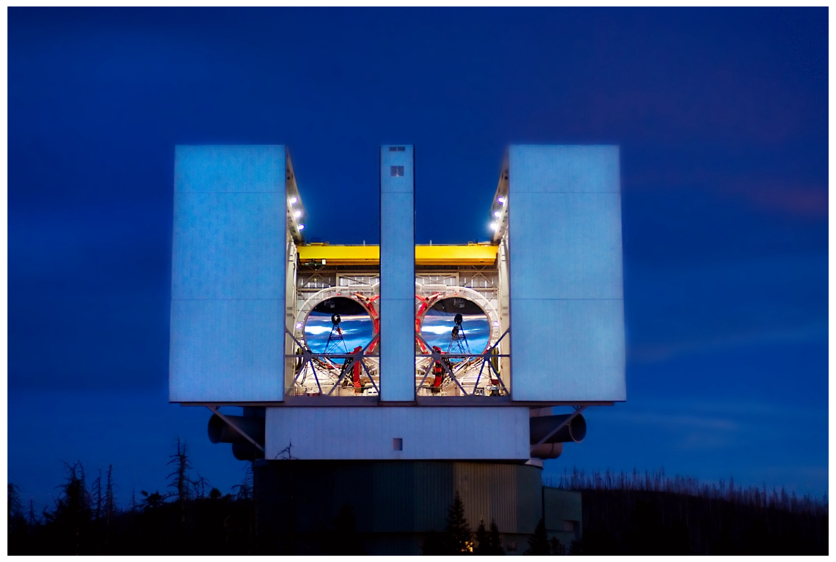
Nulling interferometry



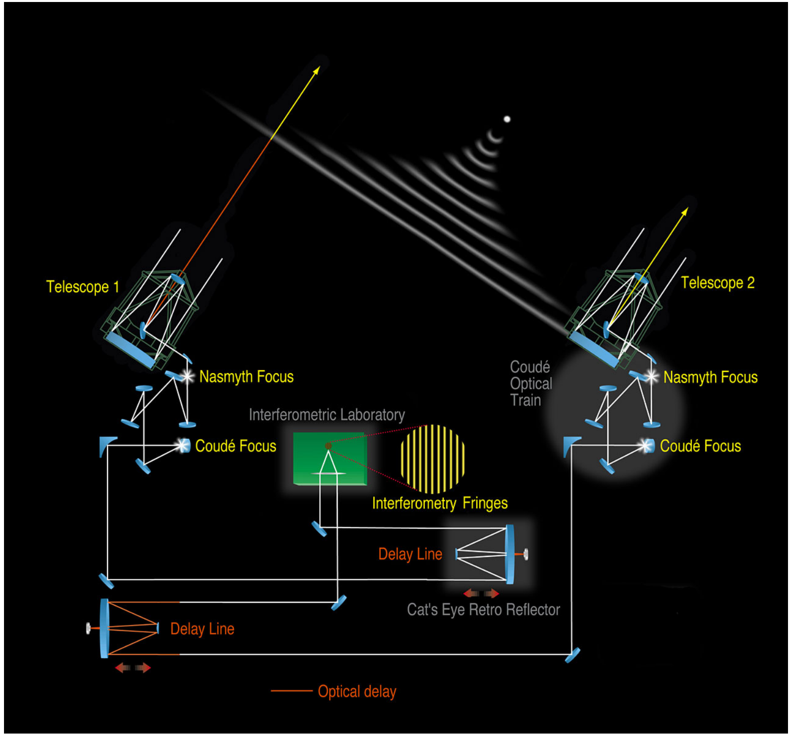
Denis Defrère
KU Leuven

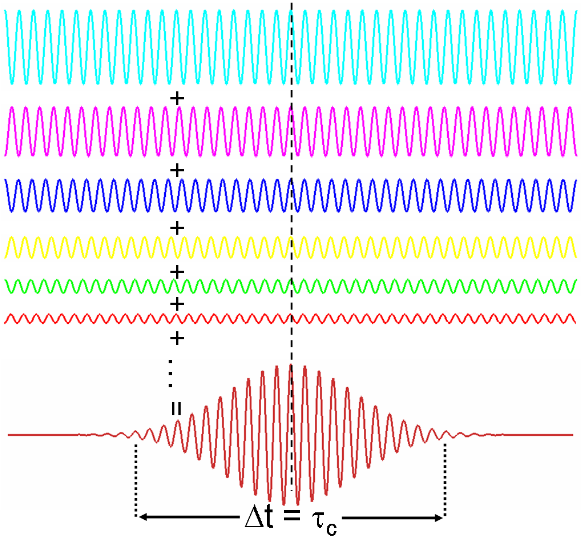
June 28th, 2024

Overview

- Principles of nulling interferometry
- Current and past nulling interferometers
- Science with nulling interferometers
- Space nulling interferometers: concepts and science
- Summary

Principles of interferometry





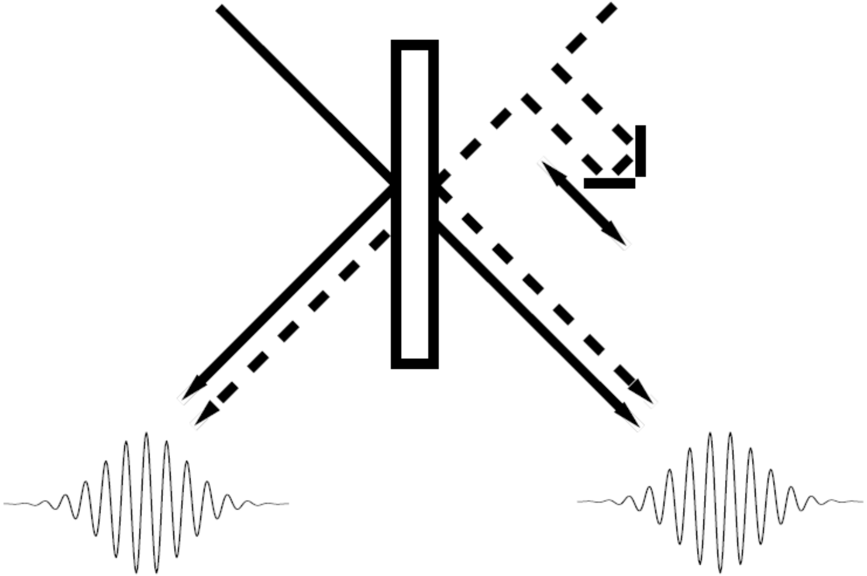
Coherence time = $\Delta t = \frac{\lambda^2}{c\Delta\lambda}$

Coherence length = $L = \frac{\lambda^2}{\Delta\lambda}$

Image credit: ESO

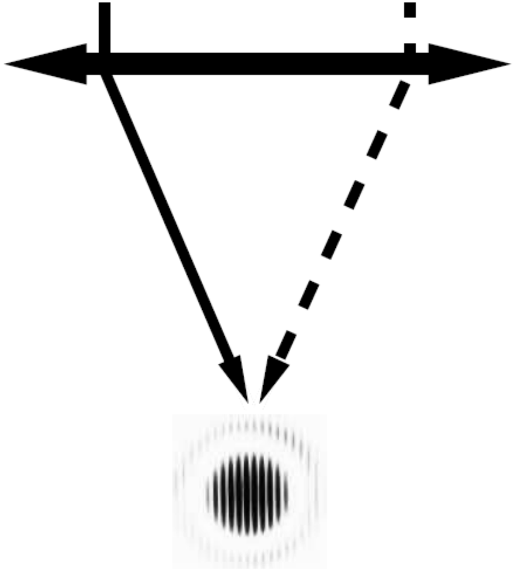
Principles of interferometry

Coaxial
(pupil plane combination)



temporal fringes

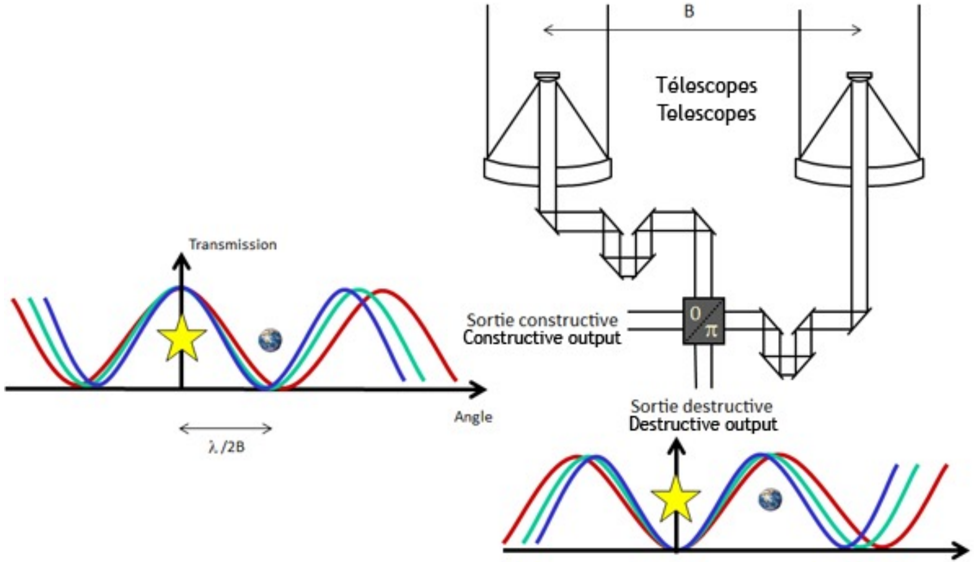
Multiaxial
(image plane combination)



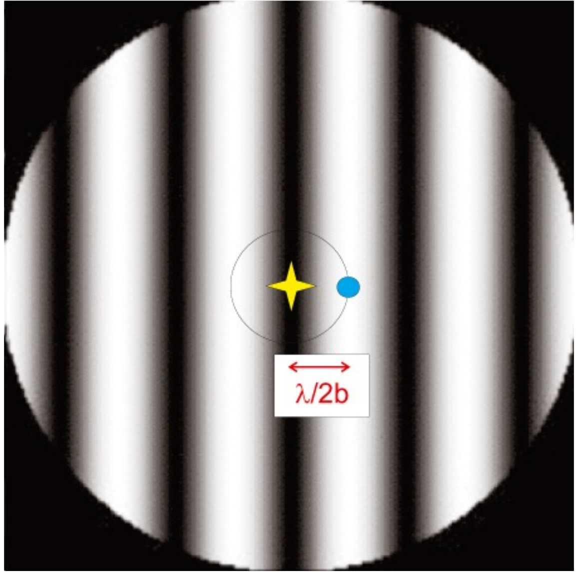
spatial fringes

Principles of nulling

- First proposed by Bracewell in 1978 to image non-solar planets with a rotating nuller (Nature, 274, 1978):



Transmission map (2T)

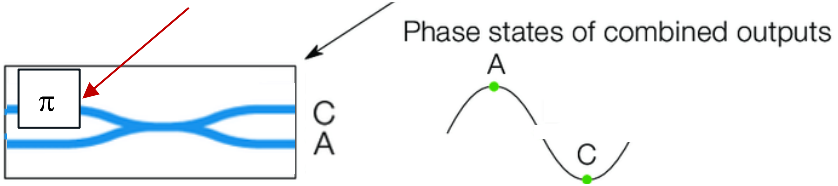


Principles of nulling

- First proposed by Bracewell in 1978 to image non-solar planets with a rotating nuller (Nature, 274, 1978):

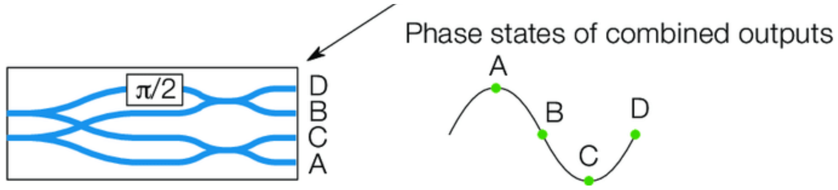
AC (Nulling)

Achromatic!

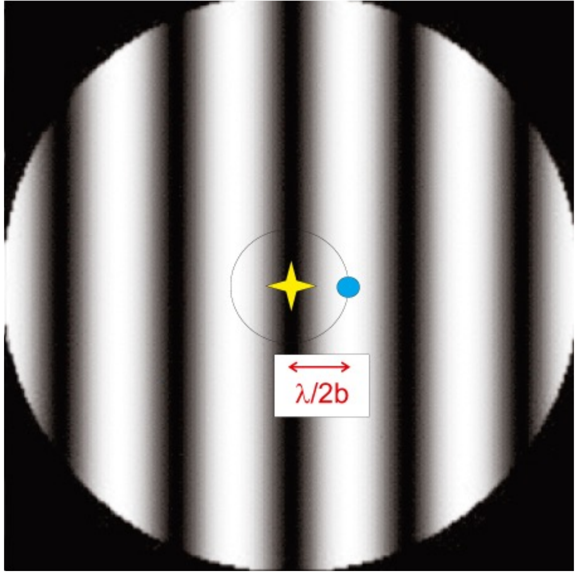


FT keeps the phase here

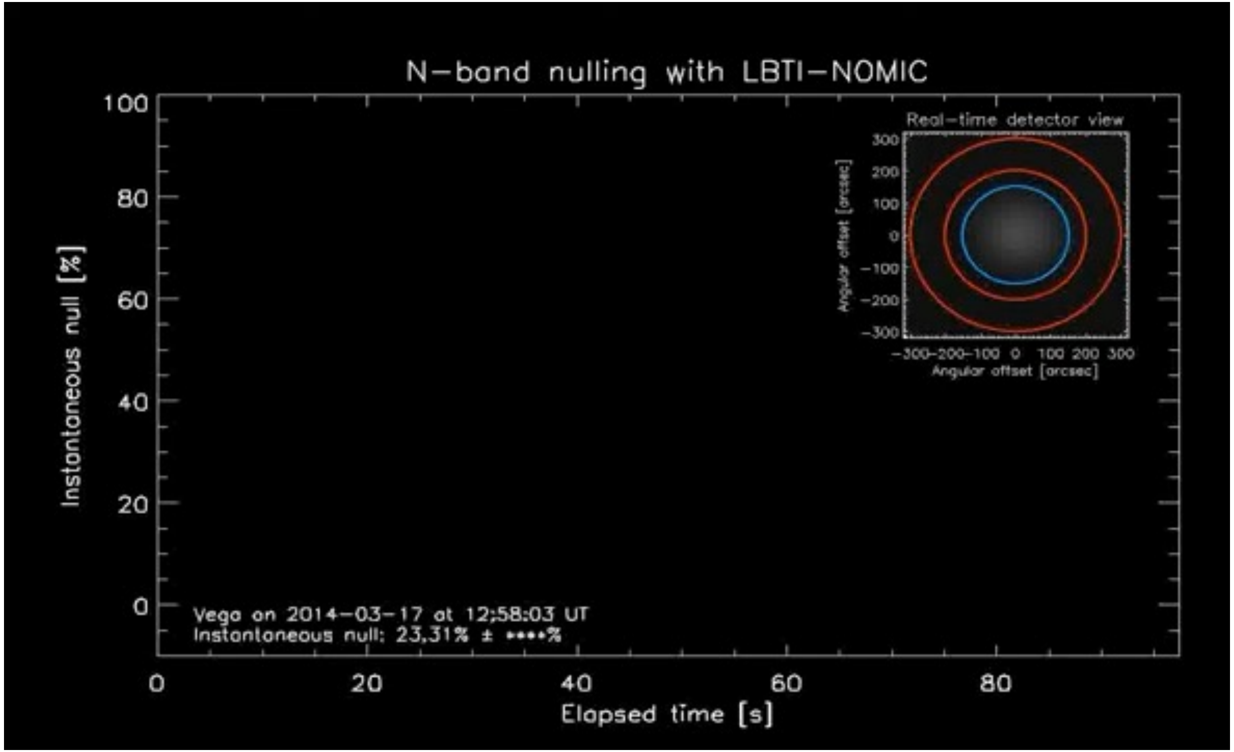
ABCD (e.g., GRAVITY)



Transmission map (2T)



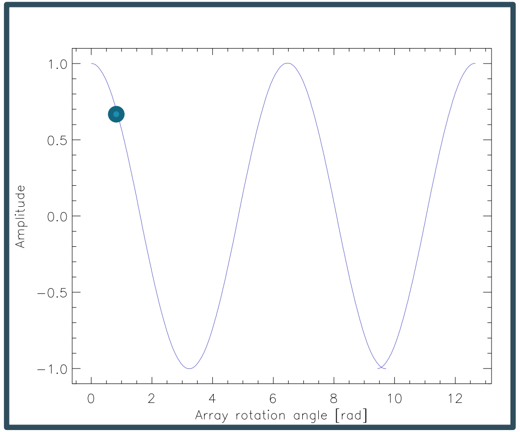
Example of closed-loop nulling at the LBTI



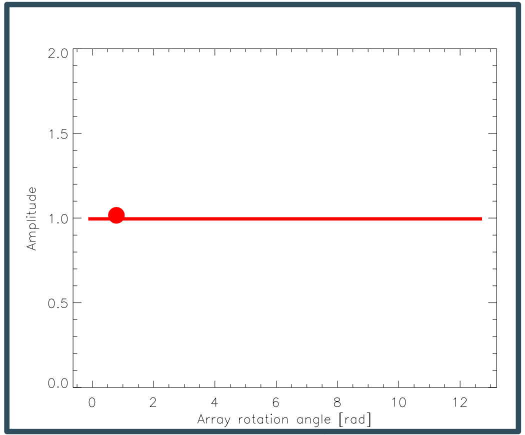
https://www.youtube.com/watch?v=WdZEjOtqVmM

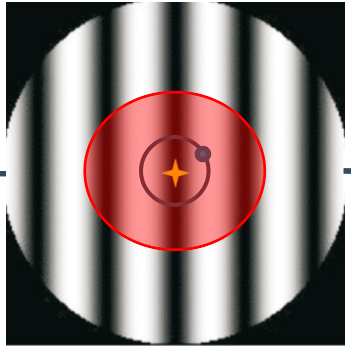
Bracewell 1978: “*a rotating nulling interfertometer to detect non-solar planets*”

Signal modulation



No signal modulation





Planet signal

Symmetric sources
(e.g., star, disk)

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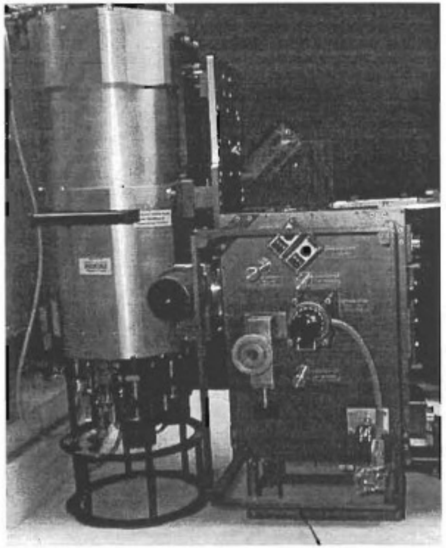
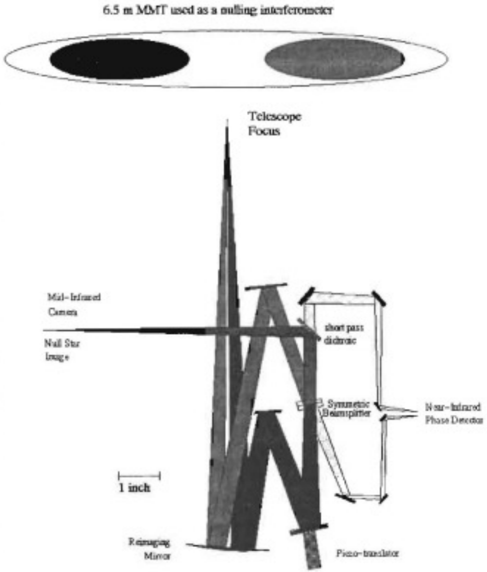
First generation: MMT

- First on-sky telescope implementation by Hinz et al. in 1998 on the Multiple Mirror Telescope in Arizona (Hinz et al., Nature, 395, 1998):



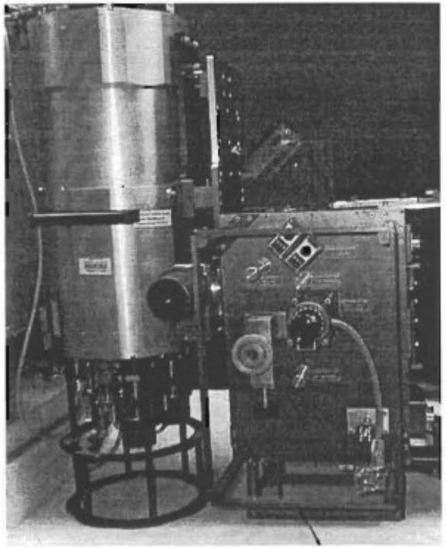


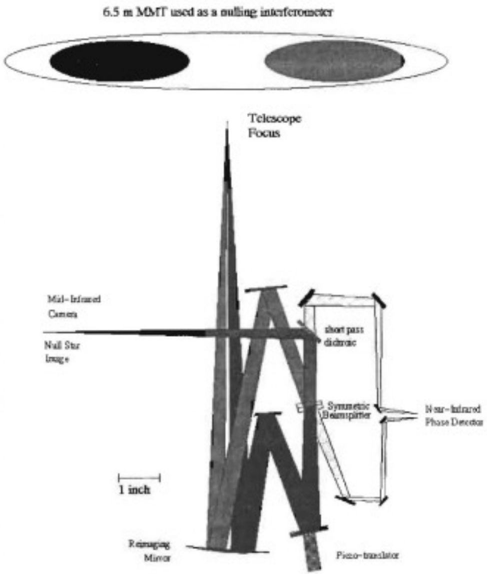
Optical layout of the Bracewell Infrared Nulling Cryostat (BLINC)

Multiple Mirror Telescope – Mount Hopkins (Arizona)

First generation: MMT

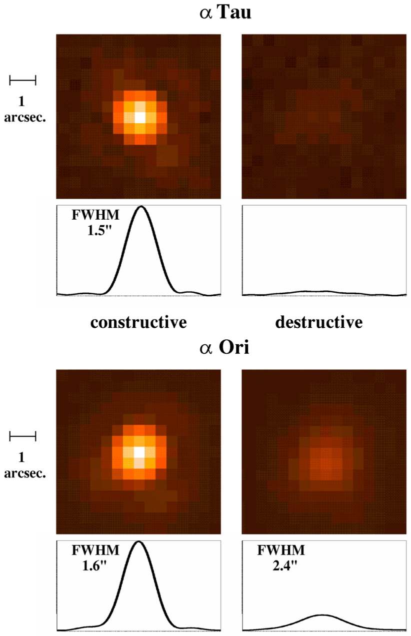
- First on-sky telescope implementation by Hinz et al. in 1998 on the Multiple Mirror Telescope in Arizona (Hinz et al., Nature, 395, 1998):





Optical layout of the Bracewell Infrared Nulling Cryostat (BLINC)

single 50 msec. exposures with 10 µm camera



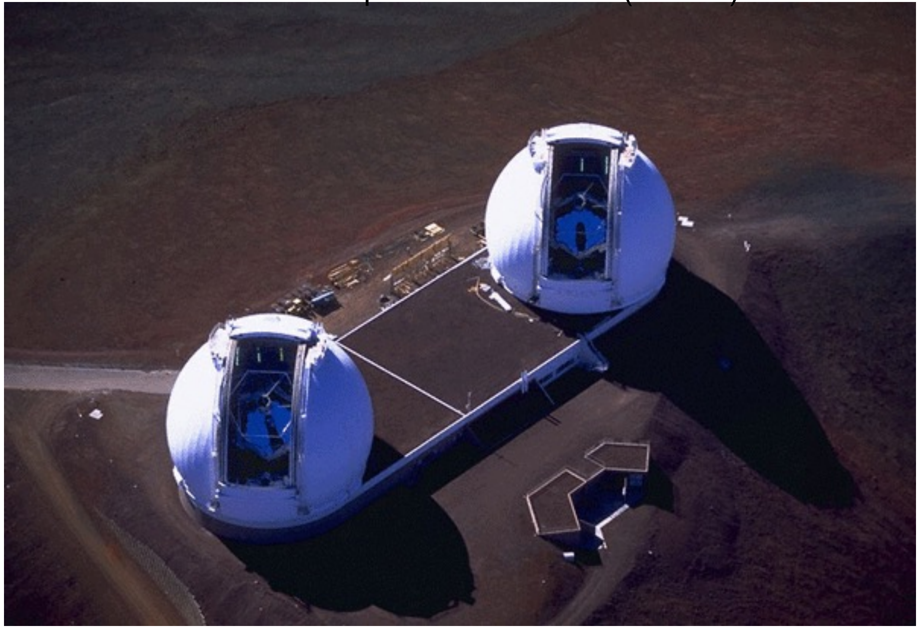
For unresolved star, destructive/ constructive peak ratio = 0.04

For α Ori, peak ratio = 0.18
Residual flux is a direct thermal image of the extended dust nebula

Second generation: Keck Nuller

- First telescope implementation of a four-beam interferometric nuller (Colavita et al. 2010, Serabyn et al. 2012);

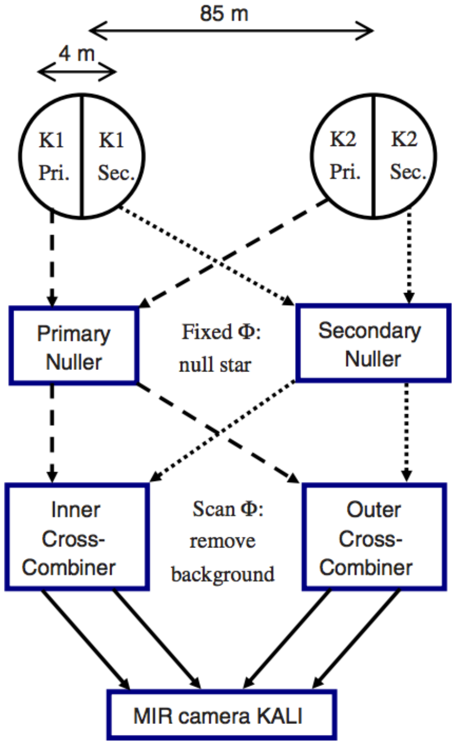
Keck telescopes – Mauna Kea (Hawaii)

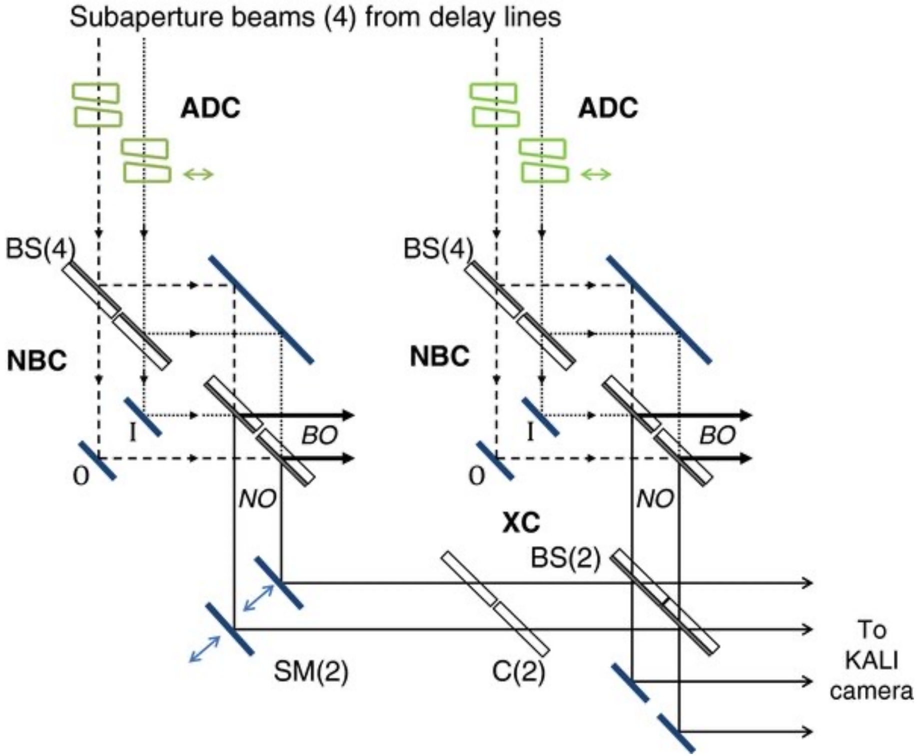


Key instrumental features:

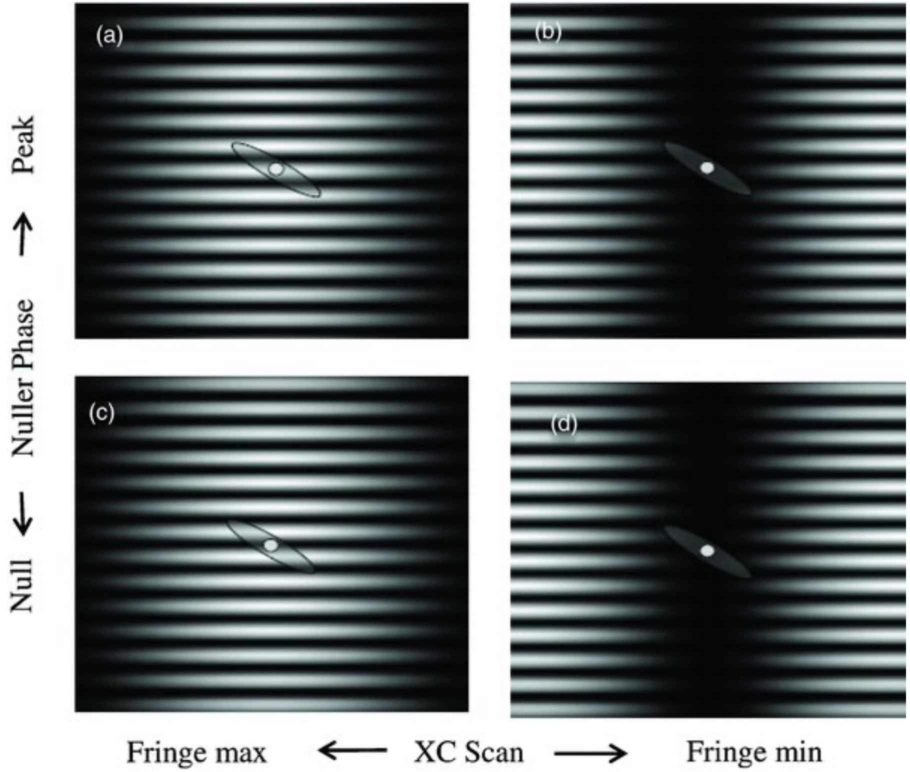
- Waveband: N (8 to 13 microns)
- Spectral resolution: 20 (providing 10 spectral channels across the N band)
- Spatial resolution 10 mas at 8 microns to 15 mas at 13 microns (defined as the nuller's 50% transmission point)
- Sensitivity of 1.5 Jy at 10 microns
- Effective field of view: 0.4″ x 0.1″ (in radius)

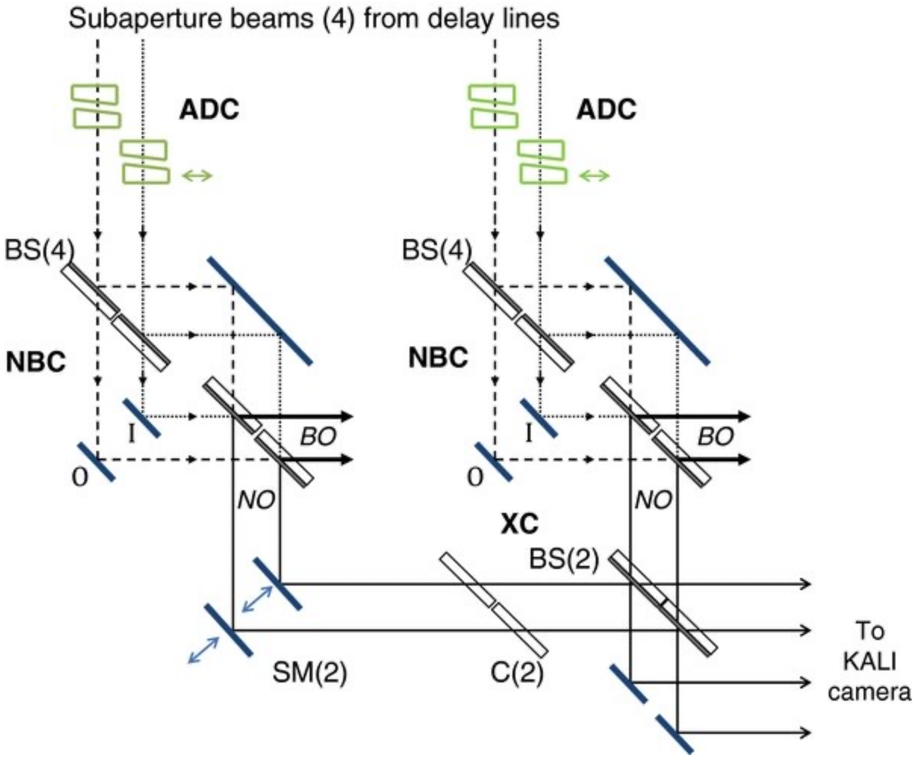
Second generation: Keck nuller





Second generation: Keck nuller





Third generation: LBTI nuller

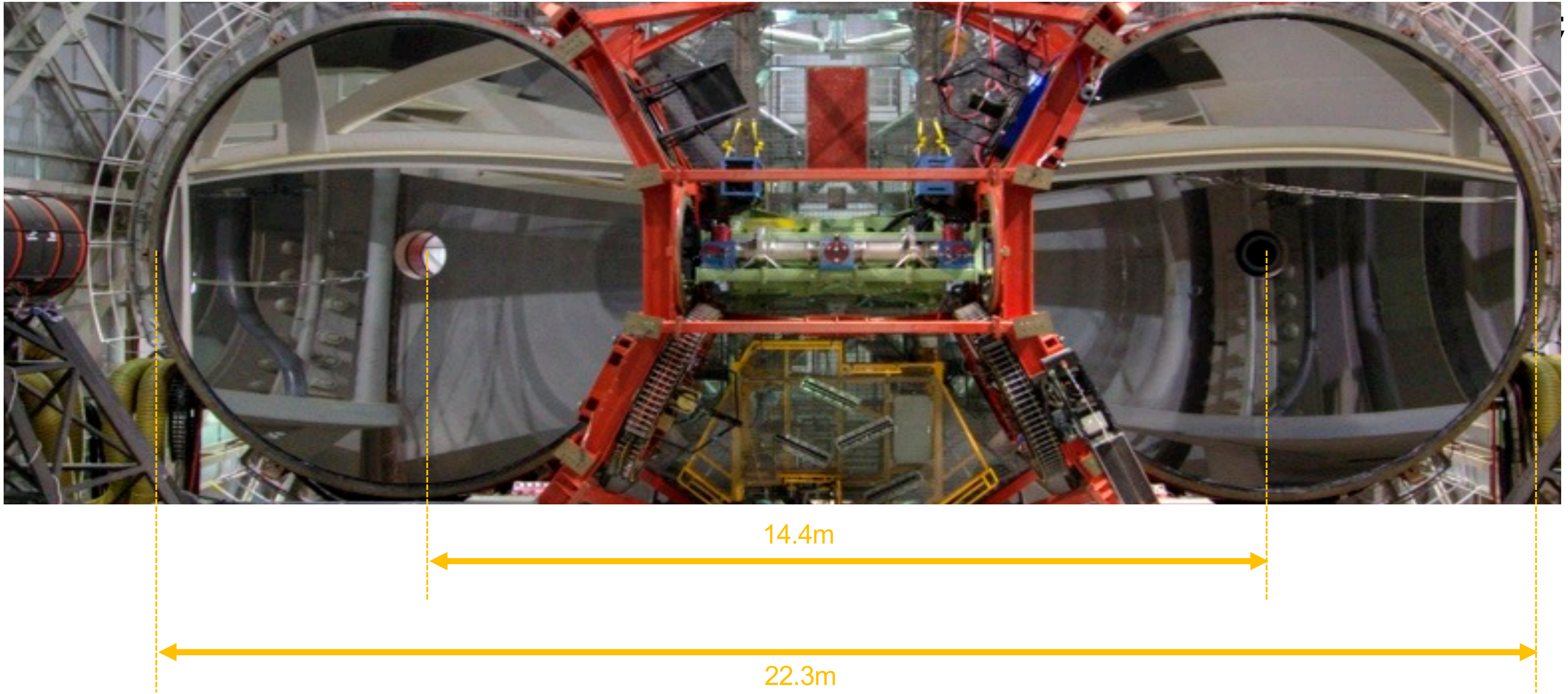
The Large Binocular Telescope Interferometer (LBTI, Hinz et al. 2016, Ertel et al. 2020);

Large Binocular Telescope – Mount Graham (Arizona)

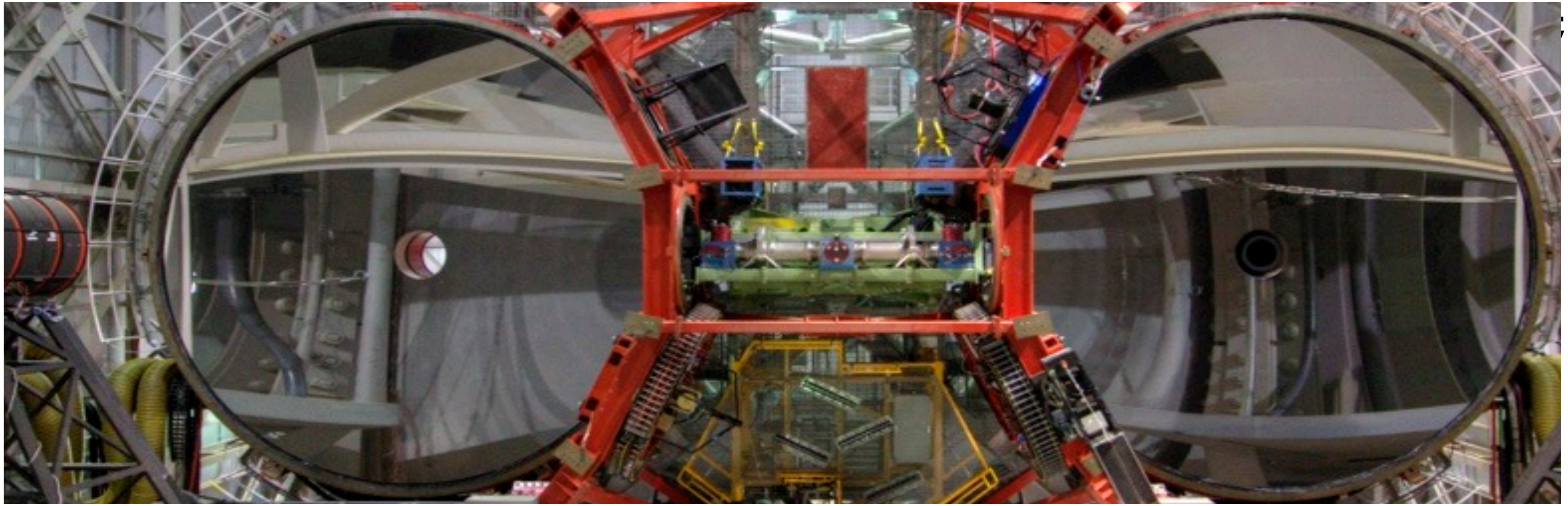
Key instrumental features:

- Waveband: N (8 to 13 microns)
- Spectral resolution: broadband (grism R=100 not commissioned for nulling)
- Spatial resolution: 60 mas at 8 microns to about 100 mas at 13 microns (defined as the nuller’s 50% transmission point)
- Sensitivity of 0.8 mJy at 10 microns (5σ in 1 hour)
- Effective field of view: 18” x 18”

Third generation: LBTI nuller



Third generation: LBTI nuller

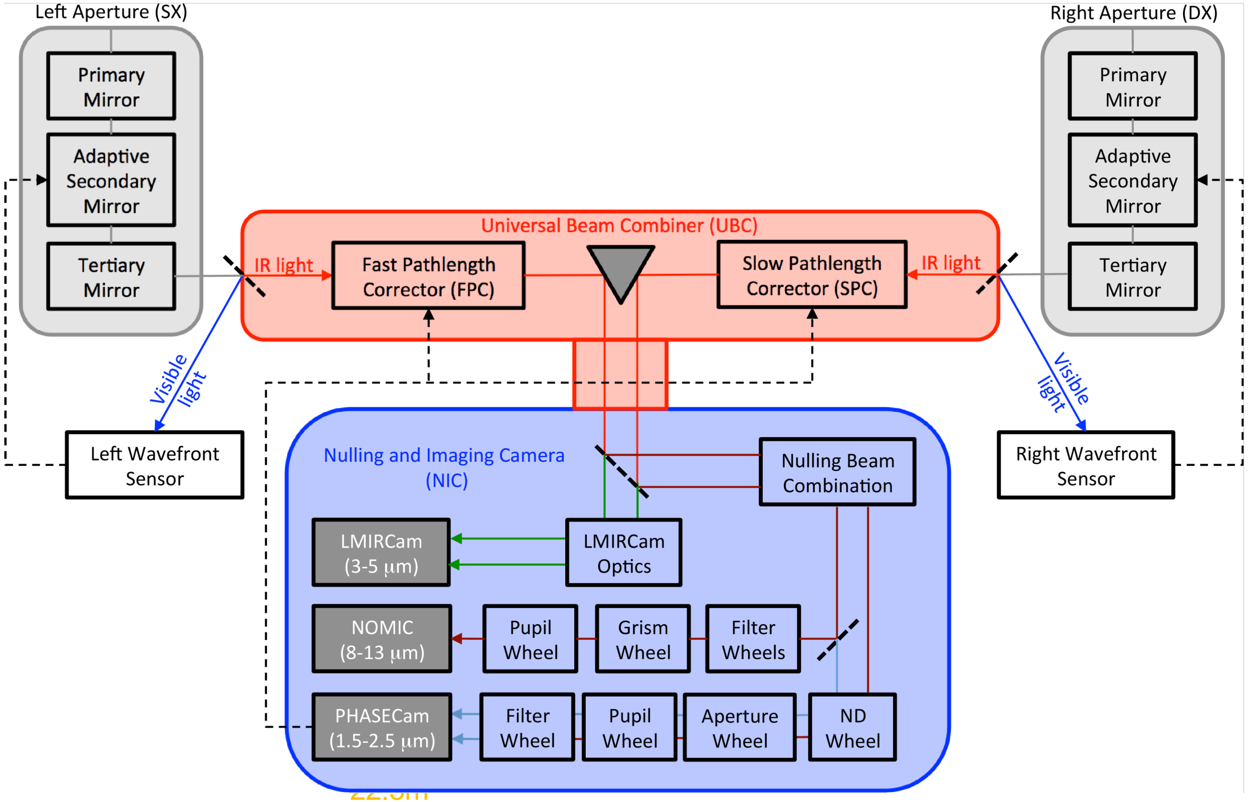


Resolution
Beam combination provides the equivalent resolution of a 22.7-m telescope.

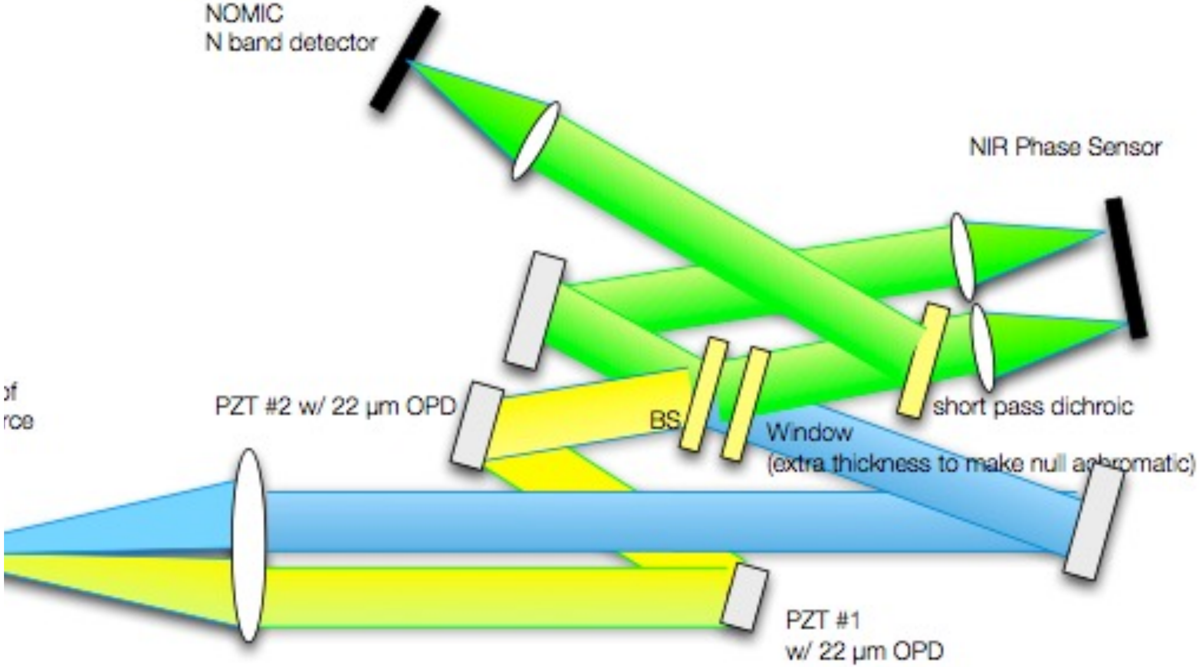
High Contrast
The AO system creates an image with a Strehl of >90% at 3.8 µm.

Sensitivity
LBT has two 8.4-m mirrors mounted on a single structure (collecting area of a single 11.8-m aperture)

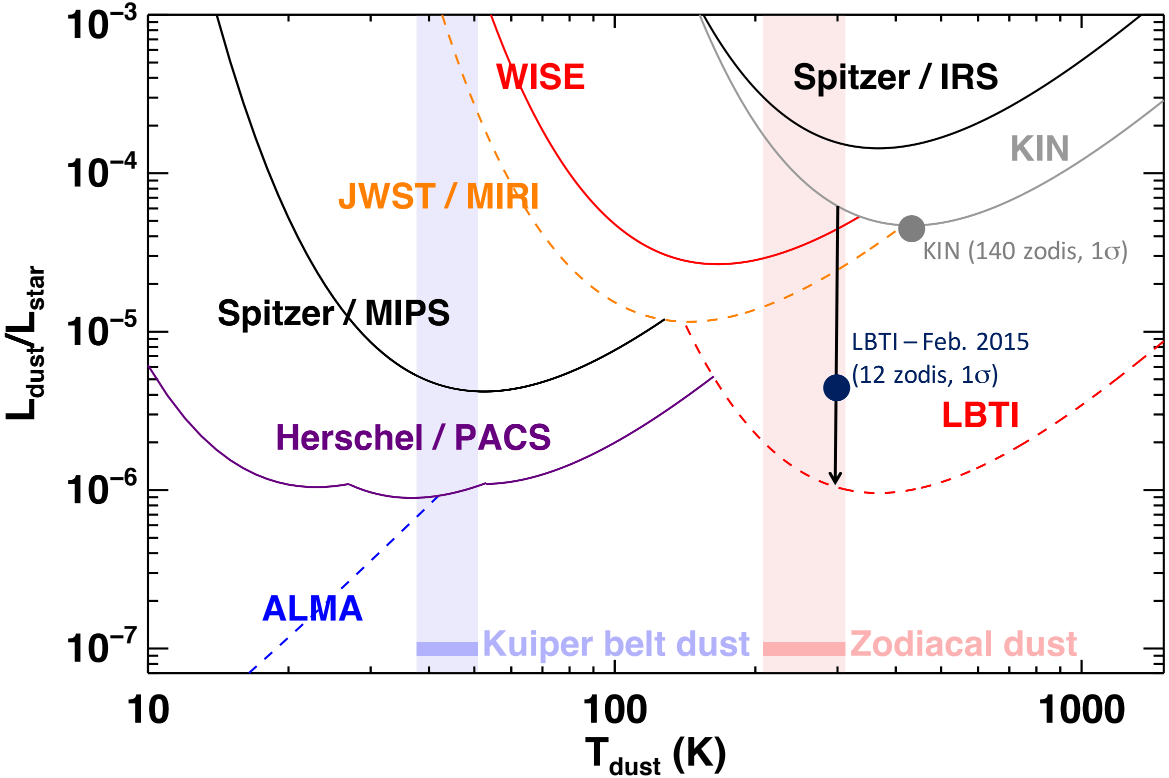
Third generation: LBTI nuller



Third generation: LBTI nuller



Third generation: LBTI nuller

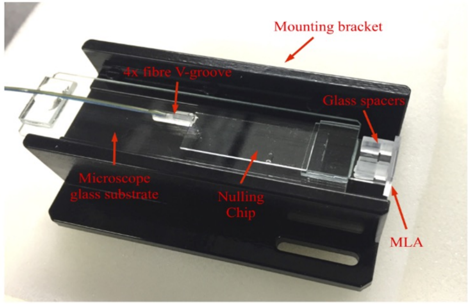


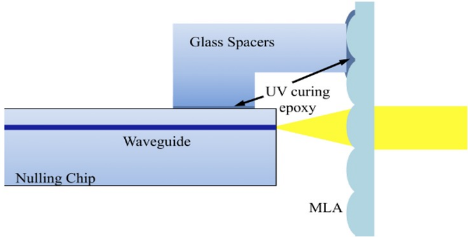
Single-aperture nulling experiments

- Palomar Fiber Nuller (PFN): K band (2.2 microns), multi-axial combination, fiber injection (Mennesson et al. 2011)

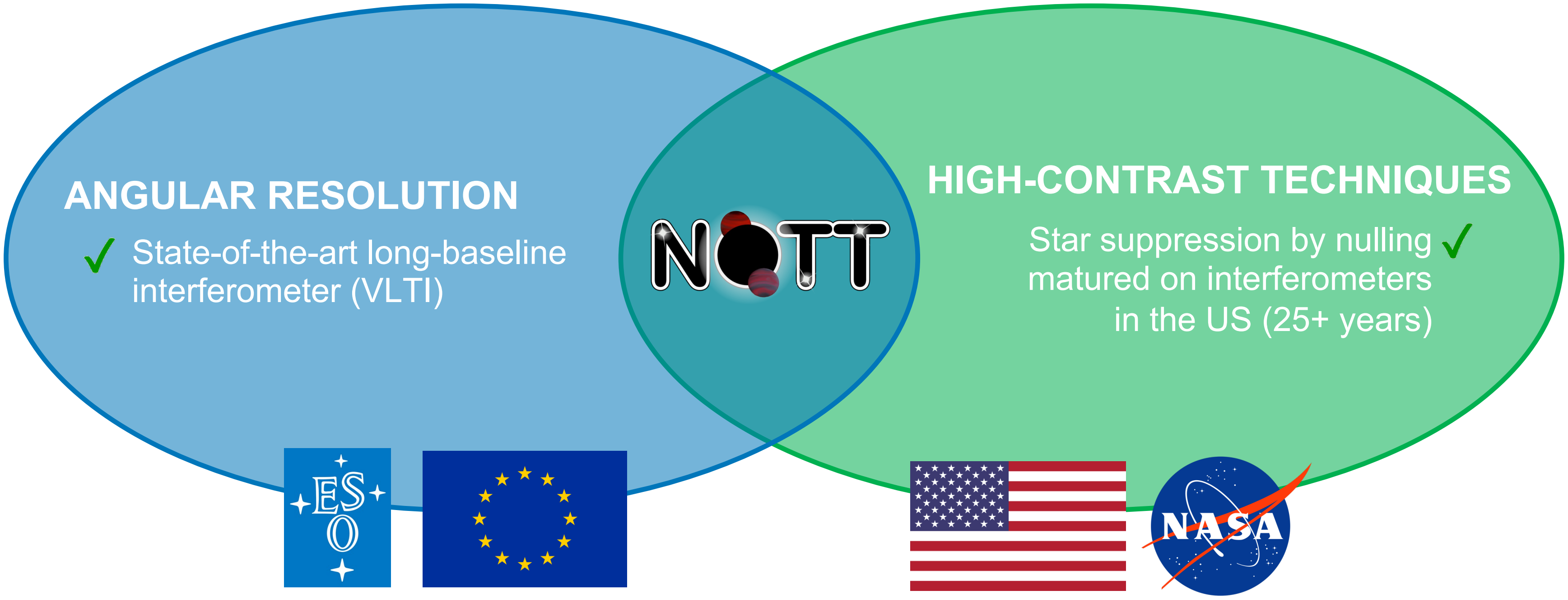
- GLINT @ SCExAO: H band (1.6 microns), first on-sky photonic nuller (Norris et al. 2019)

Subaru telescope (left) – Mauna Kea (Hawaii)





Next-generation: Asgard/NOTT



ANGULAR RESOLUTION

✓ State-of-the-art long-baseline interferometer (VLTI)

HIGH-CONTRAST TECHNIQUES

Star suppression by nulling ✓ matured on interferometers in the US (25+ years)

Next-generation: Asgard/NOTT

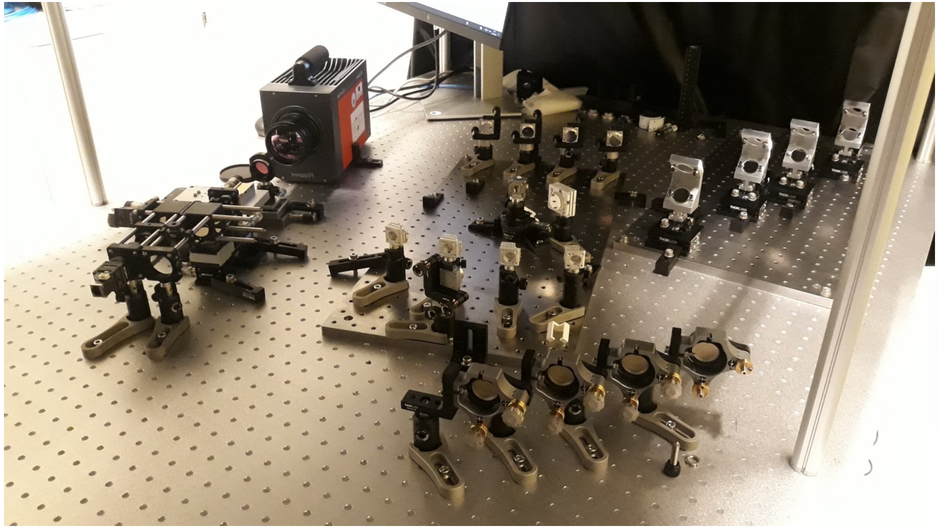
Cerro Paranal (Chile)

Recommended as visitor instrument in June 2023 (Defrère et al. 2018, 2022, 2024)

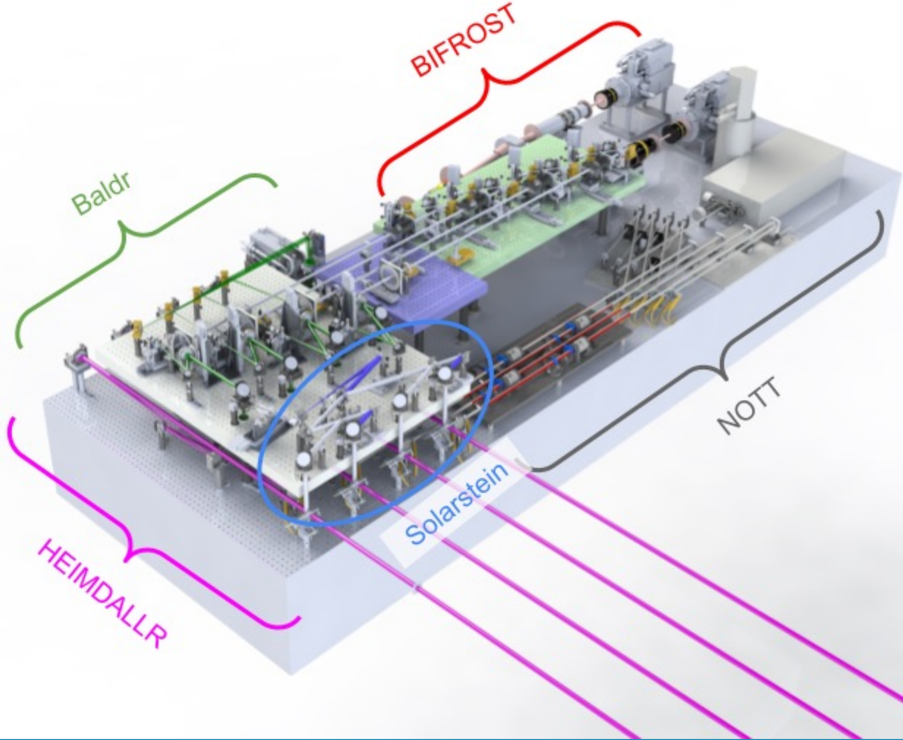
Key instrumental features:

- Waveband: L’ (3.5 to 4 microns)
- Spectral resolution: 40, 200
- Spatial resolution: 2 mas with 200m baseline (defined as the nuller’s 50% transmission point)
- Effective field of view: ~100mas (UT), ~400mas (AT)

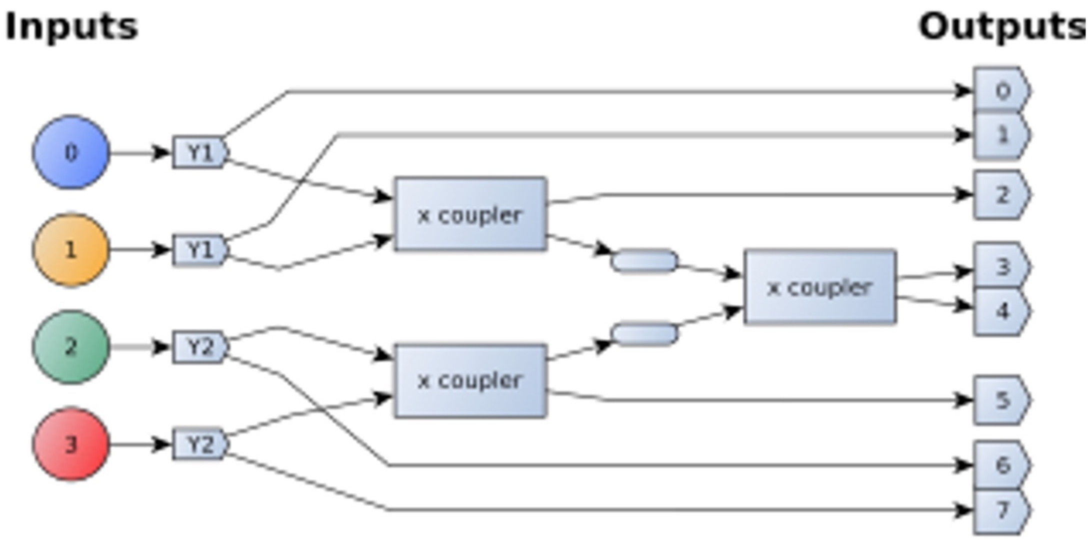
Next-generation: Asgard/NOTT

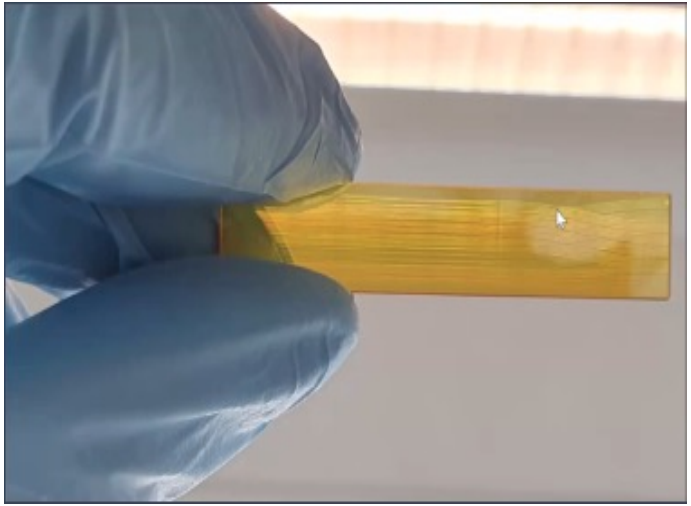


First warm nulls in 2024 (Garreau et al. 2024)



Next-generation: Asgard/NOTT

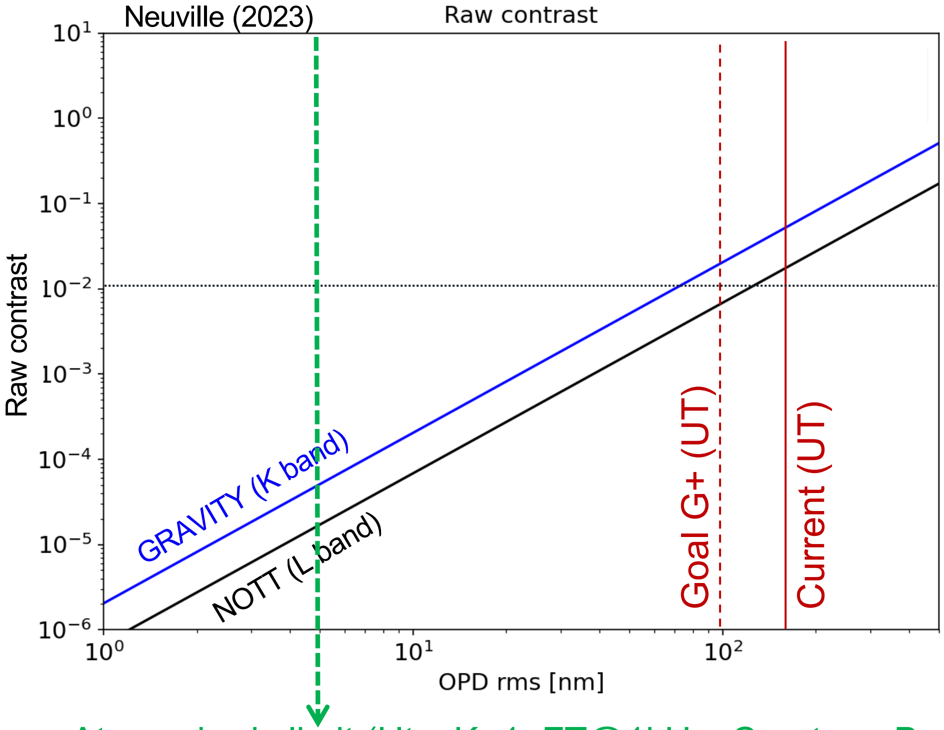




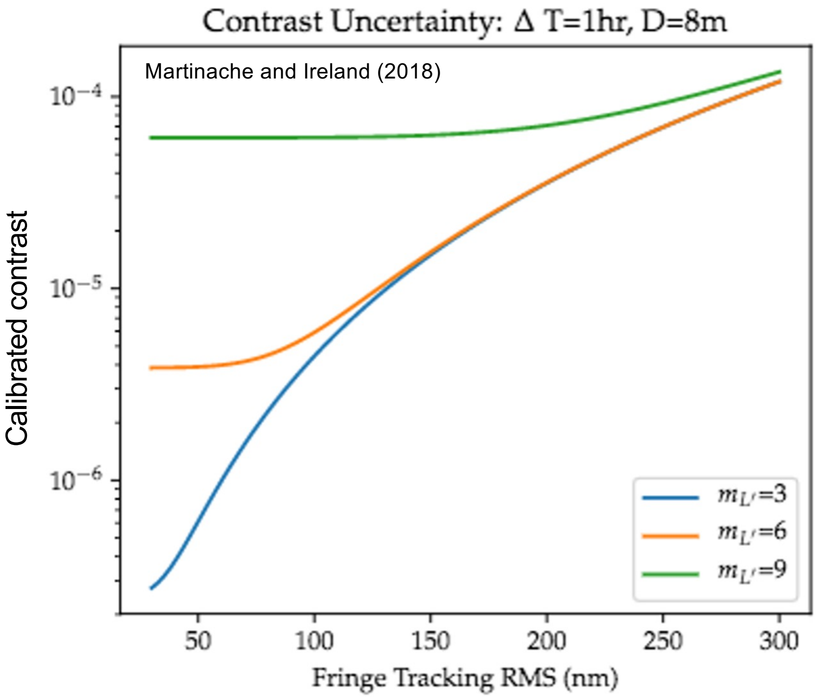
GLS (developped at Macquarie University and tested at Univerity of Cologne). Prototype also manufactured in $LiNbO_3$ and SiO

	KIN	LBTI	PFN	NOTT
Separate telescopes?	Yes	Yes	No	Yes
Number of beams	4	2	2	4
Common telescope mount?	No	Yes	Yes	No
Interferometric mode	Michelson	Michelson	Fizeau	Michelson
Baseline rotation?	Earth rotation	Earth rotation	Unrestricted baseline rotation	Earth rotation
Long Delay lines?	Yes	No	No	Yes
Waveband	MIR N-band	MIR N-band	NIR Ks-band	L'-band
Fringe tracking	Shorter (NIR) wavelengths	Shorter (NIR) wavelengths	Extreme (VIS) AO system	Shorter (NIR) wavelengths
Modulation	Phase scan	Spatial nodding	Chopper wheel	Phase scan
Calibration	Reference stars	Reference stars	Reference stars only needed below ~ 10-3	Reference stars
Beam combiner geometry	Co-axial	Co-axial	Multi-axial	Co-axial
Beam combining element	Dual beamsplitter	Single beamsplitter	Single-mode fiber	Integrated optics
Dispersion compensator	Glass	Glass	Glass	Glass + gas cell
Dispersion compensator phase shift	pi	p/2	p	p
Disp. comp. glass shape	Wedges	Flat	Chevron	Wedges
Glass thickness modulation	Translation	Static	Rotation	Rotation
Spatial filtering	Pinhole	Aperture photometry	Single-mode fiber	Integrated optics
Number of spectral channels	~ 10	1	1	5
Data product	Fringe scan intensities	Images	Single-mode intensity measurements	Single-mode intensity measurements
Data reduction	Visibility determination	Null self-calibration	Null self-calibration	Null self-calibration
Null accuracy	**10^{-3}**	**10^{-4}**	**10^{-4}**	**10^{-5} (goal)**
Dominant noise terms	**Thermal background**	**Thermal background & low frequency detector noise**	**Phase fluctuations and variable dispersion effects**	**Phase fluctuations and variable dispersion effects**

Nulling at the VLTI



Atmospheric limit (Uts, K=1, FT@1kHz, Courtney-Barrer et al. 2022)



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Highlights from the KIN

- Evolved stars with known dust: RS CrB and TU Tau (Mennesson et al. 2005)
- Evolved stars with suspected dust: X Gem and RS Oph (Barry et al. 2008)
- Young debris disks (e.g., Stark et al. 2009)
- Young stellar objects (Mennesson et al. 2012)
- Exozodiacal disks:
  - Individual stars: Fomalhaut (Lebreton et al. 2013, Mennesson et al. 2013, eta Crv (Defrère et al. 2015), eta Crv (Lebreton et al. 2016)
  - Survey results (Millan-Gabet et al. 2011, Mennesson et al. 2014)

Exozodiacal dust

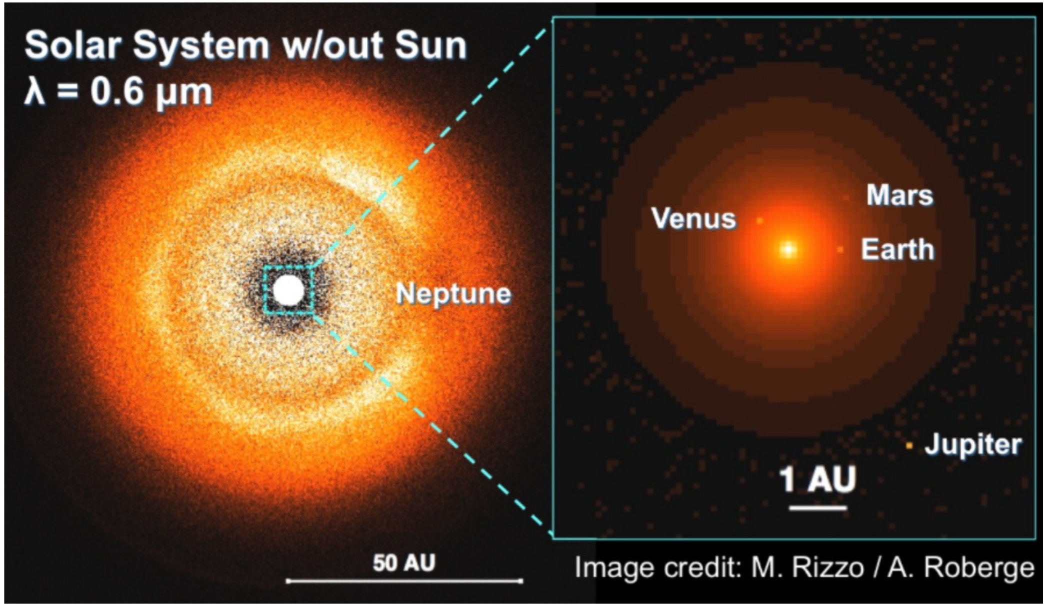
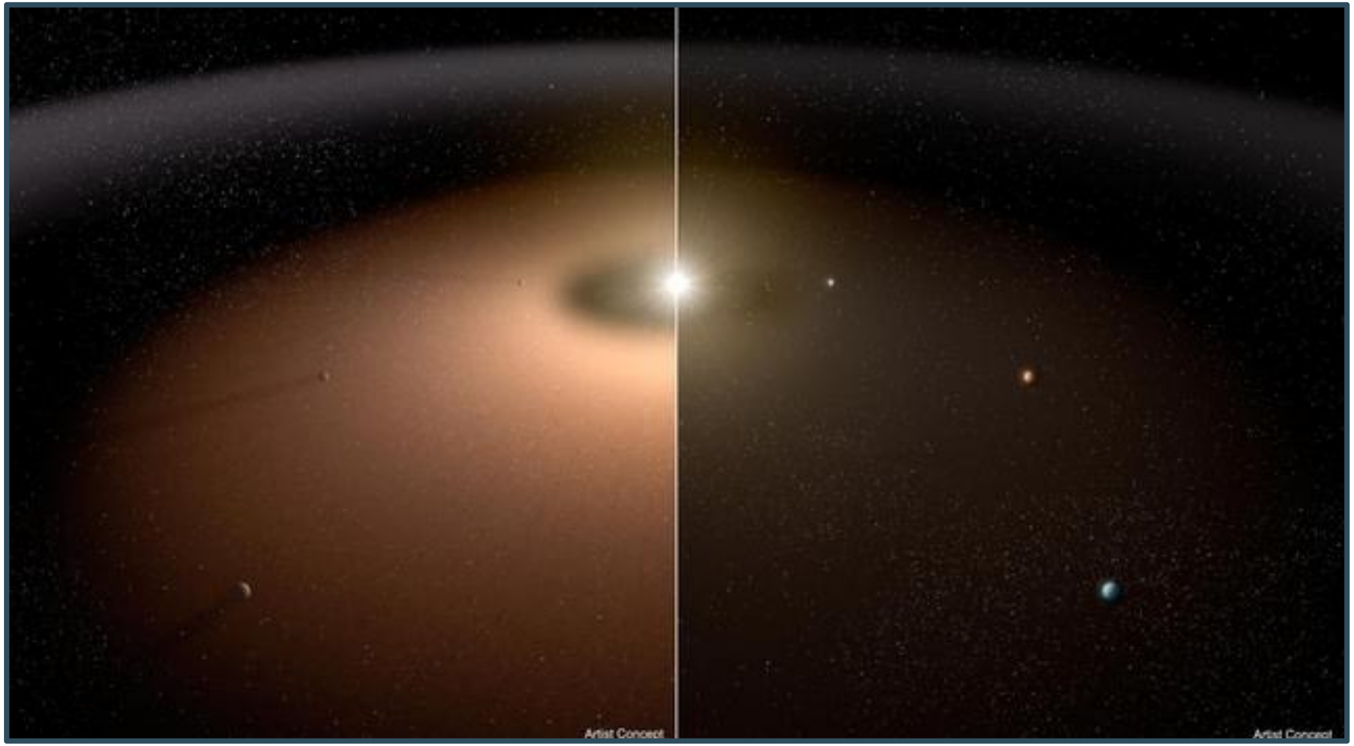


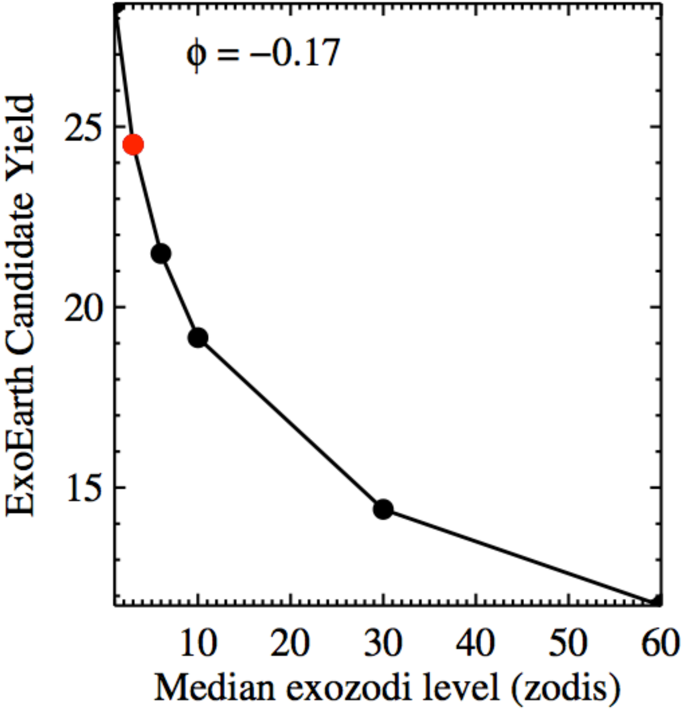
Image credit: M. Rizzo / A. Roberge

- Dust inside a few AU
- Temperature: a few 100K to 2000K (Kimura & Mann 1998, Hahn et al. 2002)
- Comet evaporation (Nesvorny et al. 2010)
- Asteroid collision & P-R drag (Dermott et al. 2002)
- Complex local structure (planetary interaction, local dust creation)

Exozodiacal dust



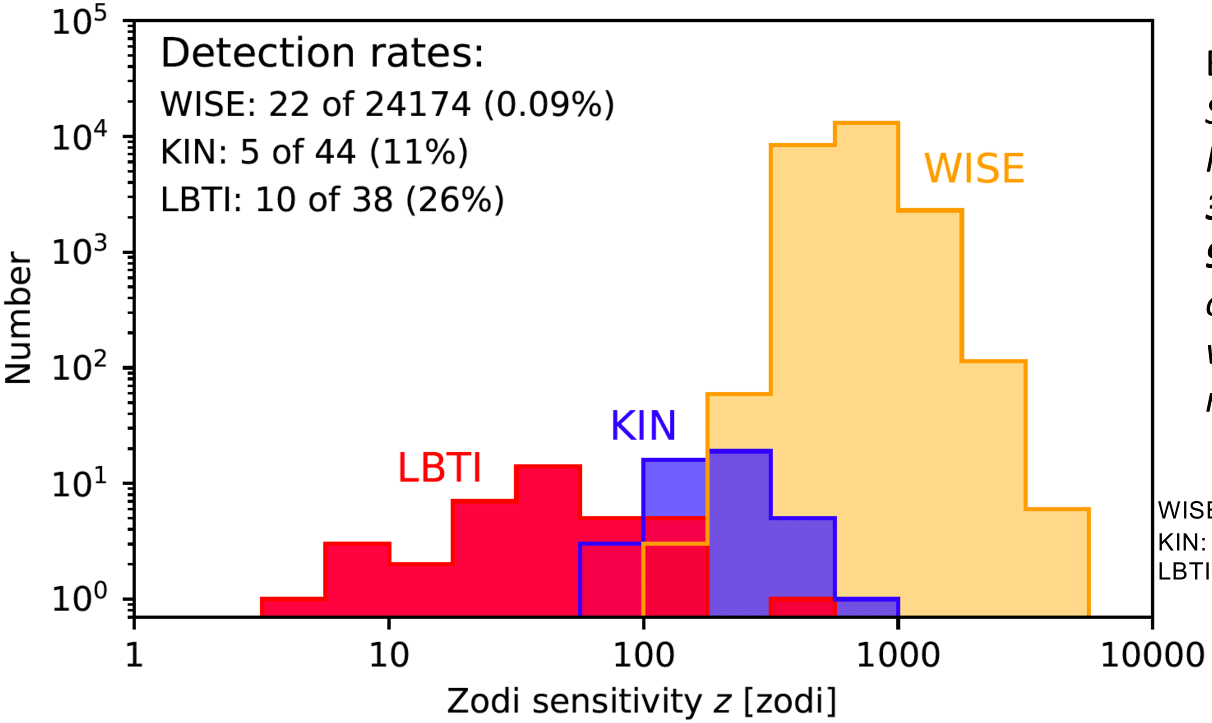
Exozodiacal dust



Reduce exozodi by 10x, increase yield by ~ 2x

Stark et al., 2014, 2015

Prevalence of exozodiacal dust

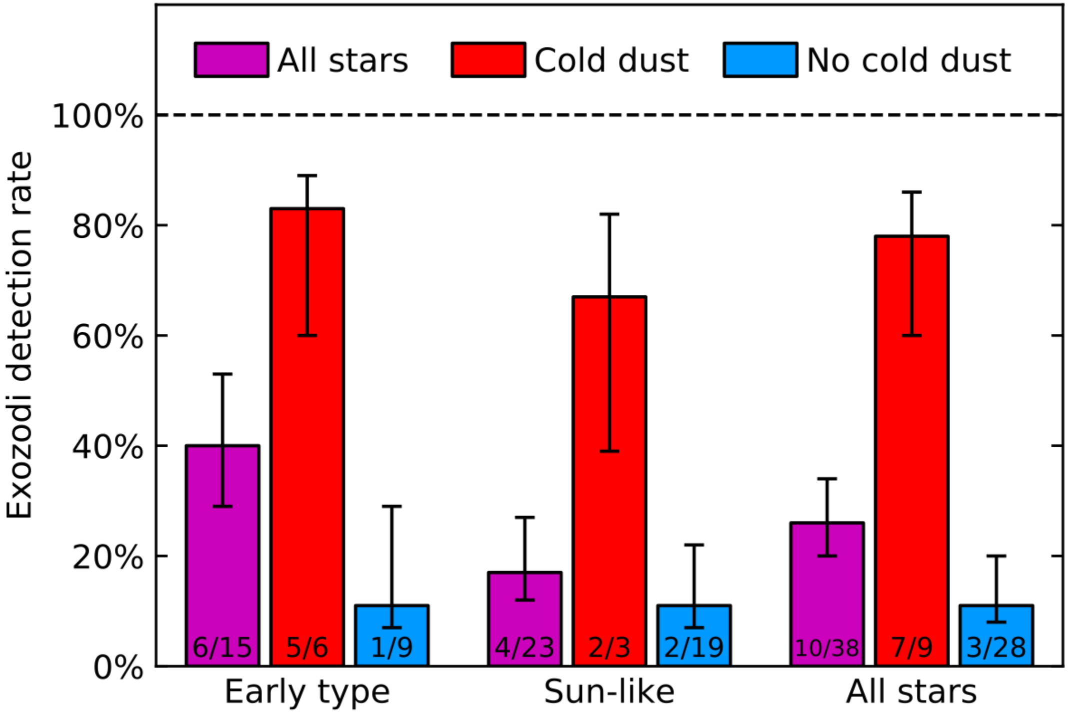


Ertel et al. 2020: *The majority of Sun-like stars have relatively low HZ dust levels (**best-fit median: 3 zodis, 1 σ upper limit: 9 zodis, 95% confidence**: 27 zodis based on our N band measurements), while ~20% are significantly more dusty.*

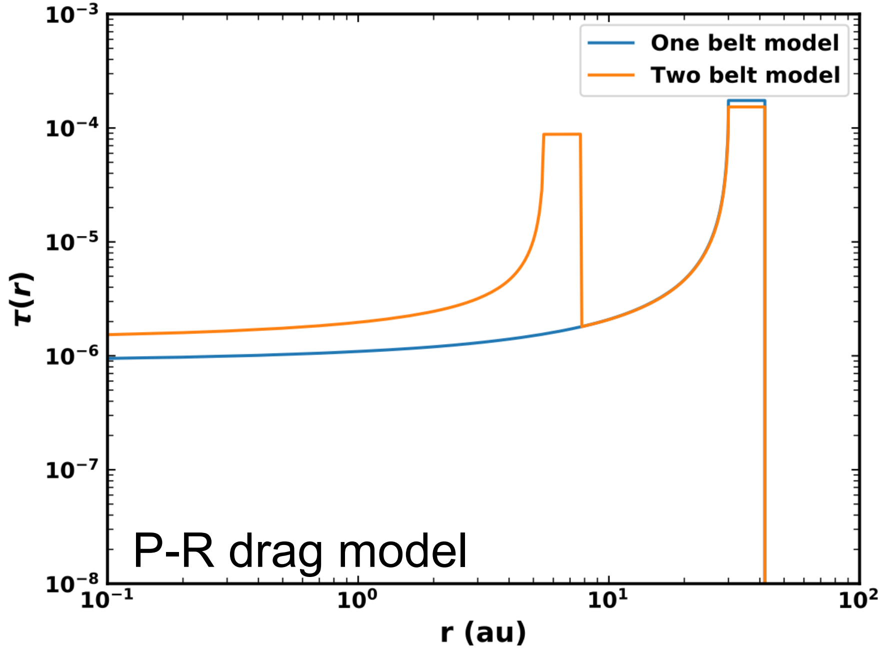
WISE: Kennedy et al. (2013)
KIN: Mennesson et al. (2014)
LBTI: Ertel et al. (2018, 2020)

Correlation with outer cold belt

Ertel et al. 2020

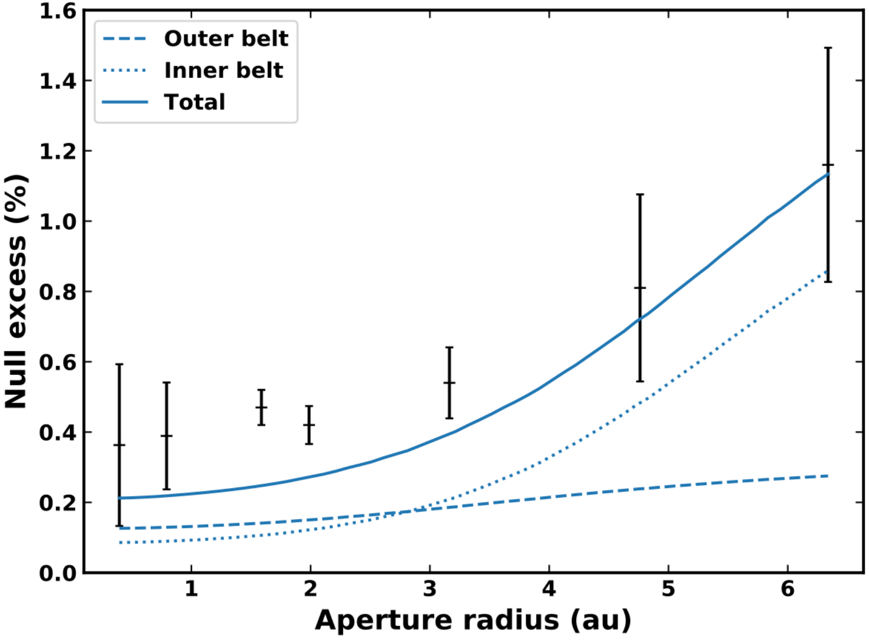


An example: β Leo

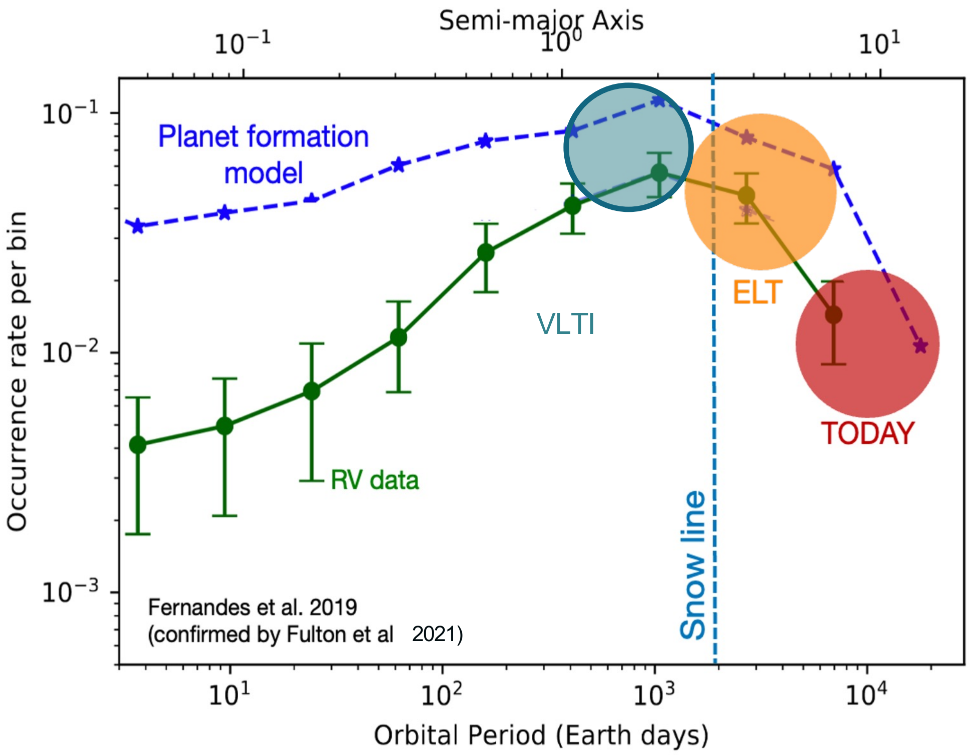


P-R drag model

Defrère et al. 2021

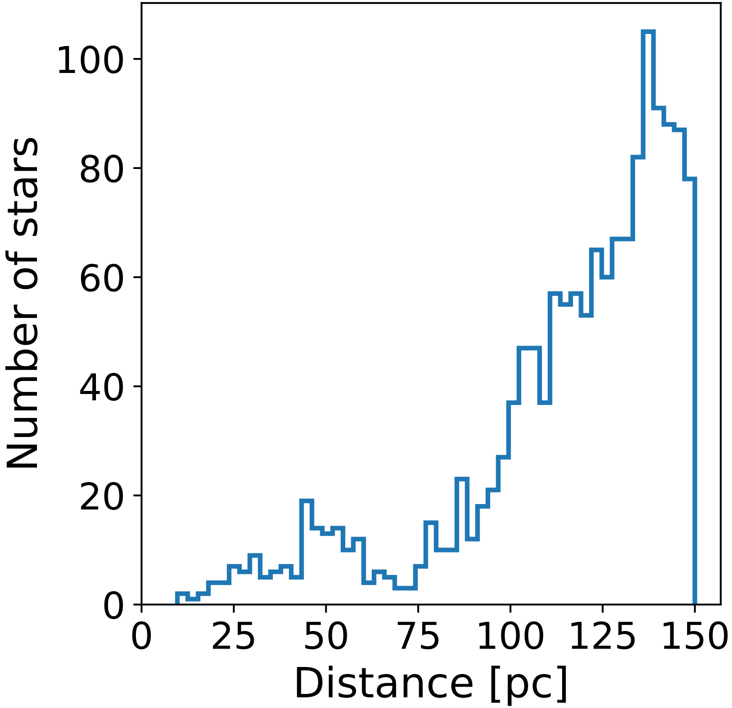


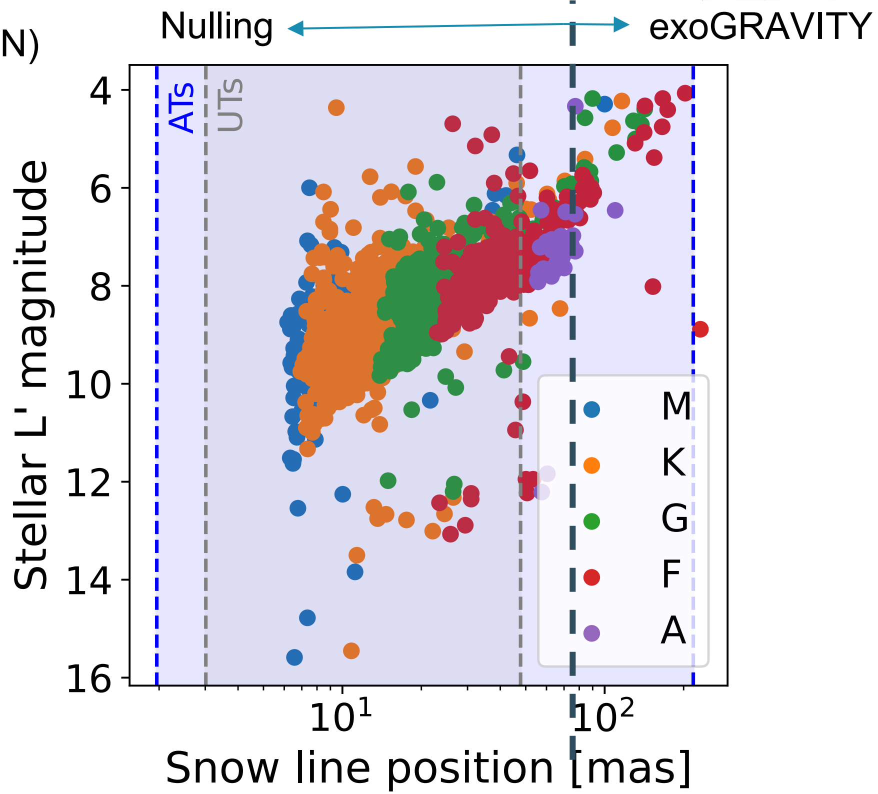
Exoplanet imaging with VLTI



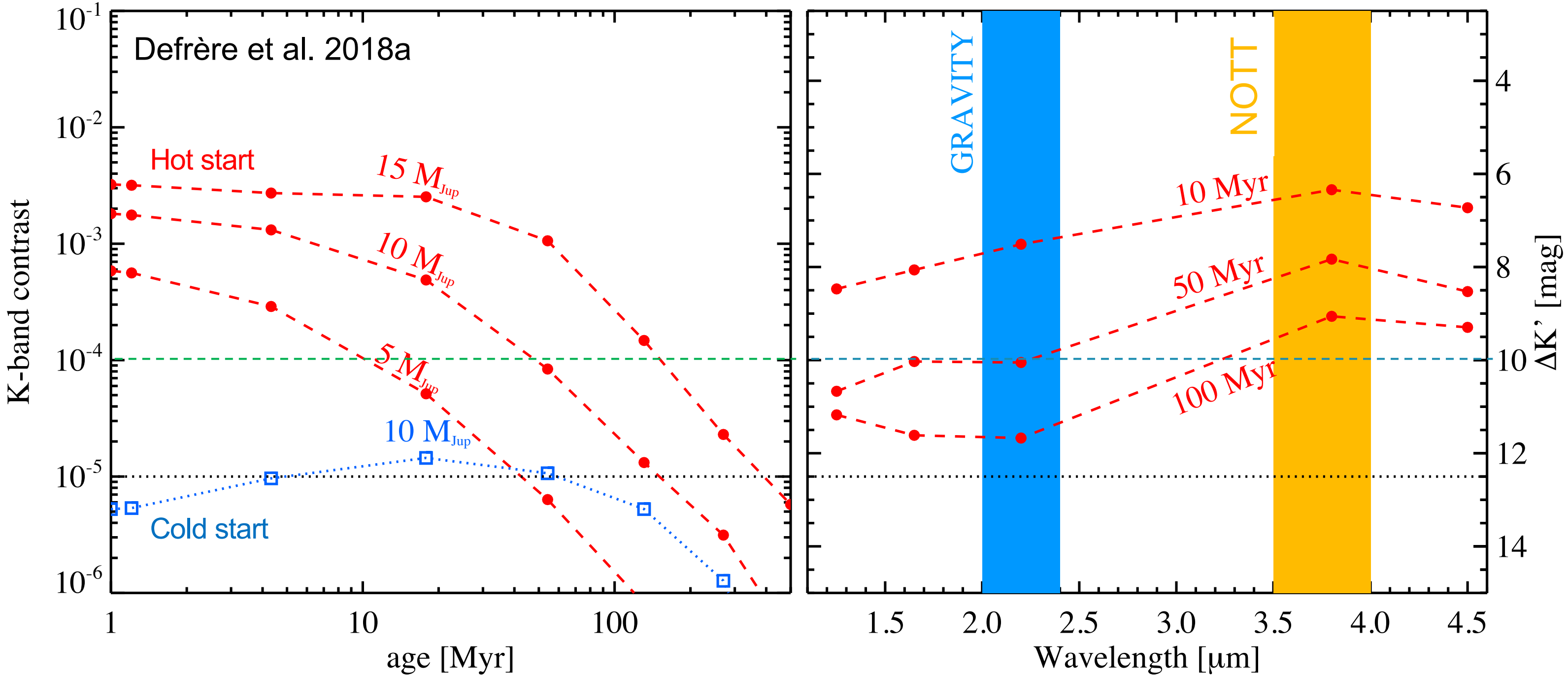
Exoplanet imaging with nulling at VLTI

Catalog of 1300 nearby young stars (<300Myr, GAIA-BANYAN)

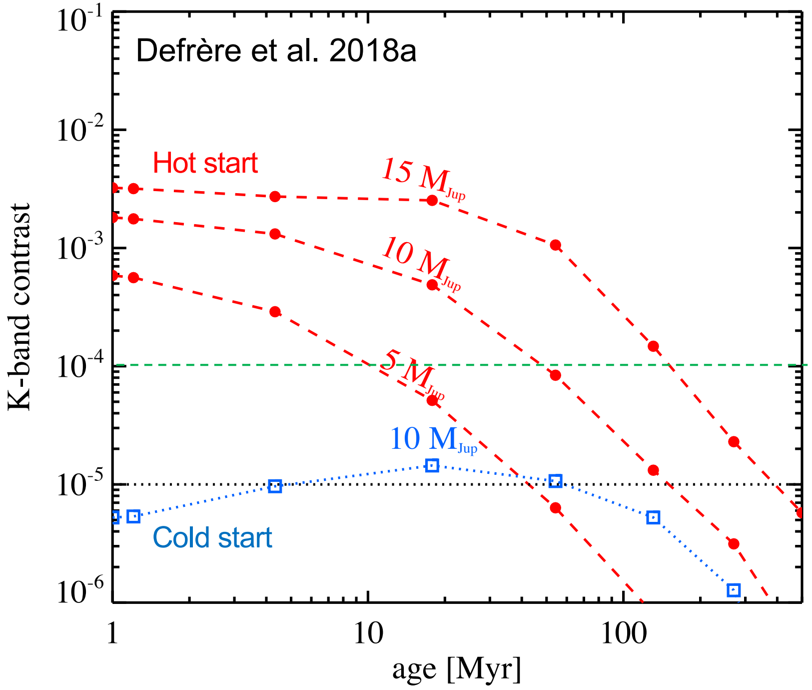


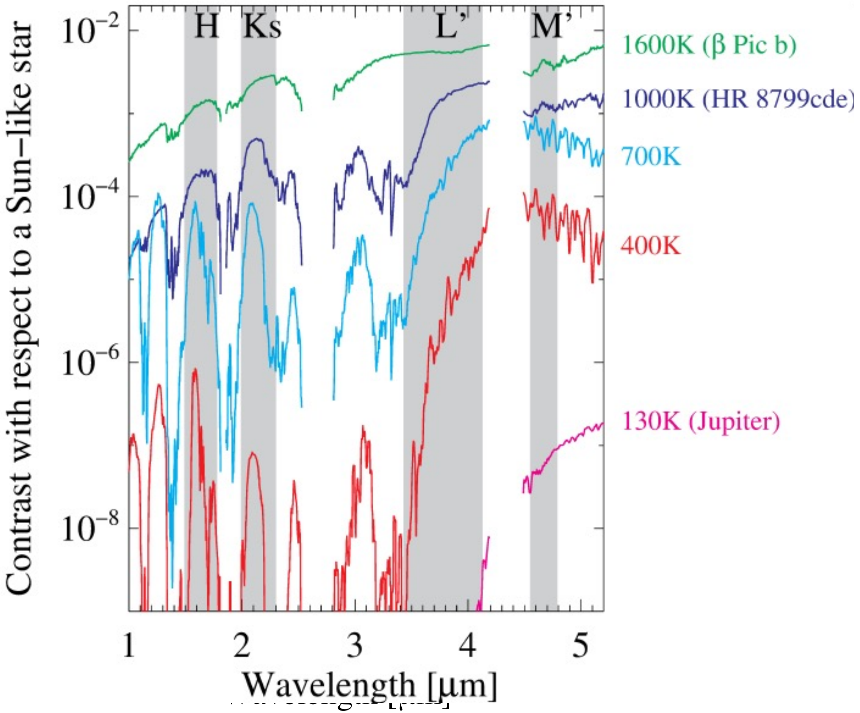


Exoplanet imaging with nulling at VLTI



Exoplanet imaging with nulling at VLTI





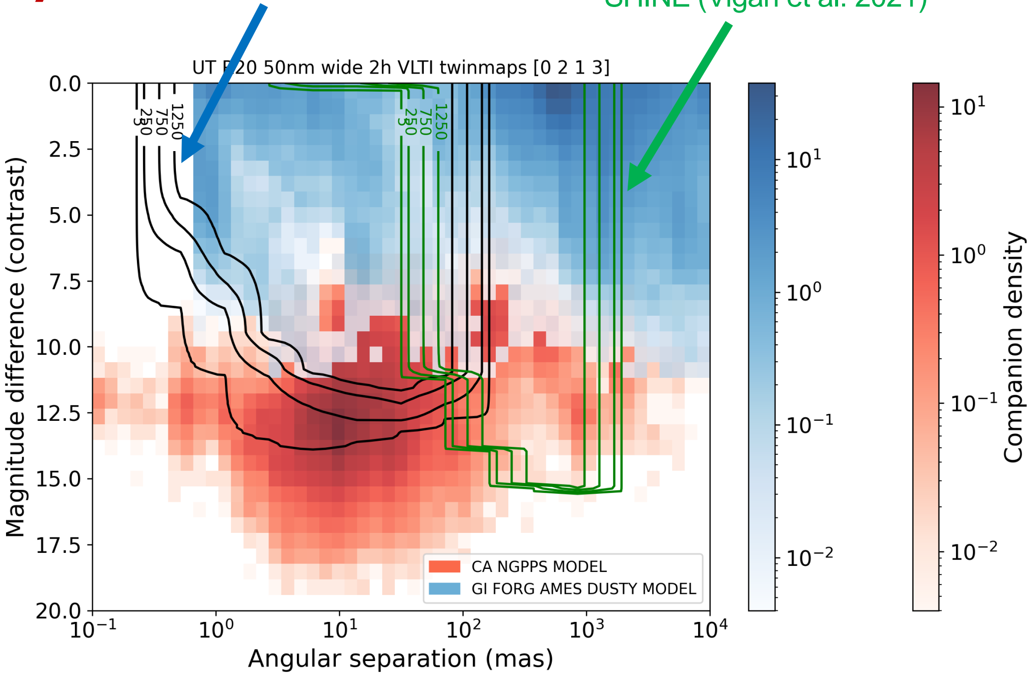
Exoplanet imaging with nulling at VLTI

Exoplanet parameter space and yield

- Exoplanet yield prediction based on latest GAIA young star catalog (J. Gagné priv. comm) and core accretion model (Bern model)
- Approximately 5 young giant exoplanets detected by GAIA can be characterized
- Mostly young giant exoplanets near the snow line
- Performance based on Laugier et al. (2023)

NOTT (Dandumont in prep)

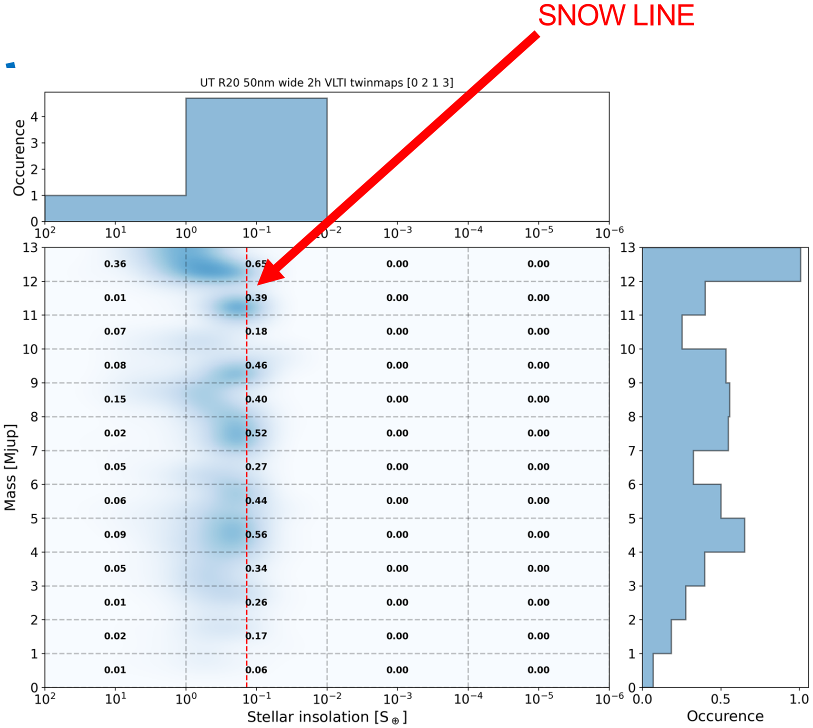
SHINE (Vigan et al. 2021)



Exoplanet imaging with nulling at VLTI

Exoplanet parameter space and yield

- Exoplanet yield prediction based on latest GAIA young star catalog (J. Gagné priv. comm) and core accretion model (Bern model)
- Approximately 5 young giant exoplanets detected by GAIA can be characterized
- Mostly young giant exoplanets near the snow line
- Performance based on Laugier et al. (2023)



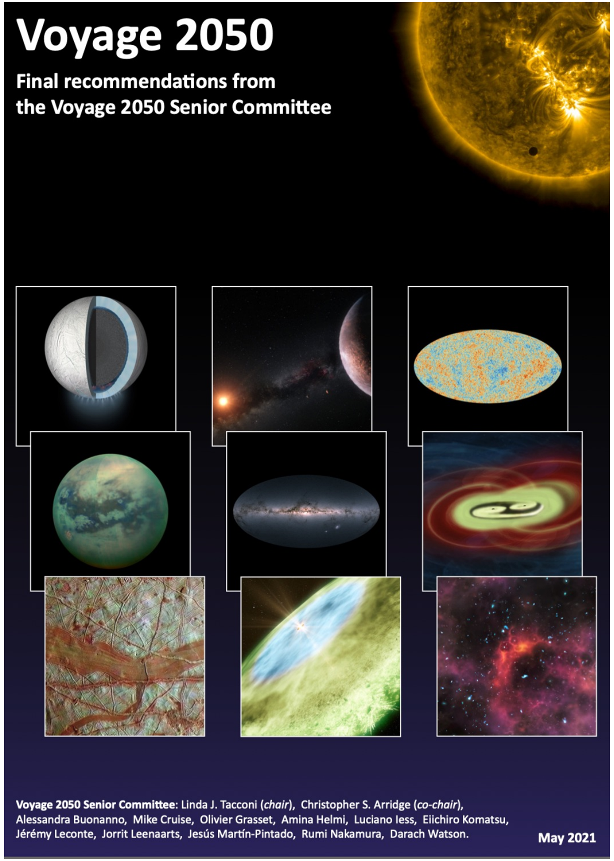
Overview

- Principles of nulling interferometry
- Current and past nulling interferometers
- Science with nulling interferometers
- Space nulling interferometers: concepts and science
- Summary

Exoplanet mission landscape

ESA’s science vision

From temperate exoplanets to the Milky Way
“…the characterisation of temperate exoplanets in the mid-infrared, through a first spectrum of direct thermal emission from exoplanet atmospheres to better understand if they harbour truly habitable surface conditions, would be an outstanding breakthrough”.



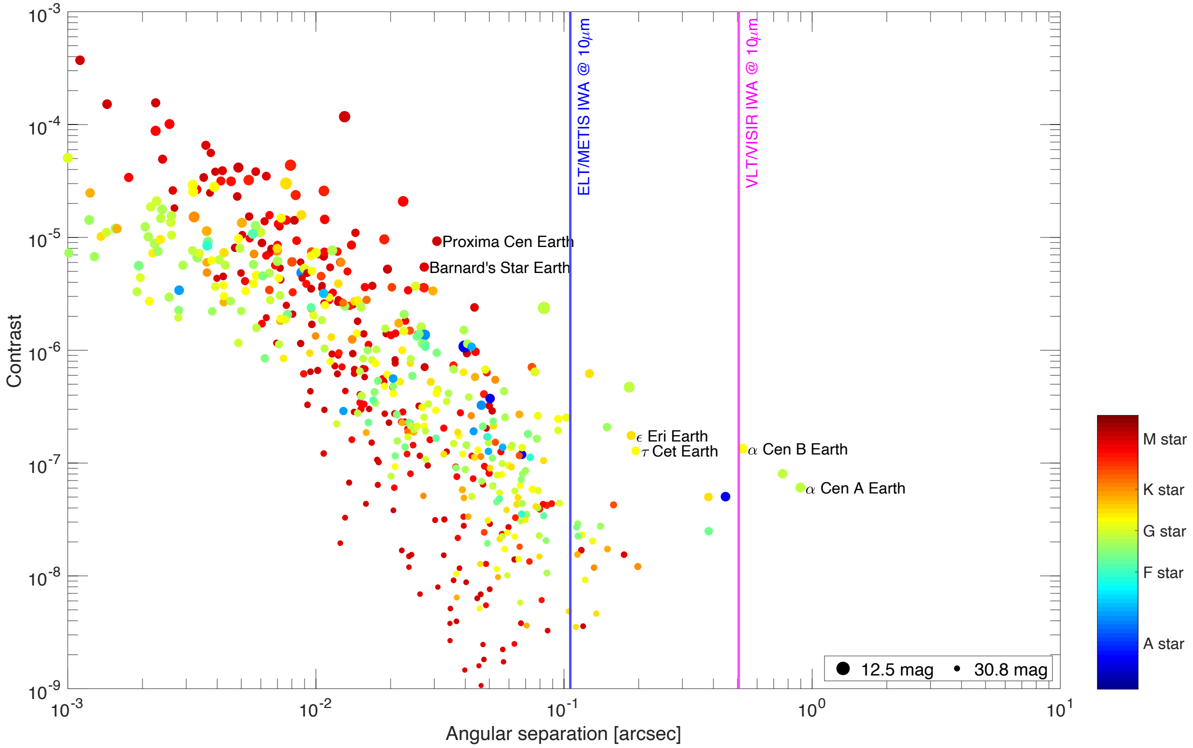
Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee

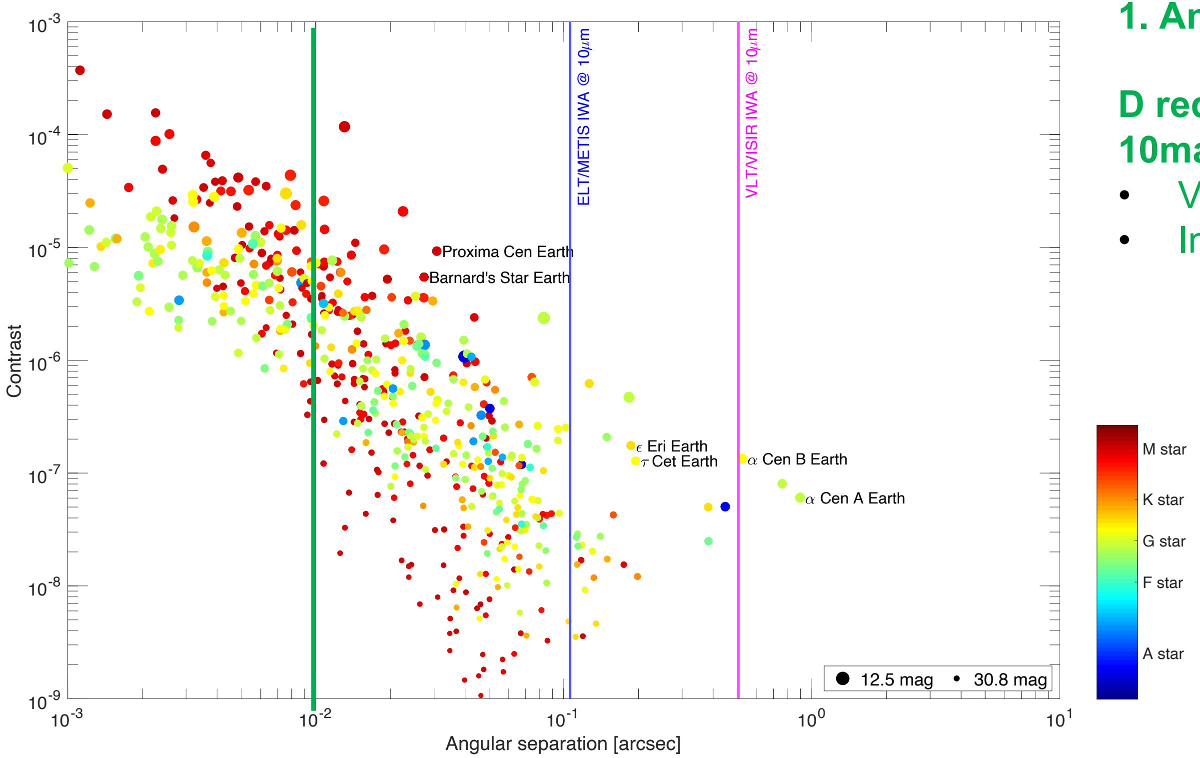
Voyage 2050 Senior Committee: Linda J. Tacconi (*chair*), Christopher S. Arridge (*co-chair*), Alessandra Buonanno, Mike Cruise, Olivier Grasset, Amina Helmi, Luciano Iess, Eiichiro Komatsu, Jérémy Leconte, Jorrit Leenaarts, Jesús Martín-Pintado, Rumi Nakamura, Darach Watson.

May 2021

Requirements



Requirements

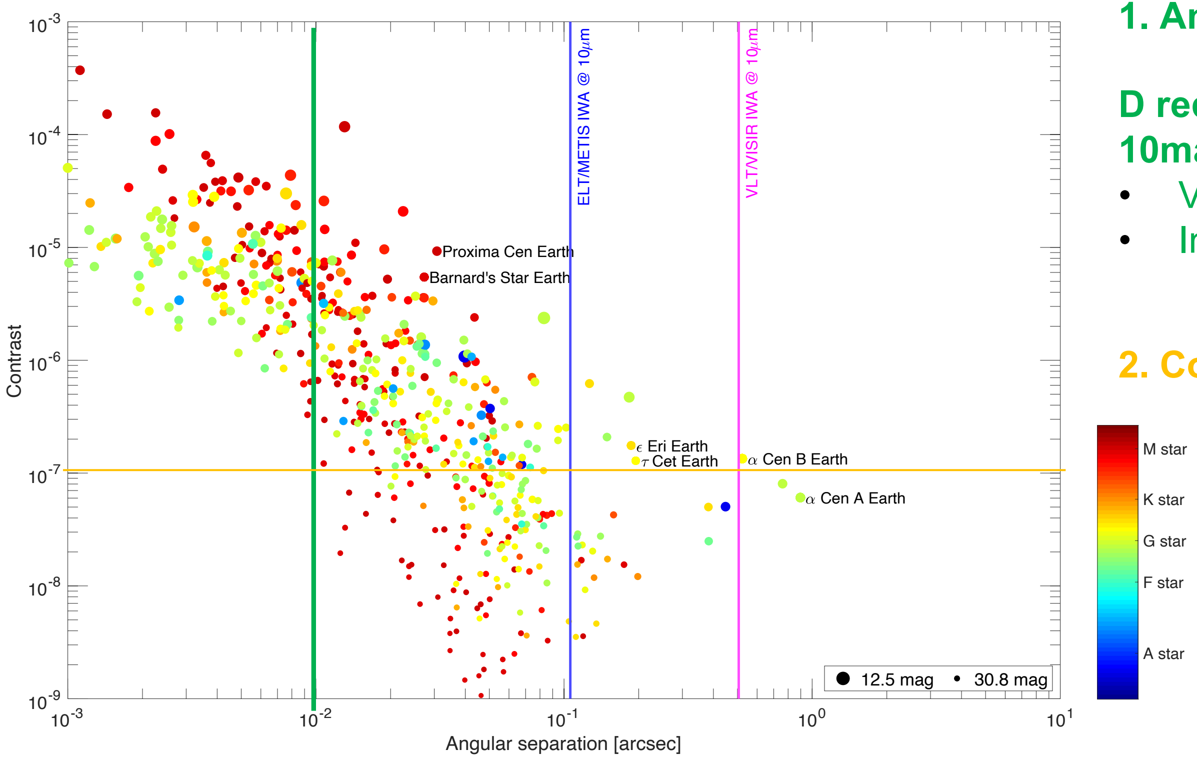


1. Angular resolution

D required for IWA (2λ/D) = 10mas:

- Visible (550nm): ~24m
- Infrared (10μm): ~400m

Requirements



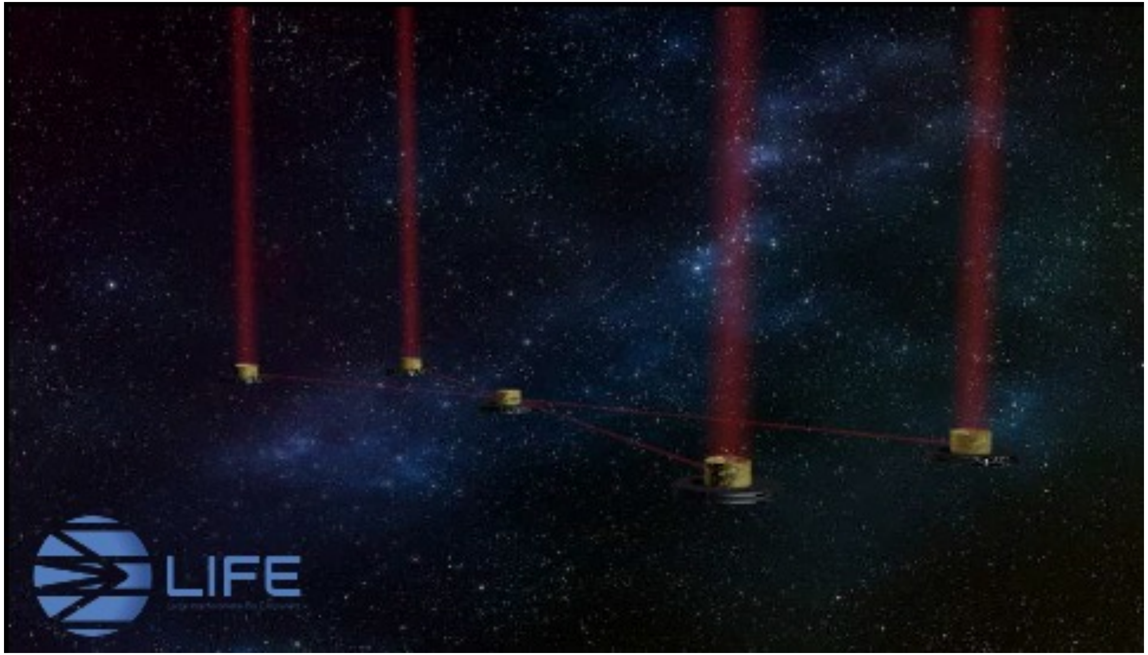
1. Angular resolution

D required for IWA (2λ/D) = 10mas:

- Visible (550nm): ~24m
- Infrared (10μm): ~400m

2. Contrast: ~10^{-7}

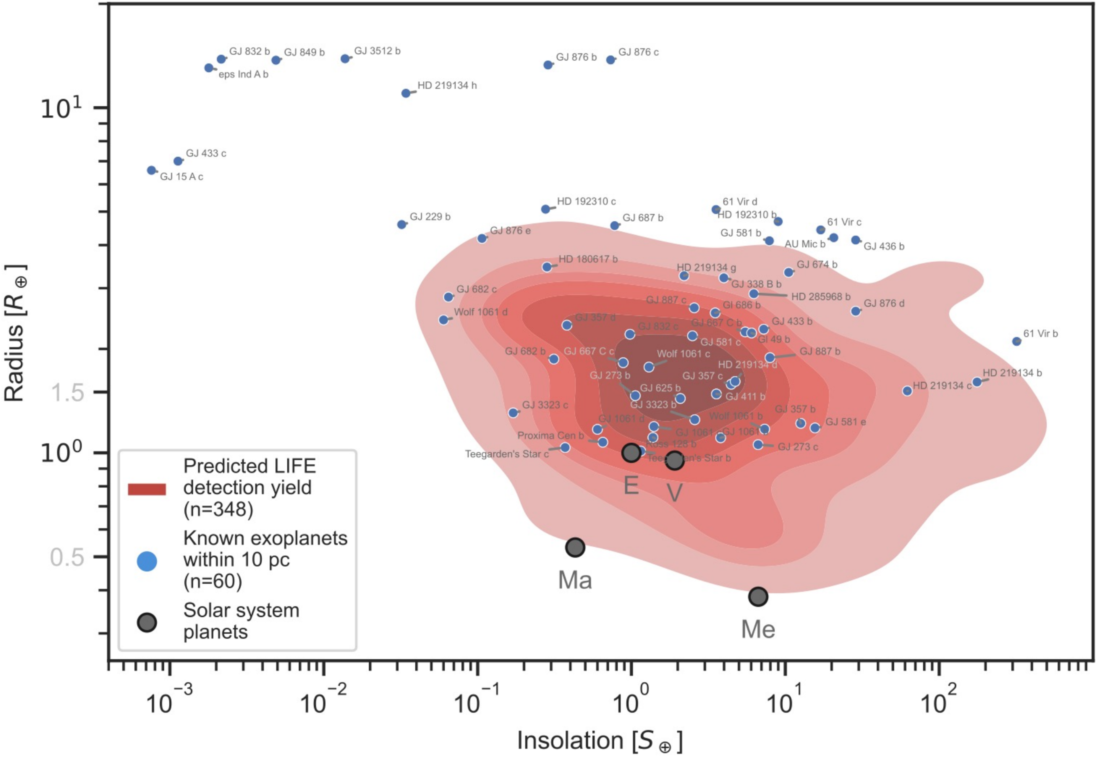
Large Interferometer For Exoplanets (LIFE)



- Key instrument features
  - Mid-infrared (4 to 18 µm, TBC)
  - Spectral resolution (~50, TBC)
  - Formation flying (array rotation and collision avoidance)
  - Imaging baselines up to ~km (TBD)
  - Passive cooling (~40K) and low noise detectors
  - Ultra-stable nulling combination with fine metrology (OPD and tip/tilt)
  - Optimized beam combination strategies

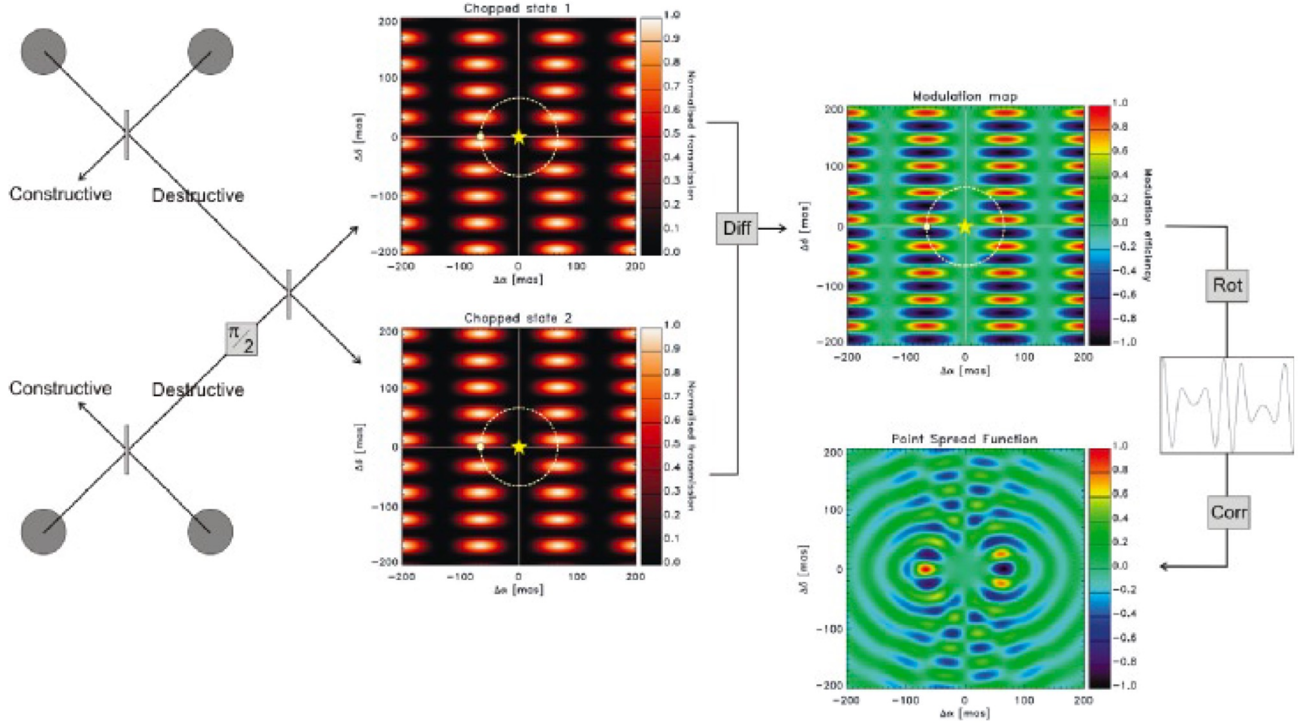
See more information and references on: https://life-space-mission.com

Large Interferometer For Exoplanets (LIFE)



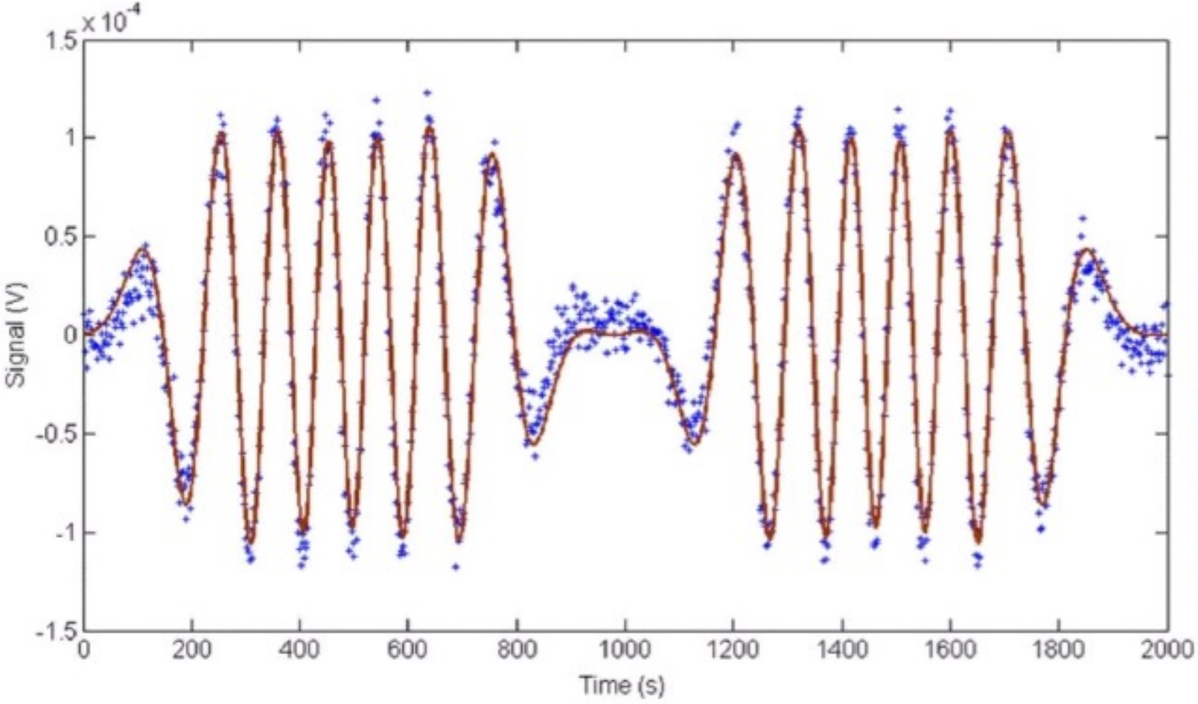
Quanz et al. 2021

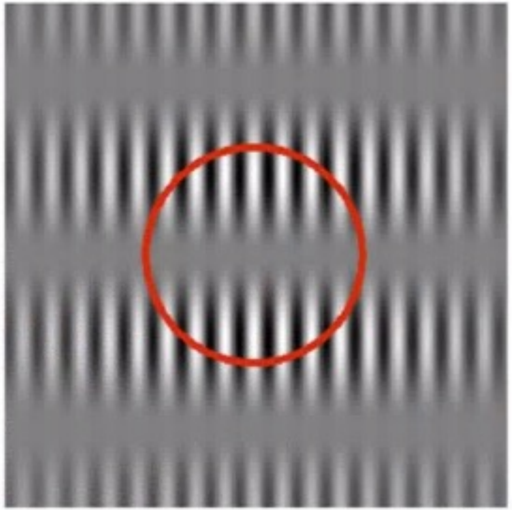
LIFE beam combination scheme



Defrère et al. 2010

Lab demonstration at JPL



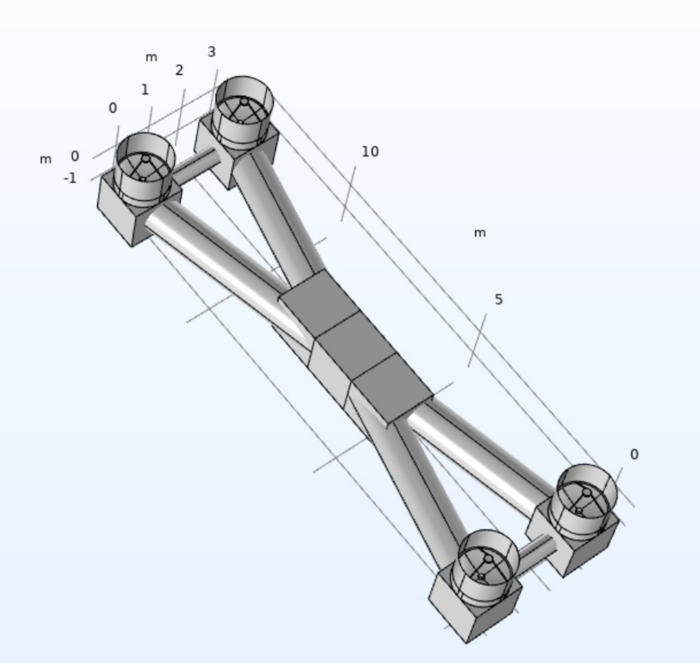


Martin et al. 2012

Nulling on single spacecraft

- Mid-IR single-spacecraft nuller
- Can fit in Ariane 6 fairing (baselines ~15m)
- Technology demonstration mission (reduce risks)
- Science precursor (nearby planets that can be resolved)

Loicq et al. 2024



Summary

- Three generations of nulling interferometers developped in the US over the past 25+ years with key results on exozodiacal disks
- Current state-of-the-art contrast performance: 10^{-4} (both K and N bands)
- New project for the VLTI (Asgard/NOTT, visitor), with a strong exoplanet science case
- Strong exoplanet science case for nulling in space and mission concepts being investigated (e.g., LIFE)

Summary

- Interferometry is a direct imaging technique, complementary to AO imaging
- Nulling interferometry to remove the stellar light, like coronagraphy for single-dish imaging
- Several ground-based nulling instruments (MMT, Keck nuller, LBTI), proved key technologies and shed new light on exozodiacal disks
- Asgard/NOTT, ERC-funded project under development for the VLTI (to image young exoplanets near the snow line)
- Space nulling required for the direct characterization of a large sample of rocky exoplanets

Further references

- Unveiling exozodiacal light (includes the history of nulling, Spalding et al. 2022): link
- Review and scientific prospects of high-contrast optical stellar interferometry (Defrère et al. 2020): link
- Theory of nulling interferometry (Serabyn): link
- LIFE space mission website: life-space-mission.com
- Asgard/NOTT website: denis-defrere.com/asgard.php
- More information: denis-defrere.com/teaching.php

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