DIRECT OBSERVATION OF EXOPLANETS WITH GRAVITY

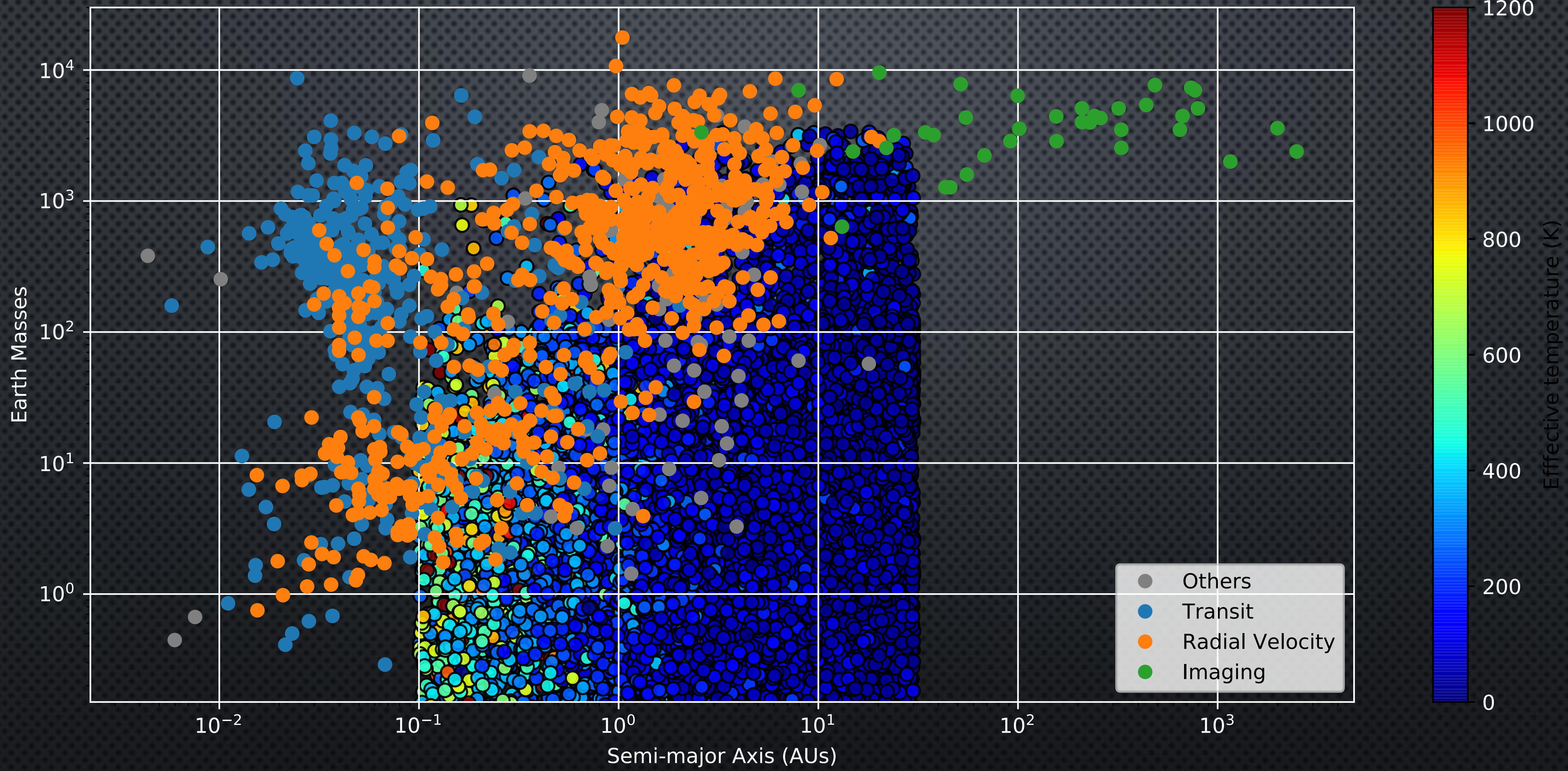
VLTI SCHOOL 2021

S. LACOUR

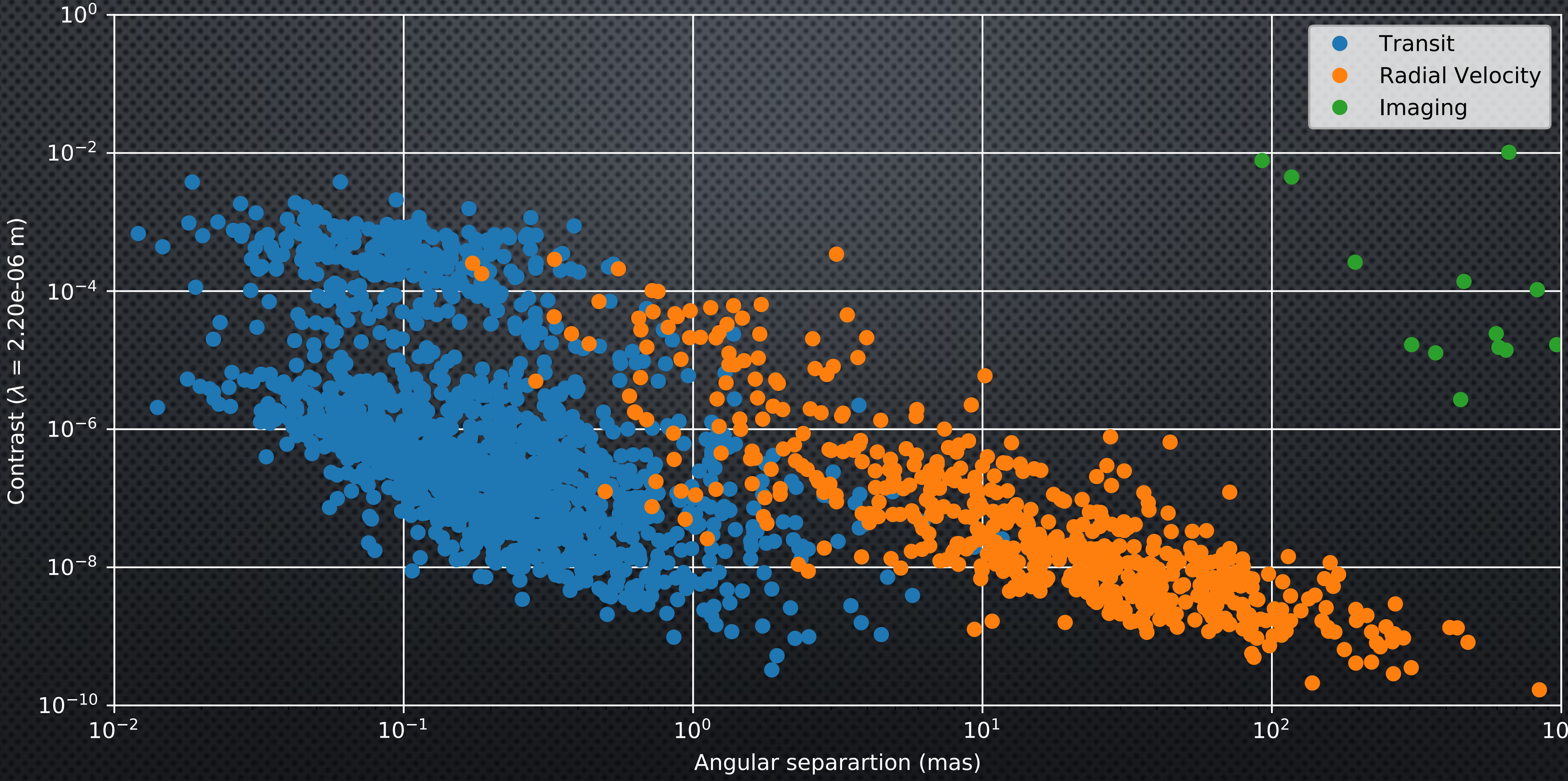
ON THE DIFFICULTY OF DIRECT DETECTION

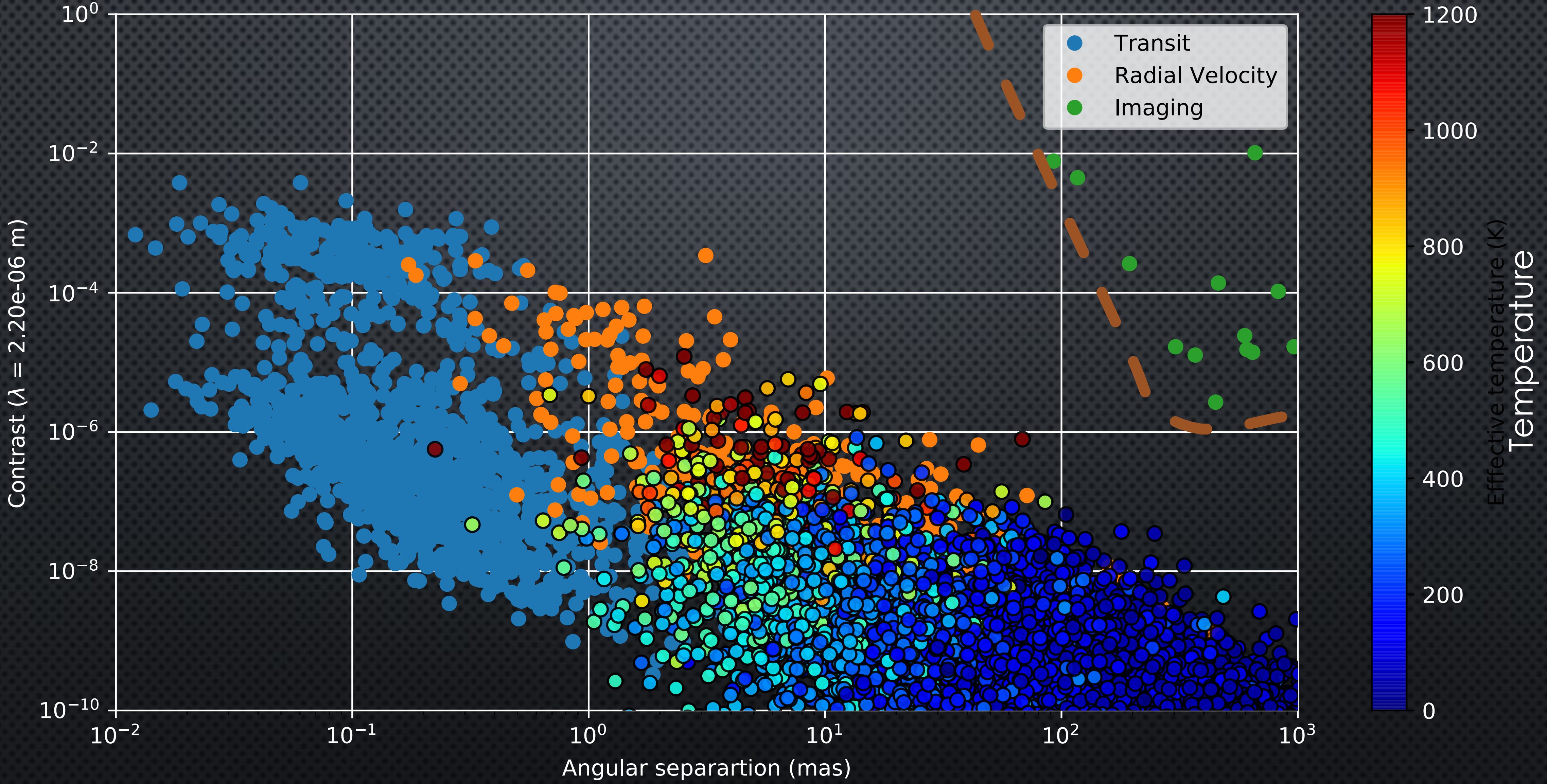

Others
Transit
Radial Velocity
Imaging
Earth Masses
10^4
10^3
10^2
10^1
10^0
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
Semi-major Axis (AUs)

NASA Exoplanet Archive
NASA Exoplanet Science Institute

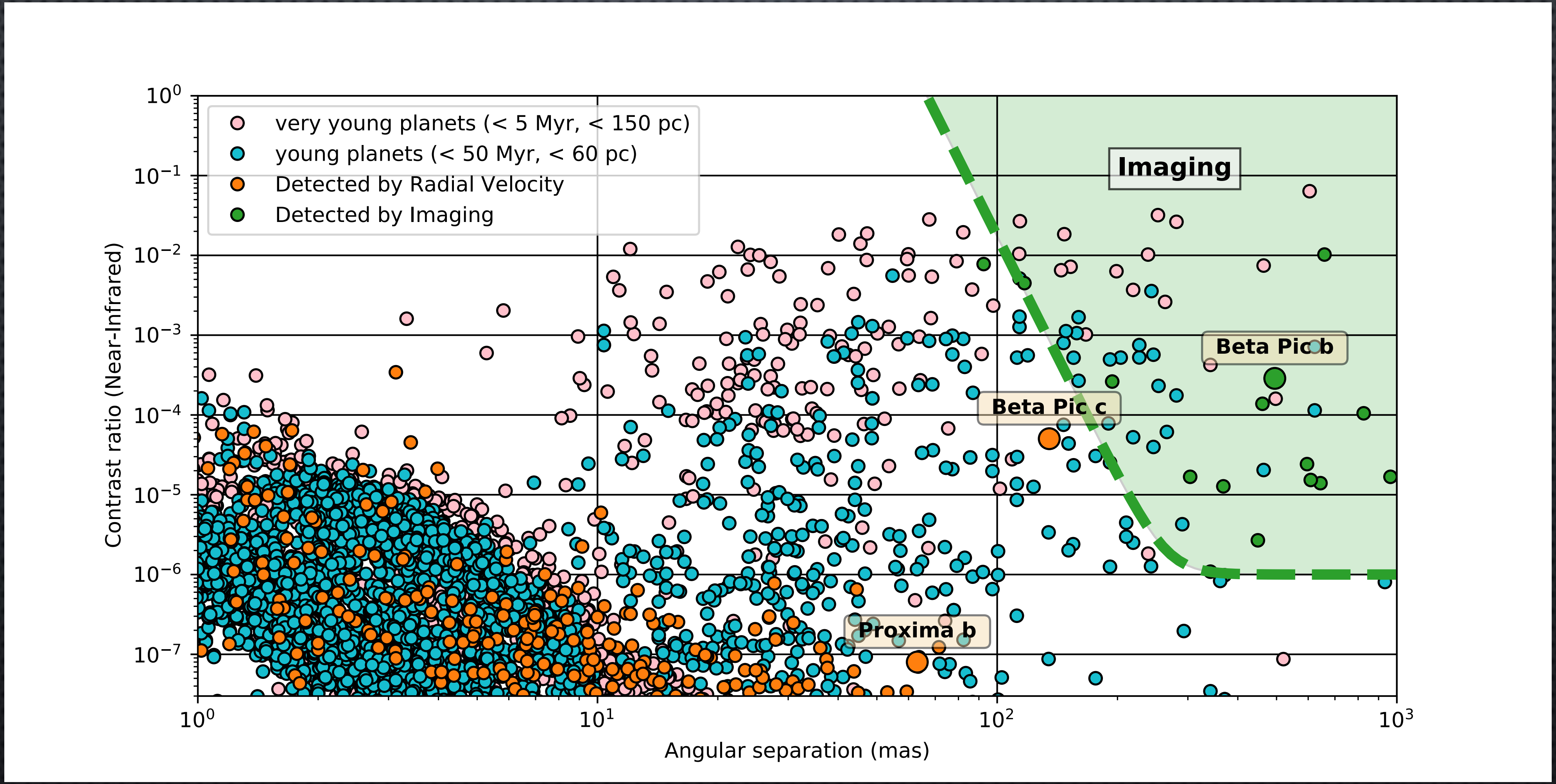


Synthetic population from Kopparapu et al. 2018
dist<30pc, 0.1AU<a<30AU

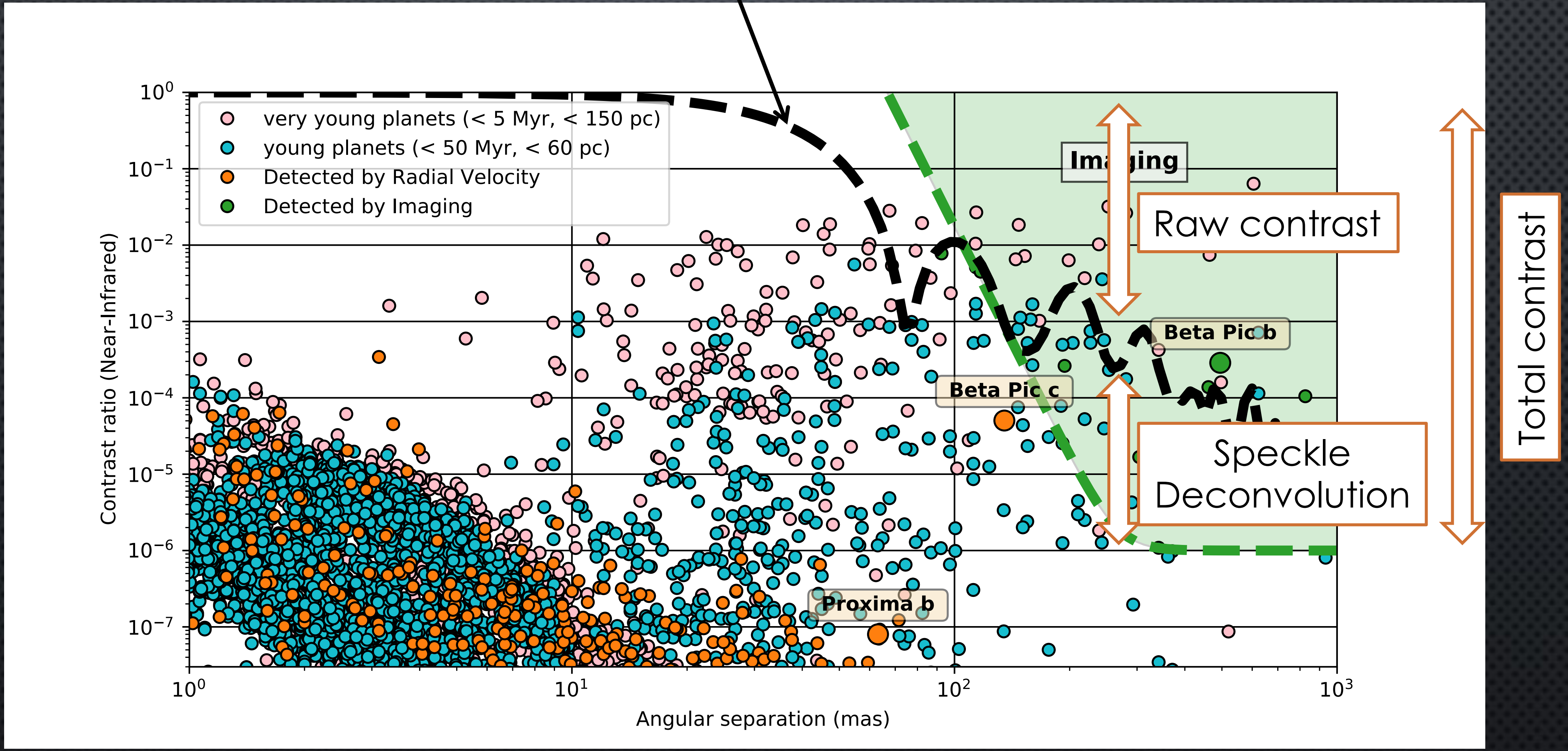

Transit
Radial Velocity
Imaging
Contrast (λ = 2.20e-06 m)
Angular separartion (mas)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}


Transit
Radial Velocity
Imaging
Contrast (λ = 2.20e-06 m)
Angular separartion (mas)
Effective temperature (K)
Temperature
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1200
1000
800
600
400
200
0

Bern model of planet formation and evolution (Mordasini et al. 2012)
Including the Young Stellar formation regions (Cha, Sco-Cen)
Including Young moving groups (Beta Pictoris, TW Hya, Carina, etc..)

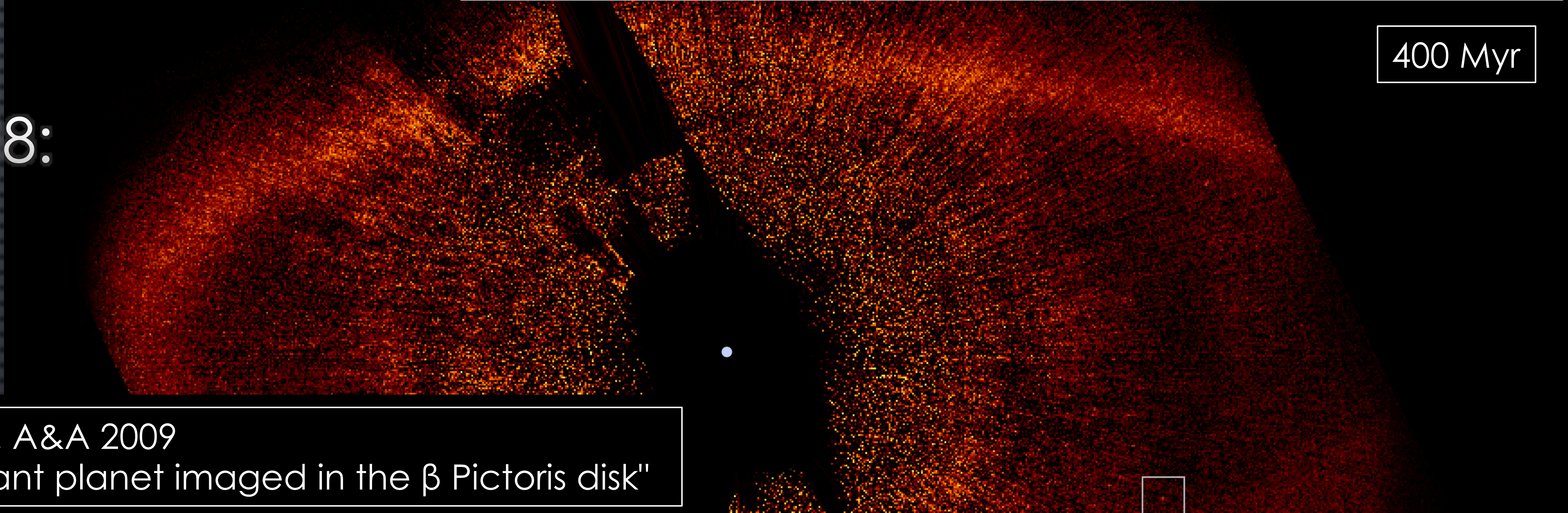


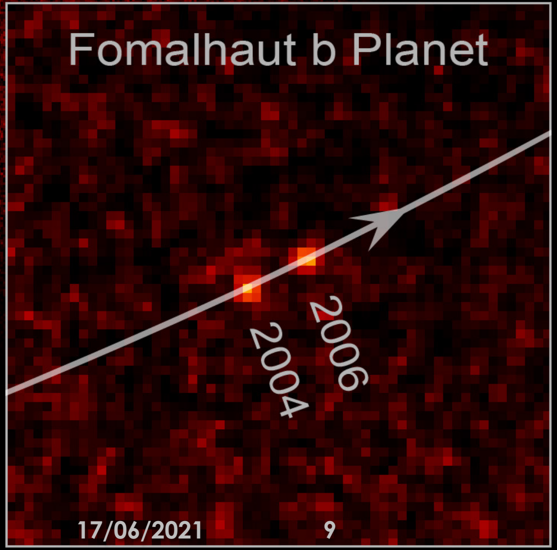
Stellar light (Extreme AO, 95%Strehl)



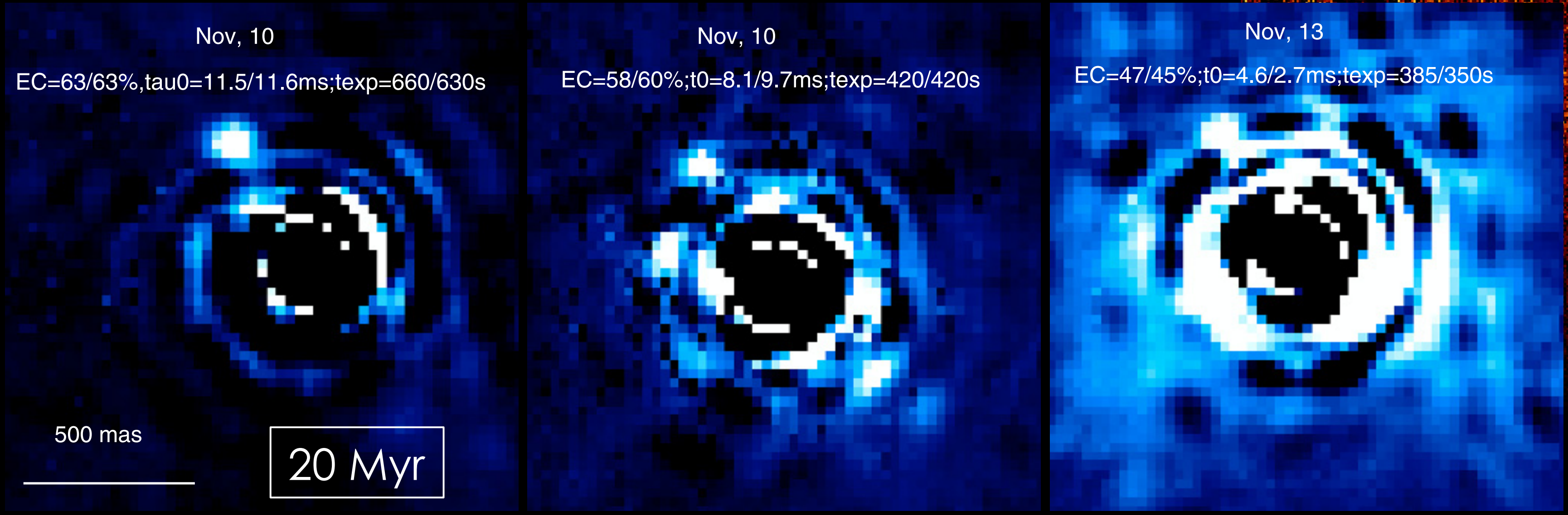
2008:

P. Kalas et al. Science 2008
"Optical Images of an Exosolar Planet 25 Light-Years from Earth"

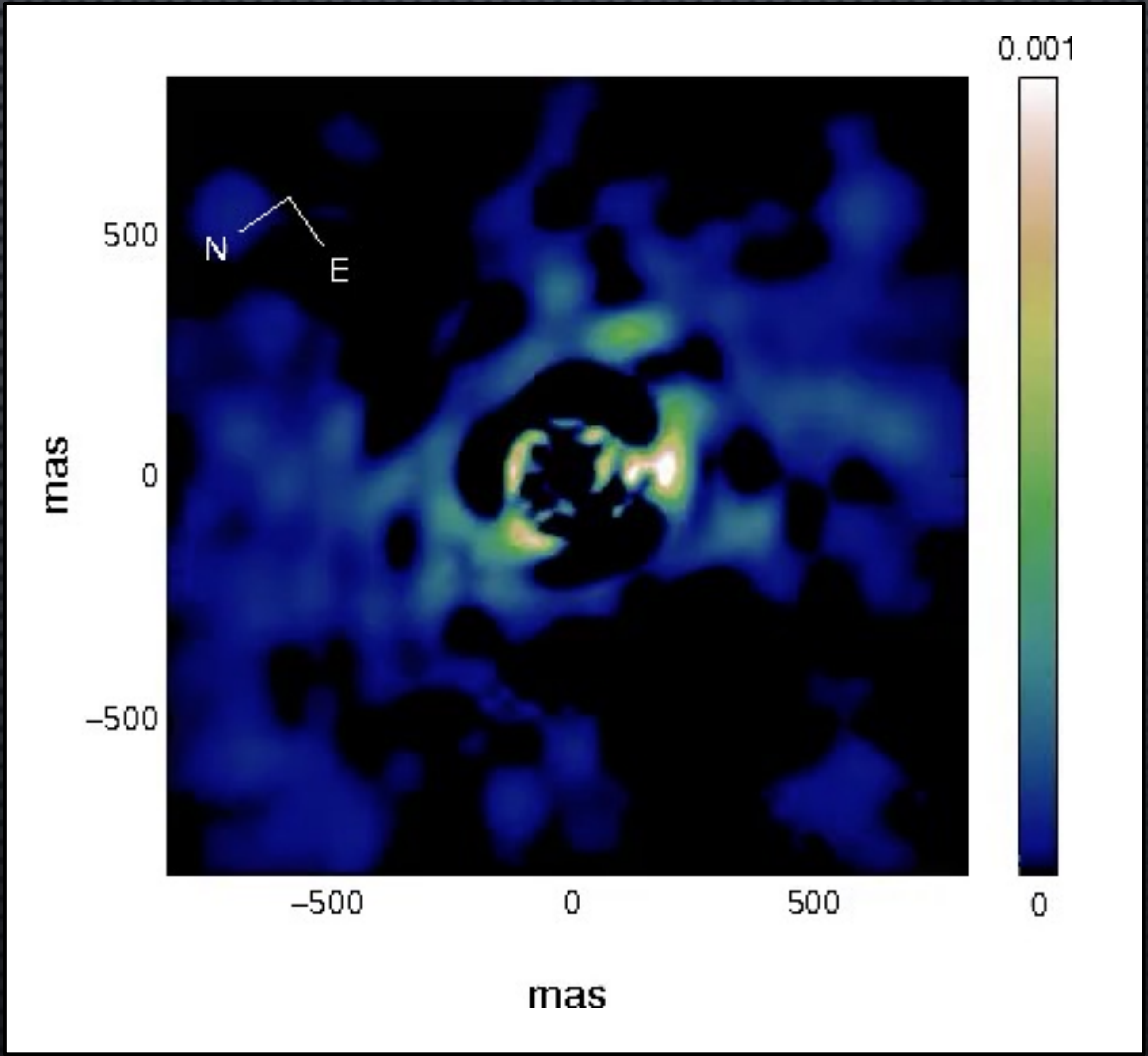




Lagrange et al. A&A 2009
"A probable giant planet imaged in the β Pictoris disk"



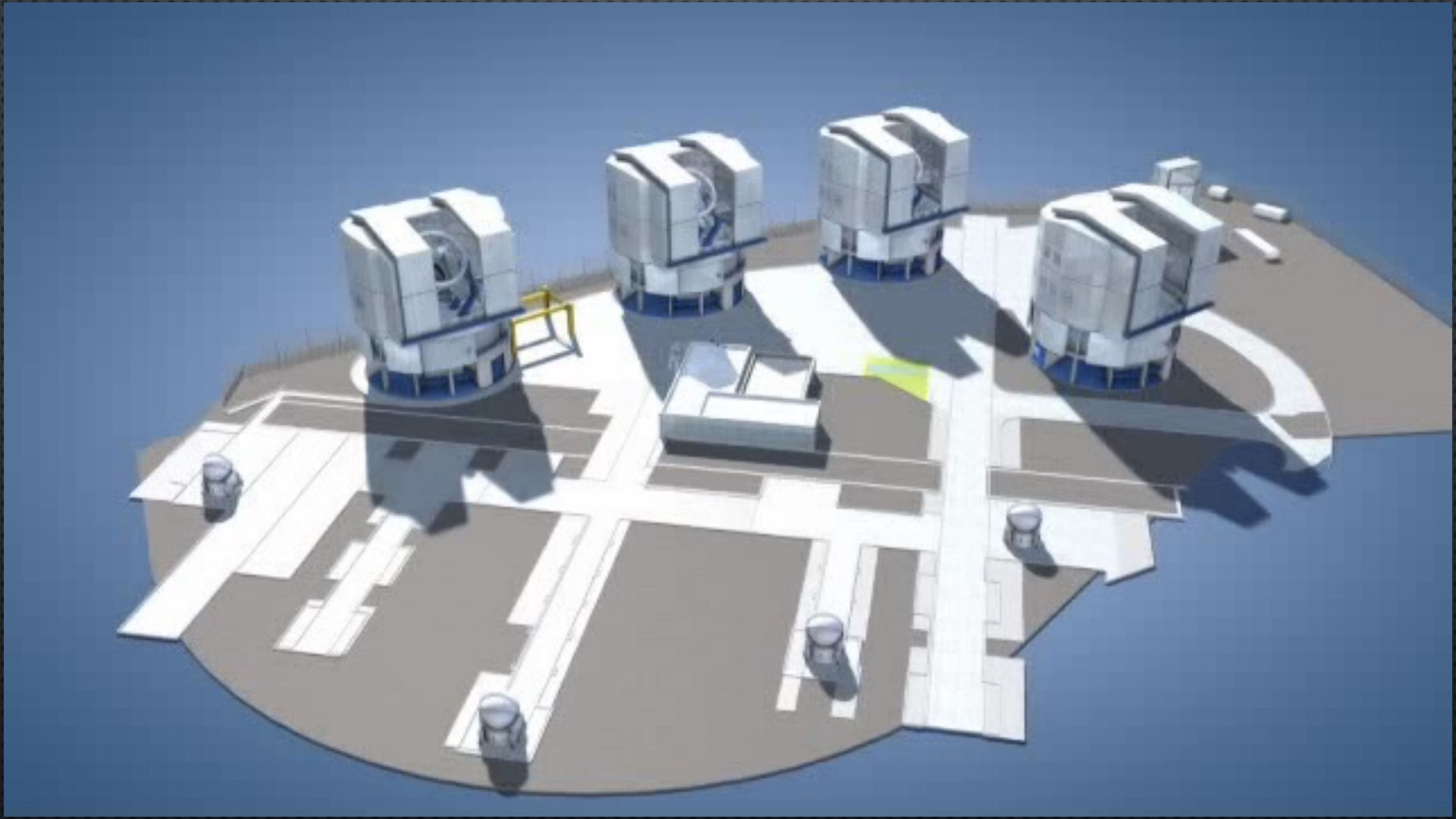
2009:



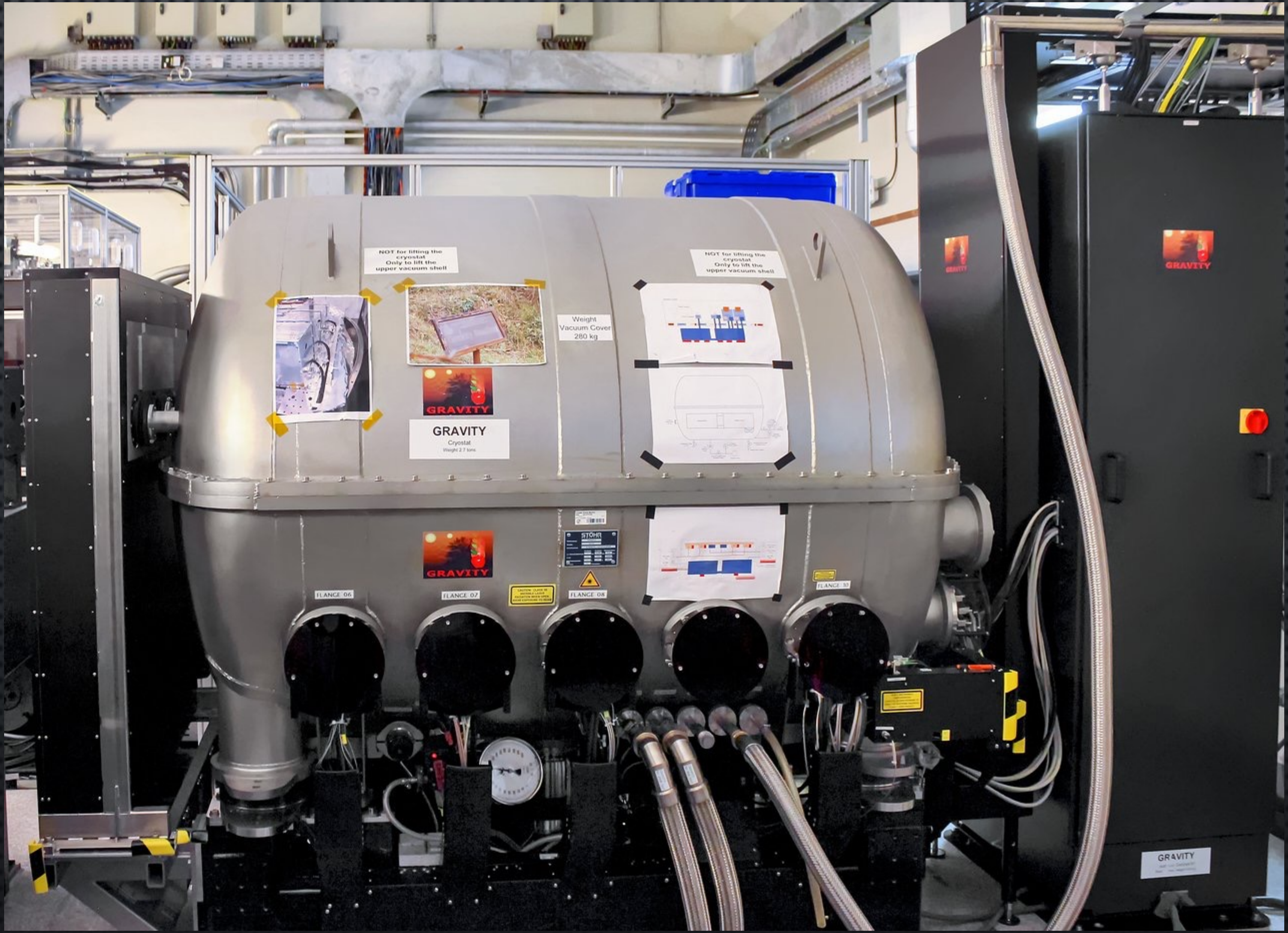
NACO / Beta Pictoris

THE GRAVITY INTERFEROMETER

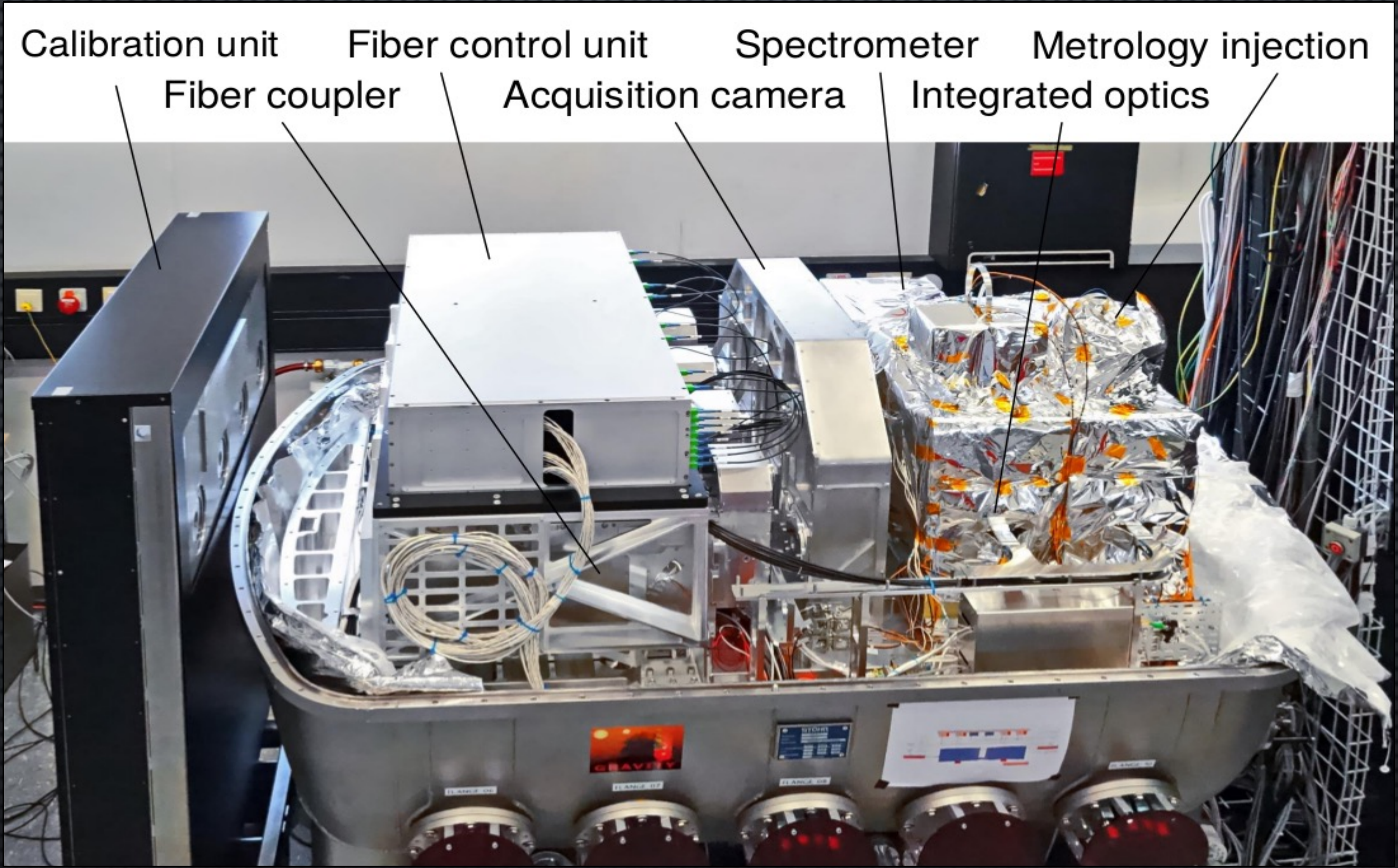
GRAVITY @ ESO VLTI



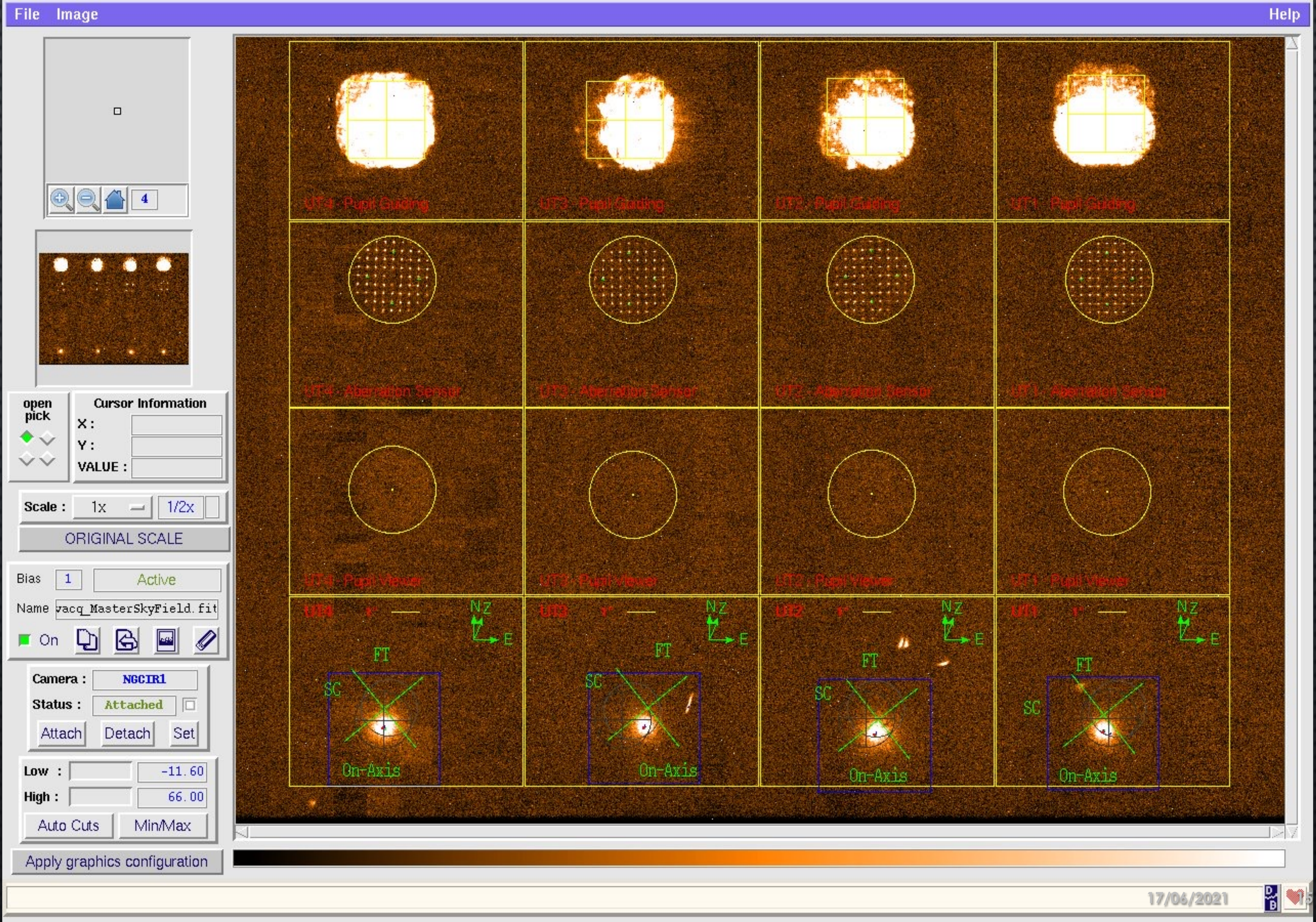
Courtesy of ESO



The GRAVITY cryostat

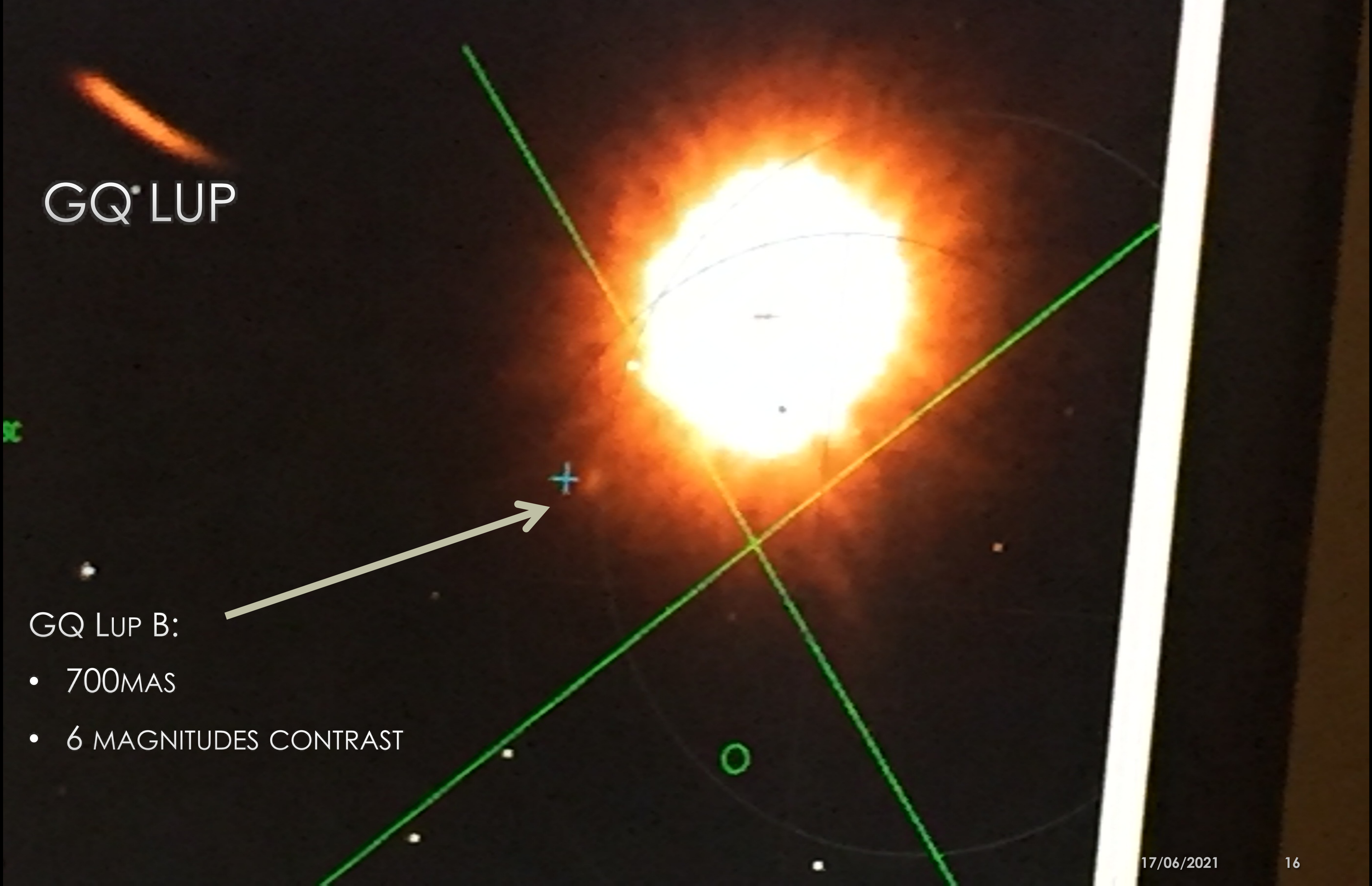


Haug, Thiel, Hausmann & the GRAVITY collaboration



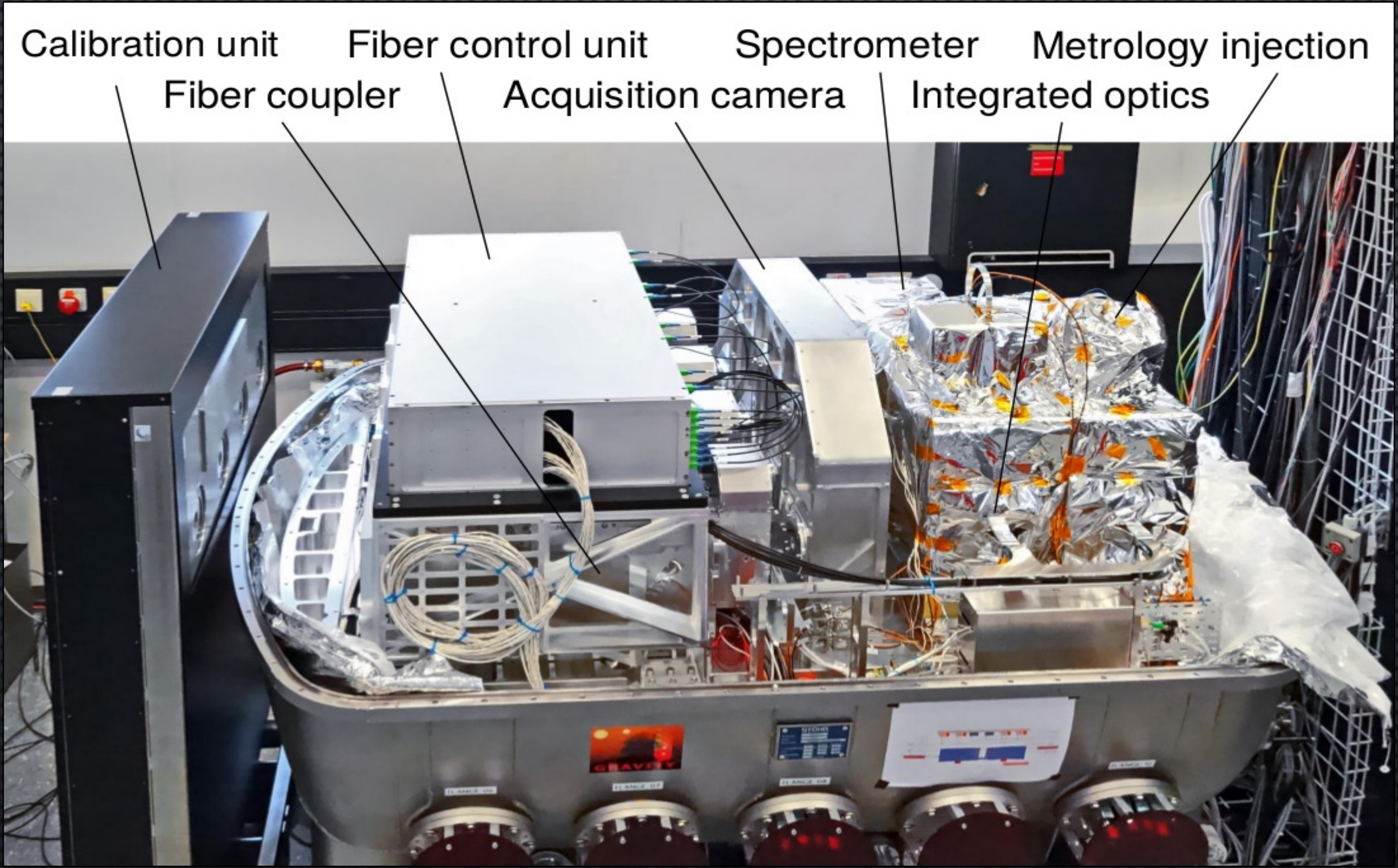
File
Image
Help
4
open
pick
Cursor Information
X :
Y :
VALUE :
Scale :
1x
1/2x
ORIGINAL SCALE
Bias
1
Active
Name
vacq_MasterSkyField.fit
On
Camera :
NGCIR1
Status :
Attached
Attach
Detach
Set
Low :
-11.60
High :
66.00
Auto Cuts
Min/Max
Apply graphics configuration
UT4 - Pupil Guiding
UT3 - Pupil Guiding
UT2 - Pupil Guiding
UT1 - Pupil Guiding
UT4 - Aberration Sensor
UT3 - Aberration Sensor
UT2 - Aberration Sensor
UT1 - Aberration Sensor
UT4 - Pupil Viewer
UT3 - Pupil Viewer
UT2 - Pupil Viewer
UT1 - Pupil Viewer
UT4
UT3
UT2
UT1
FT
SC
On-Axis
N
Z
E
17/06/2021

GQ LUP



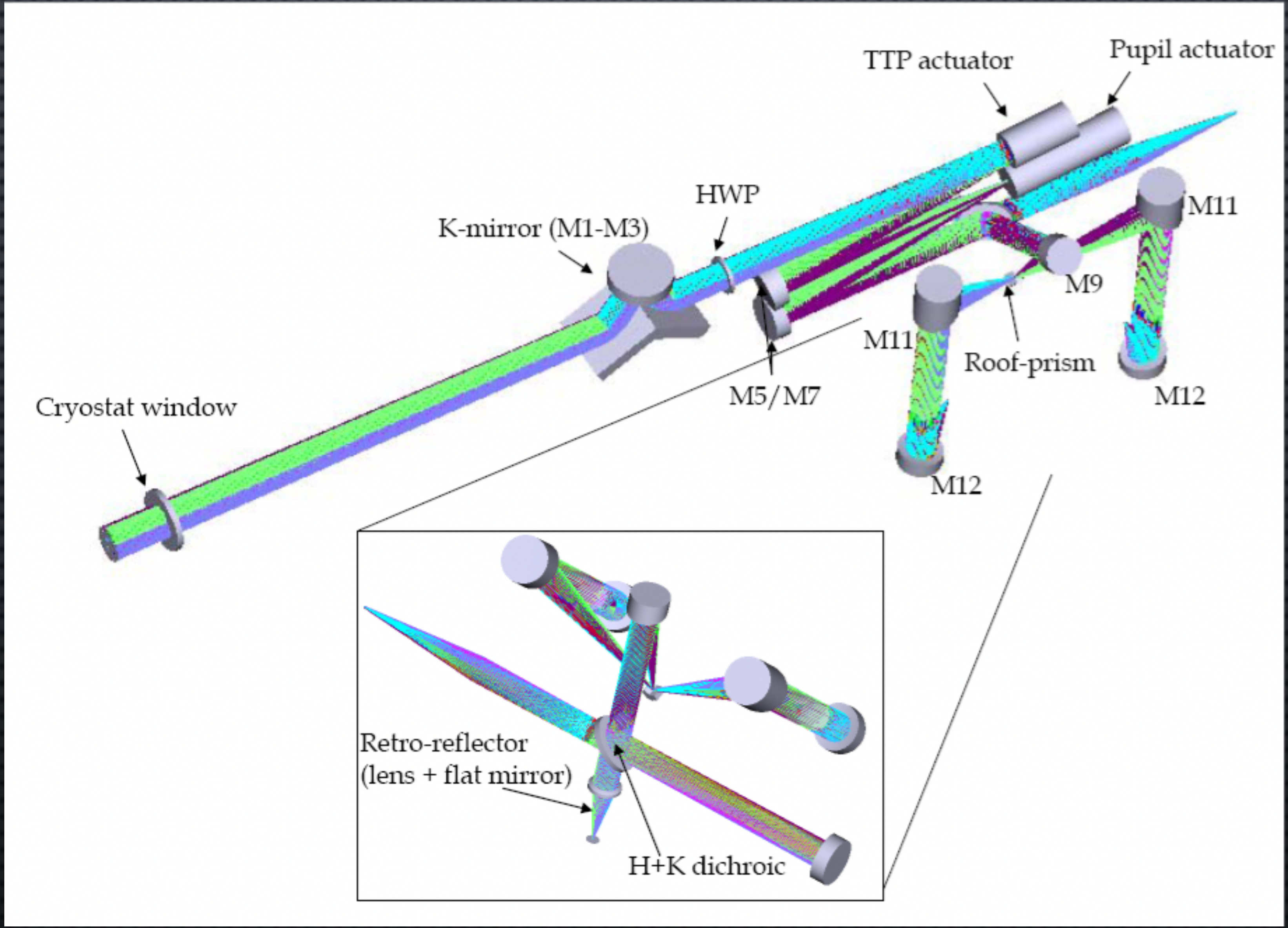
GQ Lup B:

- 700mas
- 6 magnitudes contrast

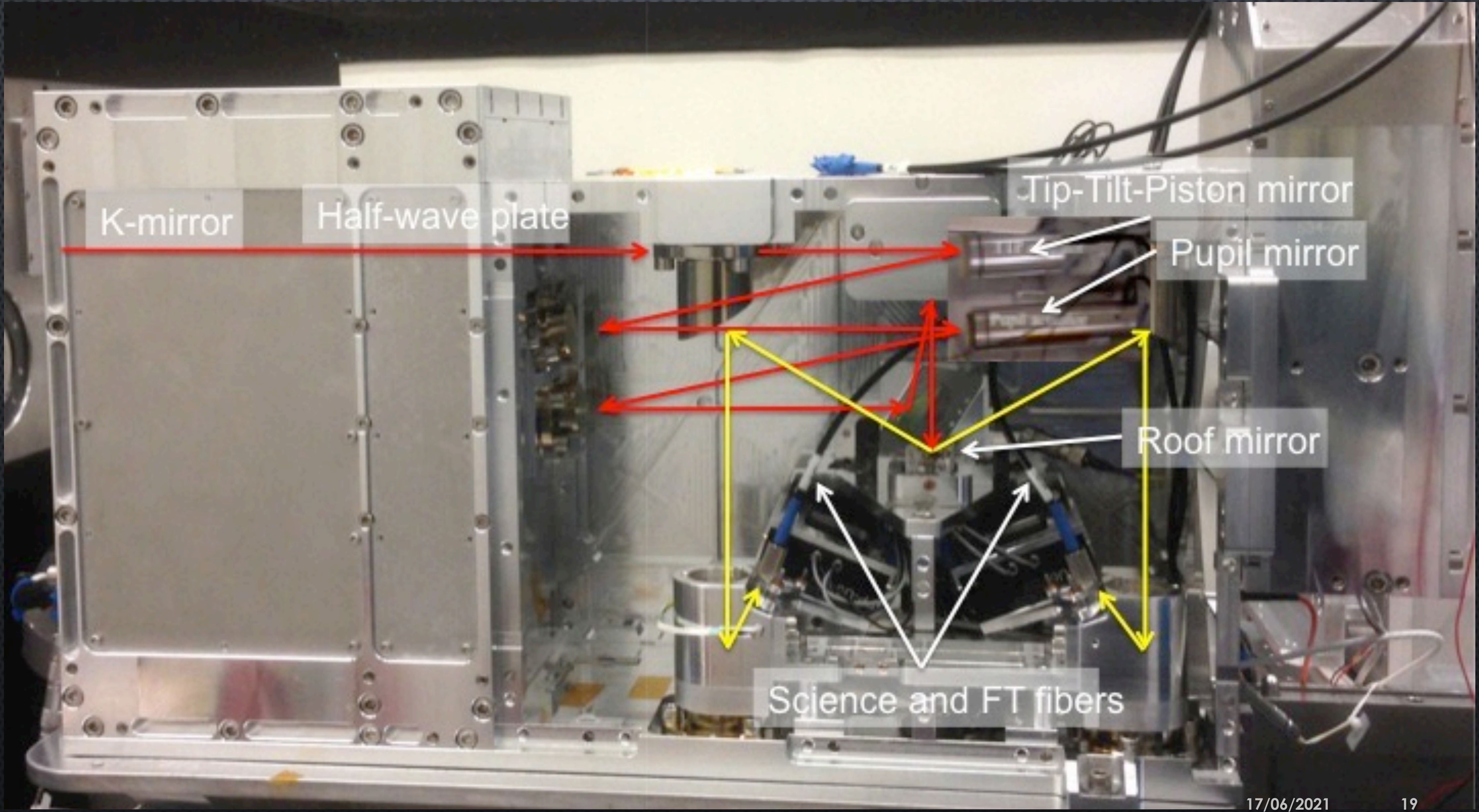


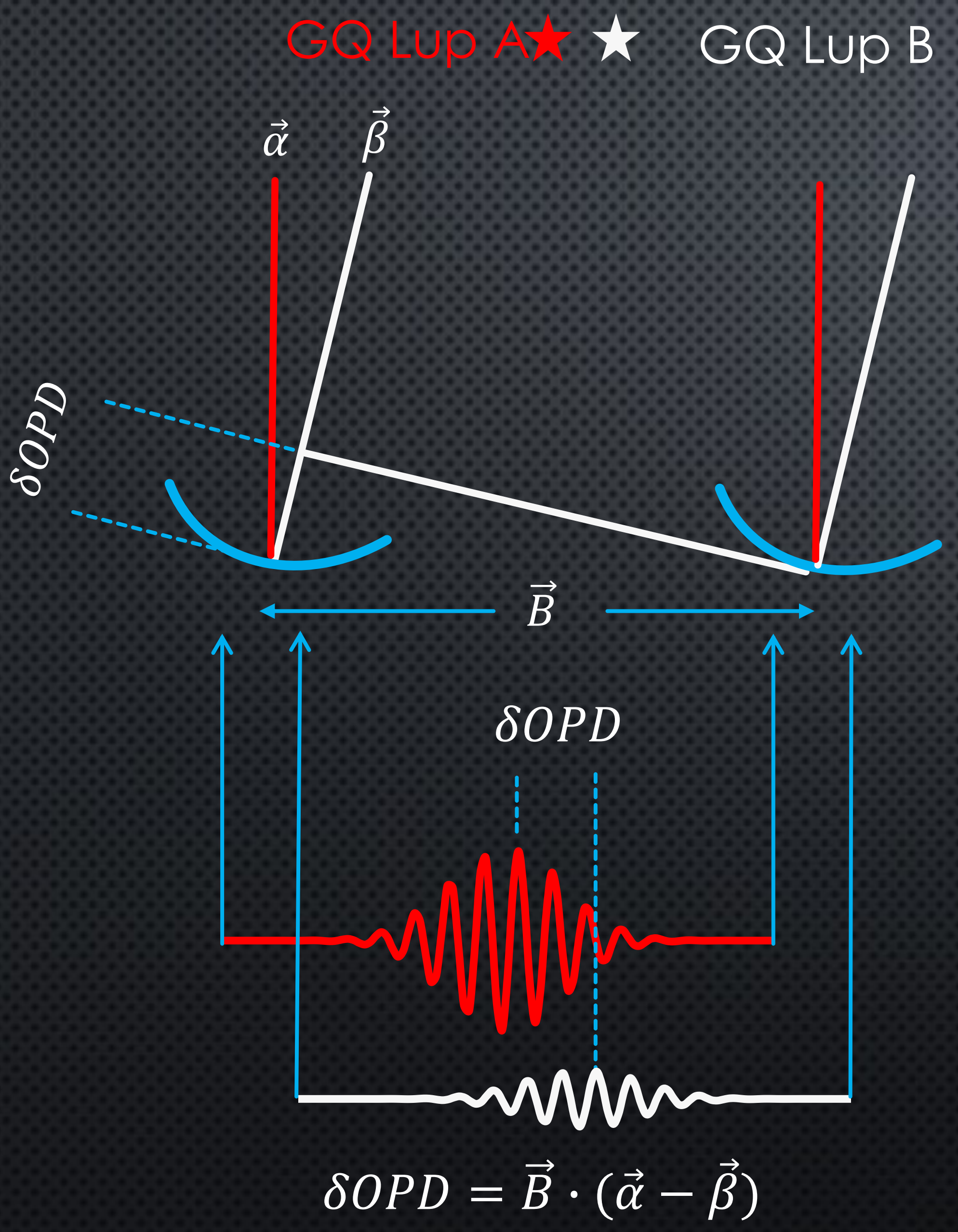
Haug, Thiel, Hausmann & the GRAVITY collaboration

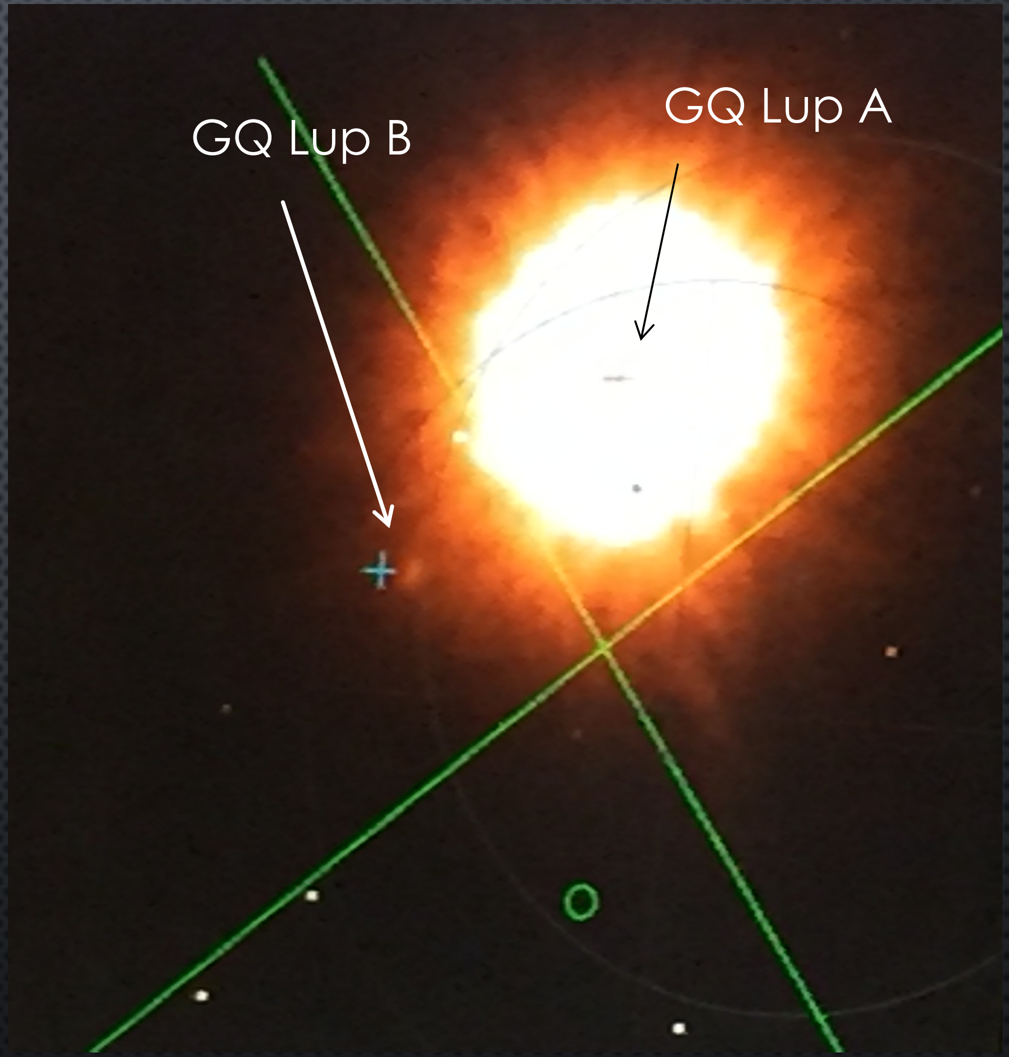
FIBERCOUPLER

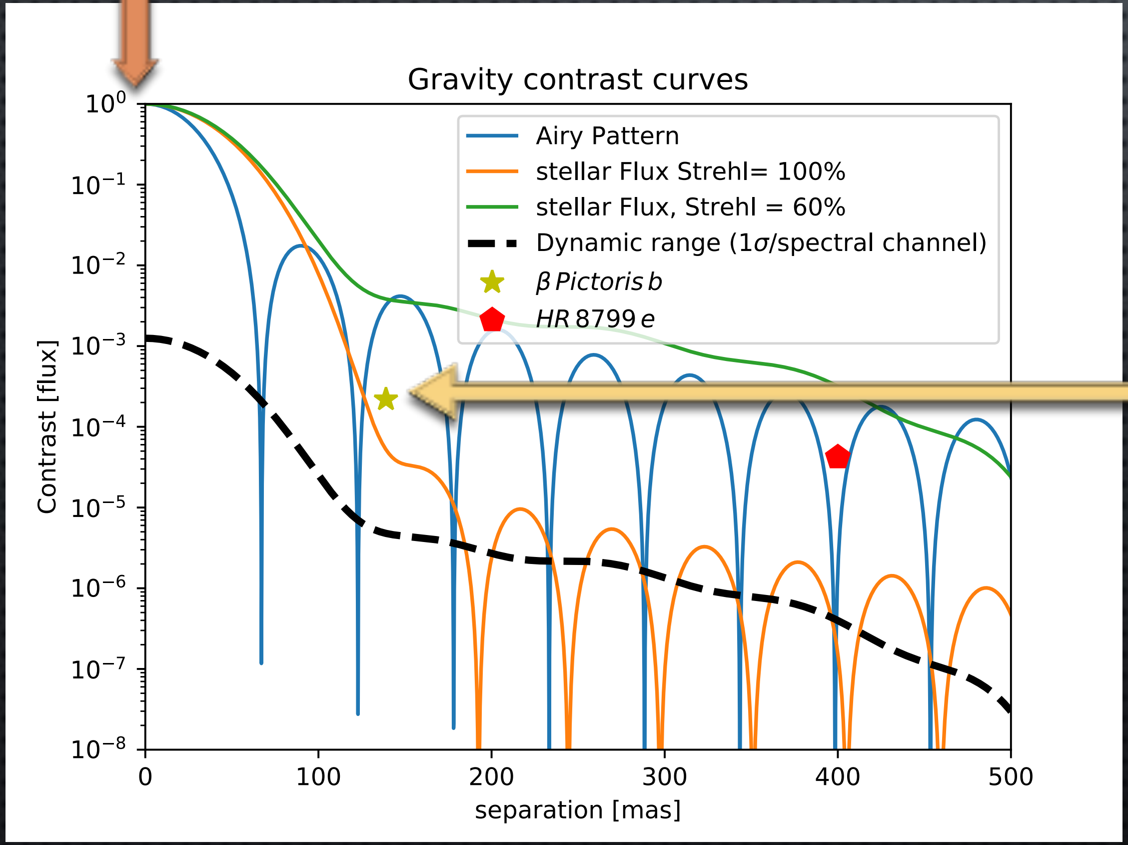


FIBERCOUPLER

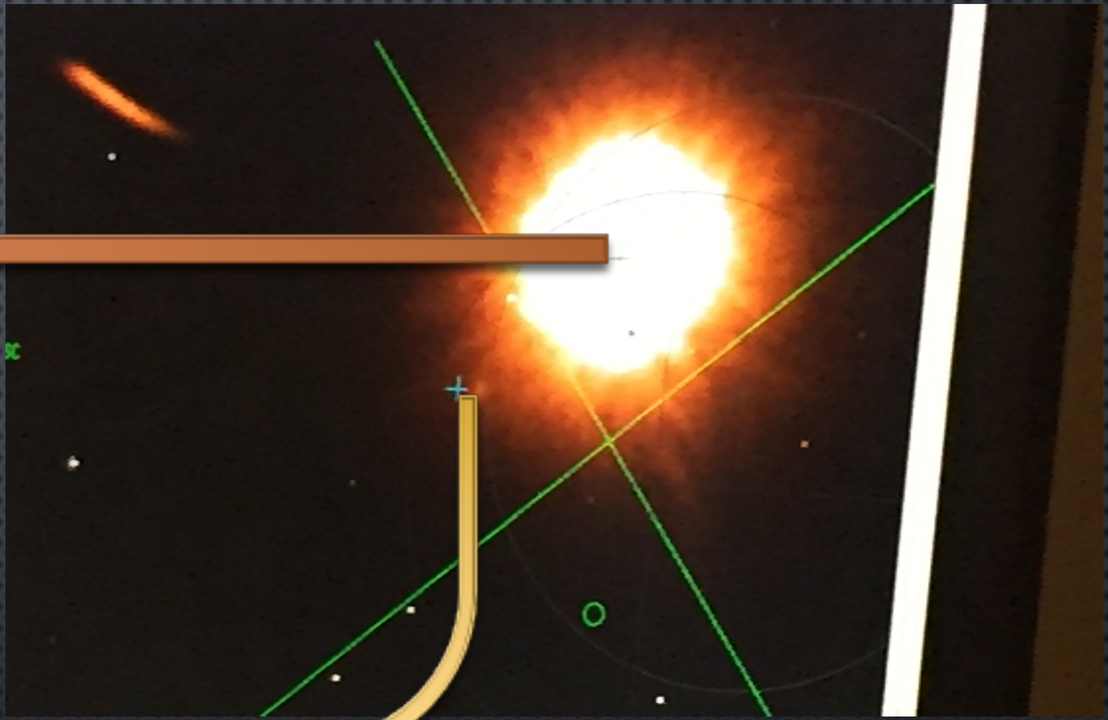



GQ Lup A★ ★ GQ Lup B
$\vec{\alpha}$
$\vec{\beta}$
δOPD
$\vec{B}$
δOPD
$\delta OPD = \vec{B} \cdot (\vec{\alpha} - \vec{\beta})$

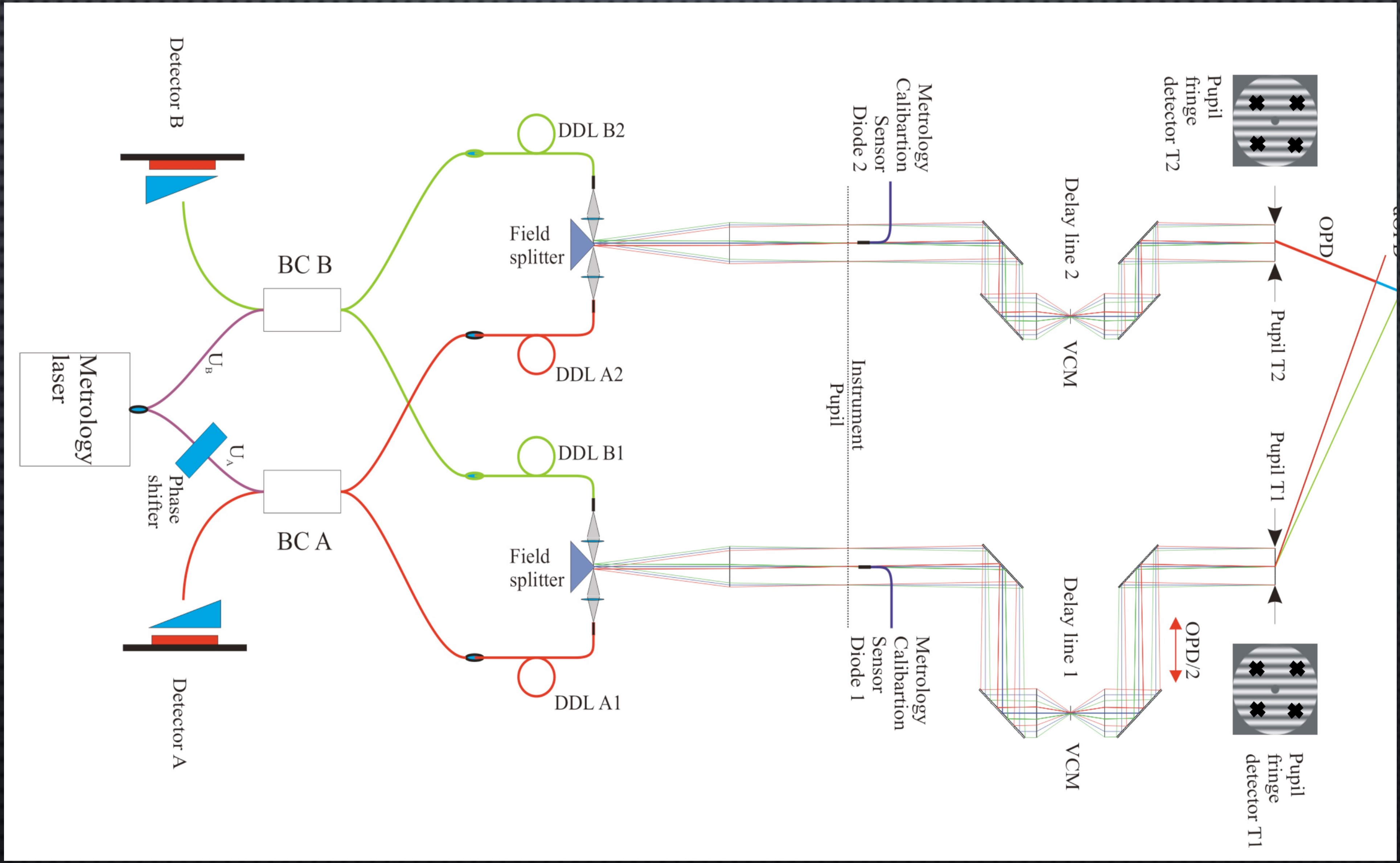

GQ Lup B
GQ Lup A



Gravity contrast curves
Airy Pattern
stellar Flux Strehl= 100%
stellar Flux, Strehl = 60%
Dynamic range (1σ/spectral channel)
β Pictoris b
HR 8799 e
Contrast [flux]
separation [mas]



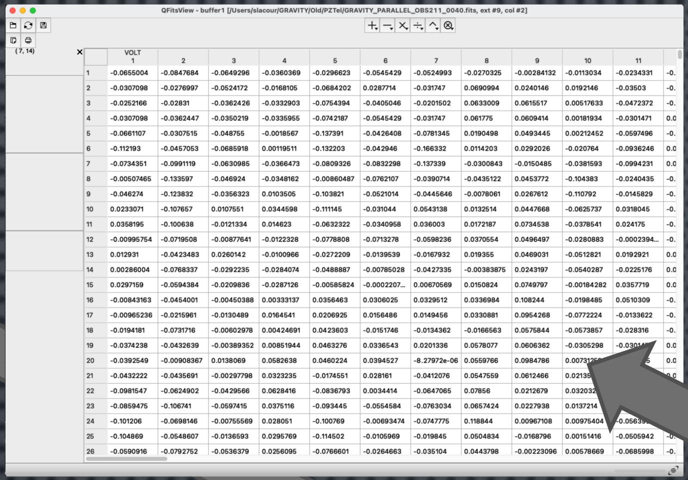
$$\delta OPD = \vec{B} \cdot (\vec{\alpha} - \vec{\beta})$$

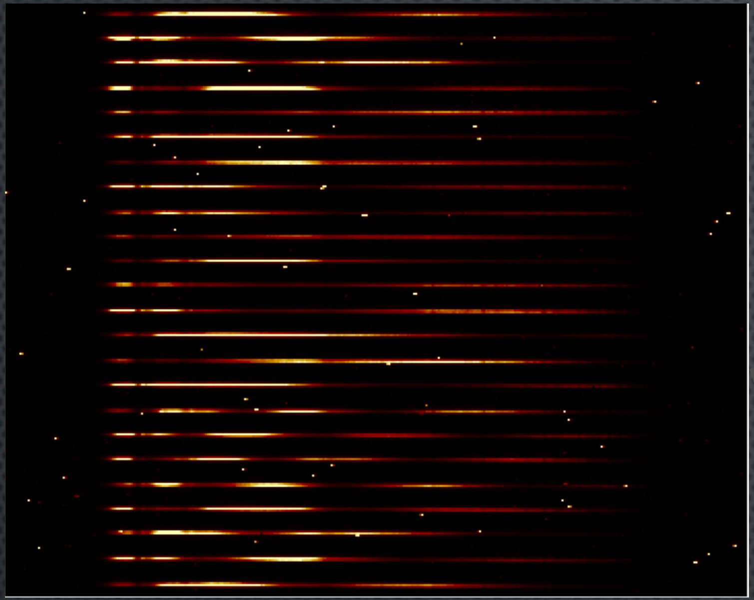


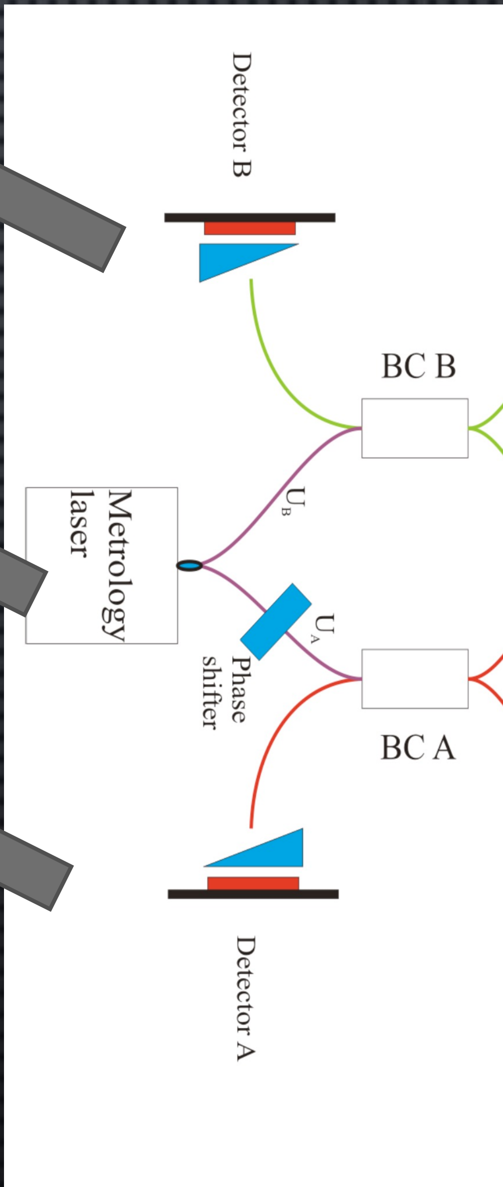
Metrology phases

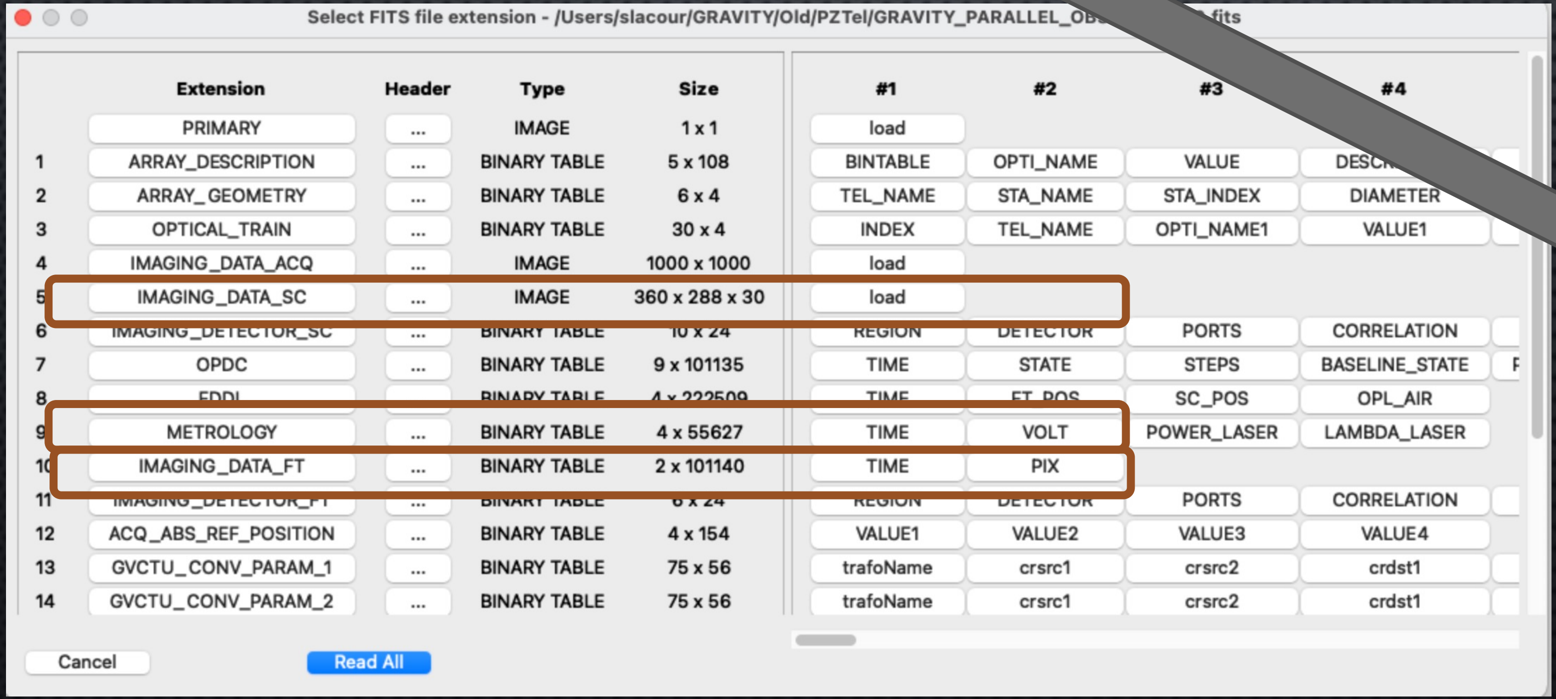
Fringe Tracker visibilities

Science camera visibilities





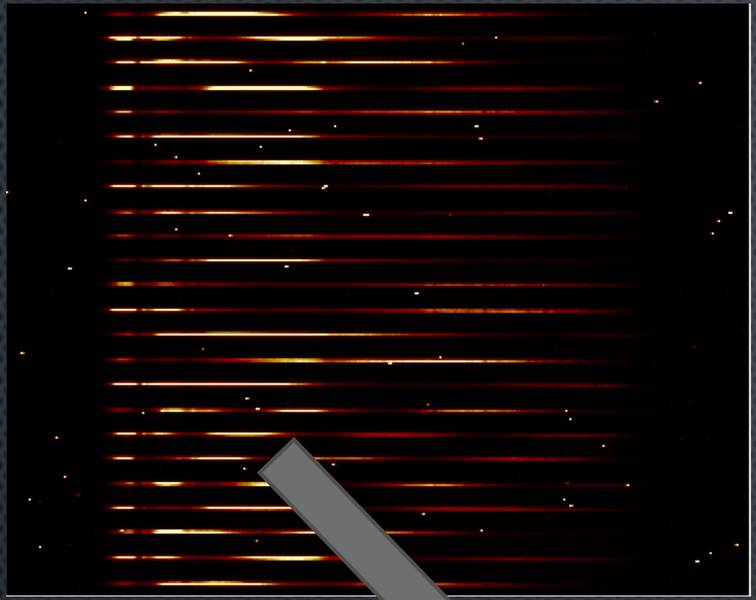




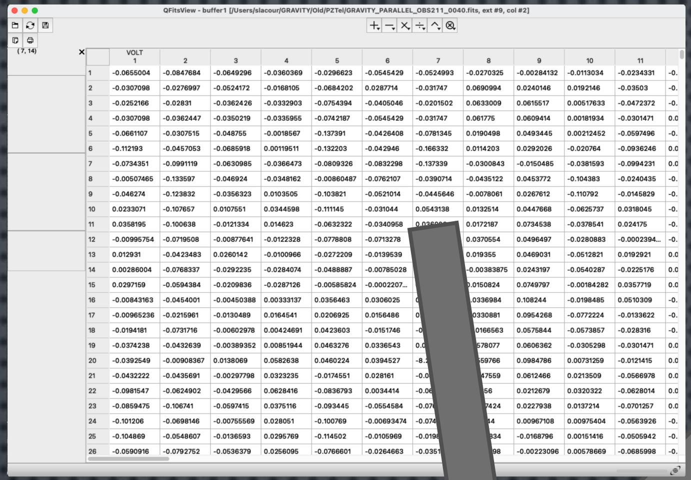
Select FITS file extension - /Users/slacour/GRAVITY/Old/PZTel/GRAVITY_PARALLEL_OB...fits

	Extension	Header	Type	Size	#1	#2	#3	#4
	PRIMARY	...	IMAGE	1 x 1	load			
1	ARRAY_DESCRIPTION	...	BINARY TABLE	5 x 108	BINTABLE	OPTI_NAME	VALUE	DESC...
2	ARRAY_GEOMETRY	...	BINARY TABLE	6 x 4	TEL_NAME	STA_NAME	STA_INDEX	DIAMETER
3	OPTICAL_TRAIN	...	BINARY TABLE	30 x 4	INDEX	TEL_NAME	OPTI_NAME1	VALUE1
4	IMAGING_DATA_ACQ	...	IMAGE	1000 x 1000	load			
5	IMAGING_DATA_SC	...	IMAGE	360 x 288 x 30	load			
6	IMAGING_DETECTOR_SC	...	BINARY TABLE	10 x 24	REGION	DETECTOR	PORTS	CORRELATION
7	OPDC	...	BINARY TABLE	9 x 101135	TIME	STATE	STEPS	BASELINE_STATE
8	FDDL	...	BINARY TABLE	4 x 222509	TIME	FT_POS	SC_POS	OPL_AIR
9	METROLOGY	...	BINARY TABLE	4 x 55627	TIME	VOLT	POWER_LASER	LAMBDA_LASER
10	IMAGING_DATA_FT	...	BINARY TABLE	2 x 101140	TIME	PIX		
11	IMAGING_DETECTOR_FT	...	BINARY TABLE	6 x 24	REGION	DETECTOR	PORTS	CORRELATION
12	ACQ_ABS_REF_POSITION	...	BINARY TABLE	4 x 154	VALUE1	VALUE2	VALUE3	VALUE4
13	GVCTU_CONV_PARAM_1	...	BINARY TABLE	75 x 56	trafoName	crsrc1	crsrc2	crdst1
14	GVCTU_CONV_PARAM_2	...	BINARY TABLE	75 x 56	trafoName	crsrc1	crsrc2	crdst1

Cancel Read All



Metrology phases



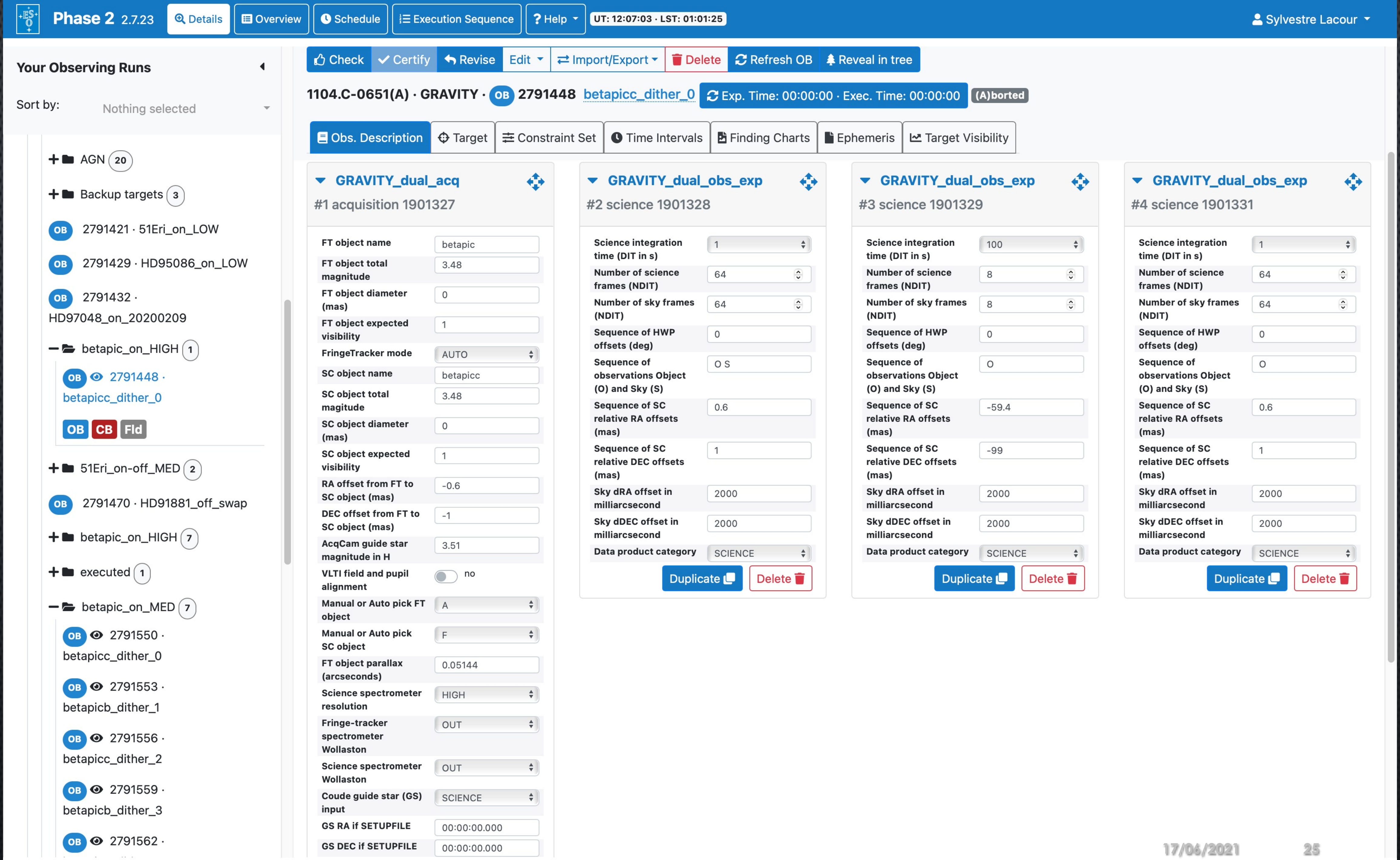
Fringe Tracker visibilities

Science camera visibilities

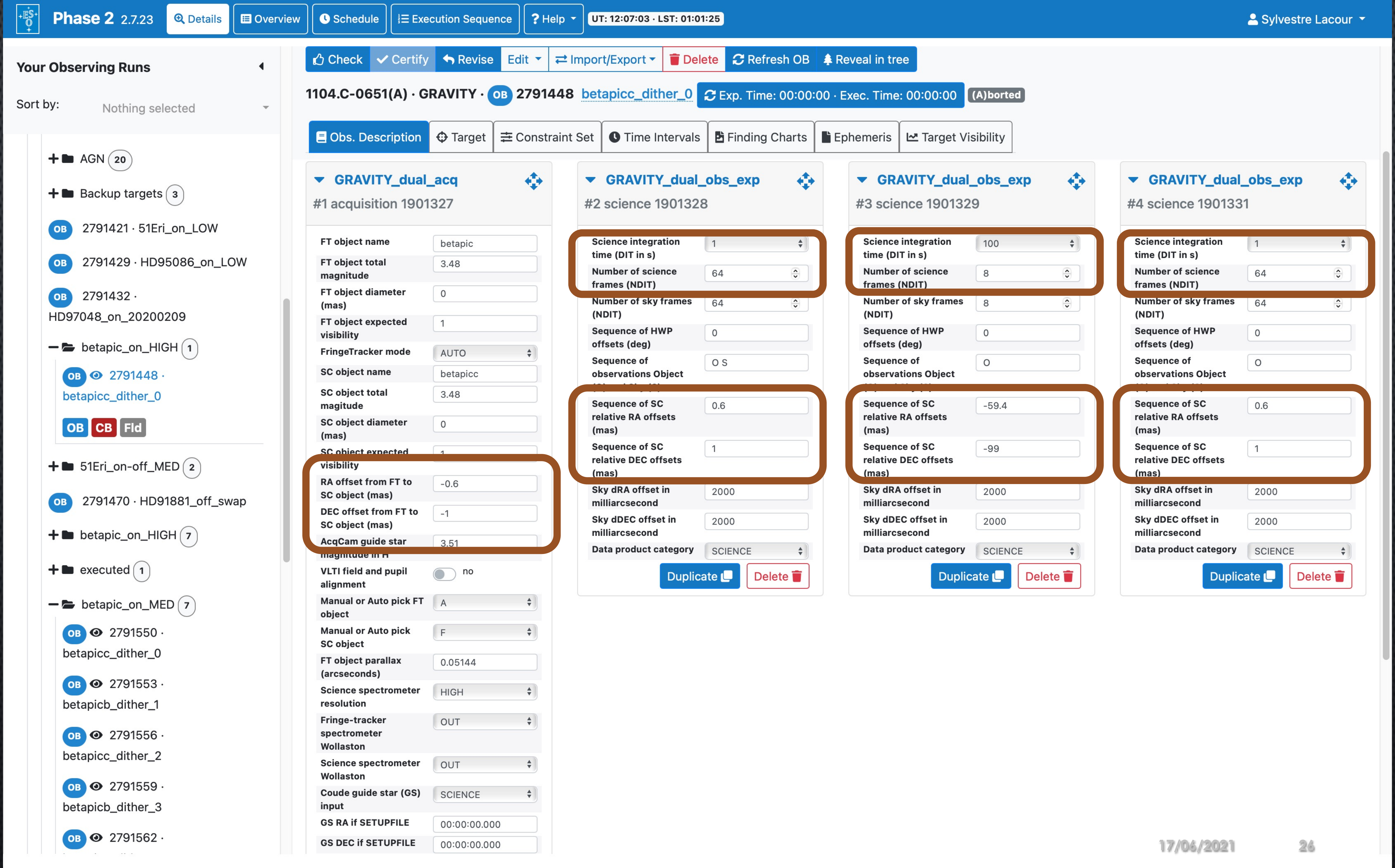
$$VISDATA_{\text{phasedFT}} = VISDATA \times exp\left(i\left[PHASE\_REF - PHASE\_MET\_TELFC - \frac{2\pi}{\lambda}OPD\_DISP\right]\right)$$

&

$$VISDATA_{\text{phasedXY}} = VISDATA_{\text{phasedFT}} \times exp\left(i\frac{2\pi}{\lambda}(UCOORD \times X + VCOORD \times Y)\right)$$



Phase 2 2.7.23
Details
Overview
Schedule
Execution Sequence
Help
UT: 12:07:03 · LST: 01:01:25
Sylvestre Lacour
Your Observing Runs
Sort by:
Nothing selected
AGN 20
Backup targets 3
OB 2791421 · 51Eri_on_LOW
OB 2791429 · HD95086_on_LOW
OB 2791432 · HD97048_on_20200209
betapic_on_HIGH 1
OB 2791448 · betapicc_dither_0
OB CB Fld
51Eri_on-off_MED 2
OB 2791470 · HD91881_off_swap
betapic_on_HIGH 7
executed 1
betapic_on_MED 7
OB 2791550 · betapicc_dither_0
OB 2791553 · betapicb_dither_1
OB 2791556 · betapicc_dither_2
OB 2791559 · betapicb_dither_3
OB 2791562 ·
Check
Certify
Revise
Edit
Import/Export
Delete
Refresh OB
Reveal in tree
1104.C-0651(A) · GRAVITY · OB 2791448 betapicc_dither_0
Exp. Time: 00:00:00 · Exec. Time: 00:00:00
(A)borted
Obs. Description
Target
Constraint Set
Time Intervals
Finding Charts
Ephemeris
Target Visibility
GRAVITY_dual_acq
#1 acquisition 1901327
FT object name betapic
FT object total magnitude 3.48
FT object diameter (mas) 0
FT object expected visibility 1
FringeTracker mode AUTO
SC object name betapicc
SC object total magitude 3.48
SC object diameter (mas) 0
SC object expected visibility 1
RA offset from FT to SC object (mas) -0.6
DEC offset from FT to SC object (mas) -1
AcqCam guide star magnitude in H 3.51
VLTI field and pupil alignment no
Manual or Auto pick FT object A
Manual or Auto pick SC object F
FT object parallax (arcseconds) 0.05144
Science spectrometer resolution HIGH
Fringe-tracker spectrometer Wollaston OUT
Science spectrometer Wollaston OUT
Coude guide star (GS) input SCIENCE
GS RA if SETUPFILE 00:00:00.000
GS DEC if SETUPFILE 00:00:00.000
GRAVITY_dual_obs_exp
#2 science 1901328
Science integration time (DIT in s) 1
Number of science frames (NDIT) 64
Number of sky frames (NDIT) 64
Sequence of HWP offsets (deg) 0
Sequence of observations Object (O) and Sky (S) O S
Sequence of SC relative RA offsets (mas) 0.6
Sequence of SC relative DEC offsets (mas) 1
Sky dRA offset in milliarcsecond 2000
Sky dDEC offset in milliarcsecond 2000
Data product category SCIENCE
Duplicate
Delete
GRAVITY_dual_obs_exp
#3 science 1901329
Science integration time (DIT in s) 100
Number of science frames (NDIT) 8
Number of sky frames (NDIT) 8
Sequence of HWP offsets (deg) 0
Sequence of observations Object (O) and Sky (S) O
Sequence of SC relative RA offsets (mas) -59.4
Sequence of SC relative DEC offsets (mas) -99
Sky dRA offset in milliarcsecond 2000
Sky dDEC offset in milliarcsecond 2000
Data product category SCIENCE
Duplicate
Delete
GRAVITY_dual_obs_exp
#4 science 1901331
Science integration time (DIT in s) 1
Number of science frames (NDIT) 64
Number of sky frames (NDIT) 64
Sequence of HWP offsets (deg) 0
Sequence of observations Object (O) and Sky (S) O
Sequence of SC relative RA offsets (mas) 0.6
Sequence of SC relative DEC offsets (mas) 1
Sky dRA offset in milliarcsecond 2000
Sky dDEC offset in milliarcsecond 2000
Data product category SCIENCE
Duplicate
Delete


Phase 2 2.7.23
Details
Overview
Schedule
Execution Sequence
Help
UT: 12:07:03 · LST: 01:01:25
Sylvestre Lacour
Your Observing Runs
Sort by:
Nothing selected
AGN 20
Backup targets 3
OB 2791421 · 51Eri_on_LOW
OB 2791429 · HD95086_on_LOW
OB 2791432 · HD97048_on_20200209
betapic_on_HIGH 1
OB 2791448 · betapicc_dither_0
OB CB Fld
51Eri_on-off_MED 2
OB 2791470 · HD91881_off_swap
betapic_on_HIGH 7
executed 1
betapic_on_MED 7
OB 2791550 · betapicc_dither_0
OB 2791553 · betapicb_dither_1
OB 2791556 · betapicc_dither_2
OB 2791559 · betapicb_dither_3
OB 2791562 ·
Check
Certify
Revise
Edit
Import/Export
Delete
Refresh OB
Reveal in tree
1104.C-0651(A) · GRAVITY · OB 2791448 betapicc_dither_0
Exp. Time: 00:00:00 · Exec. Time: 00:00:00
(A)borted
Obs. Description
Target
Constraint Set
Time Intervals
Finding Charts
Ephemeris
Target Visibility
GRAVITY_dual_acq
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FT object expected visibility 1
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VLTI field and pupil alignment no
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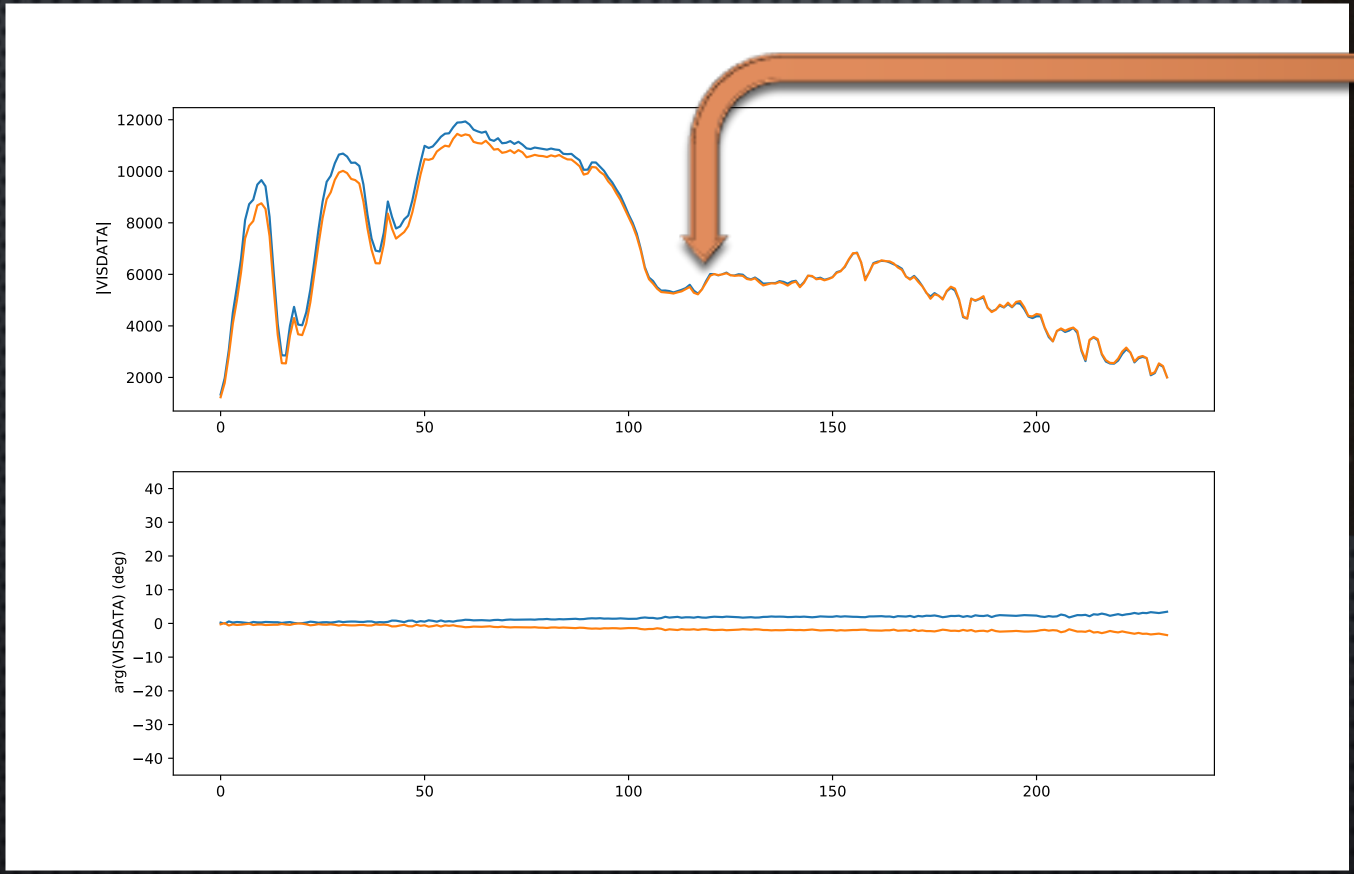
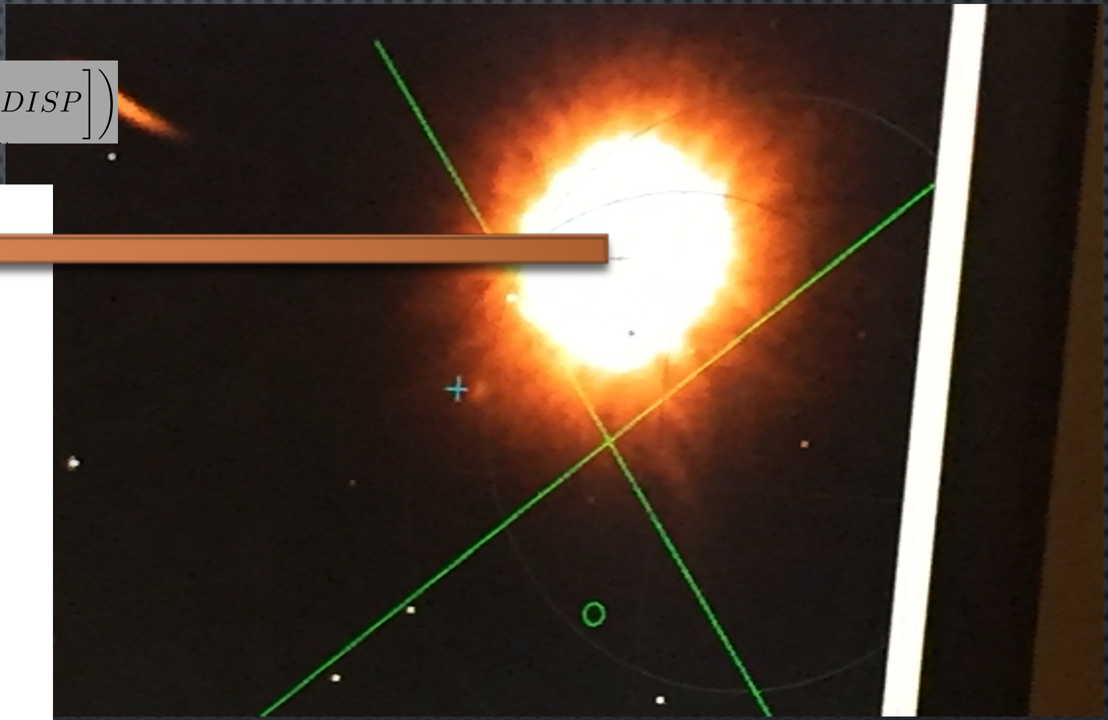
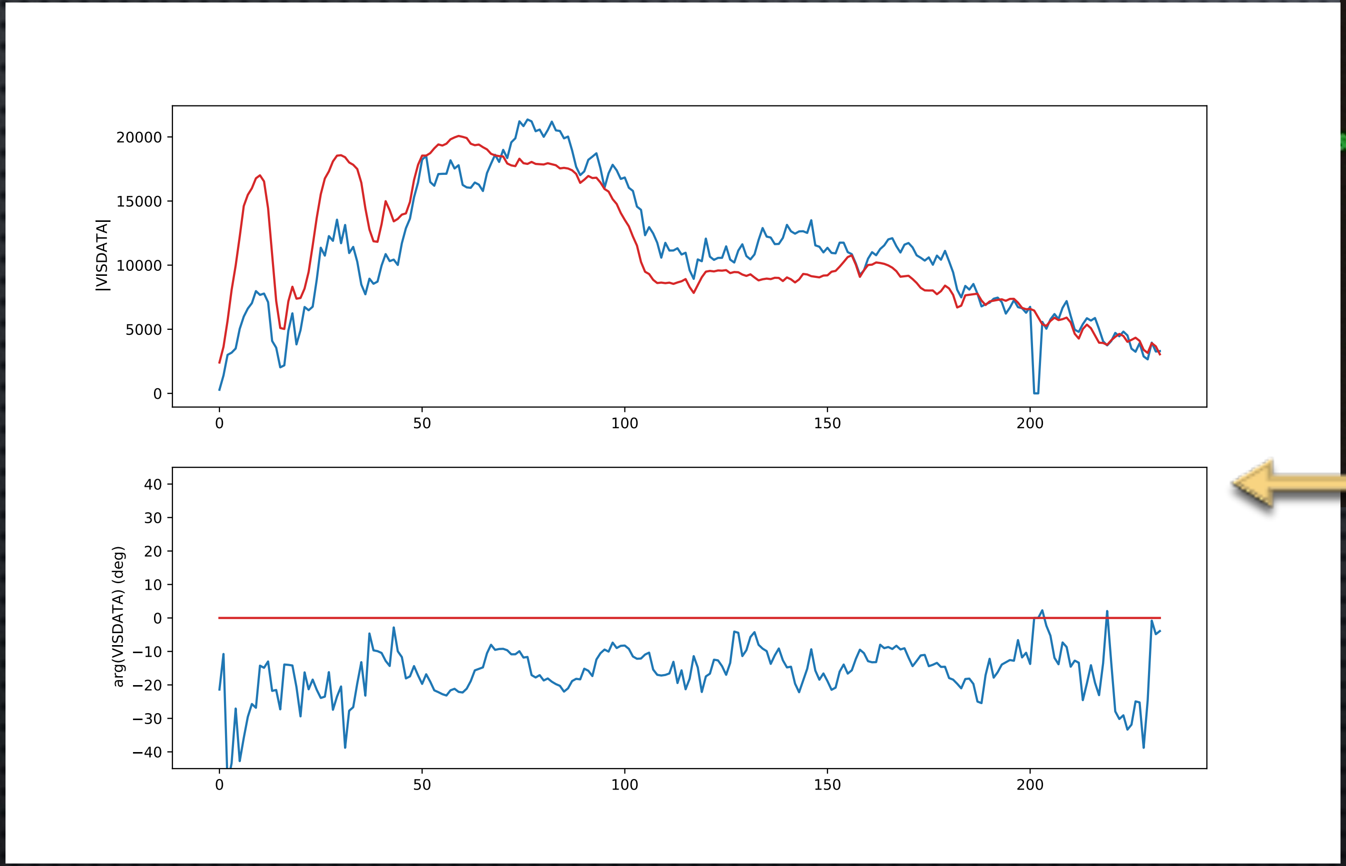
Science spectrometer Wollaston OUT
Coude guide star (GS) input SCIENCE
GS RA if SETUPFILE 00:00:00.000
GS DEC if SETUPFILE 00:00:00.000
GRAVITY_dual_obs_exp
#2 science 1901328
Science integration time (DIT in s) 1
Number of science frames (NDIT) 64
Number of sky frames (NDIT) 64
Sequence of HWP offsets (deg) 0
Sequence of observations Object O S
Sequence of SC relative RA offsets (mas) 0.6
Sequence of SC relative DEC offsets (mas) 1
Sky dRA offset in milliarcsecond 2000
Sky dDEC offset in milliarcsecond 2000
Data product category SCIENCE
Duplicate
Delete
GRAVITY_dual_obs_exp
#3 science 1901329
Science integration time (DIT in s) 100
Number of science frames (NDIT) 8
Number of sky frames (NDIT) 8
Sequence of HWP offsets (deg) 0
Sequence of observations Object O
Sequence of SC relative RA offsets (mas) -59.4
Sequence of SC relative DEC offsets (mas) -99
Sky dRA offset in milliarcsecond 2000
Sky dDEC offset in milliarcsecond 2000
Data product category SCIENCE
Duplicate
Delete
GRAVITY_dual_obs_exp
#4 science 1901331
Science integration time (DIT in s) 1
Number of science frames (NDIT) 64
Number of sky frames (NDIT) 64
Sequence of HWP offsets (deg) 0
Sequence of observations Object O
Sequence of SC relative RA offsets (mas) 0.6
Sequence of SC relative DEC offsets (mas) 1
Sky dRA offset in milliarcsecond 2000
Sky dDEC offset in milliarcsecond 2000
Data product category SCIENCE
Duplicate
Delete

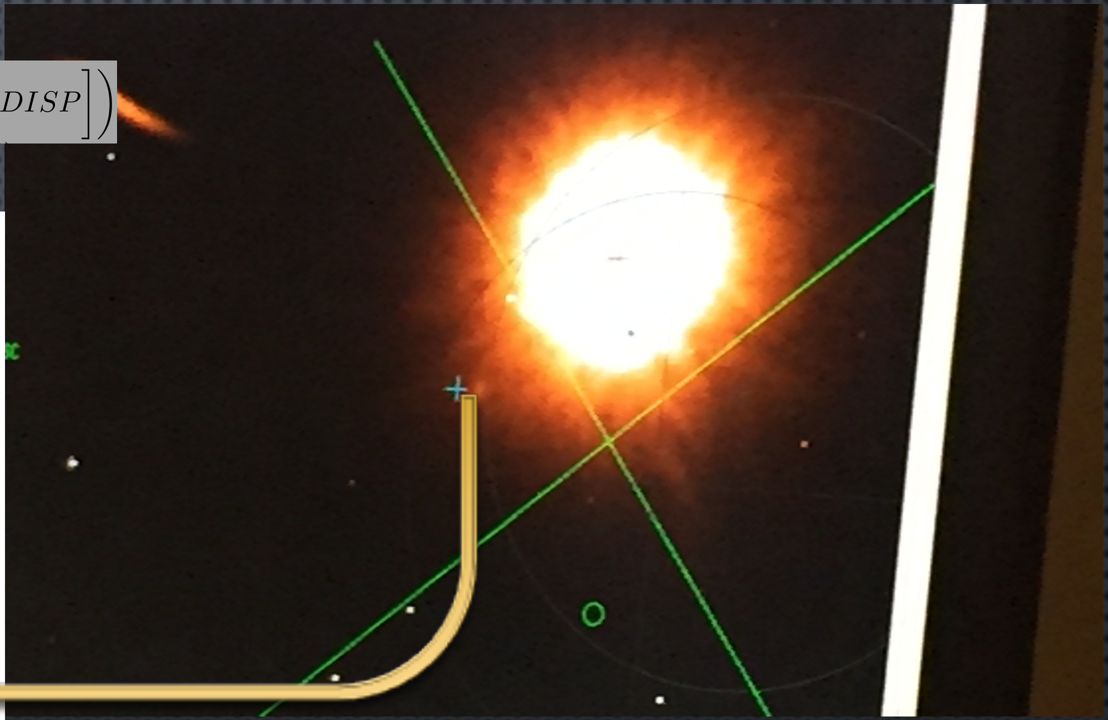
$$VISDATA_{\text{phasedFT}} = VISDATA \times exp\left(i\left[PHASE\_REF - PHASE\_MET\_TELFC - \frac{2\pi}{\lambda}OPD\_DISP\right]\right)$$

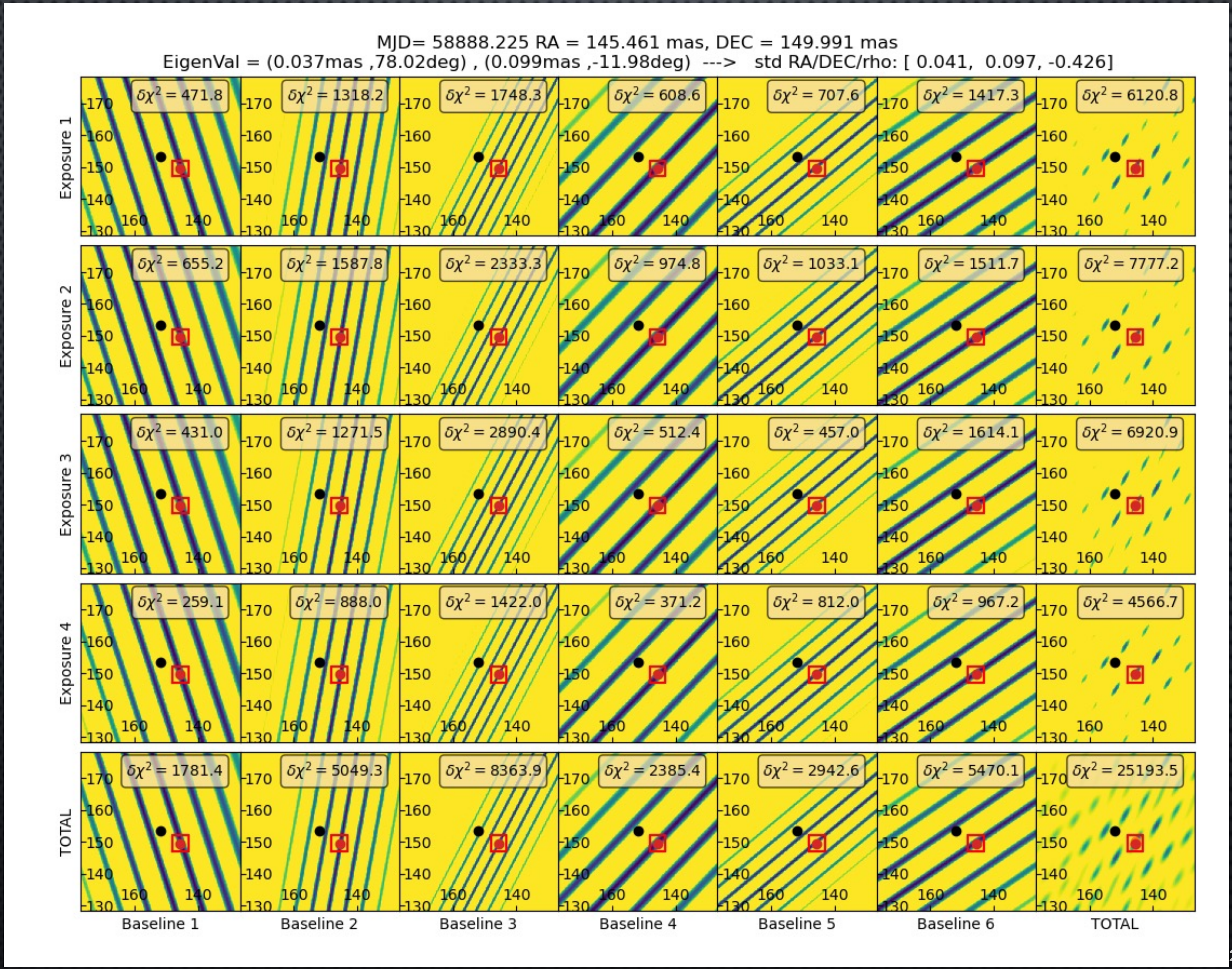




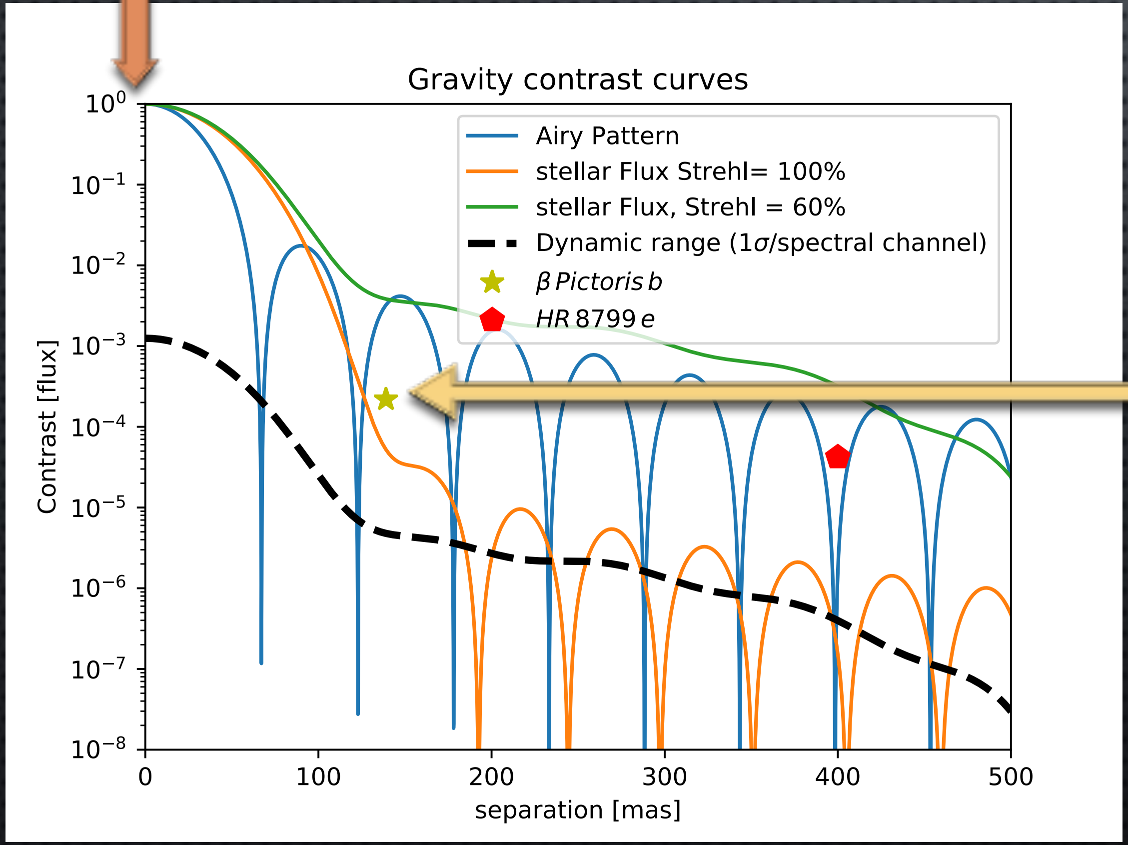
$$VISDATA_{\text{phasedFT}} = VISDATA \times exp\left(i\left[PHASE\_REF - PHASE\_MET\_TELFC - \frac{2\pi}{\lambda}OPD\_DISP\right]\right)$$

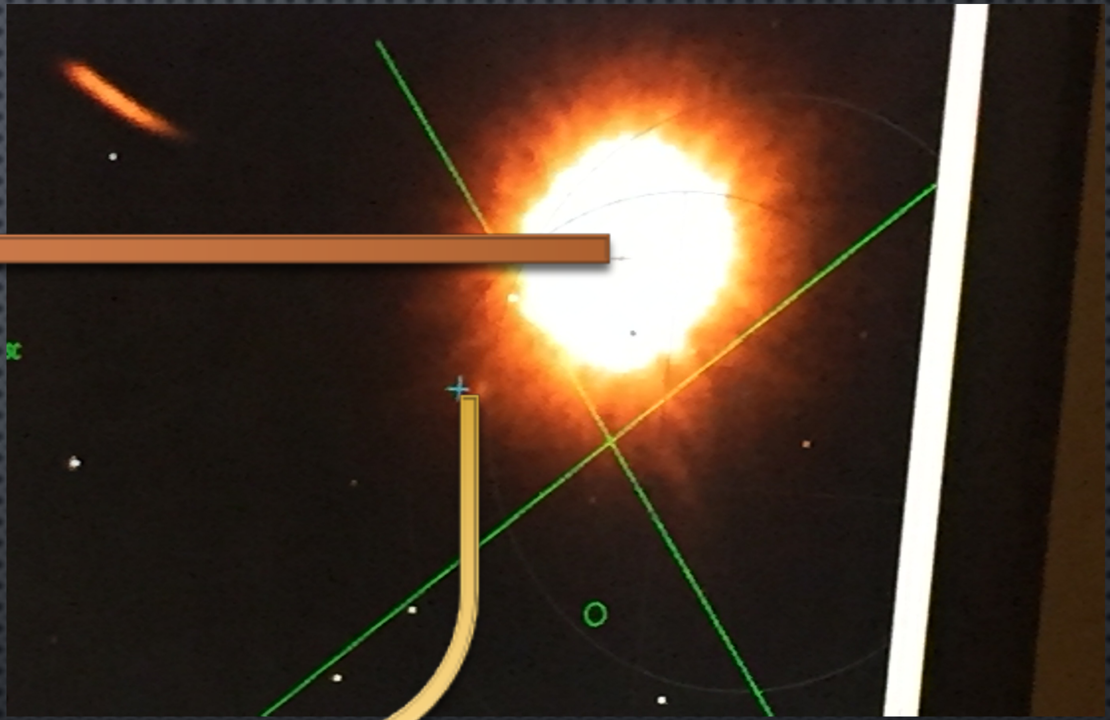


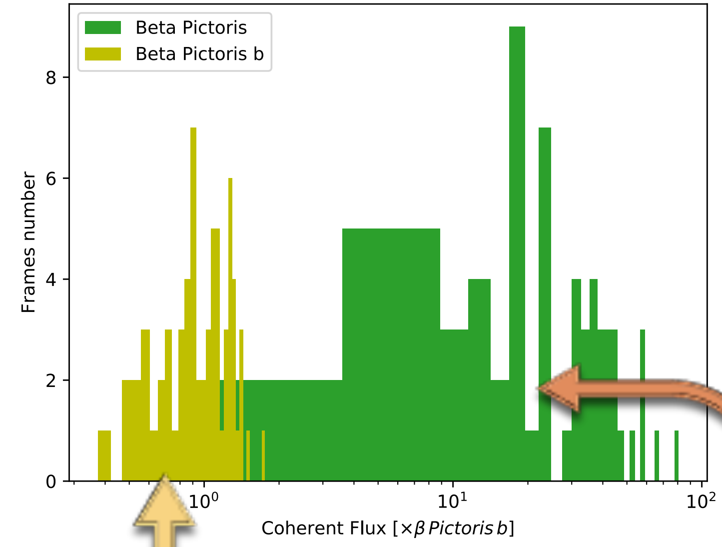


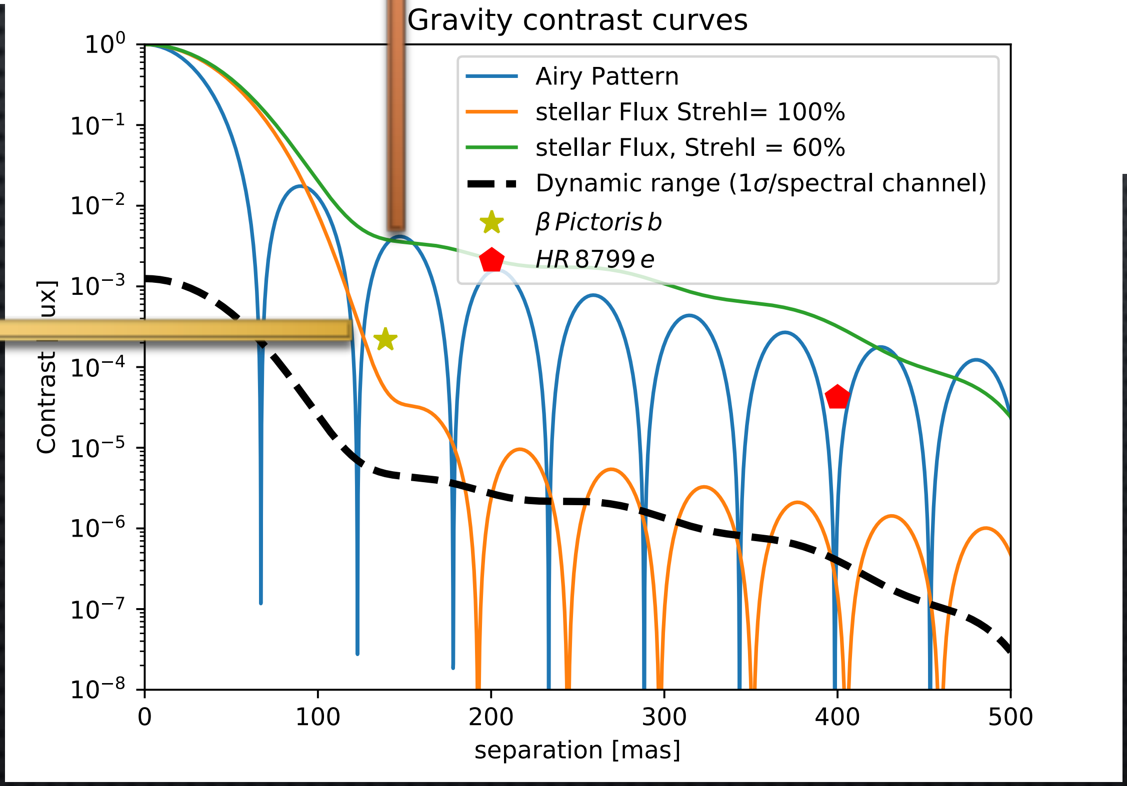


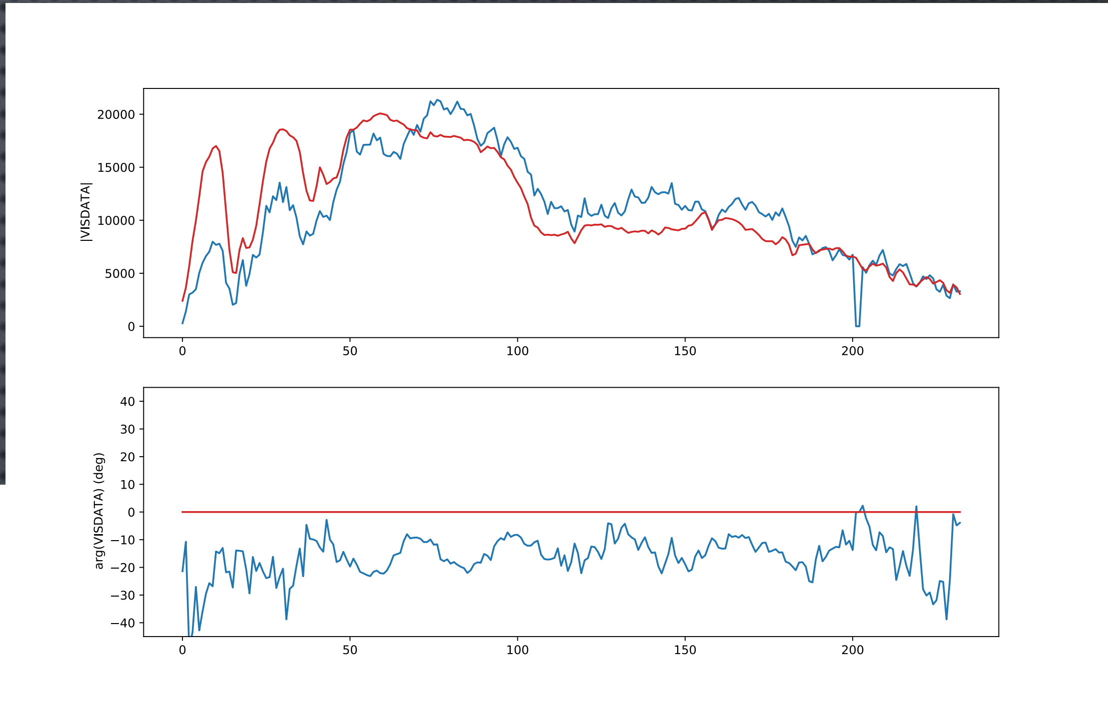
MJD= 58888.225 RA = 145.461 mas, DEC = 149.991 mas
EigenVal = (0.037mas ,78.02deg) , (0.099mas ,-11.98deg) ---> std RA/DEC/rho: [0.041, 0.097, -0.426]
Exposure 1
$\delta\chi^2 = 471.8$
$\delta\chi^2 = 1318.2$
$\delta\chi^2 = 1748.3$
$\delta\chi^2 = 608.6$
$\delta\chi^2 = 707.6$
$\delta\chi^2 = 1417.3$
$\delta\chi^2 = 6120.8$
Exposure 2
$\delta\chi^2 = 655.2$
$\delta\chi^2 = 1587.8$
$\delta\chi^2 = 2333.3$
$\delta\chi^2 = 974.8$
$\delta\chi^2 = 1033.1$
$\delta\chi^2 = 1511.7$
$\delta\chi^2 = 7777.2$
Exposure 3
$\delta\chi^2 = 431.0$
$\delta\chi^2 = 1271.5$
$\delta\chi^2 = 2890.4$
$\delta\chi^2 = 512.4$
$\delta\chi^2 = 457.0$
$\delta\chi^2 = 1614.1$
$\delta\chi^2 = 6920.9$
Exposure 4
$\delta\chi^2 = 259.1$
$\delta\chi^2 = 888.0$
$\delta\chi^2 = 1422.0$
$\delta\chi^2 = 371.2$
$\delta\chi^2 = 812.0$
$\delta\chi^2 = 967.2$
$\delta\chi^2 = 4566.7$
TOTAL
$\delta\chi^2 = 1781.4$
$\delta\chi^2 = 5049.3$
$\delta\chi^2 = 8363.9$
$\delta\chi^2 = 2385.4$
$\delta\chi^2 = 2942.6$
$\delta\chi^2 = 5470.1$
$\delta\chi^2 = 25193.5$
Baseline 1
Baseline 2
Baseline 3
Baseline 4
Baseline 5
Baseline 6
TOTAL

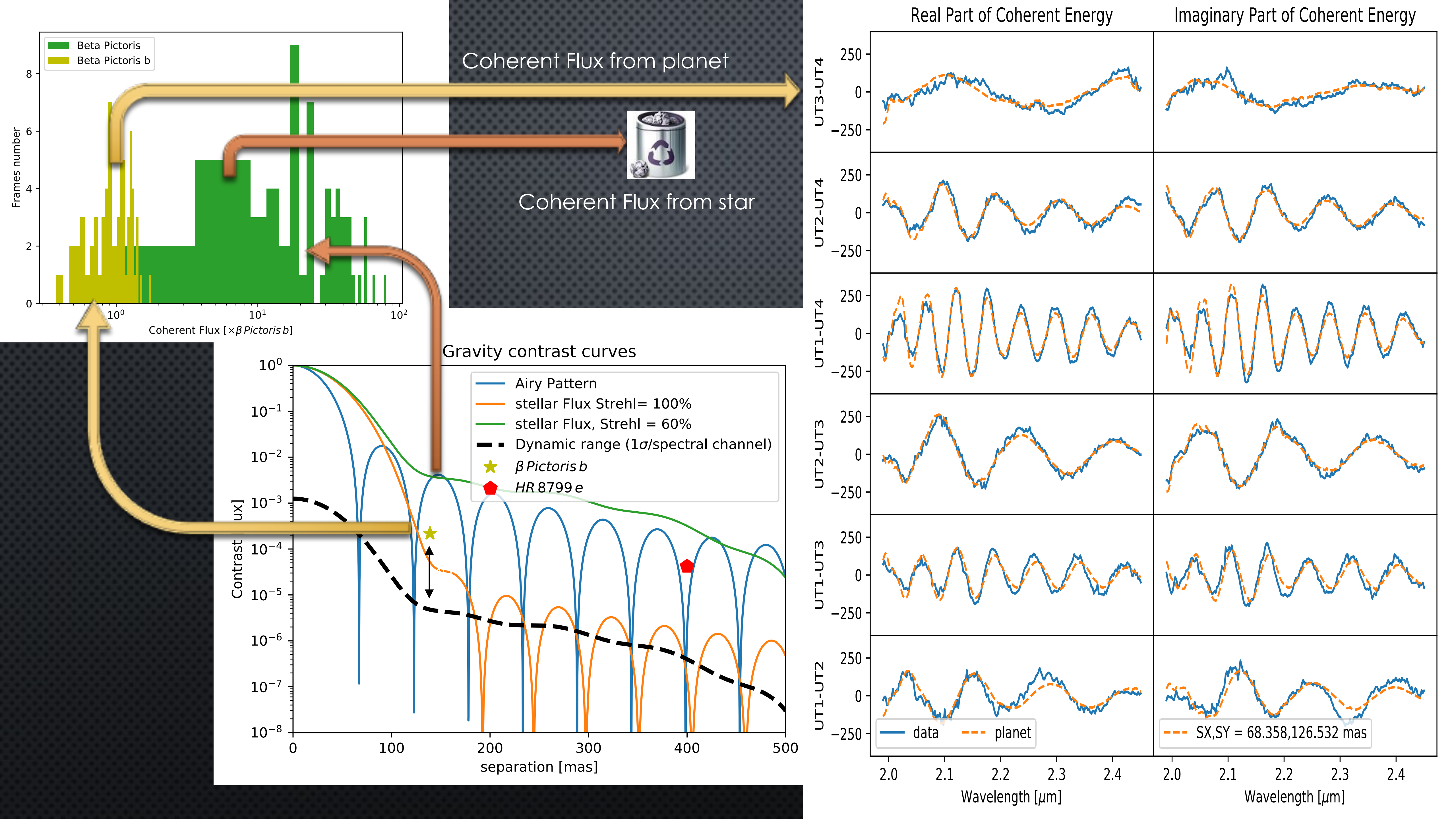

Gravity contrast curves
Airy Pattern
stellar Flux Strehl= 100%
stellar Flux, Strehl = 60%
Dynamic range (1σ/spectral channel)
β Pictoris b
HR 8799 e
Contrast [flux]
separation [mas]
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
100
200
300
400
500




Beta Pictoris
Beta Pictoris b
Frames number
Coherent Flux [×β Pictoris b]
0
2
4
6
8
10^0
10^1
10^2

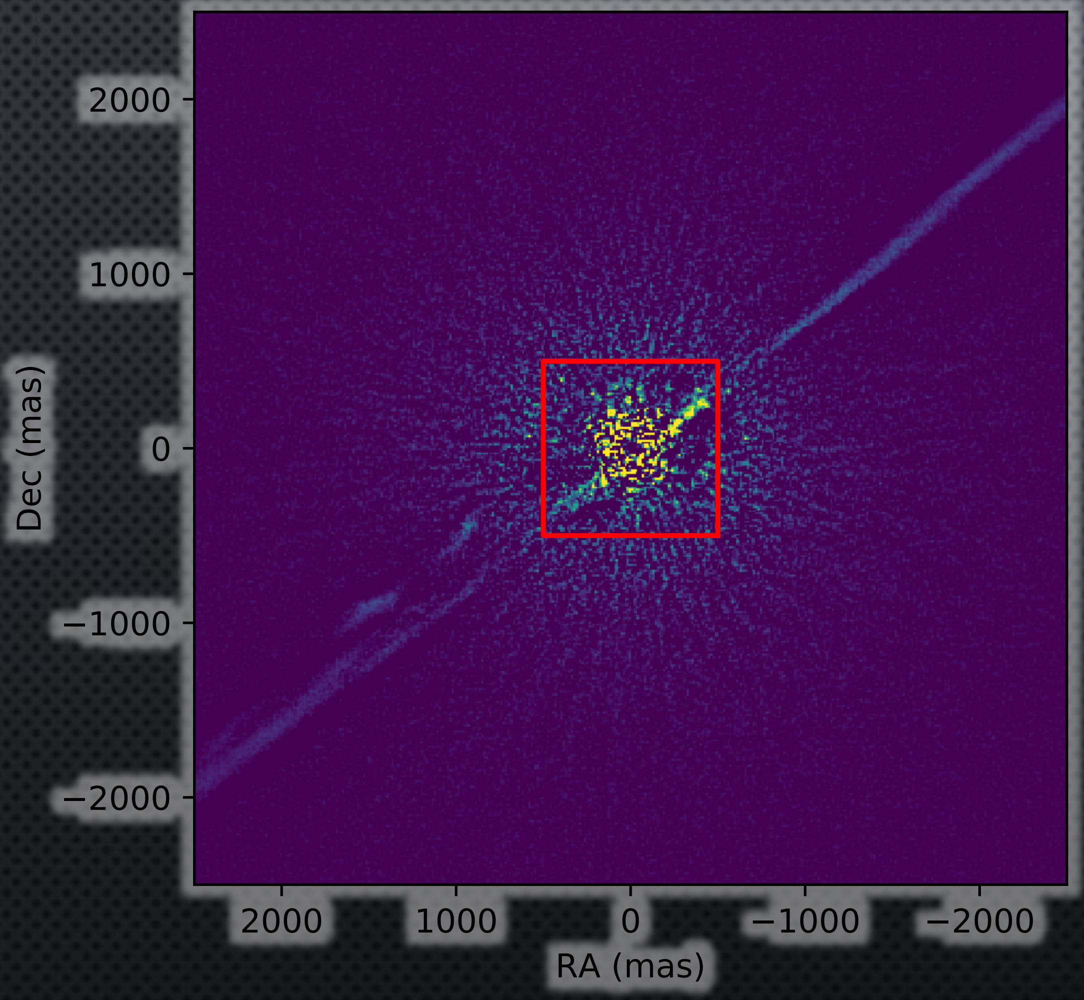

Gravity contrast curves
Airy Pattern
stellar Flux Strehl= 100%
stellar Flux, Strehl = 60%
Dynamic range (1σ/spectral channel)
β Pictoris b
HR 8799 e
Contrast [flux]
separation [mas]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
0
100
200
300
400
500

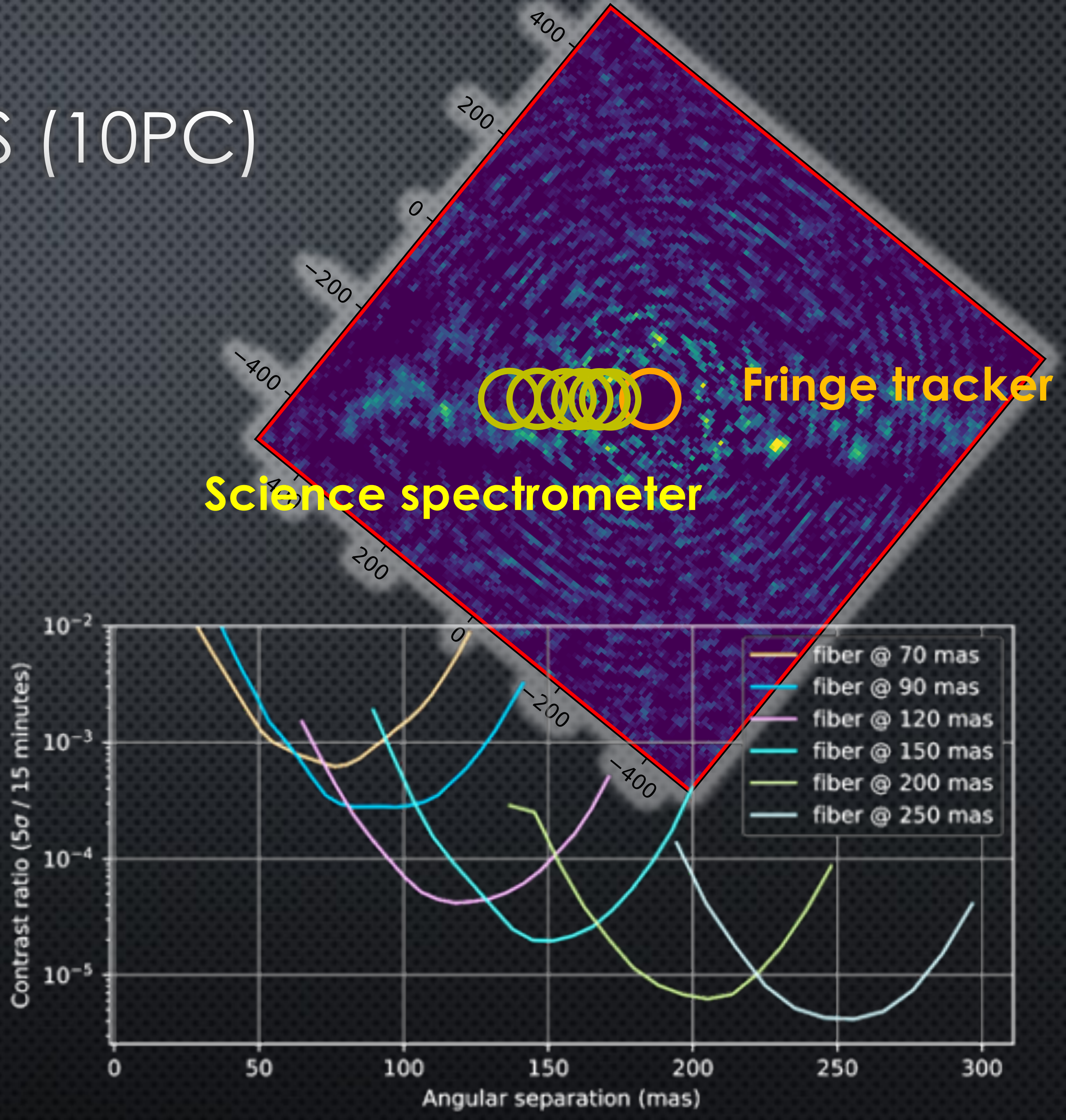

|VISDATA|
0
5000
10000
15000
20000
0
50
100
150
200
arg(VISDATA) (deg)
-40
-30
-20
-10
0
10
20
30
40
0
50
100
150
200



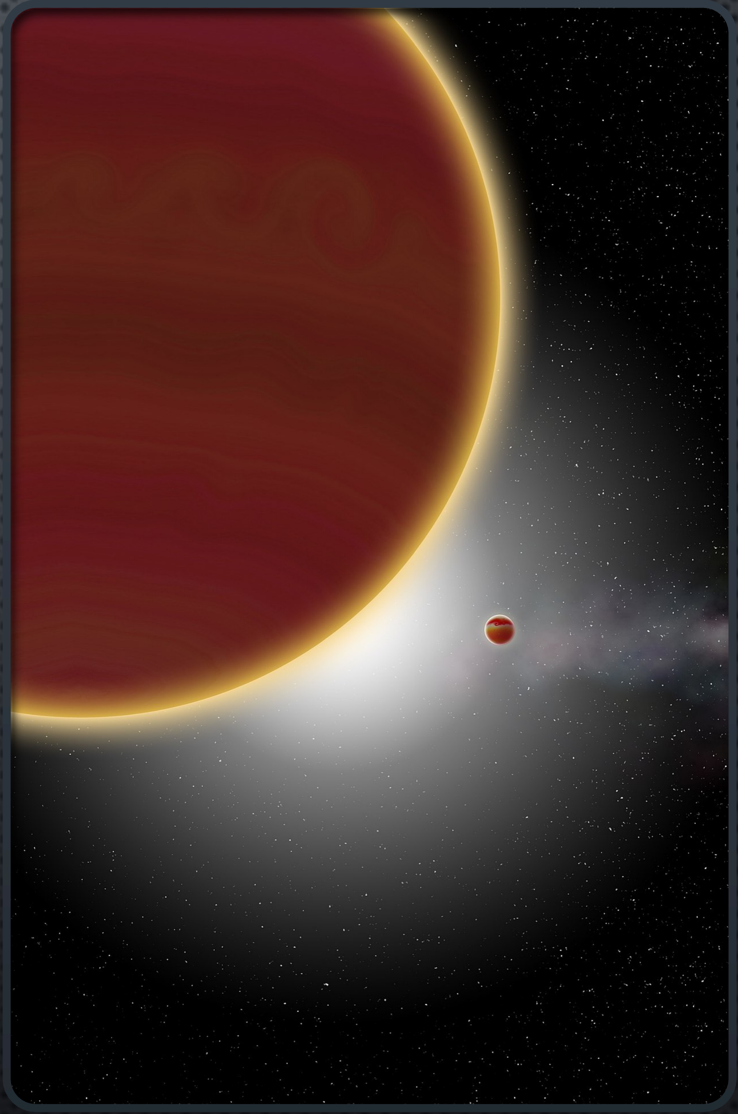
Beta Pictoris
Beta Pictoris b
Frames number
Coherent Flux [×β Pictoris b]
Coherent Flux from planet
Coherent Flux from star
Gravity contrast curves
Airy Pattern
stellar Flux Strehl= 100%
stellar Flux, Strehl = 60%
Dynamic range (1σ/spectral channel)
β Pictoris b
HR 8799 e
Contrast [flux]
separation [mas]
Real Part of Coherent Energy
Imaginary Part of Coherent Energy
UT3-UT4
UT2-UT4
UT1-UT4
UT2-UT3
UT1-UT3
UT1-UT2
data
planet
SX,SY = 68.358,126.532 mas
Wavelength [μm]

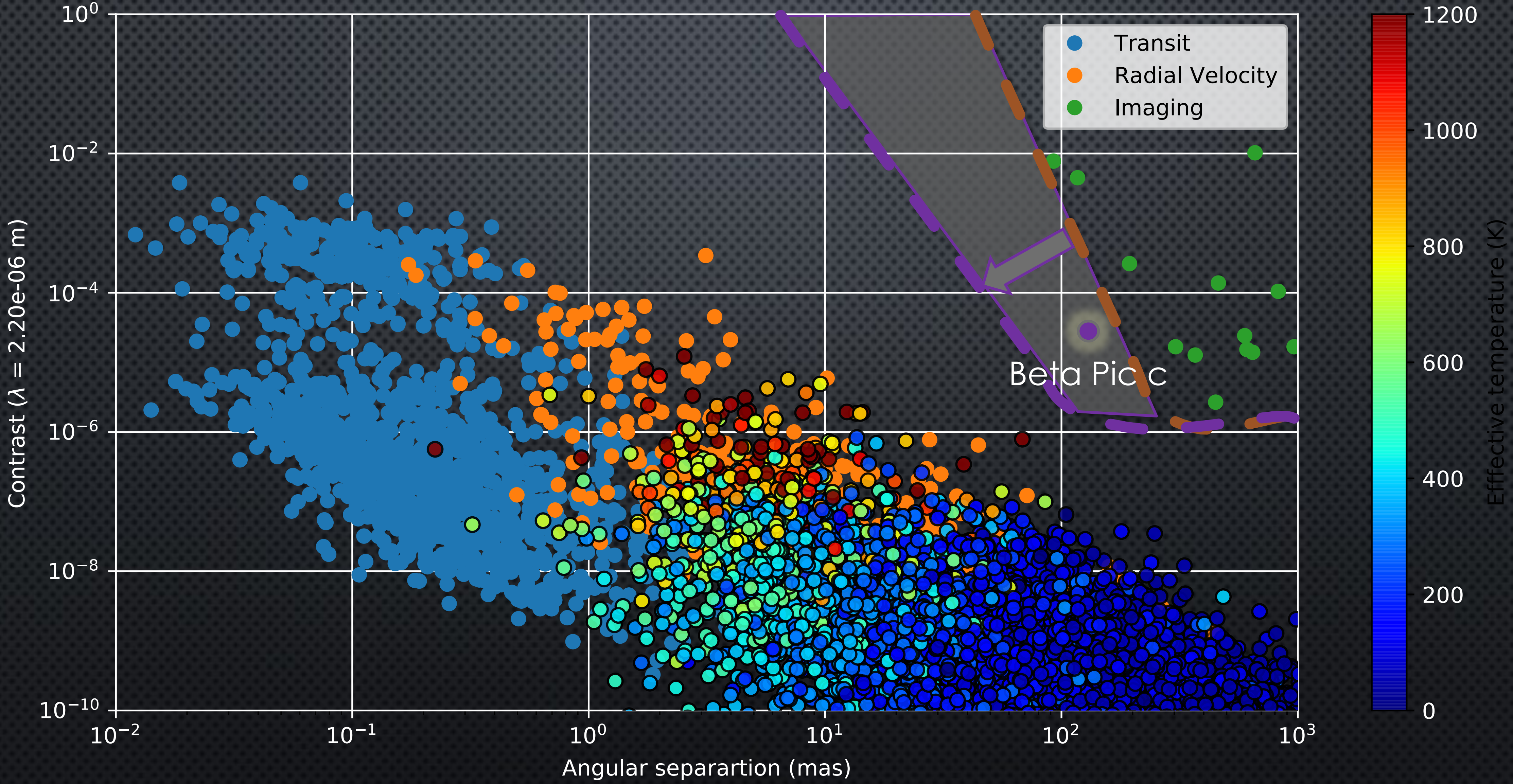
AU MIC OBSERVATIONS (10PC)



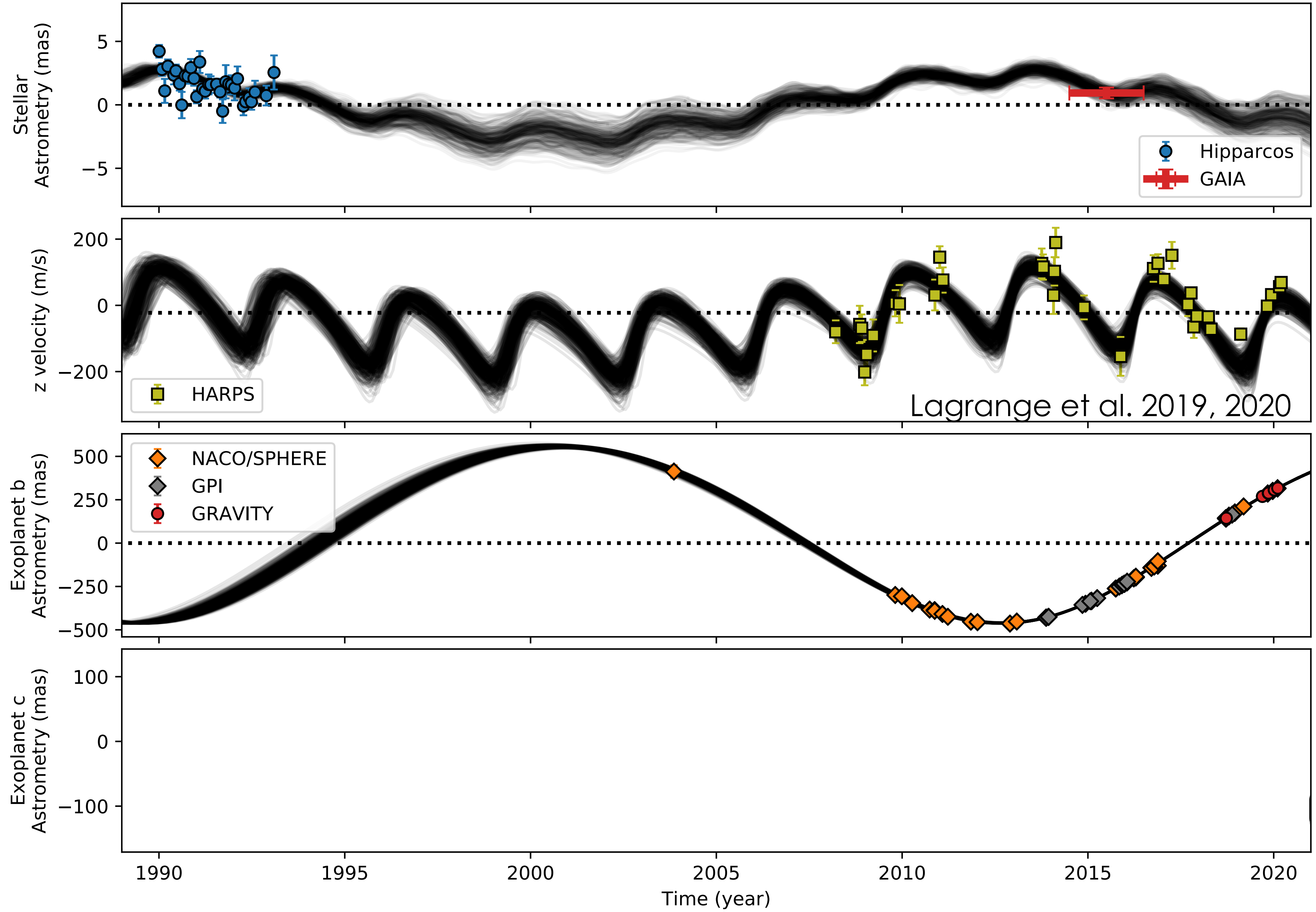


RESULTS FROM OPTICAL INTERFEROMETRY



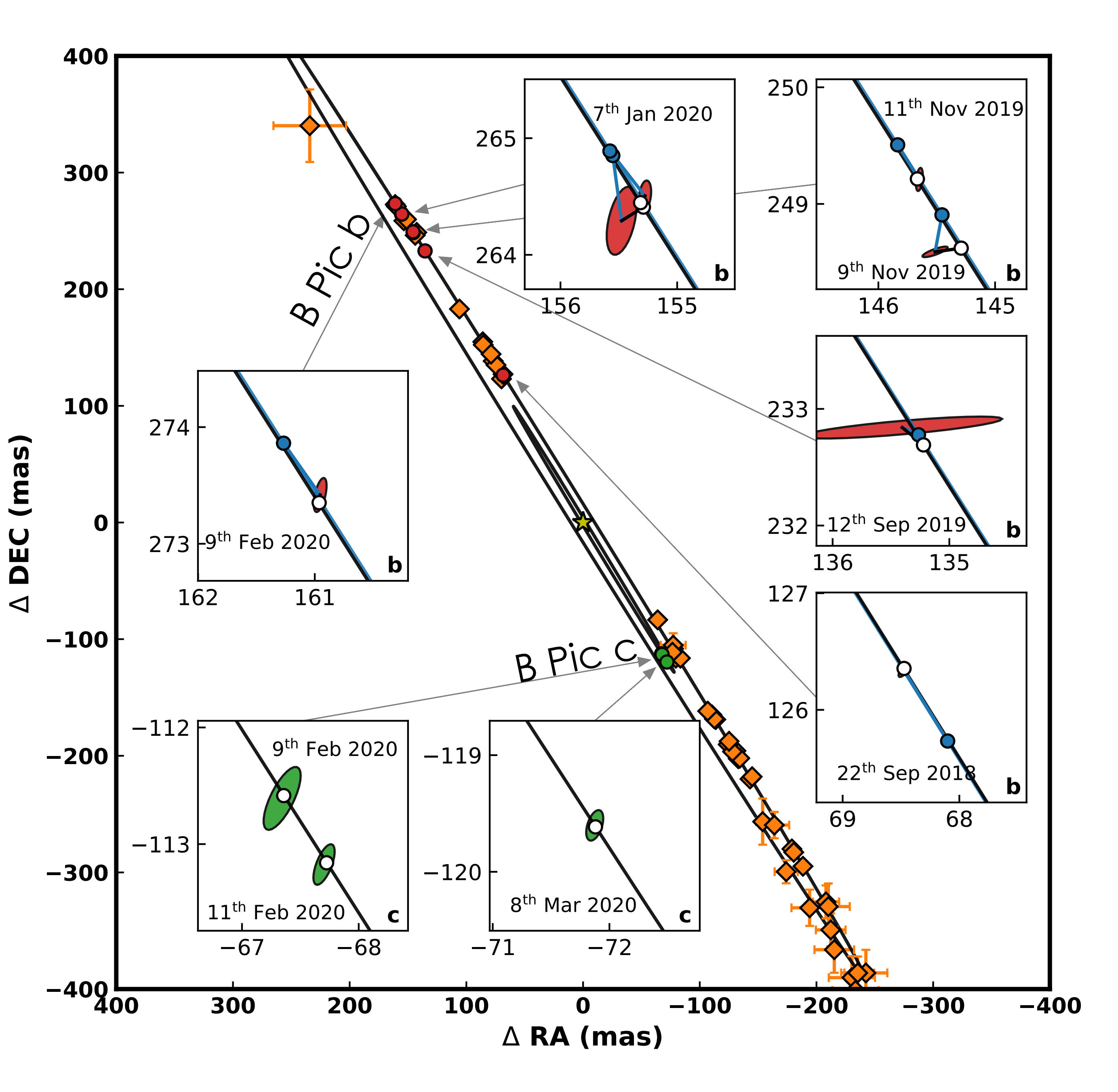

Transit
Radial Velocity
Imaging
Beta Pic c
Contrast (λ = 2.20e-06 m)
Angular separartion (mas)
Effective temperature (K)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1200
1000
800
600
400
200
0

Beta Pictoris planets

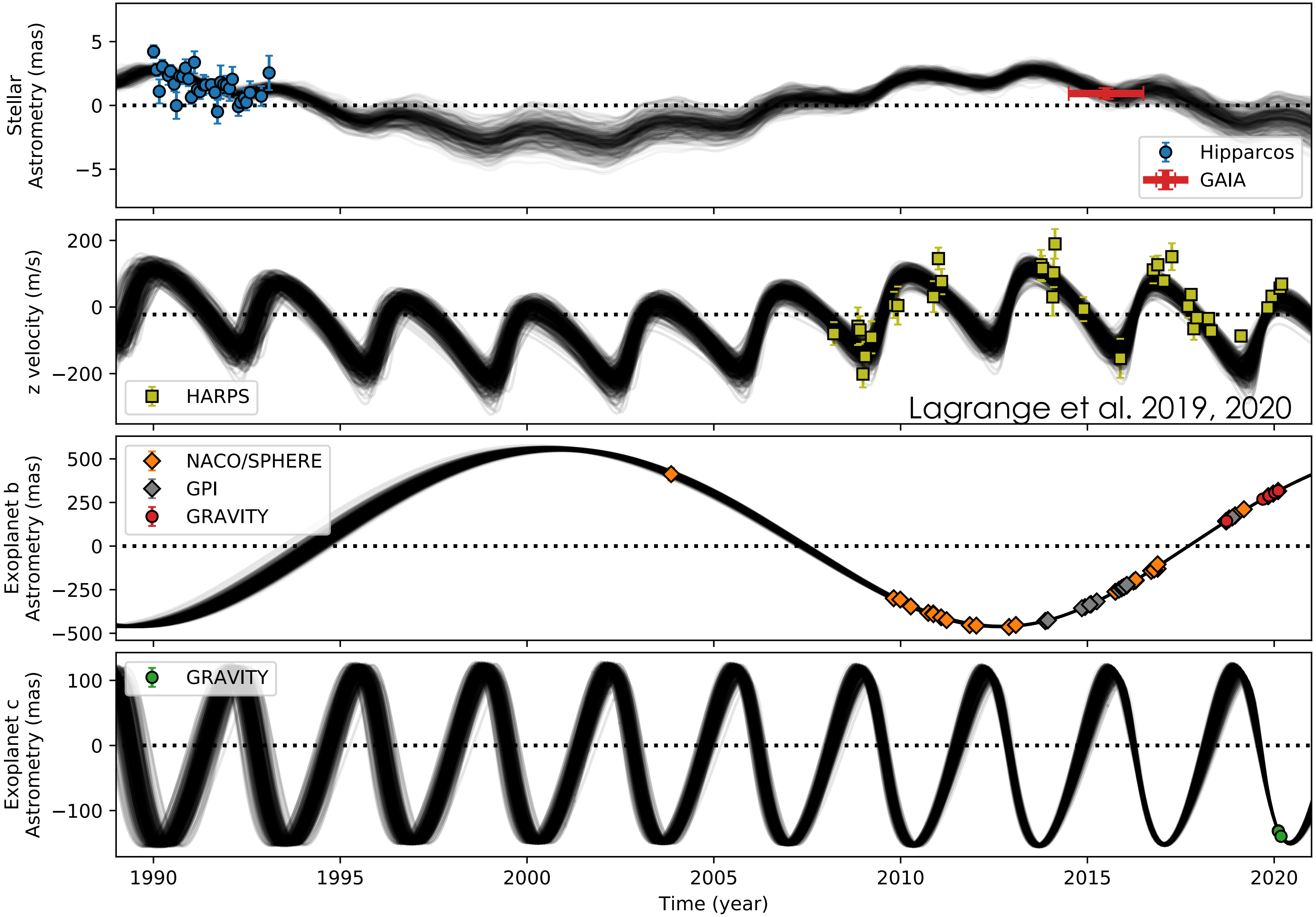


BETA PICTORIS B & C

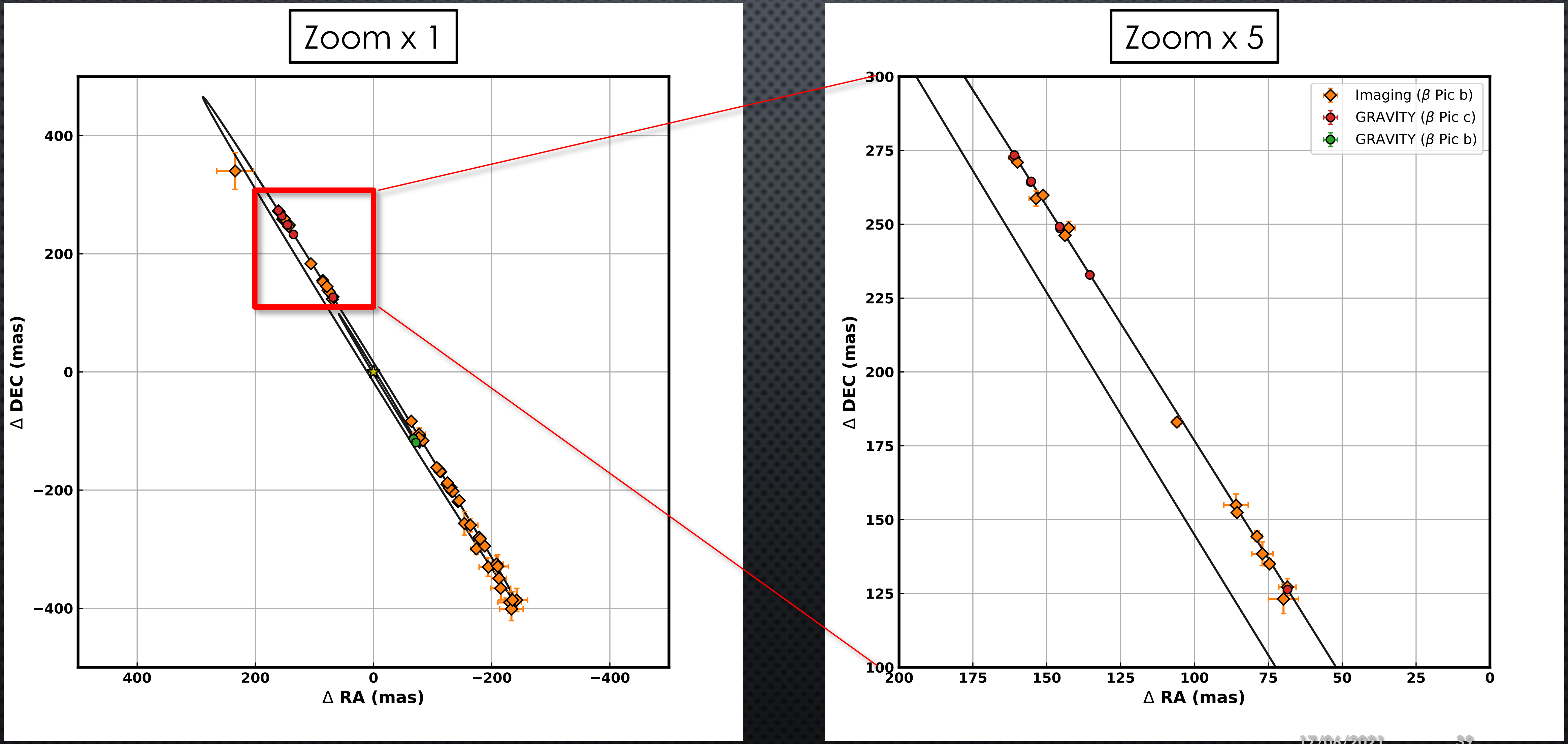
Nowak et al. (2020)
Lagrange et al. (2020)
→ Press release tomorrow



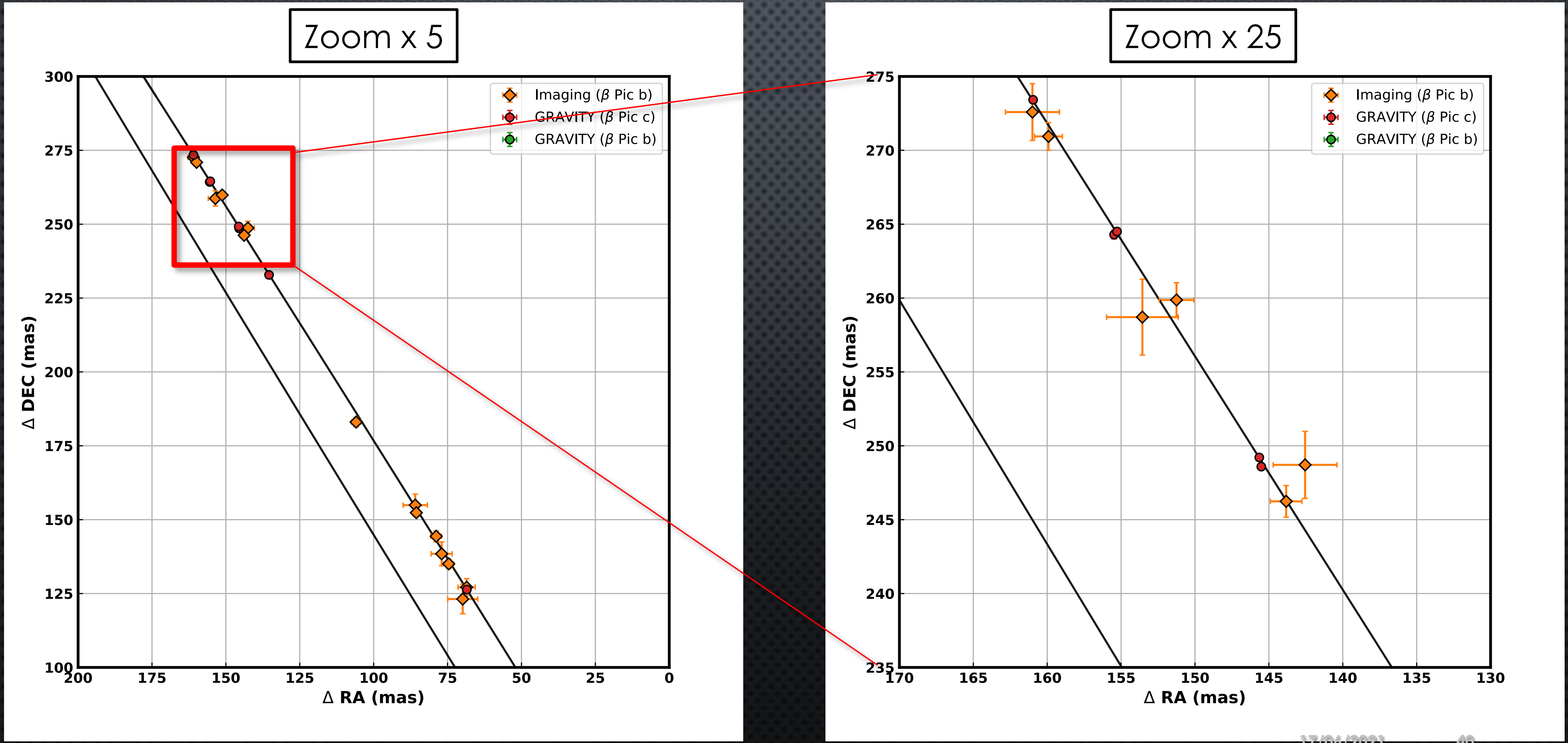
Beta Pictoris planets



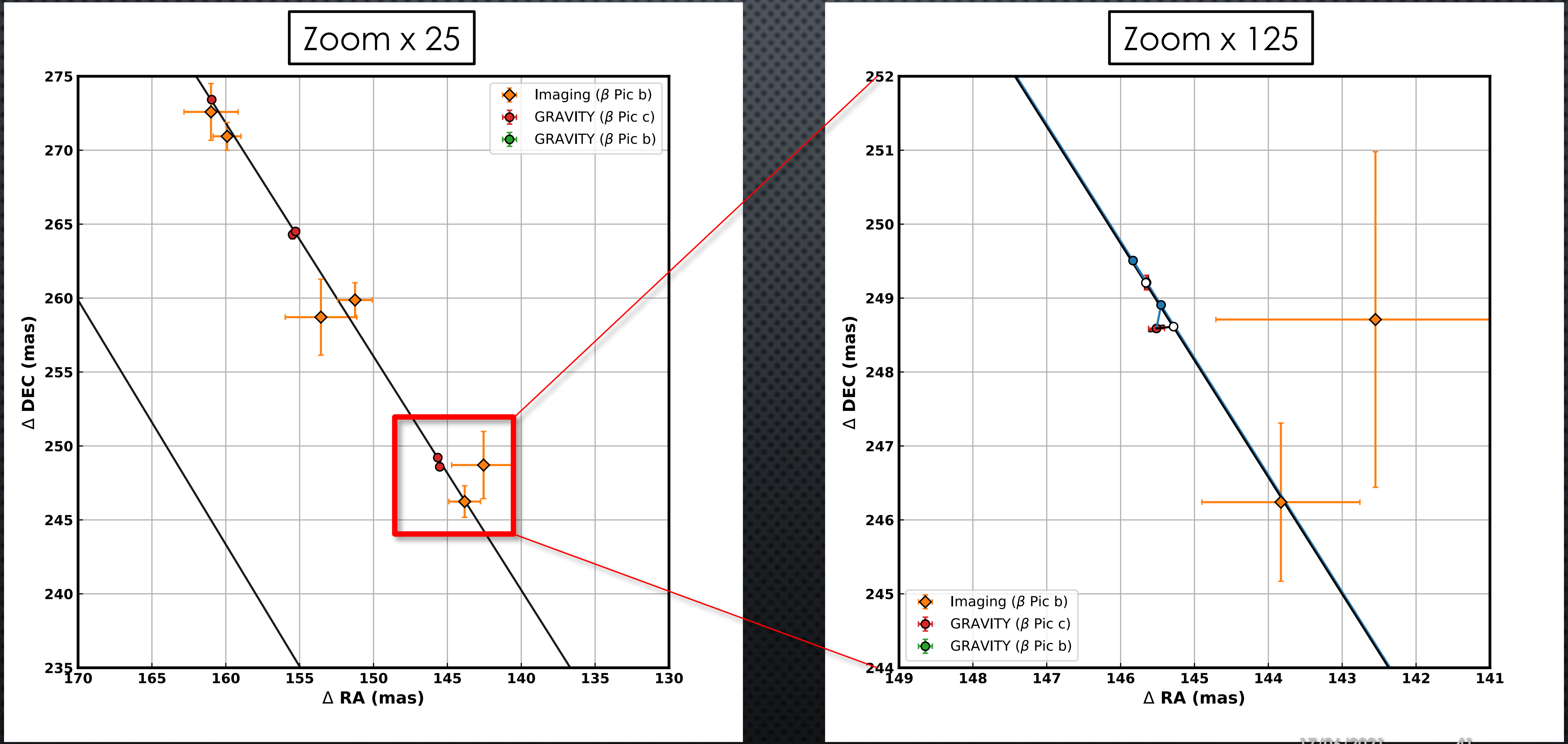
BETA PICTORIS B & C



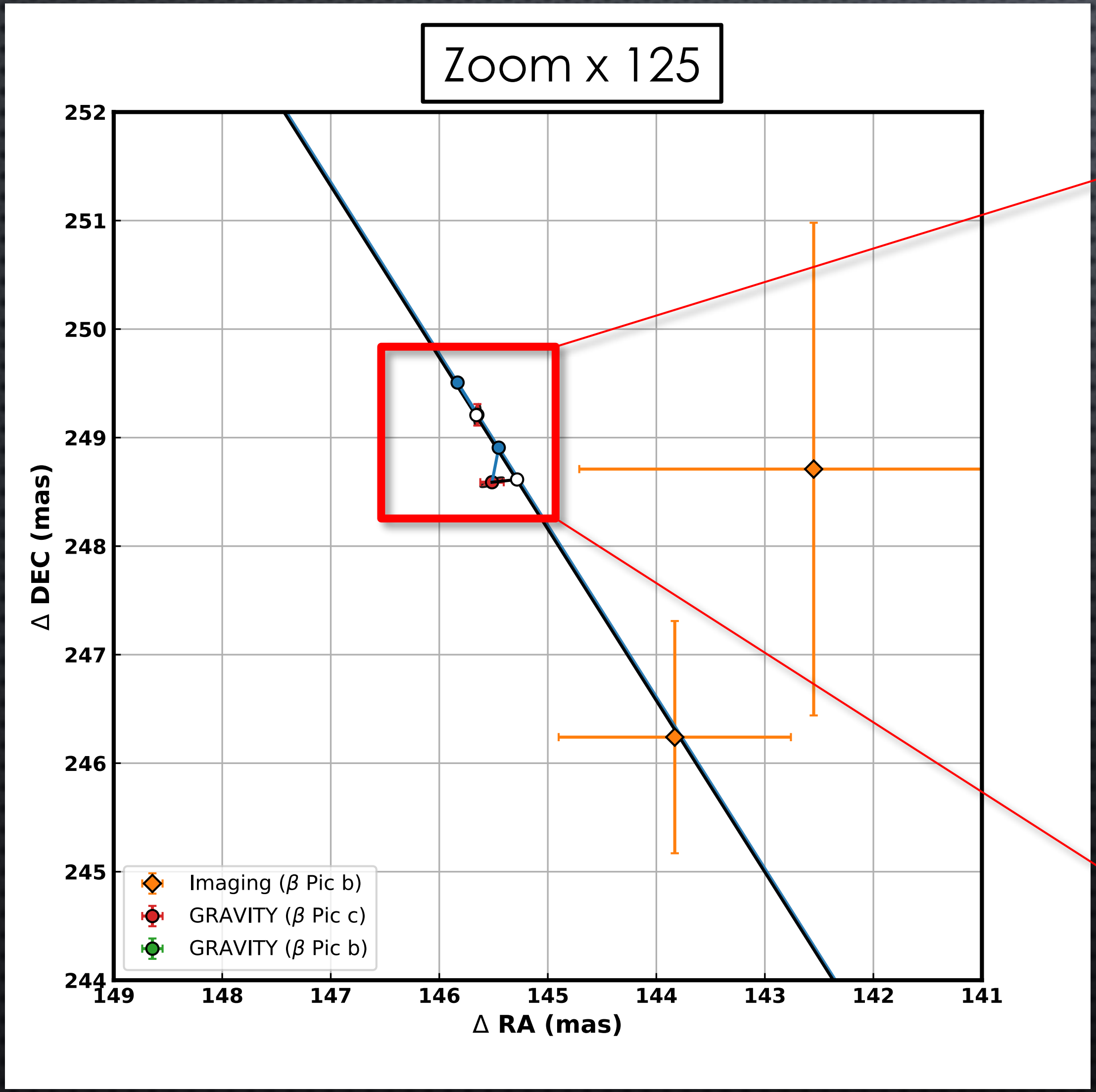
BETA PICTORIS B & C

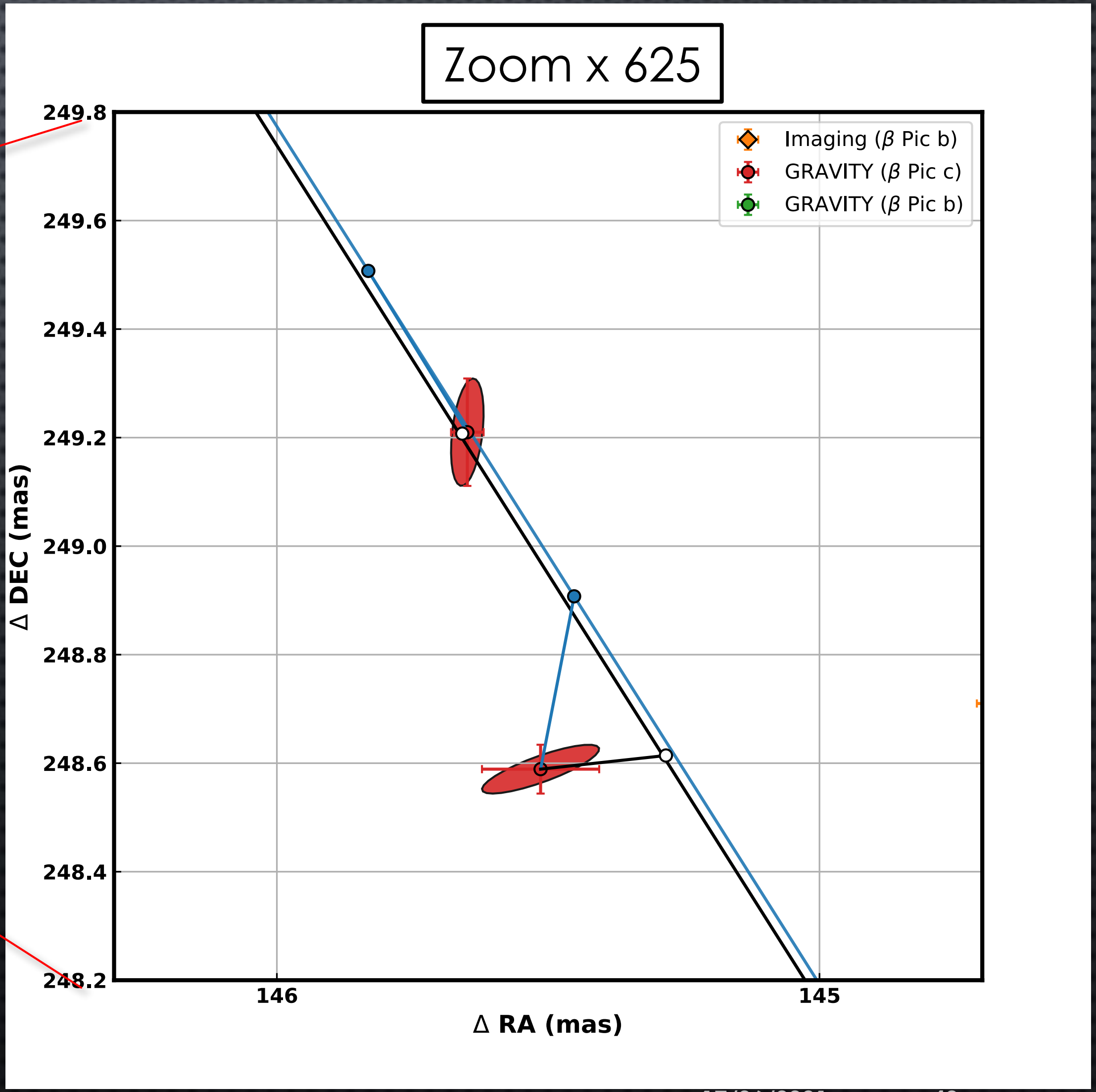


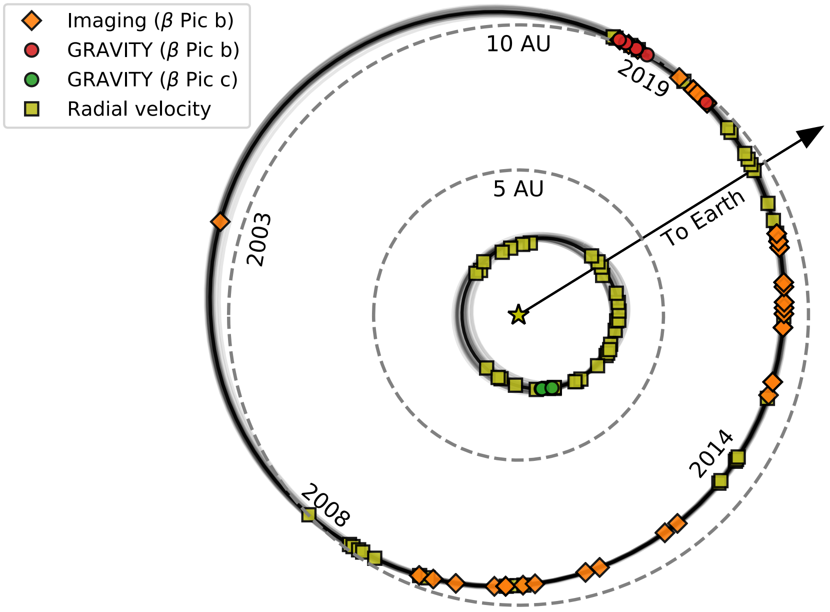
BETA PICTORIS B & C

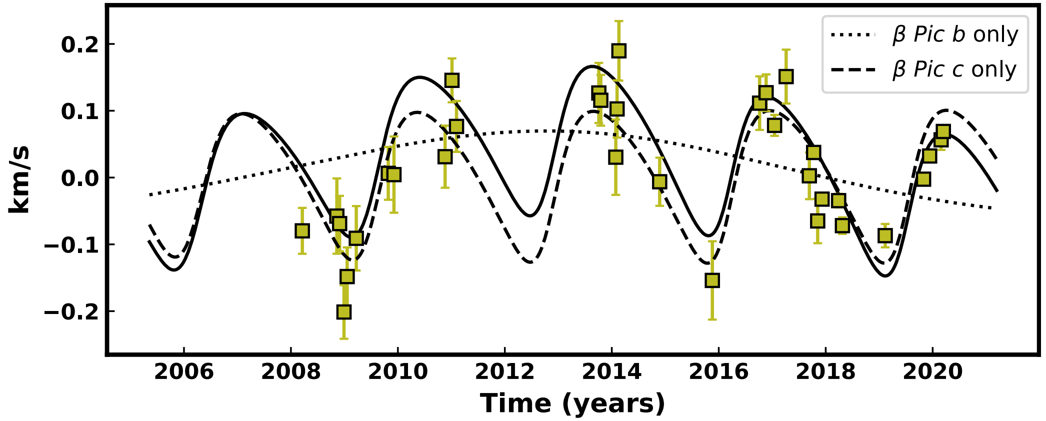


BETA PICTORIS B & C









Parameter	Prior distribution	Posteriors (1σ)		Unit
Star		β Pictoris		
Stellar mass	Gaussian (1.77 ± 0.02)	1.82 ± 0.03		$M_\odot$
Parallax	Uniform	51.42 ± 0.11		mas
proper motion	Uniform	ra=4.88 ± 0.02, dec=83.96 ± 0.02		mas/yr
RV v_0	Uniform	-23.09 ± 8.44		m/s
RV jitter	Uniform	31.21 ± 8.09		m/s
Planets		β Pictoris b	β Pictoris c	
Semi-major axis	Log Uniform	9.90 ± 0.05	2.72 ± 0.02	au
Eccentricity	Uniform	0.10 ± 0.01	0.37 ± 0.12	
Inclination	Sin Uniform	88.99 ± 0.01	89.17 ± 0.50	deg
PA of ascending node	Uniform	31.82 ± 0.02	30.98 ± 0.12	deg
Argument of periastron	Uniform	196.9 ± 3.5	66.2 ± 2.5	deg
Epoch of periastron	Uniform	0.72 ± 0.01	0.83 ± 0.02	
Planet mass	Gaussian (15.4 ± 3.0)	9.0 ± 1.6		M_{jup}
	Log Uniform		8.2 ± 0.8	M_{jup}
Period	—	23.28 ± 0.46	3.37 ± 0.04	years
Δm_K	—	8.9 ± 0.1	10.8 ± 0.1	mag

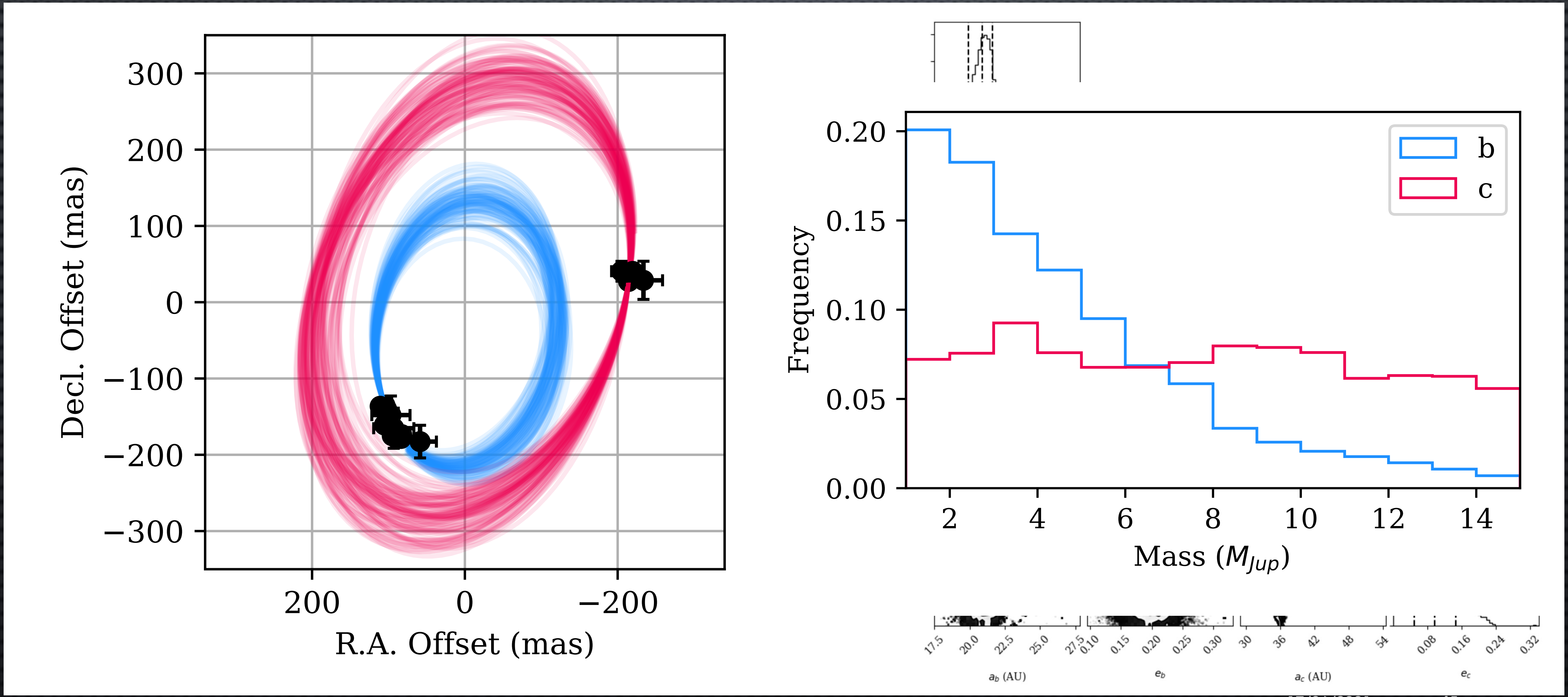
Nowak et al. (2020)

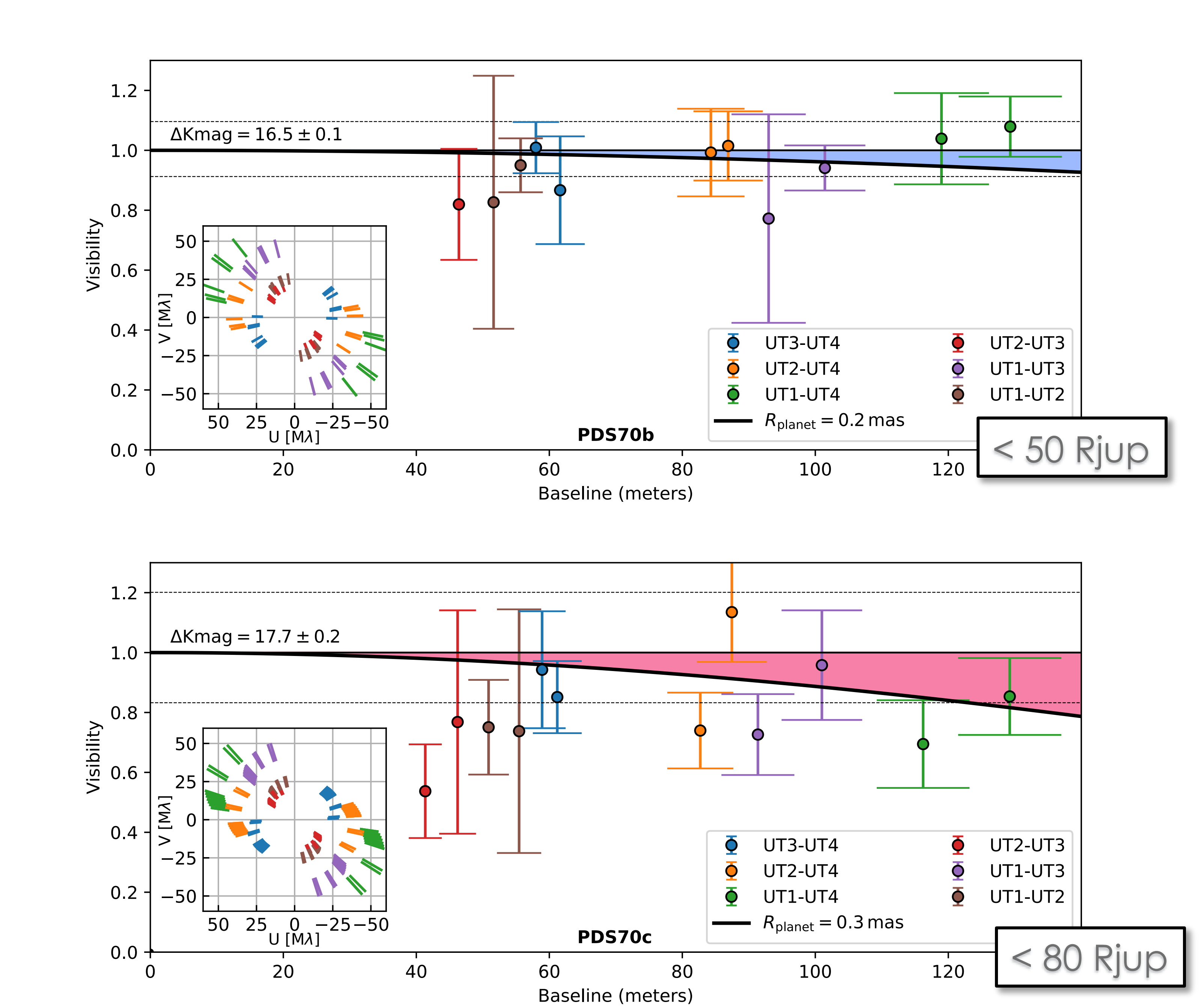
PDS 70 B & C

PDS 70 B & C

Gaussian prior on coplanarity
with disk : Sigma = 10 degrees
+
Gaussian prior on coplanarity
between b & c

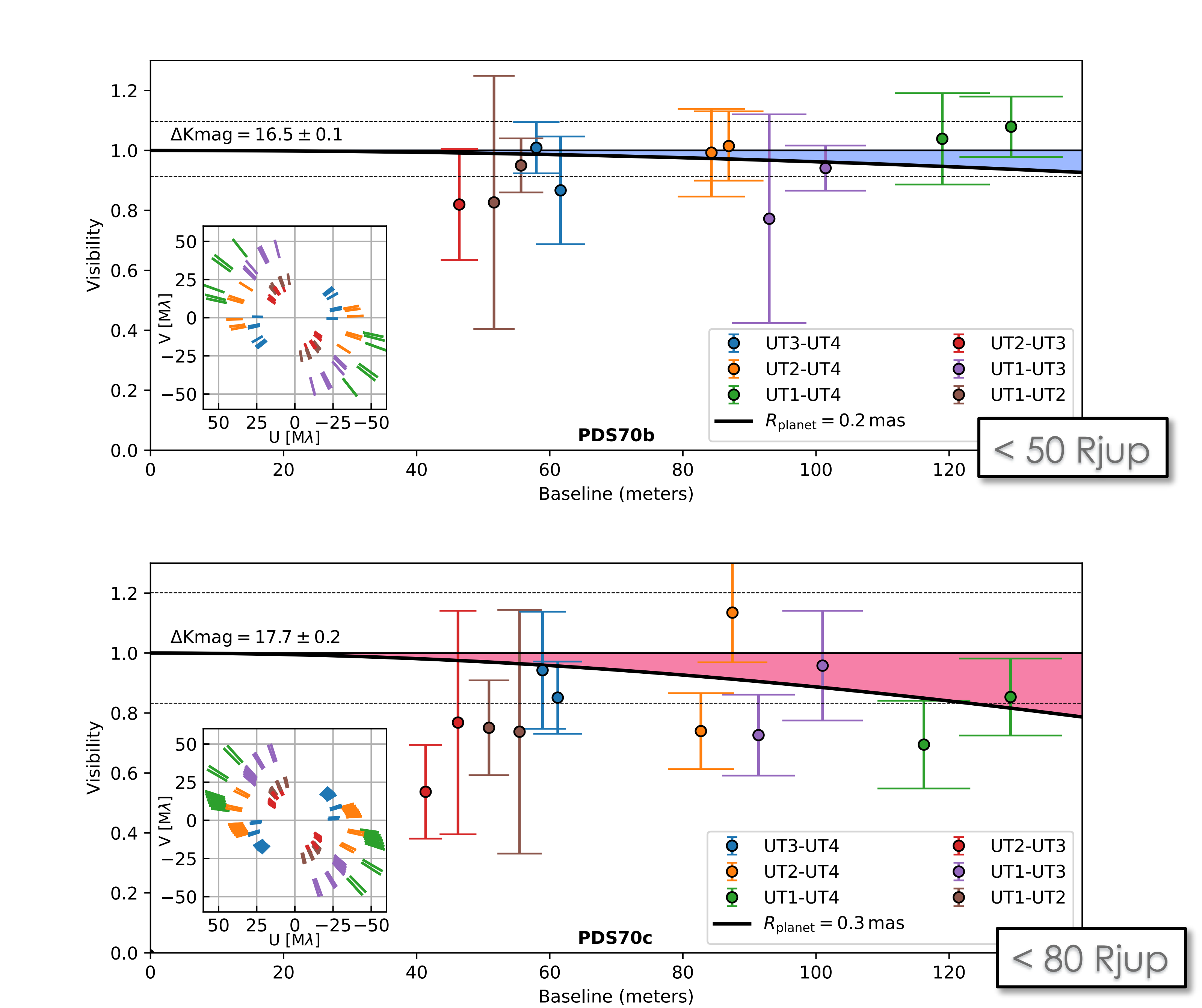
Wang et al. (work in progress)

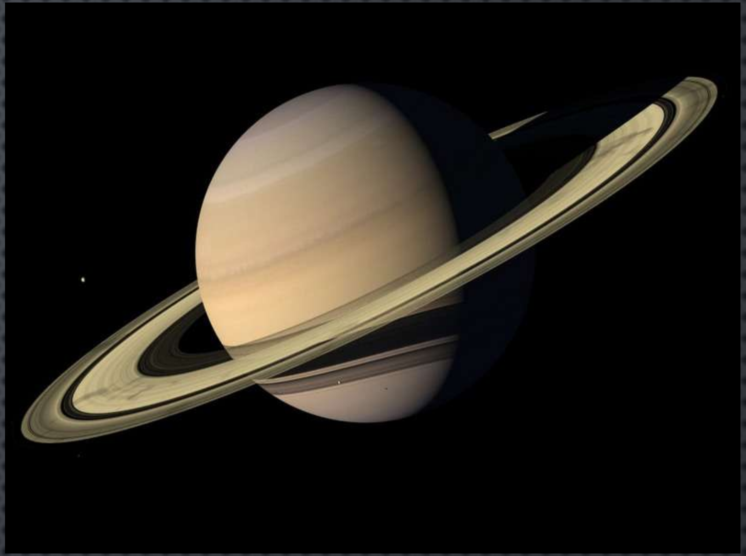




ΔKmag = 16.5 ± 0.1
Visibility
Baseline (meters)
PDS70b
UT3-UT4
UT2-UT4
UT1-UT4
UT2-UT3
UT1-UT3
UT1-UT2
R_{planet} = 0.2 mas
V [Mλ]
U [Mλ]
< 50 Rjup
ΔKmag = 17.7 ± 0.2
PDS70c
R_{planet} = 0.3 mas
< 80 Rjup

2000 Rjup



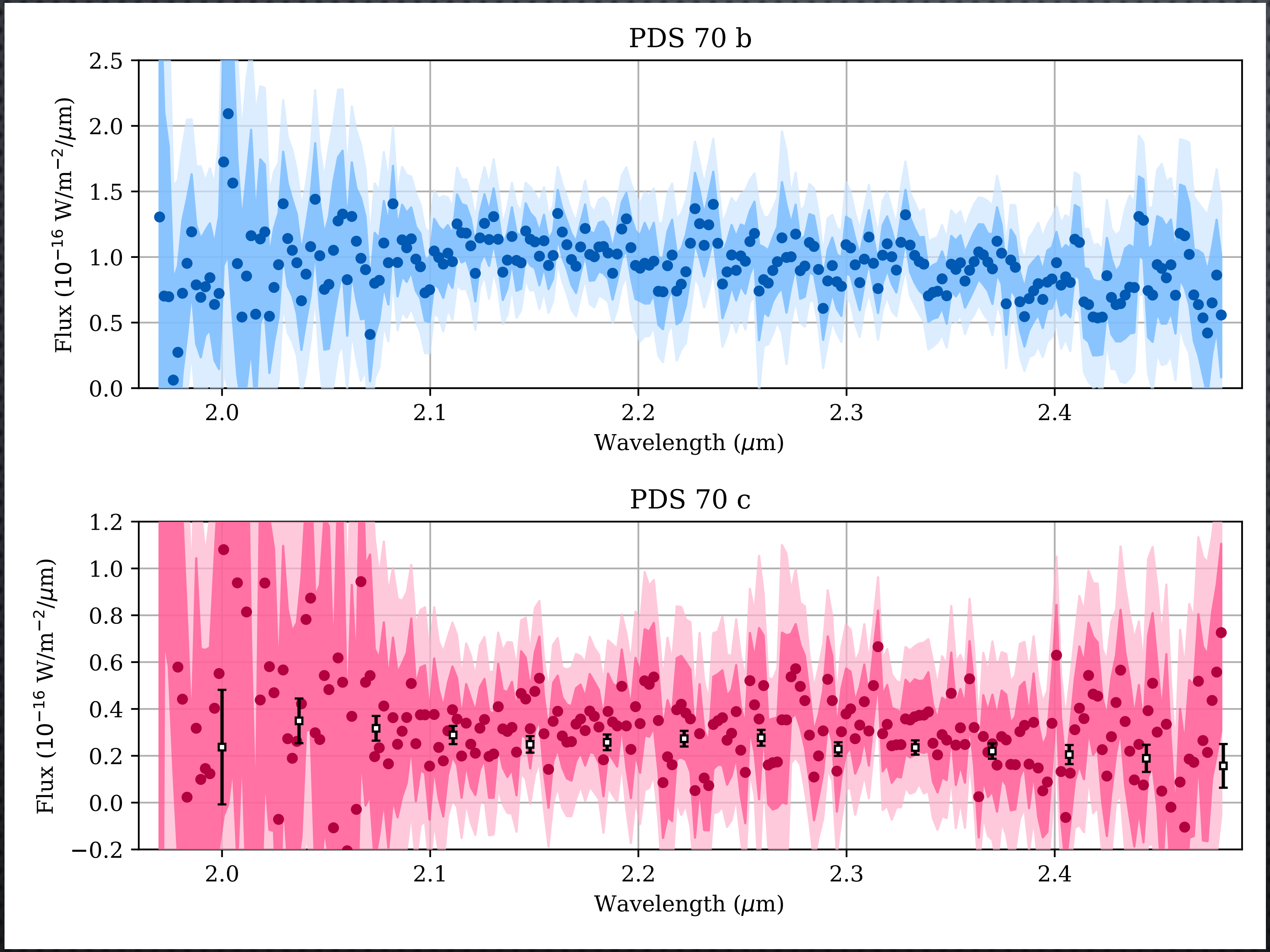


With circumplanetary model, for PDS70b:

Rcpd < 1mas (0.1au)

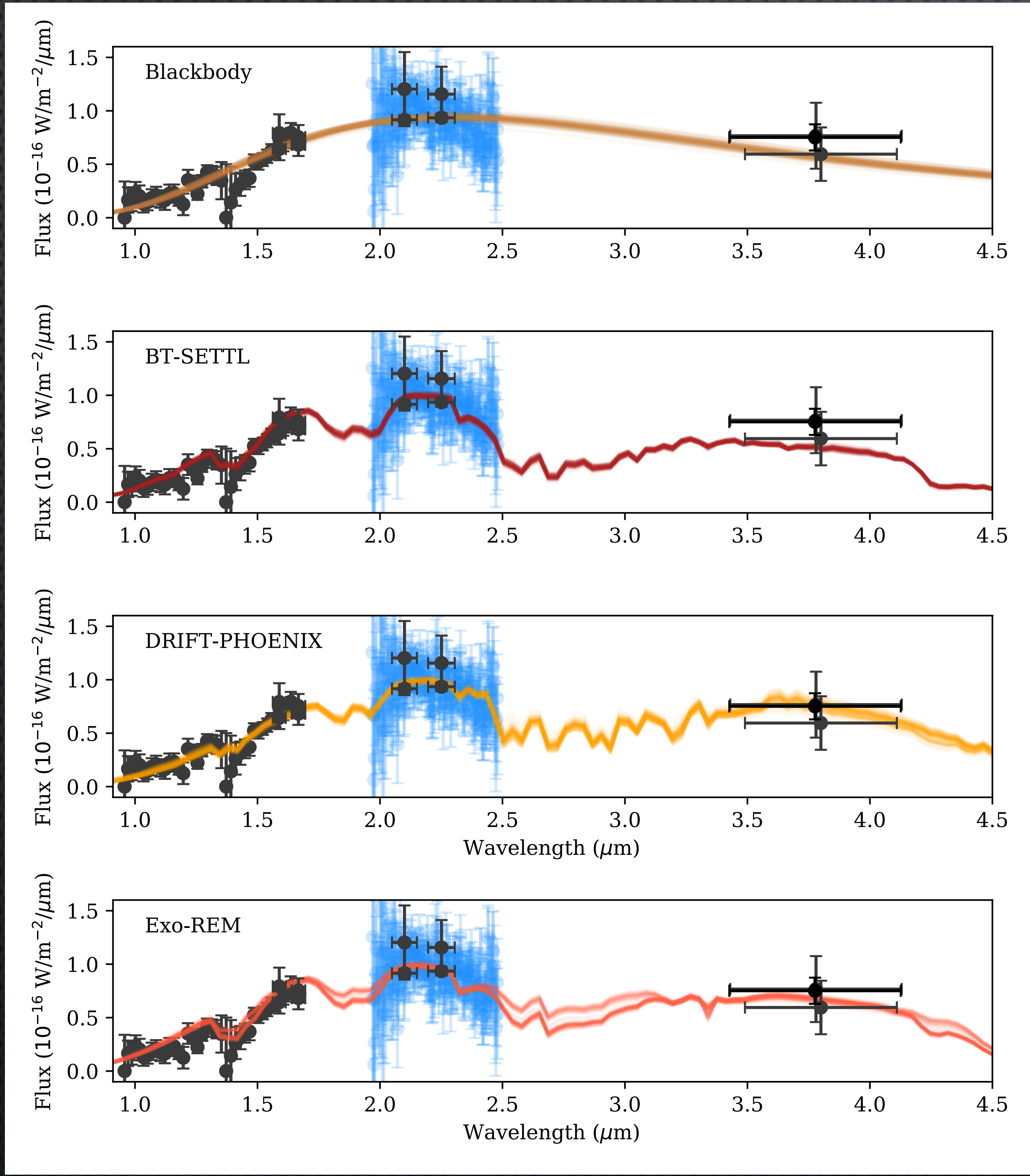
R Hill = 1.6 au

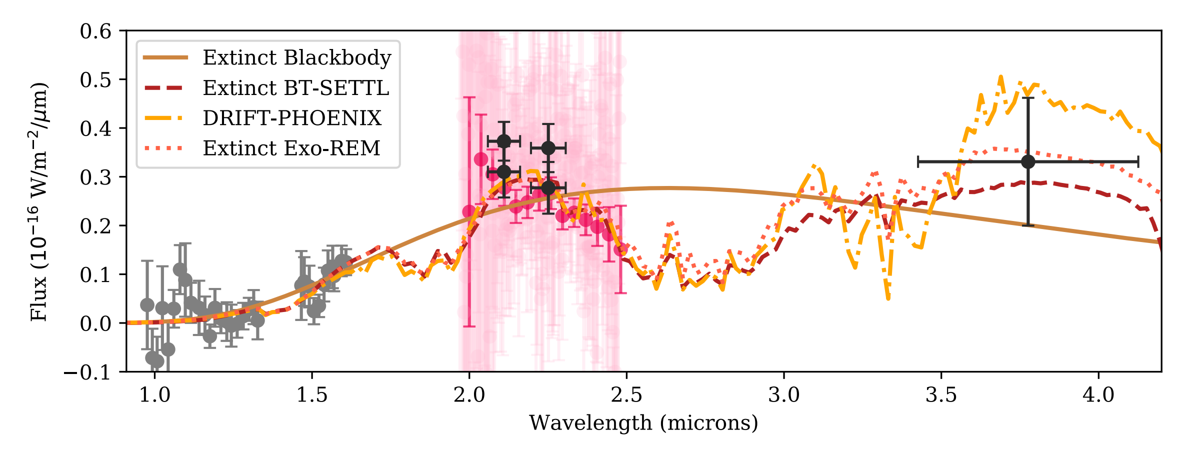
R Bondi = 8 au



K BAND SPECTRA

(J. WANG ET AL. IN PREPARATION)

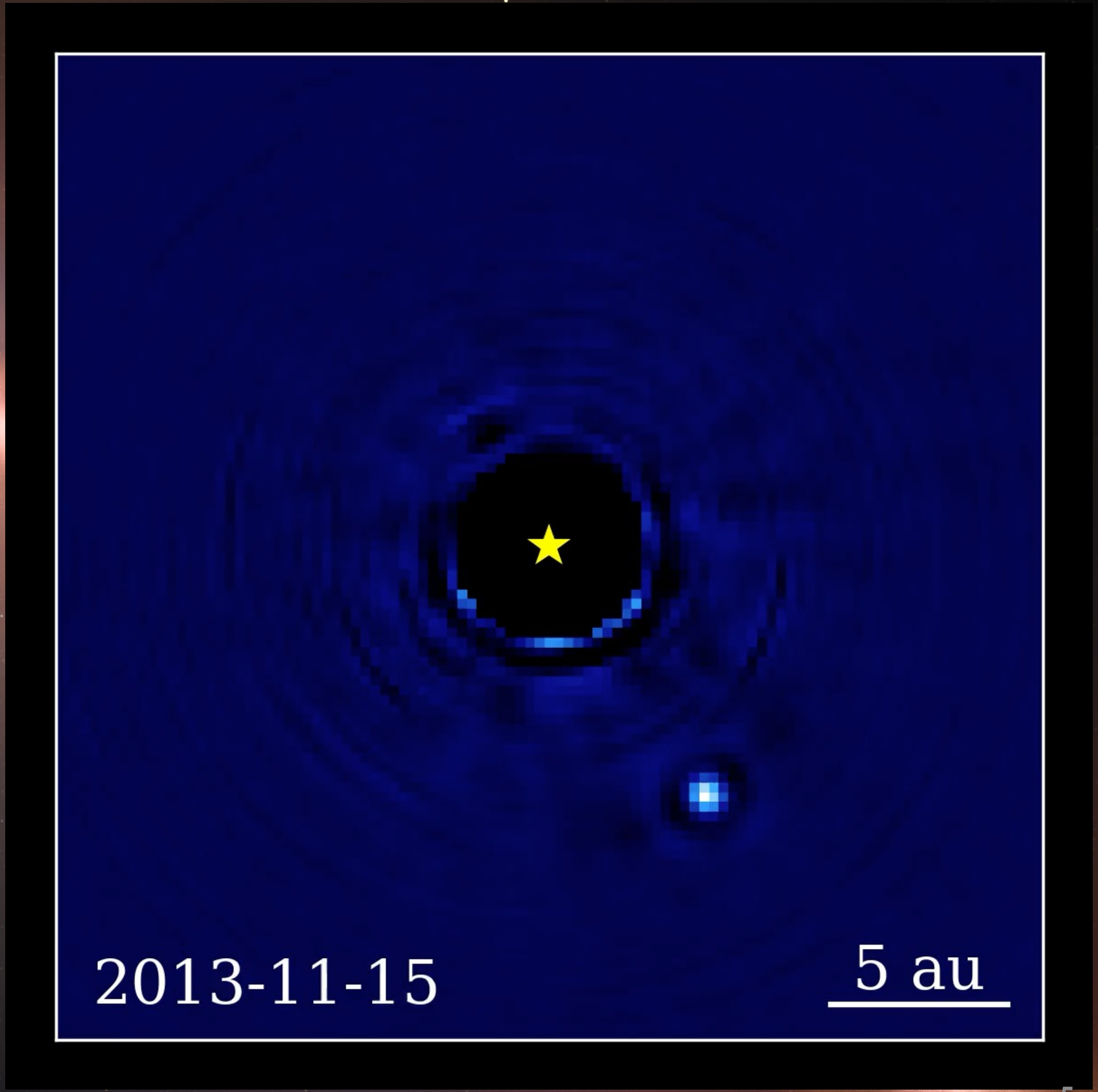




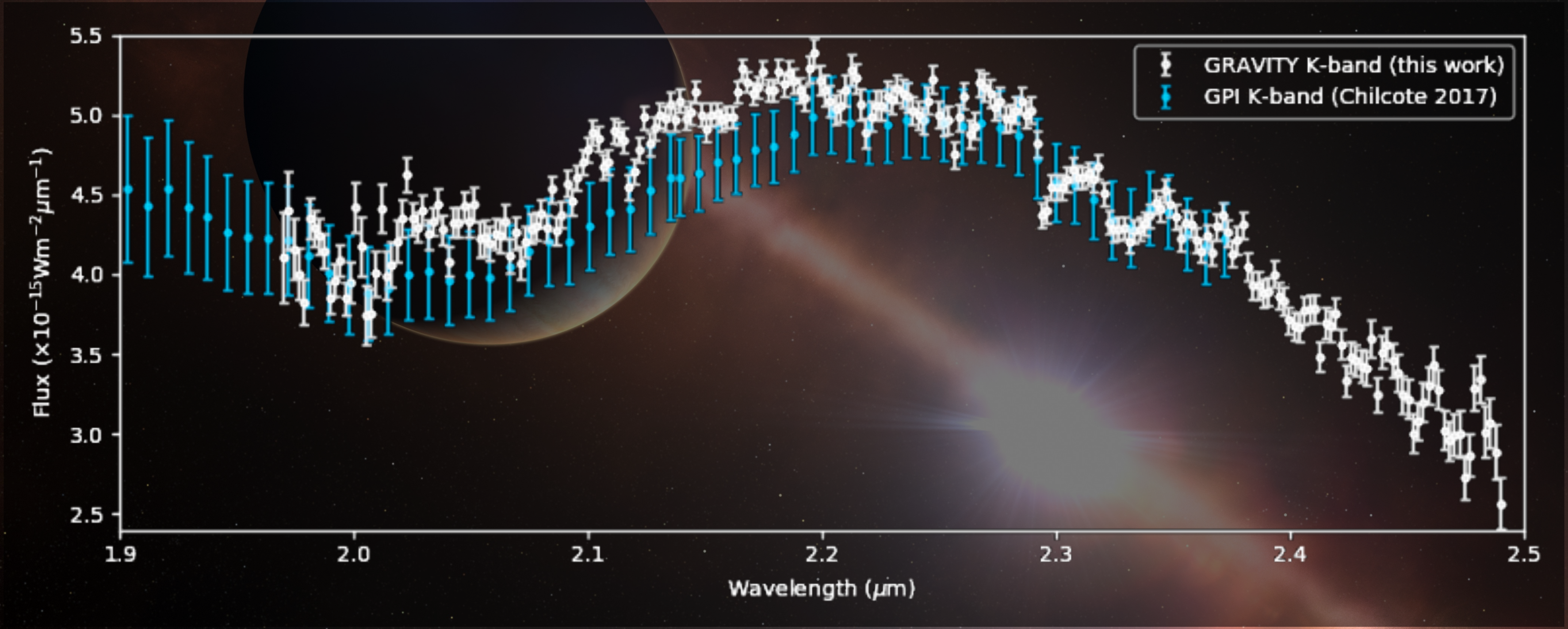
- Planetary-Type atmosphere
- No Black body CPD
- Need to add extinction

BETA PICTORIS B

- 23 MYR OLD
- 20 PC
- ~ 12 MJUP PLANET

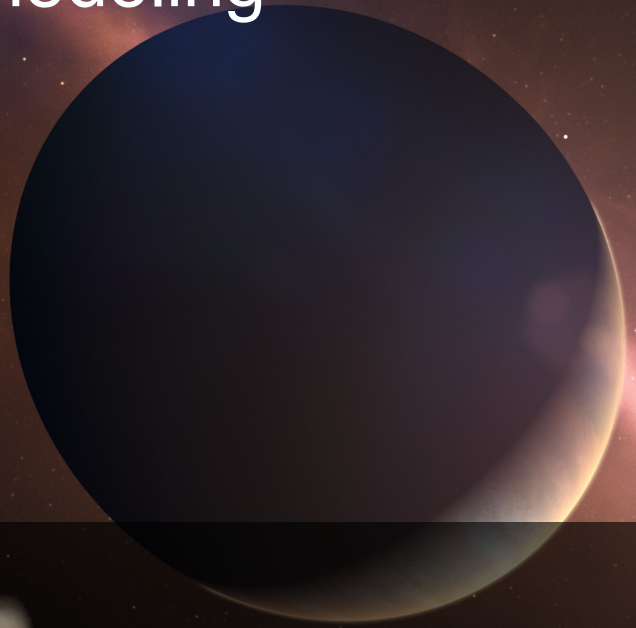


Beta Pictoris b



Gravity Collaboration: M. Nowak et al. (2020)

Spectral Modeling



Self-consistent

Chemical Modeling
Cloud Modeling
Radiative-convective temperature
=> “correct” / slow / can use sparse data

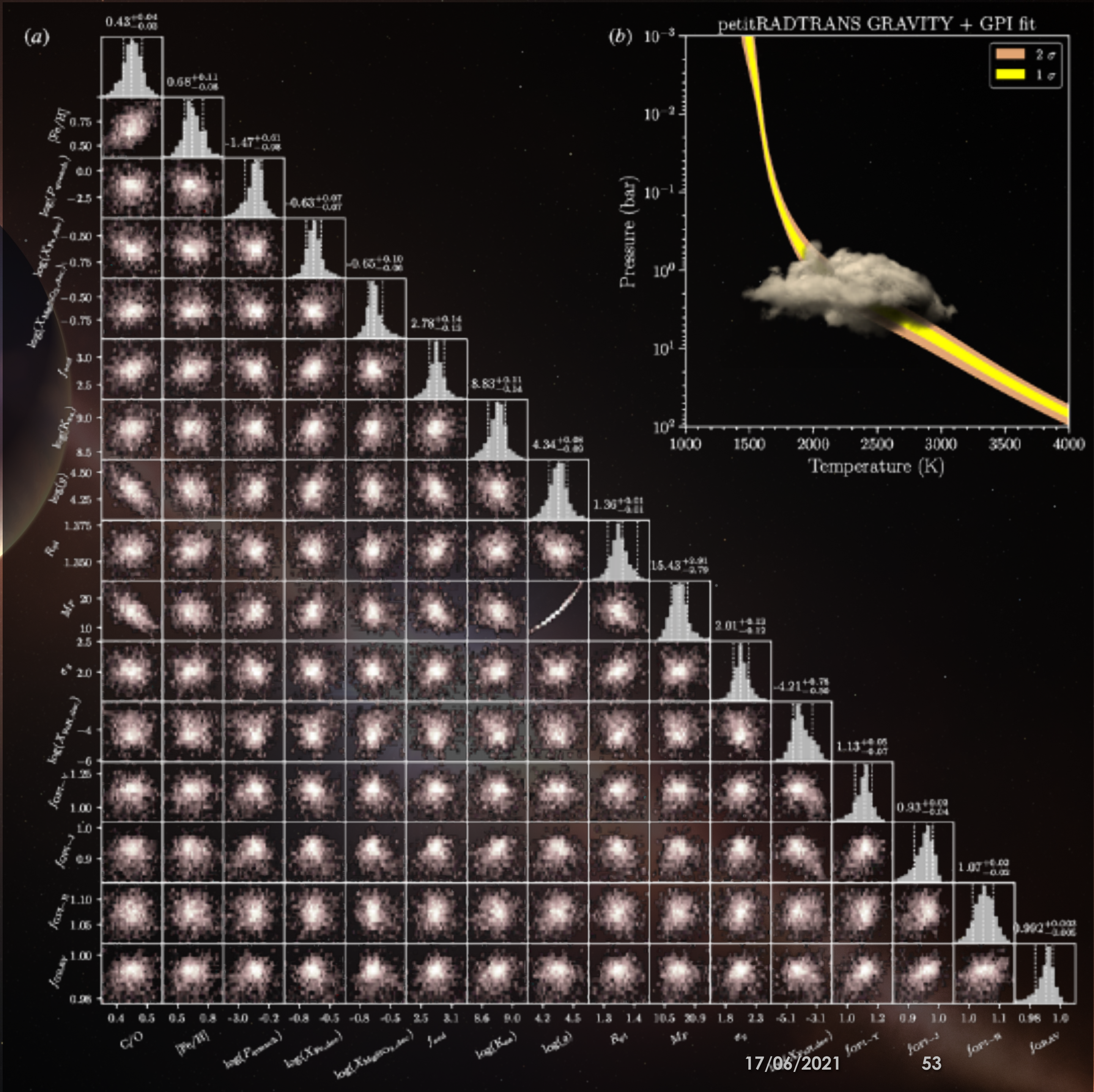
Free retrieval

Abundance
Cloud opacity
Temperature

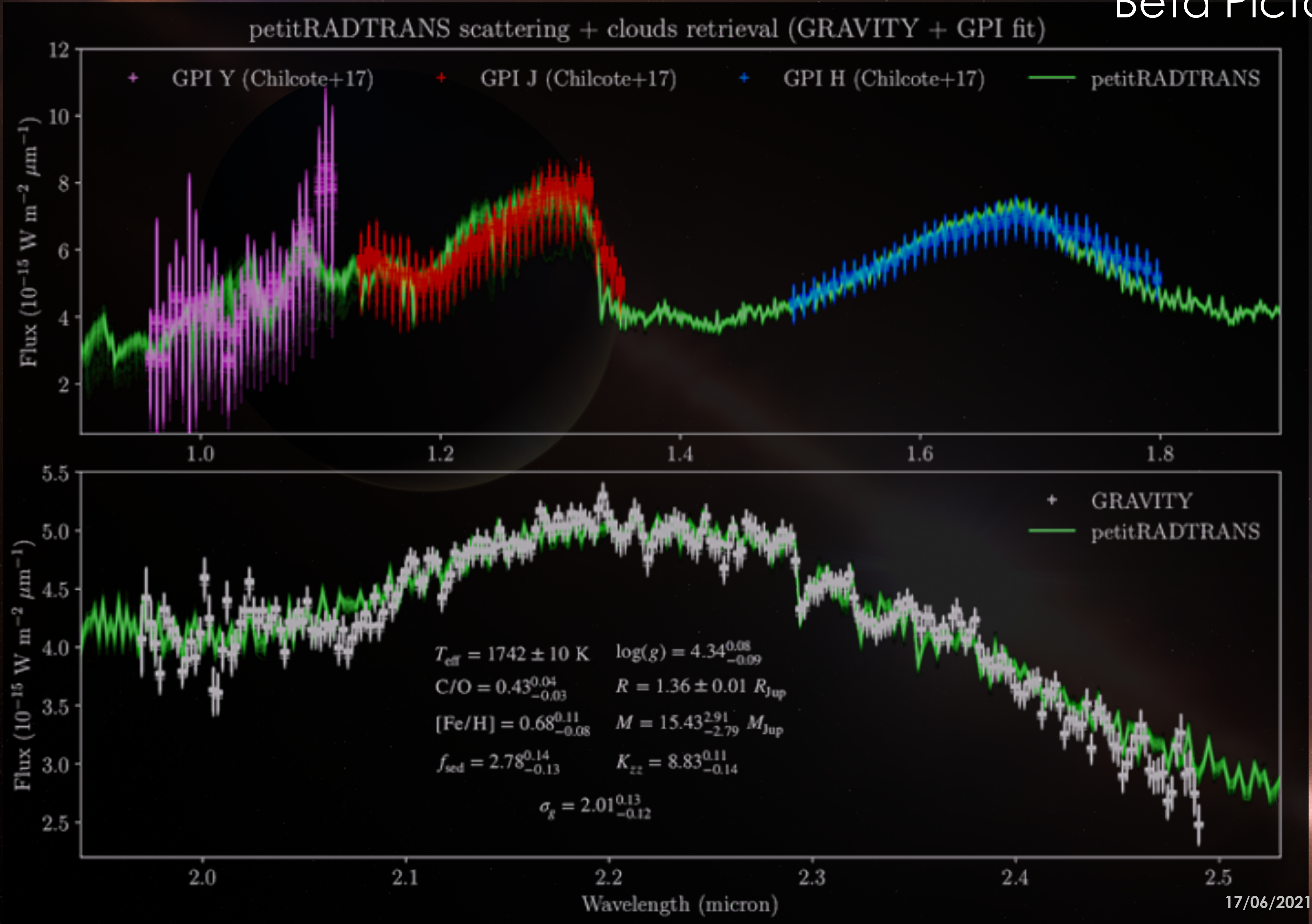
Parametrize!

=> “data speak” / fast / compare models

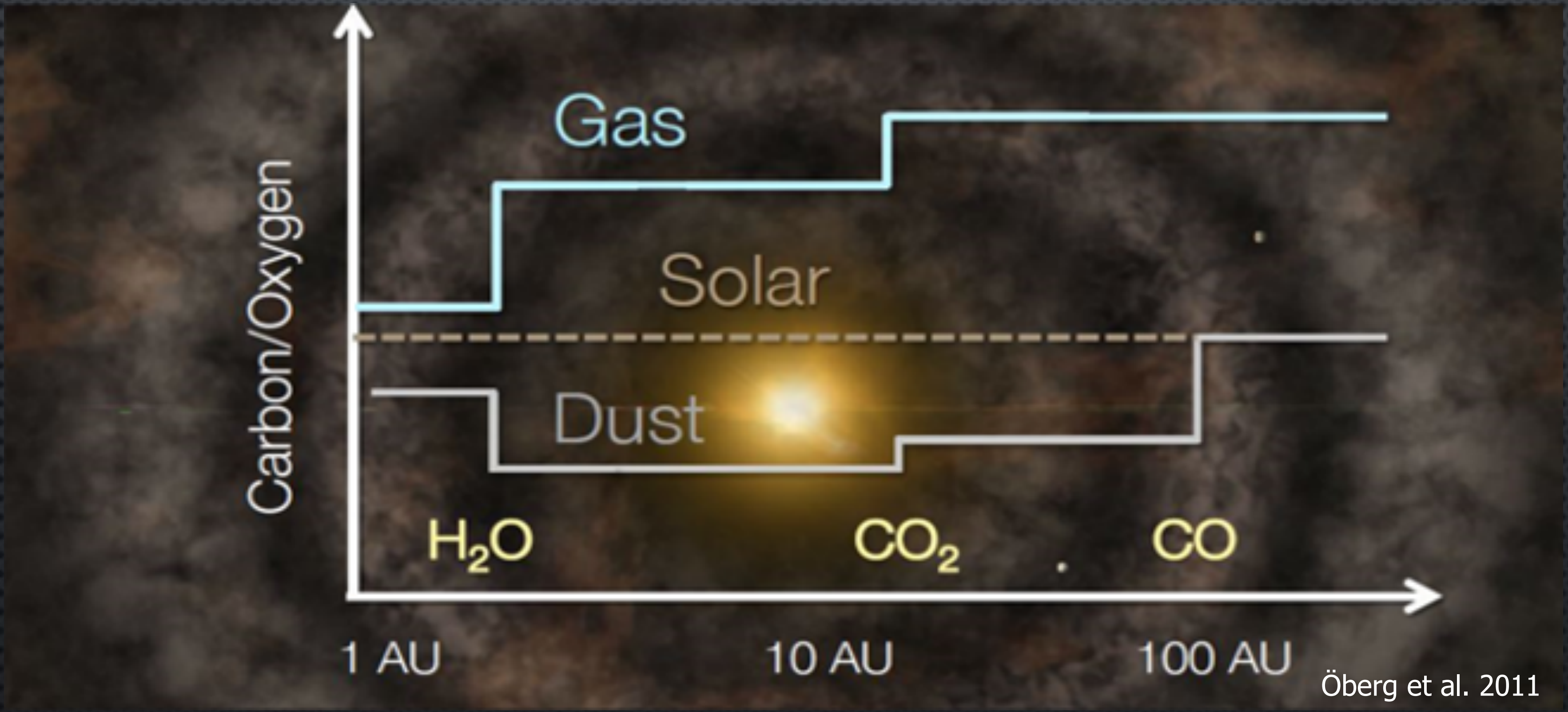
- complicated
- unknown
- love to blow up self-consistent codes


(a)
(b)
petitRADTRANS GRAVITY + GPI fit
2 σ
1 σ
Pressure (bar)
Temperature (K)
C/O
[Fe/H]

Beta Pictoris b

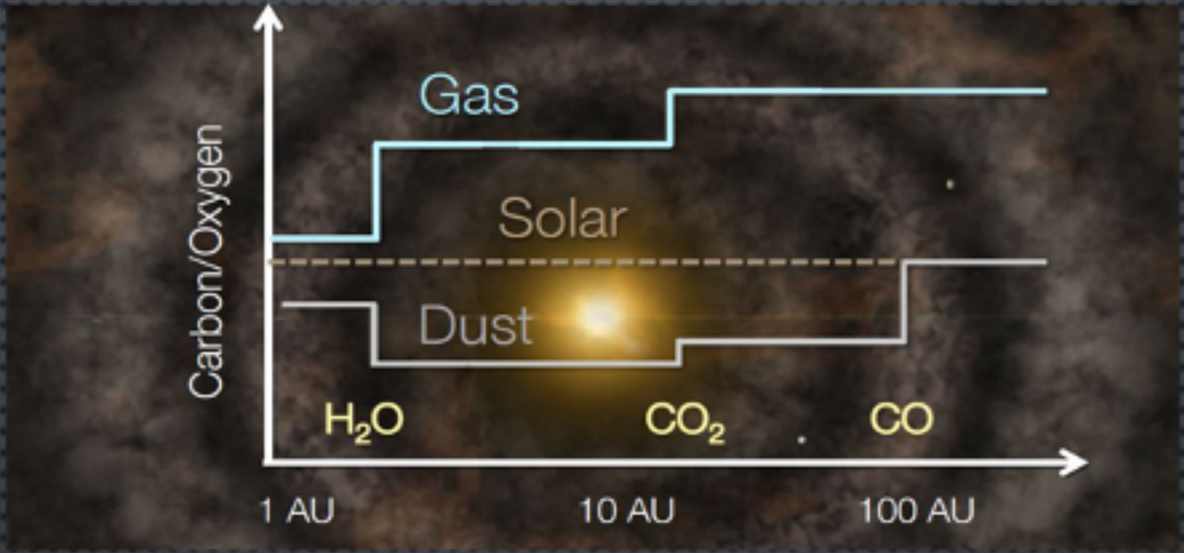


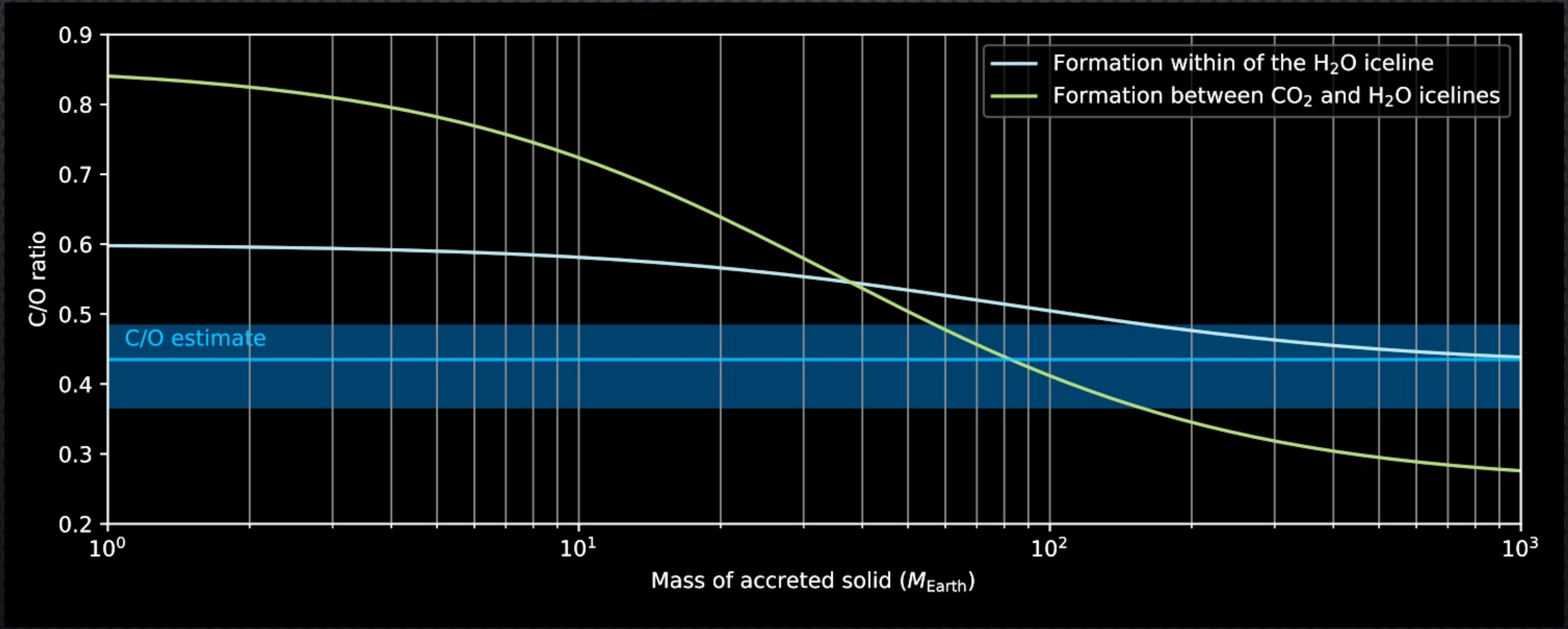
Planet composition varies with disk radius



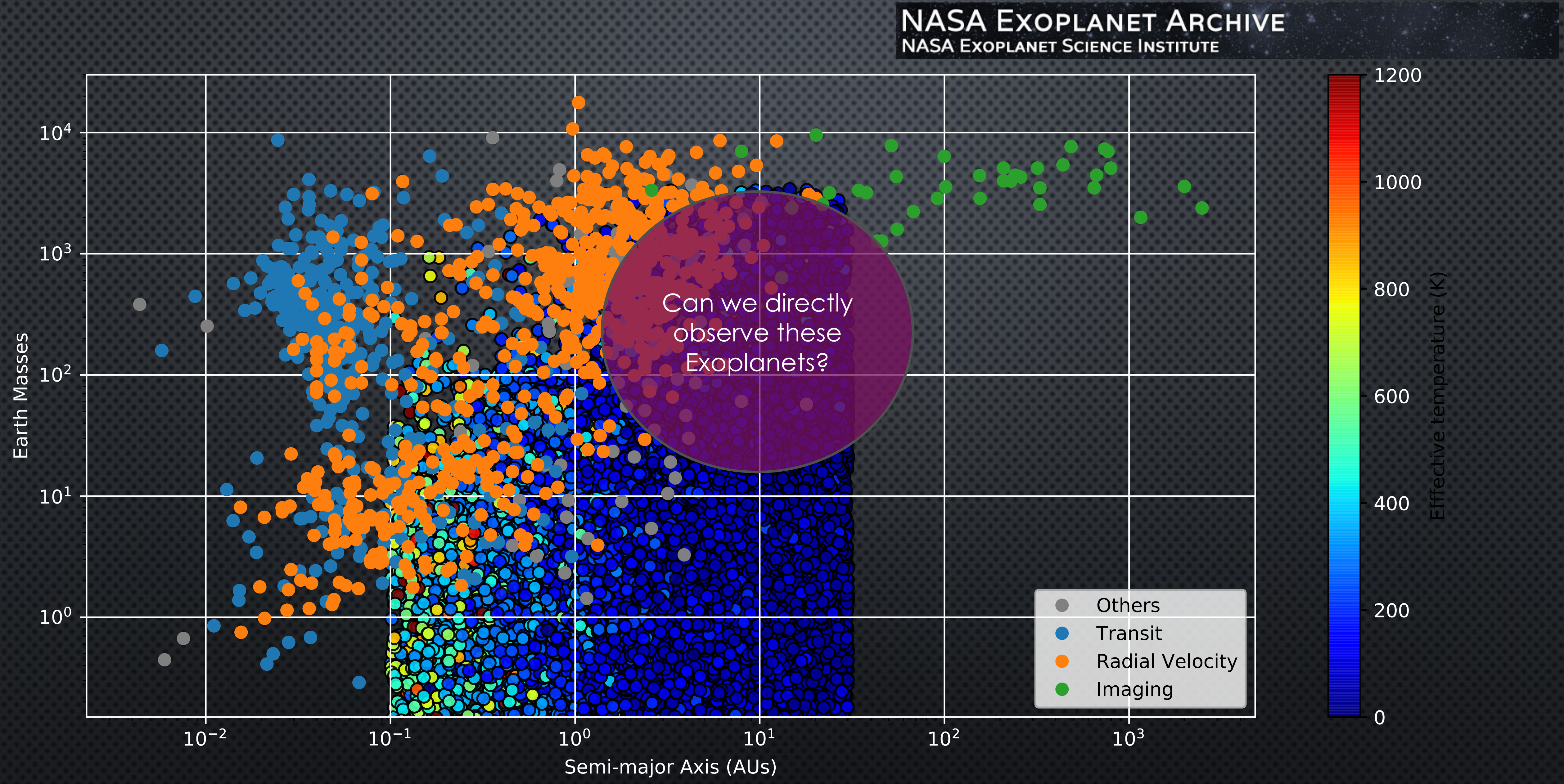
Öberg et al. 2011

This simple picture ignores chemistry (freeze out only)

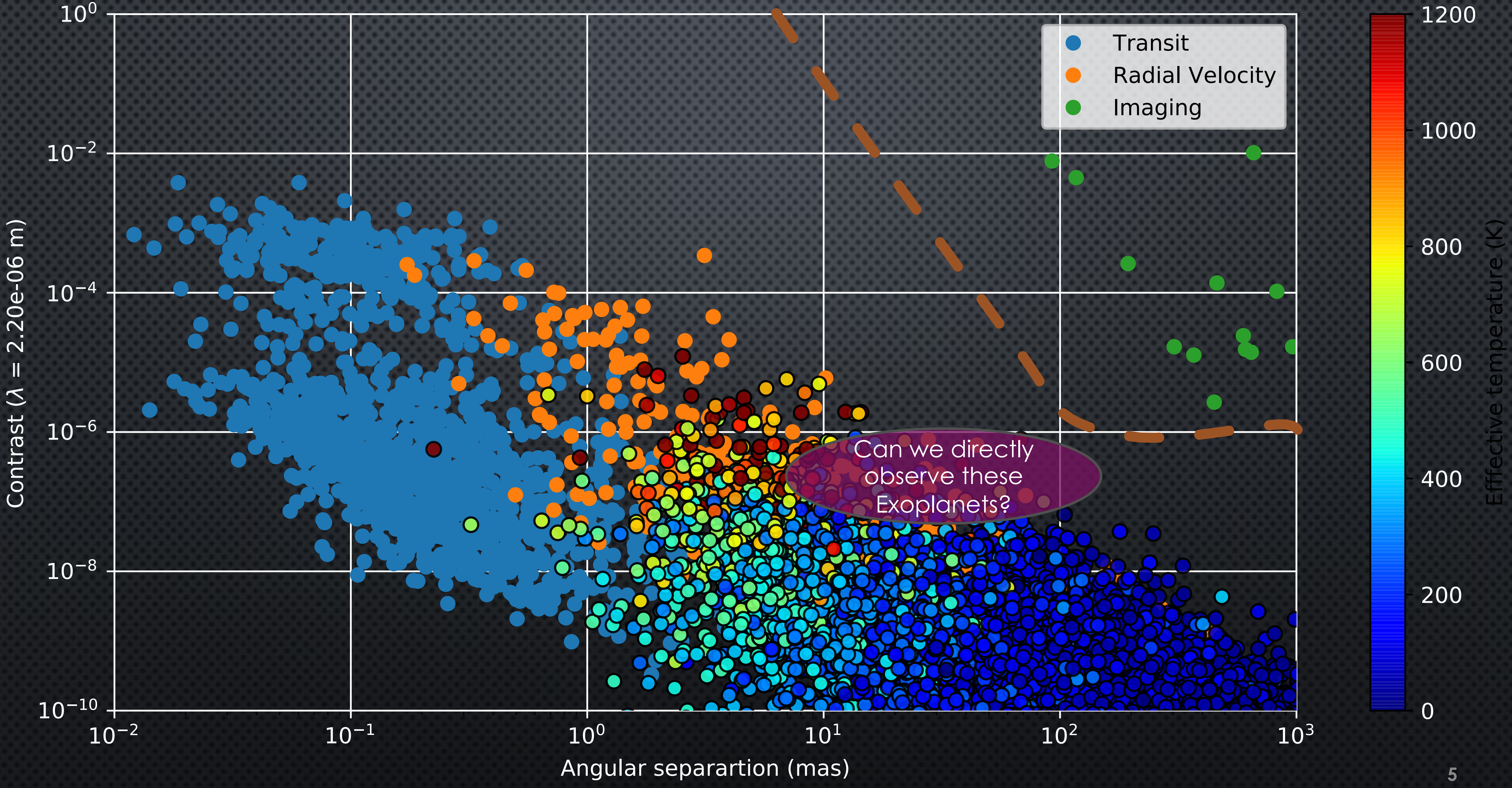

Gas
Solar
Dust
Carbon/Oxygen
H_2O
CO_2
CO
1 AU
10 AU
100 AU

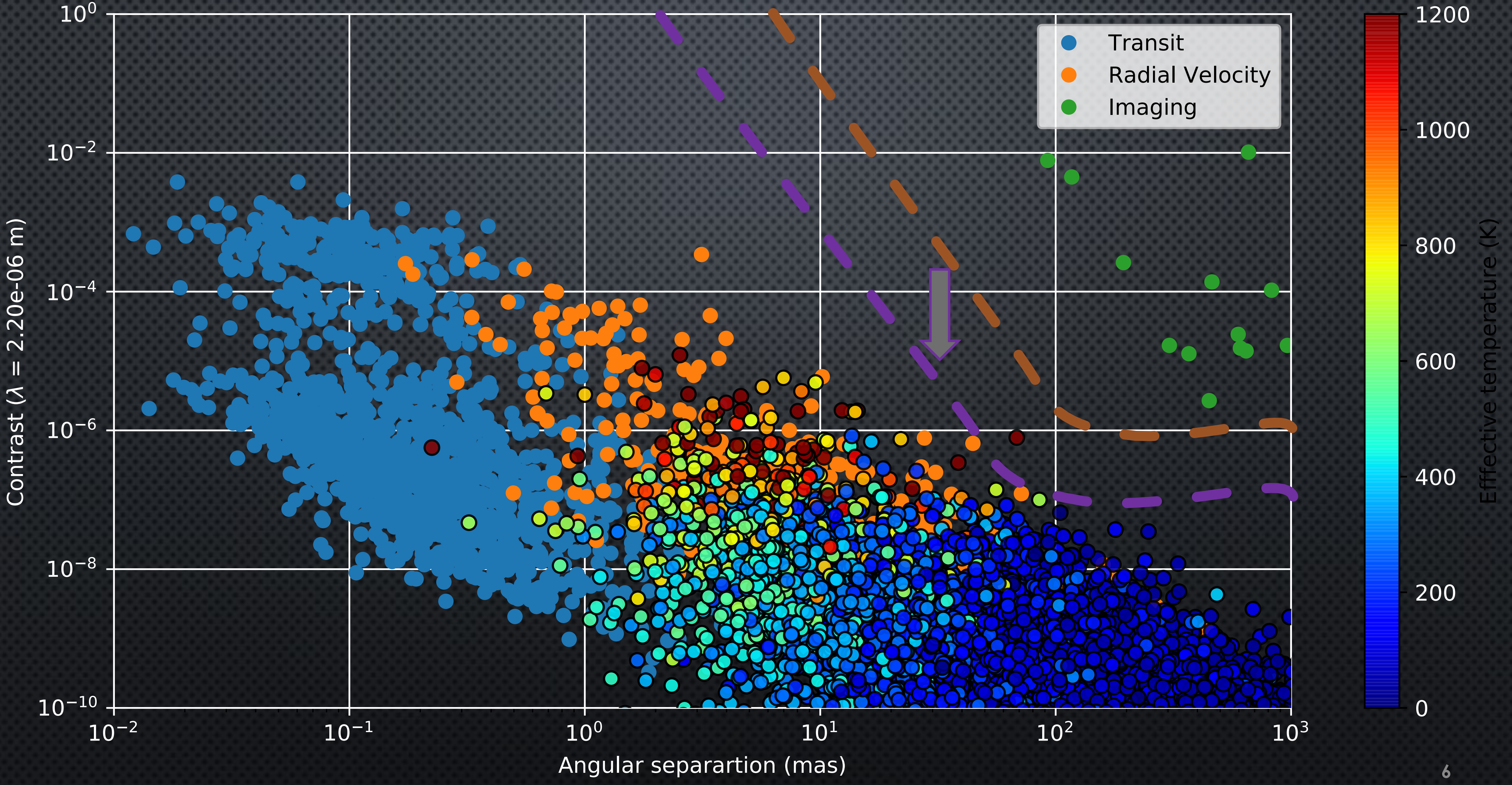

Formation within of the H_2O iceline
Formation between CO_2 and H_2O icelines
C/O estimate
C/O ratio
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
10^0
10^1
10^2
10^3
Mass of accreted solid (M_{Earth})

PROSPECTS FOR OPTICAL INTERFEROMETRY



Synthetic population from Kopparapu et al. 2018

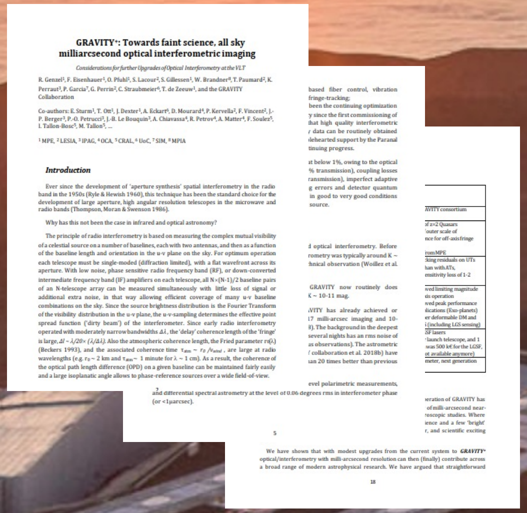

Transit
Radial Velocity
Imaging
Can we directly observe these Exoplanets?
Contrast (λ = 2.20e-06 m)
Angular separartion (mas)
Effective temperature (K)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
1200
1000
800
600
400
200
0



Transit
Radial Velocity
Imaging
Contrast (λ = 2.20e-06 m)
Angular separartion (mas)
Effective temperature (K)
10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
1200
1000
800
600
400
200
0

GRAVITY+ : Towards faint science, all sky milliarcsec optical interferometric imaging

STC recommends immediate start



Improved Sensitivity

Off Axis Tracking

Adaptive Optics

Laser Guide Stars

ExoGRAVITY+ : exoplanets are design-driver science case

Credit: ESO, Huedepohl