**Steph Sallum Sagan Summer Workshop July 26, 2024**

# **Aperture Masking Interferometry in Astronomy**

# **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.**

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



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!



### **Aperture Masking Interferometry Transforming a filled aperture into an interferometric array via a pupil-plane mask.**



*Image credit: Peter Tuthill*

## **Aperture Masking Interferometry Transforming a filled aperture into an interferometric array via a pupil-plane mask.**



*Image credit: Peter Tu...* 



# **Young's Double Slit Experiment (1801)**





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













































### **Non-Redundant Masking Using NRM to measure stellar diameters was first suggested by Fizeau in 1868!**



### **Pupil Image Complex Visibilities**



**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 van Cittert-Zernike Theorem: 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://commons.wikimedia.org/wiki/User:Berto) [https://twitter.com/j\\_bertolotti/status/](https://twitter.com/j_bertolotti/status/1674801693228417031?s=20) [1674801693228417031?s=20](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.



 $\Phi(u_1,v_1) = \Phi(i(u_1,v_1) + (\Delta \Phi_2 - \Delta \Phi_1))$  $+ \Phi(u_2,v_2) = \Phi(i(u_2,v_2) + (\Delta \Phi_2 - \Delta \Phi_2))$  $+$   $\Phi$ (u<sub>3</sub>,v<sub>3</sub>) =  $\Phi$ i(u<sub>3</sub>,v<sub>3</sub>) + ( $\Phi$ <sub>1</sub>- $\Delta\Phi$ <sub>3</sub>)

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





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



# What about a redundant aperture?  $ΔΦ<sub>2</sub>$ ΔΦ<sup>1</sup> ΔΦ<sup>4</sup>  $ΔΦ<sub>3</sub>$

 $\Phi_i$ 















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





Binary Image **Fourier Phase** 

**The phase signal seen by a particular baseline depends on its orientation and its length!**



**Baselines oriented this way see phase that changes sinusoidally with length.**



**Baselines oriented this way see phase that doesn't change with length.**













































































## **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](https://www.jb.man.ac.uk/ira4/IRA4%20SuppMat_Chapter9.htm)

# **Images to Source Brightness Distribution**









# **NRM Contrast**

- NRM's self-calibrating observables enable "*superresolution*": 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

![](_page_42_Picture_5.jpeg)

# Ground-Based AMI

![](_page_43_Picture_1.jpeg)

15 '00

:>

![](_page_44_Figure_5.jpeg)

### **Early Demonstrations with UH 88, AAT, Hale** "0 ! un Ulfi & , AVAI, F g 0.10 fluctuations to - 0.5-1 arc s; that is, -10-50 times worse than the theoretical diffraction limit. In contrast, the measurement of visibilities and closure phases of fringe patterns in short-exposure images, taken through an aperture mask comprising a non-redun- $\blacksquare$  of the prospect of  $\blacksquare$ diffraction-limited imaging using methods well established in very long baseline interferometry (VLBI) at radio wavelengths. Here down in conditions of poor signal-to-noise ratio. Except for simple cases such as binary stars, or where a bright star at one , no image allows speckle reliable diffraction-limited optical images have been obtained by any of these techniques. In radioastronomy, on the other

![](_page_44_Picture_1.jpeg)

![](_page_44_Figure_2.jpeg)

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**

![](_page_45_Picture_5.jpeg)

**WR 98A**

![](_page_45_Picture_3.jpeg)

![](_page_45_Picture_4.jpeg)

**Red Rectangle WR 104**

![](_page_45_Picture_9.jpeg)

2.20  $\mu$ m (K<sub>S</sub>)

**MWC 349A**

**WR <sup>140</sup> WR <sup>112</sup>**

![](_page_45_Picture_13.jpeg)

WR140 1999 Jul

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

![](_page_45_Picture_18.jpeg)

### **AMI** + Adaptive Optics on 10m Class Telescopes The Astrophysical Journal, 745:5 (12pp), 2012 January 20 Kraus & Ireland

Carlingian Riverse Related CO10: Delastic et al. 0000: Qalliweat al. 0015, 0000 e.g. Kraus & Ireland ZUTZ, Blake et al. 2022; Sallum et al. 2015, 202  $\alpha$ e.g. Kraus & Ireland 2012; Blakely et al. 2022; Sallum et al. 2015, 2023

![](_page_46_Figure_2.jpeg)

![](_page_46_Figure_1.jpeg)

![](_page_46_Picture_4.jpeg)

tions the mage to this test we obtain that discussed in the previous paragraph. Furthermore, an image was directly reconstructed from simulated data of a  $\overline{\phantom{a}}$  point-source model, consisting of LkCa  $15$ candidate planets. The reconstructed image clearly retains each of the three distinct point sources. In combination, the direct image reconstructions, although utilizing a significantly undersampled measurement set, yield results similar to our  $f_* = 0.9$ 

### **High-Contrast AMI Science** to squared visibility and closure phase histograms comparable to those in Figure 2. Each column shows a different observational epoch. White crosses mark the position of the central delta function. In addition, in addition. In addition, we have shown not have shown no

g. Willson et al. 2019; Sallum et al. 2019; Han et al. 2022; Vides et al. 2023 the resolved structures. The colour scale in the images refers to the flux as a fraction of the peak flux after subtracting the central source. Southern Bar  $\Box$ willson et al. 2019: dust production rate is smoothly reduced to a local minimum at periassallum et al. 2019: Han et al. 2022: \ the outline of the model on the corresponding *φ* = 0.592 Lp-band obser-

![](_page_47_Figure_1.jpeg)

![](_page_47_Figure_2.jpeg)

### **Spectrally-Dispersed AMI on Integral Field Spectrographs** The Astronomical Journal, 157:249 (17pp), 2019 June Greenbaum et al. The Astronomical Journal, 157:249 (17pp), 2019 June Greenbaum et al.

![](_page_48_Figure_1.jpeg)

e.g. Cheetham et al. 2016; Greenbaum et al. 2019 e.g. Cheetham et al. 2016: Greenbaum et al. 2019 data are calibrated with the second half, overestimating performance. The right panel shows snapshots of the data. The IFS provides twice the sensitivity and smooths Greenhaum et al. 2010

![](_page_48_Picture_3.jpeg)

![](_page_48_Picture_4.jpeg)

![](_page_48_Picture_5.jpeg)

![](_page_48_Picture_9.jpeg)

tix in August 2018, labeled part A and part B. The first HAM

device, part A, was manufactured using a 1 inch flat calcium flu-

oride (CaF $2$ ) substrate with a thickness of  $5$ 

ond HAM device, part B, was fabricated using a 1 inch wedged

 $\mathcal{L}_{\mathcal{L}}$  substrate with a thickness of 1 mm.

the same three-layered liquid-crystal multi-twist retarder film,

aimed at  $\mathbb{R}$ 

Both devices have an antireflection coating for this bandpass on

the backside of the substrates. The phase pattern with a diameter

of 25.4 mm was generated with 5 micron pixels. The polarization

leakage measured by the manufacturer is less than 3% between 1

and 2.5 µm. Additional alignment markings have been added to

the pattern, outside of the pupil diameter of 13.5 mm. An image

of the optic between polarizers is shown in Fig. 4a. In addition,

the optic was inspected under a microscope between polarizers.

monochromatic PSF. (*c) Simulated PSF. (c) Simulated PSF. (c) Simulated PSF. (c) Simulated PSF with 30% bandwidth.* 

![](_page_49_Figure_4.jpeg)

![](_page_49_Picture_2.jpeg)

Fig. 5: Manufacturing of HAM v1.5. (*a*) Images of the diced

ferred with HAM as a function of wavelength, expressed in wavelength, expressed in the wavelength, expressed in

# **Holographic Aperture Masking**

![](_page_49_Picture_1.jpeg)

Fig. 3: Design of the HAM mask for OSIRIS. (*a*) Phase pattern of the HAM optic, masked by the amplitude mask. (*b*) Simulated

Two prototype Ham devices  $\mathbf{H}$ 

Fig. 16: Recovered brightness ratio of the binary as a function of wavelength. The green line shows the expected brightness ratio Doelman et al. 2021

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

![](_page_50_Picture_1.jpeg)

### **NIRISS AMI** Publications of the Astronomical Society of the Pacific, 135:015003 (20pp), 2023 January Sivaramakrishnan et al.

![](_page_51_Picture_1.jpeg)

### Sivaramakrishnan et al. 2023

![](_page_51_Figure_3.jpeg)

Publications of the Astronomical Society of the Pacific, 135:015003 (20pp), 2023 January Sivaramakrishnan et al.

## **NIRISS AMI**

![](_page_52_Figure_1.jpeg)

![](_page_52_Picture_2.jpeg)

Sivaramakrishnan et al. 2023; Greenbaum 2014 AMI and KPI. Figure 1 shows the AMI NRM pupil, its PSF,

![](_page_52_Picture_5.jpeg)

![](_page_52_Picture_3.jpeg)

![](_page_52_Picture_8.jpeg)

![](_page_52_Picture_7.jpeg)

![](_page_52_Figure_6.jpeg)

## **Deep JWST AMI Mass Sensitivity Comparison to NIRCam Coronagraphy**

![](_page_53_Figure_1.jpeg)

Ray et al. 2024

- Maximum contrast:  $\sim$ 7.2 mag at  $\geq \lambda$  / D
- Note: this is deeper than deep Keck/NIRC2 performance
- Expected contrast: ~10.5 mag at  $\geq \lambda$  / 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!

### **ERS 1386 AMI Observed Contrast Comparison to Photon Noise Predictions**

Sallum et al. 2024

![](_page_54_Figure_11.jpeg)

![](_page_54_Picture_12.jpeg)

### **Resolving WR 137 with** *JWST* **AMI Colliding Winds Plus Data Reduction and Image Reconstruction Tests**

![](_page_55_Figure_1.jpeg)

![](_page_55_Figure_2.jpeg)

Lau et al. 2024

![](_page_55_Picture_4.jpeg)

![](_page_55_Picture_13.jpeg)

# **PDS 70 Observed by**  $JV_{\frac{1}{2}}$

![](_page_56_Figure_1.jpeg)

Blakely et al. 2024 positions of PDS 70 and co. The time of the predicted on the planets are centered on the planets at the planet 13

![](_page_56_Figure_3.jpeg)

Contrast (as

![](_page_56_Picture_5.jpeg)

![](_page_56_Picture_6.jpeg)

![](_page_56_Picture_7.jpeg)

![](_page_56_Picture_8.jpeg)

# **Looking Ahead: AMI on the ELTs**

![](_page_57_Figure_2.jpeg)

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/ImPlanelA>
- 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**

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

- Lawson 2000, Principles of Long Baseline Stellar Interferometry, [https://](https://ecommons.cornell.edu/items/8892b20f-eeb0-4dae-a845-ab1c53a31d19) [ecommons.cornell.edu/items/8892b20f-eeb0-4dae-a845-ab1c53a31d19](https://ecommons.cornell.edu/items/8892b20f-eeb0-4dae-a845-ab1c53a31d19)
- [Tuthill et al. 2000, Michelson Interferometry with the Keck](https://ui.adsabs.harvard.edu/abs/2000PASP..112..555T/abstract) I Telescope, [https://](https://ui.adsabs.harvard.edu/abs/2000PASP..112..555T/abstract) [ui.adsabs.harvard.edu/abs/2000PASP..112..555T/abstract](https://ui.adsabs.harvard.edu/abs/2000PASP..112..555T/abstract)
- 
- [Martinache 2010, Kernel Phase in Fizeau Interferometry, https://](https://ui.adsabs.harvard.edu/abs/2010ApJ...724..464M/abstract) [ui.adsabs.harvard.edu/abs/2010ApJ...724..464M/abstract](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>

![](_page_59_Picture_12.jpeg)

## **Thanks!**