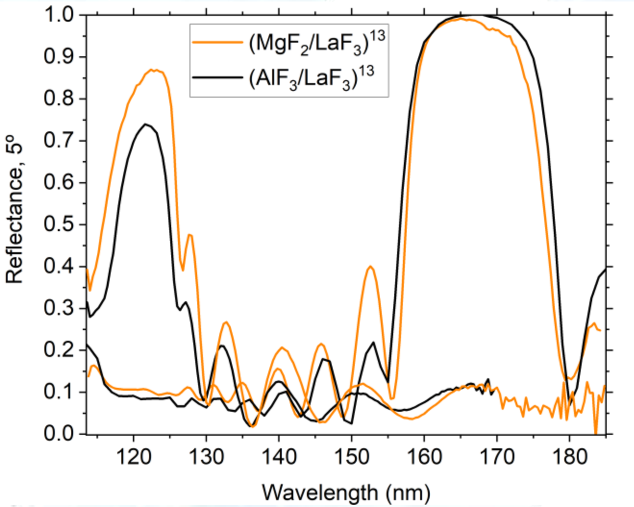

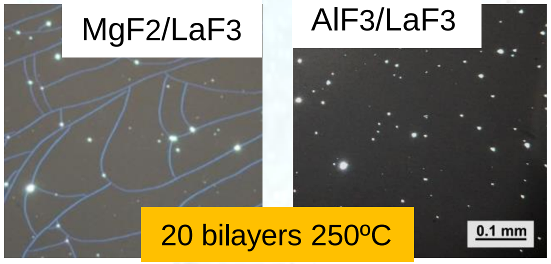

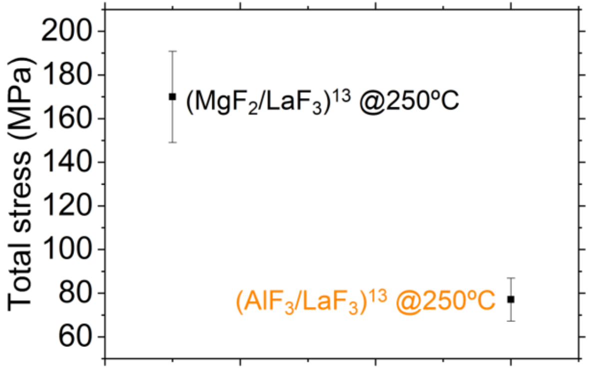

$(AlF_3/LaF_3)^m$:

- ✓ higher reflectance
- ✓ lower stress

Reflectance and mechanical stability will depend on:

1. Design (number of bilayers)
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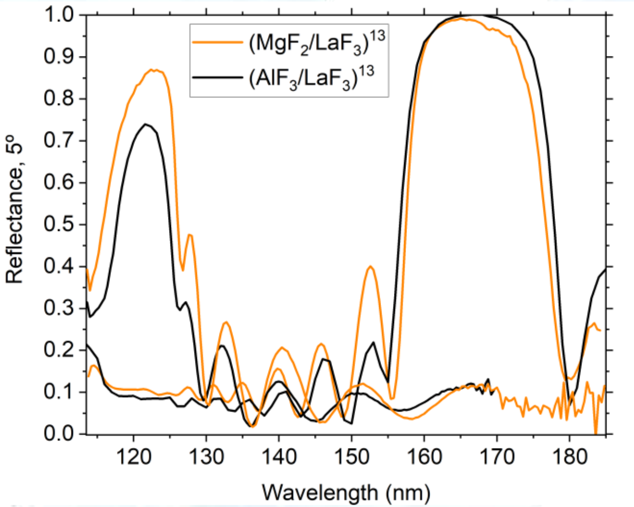
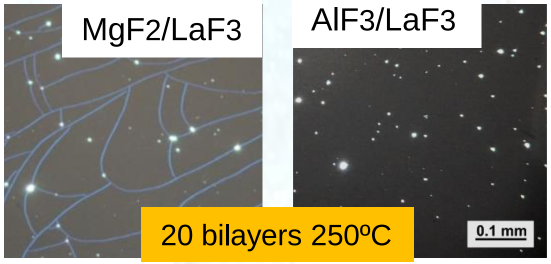
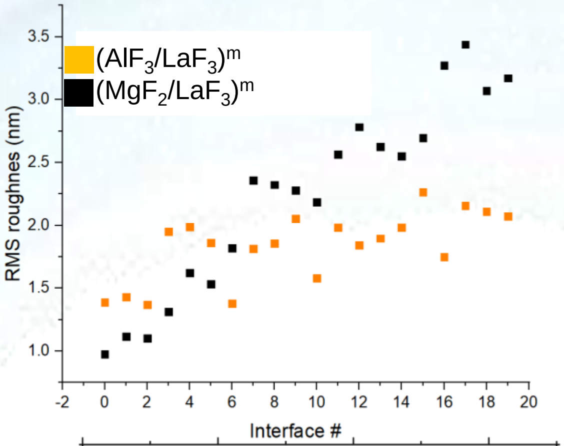
3. Substrate
4. **Coating materials**

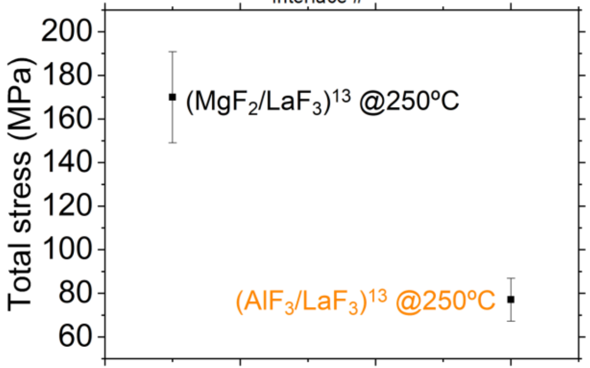
Results: tunable bands in the FUV @ λ≥120 nm

4. Coating materials



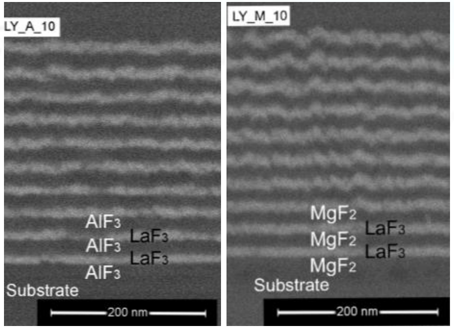






$(AlF_3/LaF_3)^m$:

✓ higher reflectance
✓ lower stress
✓ smaller roughness



Reflectance and mechanical stability will depend on:

1. Design (number of bilayers)
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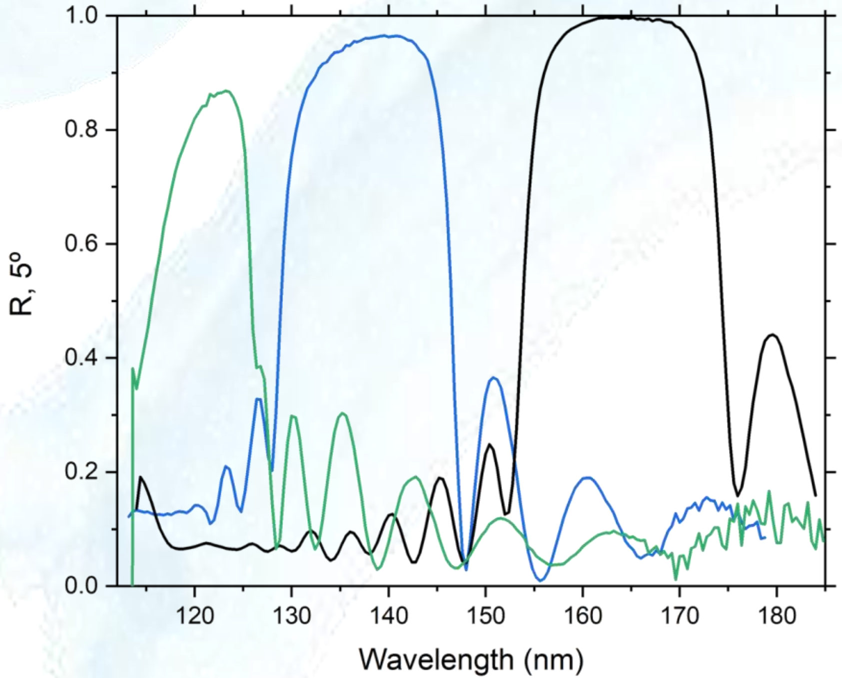
3. Substrate
4. **Coating materials**

Results: tunable bands in the FUV @ λ≥120 nm

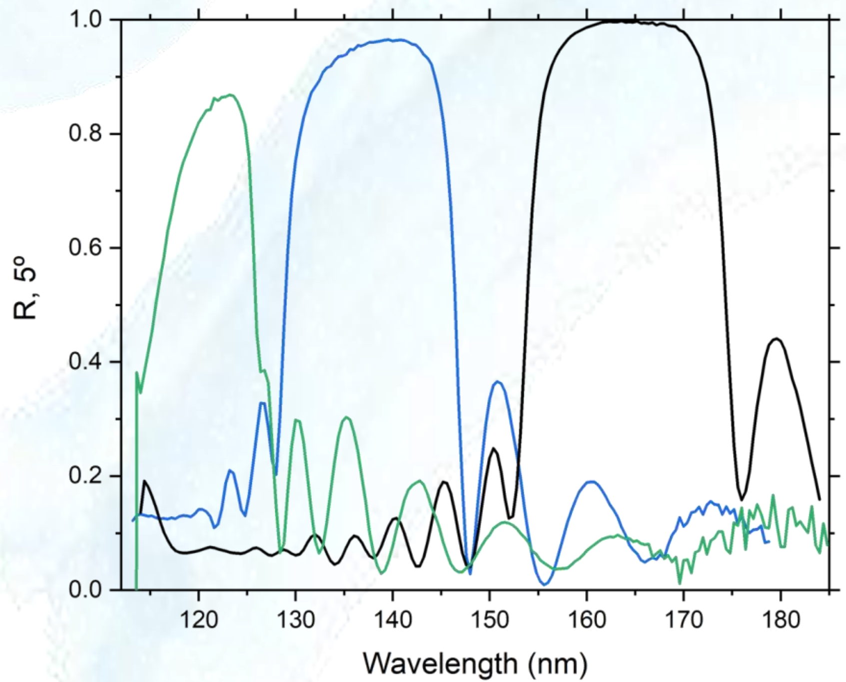
SUMMING UP:



Best result:
$(AlF_3/LaF_3)^m$ at
~250ºC

Results: tunable bands in the FUV @ λ≥120 nm

SUMMING UP:

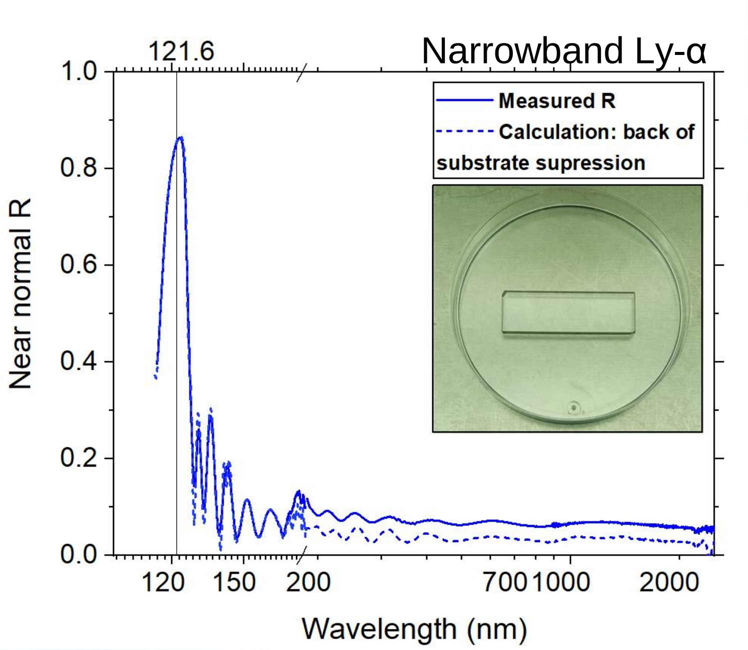


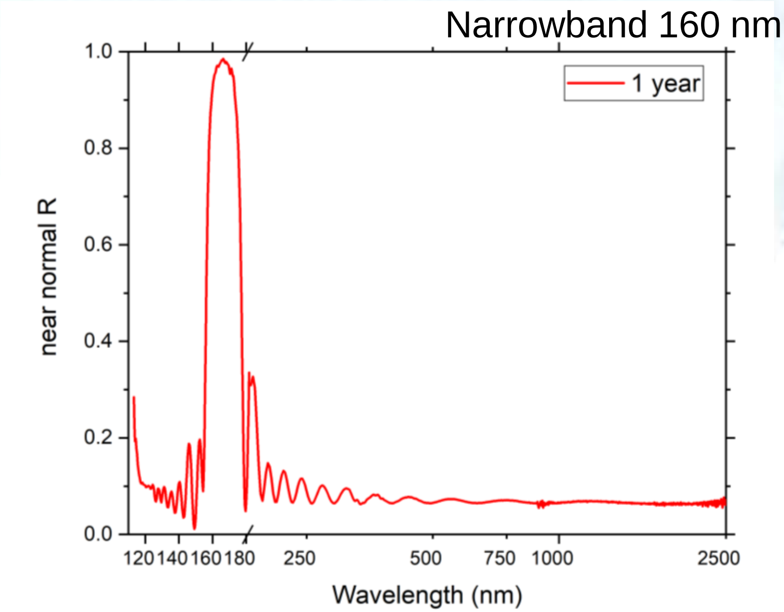
Best result:
$(AlF_3/LaF_3)^m$ at ~250ºC

- Tuneable in any wavelength λ ≥ 120 nm
- FWHM ~ 10 – 20 nm
- Reflectance > 85%

Results: tunable bands in the FUV @ λ≥120 nm

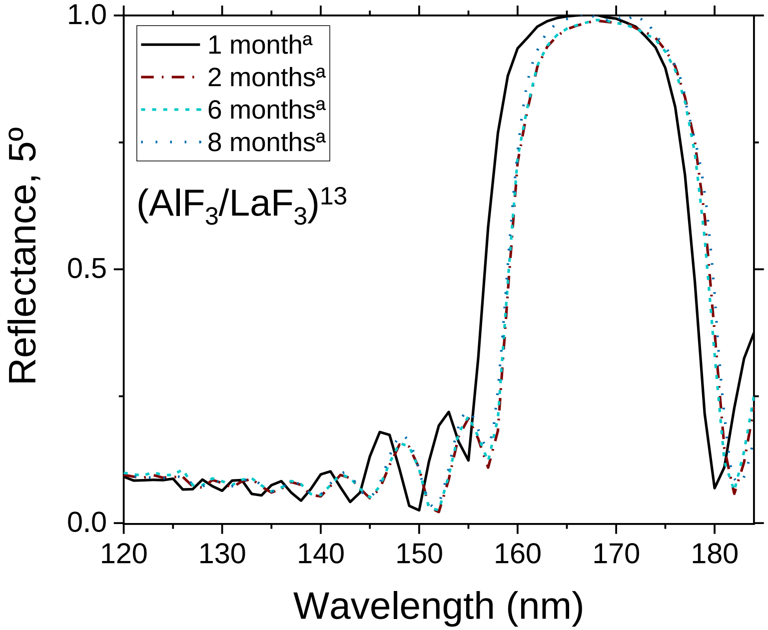
Reflectance in the visible and NIR:





Results: tunable bands in the FUV @ λ≥120 nm

Ageing in different environments:

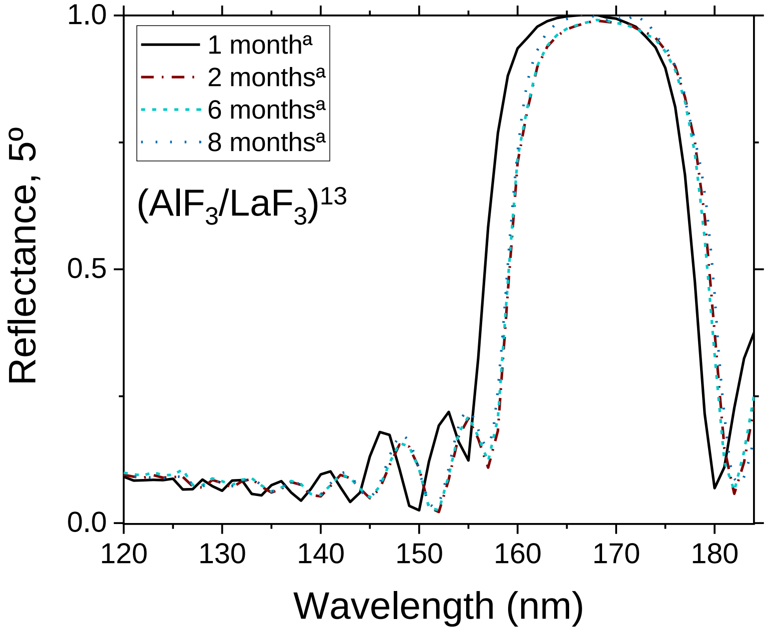


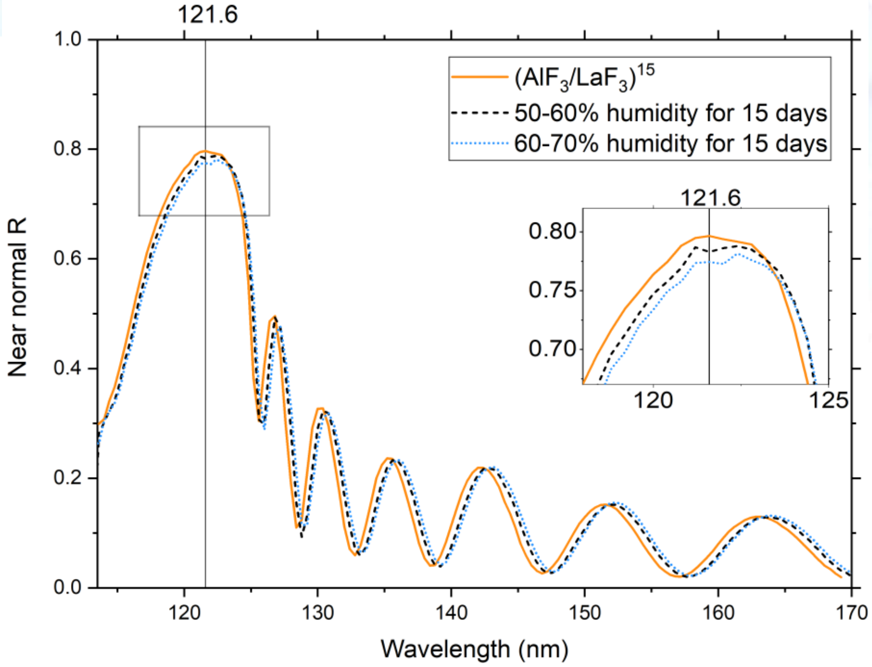
[a]Measured at NASA/Goddard

Relatively good ageing on different environments

Results: tunable bands in the FUV @ λ≥120 nm

Ageing in different environments:



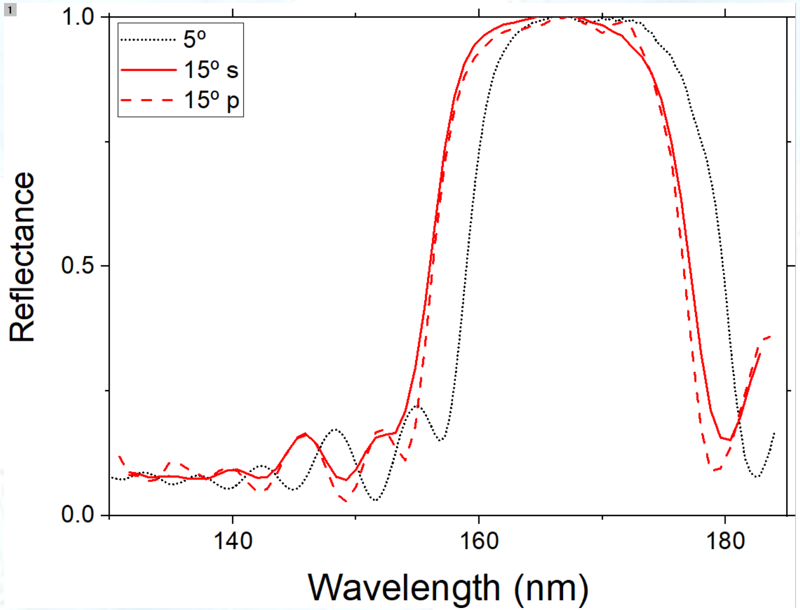


[a]Measured at NASA/Goddard

Relatively good ageing on different environments

Results: tunable bands in the FUV @ $\lambda \geq 120$ nm

Angle effect:

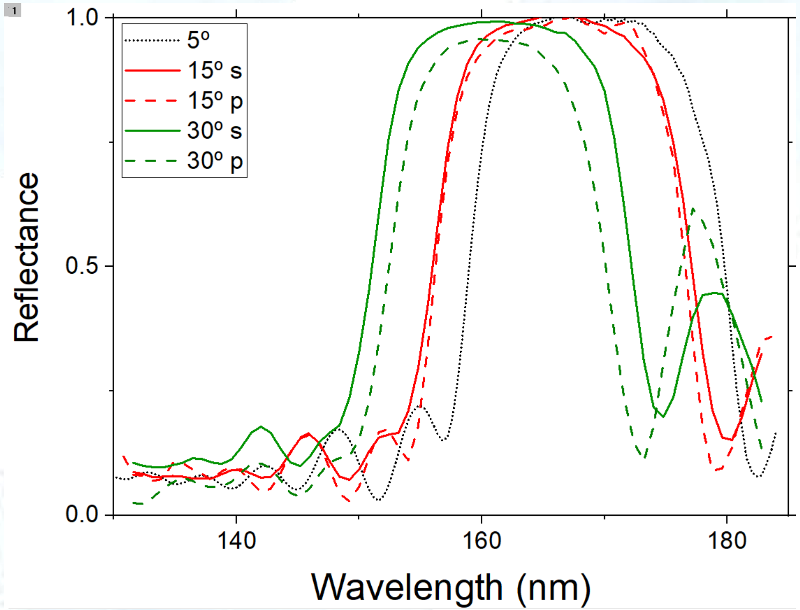


$(AlF_3/LaF_3)_{13}$

At 45º Band shifts ~15 nm
Coating can be designed to work at any angle
by changing the thicknesses

Results: tunable bands in the FUV @ λ≥120 nm

Angle effect:



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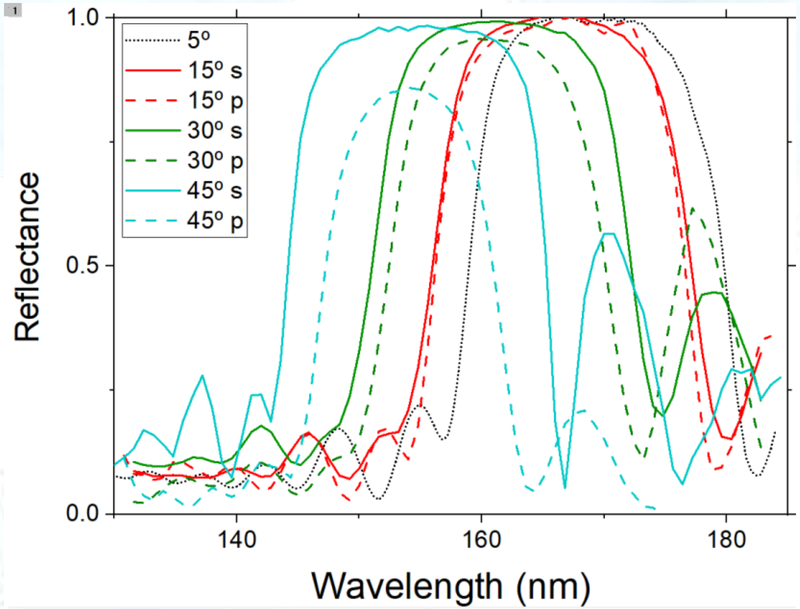

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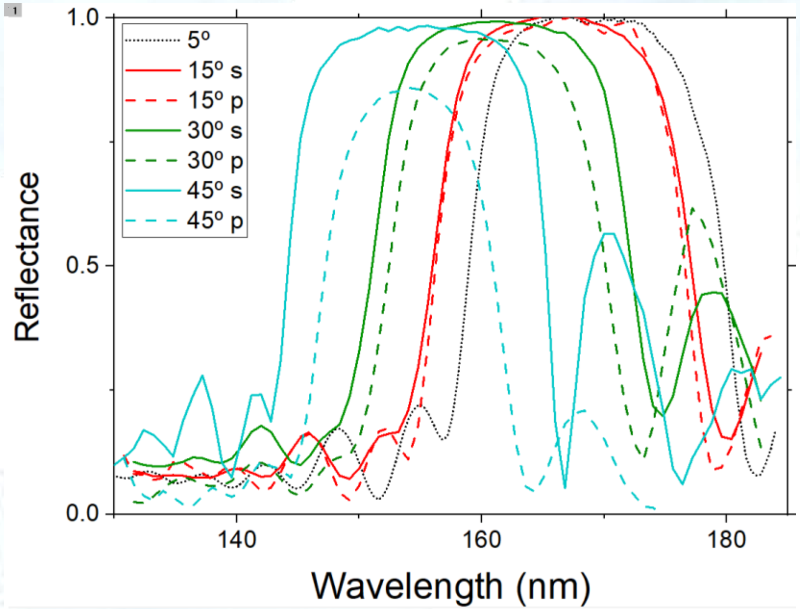

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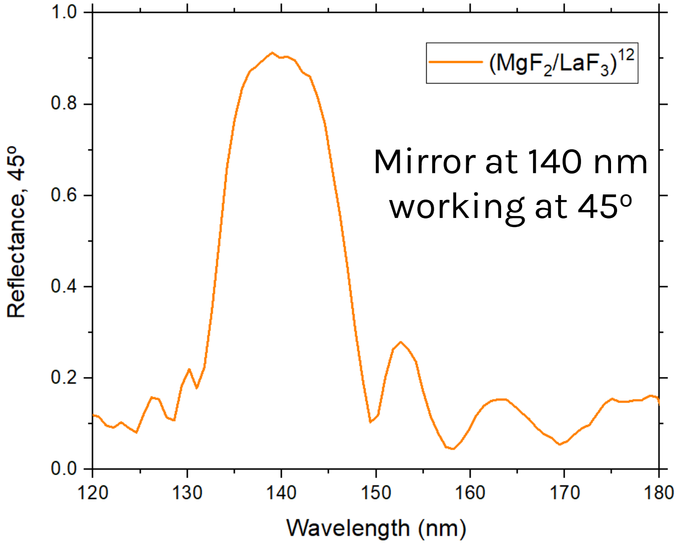
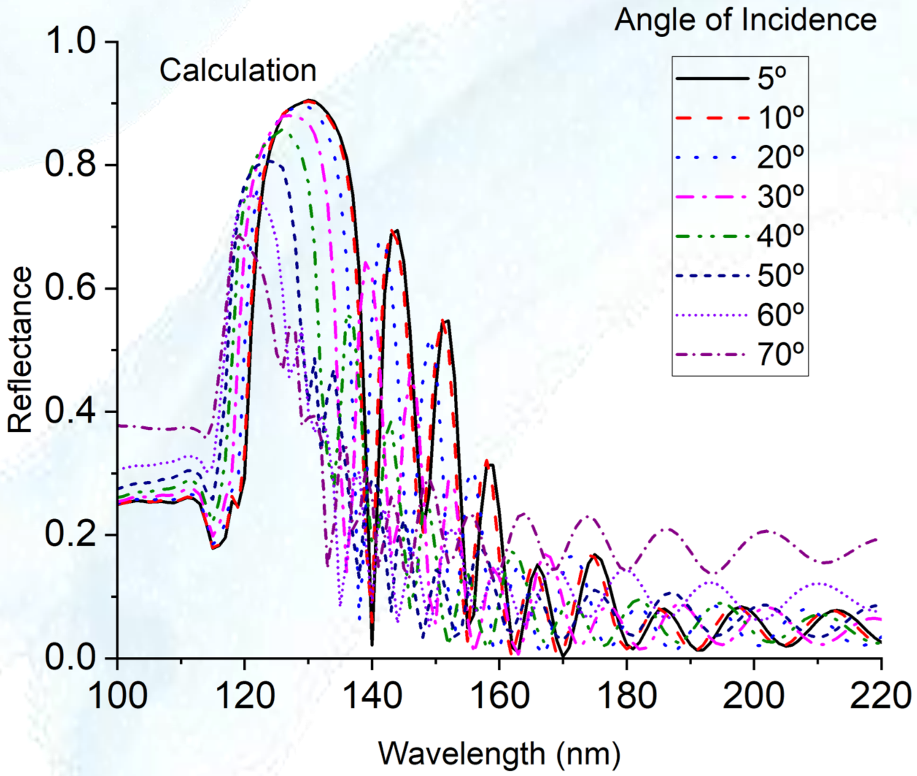


Results: tunable bands in the FUV @ λ≥120 nm

Angle effect:



Special design to reduce the band shift with the angle of incidence

Outline

- **Our group**
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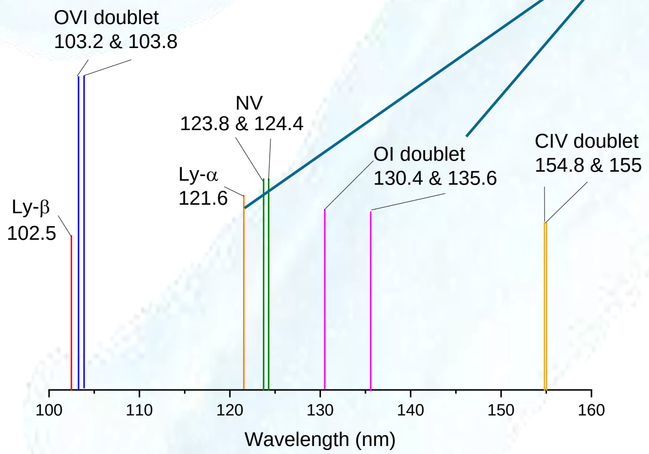
  - Future observatories
- **Experimental and facilities**
- **Results**
  - Tunable narrow bands in the FUV
  - Spectral line selection
  - Narrow bands in the LUV
  - Other coatings
- **Conclusions**

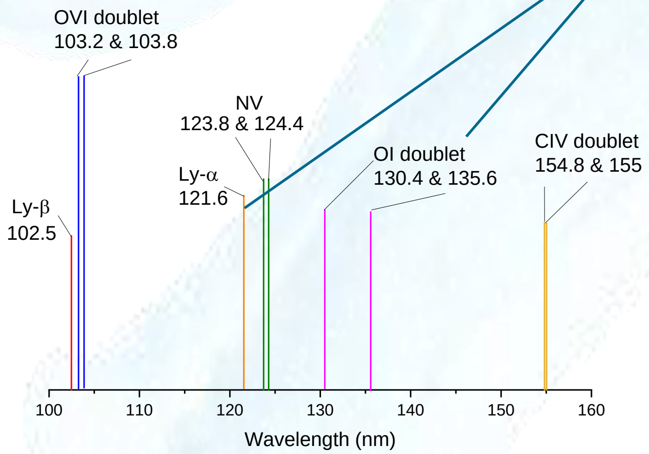
Results: spectral line selection



Two close lines can mask one another:

- H Ly-α observations in the atmosphere can be masked with the OI geocoronal emission
- OI observations for exoplanet searching can be masked with the strong Ly-α solar emission

Results: spectral line selection



Two close lines can mask one another:

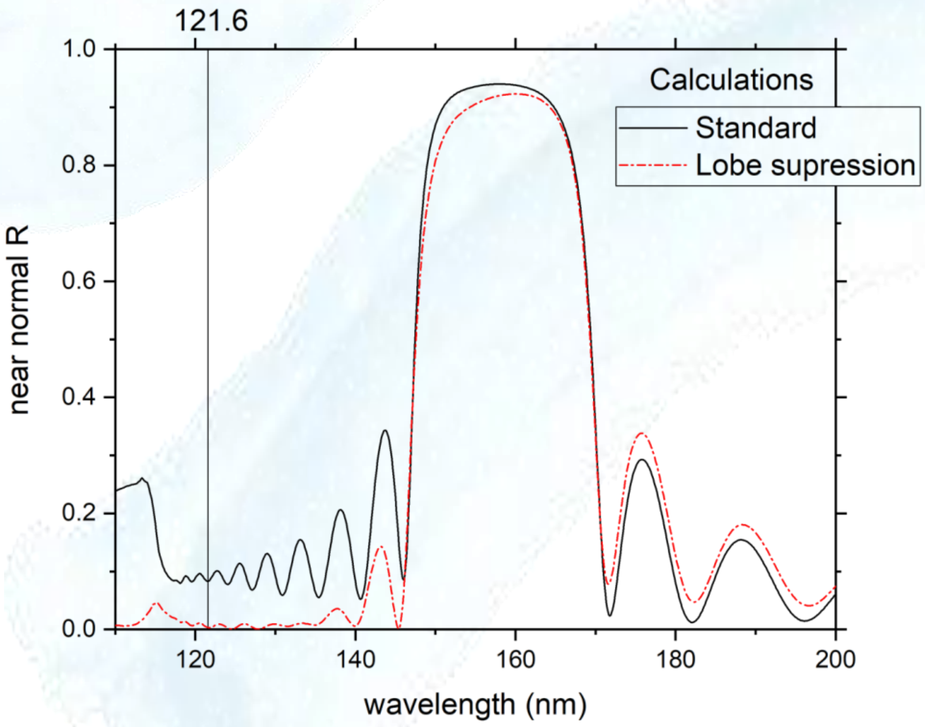
- H Ly-α observations in the atmosphere can be masked with the OI geocoronal emission
- OI observations for exoplanet searching can be masked with the strong Ly-α solar emission

Design coatings to reflect one λ and to reject a close λ

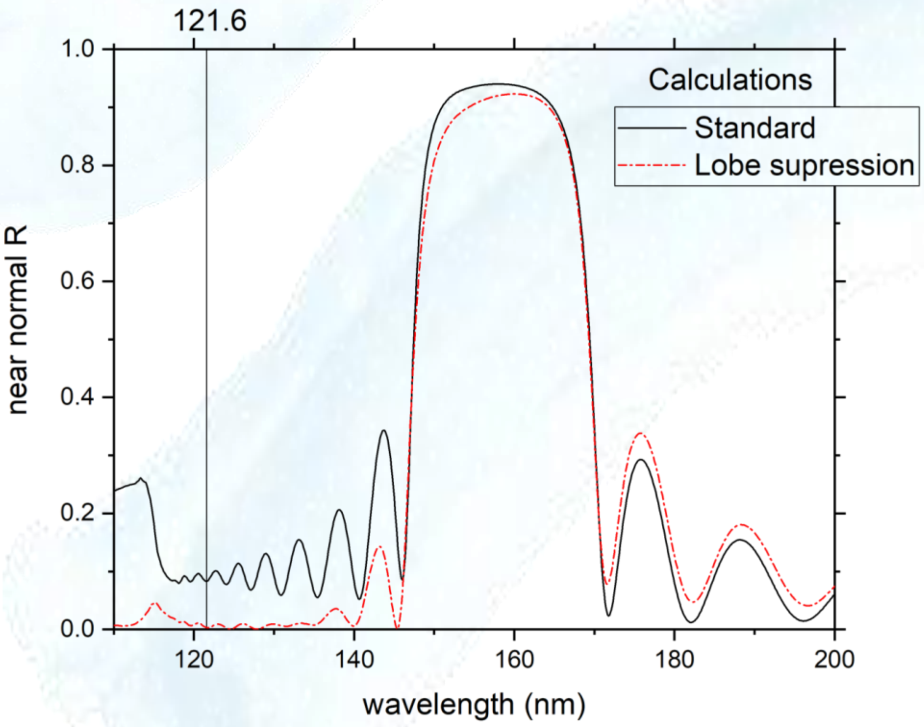
~~quarterwave designs~~

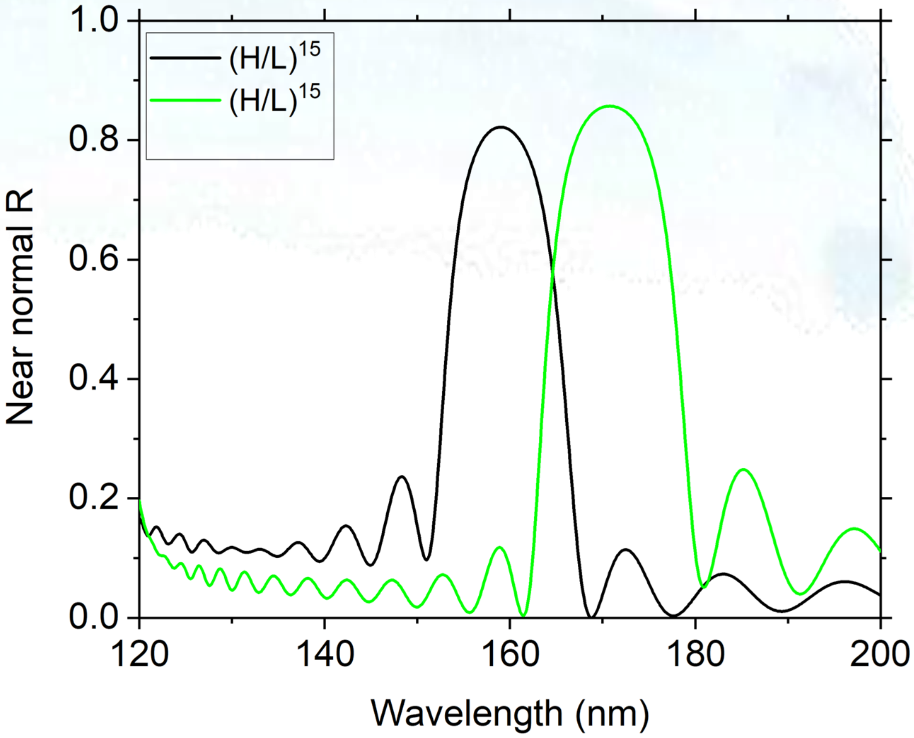
aperiodic thickness

Results: spectral line selection



Results: spectral line selection





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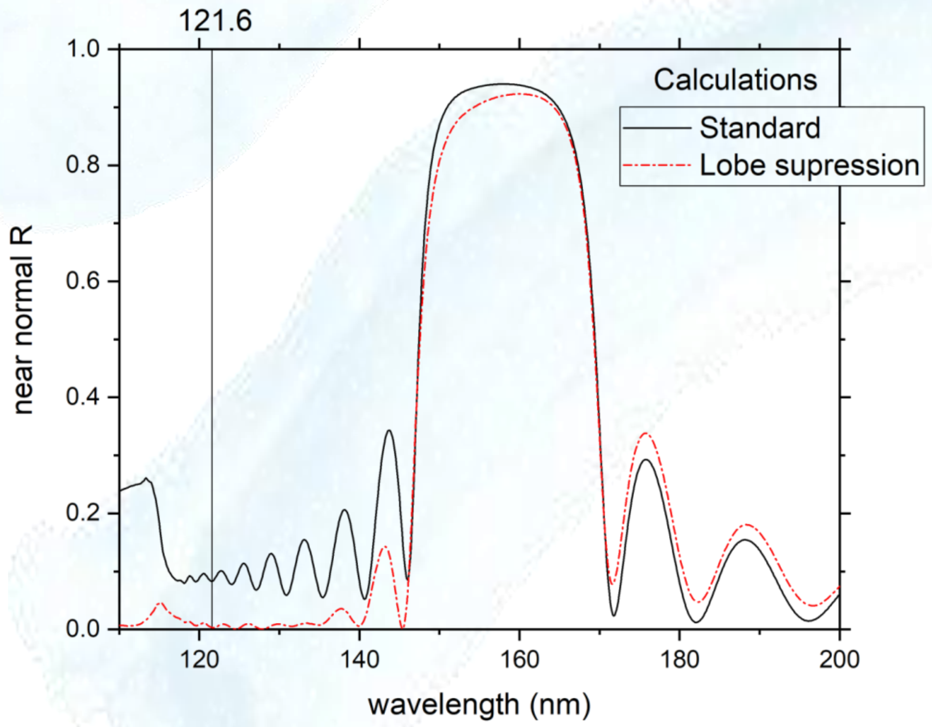
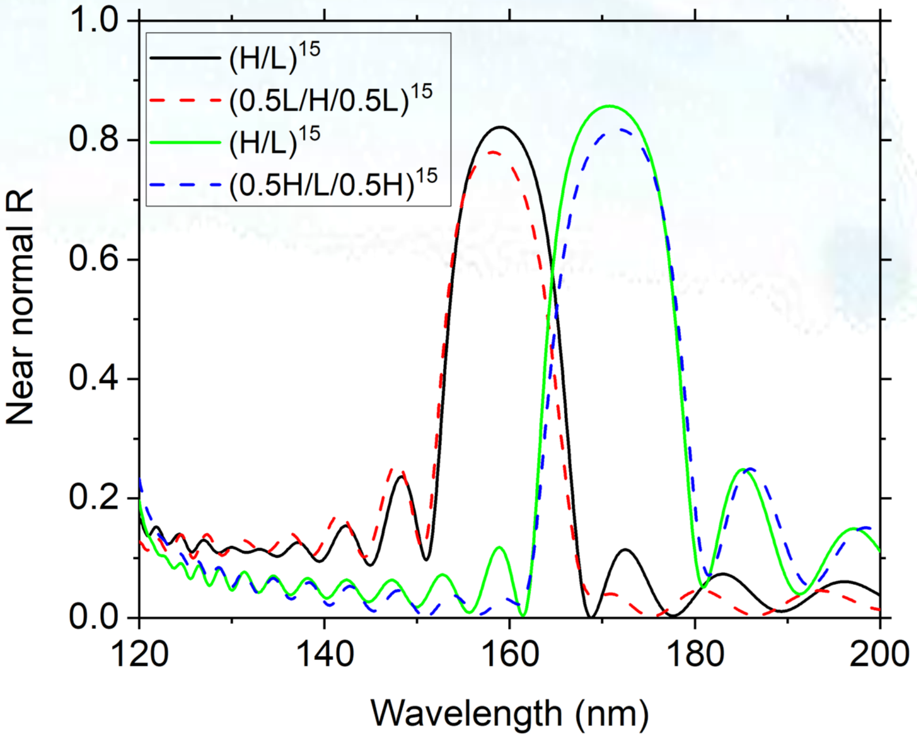
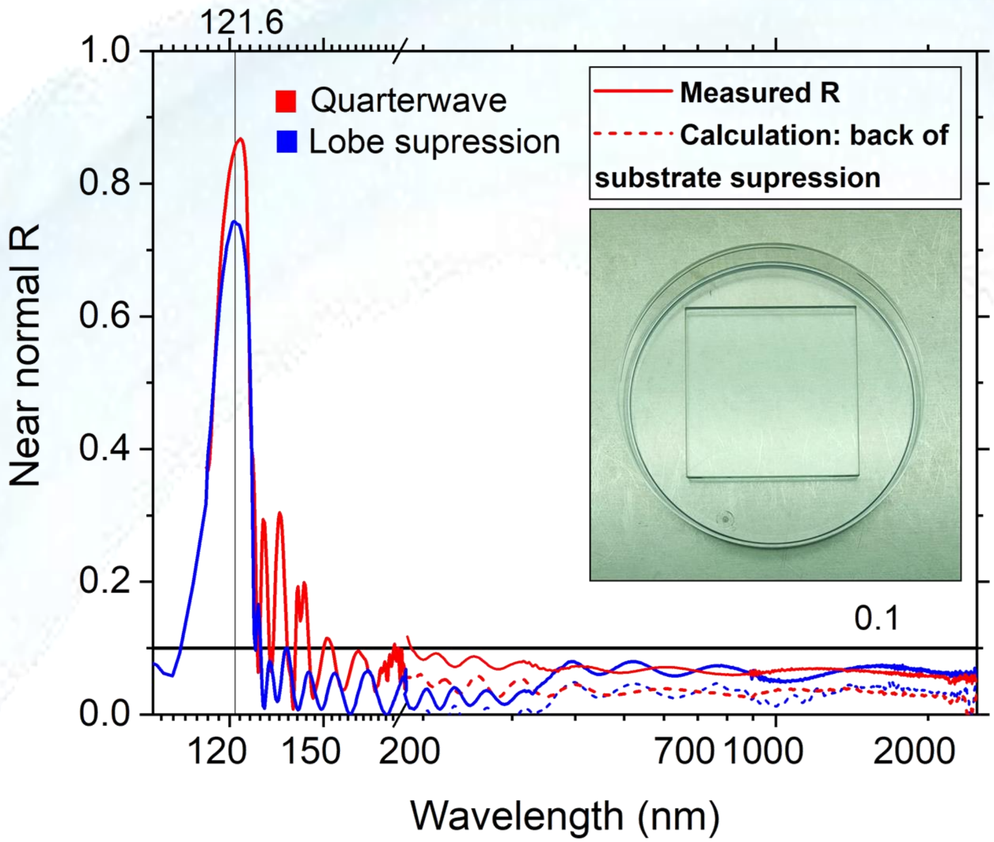
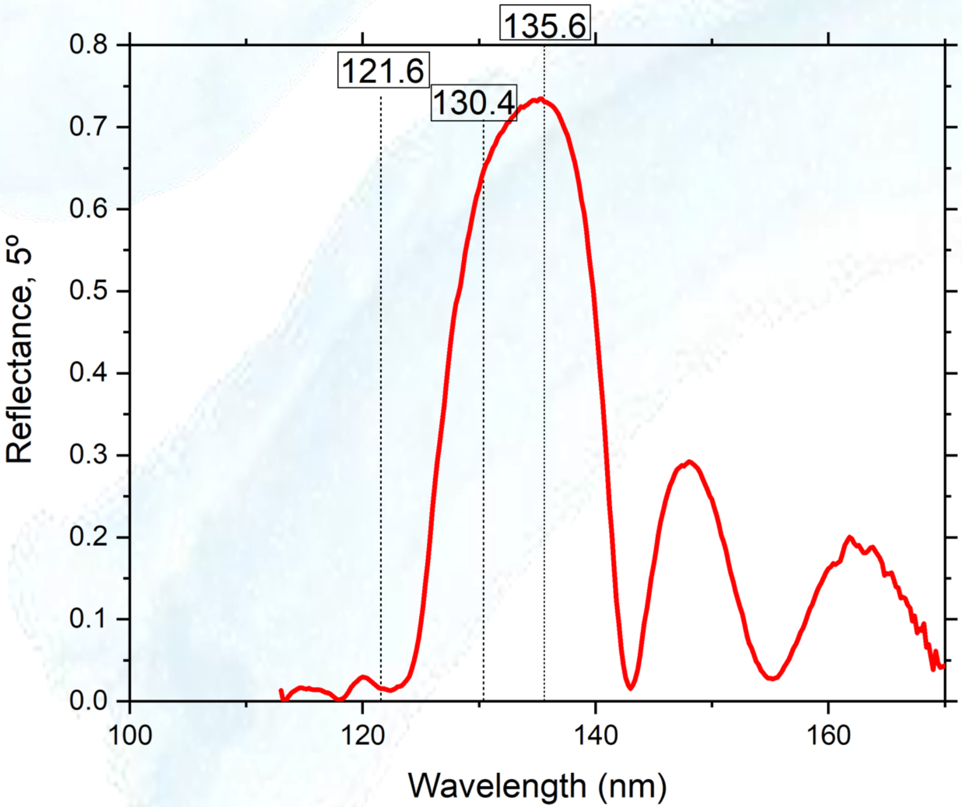




Results: spectral line selection



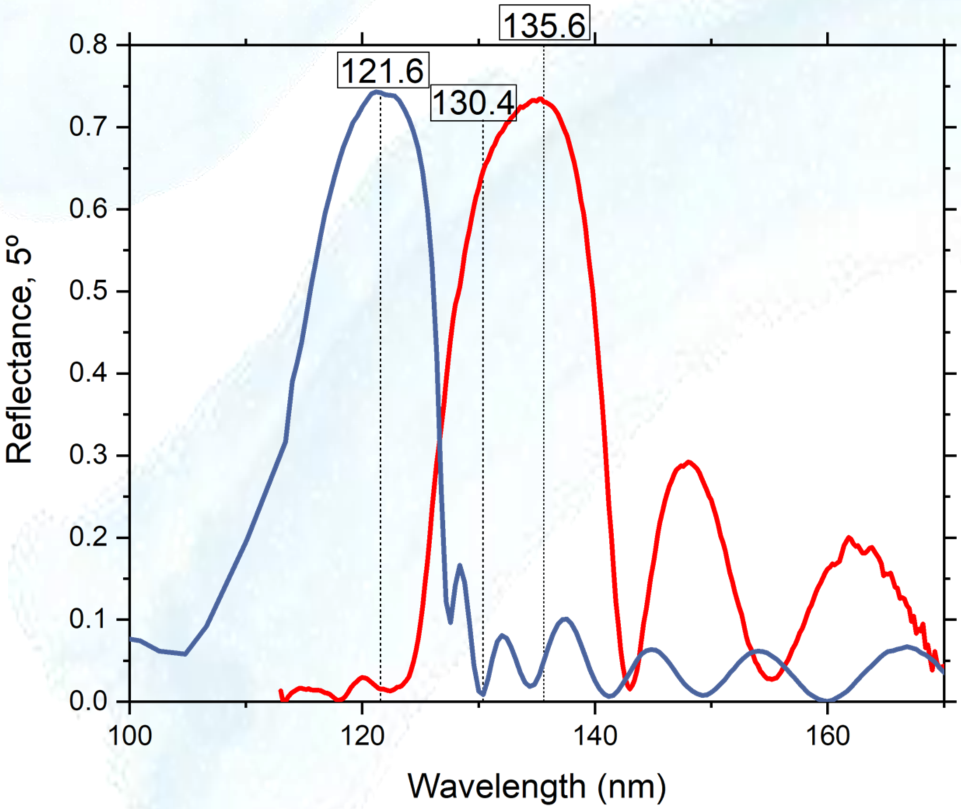
Results: spectral line selection



- Maximum at the OI doublet (130.4 & 135.6 nm) and minimum at Ly-α (121.6 nm)

Exoplanet observation HD 209458 at OI lines
A. Vidal-Madjar et al. 2004

Results: spectral line selection



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A. Vidal-Madjar et al. 2004

Proposed
GLIDE and SIHLA missions imagining at Ly-α
G. D. Krebs, "GLIDE"
L. Paxton et al. 2020

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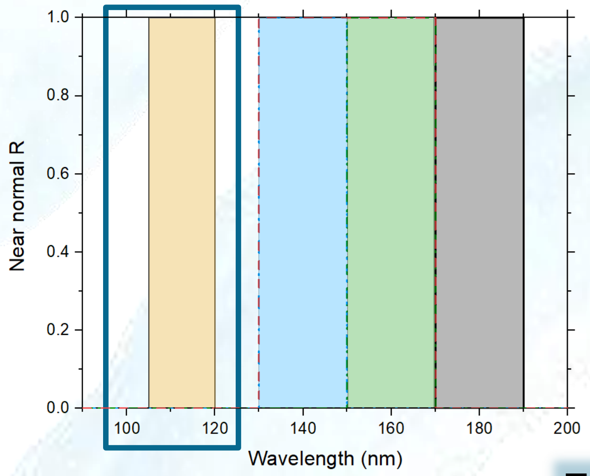
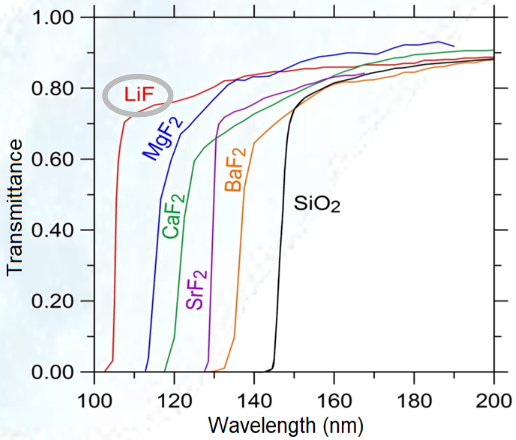
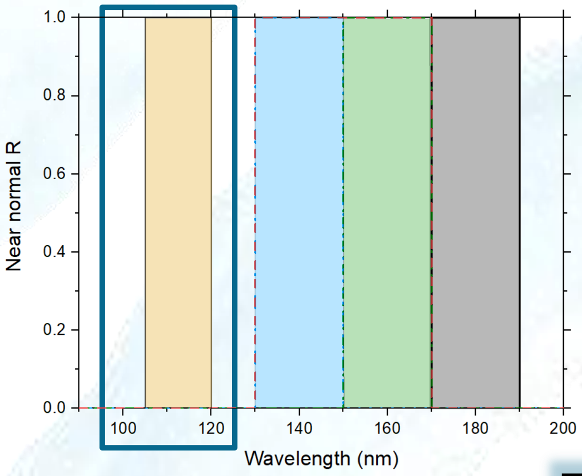
Results: narrowbands in the LUV

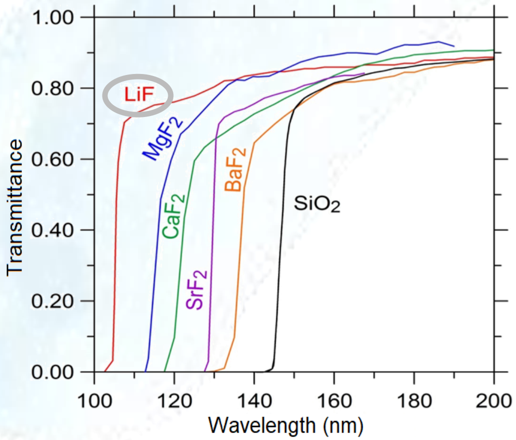




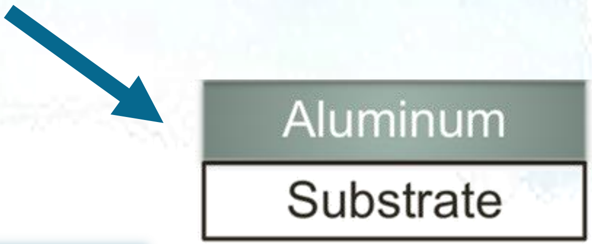
There is no suitable combination of fluorides below 120 nm

Results: narrowbands in the LUV





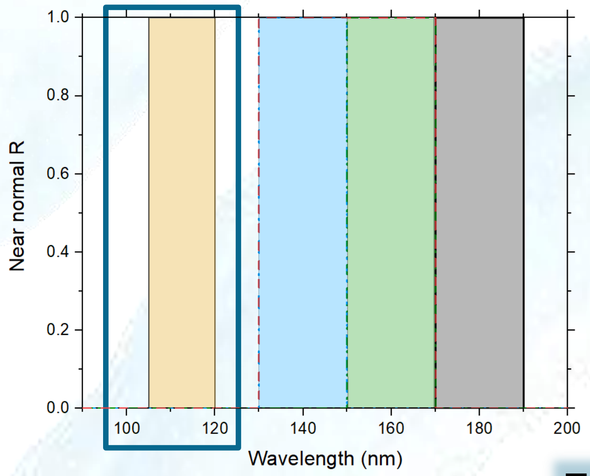
Evaporation

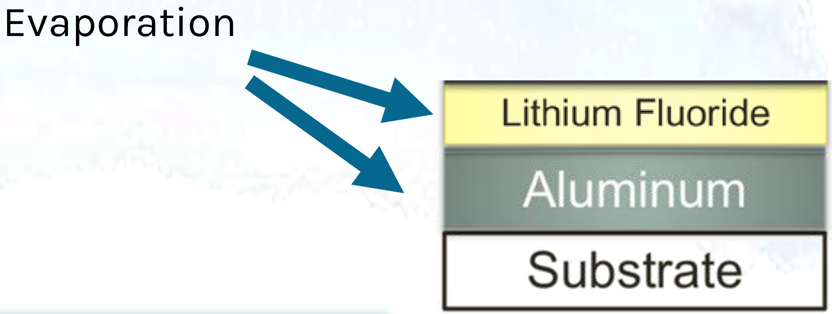


There is no suitable combination of fluorides below 120 nm

- Broadband Al mirrors reflect >80% up to 83 nm

Results: narrowbands in the LUV





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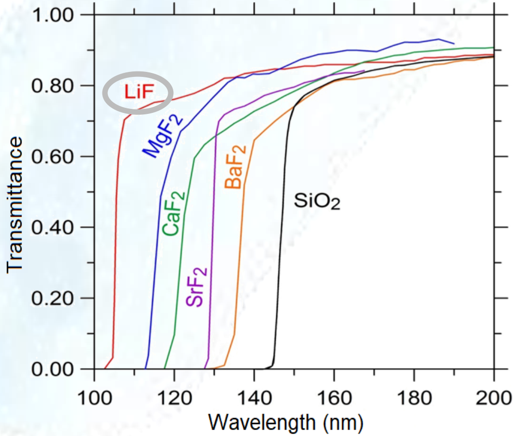
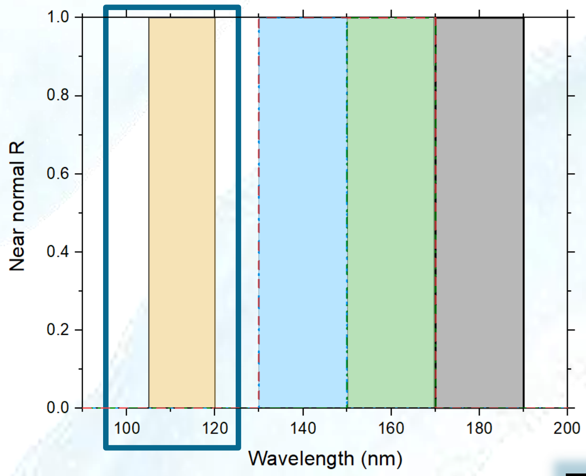
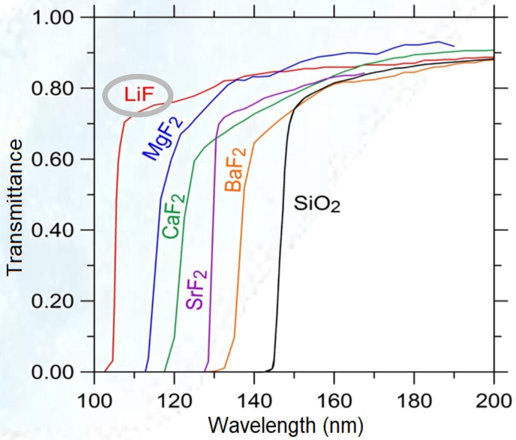
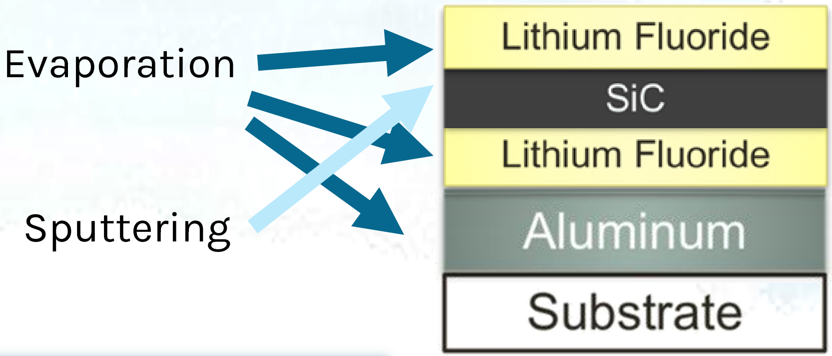


- Broadband Al mirrors reflect >80% up to 83 nm
  - but it must be protected with a fluoride to avoid oxidation

Results: narrowbands in the LUV







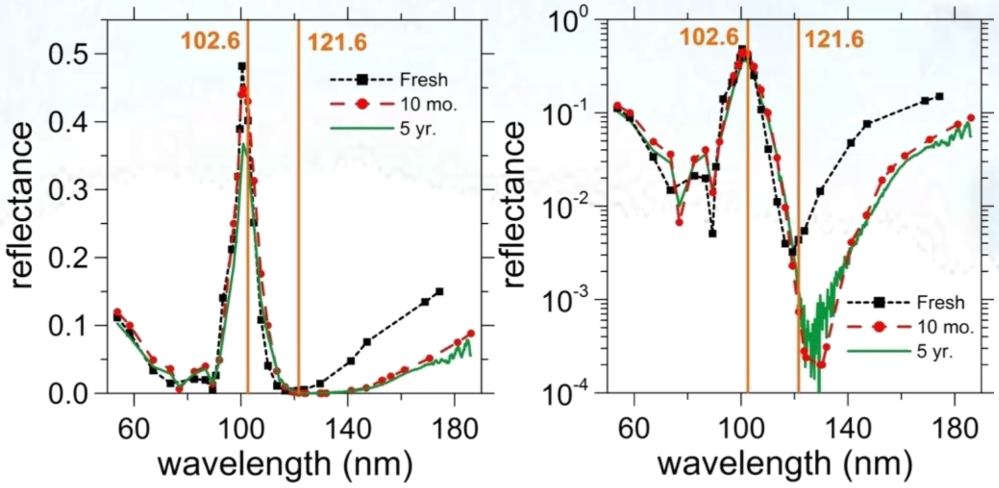
There is no suitable combination of fluorides below 120 nm

- Broadband Al mirrors reflect >80% up to 83 nm
  - but it must be protected with a fluoride to avoid oxidation
    - to make a narrowband we added SiC

Results: narrowbands in the EUV

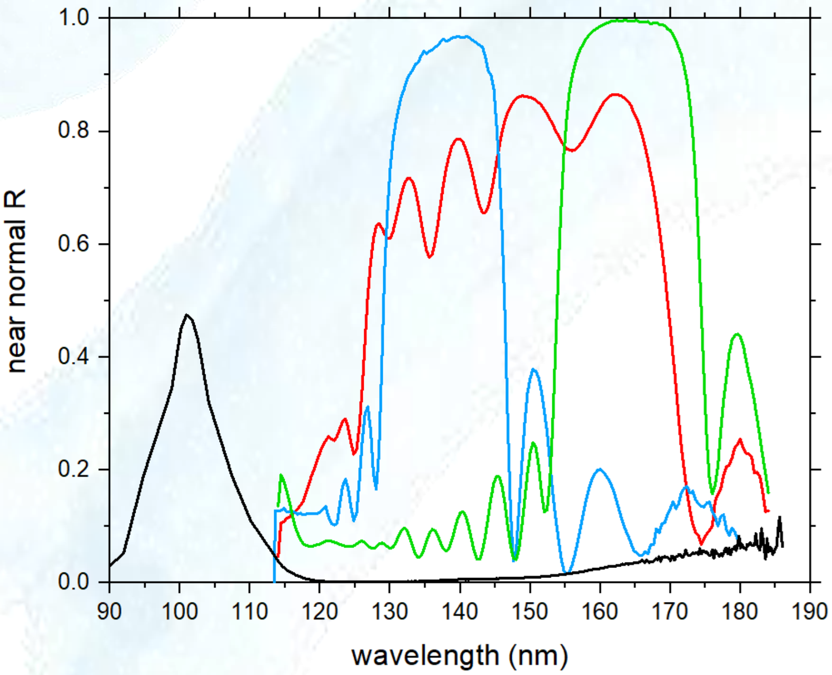
First narrowband coatings peaked close to:

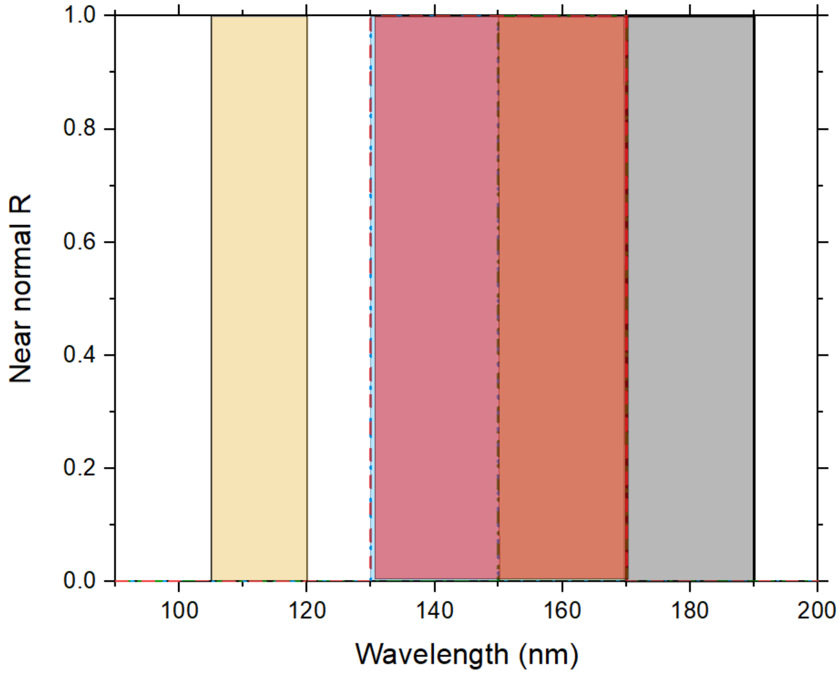
- H Ly β, 102.6 nm
- O VI, 103.2, 103.8 nm
- Strong rejection@ 121.6 nm



Rodríguez de Marcos et al. 2018
Optics Express, 2018, 26(19), pp. 25166-25177

Results: narrowbands in the EUV/FUV





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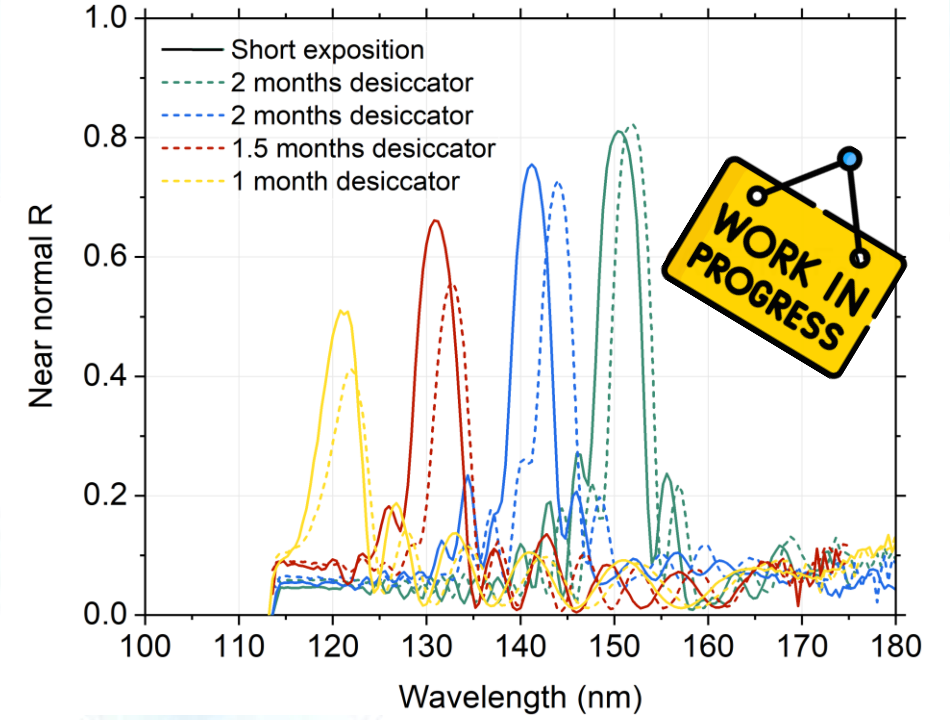
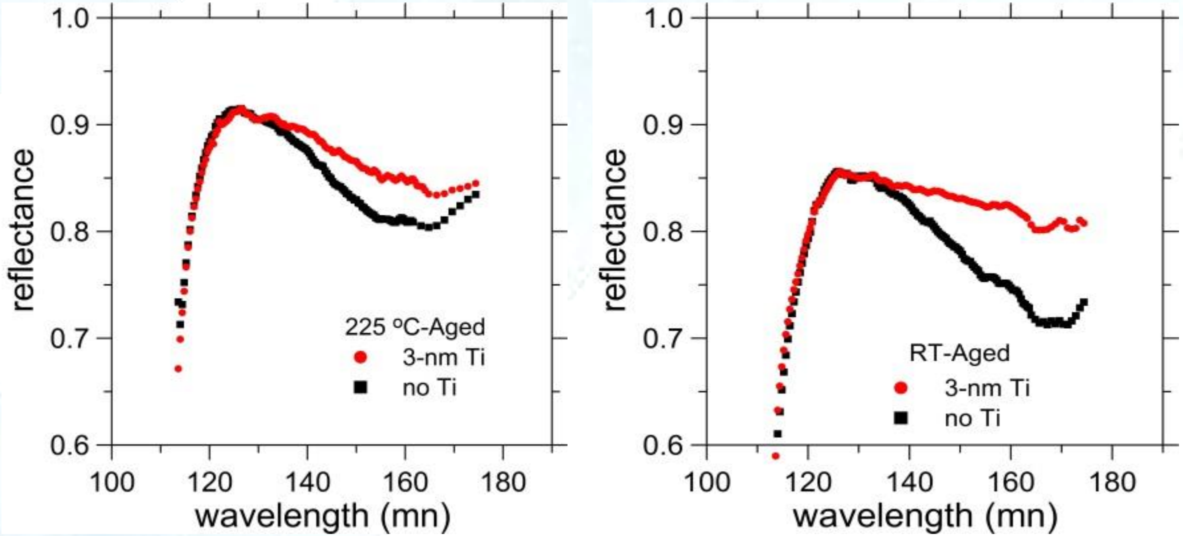
Results: other coatings, super narrowband filters



Supernarrowband filters
120-200 nm+

The selection of fluoride materials in the multilayer can provide multilayers with a reduced bandwidth FWHM 20 nm → 4.5 nm

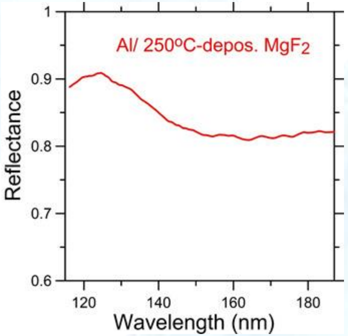
Results: other coatings, improved broadband Al mirrors with Ti-seed



Reduction of the reflectance dip when adding a Ti-seed

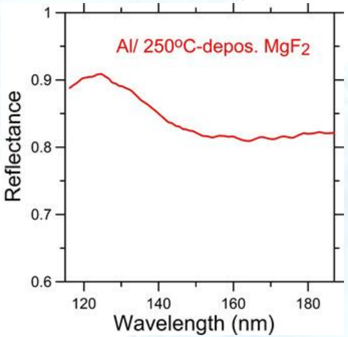
Results: other coatings

High reflectance broadband mirrors

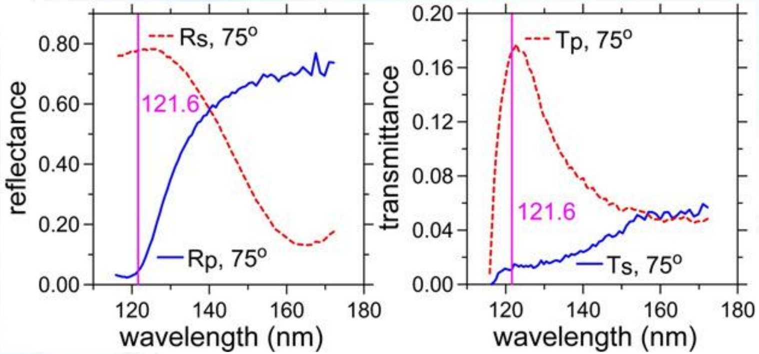


Results: other coatings

High reflectance broadband mirrors

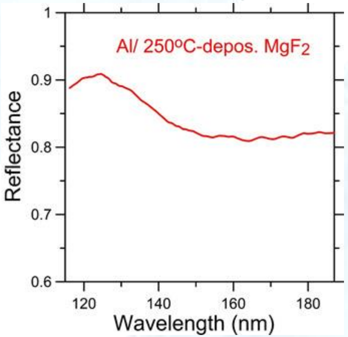


Polarizers



Results: other coatings

High reflectance broadband mirrors



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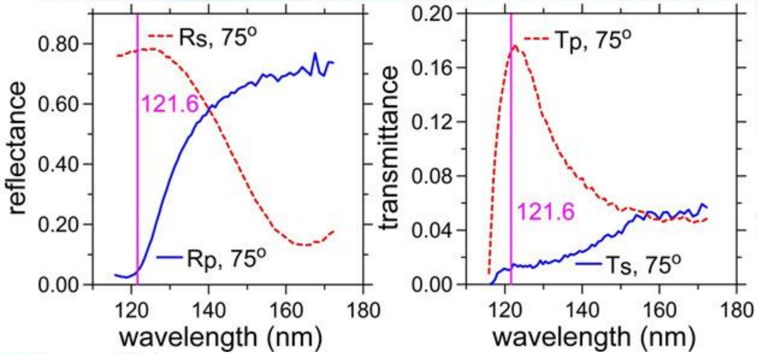
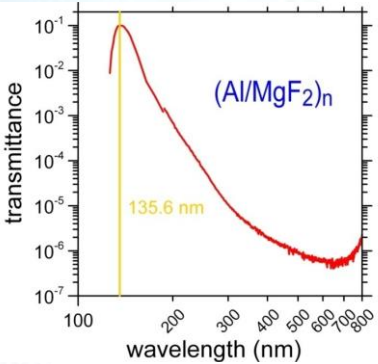
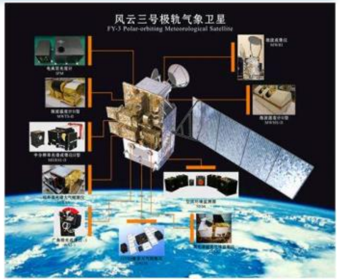


Transmitance filters

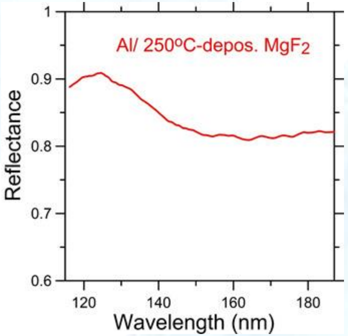


Ionospheric Photometer Satellite: FY-3D

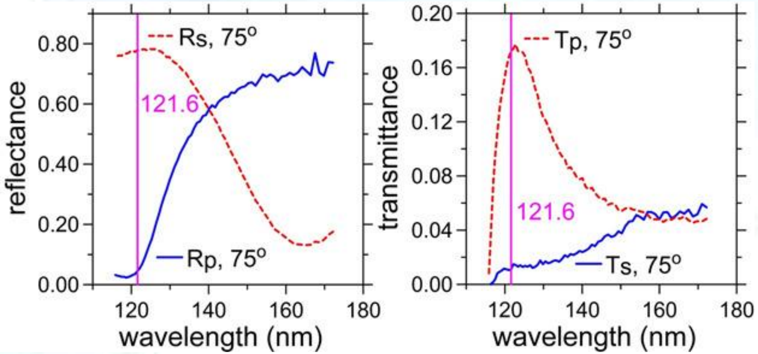


Results: other coatings

High reflectance broadband mirrors

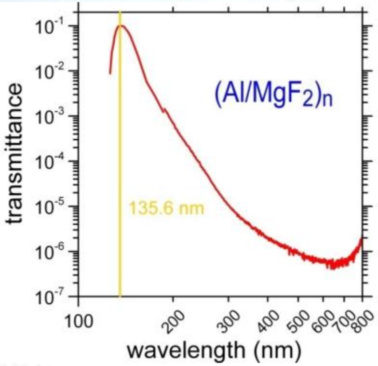


Polarizers

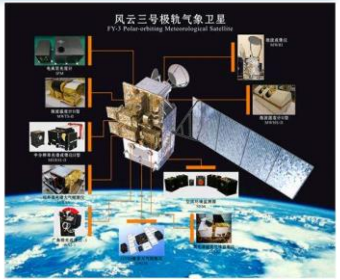


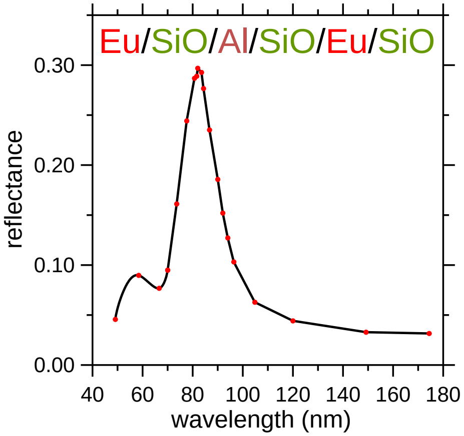
First Multilayers in the EUV

Transmitance filters



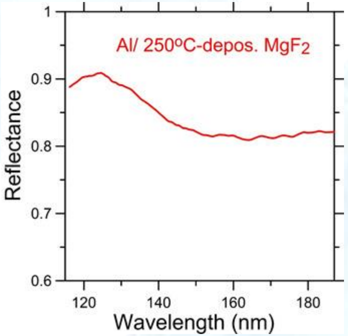
Ionospheric Photometer Satellite: FY-3D



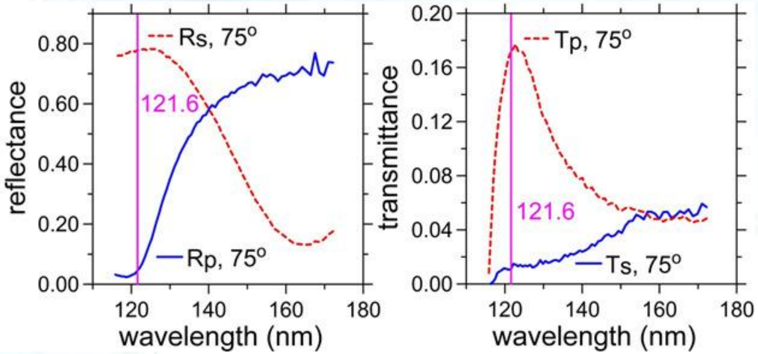


Results: other coatings

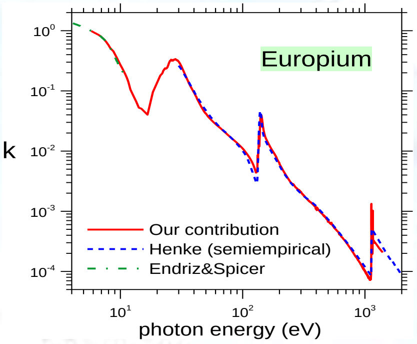
High reflectance broadband mirrors



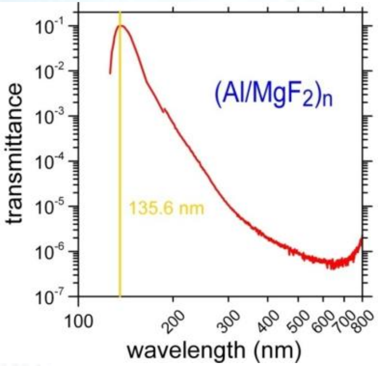
Polarizers



Characterization of materials (n,k)



Transmitance filters



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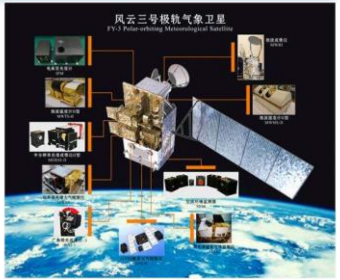
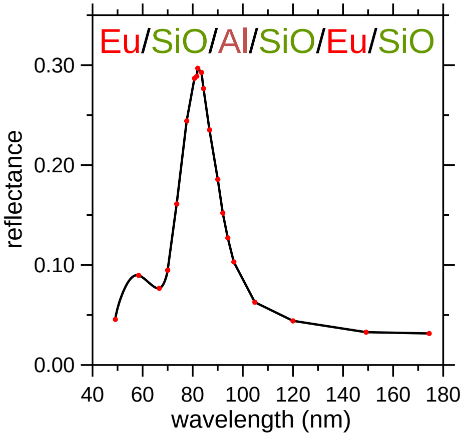


First Multilayers in the EUV



Outline

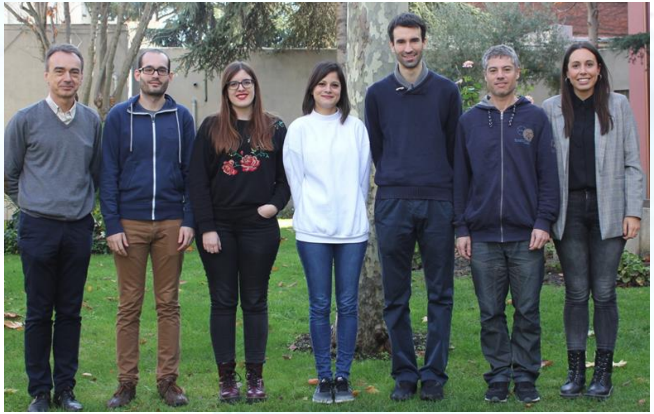
- **Our group**
- **Motivation:**
  - FUV and EUV astronomy
  - Future observatories
- **Experimental and facilities**
- **Results**
  - Tunable narrow bands in the FUV
  - Spectral line selection
  - Narrow bands in the LUV
  - Other coatings
- **Conclusions**

Conclusions

- Improved technology on high reflectance filters, broadband mirrors, transmittance filters and polarizers for the FUV and EUV

- Designs in the FUV-EUV to fit the needs of the astrophysics community

Thank you!



Contact:

Paloma López Reyes
paloma.lopez@csic.es

Juan Larruquert
j.larruquert@csic.es

Follow us on twitter!
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https://gold.io.csic.es/

GOLD

Grupo de Optica de Láminas Delgadas

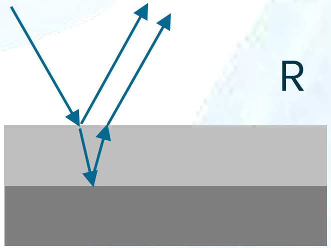
CSIC
CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

IO

We acknowledge Agencia Estatal de Investigación for funding this research (Refs. BES-2017-081909, PID2019-105156GB-I00)

Results: tunable bands in the FUV @ λ≥120 nm

1. Design: bilayer number



Reflectance and mechanical stability will depend on:

1. **Design (number of bilayers)**
2. Deposition temperature
3. Substrate
4. Coating materials

Results: tunable bands in the FUV @ λ≥120 nm

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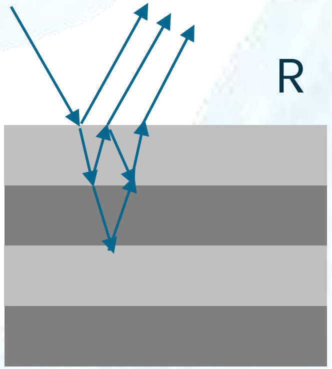

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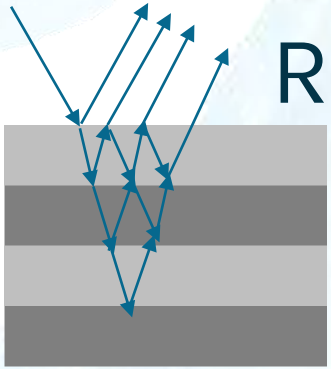

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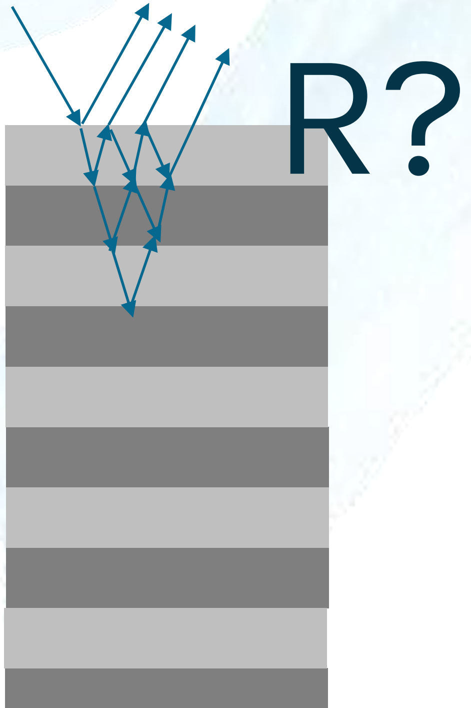
\+ Contribution of more interfaces

− More thickness -> more cracks



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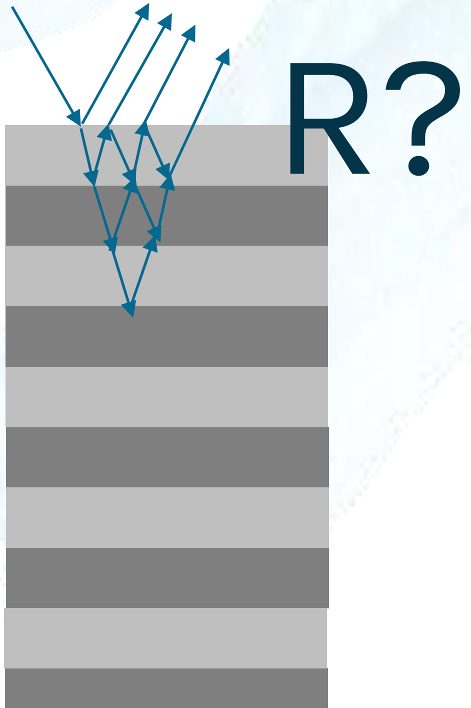
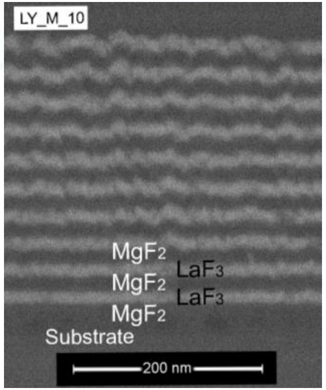
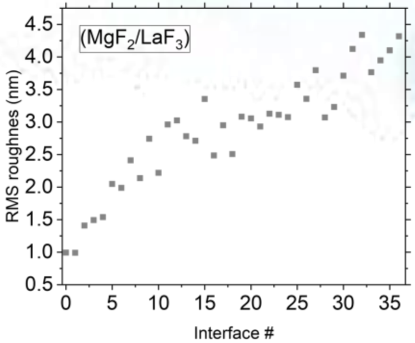
More interfaces -> more roughness







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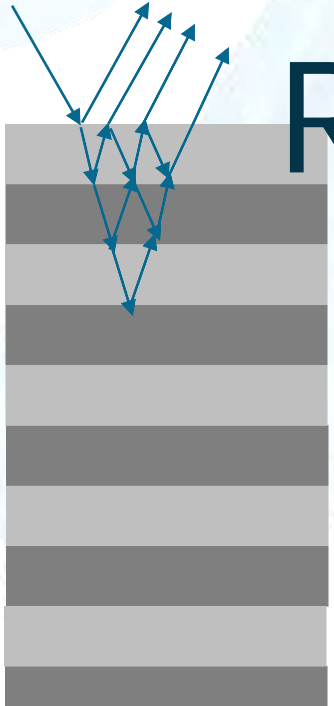
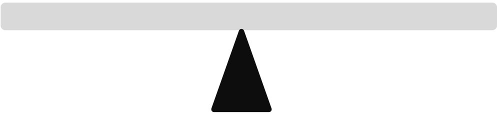


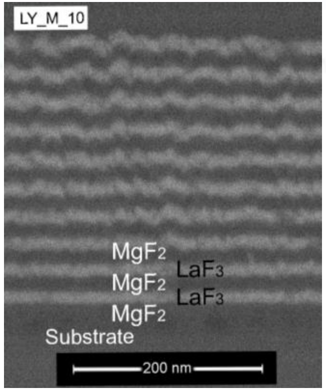
R?

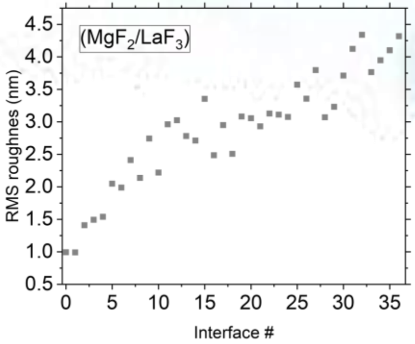
~13 – 15 bilayers is a good trade-off for fluorides in FS

No. of interfaces to increase R

Limit no. of interfaces to control cracks and scattering







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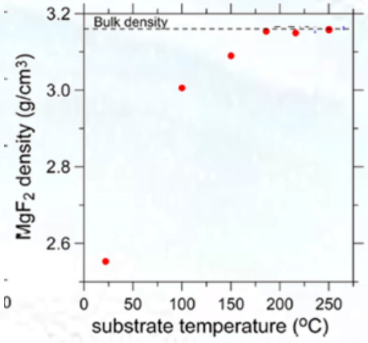
2. Deposition temperature

R?

✚ Fluorides' density increases



L.V. Rodríguez-de Marcos, Optics Express 26: 9363-9372 (2018)

Reflectance and mechanical stability will depend on:

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2. Deposition temperature

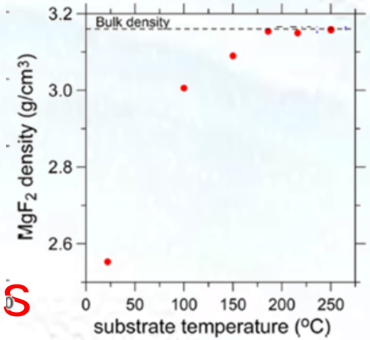
R?

+ Fluorides' density increases

− More thermal stress -> more cracks

More roughness -> more scattering

$$\sigma_{therm} = \left(\frac{E}{1-\nu}\right)_{film} \left(\alpha_{sub} - \alpha_{film}\right)\left(T - T_d\right)$$



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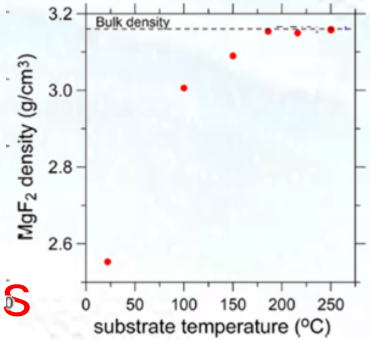

L.V. Rodríguez-de Marcos, Optics Express 26: 9363-9372 (2018)

$$\sigma_{therm} = \left(\frac{E}{1-\nu}\right)_{film} (\alpha_{sub} - \alpha_{film})(T - T_d)$$

Increase T to increase R

Limit T to control cracks and scattering

Find a balance

Reflectance and mechanical stability will depend on:

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Results: tunable bands in the FUV @ λ≥120 nm

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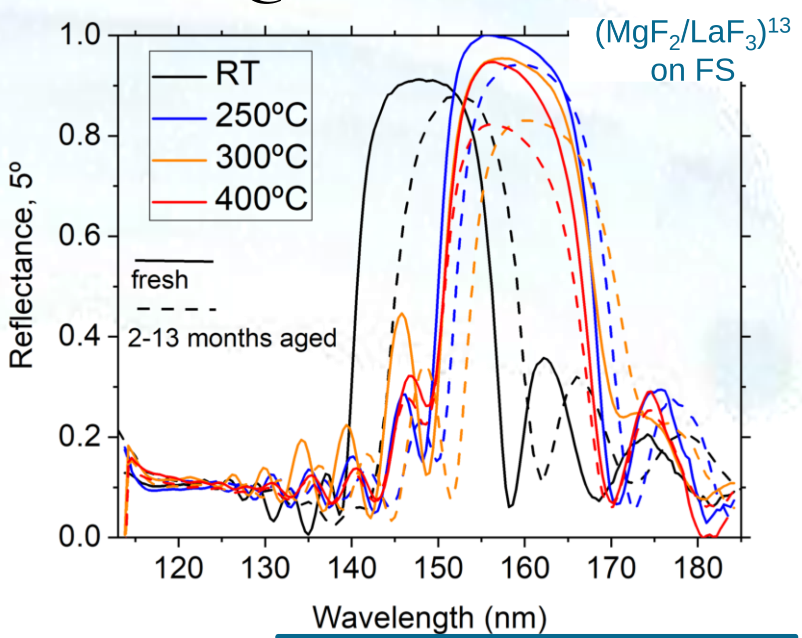

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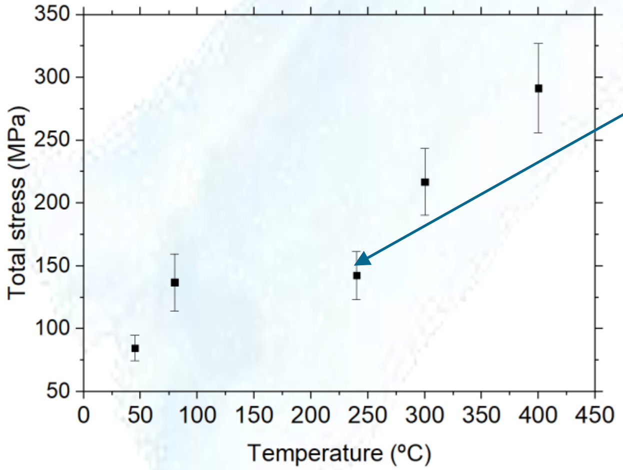

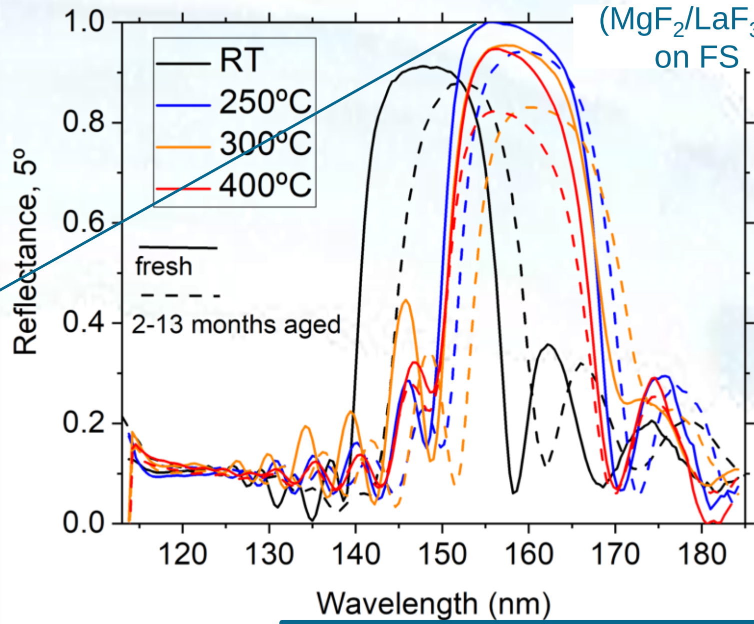

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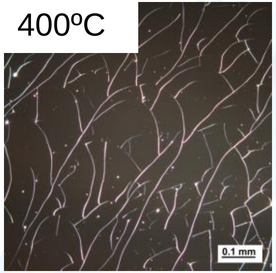

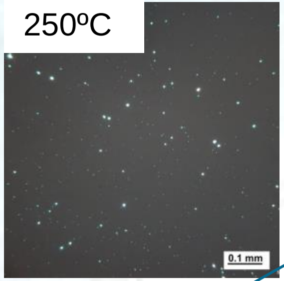

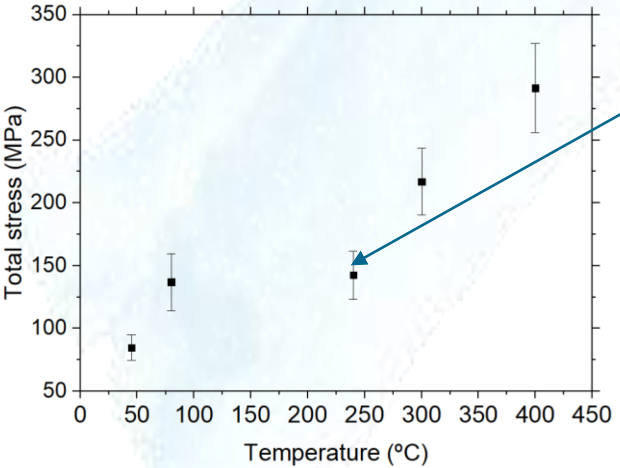

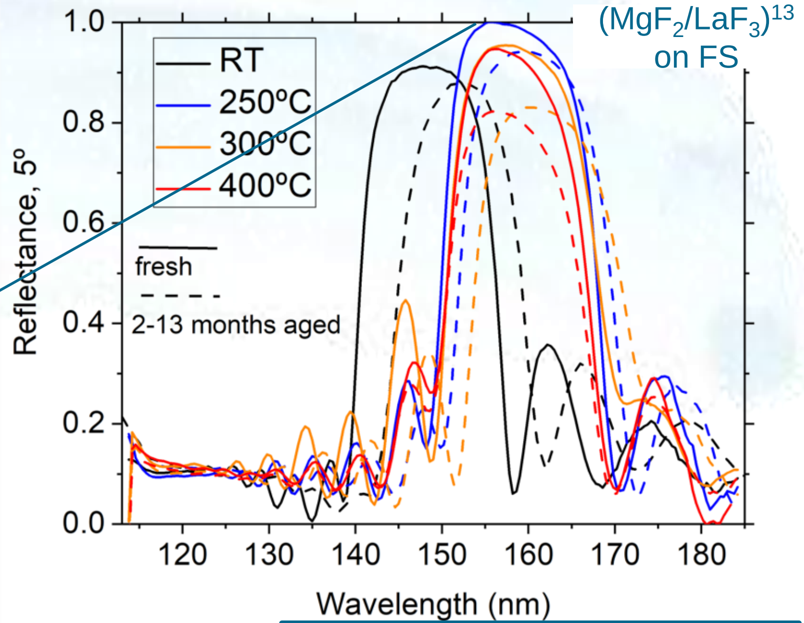

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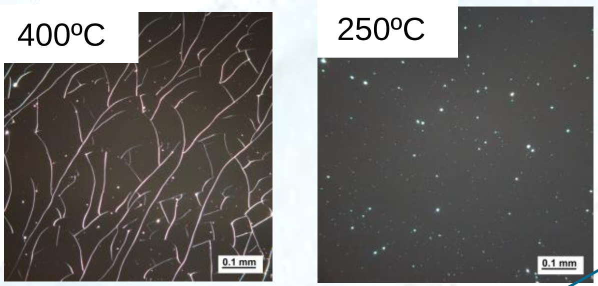

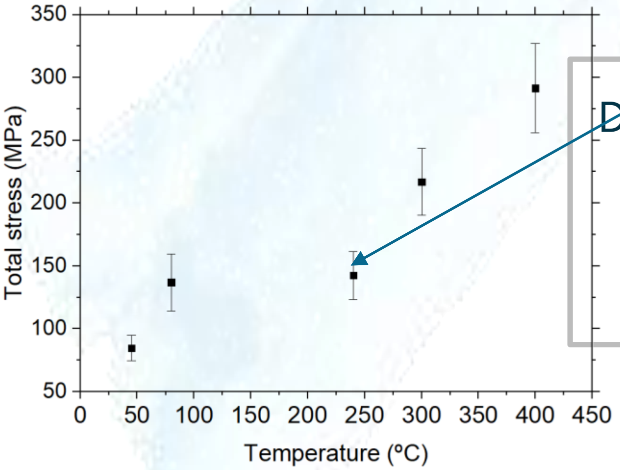

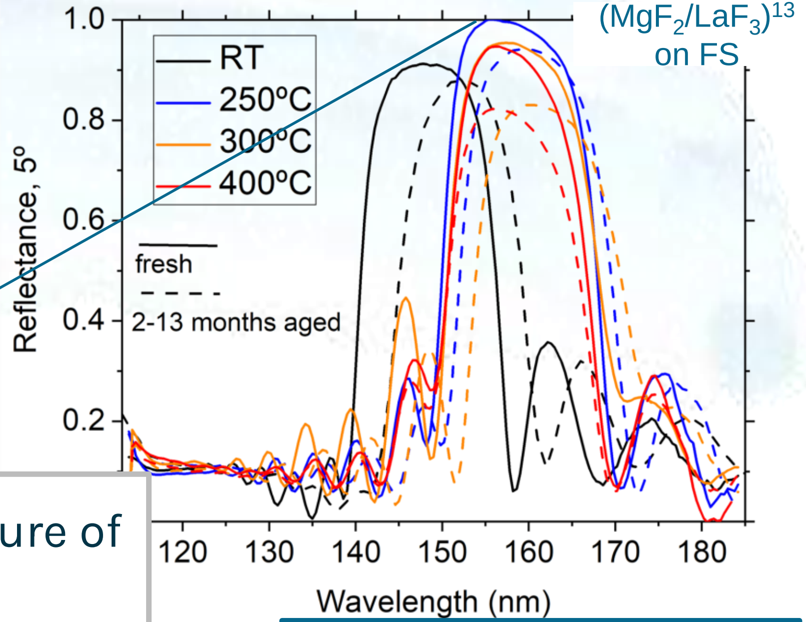

Deposition temperature of
~250ºC
good trade off for
$(MgF_2/LaF_3)^{13}$ MLs

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