General Astrophysics Needs and Coronagraphy

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Towards Starlight Suppression for the Habitable Worlds Observatory Workshop
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A Brief Reminder – HabEx and LUVOIR

- During both pre-Decadal studies, the needs of general astrophysics were balanced against the demands of coronagraphy
- One example: the f/2.2 “beam speed limit” which imposed a longer focal length on all instruments
- While LUVOIR-A was on-axis, both HabEx and LUVOIR-B ended up being off-axis systems to simplify the coronagraphic systems
- Coatings friendly to general astrophysics – MgF2 for HabEx, eLiF for LUVOIR – were adopted with the understanding that they would not deform the wavefront to an uncorrectable state
- Both HabEx and LUVOIR baselined general astrophysics instruments that included a wide-field vis-NIR imager and a wide-field UV MOS spectrograph with an imaging mode (LUVOIR-A also carried a UV spectropolarimeter)

Science Drivers – General Astrophysics Capabilities

- At the recent HWO conference, we heard a lot about general astrophysics science drivers and what demands they might place on the HWO instrument complement (in addition to the coronagraph):
  - UV MOS spectroscopy down to 100nm with spectral resolutions as high as 100k
  - Wide field vis-NIR diffraction limited imager with FOV as large as 6 arcmin (LUVEx was 2’) with spectral coverage from the NUV to 1.8 microns
  - Some aspirational goals for access to 2.1, 2.5 and even 5 microns were voiced
  - Strong support for a UV IFS to be considered even though this was not a featured instrument on LUVEx
  - Some demand for medium band imaging in the UV

Concerns Being Expressed

- A large part of the general astrophysics drivers demand UV throughput
- Memories of the challenges posed by historic missions have raised questions:
  - Heritage (linked to the histories of FUSE and EUVE)
  - Manufacturing
  - Reflectivity (UV through the optical)
  - Durability
  - Are ultra-high-contrast exoplanet observations compatible with a UV-sensitive telescope?
  - Does pushing HabWorlds' wavelength coverage below the short wavelength cutoff of Hubble (115nm) increase the technical challenges?
  - Can the polarization aberrations induced by an off-axis telescope be corrected by coating thickness variations?
  - Coating uniformity – analysis seems to suggest inter-segment variation of as much as 3% is correctable via DM – intra-segment is unclear

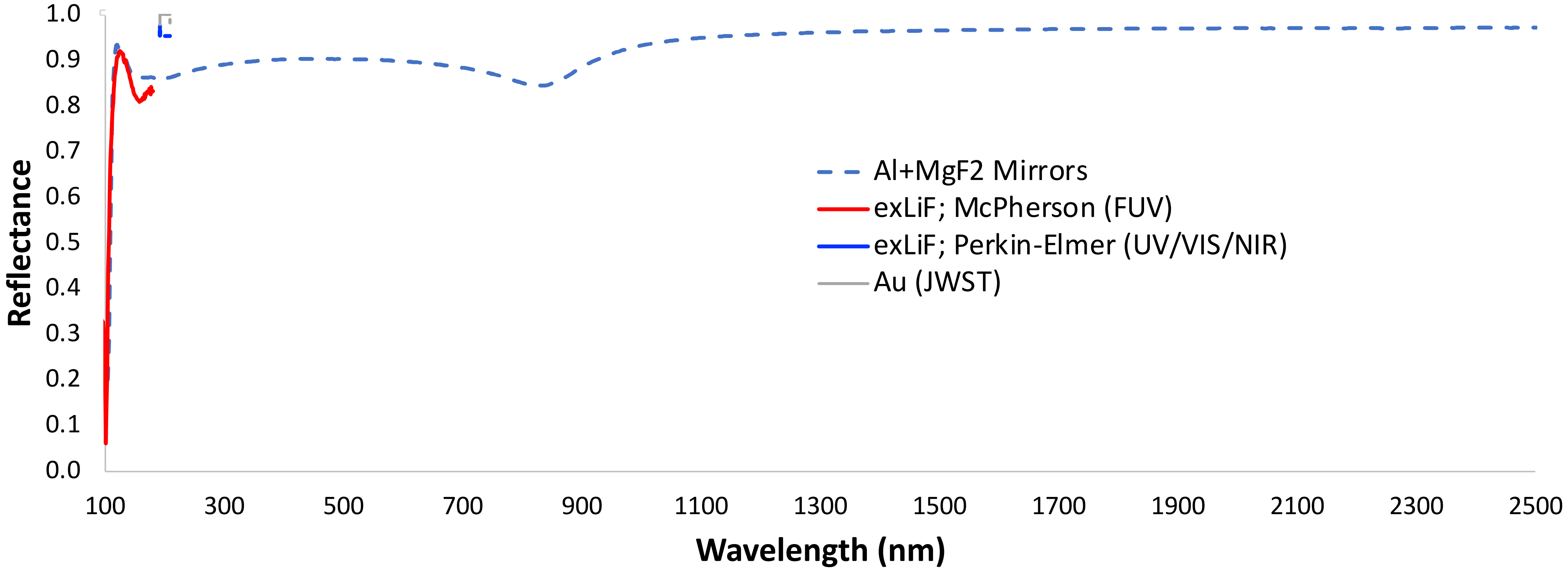
Working Groups Studying the Problems

- At this time, there are several working groups that are already thinking about these challenges:
  - **UV Technology Working Group** – convened by COPAG and chaired by Prof. Sarah Tuttle (UW), is authoring a white paper that identifies science drivers and necessary capabilities, and outlines the current tech state of the art with the aspiration to define a roadmap to deliver the tech performance needed to enable general astrophysics while coexisting with coronagraphy
  - **UV-Vis coronagraphic channel working group** – led by Dr. Roser Juanola Parramon (GSFC), is currently looking at how / whether a UV coronagraphic channel is justified – science and risk driven – also aiming to author a white paper on their findings – covers very similar issues as above – but only concerned with the NUV down to 250nm (currently)
  - **Tech Roadmap Mirrors/Thermal/Coatings (MTC) Working Group** – led by Sang Park (CfA), is working on identifying SOTA manufacture and testing capabilities together with trades and risk postures to define a tech roadmap for delivering OTA performance for HWO – is intended as input to the START and TAG groups once formed

Some Immediate Statements

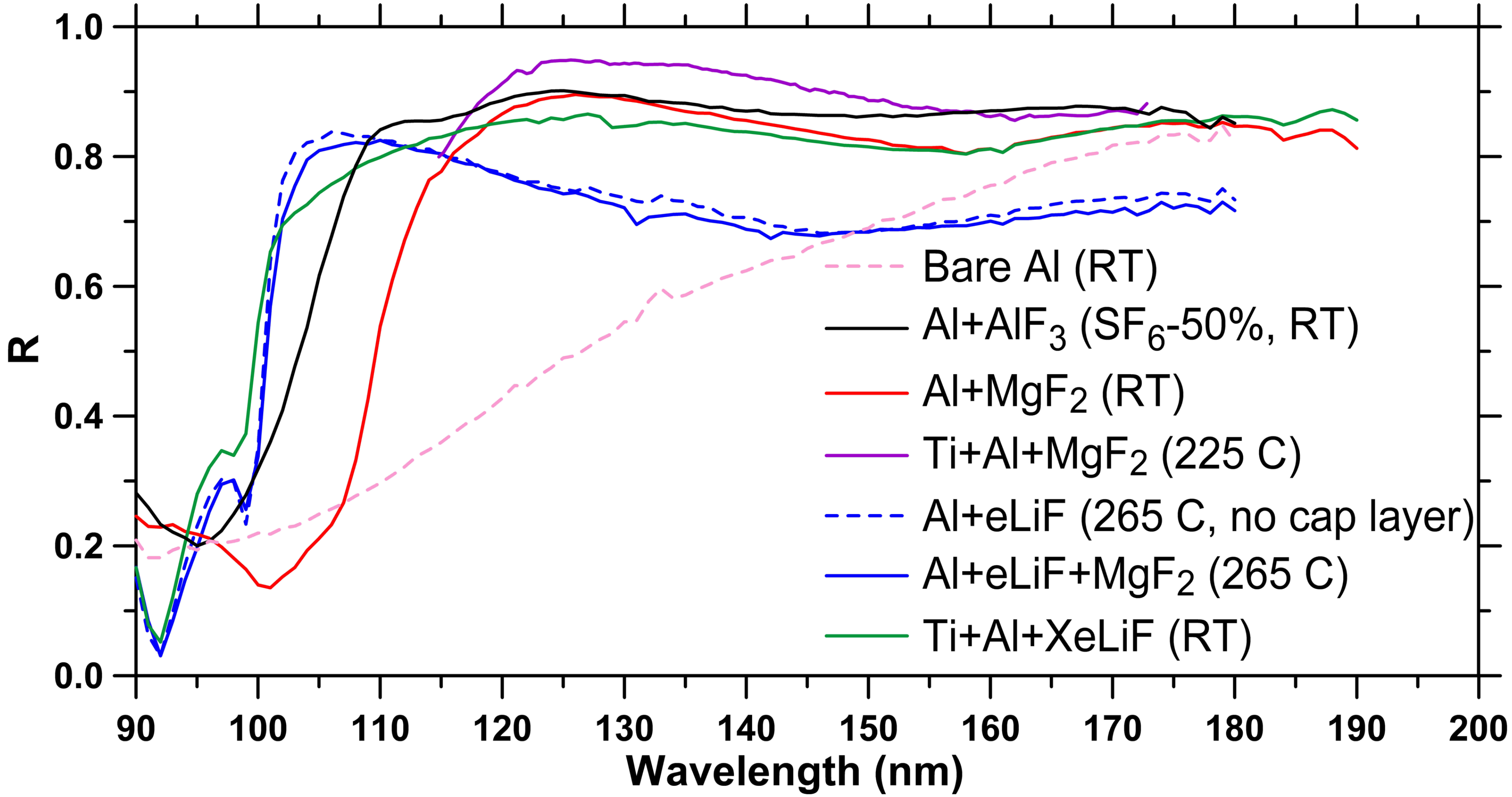
- Based on the concerns being expressed, and drawing upon demonstrated technical performance, we can make certain statements out of the gate:
  - eLiF coatings with the current SOTA have been deposited on mirrors up to 130mm in size, and have been or are being flown, and are at TRL 6
  - eLiF coatings have been demonstrated to be robust to storage in high humidity and elevated temperature for up to 2 months without degradation
  - Protected LiF coatings over aluminum deliver an acceptable level of reflectivity across the entire anticipated HWO band

Broadband Reflectance: *ex*LiF *vs.* Au

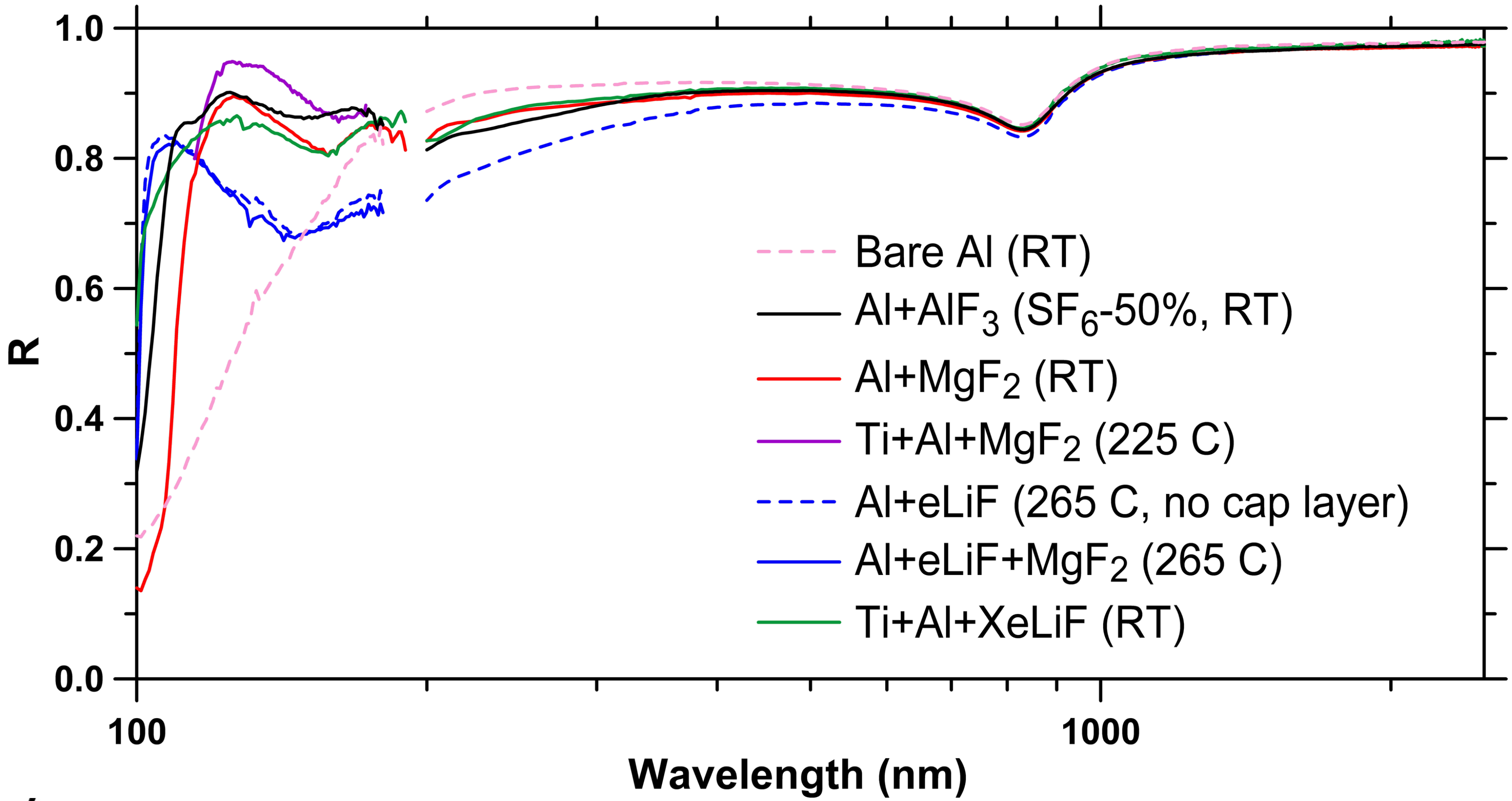


Note: exLiF = (Al+XeF2+LiF+XeF2)

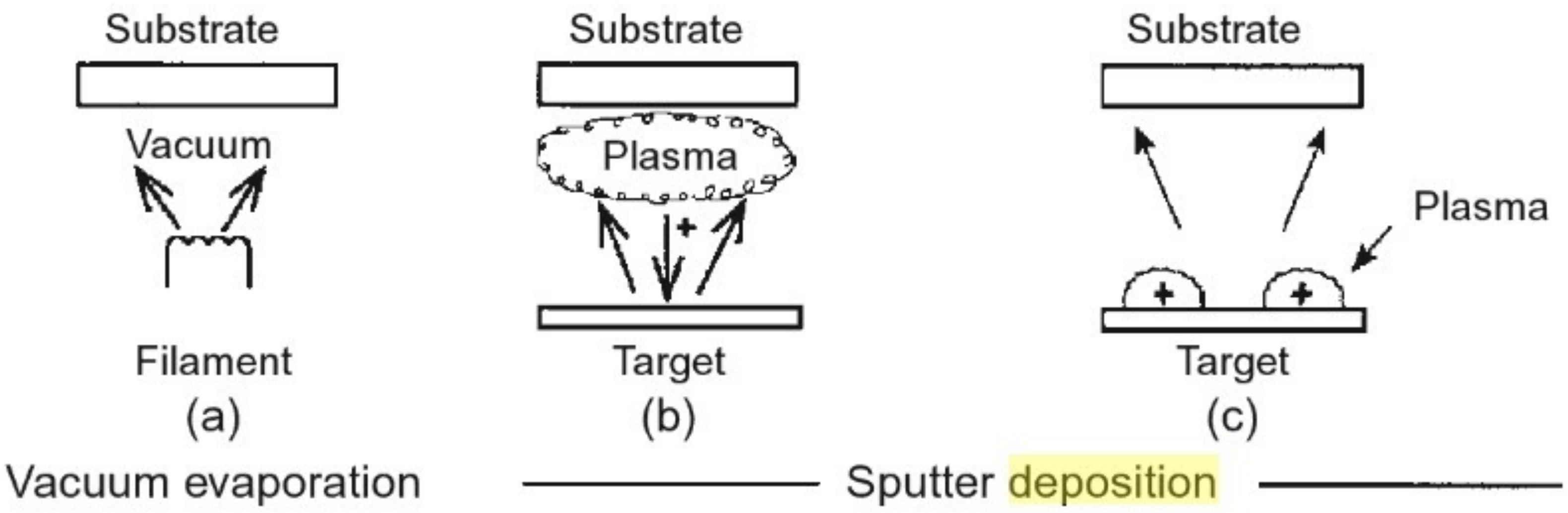
Other Protected LiF Coatings – FUV Performance



Other Protected LiF Coatings – Performance Across the HWO Band



Optical Coating Deposition Processes



PVD

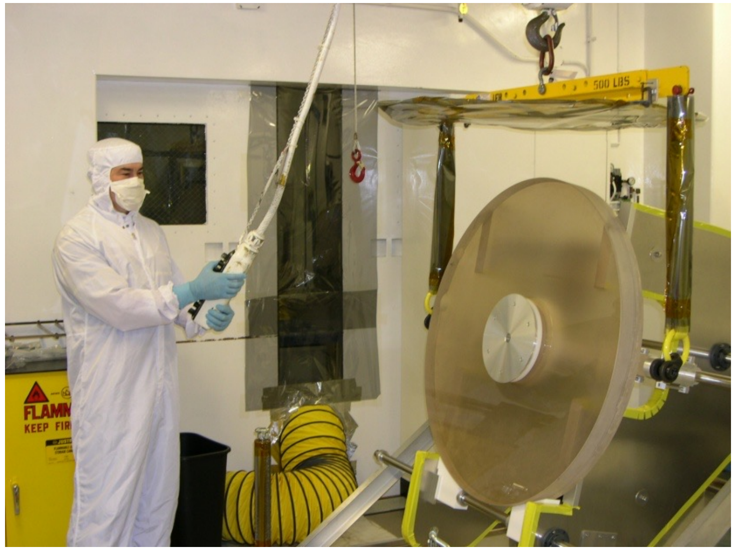
- Material is heated until it reaches vapor form
- Material is deposited on the substrate where it condenses
- Typical deposition rates are 10-100 Å/Sec.

Sputtering

- Non-thermal evaporation process
- Atoms from a target are ejected by momentum transfer from energetic atom-size particles
- Particles are energized by an ion gun
- Deposition rate are much lower than PVD 1-5 Å/Sec.

GSFC 2-meter Coating Facility

- Capable of performing conventional PVD, Ion Beam Sputtering,
- Fitted w/ heatesr to perform PVD deposition with substrates at elevated Temperatures (220-260 ˚C).
- Ongoing effort to optimize coating parameter for high FUV reflectance

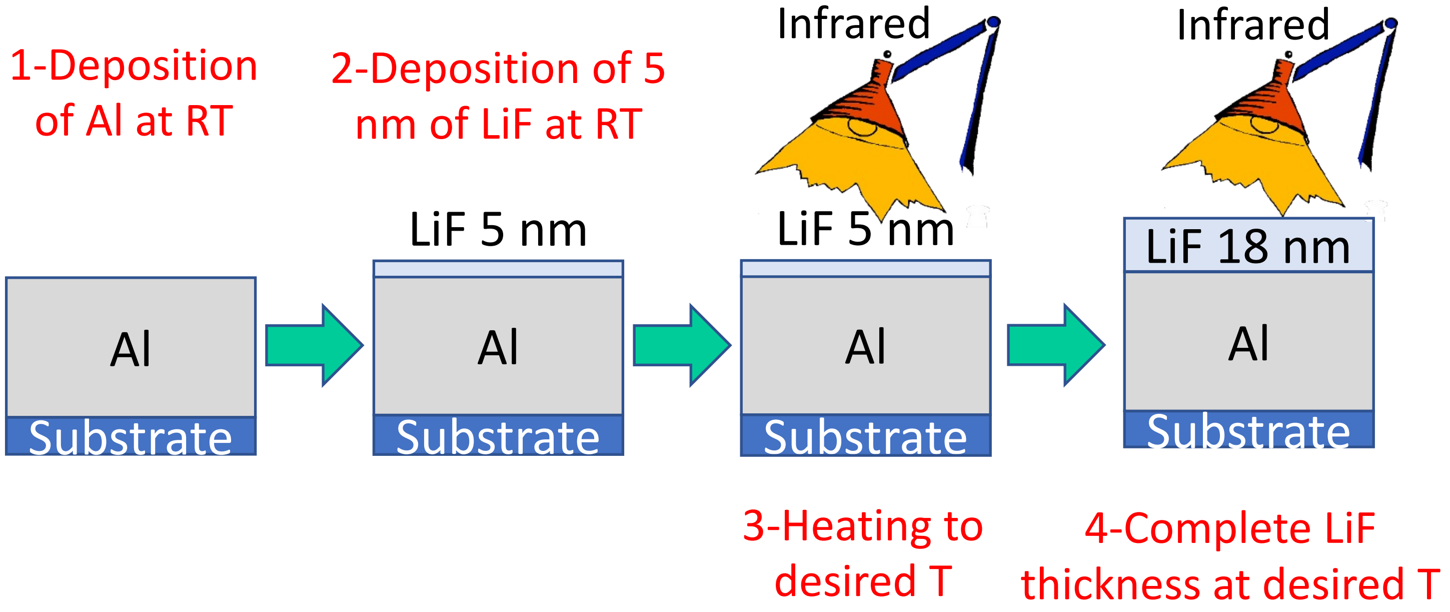


FIREBALL 1.2m primary mirror loading

Mirror mounted in 2-meter chamber prior to coating

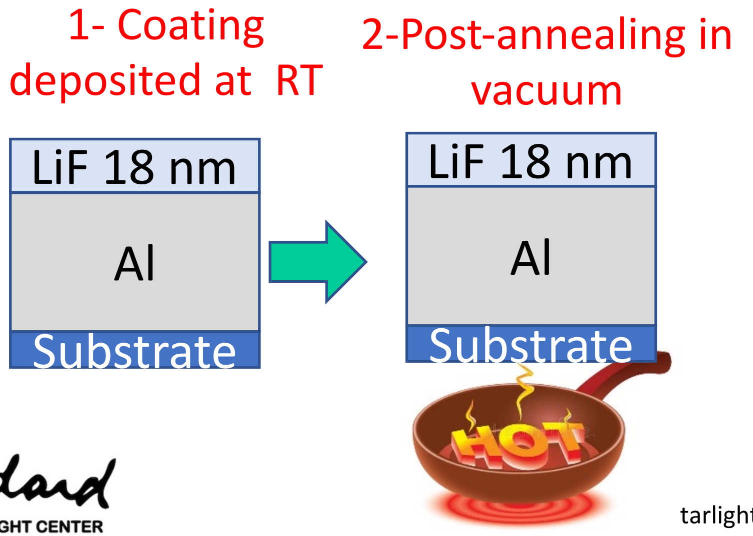
Missions supported: Astronomical Observatory (OAO) & Ultraviolet Explorer (IUE)
FUSE, HST (COSTAR, GHRS & COS)

3-step deposition vs annealing



3-step process (used with SISTINE optics)

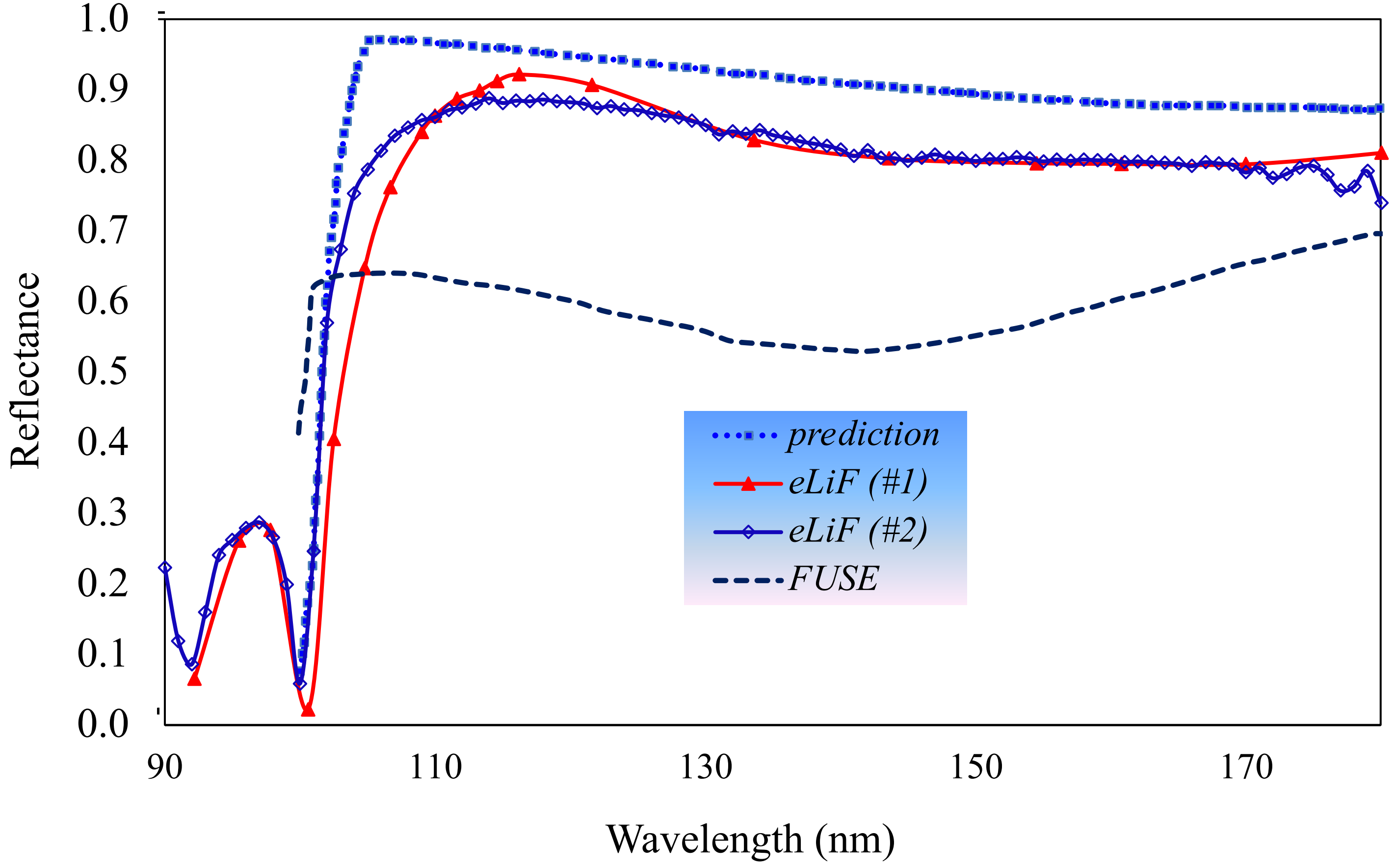
Issues: LiF transparent to IR, and Al reflects 97% of IR → Chamber outgas

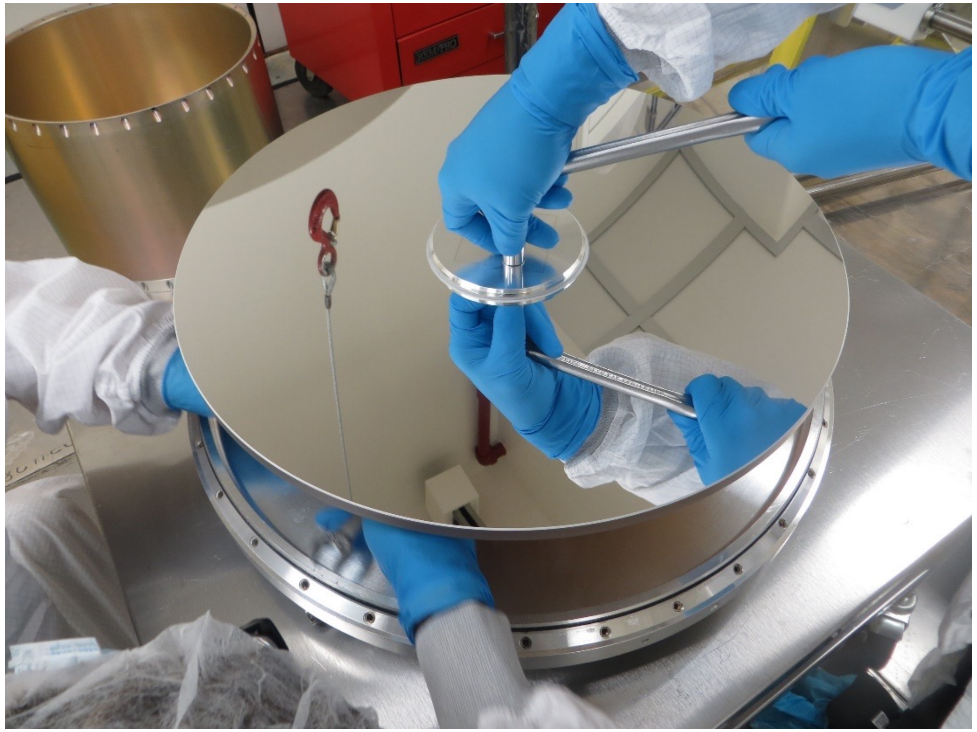


Annealing process (SPRITE)

Advantages: i) Less complicated, ii) local heating, iii) conduction instead of radiation

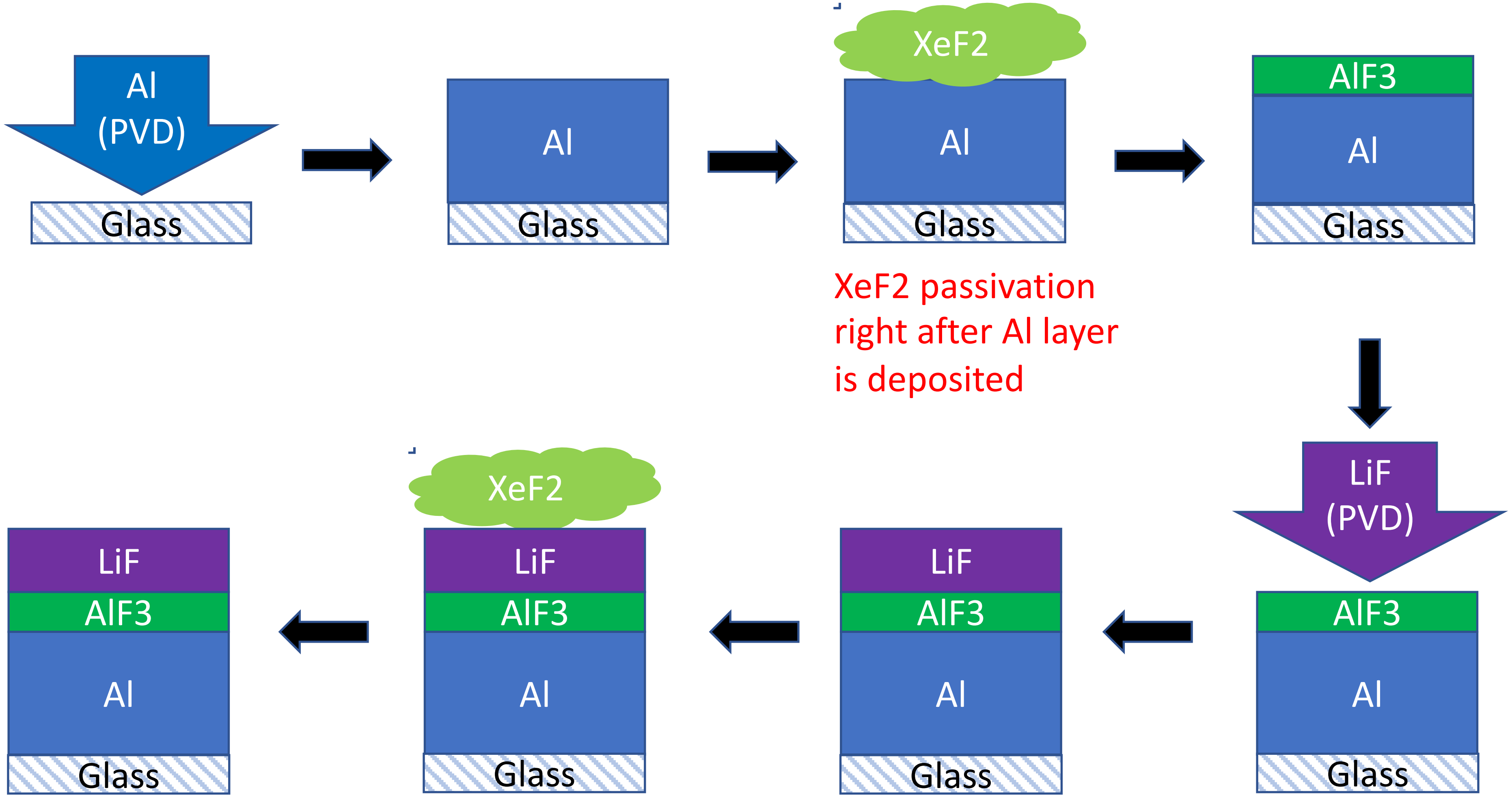
Optimization Al+LiF (eLiF) Hot Coatings





The SISTINE 0.5m primary mirror (PI: Kevin France/U of C) after coating with Al+LiF in 2-meter chamber at GSFC.

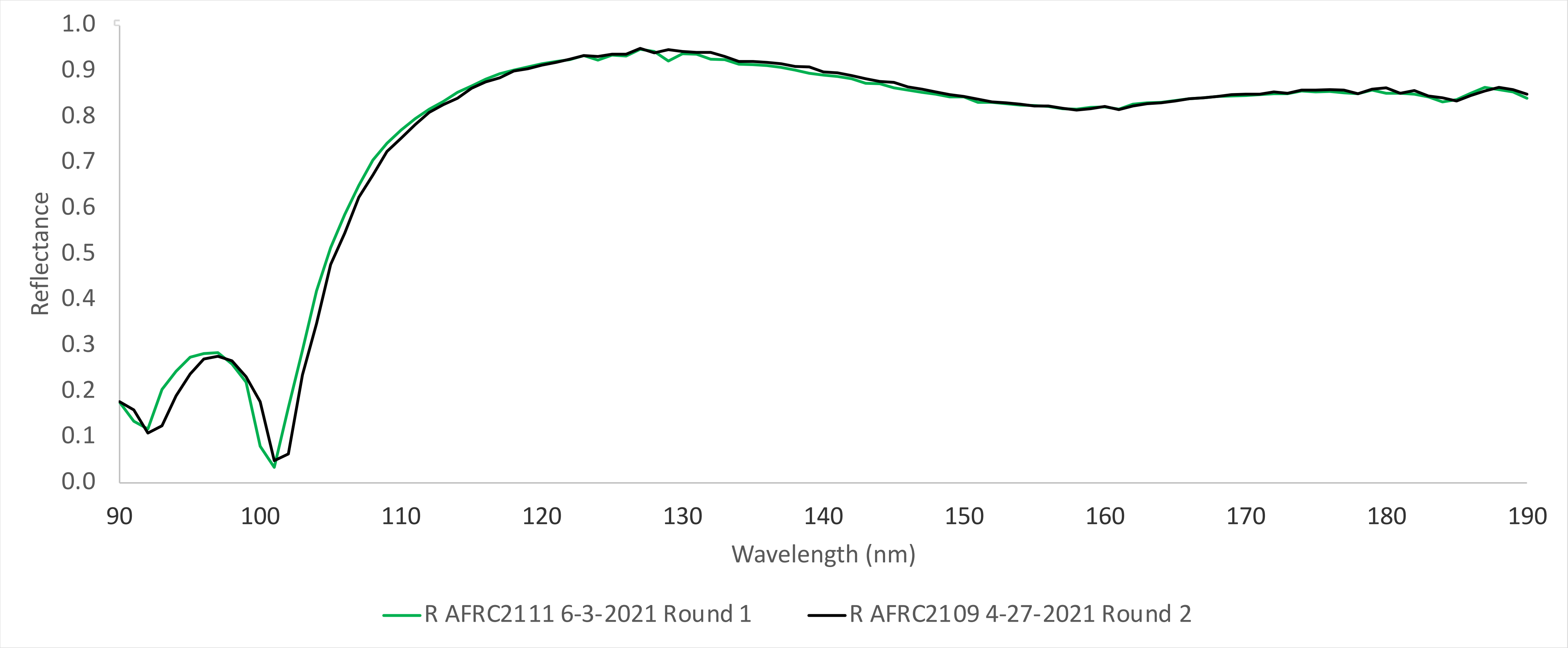
Reactive Physical Vapor Deposition (rPVD)



XeF2 passivation right after Al layer is deposited

Reflectance Result rPVD: Al+LiF (xeLiF)

Highest R at H Lyman-alpha **ever reported** ☺, obtained twice ☺



PVD *versus* ALD

- PVD is a well established process
- Uniformity required for HWO (for 1+m mirrors) would be extremely challenging
- Further investments will be needed to demonstrate

- ALD has the potential to deliver the uniformity required for HWO
- On the other hand, ALD has not been done on 1+ meter scale substrates (as far as I know)
- ALD will require high cost$

Contamination Control

- Throughput in the UV is also very sensitive to the influence of both particulates and volatiles
- Particulates will scatter the UV light before it gets through the instrument
- Volatiles will absorb UV light before it can be detected
- Industry standards exist for describing the size and scale of contamination and for understanding the impact on throughput: IEST-STD 1246
- Previous analysis for a FUV cubesat mission in development, SPARCS, can illustrate the impacts
- Effective contamination control policies affect choice of materials (outgassing), cleanroom level, use of dry nitrogen purge, use of PPE and equipment bagging, baking out, measurement using RGA's and TQCM's
- On-orbit strategies can include vent path design in instruments, as well as heaters to bake-out critical surfaces (mirrors, detectors), and use of cold-cups to attract volatiles

Analysis courtesy of Jim Austin Consulting

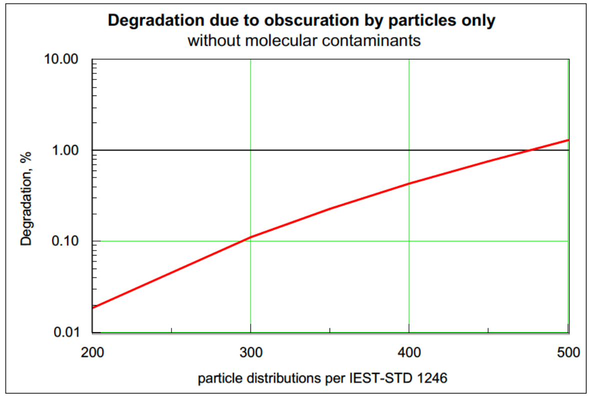


Figure B.   Degradation of NUV band vs particle Levels without molecular contaminants

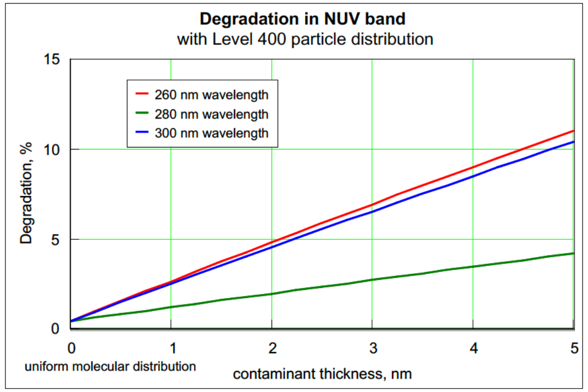


Figure C.   Degradation of NUV wavelengths

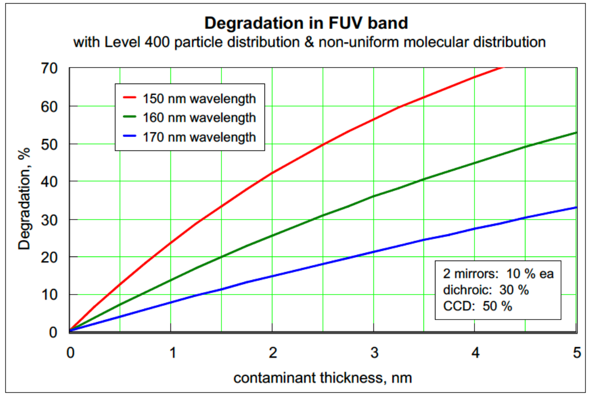
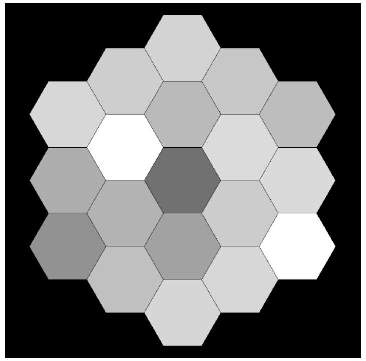
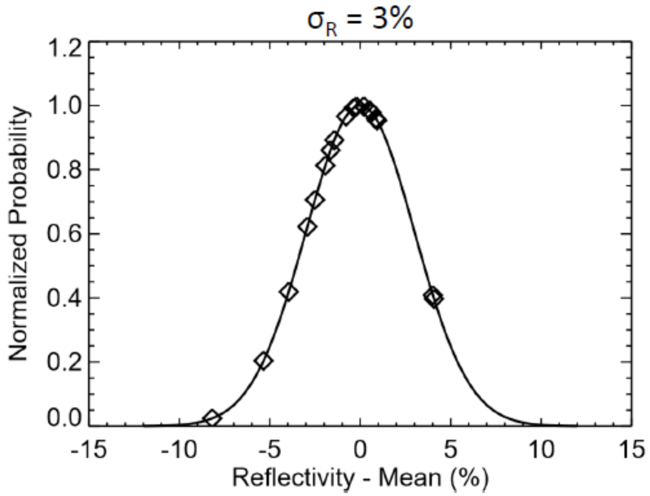


Figure E.   Degradation of FUV wavelengths with 50 % of total molecular contaminants on the CCD

Technical Drivers from Coronagraphy



- Coronagraphy is most concerned about minimizing wavefront deformation by the OTA as well as controlling polarization effects
- As a result, areas of particular interest include:
  - How well can any coating (this isn't a UV problem) be deposited on a 1m mirror blank?
  - John Krist (JPL) investigated coronagraphic tolerance on inter-segment pupil reflectance uniformity, for the 5-segment-diameter USORT segment pattern.
  - How uniform can the coating reflectivity be? – modelling and analysis show that 3% standard deviation inter-segment distribution can be corrected by DMs, such non-uniformities represent the largest disjoint to the wavefront – intra-segment uniformity is expected to be much better, but how good does it need to be? Numbers as small as 0.1% were mentioned by Laurent Pueyo at one point.
  - Can scattering be mitigated? Scattering increases as you go into the UV, but this can be reduced by better polishing – we are used to seeing $\lambda/20$ surface roughness specs for coronagraphy, but better than this is achievable and could help in the UV



σ_R	Open Loop 3.5 – 4.5 λ/D	Post-WFC 3.5 – 4.5 λ/D	Open Loop 4.5 – 12 λ/D	Post-WFC 4.5 – 12 λ/D
0%	1.4e-10	1.3e-10	5.0e-11	3.7e-11
1%	1.9e-7	1.7e-10	7.0e-8	4.1e-11
2%	6.7e-7	1.9e-10	1.6e-7	4.7e-11
3%	1.5e-6	2.3e-10	3.2e-7	5.8e-11

Sources of Coating Non-Uniformity

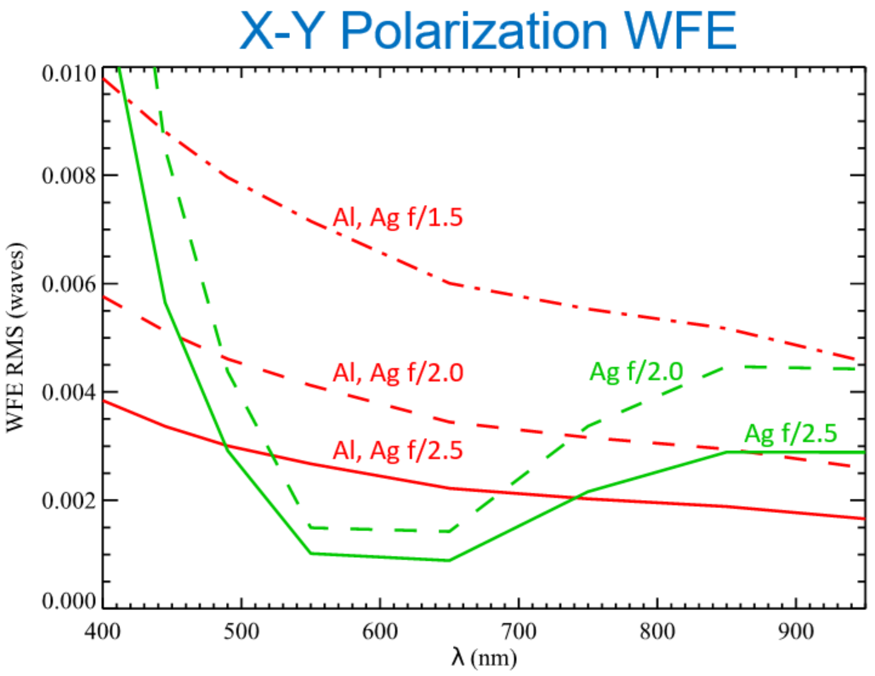
1. General: Vacuum chamber
   a) Chamber configuration: chamber geometry, deposition source geometry, plasma direction, precursor configuration, vacuum pumps location, etc
   b) Contamination/chamber cleanliness: Areas of substrate closer to walls or other hardware may get more water/contaminant content → Stoichiometry and/or O content variations
2. General: Substrate
   a) Size and shape of the substrate → affects uniformity of the coating
   b) Substrate roughness /polishing : The finishing quality of the substrate can lead to non-uniformities in the coating.
   c) Substrate cleaning: some areas are more difficult to clean than others, which can lead to non-uniformities
3. Deposition technique (PVD, sputtering, ALD, plasma passivation)
   a) Plasma passivation
      i. Gas Distribution uniformity
      ii. Plasma uniformity
      iii. Work in progress: Ask experts for more

Sources of Coating Non-Uniformity

3. Deposition technique (PVD, sputtering, ALD, plasma passivation)
   b) PVD
      i. Deposition source configuration / masks
      ii. Deposition rate radial variation for large substrates: If it is not constant across the substrate, this can lead to non-uniformity in the thickness and density
      iii. Angle of incident atoms for large substrates: if it is not constant across the substrate, this can lead to non-uniformity in the thickness and density
      iv. Hot process / annealing: Temperature gradients in the substrate cause variations in the coating thickness and density.
      v. Work in progress: Ask experts for more
   c) ALD
      i. Precursors configuration in the chamber
      ii. Heating: Temperature gradients in the substrate cause variations in the coating thickness and density
      iii. Work in progress: Ask experts for more
4. Others:
   a) Coating stress: May deform the coating non-uniformly
   b) Mechanical stress: The coating process or the substrate holding fixture can induce mechanical stress into the substrate, which can cause non-uniformities in the coating.
   c) Aging and degradation: Aging and degradation over time is typically non-uniform even across 2” x 2” samples (some areas are worst than others).
   d) Interferential effects: Thickness non-uniformity can be amplified when translated into reflectance non-uniformity due to interferential effects.
   e) Coating “polishing”: Strategies such as ion beam polishing may correct thickness / roughness non-uniformities

Technical Drivers from Coronagraphy

- Polarization Aberrations are a concern. Over and above the "beam speed limit", optical systems (both on- and off-axis) will impose polarization aberrations such as astigmatism and tilt, at any wavelength.
- Modelling of the HabEx off-axis design by Krist has shown the magnitude of the wavefront error between X and Y polarizations as a function of beam speed, coating material and wavelength
- The magnitude of the effect is larger in the UV – recall that the UV coronagraphic channel is only considering going down to 250nm for their work
- Polarization-dependent terms will undermine the ability of the coronagraphs to deliver a well corrected wavefront – polarization aberration affects cross-terms at only 10^{-4} - 10^{-5} of light BUT with huge phase errors
- This is not wavefront correction (WFC) correctable – use of a polarizer still leaves some cross-terms in place
- Contrast degradation due to polarization aberrations is especially pronounced at short wavelengths. However, the effect projects mainly into astigmatism. Thus, degradation occurs at small working angles.
- Mitigation
    - Most UV targets are at large working angles in terms of λ/D. Coronagraphs can be designed to mitigate effects of polarization aberration
    - 100 mas → 12 λ/D @ λ = 250 nm, D = 6 m



Where Work is Needed

- Much of this work is moving rapidly
- Things that we need to either demonstrate or deliver a roadmap to achieve include:
  - Analysis about state of the art coating deposition (irrespective of the UV) and how uniformly it can be deposited on a 1m mirror blank, and how repetitive it can be between segments
  - Analysis of the differences between protected LiF and MgF2 mirror coatings with particular concern about uniformity, polarization effects, durability, handling (inc. contamination control / heating), scattering
  - Analysis about what measures in depositing mirror coatings can be implemented to mitigate polarization aberrations across a segmented aperture (the possibility of correcting using coating thickness across the OTA is considered in the backup slides – it appears to be physically impractical)
  - Definition of a tech development roadmap to deliver the needs of general astrophysics while ensuring that the demands of 10^{10} coronagraphy are met

Backup Slides

Polarization Aberration Correction

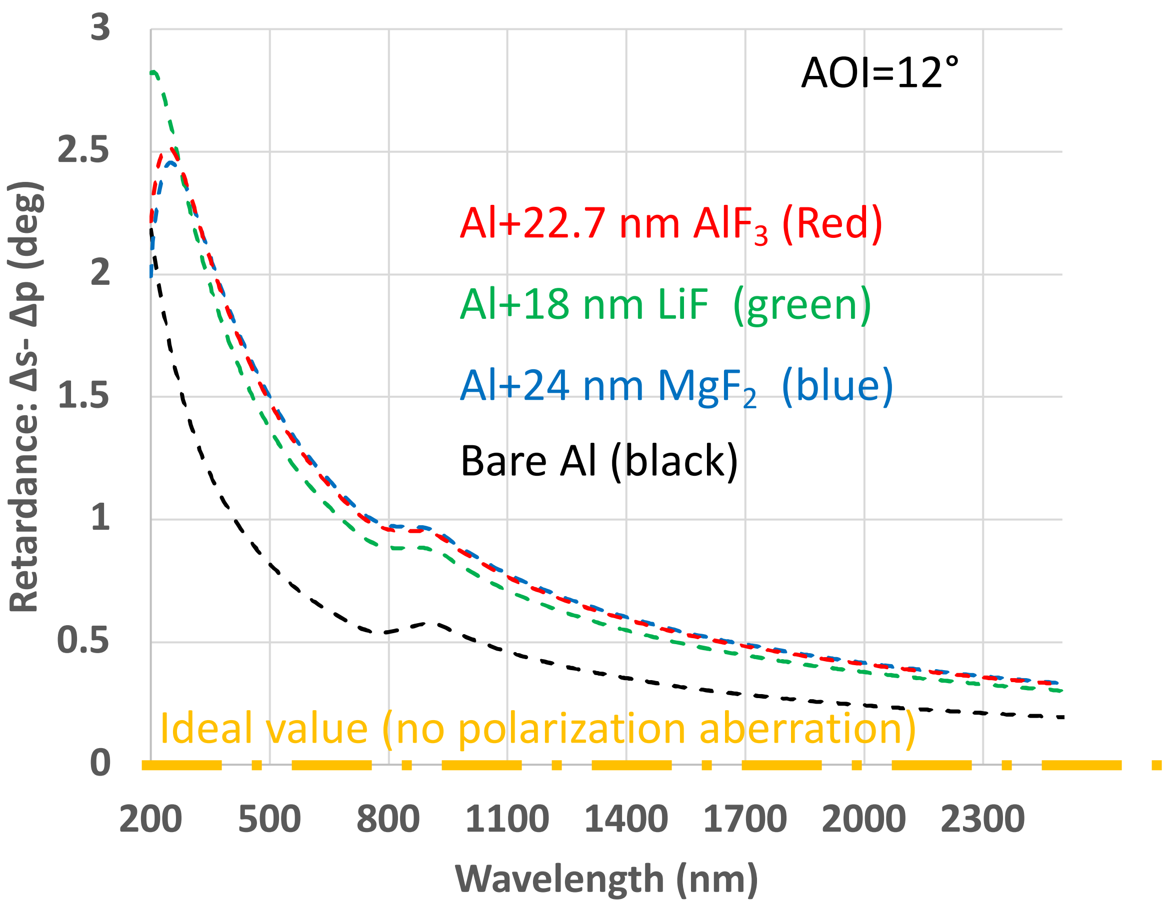
“Polarization Aberrations are a concern. It is theoretically possible to correct for this with dielectric mirror coatings that have a gradient in thickness across the aperture”

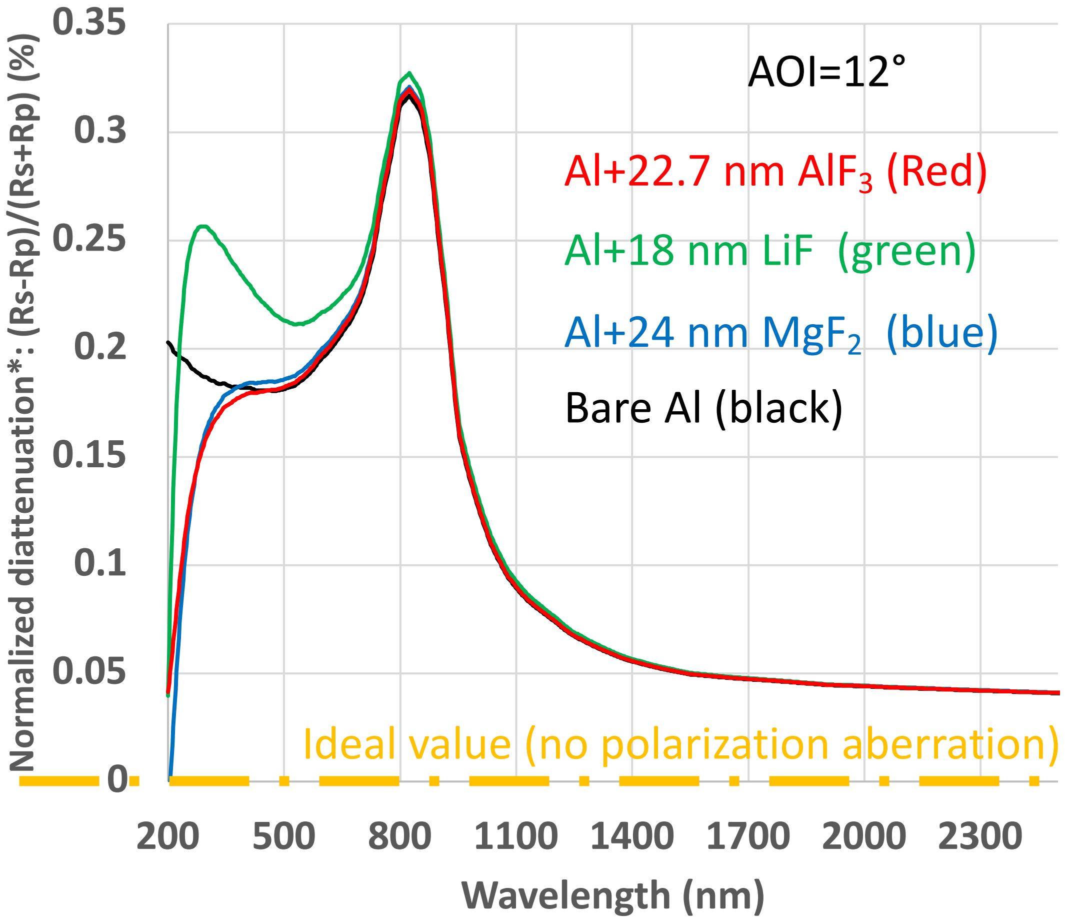
- Short answer: It is possible to achieve full compensation **for a single wavelength or a narrow spectral band**, such as collectors for EUV lithography tools operating with AOIs ranging from 0 to >30°. However, getting this compensation becomes **significantly challenging in a broad spectral range, like 200-1000 nm**. This challenge is due to the spectral dispersion of the optical constants (n+ik) of fluorides within the 200-1000 nm range, and the huge variation in optical thickness of the thin fluoride layer relative to incident wavelengths at 200 nm and 1000 nm. In short, **the gradient in physical thickness across the aperture would only be valid in a narrow wavelength range, with the amplitude of the gradient dependent on the spectral range.**
- For example, in the case of the eLiF layer within an Al+eLiF coating, maintaining Rx-Ry<0.001 (arbitrary threshold) at AOI 0-12° would require an amplitude of just 1 nm at 200 nm wavelength (from 18 nm to 19 nm), 28 nm at 400 nm wavelength (from 18 nm to 46 nm), 56 nm at 600 nm wavelength (from 18 nm to 74 nm), and over 100 nm at 1000 nm wavelength (see slides 3-6). Here we see that **the longer the wavelength, the larger the amplitude of the gradient in eLiF thickness is needed**. Such large gradients are **impractical**, plus the FUV R of the coatings is greatly impacted if the amplitude of the gradient exceeds a 5-10 nms

Polarization Aberration Correction

- Calculations for the phase retardance are shown in the next few slides as well. And more bad news here, as we note that the spectral dependence of the phase aberration is different of that of the amplitude. So here is another additional problem: for Al+any fluoride, diattenuation of peaks at ~ 820 nm (independently of AOI, fluoride choice, and fluoride thickness -if it is not abominably thick-) because of the Al exciton, but the phase retardance steadily increases as the wavelength decreases (see slide 2). **This make it hard to simultaneously compensate for both effects with an eLiF thickness gradient.**
- One possible strategy would be to introduce a gentle gradient (18 nm at 0° incidence to ≈22 nm at 12°) to reduce retardance in the UV, which would not impact much the FUV R of the coating, but this gradient would ironically slightly increase diattenuation in the 700-900 nm range.
- The opposite strategy is even worse. If a gradient in eLiF thickness is introduced to compensate the diattenuation peak in the 700-900 nm range, then a) the amplitude of the thickness gradient would be of dozen of nanometers, thus completely obliterating the FUV performance of the coating, and b) it would increase the retardance at 200 nm wavelength.
- And technical considerations have been left aside… ☺

Comparison Bare Al, Al/MgF_2, Al/LiF, and Al/AlF_3





* Using Rs and Rp instead of rs and rp for simplicity, so technically is not diattenuation (but a close cousin ☺)

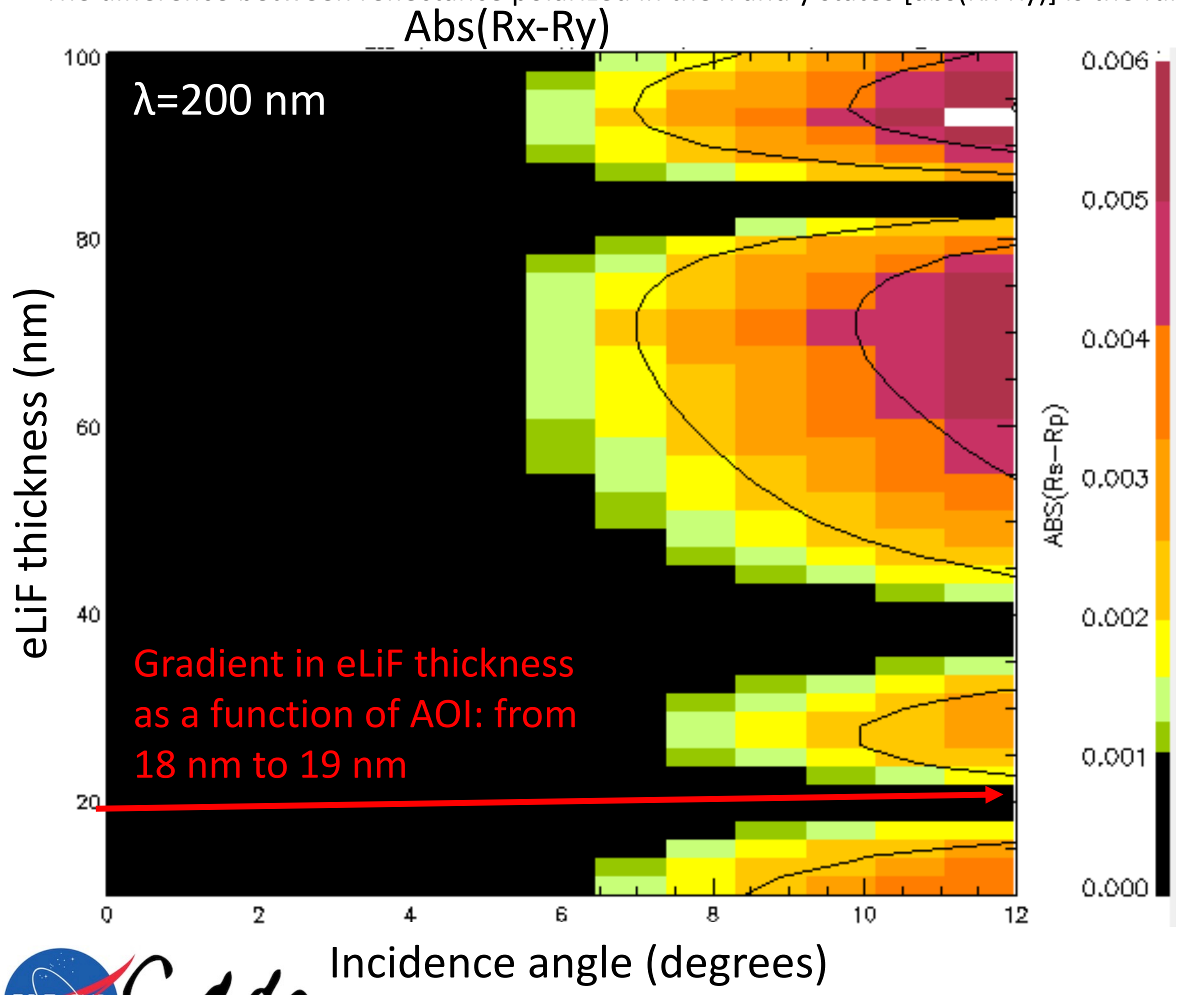
Simulation conditions:

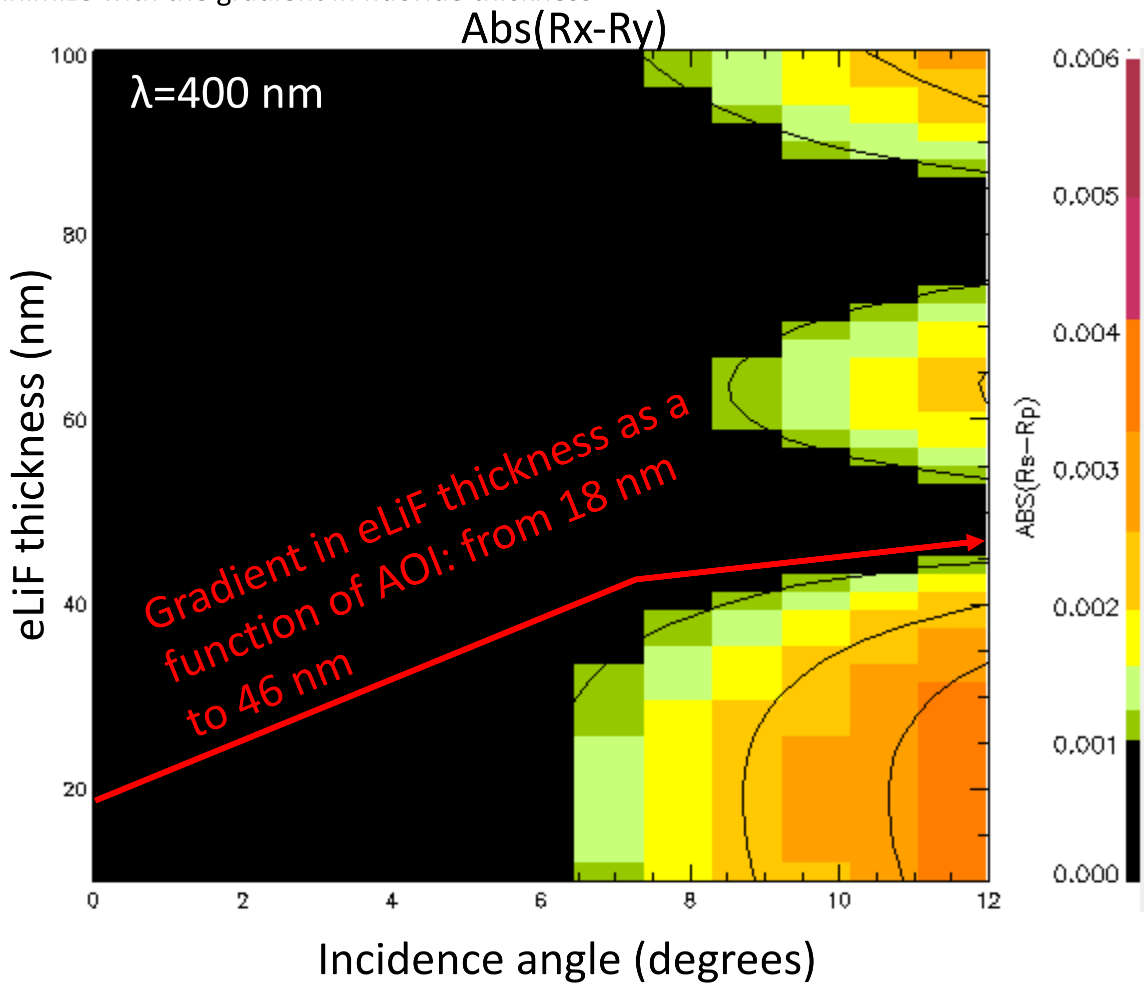
- Mirror angle of incidence (AOI) = [0,12°]
- Coating: 70 nm Al + 18 nm eLiF, surface roughness 0.5 nm (Al) and 1.5 nm (eLiF)
- eLiF starting thickness: 18 nm (FUV-optimized)
- Wavelengths: 200 nm, 400 nm, 600 nm, 1000 nm.
- 2D plot for each wavelength, in which black colour indicates abs(Rx-Ry)<0.001 as a function of fluoride thickness and AOI

black colour indicates abs(Rx-Ry)<0.001*

*this value should be refined following coronagraph requirements

The difference between reflectance polarized in the x and y states [abs(Rx-Ry)] is the function to minimize with the gradient in fluoride thickness





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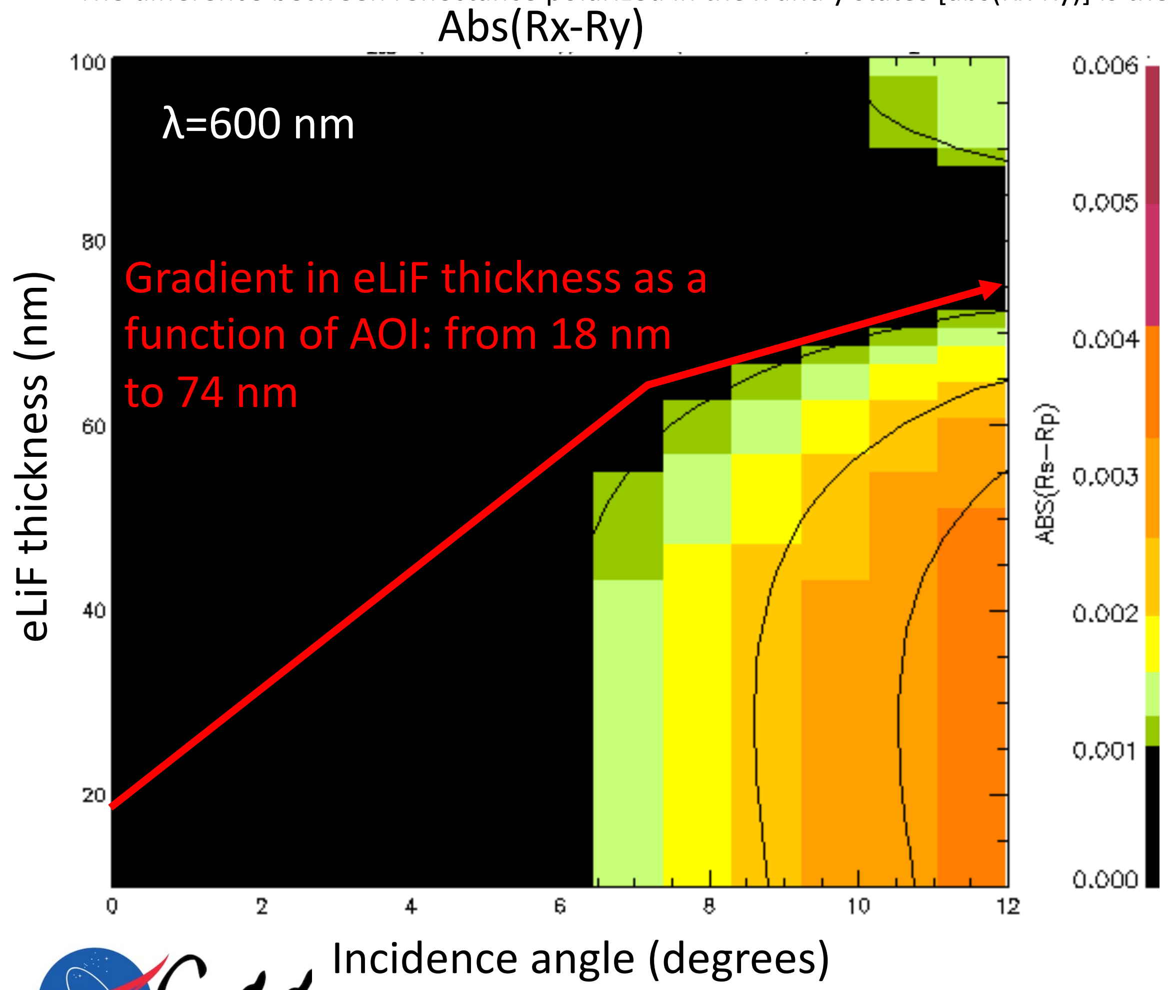

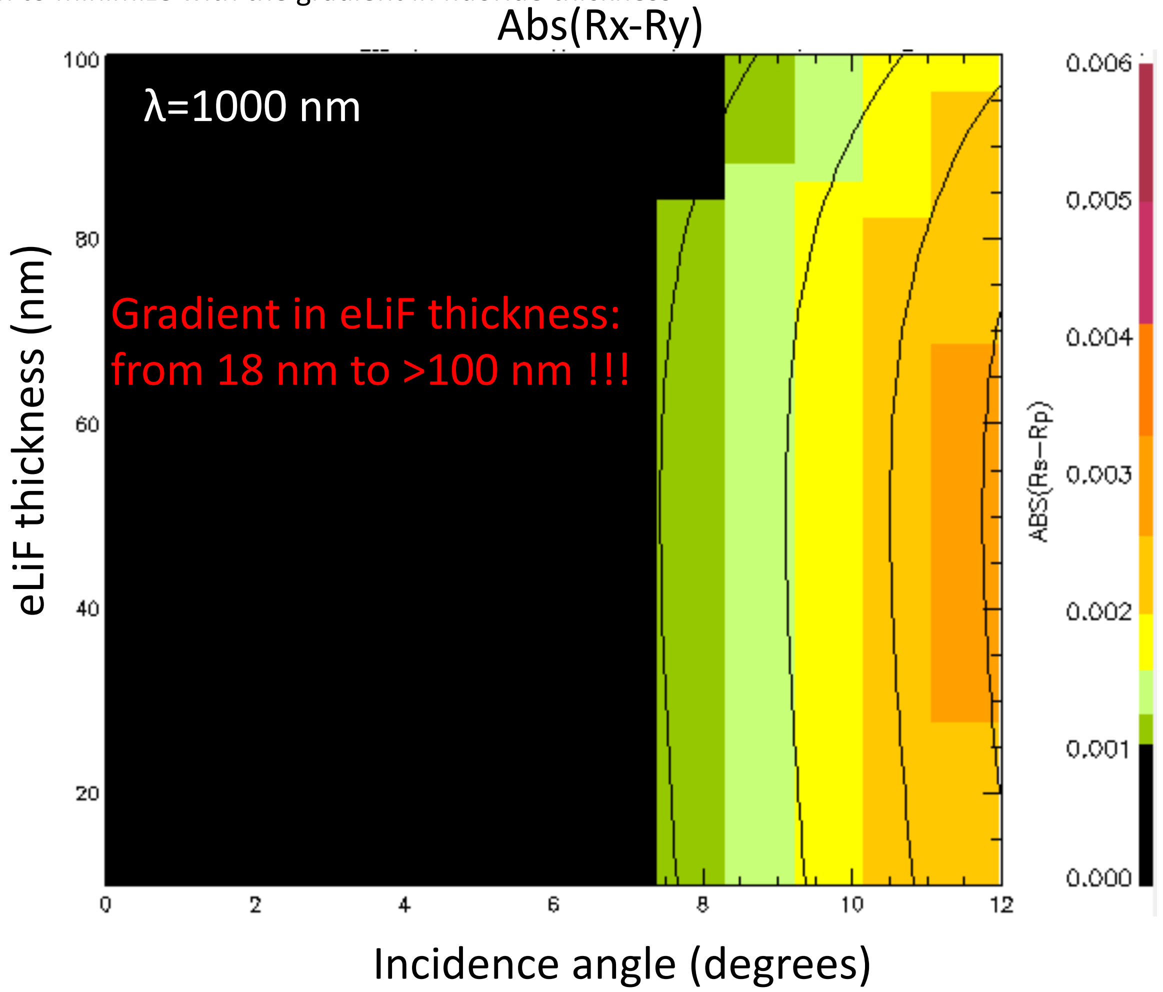

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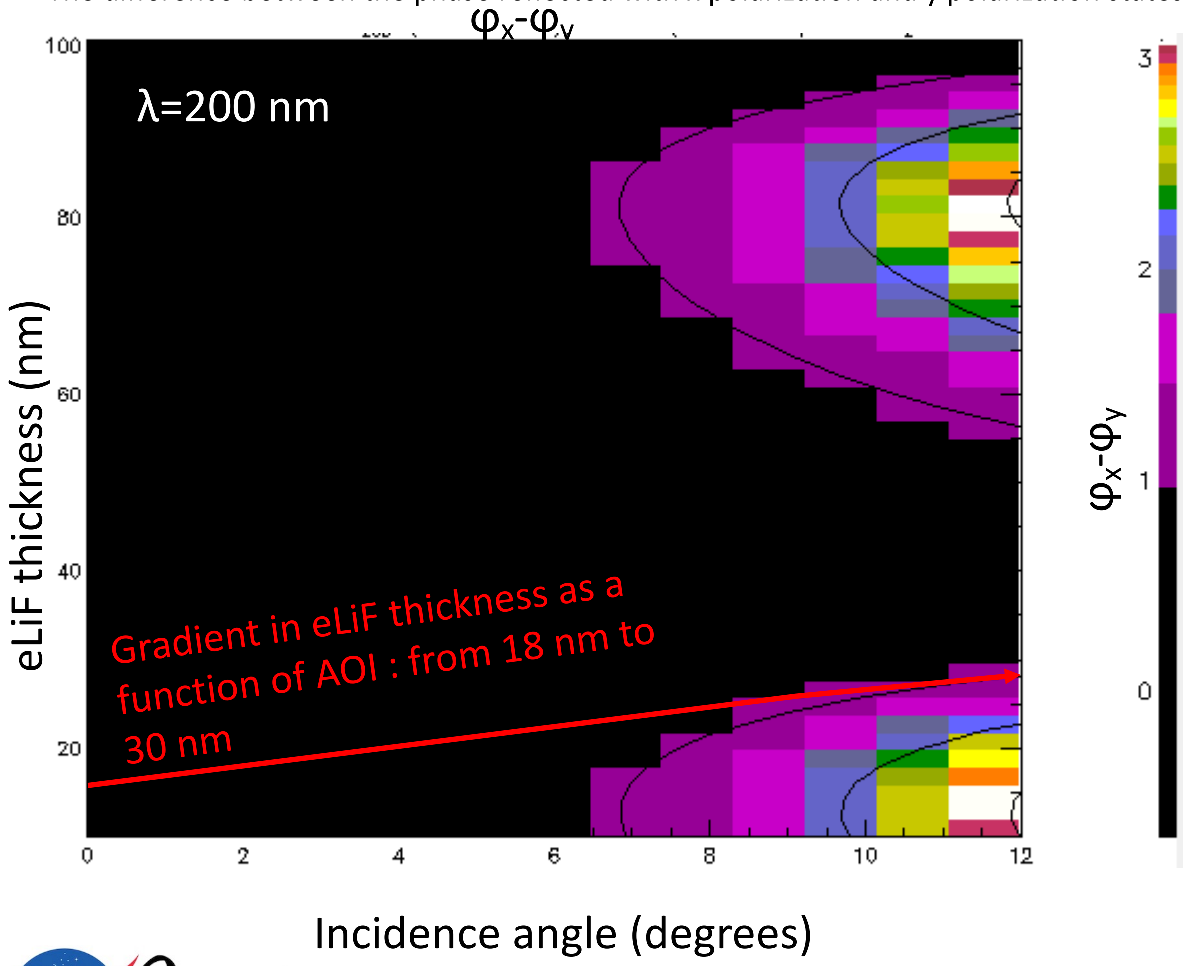
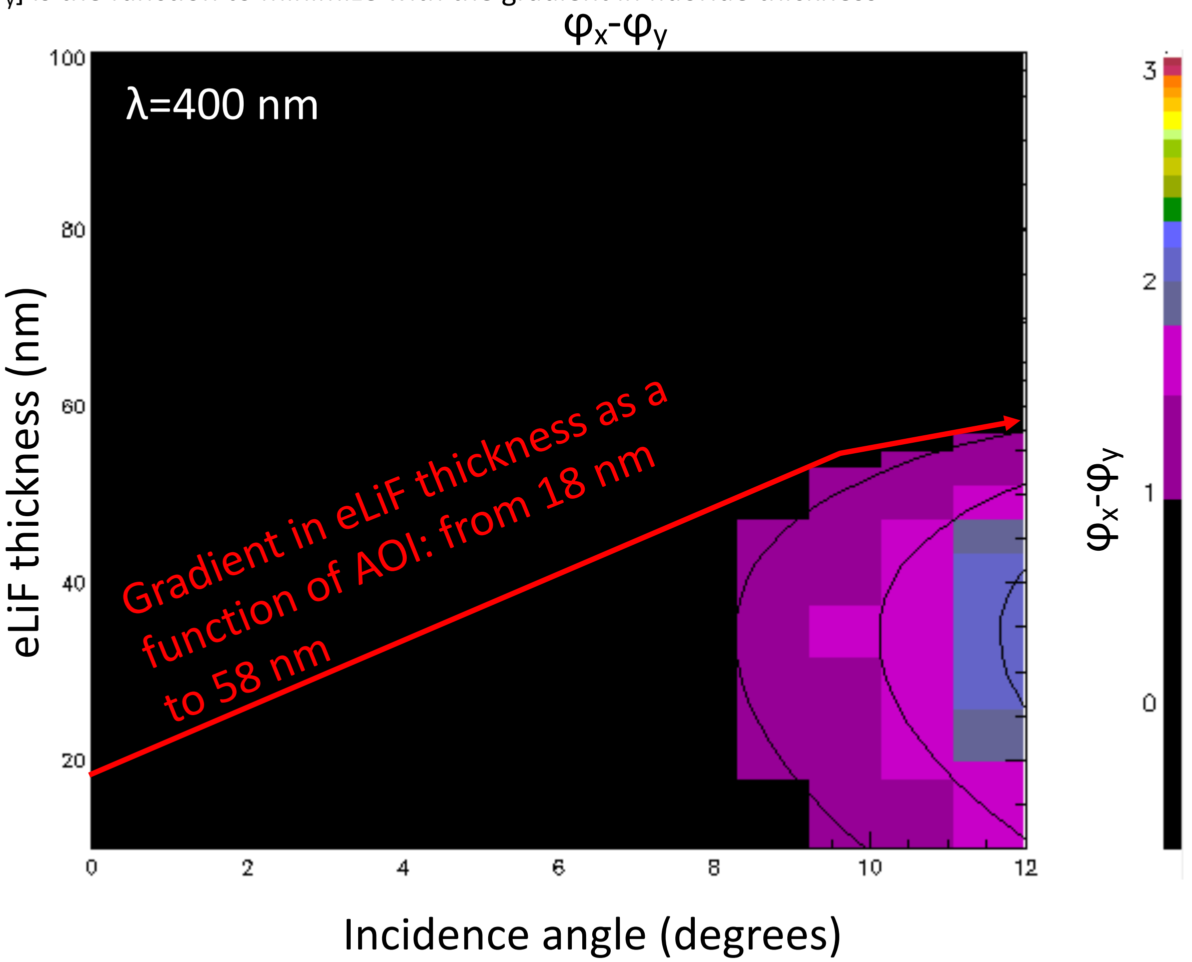
- Wavelengths: 200 nm, 400 nm, 600 nm, 1000 nm.
- 2D plot for each wavelength, in which black colour indicates φ_x-φ_y <1° as a function of fluoride thickness and AOI.

black colour indicates φ_x-φ_y<1 deg*
*this value should be refined following coronagraph requirements

The difference between the phase reflected with x polarization and y polarization states [φ_x-φ_y] is the function to minimize with the gradient in fluoride thickness





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The difference between the phase reflected with x polarization and y polarization states [φ_x-φ_y] is the function to minimize with the gradient in fluoride thickness