Leibniz-Institut für
Astrophysik Potsdam

Novel Concepts: Photonics for Astronomical Instruments

Aline N. Dinkelaker

Outline

1. Astrophotonics Introduction
2. Manufacturing Methods
3. Components and Devices
4. Astrophotonics for Interferometry

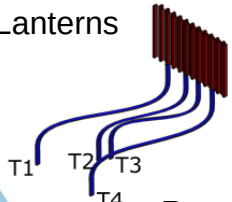
Astrophotonics

Chip and fiber-based photonic devices can be used at various points in astronomical instrumentation

OH Suppression Filters /
Phase Masks / FBGs

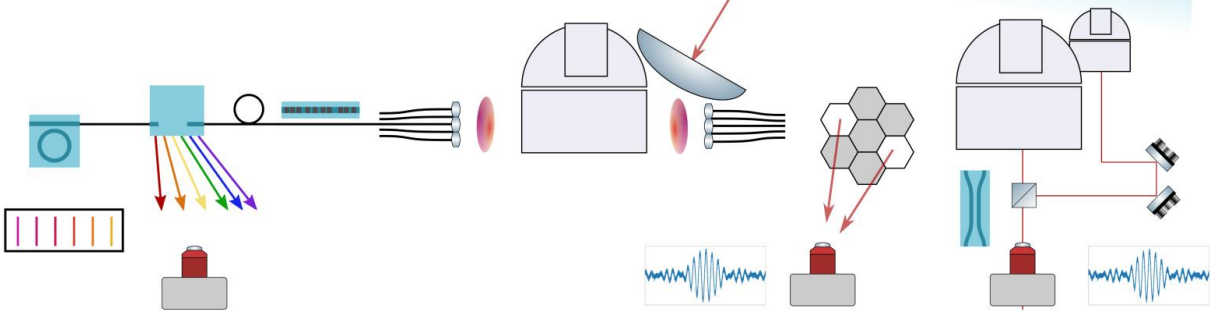
Photonic Lanterns

Dispersers / AWG



Remappers

References /
Frequency Combs

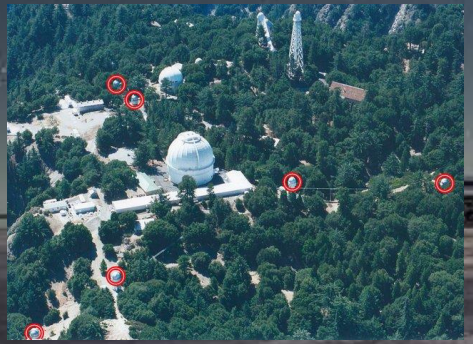


Beam Combiners

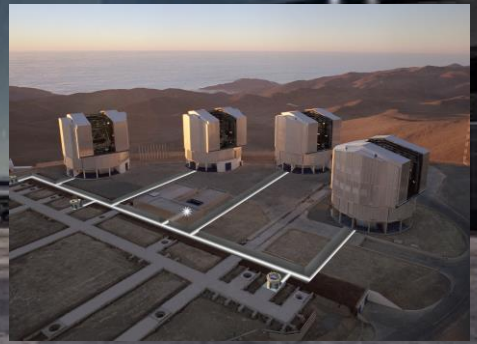
 Image credits (left to right): D. Bodenmüller, A. Stoll, A. Rahman, J. Rypalla, A. Nayak, A. Dinkelaker (AIP)

ELT

https://elt.eso.org/



CHARA, Credit: The Observatories of the Carnegie Institution



VLTI, Credit: ESO

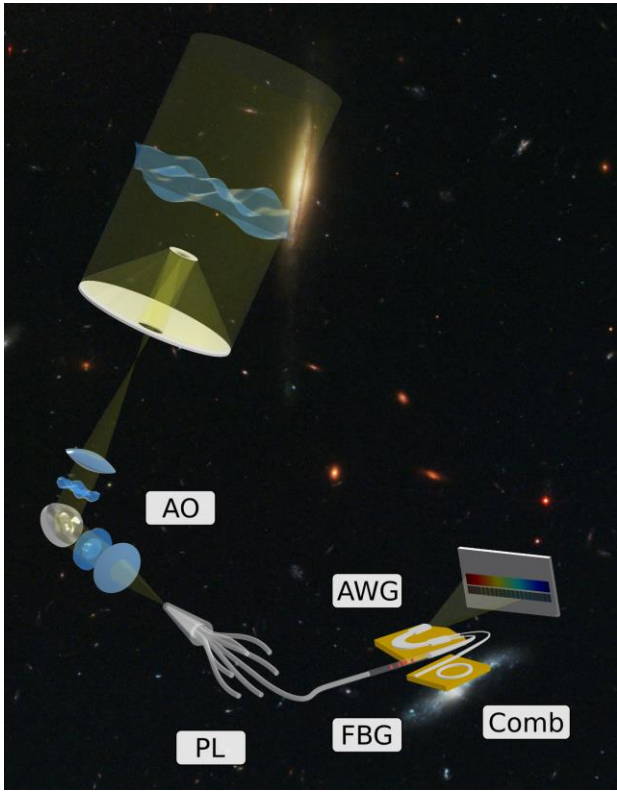
MROI, Credit: MRO

JWST, Credit: NASA GSFC/CIL/Adriana Manrique Gutierrez

Motivation: Photonic Building Blocks for Astronomy

Potential for…

- Reduced size, weight & cost of instruments
- Increased environmental stability
- Modularity for incremental extension and updates
- Full instrument integration

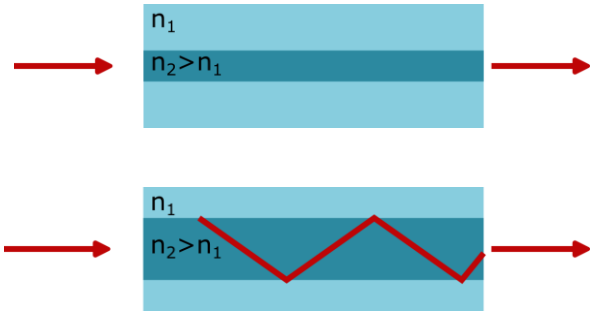


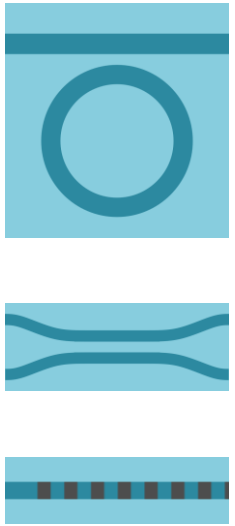
Picture on the right from Dinkelaker+2021, EPN 52/1: M. Diab (devices), background photo credit: NASA/ESA The Hubble Heritage Team and A. Riess (STScI)

Motivation: Photonic Building Blocks for Astronomy

Utilize unique properties of photonics:

- Spatial filtering (typically single-mode)
- Mode conversion
- Guiding (e.g. curved waveguides)
- Coupling / evanescent effects



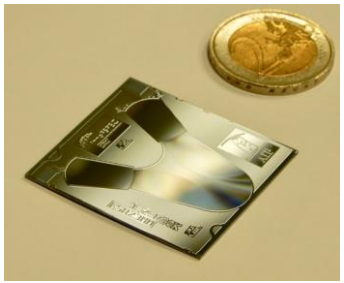


Simulation and modelling → Manufacturing → Laboratory Characterisation → On-sky Testing

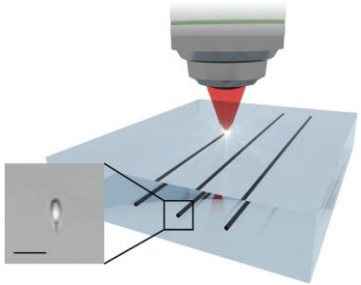
Image (modes of light, bottom left) taken from:Velázquez-Benítez et al., Sci Rep 8, 8897 (2018).

Manufacturing

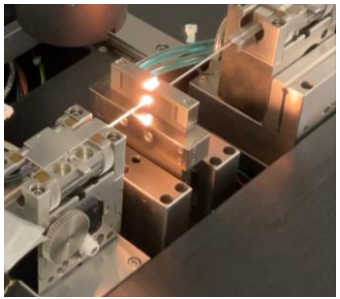
- Lithography
- Direct laser writing / ultrafast laser inscription (ULI)
- Glass heating and tapering
- 3D printing
- Etching
- …



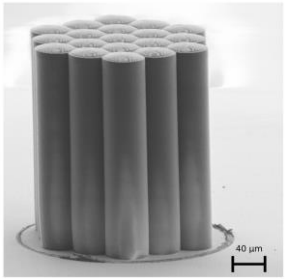
AWG chip: A. Stoll, Hernandez+(2020, SPIE)



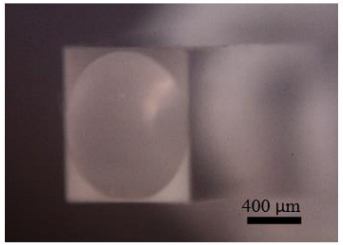
Piacentini+(2020)



J. Rypalla (AIP)



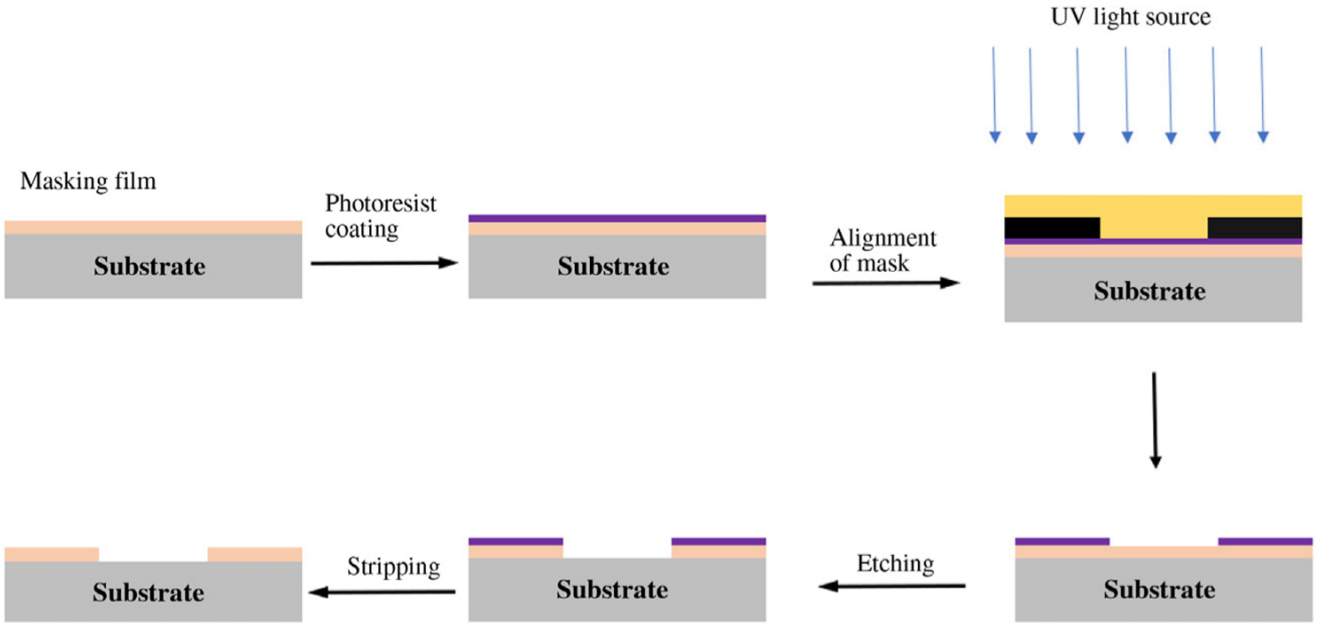
Anagnos+(2021, Appl. Opt.)



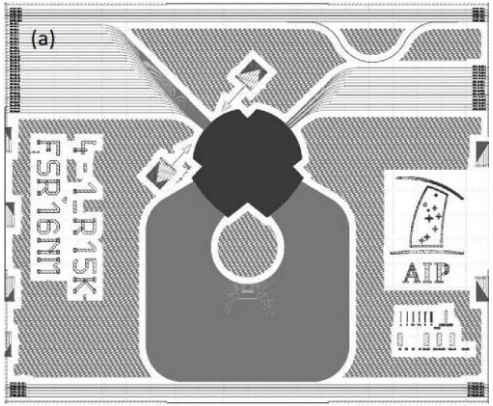
Ross+(2020, Proc. of SPIE Vol. 11451, 114510P)

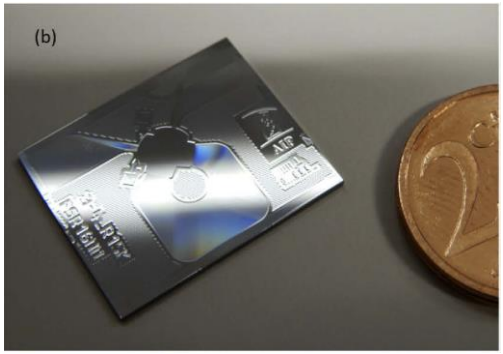
Manufacturing

Schematic representation of the photolithographic process sequence



Credit: Yilbas, B. et al. (eds Yilbas, B. S., Al-Sharafi, A. & Ali, H.) 45–98 (Elsevier, 2019)

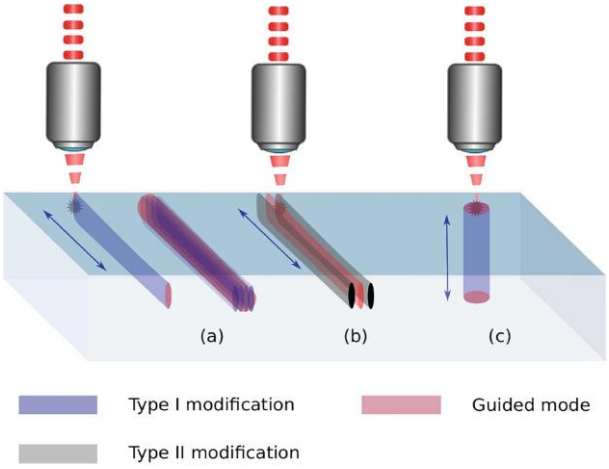




Credit: Stoll+2020

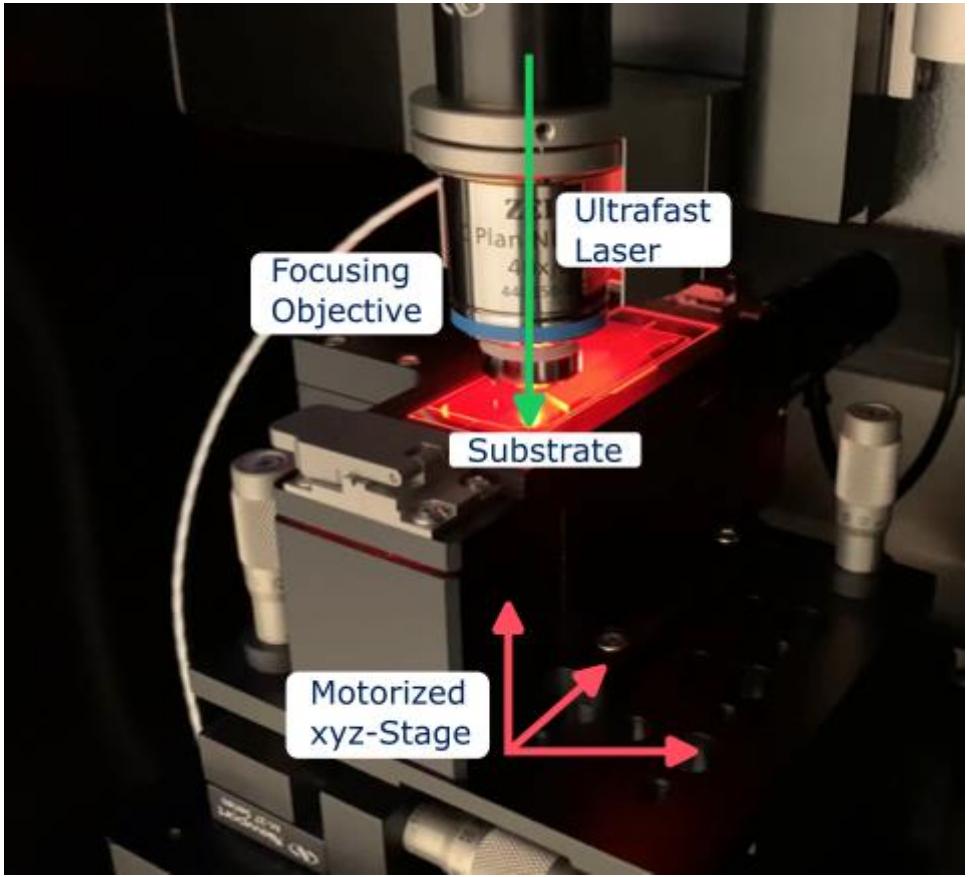
Manufacturing

Example of the ULI process



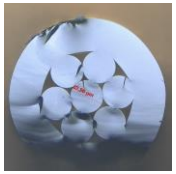
ULI modification types for different writing schemes

Image from: Ghafur, O. et al., (eds Stoian, R. & Bonse,J.) 759–786 (Springer International Publishing, Cham, 2023).



MKS FemtoFBG, image credit: A.Mayer (AIP)

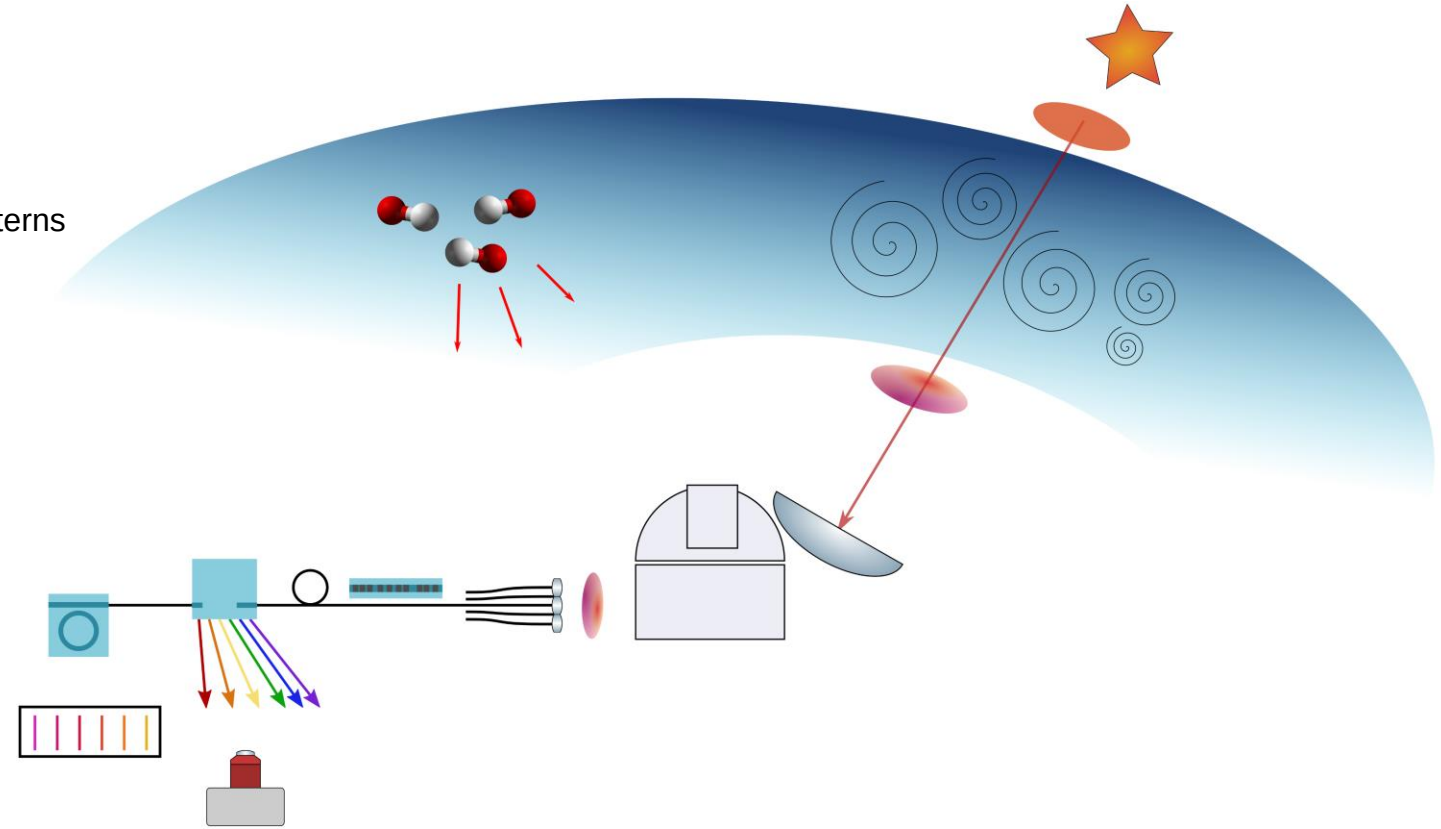
Astrophotonic Components



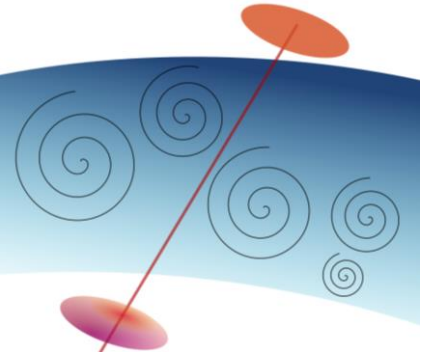
Photonic Lanterns

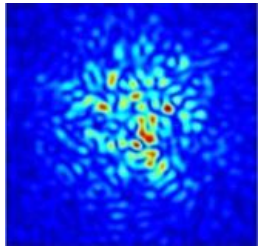
Dispersers / AWG

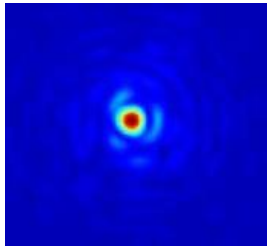
References /
Frequency Combs

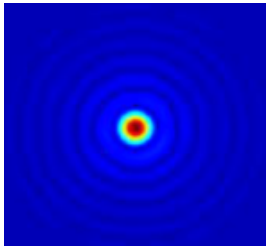


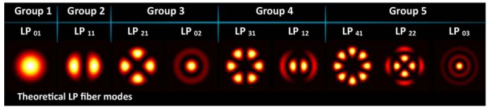
Photonic Lanterns





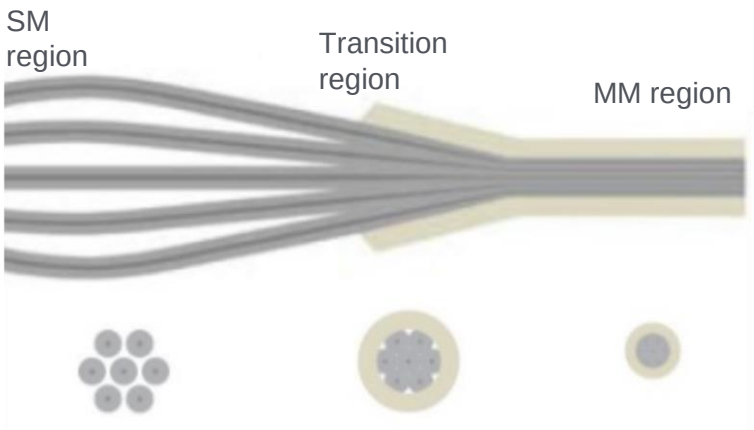


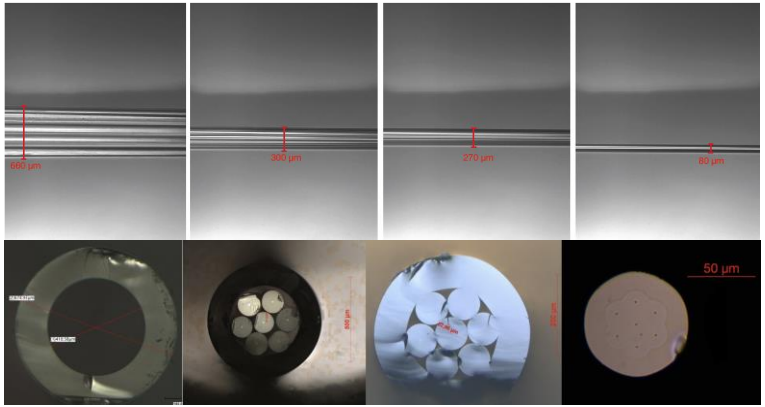




Wavefront corrections with adaptive optics

MM-SM photonic lantern

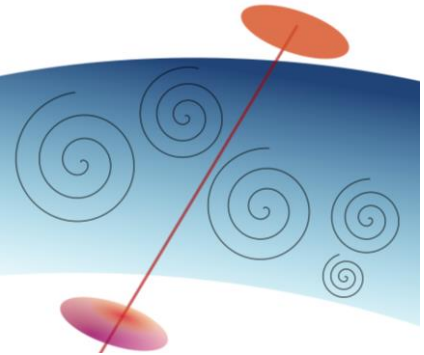


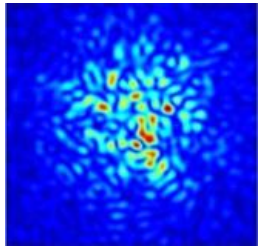


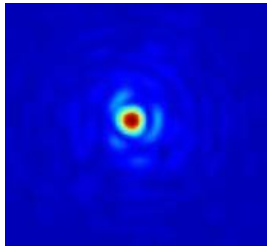
See also: Davenport+(2021), for ULI PLs, see e.g. Thomson+(2011)

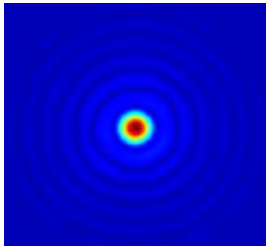
Images: top, left: M. Diab (AIP), right (photos): J. Rypalla (AIP), (top right) taken from:Velázquez-Benítez+(2018).

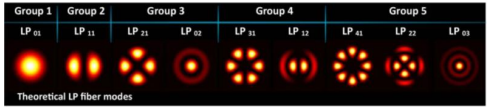
Photonic Lanterns





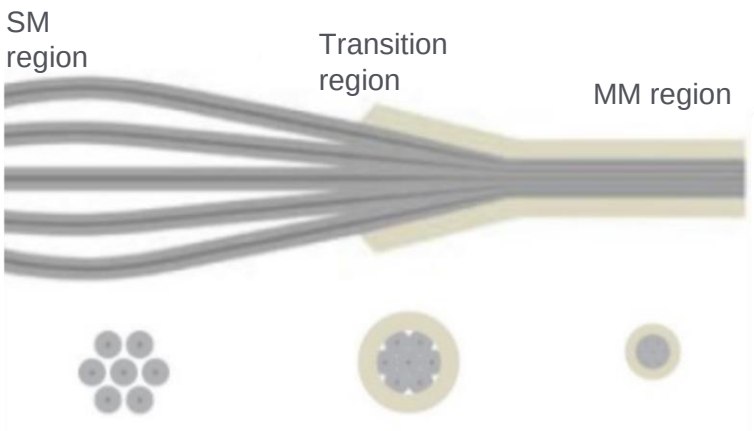






Wavefront corrections with adaptive optics

MM-SM photonic lantern



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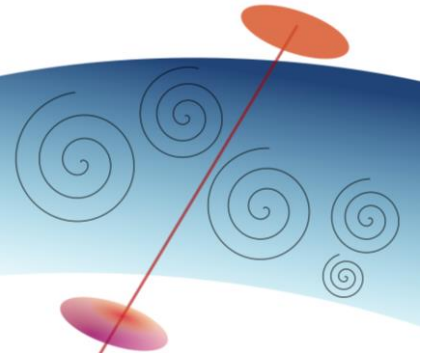
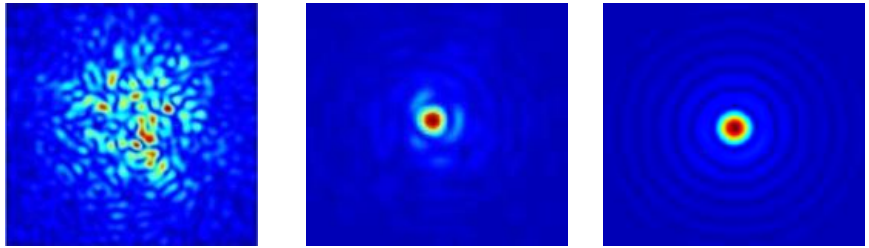
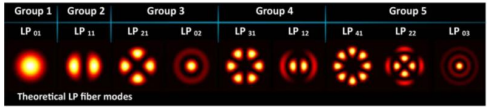
Photonic Lanterns



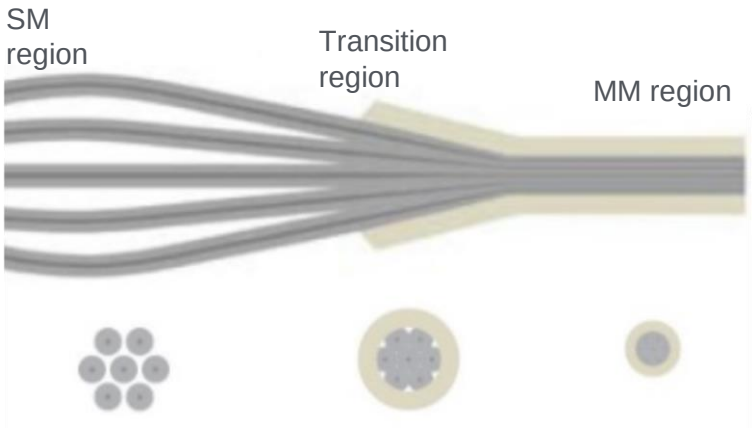


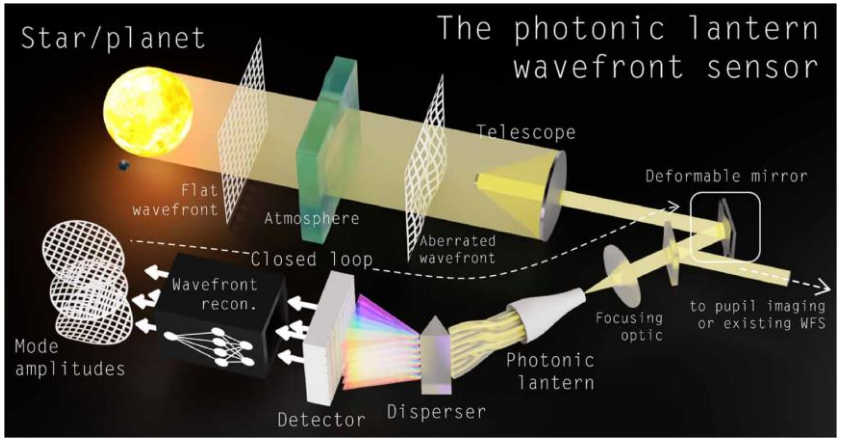


Wavefront corrections with adaptive optics

PLs can also be used for WFS

MM-SM photonic lantern

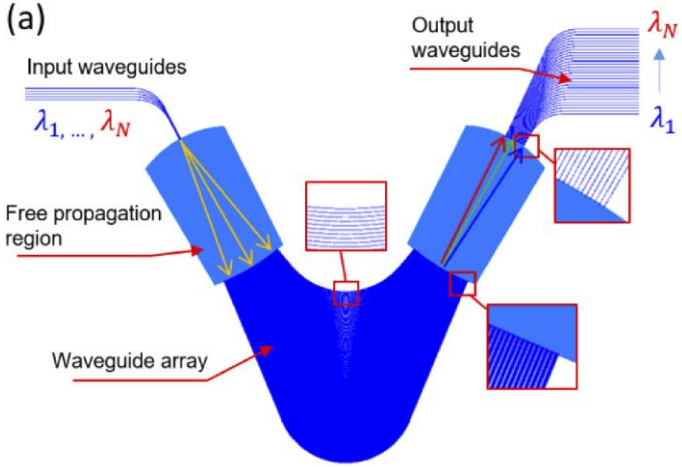


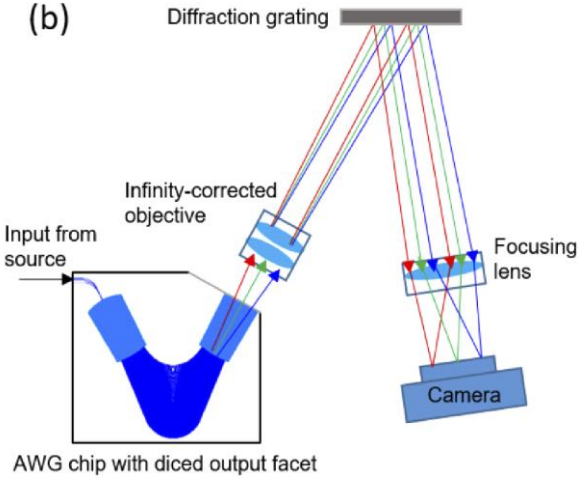


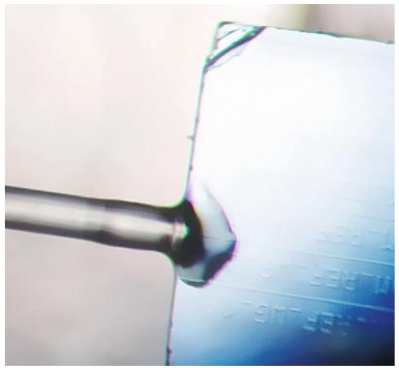
See "Astrophotonics Roadmap" (Jovanovic+2023,, Chapter 3: Photonic lantern wavefront sensing and control

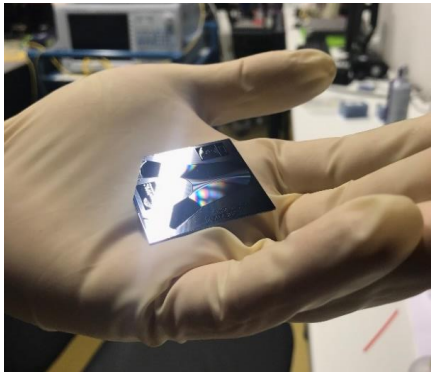
Images: top, left: M. Diab (AIP), (top right) taken from:Velázquez-Benítez+(2018), (bottom right): Jovanovic+(2023), Astrophptonics Roadmap, Chapter 3.

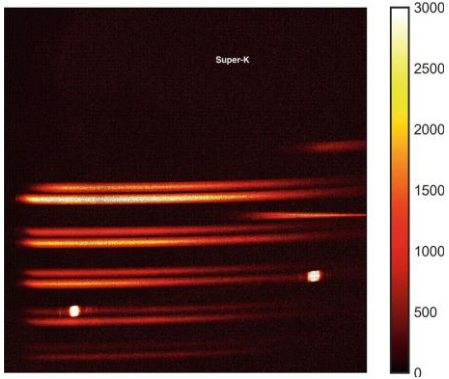
Arrayed Waveguide Gratings – Spectrograph on a Chip











AWG examples parameters

Platform (NIR):

Silica-on-silicon (SoS)

Array:

hundreds (~400 – 700) of waveguides

Transmission:

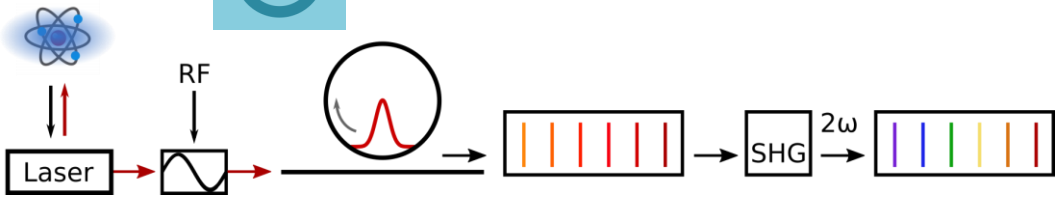
~70%

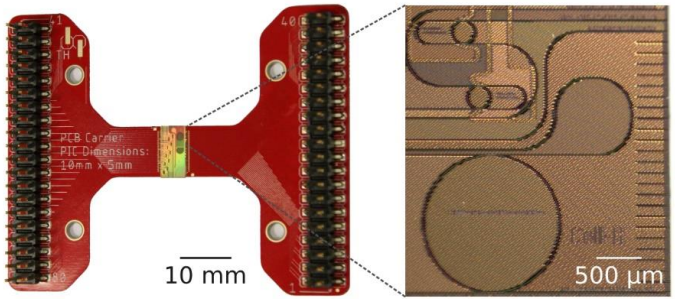
Resolving power $R = \frac{\lambda}{\Delta\lambda}$*:*

10,000 –30,000 (high)

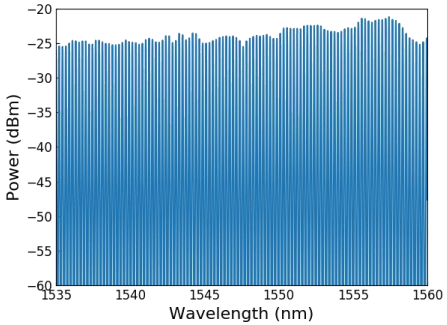
Images: A. Stoll+2020 (top), Madhav+2023, Astro. Nachr. (bottom left and right), A. Stoll+2017 (bottom center)

Chip-based Frequency Comb (Astrocomb)

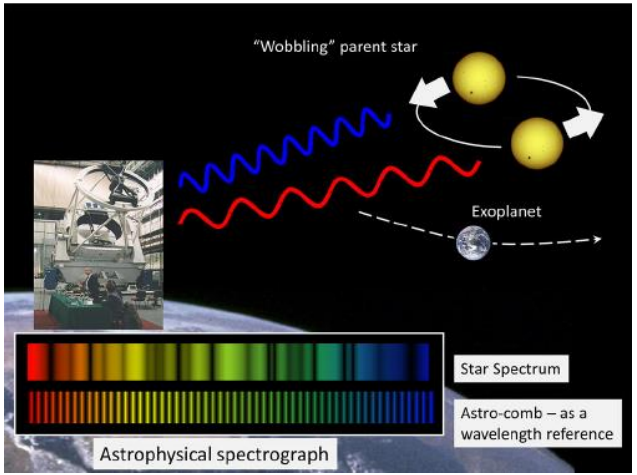




Silicon-Nitride Chip with micro-ring resonator

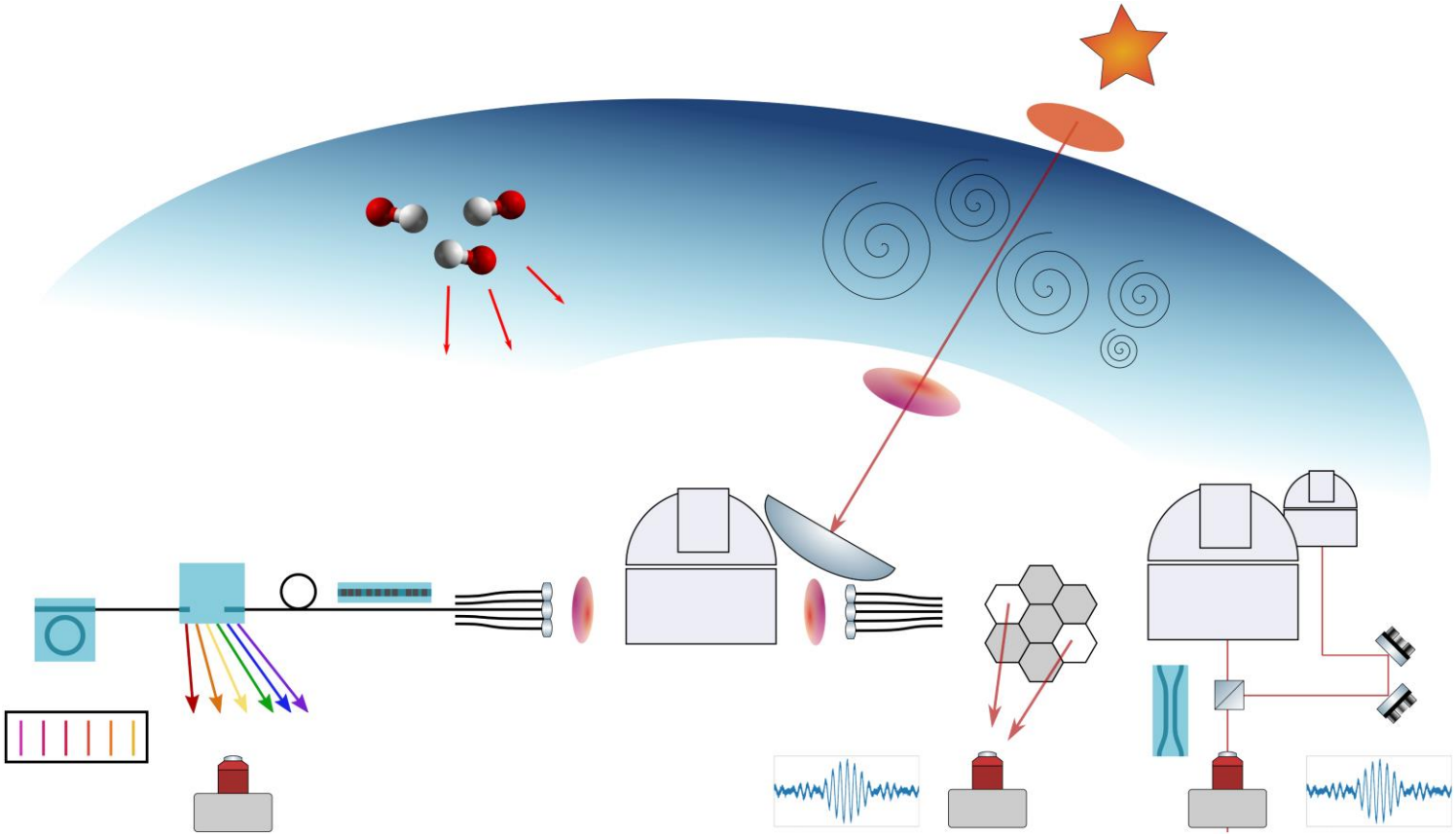


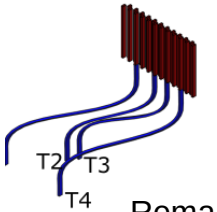
Spectra with f_{rep}=28.55 GHz,
Expected stability Δf_{Center} < 250 kHz



Chih-Hao Li, SPIE News (2015): https://spie.org/news/5730-a-green-astro-comb-to-search-for-earth-like-exoplanets

Astrophotonics for Interferometry





Remappers

Beam Combiners

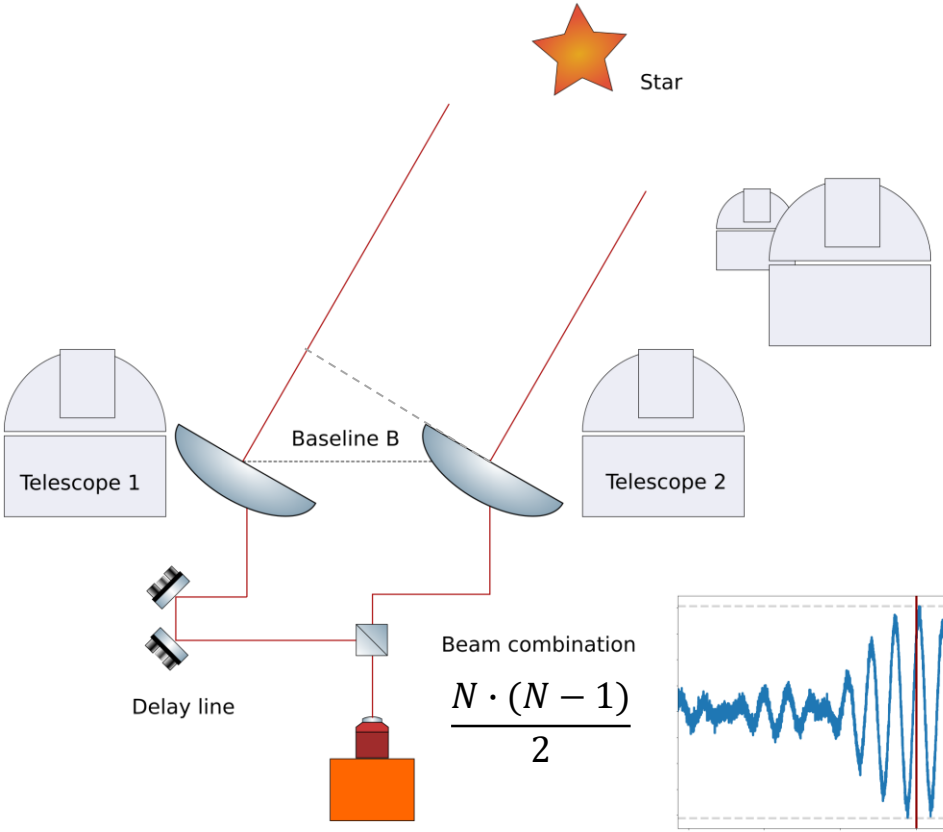
 Image credits : A. Nayak, A. Dinkelaker (AIP)

Astrophotonics for Interferometry

High angular resolution astronomy:
“virtual“ large telescope with $\Delta\theta \propto \frac{\lambda}{B}$

Van Cittert-Zernike theorem:

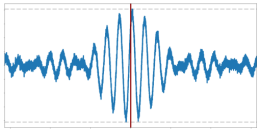
Relates **coherence** of light to **brightness distribution** of object



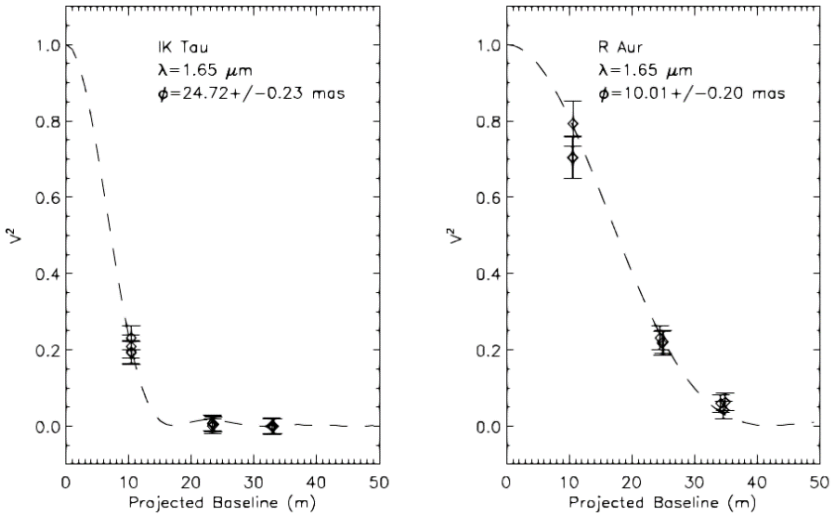
Astrophotonics for Interferometry

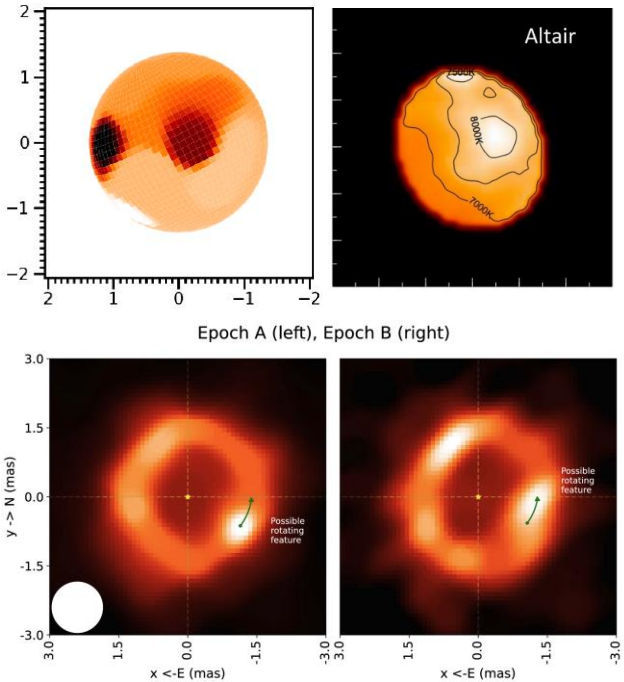
Complex visibility: **visibility** and **phase** from fringe pattern

- Visibility = 1 for point source
- Visibility = 0 for fully resolved source



Measure visibility for different **baselines B**



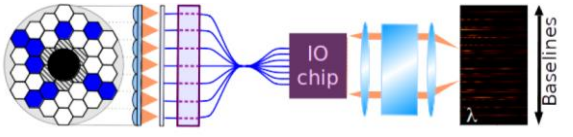


Left: "First Surface-resolved Results with the IOTA Imaging Interferometer: Detection of Asymmetries in AGB stars" (Ragland+ 2006). Reconstructed images: top: Martinez+(2021, ApJ) and Monnier+(2007), bottom: Ibrahim+(2023, ApJ)

Astrophotonics for Interferometry

High angular resolution astronomy:
“virtual“ large telescope with $\Delta\theta \propto \frac{\lambda}{B}$

Long baseline interferometry
OR
Using sub-apertures of a single telescope



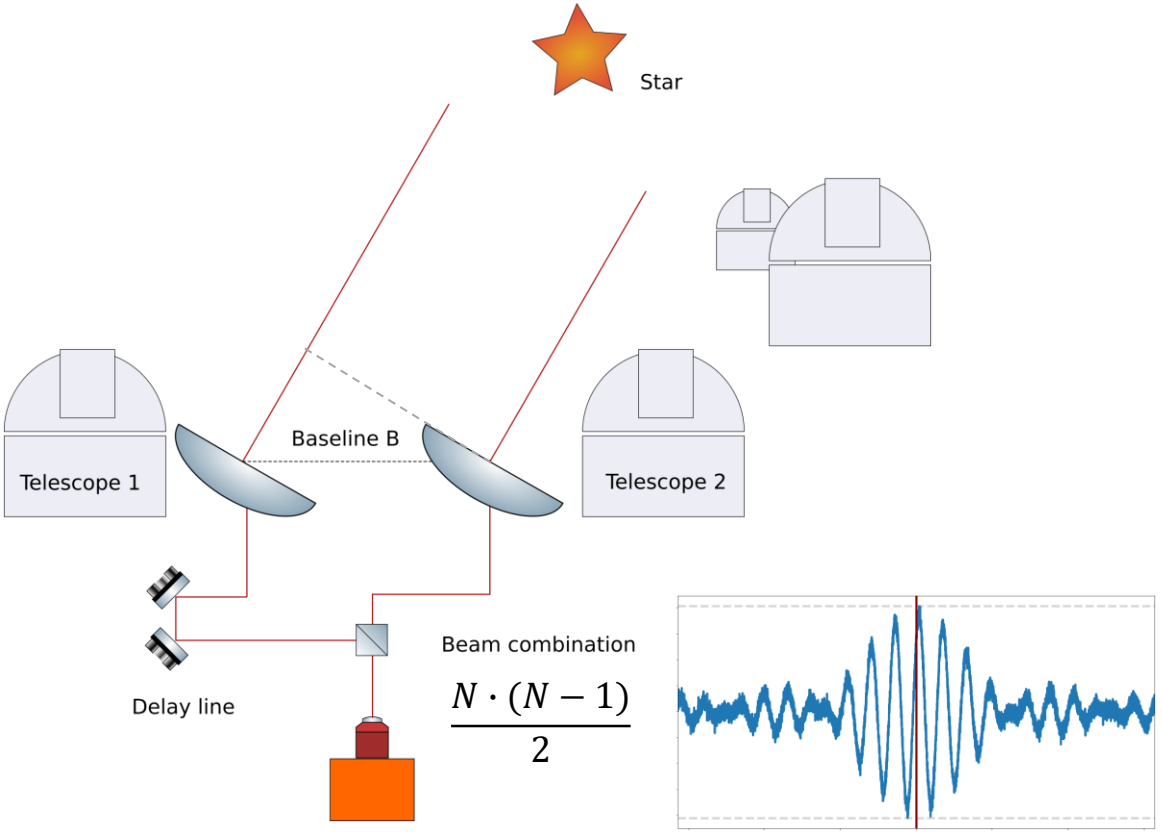
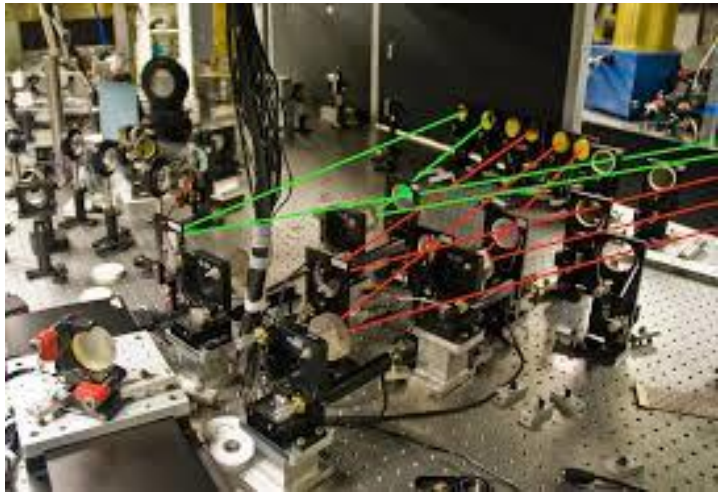


Image (left): Barjot+(2020, Proc. SPIE 11446, 2022, arxiv)

Free space optics

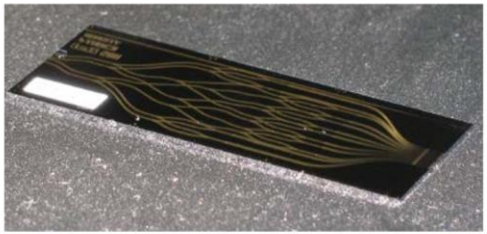
CLASSIC and CLIMB beam combiners at CHARA



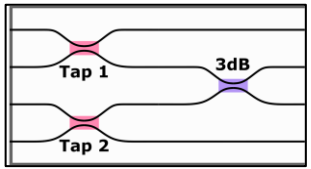
Photonics

2D (planar)

GRAVITY beam combiner

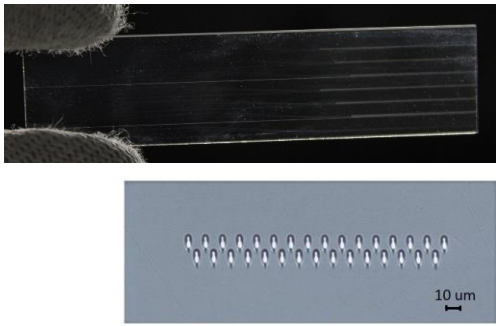


CHARIOT (2-T, K-band)

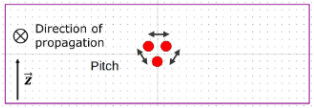


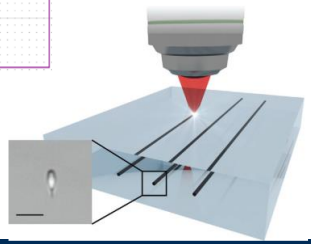
3D

DBC



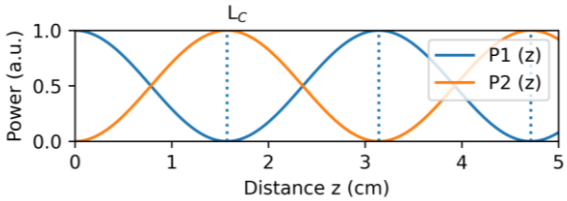
Tricoupler



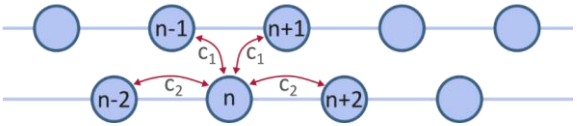


Credit: CLASSIC/CLIMB: Ten Brummelaar+(2013), GRAVITY: GRAVITY collaboration (2017), 3D Beam combiner manufactured by Politecnico Milano, Pedretti+ 2018 (arxiv 1809.01260v1), ULI image: Piacentini+(2020), K-band beam combiner: Benoît+2021, tricoupler for GLINT: Martinod+(2021)

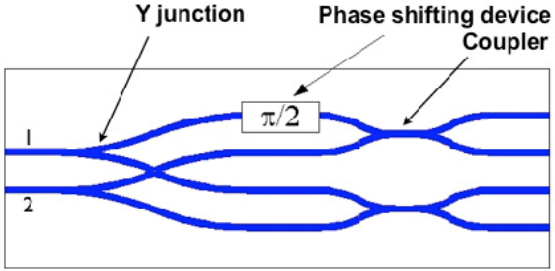
Photonic Beam Combiners



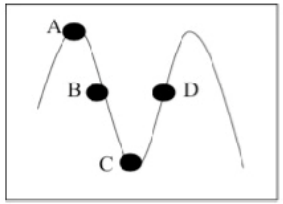
Discrete Beam Combiner (DBC)



ABCD (Cascading) Beam Combiner



φ_{12}^1
φ_{12}^2
φ_{12}^3
φ_{12}^4



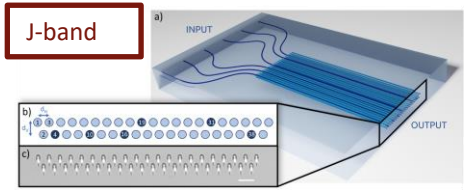
$$\varphi_{12}^2 = \varphi_{12}^1 + \pi$$
$$\varphi_{12}^3 = \varphi_{12}^1 + \pi/2$$
$$\varphi_{12}^4 = \varphi_{12}^3 + \pi = \varphi_{12}^2 + \pi/2$$

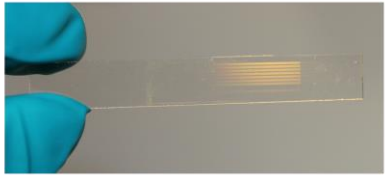
Image credits: (Bottom right) Benisty+2009. (Bottom left): Schematic based on Osellame+ 2012. For DBCs, see: Diener+2017, Pedretti+2018, Saviauk+2013, Minardi+2010, Nayak+2021.

Photonic Beam Combiners

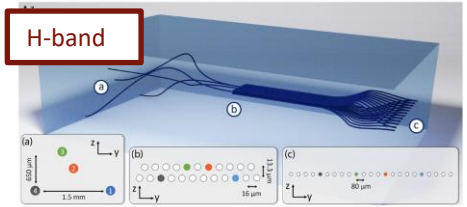
Discrete Beam Combiner (DBC)

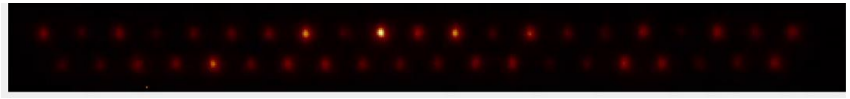
J-band





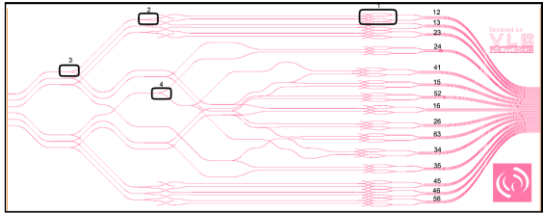
H-band



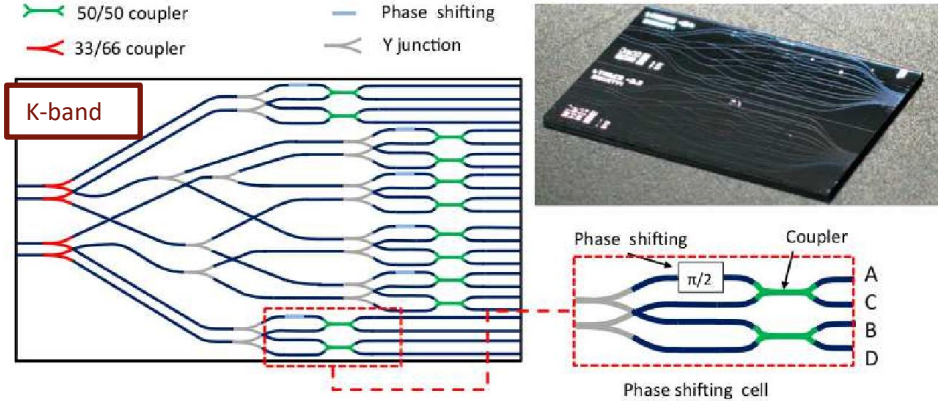


ABCD (Cascading) Beam Combiner

H-band



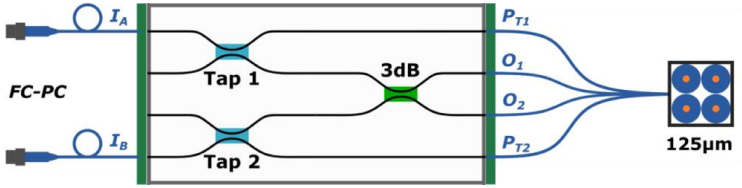
K-band

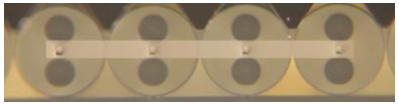


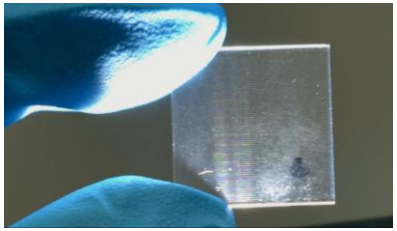
Images (DBC): Dinkelaker+(2023, AO), Nayak+(2021). See also „Astrophotonic Technologies“ (arxiv / SPIE) . Images (ABCD): Pennetier+(2022, SPIE), Blind+(2015)

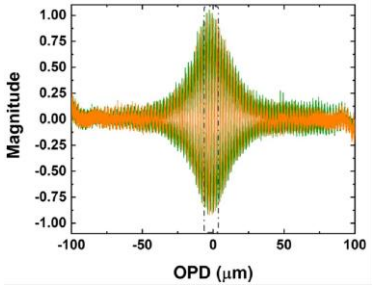
K-band ULI Beam Combiner (CHARIOT)

- 2 - 2.5 µm wavelength range (K-band)
- ULI in Infrasil (fabrication by HWU)
- 2-telescope combiner with fiber interface





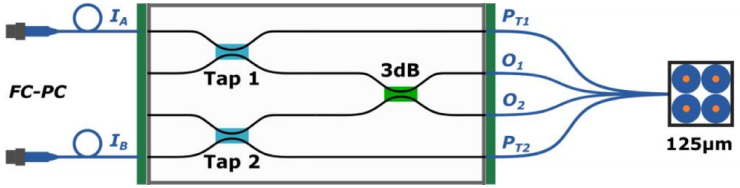


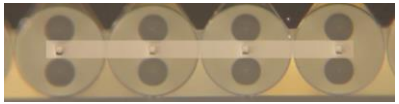


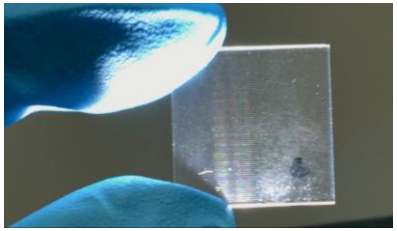
Images: Siliprandi+ (2024, AO), plot: Benoît+ (2021, JOSA B), see also: Labadie (2022,SPIE)

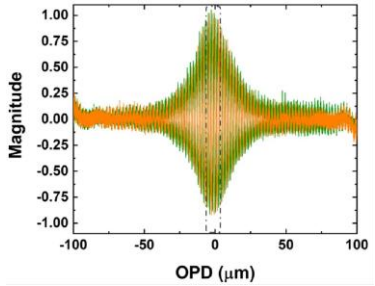
K-band ULI Beam Combiner (CHARIOT)

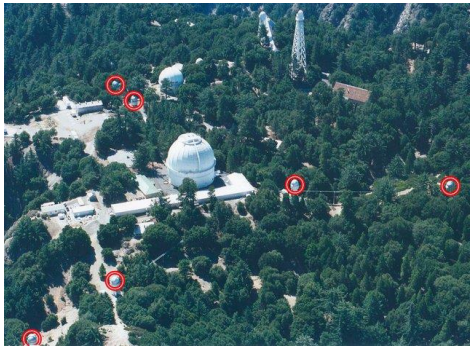
- 2 - 2.5 µm wavelength range (K-band)
- ULI in Infrasil (fabrication by HWU)
- 2-telescope combiner with fiber interface

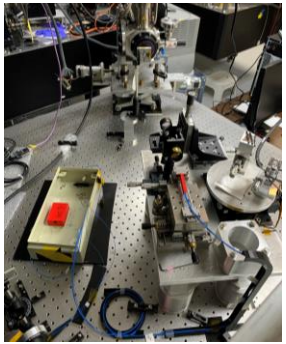


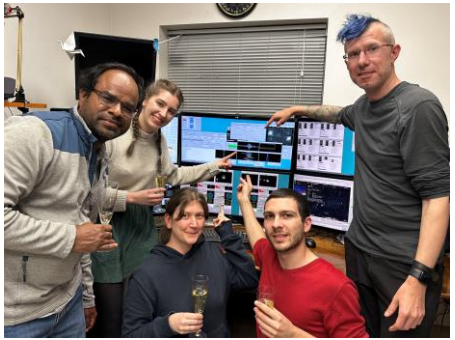


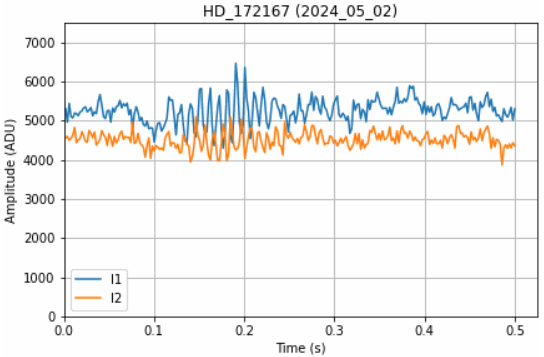










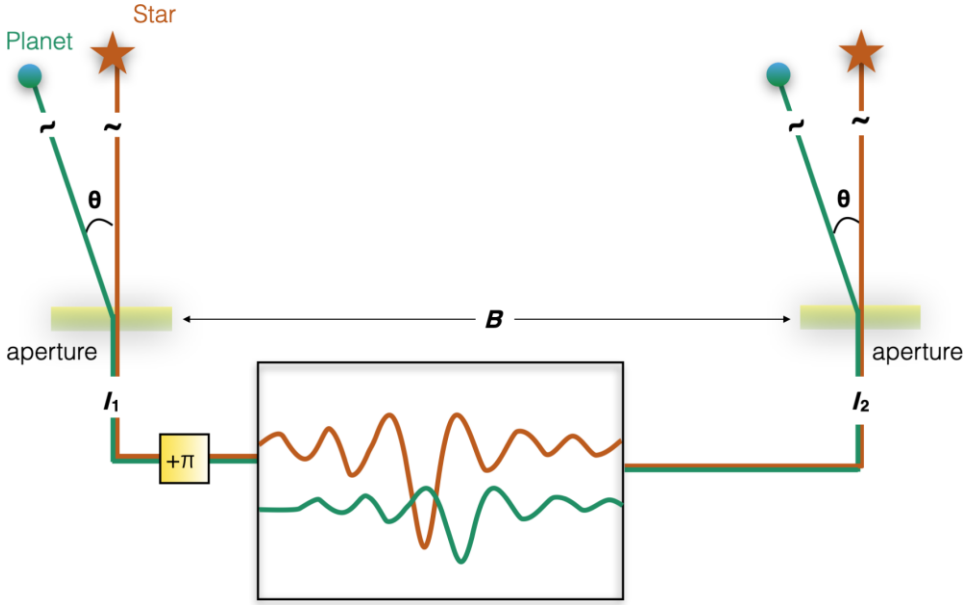


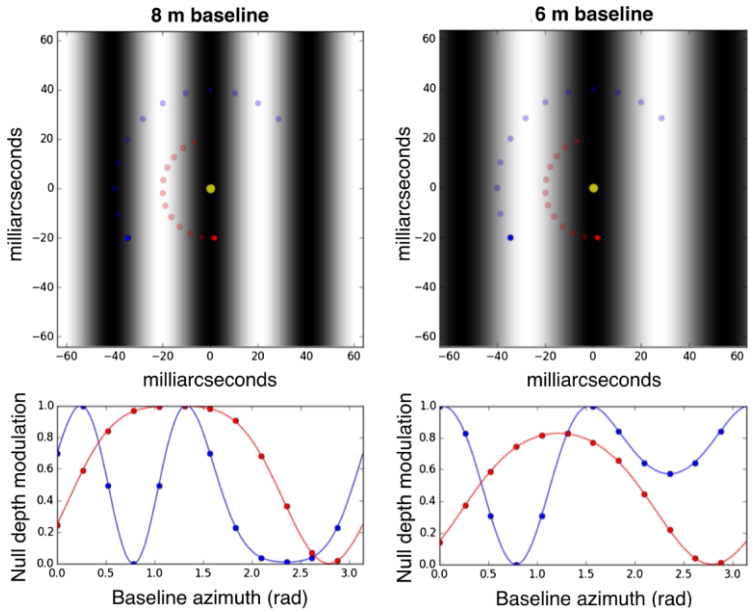
The CHARA Array and CHARIOT setup. Celebrating on-sky fringes with CHARIOT (May 2nd 2024): N. Anugu, A.V. Mayer, A.N. Dinkelaker, K. Barjot, N. Scott

Images: top: Siliprandi+ (2024, AO), Benoît+ (2021, JOSA B), bottom: CHARA: The Observatories of the Carnegie Institution, CHARIOT: Alyssa V. Mayer, see also: Mayer+(2024, SPIE), Scott+(2024, AAS), group picture: Gail Schaefer

Nulling Interferometry

Destructive interference of star light (on-axis) by adding a **phase shift**.
Goal: high contrast imaging of faint objects (dust, exoplanets) **close to the host star.**



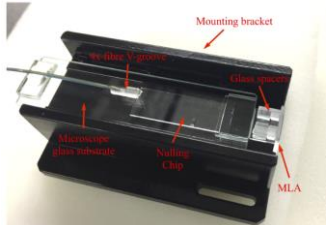


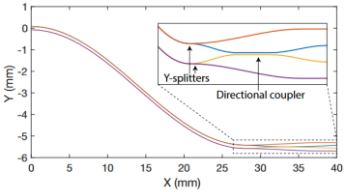
Images taken from: Lagadec T, Norris B, Gross S, et al. "The GLINT South testbed for nulling interferometry with photonics: Design and on-sky results at the Anglo-Australian Telescope." Publications of the Astronomical Society of Australia. 2021;38:e036. doi:10.1017/pasa.2021.29.

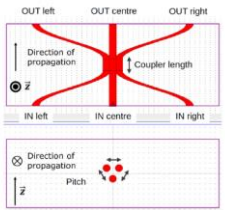
More information on nulling: Bracewell RN (1978) "Detecting nonsolar planets by spinning infrared interferometer". Nature 274:780–781. J. R. P. Angel and N. J. Woolf: "An Imaging Nulling Interferometer to Study Extrasolar Planets." 1997, ApJ 475 373, DOI 10.1086/303529. Examples with free-space optics: Keck interferometer, LBT. See also Palomar Fiber Nuller (PFN): Mennesson+ (2011, APJ), Hanot+(2011, APJ), Serabyn+ (2019,MNRS)

Astrophotonics for Nulling Interferometry

GLINT

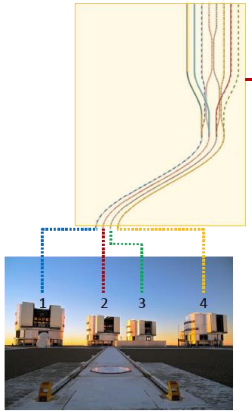


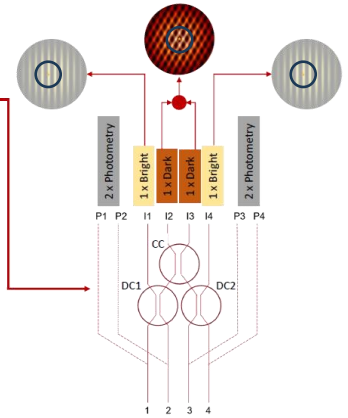




- H-band (~1550 nm) at Subaru (GLINT South at AAT).
- Photonic nuller: ULI in boro-alumino-silicate glass.
- Photonic 3D tricoupler and phase shifter.

NOTT





- L'-band (3.5 - 4 µm) nulling interferometer for ASGARD at VLTI.
- Photonic nuller: ULI in Gallium-Lanthanum-Sulphide (GLS) glass.

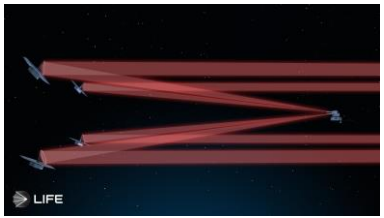
Fiber and **photonic-lantern** based nulling technologies

- Palomar Fiber Nuller (PFN)
- Vortex fiber nulling
- Mode-selective photonic lanterns

See e.g. Mennesson+ (2011, APJ), Serabyn+ (2019,MNRS), Xin+(2022, APJ), Echeverri+(JATIS, 2023)

LIFE

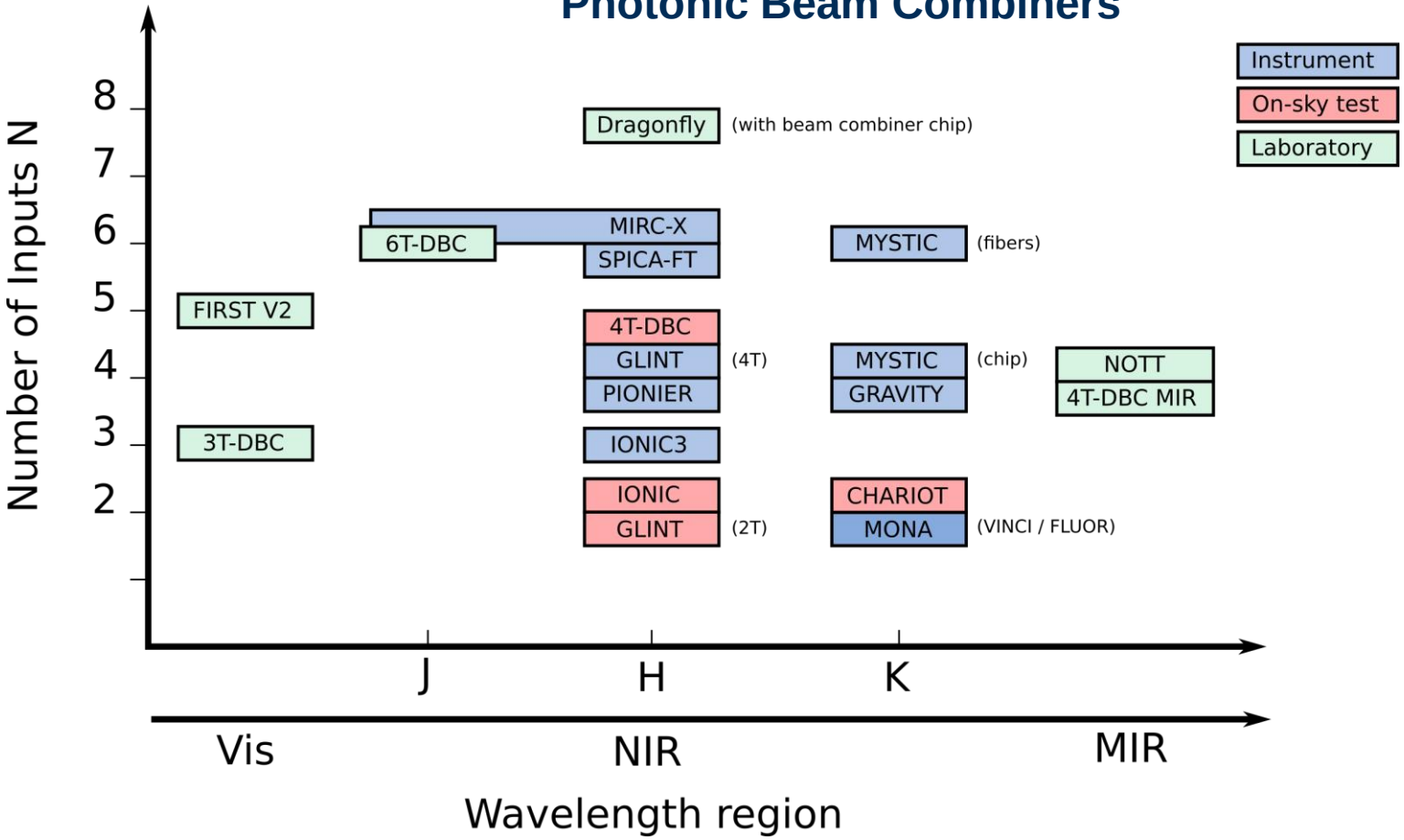
- Proposed space nulling interferometer.
- Mid-infrared (MIR), 4 -18.5 µm.
- Photonic beam combiner?
  →Technology development ongoing.



See e.g. Quanz+(2022, A&A), https://life-space-mission.com/

Images: (GLINT): Norris+ (2020, MNRS), right: Martinod+(2021, AO) and Klinner-Teo+(2022, JATIS). (NOTT): Sanny+(2022, SPIE 12183), see also: G. Garrau+(2024, JATIS). LIFE image from LIFE website

Photonic Beam Combiners



For more details and references, see Labadie (2022, SPIE), see also Dinkelaker (2024, SPIE)

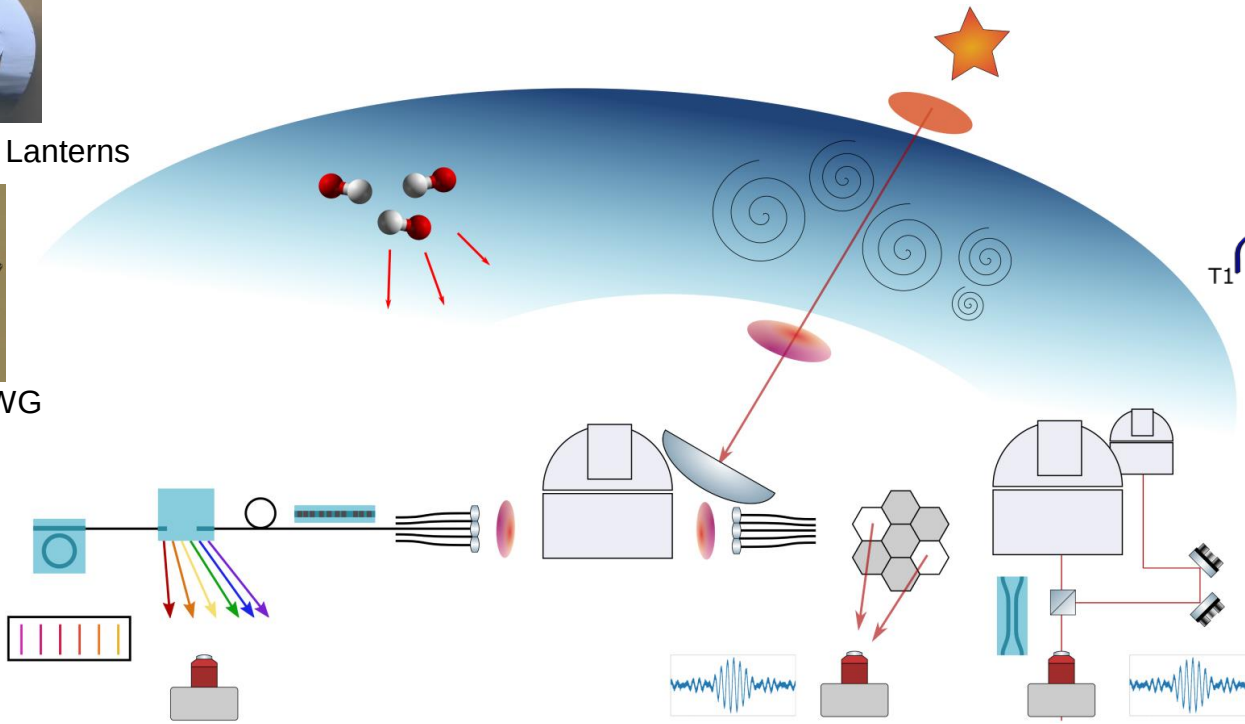
Summary

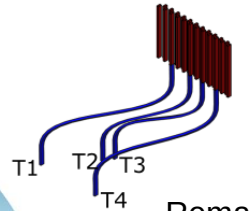
Chip and fiber-based photonic devices can be used in astronomical instrumentation to achieve high spectral resolution, high angular resolution, and high contrast.

Photonic Lanterns

Dispersers / AWG

References / Frequency Combs





Remappers

Beam Combiners

 Image credits (left to right): D. Bodenmüller, A. Stoll, A. Rahman, J. Rypalla, A. Nayak, A. Dinkelaker (AIP)

Outlook

Increased integration, e.g.

- Photonic integrated circuits (PIC) with multiple components
- Integration of detectors
- Compact cryo-cooled devices
- Active photonics

Overcoming challenges, e.g.

- Stable coupling and efficient interfacing
- Increase throughput
- Broadband operation
- Extend accessible wavelength range (explore materials and fabrication parameters)
- Deterministic and repeatable fabrication

JPhys Photonics

ROADMAP • OPEN ACCESS

2023 Astrophotonics Roadmap: pathways to realizing multi-functional integrated astrophotonic instruments

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– Hide full author list

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See also:

- *A.N. Dinkelaker: „Astrophotonic Technologies“ (2024), Proc. of SPIE 13095 (available on arxiv),*
- *M.M. Roth, K. Madhav, A. Stoll, D. Bodenmüller, A.N. Dinkelaker, A. Rahman, E. Hernandez, A. Günther, S. Vjesnica, "Astrophotonics: photonic integrated circuits for astronomical instrumentation“ (2023), Proc. SPIE 12424,*
- *S. Minardi, R. J. Harris, and L. Labadie, “Astrophotonics: astronomy and modern optics,” The Astronomy and Astrophysics Review, vol. 29, no. 1, p. 6, (2021),*
- *B. Norris and J. Bland-Hawthorn, “Astrophotonics: The Rise of Integrated Photonics in Astronomy,” OPN, vol. 30, no. 5 (2019),*
- *P. Gatkine et al. “State of the Profession: Astrophotonics,” Bulletin of the AAS, vol. 51, no. 7, (2019), https://baas.aas.org/pub/2020n7i285,*

and many more.

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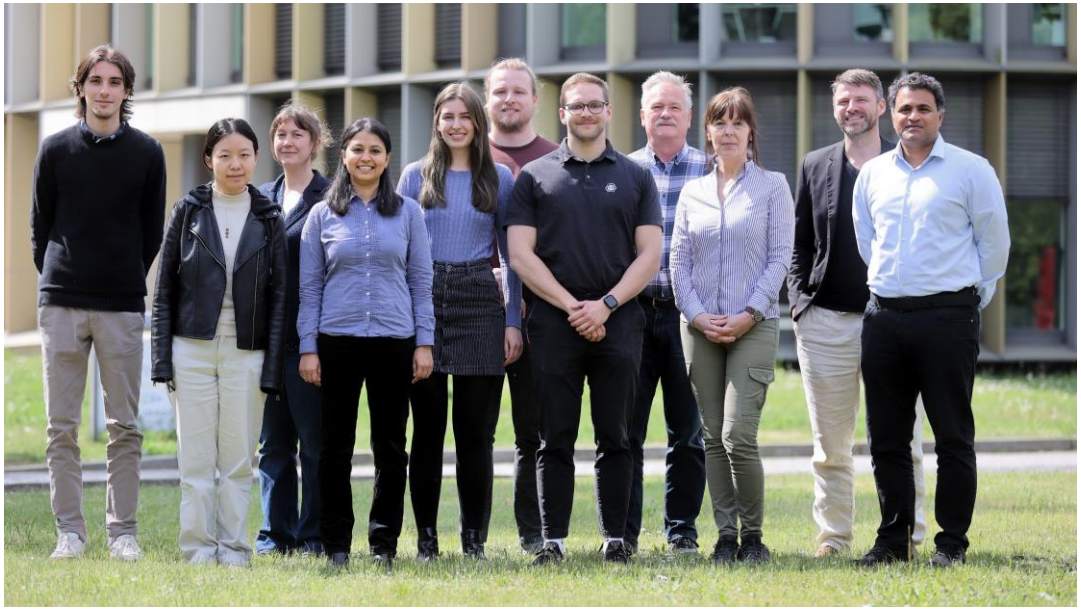

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Thank you