AIP

EPIC
EUROPEAN PHOTONICS INDUSTRY CONSORTIUM

innoFSPEC
Innovative faseroptische Spektroskopie und Sensorik

OpTecBB

Universität Potsdam

Spectroscopy from Space: a Spectrograph on a Chip

Martin M. Roth
Leibniz Institute for Astrophysics Potsdam (AIP)
University of Potsdam

Outline

(1) Astronomical instrumentation

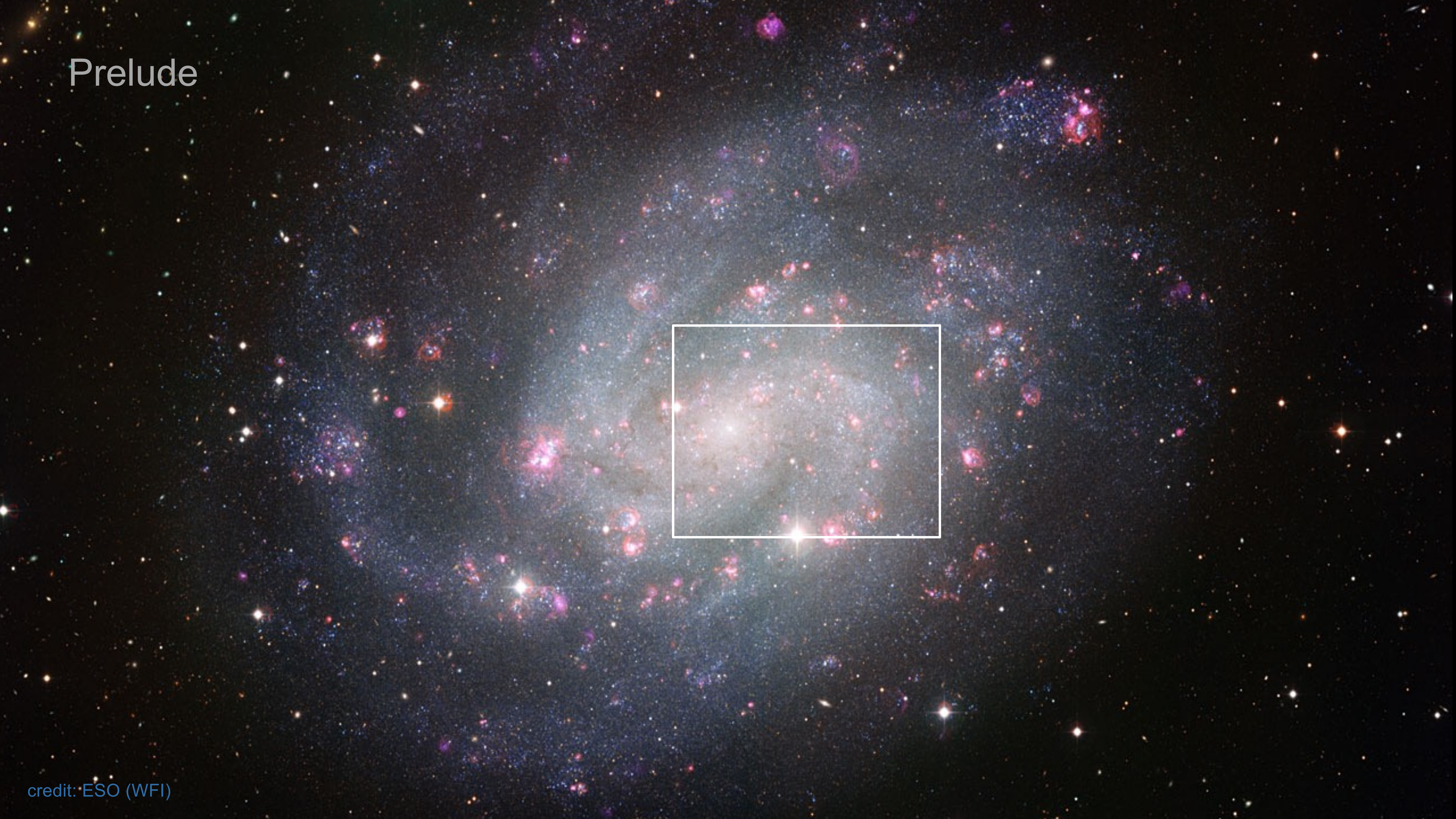
(2) A brief history of Astrophotonics

(3) Integrated photonic spectrographs

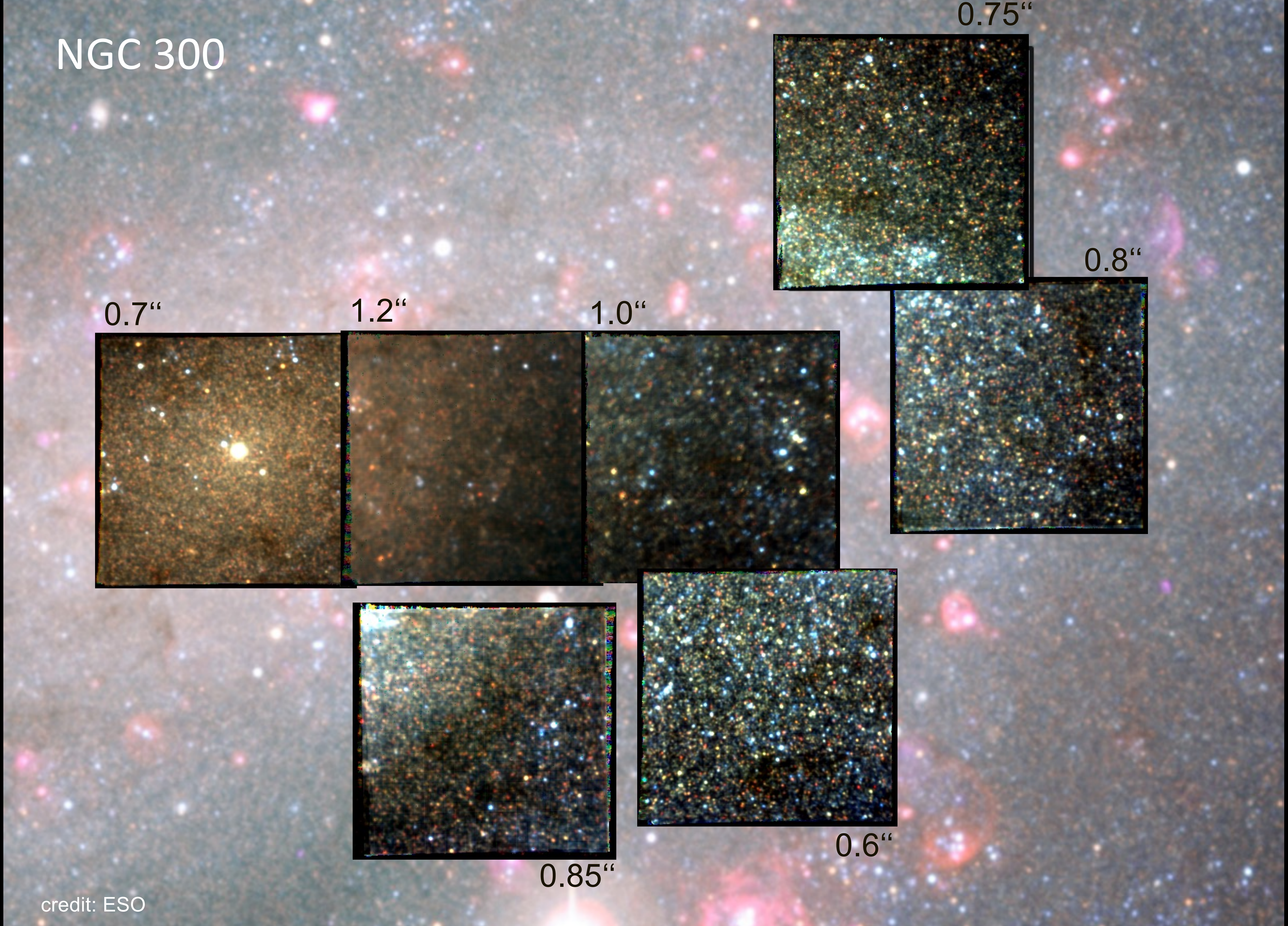
(4) Microresonator frequency combs

(5) Summary & Outlook

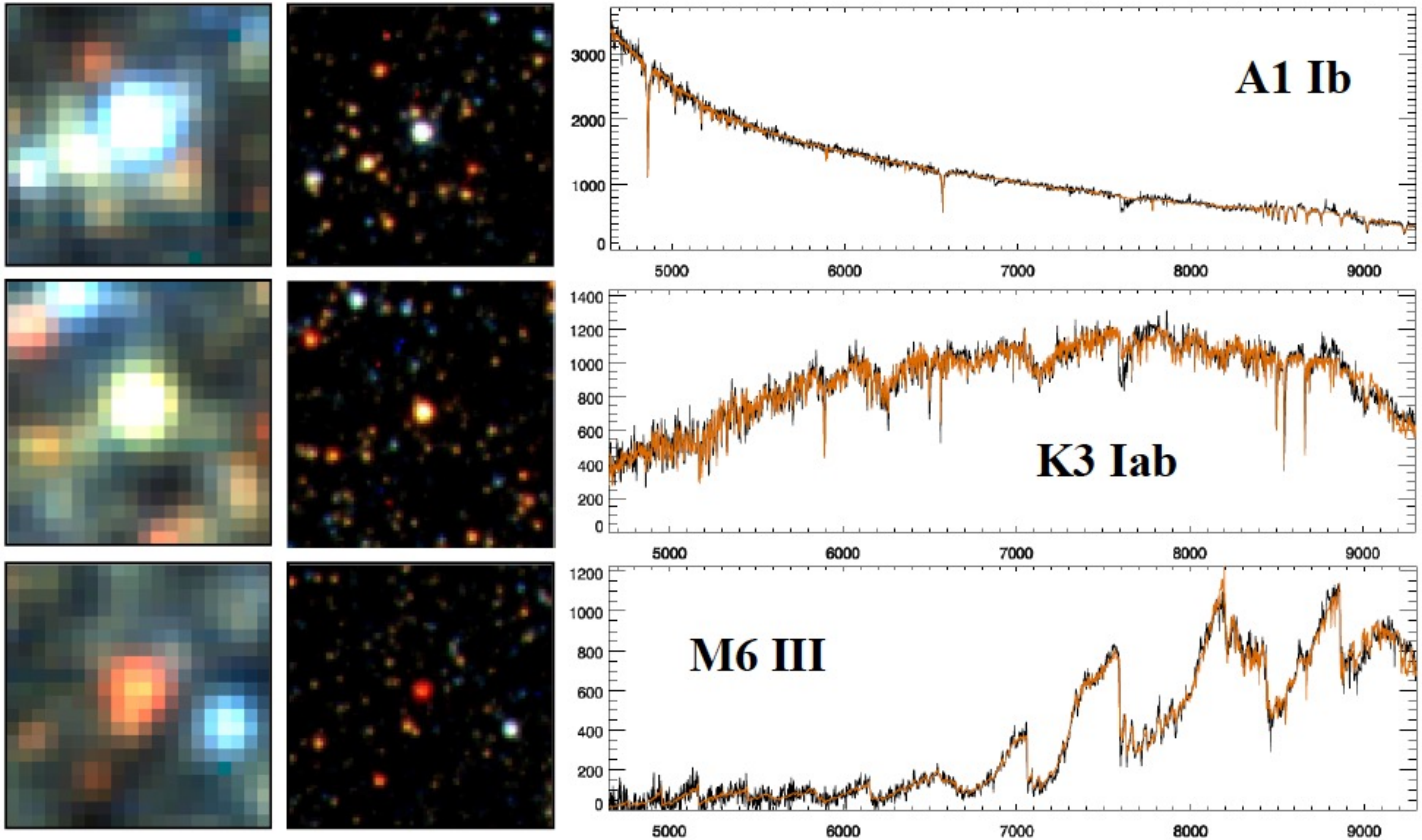
Prelude



credit: ESO (WFI)

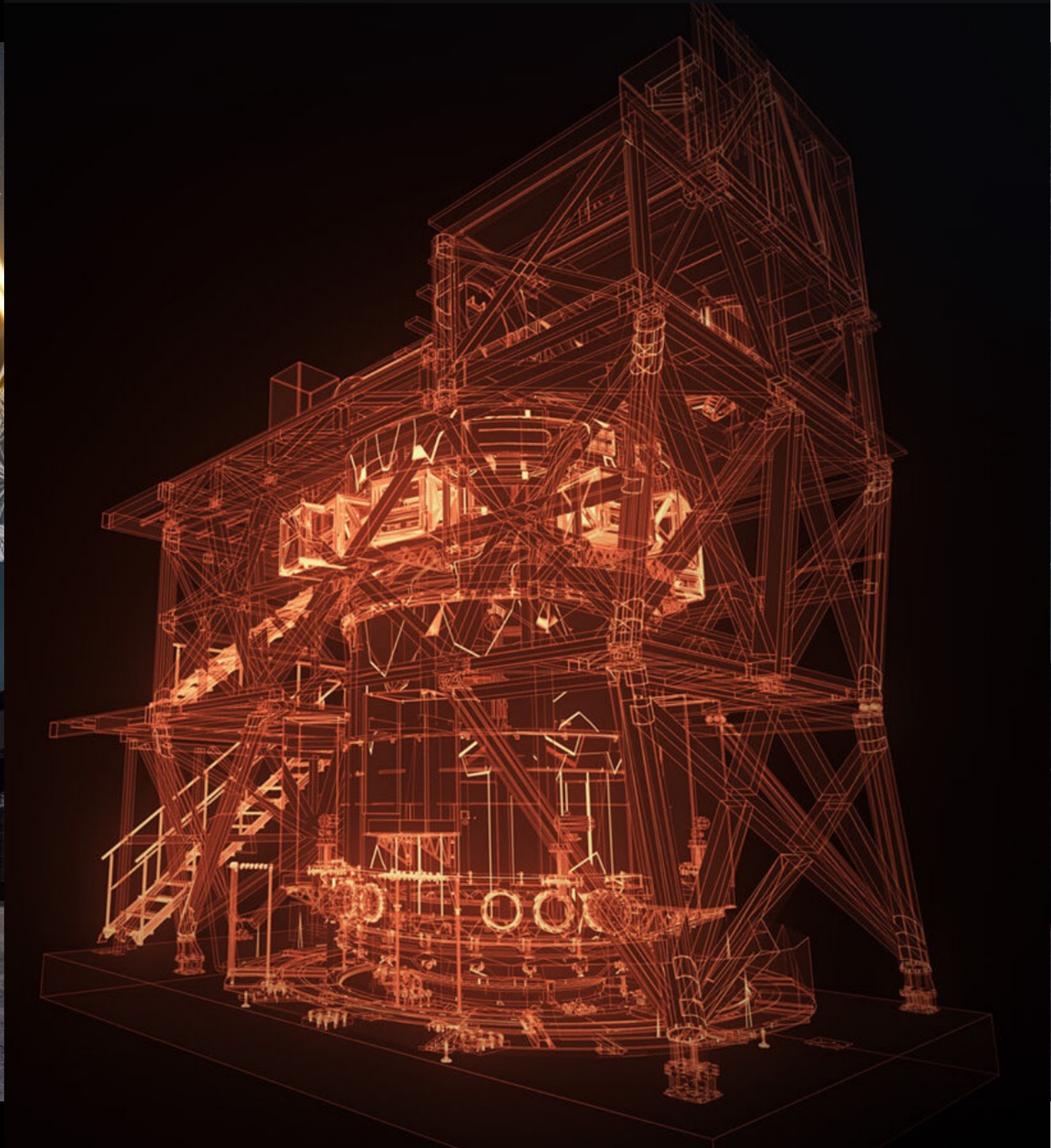

NGC 300
0.75''
0.8''
0.7''
1.2''
1.0''
0.85''
0.6''
credit: ESO

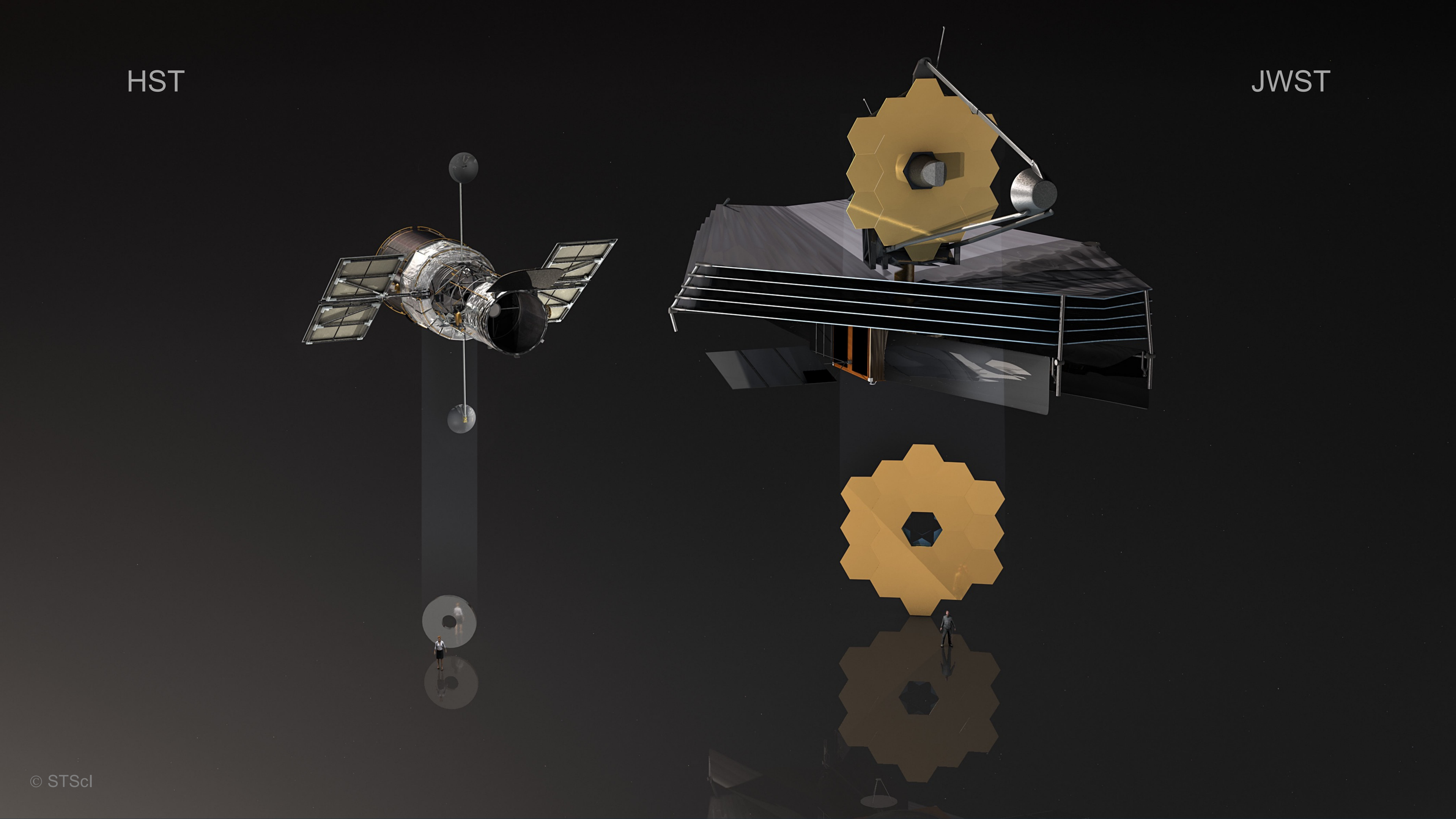
Example spectra:



(1) Astronomical Instrumentation

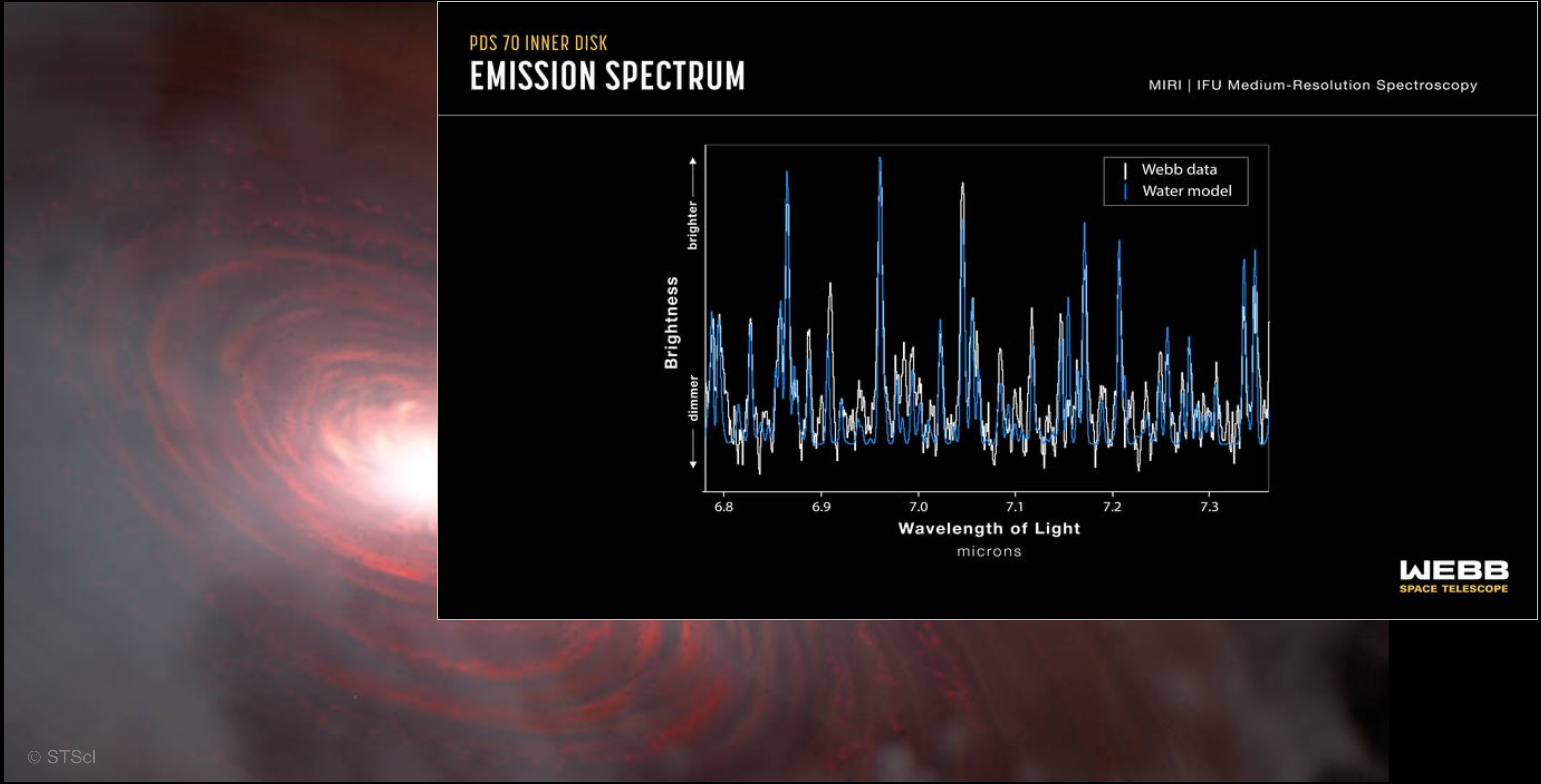

ESO Webcam 18 Sept 2023
© ESO

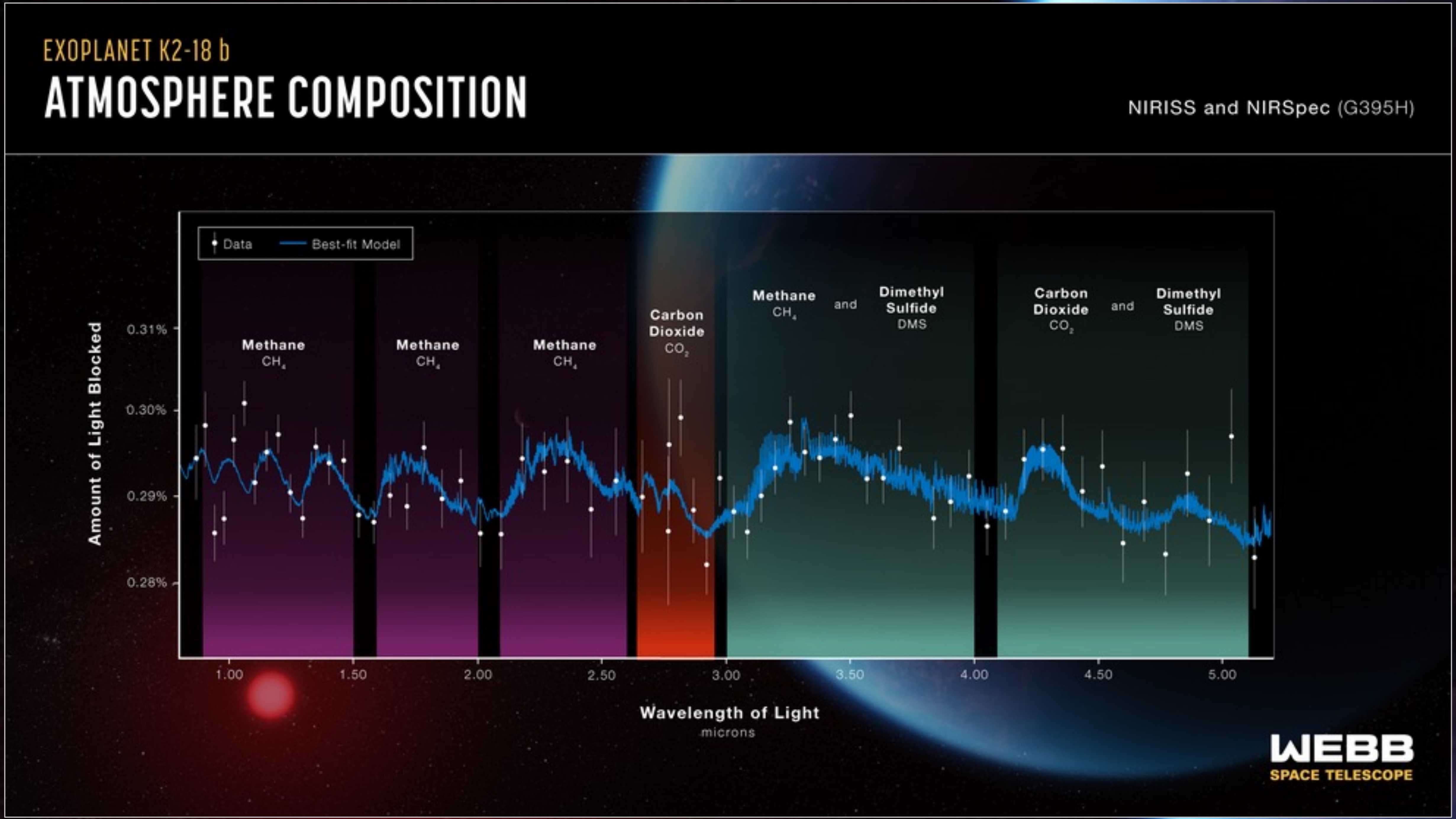

© ESO



HST
JWST
© STScI

© STScI

Herbig-Haro Object HHS 211


PDS 70 INNER DISK
EMISSION SPECTRUM
MIRI | IFU Medium-Resolution Spectroscopy
Webb data
Water model
Brightness
brighter
dimmer
6.8
6.9
7.0
7.1
7.2
7.3
Wavelength of Light
microns
WEBB
SPACE TELESCOPE
© STScI



EXOPLANET K2-18 b
ATMOSPHERE COMPOSITION
NIRISS and NIRSpec (G395H)
Data
Best-fit Model
Methane
CH₄
Carbon Dioxide
CO₂
and
Dimethyl Sulfide
DMS
0.31%
0.30%
0.29%
0.28%
Amount of Light Blocked
1.00
1.50
2.00
2.50
3.00
3.50
4.00
4.50
5.00
Wavelength of Light
microns
WEBB
SPACE TELESCOPE

(2) A brief history of Astrophotonics

2004

Bland-Hawthorn (2004), AAONL Vol. 106

NUMBER 106 DECEMBER 2004

AAO NEWSLETTER

ANGLO-AUSTRALIAN OBSERVATORY

Astrophotonics comes of age

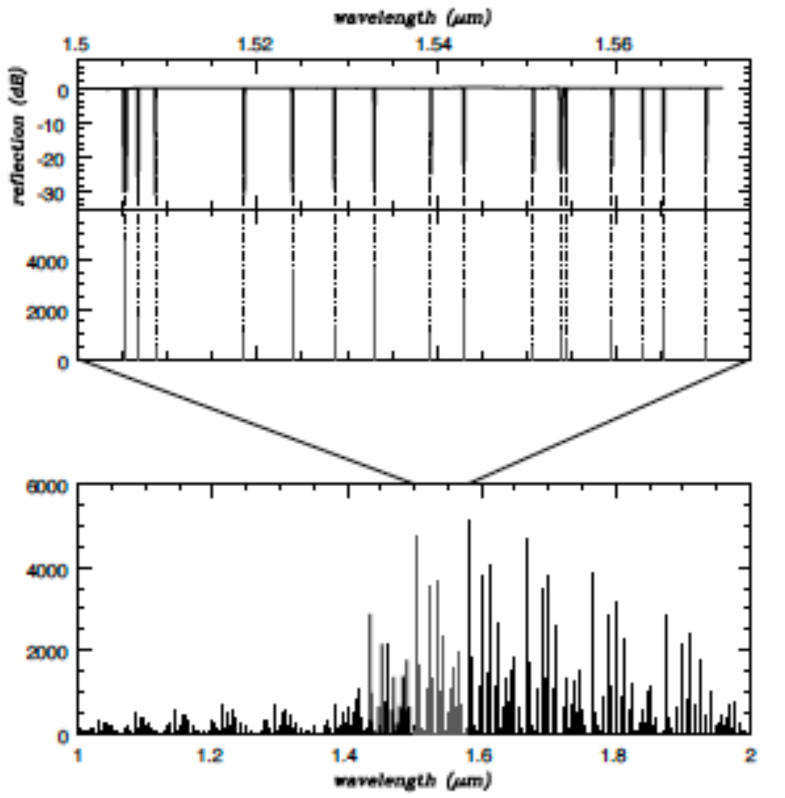


Fig. 1: The top panel is the wavelength response of a new technology OH-suppressing fibre developed and patented by the AAO and industrial partner Redfern Optical Components (ROC). The middle panel shows how the rejection bands line up perfectly with the H-band sky spectrum. The bottom panel illustrates the region of the spectrum treated by our first prototype (see Bland-Hawthorn, Englund & Edvell 2004; hereafter BEE).

contents

Astrophotonics. In a very real sense, the era of astrophotonics – a term coined by R.M. Sharples – is born. Of course, fibres have been used for 25 years in optical astronomy. But for the most part, the "manipulation of light by materials" was basically limited to transporting light from individual points in the focal or pupil plane, then reformatting the information elsewhere within the instrument. In fact, one can envisage many complex functions beyond the suppression technique described here, and one can also envisage fully 3D photonic devices rather than 1D photonic fibres. We are investigating a range of technologies with different partners. In a future issue, Roger Haynes and PhD student Jackie Marcel, also of the AAO's Instrument Science group, will report on important technologies under development with industrial partners and the University of Durham.

innoFSPEC

Innovative faseroptische Spektroskopie und Sensorik

since 2008

innoFSPEC Potsdam: innovative fiber-coupled spectroscopy and sensing

Forschungslabor

Martin Roth

Kalaga Madhav

Forschungslabor

Ilko Bald

Oliver Reich

Marvin Münzberg

Anika Krause

H.-G. Löhmannsröben

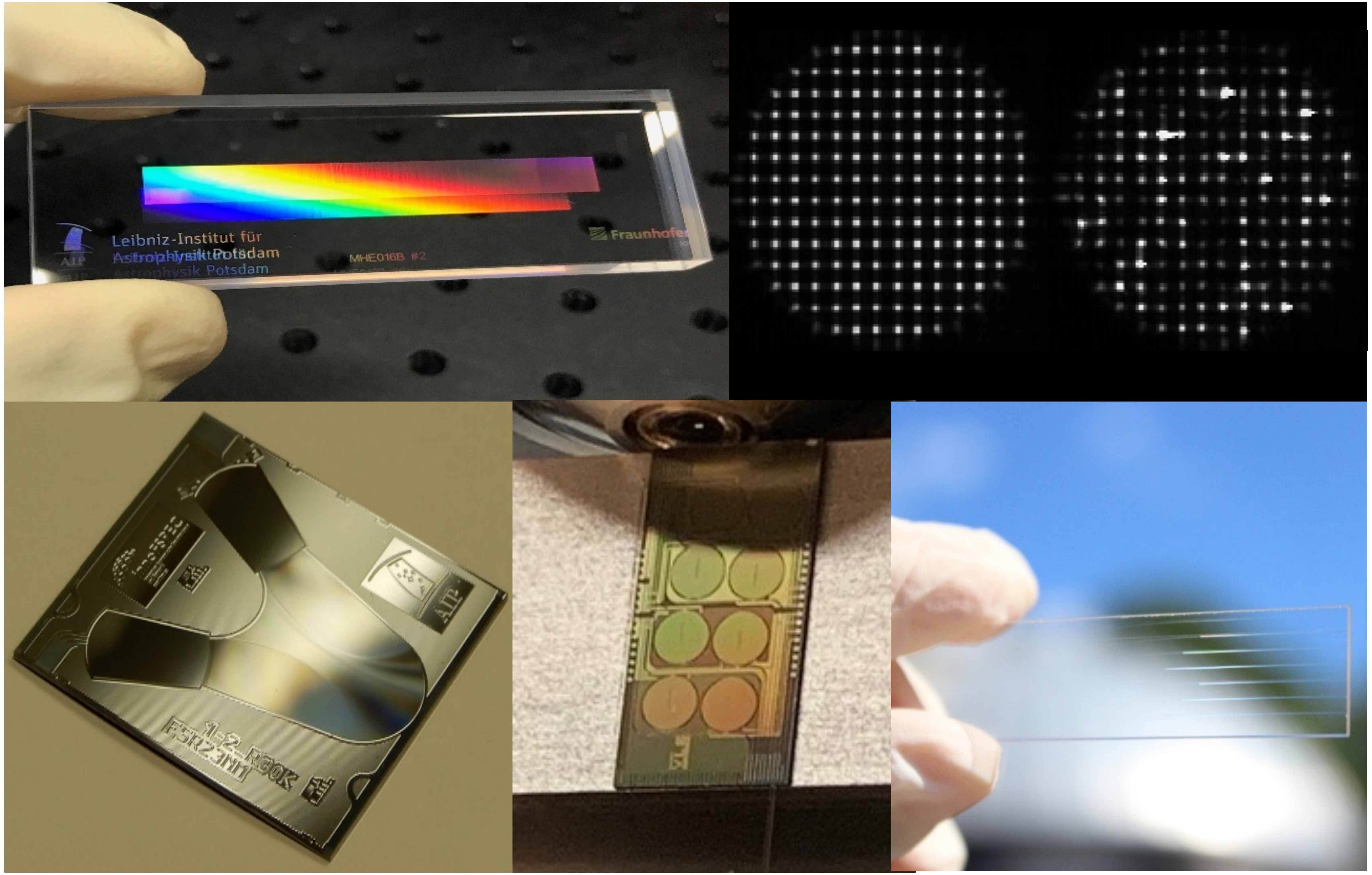
innoFSPEC TRANSFERLABOR

Hans-Hennig von Grünberg

Anne Hartwig


© AIP

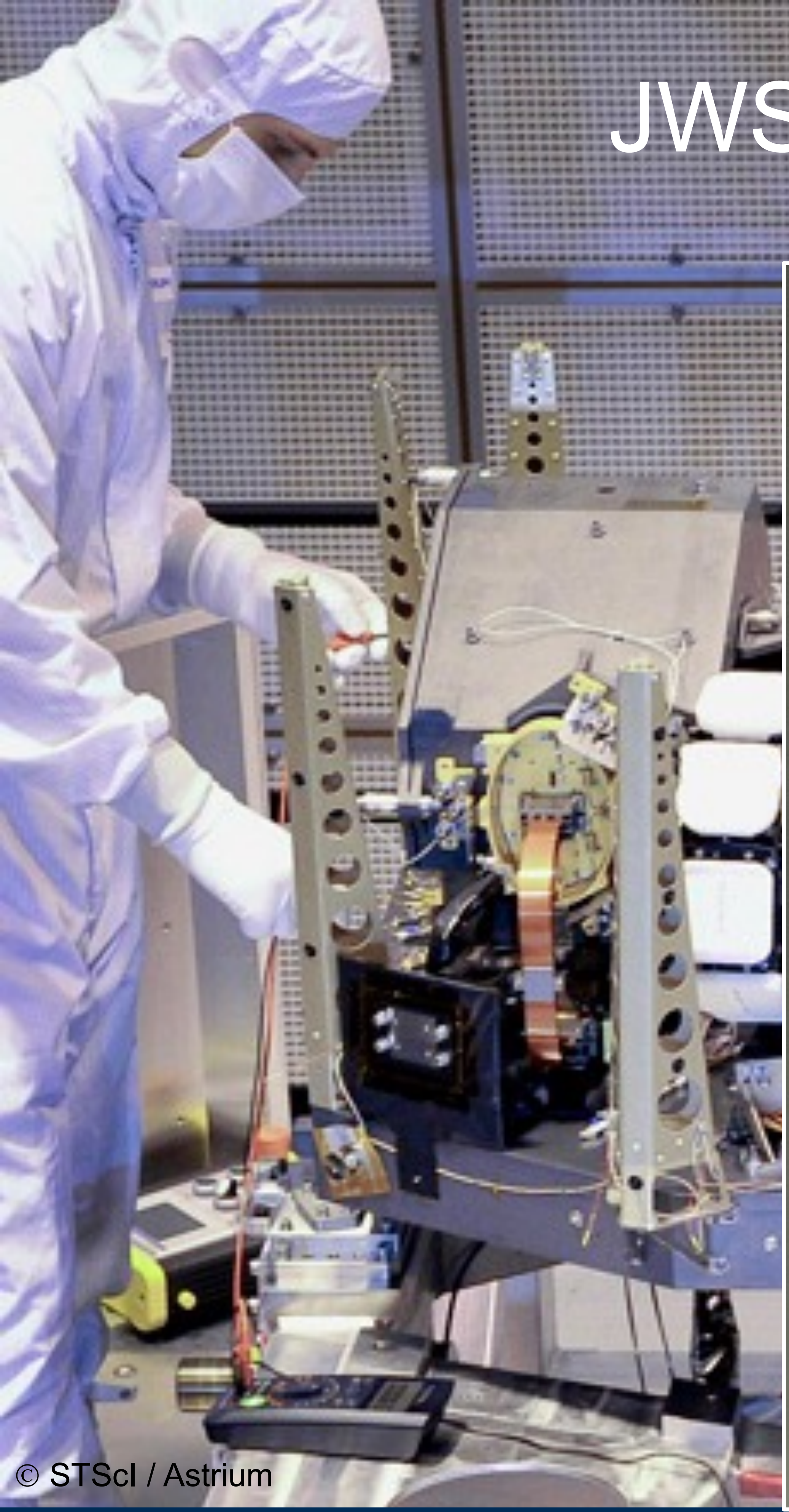
Research Activities at innoFSPEC Potsdam:

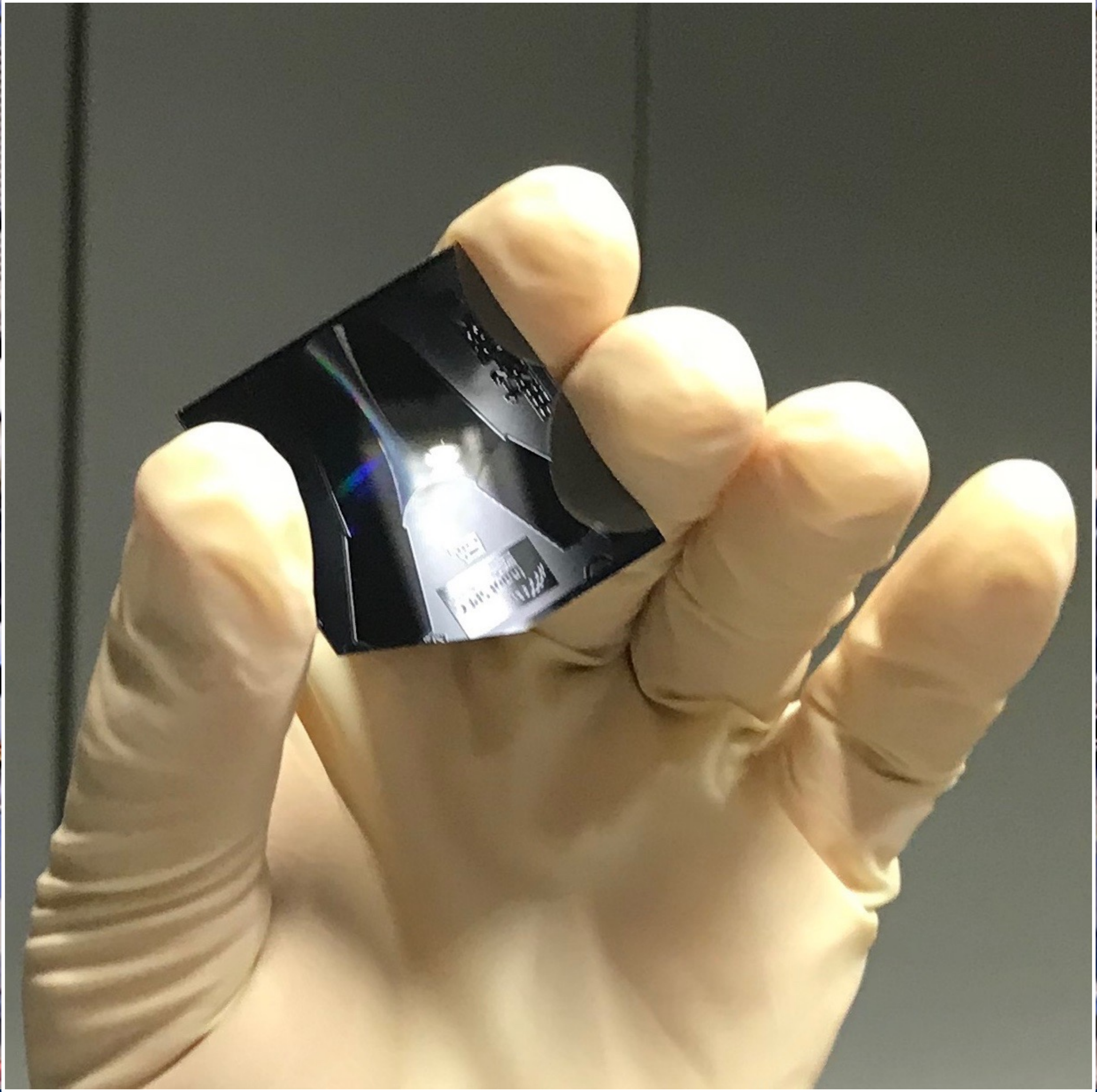


1. OH Suppression Filters & Phase Masks
2. Adaptive Optics & Photonic Lanterns
3. Arrayed Waveguide Gratings
4. Frequency Combs
5. Pupil Remappers & Beam Combiners

(3) Integrated photonic spectrographs

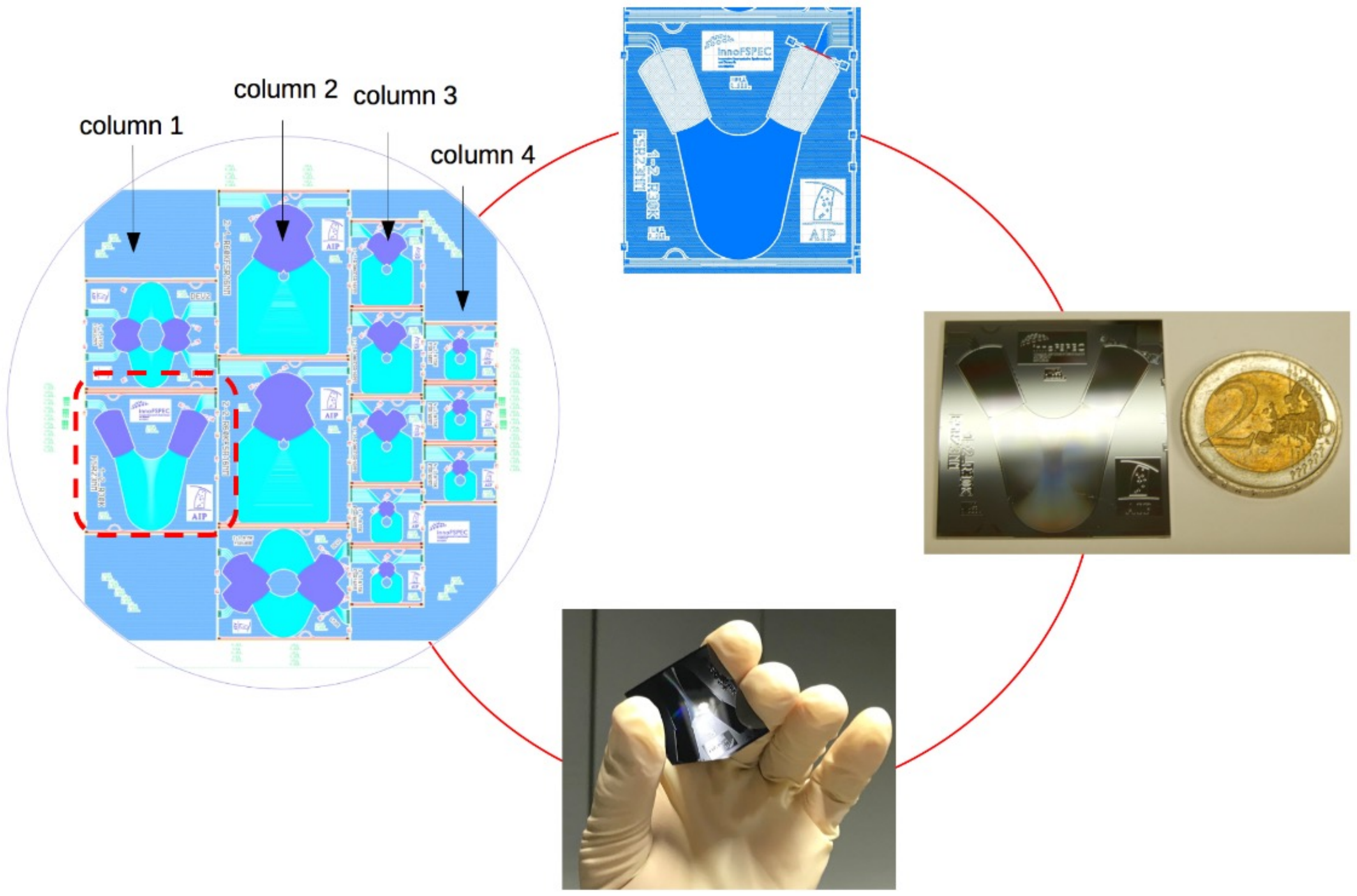
JWST NIRspec



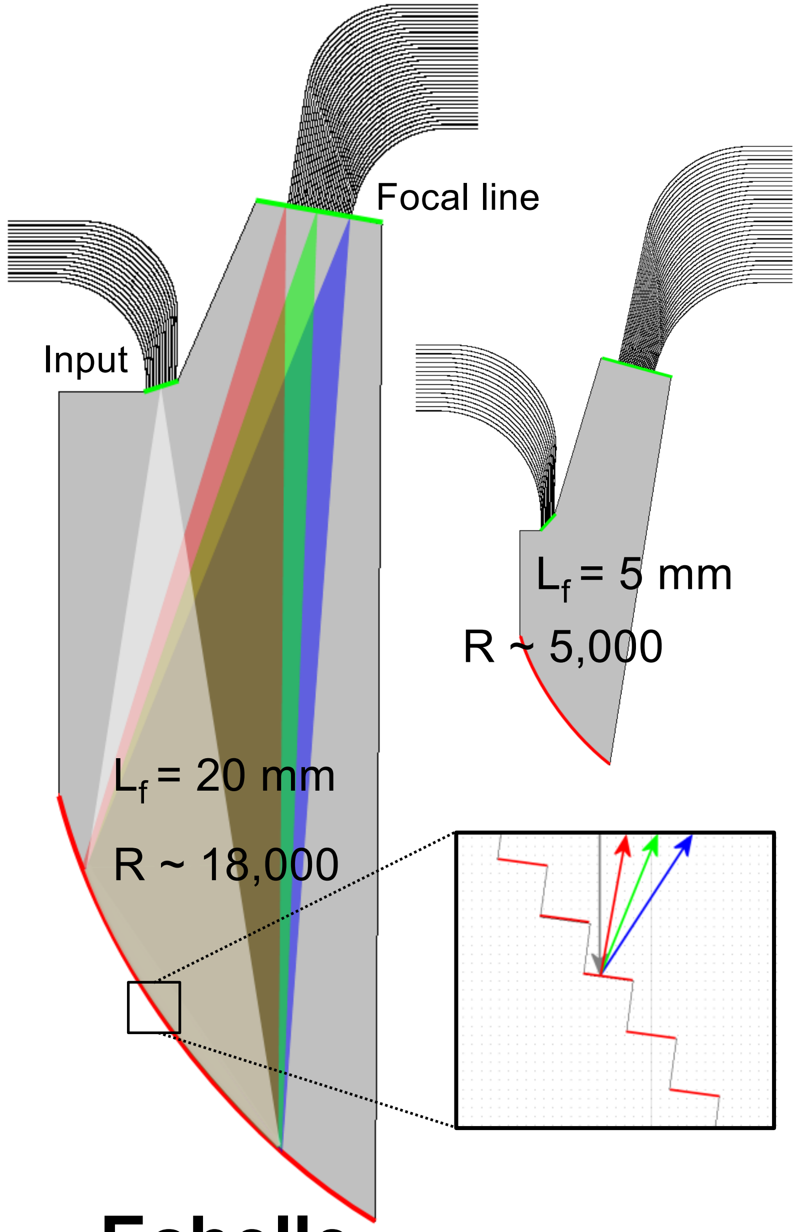


Integrated photonic spectrograph

Goal: Numerical simulations, design, fabrication and testing of AWG devices and echelle grating devices for deployment in a miniature spectrometer.



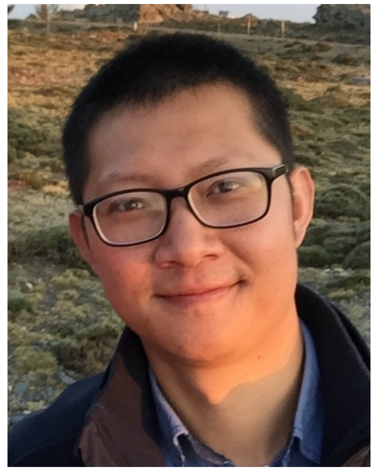
AWG



Echelle

Team:

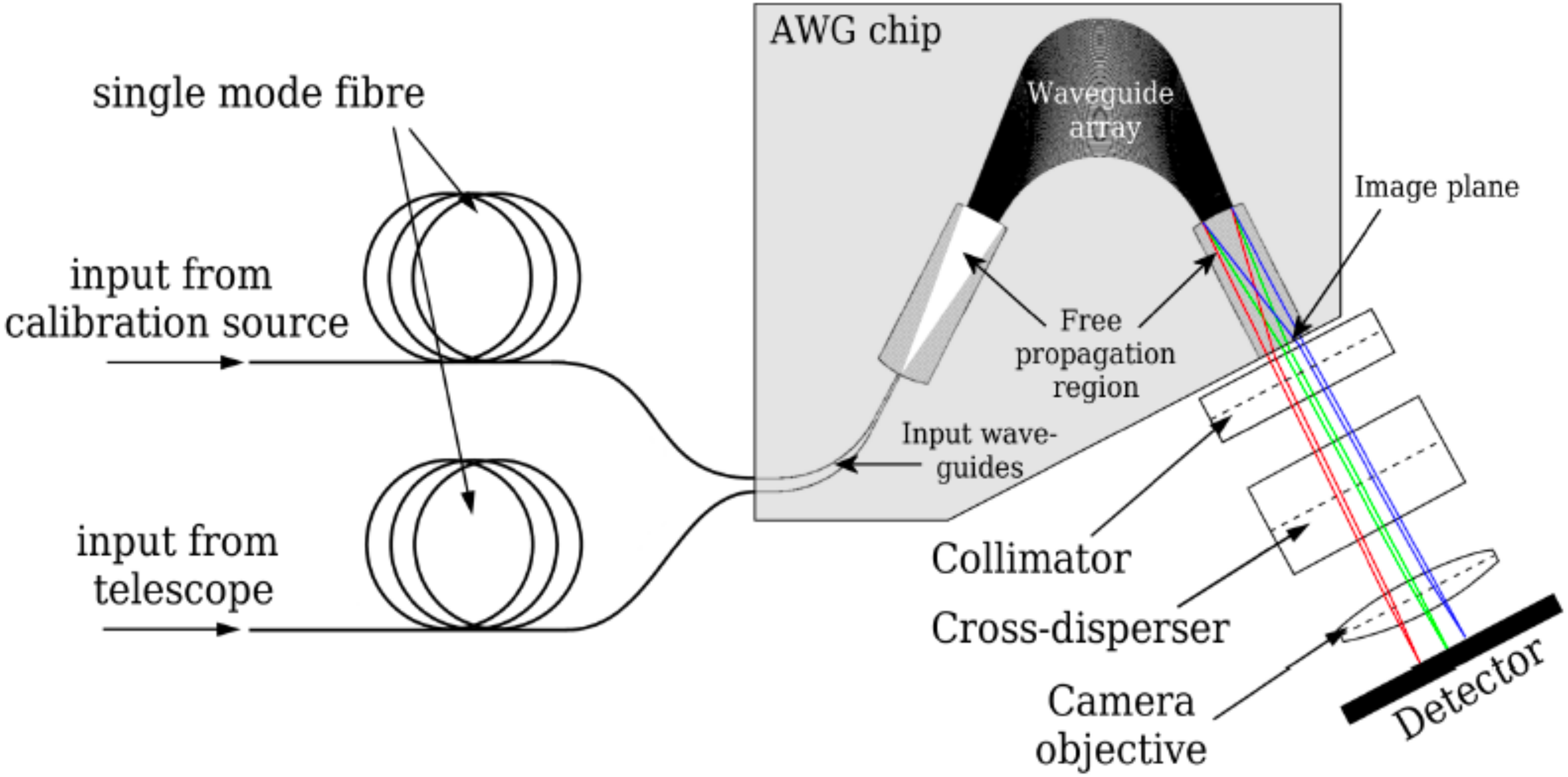
Dr. Andreas Stoll

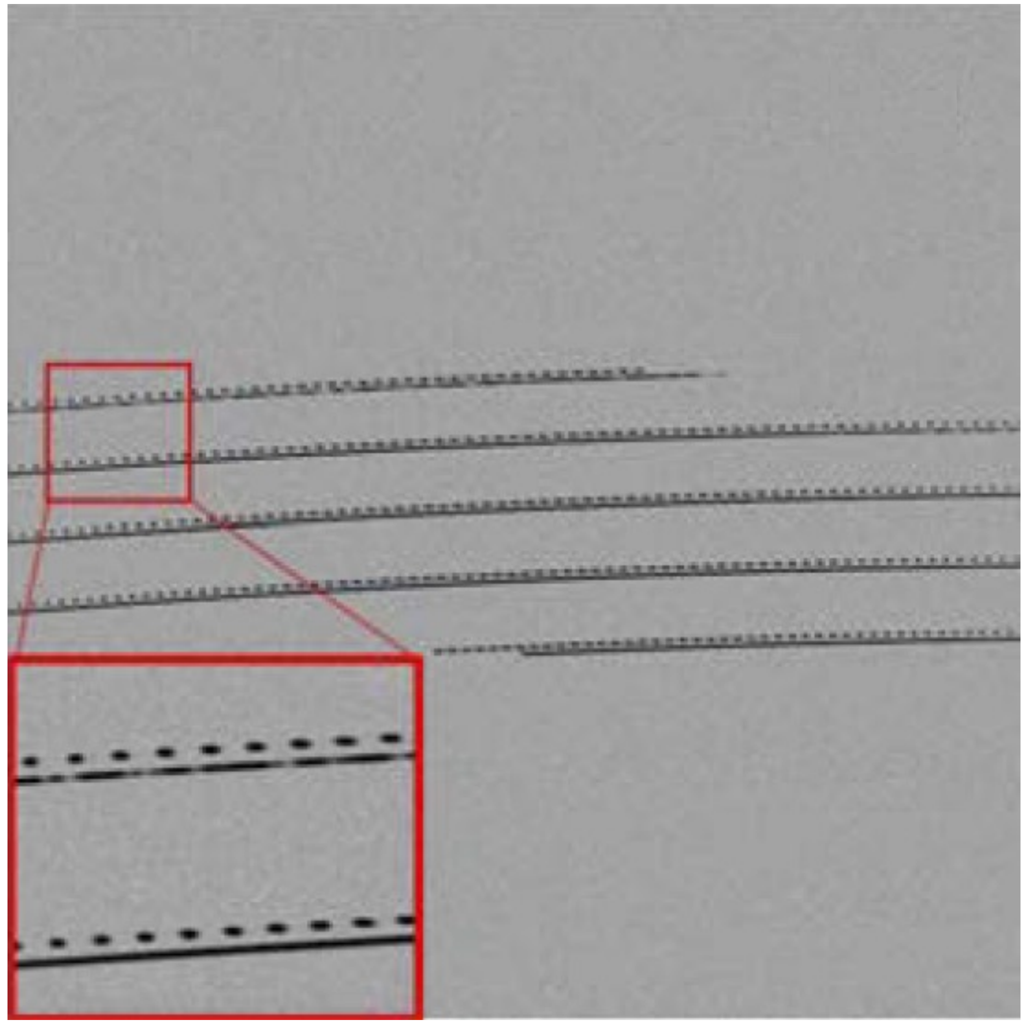


Dr. Ziyang Zhang

Wang Yu

AWG spectrograph principle of operation:





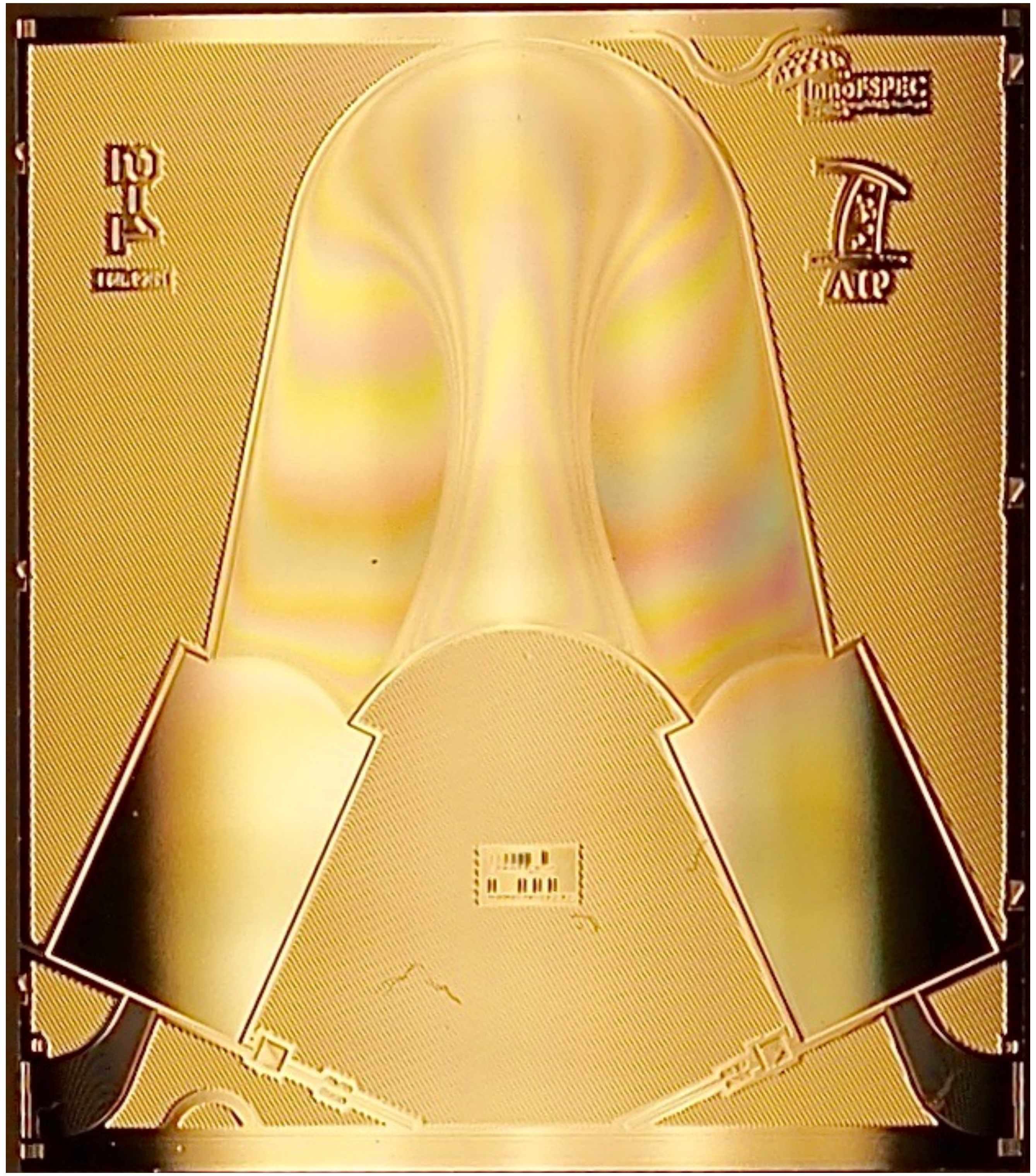
Generation 0: first experiments on Si_3N_4 platform

- collaboration with TU Berlin and Leibniz IHP

Fernando, H.N. J., Stoll, A., Eisermann, R., Boggio, J. C., Zimmermann, L., Haynes, R., Roth, M. M. (2012)

Planar integrated photonics spectrograph on silicon-nitride-on-insulator: densely integrated systems for astrophotonics and spectroscopy

Navarro, Ramón / Cunningham, Colin R. / Prieto, Eric (Eds.)
Modern Technologies in Space- and Ground-based Telescopes and Instrumentation II , Vol. 8450
SPIE Conference Series, p. 845046



Exploration

Stoll, A., Zhang, Z., Haynes, R. Roth, M. (2017)

High-Resolution Arrayed-Waveguide-Gratings in Astronomy: Design and Fabrication Challenges

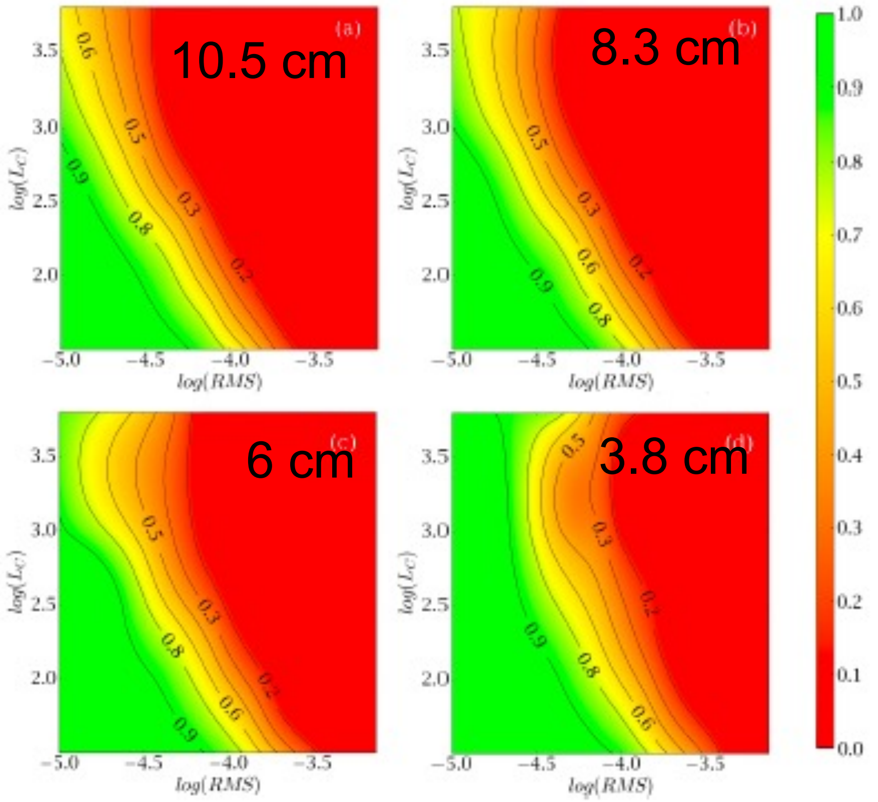
Photonics for Solar Energy Systems IX , Vol. 4, No. 4 p. 30

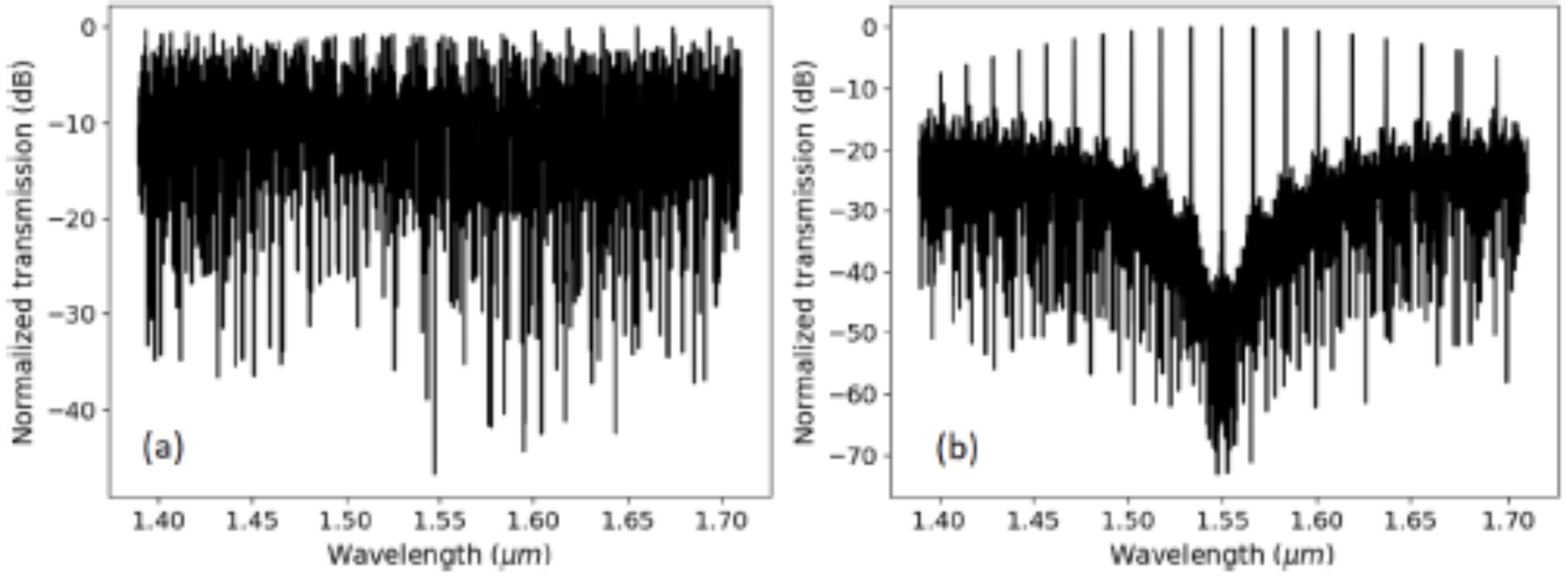
Stoll, Andreas / Madhav, Kalaga / Roth, M. (2020)

Performance limits of astronomical arrayed waveguide gratings on a silica platform

Optics Express , Vol. 28, No. 26, p. 39354

AWG figure of Merit (FOM) as function of AWG size (WG length) and refractive index variation across the chip





Simulated AWG spectra with optical path length errors, without/with trimming

Generation I.

- Silica on silicon platform
- Atmospheric pressure chemical vapor deposition (APCVD)

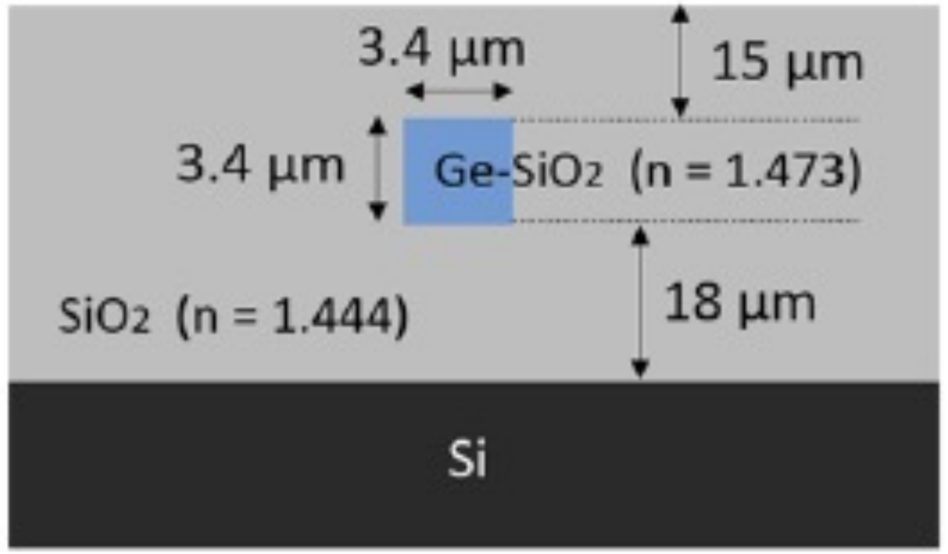
Stoll, A. Madhav, K. V., Roth, M. M. (2021)

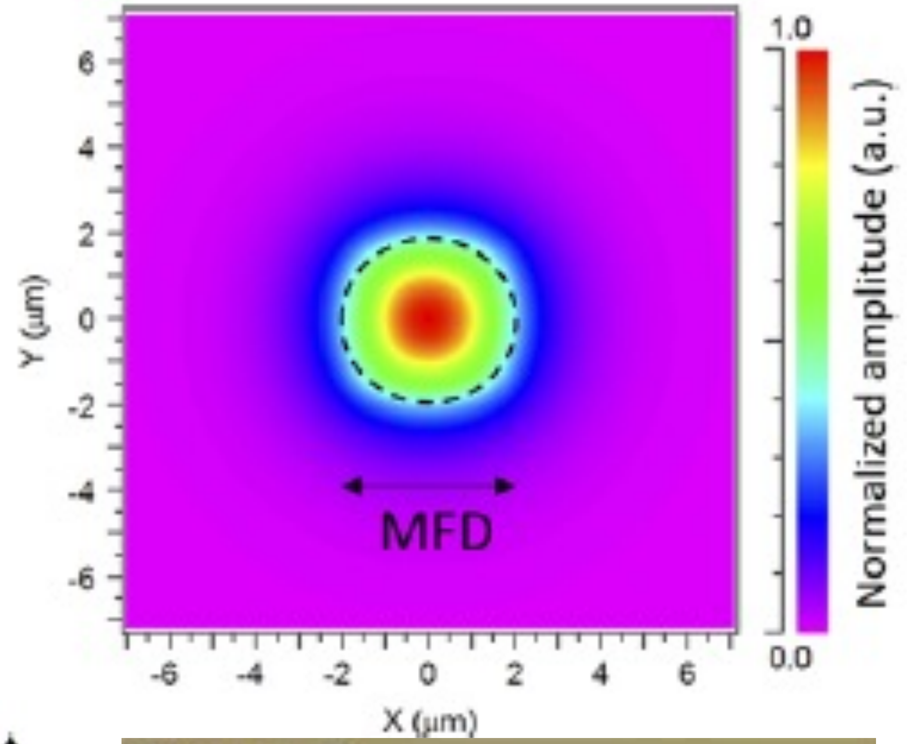
Design, simulation and characterization of integrated photonic spectrographs for astronomy: generation-I :
AWG devices based on canonical layouts

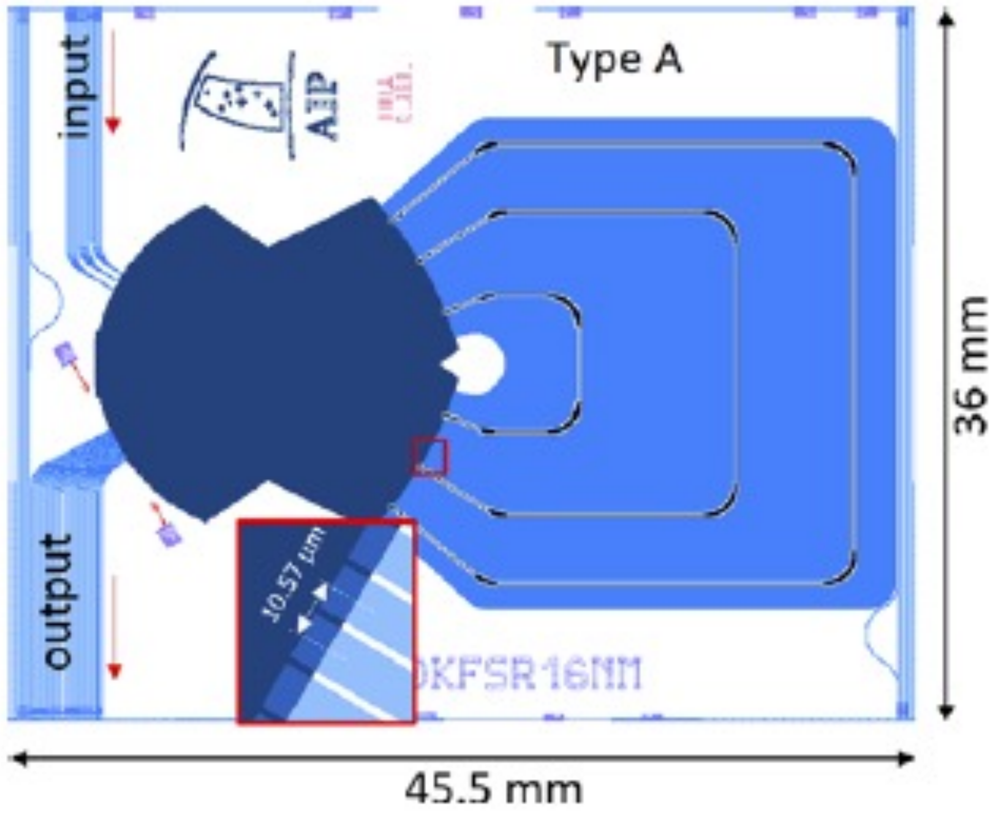
Optics Express , Vol. 29, No. 16, p. 24947

Manufacturer:

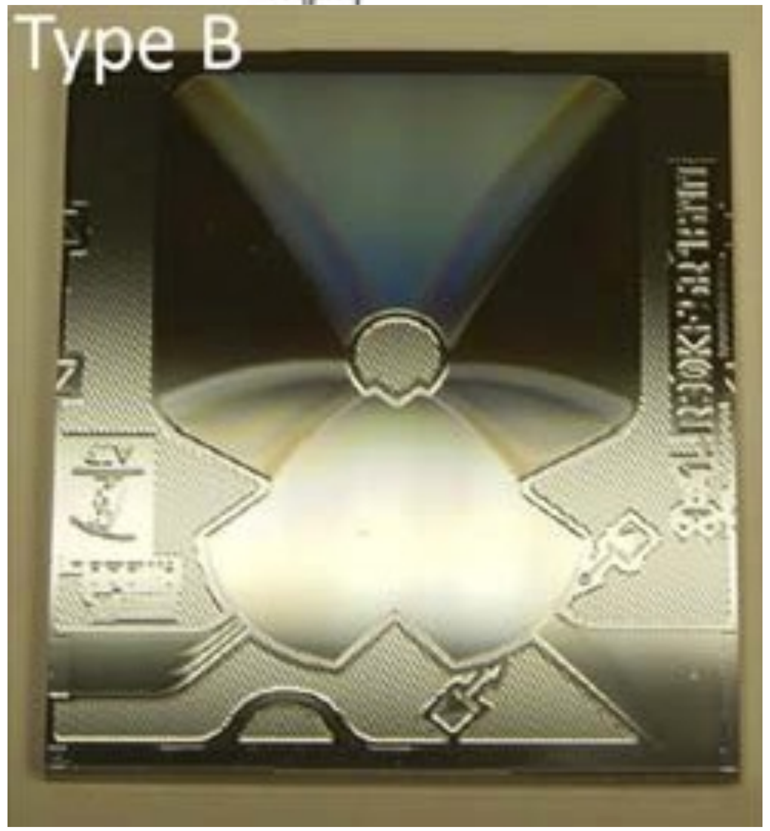
Enablence







AWG lithographic mask



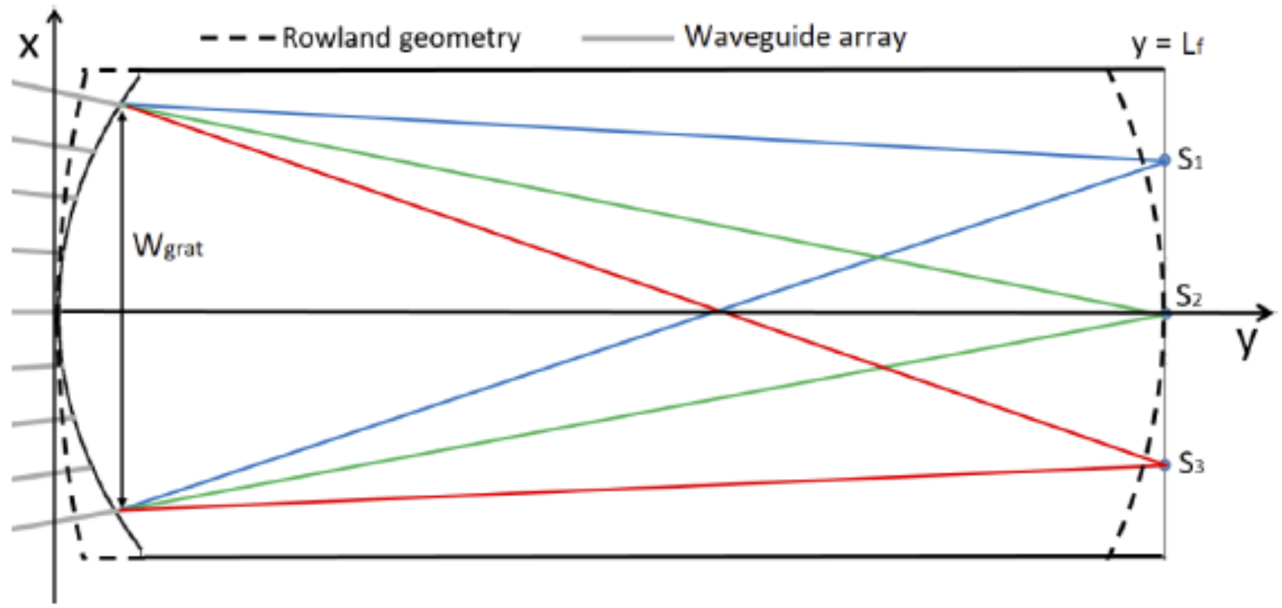
Generation II.

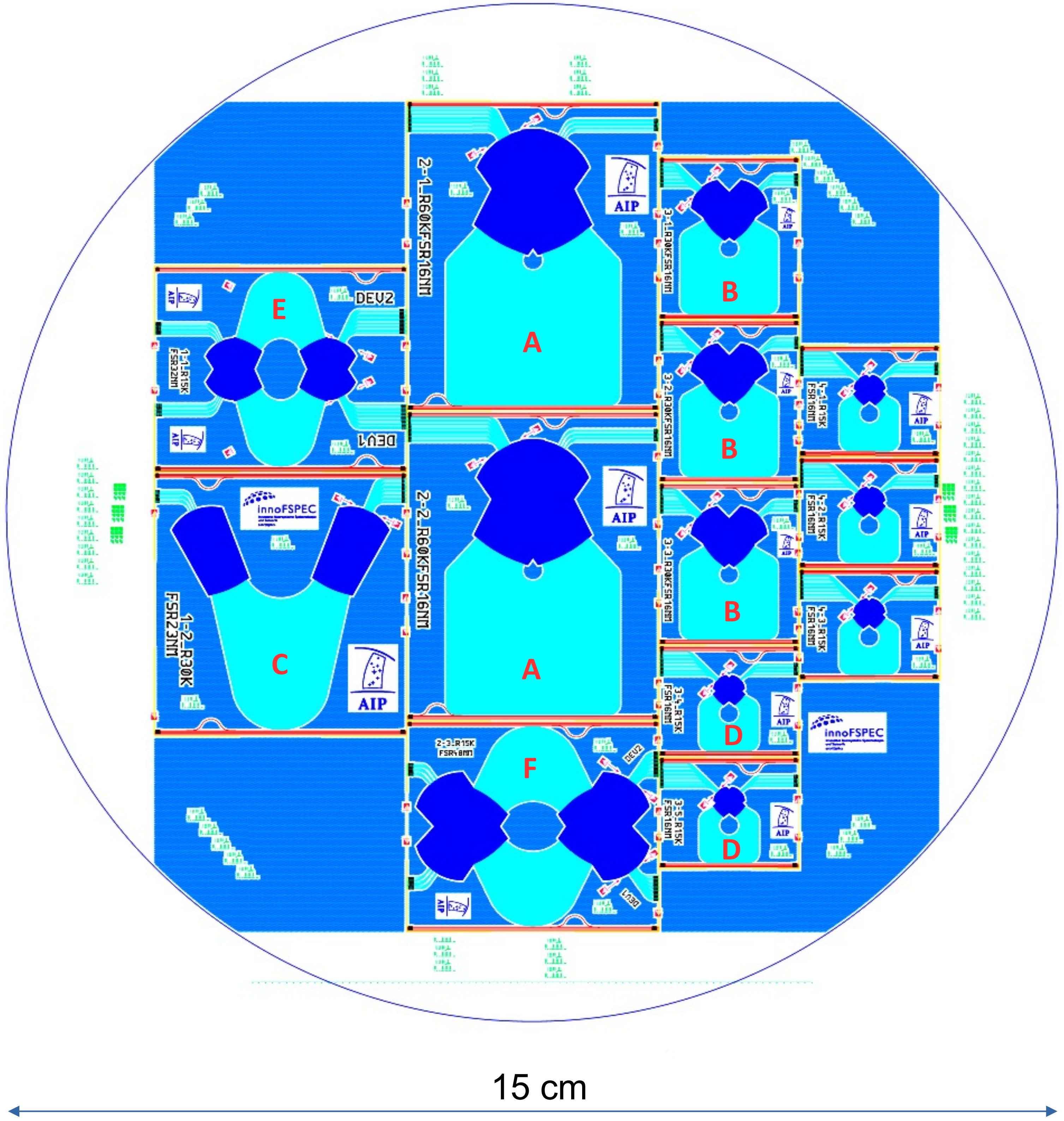
- Silica on silicon platform (as Gen I)
- Three-stigmatic-point design (field-flattened output)
- Optimization through numerical simulations

Stoll, A., Madhav, K., Roth, M. (2021)

Design, simulation and characterization of integrated photonic spectrographs for astronomy II: low-aberration Generation-II AWG devices with three stigmatic points

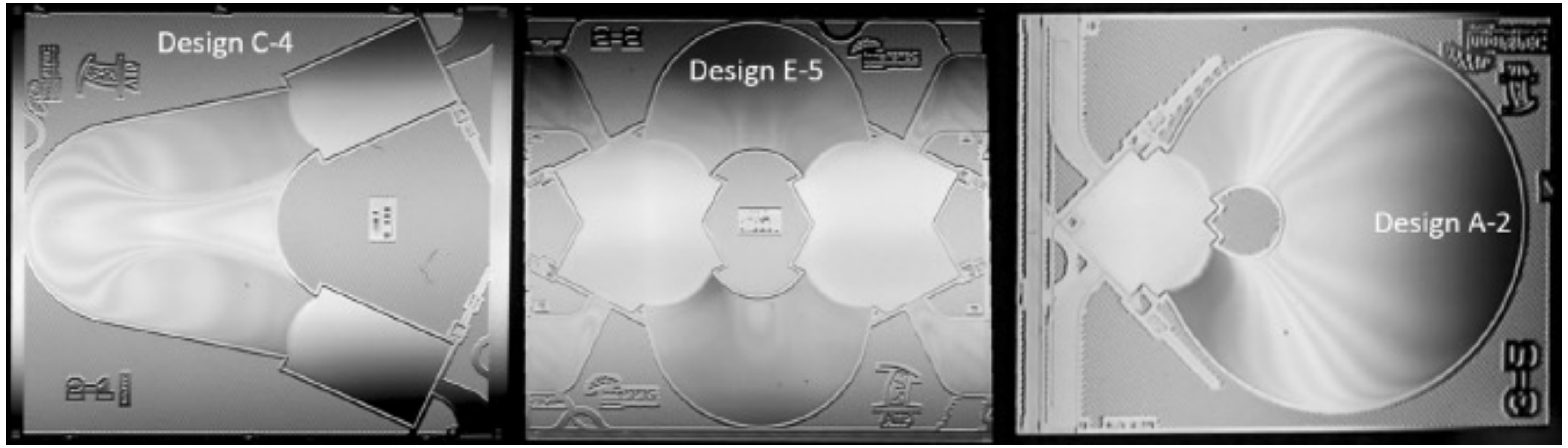
Optics Express , Vol. 29, No. 22, p. 36226



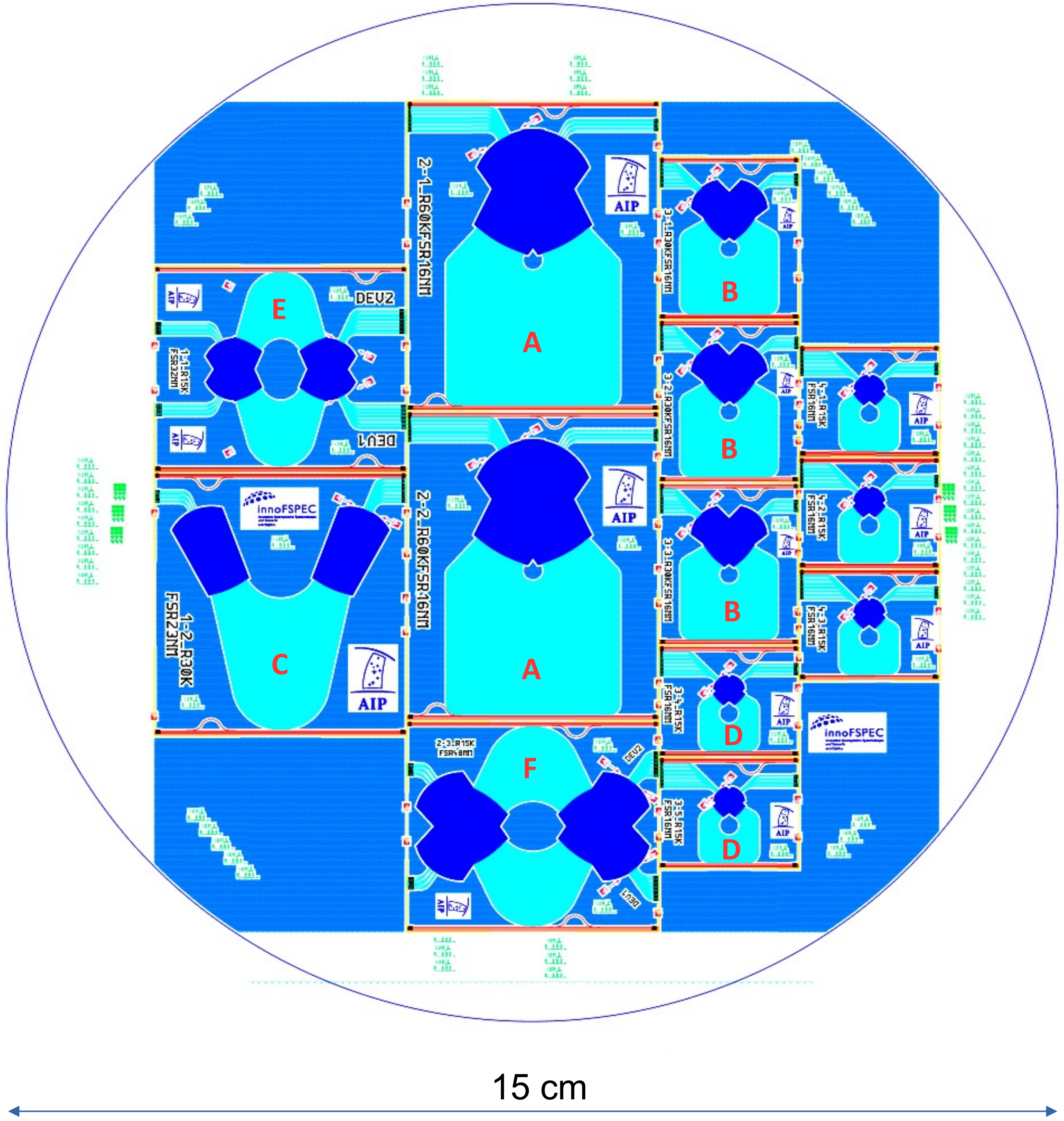


AWG lithographic mask

Generation II.

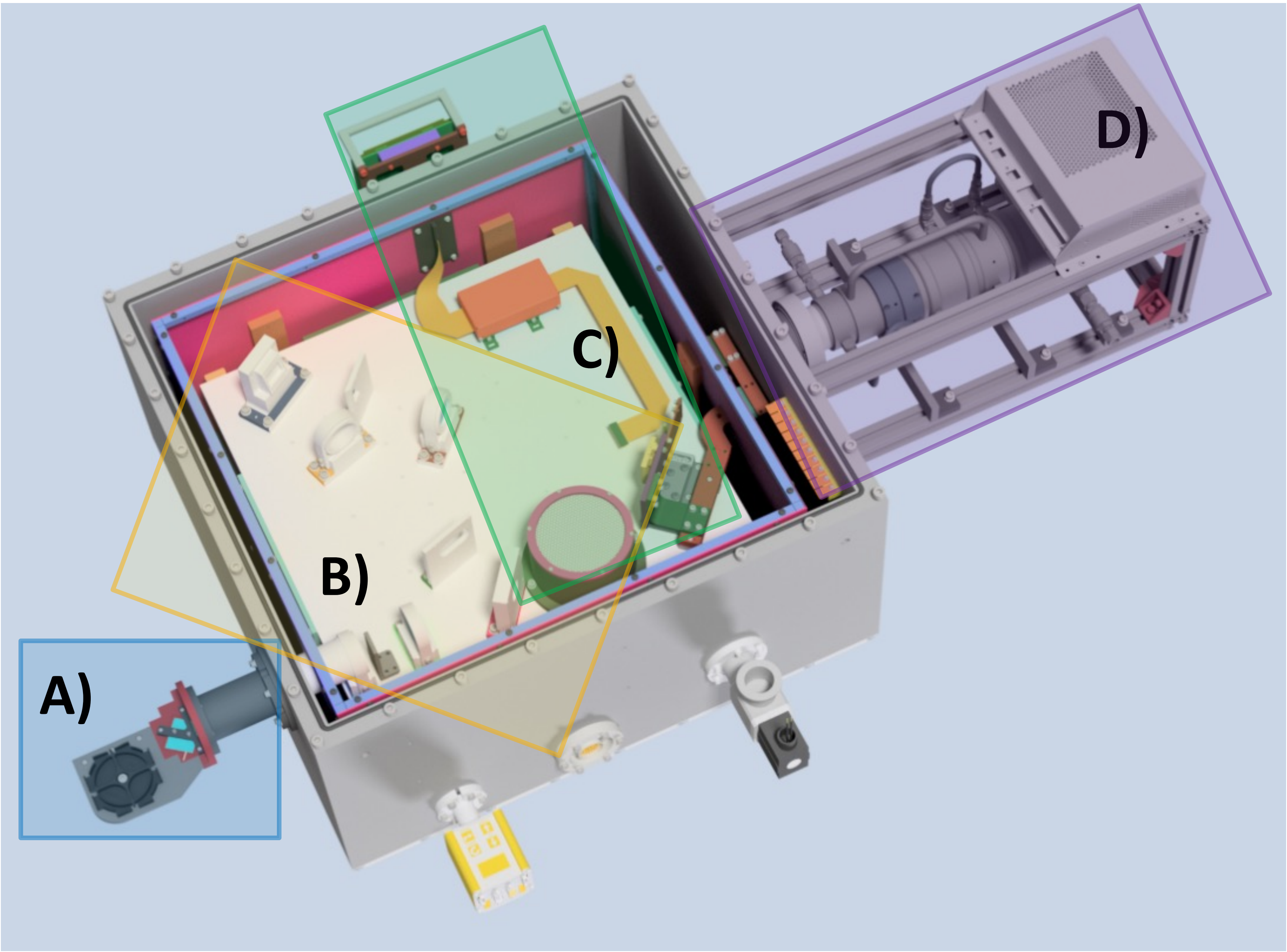


Design	A-1	A-2	B-3	B-5	C-4	D-3	E-5
FSR (nm)	11.9	11.9	16.1	16.1	22.6	32.2	47.4
IL (dB)	1.45	2	1.99	3	2.2	1.66	1.65
$\Delta\lambda$ (pm)	96	70	78	56	77.5	146	152
$PD\lambda$ (pm)	28	27	39	57	40	48	65
R simulated	17,400	24,600	23,100	34,800	23,300	11,500	11,800
R measured (TE)	16,100	22,000	20,000	27,600	20,000	10,600	10,200
R_{direct} (TE)	20,540	29,490	25,270	36,000	25,760	13,880	12,880
R_{direct} (unpolarized)	18,600	24,000	18,300	-	16,700	12,100	9,600
ΔR	0.08	0.06	0.06	0.14	0.156	0.075	0.084

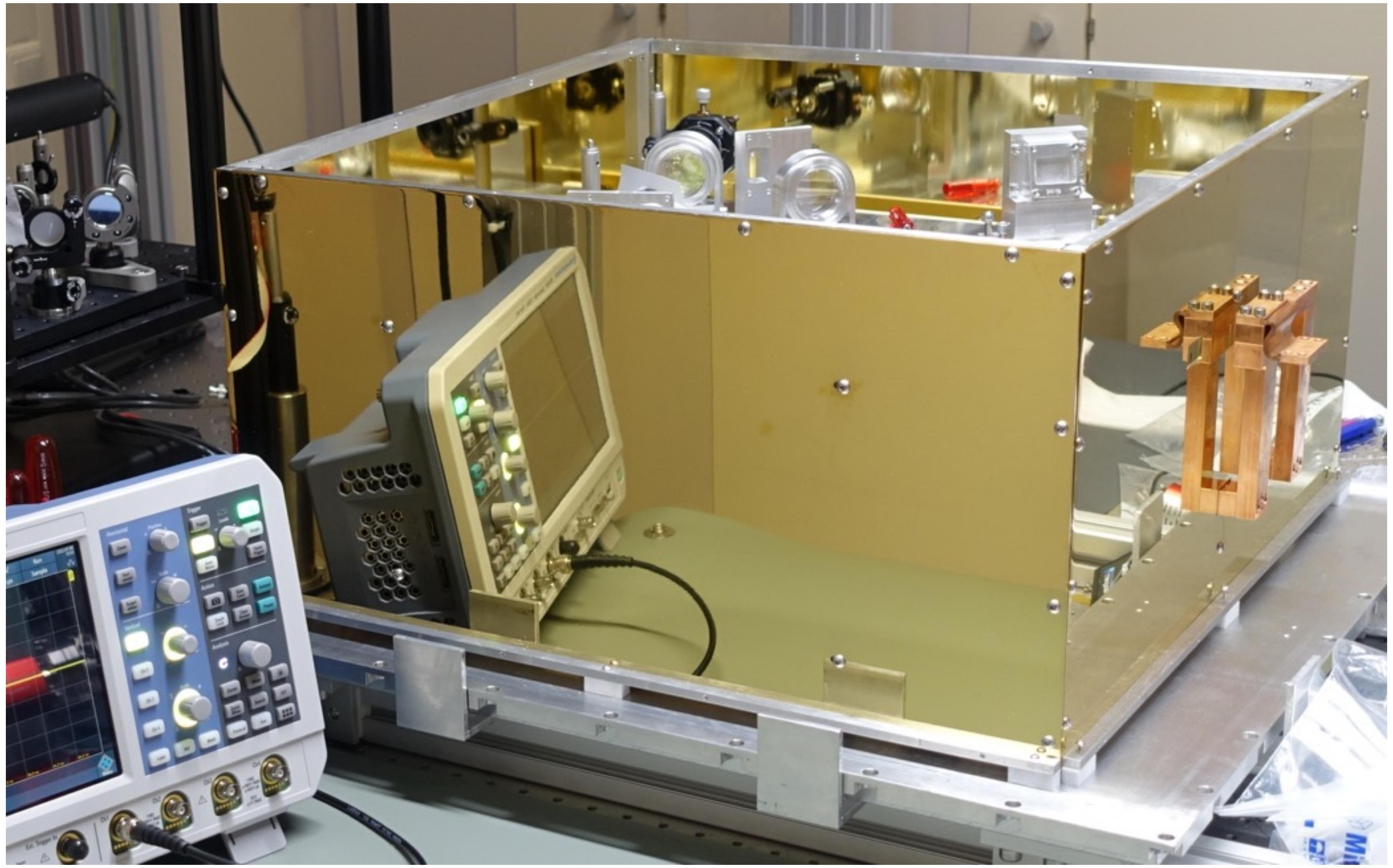


AWG lithographic mask

Potsdam Arrayed Waveguide Spectrograph (PAWS)



CAD View

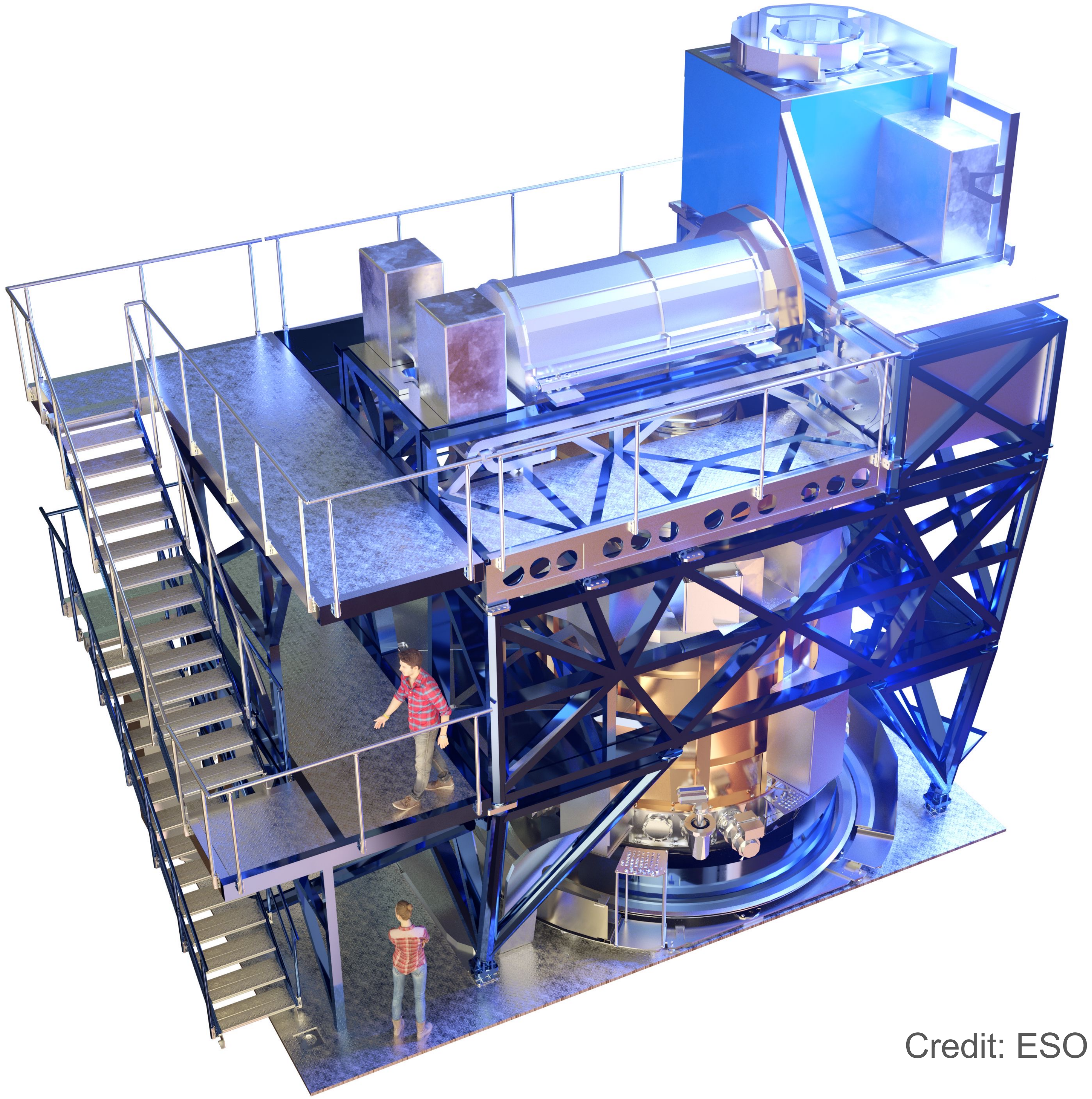


PAWS assembled in the lab

Applications

- „technology push“
- future observatories in space
- PIMMS

  Bland-Hawthorn et al. (2012)
  PIMMS: photonic integrated multimode microspectrograph
  Proc. SPIE, Volume 7735, id. 77350N

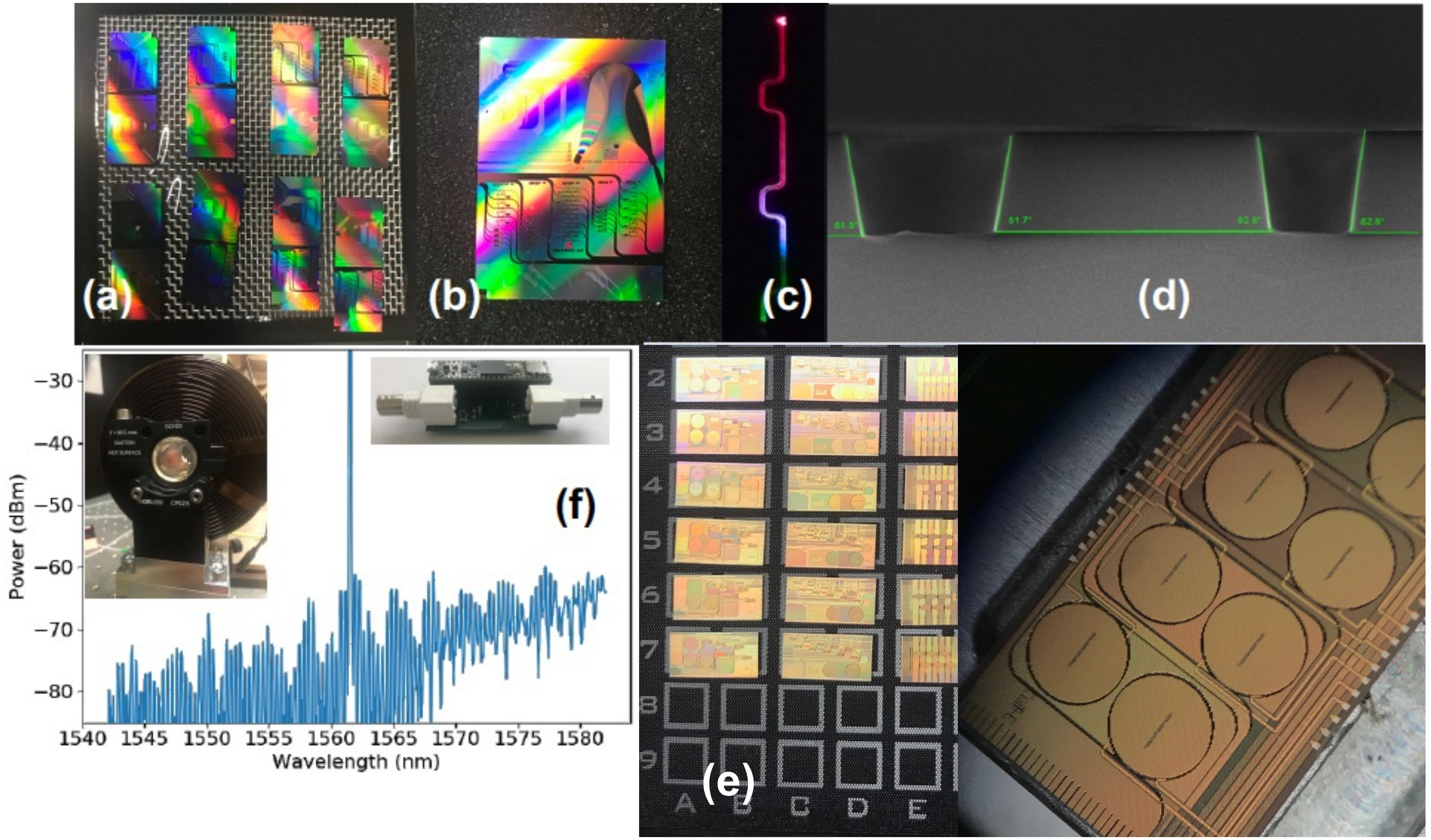


Credit: ESO

(4) Microresonator frequency combs

Microresonator Frequency Comb

Goal: Develop miniaturized, actively stabilized NIR frequency combs based on integrated micro-ring resonators for the calibration of high-res and low-res spectrographs.



Team:

Dr. Jose Chavez Boggio

Daniel Bodenmüller

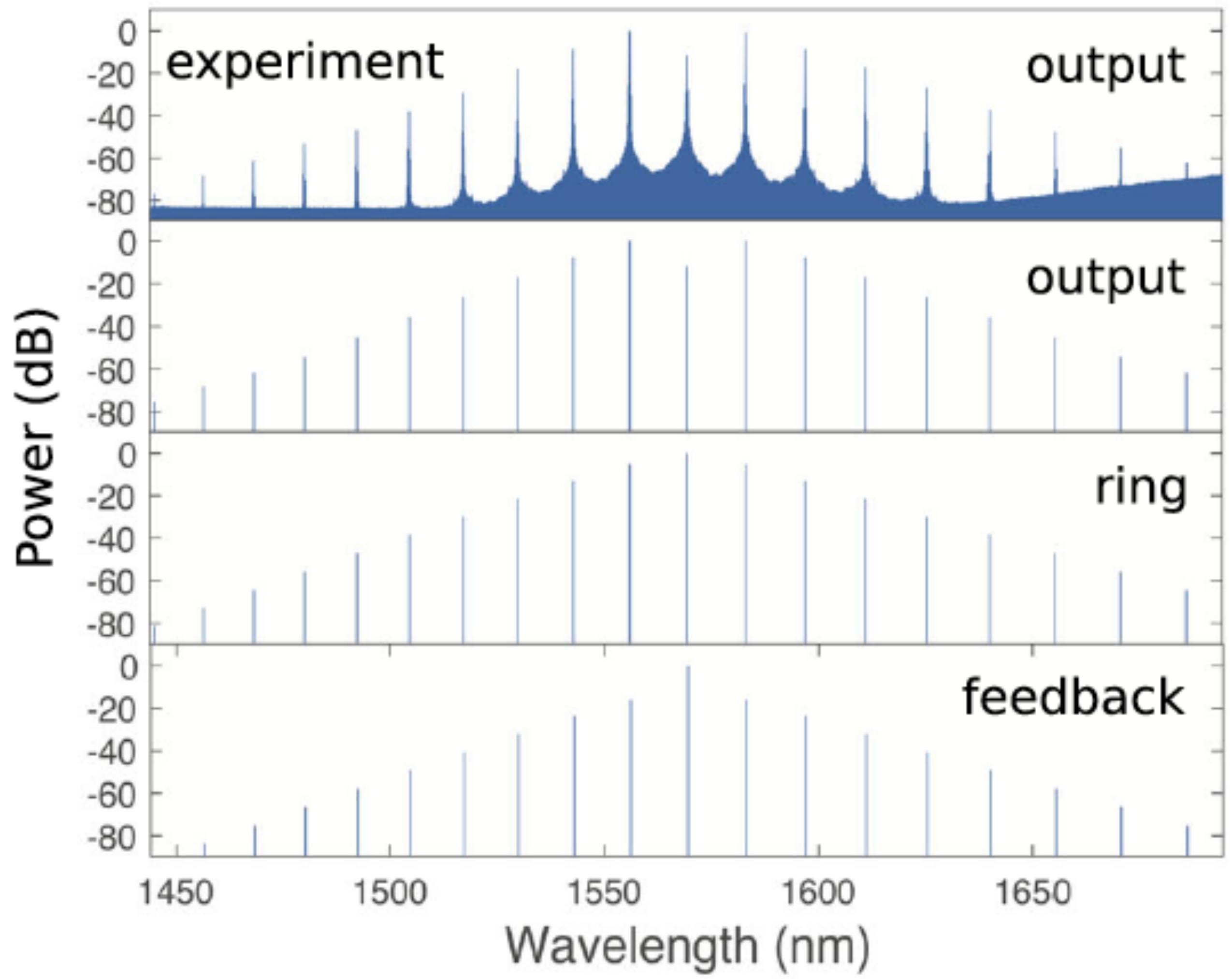
Microresonator Frequency Comb

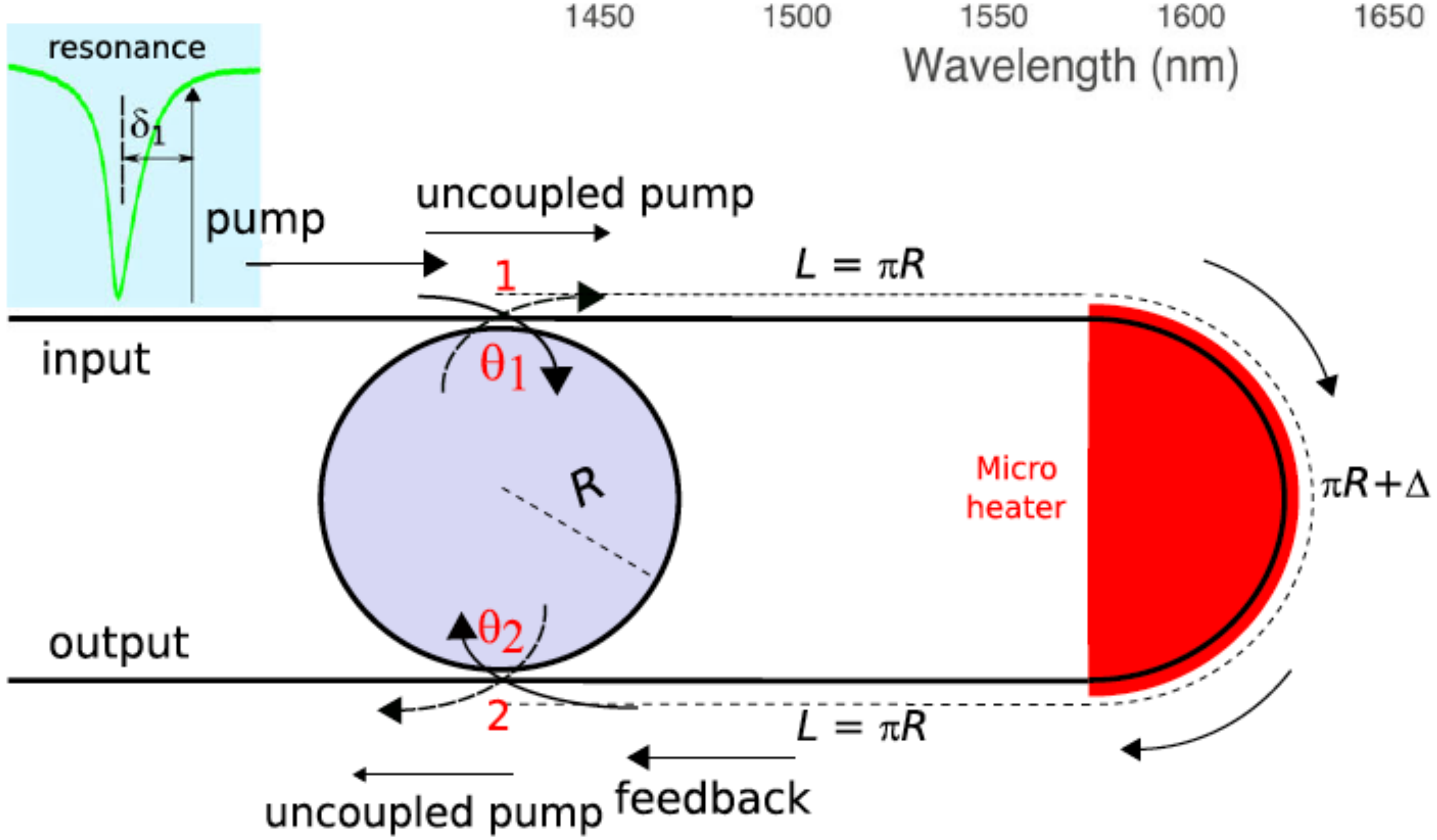
- Si3N4 platform
- Ring resonator
- Feedback-loop
- Rubidium stabilized

Boggio, J. M. Chavez, Bodenmüller, D., Ahmed, S., Wabnitz, S., Modotto, D., Hansson, T. (2022)

Efficient Kerr soliton comb generation in micro-resonator with interferometric back-coupling

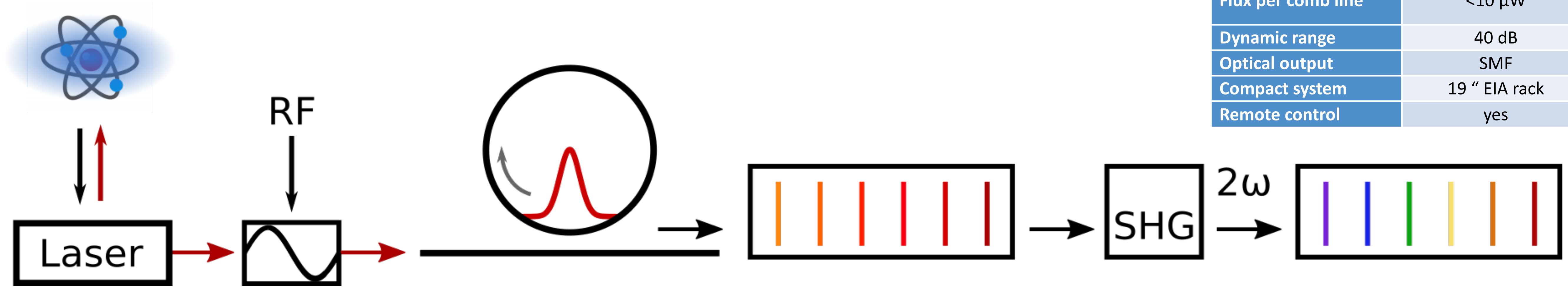
Nature Communications , Vol. 13, p. 1292

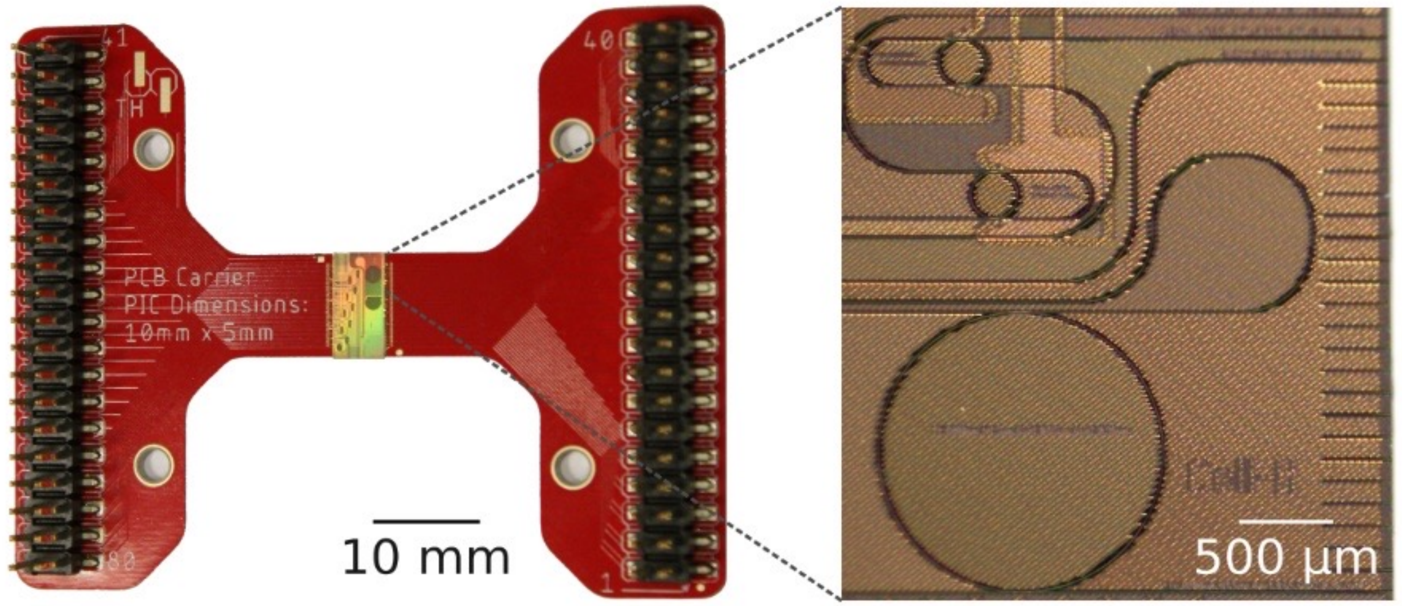




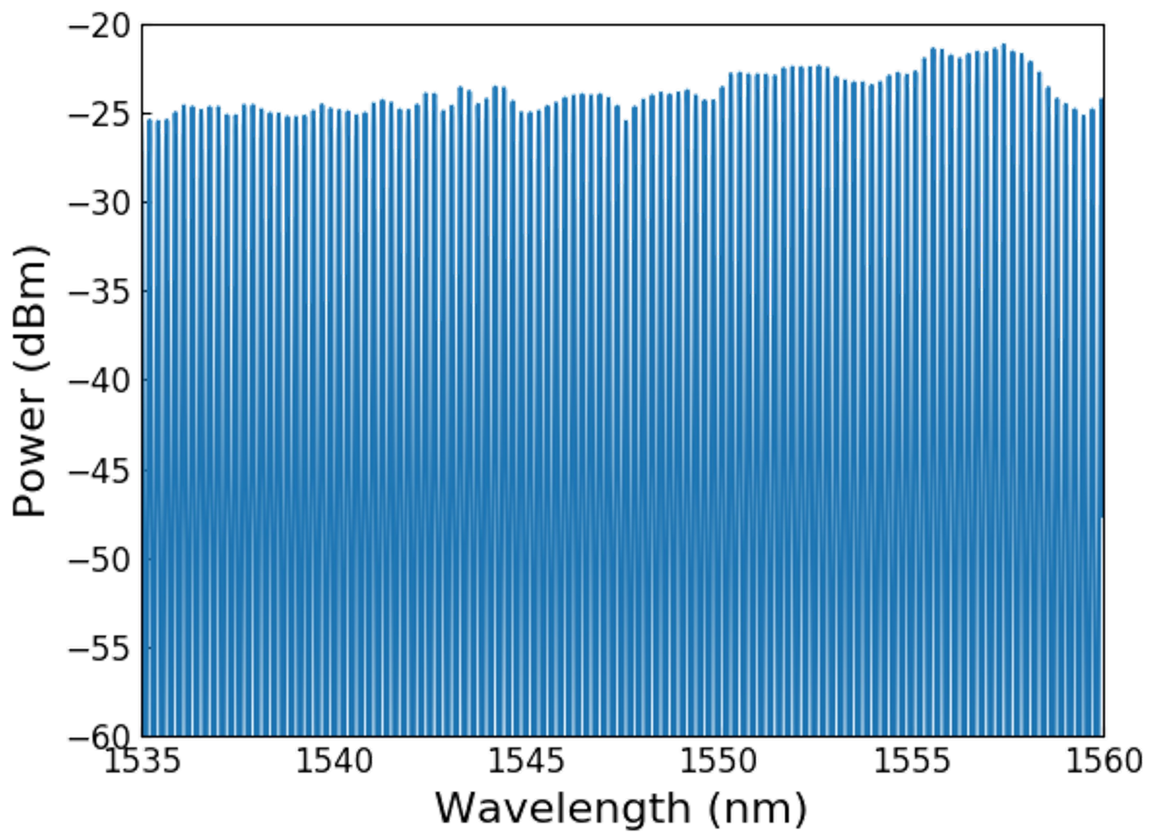
Potsdam Frequency Comb (POCO)

	POCO	BluePOCO
Wavelength coverage	1.475-1.675 µm	0.35-0.80 µm
Line spacing	f_{rep} = 28.55 GHz 172.2 GHz 344.5 GHz	23 GHz
Frequency accuracy	<1MHz	TBD
Intrinsic line width	<200 kHz	<200 kHz
Flux per comb line	<10 µW	TBD
Dynamic range	40 dB	TBD
Optical output	SMF	SMF
Compact system	19 " EIA rack	19 " EIA rack
Remote control	yes	yes

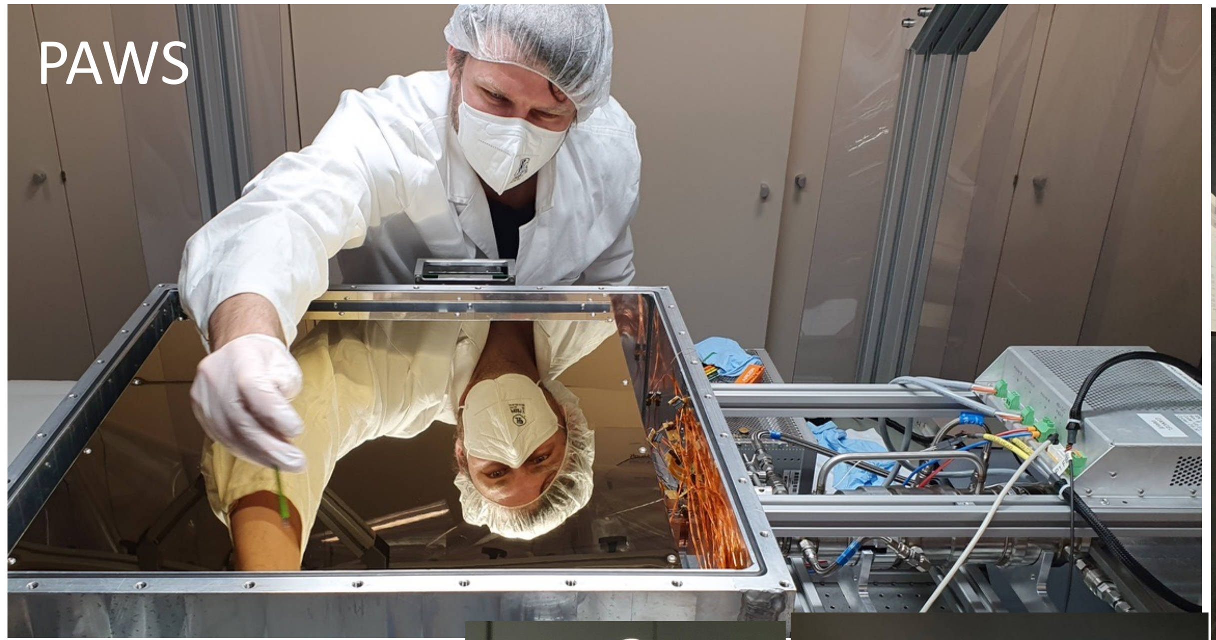


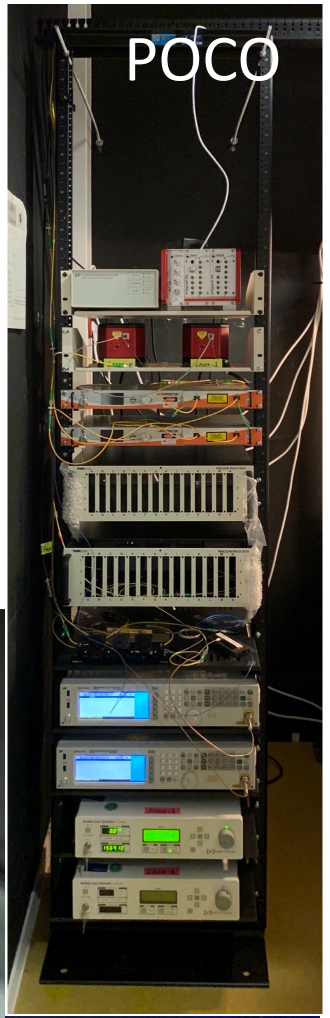


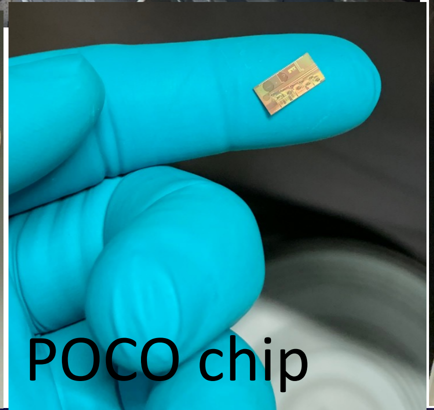
Silicon-Nitride Chip with micro-ring resonator

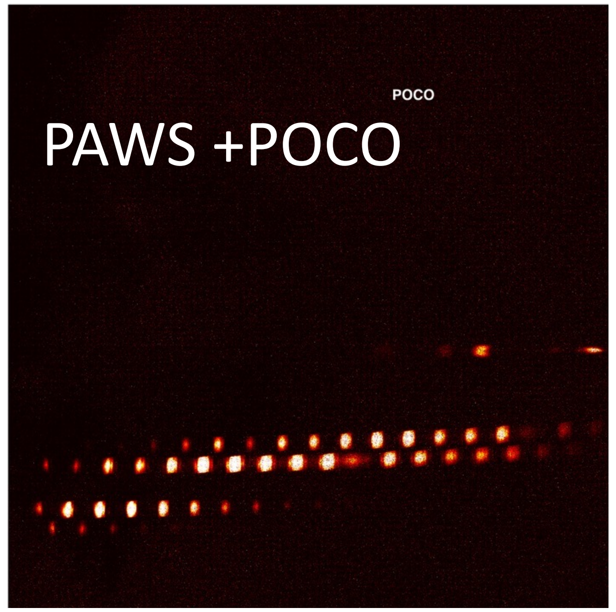


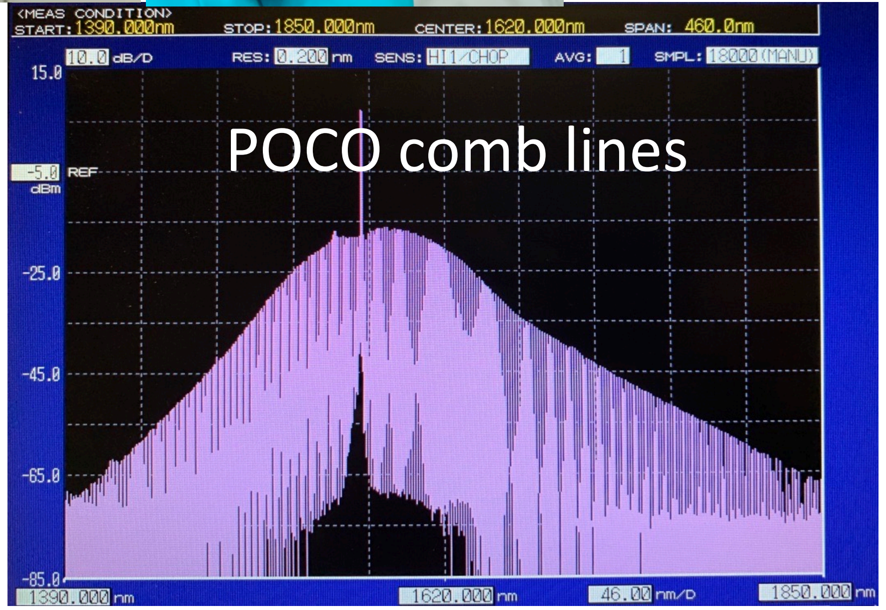
- **Potsdam Arrayed Waveguide Spectrograph (PAWS)**
  - Uses a custom designed Arrayed Waveguide Grating (AWG) and Teledyne H2RG science grade detector
- **Potsdam frequency comb (POCO)**
  - Tuneable “Turn-key“ H-band astronomical comb (VIS in progress)
  - Uses a micro-ring resonator to generate calibration lines
  - 25 cm/s radial velocity stability
- **First light of PAWS achieved in the lab**
- **PAWS can be calibrated using POCO**
- **AIP‘s fibre network was used to calibrate PAWS with POCO**

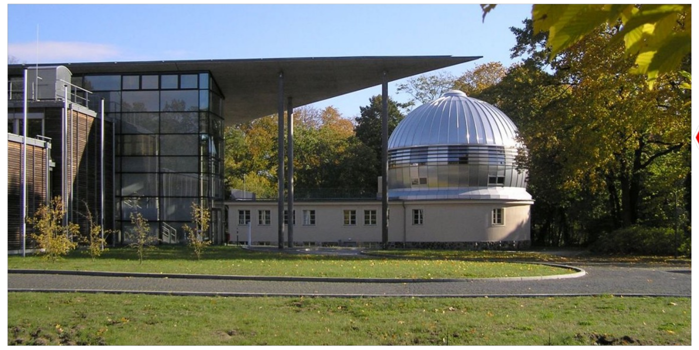












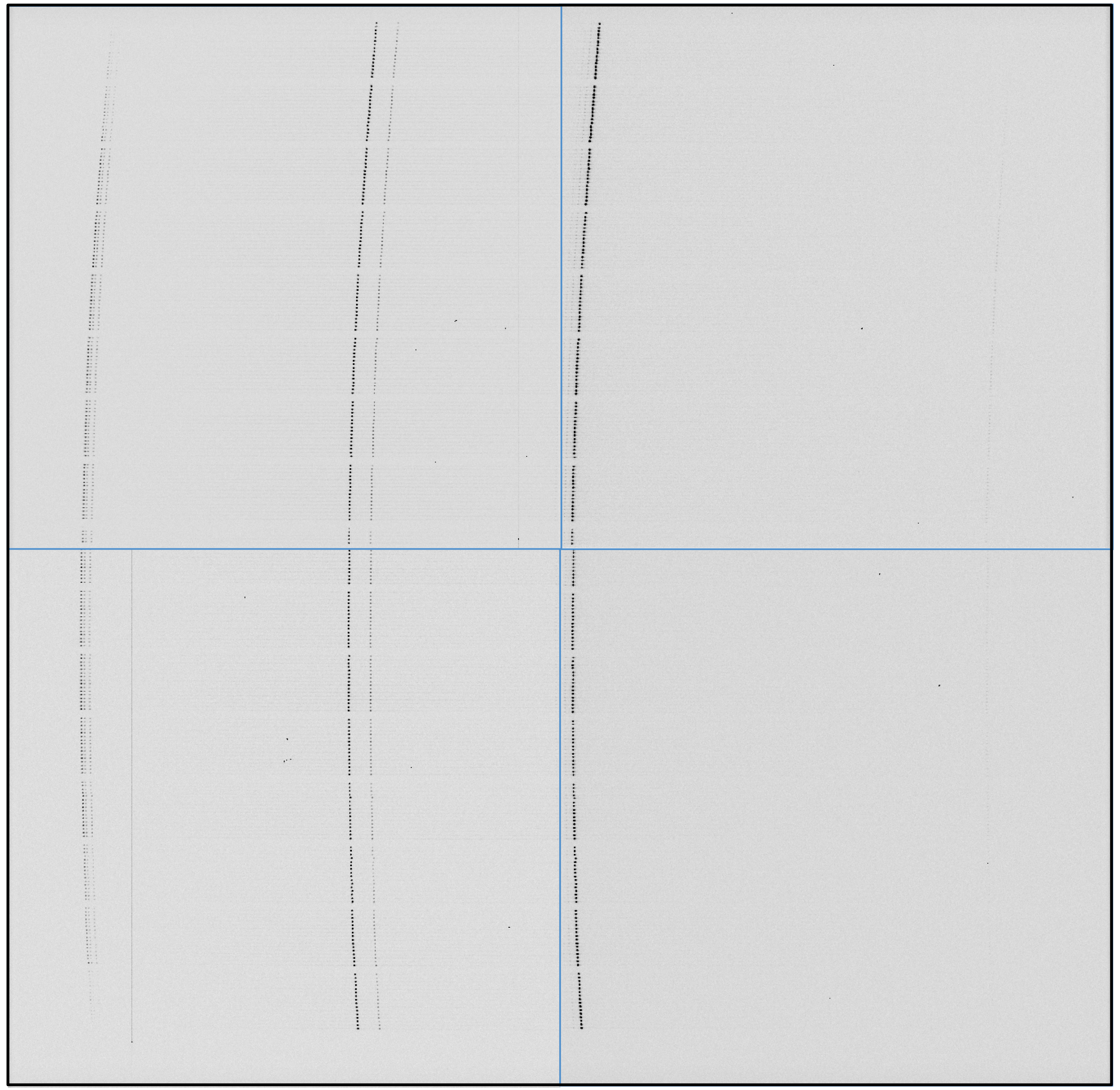
Leibnizhaus

Schwarzschildhaus

Applications

- Affordable wavelength calibration units
- BlueMUSE Calibration Unit – LSF
- Hybrid integration into AWG spectrograph

Roth, M.M., Weilbacher, P.M., Kelz, A., Madhav, K., Hernandez, E., Richard, J., Giroud, R., Bacon, R. (2022), Ground-based and Airborne Instrumentation for Astronomy IX SPIE Conference Series, Vol .12184, 121845S



(5) Summary, conclusions

- Integrated Optics for astronomical instrumentation demonstrated:
  - AWG-based spectrometer (SoS) → PAWS demonstrator
  - Kerr soliton comb in microresonator with feedback (Si_3N_4) → POCO
- Transition from „blue sky“ research to applications
- Growing attention in the community

GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

ZENTREN FÜR
INNOVATIONSKOMPETENZ
UNTERNEHMEN REGION
Die BMBF-Innovationsinitiative
Neue Länder

Acknowledgements

Dr. Stefano Minardi
Dr. Kalaga Madhav