MIRC-X/MYSTIC instrument overview and science highlights

Claire L. Davies

c.davies3@exeter.ac.uk

On behalf of the MIRC-X/MYSTIC consortium:

John D. Monnier (Michigan PI), **Stefan Kraus** (Exeter PI)

Jean-Baptiste le Bouquin (IPAG/Michigan), Narsireddy Anugu (Exeter/Michigan, now Arizona),
Benjamin R. Setterholm (Michigan), Tyler Gardner (Michigan), Aaron Labdon (Exeter, soon ESO Santiago),
Lurent Jocou (IPAG), Cyprien Lanthermann (Grenoble, now CHARA), Jacob Ennis (Michigan),
Theo ten Brummelaar (CHARA)

European Research Council
Established by the European Commission

Place-holder for speaker-view video

Talk outline

1. MIRC highlights
2. Motivation for development: science goals of the MIRC-X/MYSTIC project
3. Technical developments
4. Science highlights
5. Future timeline

Place-holder for speaker-view video

MIRC highlights

Imaging rapid rotators

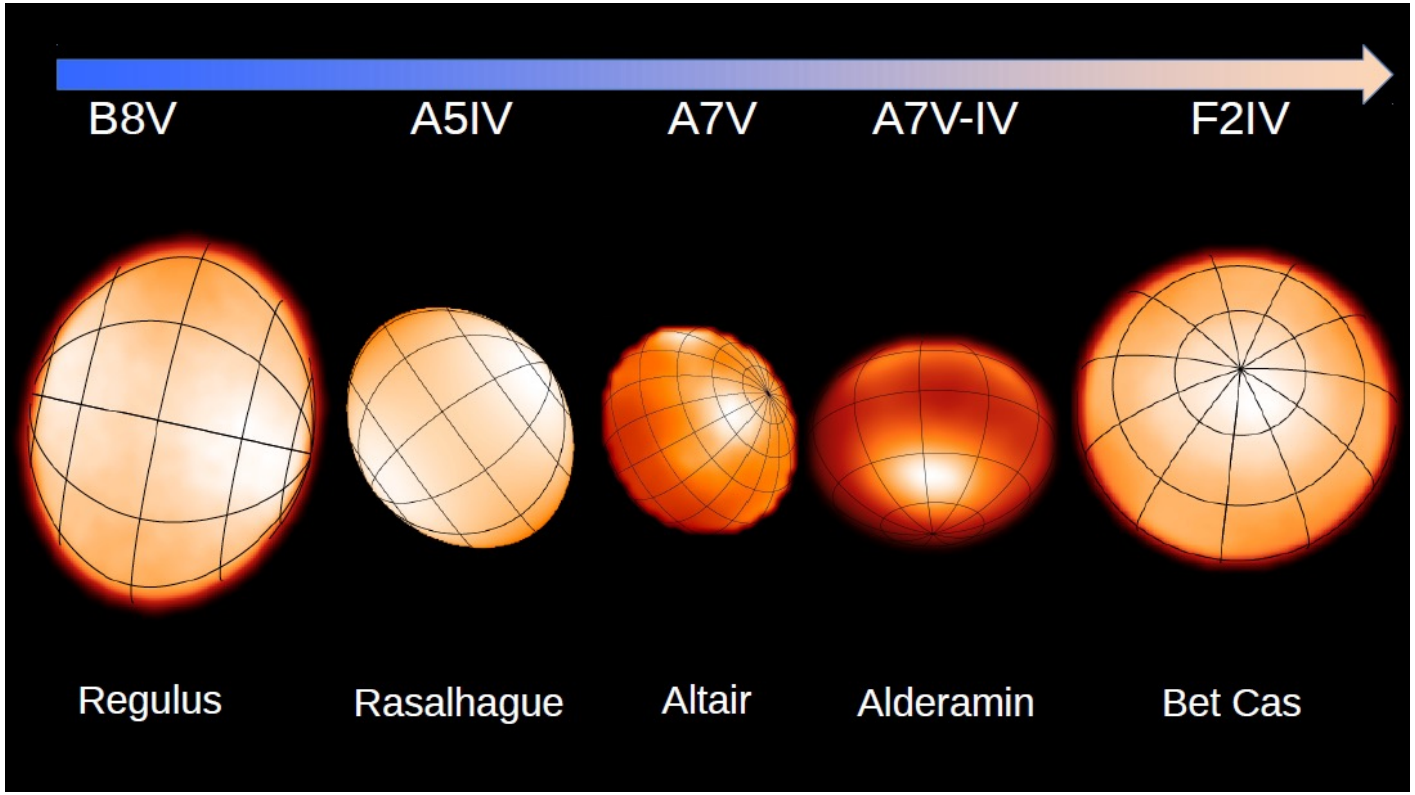
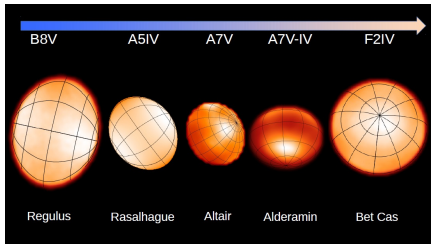


Image credit: J. D Monnier. Based on results from Che+2011; Zhao+2009; Monnier+2007.

Place-holder for speaker-view video

MIRC highlights

Imaging rapid rotators



Imaging nova explosions

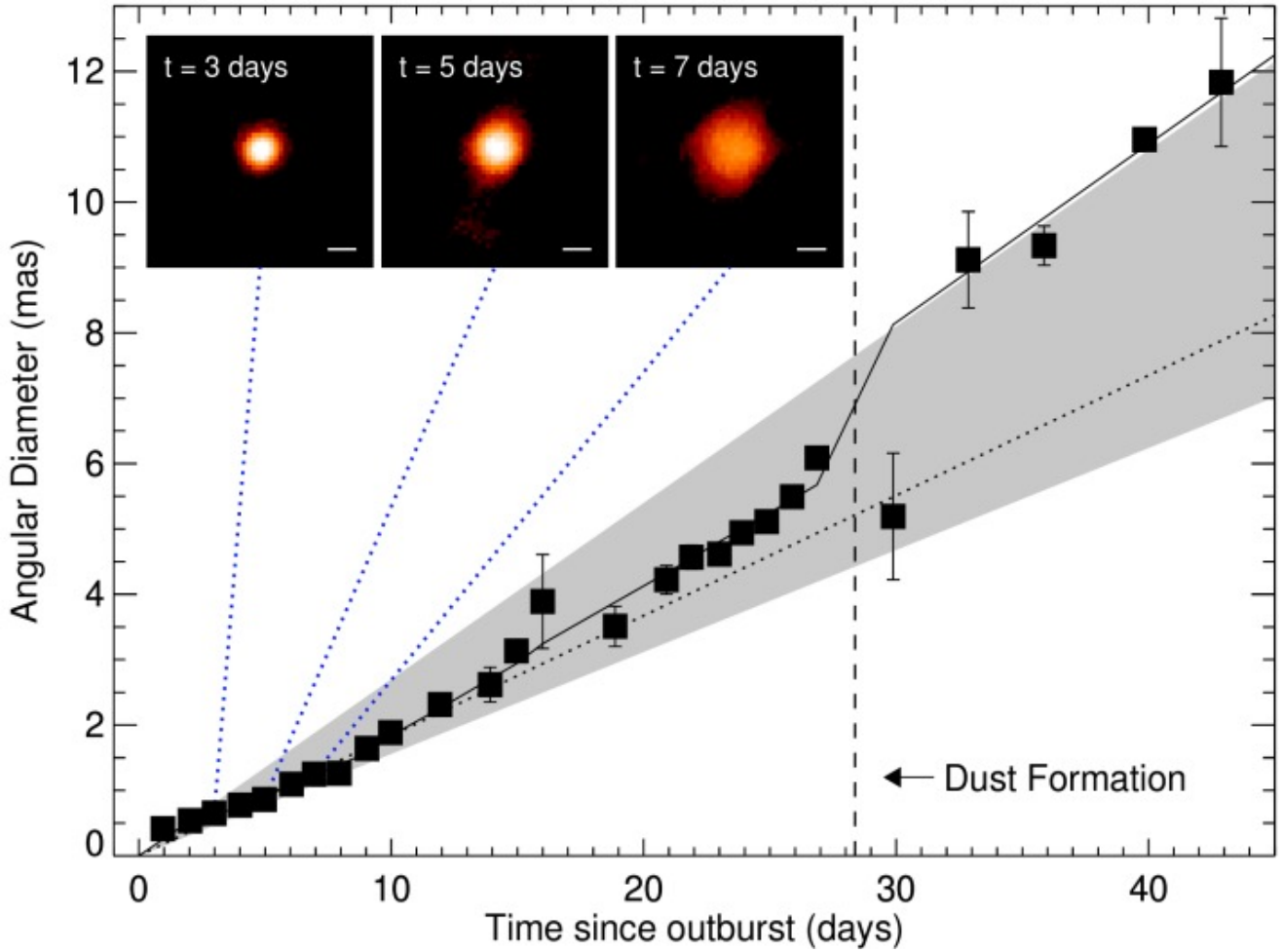


Image credit: Schaefer+2014

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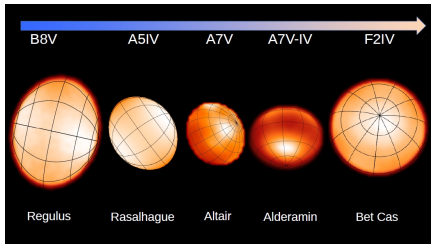
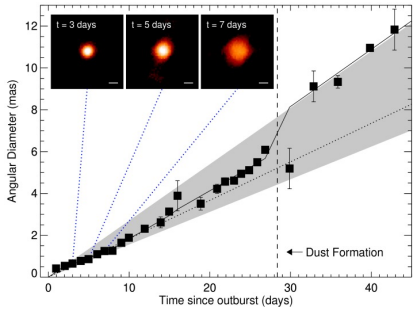
MIRC highlights

Imaging rapid rotators



Imaging nova explosions



Imaging spotted magnetic stars

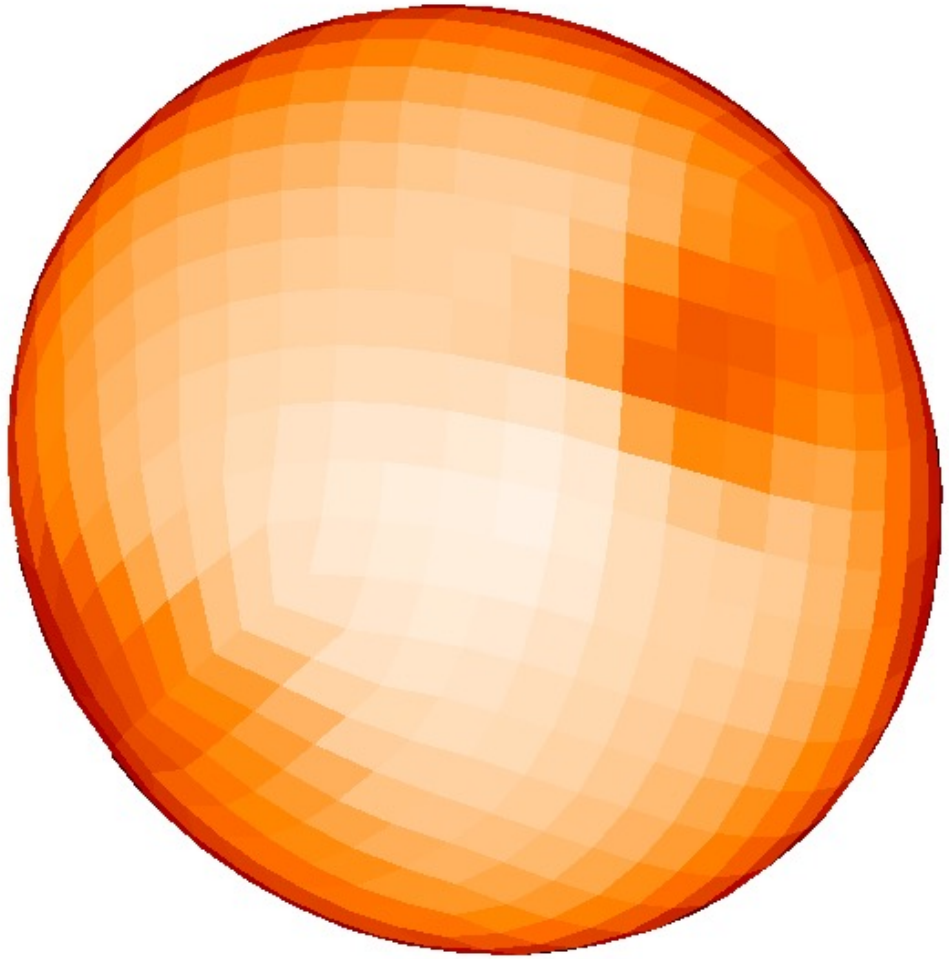
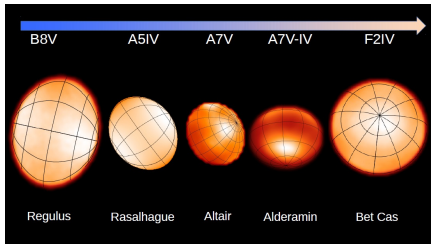


Image credit: Roettenbacher+2016

Place-holder for speaker-view video

MIRC highlights

Imaging rapid rotators



Imaging interacting binary stars

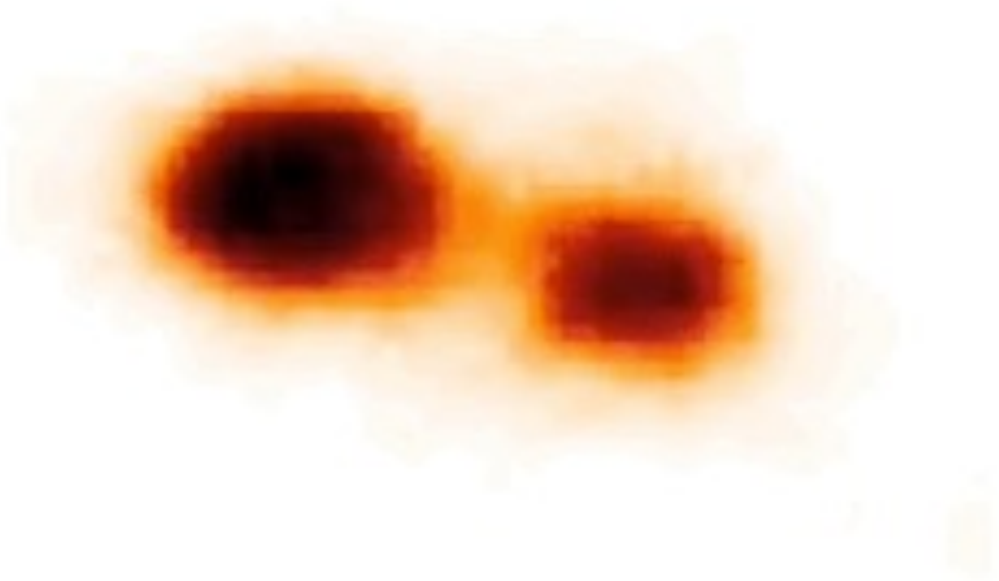
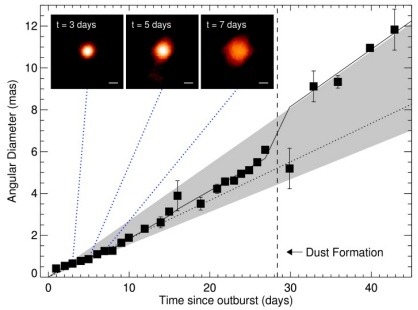
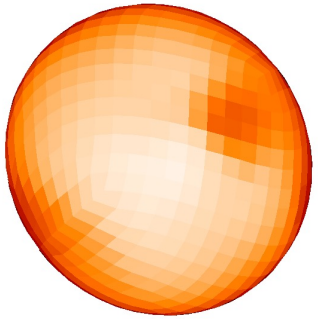


Image credit: Zhao+2008

Imaging nova explosions



Imaging spotted magnetic stars



Place-holder for speaker-view video

Science drivers for instrument developments

Imaging young stellar objects to characterise physical conditions of planet formation and probe time-variable structures

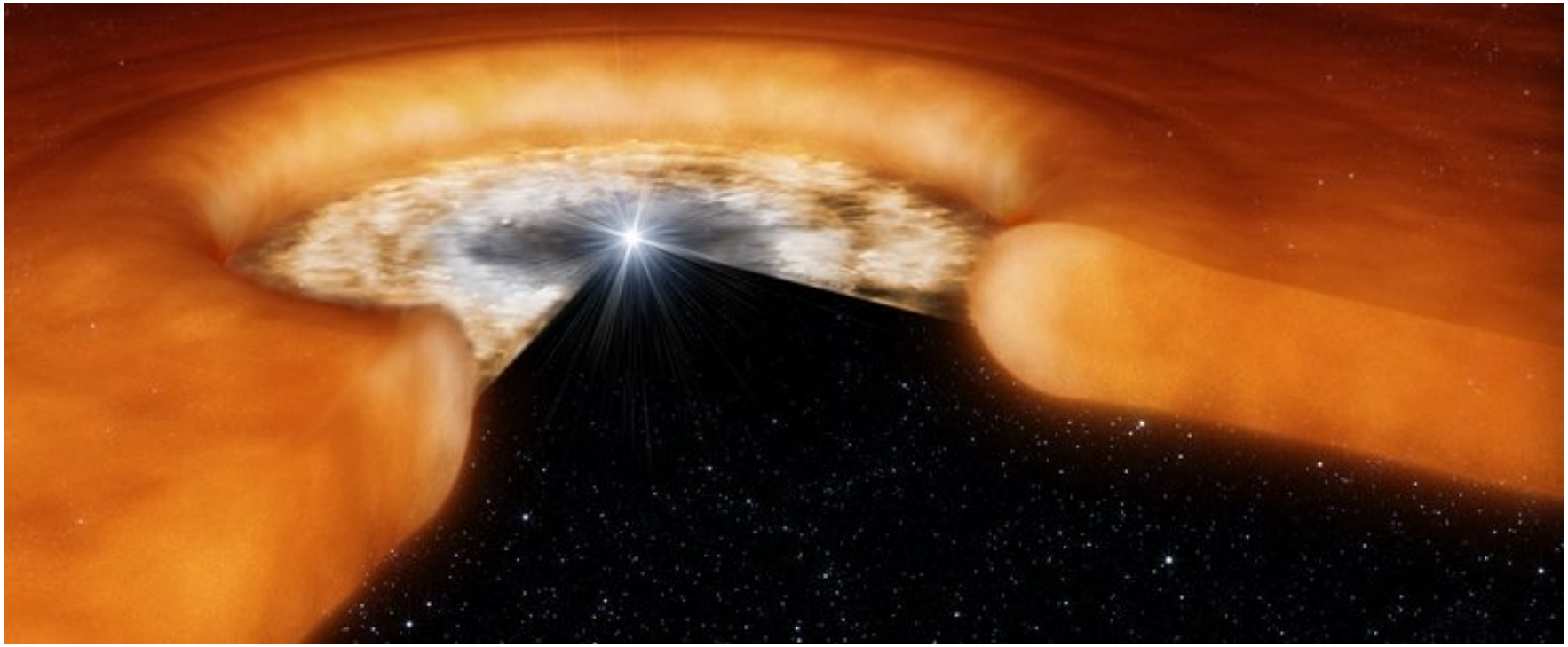


Image credit: ESO/L. Calçada

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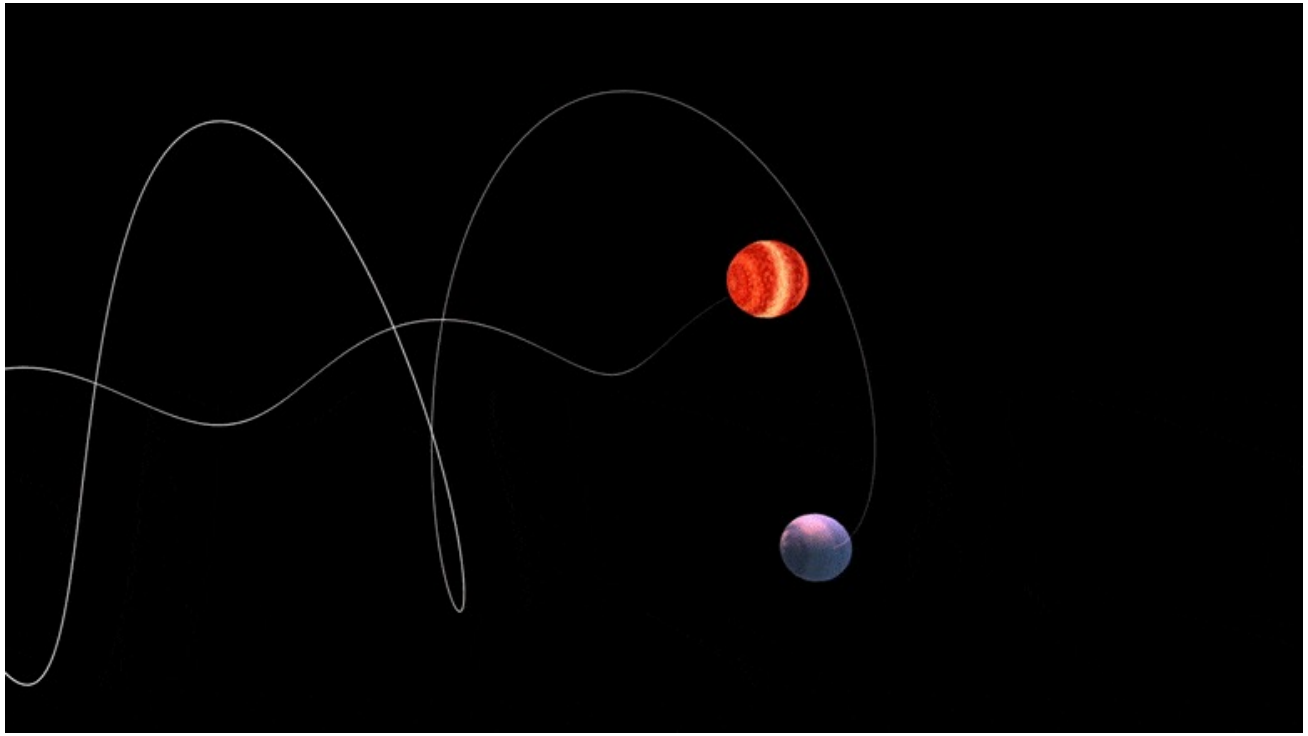
Place-holder for speaker-view video

Science drivers for instrument developments

Imaging young stellar objects to characterise physical conditions of planet formation and probe time-variable structures

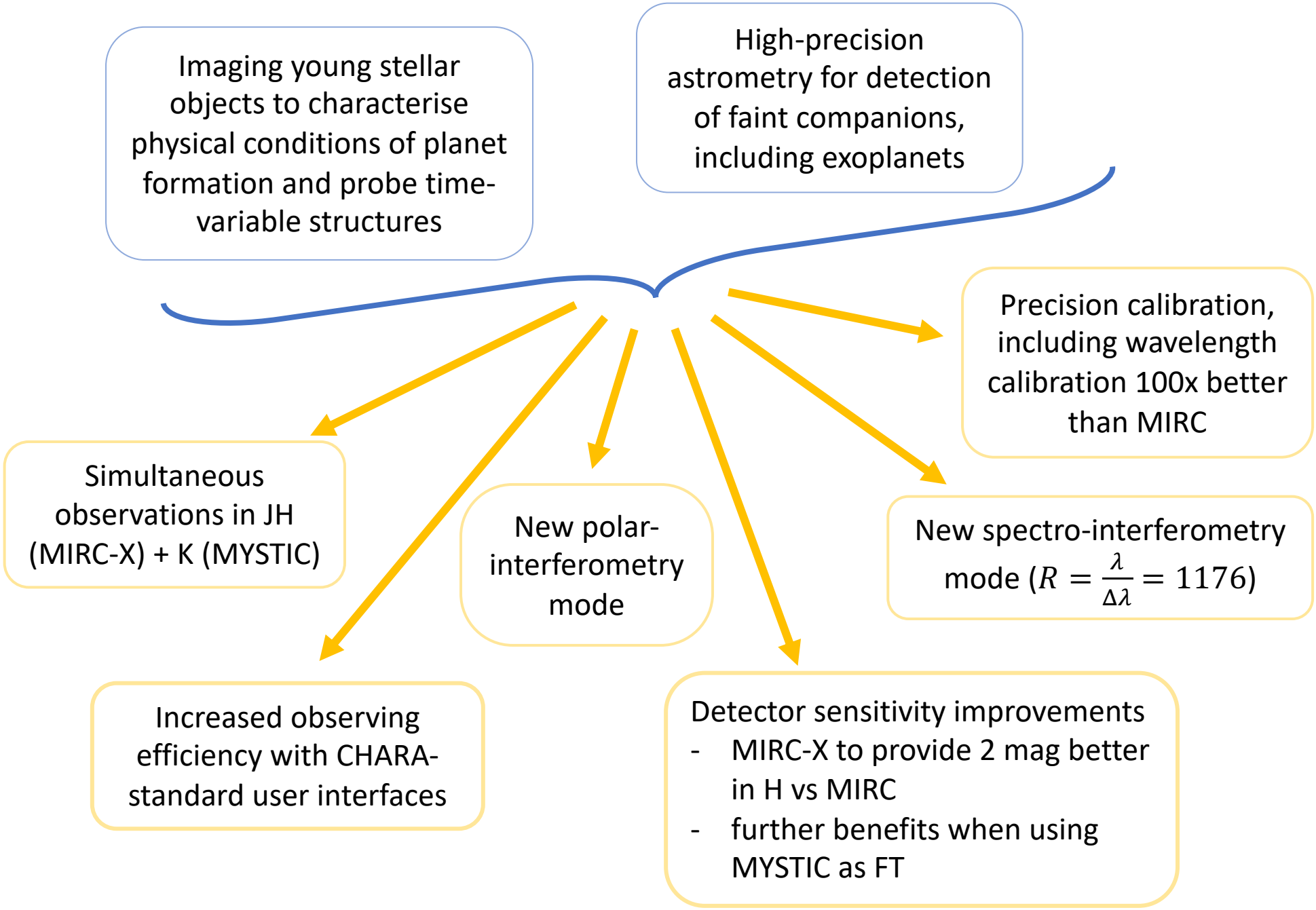
High-precision astrometry for detection of faint companions, including exoplanets



Animation credit: Bill Saxton, NRAO/AUI/NSF

Place-holder for speaker-view video

Science drivers for instrument developments



Place-holder for speaker-view video

Instrument developments

MIRC-X and MYSTIC built and tested in lab at Michigan.

July 2017: Installation and on-sky commissioning of MIRC-X

November 2018: First release of the MIRC-X reduction/calibration pipeline

November 2019: MIRC-X J-band commissioning & first light with waveplates

June 2020: on-sky commissioning of polarisation mode

Still to come:

- Final hardware installation for polar-interferometry mode
- MYSTIC installation and commissioning

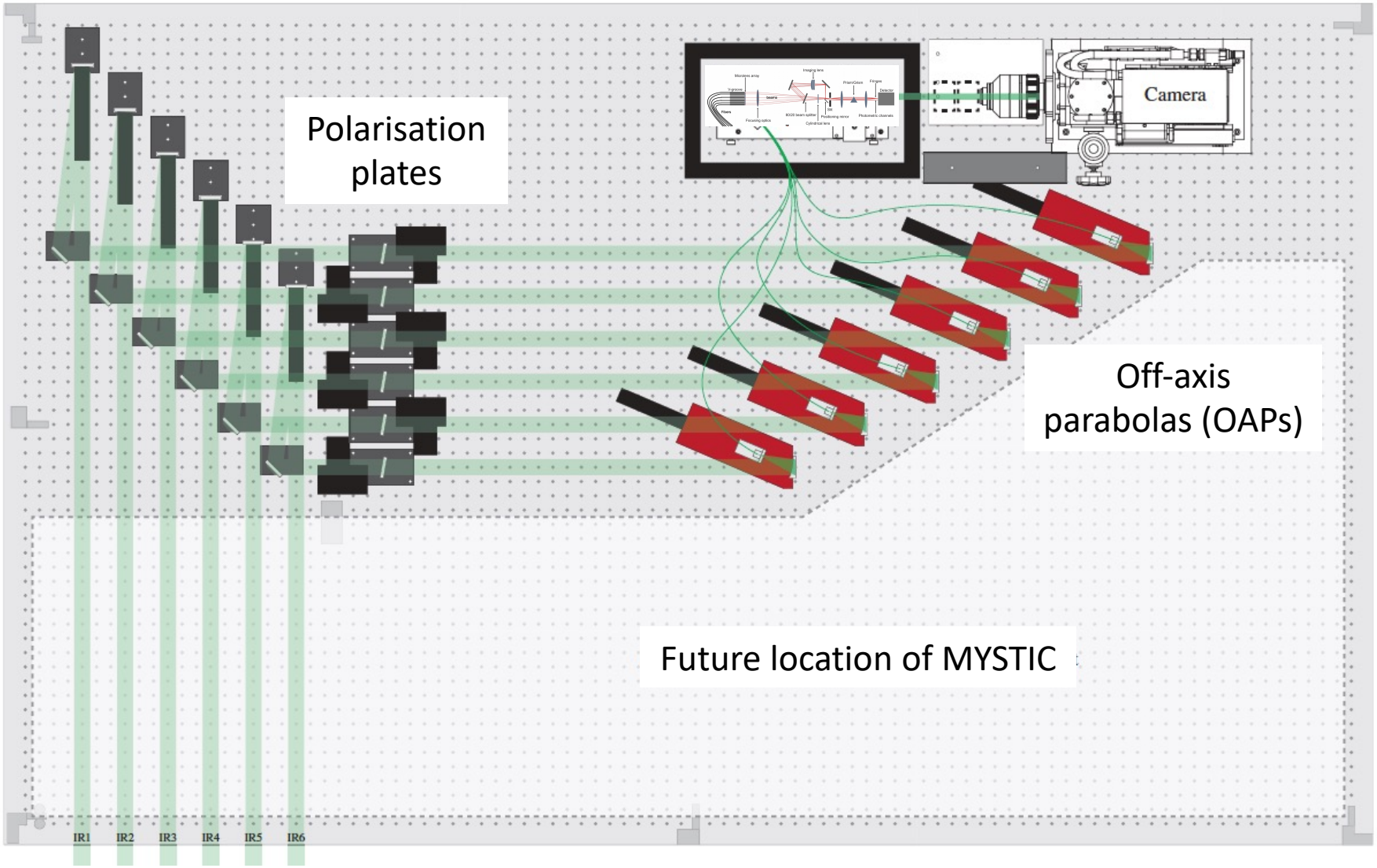
Place-holder for speaker-view video

Instrument developments: Optics layout

Video courtesy of Mr. Carel Struycken: http://chara.gsu.edu/files/mtwilson_vr_tour/

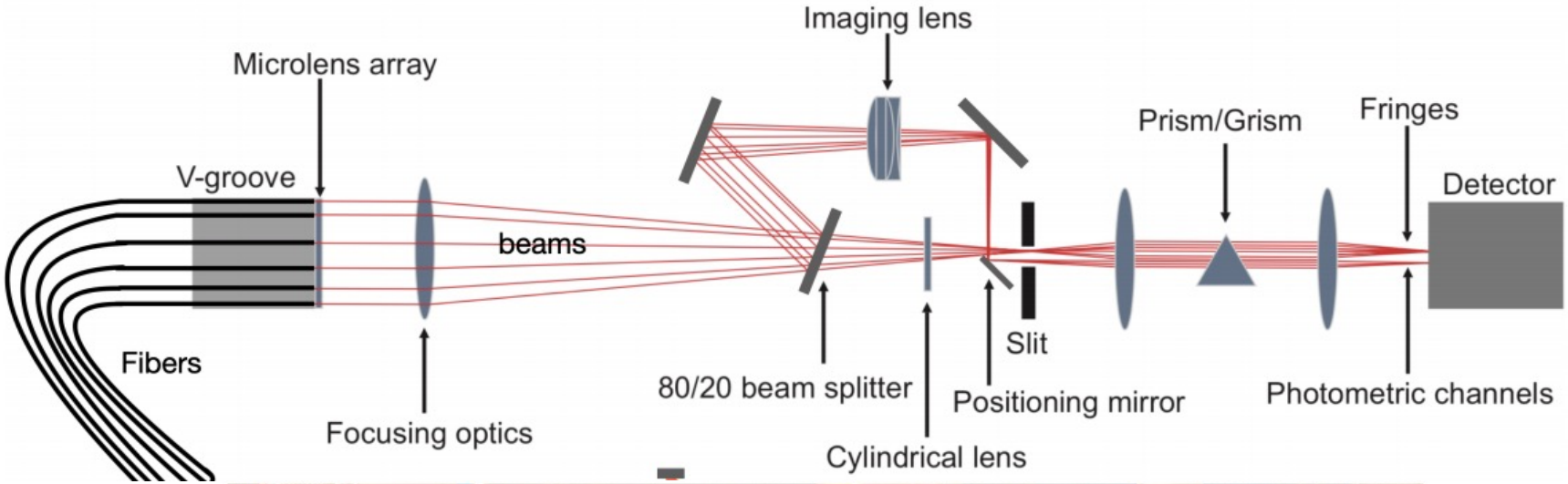
Place-holder for speaker-view video

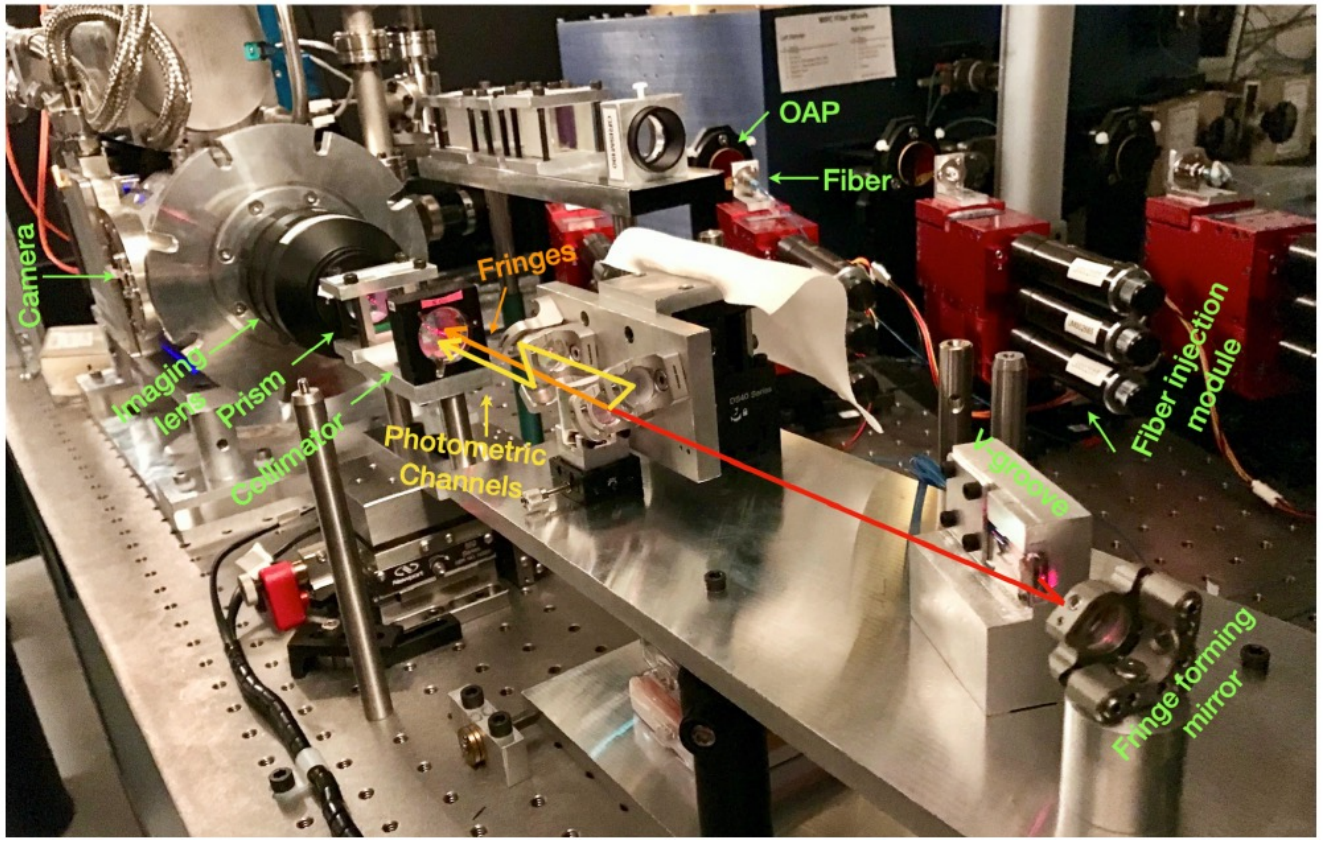
Instrument developments: Optics layout



Place-holder for speaker-view video

Instrument development: Optics layout

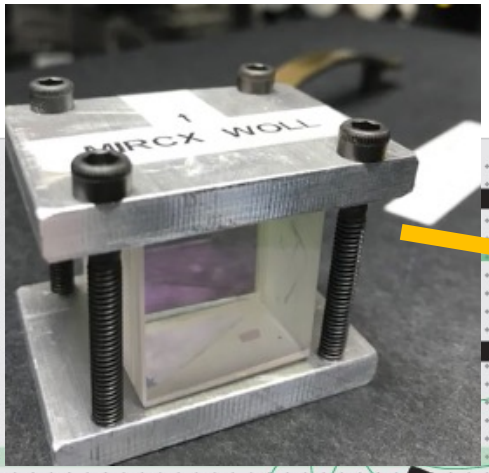




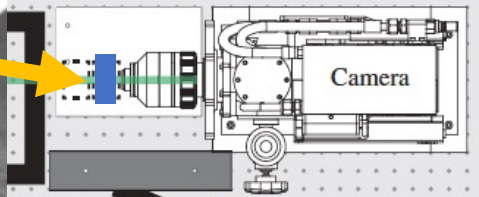
Place-holder for speaker-view video

Still in progress: Polar-interferometry

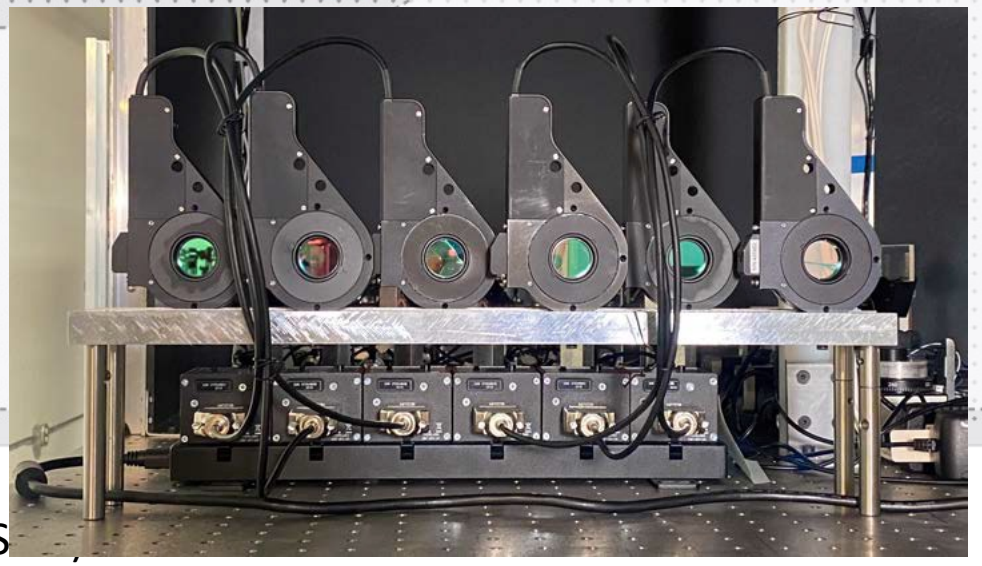
Pick-off mirrors



Polarisation plates



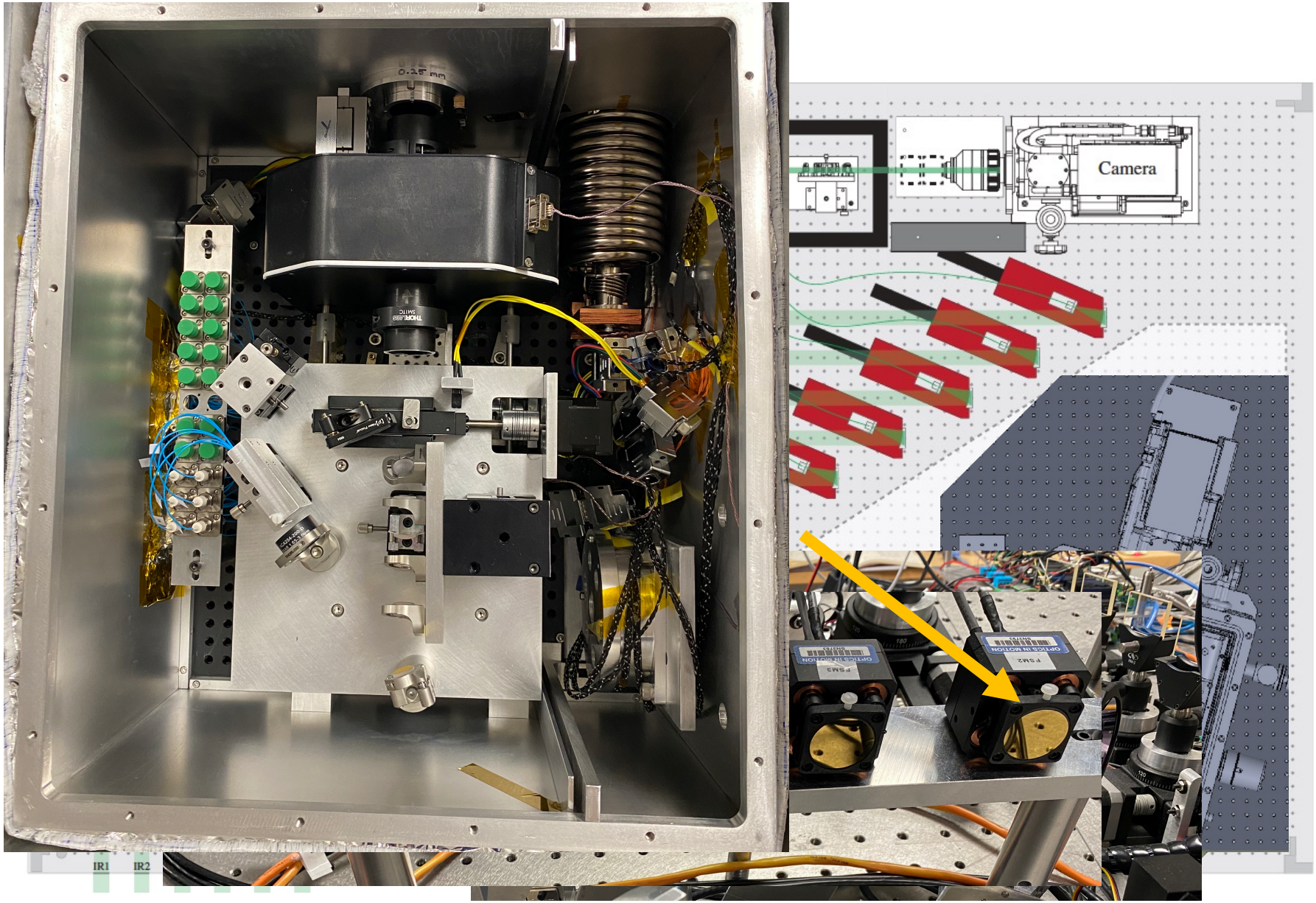
Off-axis parabolas (OAPs)



Find out more: Setterholm+(2020, S

Place-holder for speaker-view video

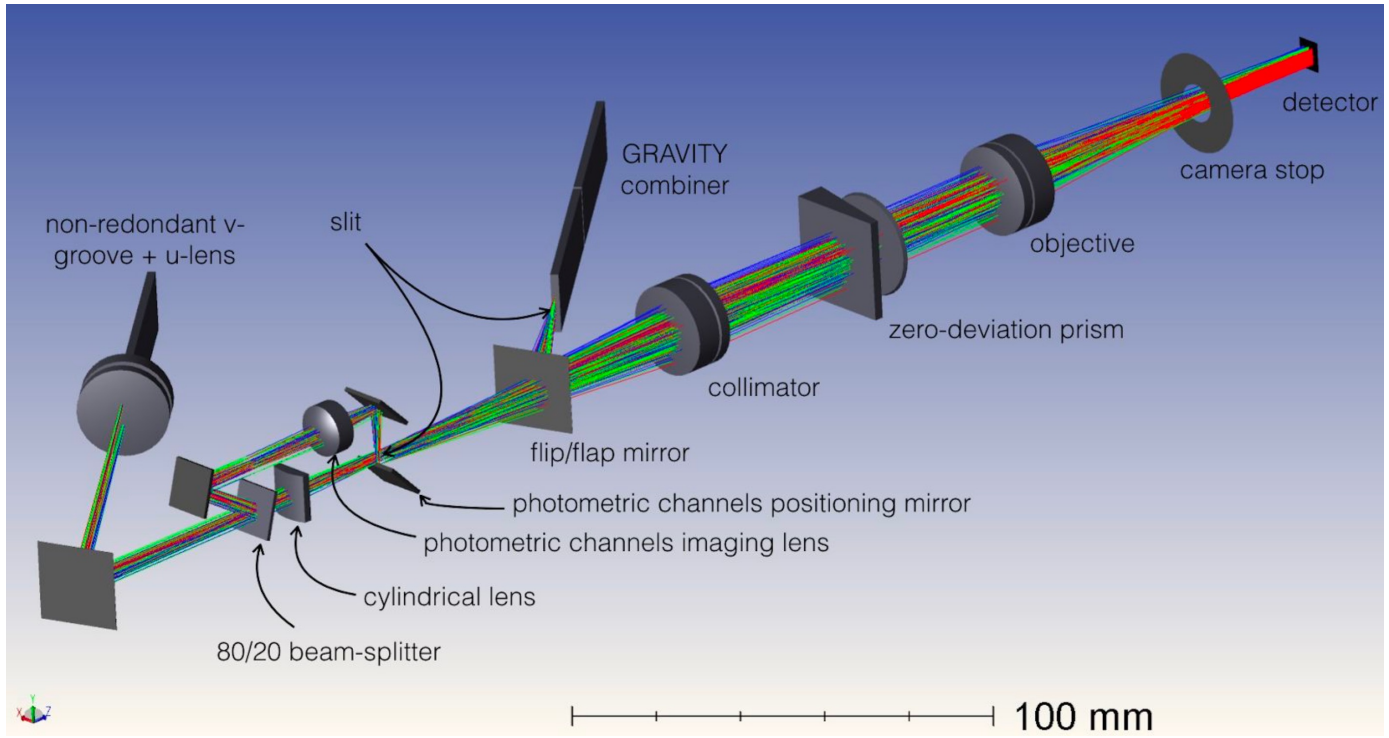
Still in progress: MYSTIC



Find out more: Monnier+(2018, SPIE)

Place-holder for speaker-view video

Still in progress: MYSTIC



MIRC-style combiner

- 6 beams = 15 fringes
- Image plane design
- with photometric channels split with custom polarisation-neutral beam splitter

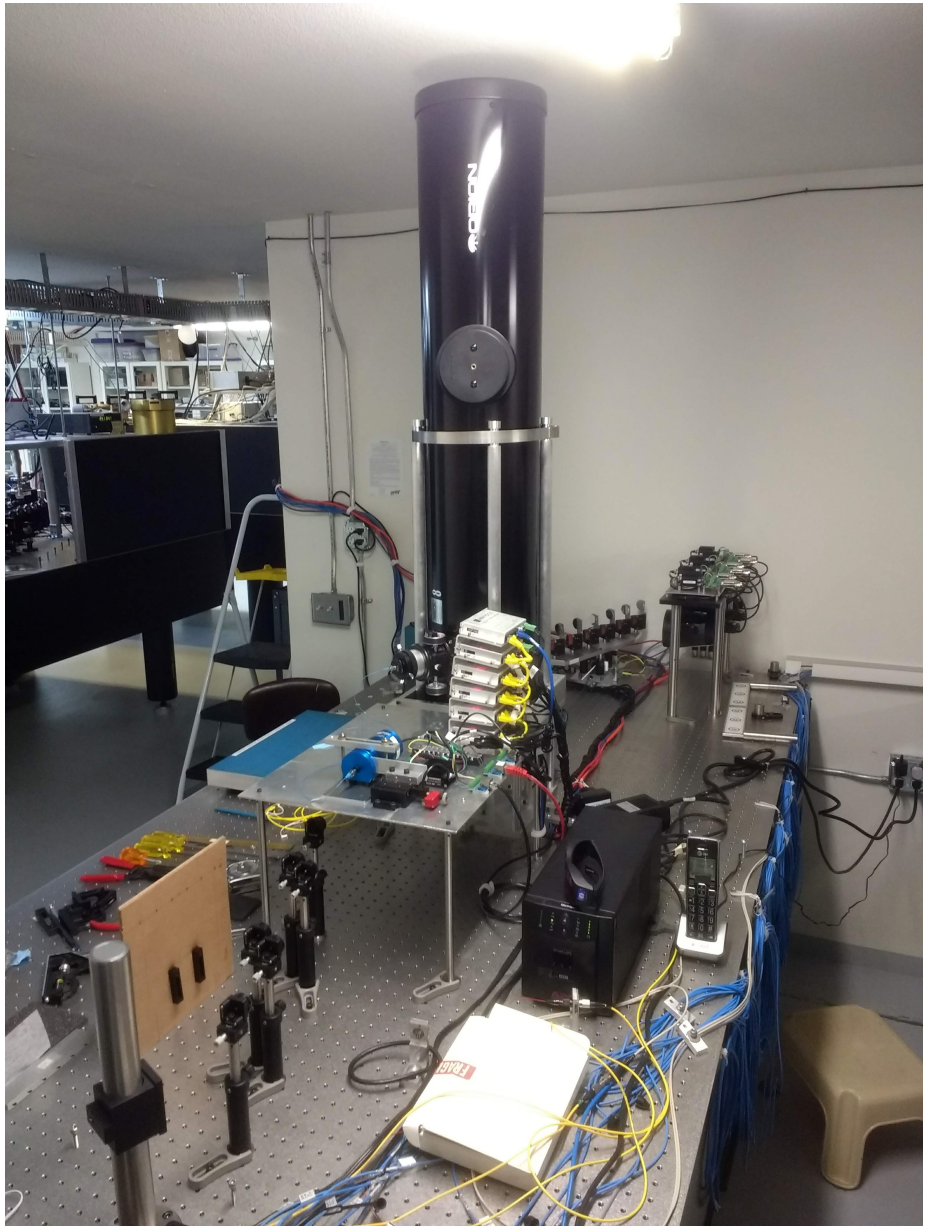
GRAVITY combiner

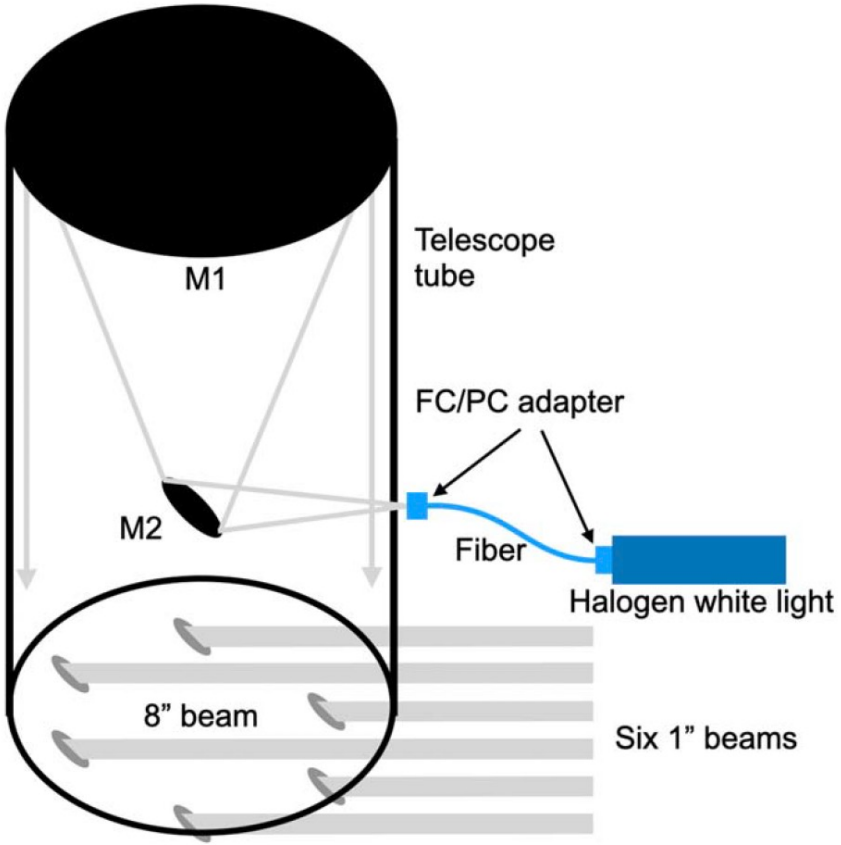
- 4 beams = 6 fringes
- 4 outputs/fringe ABCD => 24 outputs
- 180 mu separation
- MORE SENSITIVE: fewer pixels, lower spectral resolution

Find out more: Monnier+(2018, SPIE)

Place-holder for speaker-view video

Instrument developments: STS





Find out more: Anugu+(2020)

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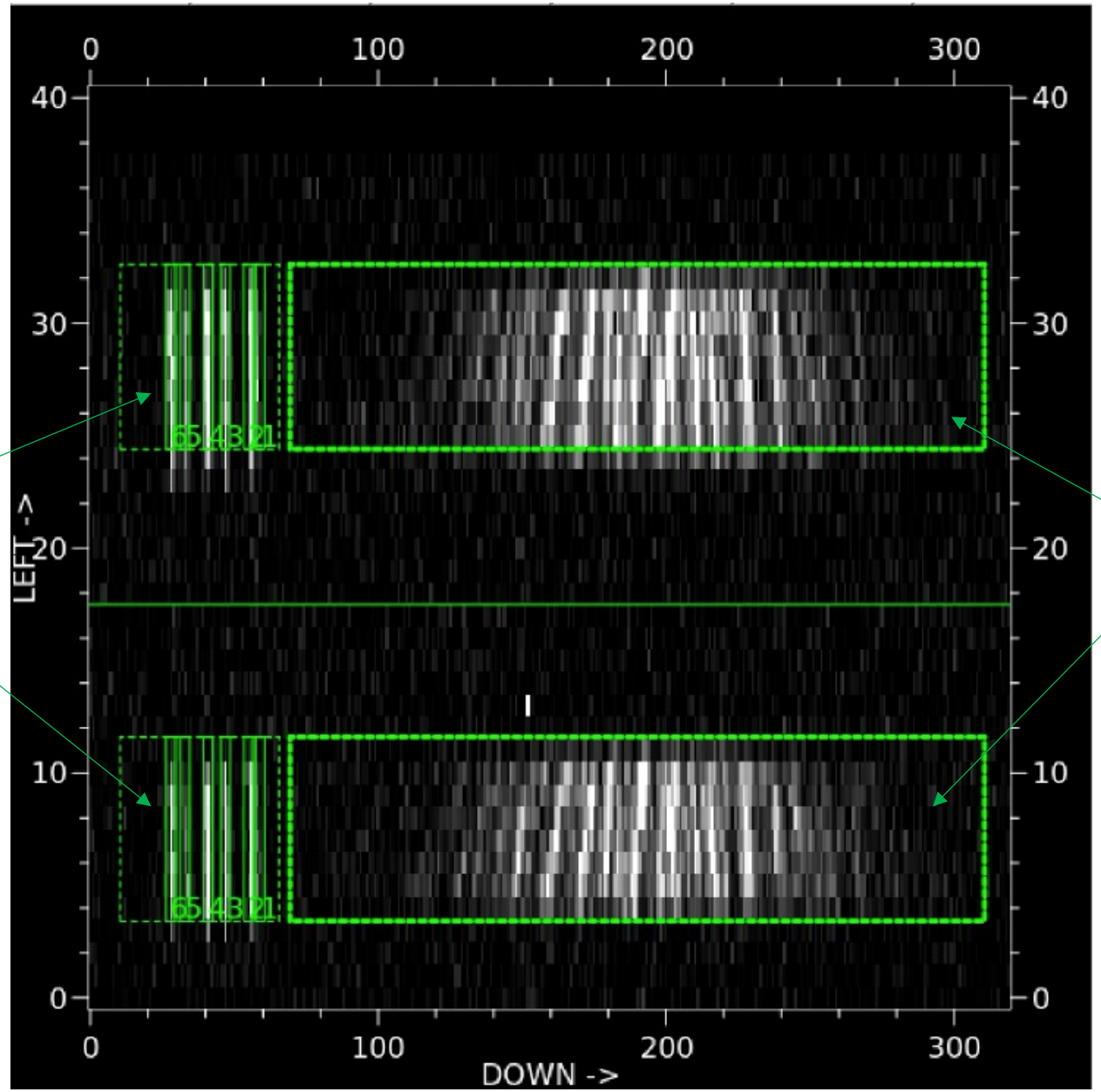
Instrument developments: Optics layout



Photometric channels

6T Fringes

NB: upper and lower panels show orthogonal polarisations

Place-holder for speaker-view video

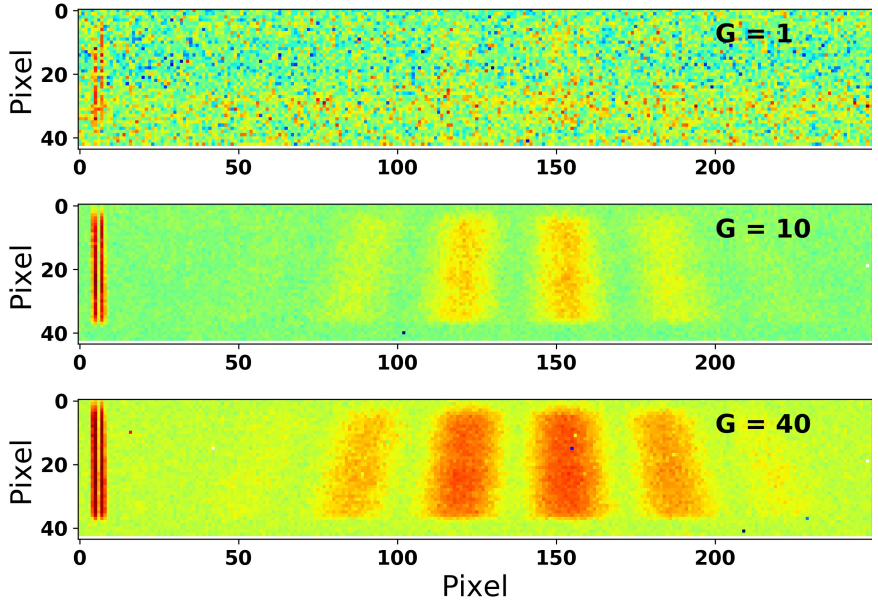
Instrument development: C-RED ONE camera

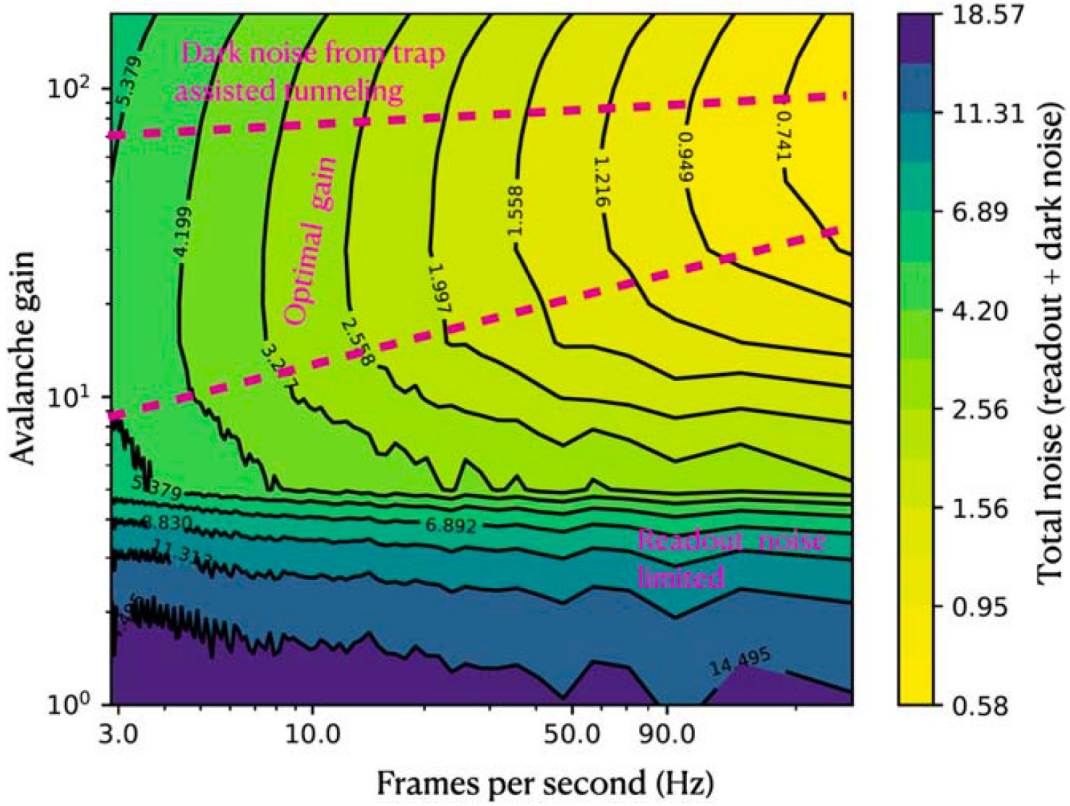
MIRC-X and MYSTIC use C-RED ONE e-APD camera, an ultra-low read-noise camera from First Light Imaging (Gach+2016)

Cooled to 80 K using pulse-tube cryocooler.

Evacuated to $<10^{-7}$ mbar.

Avalanche gain technology:





Customised, IOTA-style (N_{reads} x N_{loops}) readout mode reduces readout noise.

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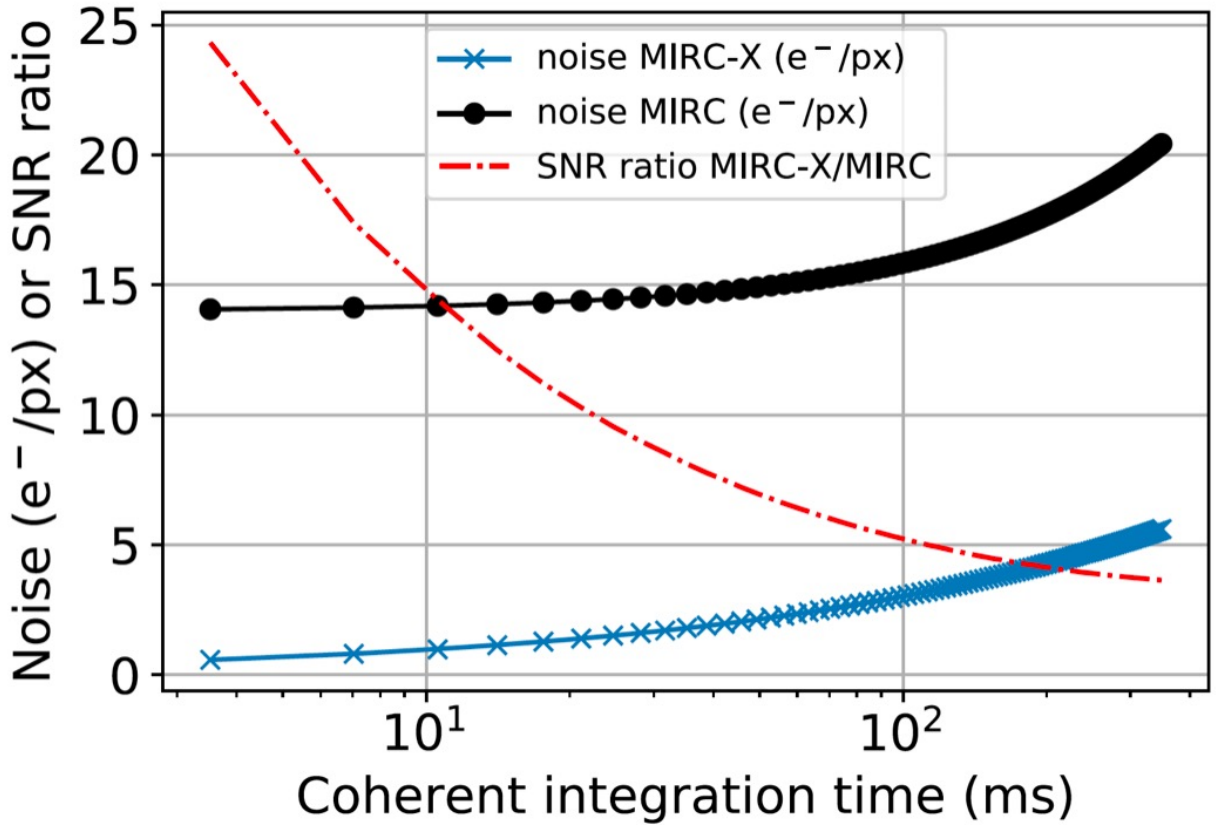
Instrument developments: C-RED ONE camera

Results:



Old MIRC noise level

New MIRC-X noise level

More information:

Anugu+(2018 SPIE, 2020); Lanthermann+(2018 SPIE, 2019 SPIE)

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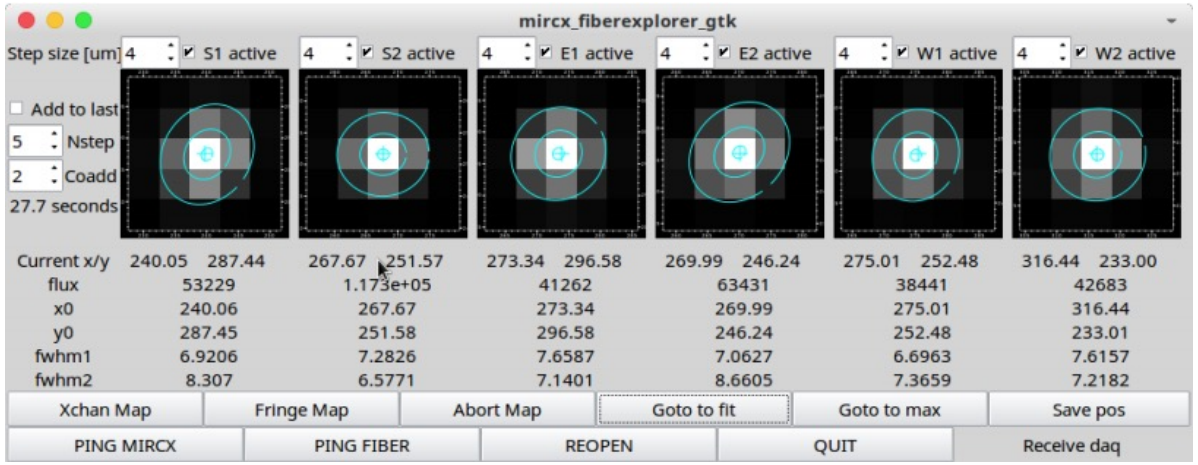
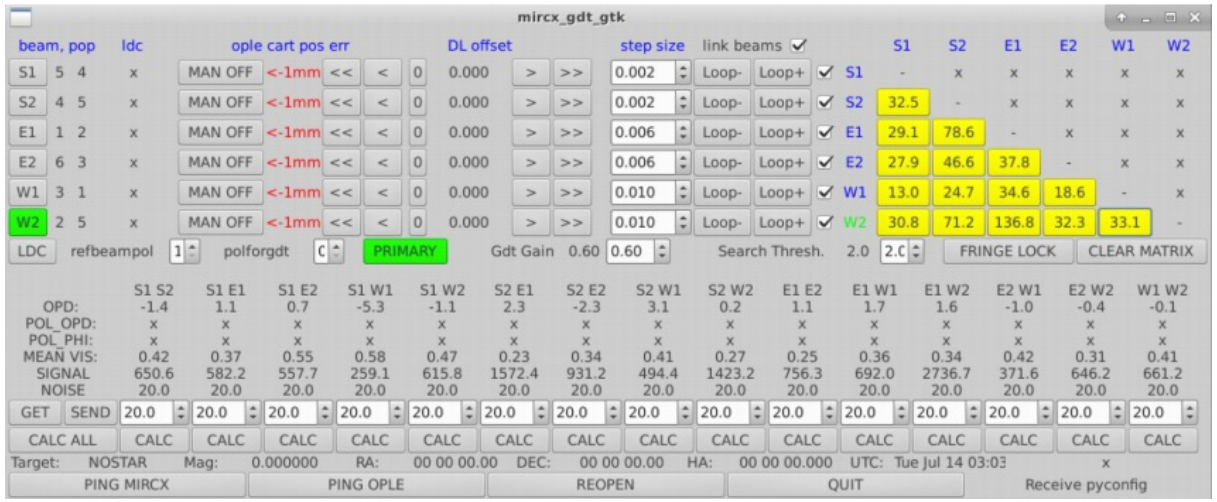
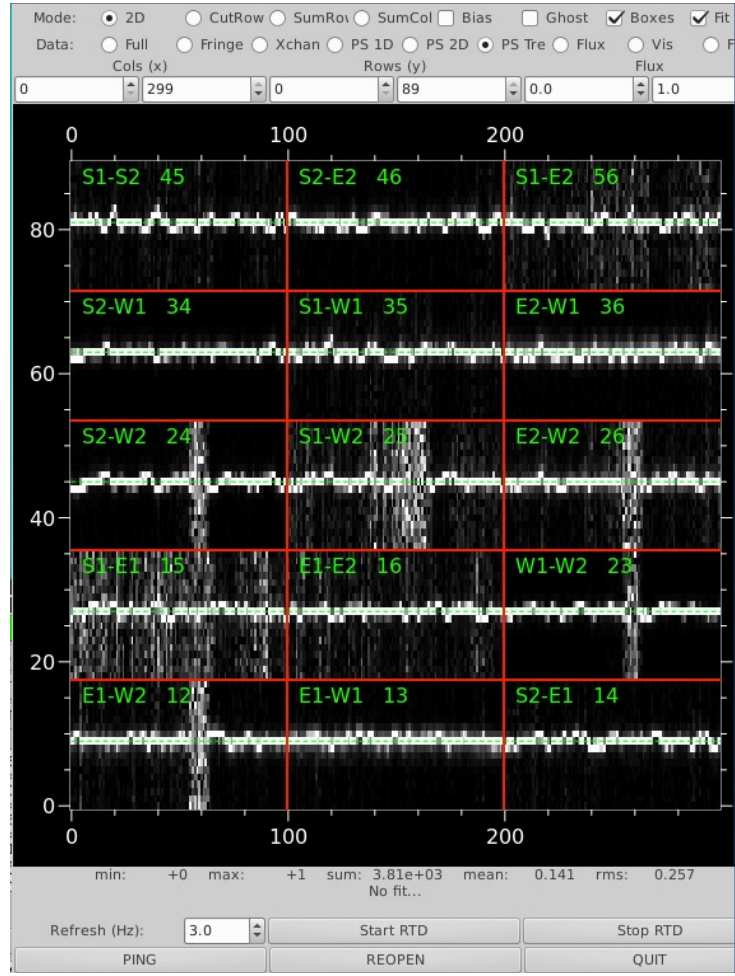
Instrument developments: Software

Operational software







More info: Anugu+(2020);
User manual: http://chara.gsu.edu/wiki/doku.php?id=chara:instruments

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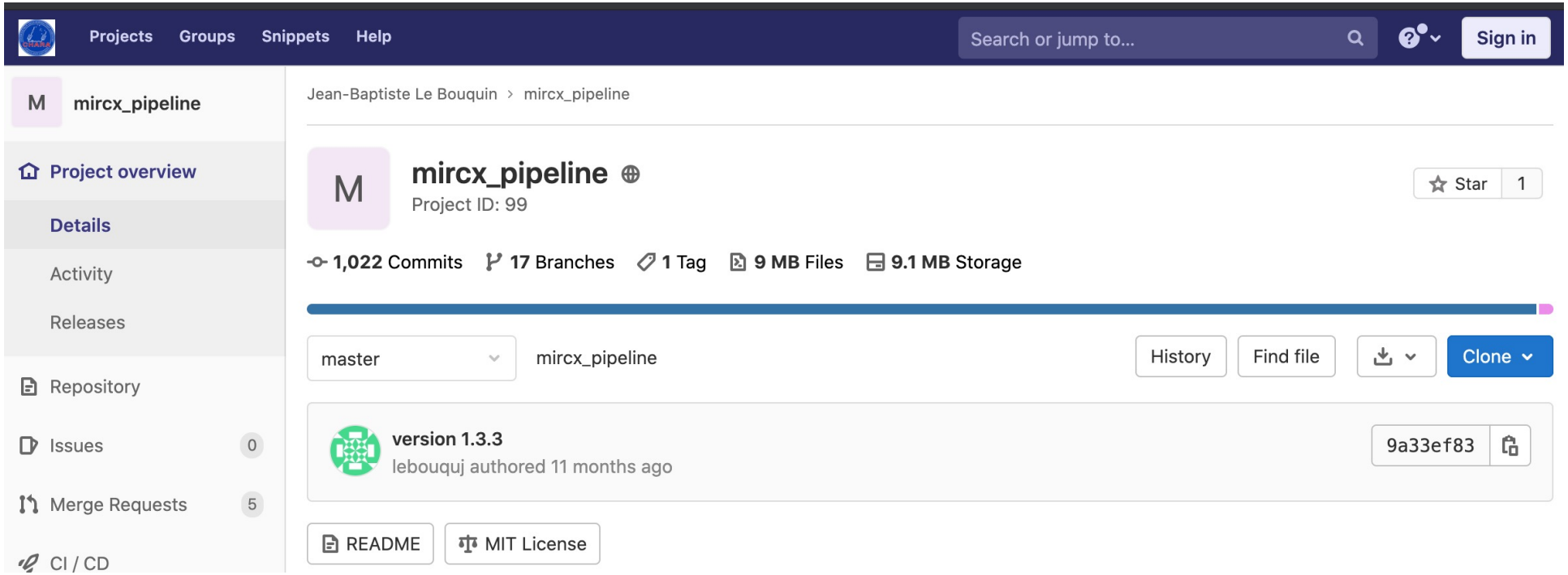
Instrument developments: Software

Access the pipeline: https://gitlab.chara.gsu.edu/lebouquj/mircx_pipeline:



Summary report from mircx_redcal_wrap.py

ncohrent=10; ncs=1; nbs=0; snr_thresh=2.0; flux_thresh=10.0; bbias=T

2019Oct03

Reduced files located in:

PI(s): Kraus

Observer(s): Slimfringe

Program ID(s): 2019B-M6

Target summary

Target ID	used as	UD diam. for CALs (mas)	H-mag
HD 38633	CAL	0.401713 ± 0.010097	5.638
HD 31293	SCI		5.062
SAO 77739	CAL	0.374342 ± 0.009316	6.076
HD 200060	CAL	0.516858 ± 0.013578	5.082
HD 195988	CAL	0.295016 ± 0.006826	5.844
HD 243531	SCI		–
HD 37741	CAL	0.346250 ± 0.007863	5.866
HD 29835	CAL	0.555143 ± 0.012633	5.135
2MASS J20230361+3929498	SCI		5.8
HD 22269	CAL	0.576700 ± 0.014088	4.778
2MASS J05452235+0904123	SCI		–
HD 42618	CAL	0.375841 ± 0.008703	5.385

Calibrator test: goodness of fit of UDD model with added companion in CANDID

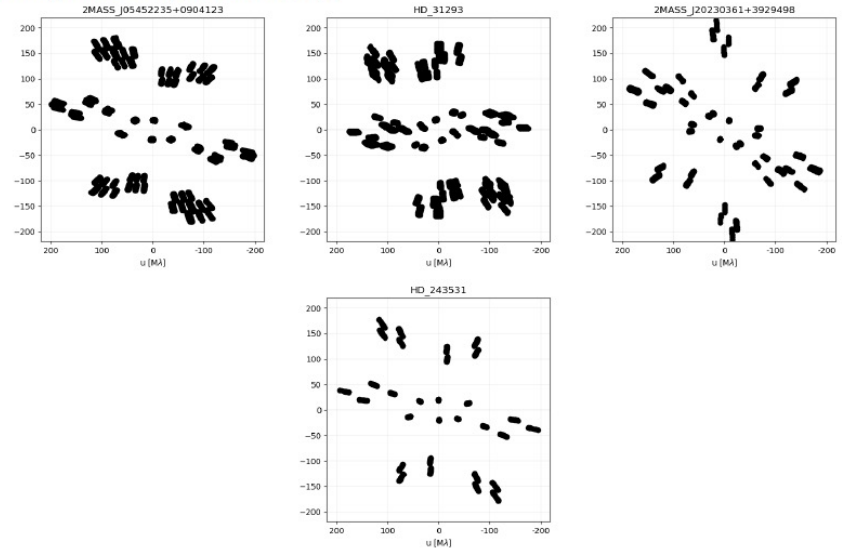
Cal ID	UDD (mas)	UDD fit	nsigma	sep (mas)	PA (deg)	ΔMag
HD 38633	0.429±0.003	free: reliable	4.1	24.22±0.04	-159.3±0.1	4.54
SAO 77739	0.223±0.010	free: unreliable	1.3	6.11±0.05	168.7±0.4	4.54
HD 200060	0.495±0.003	free: reliable	3.0	6.20±0.03	-104.5±0.2	4.24
HD 195988	0.357±0.004	free: overkill	14.7	1.52±0.01	-8.1±0.4	2.46
HD 37741	0.256±0.005	free: unreliable	1.4	9.71±0.06	27.2±0.3	5.49
HD 29835	0.647±0.002	free: overkill	6.9	1.51±0.01	-179.1±0.4	3.06
HD 22269	0.432±0.004	free: unreliable	1.2	5.90±0.07	-76.3±0.3	4.67
HD 42618	0.208±0.013	free: reliable	1.5	19.09±0.06	4.6±0.1	4.30

CANDID plots are located in the following folder on yso:
/data/MIRCX/reduced/2019Oct03_nbs0ncs1bbiasTmitp30/snr2p0fth10p0mito150/oifits_nc10 and are included in the longform version of this report

Reduced data summary

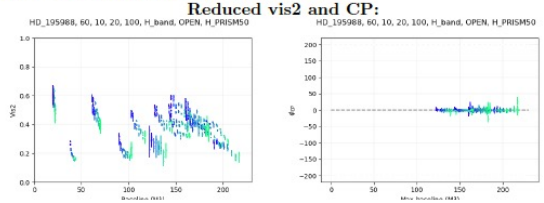
	Start (UTC)	File num.	Target	Gain	Nco	Nps	Frm /rst	Filter1	Filter2	Config
0	02:56:41	00037	HD 195988	60	10	20	100	H band	OPEN	H PRISM50
3	04:10:17	00253	2MASS J20230361+3929498	60	10	20	100	H band	OPEN	H PRISM50
7	04:44:24	00469	HD 200060	60	10	20	100	H band	OPEN	H PRISM50
11	05:23:58	00685	2MASS J20230361+3929498	60	10	20	100	H band	OPEN	H PRISM50
15	06:56:55	00901	HD 22269	60	10	20	100	H band	OPEN	H PRISM50
19	07:42:12	01117	HD 31293	60	10	20	100	H band	OPEN	H PRISM50
34	09:02:15	01751	HD 29835	60	10	20	100	H band	OPEN	H PRISM50
37	09:27:12	01925	HD 31293	60	10	20	100	H band	OPEN	H PRISM50
41	10:03:45	02140	SAO 77739	60	10	20	100	H band	OPEN	H PRISM50
43	11:06:10	02293	HD 243531	60	10	20	100	H band	OPEN	H PRISM50
45	11:27:49	02455	2MASS J05452235+0904123	60	10	20	100	H band	OPEN	H PRISM50
48	11:54:26	02644	HD 37741	60	10	20	100	H band	OPEN	H PRISM50
50	12:14:41	02806	2MASS J05452235+0904123	60	10	20	100	H band	OPEN	H PRISM50
53	12:36:49	02995	HD 38633	60	10	20	100	H band	OPEN	H PRISM50
55	12:56:36	03157	2MASS J05452235+0904123	60	10	20	100	H band	OPEN	H PRISM50
60	13:29:41	03395	HD 42618	60	10	20	100	H band	OPEN	H PRISM50

Full night *uv*-coverage for SCI target(s)



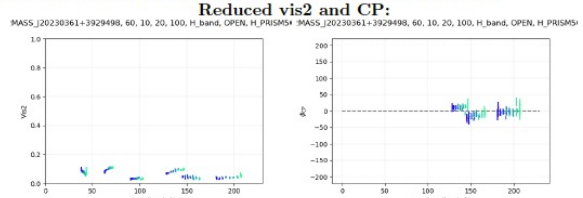
HD 195988, 60, 10, 20, 100, H band, OPEN, H PRISM50

Reduced vis2 and CP:

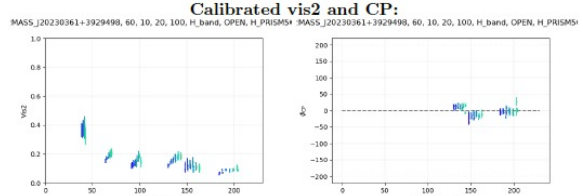


2MASS J20230361+3929498, 60, 10, 20, 100, H band, OPEN, H PRISM50

Reduced vis2 and CP:



Calibrated vis2 and CP:



SIMBAD: Query by identifiers

Query an identifier

Identifier :

Examples
sirius, M31, MCG+02-60-010
How to write an identifier can be found in the dictionary of nomenclature
IAU format can also be used, with the following format:
`iau [J|B]1230+08 [* enlarging-factor ] [= Object-type ]`

you can choose to query : only this object

around the object, define a radius : 2 arc min

submit id | clear

```
#NAME,RA,DEC,HMAG,VMAG,ISCAL,MODEL_NAME,PARAM1,PARAM2
HD 45824,97.71324749999998,26.643716388888887,5.6,7.867,CAL,UD_H,0.385330,0.008495
HD 46714,98.71905958333332,0.019625277777777776,4.408,8.666,CAL,UD_H,0.861108,0.074890
HD 35850,81.76984729166666,-11.900965944444446,5.087,6.3,CAL,UD_H,0.418136,0.010065
HD 97633,168.56001858333332,15.429570583333332,3.19,3.33,CAL,UD_H,0.798749,0.084277
HD 141795,237.70402591666664,4.4777308611111115,3.44,3.71,CAL,UD_H,0.684815,0.063065
HD 32630,76.628722375,41.23447575,3.761,3.18,CAL,UD_H,0.387935,0.039579
HD 120315,206.8851573333333,49.31326672222222,2.408,1.85,CAL,UD_H,0.765260,0.091078
HD 176437,284.7359266666666,32.68955555555555,3.227,3.25,CAL,UD_H,0.720574,0.082958
HD 184006,292.42649466666666,51.72977938888889,3.691,3.76,CAL,UD_H,0.647820,0.064206
HD 129502,220.7650950833333,-5.658203527777778,3.069,3.87,CAL,UD_H,0.942695,0.091358
HD 37202,,,,,SCI,,,
2MASS J19524977+4836263,298.2074295833333,48.607353333333336,5.631,9.538,CAL,UD_H,0.459710,0.010536
2MASS J21281481+6005284,322.0618708333333,60.09125277777778,5.497,10.194,CAL,UD_H,0.520285,0.012450
HD 114710,197.96830745833333,27.878181527777777,2.992,4.23,CAL,UD_H,1.078411,0.101775
HD 119035,205.06490529166663,31.012035277777777,4.052,6.21,CAL,UD_H,0.753610,0.068201
HD 14055,34.328612625,33.84719305555556,3.862,4.03,CAL,UD_H,0.549724,0.050968
HD 142860,,,,,SCI,,,
```

Portal | Simbad | VizieR | Aladin | X-Match | Other | Help

VizieR

Search Criteria

Save in CDSportal

Keywords Back

- II/346/jsdc_v2

Tables Add

II/346
..jsdc_v2
..jsdc_dis

Choose

Preferences

max: 50

HTML Table

All columns

Compute

Distance ϱ

Position angle θ

Distance (x,y)

Galactic

Simple Target | List Of Targets

Fast Xmatch with large catalogs or Simbad

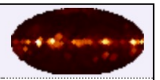
Target Name (resolved by Sesame) or **Position**: Clear HD 38633 J2000

Target dimension: 2 arcmin

NB: The epoch used for the query is the original epoch of the table(s) Radius Box size

II/346 JMMC Stellar Diameters Catalogue - JSDC. Version 2 (Bourges+, 2017) figures ReadMe+ftp

Post annotation Similar Catalogs 2014ASPC..485..223B



1.II/346/jsdc_v2 Stellar diameters catalogue, version 2 *(465877 rows)*

Simple Constraint | List Of Constraints Submit Reset All

Query by Constraints applied on Columns *(Output Order:* + - *)*

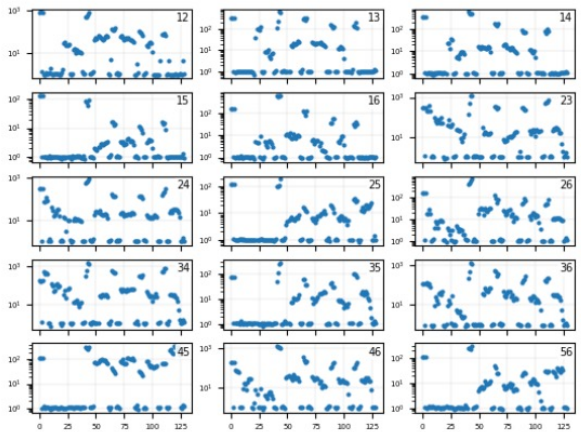
Show	*Sort*	*Column*	Clear	*Constraint*	*Explain* (*UCD*)
☐	○	recno			Record number assigned by the VizieR team. Should Not be used for identification. (meta.record)
☐	○	Dis			(n)indicates differences between JSDC V1 and V2 (meta.note)
☑	○	Name		(char)	Normalised star name (preferably HD) (meta.id;meta.main)
☐	○	SpType		(char)	Spectral Type from Simbad (src.spType)

Delay line offsets

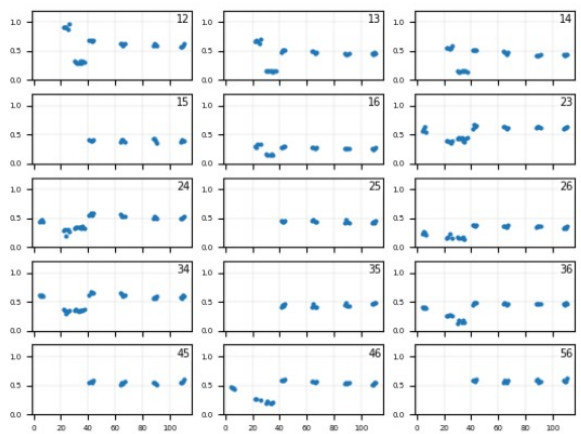
UTC-OBS	CONF_NA	POP	HA	S1	S2	E1	E2	W1	W2
02:29:57	H_PRISM50	551115	00:00:00	0.029	0.016	0.059	-0.052	-0.031	0.000
03:34:47	H_PRISM50	551115	-00:07:52	0.000	-1.597	0.001	0.920	-1.454	0.000
03:39:57	H_PRISM50	551115	-00:02:41	0.000	-1.641	0.001	0.861	-1.480	0.000
04:10:02	H_PRISM50	551115	00:23:10	0.000	-2.048	0.001	0.097	-1.113	0.000
04:19:56	H_PRISM50	551115	00:33:05	0.000	-2.103	0.001	0.077	-1.170	0.000
04:50:19	H_PRISM50	551315	-02:53:17	0.000	-0.515	2.183	2.403	0.005	0.000
04:59:58	H_PRISM50	551315	-02:43:36	0.000	-0.647	1.948	2.209	-0.165	0.000
05:45:07	H_PRISM50	551315	-02:38:14	0.000	-0.611	1.838	2.181	-0.157	0.000
05:50:00	H_PRISM50	551315	-02:33:20	0.000	-0.662	1.755	2.125	-0.230	0.000
06:00:01	H_PRISM50	551315	-02:23:17	0.000	-0.742	1.547	2.003	-0.318	0.000
06:56:02	H_PRISM102	552415	-03:04:31	0.738	0.200	1.708	2.319	0.356	0.000
07:00:01	H_PRISM102	552415	-03:00:31	0.704	0.184	1.637	2.278	0.324	0.000
07:30:11	H_PRISM102	552415	-03:21:46	1.012	0.379	1.987	2.469	0.289	0.000
07:39:59	H_PRISM102	552415	-03:11:57	0.882	0.296	1.824	2.374	0.289	0.000
07:49:59	H_PRISM102	552415	-03:01:55	0.813	0.270	1.681	2.293	0.327	0.000
08:00:00	H_PRISM102	552415	-02:51:52	0.718	0.209	1.553	2.210	0.238	0.000
08:29:59	H_PRISM102	552415	-02:19:32	0.379	-0.032	1.198	1.983	-0.034	0.000
09:00:00	H_PRISM102	552415	-01:51:42	0.230	-0.174	0.854	1.735	-0.300	0.000
09:10:00	H_PRISM102	552415	-01:41:41	0.166	-0.232	0.720	1.628	-0.400	0.000
09:20:01	H_PRISM102	552415	-01:31:40	0.080	-0.302	0.654	1.576	-0.495	0.000
09:52:39	H_PRISM102	551315	-01:25:21	-0.009	-0.385	0.595	1.625	-0.561	0.000
10:00:01	H_PRISM102	551315	-01:17:55	-0.037	-0.413	0.502	1.541	-0.615	0.000
10:20:32	H_PRISM102	551315	-00:30:57	-0.296	-0.723	0.079	1.142	-1.035	0.000
10:30:01	H_PRISM102	551315	-00:21:27	-0.280	-0.723	0.062	1.128	-1.086	0.000
10:40:00	H_PRISM102	551315	-00:11:26	-0.321	-0.773	-0.013	1.057	-1.159	0.000
11:10:01	H_PRISM102	551315	-00:38:48	-0.257	-0.628	0.185	1.282	-0.912	0.000
11:43:49	H_PRISM102	551135	00:52:32	-0.538	-1.072	0.121	0.677	-1.339	0.000
11:50:01	H_PRISM102	551135	00:58:46	-0.537	-1.084	0.121	0.668	-1.382	0.000
12:00:01	H_PRISM102	551135	01:08:47	-0.569	-1.130	0.121	0.609	-1.416	0.000

* = cross-fringe with S1
† = cross-fringe with S2
‡ = cross-fringe with E1
§ = cross-fringe with E2
‖ = cross-fringe with W1
¶ = cross-fringe with W2

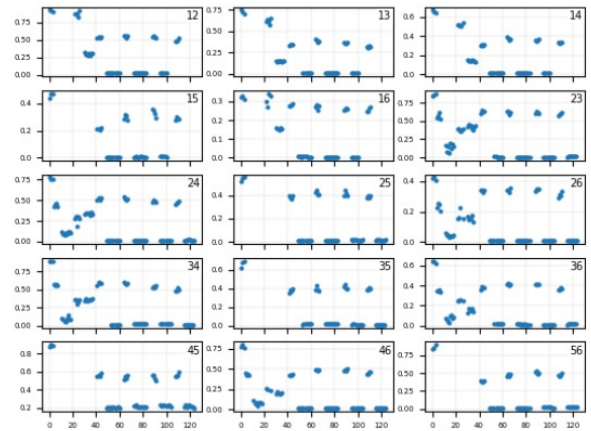
SNR



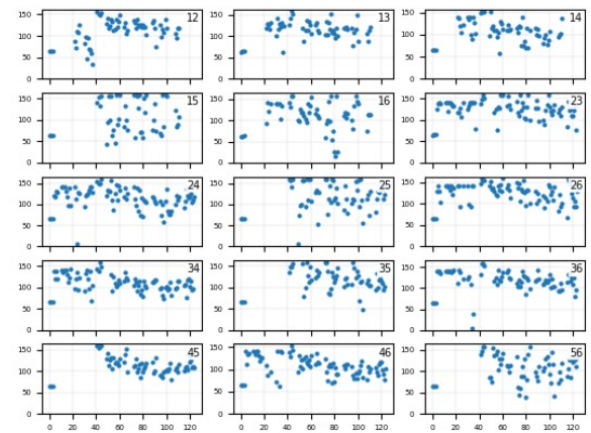
Transfer Function



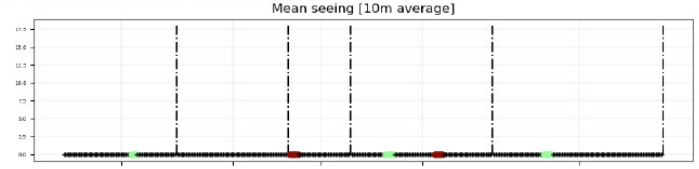
Vis2



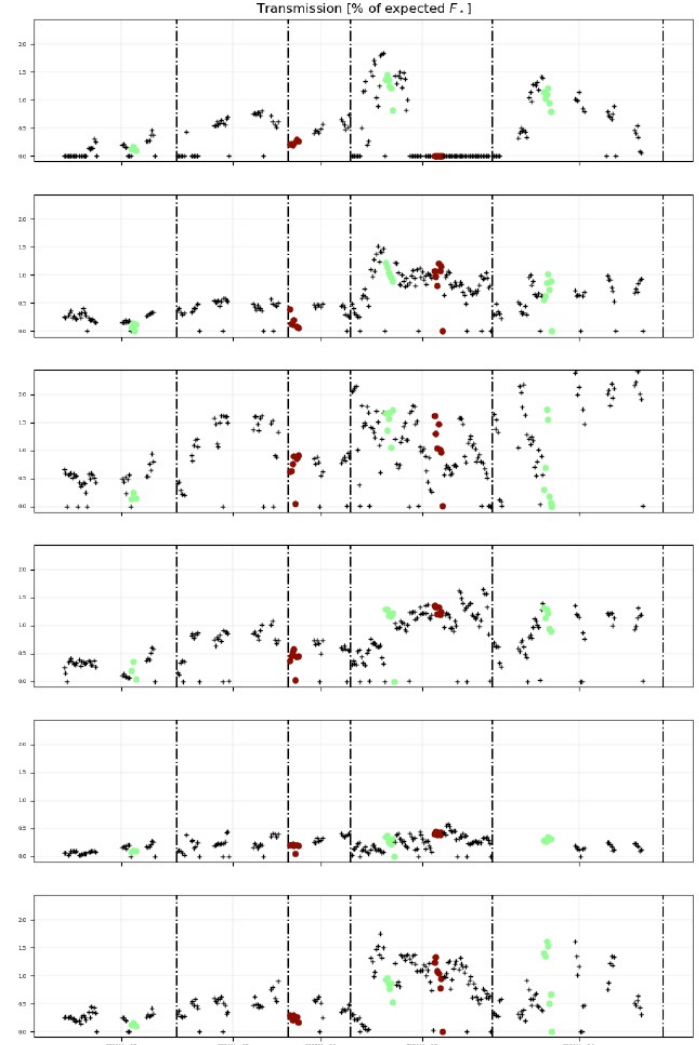
Decoherence Half Time [ms]



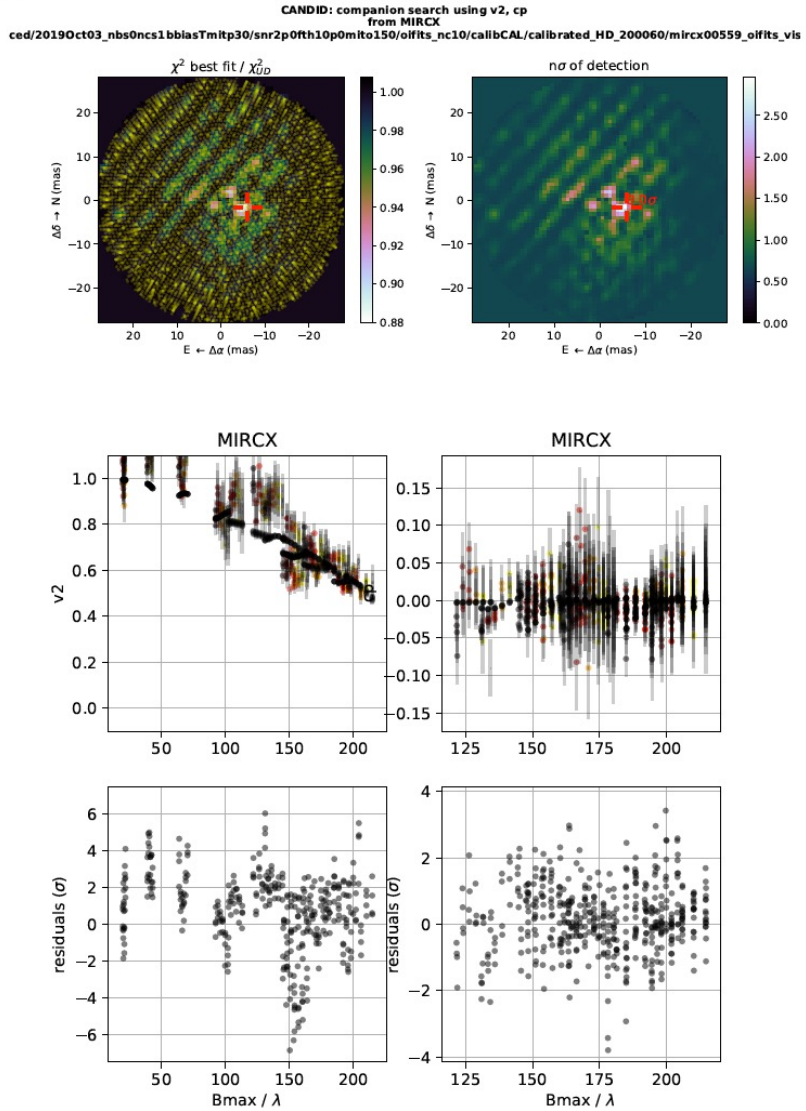
Mean seeing [10m average]



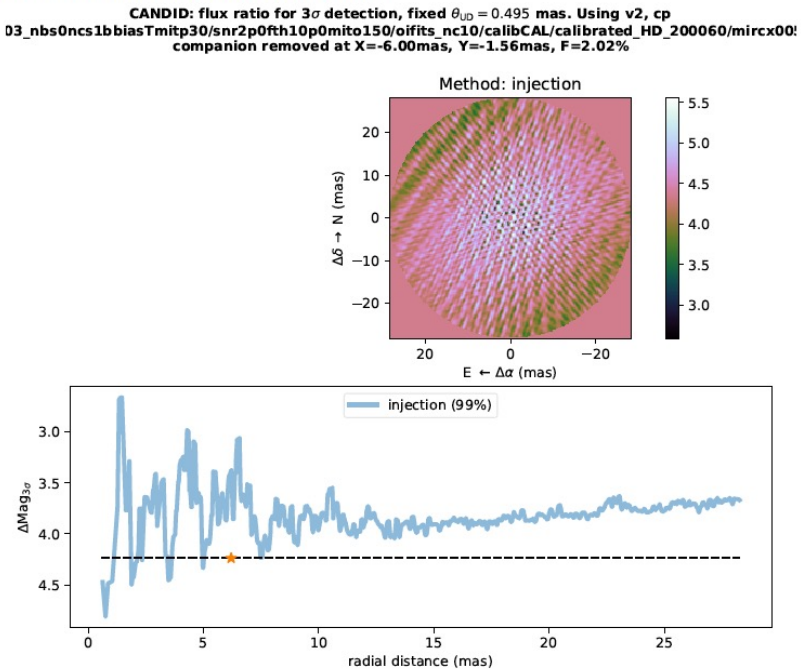
Transmission [% of expected $F_\star$]



CANDID output: fitMap with free UDD for HD 200060



CANDID output: detectionLimit for HD 200060

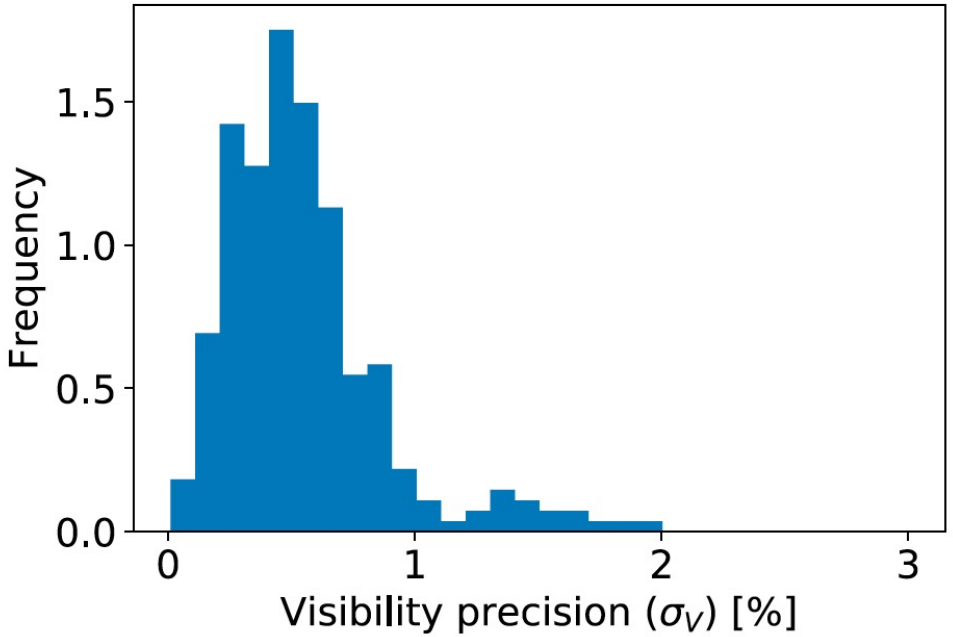


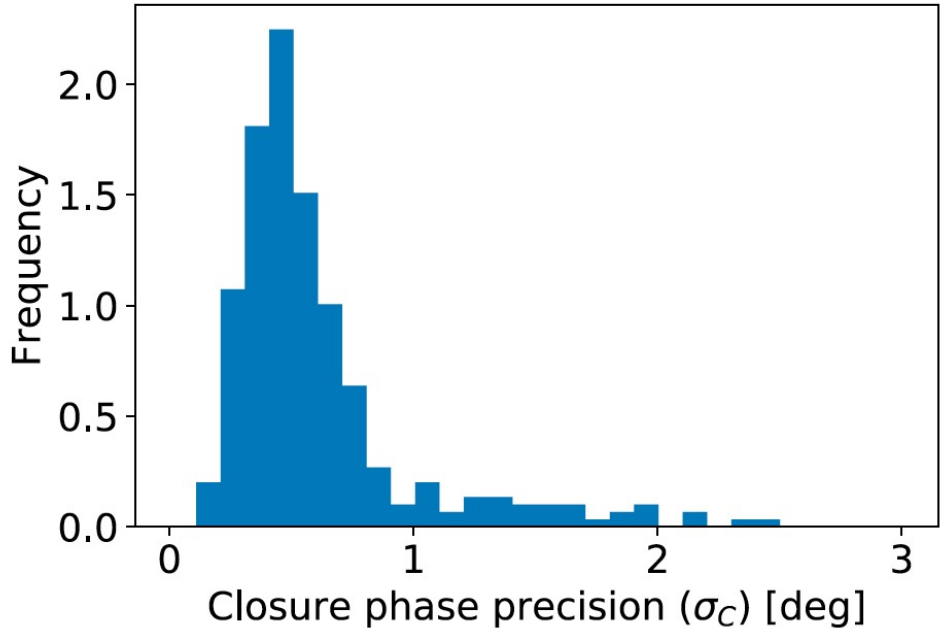
Place-holder for speaker-view video

Performance assessments

Attain raw visibility precision better than 1%

Attain raw closure phase precision better than 1°



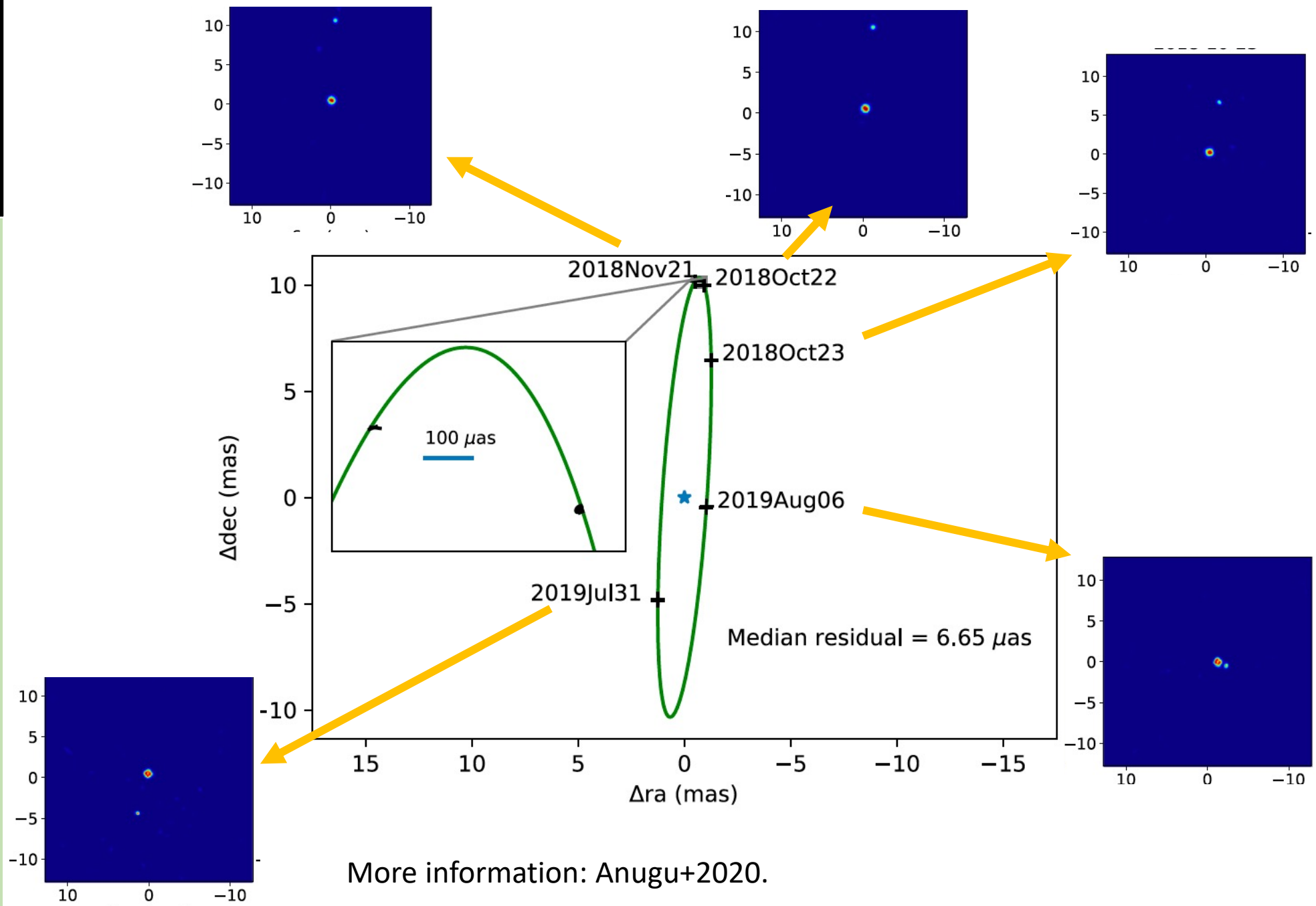


Routinely observe down to 7th mag; faintest fringes tracked on 8.2 (H) magnitude star.

More information: Anugu+(2020)

Place-holder for speaker-view video

Science highlights: ϕ_{CP} calibration using ι Peg

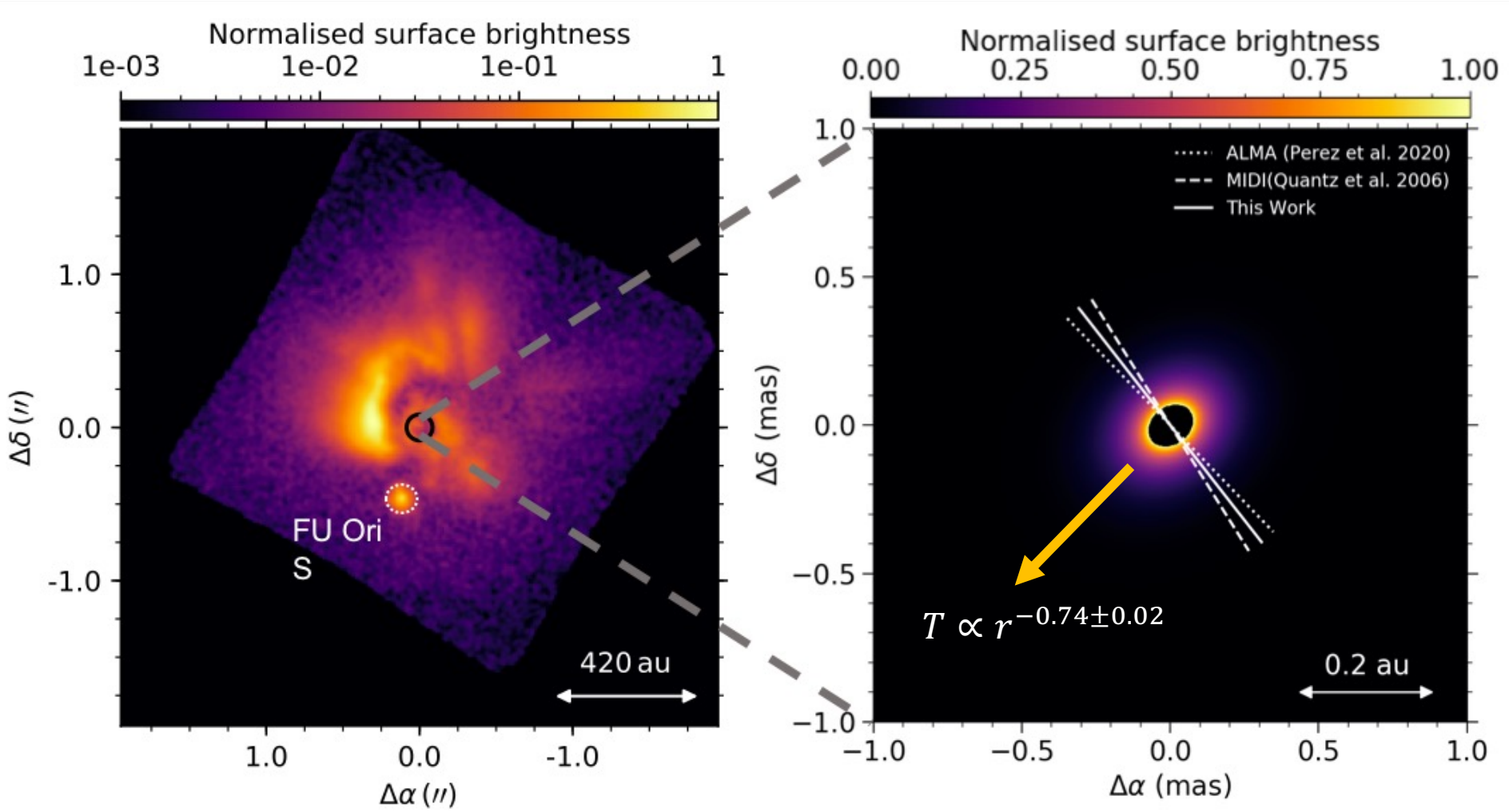


More information: Anugu+2020.

Place-holder for speaker-view video

Science highlights: Simultaneous JH-band observations

Outbursting young stellar object, FU Ori



More information: Labdon+(2021)

Place-holder for speaker-view video

Science highlights: High-precision differential astrometry

ARrangement for Micro-Arcsecond Differential Astrometry (ARMADA)

GRISM190 spectral mode ($R = \frac{\lambda}{\Delta\lambda} = 190$; i.e. each star's interferogram is 190 fringes long).

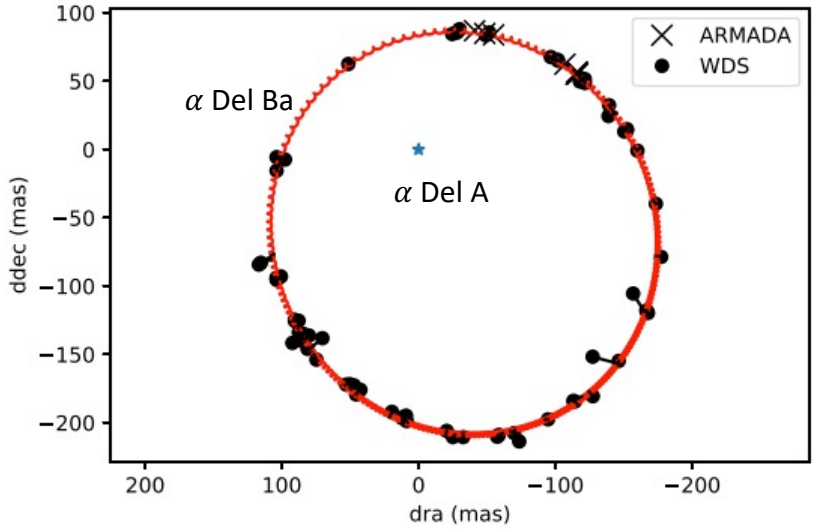
→ Creates λ-dependent variations in the fringe phase (directly related to the binary sep).

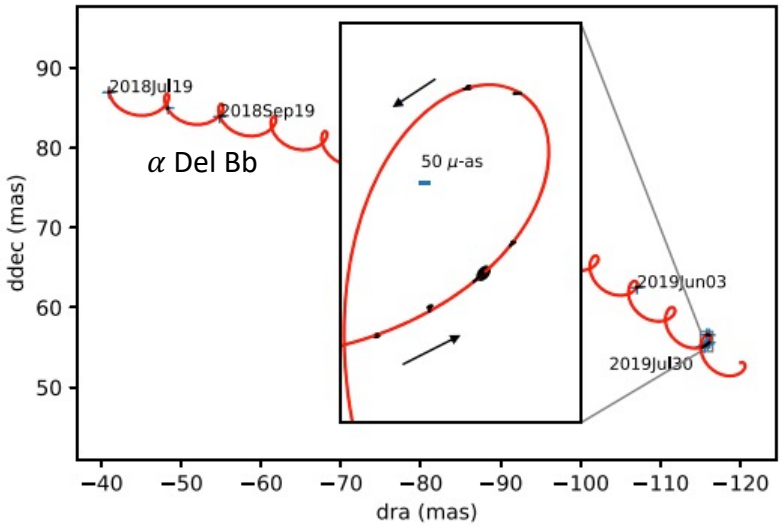
→ Avoids differential delay lines BUT requires high-precision wavelength calibration.

In general, MIRC-X limited to $\frac{\lambda}{\Delta\lambda}$ precision of 10^{-3} (100 µas astrometry limit for ~0.1'' binaries).

→ 6-beam optical etalon system provides additional λ calibration during ARMADA survey observations.

→ Attains $\frac{\lambda}{\Delta\lambda} \sim 10^{-4}$: 10 µas astrometry limit for <0.2'' binaries



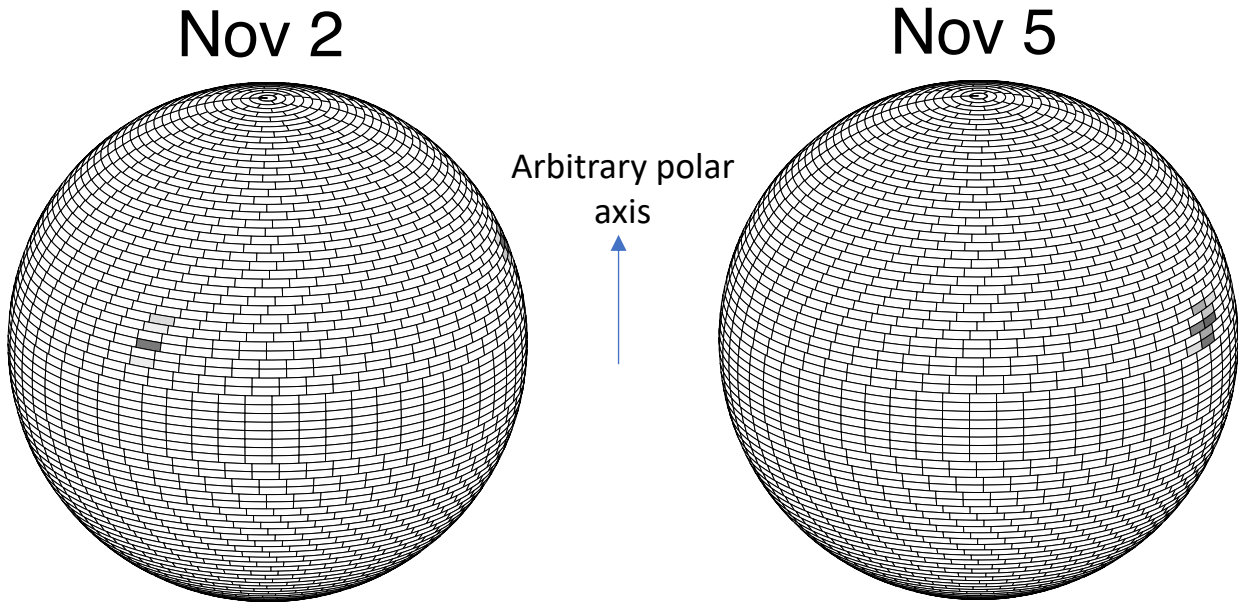


More information: Gardner+(2021)

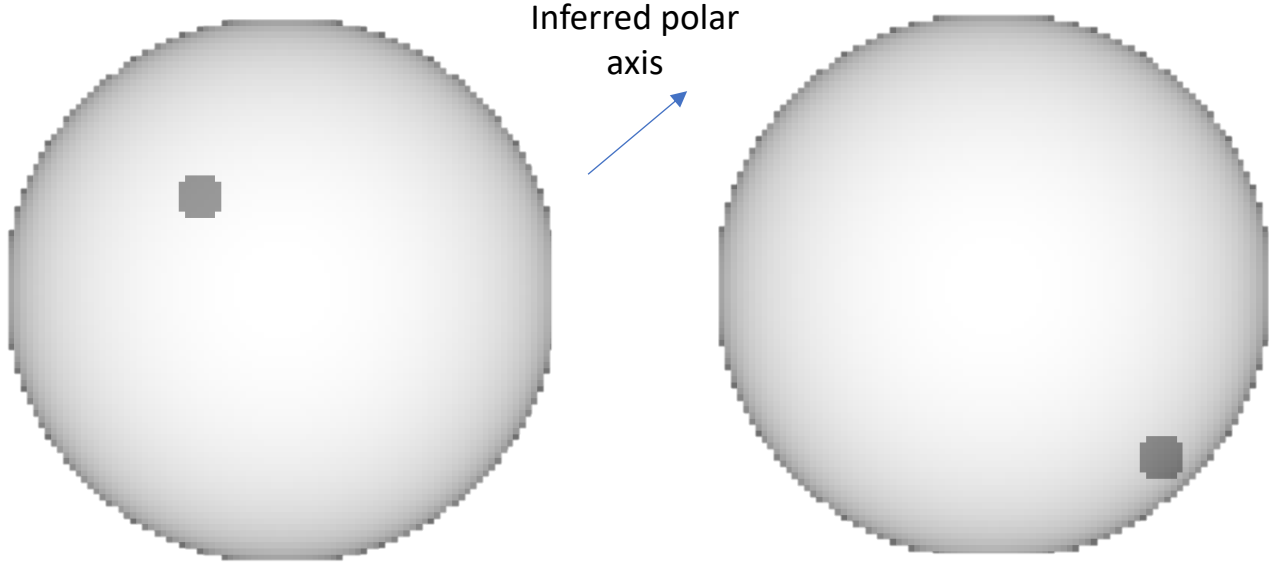
Place-holder for speaker-view video

Science highlights: Stellar surface imaging of ε Eri

TESS lightcurve inversion reconstructions (no PA info)

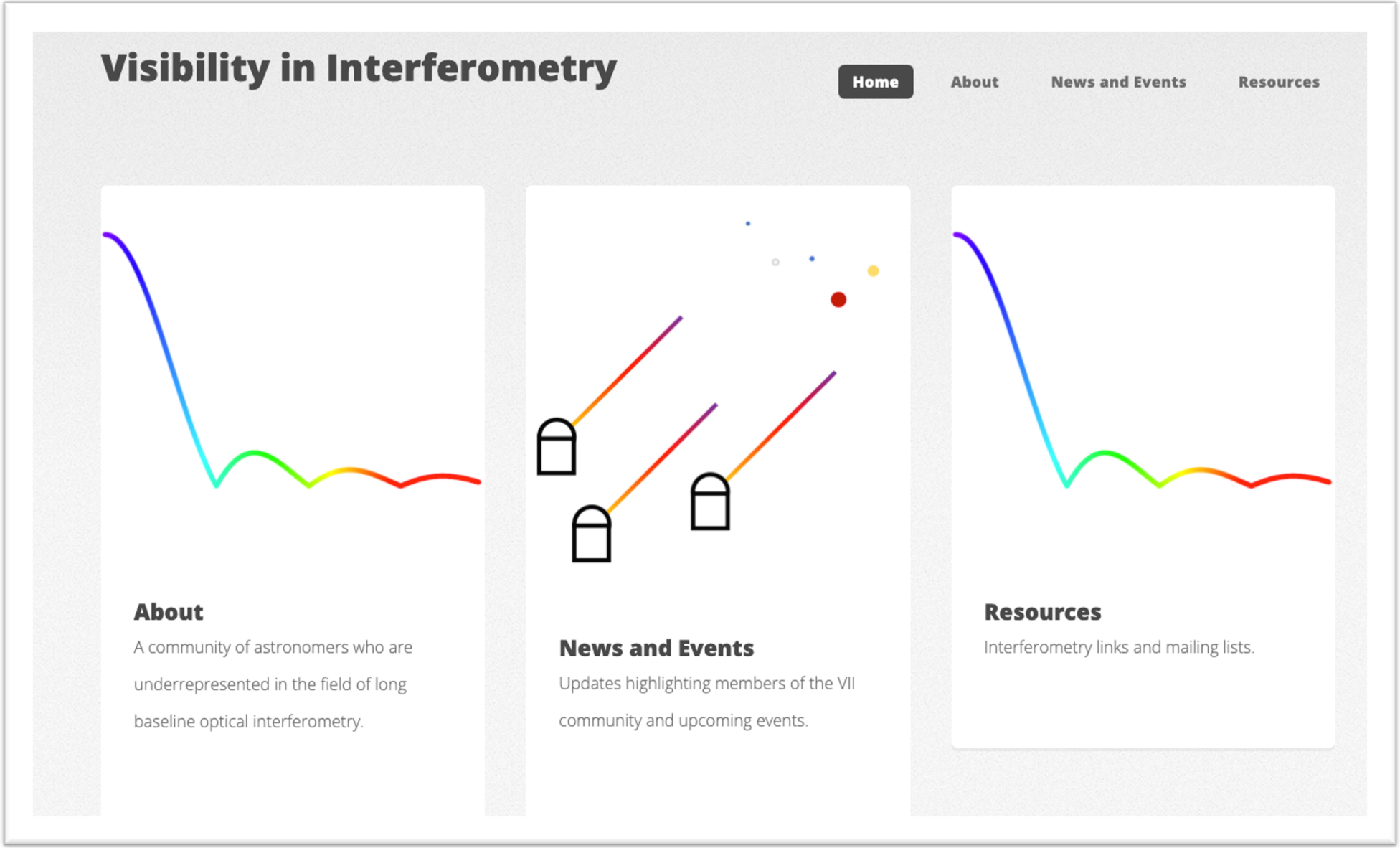


MIRC-X reconstructed images (PA info)



Results preliminary: in preparation for submission - look out for Roettenbacher+(202?)

visibilityininterferometry.github.io

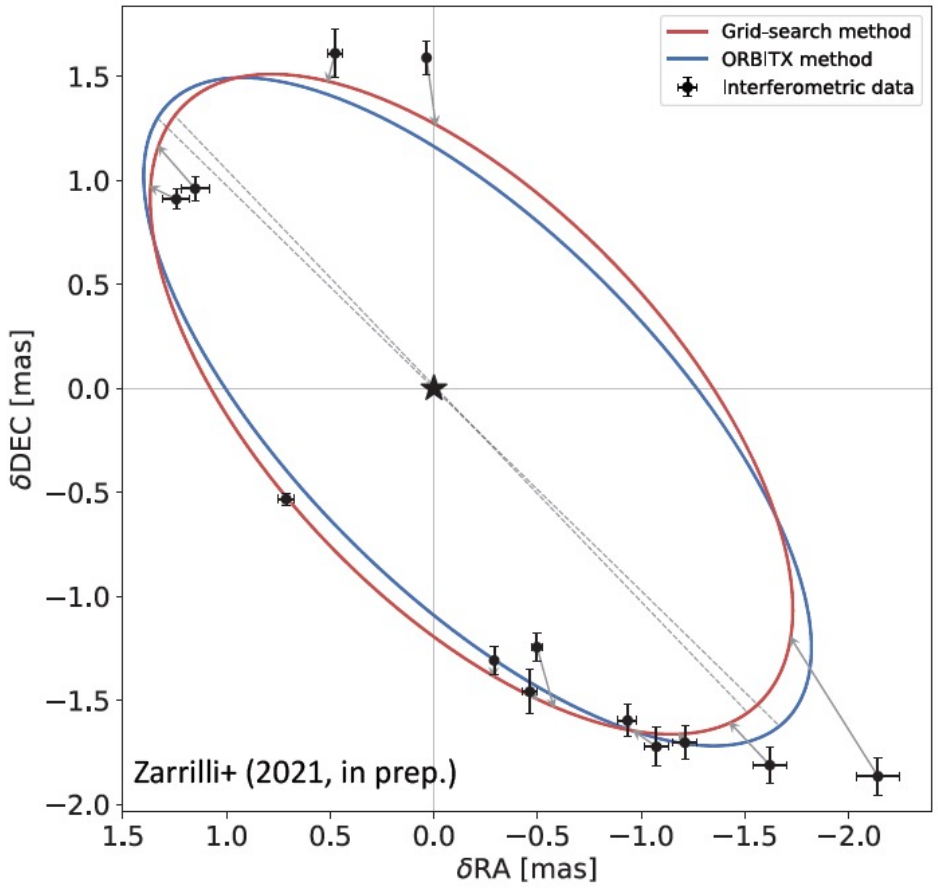


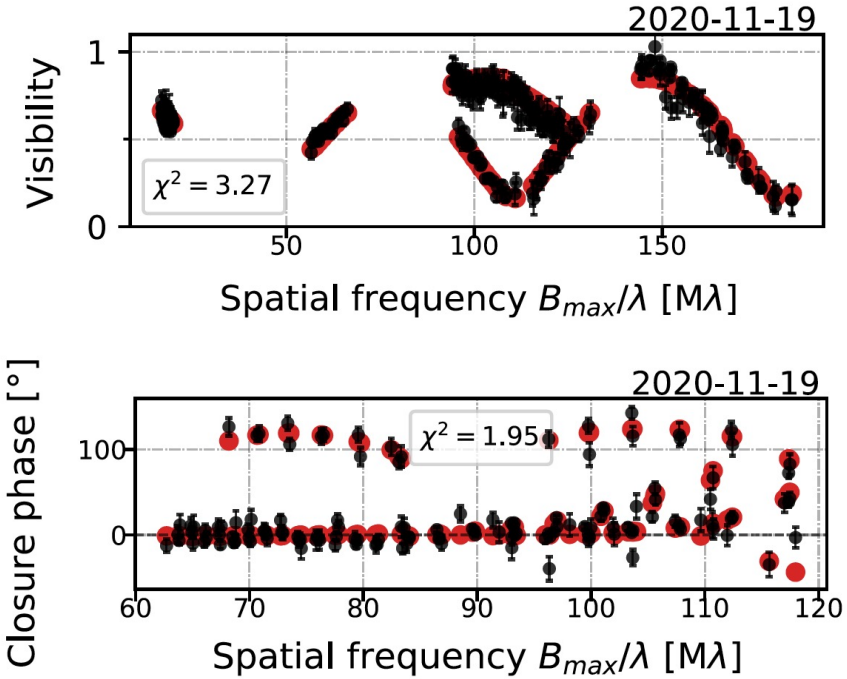
Female interferometrists Google Sheet: http://tiny.cc/VII_interferometrists

Place-holder for speaker-view video

Science highlights: Stellar multiplicity in YSOs

MWC 166



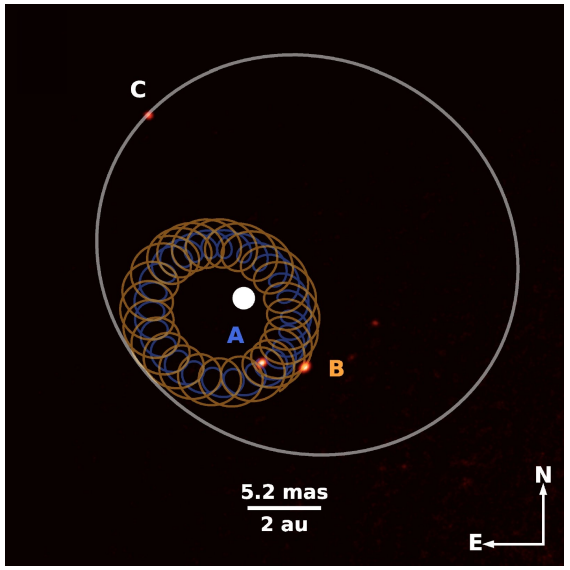


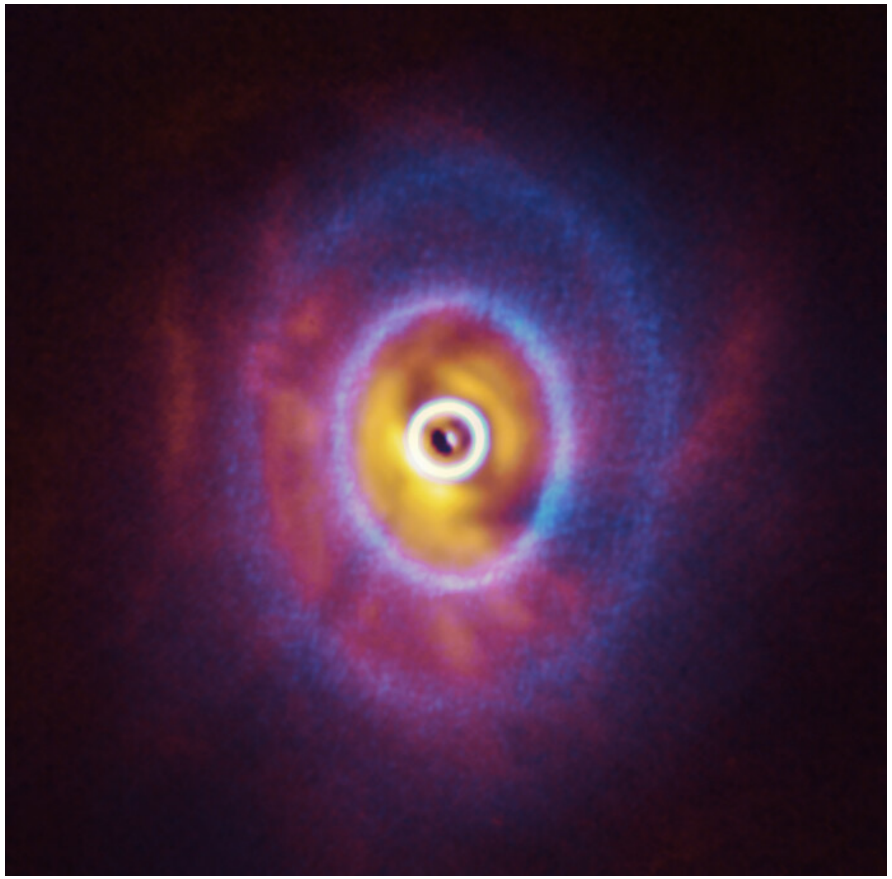
Results preliminary: in preparation for submission - look out for Zarrilli+(202?)

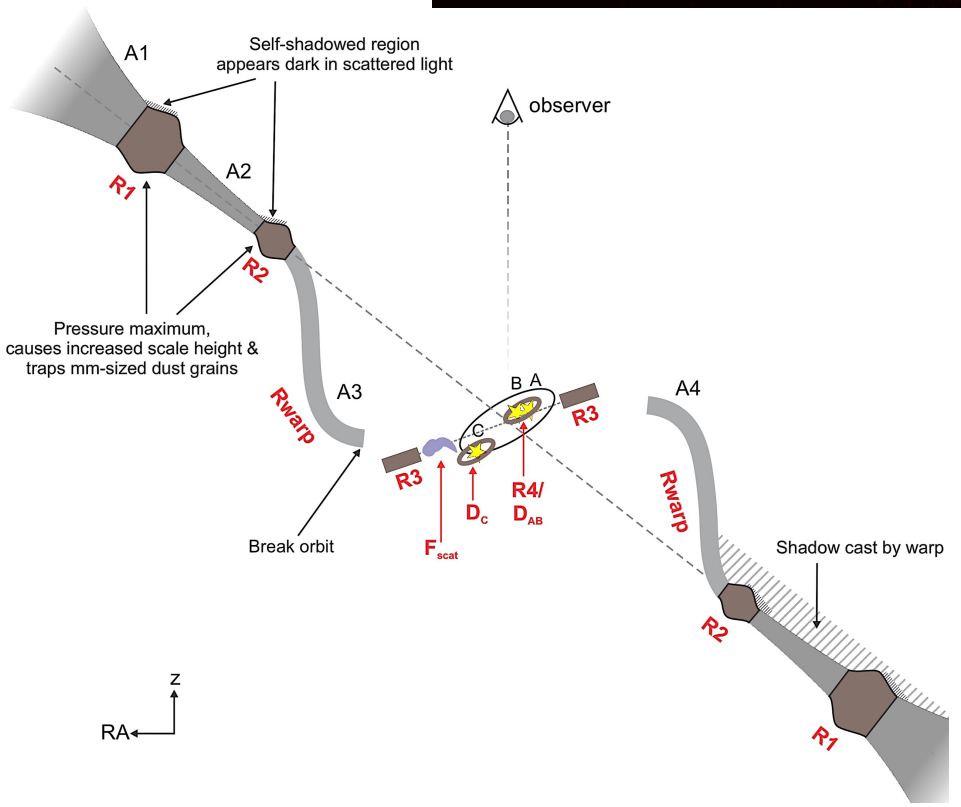
Place-holder for speaker-view video

Science highlights: Stellar multiplicity in YSOs

GW Ori





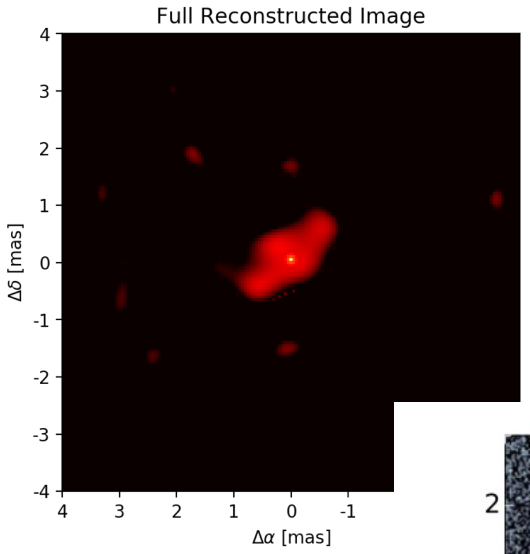


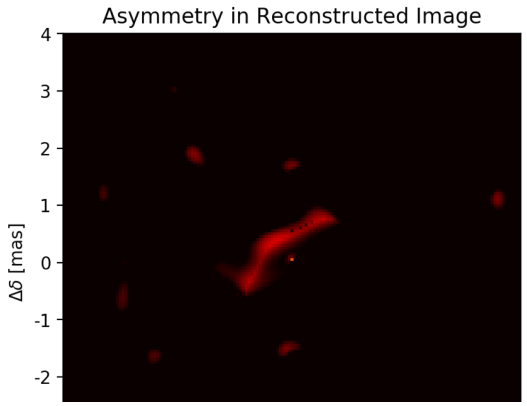
More information: Kraus+(2020)

Place-holder for speaker-view video

Science highlights: Dusty environments of single YSO systems

SU Aur (results preliminary: in preparation for submission - look out for Labdon+202?)





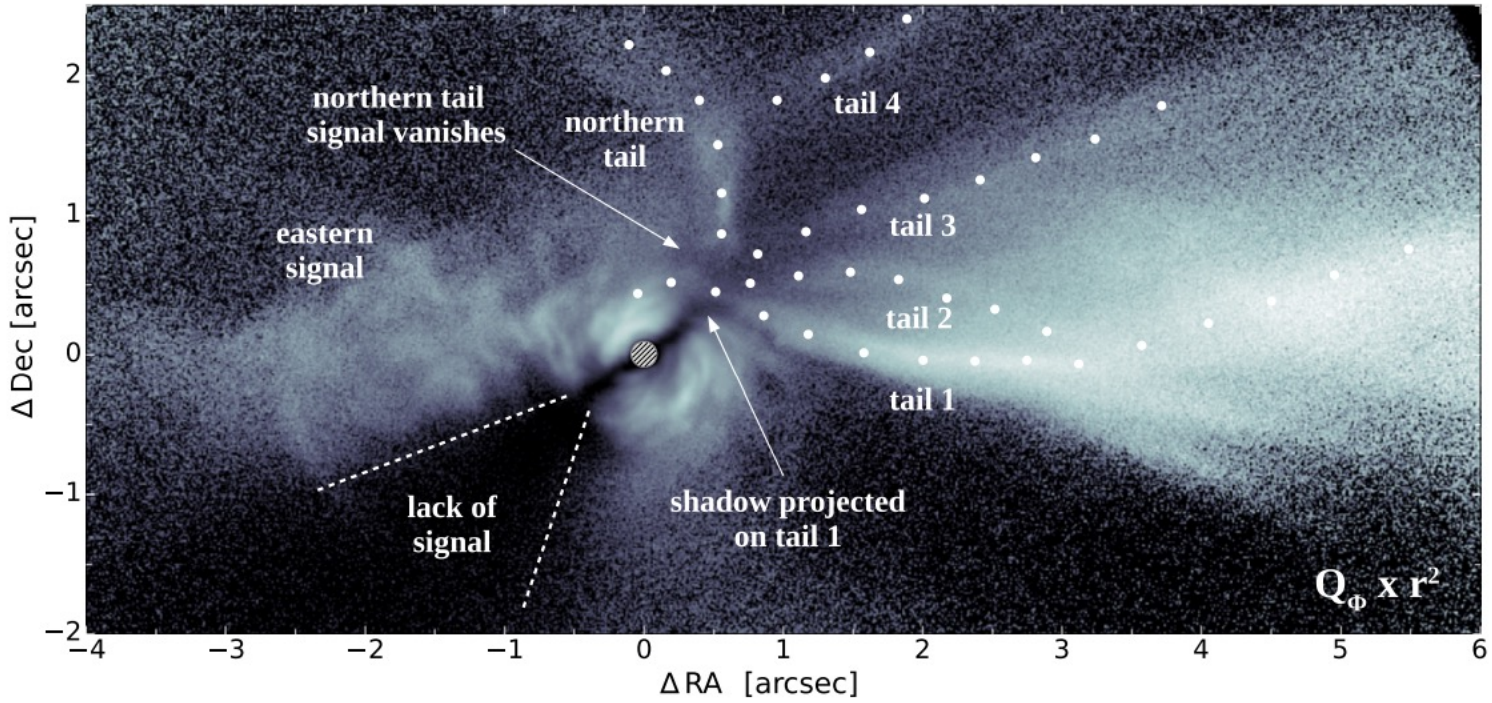
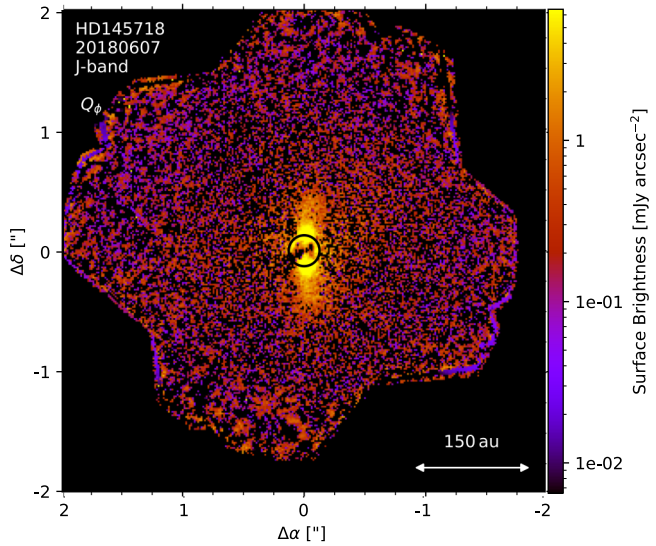


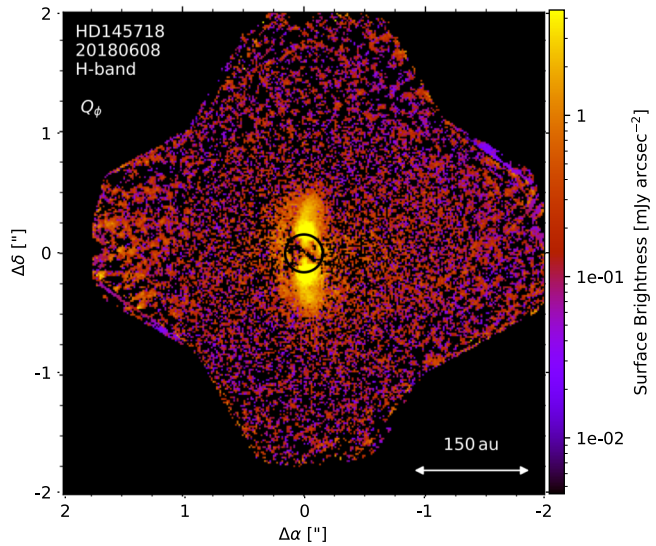
Image credit: Ginski+(2021)

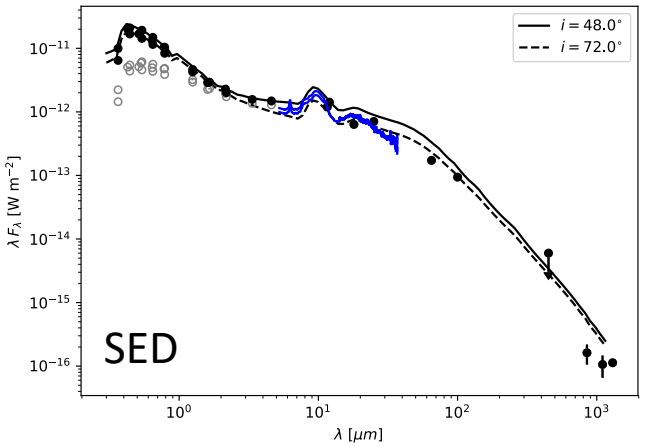
Place-holder for speaker-view video

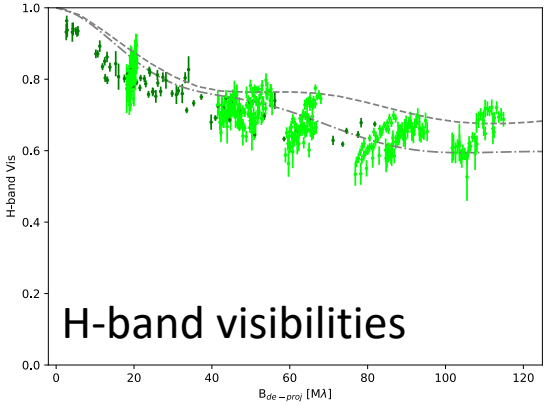
Science highlights: Dusty environments of single YSO systems

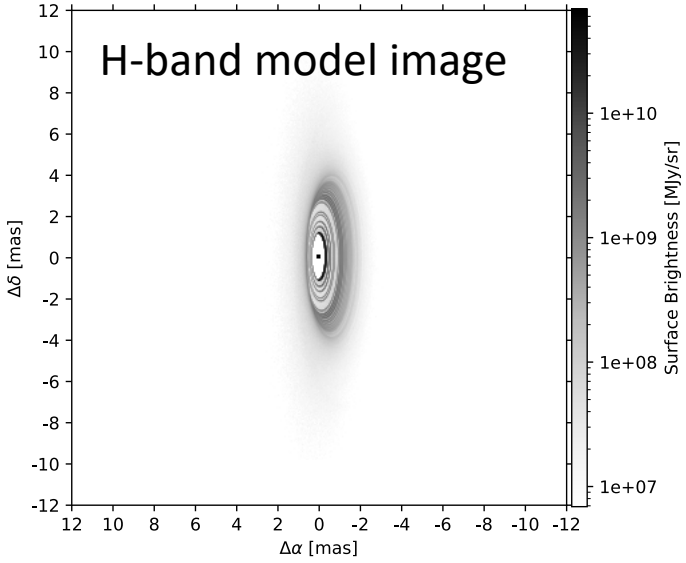
HD 145718 (Results preliminary: in preparation for submission - look out for Davies+202?)











Claire L. Davies // MIRC-X & MYSTIC // c.davies3@exeter.ac.uk

Place-holder for speaker-view video

Still to come...

June 2021: Final hardware assembly for polarisation mode

July 2021: Installation of MYSTIC at CHARA

August 2021: Lab commissioning of MYSTIC at CHARA

September 2021: NOAO call for proposals for CHARA observations
(see www.chara.gsu.edu/observers/applying-for-chara-time)

First half of 2022:

- On-sky commissioning of MYSTIC
- Release of the polar-interferometric data reduction pipeline

January 2022: Visibility in Interferometry network lunch at AAS

April 25-29 2022: "Sharpest Eyes on the Sky" CHARA+VLTI conference, Exeter, UK
(including a Visibility in Interferometry network lunch)