STATUS OF SPACE BASED CORONOGRAPHIC MISSIONS

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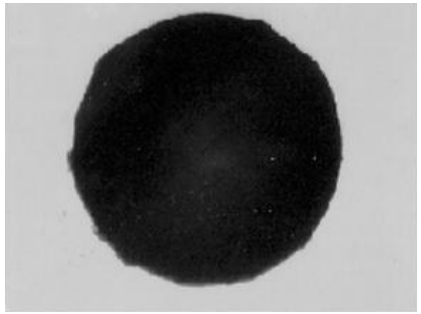
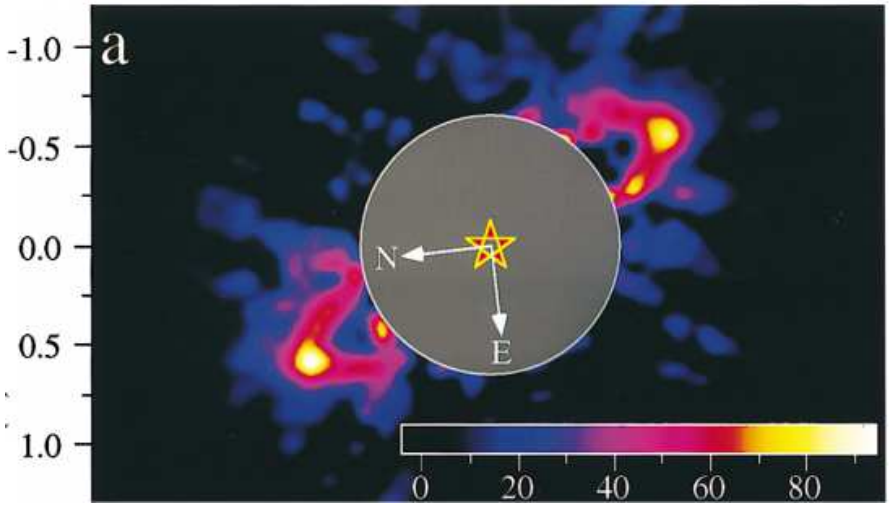
HST – NICMOS/STIS

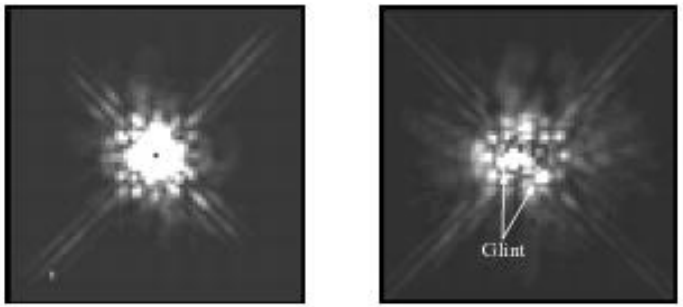
http://www.stsci.edu/hst/nicmos/

- occulting hole in the Camera 2 FDA mirror
- internal cryogenic mask located at the Lyot plane.
- glints limit to > 0,4 arcsec
- contrast : ~10^{-4} @ 0,4 arcsec
- image example :



HR4796A circumstellar disk (Schneider et al, 1999)



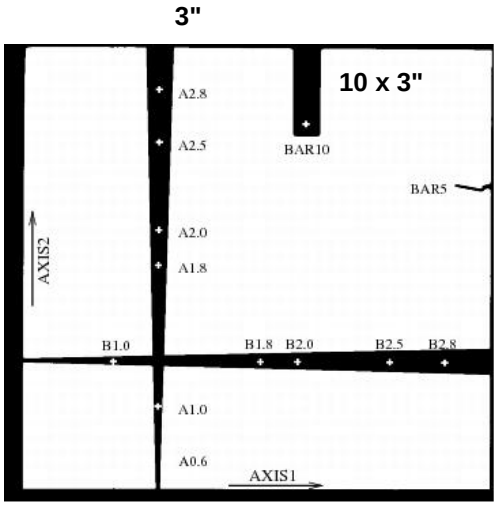


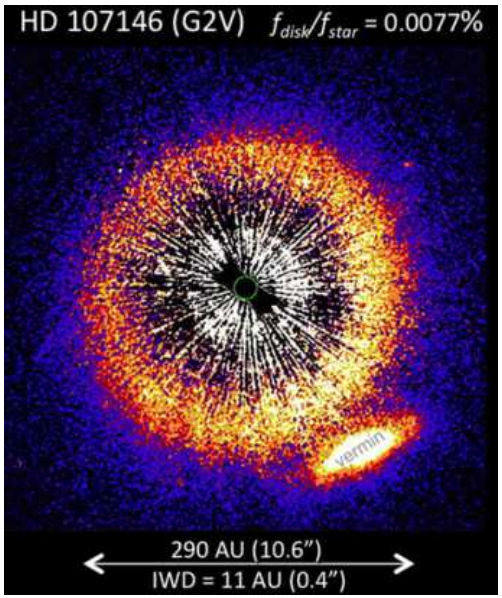
outside hole within hole

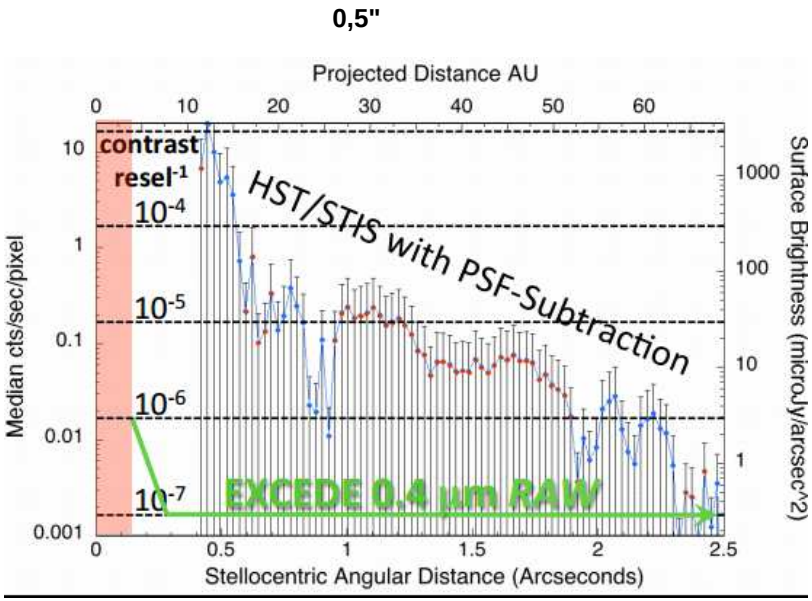
HST – STIS

- 1 occulting bar + 2 wedges
- limited apodization via a Lyot stop
- status : still in operation
- Schneider et al 2014

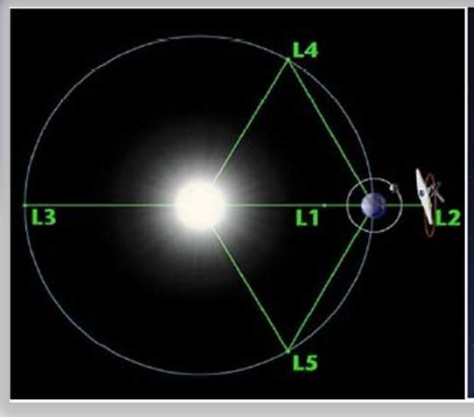
http://www.stsci.edu/hst/stis/

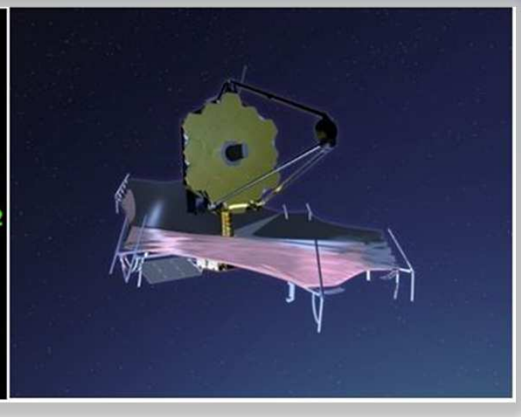




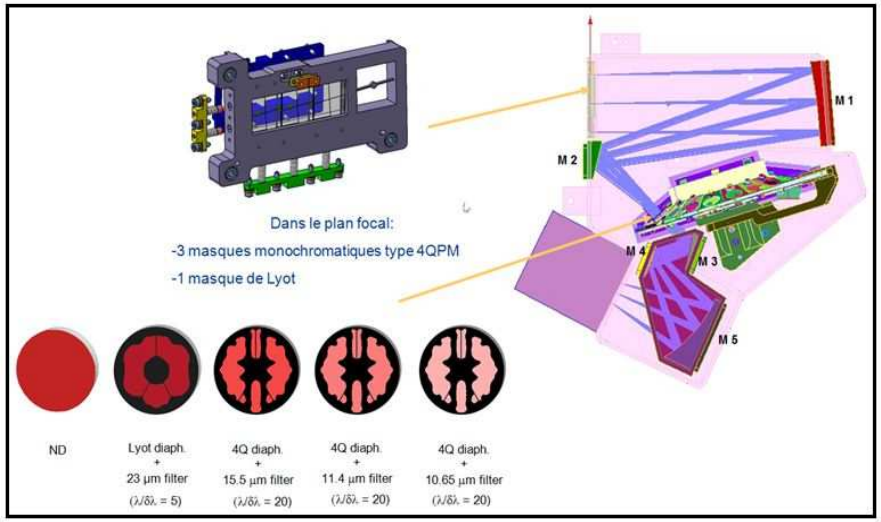


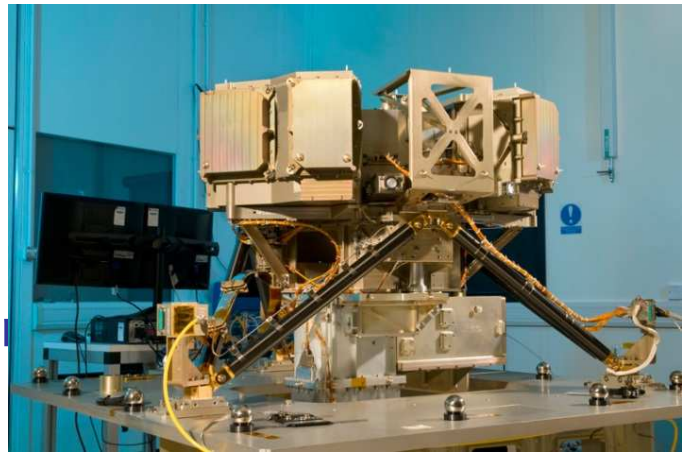
JWST/ MIRI (1/2)





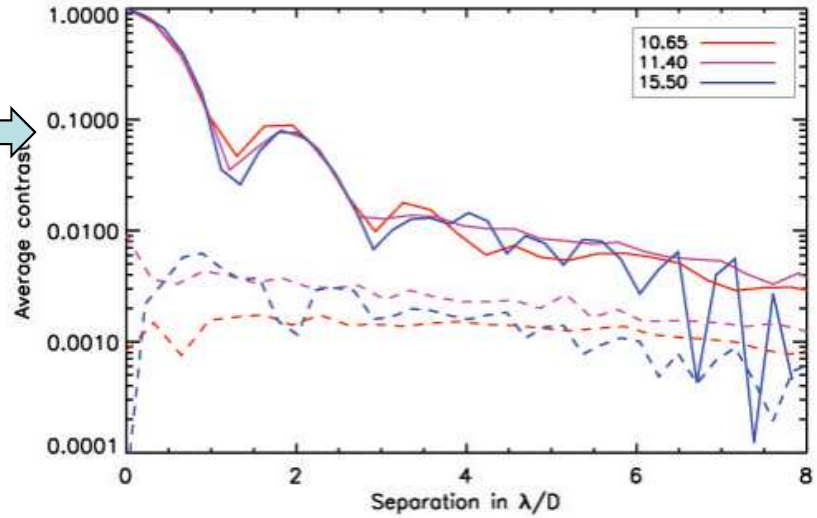
- MIRIM : imager, under french leadership, with coronographic capability
- Goals :
  - Jovian planets around close stars
  - Circumstellar disks, AGN
- 3 4QPM : 10.65/ 11.4/15.5µm, 1 Lyot at 23 µm
- Lyot stops on filter wheel
- fine pointing using FSM : few mas 1 sigma
- status :
  - AIT phase at NASA Goddard
  - February 20, 2014 : mounted on instrument payload
  - Launch end 2018



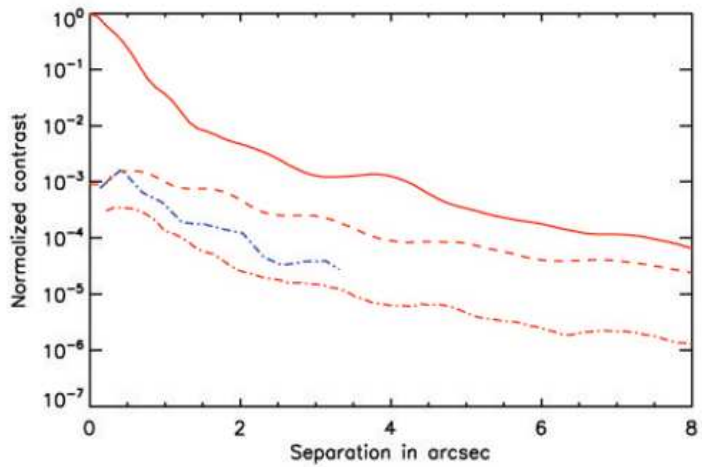


JWST/MIRI (2/2)

- corono : lab. perfomance, (bocaletti 2014)
- corono + telescope : simulations, depends on
  - Pointed target
  - Assumption on WFE error
  - Assumption on noises
  - Reference star substraction process
- ~10^{-5} contrast @ 4-6 λ/D seems achievable (10 µm)

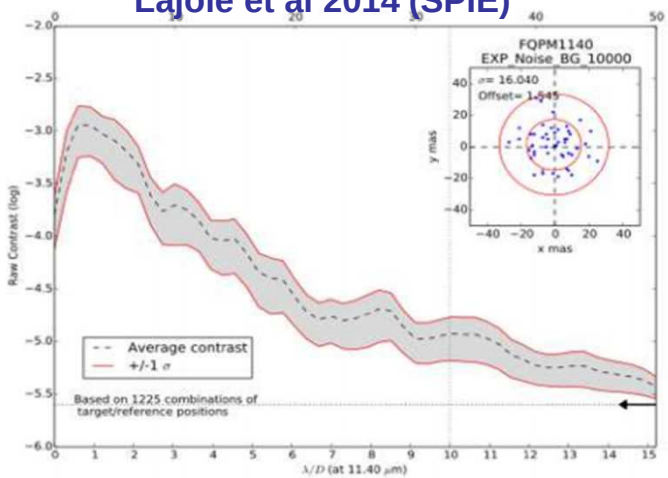


Bocaletti et al – 2014



F1140C, No noise, WFE 130 nm, PSF plain, with corono dotted, with ref image sub. dash dotted – blue WFE more pessimistic

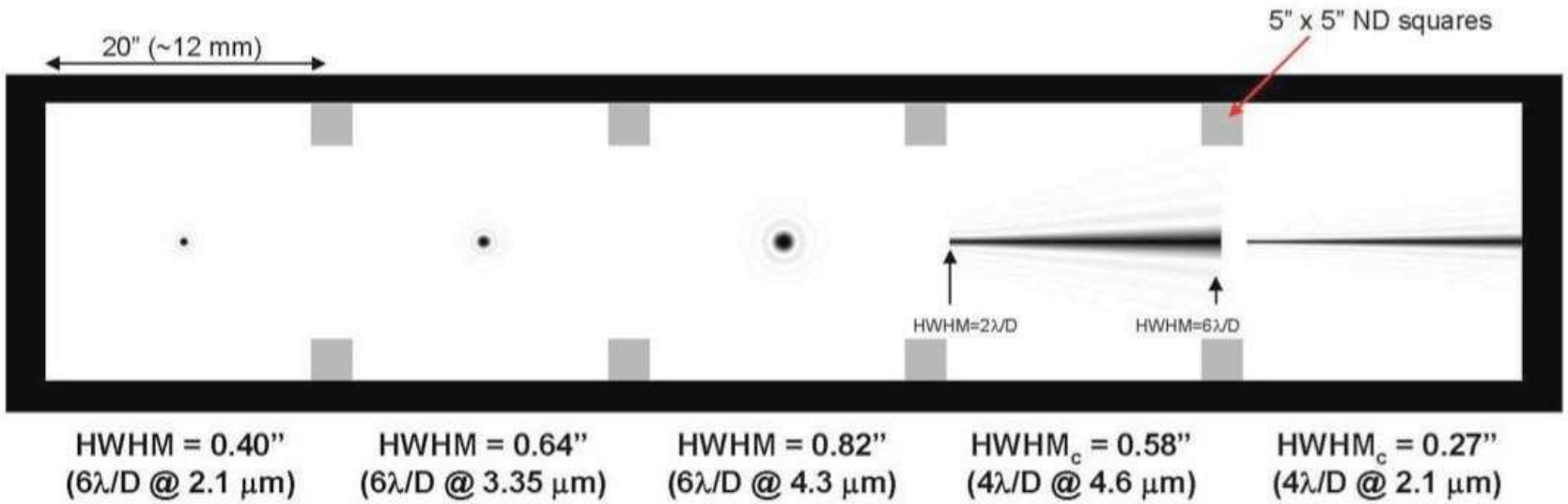
Lajoie et al 2014 (SPIE)



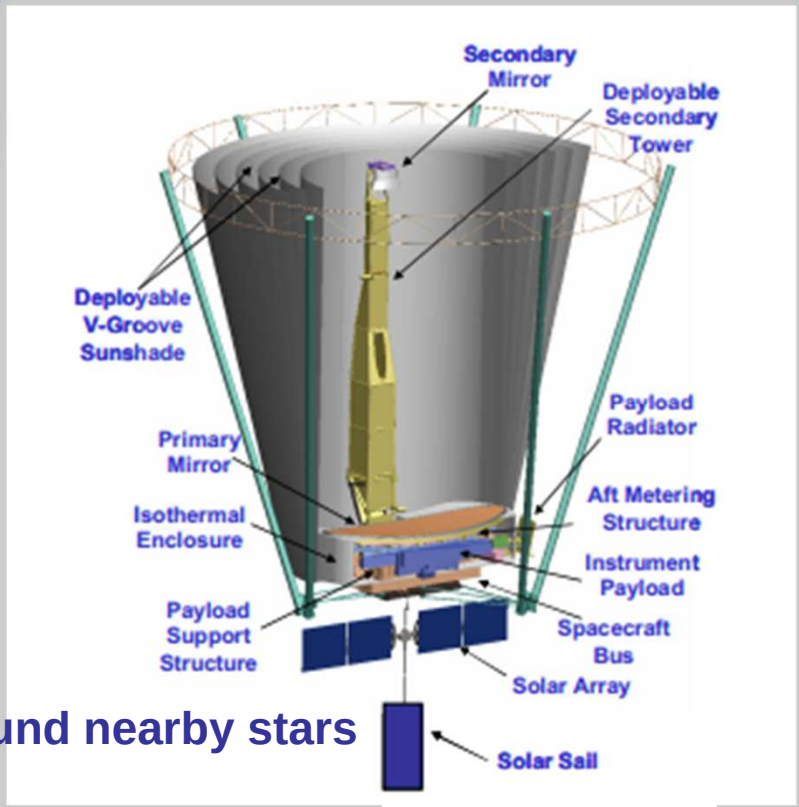
Include pointing errors, more pessimistic WFE

JWST/ NIRCAM

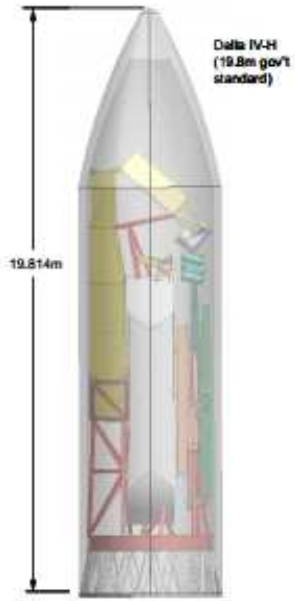
- Nircam has also a coronographic mode
- five occulters on a transparent plate
- 3 radially-symmetric occulters with “sombrero” profiles
- 2 wedge-shaped occulters with sinc2 profiles
- Apodized masks in the lyot plane on a wheel



TPF-C (1/2)

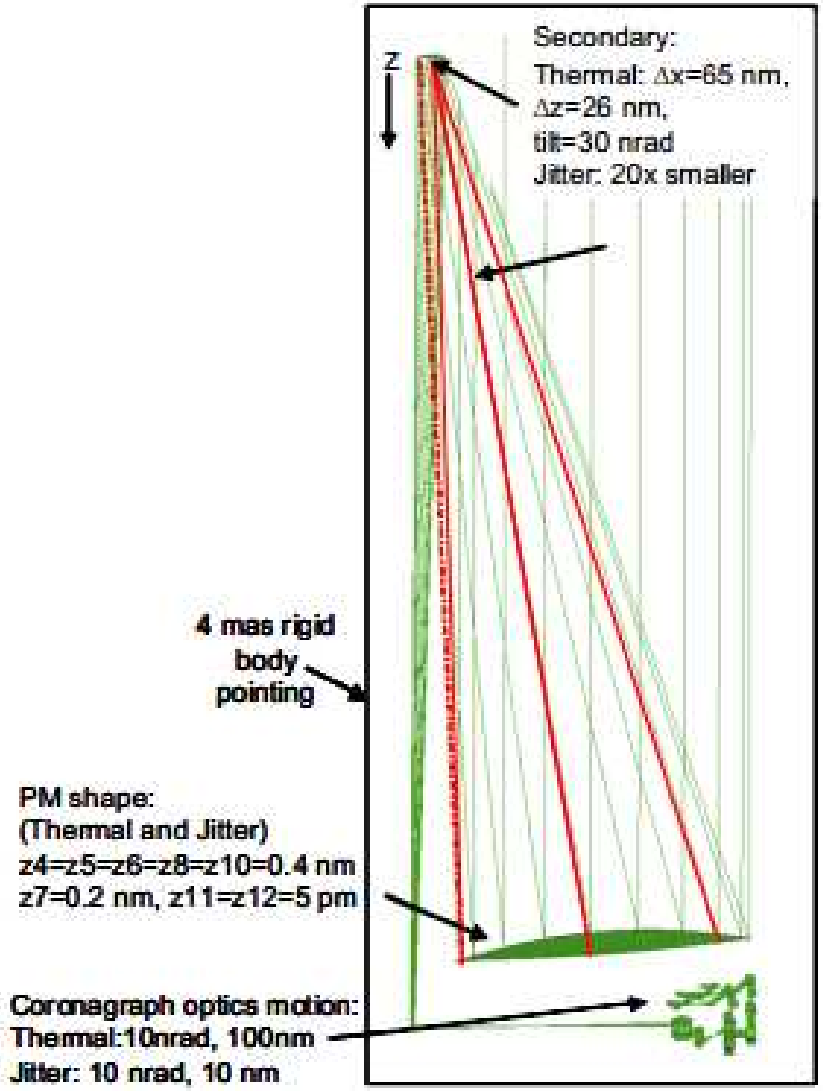


- studies in the US 2000-2008
- main document (JPL)
  - TPF-C flight Baseline Mission Concept (2009)
- goals :
  - Main : discover and study exo-earths in the HZ around nearby stars
  - others : giant planets, disks, general astrophysics
- spectral range : 0,5-1,1 µm, spectral resolution : $\lambda/\Delta\lambda=70$
- deployable M2 and sun shade
- L2 orbit, launcher Delta IVH, launch mass 8 tons
- cost = JWST class…
- status : cancelled in 2008



TPF-C (2/2)

- **FB1 optical design**
  - **FOV = +/- 5 arcsec**
  - **order 8 Lyot coronograph @ 4 λ/D**
  - **10^{-10} contrast**
  - **IWA = 65 mas, OWA = 500 mas**
  - **M1 : 8 x 3,5 m elliptical, off-axis – f1=13,4 m**
  - **EFL = 140 m, tel height=12 m**
  - **Off axis Ritchey-Chretien**
  - **straylight level 6 10^{-11} of stellar peak brightness**
  - **4 IFS - Δλ/λ=20%**
  - **1 Wide field camera**



SPICES (1/2)

- proposed for M3 CV Call in 2010 – (Seacoast => SPICES)
- european consortium led by A. Boccaletti
- main document : CV M3 proposal
- spectro-polarimetry in the visible, with main goals :
  - Long period giants (0,5-10 AU), < 20pc
  - Close super earths (0,5-2 AU), < 5pc
  - Atmosphere properties, formation process, exozodi,…
- 400-800 nm, 2 bands
- spectral resolution : $\lambda/\Delta\lambda$=50-100
- L2 orbit, Soyuz, launch mass ~2 t
- cost = > ~ 600 ME=> not a M mission
- Current status : not submitted to M4 call

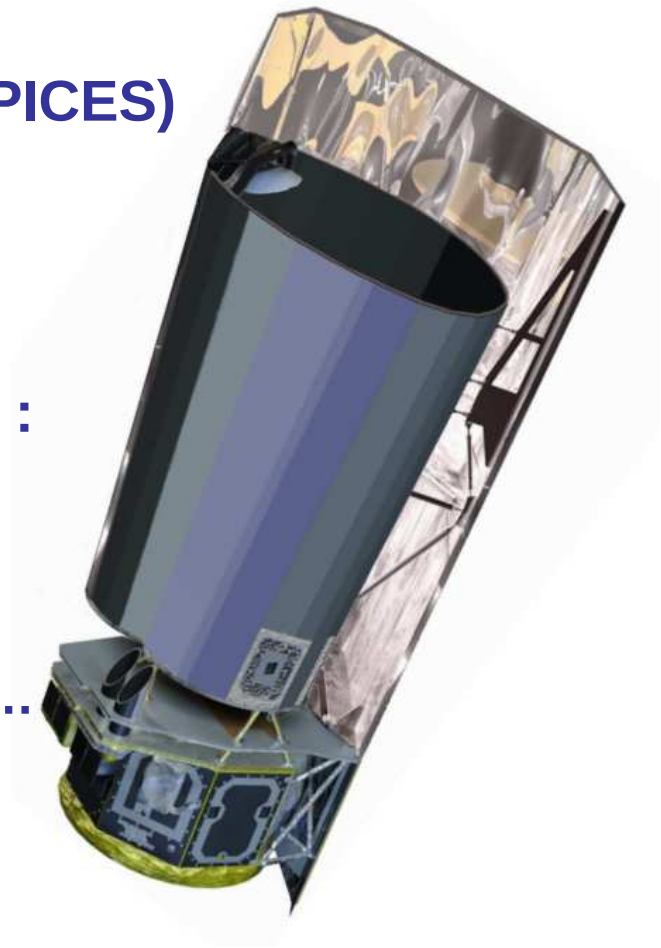
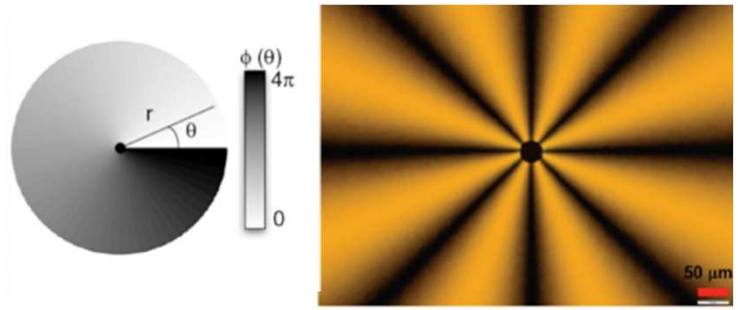


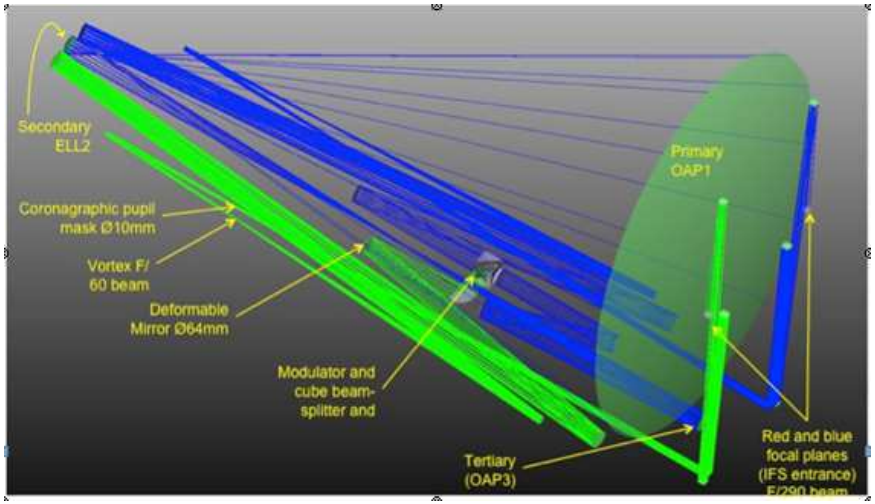
Table 10: Summary of pointing requirements for SPICES

	Spacecraft	Telescope	Coronagraph
1st stage	>10"		
2nd stage	10 - 100mas	1-10 mas	
3rd stage			0.1 mas

SPICES (2/2)

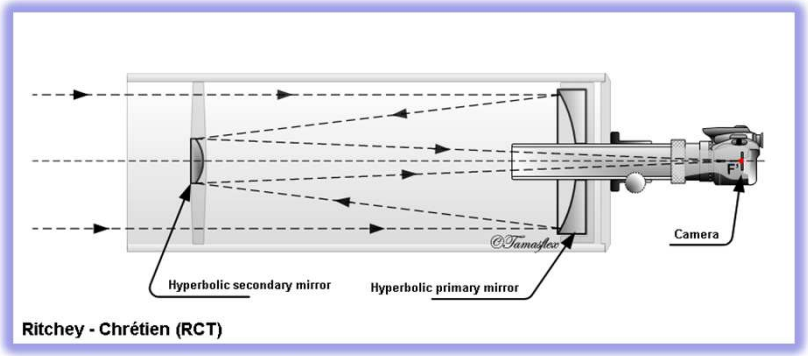
- optical design
  - 3 mirrors afocal telescope (2 OAP: + 1 pure elliptical concave mirror)
  - 64 mm pupil on DM
  - M1 : 1,5 m
  - FOV = +/- 6 to 12 arcsec
  - 10^{-9} to 10^{-10} contrast
  - Charge 4 Vortex corono. 1.8 λ/D – 2.4 λ/D
  - IWA = > 100 mas
  - WFE static : 20 nm rms, fine control : 10 pm rms (SCC/EFC + 64 x 64 boston DM)
  - 2 IFS





WFIRST-AFTA
Wide Field Infrared Survey Telescope

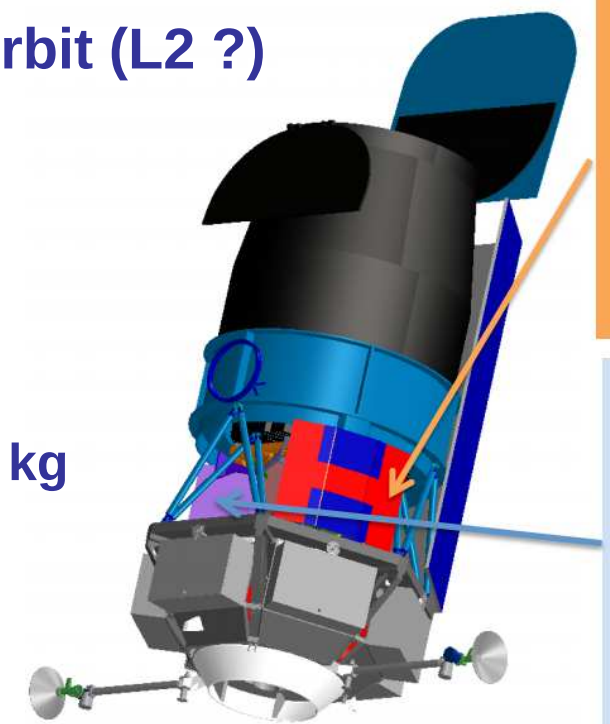
- Doc : WFIRST-AFTA SDT Interim Report – 04/2014, WFIRST conf. 11/2014
- WFIRST : NIR mission recommanded in 2010 US decadal survey, answer to *New Worlds, New Horizons* (NWNH)
- AFTA = Air Force Telescope Assembly, Ritchey-Chretien, D=2,4m 250M$



- Goals :
  - Determine the nature of the dark energy
  - statistical census of planetary systems through microlensing survey
  - Survey the NIR sky / provide the community with a wide field telescope for pointed wide observations
  - giant planets and debris disks with coronograph

WFIRST-AFTA DESCRIPTION

- launch 2020-2025
- Cost class : 1-1,5 Billion $
- geosynchronous orbit (L2 ?)
- mass
  - Satelllite : ~7,5 t
  - Telescope : ~ 1,8 t
  - Instrument : ~ 700 kg



Wide-Field Instrument

- *Imaging & spectroscopy over 1000s of sq. deg.*
- *Monitoring of SN and microlensing fields*
- 0.7 – 2.0 micron bandpass
- 0.28 deg^2 FoV (100x JWST FoV)
- 18 H4RG detectors (288 Mpixels)
- 6 filter imaging, grism + IFU spectroscopy

Coronagraph

- *Imaging of ice & gas giant exoplanets*
- *Imaging of debris disks*
- 400 – 1000 nm bandpass
- $\leq 10^{-9}$ contrast (after post-processing)
- 100 milliarcsec inner working angle at 400 nm

WFIRST-AFTA STATUS

- **Status (from a NASA talk, nov. 2014) :**
  - **Currently in “pre-formulation phase” - (pre-phaseA)**
  - **AFTA endorsed by NRC study report released March 2014.**
  - **Interim SDT report posted April 30, 2014**
  - **SDT final report due Jan 2015**
  - **FY14 appropriation ($56M) supports preformulation of WFIRST/AFTA, including**
    - technology development for detectors and
    - coronograph (with STMD)
- **coronograph instrument still to be confirmed in 2015**

WFIRST-AFTA : NRC REVIEW ON CORONOGRAPH

- US National Research Council review Performed in January-February 2014 to determine if WFIRST-AFTA meets the WFIRST requirement in NWNH

Finding 2-6: Introducing a technology development program onto a flagship mission creates significant mission risks resulting from the schedule uncertainties inherent in advancing low technical readiness level (TRL) hardware to flight readiness.

Finding 1-7: The WFIRST/AFTA coronagraph satisfies some aspects of the broader exoplanet technology program recommended by NWNH by developing and demonstrating advanced coronagraph starlight suppression techniques in space.

Recommendation 2-1: NASA should move aggressively to mature the coronagraph design and develop a credible cost, schedule, performance, and observing program so that its impact on the WFIRST mission can be determined. Upon completion … an independent review

WFIRST-AFTA : A EUROPEAN CONTRIBUTION ?

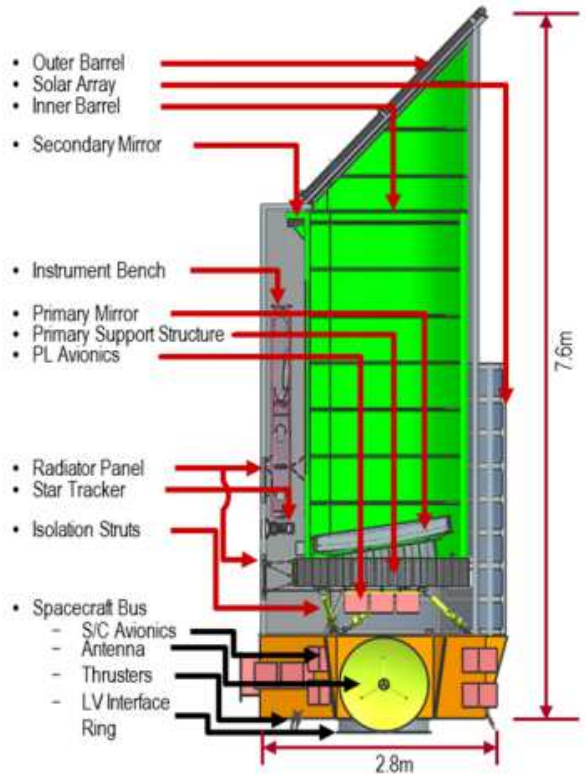
- french and UK scientist expressed interest to participate to a coronograph instrument in WFIRST-AFTA
- experience of LAM, LESIA, OCA LAGRANGE in coronography, ground or space based (MIRI, SPHERE, THD SCC, SPEED,…)
- CNES R and D contributes to a high expertise level and detailed exeprimental work in the field
- CNES supports and encourages participation in WFIRST-AFTA based on a TBD contribution in the appropriate labs
  - Cornograph seems excluded, as well as fine WFE measurement/control
  - Another subpart of the instrument has to be identified : Optics ? Detectors ? Electronics ? Tests ?
- a consortium should be build to organize this and study the various possibilities
- planning is important for CNES => When will the funding will be necessary ?

CNES R and D EFFORT

- **CNES R and D in HRA and coronography**
  - **2000- 2003 : LESIA, support to first 4QPM=> MIRI**
  - **2003-2010 : IR interferometry (Synapse, Persée,…), european priority**
  - **2010-2014 : LESIA, Self Cohernet Camera, 1 PhD**
  - **2014 : + ONERA phase diversity for coronography, 1 PhD**
  - **2015 :**
    - PIAA for SPEED at OCA and Vortex at LESIA
    - prospective action with LAM, possibility of making a boston-like DM in Europe (german design, switzerland fab., test at LAM – 32 x 32 actuators)
- **simple breadboard at CNES started in 2014, monochromatic, 10^{-7} contrast**
  - **DM techno/WFE sensing complementary to OTOS (earth observation)**
  - **Goal : better understand the basics to better adress key questions for space application in the future : space qualification, pointing, thermal stability**

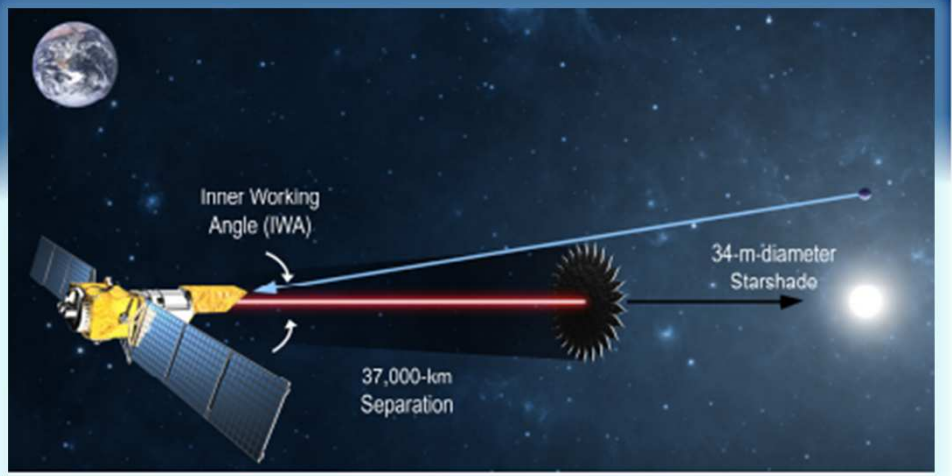
Exo-C

- EXO-C (~US version of SPICES) – interim report April 2014
  - 1,5 m, unobscured Cassegrain, 450-1000 nm
  - 1 × 1 arcmin FOV
  - Earth trailing orbit
  - 10^{-9} raw contrast, ~ 2 –20 λ/D ,
  - PIAA/Vorte/hybrid Lyot +DM
  - Pointing stability 0,1 mas at instrument level
  - Launch mass ~1.8t
  - Launch date : 2024 (2017 start)
  - 750 M$ estimated cost (Kepler heritage)
  - Status : final report jan. 15, evaluation by NASA in 2015 (probe class mission)



Pointing Requirements	
Telescope Pointing (Angle in the sky, 1σ RMS)	
Accuracy	1.2 milliarcsec (Line-of-sight tip/tilt)
	10 arcsec (Line-of-sight roll)
Stability (1000s)	6 milliarcsec* (Line-of-sight tip/tilt)
	10 arcsec (Line-of-sight roll)
Instrument Pointing (Angle in the sky, 1σ RMS):	
Accuracy	0.08 milliarcsec (Line-of-sight tip/tilt)
Stability (1000s)	0.4 milliarcsec (Line-of-sight tip/tilt)

Exo-S



- **EXO-S – NASA interim report April 2014**
  - **Jupiter down to earth around close stars**
  - **Occulter at long distance in front of telescope**
  - **Classical visible telescope (Nextview, 1,1 m)**
  - **10^{-10} contrast IWA 75 to 115 mas, FOV 1 arcmin**
  - **Mass : 1,2 + 1,4 t**
  - **D : control +/- 250 km**
  - **Relative DX/DY : control +/- 1 m, sensing 20 cm (1 mas)**

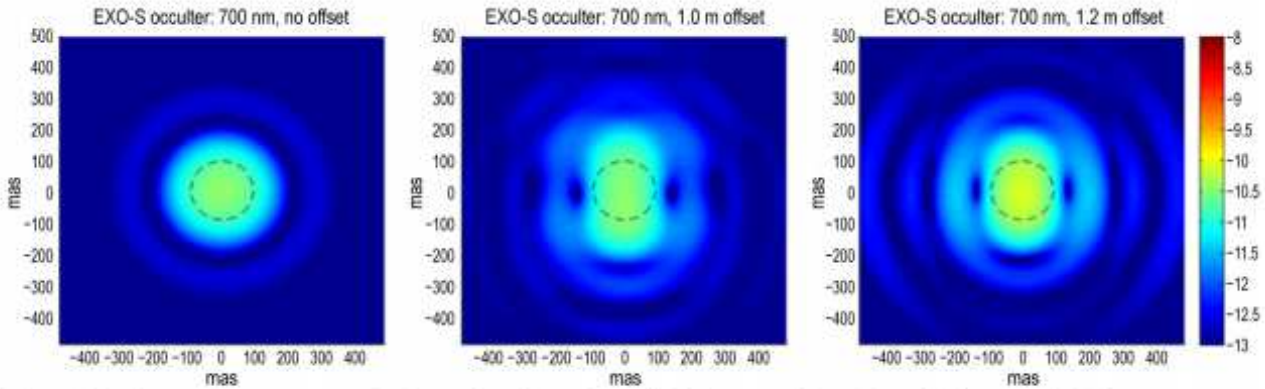


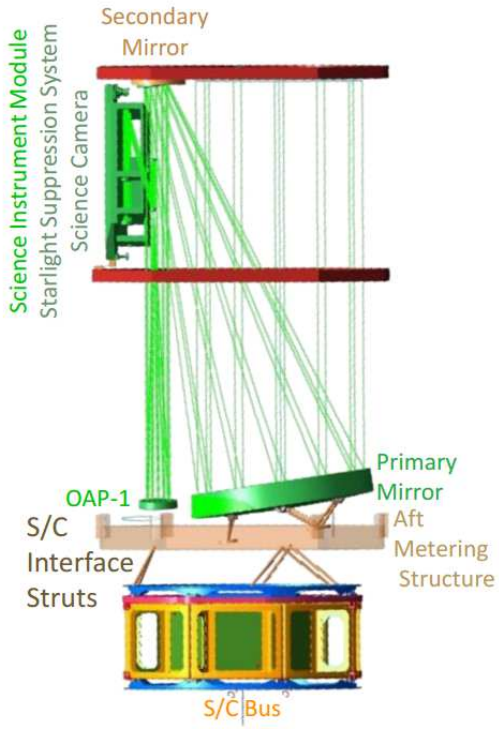
Figure 6.1-1. Image plane contrast at 700 nm with no lateral error (left), 1 m error (center), and 1.2 m error (right).

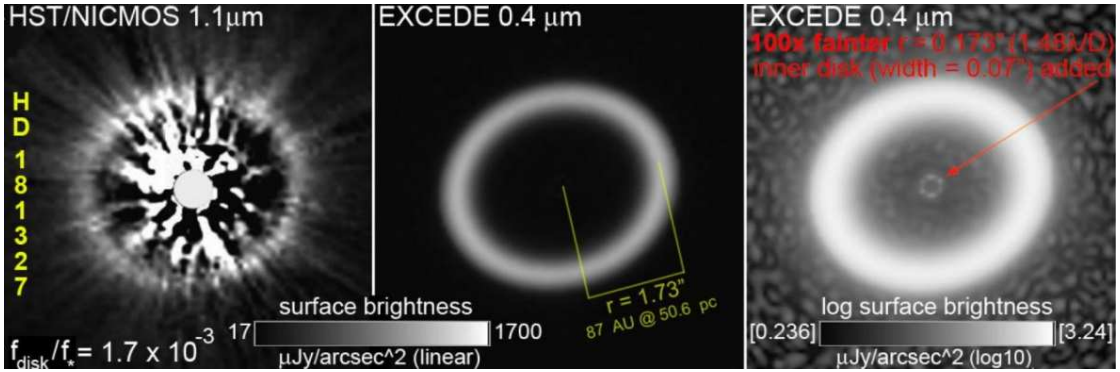
Straylight ?

Key Challenges	Driving Spec	Technology Status
Dynamic stability	Deformations < 15 ppm after 10 s	Verified by analysis with large margins
Thermal stability	Non-uniform deformations ≤ 7.5 ppm	Verified by analysis with large margins
Manufacturing tolerance	Petal width < 100 µm (4 mil)	Demonstrated per TDEM-2009
Deployment tolerance	In-plane petal root position ≤ 0.5 mm	Demonstrated per TDEM-2010
Edge-scattered sunlight	Edge radius curvature <1 µm	Demo in progress per TDEM-2012
Laboratory contrast demo and model validation	10^{-10} contrast at flight Fresnel Number	Demo in progress per TDEM-2012
Formation flying	Sensing for lateral control ±1 m	Requires technology demonstration
Deploy control system	Avoid petal contact	Requires significant engineering effort
Launch restraint	Axial loads ≤ 10 g's	Requires significant engineering effort

Smaller missions : excede

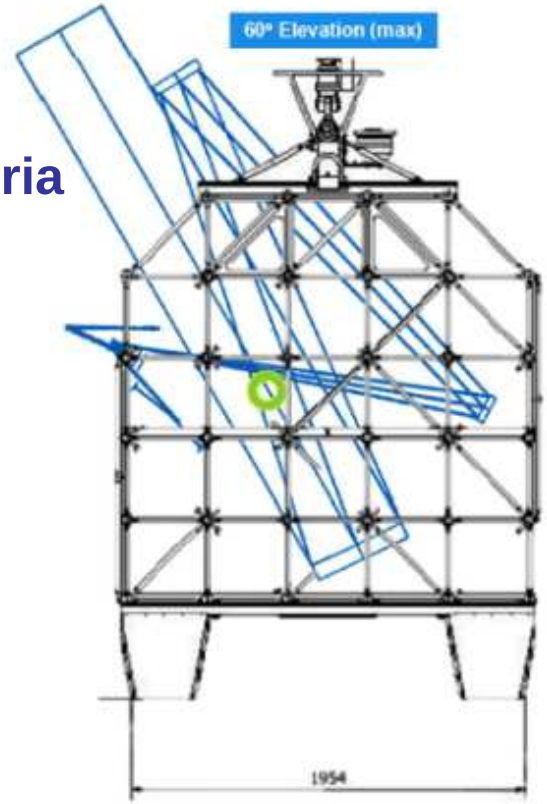
- **Excede (G. Schneider presentations)**
  - **Nasa Ames / university of Arizona – G. Schneider / O. Guyon**
  - **Circumstellar disks + technological**
  - **Raw contrast goal $10^{-6\ to-7}$ @ 1,2-2 λ/D**
  - **IWA 0,14”@ 0,4 µm, PIAA coronograph**
  - **0,7 m off axis telscope**
  - **Status : 2013 => approved for two-year Tech. Dev program**

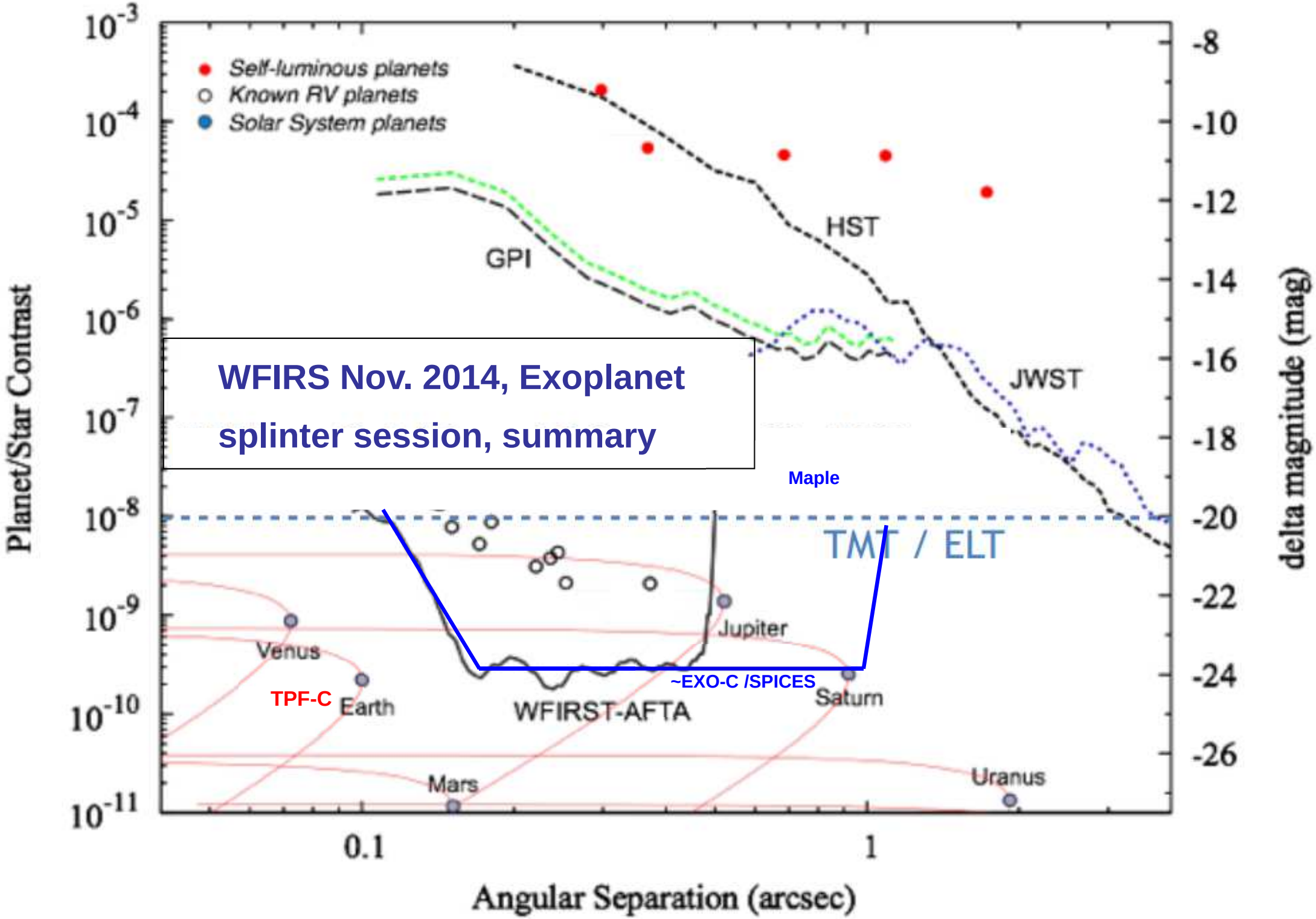




Smaller missions : maple

- Maple – (Christian Marois – SPIE paper)
  - National Research Council of Canada, University of Victoria
  - Stratospheric balloon
  - Few Jovians/ ice-giant around nearest stars. + techno.
  - contrast goal few 10^{-8} @ 1,7 λ/D
  - Vortex coronograph + SCC
  - 0,5 m off axis telescope, 3 spherical mirrors (M1, M2, M3)
  - CNES Carmes gondola
  - Pointing requirement : 5 mas RMS, very challenging under a balloon
  - Status : ?



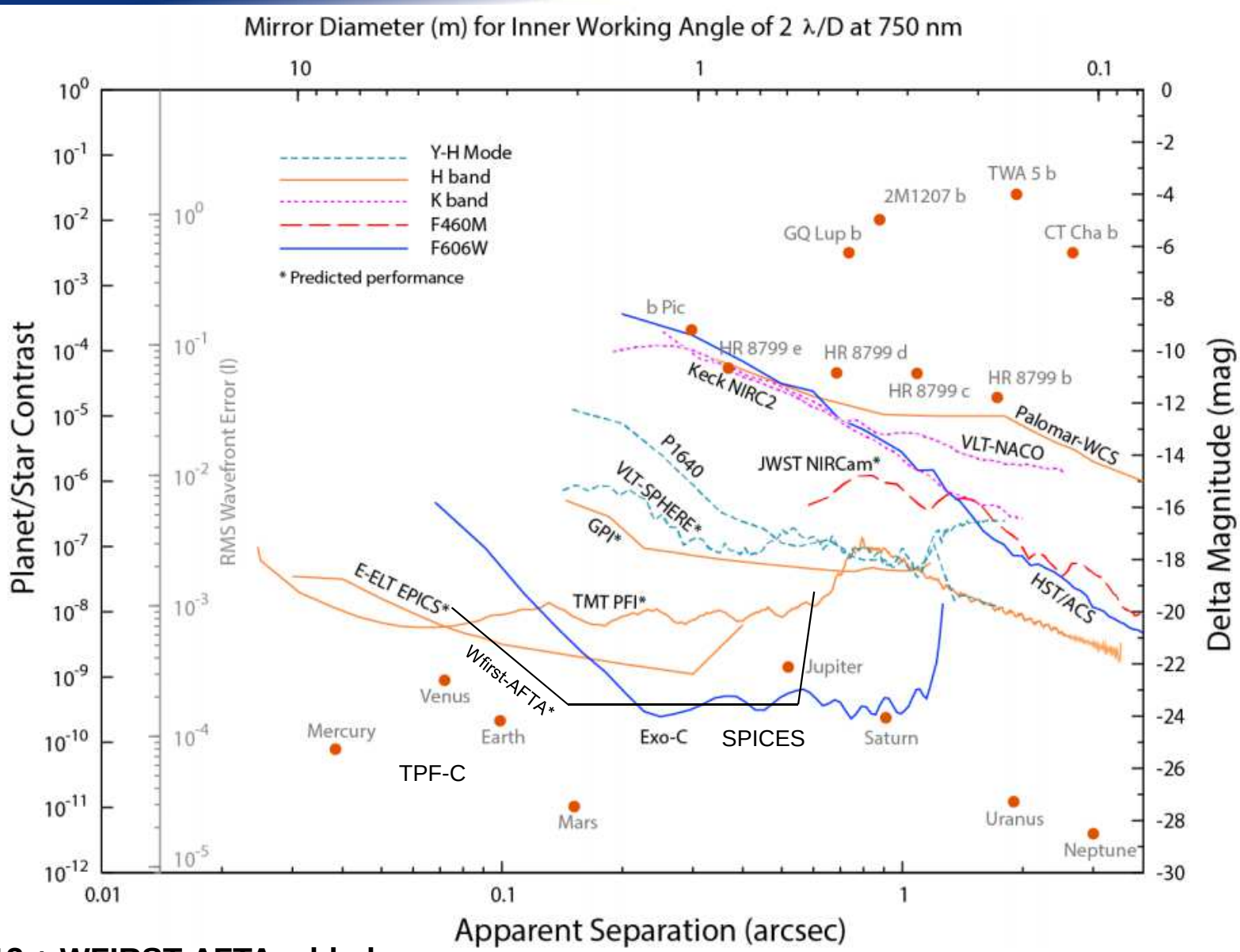


WFIRS Nov. 2014, Exoplanet splinter session, summary

Conclusion

- Cost of a dedicated mission is very high (> M size mission), even for a reduced size telescope due to :
  - very demanding performances : pointing, telescope stability, WFE fine control, straylight,…
  - Low TRL of new key components and technology : DM, coronographs, WFE measurement
- small FOV of a dedicated mission make it difficult to include more general purpose astrophysics
- transit analysis is currently preferred because more mature
- ESA : no directing imaging mission before… L4 (means launch 2040) if recent long term programmation remains unchanged (L2 Athena, L3 Lisa)
- try to couple coronography with other mission, although the telescope is no more optimized
  - Astrometry+corono (as proposed by O. guyon)
  - Dark energy + corono = WFIRST-AFTA + Corono
- if no coronograph on WFIRST, then Exo-C/Exo-S ?
- Or go to smaller mission for techno demonstration (Excede, Mapple ?)

PERFORMANCES COMPARISON



Lawson 2013 + WFIRST-AFTA added