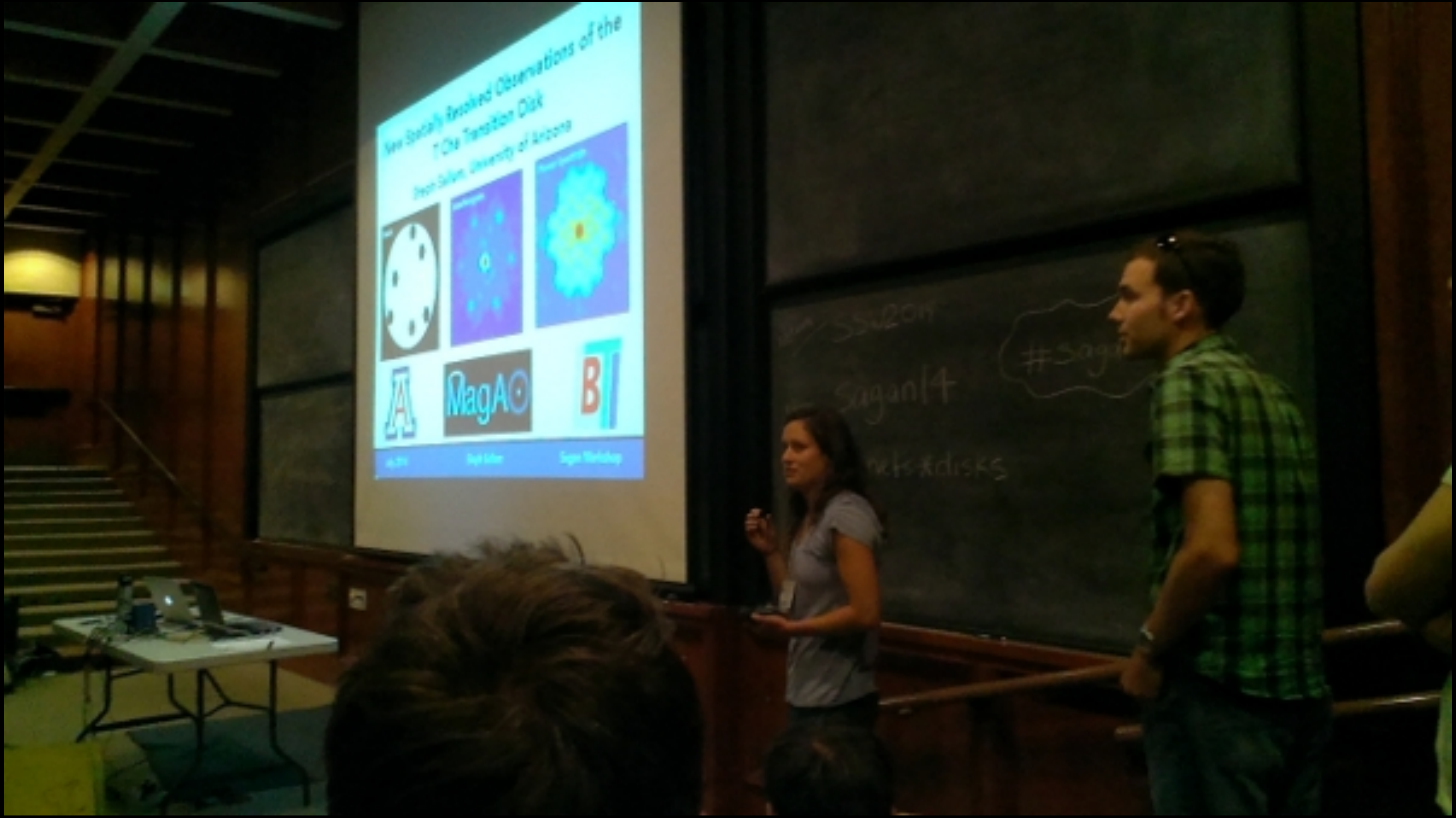
Aperture Masking Interferometry in Astronomy

Steph Sallum
Sagan Summer Workshop
July 26, 2024

10 years ago at the Sagan Workshop…



"Her slides were very patriotic."

https://xwcl.science/magao-c/sagan-2014-imaging-planets-and-disks/

Some (Very) Quick Motivation

Direct imaging observations suffer from uncorrected phase errors.

Observing (and post processing) strategies that can remove these phase errors would allow us to access small angular separations, benefiting a wide variety of science cases!

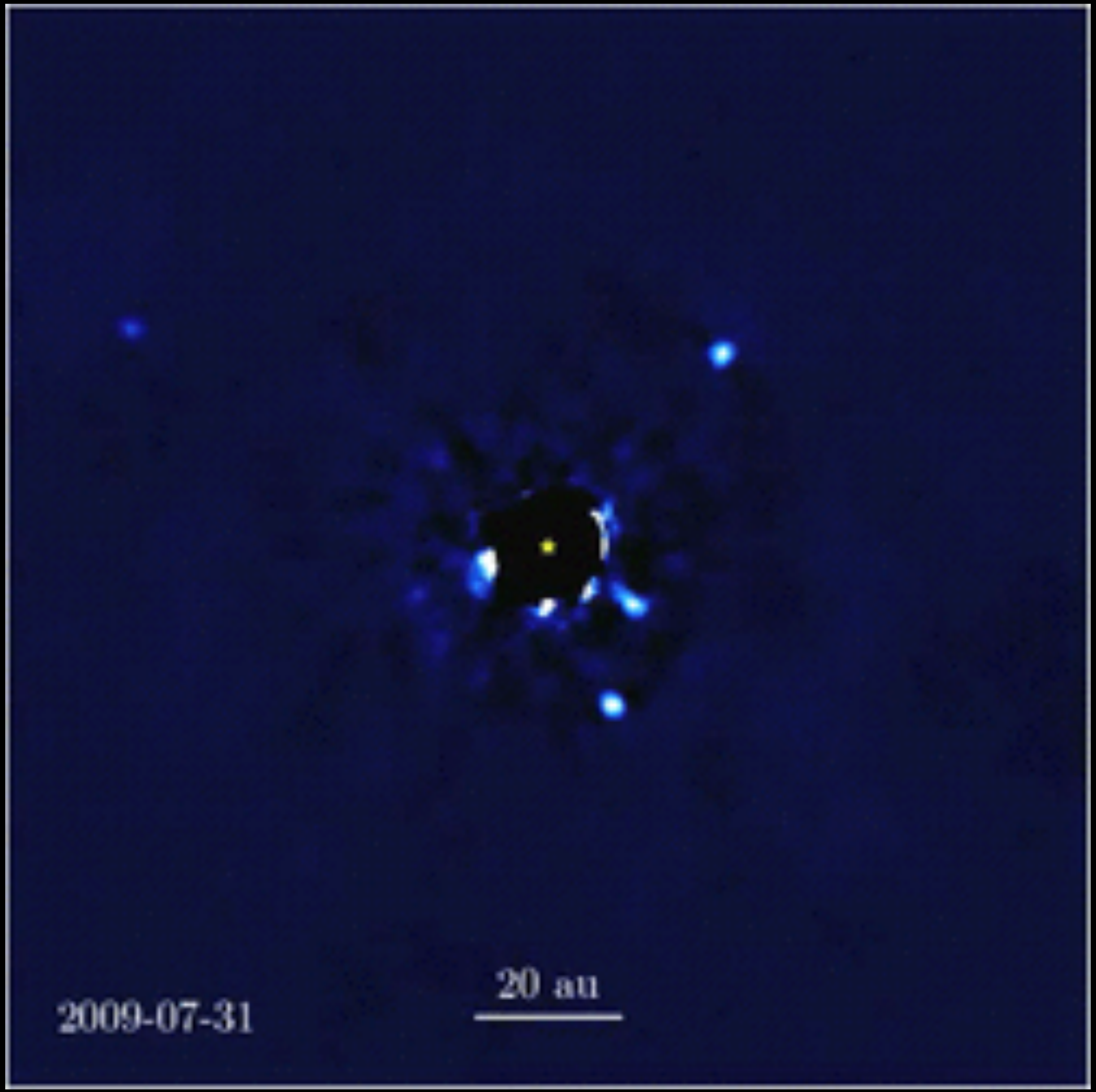
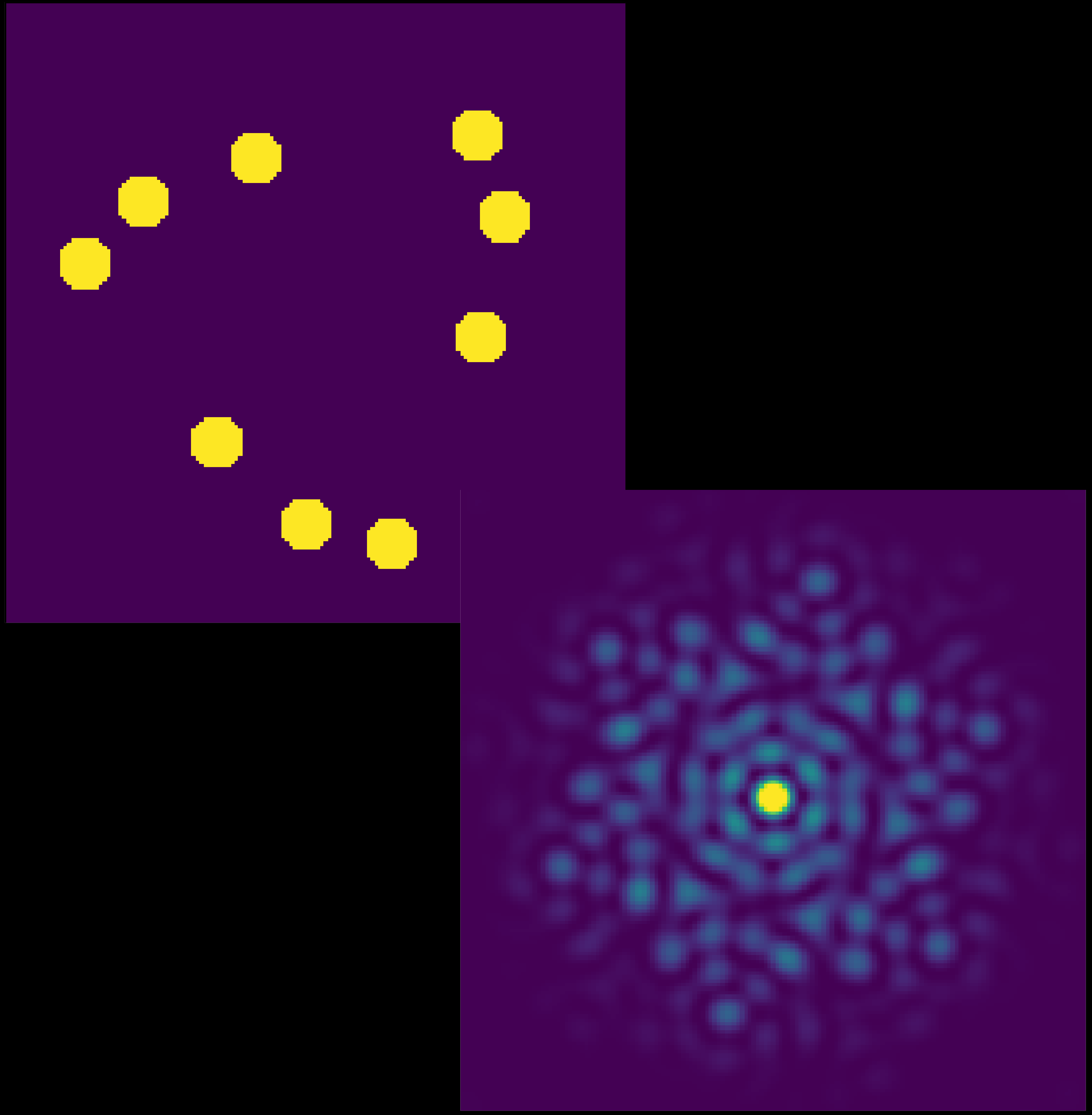


Image credit: Jason Wang (Northwestern)/William Thompson (UVic)/
Christian Marois (NRC Herzberg)/Quinn Konopacky (UCSD)

Aperture Masking Interferometry

Transforming a filled aperture into an interferometric array via a pupil-plane mask.

Image credit: Peter Tuthill



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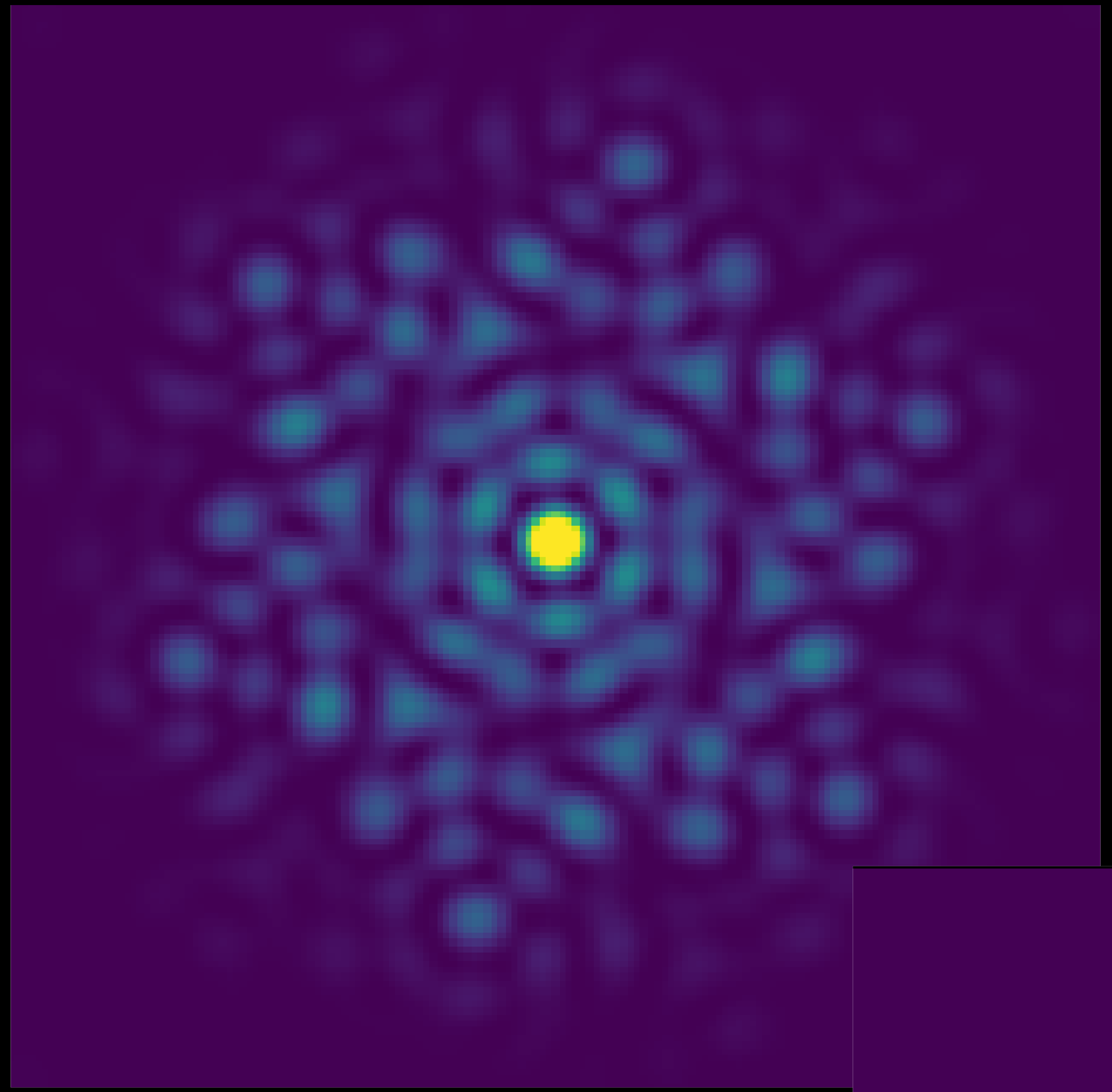
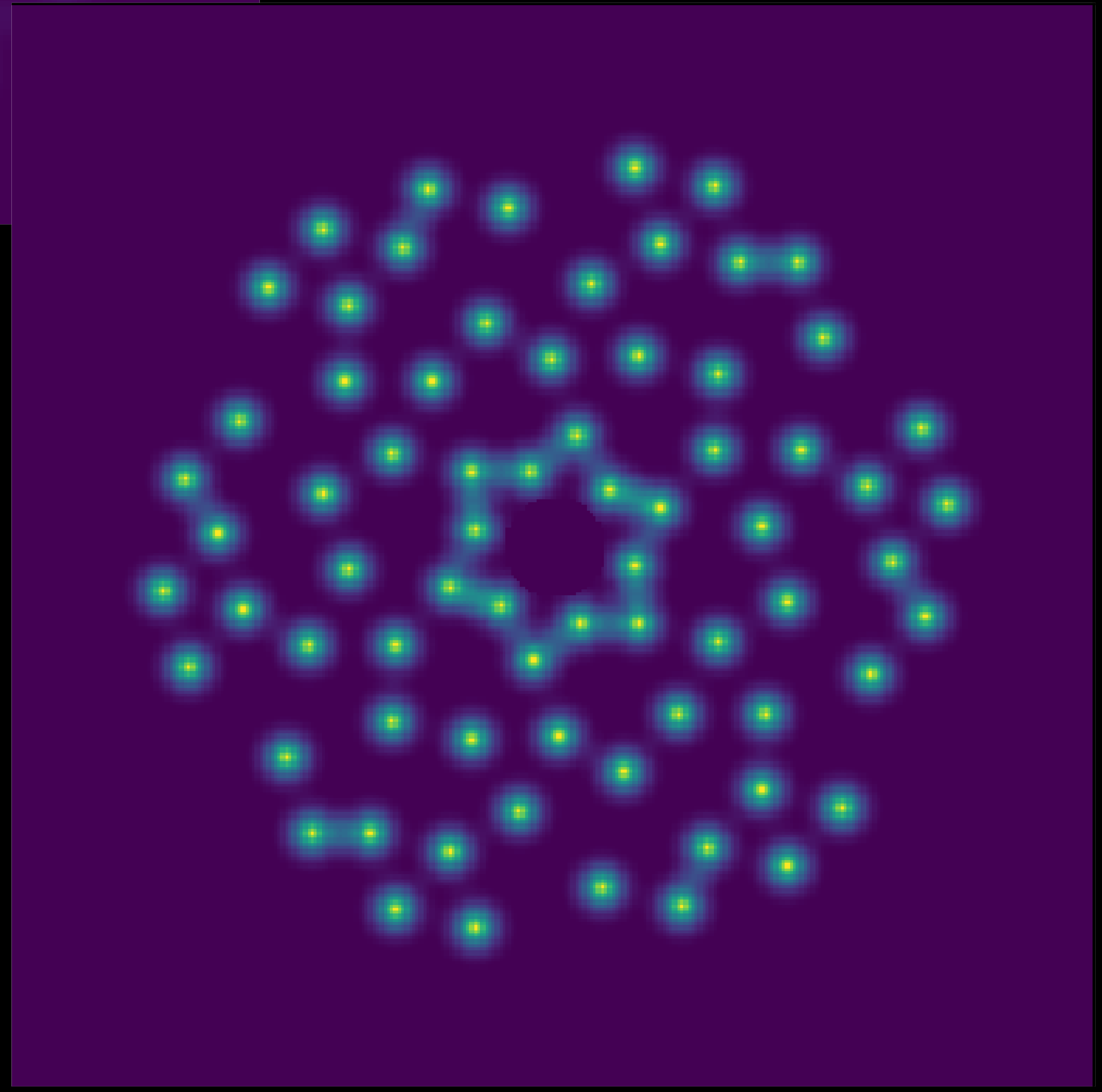
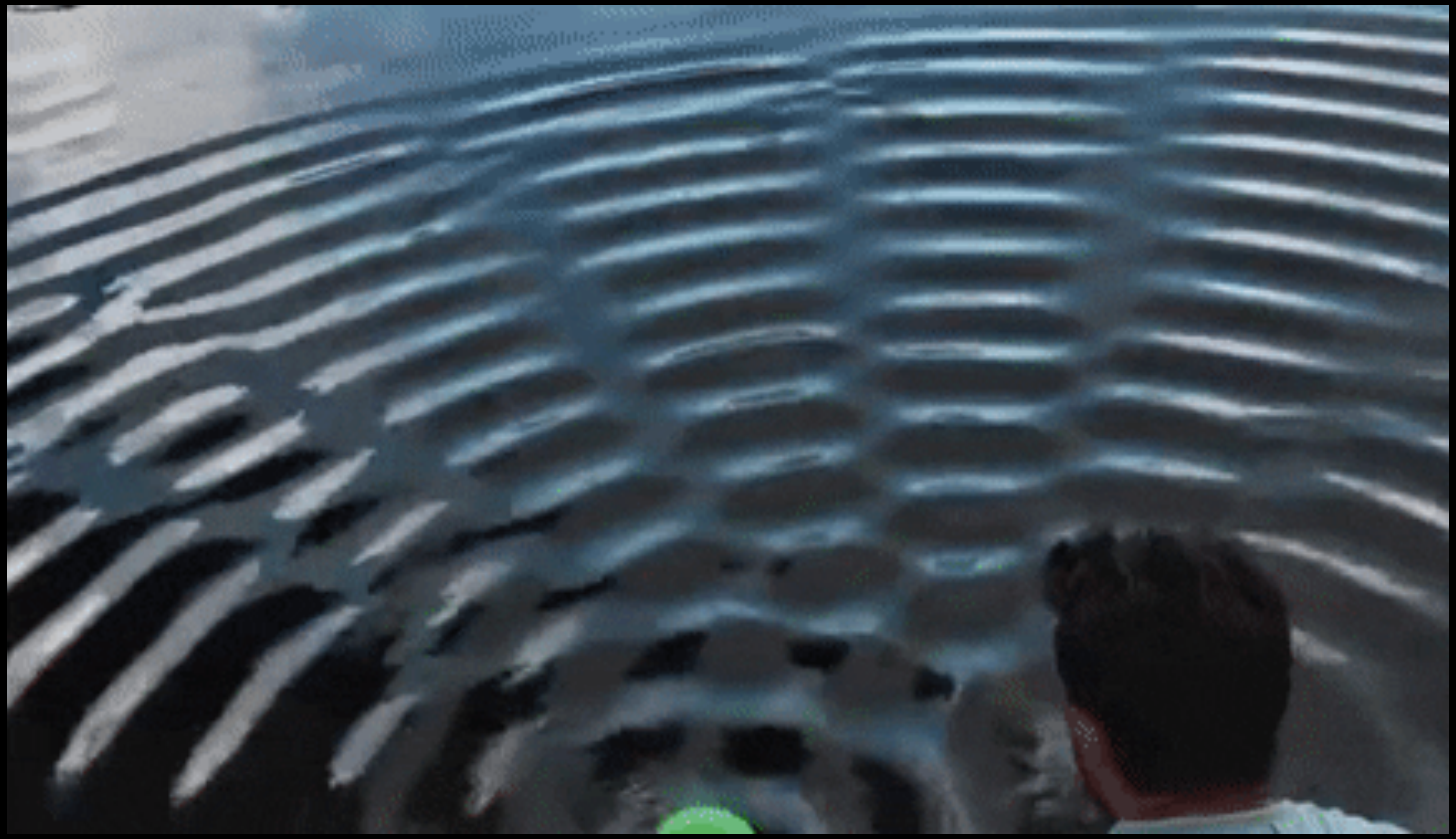
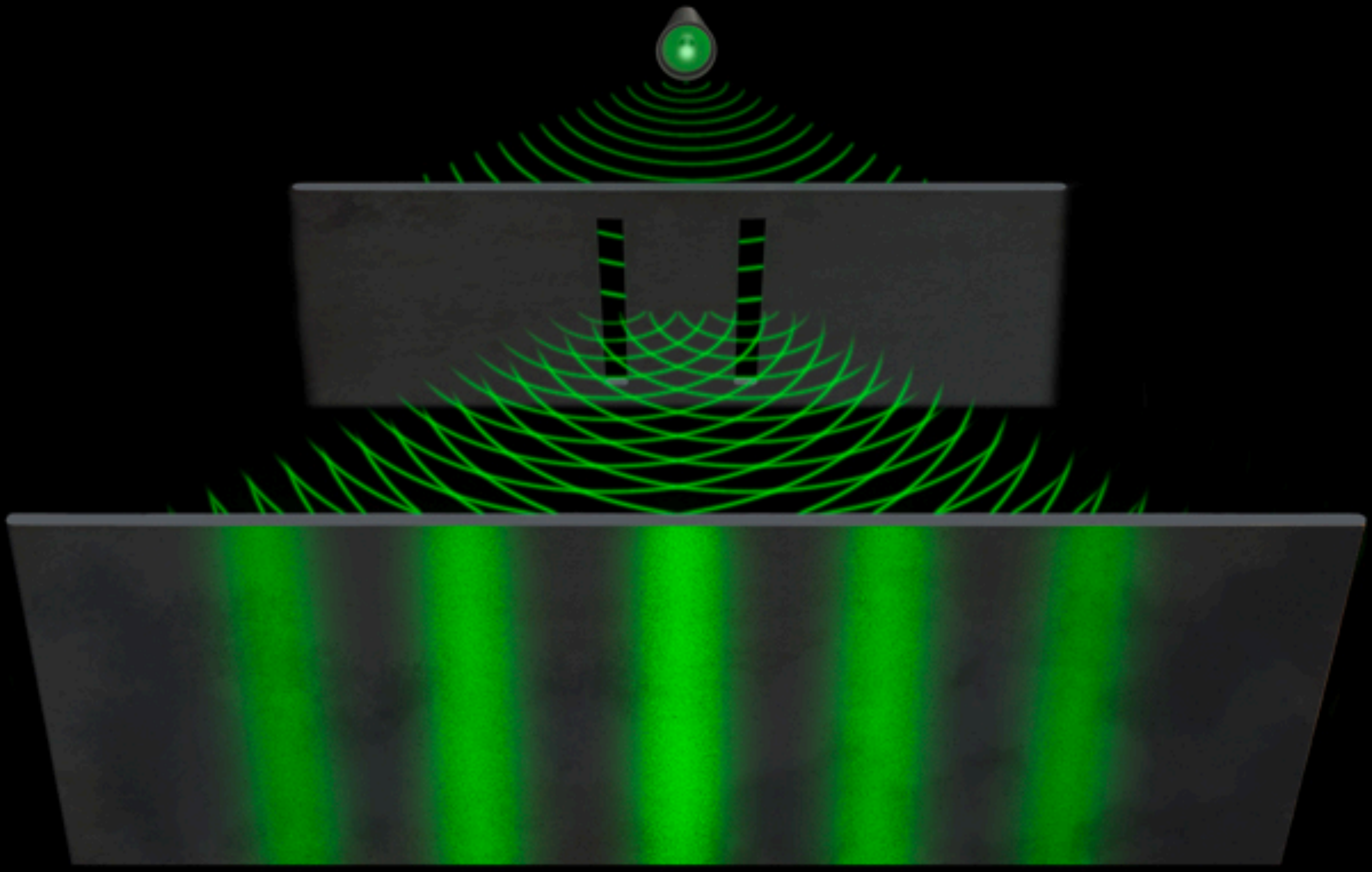




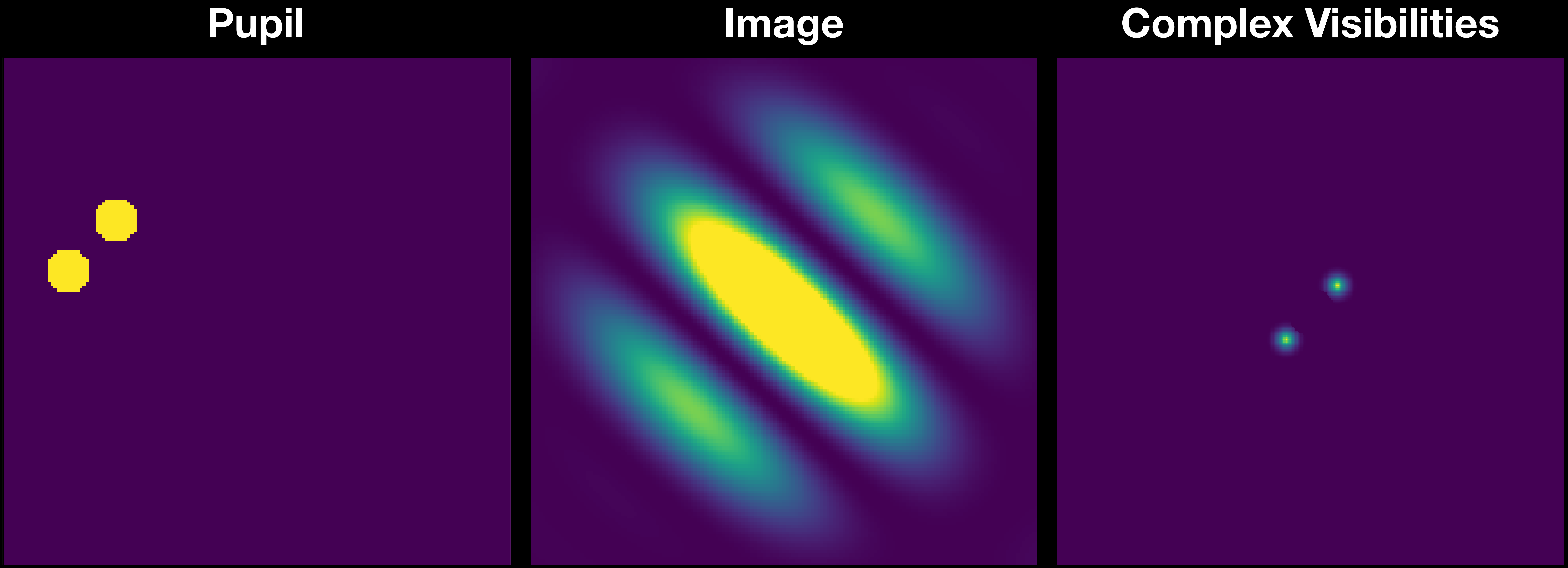
Young’s Double Slit Experiment (1801)





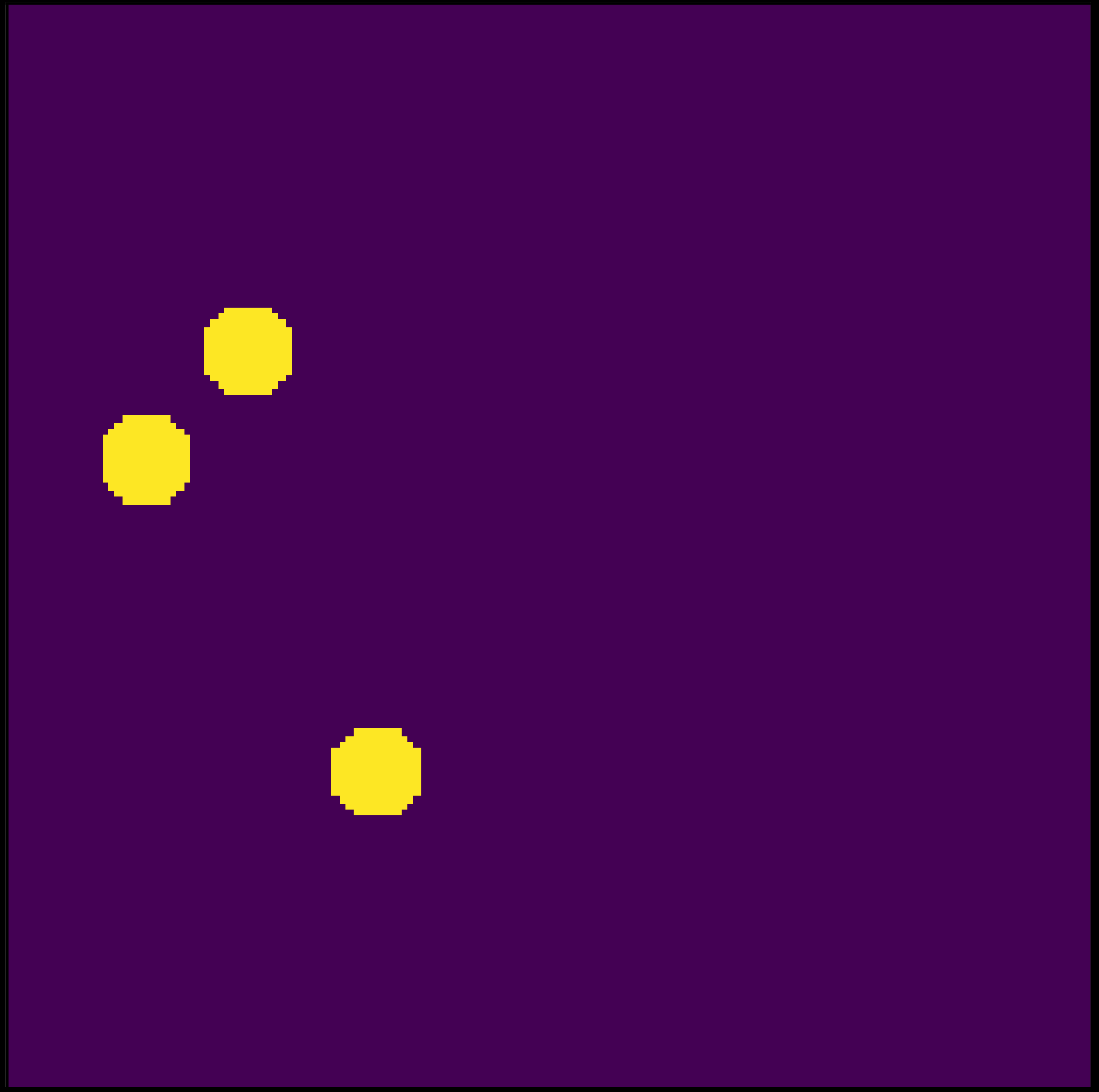
Fringe spacing depends on slit separation, modulation depends on slit size!

Non-Redundant Masking

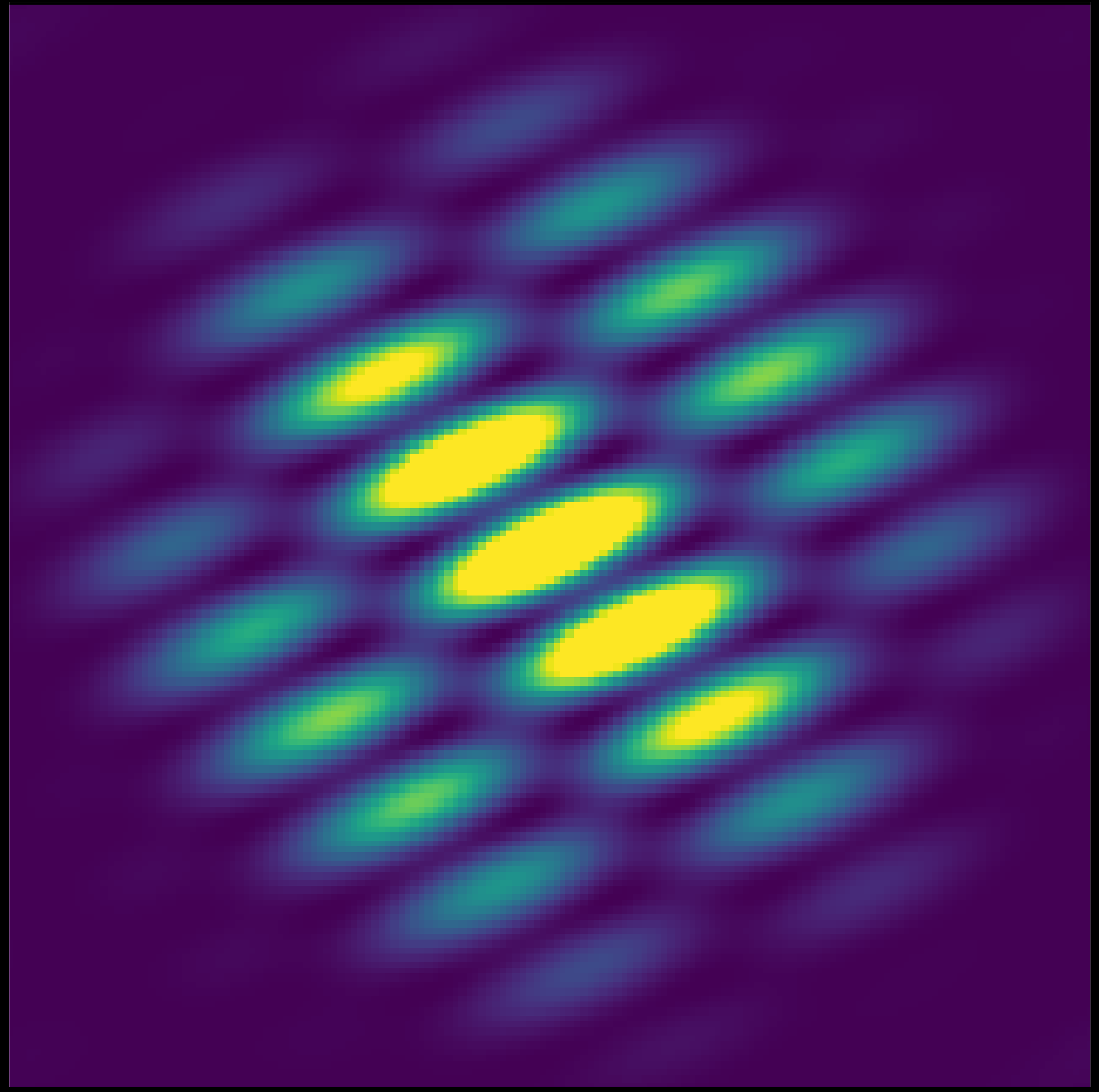


Non-Redundant Masking

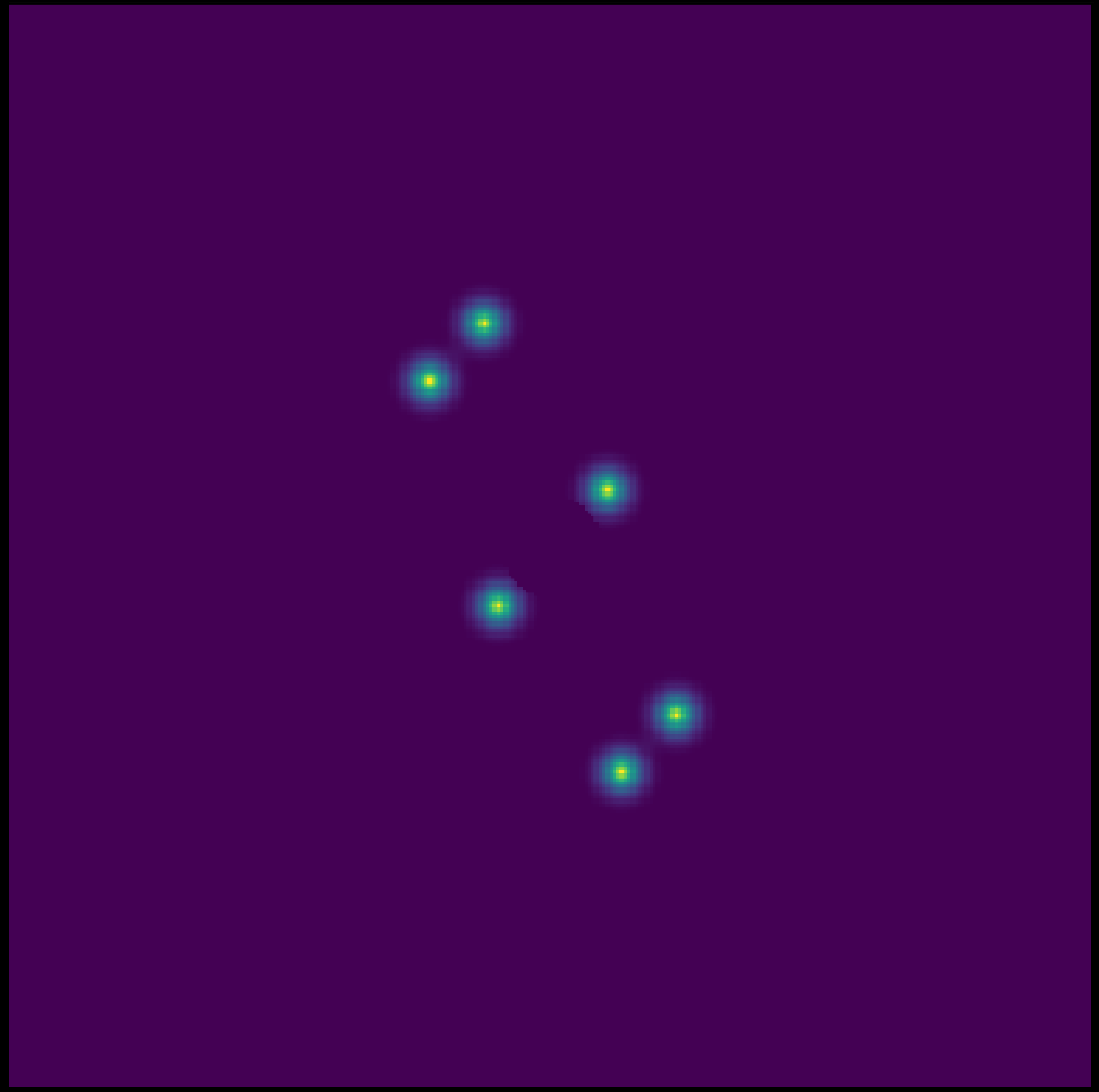
Pupil



Image



Complex Visibilities



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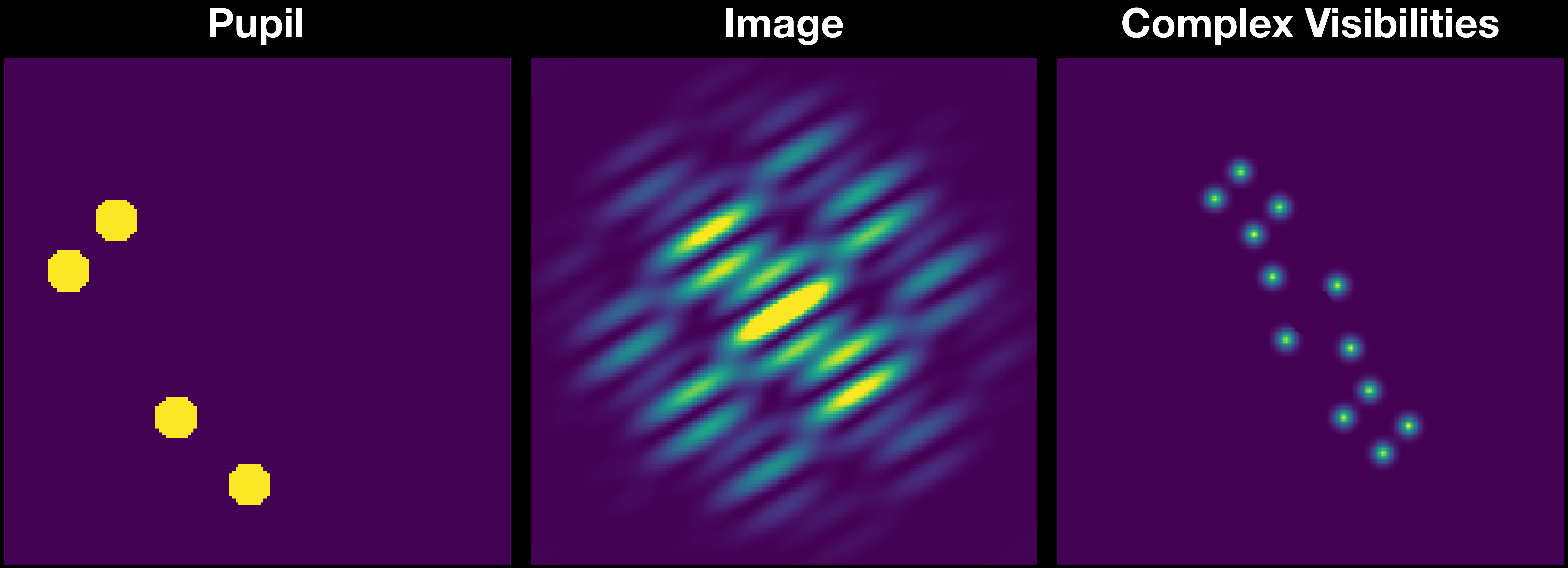

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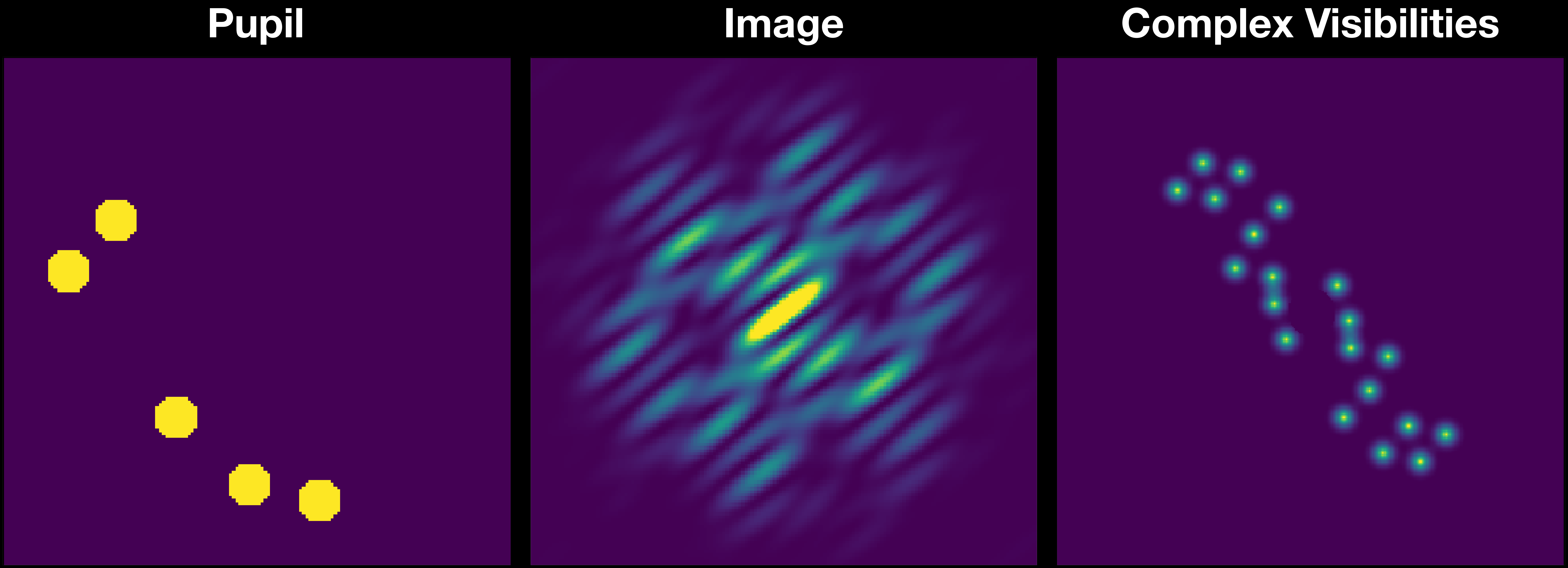
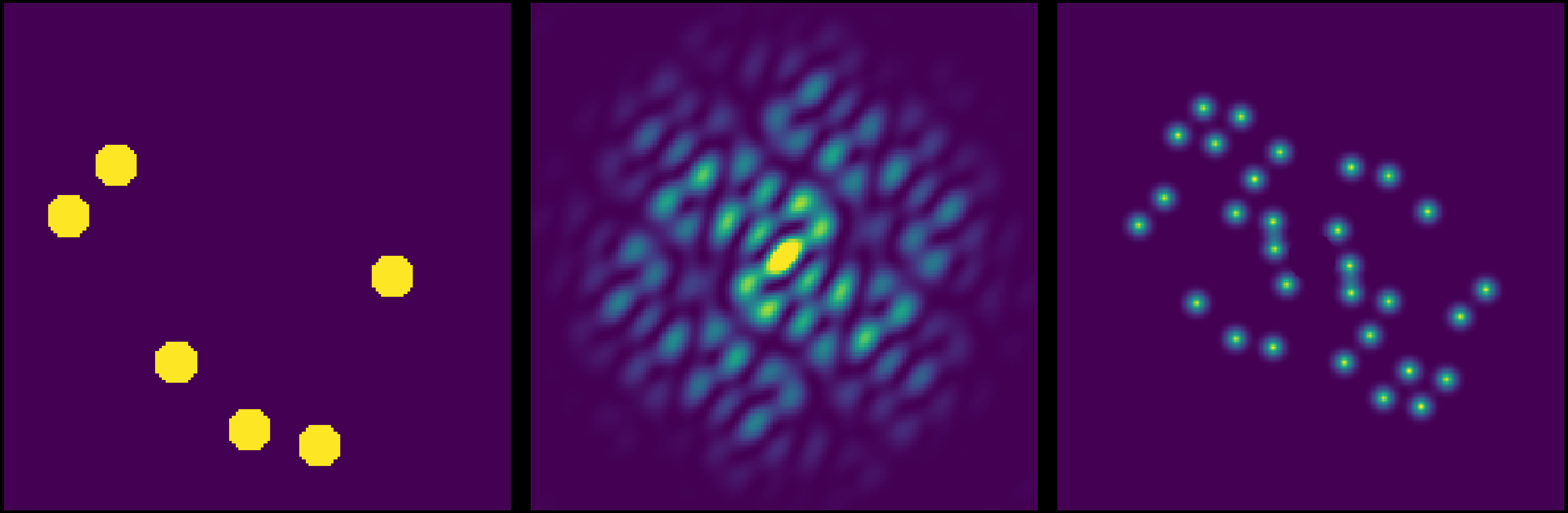


Non-Redundant Masking

Pupil

Image

Complex Visibilities



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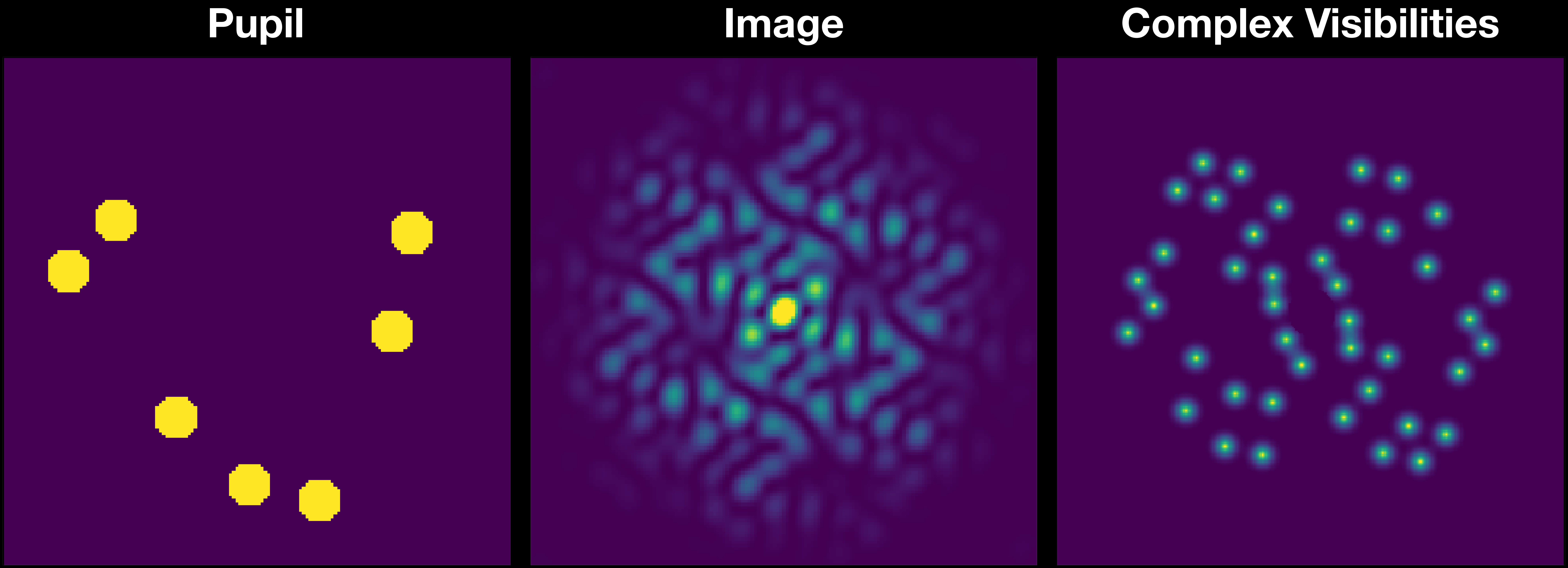

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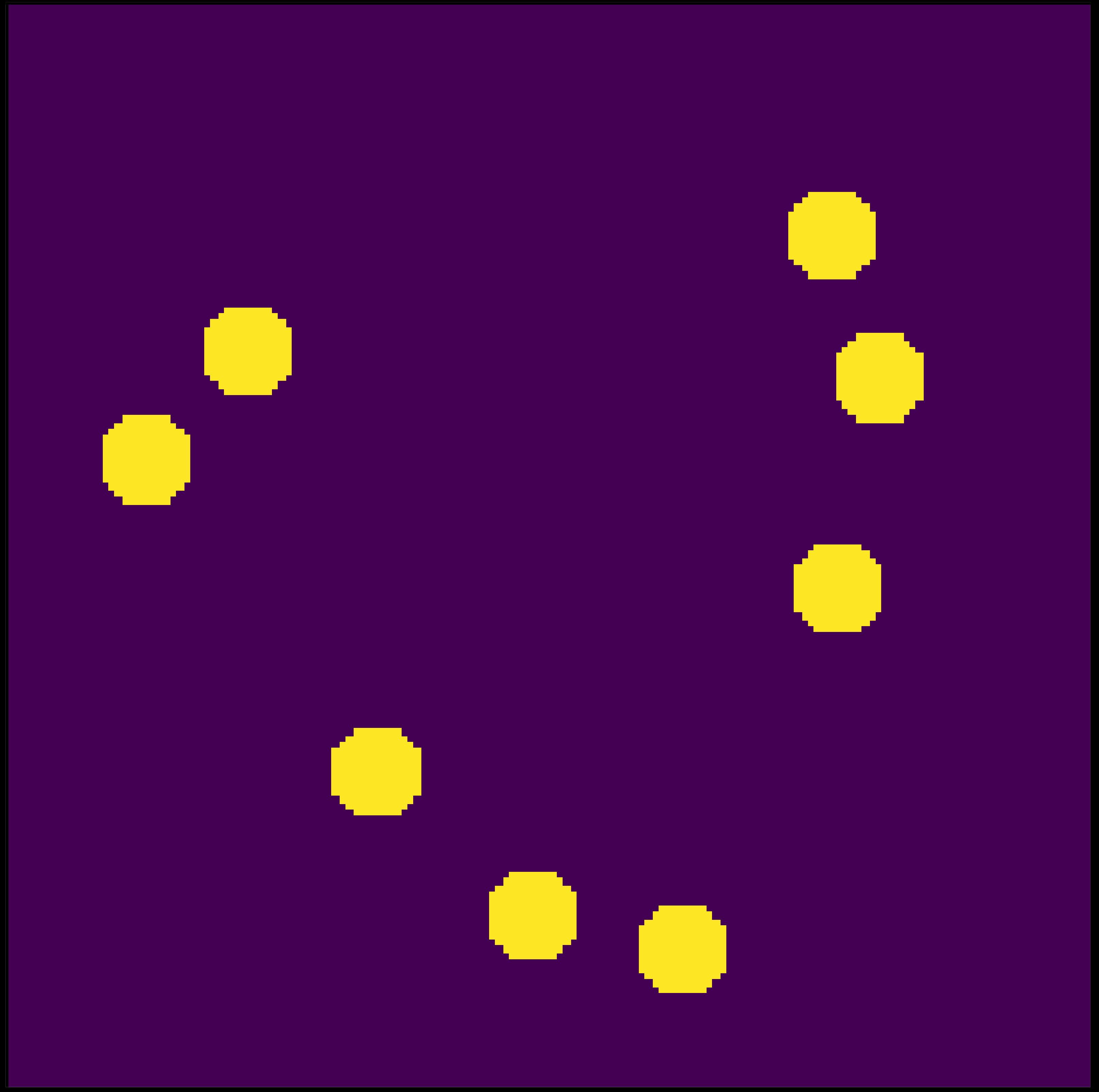

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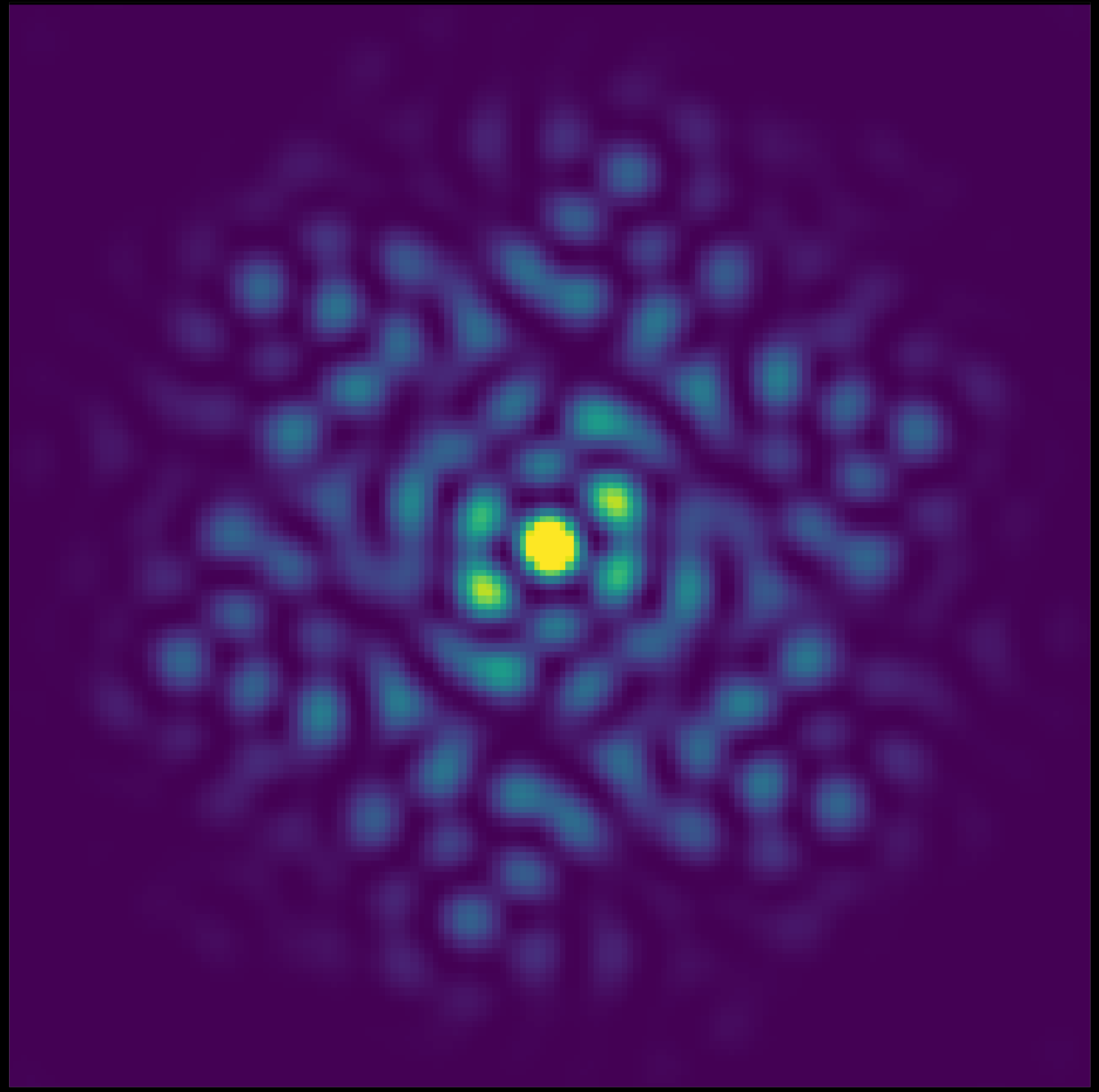

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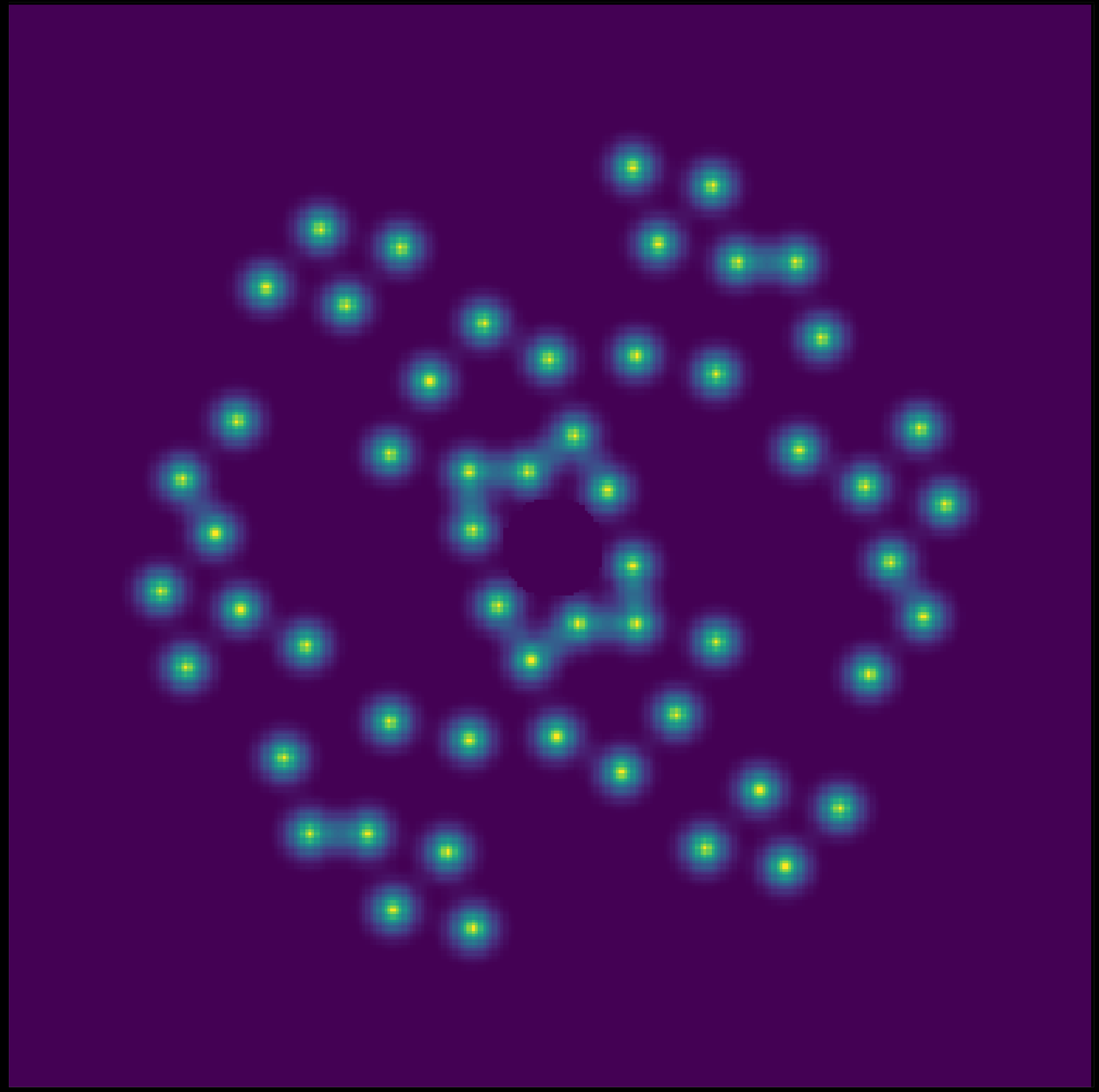

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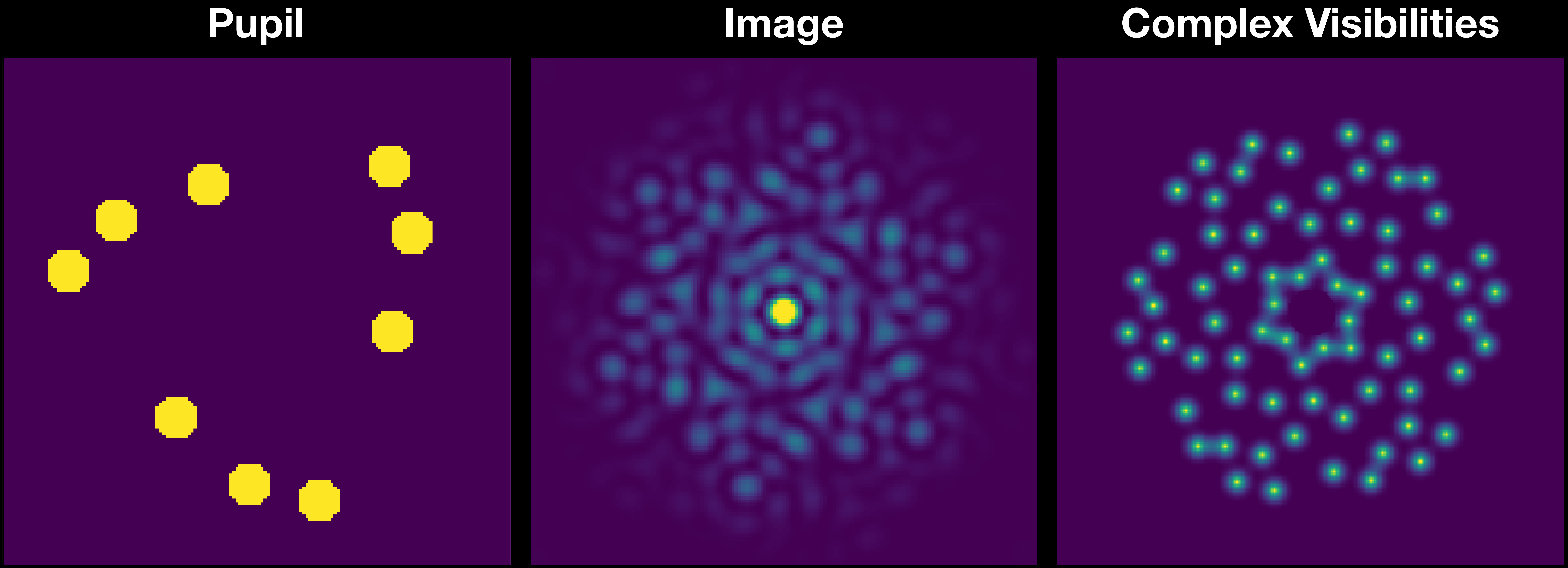
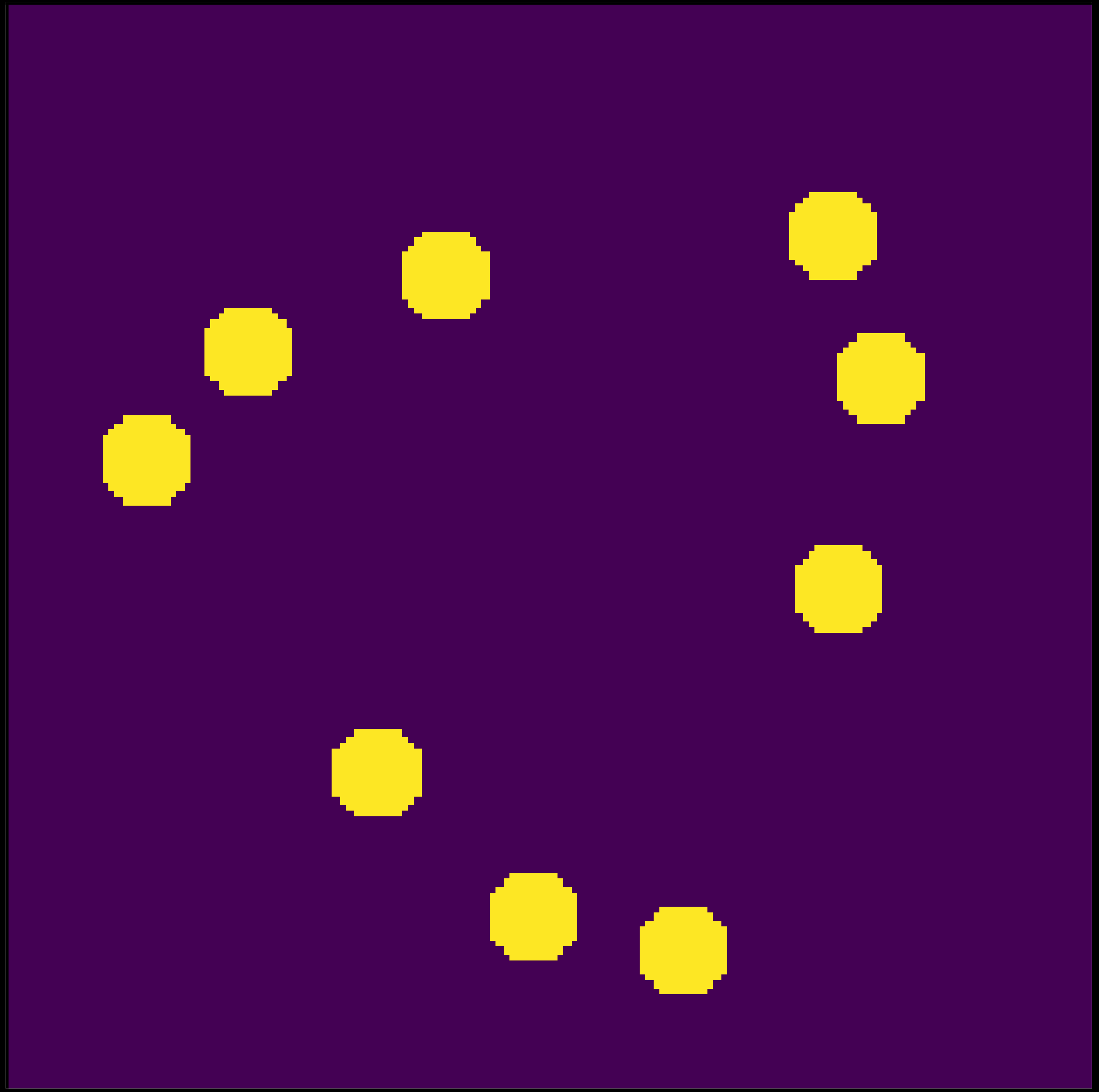


Non-Redundant Masking

Using NRM to measure stellar diameters was first suggested by Fizeau in 1868!

Pupil



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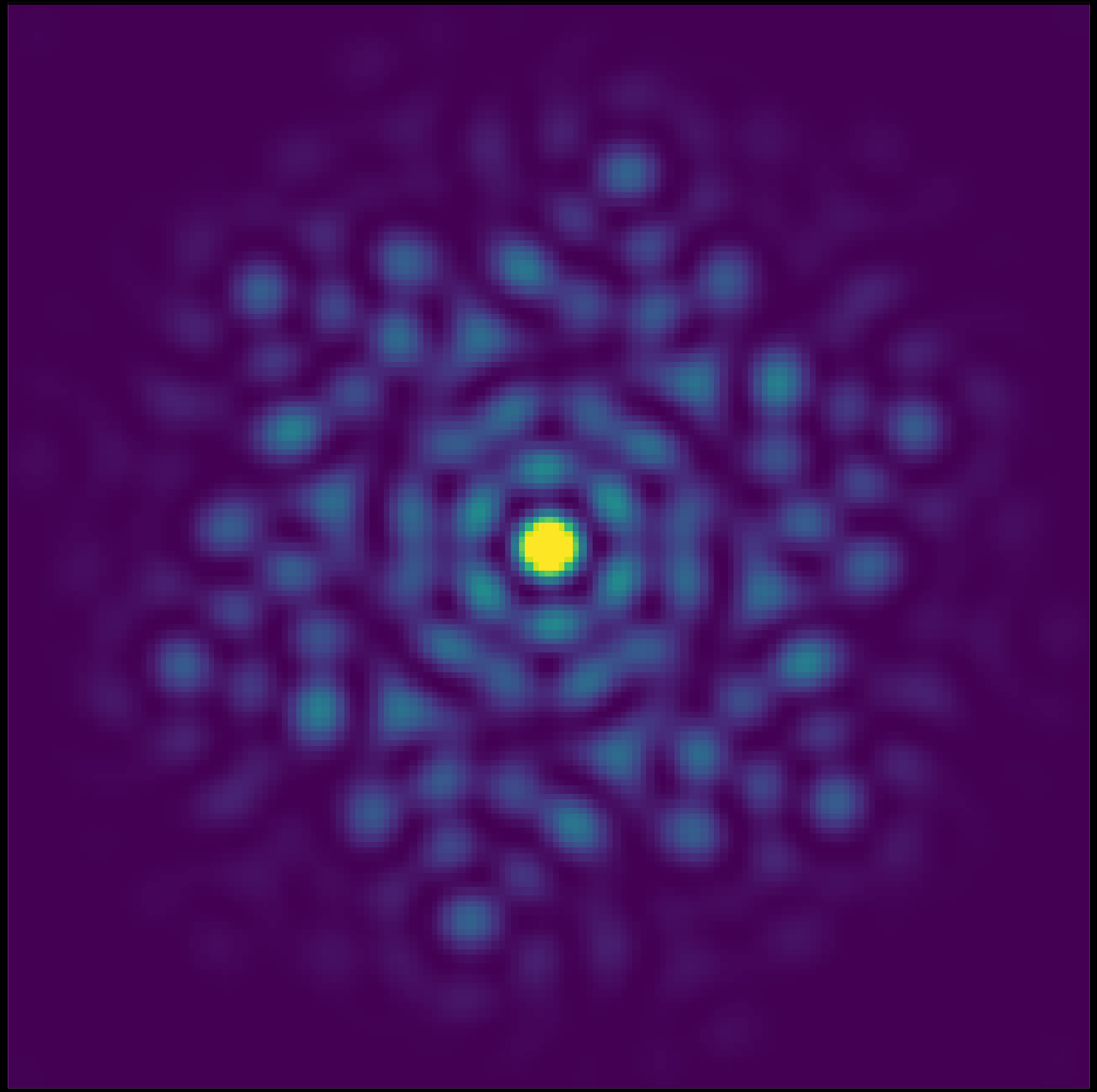

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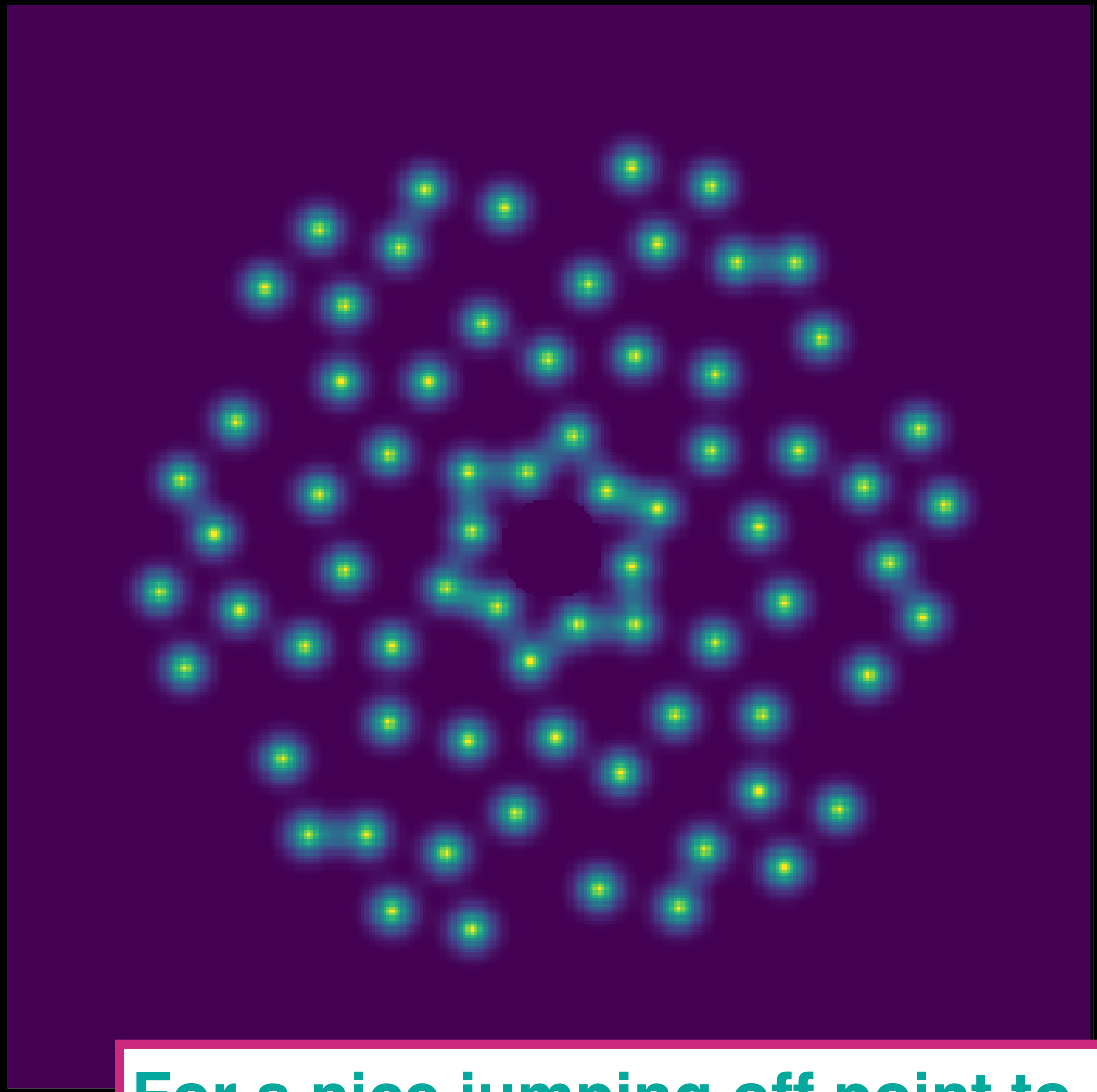
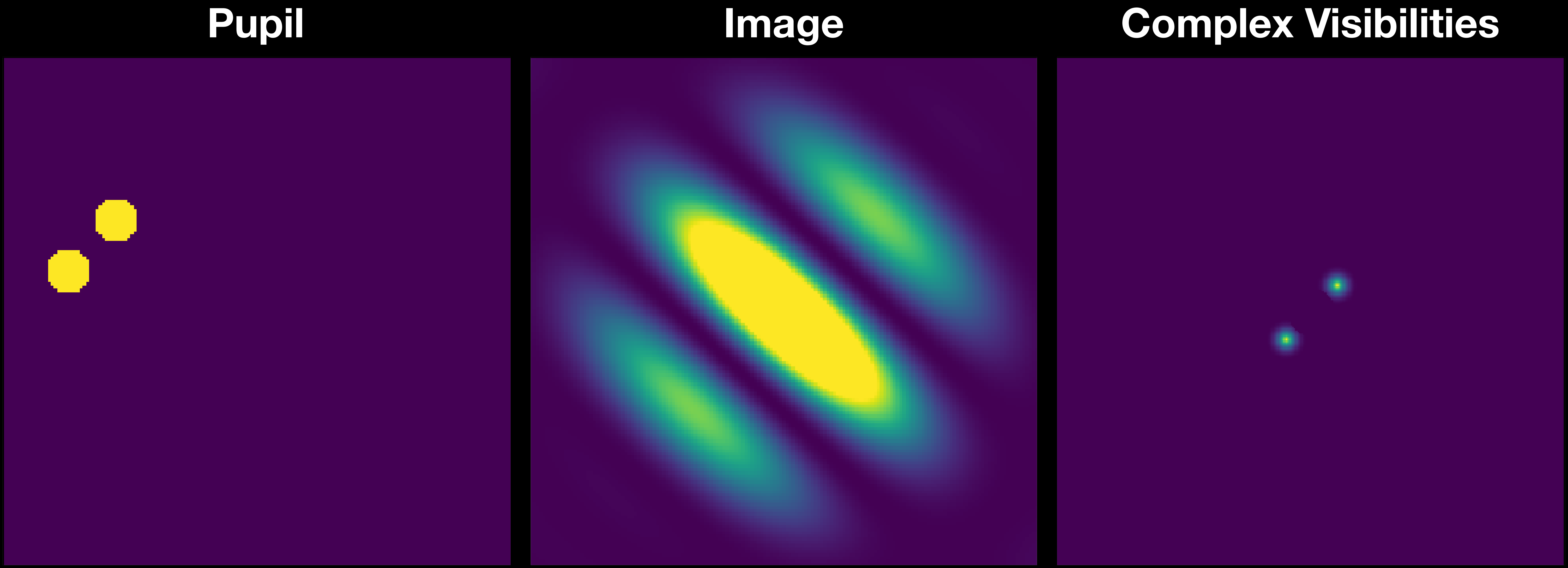


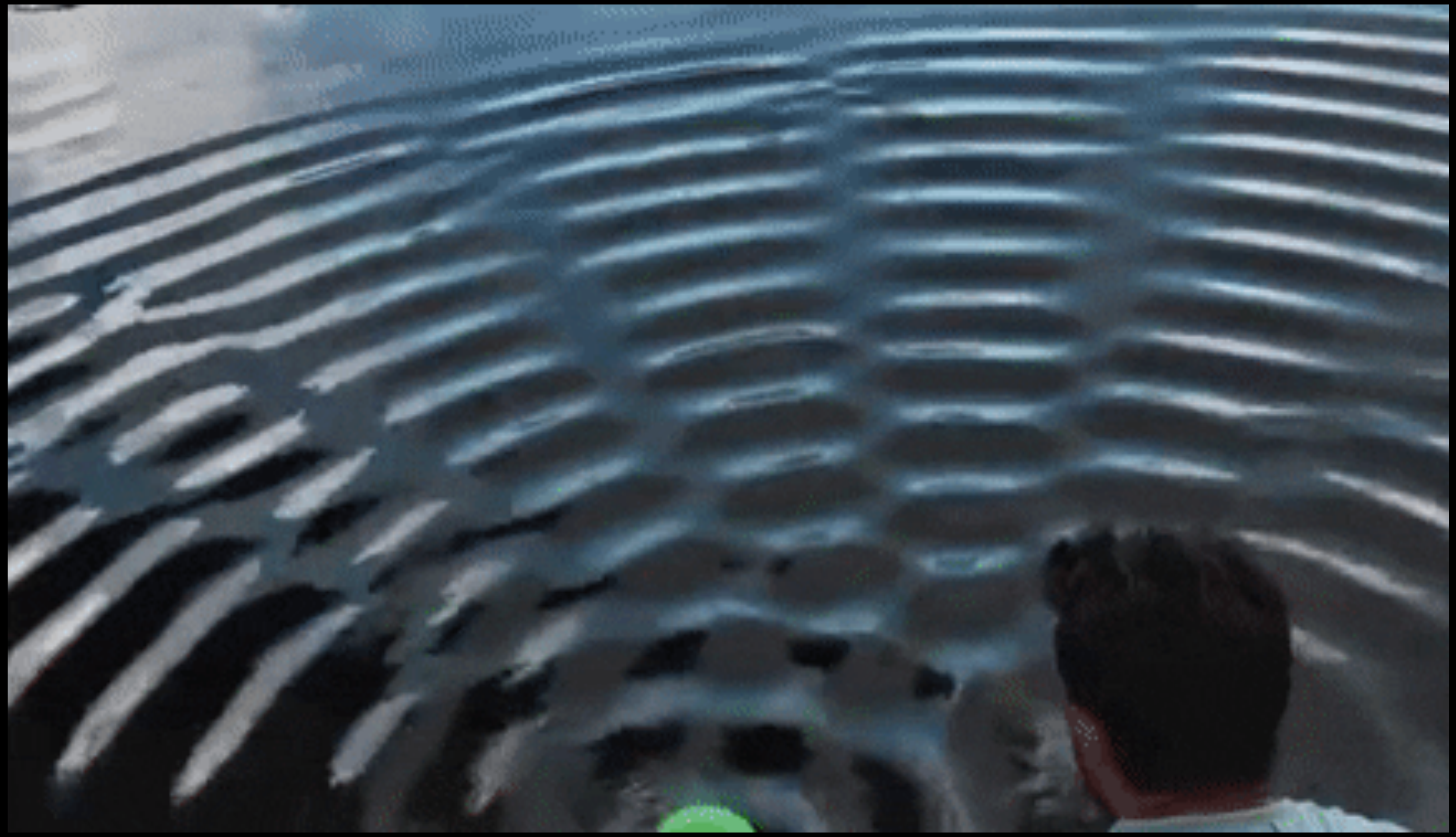
For a nice jumping off point to explore the history of AMI, see Tuthill 2012!

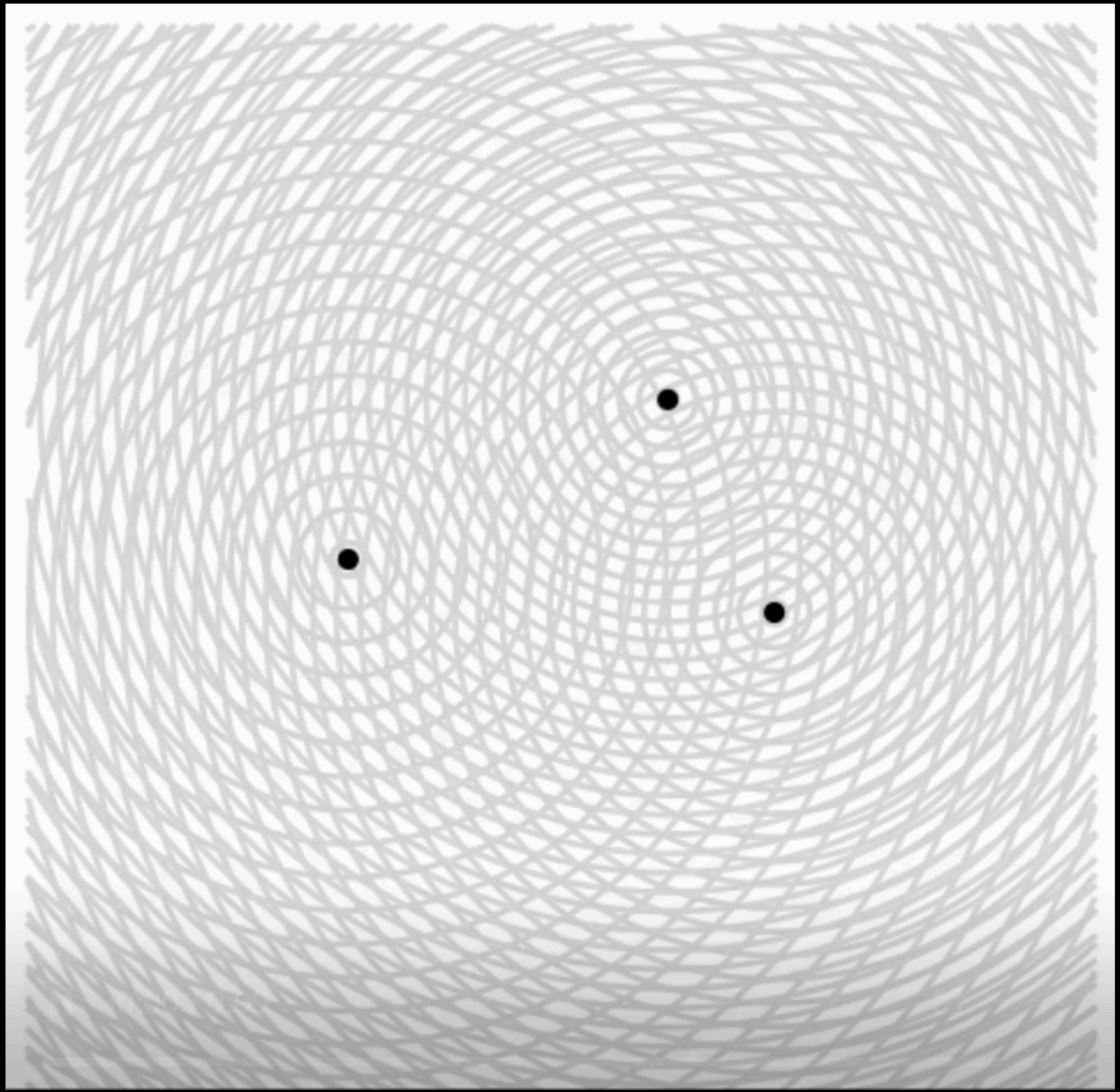
NRM fringes can be described by amplitude and phase.



Interpreting Interferometric Observables

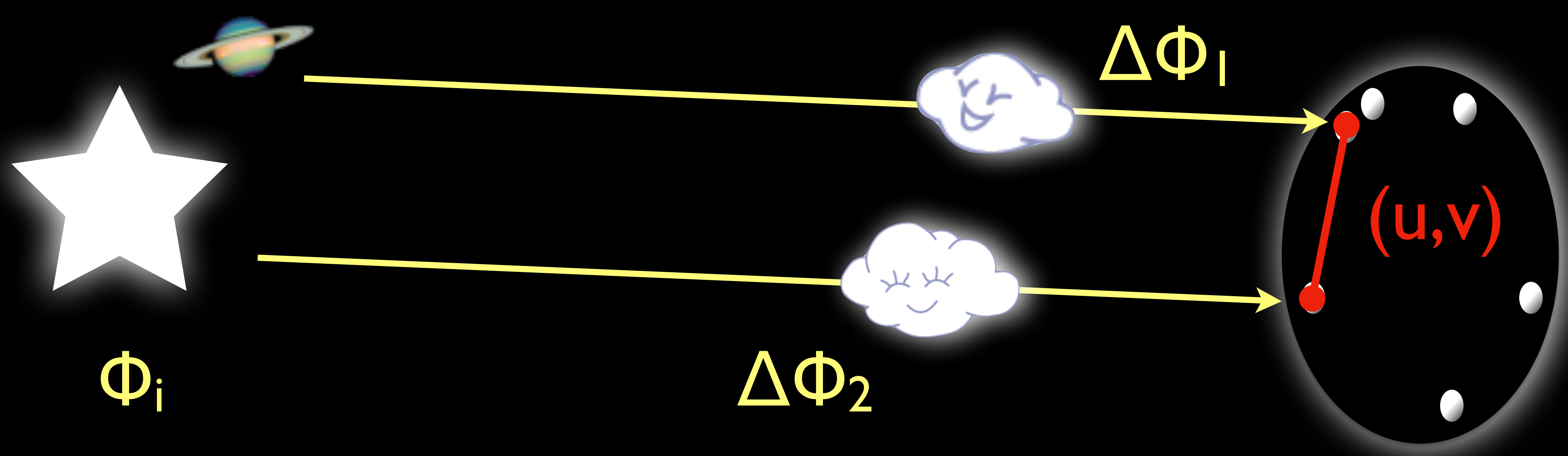
<u>van Cittert-Zernike Theorem:</u> the complex visibilities of an incoherent source at great distance are equal to the Fourier transform of the source brightness distribution

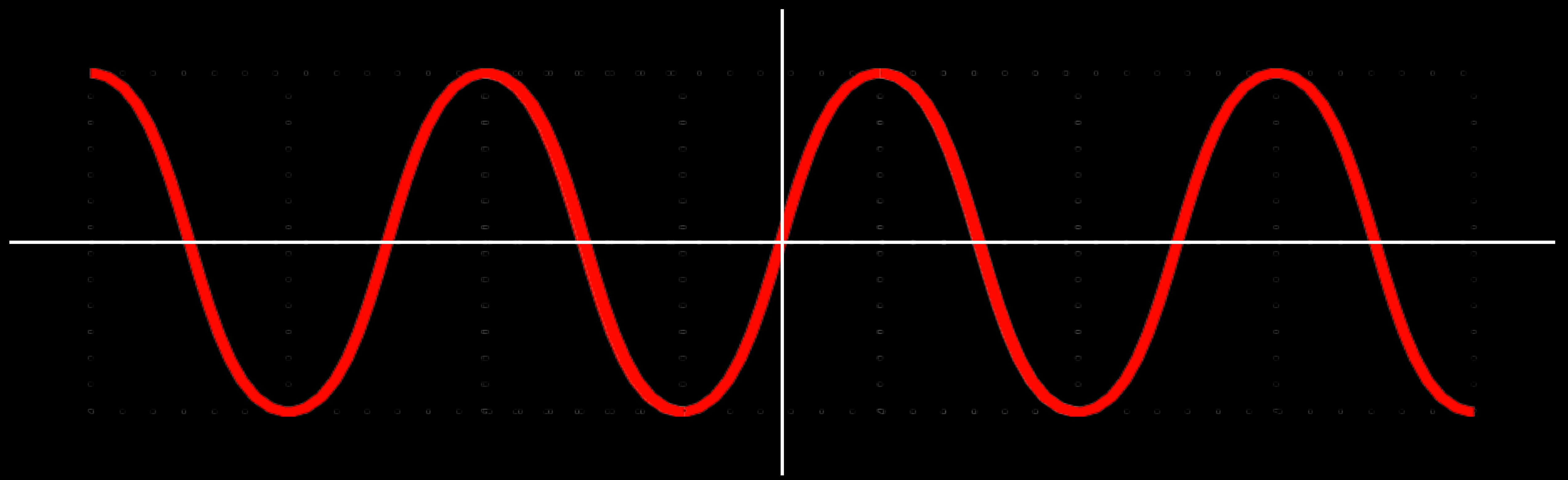


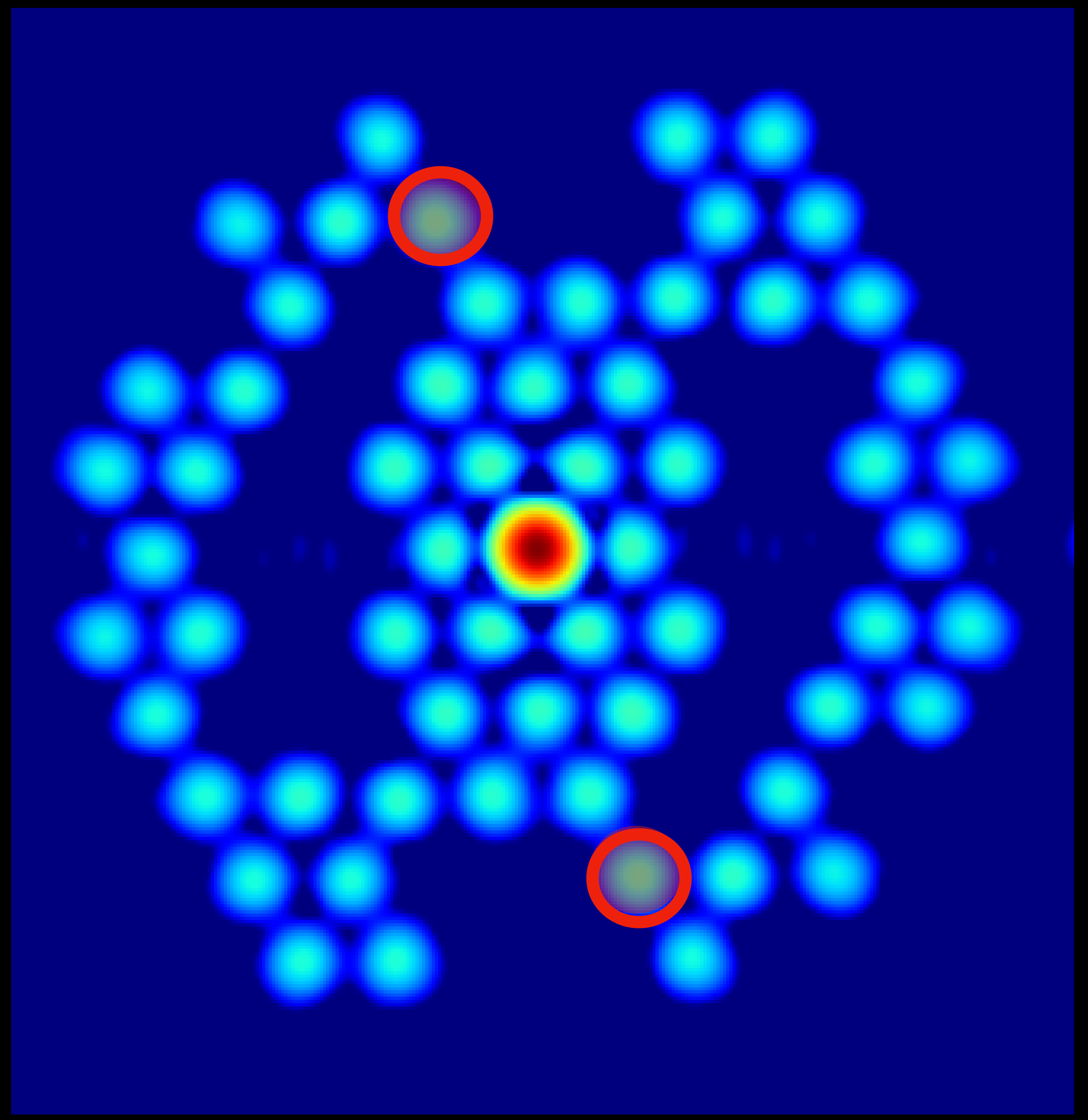


Source: Jacopo Bertolotti https://twitter.com/j_bertolotti/status/1674801693228417031?s=20

NRM observables are linear in instrumental phase…



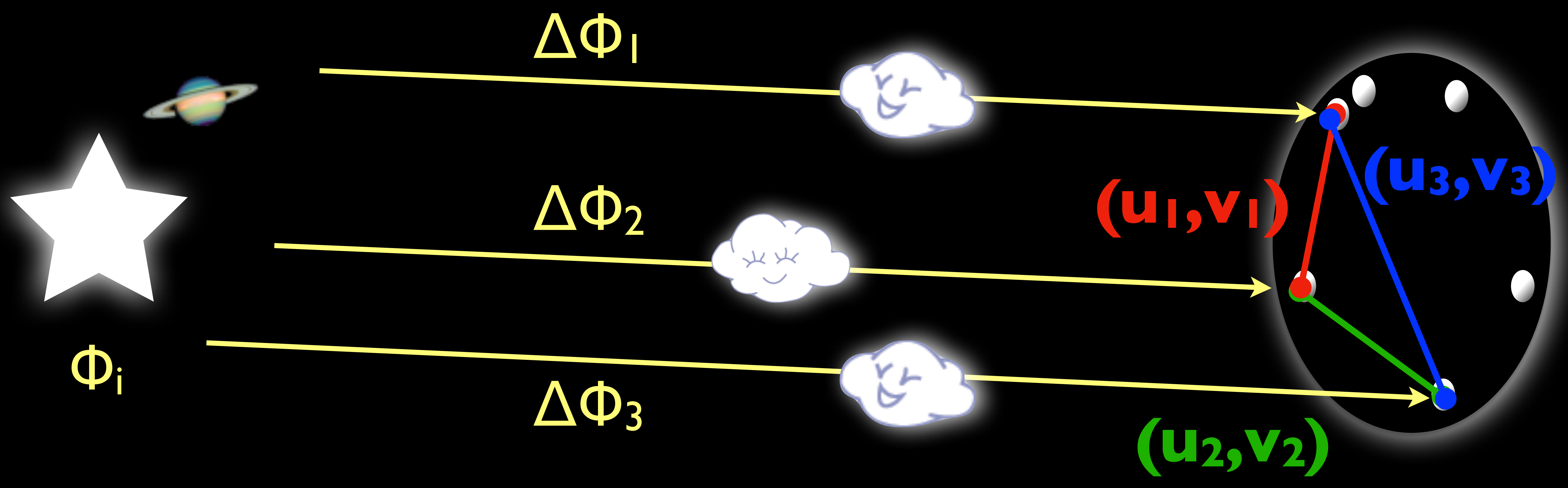


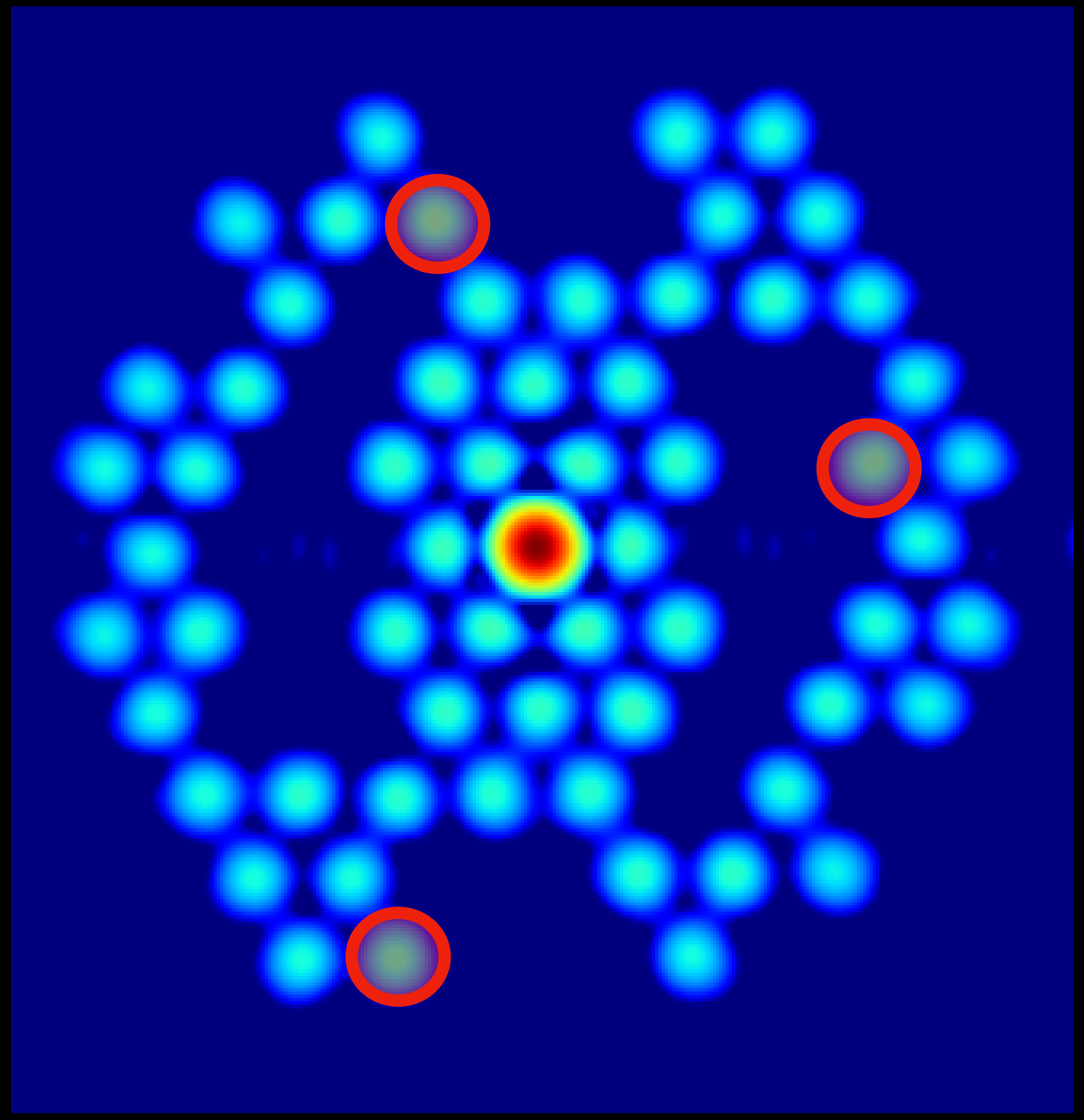


$$Ae^{i\Phi(u,v)} = Ae^{i[\Phi i + (\Delta\Phi 2 - \Delta\Phi 1)]}$$

$$\Phi(u_1,v_1) = \Phi i(u_1,v_1) + (\Delta\Phi_2 - \Delta\Phi_1)$$

…and closure phases are robust to instrumental phase.



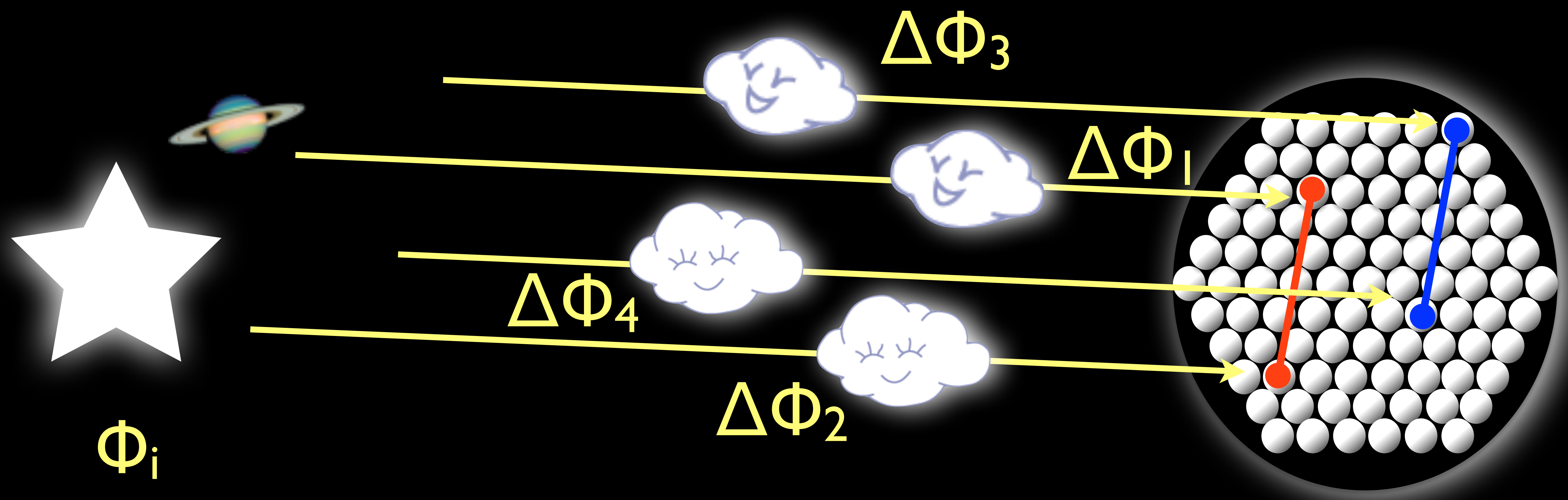


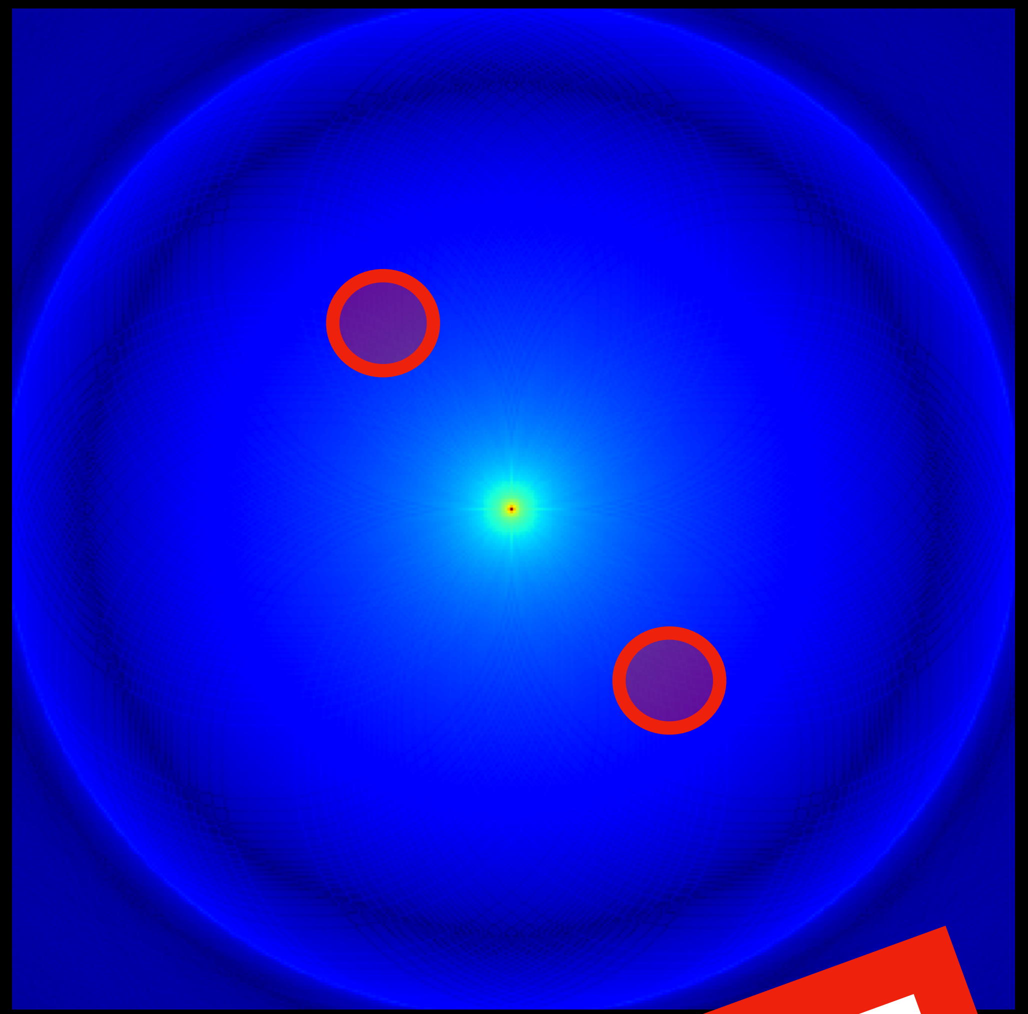
$$\Phi(u_1,v_1) = \Phi i(u_1,v_1) + (\Delta\Phi_2 - \Delta\Phi_1)$$
$$+\ \Phi(u_2,v_2) = \Phi i(u_2,v_2) + (\Delta\Phi_3 - \Delta\Phi_2)$$
$$+\ \Phi(u_3,v_3) = \Phi i(u_3,v_3) + (\Delta\Phi_1 - \Delta\Phi_3)$$

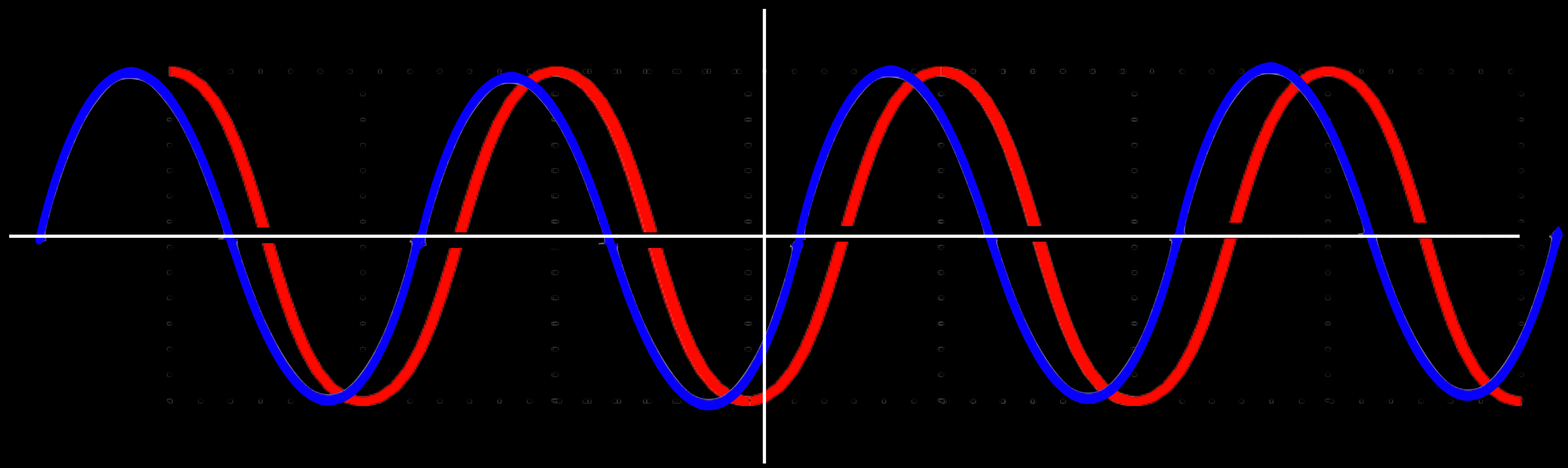
$$\Phi(u_1,v_1)+\Phi(u_2,v_2)+\Phi(u_3,v_3) = \Phi i(u_1,v_1)+\Phi i(u_2,v_2)+\Phi i(u_3,v_3)$$

For a thorough discussion of phase errors in AMI, see Ireland 2013.

What about a redundant aperture?







$Ae^{i\Phi(u,v)}$ = … - ΔΦ1)]

…]

Φ(u … (ΔΦ2 -

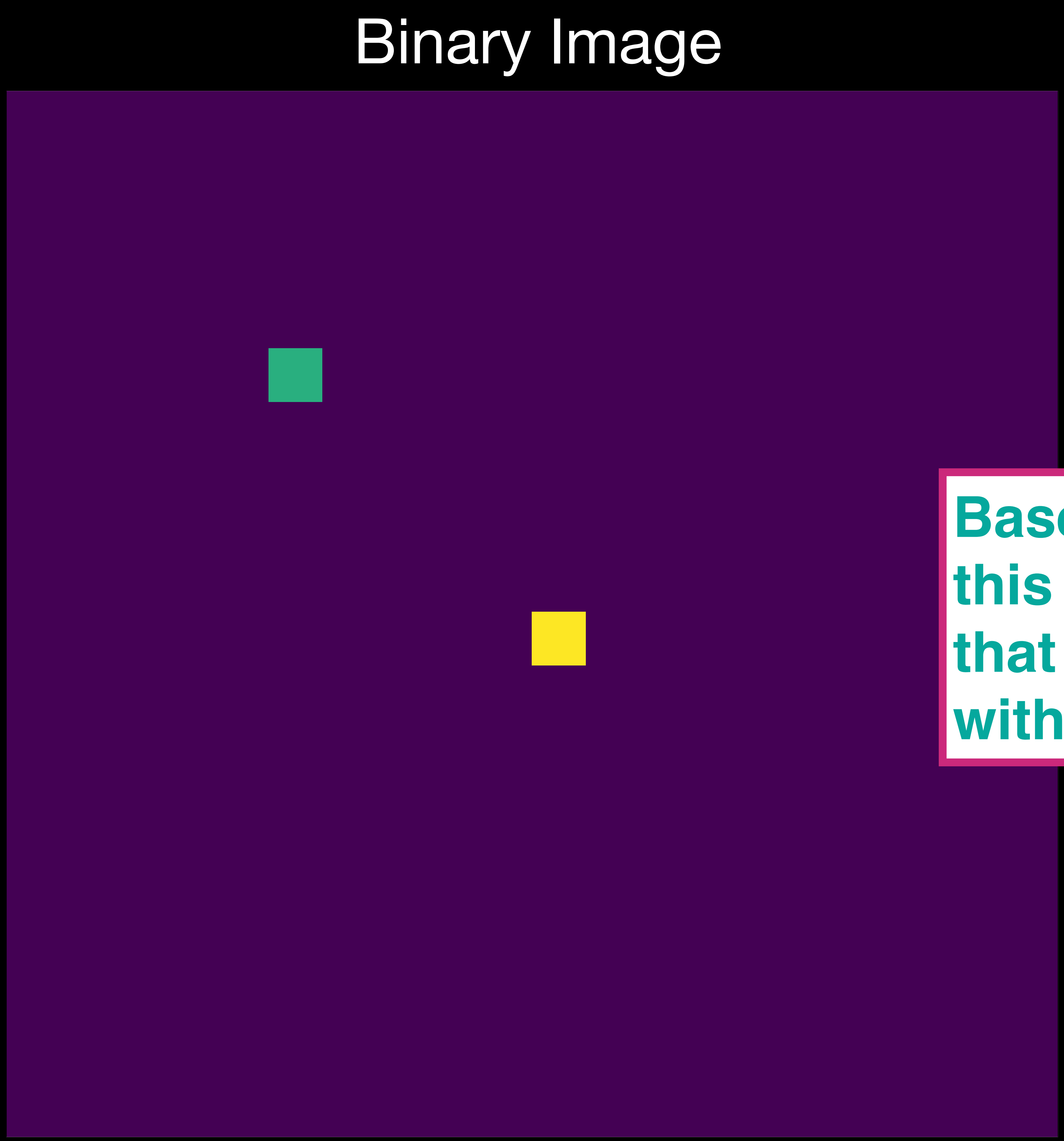
ΔΦ1)… (ΔΦ4 - ΔΦ3)]}

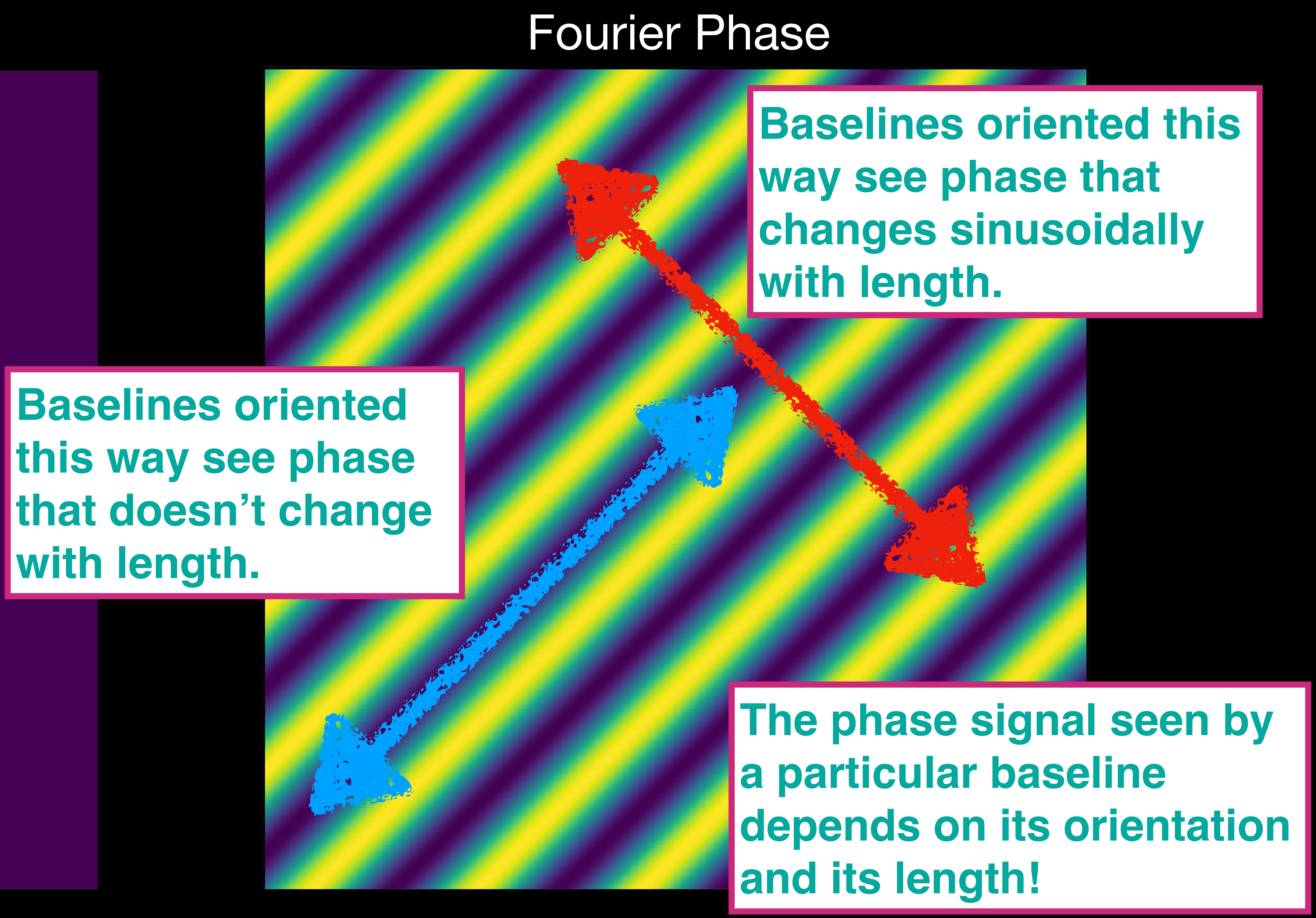
Not linear in instrumental phase :(

Note: Kernel phase interferometry can overcome this issue if you have high image quality! (Ask me after!)

Interpreting NRM Observables: Closure Phases

(Sums of) Fourier Phases Intrinsic to the Source





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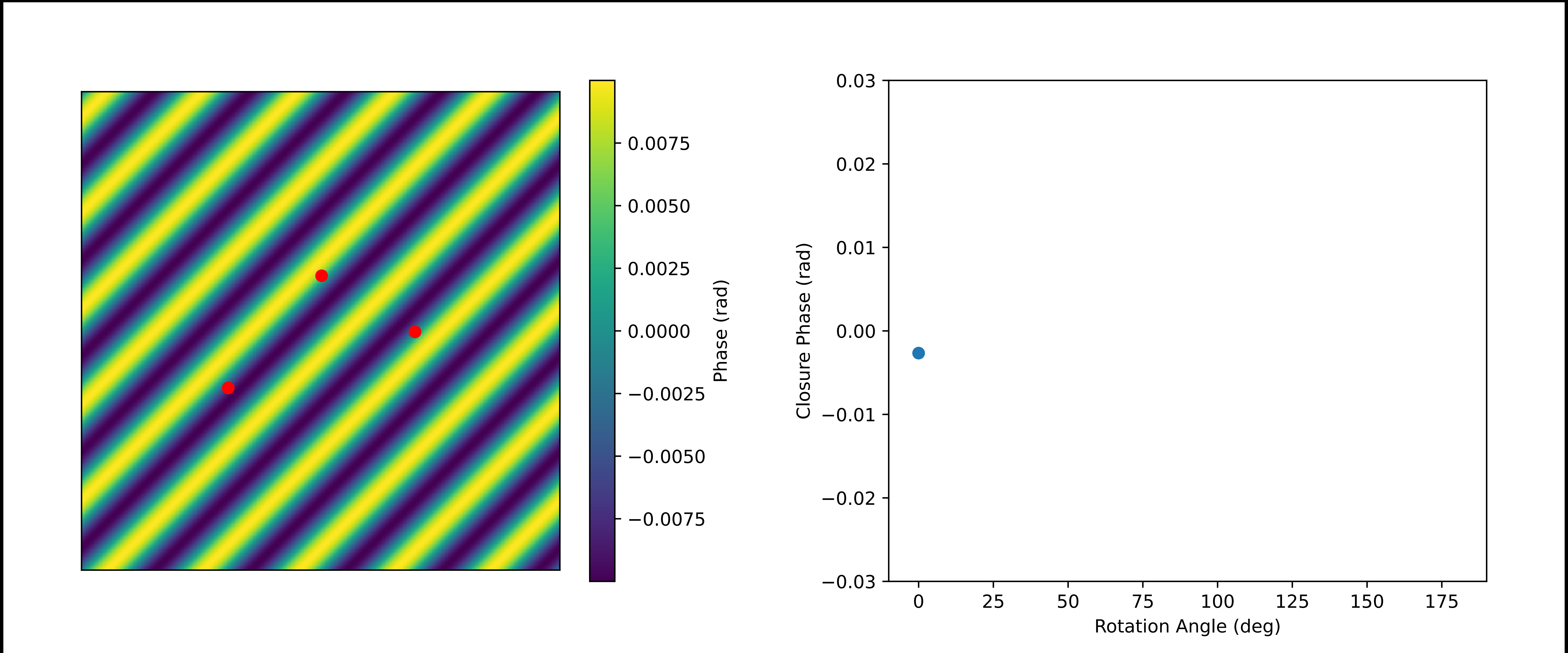

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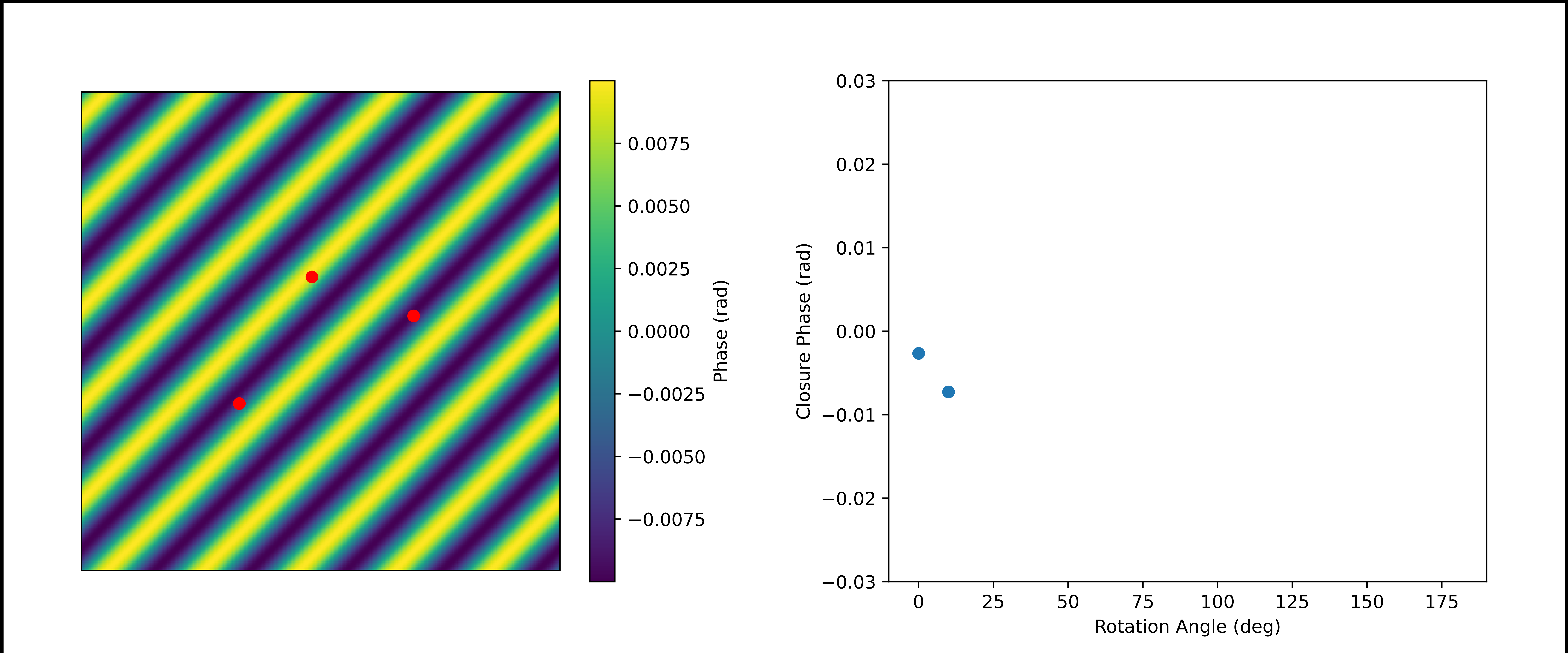

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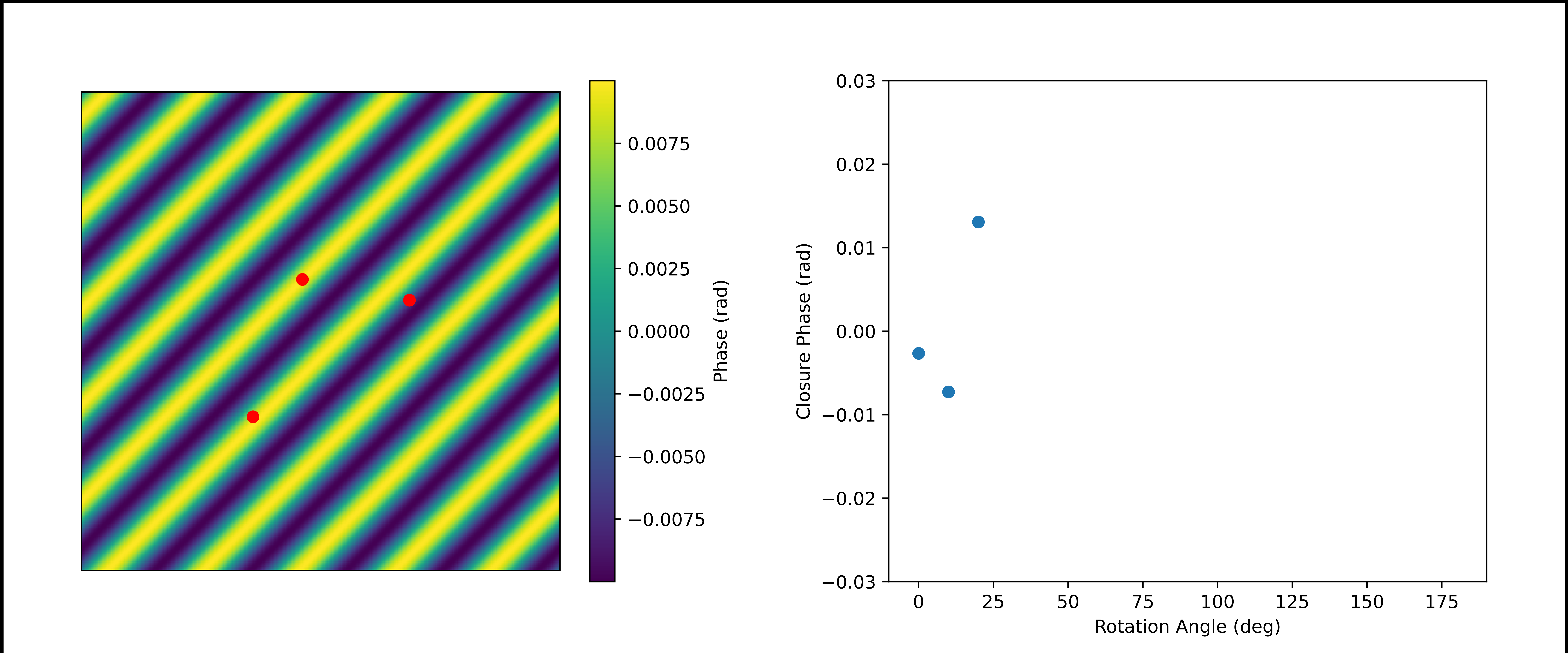

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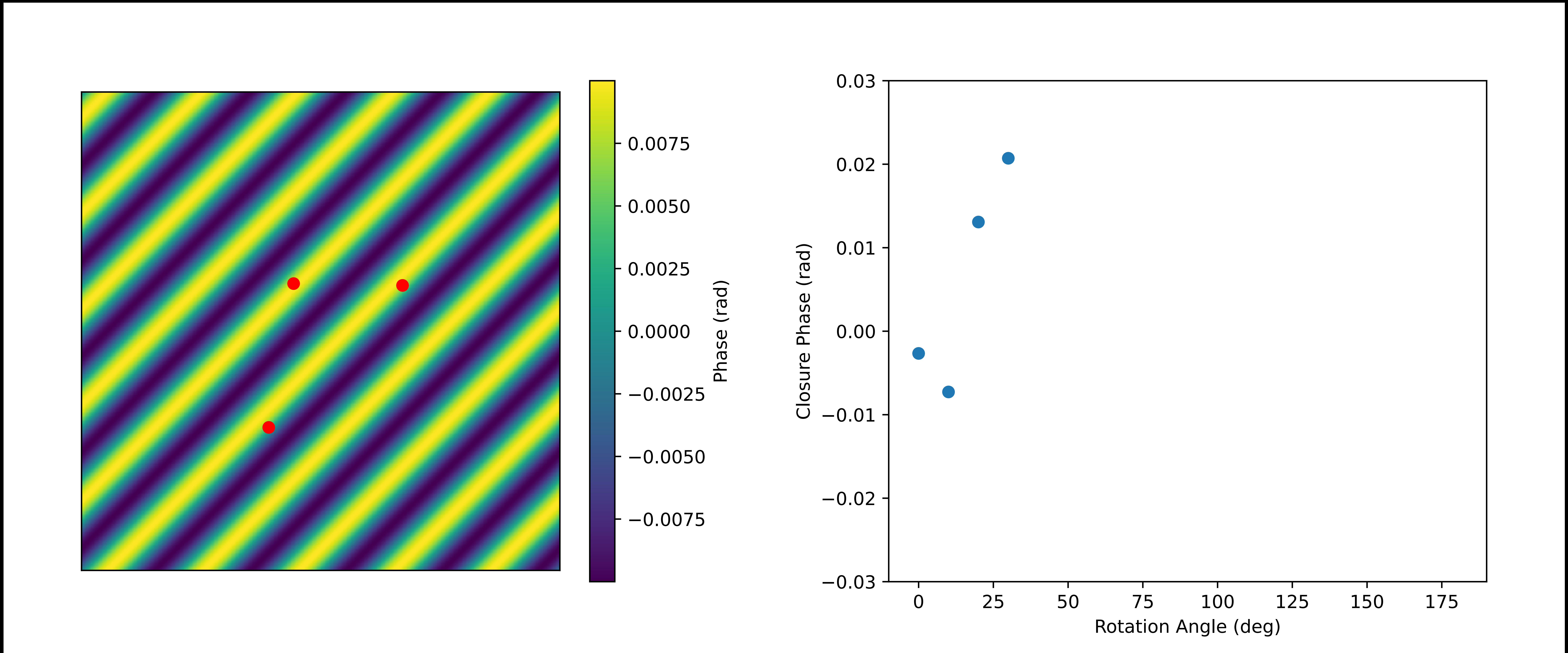

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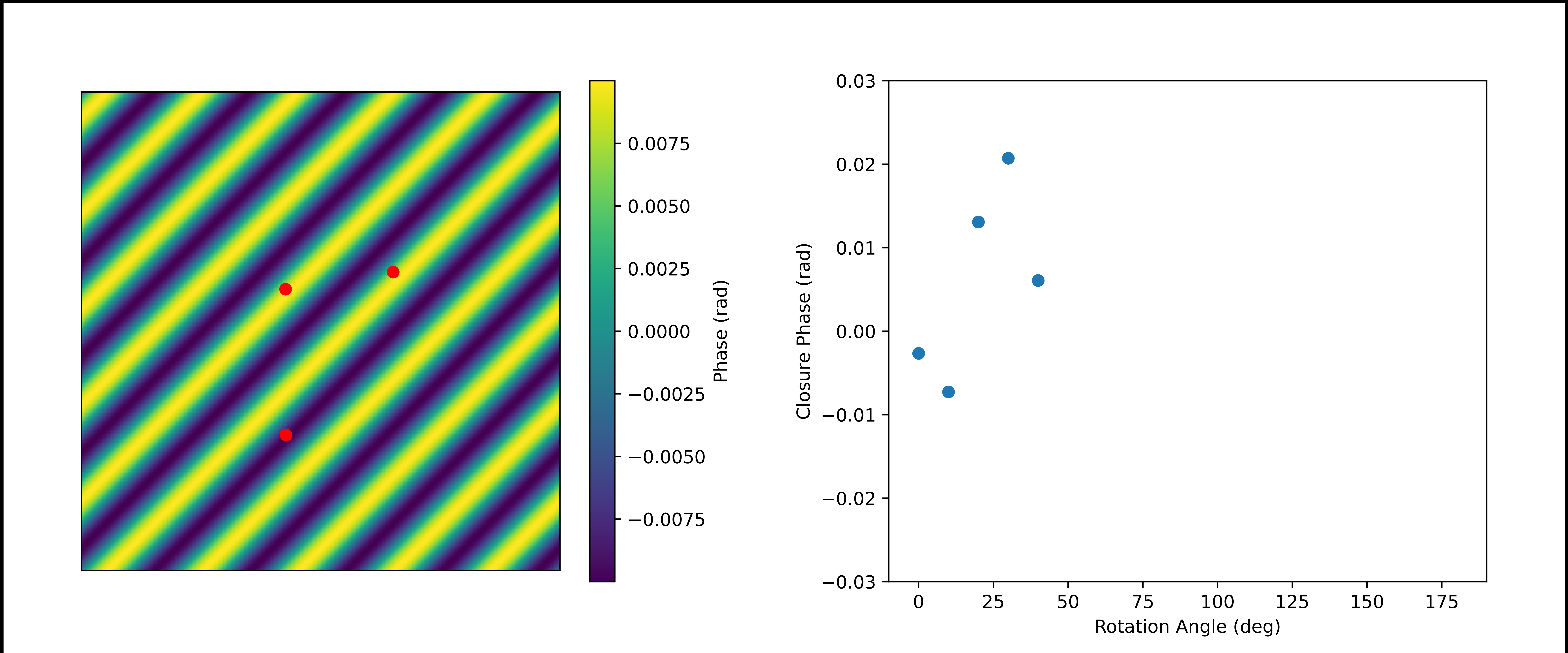

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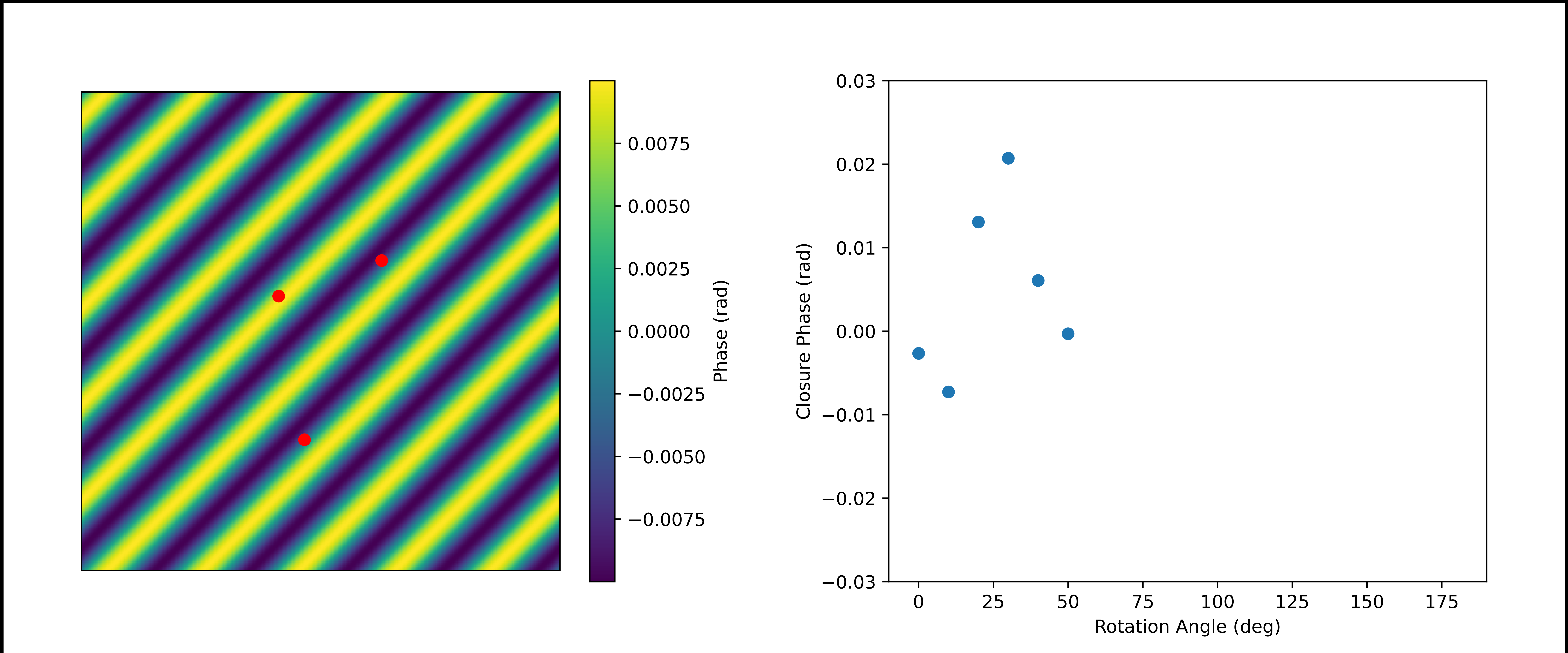

Interpreting NRM Observables: Closure Phases

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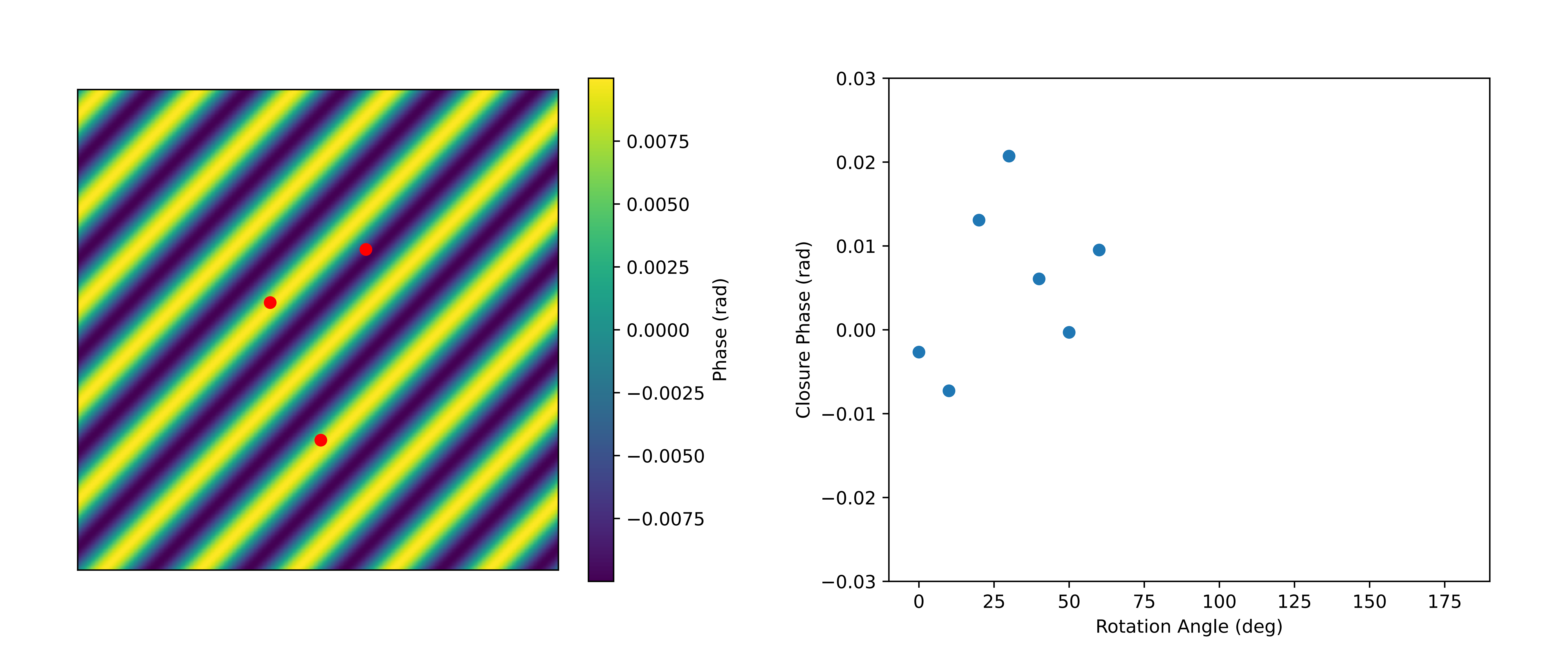

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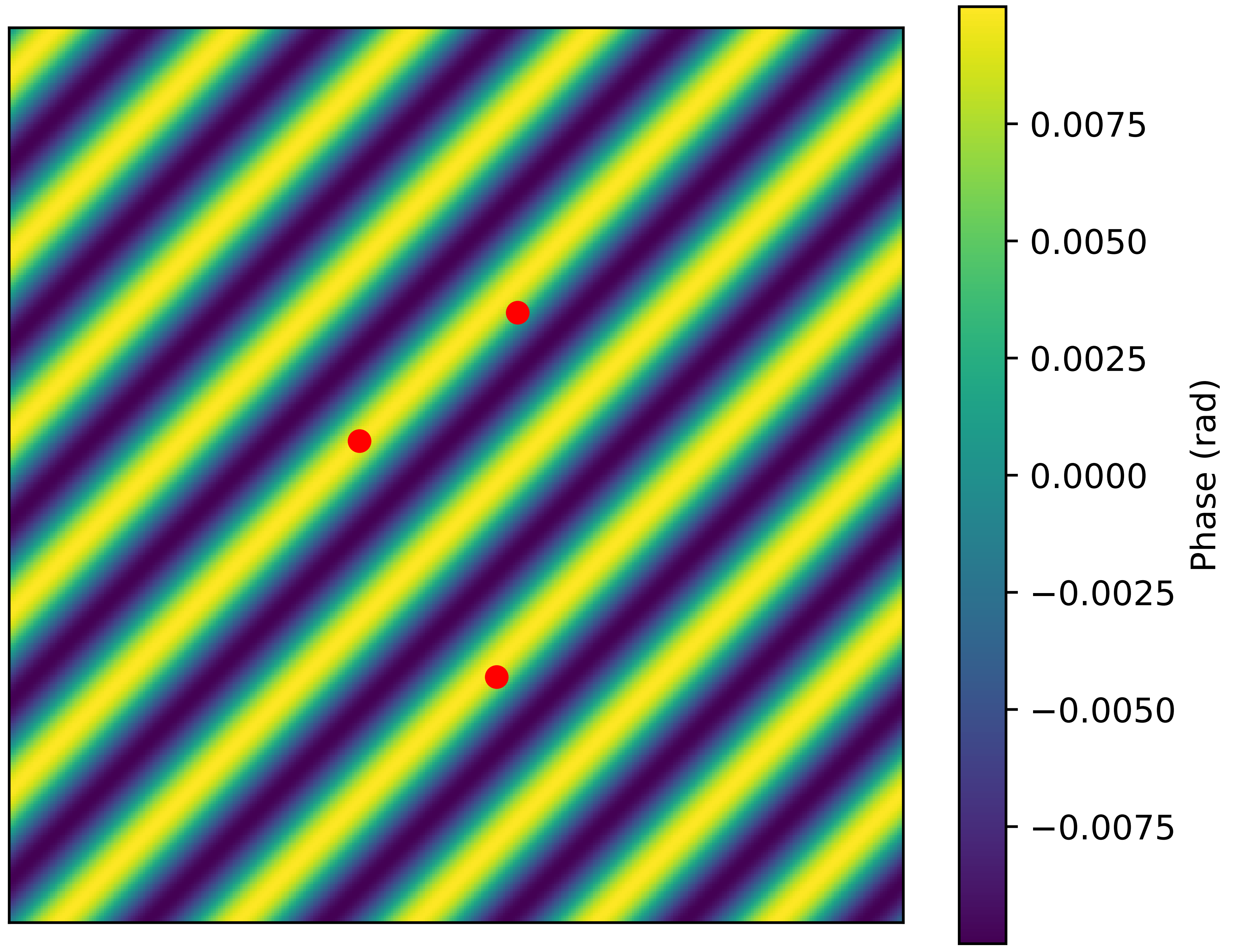

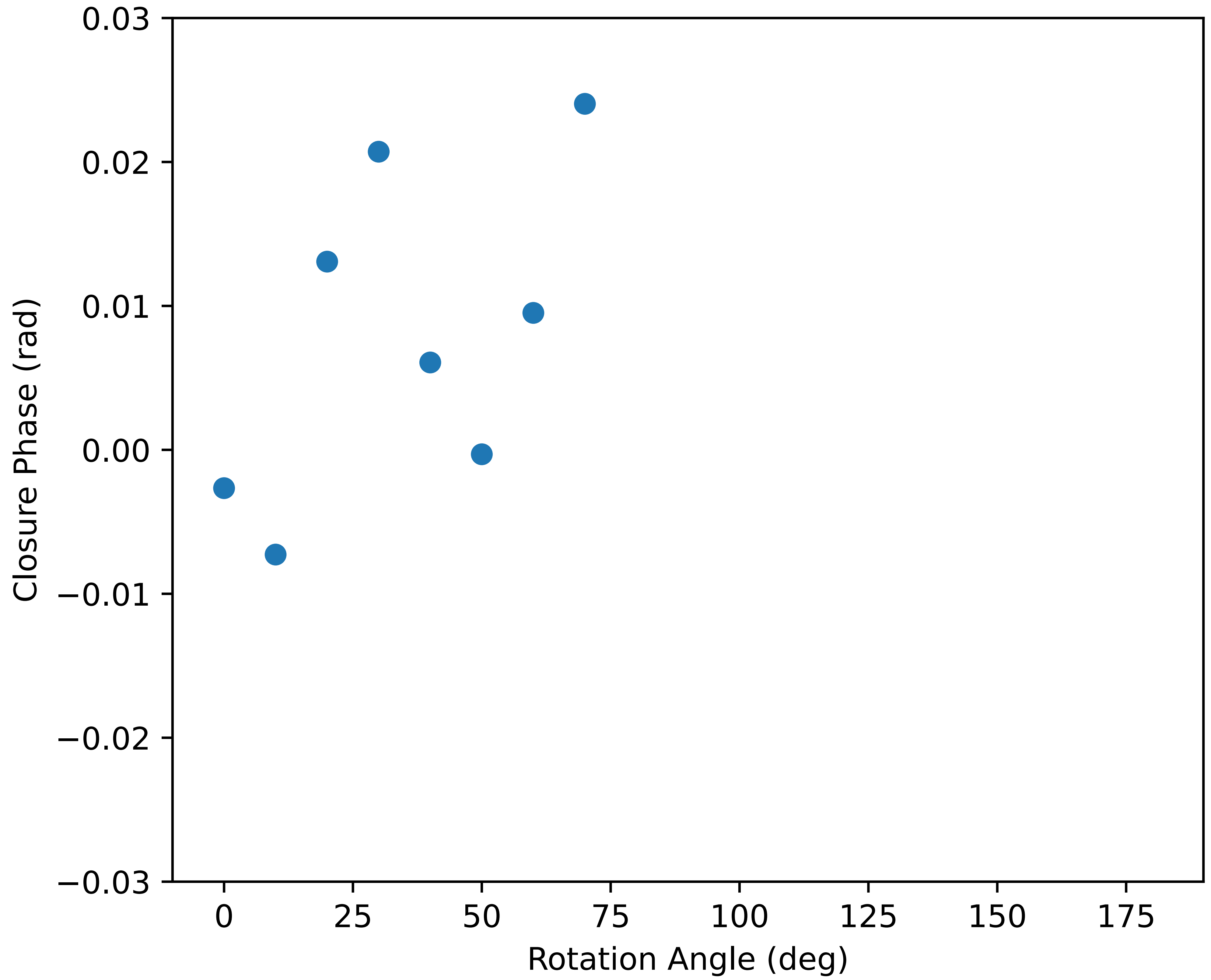

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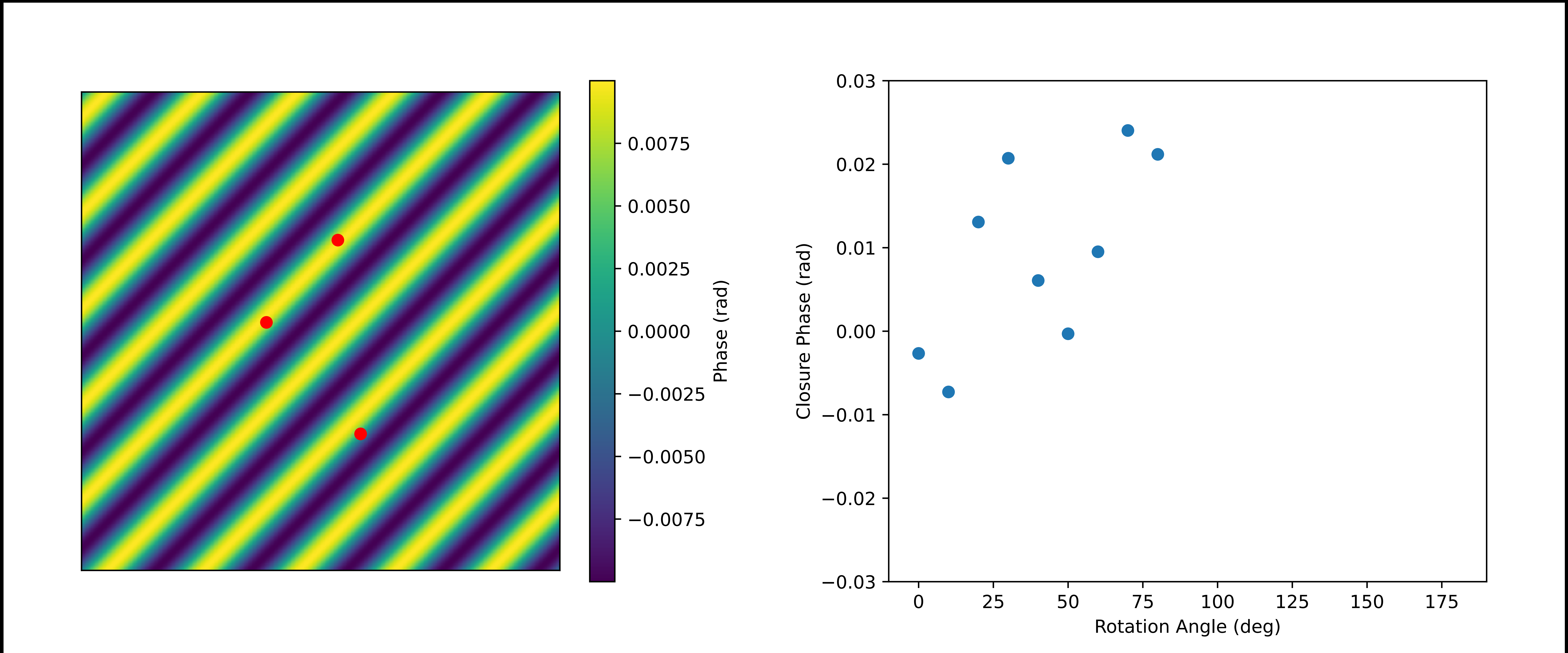

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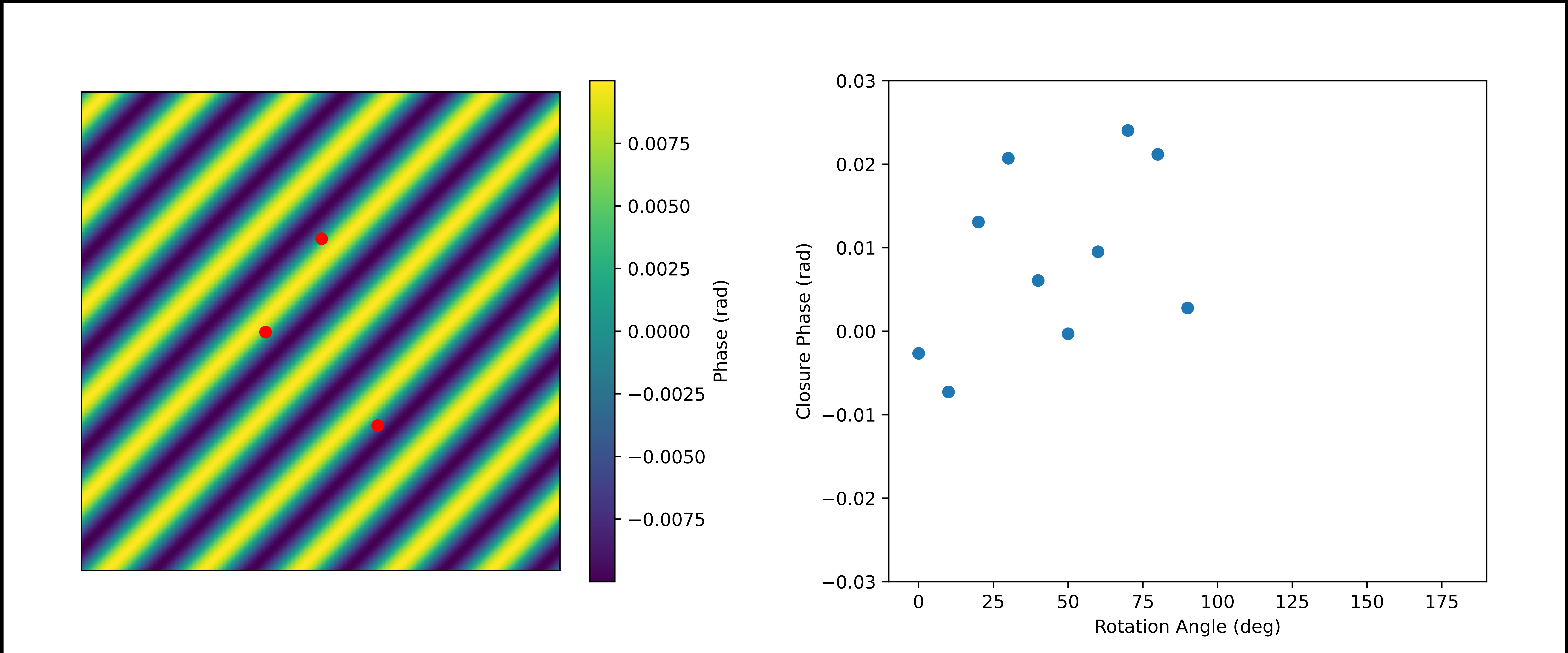

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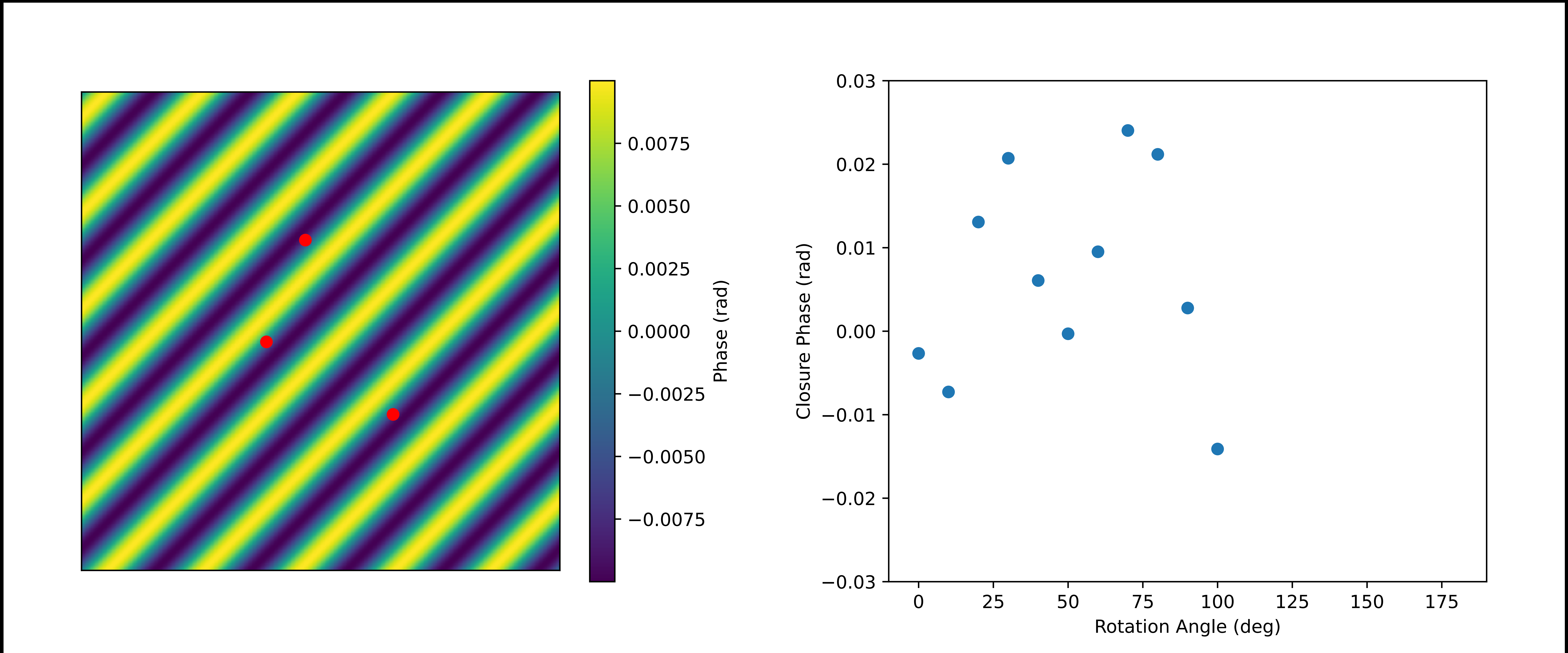

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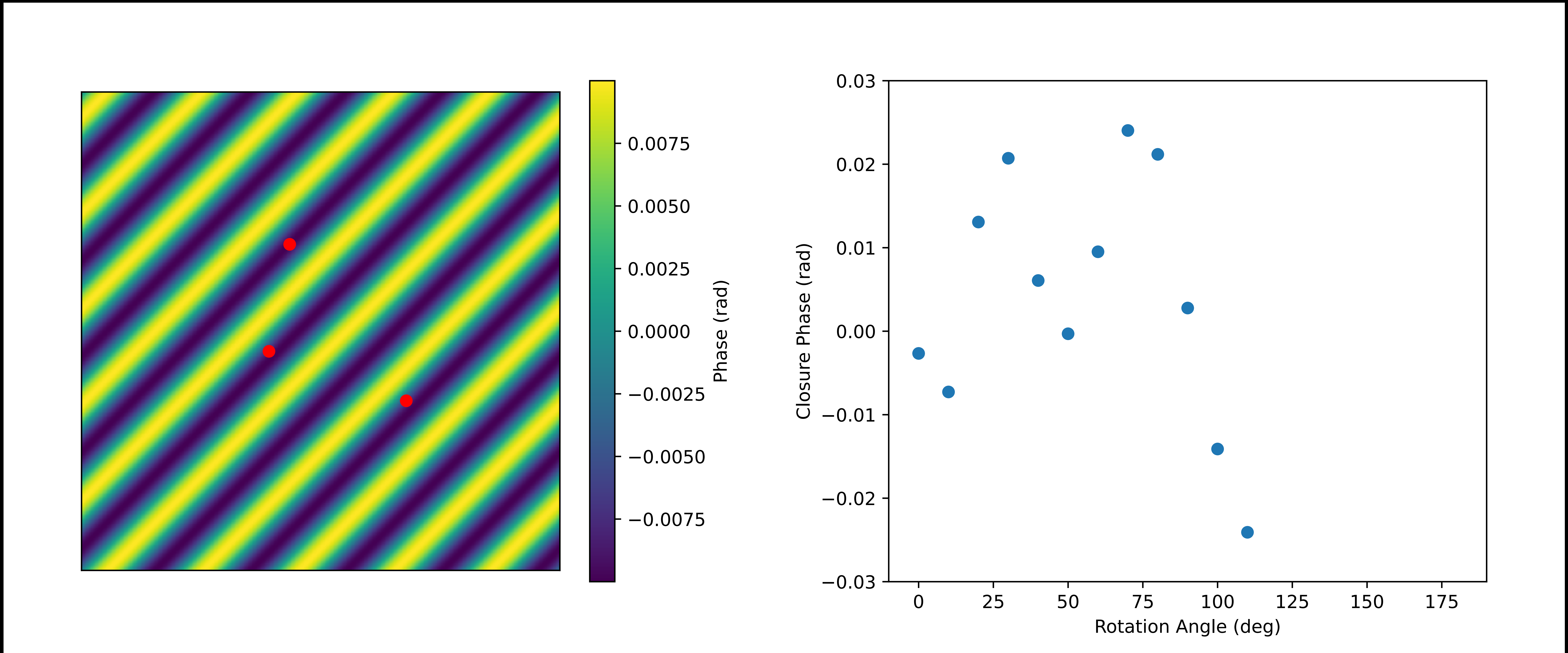

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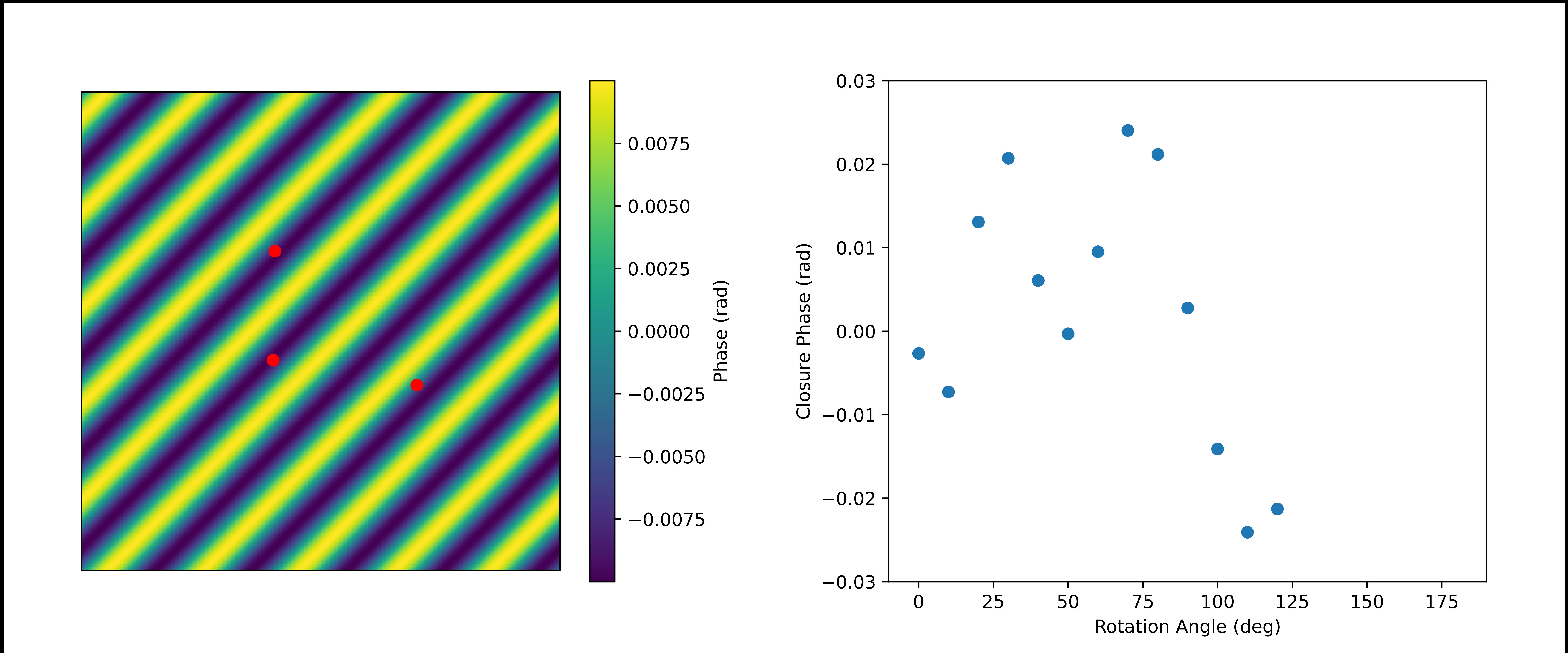

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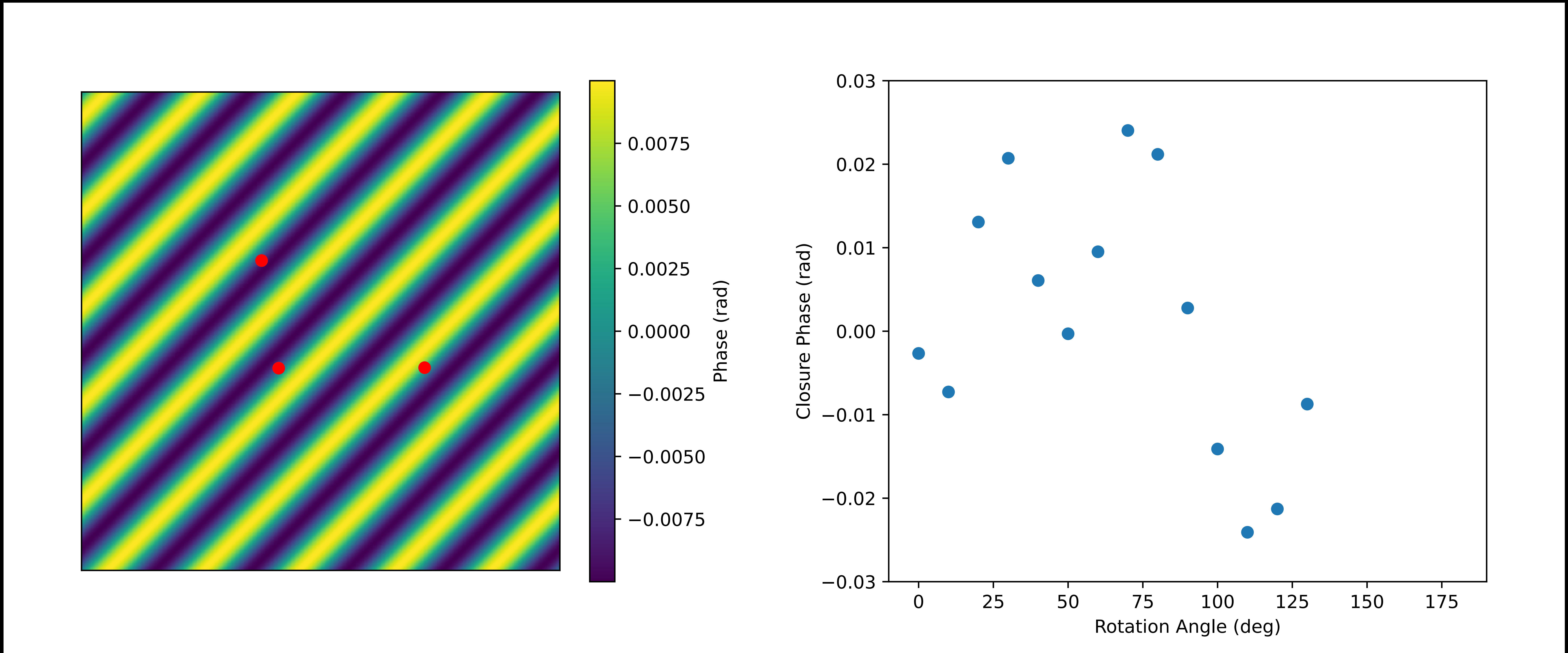

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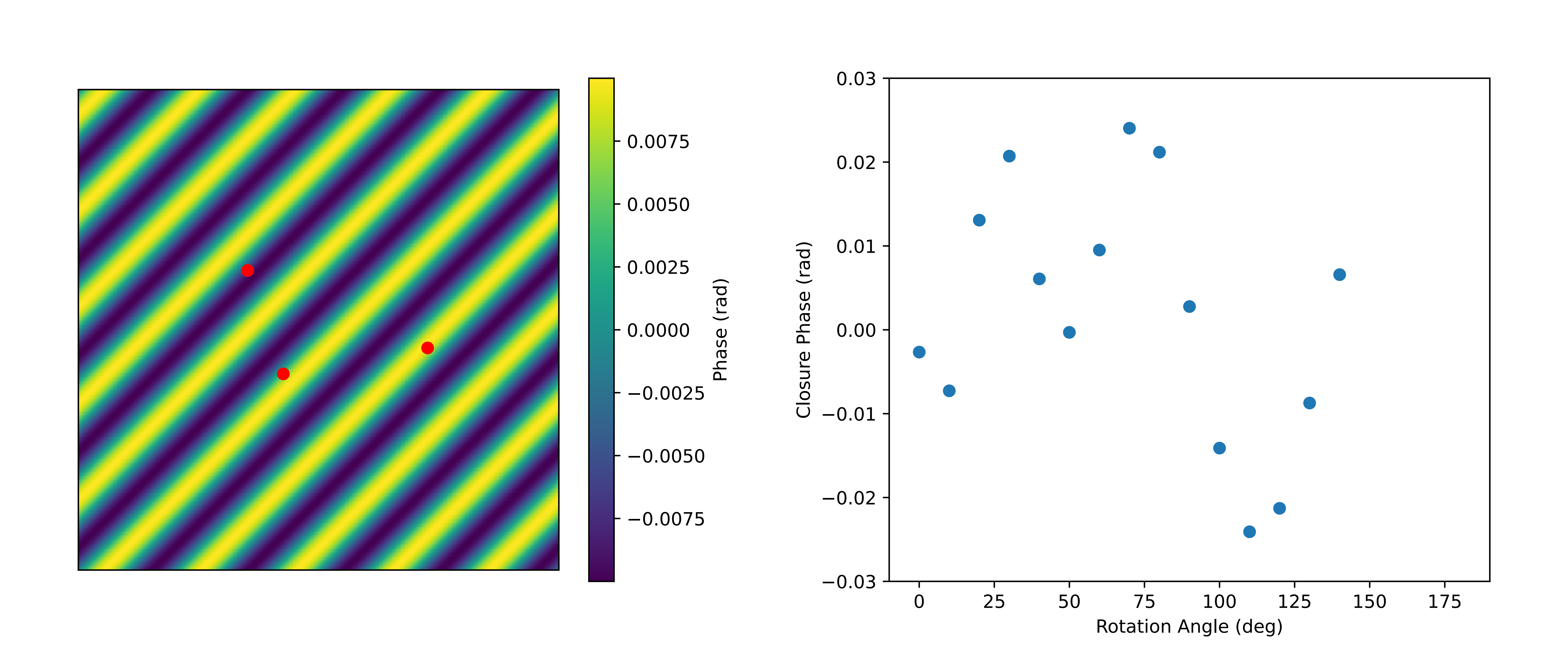

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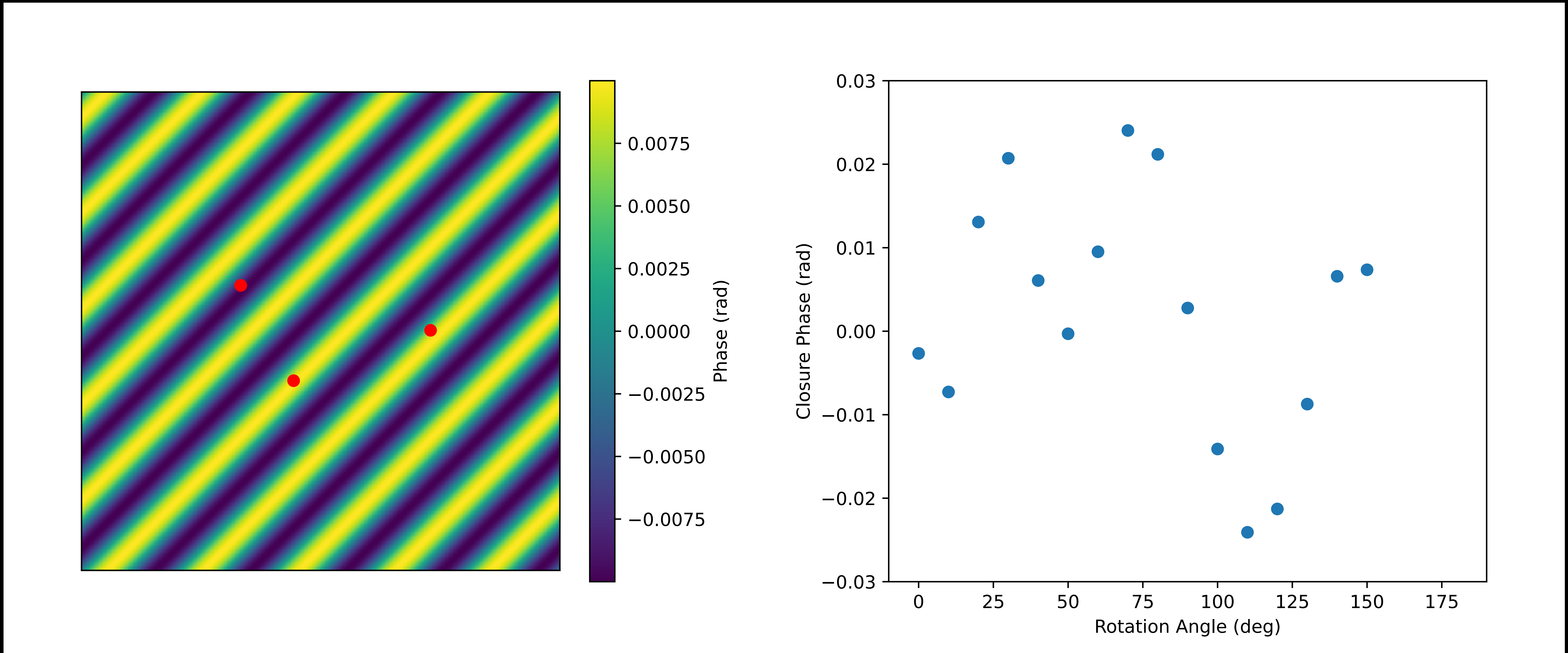

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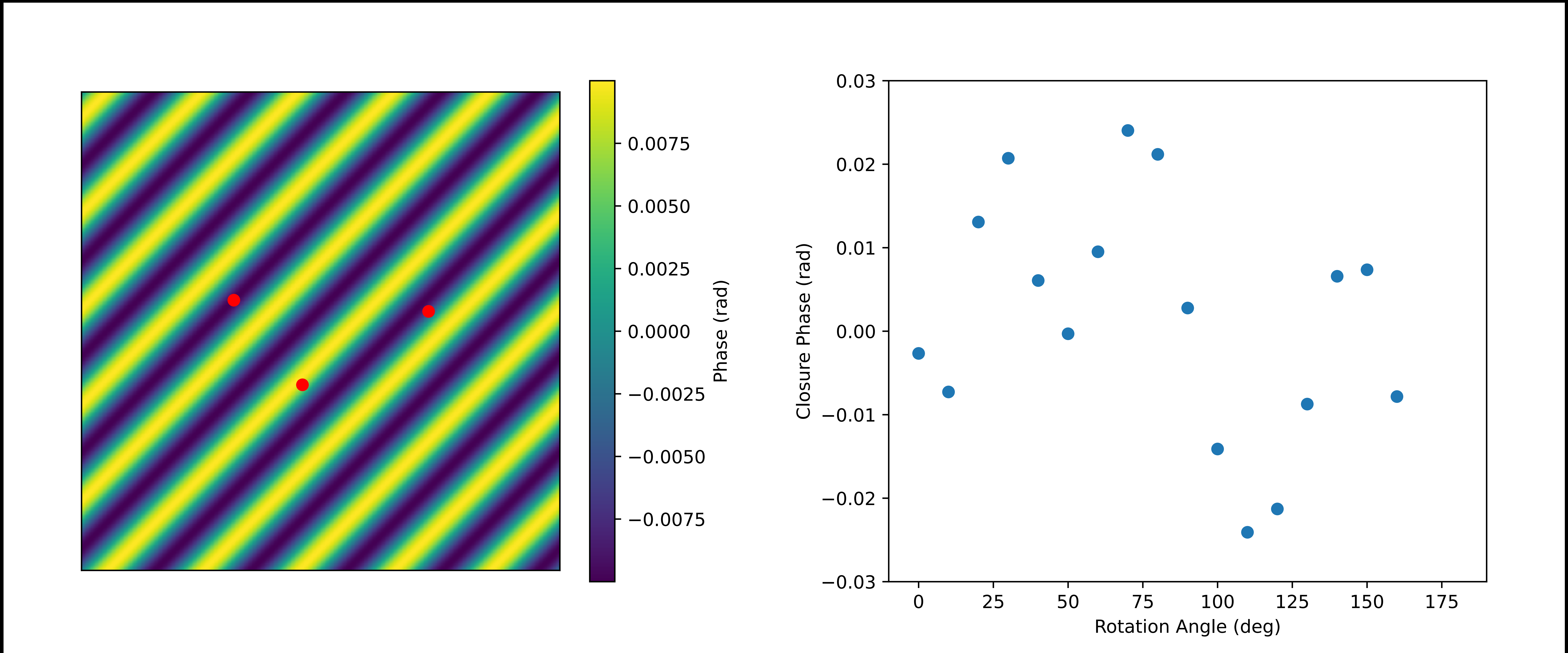

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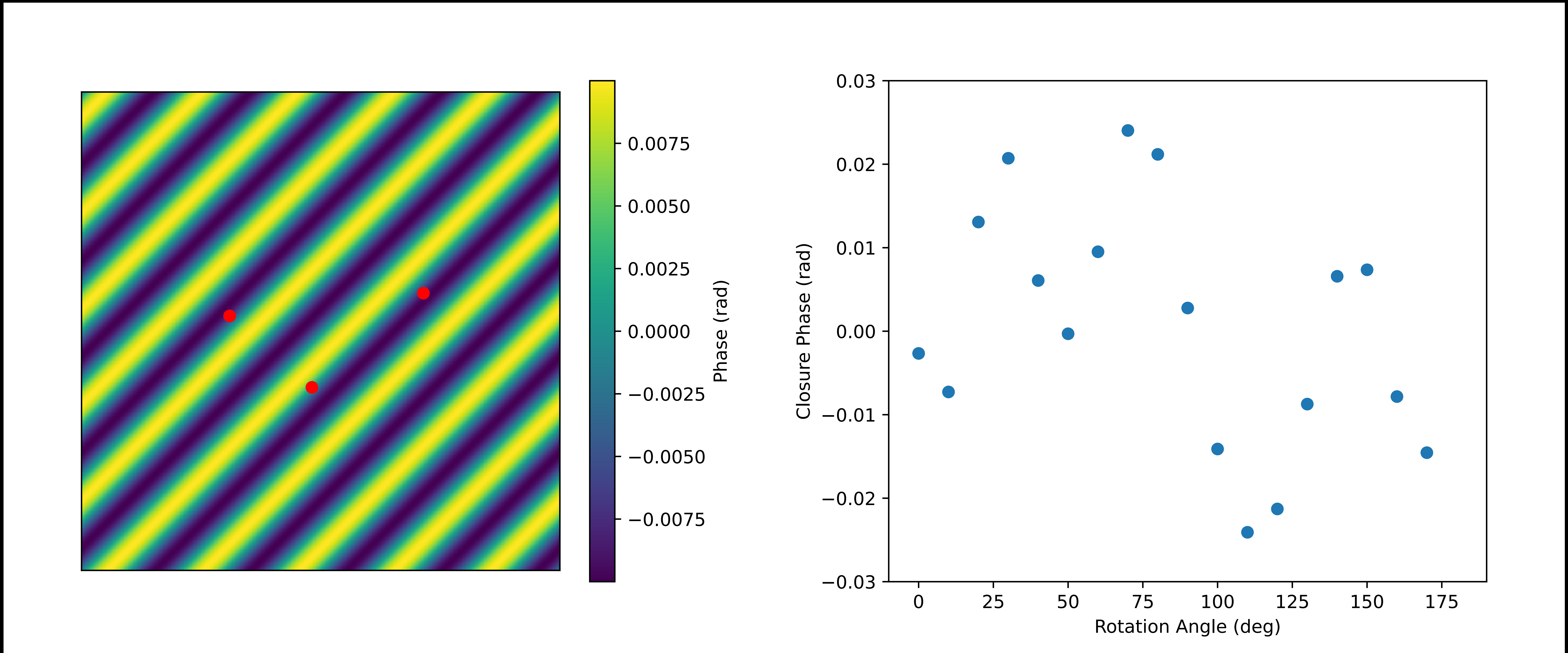

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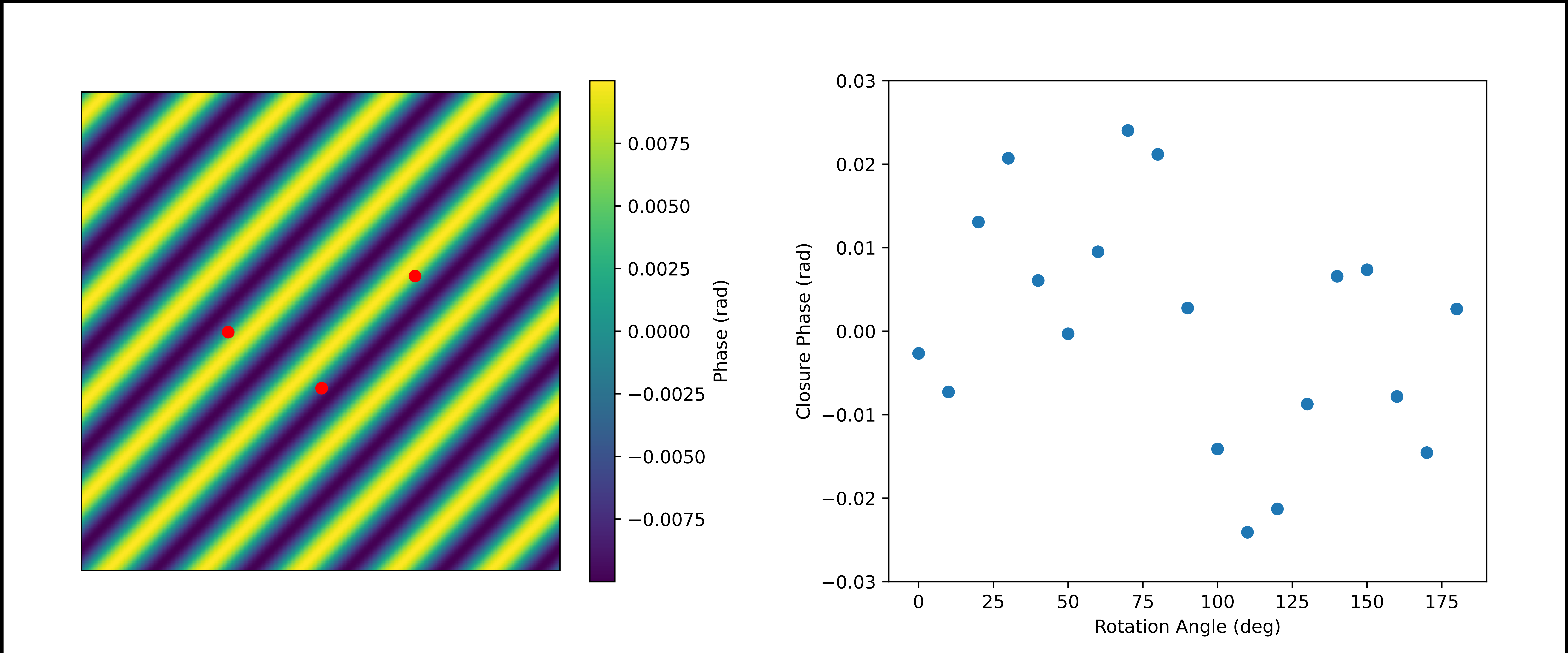
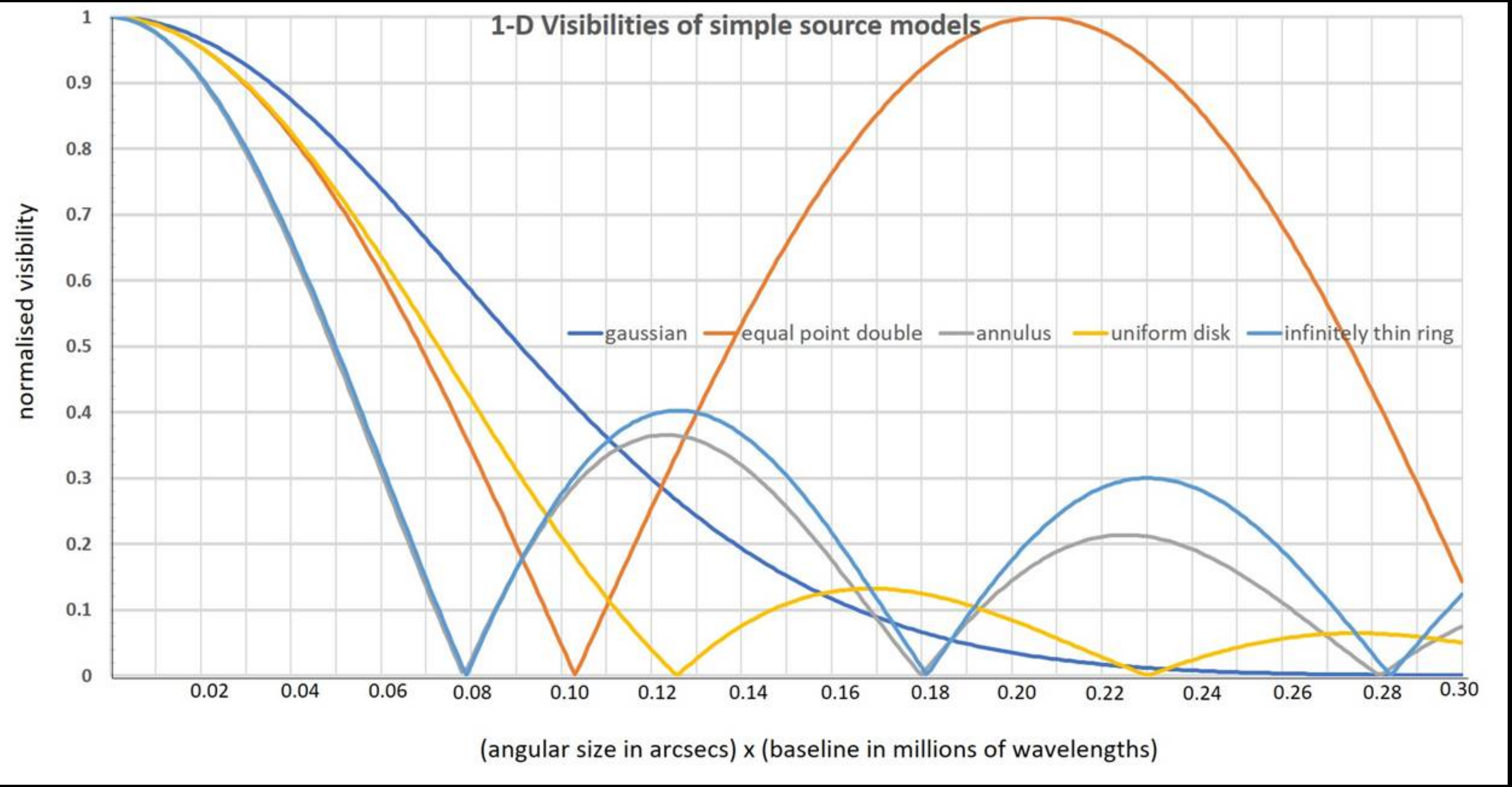


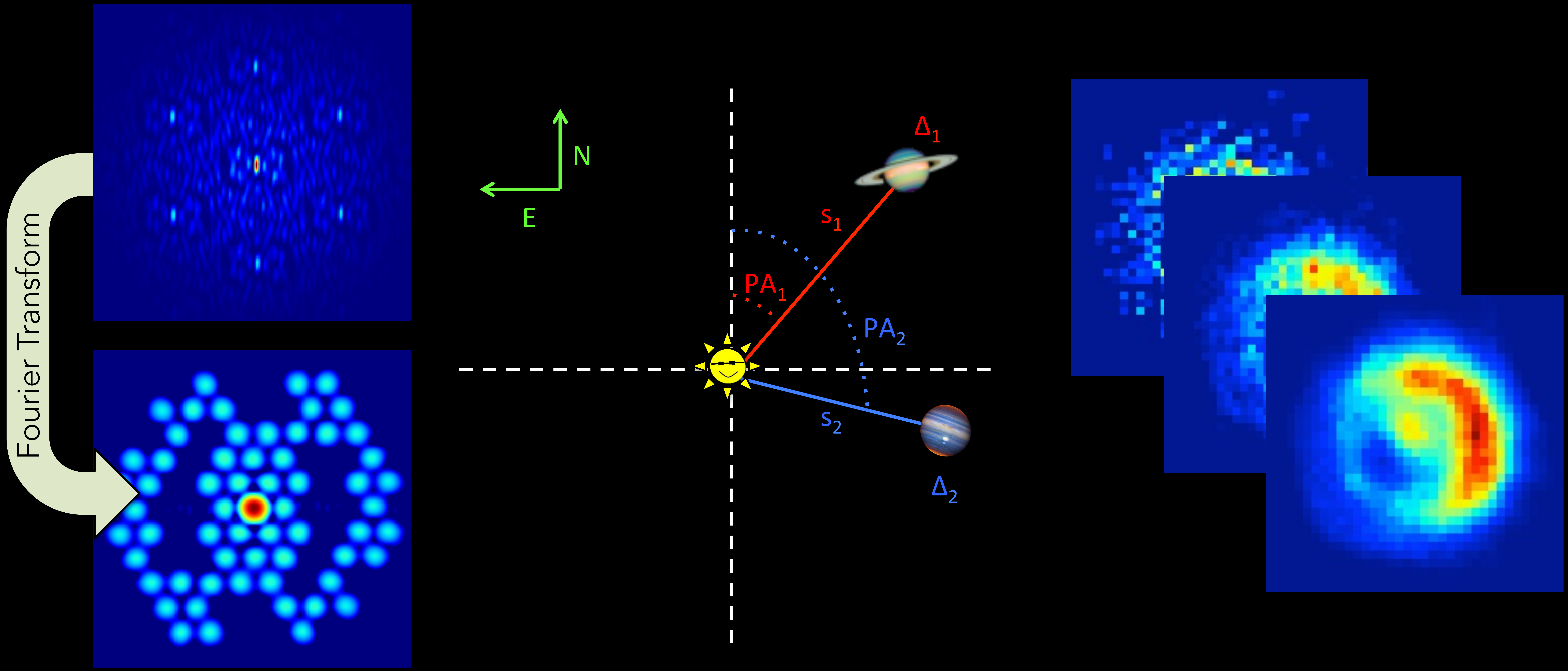
Interpreting NRM Observables: Visibilities

Fourier Amplitudes Intrinsic to the Source



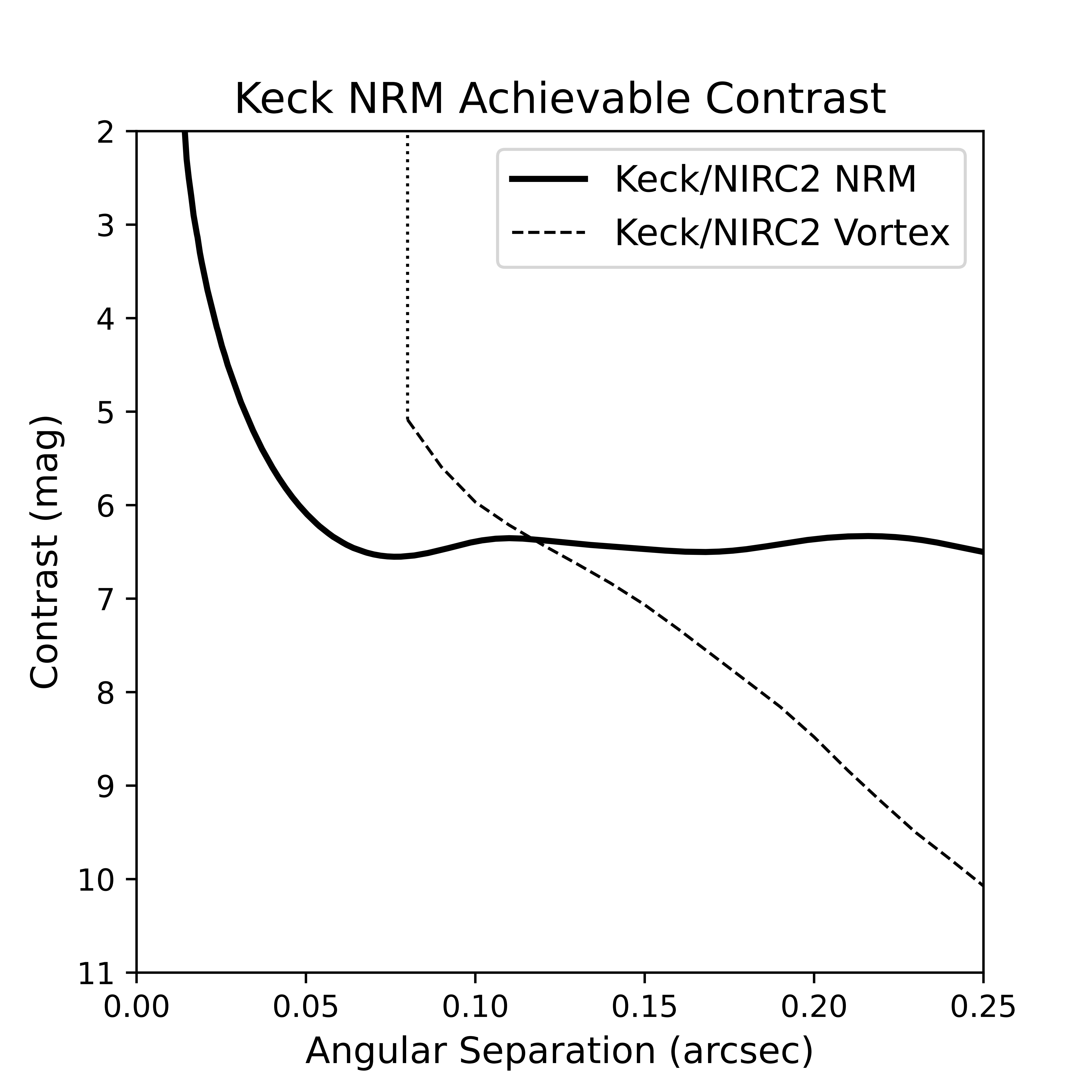
An Introduction to Radio Astronomy; https://www.jb.man.ac.uk/ira4/IRA4%20SuppMat_Chapter9.htm

Images to Source Brightness Distribution



NRM Contrast

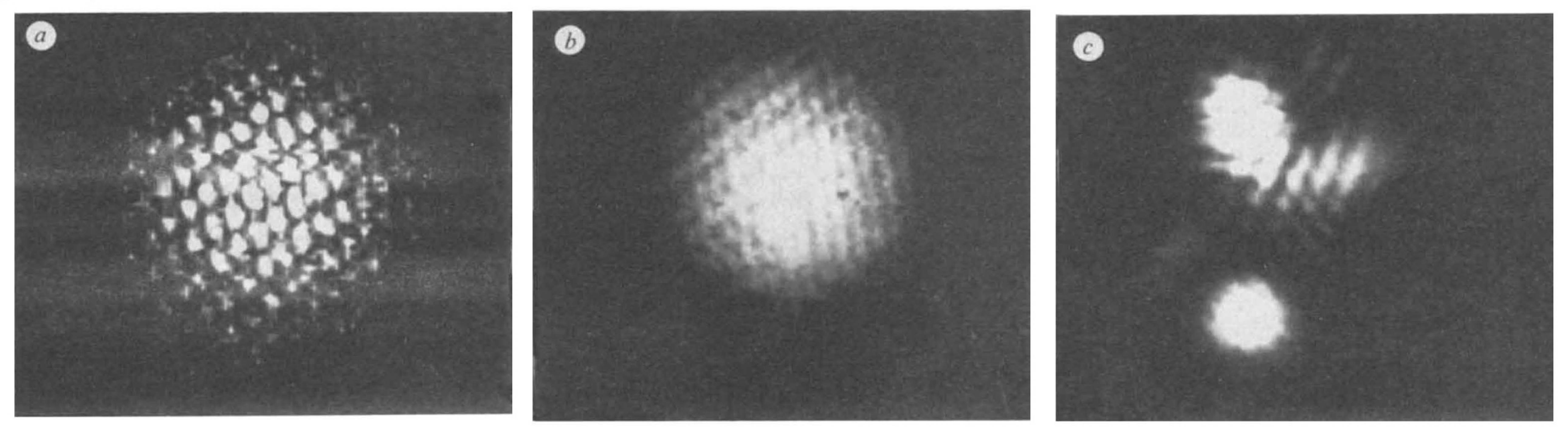
- NRM's self-calibrating observables enable "*super-resolution*": moderate contrast down to and within the diffraction limit
- We can re-project closure phases in a statistically independent way to make the wide-separation NRM contrast curve deeper (Ireland 2013; not shown on the right)



Xuan et al. 2018; Vides et al. 2023

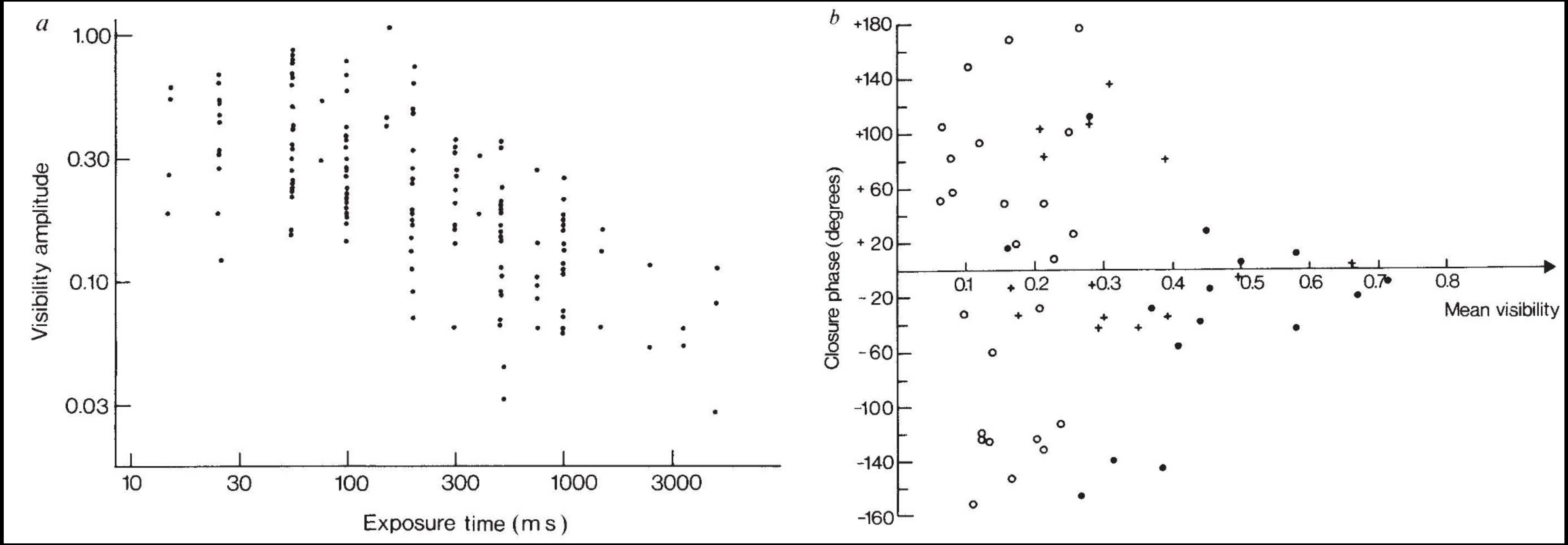
Ground-Based AMI

Early Demonstrations with UH 88, AAT, Hale



Early AMI observations did not use AO, and required short exposure times to “freeze-out” the atmosphere!

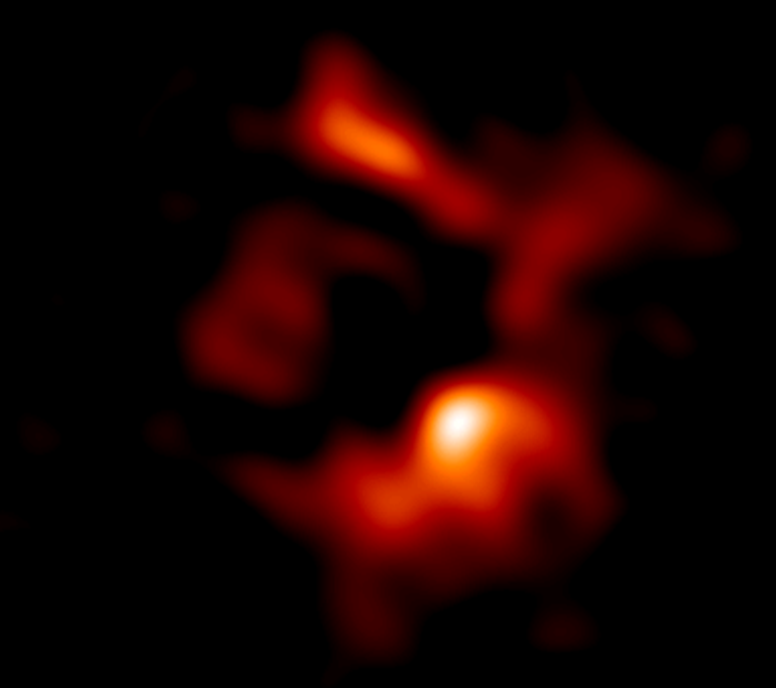
Baldwin et al. 1986; Frater et al. 1986; Readhead et al. 1988; Haniff et al. 1987



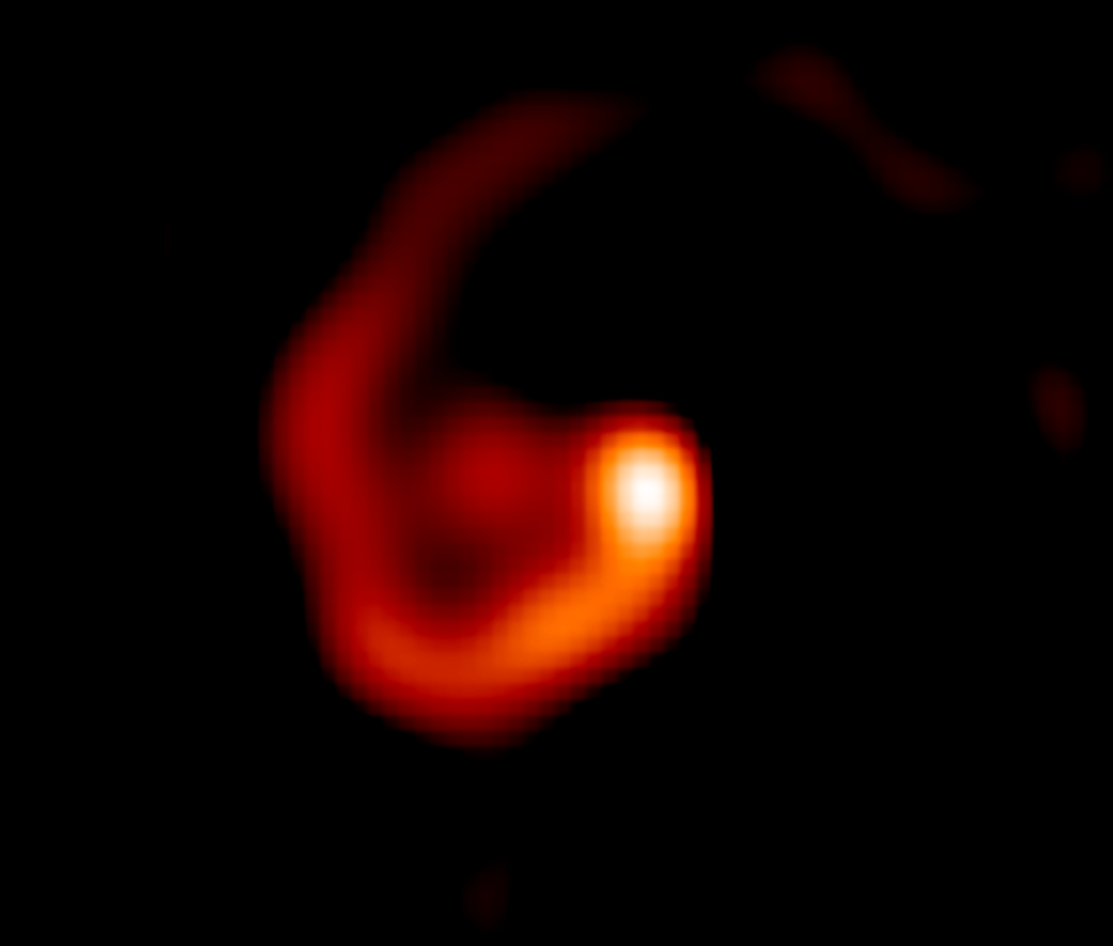
10m-Class AMI Beginning with Keck

Evolved Stars, YSOs, Colliding Binaries’ Plumes and Wakes

IRC+10216

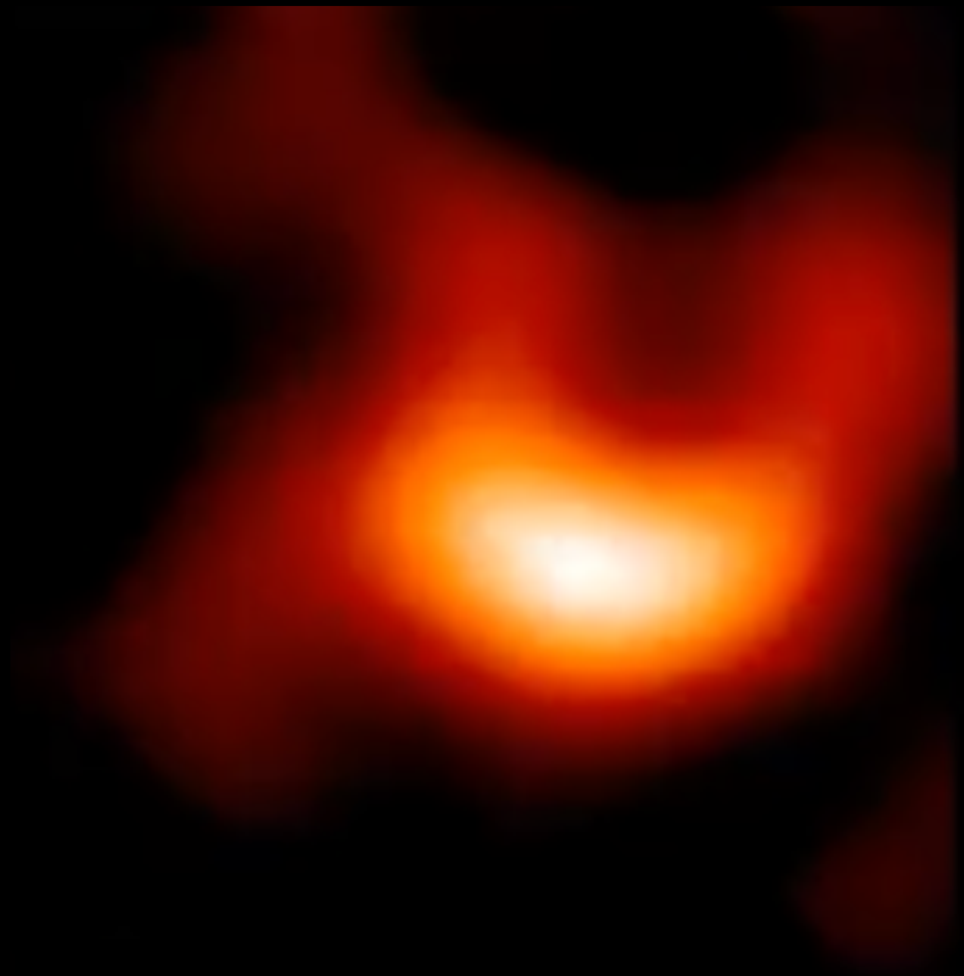


WR 98A



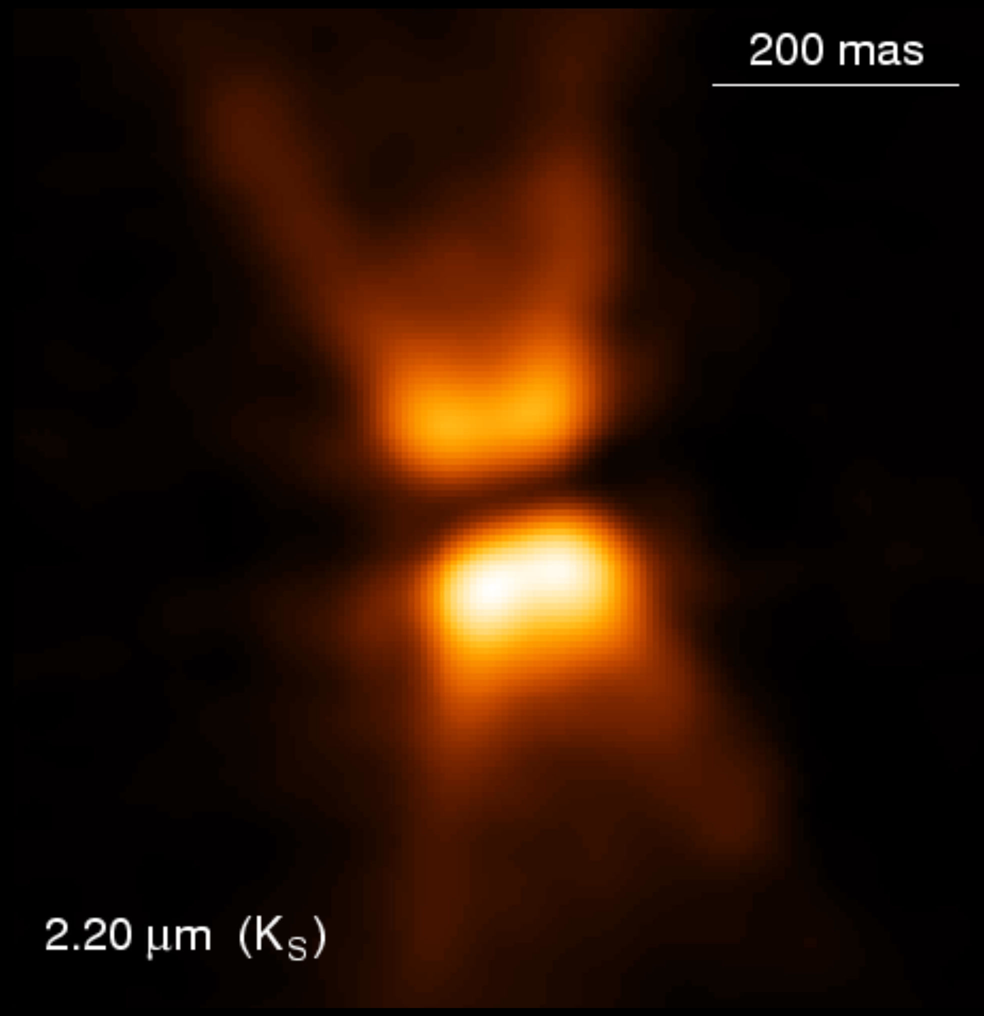
WR 140

WR 112

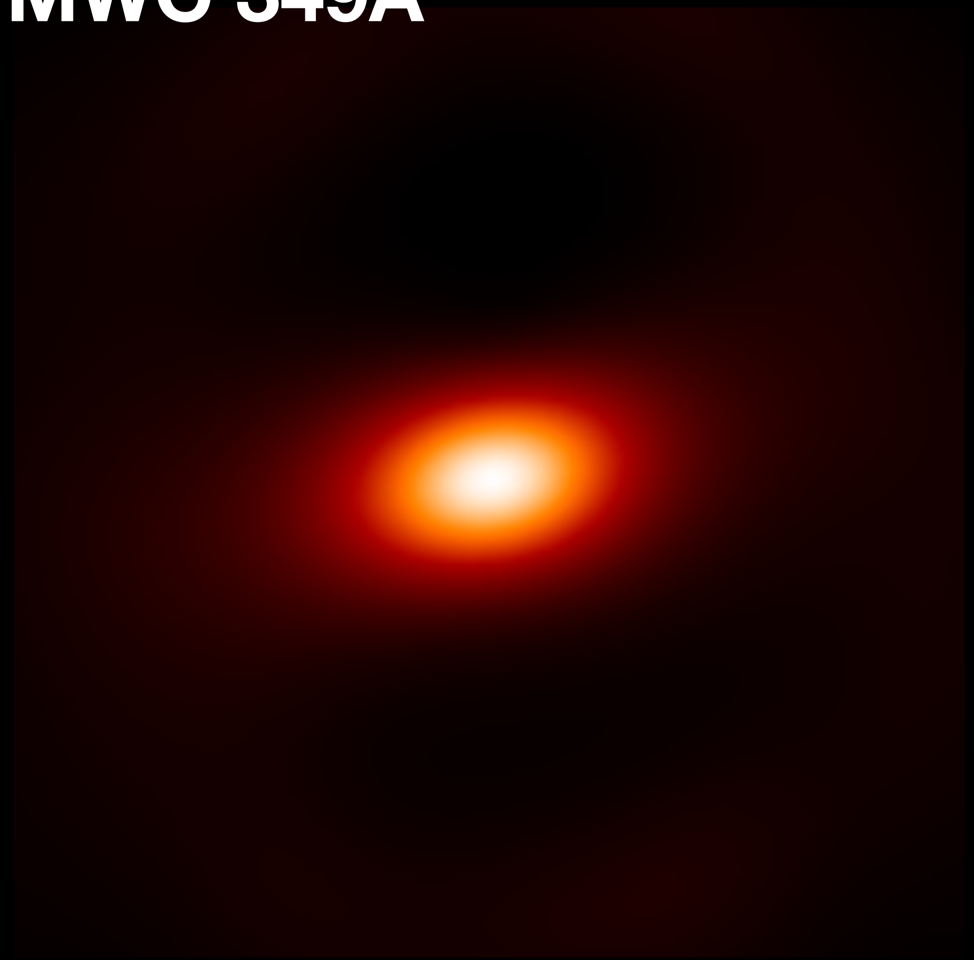


LkHα 101

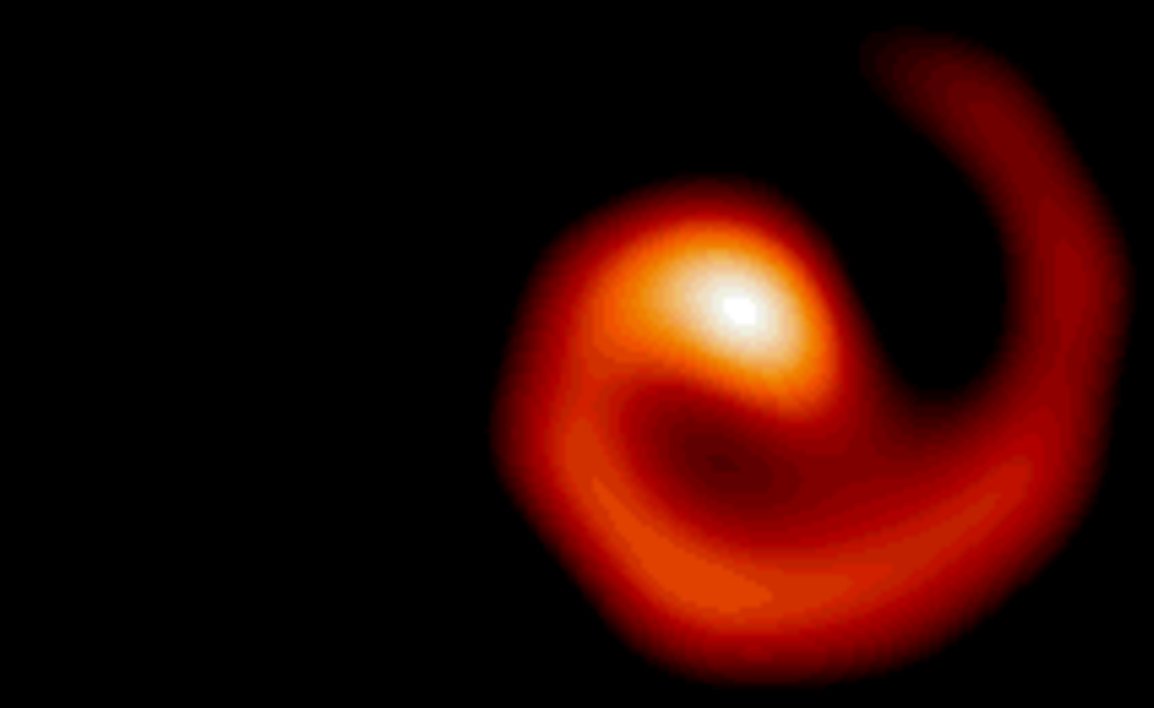
Red Rectangle



MWC 349A

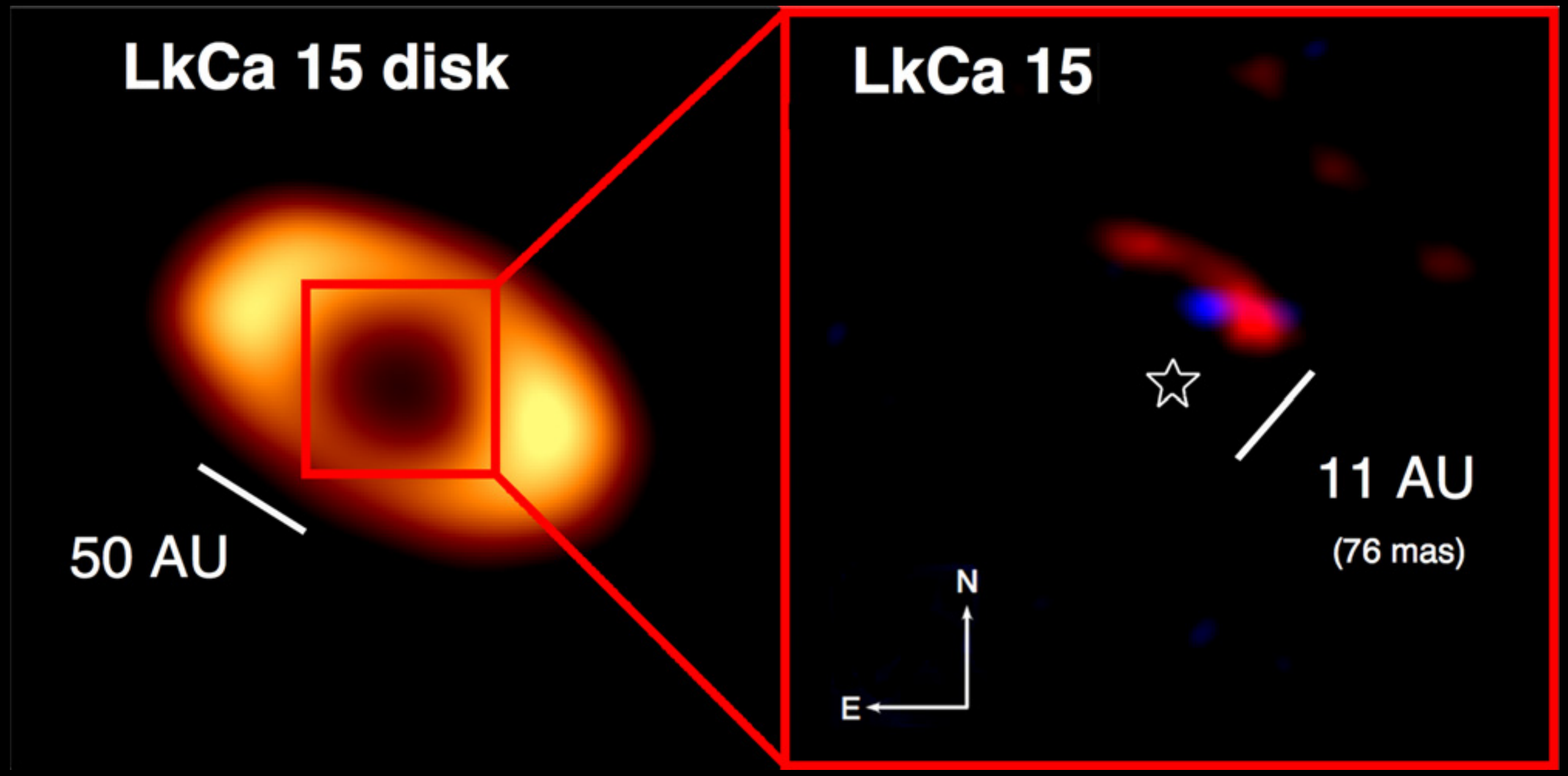


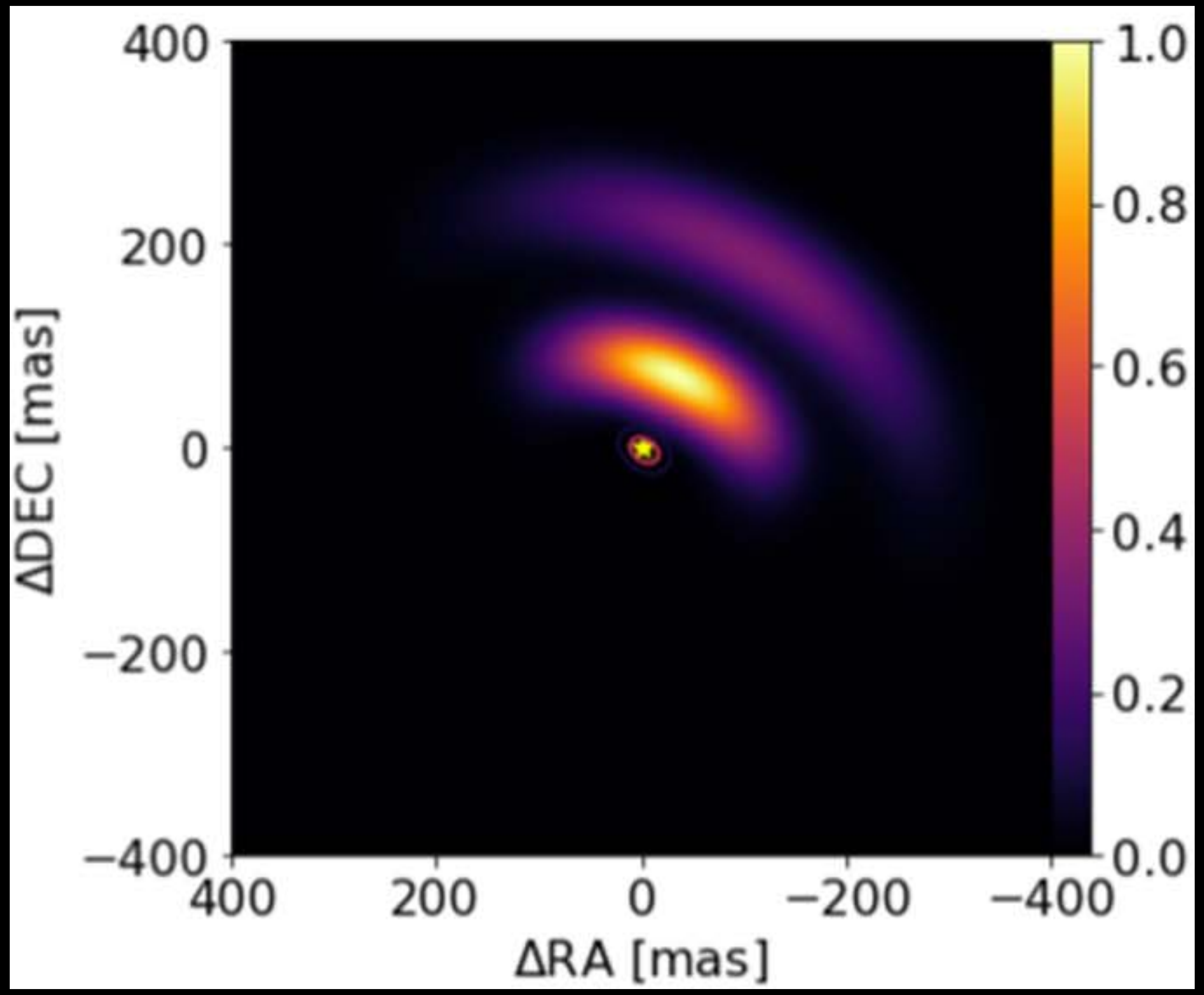
WR 104

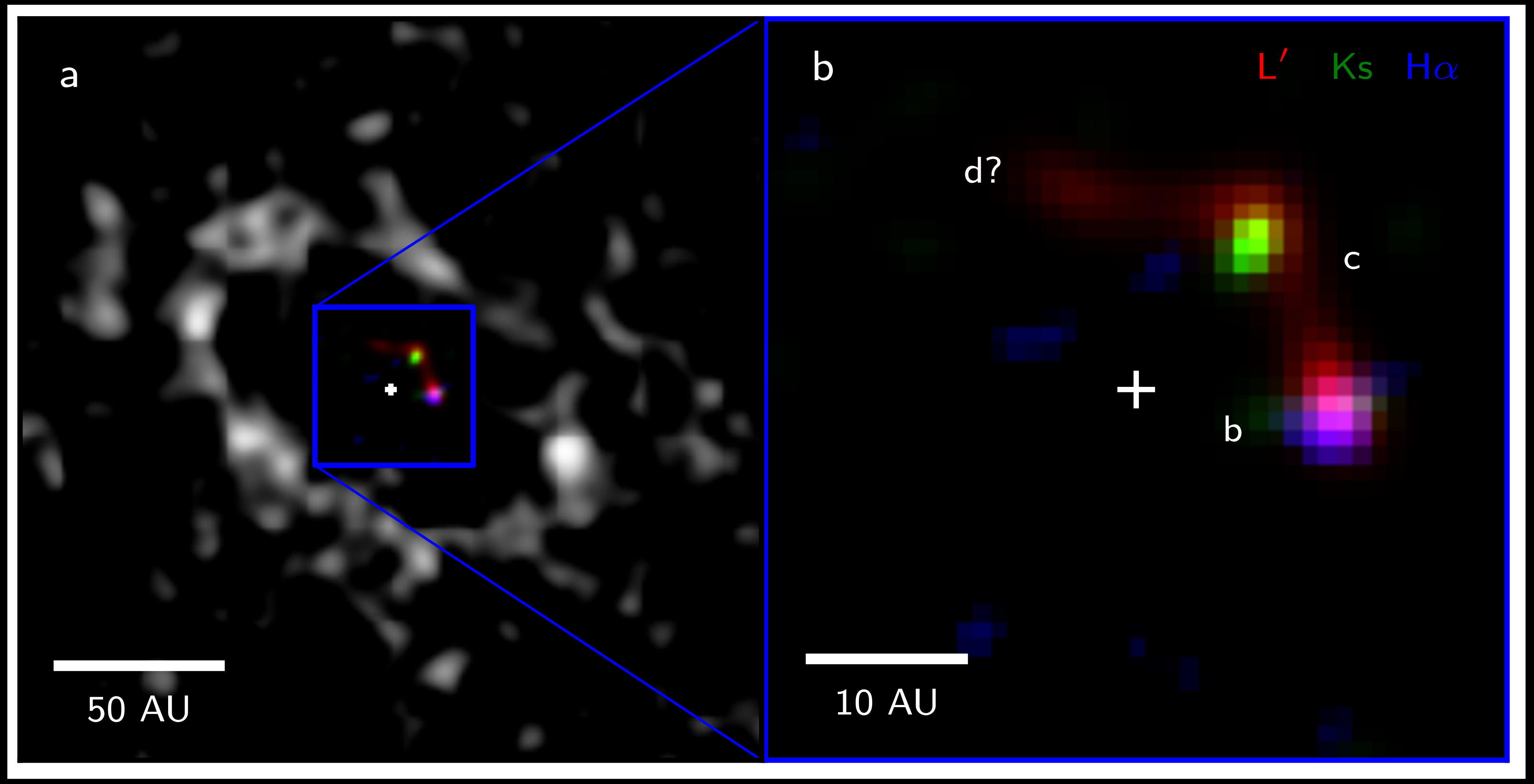


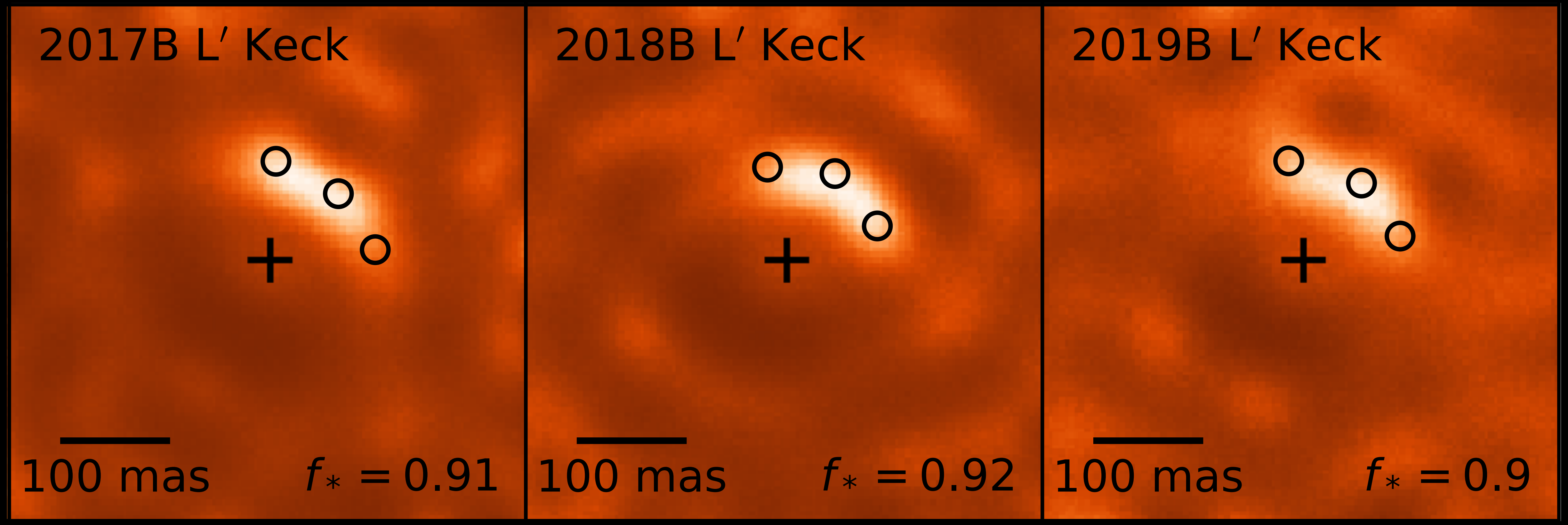
e.g. Tuthill et al. 2000, 2001; Danchi, Tuthill, & Monnier 2001

AMI + Adaptive Optics on 10m Class Telescopes



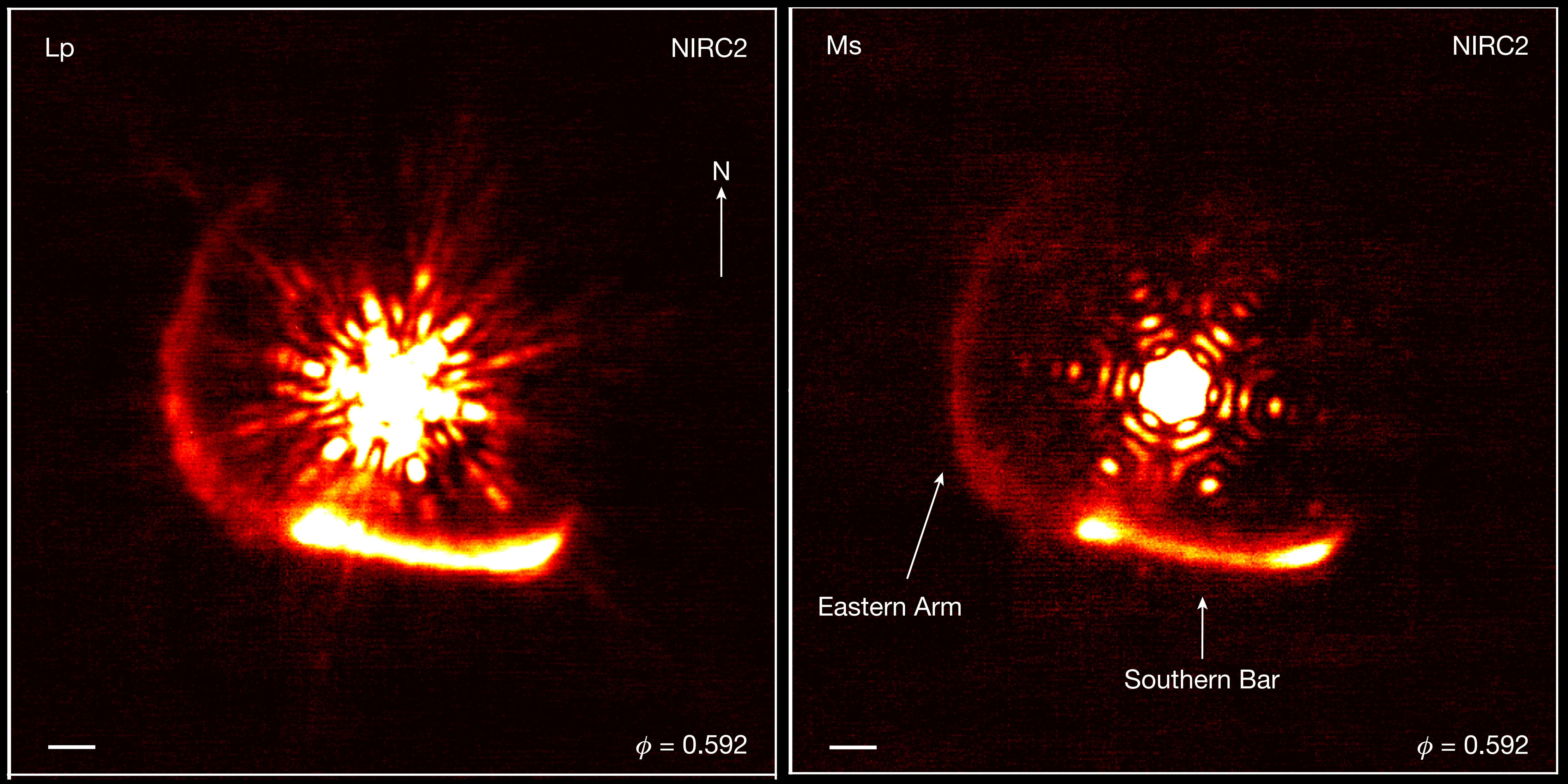


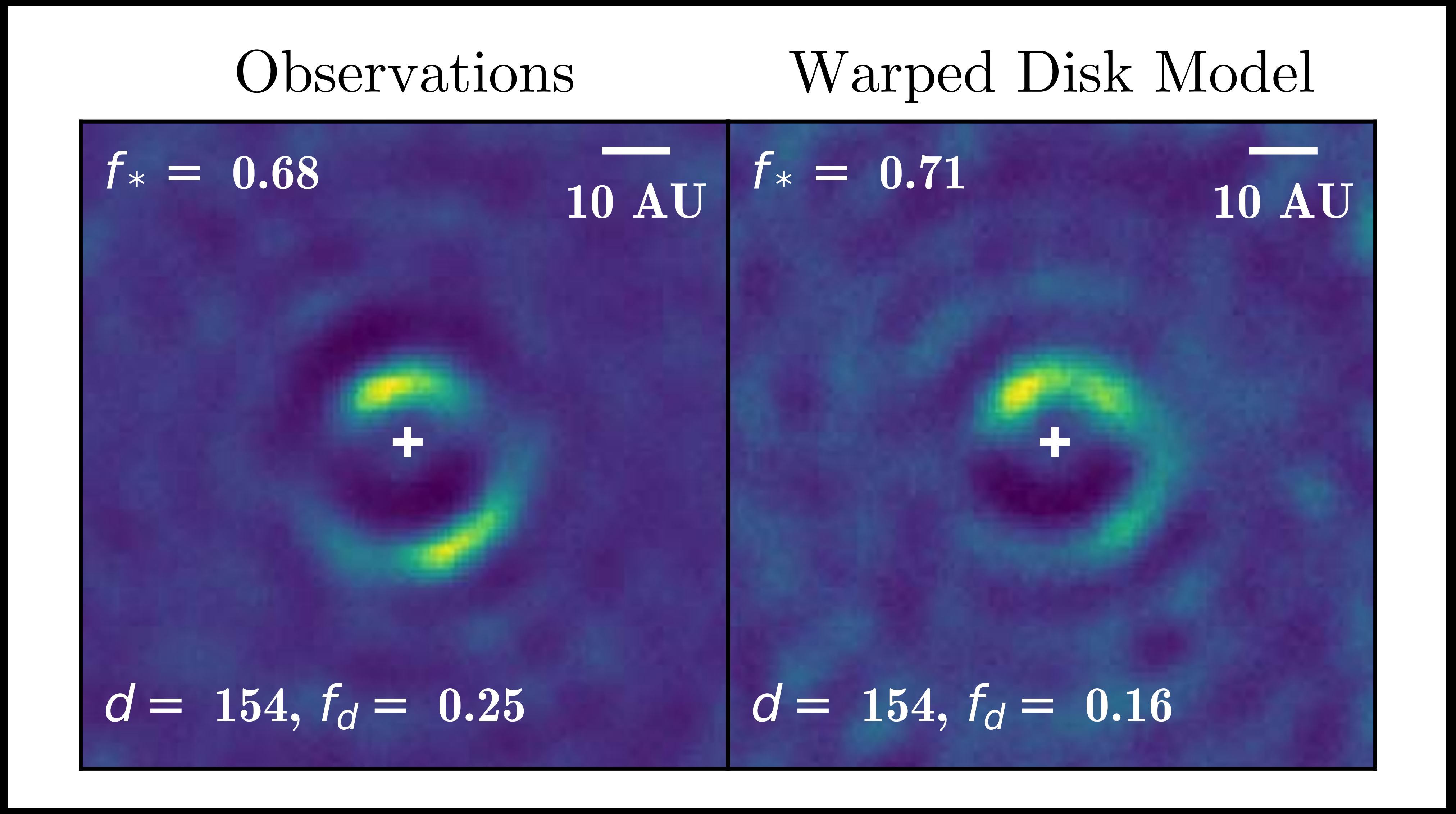


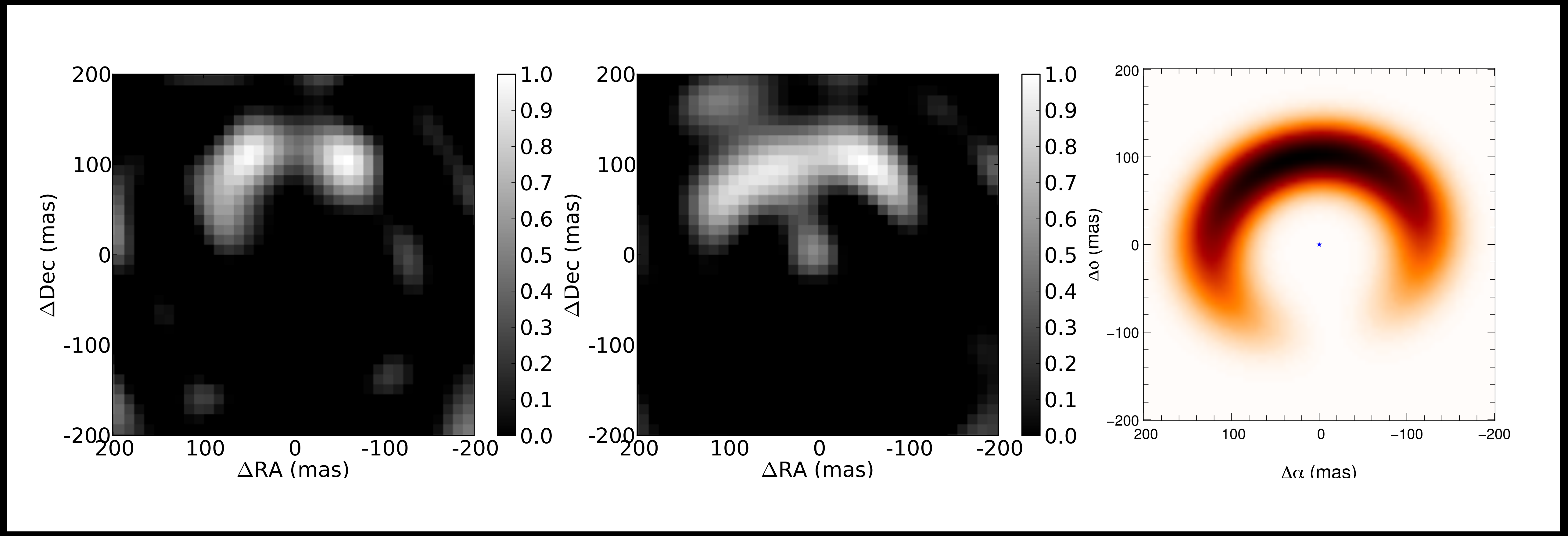


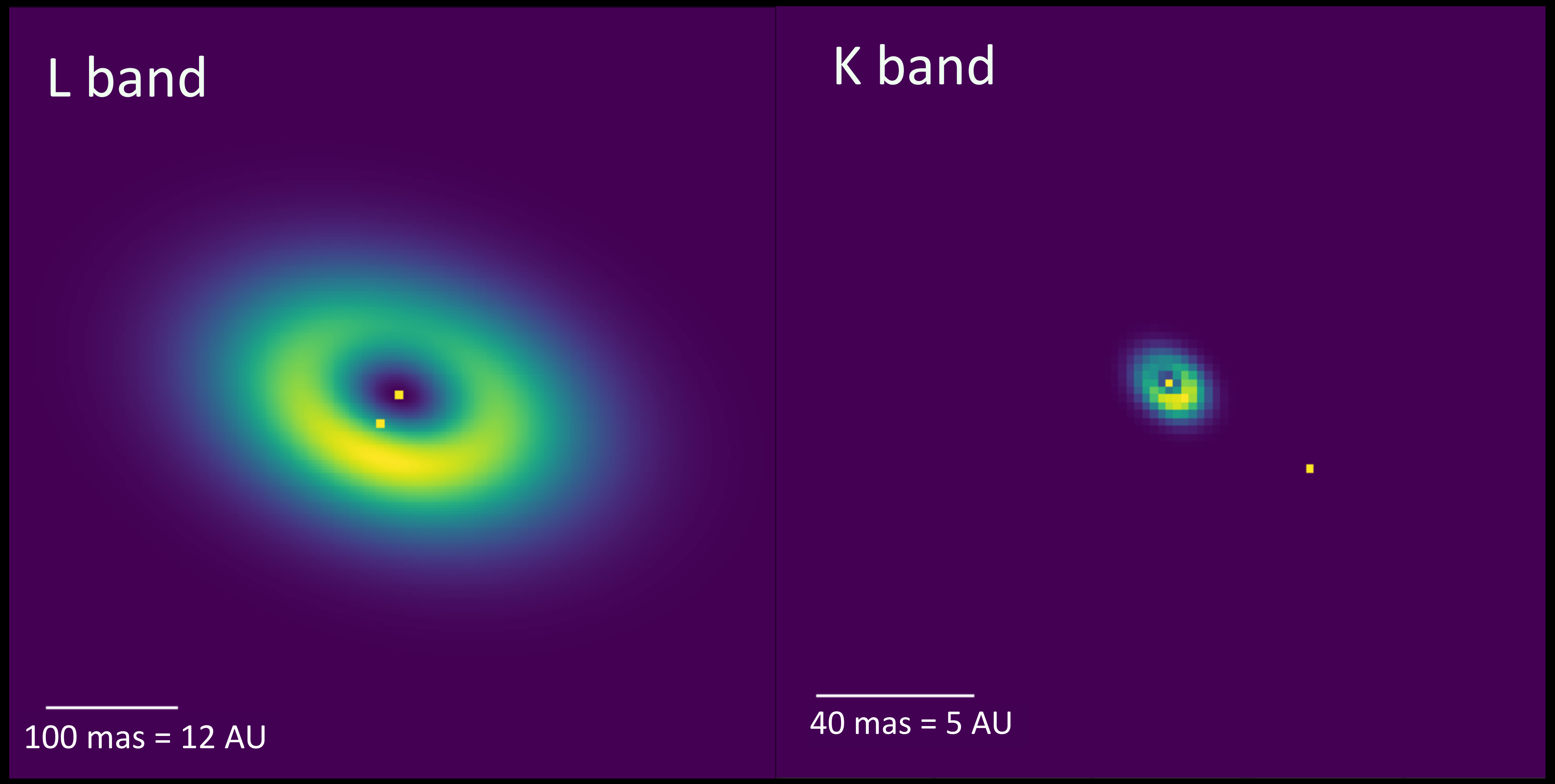
e.g. Kraus & Ireland 2012; Blakely et al. 2022; Sallum et al. 2015, 2023

High-Contrast AMI Science



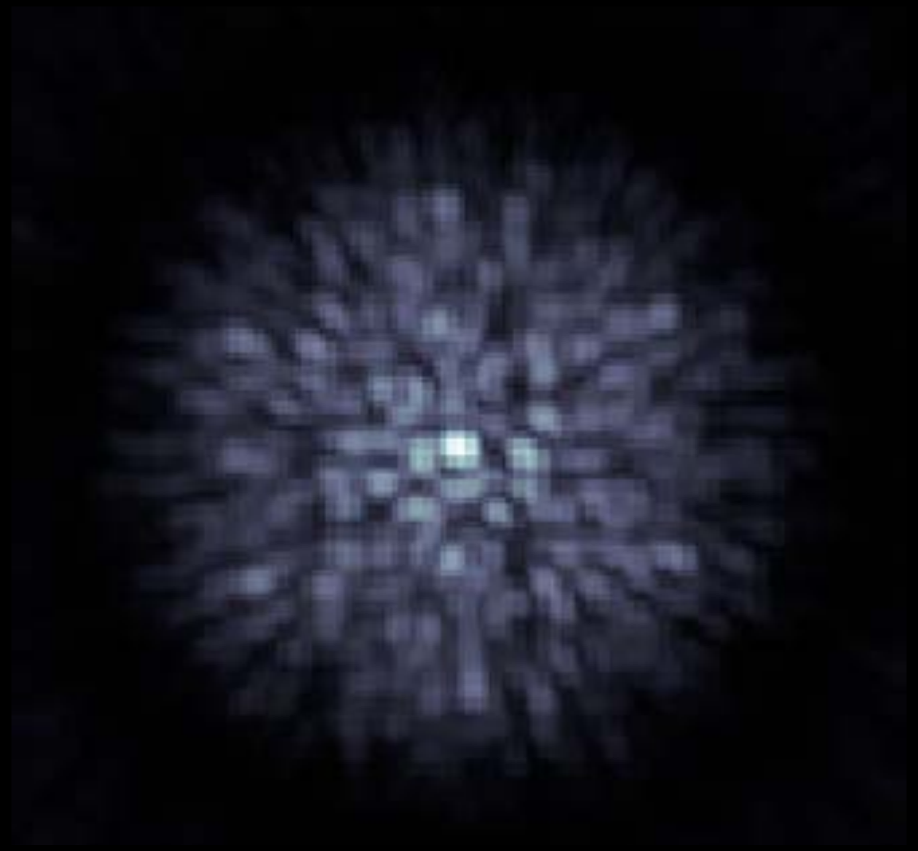


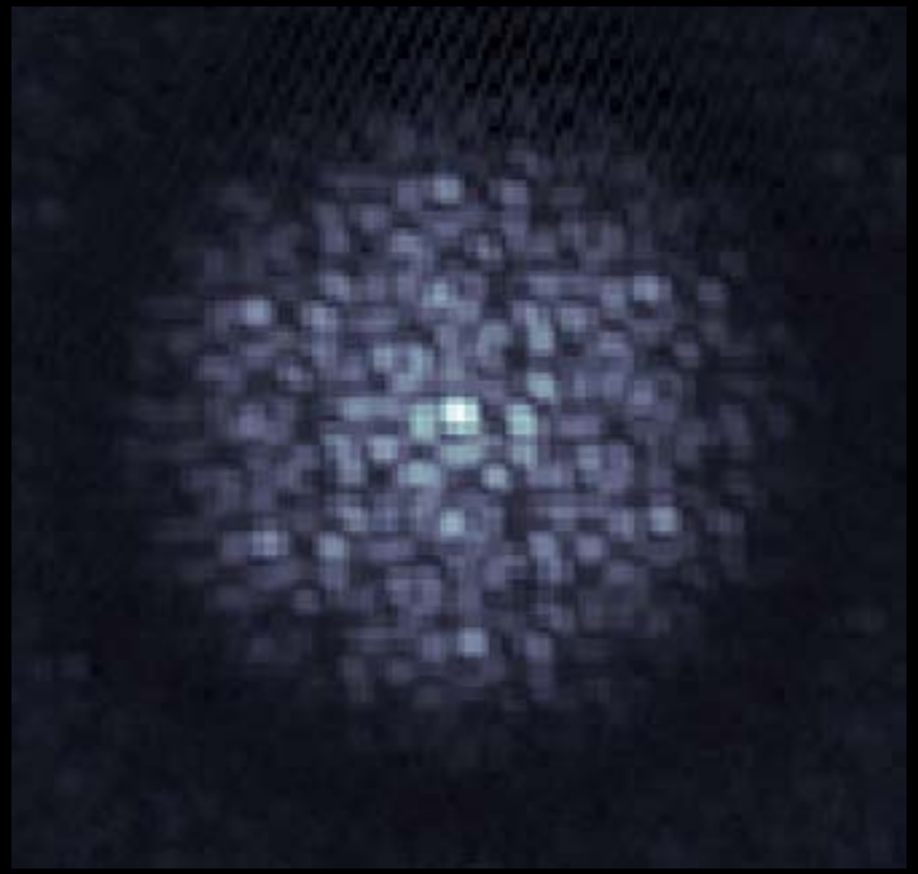


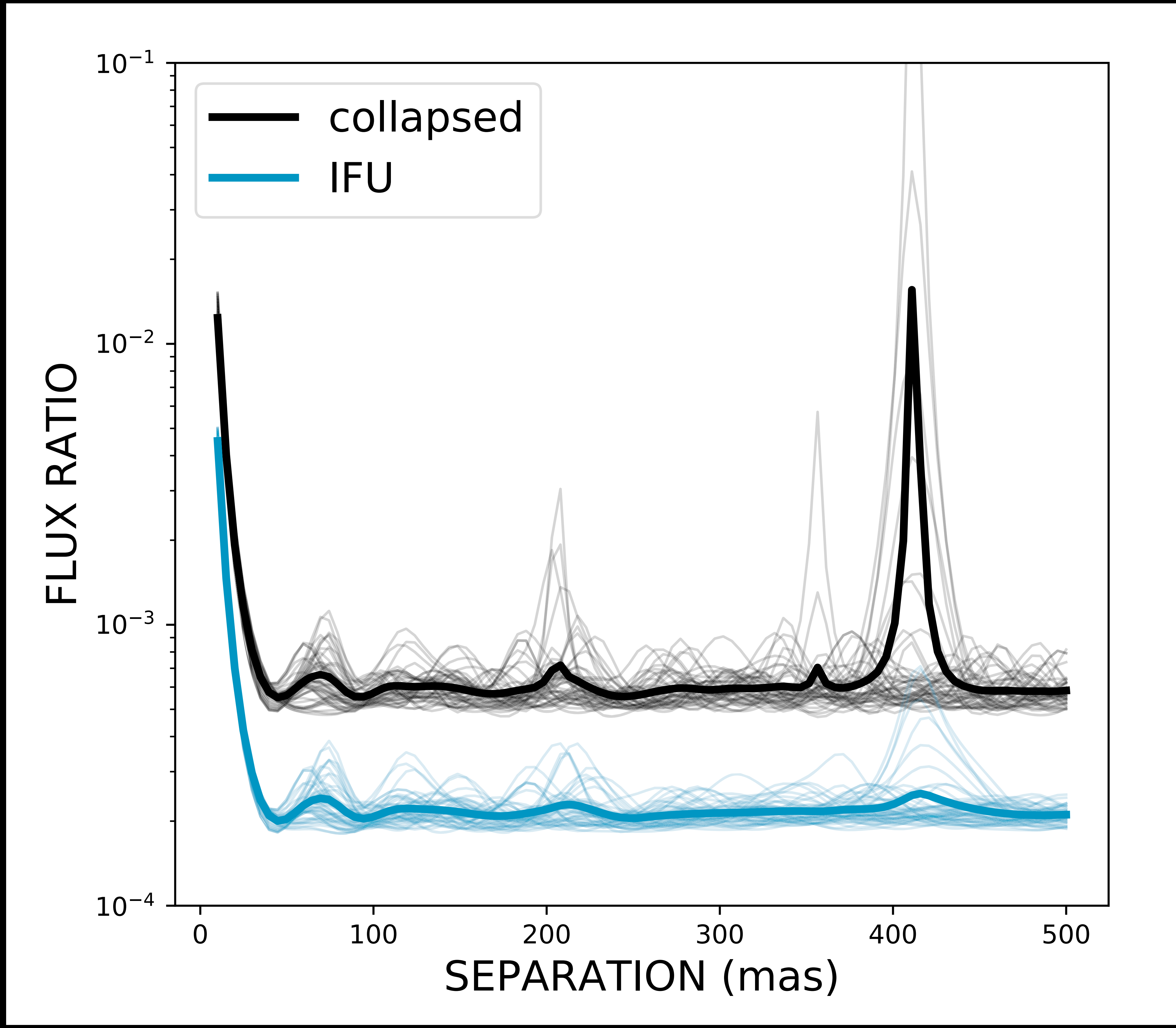


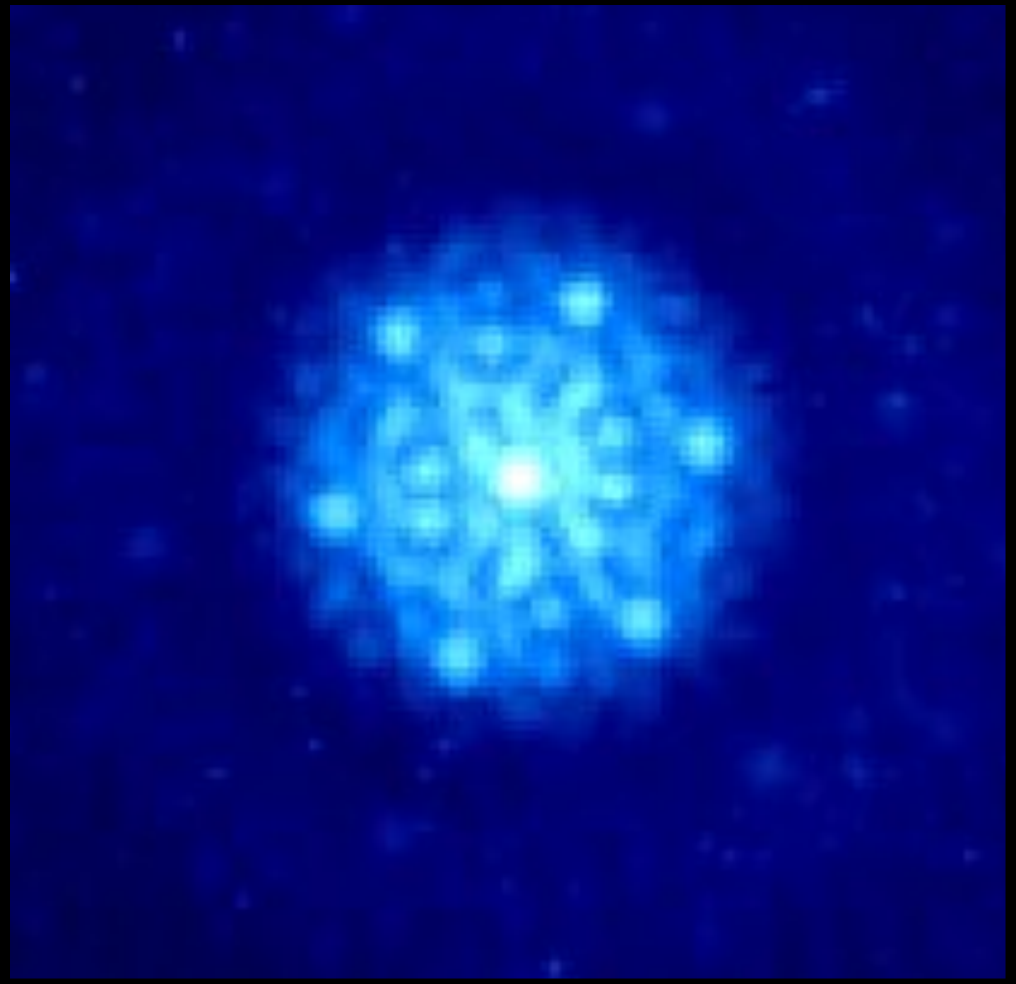
e.g. Willson et al. 2019; Sallum et al. 2019; Han et al. 2022; Vides et al. 2023

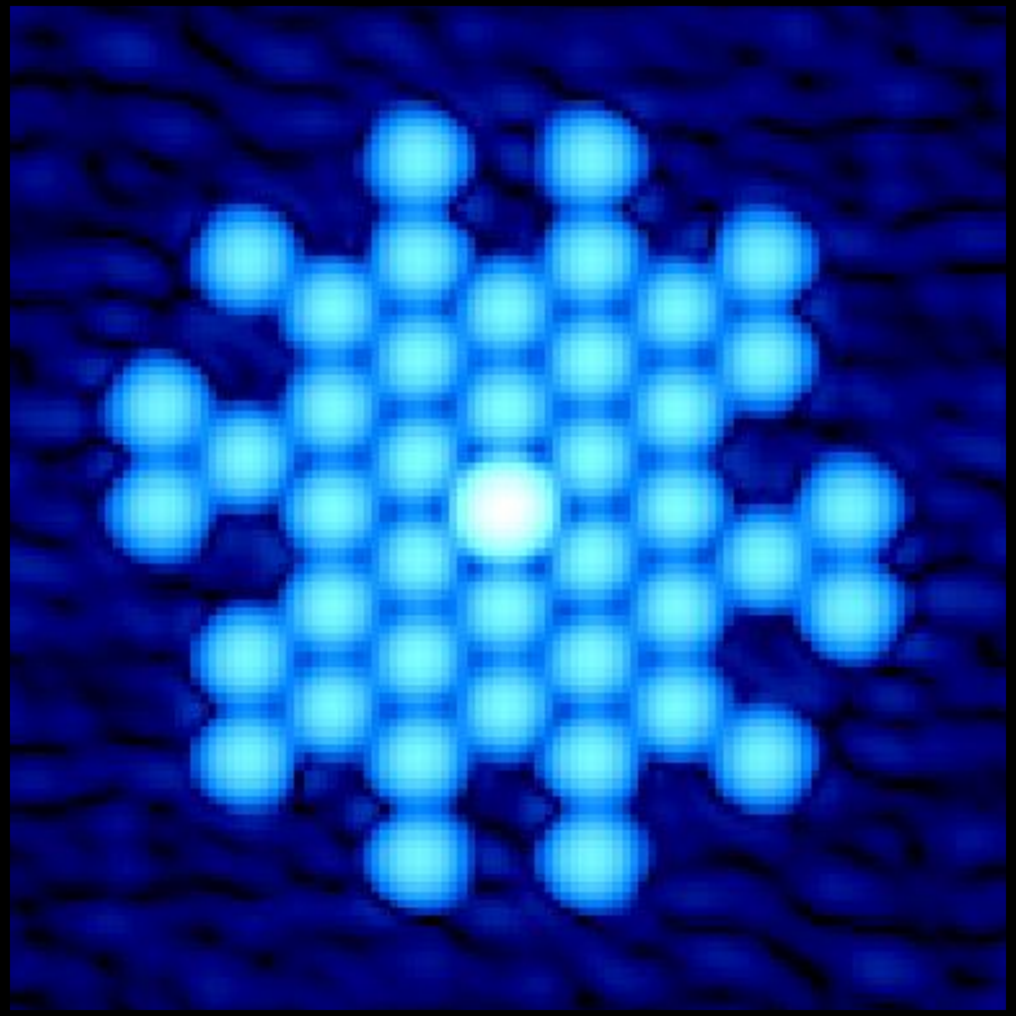
Spectrally-Dispersed AMI on Integral Field Spectrographs





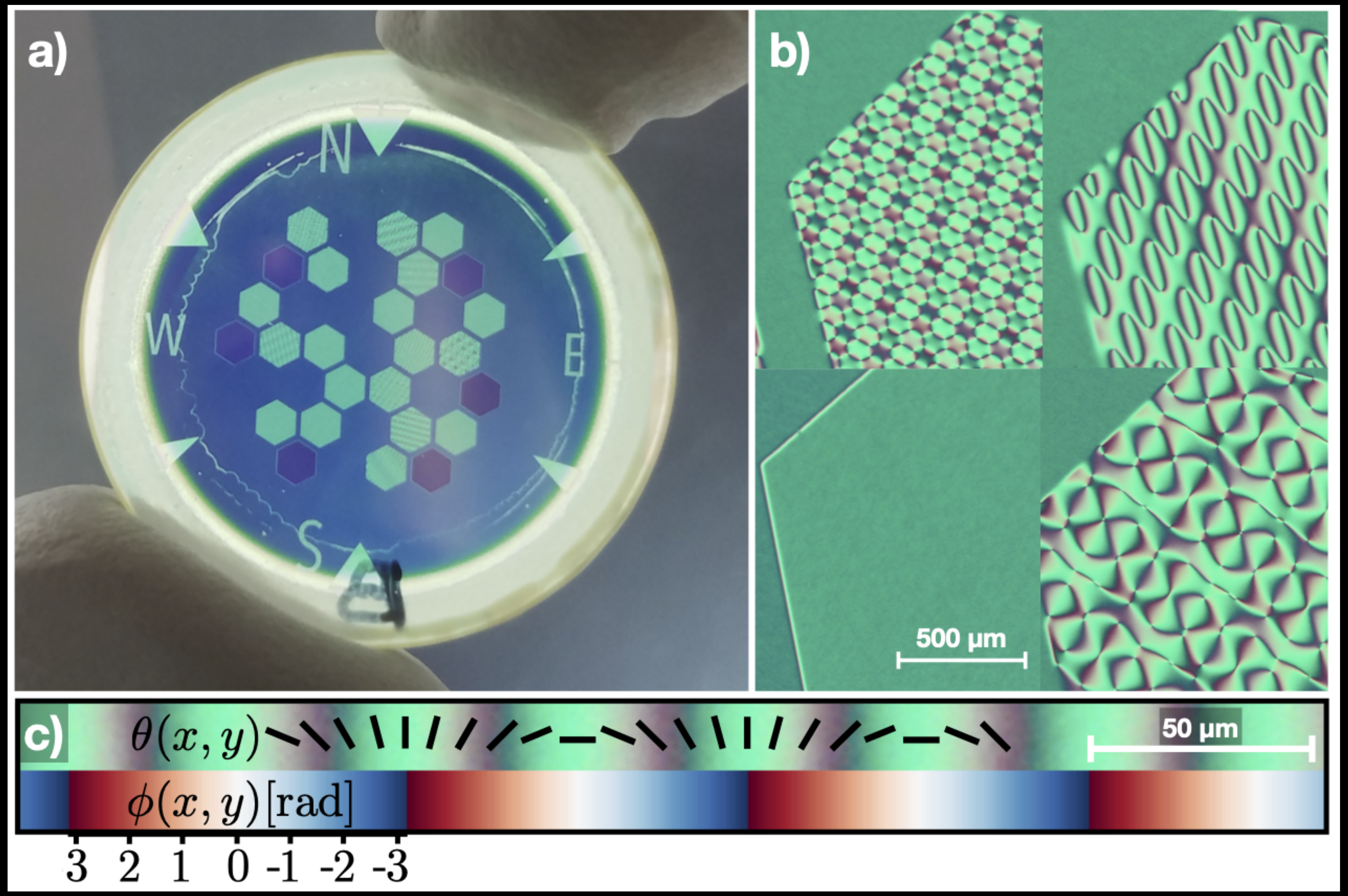


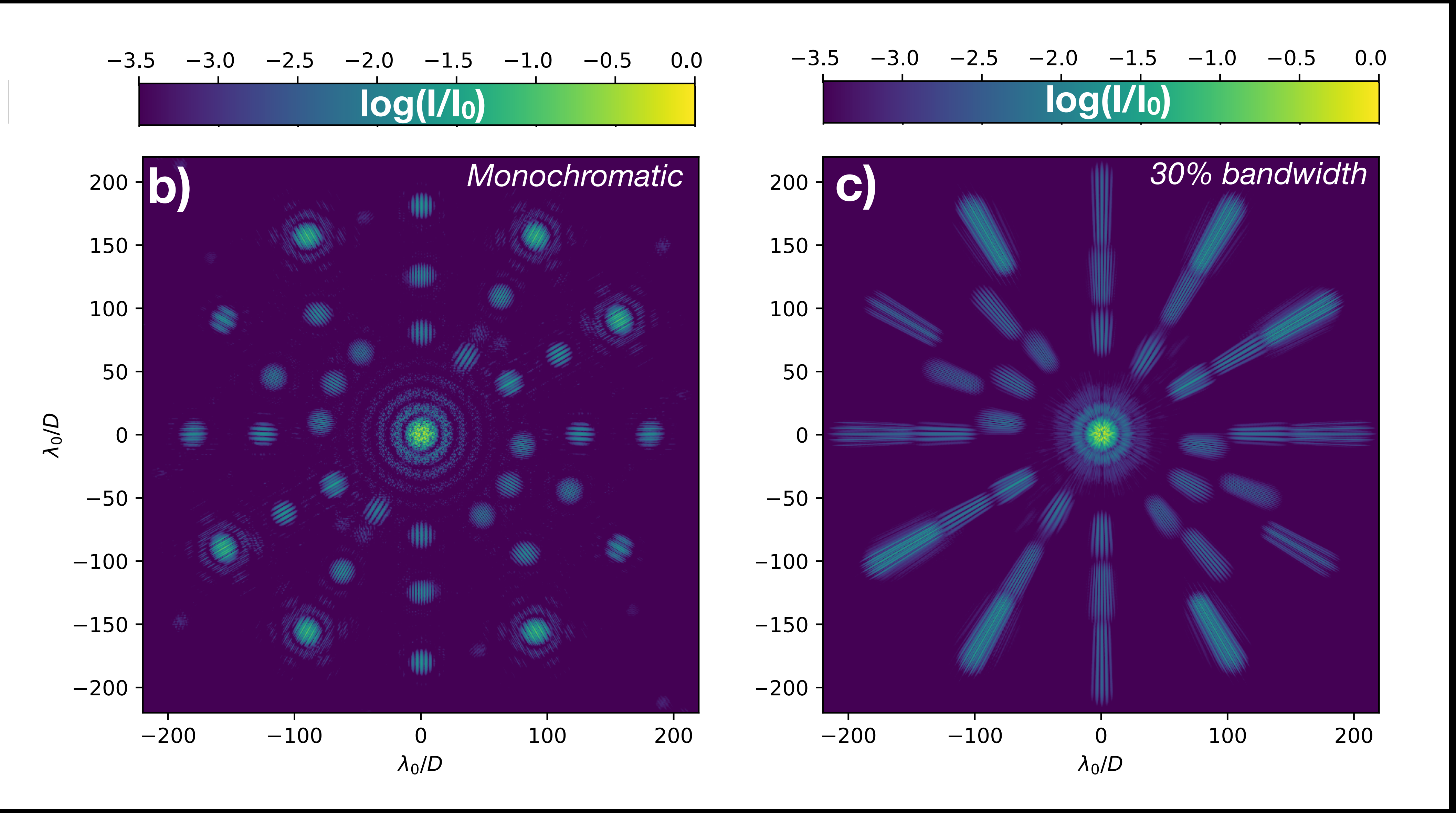


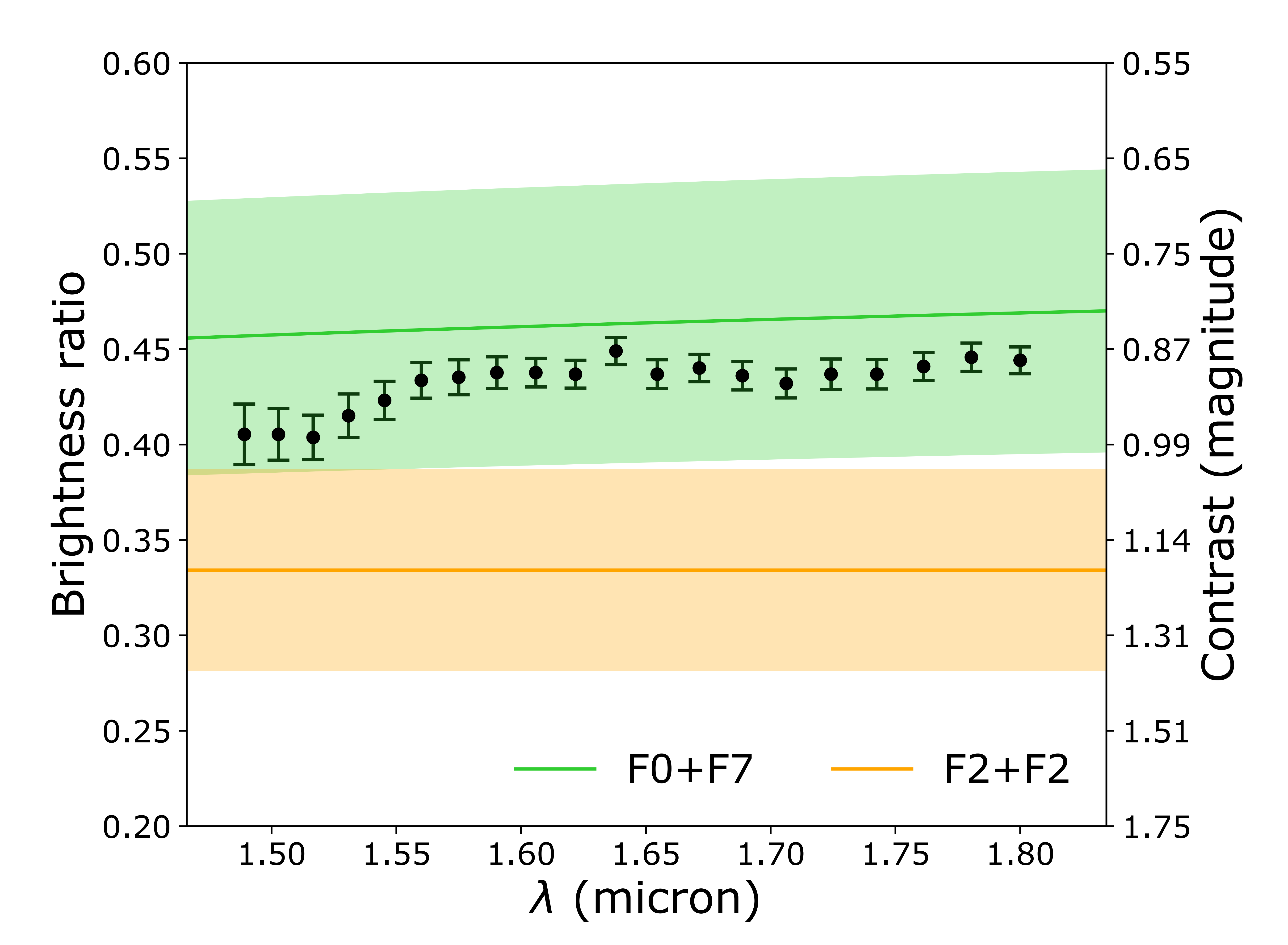


e.g. Cheetham et al. 2016; Greenbaum et al. 2019

Holographic Aperture Masking

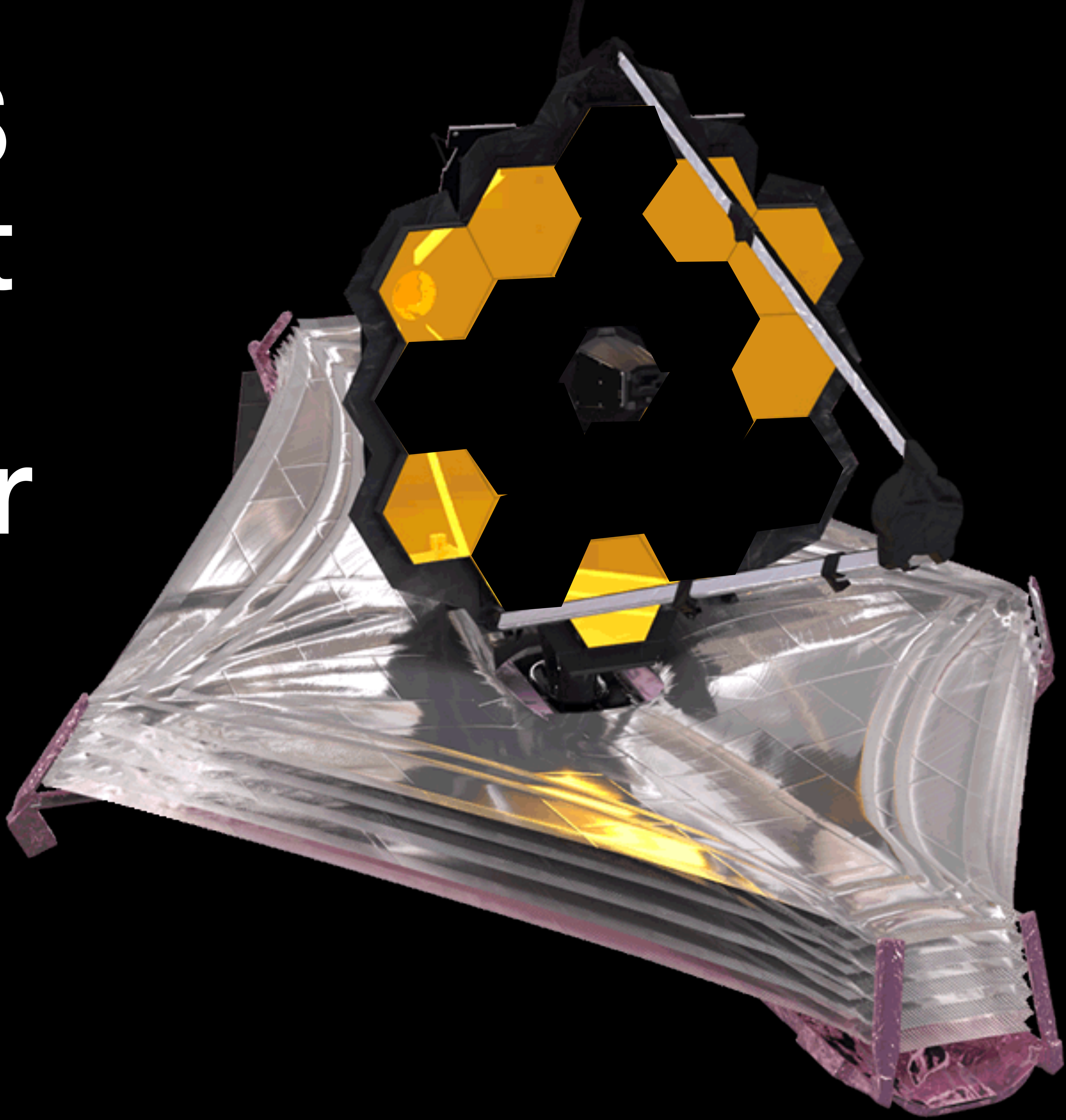




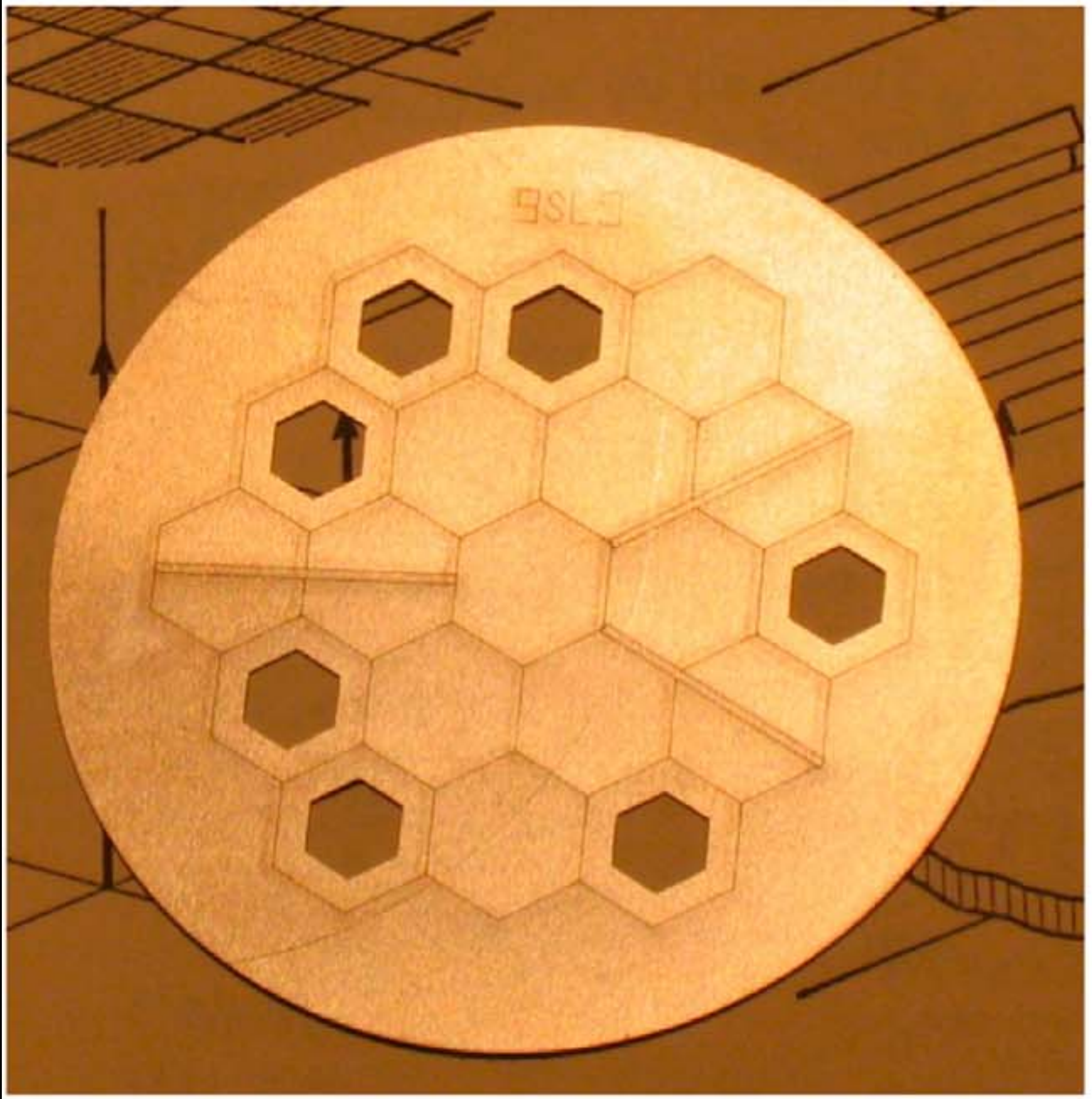


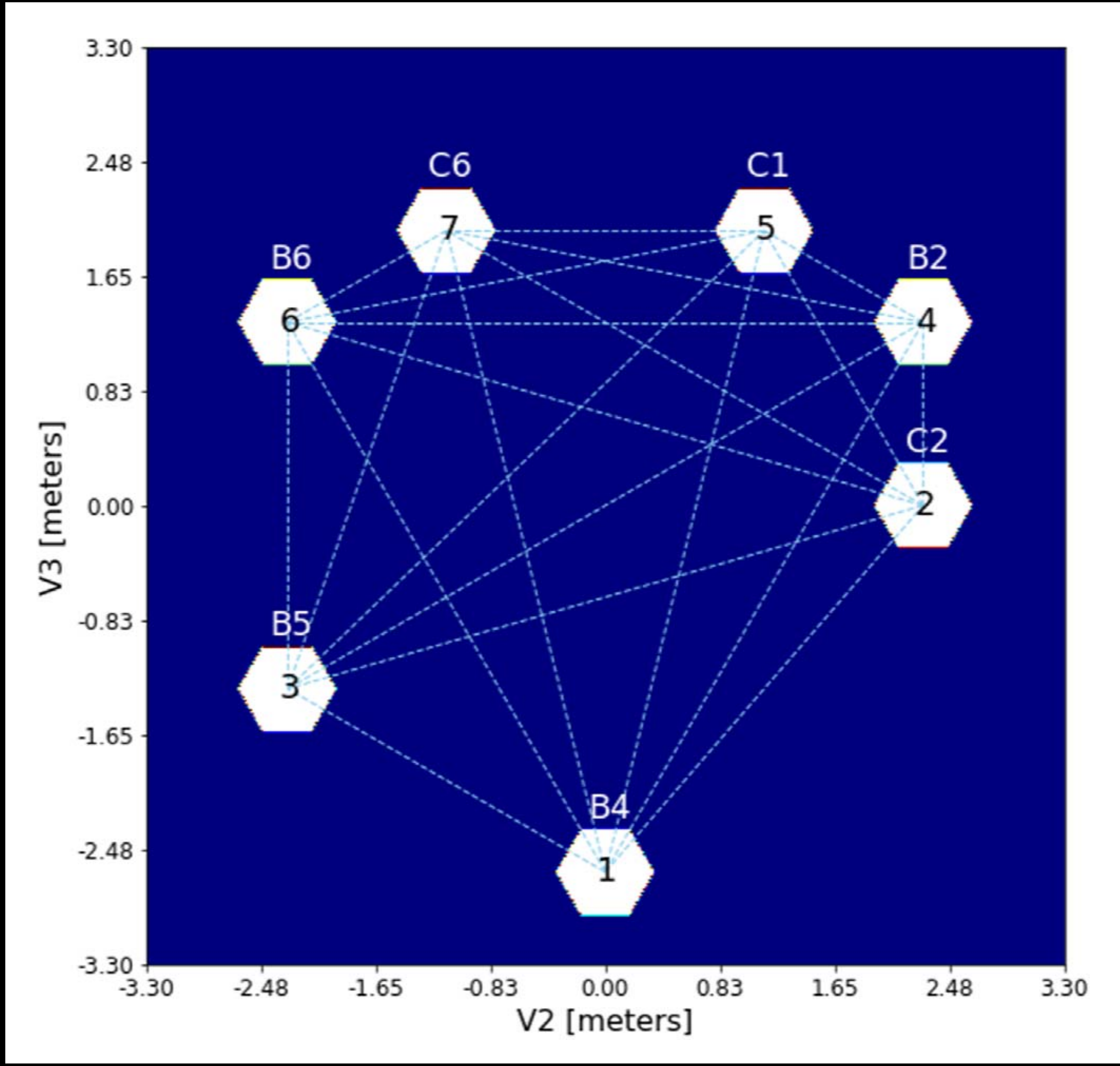
Doelman et al. 2021

JWST/NIRISS AMI: The First O/IR Space Interferometer



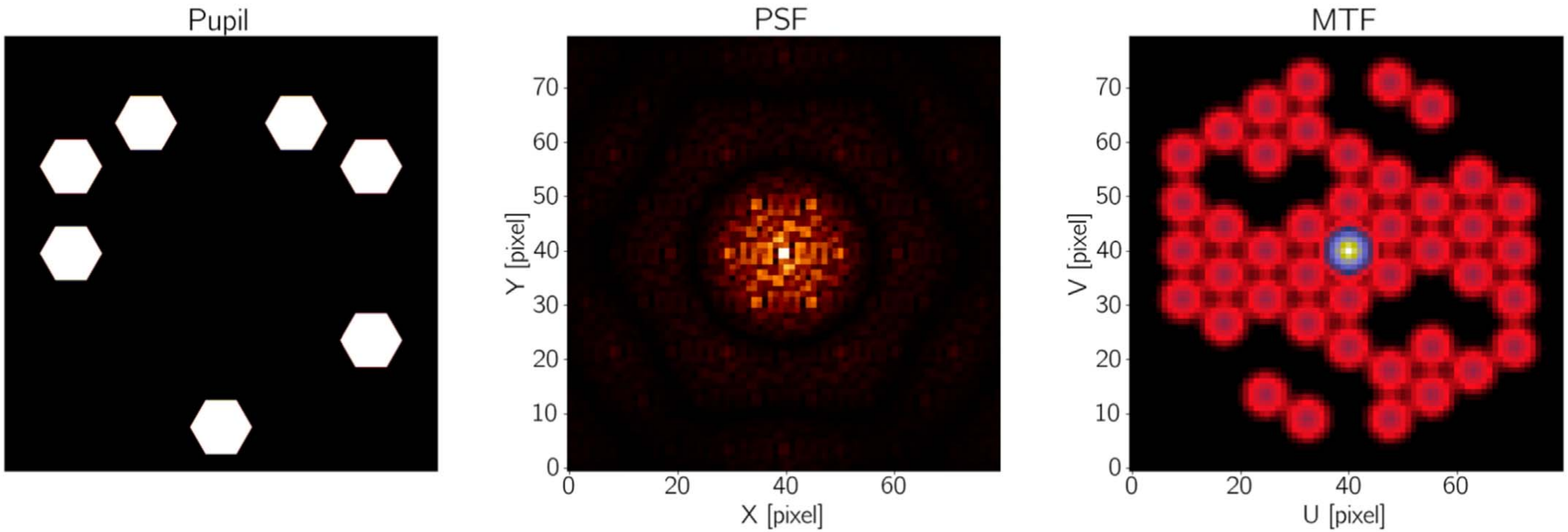
NIRISS AMI

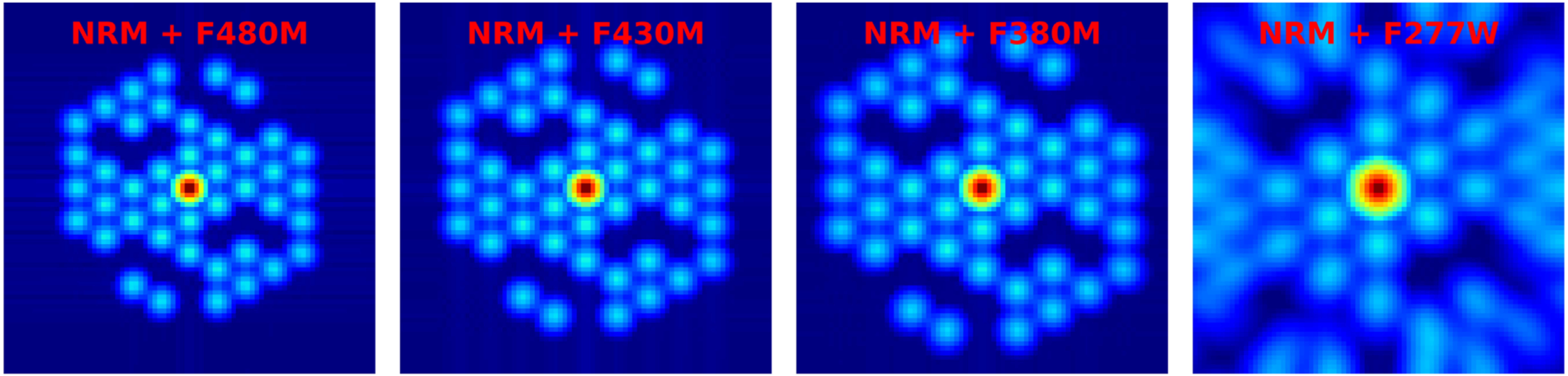




Sivaramakrishnan et al. 2023

NIRISS AMI

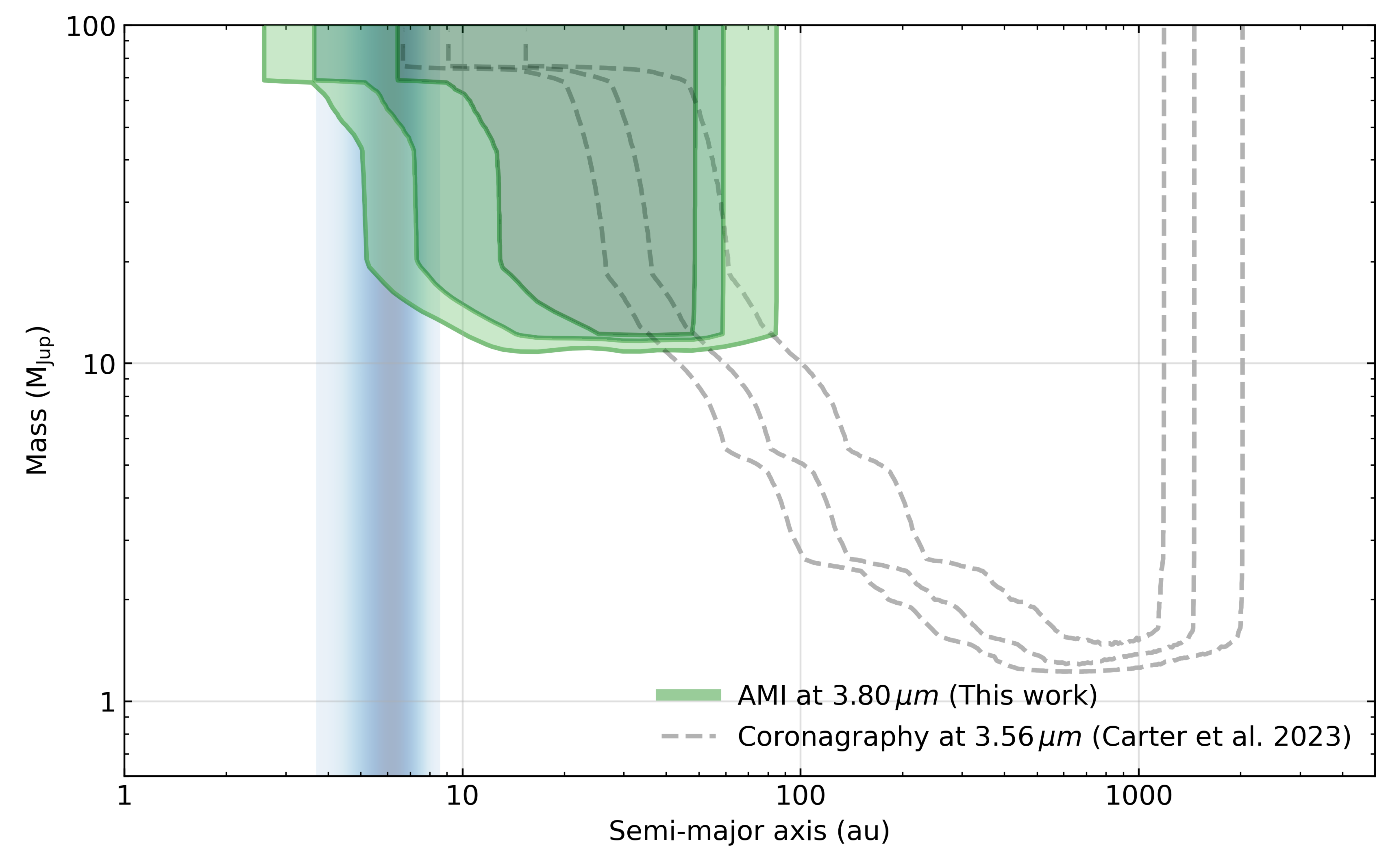




Sivaramakrishnan et al. 2023; Greenbaum 2014

Deep JWST AMI Mass Sensitivity

Comparison to NIRCam Coronagraphy

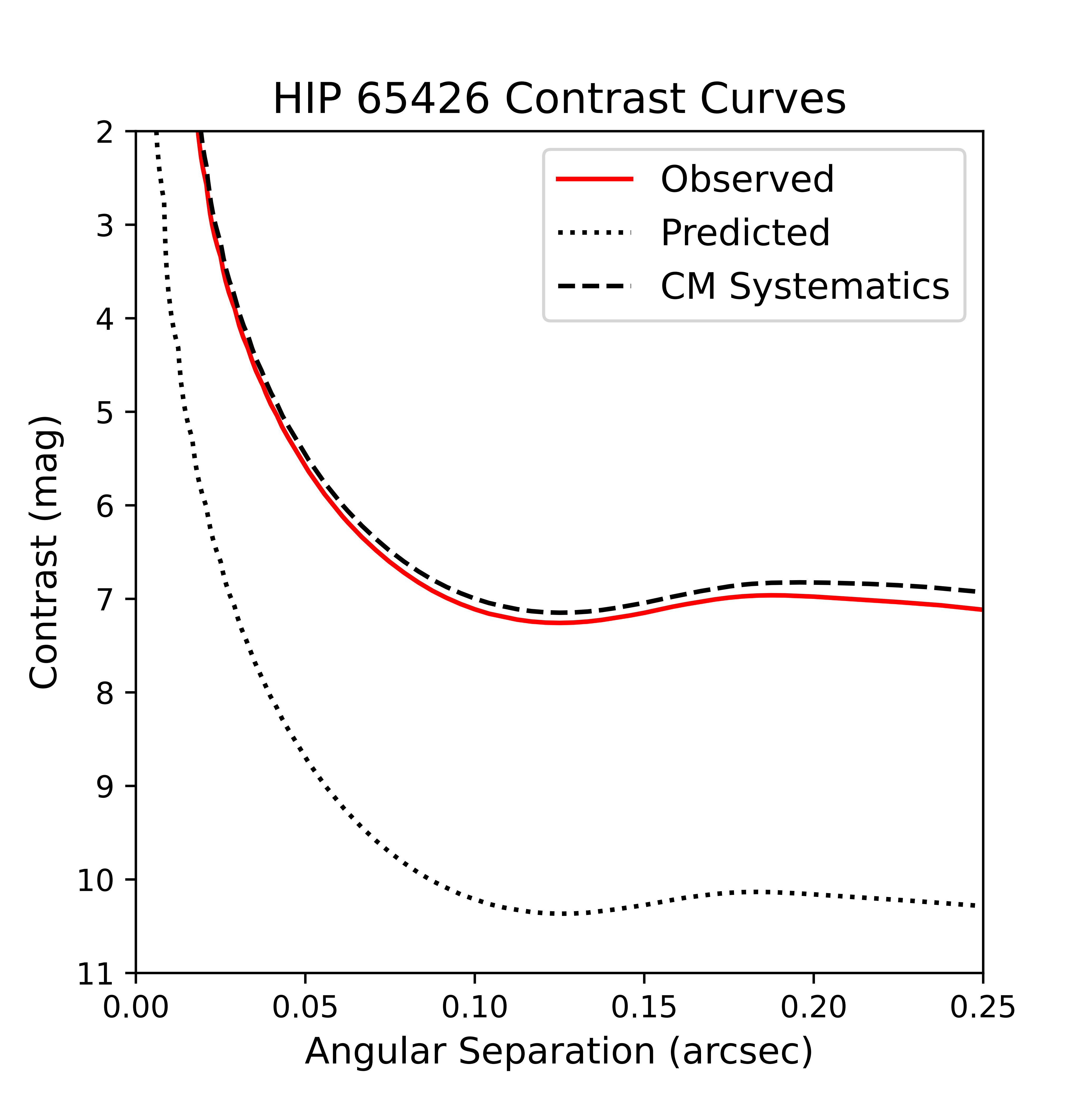


Ray et al. 2024

ERS 1386 AMI Observed Contrast

Comparison to Photon Noise Predictions

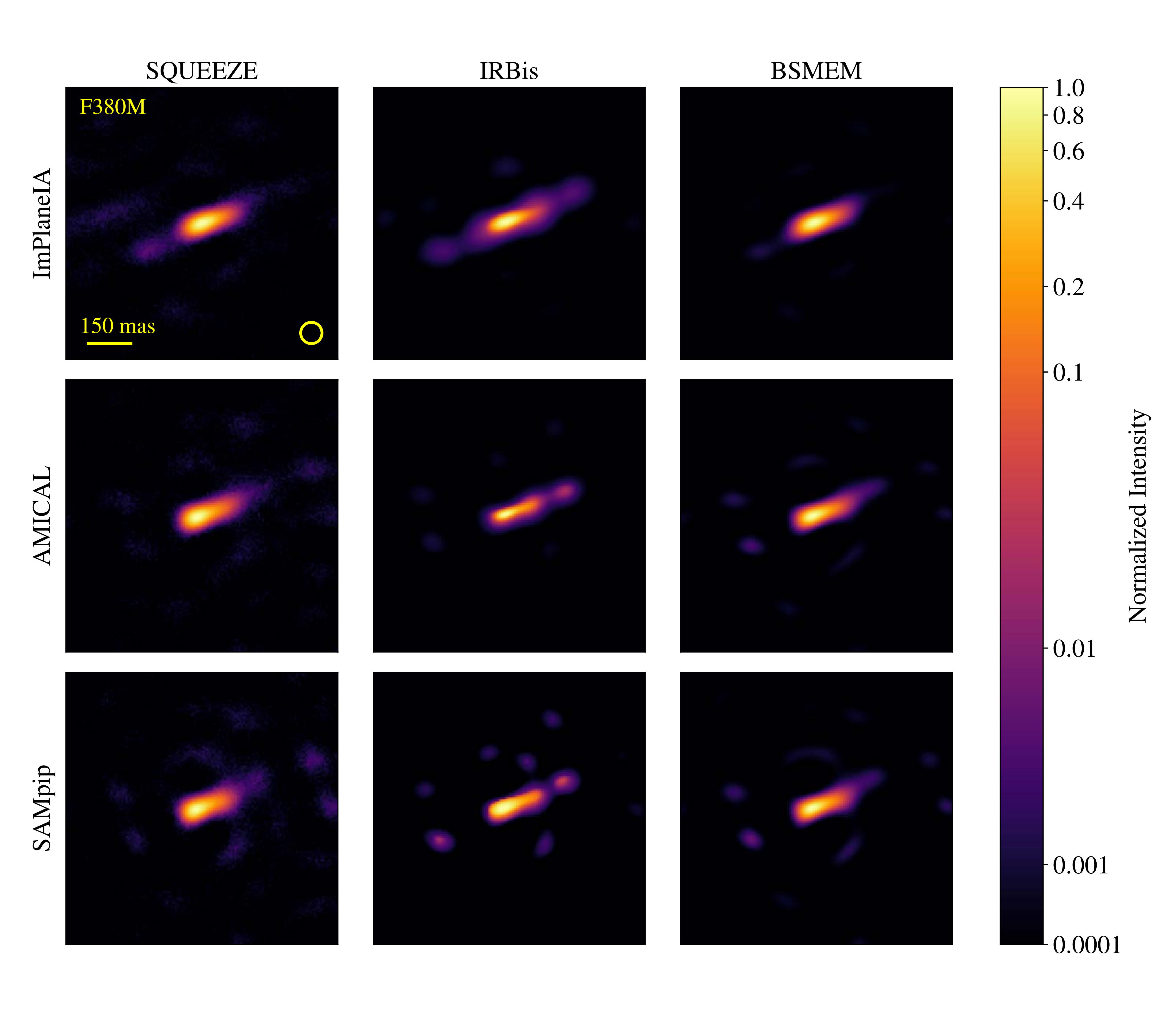
- Maximum contrast: ~7.2 mag at ⩾ λ / D
- Note: this is deeper than deep Keck/NIRC2 performance
- Expected contrast: ~10.5 mag at ⩾ λ / D
- Detector systematics (charge migration) can account for under-performance, and calibrations that eliminate charge migration bring you within a factor of a few of the photon noise floor!
- Observing strategy: look for flux-matched calibrators
- Careful calibration observations and computations in the works!

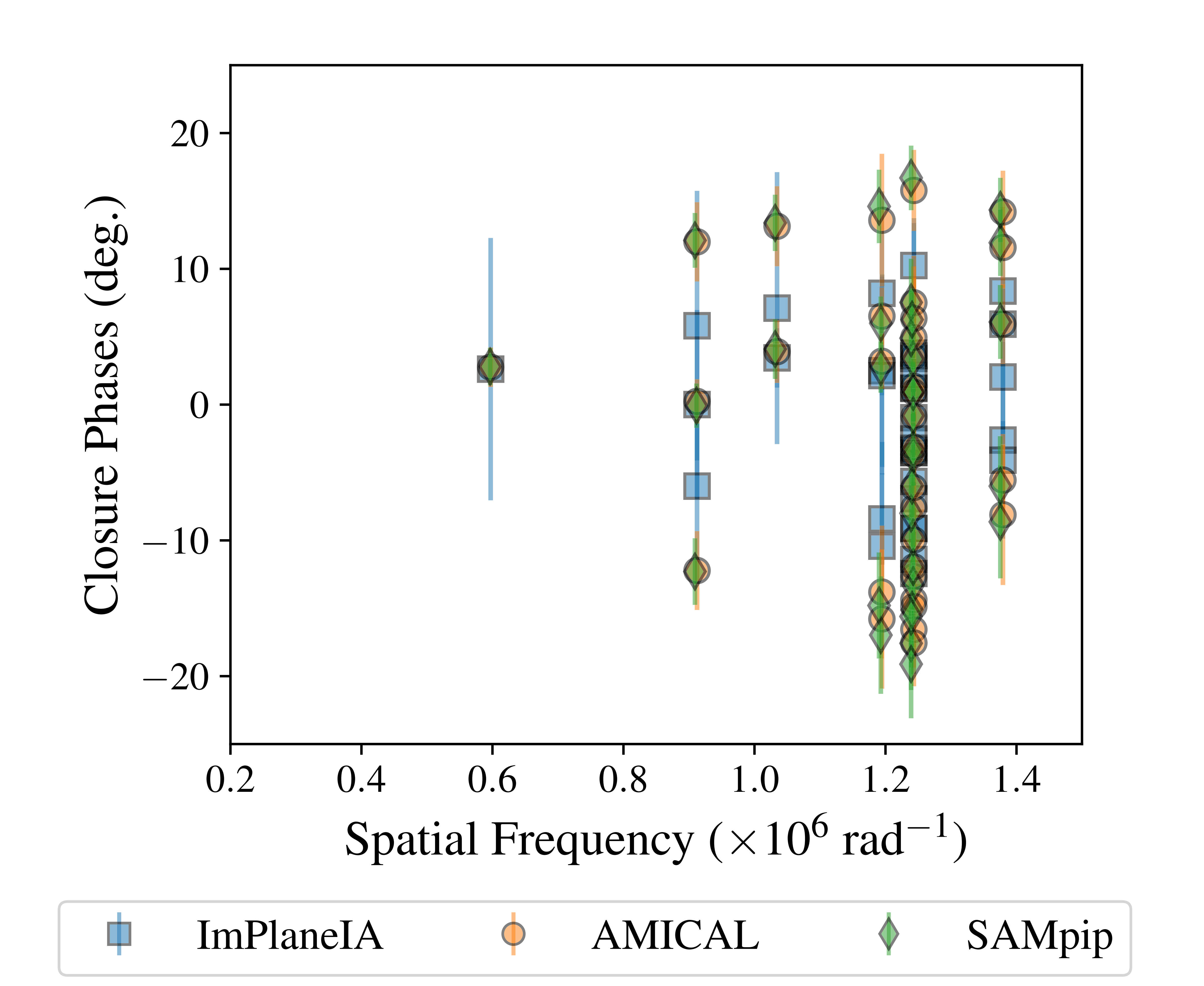


Sallum et al. 2024

Resolving WR 137 with *JWST* AMI

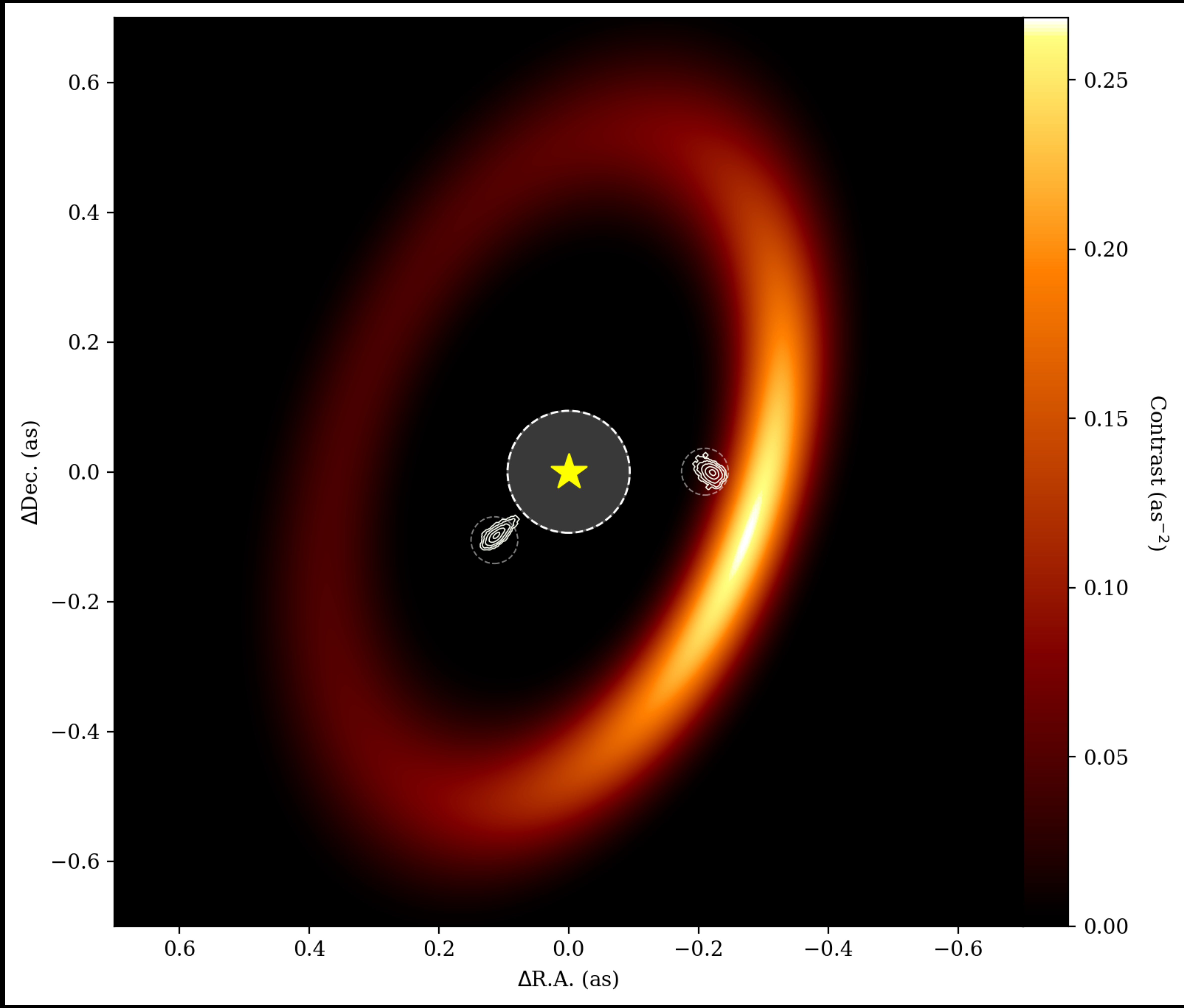
Colliding Winds Plus Data Reduction and Image Reconstruction Tests

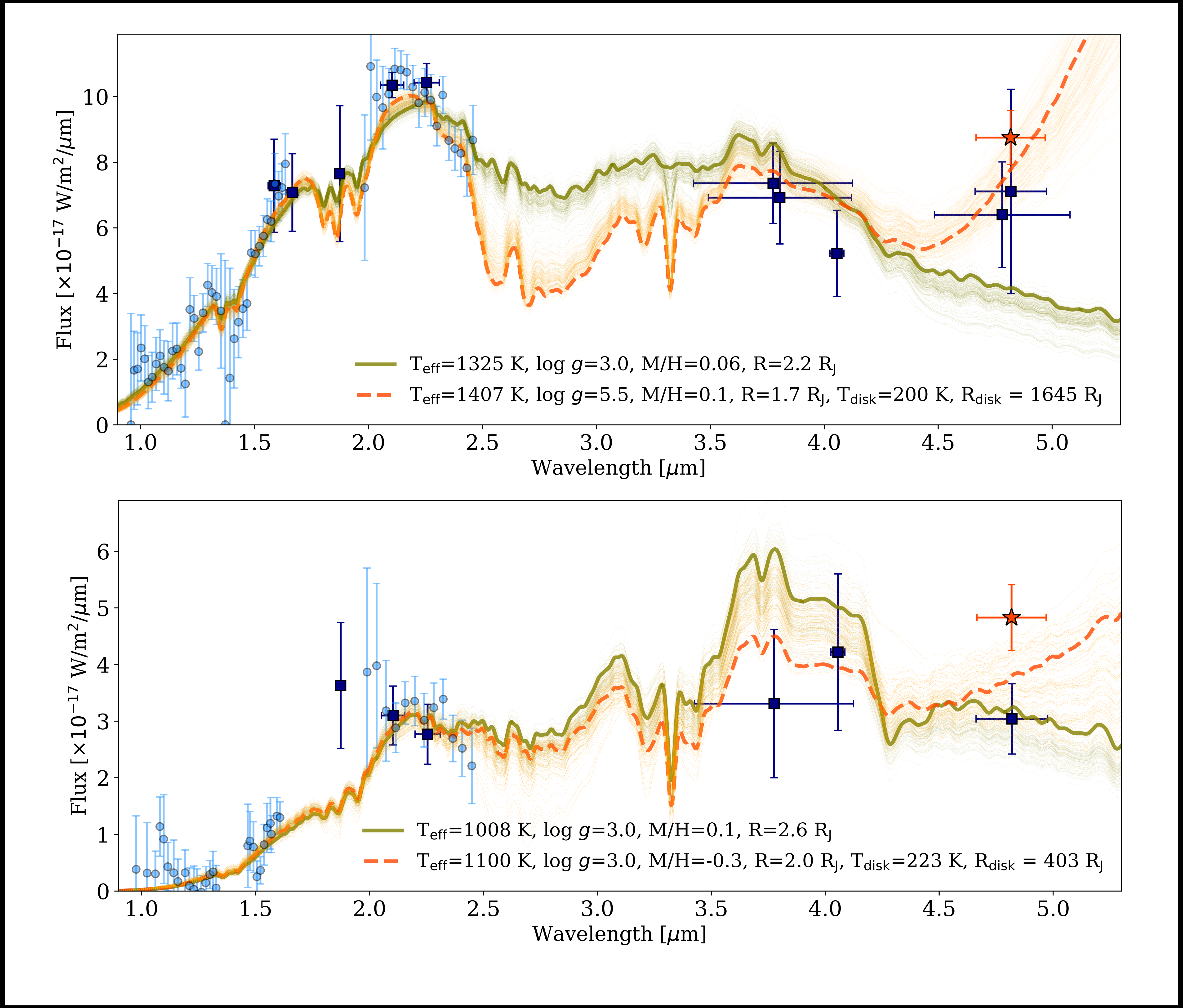




Lau et al. 2024

PDS 70 Observed by *JWST*/NIRISS AMI

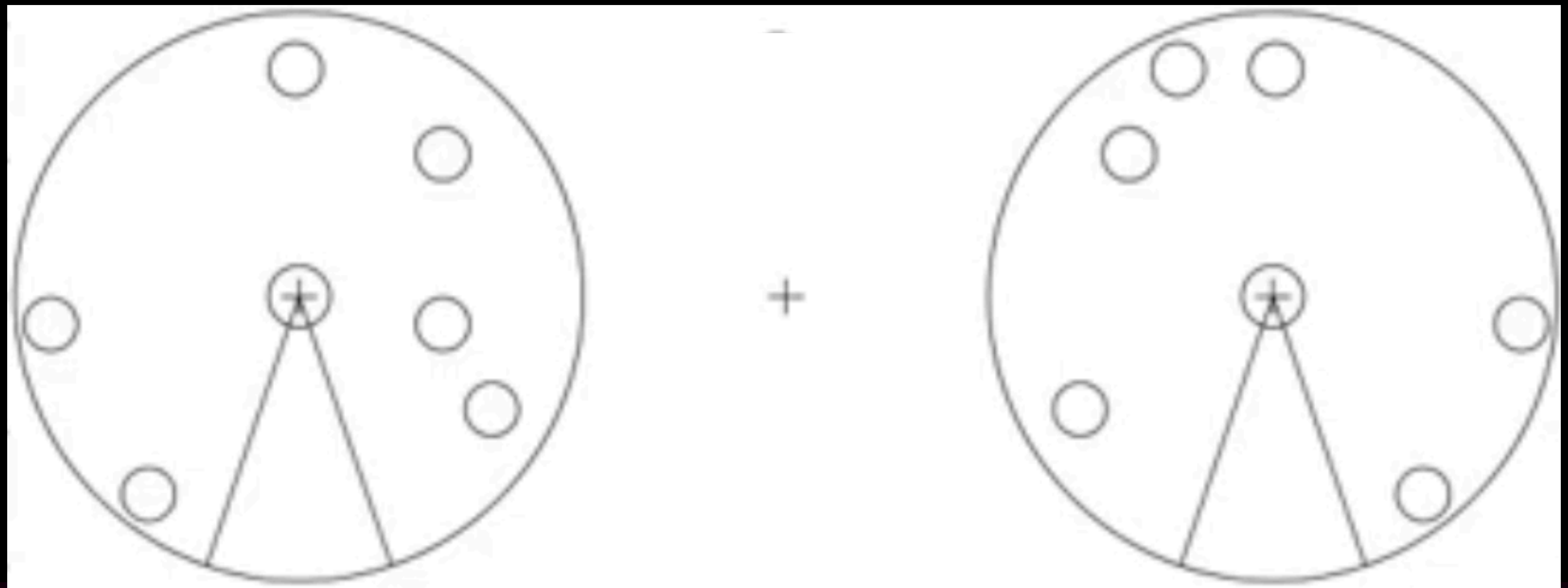


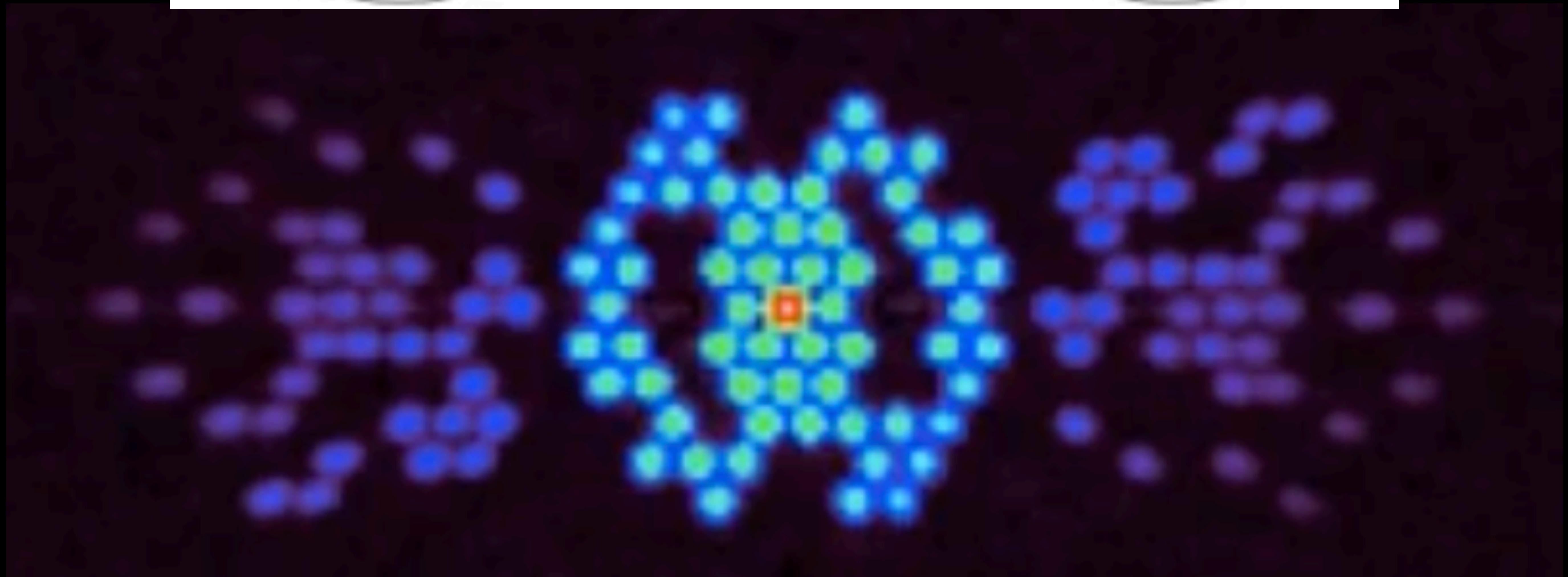


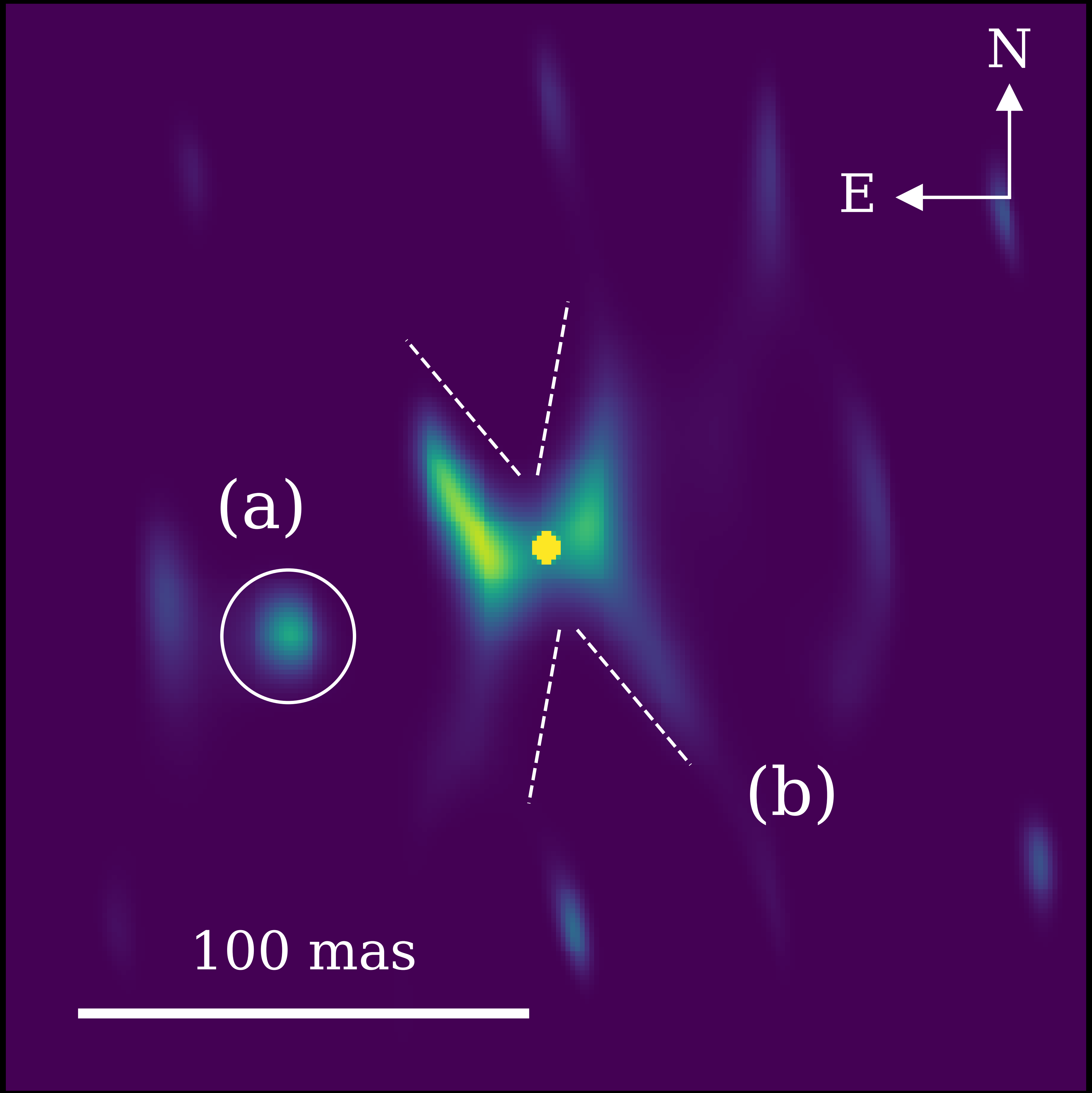
Blakely et al. 2024

Looking Ahead: AMI on the ELTs

- ELT facilities will have AMI modes, and tests with LBTI show that this is useful both scientifically and technically!







Sallum et al. 2017, 2021

AMI Data Reduction Pipelines

Lots of Work, Some Pipeline Comparisons Thanks to *JWST*

- AMiCAL - **Anthony Soulain** - https://github.com/SydneyAstrophotonicsInstrumentationLab/AMICAL
- ImplaneIA - **Alexandra Greenbaum** - https://github.com/agreenbaum/ImPlaneIA
- fouriever - **Jens Kammerer** - https://github.com/kammerje/fouriever
- SAMPip - **Joel Sánchez Bermúdez** - https://cosmosz5.github.io/CASSINI/SAMpip/
- SAMpy - **Steph Sallum** - https://github.com/JWST-ERS1386-AMI/SAMpy
- XARA - **Frantz Martinache** - https://github.com/fmartinache/xara
- ARGUS - **Sam Factor** - https://github.com/smfactor/Argus

A Handful of Interferometry and AMI References

- Lawson 2000, Principles of Long Baseline Stellar Interferometry, https://ecommons.cornell.edu/items/8892b20f-eeb0-4dae-a845-ab1c53a31d19

- Tuthill et al. 2000, Michelson Interferometry with the Keck I Telescope, https://ui.adsabs.harvard.edu/abs/2000PASP..112..555T/abstract

- Ireland 2013, Phase errors in diffraction-limited imaging: contrast limits for sparse aperture masking, https://ui.adsabs.harvard.edu/abs/2013MNRAS.433.1718I/abstract

- Martinache 2010, Kernel Phase in Fizeau Interferometry, https://ui.adsabs.harvard.edu/abs/2010ApJ...724..464M/abstract

- Tuthill 2012, The unlikely rise of masking interferometry: leading the way with 19th century technology, https://ui.adsabs.harvard.edu/abs/2012SPIE.8445E..02T/abstract

Thanks!