The VORTEX team

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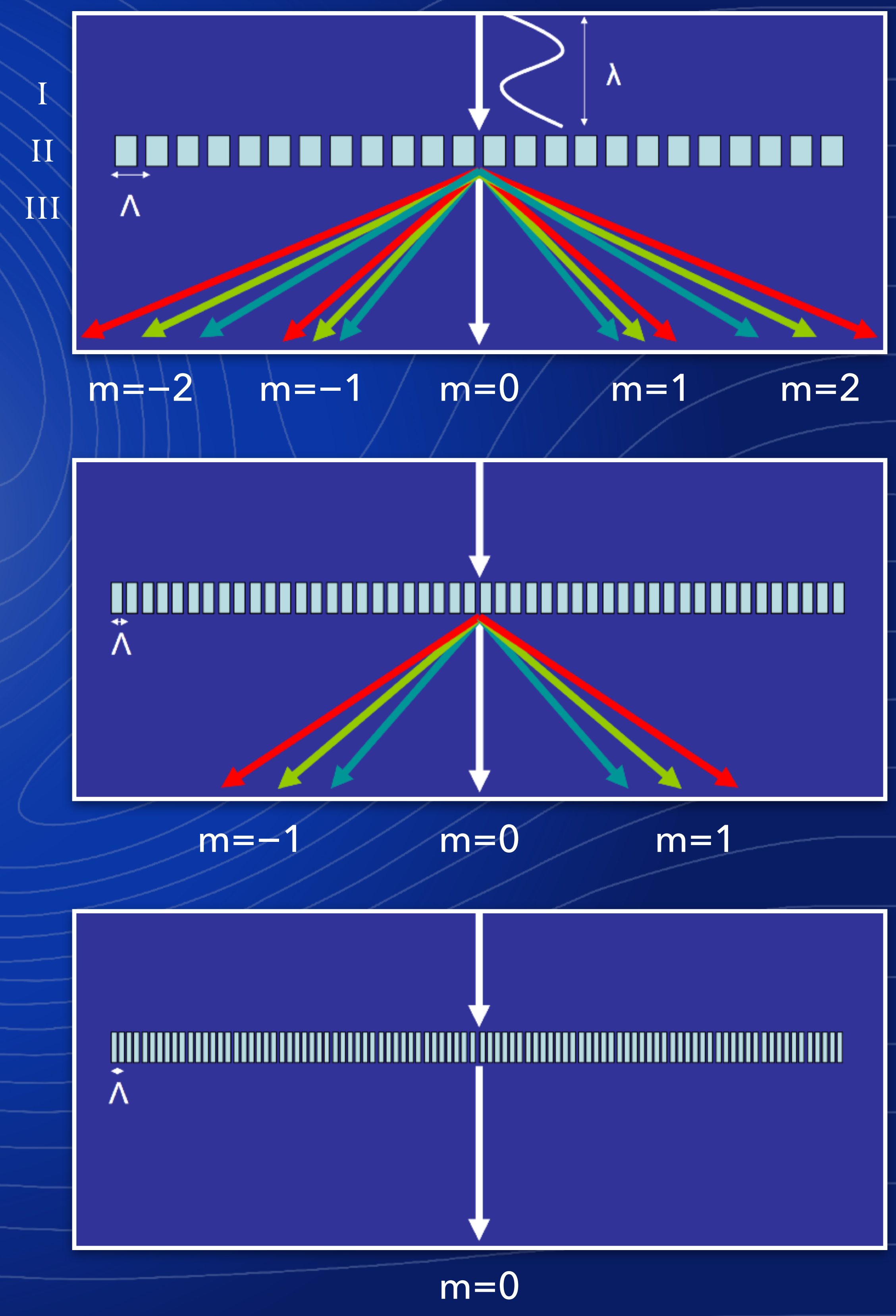
OLIVIER ABSIL

CORONAGRAPH FABRICATION TECHNOLOGIES: SUBWAVELENGTH GRATINGS

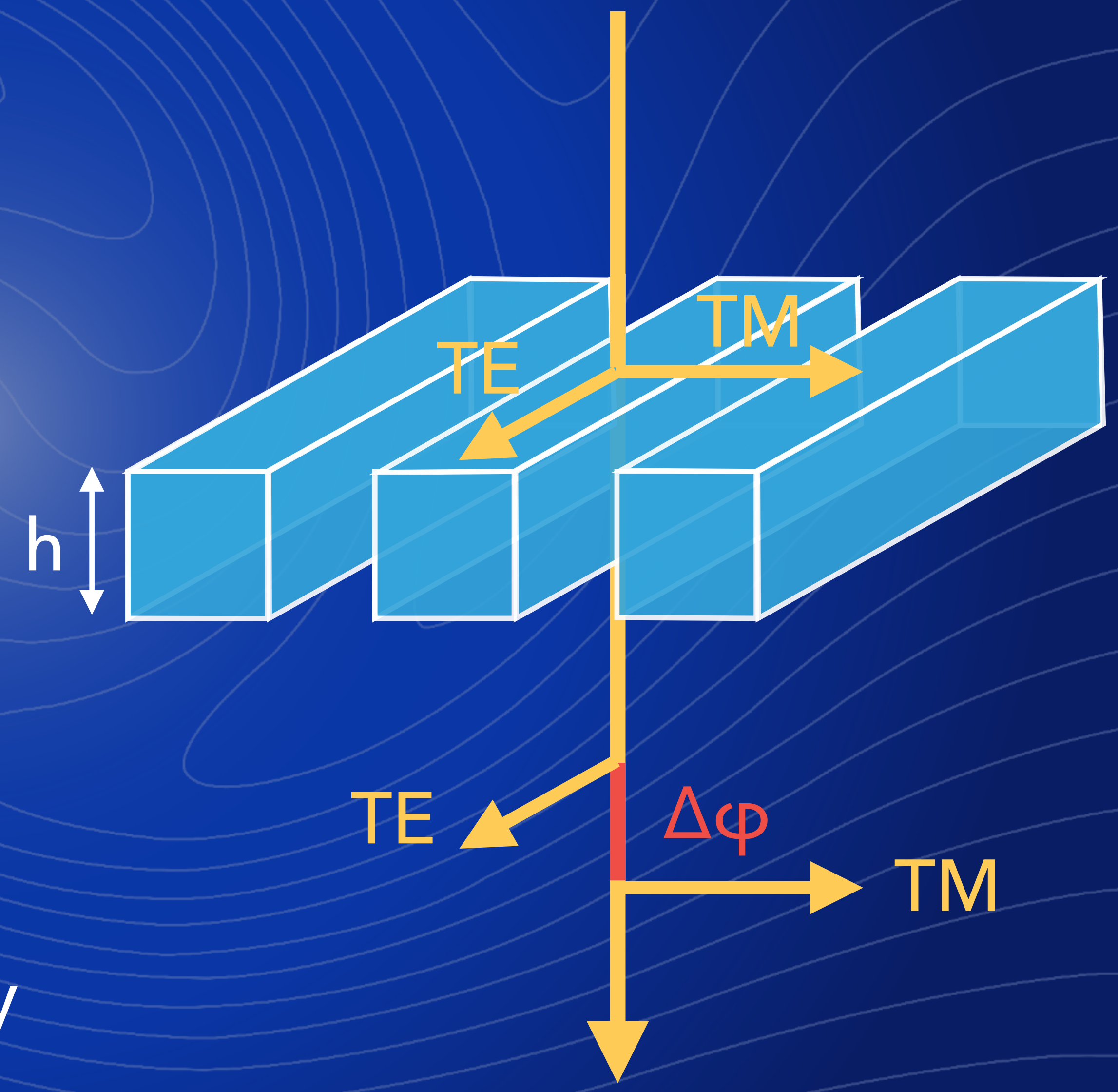
WHY SUBWAVELENGTH GRATINGS?

- Period smaller than wavelength
  - $$\frac{\Lambda}{\lambda} \leq \frac{1}{n_I \sin\theta + \max(n_I, n_{III})}$$
- Only zeroth order transmitted
  - also called zero-order grating (ZOG)
  - all other modes are evanescent
  - wavefront quality not altered
- 1D subwavelength gratings create artificial anisotropy in material



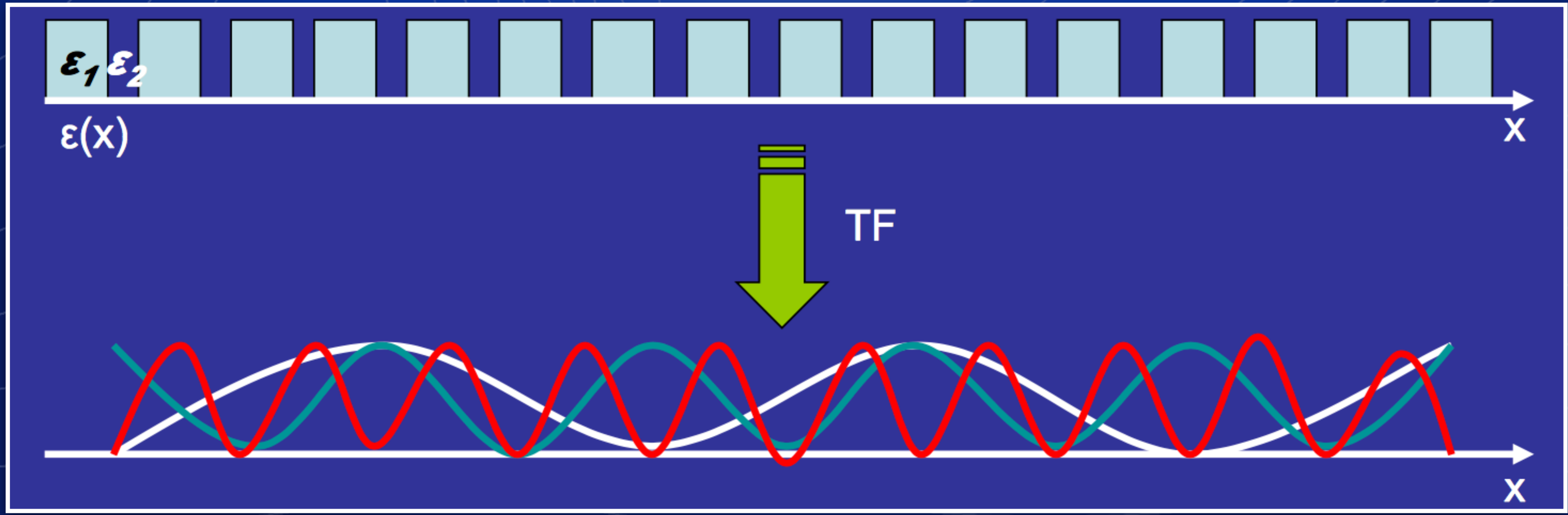
FORM BIREFRINGENCE IN SUBWAVELENGTH GRATINGS

- TE and TM polarization modes see different effective media, with refractive indices n_{TM} and n_{TE}
- Form birefringence:
  - $\Delta n(\lambda) = n_{TM} - n_{TE}$
  - creates phase shift $\Delta\varphi = 2\pi/\lambda \, h \, \Delta n$ between TE and TM modes
- Dispersion of form birefringence controlled through grating geometry
  - $\Delta n \propto \lambda \rightarrow$ achromatic phase shift



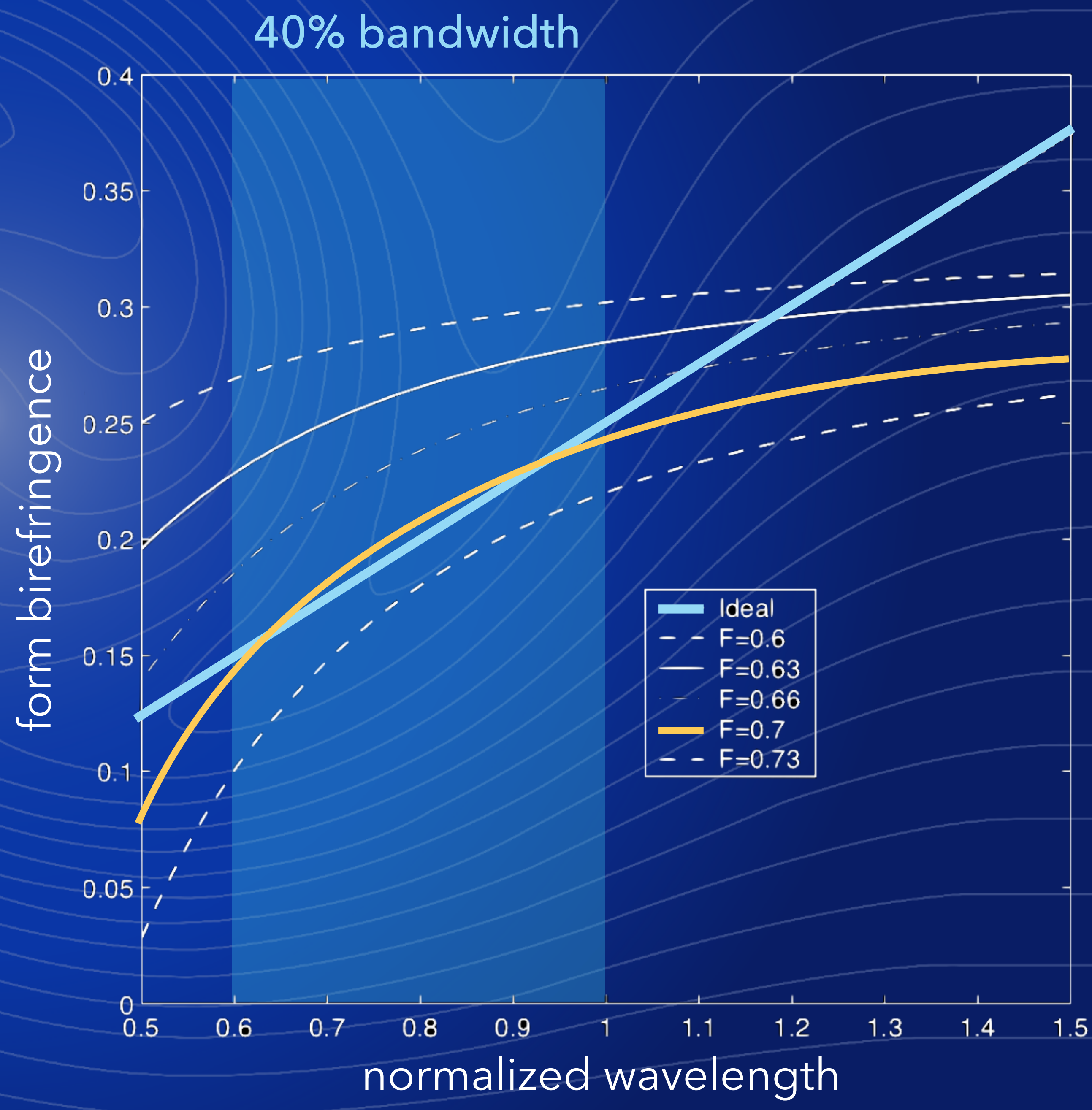
RIGOROUS COUPLED WAVE ANALYSIS (RCWA)

- To analyse response of subwavelength gratings, vectorial nature of light must be taken into account
- RCWA solves Maxwell's equations by decomposing fields and permittivities in Fourier series, and by matching them at grating boundaries
  - Still makes assumptions … if not enough, use numerical methods (FDTD)



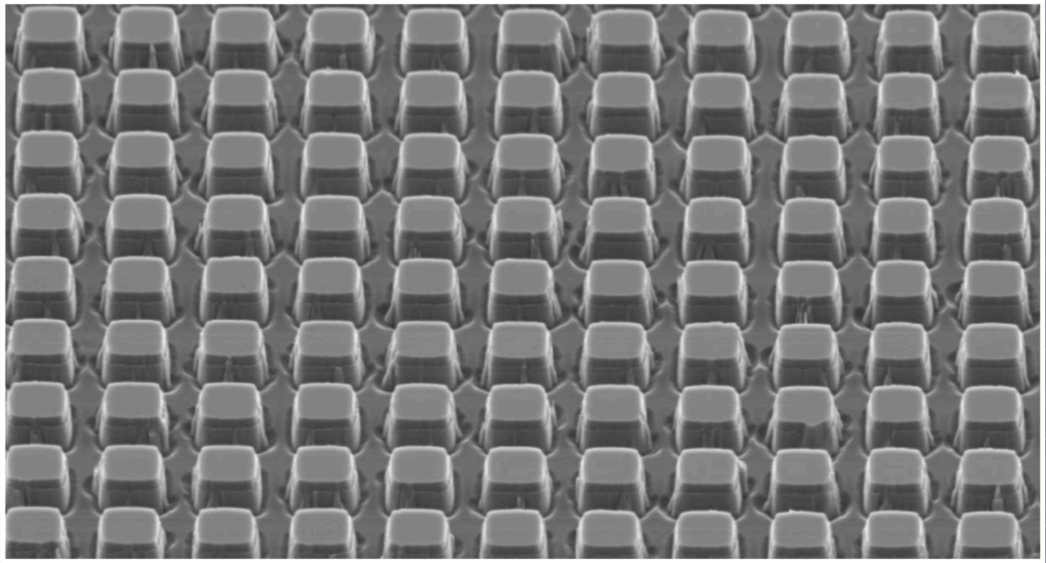
SUBWAVELENGTH GRATINGS AS PHASE RETARDERS

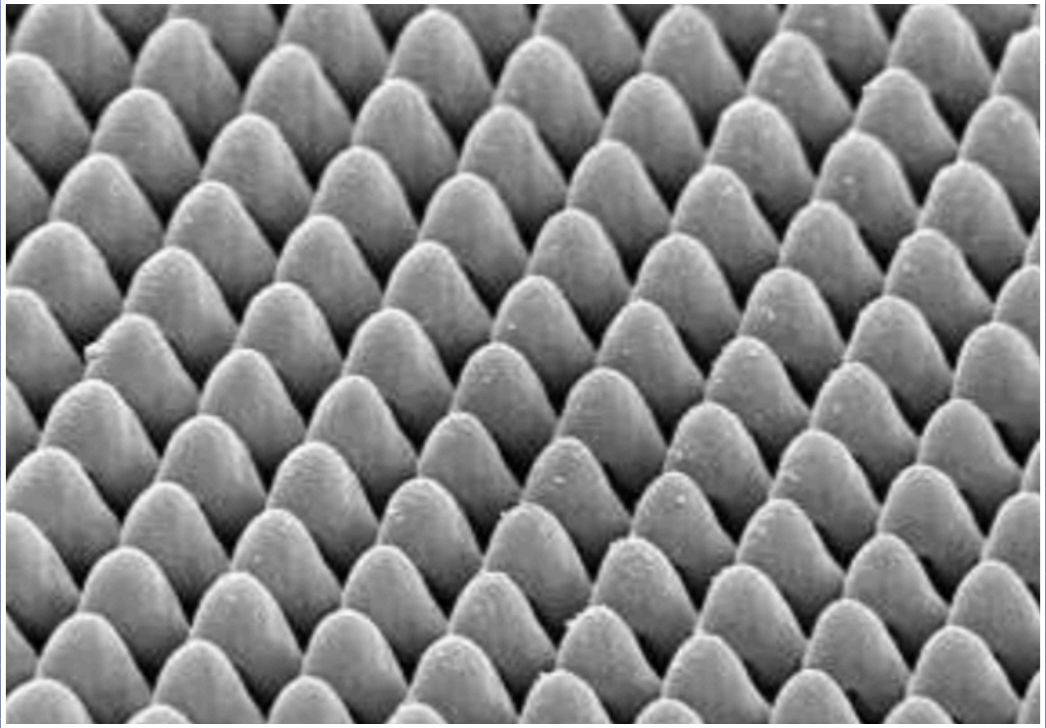
- Grating geometry can be tuned to achieve any given phase shift between TE and TM modes (in reflection or transmission)
- Can produce any kind of achromatic phase retarder
  - quarter wave plate: $\Delta n(\lambda) \approx \lambda/4h$ $\rightarrow \Delta\varphi \approx \pi/2$
  - half wave plate: $\Delta n(\lambda) \approx \lambda/2h \rightarrow \Delta\varphi \approx \pi$
- Perfect achromatic behavior only tangentially approached



SUBWAVELENGTH GRATINGS AS ANTI-REFLECTIVE STRUCTURES

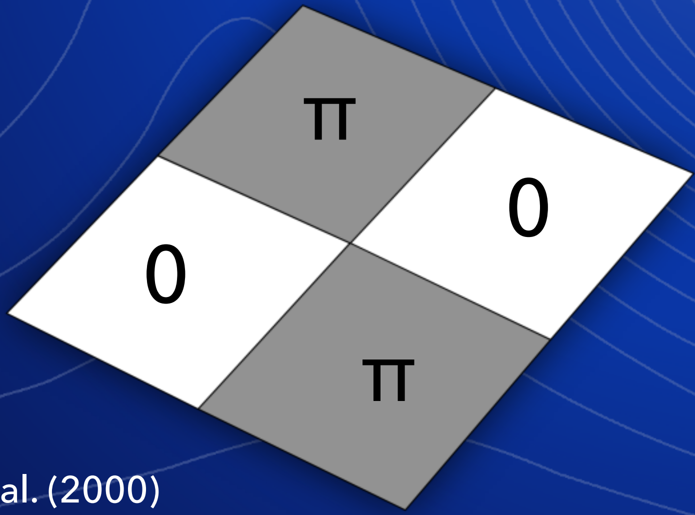
- Fresnel reflections are due to abrupt change in refractive index between two media
- 2D subwavelength grating induces index gradient, which is key to produce anti-reflective structures
- Square pattern ok, but AR gets better for smoother profiles (pyramid, egg-box, etc)



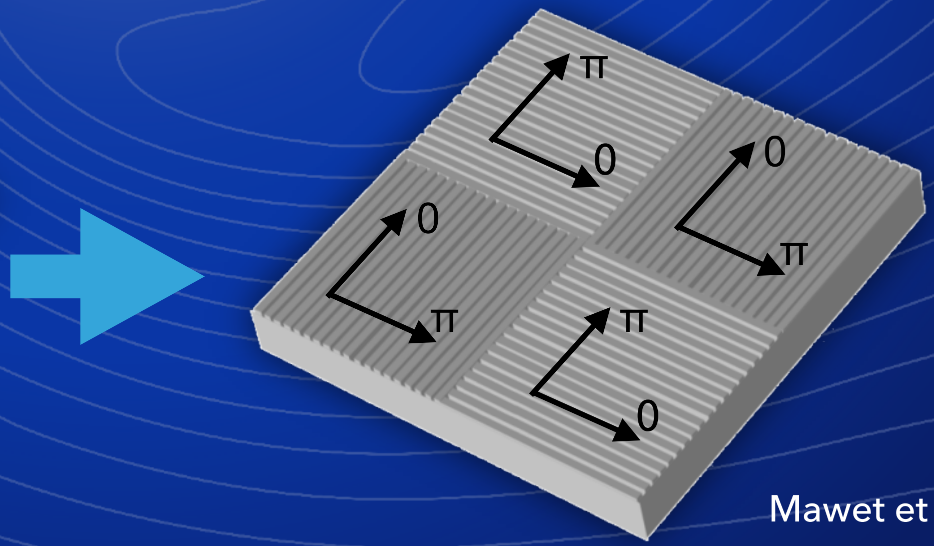


SUBWAVELENGTH GRATINGS AS CORONAGRAPHS

- Introduced by Mawet et al (2005) to achromatize the Four Quadrant Phase Mask (FQPM)
- Four half wave plates with perpendicular orientations
  - Act separately on each polarization



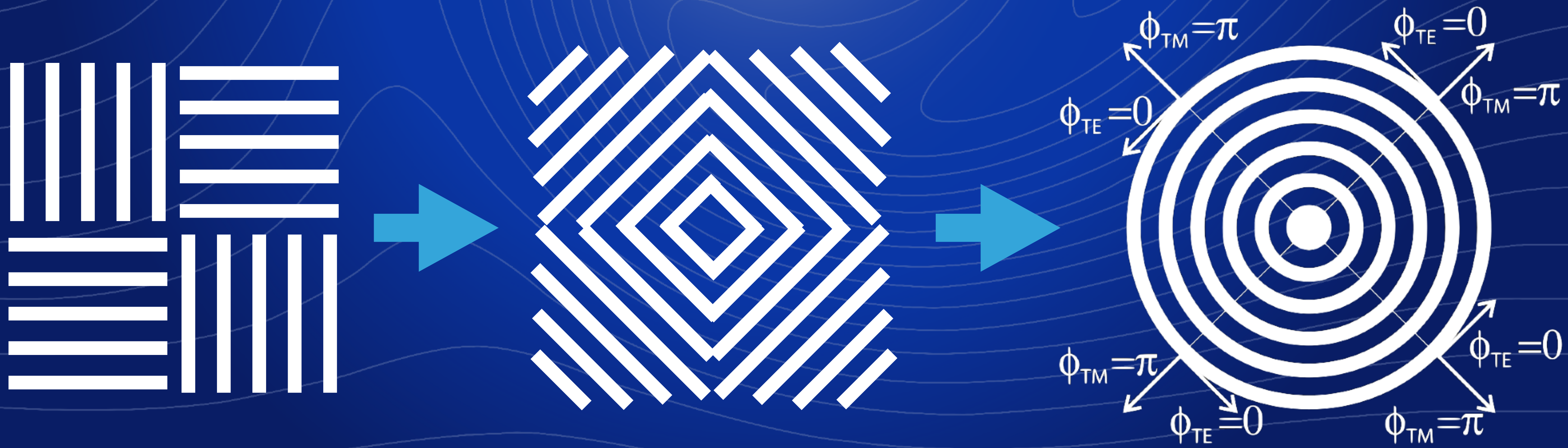
Rouan et al. (2000)



Mawet et al. (2005a)

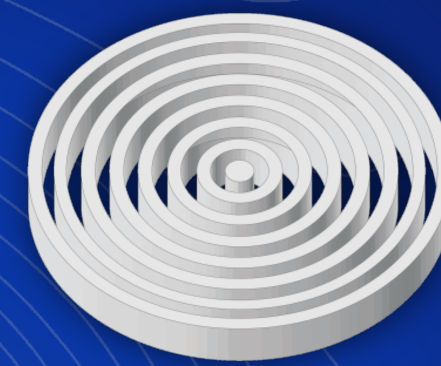
FROM FQPM TO AGPM

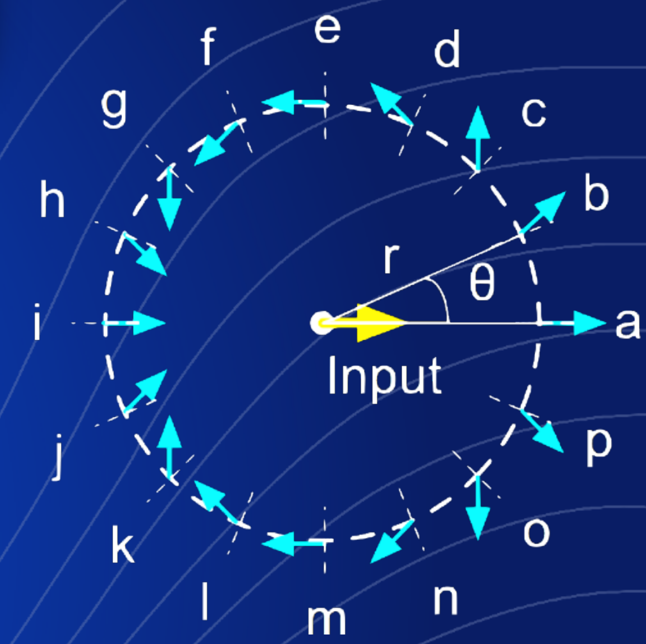
- Why not try to make the grating continuous?
- Circular grating ≈ local version of the FQPM
  - ✳ annular groove phase mask (AGPM)
  - ✳ gets rid of blind areas associated with quadrant transitions



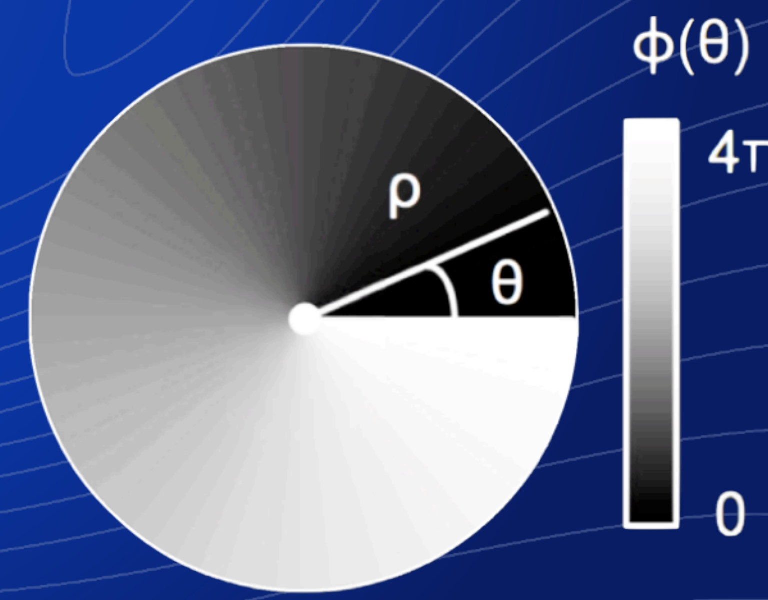
Mawet et al. (2005b)

THE VECTOR VORTEX PHASE MASK

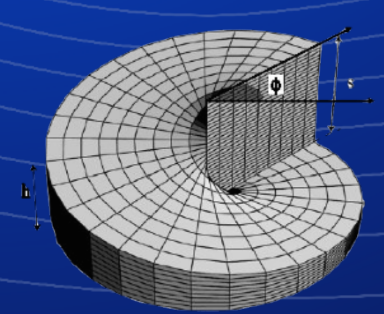




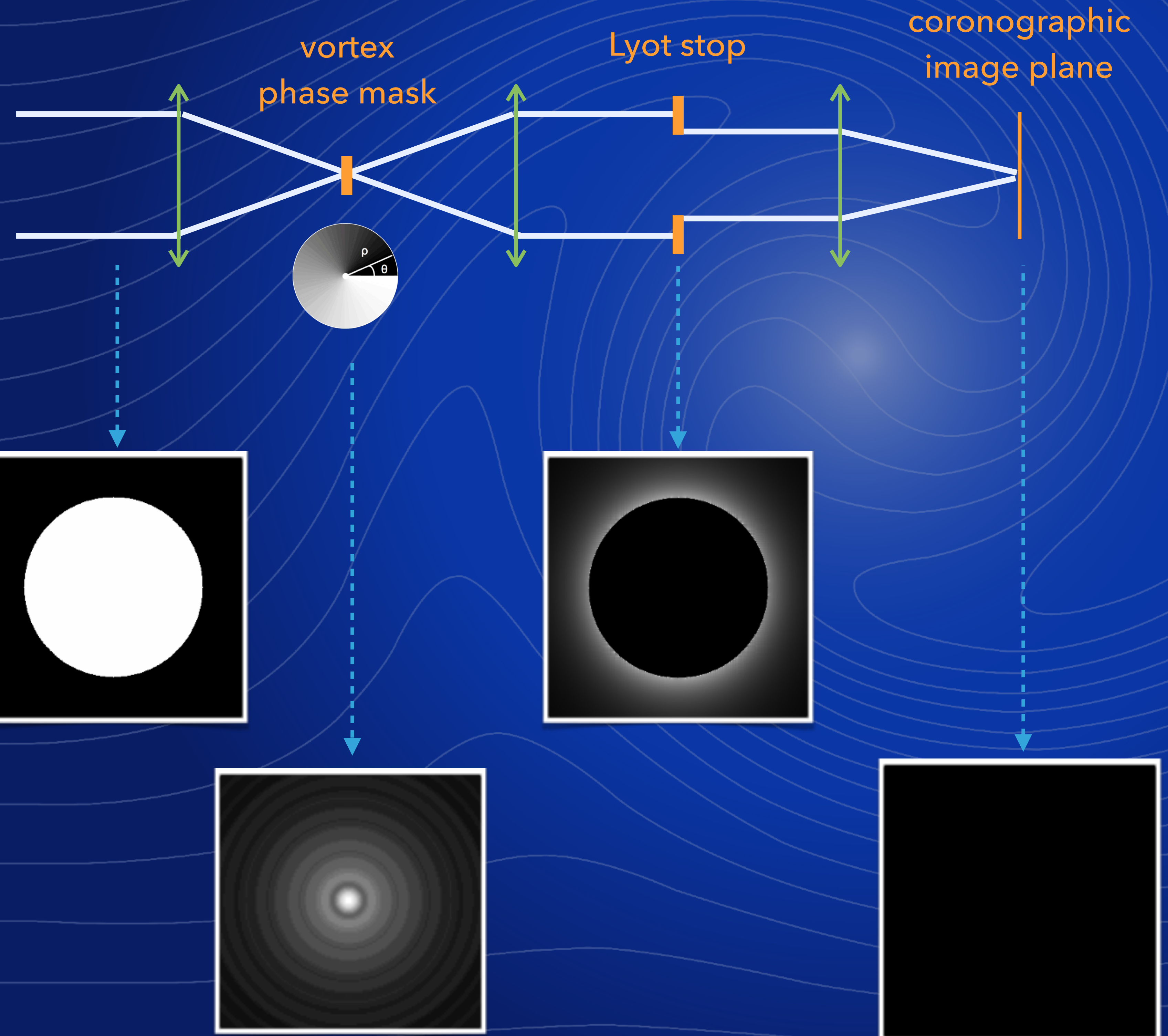
- AGPM = spatially variant half wave plate creating continuously changing phase shift for a given polarization
  - phase ramp ranges from 0 to 4π around optical axis ≙ **optical vortex**



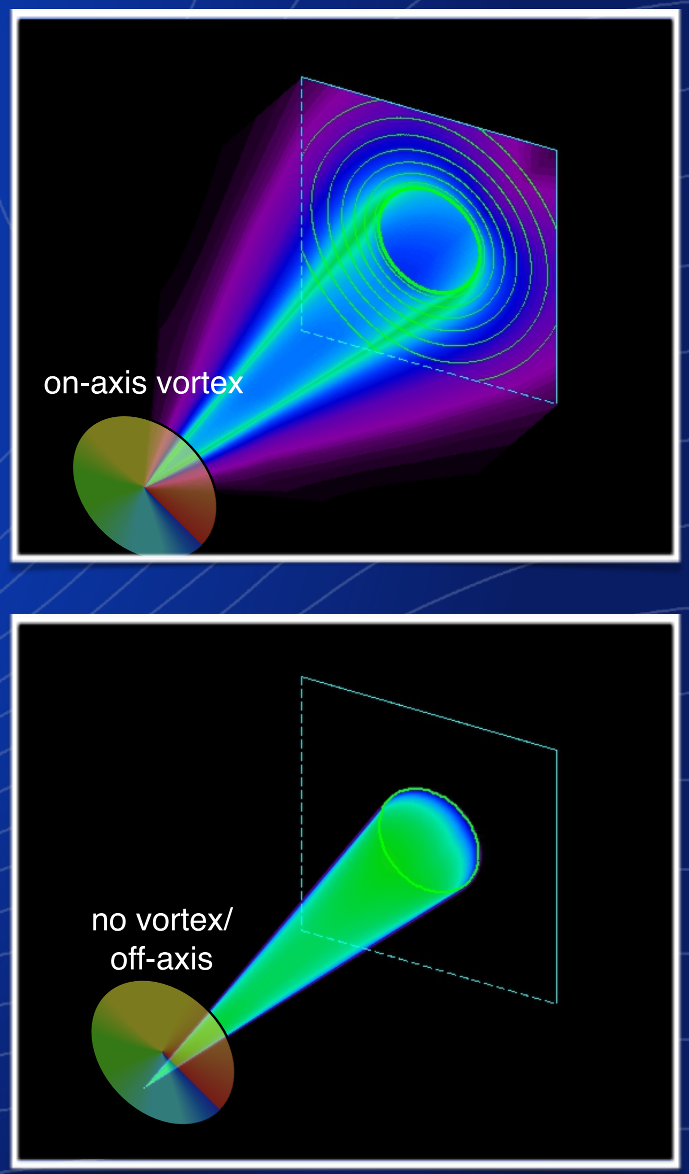
- Vector vortex implementation based on ZOGs is not unique
  - also liquid crystals and photonics crystals
- Scalar vortex also possible



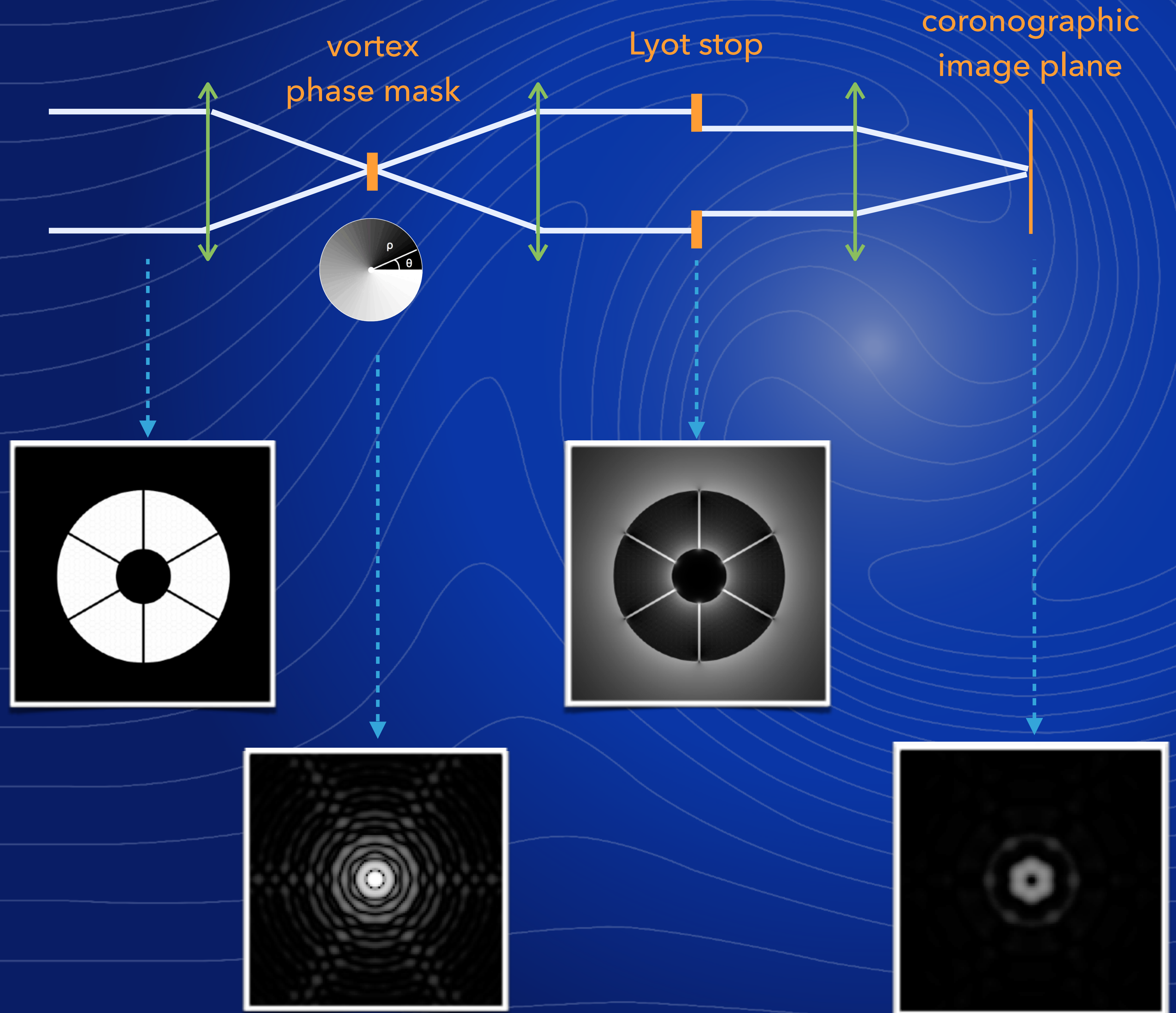
THE VORTEX CORONAGRAPH DOING ITS MAGIC



perfect on-axis cancellation
for a circular aperture



THE VORTEX CORONAGRAPH DOING ITS MAGIC



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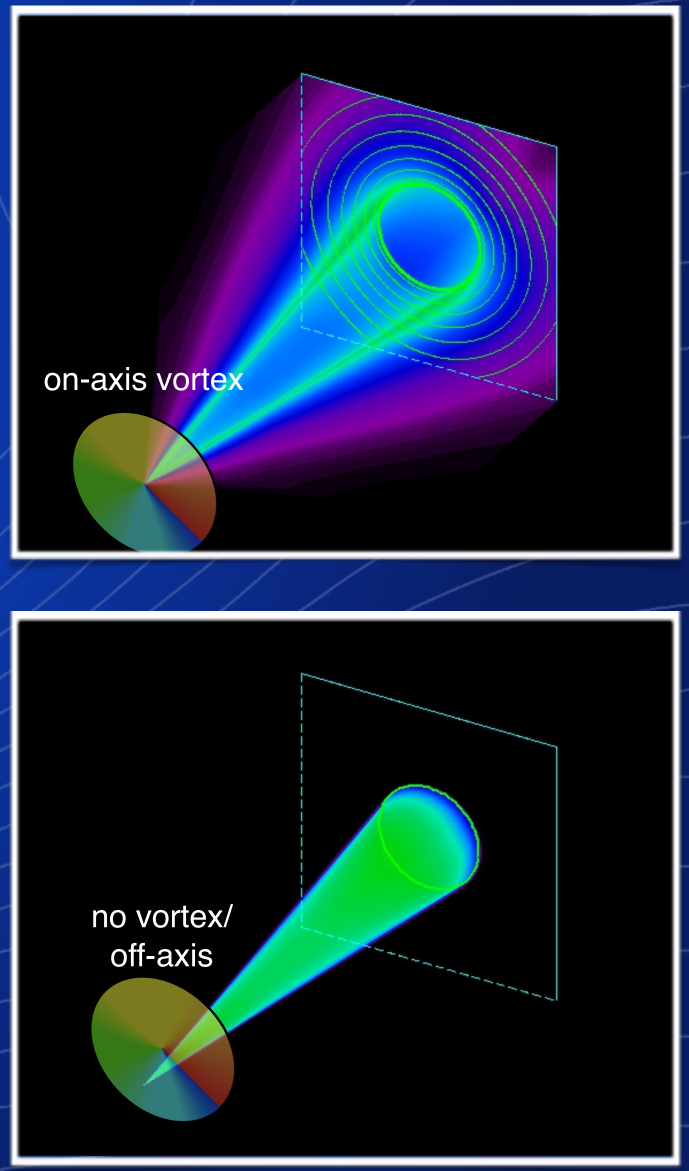


MAIN ASSETS OF THE VECTOR VORTEX CORONAGRAPH

- Small inner working angle (heritage from the FQPM)
- 360° discovery space: no more blind zones
- Achromatic by concept
  - geometric phase does not depend on wavelength
- Quasi-achromatic in its implementation (ZOG, LCP)
- High transmission and Strehl ratio

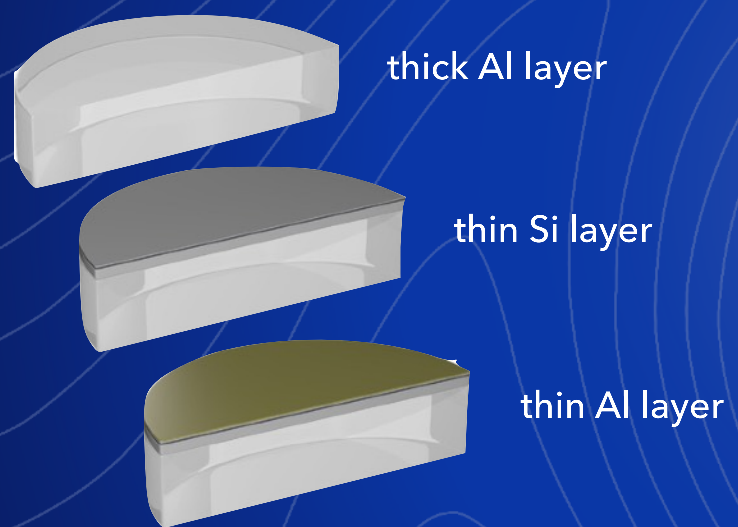
MAIN LIMITATIONS OF THE VECTOR VORTEX CORONAGRAPH

- Sensitivity to pointing errors and low order aberrations
  - with great powers comes great responsibilities:
    CONTROL YOUR TELESCOPE!
- Perfect rejection only for circular, unobscured pupil
  - perfect apodization solutions for centrally obscured pupils
  - spiders can be (partially) compensated
- Only <u>quasi</u>-achromatic in its implementation (ZOG, LCP)
- Two polarizations treated separately, can limit ultimate performance in unpolarized light

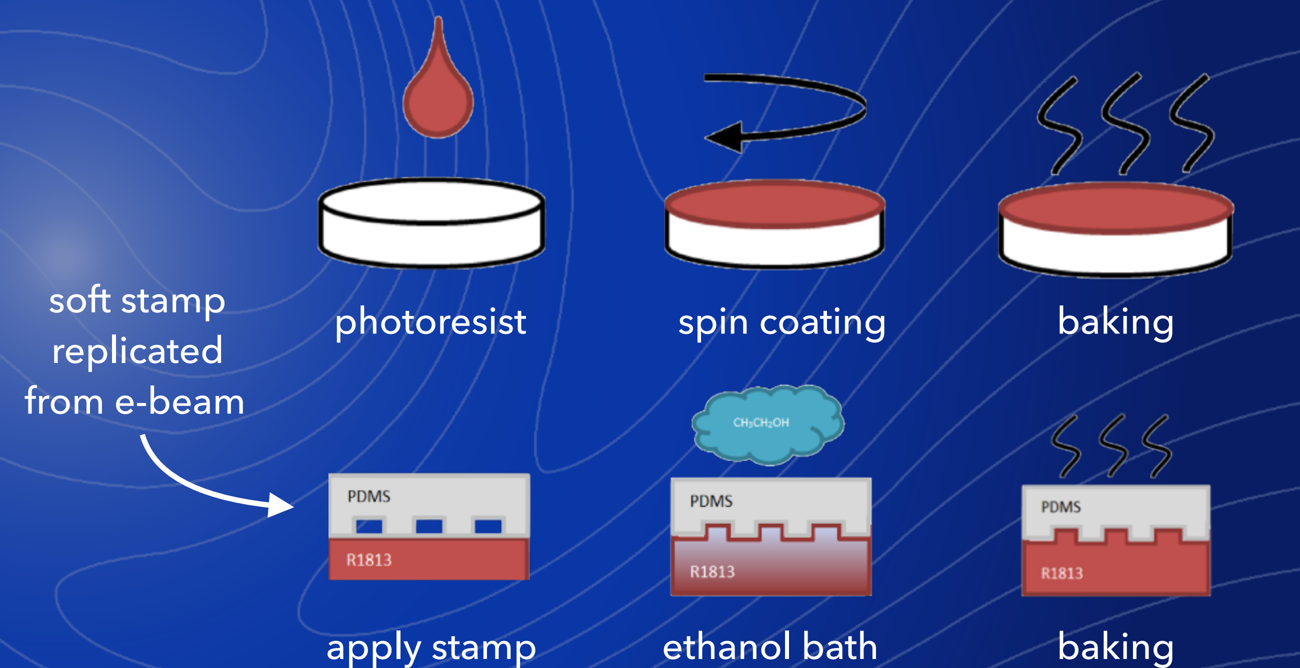
MANUFACTURING DIAMOND AGPM @ UPPSALA

Vargas Catalan et al. (2016)

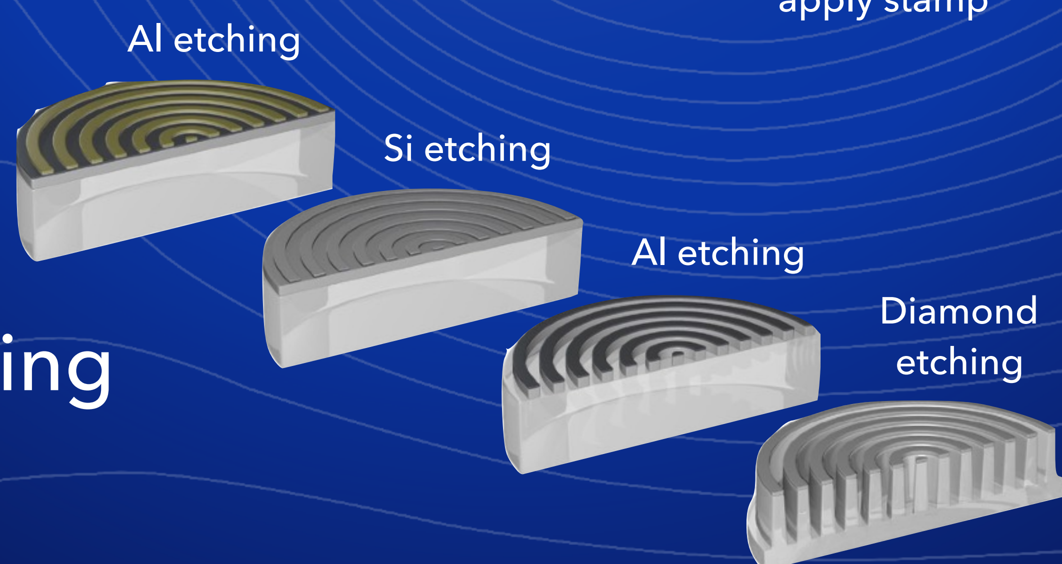
1. diamond coated with Al and Si layers (sputtering)

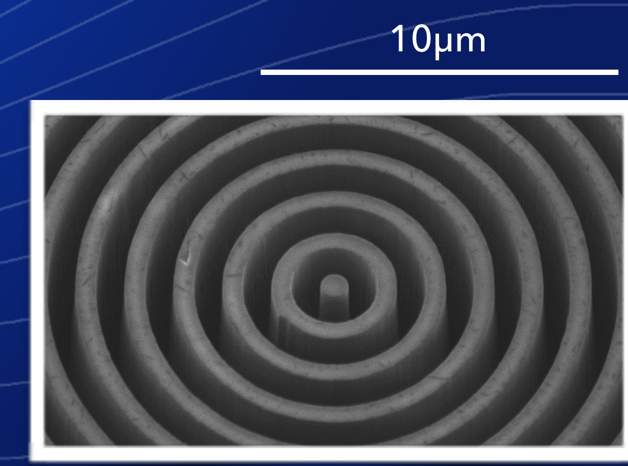


2. e-beam pattern transferred with solvent-assisted moulding

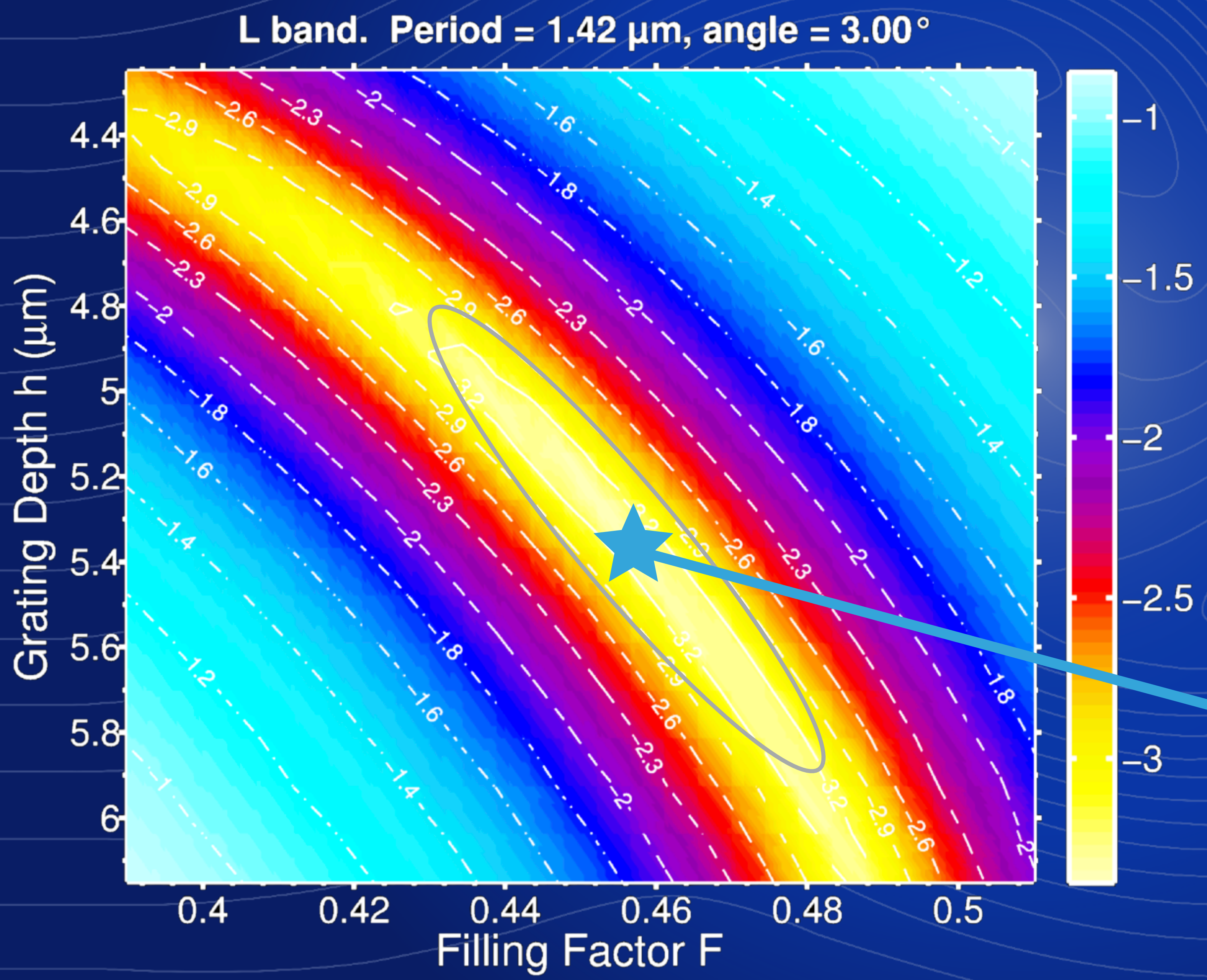


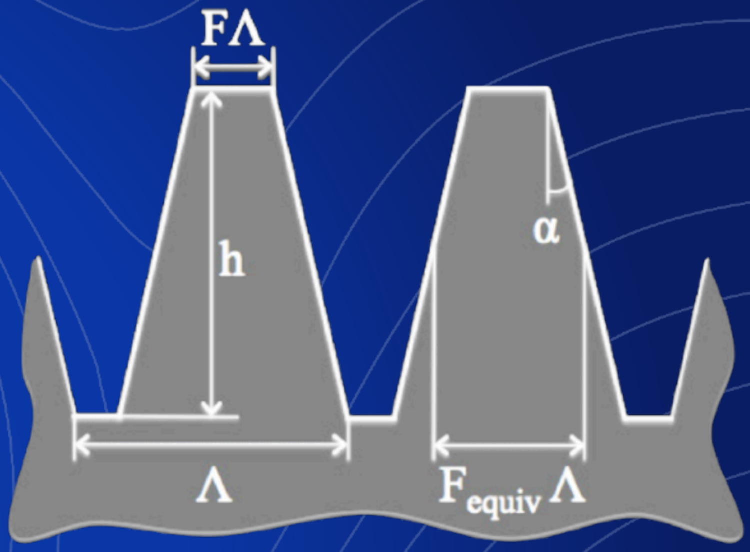
3. reactive ion etching

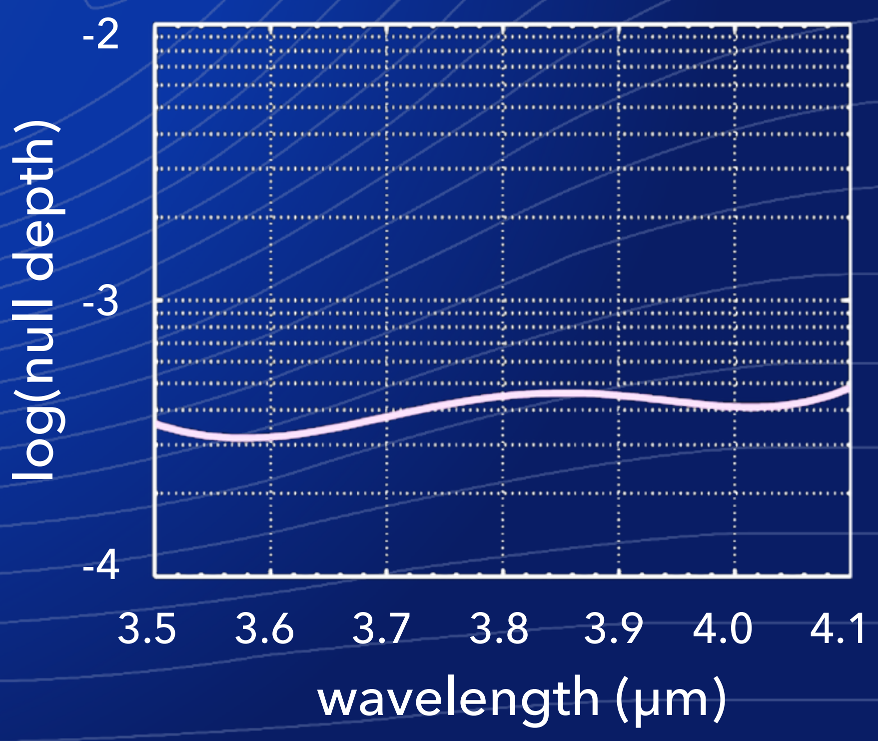




OPTIMIZING THE GRATING DESIGN

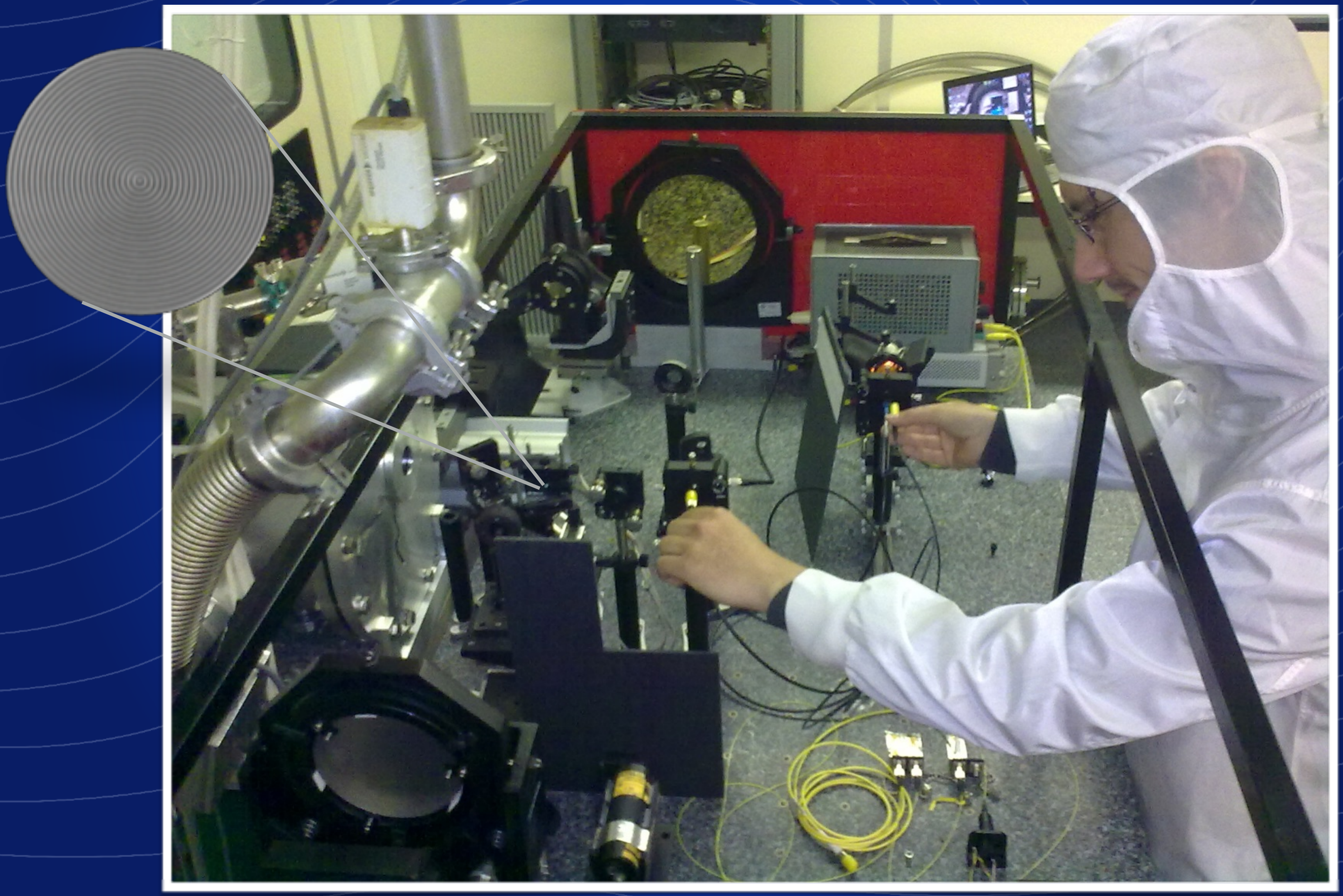






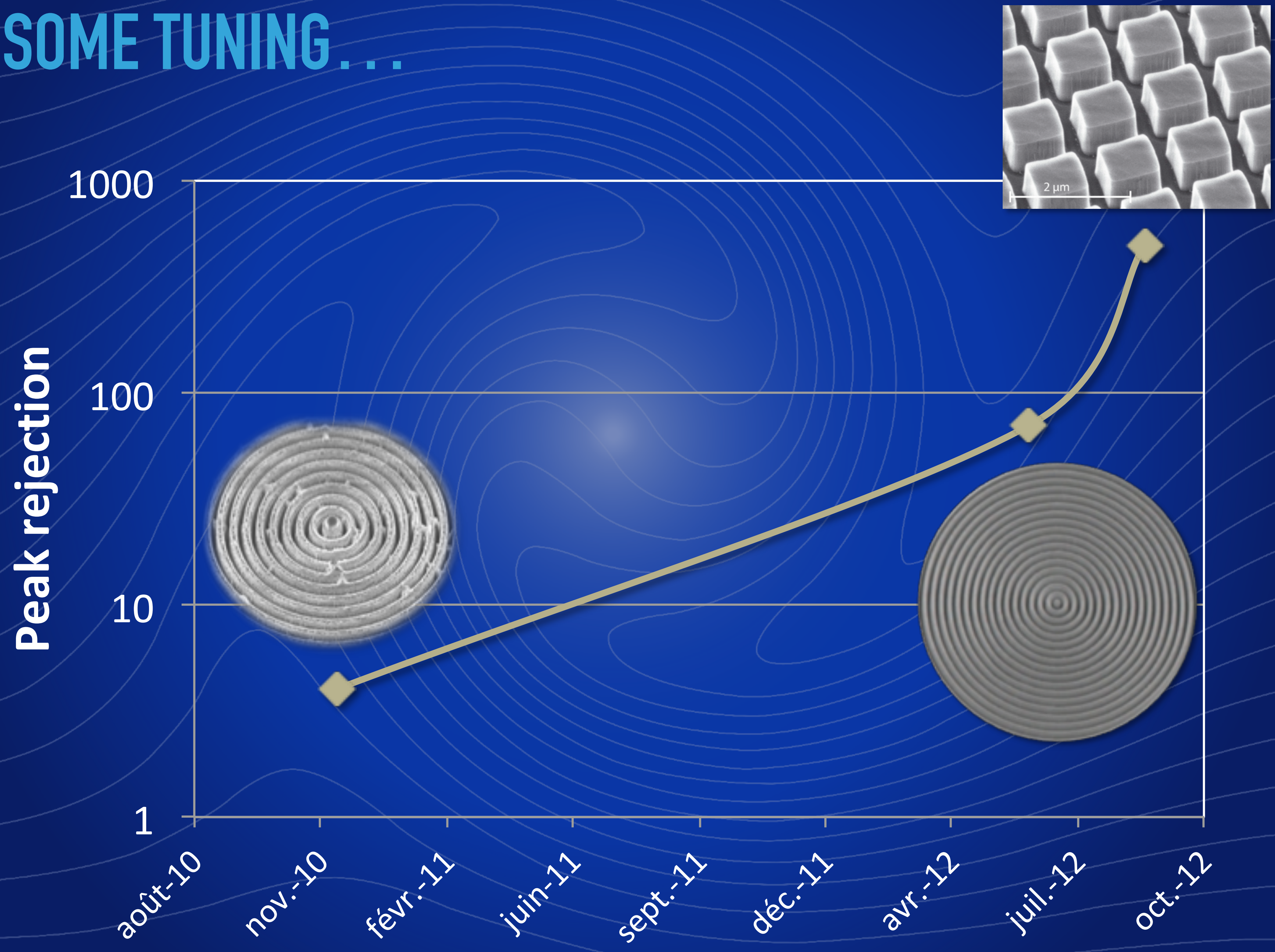
Delacroix et al. (2013)

SETTING UP THE « YACADIRE » BENCH @ MEUDON

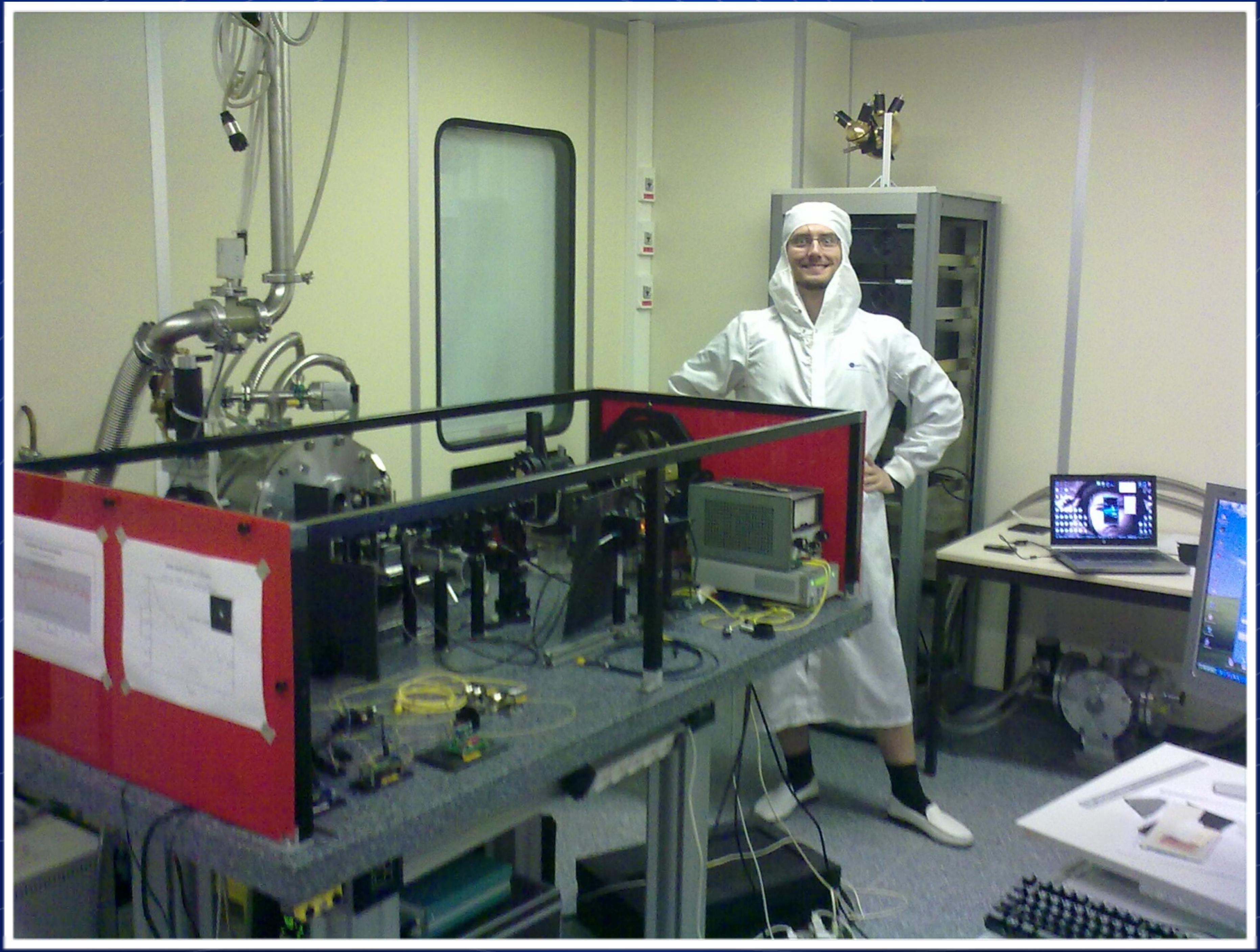


ANGUISH...

AFTER SOME TUNING…

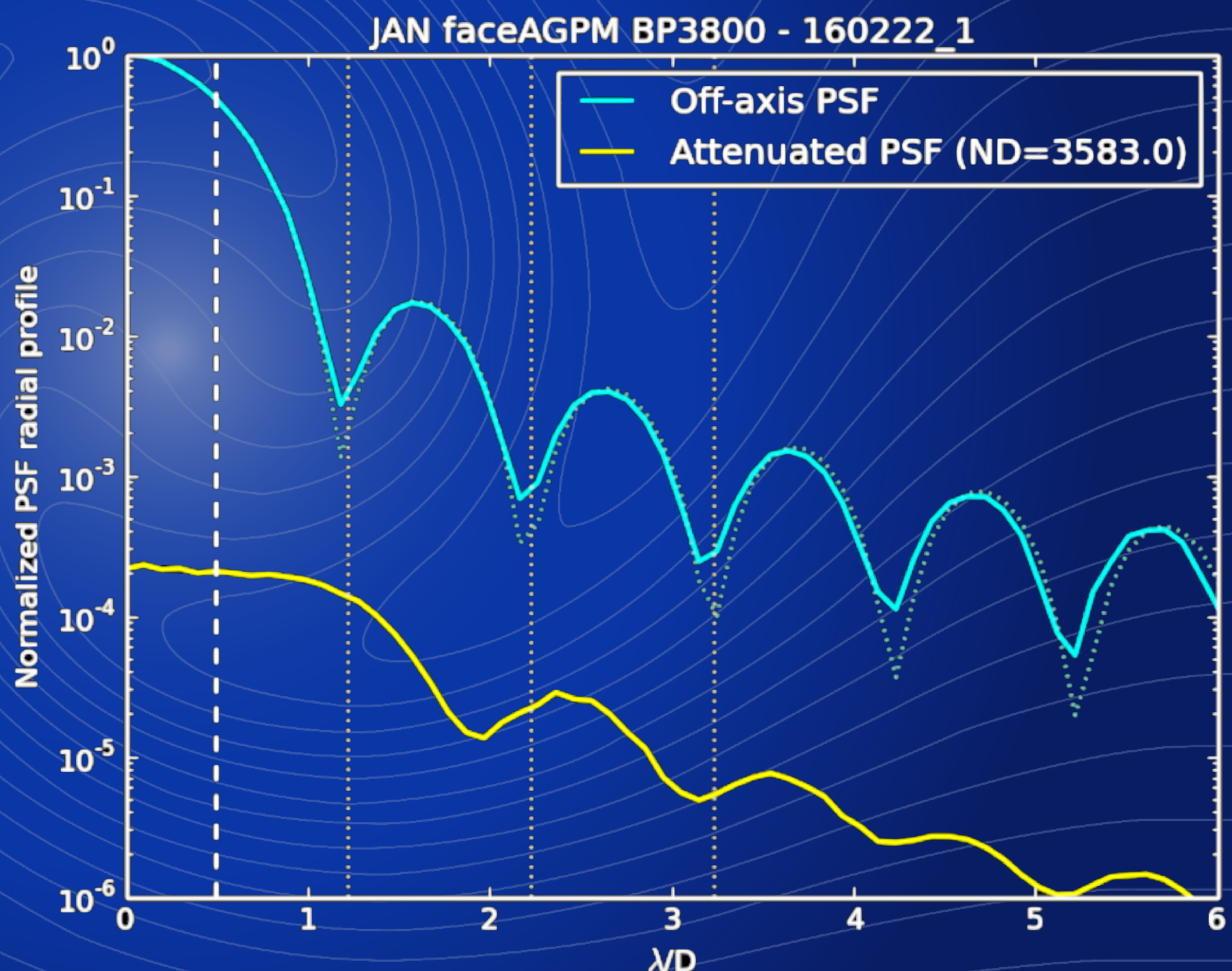


BLISS!



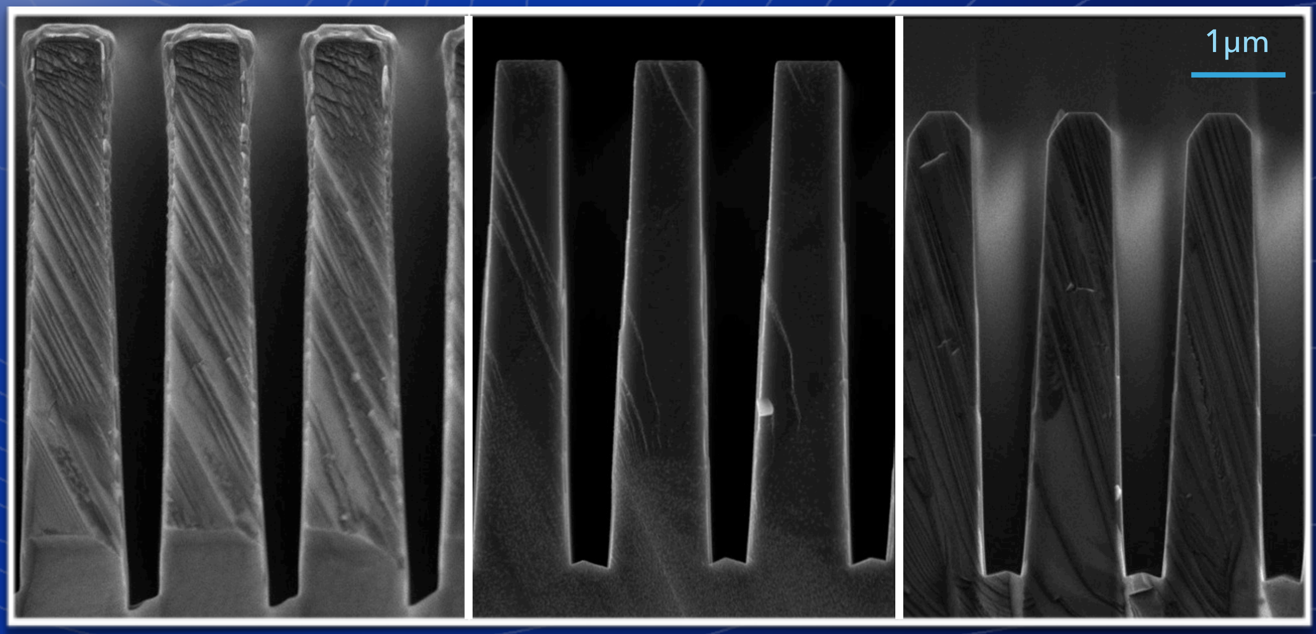
BEST PERFORMANCE IN THE LAB - 2018 UPDATE

- Dedicated IR test bench (VODCA) now available at ULiège
- 10+ science-grade L-band AGPMs etched & tested
- Broadband L (3.5-4.1µm) peak rejection up to 1500:1



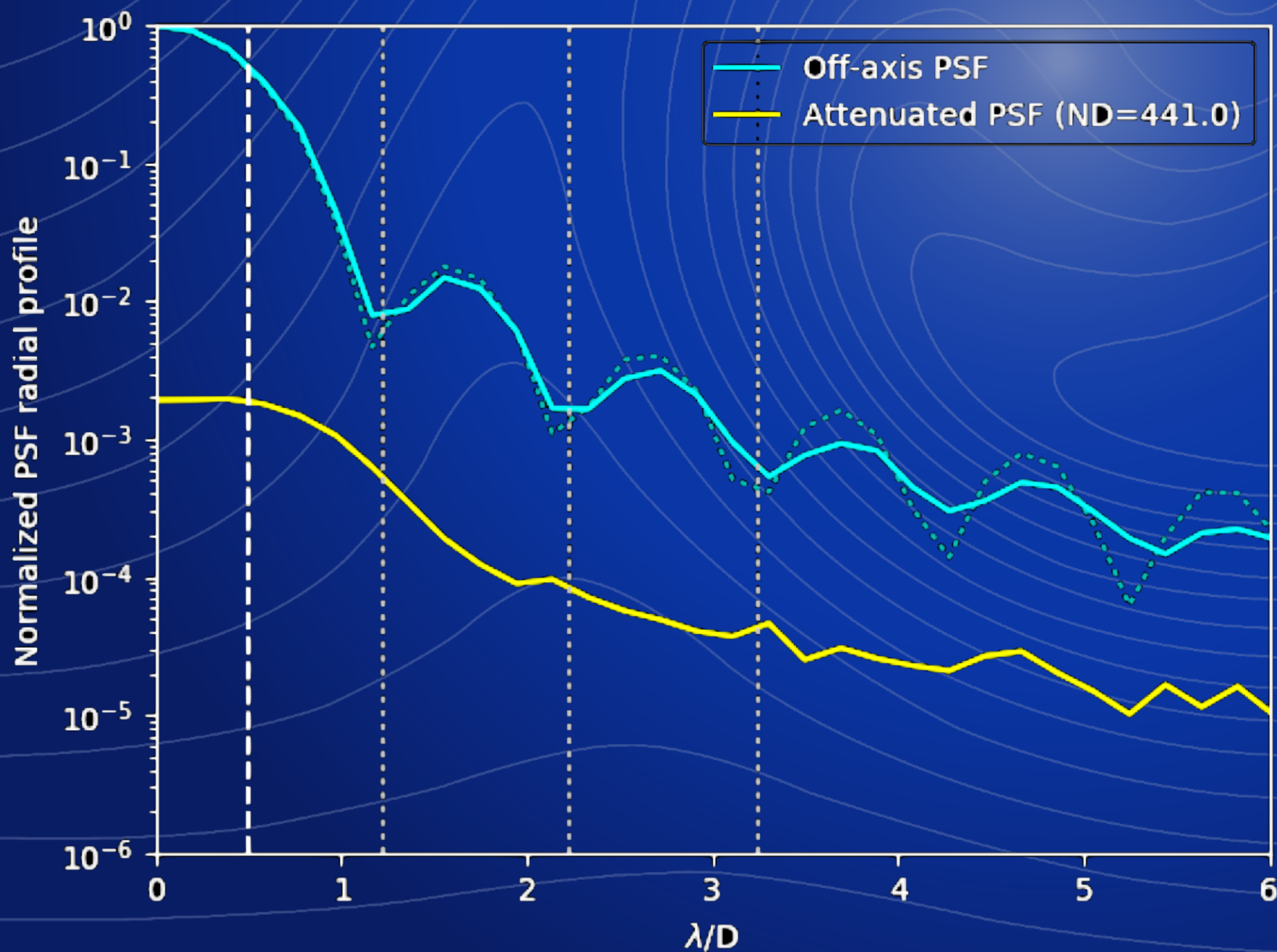
CURRENT STATUS & PERSPECTIVES

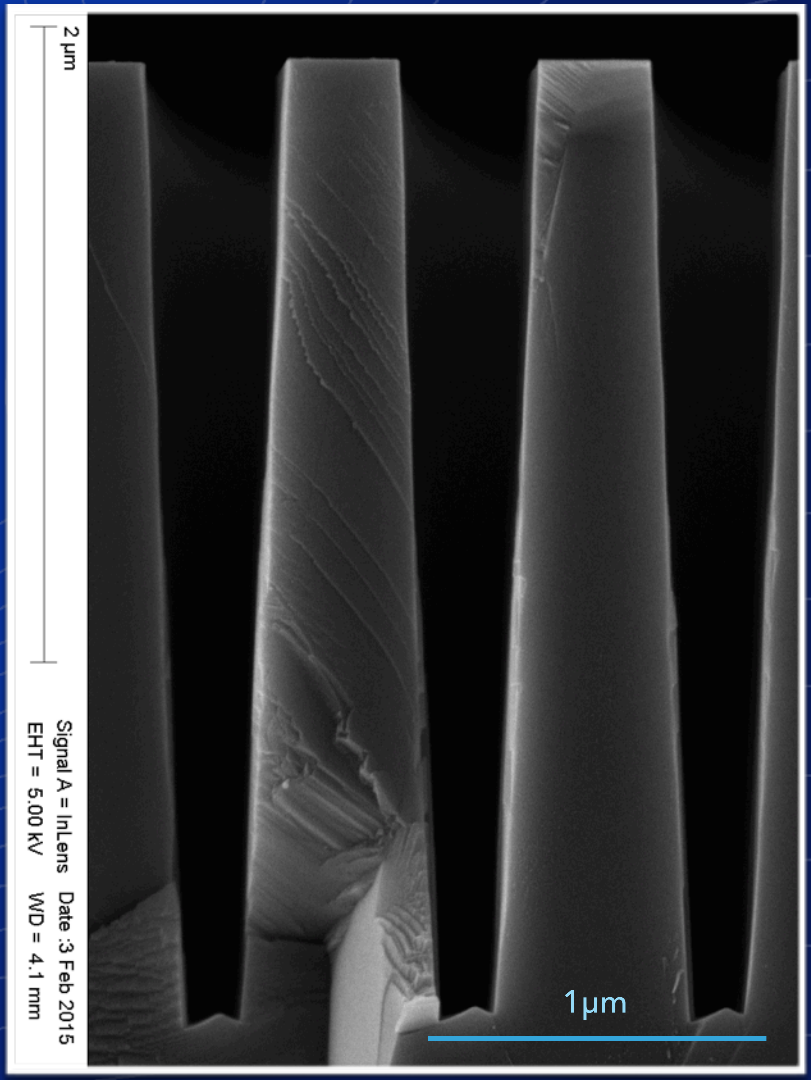
- AGPM first developed for thermal infrared (L, M, N bands)
  - excellent performance on ~20% bandwidth
  - installed at various observatories (Keck, VLT, LBT)
- Re-etching techniques validated
- Next steps
  - shorter wavelengths
  - higher topological charges



AGPM AT SHORTER WAVELENGTHS

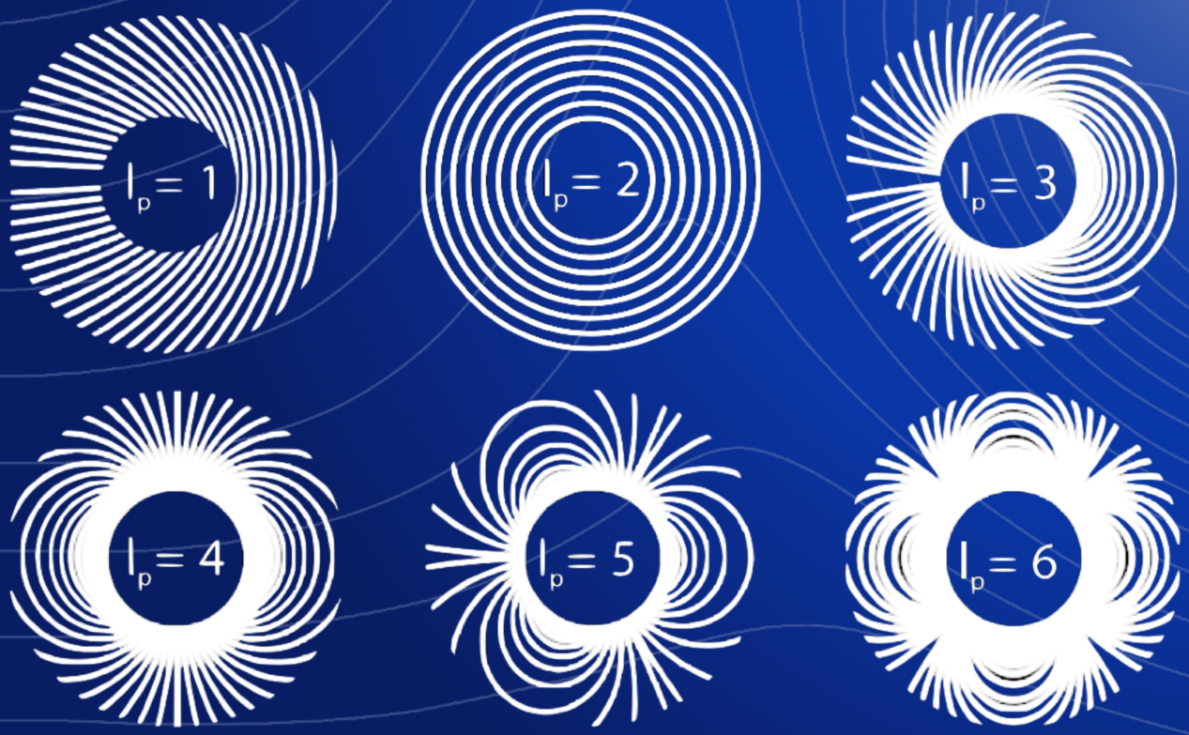
- First manufacturing tests at H and K bands
- Null depths up to 400:1

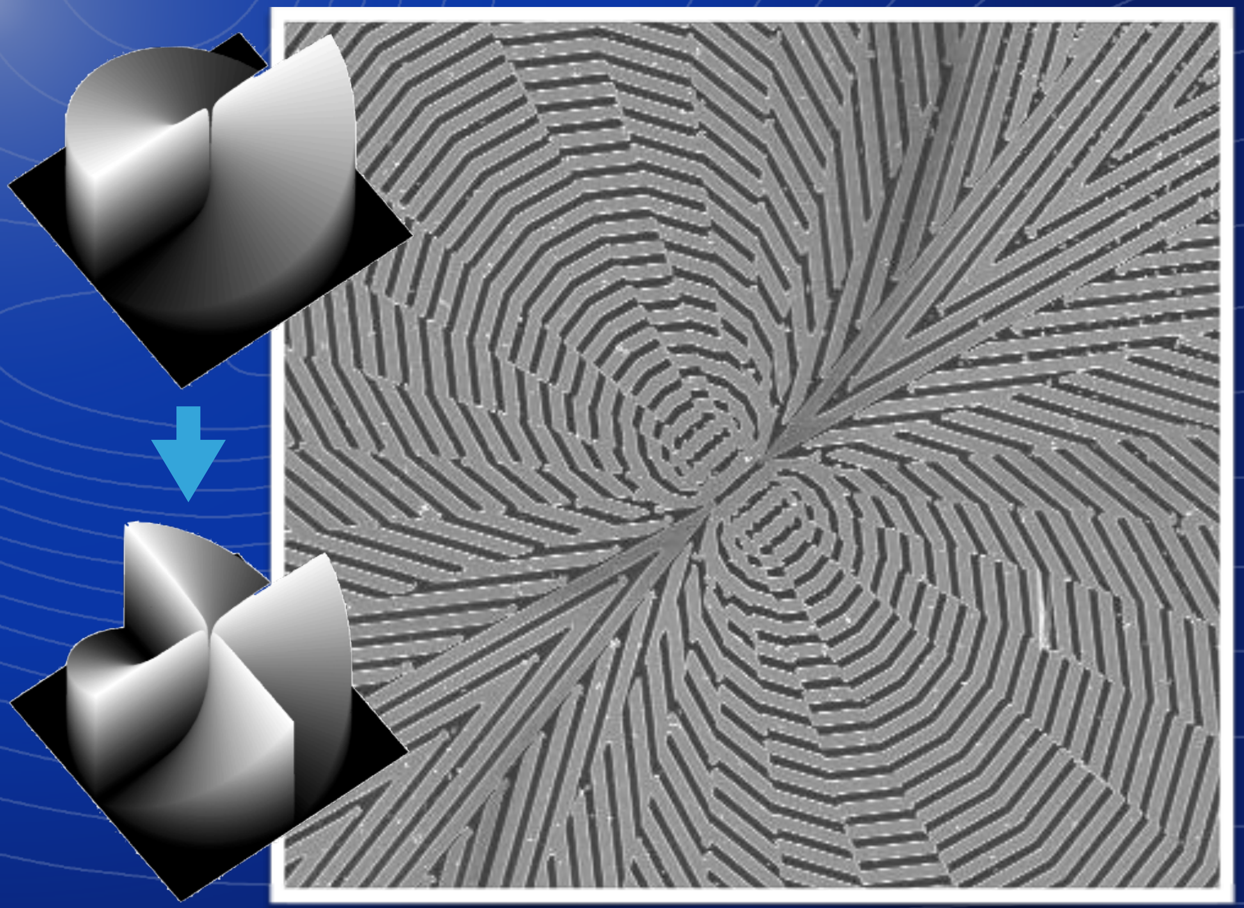




HIGHER TOPOLOGICAL CHARGES

- Increase the « speed » of the phase ramp
- Less sensitive to tip-tilt (and low-order aberrations), at expense of larger IWA
- More difficult to design than charge-2 AGPM





charge-4 vortex, work in progress

CONCLUSIONS

- Subwavelength grating = efficient technology for focal-plane phase masks
- Annular Groove Phase Mask = mature technology for thermal infrared applications
- AGPM now also available at shorter wavelengths
  - going below H-band may require to use other substrate (diamond etching reaching its limits)
- Higher topological charges being developed