SPICA *Stellar Parameters and Images with a Cophased Array*

A new visible 6T spectro-combiner for CHARA

https://lagrange.oca.eu/fr/spica-project-overview

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& C. Lim, C. Petit (ONERA), I. et M. Tallon (CRAL)

S. Kraus, S. Lacour, J.B. Le Bouquin, J. Monnier (MIRCx/MYSTIC) & S. Albrecht (Aarhus)

& the CHARA staff at Mount Wilson and Atlanta

Framework

- Up to now, ~200 different stars have their angular diameter precise at the 1% level based on different instruments (JMDC catalogue, Duvert+16): Mainly Giants, different techniques, different spectral bands…

- Why measuring many angular diameters?
  - Angular diameter + Parallax (Gaia) give the Radius, one of the primary ingredient of stellar modeling
  - Angular diameter + Fbol give the Teff with an excellent accuracy (~20-30K)
  - Planet radius is generally known though Rp/R*
  - Angular diameter and radius (pulsating stars, binaries) give the distance

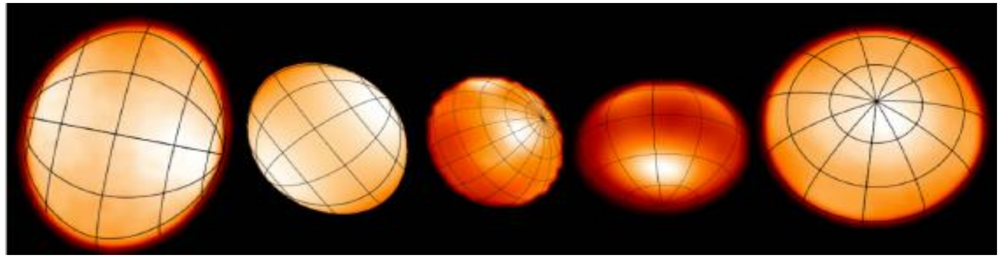
- Opportunity because space missions are now looking to brighter targets for a better characterization
- And in parallel important progresses in sensitivity and precision in optical interferometry

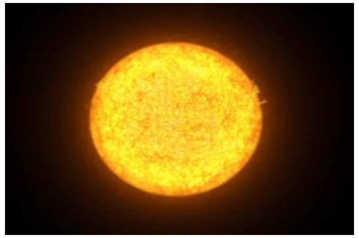
- Unique opportunity with the 300m baselines of CHARA and the access to visible wavelengths to reaching 0.1 mas of angular resolution.

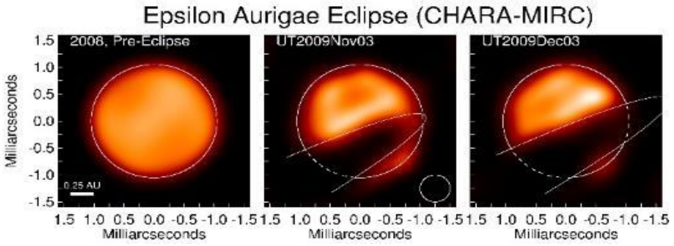
What means *large number* and *angular diameters* ?

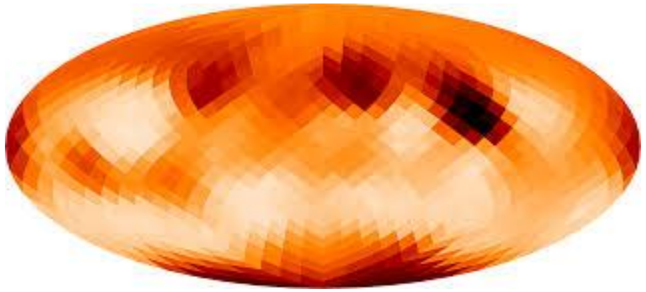
- Large Number:
  - In the past a few tens of objects only (PIONIER, CHARA)
  - For the SBC relations, 5 LC, 7SP ➔ few hundreds of stars for a good sampling of the HR diagram and to improve the precision and accuracy.
  - Almost 200 exoplanet host stars accessible to CHARA.

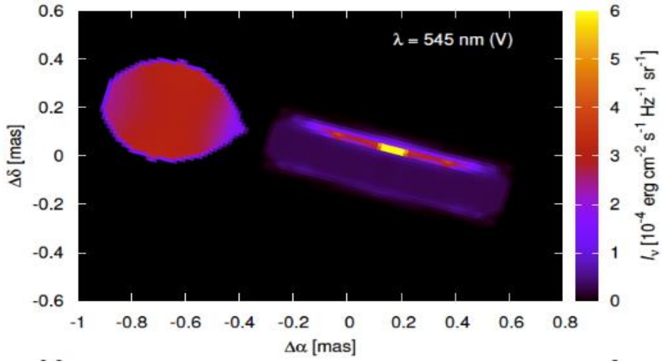
➔ ***~1000 stars***

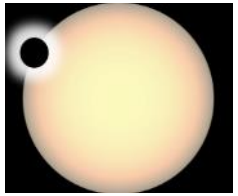
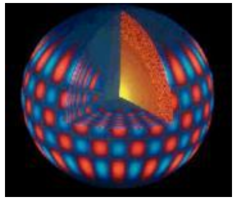








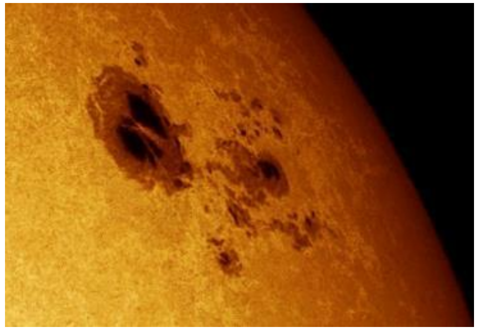


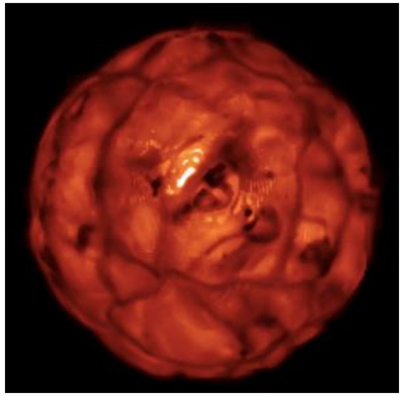
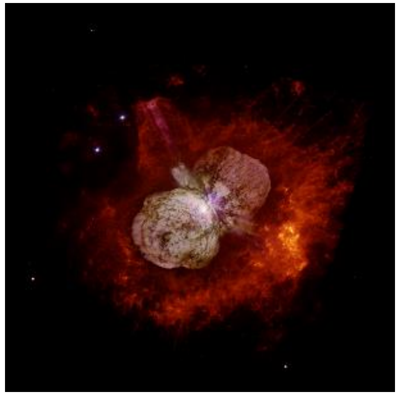
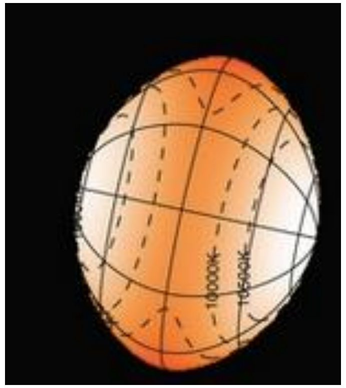

Three objectives:

1. Exoplanet Host Stars
2. Asteroseismology
3. SBCR for distances of EB and PLATO

For these three objectives, stellar activity has to be taken into account:

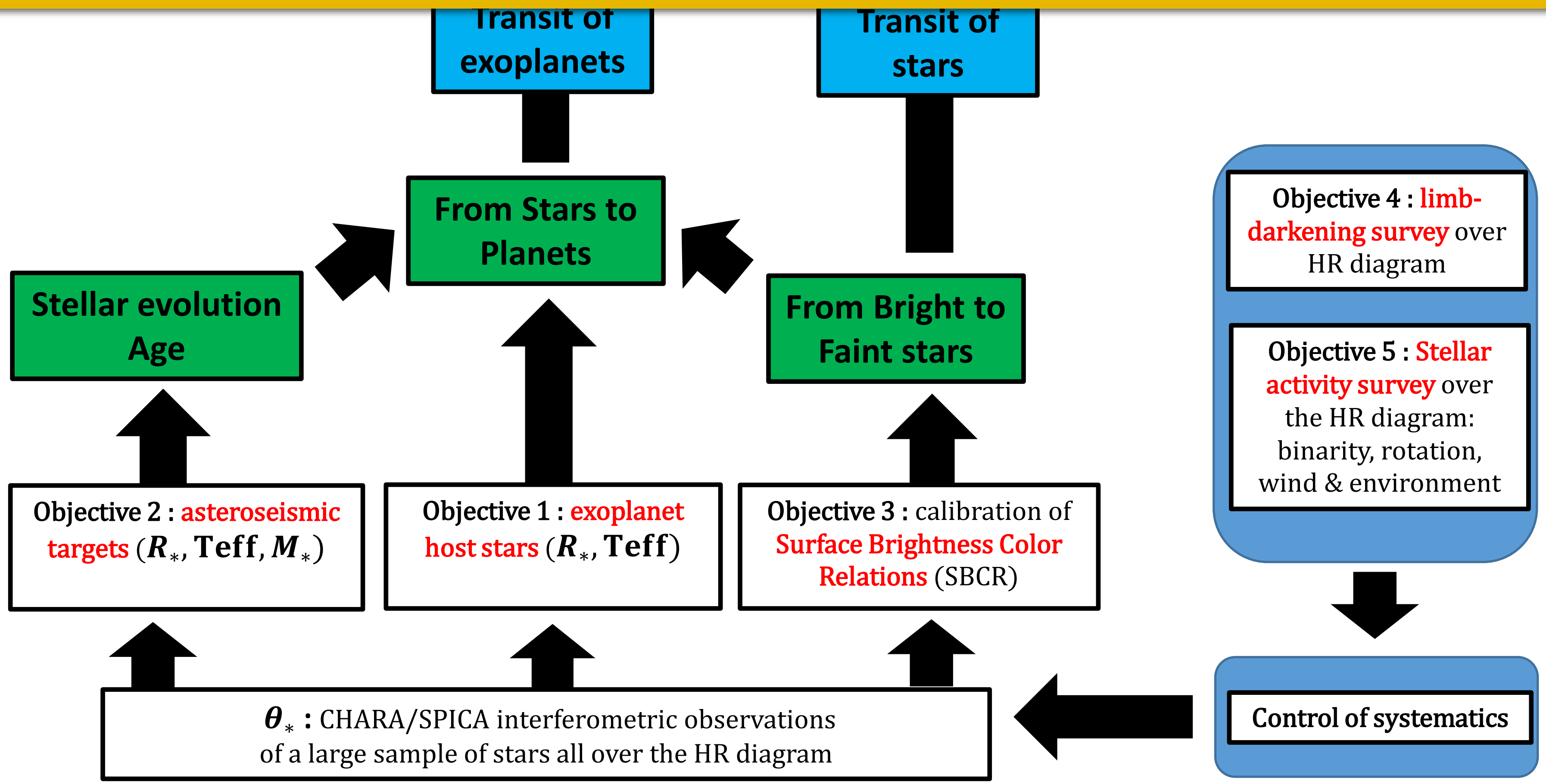


Stellar Activity

The ISSP Survey

But more generally speaking, the ultimate goal is a revolution in stellar fundamental parameters and thus on stellar physics



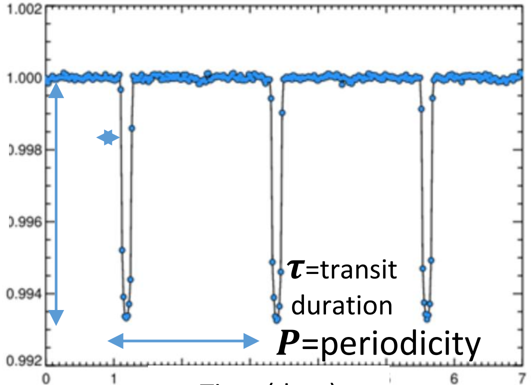
Strong links with:
- **ESA/PLATO mission**
- **Araucaria program**

Radius and Effective Temperature of exoplanet host stars

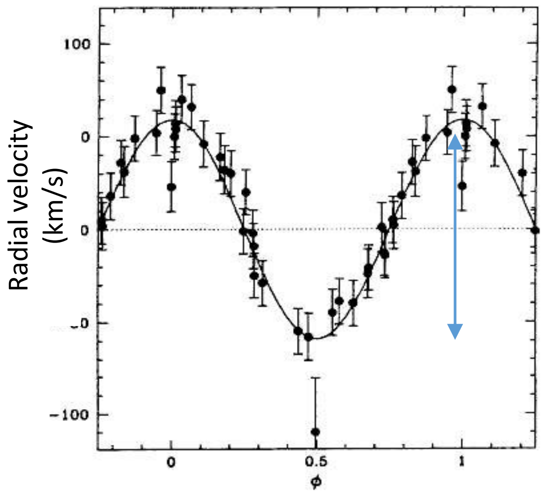
TESS, CHEOPS, PLATO…

Transit of exoplanets

PHOTOMETRY



VELOCIMETRY



SPICA

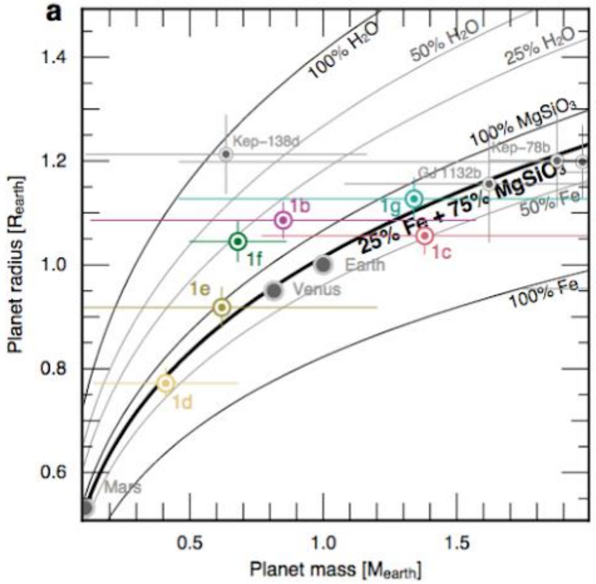
Gaia parallax and bolometric flux

$R_* - Teff$

From Stars to Planets

$$R_p = \frac{R_*}{9.2984}\sqrt{\frac{\Delta F}{F}}$$

$$M_P = c.\, M_*^{2/3} P^{1/3}$$



Stellar and Planet modelling
e.g.: Ligi+16

Observation of a large and homogeneous sample of asteroseismic targets

PLATO preparation/follow-up

Scaling Relations (SR) in the litterature
Teff from spectroscopy

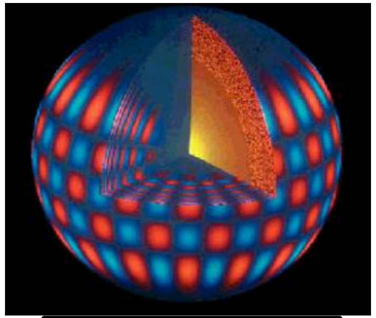
$R_{*[SR]}, M_{*[SR]}$

Comparison

'full' frequencies analysis of benchmark (b) stars

$R_{*[b]}, M_{*[b]}$

Calibration



Constraints

Stellar evolution Age

$R_{*[I]}$, $R_{*[SBCR]}$

Gaia parallax

CHARA/SPICA Angular Diameters: θ

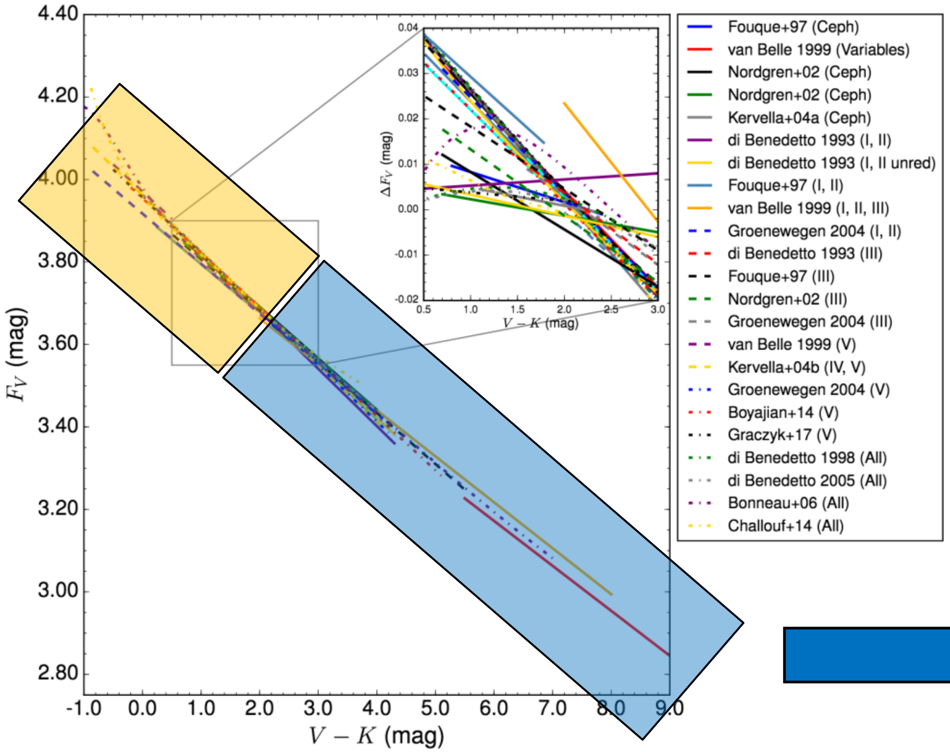
Calibration of Surface Brightness Color Relations all over the HR diagram

From bright to faint stars

$$F_V = 4.2207 - 0.1 S_V = \alpha + \beta (V - K)$$

$$S_\lambda = m_{\lambda_0} + 5 \log \theta_{LD}$$

SBCR of early-type stars:
- ➢ distance determination of M31/M33 (Araucaria)



SBCR of late type stars:
- ➢ distance determination
- ➢ of SMC/LMC (Ho)
- ➢ faint PLATO targets

Scientific Requirements: θ_{LD} and (θ_{LD} +LD) measurements

θ_{LD} only with hypothesis on the LD law

Dwarfs	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25

Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
8	0,01	0,03	0,08	0,17	0,30	0,52	0,91	1,56	2,67
9	0,00	0,02	0,05	0,11	0,19	0,33	0,58	0,99	1,69
10	0,00	0,01	0,03	0,07	0,12	0,21	0,36	0,62	1,06

$\sigma\theta/\theta=1\%$

θ_{LD} and LD from SPICA

Dwarfs	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,10	1,00	3,35	6,28	11,82	22,25	39,94	70,70	125,14
1	0,06	0,63	2,11	3,96	7,46	14,04	25,20	44,61	78,96
2	0,04	0,40	1,33	2,50	4,71	8,86	15,90	28,14	49,82
3	0,02	0,25	0,84	1,58	2,97	5,59	10,03	17,76	31,43
4	0,02	0,16	0,53	0,99	1,87	3,53	6,33	11,20	19,83
5	0,01	0,10	0,33	0,63	1,18	2,23	3,99	7,07	12,51
6	0,01	0,06	0,21	0,40	0,75	1,40	2,52	4,46	7,90
7	0,00	0,04	0,13	0,25	0,47	0,89	1,59	2,81	4,98
8	0,00	0,03	0,08	0,16	0,30	0,56	1,00	1,78	3,14
9	0,00	0,02	0,05	0,10	0,19	0,35	0,63	1,12	1,98
10	0,00	0,01	0,03	0,06	0,12	0,22	0,40	0,71	1,25

Giants	Challouf			Salsi-1			Salsi-2		
SpTy	O	B0	A0	F5	G7	K4	M0	M3	M4
V // V-K	-2	-1	0	1	2	3	4	5	6
0	0,24	1,09	3,16	6,72	11,79	20,68	36,41	62,26	106,46
1	0,15	0,69	1,99	4,24	7,44	13,05	22,97	39,28	67,17
2	0,10	0,44	1,26	2,68	4,69	8,23	14,49	24,79	42,38
3	0,06	0,27	0,79	1,69	2,96	5,20	9,15	15,64	26,74
4	0,04	0,17	0,50	1,07	1,87	3,28	5,77	9,87	16,87
5	0,02	0,11	0,32	0,67	1,18	2,07	3,64	6,23	10,65
6	0,02	0,07	0,20	0,42	0,74	1,30	2,30	3,93	6,72
7	0,01	0,04	0,13	0,27	0,47	0,82	1,45	2,48	4,24
8	0,01	0,03	0,08	0,17	0,30	0,52	0,91	1,56	2,67
9	0,00	0,02	0,05	0,11	0,19	0,33	0,58	0,99	1,69
10	0,002	0,011	0,032	0,067	0,118	0,207	0,364	0,623	1,065

DWARFS **GIANTS**

Observatoire de la CÔTE d'AZUR

CHARA

SPICA instrument in a nutshell

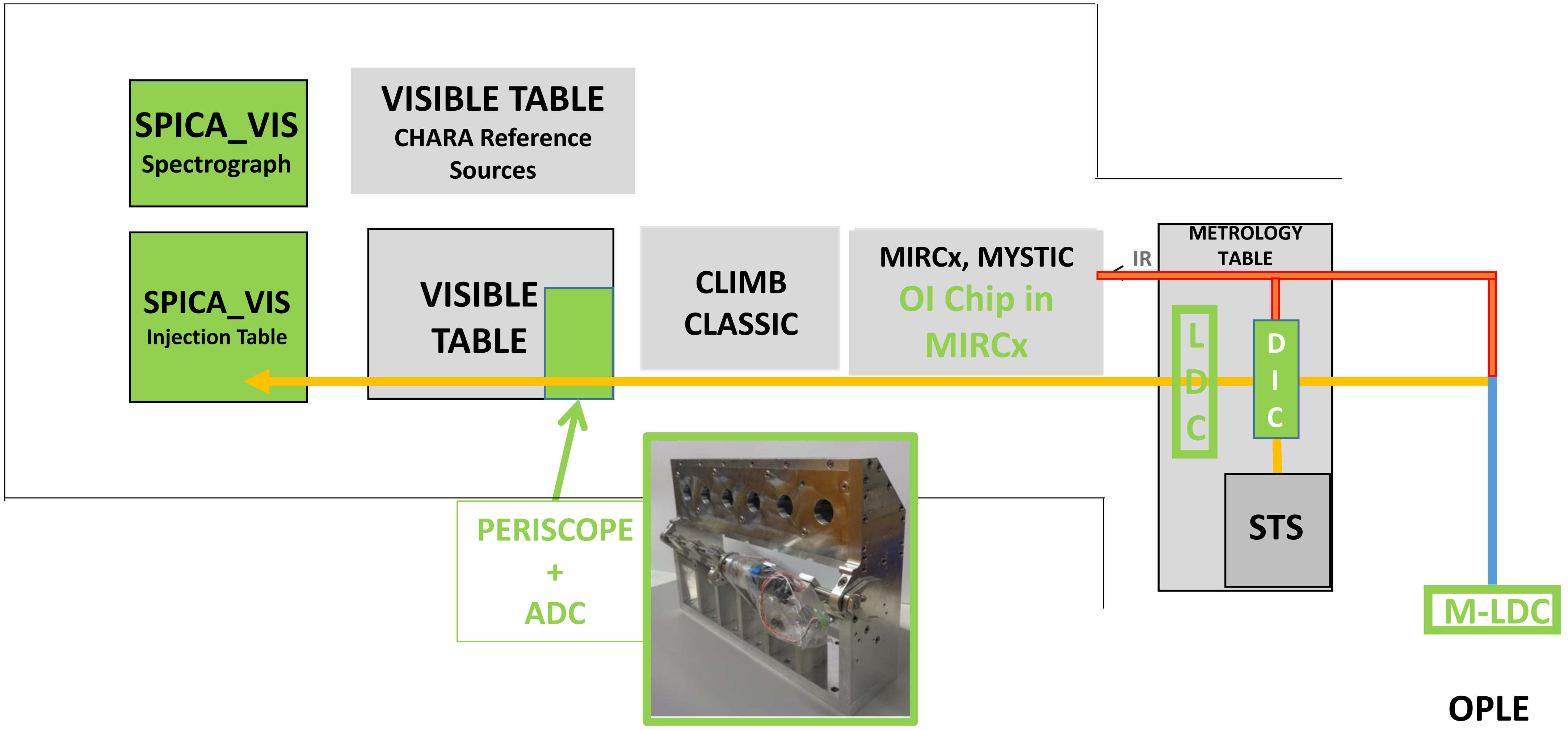
- *A H-band 6T-ABCD fringe sensor aiming at performing a group delay and phase delay tracking of the fringes.*
- A All-In-One 6T combiner (600-900nm) with three dispersion

MODES	Nb of SpCh	SpCh	Spectral Band	MagLim V^2=0.6	MagLim V^2=0.6 + FT	MagLim Vdiff	MagLim Vdiff+FT
LR: R=140	60	~5nm	300nm	**6.5**	11.5		
MR: R=4400	500	0.17nm	85nm			5.5	9.5
HR: R=13000	500	0.06nm	29nm			4.5	8.5

MagLim: V^2: SNR=10, 10mn of integration, for one spectral channel
Vdiff: [SNR=10, $\sigma\phi$<5°], V^2=0.6 in the reference channel, 30mn of integration, for one spectral channel

SNR calculator based on FRIEND calibration (Martinod+2018), CHARA-AO hypothesis **SR=5%** *, SPICA estimations*
Validation to be done on sky beginning of 2022

SPICA in the lab



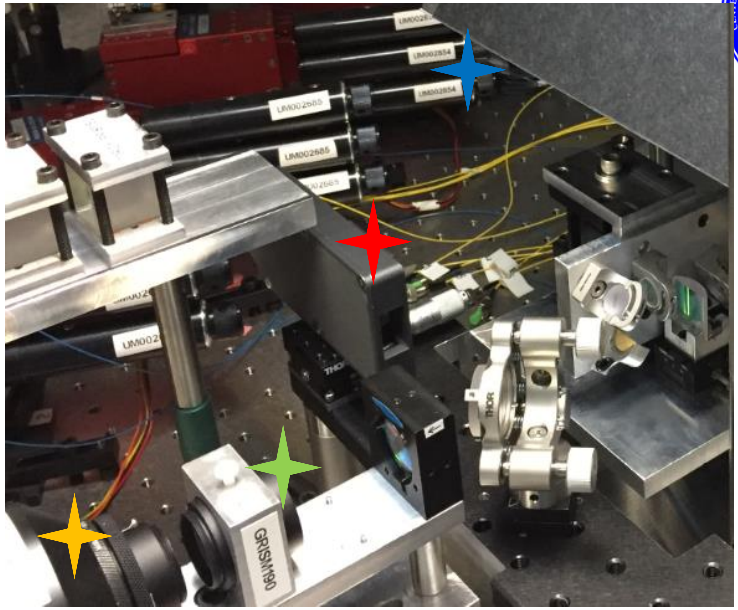
SPICA-FT

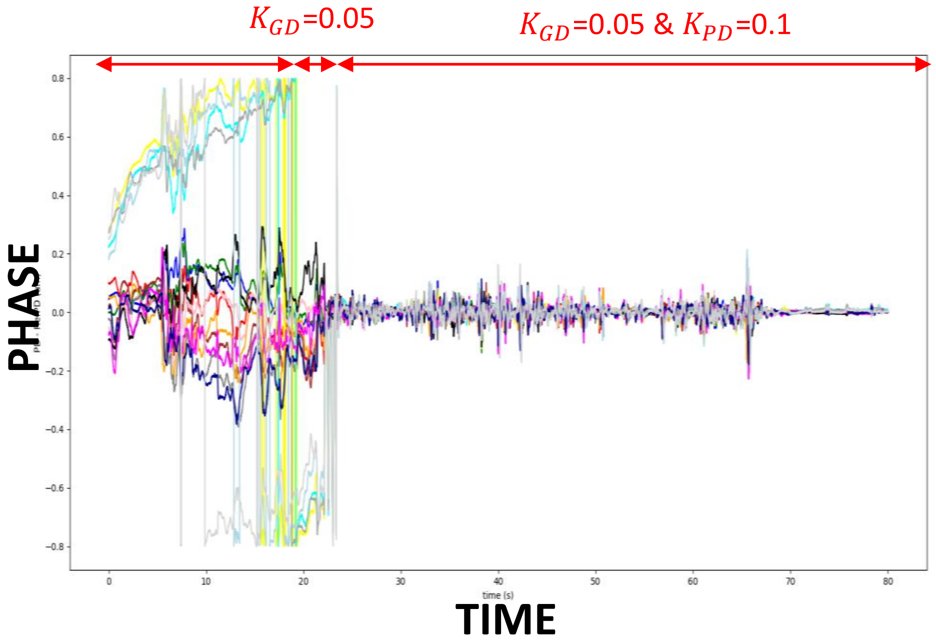
- Fibered IO device performing a **6T ABCD H band combiner**, using the **MIRCx fiber injection systems**, **the MIRCx spectrograph**, and the **CRedOne detector**.

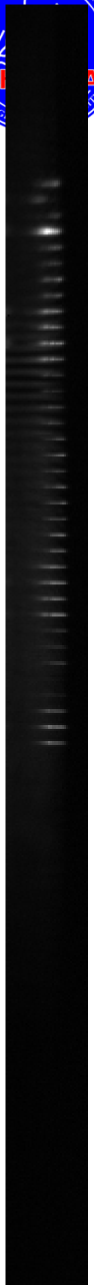
- Specifications:
  - Exposures from 20ms (GD) to 200ms (GD+PD) in the visible, $\lambda/8$ rms
  - Goal: reaching a few seconds of integration time

- First light in January 2020 (5T, GD only)
- Optimisation of the GD+PD loops on the testbed in Nice and in Mt Wilson
- Development of the State Machine
- 6T fringe search operational

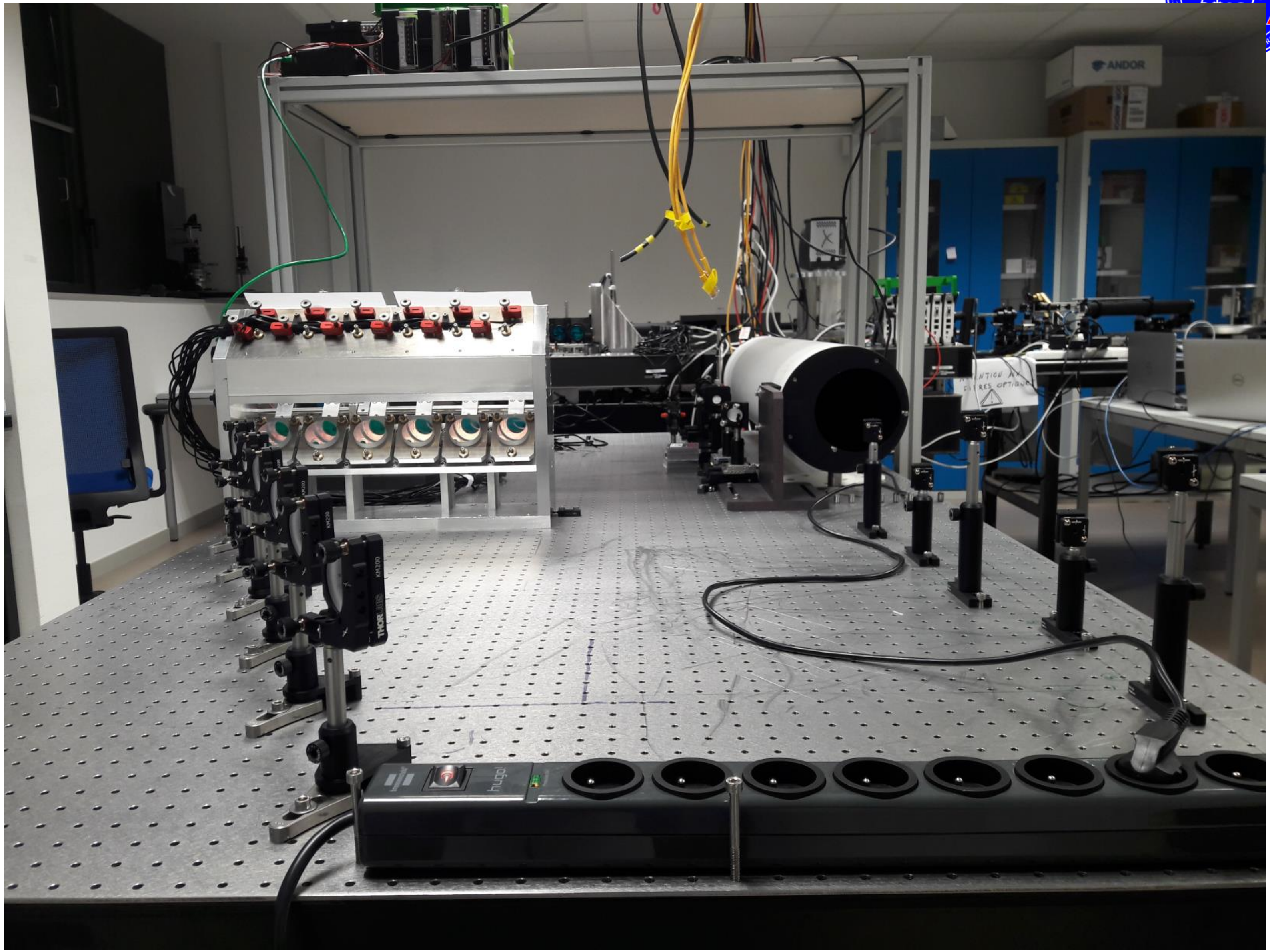
- Ongoing activities
  - More on-sky tests, also including the new OPLE control system
  - 3rd generation of the integrated optics chip: correction of internal instrumental CP, optimisation of the splitter function (summer 2021)
  - Addition of a predictive filtering (End of 2021 ?)





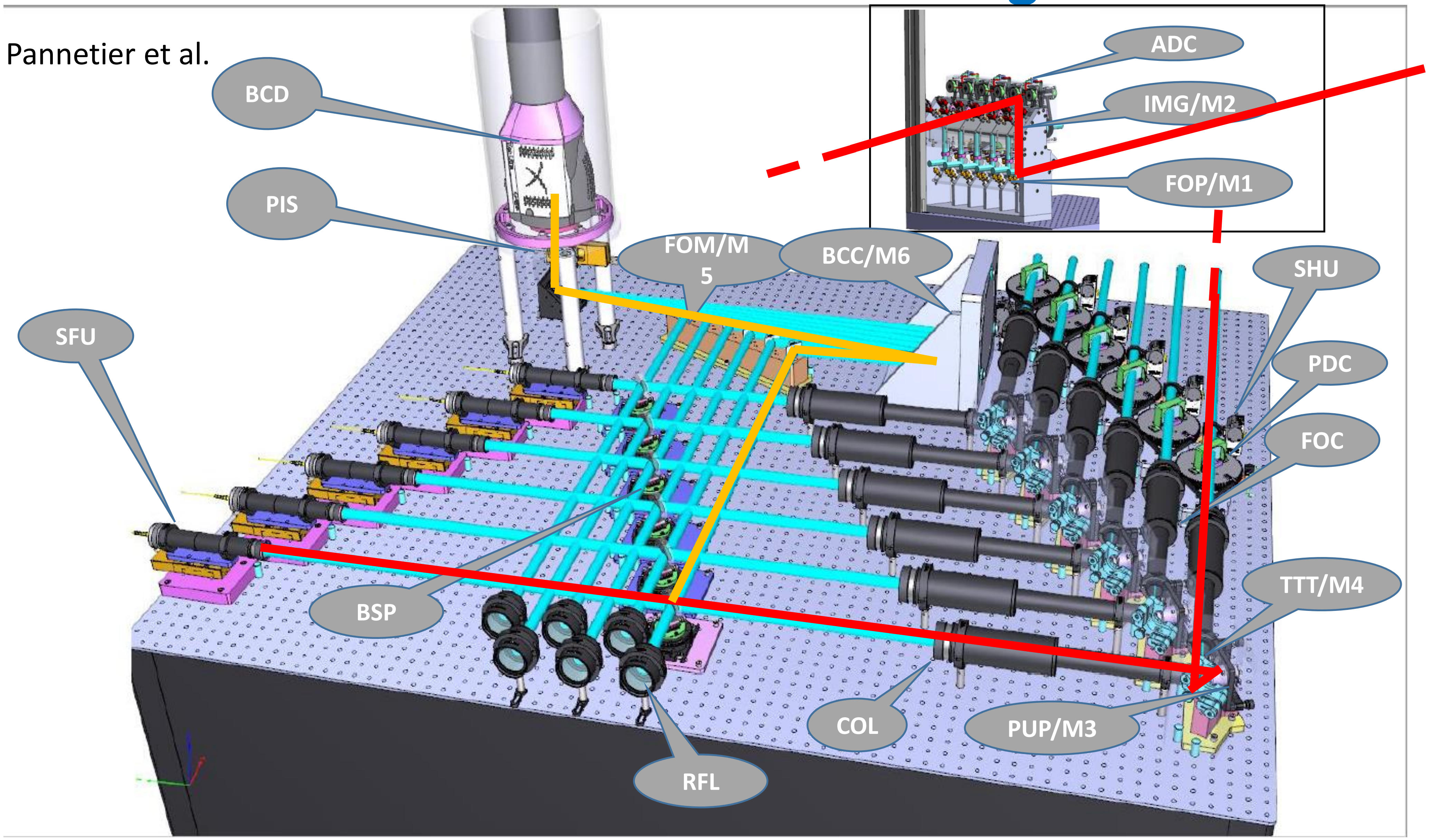


CHARA 6T simulator in Nice
+
Periscope

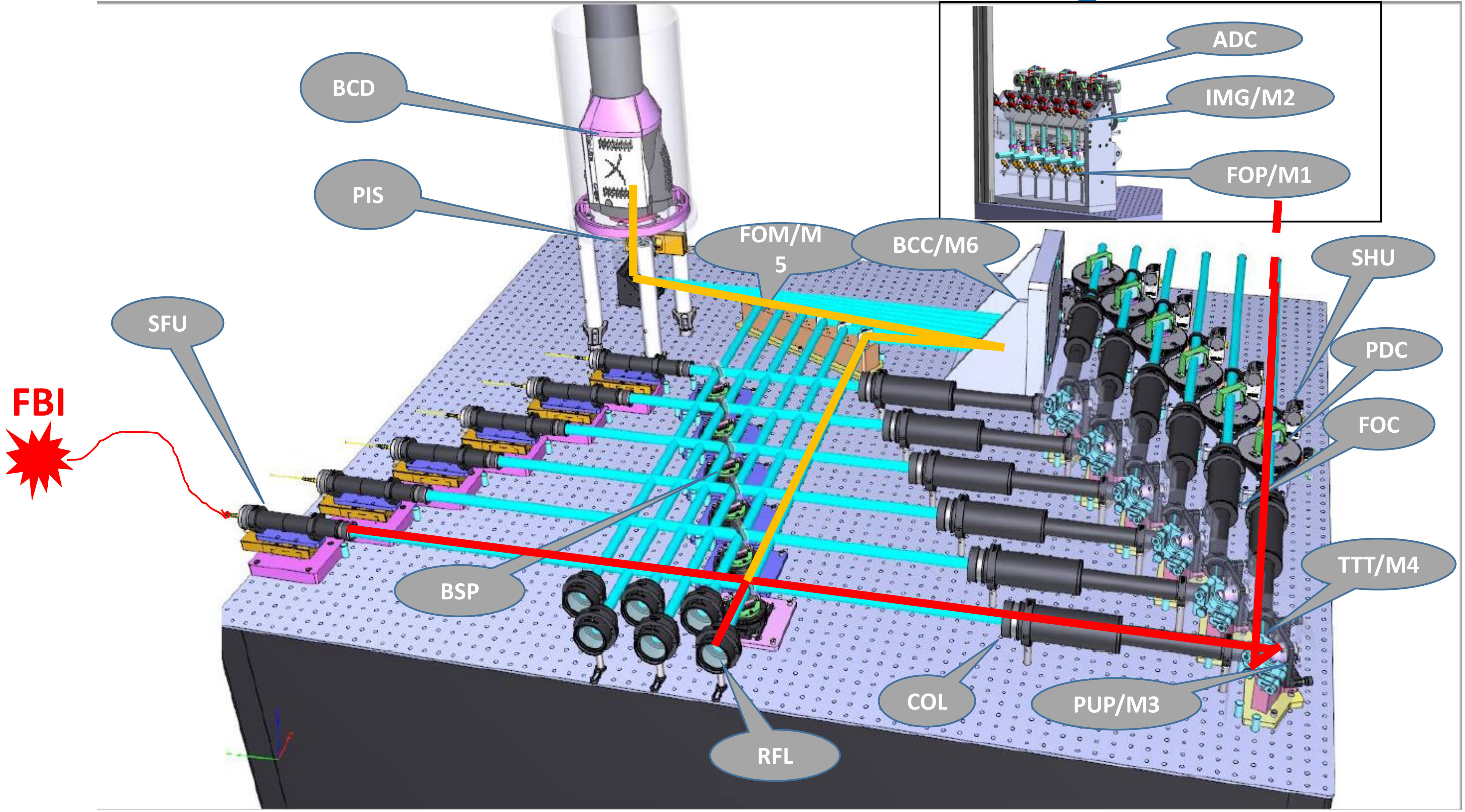


SPICA-VIS General design

SPIE 2020, Pannetier et al.



SPICA-VIS General design

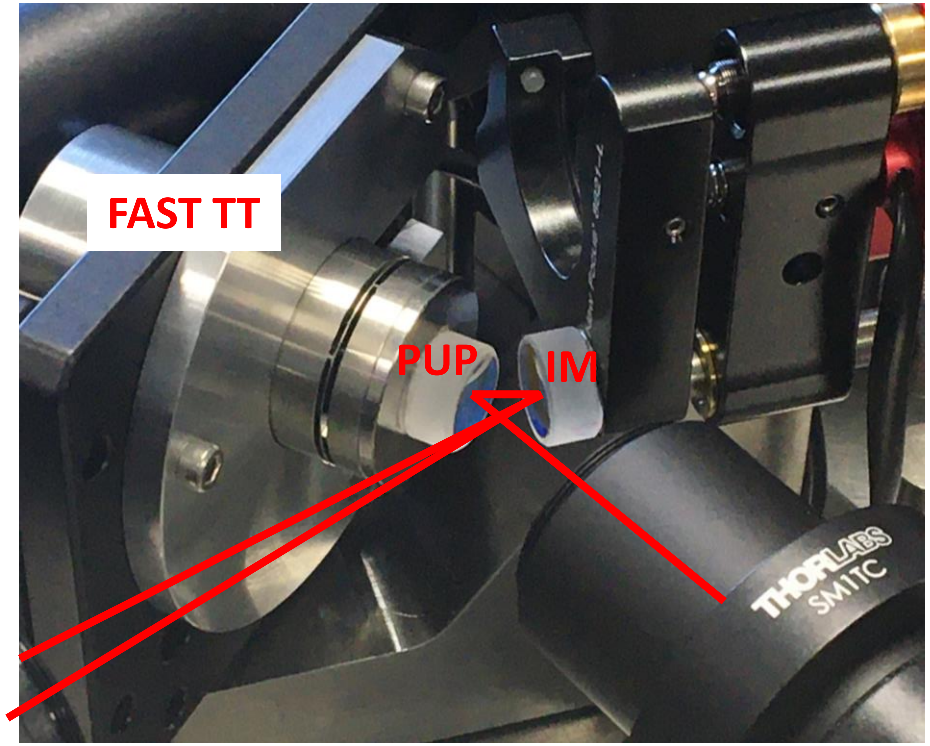


Observatoire de la CÔTE d'AZUR

SPICA-VIS injection table

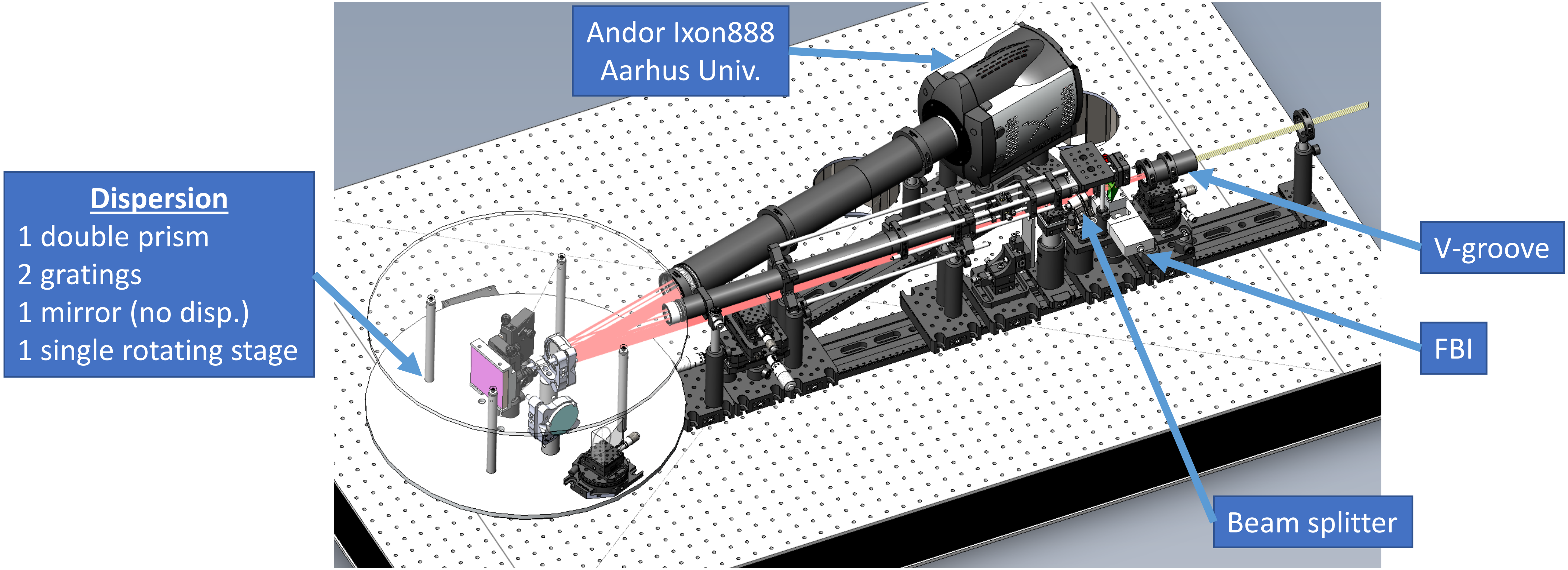
Every thing has been designed to optimize the injection in the fibres:

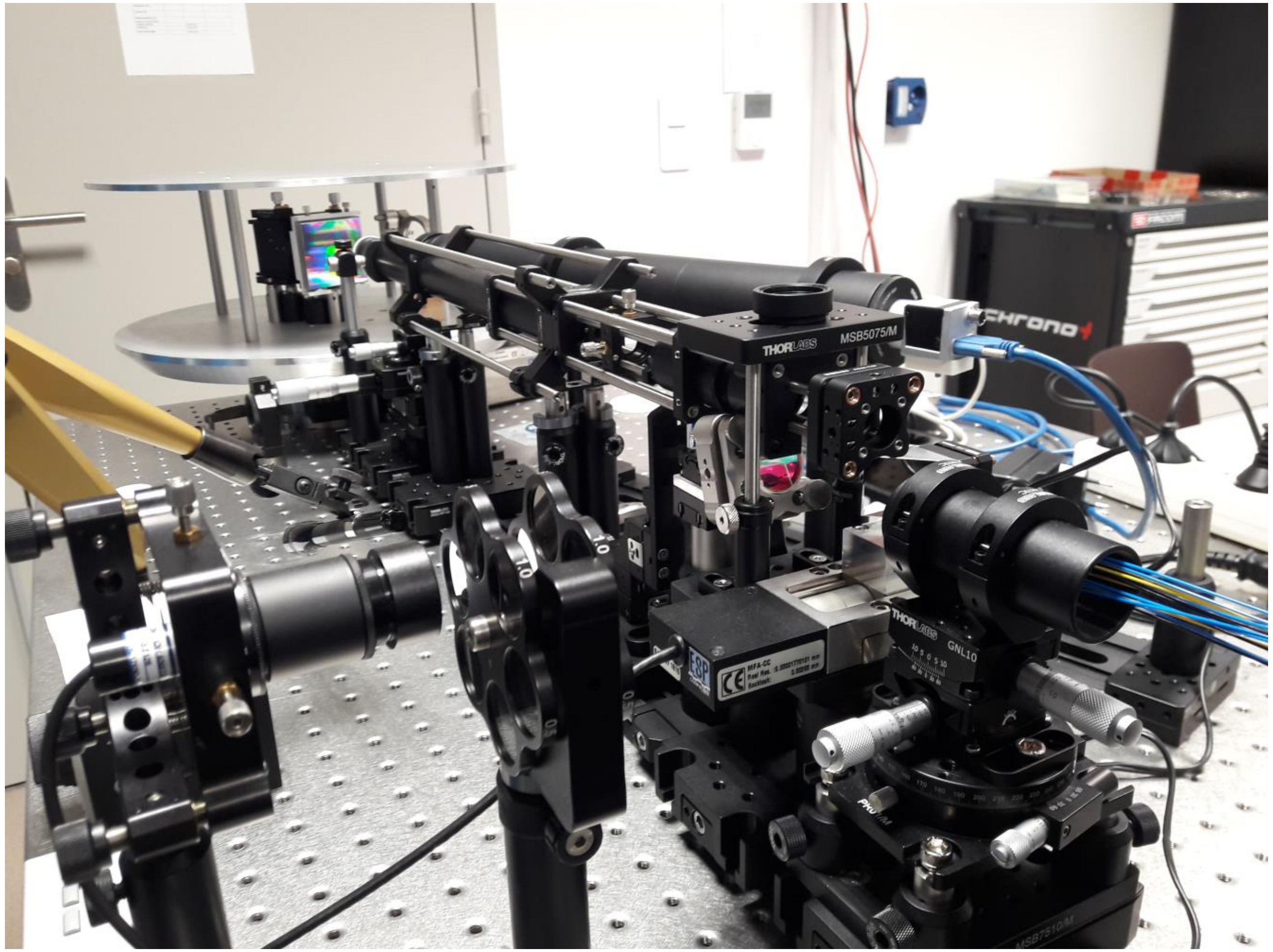
- Optical quality and high performance coatings
- Alignment in image and pupil plane control
- Fast tip/tilt correction to compensate the partial AO correction
- ADC for a good coupling all over the spectral band
- Fibre Back Illumination to avoid a time-expensive fibre explorer solution



SPICA-VIS spectrograph table

At the output of the V-groove, separation of photometric and interferometric channel
Anamorphosis of the interferometric channel and fringes in the image plane after the dispersion
Dispersion of the photometric channel in the 'pupil' plane
Optical design by CP, mechanical design by JD



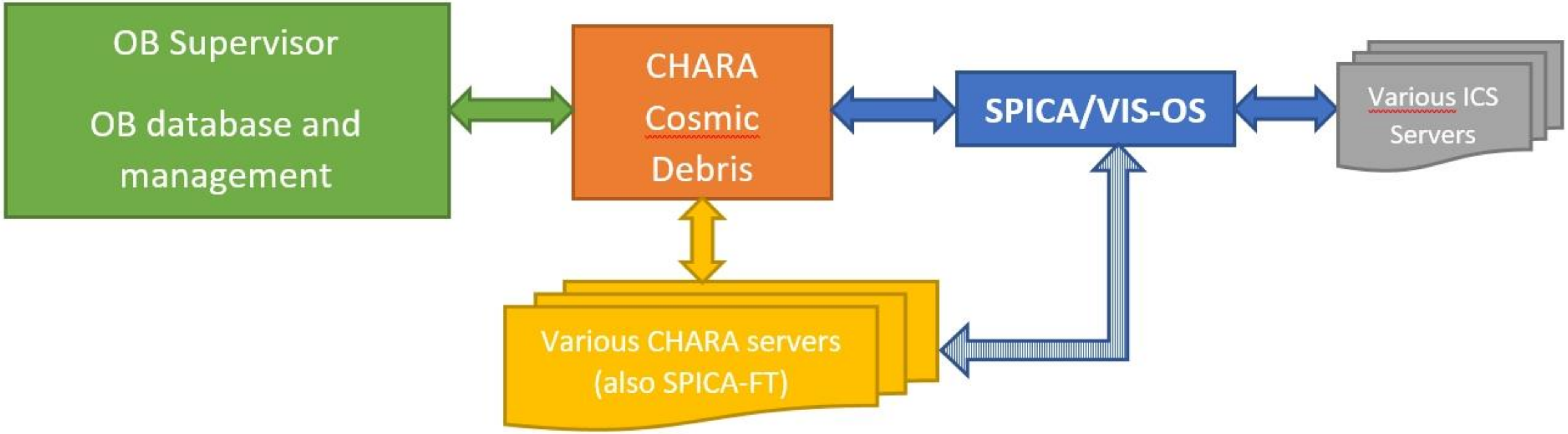


Photos: C. Pannetier

SPICA-VIS Observing Software

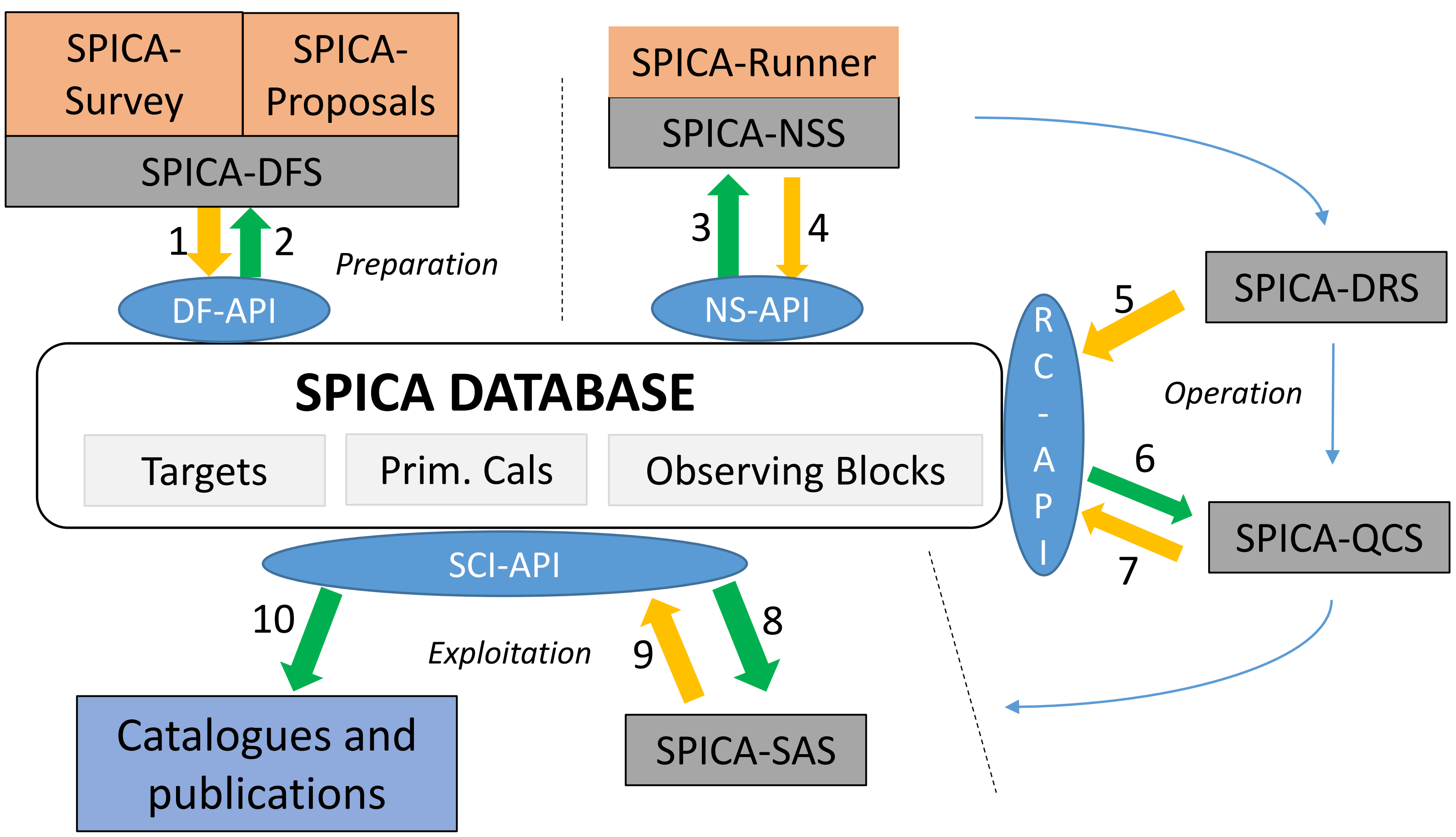
Global architecture

- CHARA Cosmic Debris is the highest client (including SPICA-FT server)
- OB supervisor for observation information (JMMC A2P2 principle adapted to CD)
- OS observation information from CD
- OS control of all SPICA-VIS devices thru servers

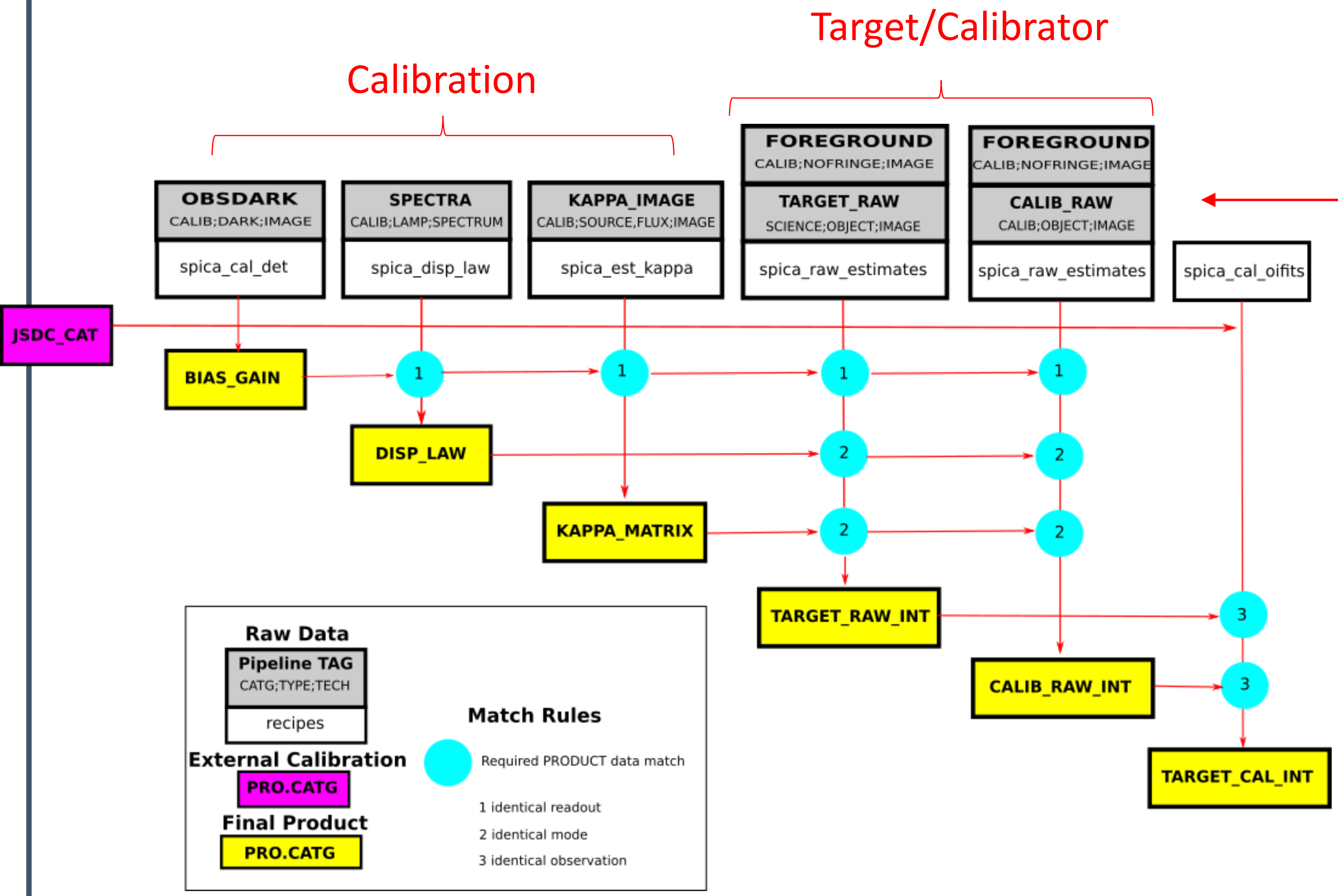


SPICA-VIS Science operation (JMMC collaboration)

Database based on ObsPortal, OIDB, JSDC, ASPRO2 at JMMC



SPICA-VIS DRS (heritage from VLTI/MATISSE & FRIEND *Martinod 2018*)



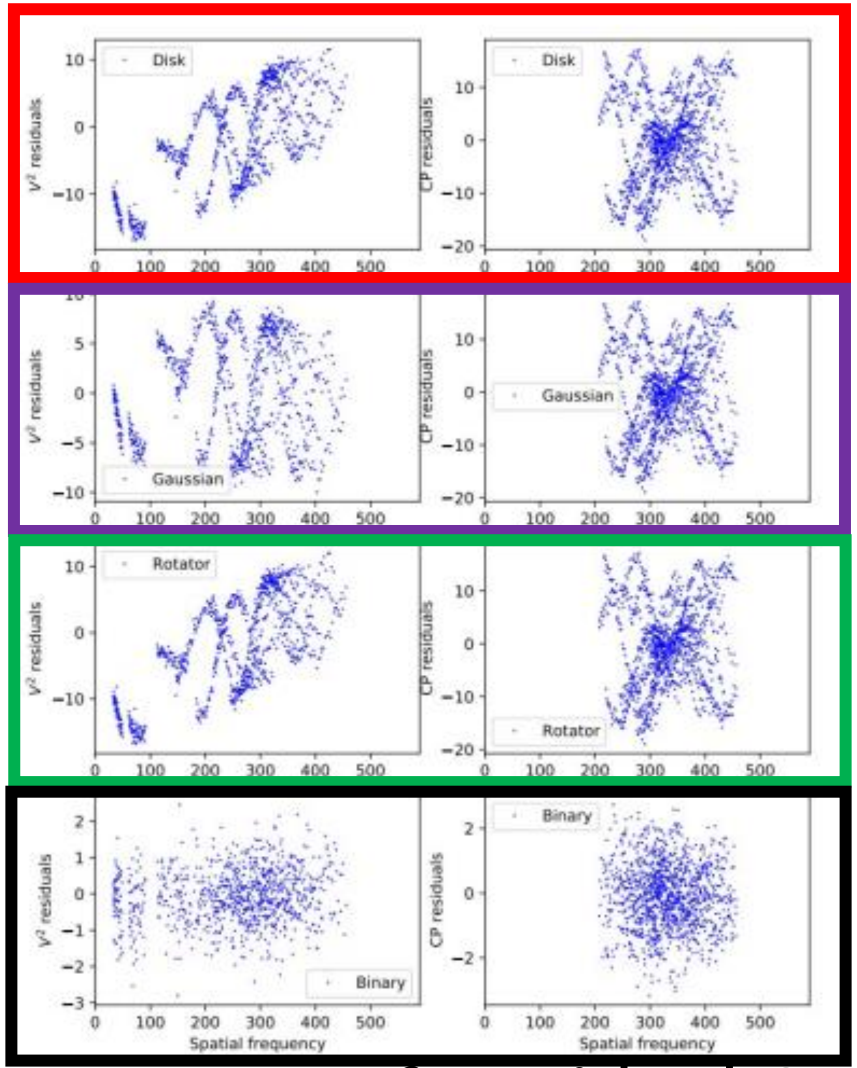
Match Rule	Keyword Name	Keyword Description
Identical Readout	HIERARCH DET NAME HIERARCH DET DIT HIERARCH DET GAIN	Detector Name Detector Frame Time Detector Gain
Identical Mode	HIERARCH INS RESOL HIERARCH INS CENTRAL WL	Spectral Resolution (LOW, MED, HIGH) Central Wavelength
Identical Observation	Identical Readout + Identical Mode + HIERARCH TPL START HIERARCH FT STATUS HIERARCH NB TEL	Starting date of observation (difference between calibrator and target should be less than xx hours) Fringe Tracker Status (NONE, TRACKING) Number of telescopes

SPICA-VIS Quality Control

Automatic fit at the end of the night on all targets and calibrators. 4 models:

1. Uniform disk
2. Uniform disk + gaussian
3. Elongated disk (fast rotators)
4. **Binary using CANDID (Antoine Mérand)**

Computations made by D. Salabert, using ASPRO2 (SPICA) and the SPICA autofitting function.

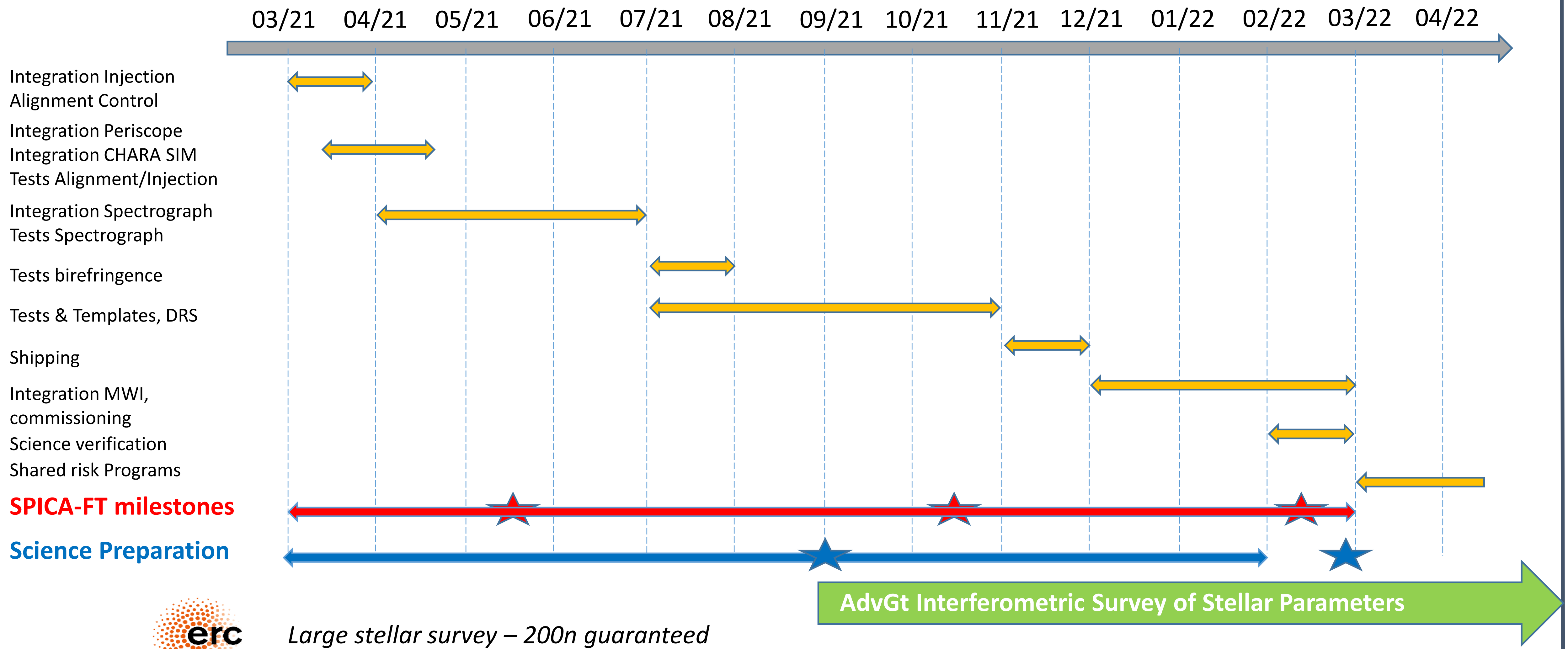


residual V² residual CP

	A	B	C
1	QCS_UD_DIAM	0.373480	
2	QCS_UD_ERRDIAM	0.001192	
3	QCS_UD_REDCHI2	59.185	
4	QCS_UD_NBDOF	2099	
5	QCS_GAUSS_DIAM	0.343815	
6	QCS_GAUSS_ERRDIAM	0.002100	
7	QCS_GAUSS_FWHM	16.635100	
8	QCS_GAUSS_ERRFWHM	165135603805.865784	
9	QCS_GAUSS_FRATIO	0.064068	
10	QCS_GAUSS_ERRFRATIO	0.003919	
11	QCS_GAUSS_REDCHI2	47.330	
12	QCS_GAUSS_NBDOF	2097	
13	QCS_ROTATOR_MAJORDIAM	0.375595	
14	QCS_ROTATOR_ERRMAJORDIAM	0.002086	
15	QCS_ROTATOR_ELONG	1.012273	
16	QCS_ROTATOR_ERRELONG	0.010056	
17	QCS_ROTATOR_PA	75.102742	
18	QCS_ROTATOR_ERRPA	20.143640	
19	QCS_ROTATOR_REDCHI2	59.141	
20	QCS_ROTATOR_NBDOF	2097	
21	QCS_BINARY_DIAM1	0.350401	
22	QCS_BINARY_ERRDIAM1	0.000160	
23	QCS_BINARY_X	1.414643	
24	QCS_BINARY_ERRX	0.000448	
25	QCS_BINARY_Y	1.413492	
26	QCS_BINARY_ERRY	0.000441	
27	QCS_BINARY_FRATIO	4.890021	
28	QCS_BINARY_ERRFRATIO	0.013444	
29	QCS_BINARY_REDCHI2	0.823	
30			

Database feeding

SPICA planning



European Research Council
Established by the European Commission

Large stellar survey – 200n guaranteed

5-year grant, many job opportunities (observation, stellar models…. **Stay tuned!)**