Future Planet Imagers

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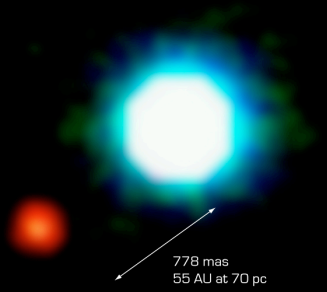
Observing planetary systems II - Santiago, March 2012

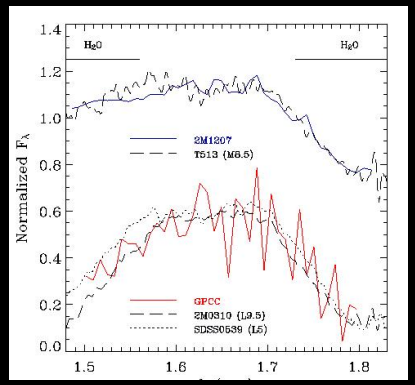
Overview

- Opening up a new observation window
  - Motivation ? Exoplanetary science impact ?
  - Where to gain and to push ?
- Development of new generation instruments = dedicated to high contrast
  - Key features, why a high-contrast imager should be specific ?
  - Strongly supported by gained experience by many actors in various fields: observers, new concepts, lab experiments, technological breakthrough..
  - Complete field of research in itself
- A taste of future :
  - Yes it will happen. It actually already does !

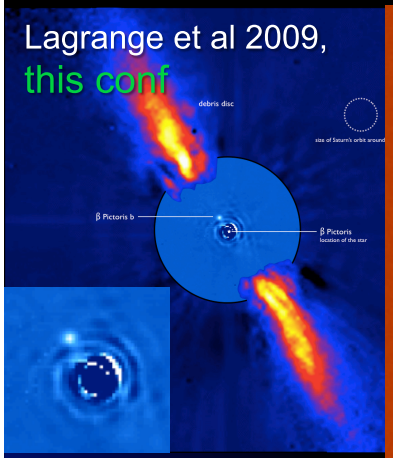
Opening up a new observational window

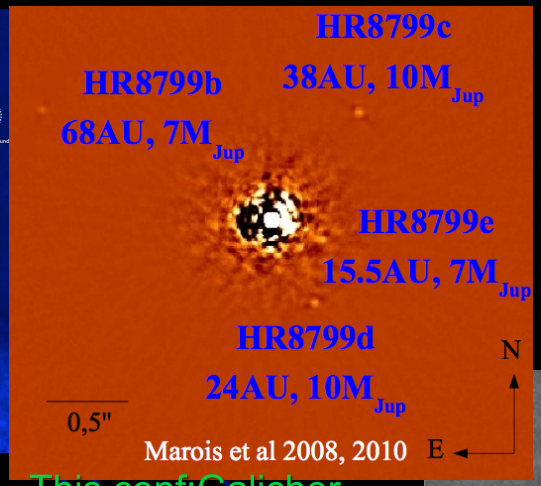
Many results and performance gain using high angular resolution imagers



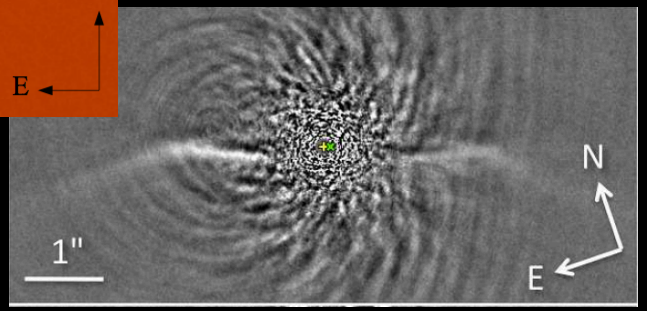


- from 90's (ADONIS) to 00's (NACO)
- entering the planetary mass domain in most favourable cases thanks to resolution
- Down to close separations and/or cooler planets in the disk of young stars, thanks to… many efforts !
- and observations of dusty disks themselves, sculped in many surprising ways





This conf:Galicher



Buenzli et al 2011
This conf: Biller et al, Milli et al

Opening up a new observational window

Scope for upcoming high contrast imagers

What impact will the future imager have on our understanding of planetary systems ?

δ knowledge = (d knowledge / d performance)

x

(d performance / d effort)

x

δ effort

Opening up a new observational window

Scope for upcoming high contrast imagers

What impact will the future imager have on our understanding of planetary systems ?

δ knowledge = (d knowledge / d performance)

X

(d performance / d effort)

X

δ effort

Very steep slope, specially at current point, very exciting !

Margin for progress: new ideas, first dedicated instruments, new techno

Incredibly active worldwide !

Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

- Enlarging the detection window of Extrasolar Giant Planets
  - System dynamics: what/where are the bodies dominating the system dynamics ?
  - Content as a function of separation
  - Current/past dynamics
    - Indication of different formation and evolution scenario
- Planets and disks in a complementary view, at different evolutionary stages
- Direct information on companion flux / colours / spectra
- What not to expect ?

Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

Is it worth ?

This conf: Alibert, Terquem, Queloz, Morbidelli, …

- Different parts of a-M diagram -> different population of planets, with different trends and statistics: metallicity, excentricities, inclination, possibly formation, evolution, min mass and period in multiple systems…
- « a lot of dynamical effects » (D. Queloz, this conf.) ; interaction between inner / outer components, and in any case you cannot afford forgetting unseen massive planets
- Different planet formation and evolution at play ?
- Planet – disks interactions (B. Dent, most speakers on Monday)
- Trend with age and stellar mass

Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

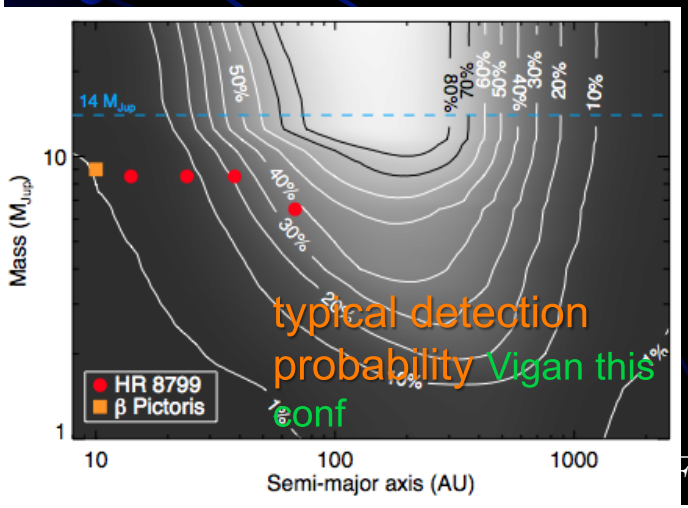
Is it worth ?

- **YES !!!**

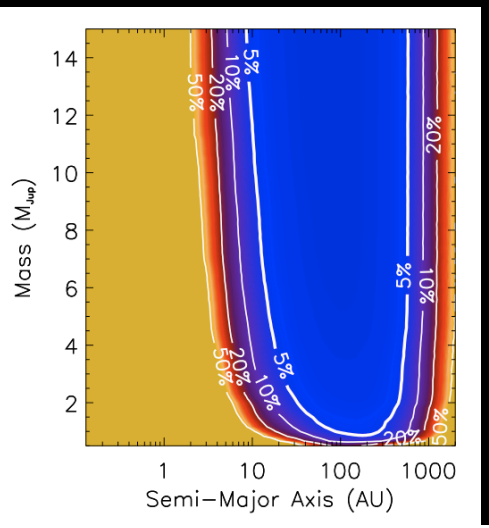
- …and we are at the very edge of the most interesting part of it in terms of mass and separation limits

- See performance achieved down to planetary mass companions at planetary separations in planetary disks !
- See statistical issues contraints: massive EGPs @ >~few 10 AUs

This conf: Vigan, Nielsen, Galicher, Rameau…



typical detection probability Vigan this conf



« fewer than 5% stars have a > 4 MJ in 18-500 AU » Nielsen this conf

Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

Is it worth ?

- **YES !!!**

- ...and we are at the very edge of the most interesting part of it in terms of mass and separation limits

- See performance achieved down to planetary mass companions at planetary separations in planetary disks !
- See statistical issues contraints: massive EGPs @ >~few 10 AUs

- We also want to learn much more about luminosity, colours, spectra and compare to models !

This conf:Schmid, Bonnefoy

- But, at the same time, we should keep the ability to address a wide sample of targets

Opening up a new observational window

Scope for upcoming high contrast imagers

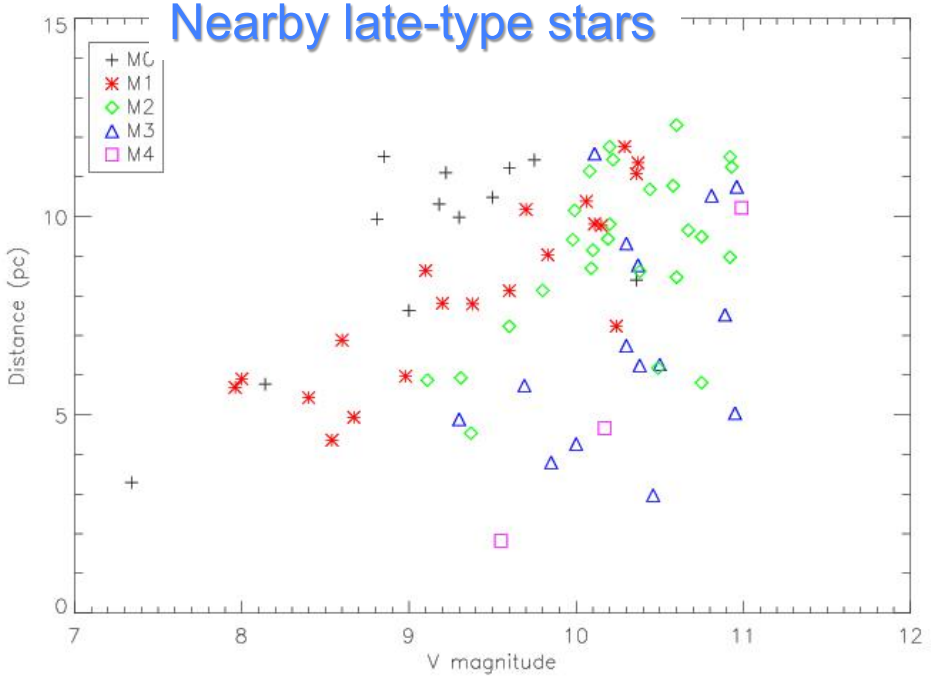
Potential goals

Is it worth ?

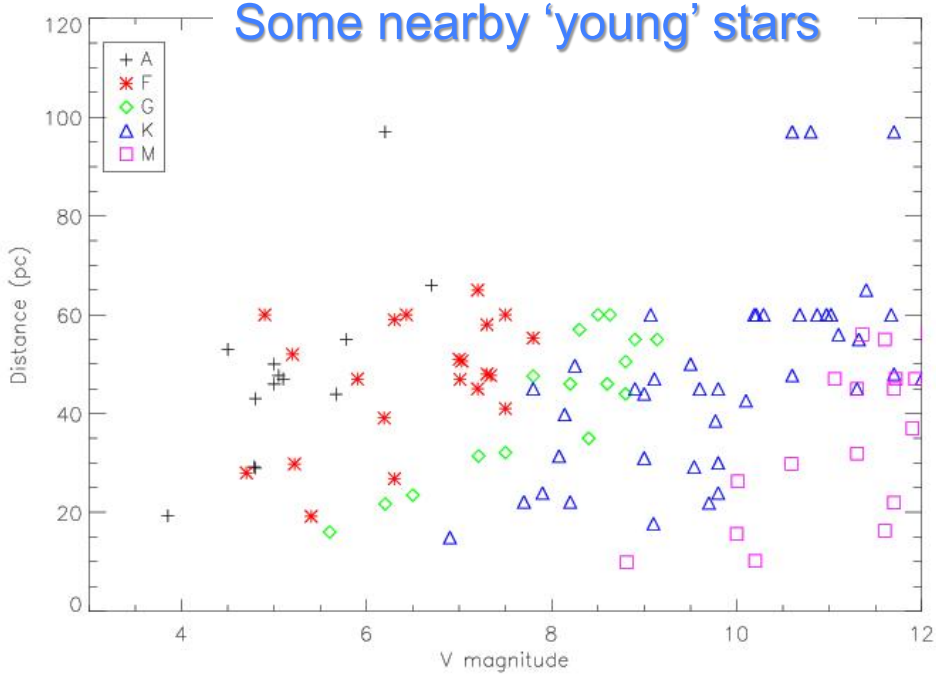
- **YES !!!**

- But, at the same time, we should keep the ability to address a wide sample of targets = **AO sensitivity issue (specially in red)--> vis mag ~10**

Nearby late-type stars



Some nearby 'young' stars



Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

Can we do it ?

- Wavefront error (WFE) handling
  - Turbulence residuals on short timescales
  - Instrument: lower level and at much slower rate
- Diffracted light suppression
- Handling the residuals

Is it worth ?

- Fast and High Order AO
- Very low, stable, achromatic and finely sensed optical WFE
- Coronagraphy
- Differential techniques / signal processing

Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

Can we do it ?

Is it worth ?

- YES !!
- Theoretical, Technological and system studies dramatic improvements
-
- Dedicated instruments
  - consistent and well-balanced design choices
  - optimized for high contrast on bright targets
  - including operation issues
- Observations organized into wide surveys

- Fast and High Order AO
- Very low, stable, achromatic and finely sensed optical WFE
- Coronagraphy
- Differential techniques / signal processing

Opening up a new observational window

Scope for upcoming high contrast imagers

Potential goals

Can we do it ?

Is it worth ?

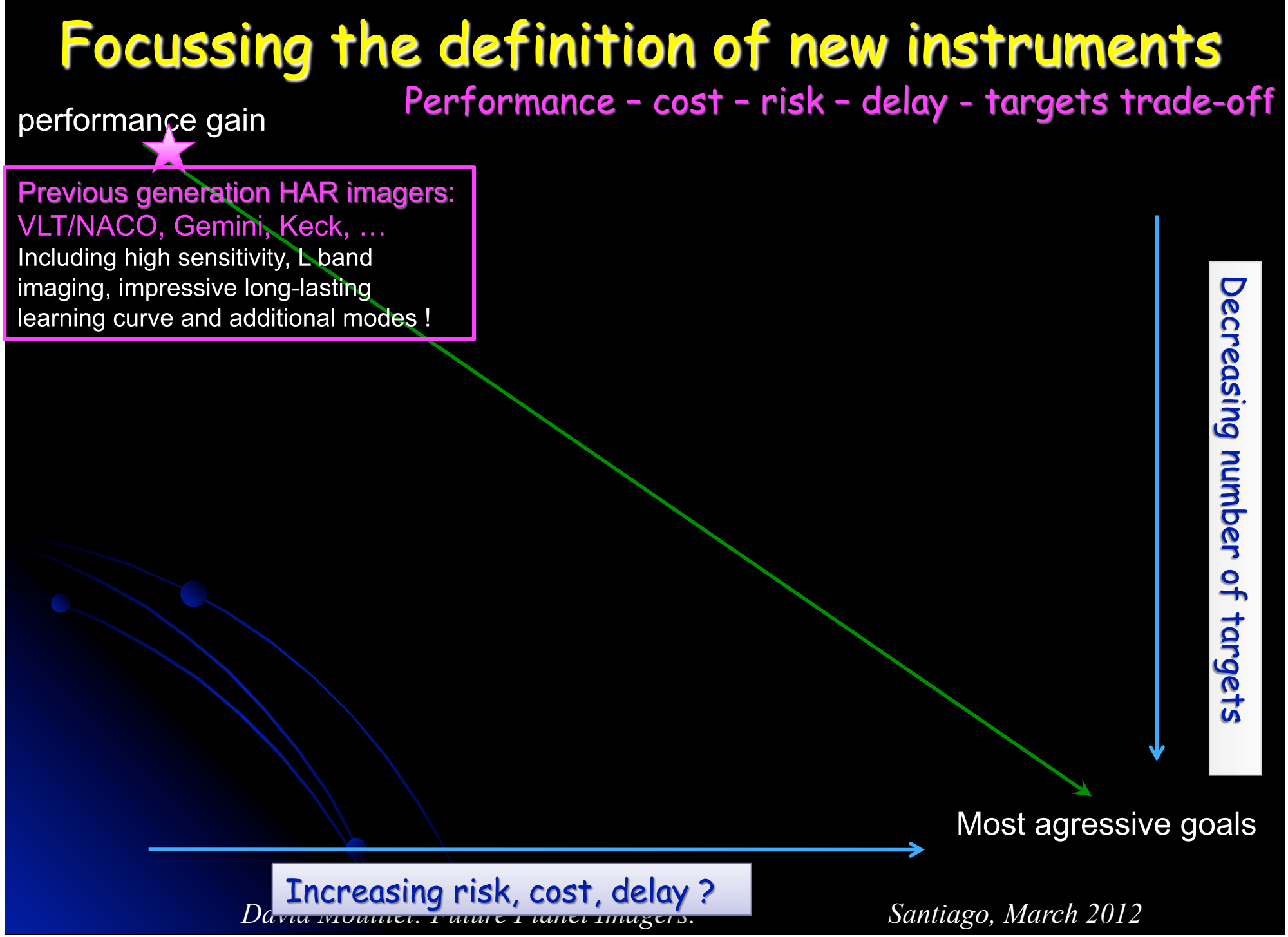
- YES !!

… assuming you solve the 2 issues of the high contrast instrument formation scenario

- The « Timescale problem »
- Performance – cost – risk – delay - targets trade-off

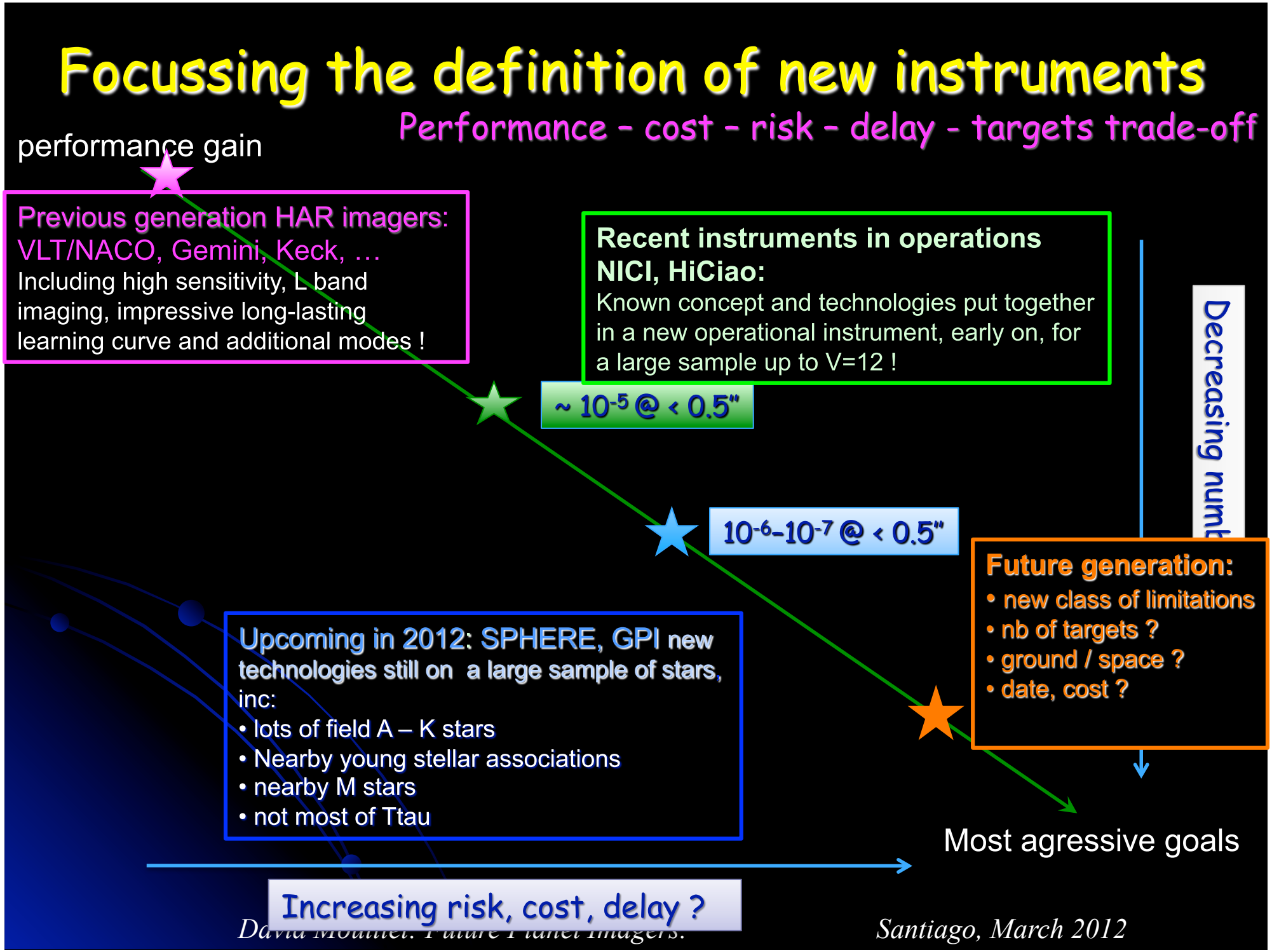
Focussing the definition of new instruments

Performance – cost – risk – delay - targets trade-off

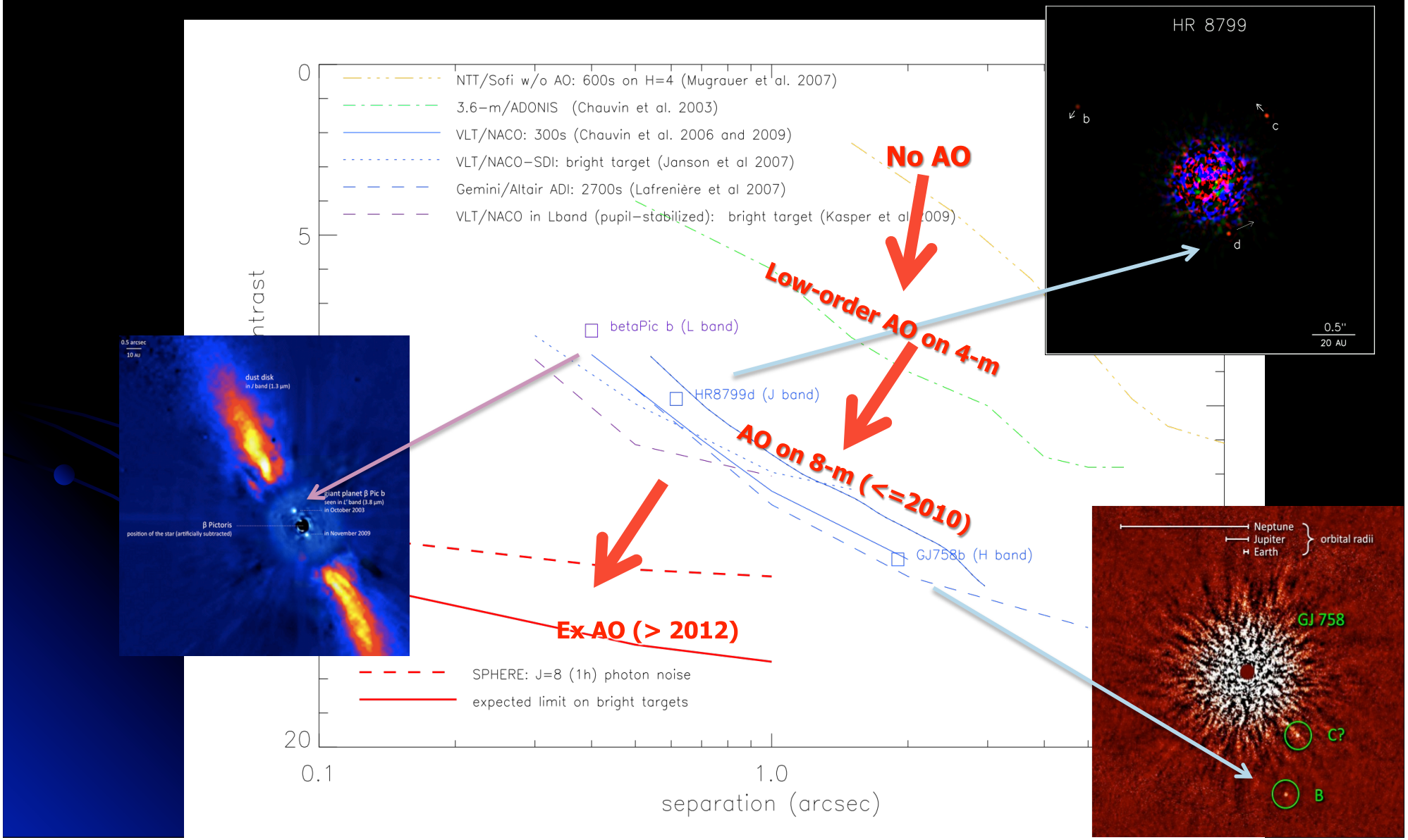


Focussing the definition of new instruments

Performance – cost – risk – delay - targets trade-off



Focussing the definition of new instruments



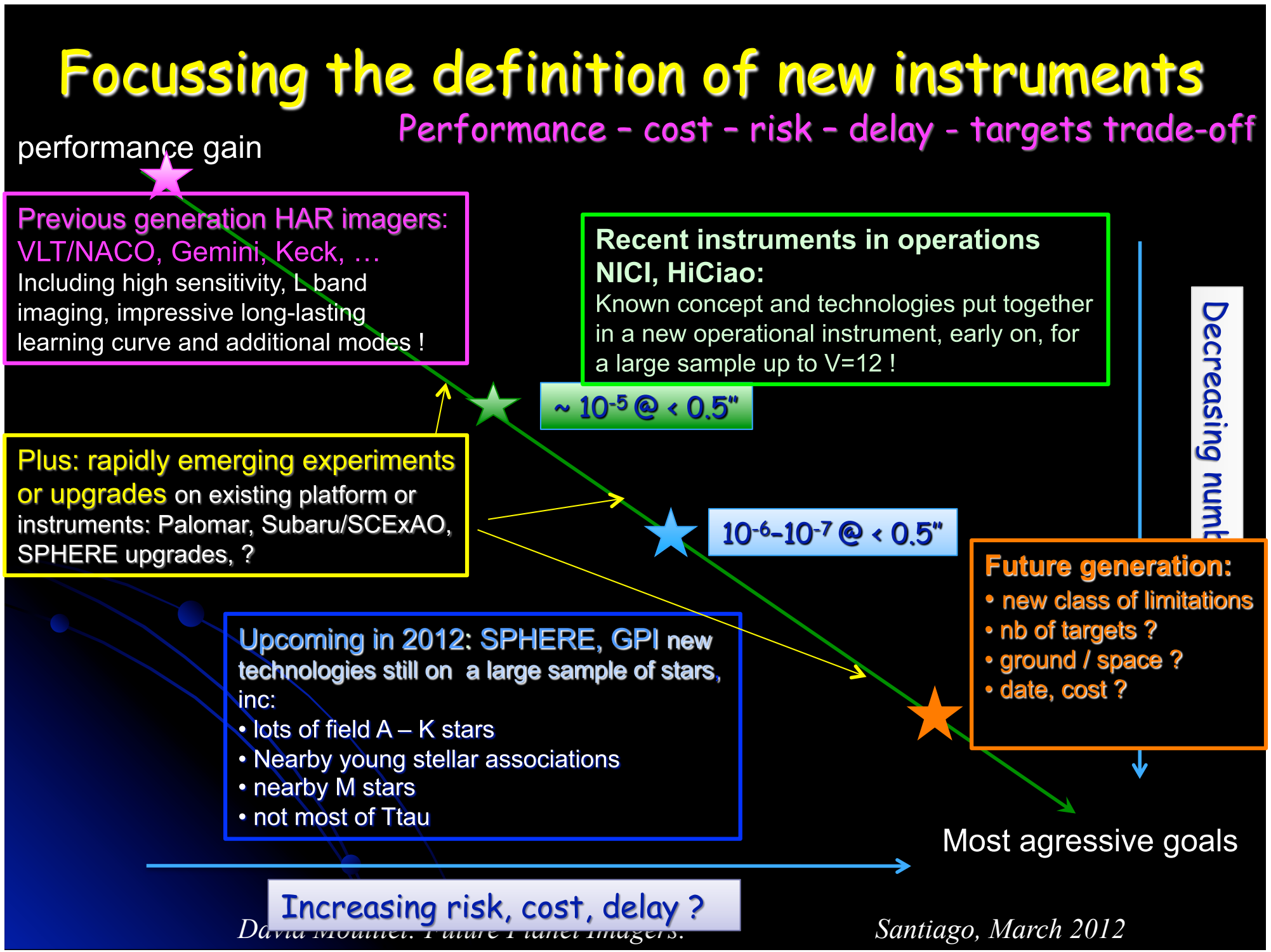
Focussing the definition of new instruments

« Timescale problem »

- Timescale for large and complex instrument development MUCH LARGER than
  - Timescale for new ideas, better instrument understanding
  - Evolution of knowledge/critical questions on planetary systems
- Different strategies:
  - Large instruments for and supported by a large community, with large enough observational window
  - Faster reactivity on existing facilities/instruments: experiments, upgrades, room for higher risk and opportunities

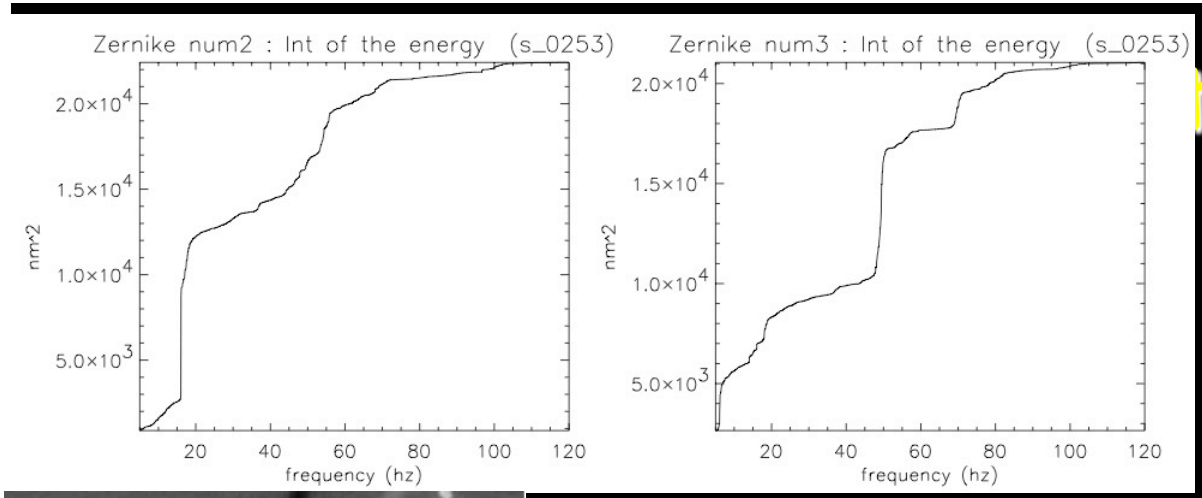
Focussing the definition of new instruments

Performance – cost – risk – delay - targets trade-off

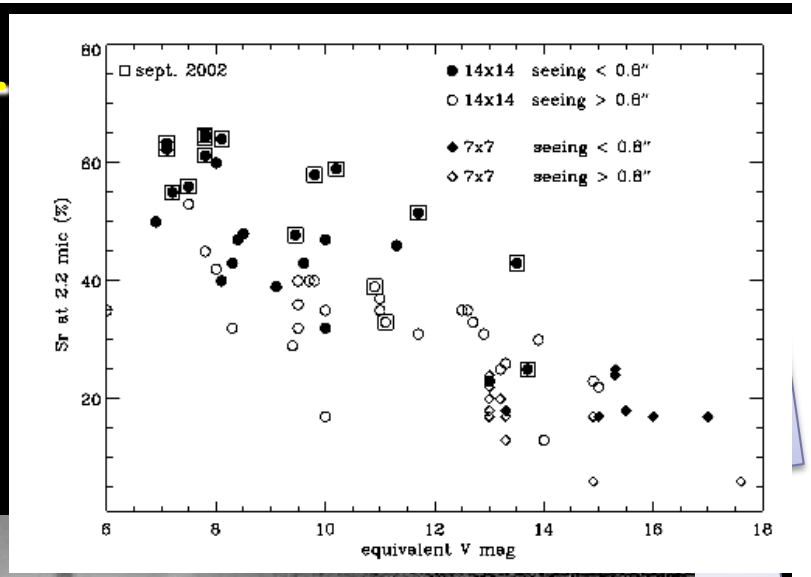


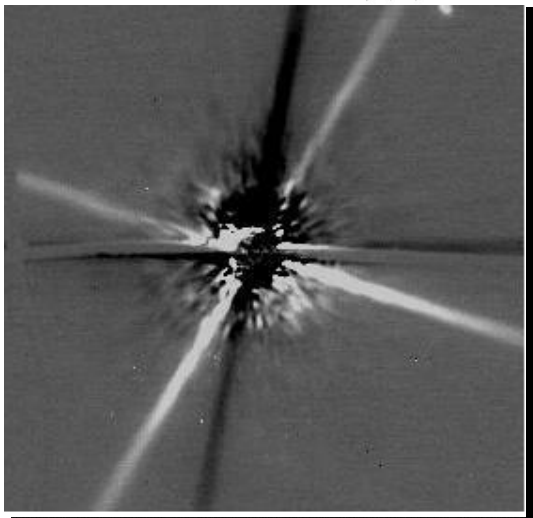
Instrument scene

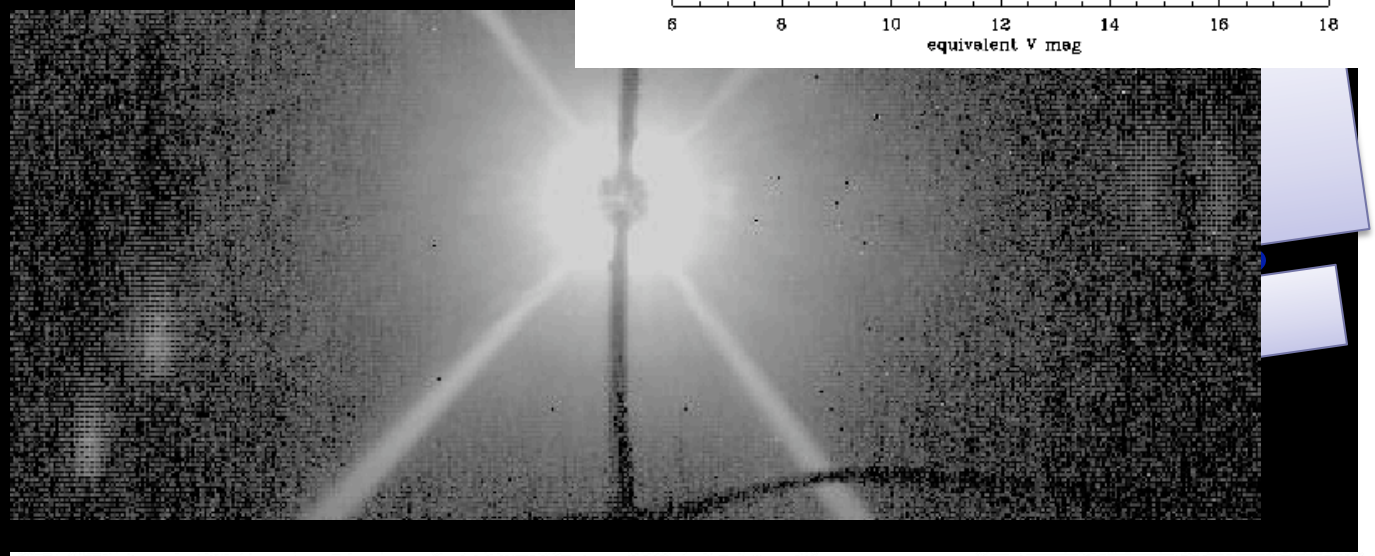
Impressive evolution and experience gain on existing instruments

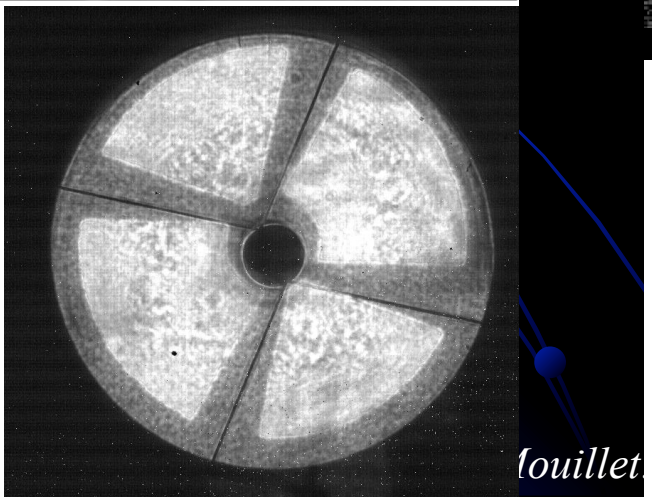

Zernike num2 : Int of the energy (s_0253)
nm^2
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
20 40 60 80 100 120
frequency (hz)

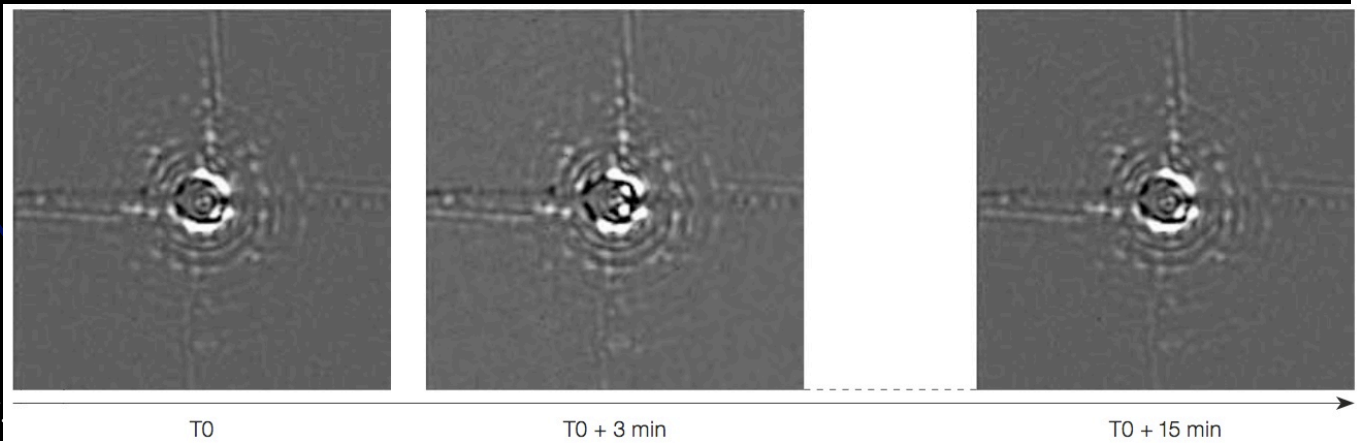
Zernike num3 : Int of the energy (s_0253)
nm^2
2.0×10^4
1.5×10^4
1.0×10^4
5.0×10^3
20 40 60 80 100 120
frequency (hz)


sept. 2002
14x14 seeing < 0.8"
14x14 seeing > 0.8"
7x7 seeing < 0.8"
7x7 seeing > 0.8"
Sr at 2.2 mic (%)
80
60
40
20
6 8 10 12 14 16 18
equivalent V mag






louillet


T0
T0 + 3 min
T0 + 15 min

Evolution: improvements and new ideas

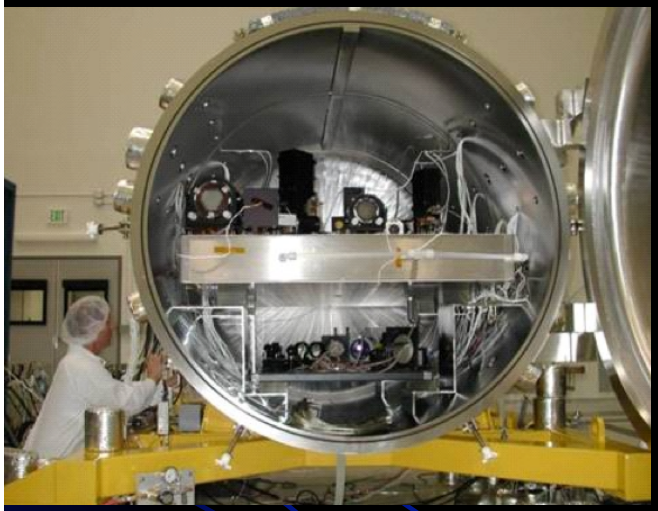
Impressive evolution and experience gain on existing instruments

- Theoretical work: understanding the image structure and what it depends on ? From the role of speckle noise to the detailed structure of high Sr coronagraphic images and chromaticity: *Racine, Sivaramakrishnan, Soummer, Cavarroc, Perrin, Give'on, Sauvage, Ygouf, …*

Evolution: improvements and new ideas

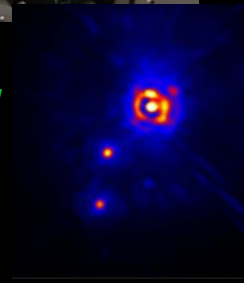
Impressive evolution and experience gain on existing instruments

- Theoretical work
- Devices and lab experiments

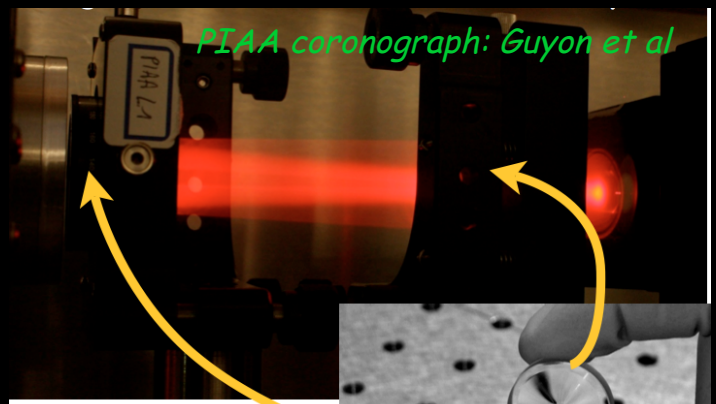


Space-motivated JPL / HCIT

ground-motivated ESO / HOT



Martinez et al 2011



PIAA coronograph: Guyon et al

kis lenses
s are 96 mm apart
ze the beam
ve the central obscuration

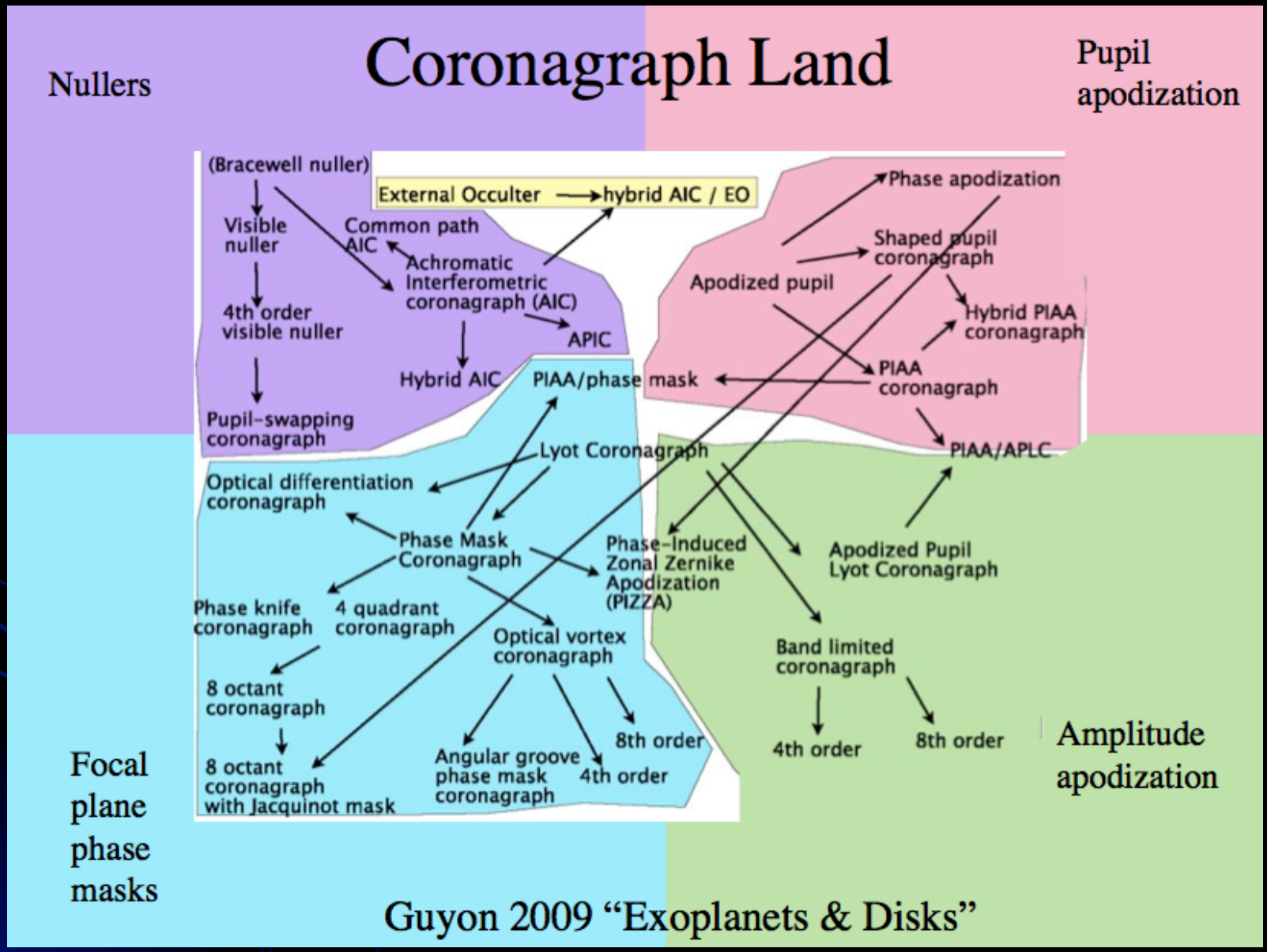
Evolution: improvements and new ideas

Devices and laboratory experiments

- Even if you have ideas, you have devices, you have lab demo and supporting simus..: the best route to take is not obvious nor universal !

- example of coronagraphy ! → you need a consistent global system analysis
  - What exactly do you require from coronagraphy ? Pure intrinsic perf w/o WFE ? Dependency on pupil shape ? Tolerance wrt WFE ? Presence or not of LOWFS ? Criticity of Inner Working Angle ? Fine properties of remaining speckles ? Chromaticity ?
  - Dominant noise is stellar halo photon noise: it goes down with observing time and target brightness, and is cancelled by coronagraph (but non perfect ? Pupil shape ?)
  - Then remains turbulence residuals: also smooths down relatively fast (but turbulence statistics variation !)
  - Then remains slow WFE: a large part can be measured / compensated for ?
  - Then remains the uncontrolled part of them: structure ? Chromaticity ?

Alessandro suggested a « geology-like » approach, what about zoology ?



Evolution: improvements and new ideas

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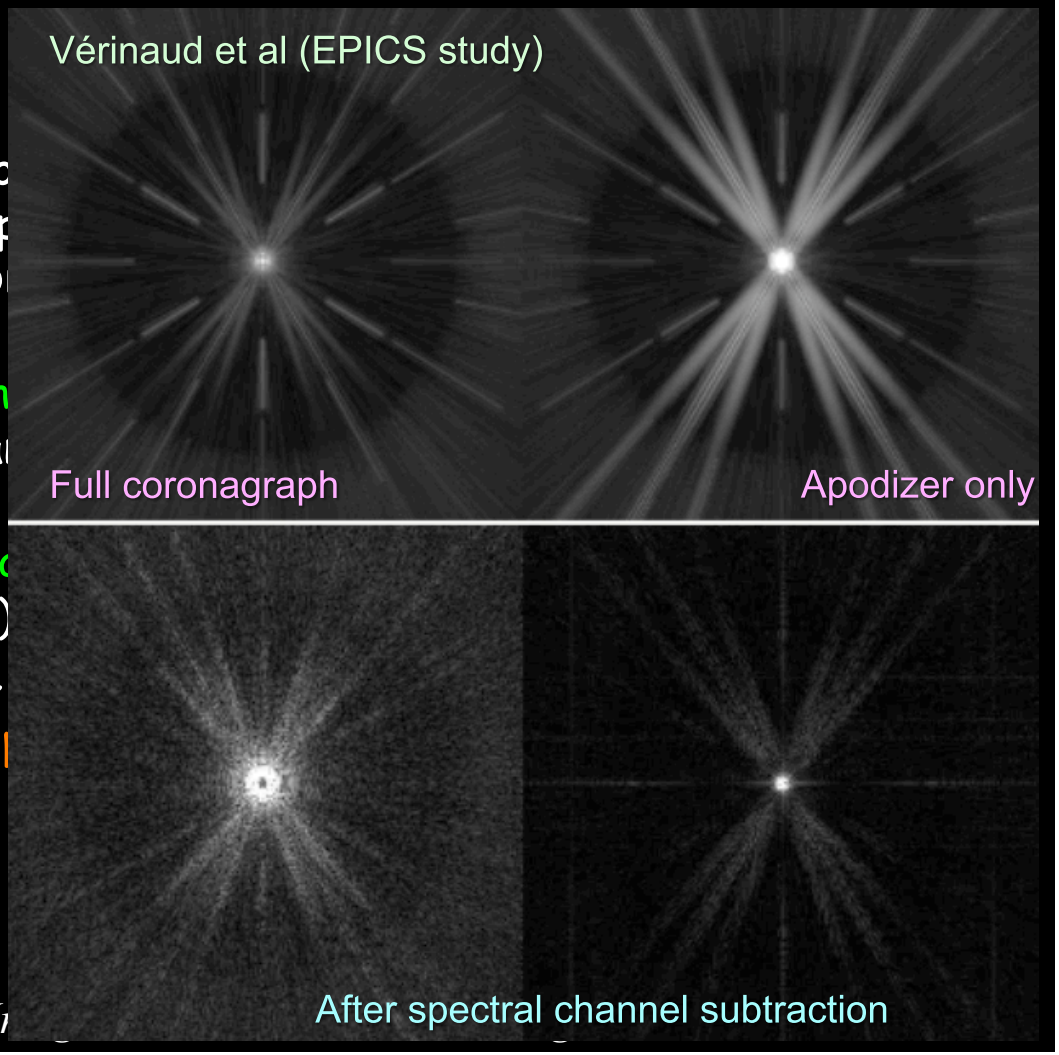
  - Then remains slow WFE: a large
  - Then remains the uncontrolled

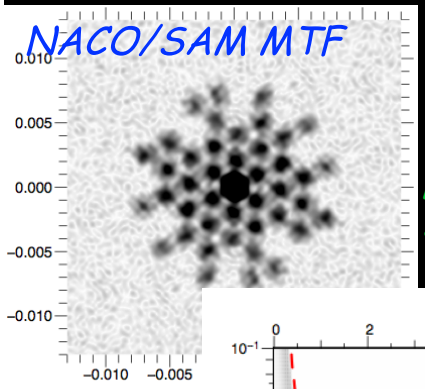


Evolution: improvements and new ideas

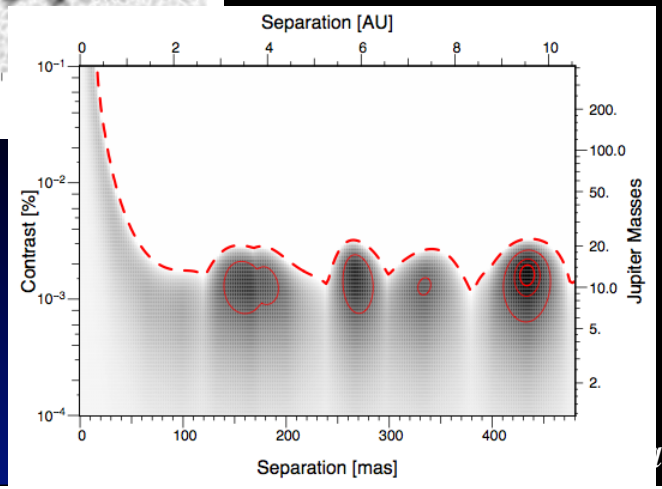
Impressive evolution and experience gain on existing instruments

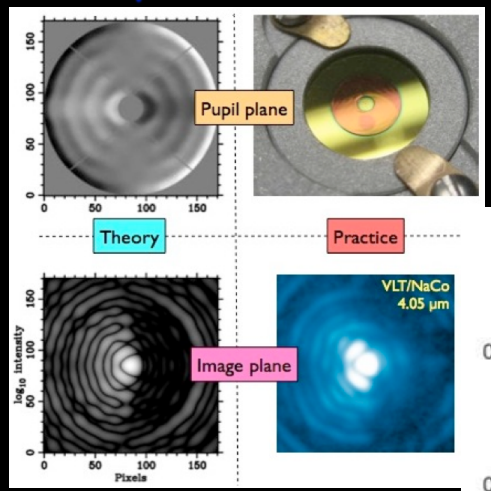
- Theoretical work
- Devices and lab experiments
- Observing modes and concepts: just look into NACO evolution ! multi-lambda/polar simultaneous imaging, phase coronagraphs, angular differential imaging, Sparse-Aperture Masking, APP

NACO/SAM MTF



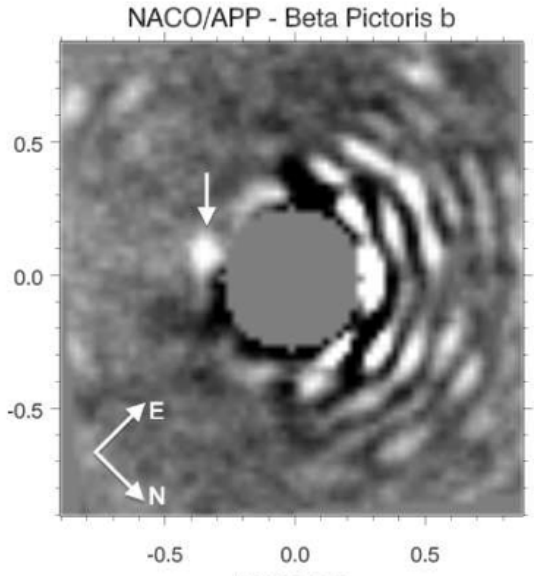
Lacour et al 2011
See also this conf: Biller, Lagrange





NACO/APP

Kenworthy et al 2010,
Quanz et al 2010
Kenworthy this conf



...net Imagers. *Sant...*

Evolution: improvements and new ideas

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- Data reduction and signal extraction

Evolution: improvements and new ideas

Data reduction and signal extraction

- Remember AO…

  Signal Processing : cannot replace a good : Observer

  it makes good Observers even better »

- You have not said everything and closed the subject when you have said « LOCI » *(Lafrenière et al 2007)*
  - Here again: conclusions/optimizations neither obvious nor universal. Bias studies in various obs cases (see eg *Milli et al , this conf*)
  - At shortest separations: all ADI approachs end-up agains fundamental limitations with variability timescales, non-converged non-gaussian statistics,
  - Multi-wavelength approachs adds-up a lot of redundant information : we need to take advantage of it. *(Sparks&Ford 2002, Thatte et al 07, Puyeo et al '11, other to come…)*
  - How to make sure we use all the accessible system information -- if not already used for on-line correction -- ?

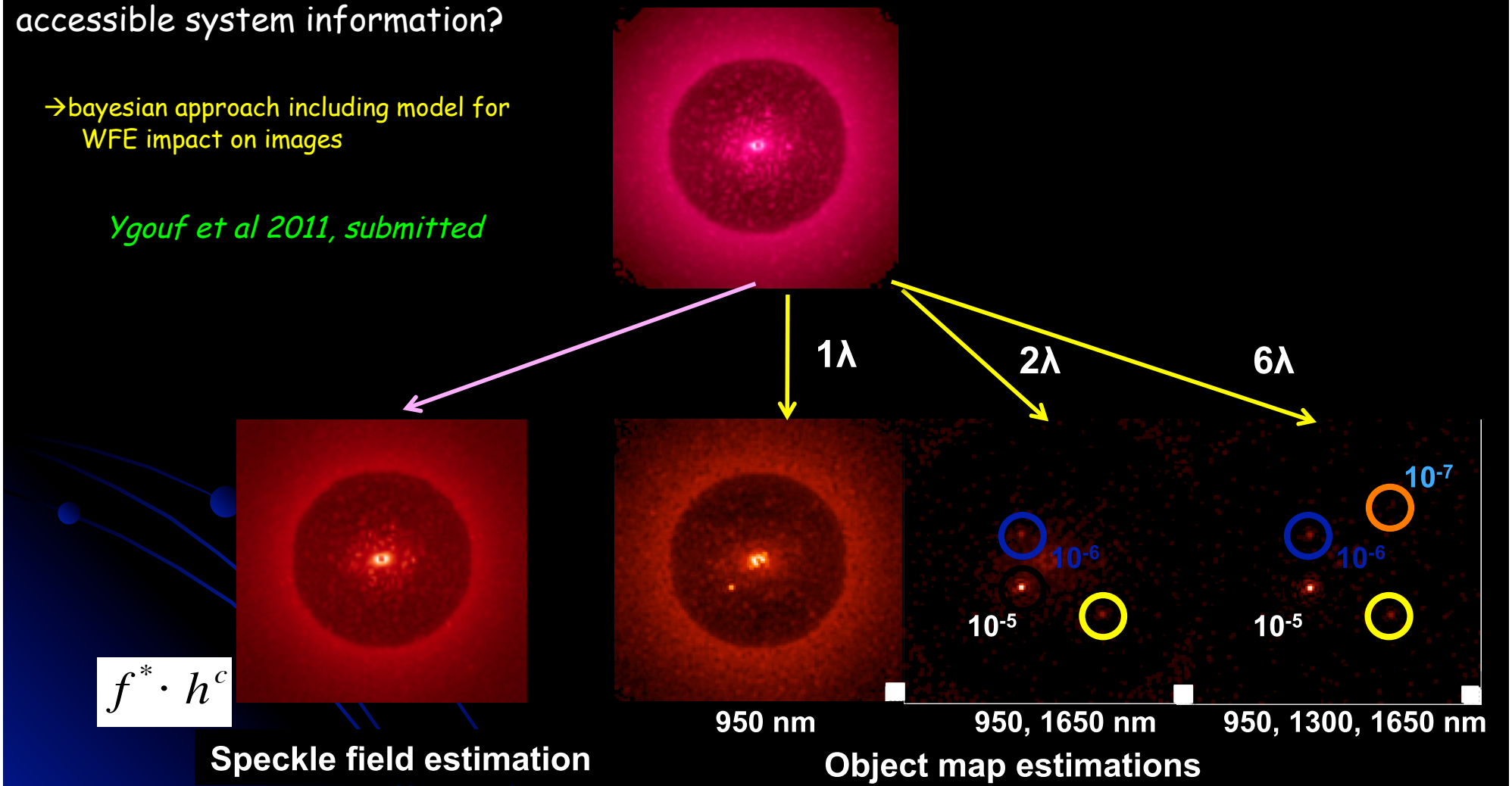
Evolution: improvements and new ideas

Data reduction and signal extraction

- How to make sure we use all the accessible system information?

→bayesian approach including model for WFE impact on images

Ygouf et al 2011, submitted



$$J\left(\{o_\lambda\},\{f_\lambda^*\},\delta_u\right) = \sum_\lambda \sum_{x,y} \frac{1}{2\sigma_n^2(x,y)} \left| i_\lambda - f_\lambda^* \cdot h_\lambda^c(\delta_u) - o_\lambda * h_\lambda^{nc} \right|^2 (x,y) + R_{x,y,\lambda}(o)$$

Planet imagers

In operation for community

Gemini / NICI

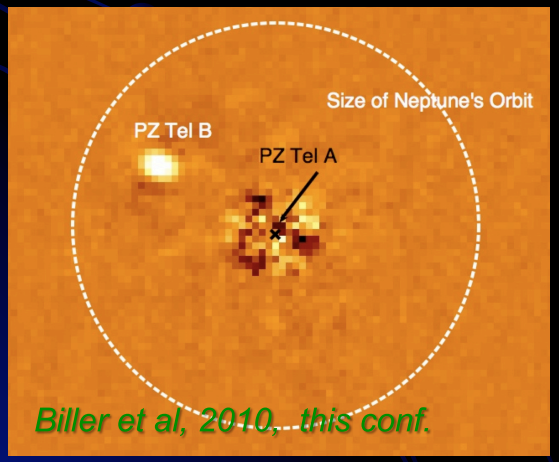
- Curvature AO
- Lyot coronagraph
- Dual imaging
- Contrast : 10^{-6} @ 1"
- Observing in consistent wide survey (Liu et al): 500 queue hrs

(see E. Nielsen this conf.)

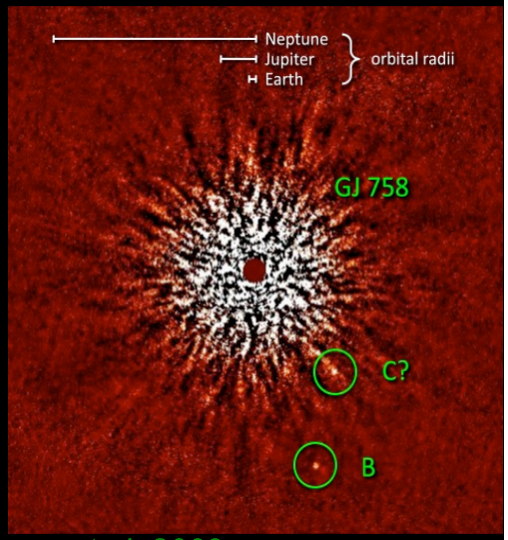
Subaru / HiCiao

Tamura et al 2006, Hodapp et al 2008

- Curvature AO (188 act)
- Lyot coronagraph
- SDI
- Contrast : 10^{-6} @ 1"
- Observing in consistent wide survey (SEEDS, Tamura et al)



Biller et al, 2010, this conf.

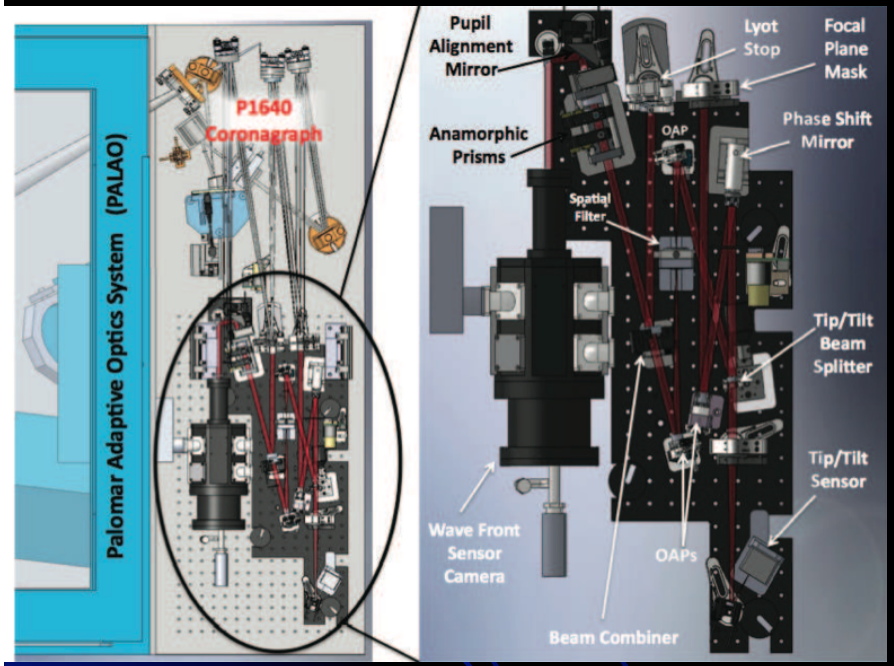


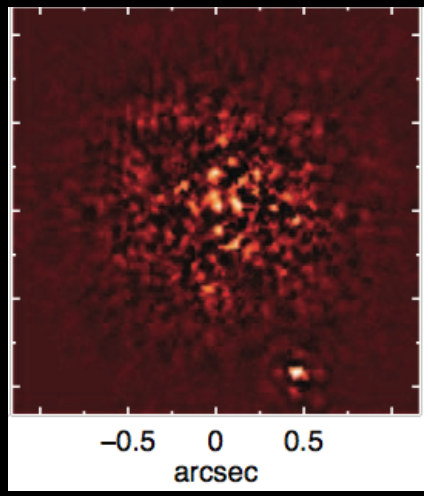
Thalmann et al, 2009

Planet imagers

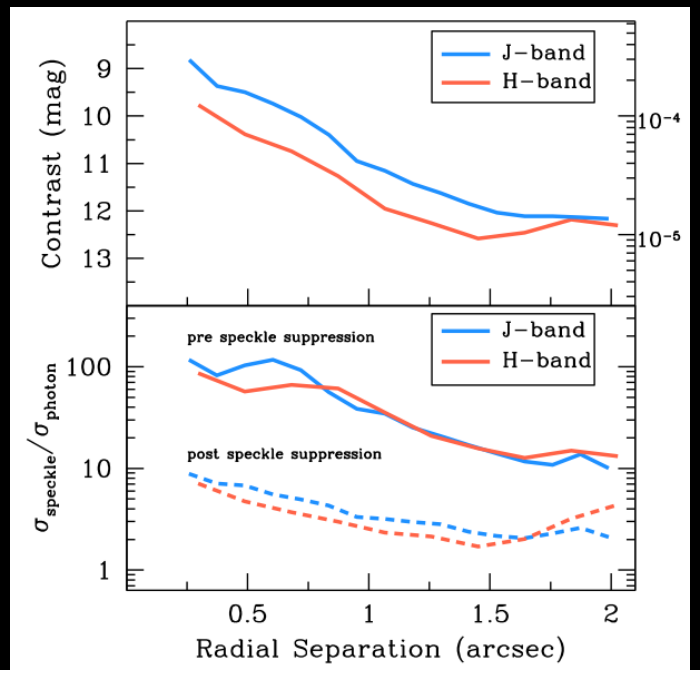
Experience and science happening at Palomar

- Palomar / P1640, including:
  - AO on 5-m + Apodized coronagraph + slow WFE JPL 'CAL' system + IFS





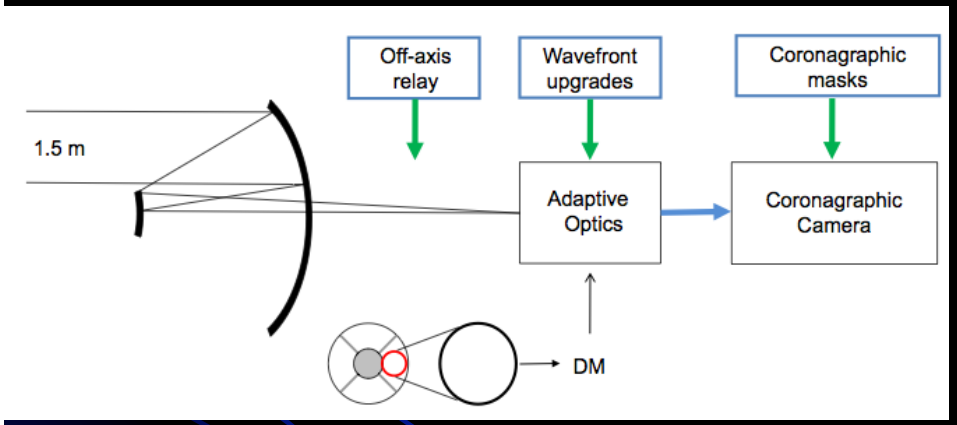
Hinkley et al 2011, Zimmerman et al 2010



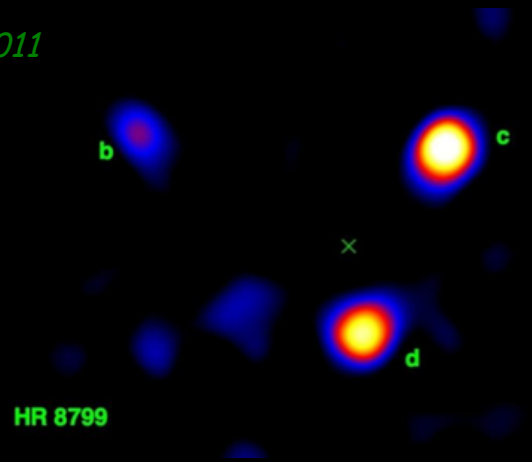
Planet imagers

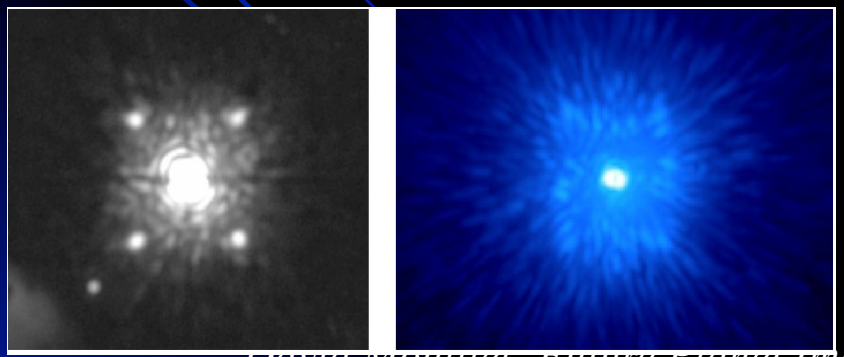
Experience and science happening at Palomar

- Palomar / P1640
- Extreme AO has already been tested ! (on top of longer lambda high Sr images)



Serabyn et al 2010,
Serabyn & Mawet 2011



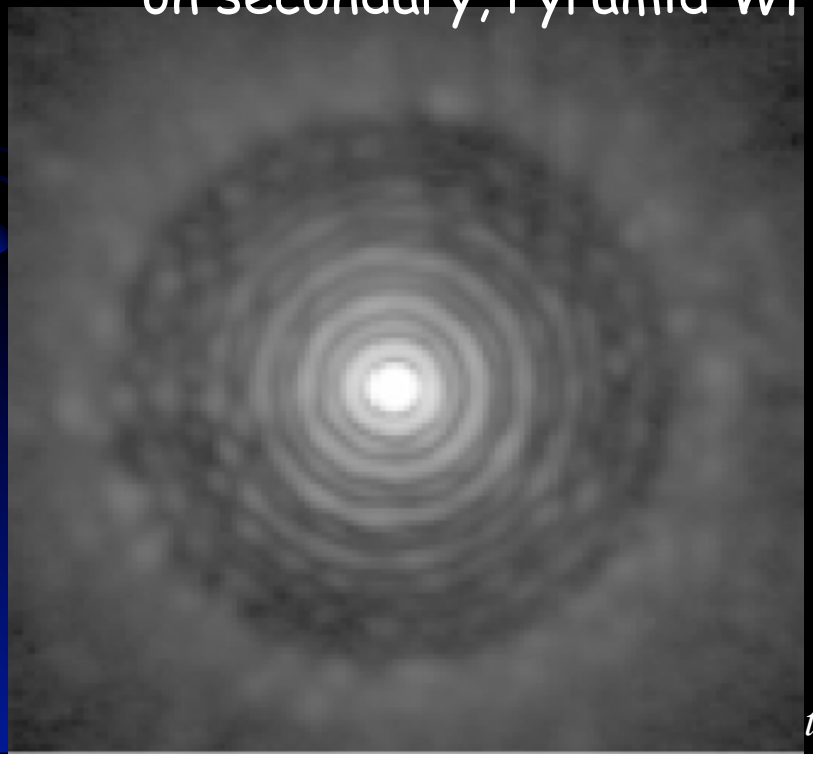


And new ideas and tests upcoming… !

Planet imagers

Experience and science happening at Palomar

- Palomar / P1640
- Extreme AO has already been tested ! (on top of longer lambda high Sr images)
  - see also high Sr image on one of the 8-m aperture of LBT ! (DM on secondary, Pyramid WFS)



Esposito et al 2011

Planet imagers

Last step of a long way towards first light

VLT / SPHERE

Beuzit et al 2008

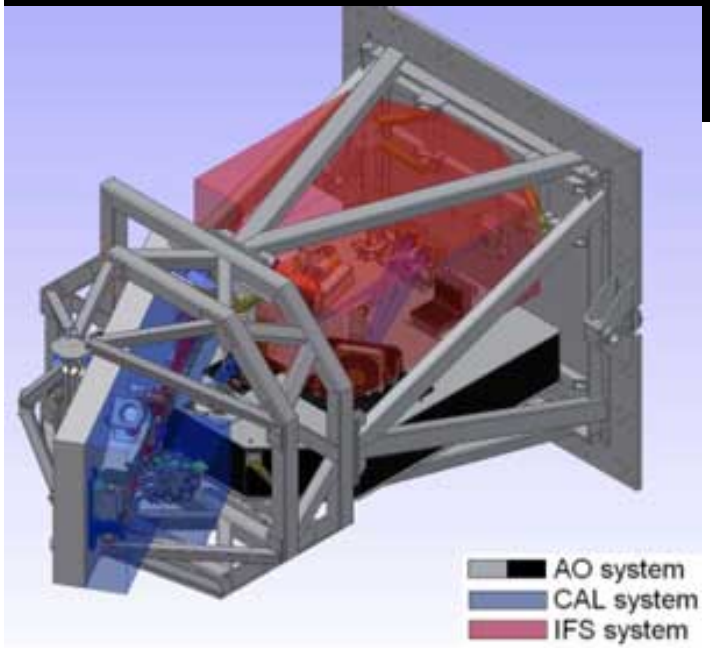
- Fast/High Order AO up to high Sr
- Effort on fine sensing of WFE down to nm range : Phase Diversity
- Small IWA coronagraphs (variety supported by servo-controlled pupil alignement) ; room for upgrades
- Multi-lambda imaging: wide IFS + dual imager, simultaneously 0.95 – 1.65 mic)
- Sensitivity: R<= 9-10
- Polarimetry
- VISIBLE : ZIMPOL
- Organized for large surveys

Gemini / GPI

Macintosh et al 2008

- Fast/High Order AO up to high Sr: MEMS
- Effort on fine sensing of WFE down to nm range : servo-loop control, «'CAL » interferometer
- Small IWA coronagraphs (Apodized Lyot coronagraphs, optimized for each spectral band)
- Multi-lambda imaging: IFS , one band at a time, Y to K
- Sensitivity: I<= 8-9
- Polarimetry
- Organized for large surveys

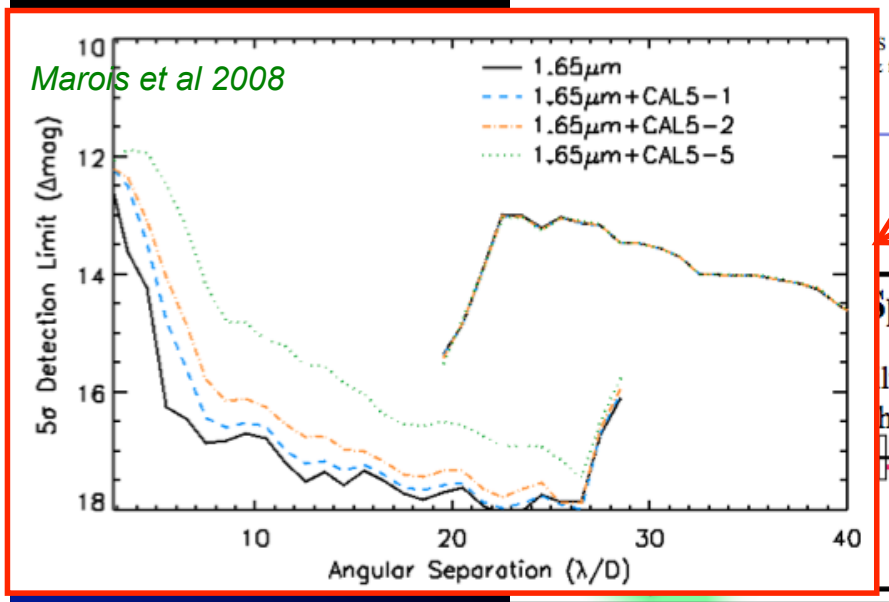
GPI

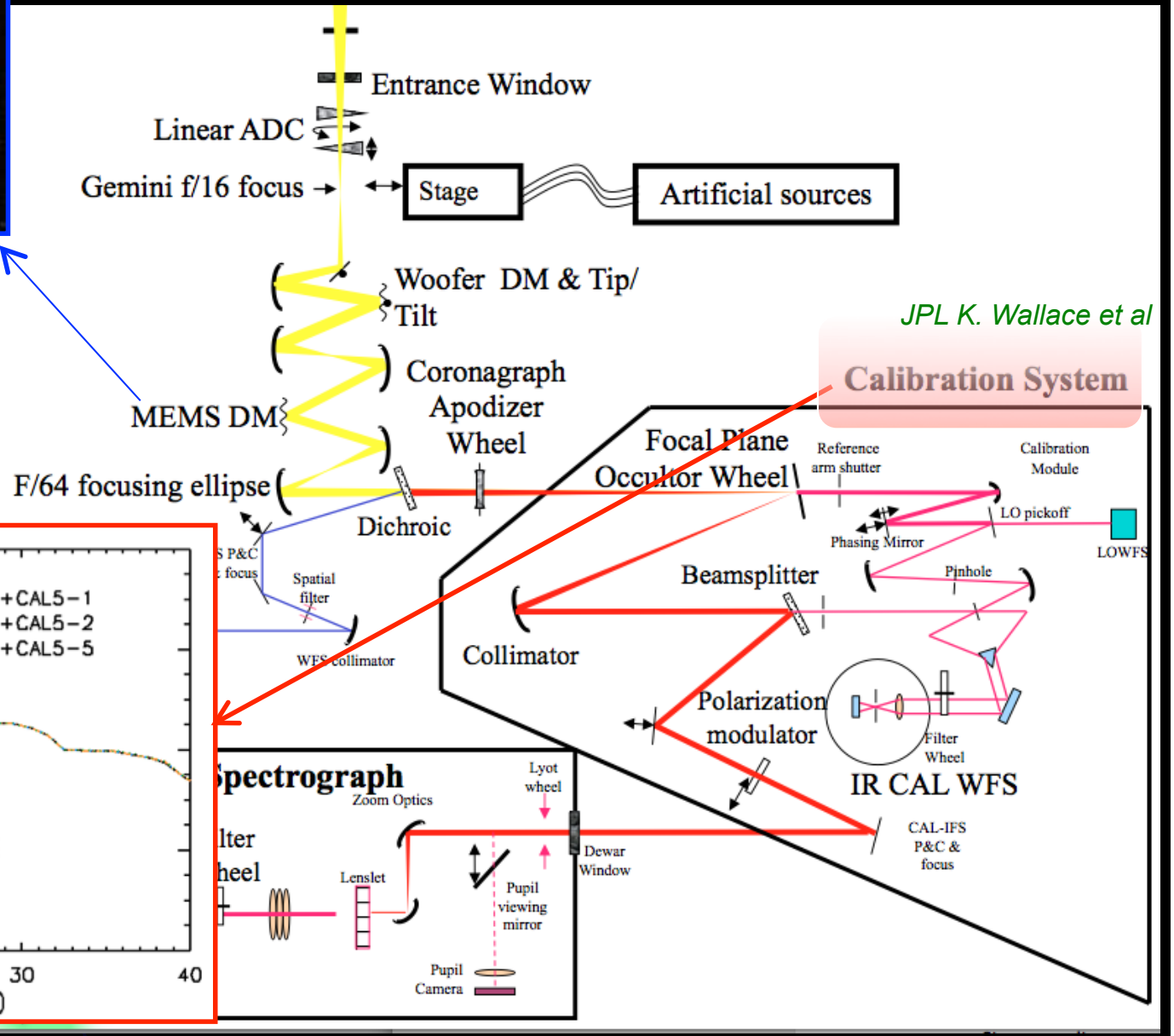


Entrance Window
Linear ADC
Gemini f/16 focus
Stage
Artificial sources
Woofer DM & Tip/ Tilt
Coronagraph Apodizer Wheel
MEMS DM
F/64 focusing ellipse
Dichroic
Visible WFS
CCD
Lenslet
Filter Wheel
WFS P&C & focus
Spatial filter
WFS collimator
Calibration System
Focal Plane Occultor Wheel
Reference arm shutter
Calibration Module
LO pickoff
Phasing Mirror
LOWFS
Beamsplitter
Pinhole
Collimator
Polarization modulator
Filter Wheel
IR CAL WFS
CAL-IFS P&C & focus
Integral Field Spectrograph
Polarizing beamsplitter
HAWAII II RG
Filter Wheel
Prism
Zoom Optics
Lenslet
Lyot wheel
Dewar Window
Pupil viewing mirror
Pupil Camera

GPI

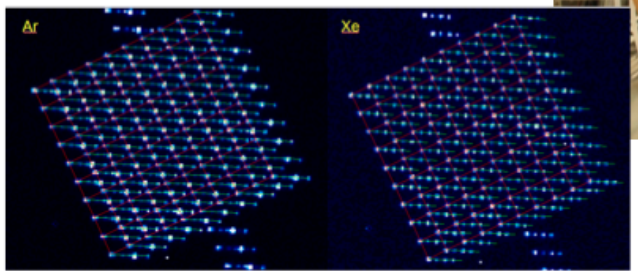
BMM micro-mirror

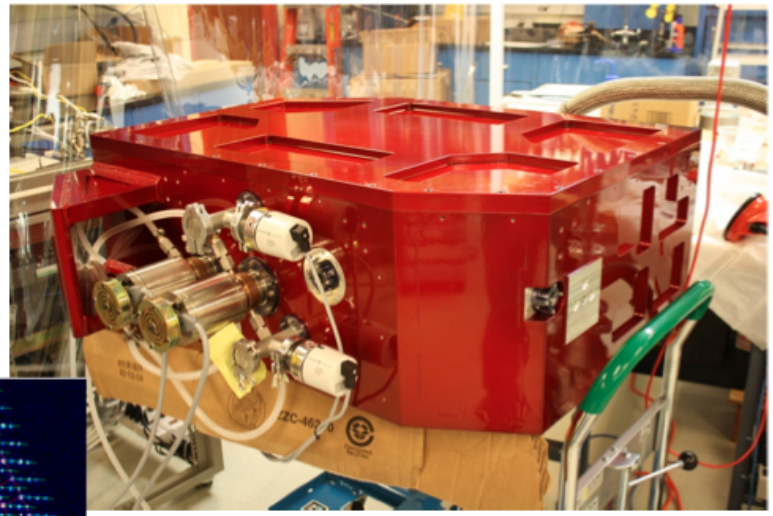




GPI

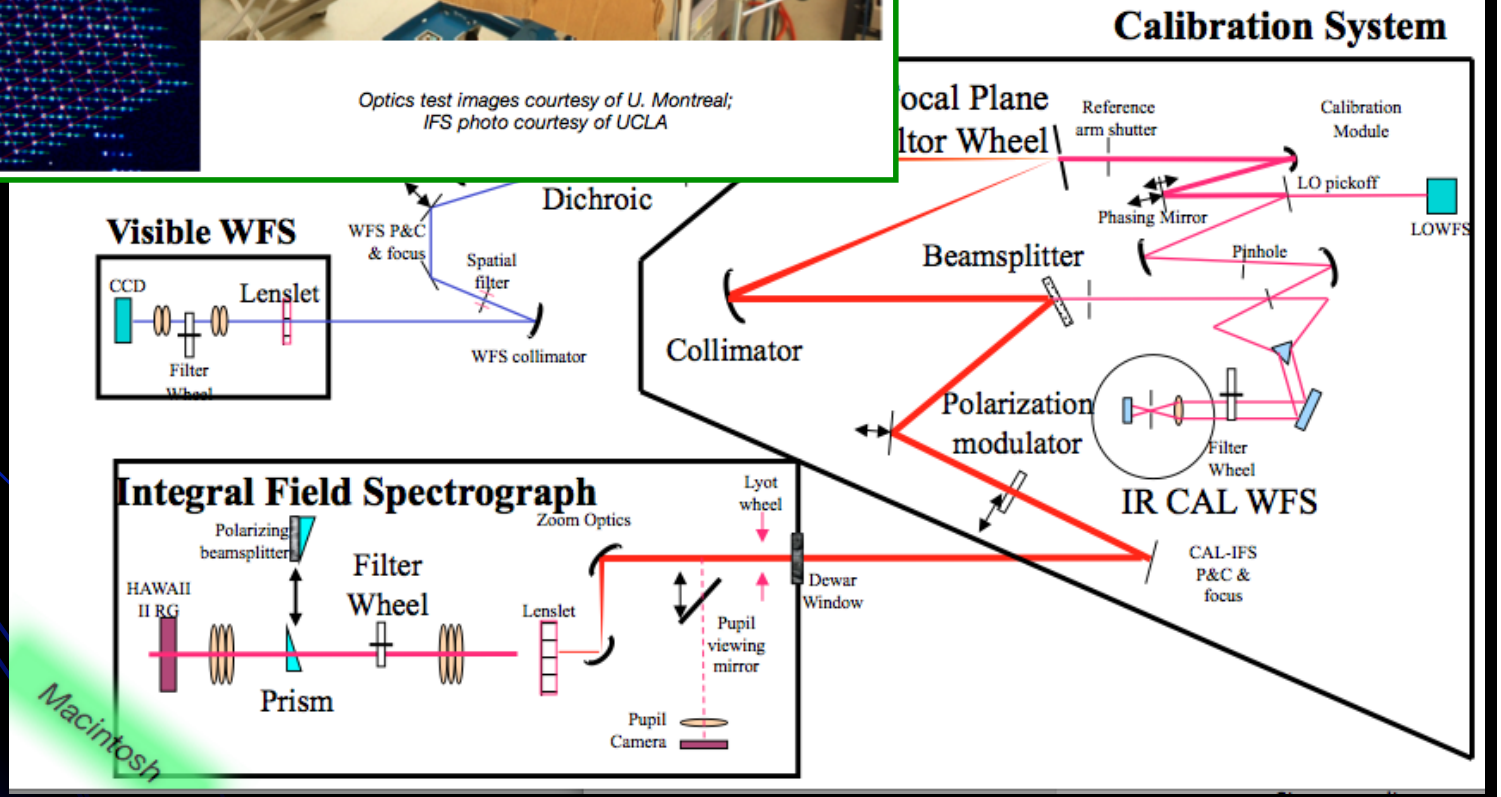
- Lenslet-based Integral Field Spectrograph
- R = 34 to 80 from Y to K
- 2.8" x 2.8" FoV
- 0.014" per pixel
- Built by UCLA (PI: Larkin) with U. Montreal and Immervision



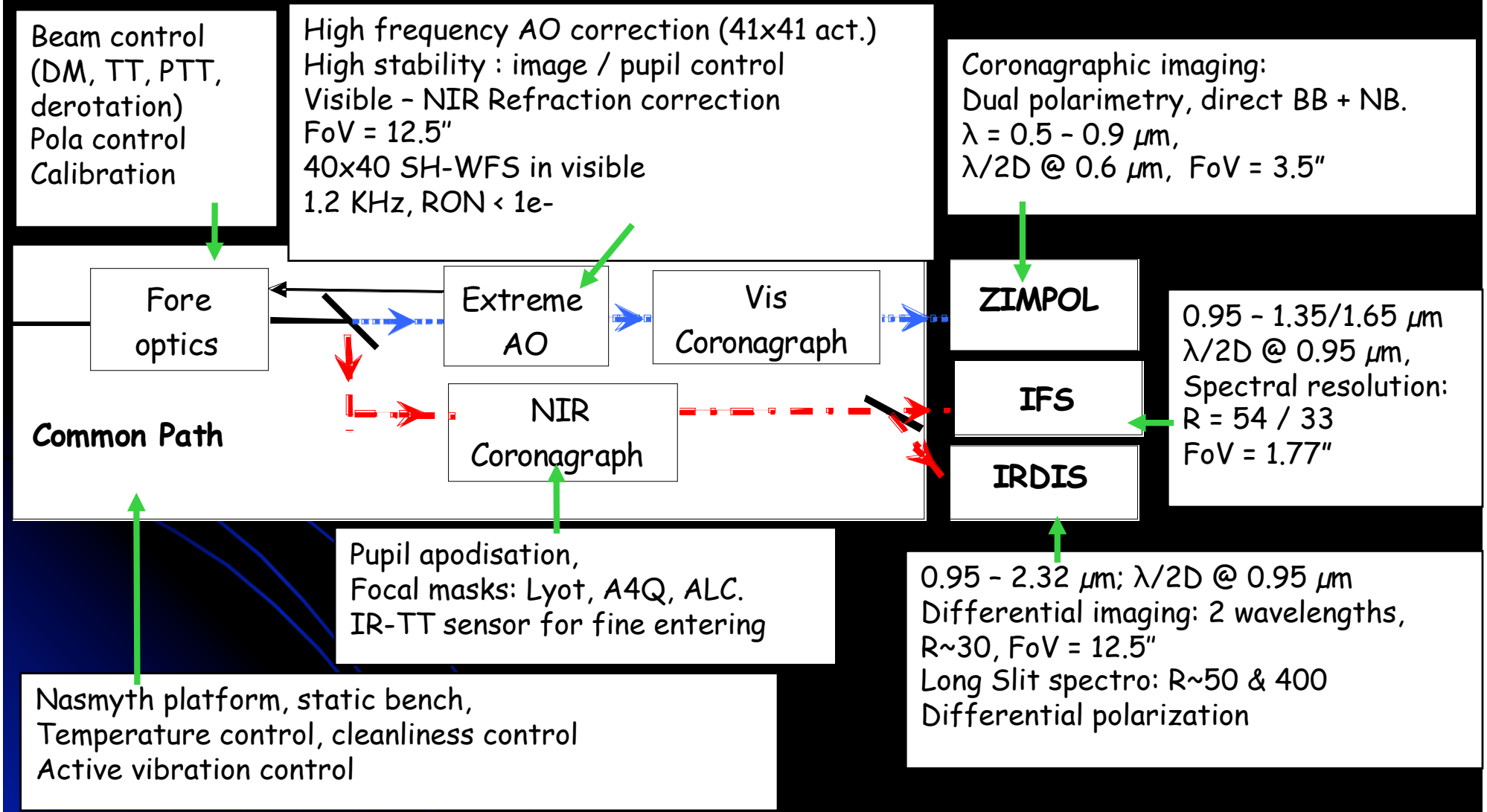


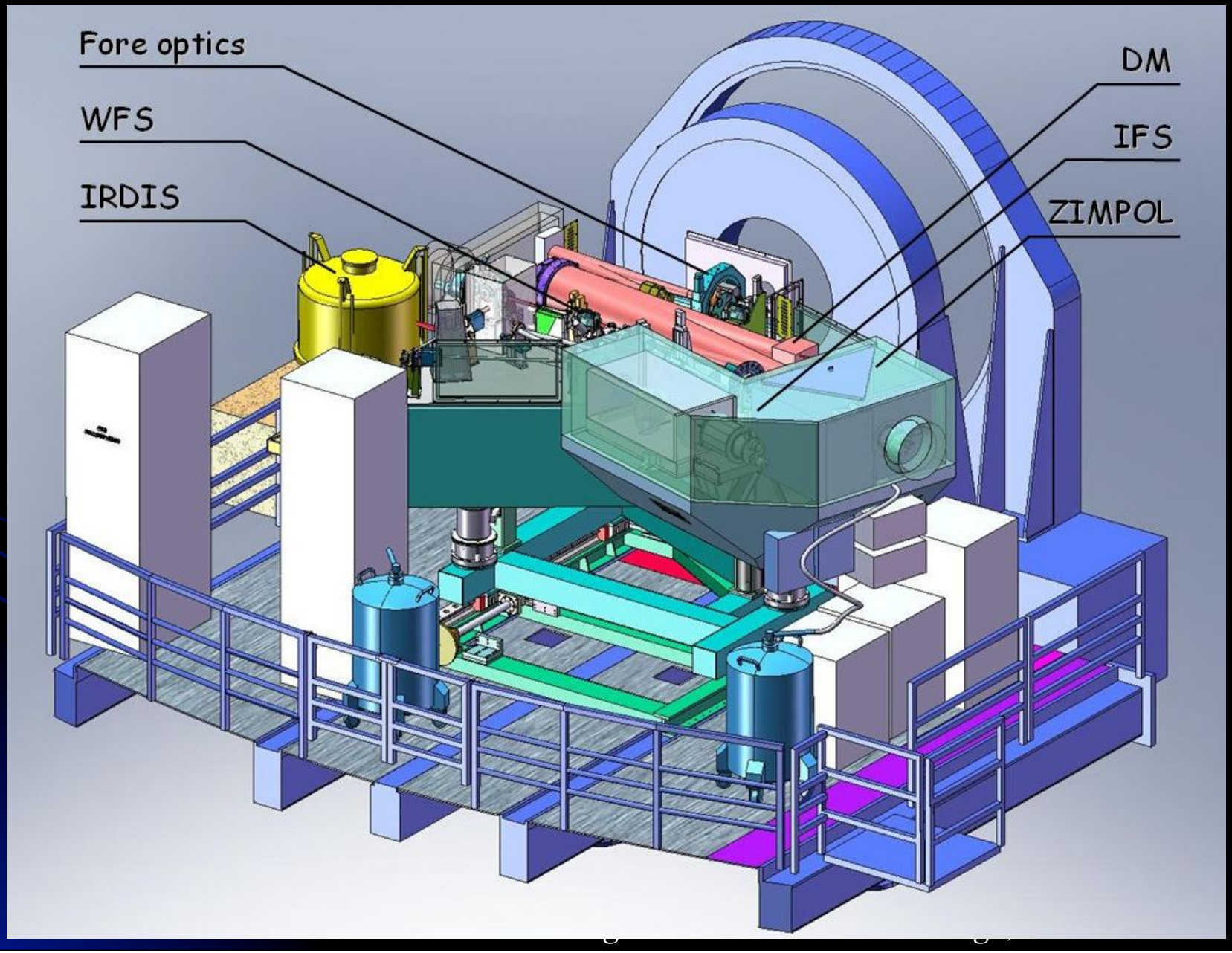
Optics test images courtesy of U. Montreal; IFS photo courtesy of UCLA

Artificial sources

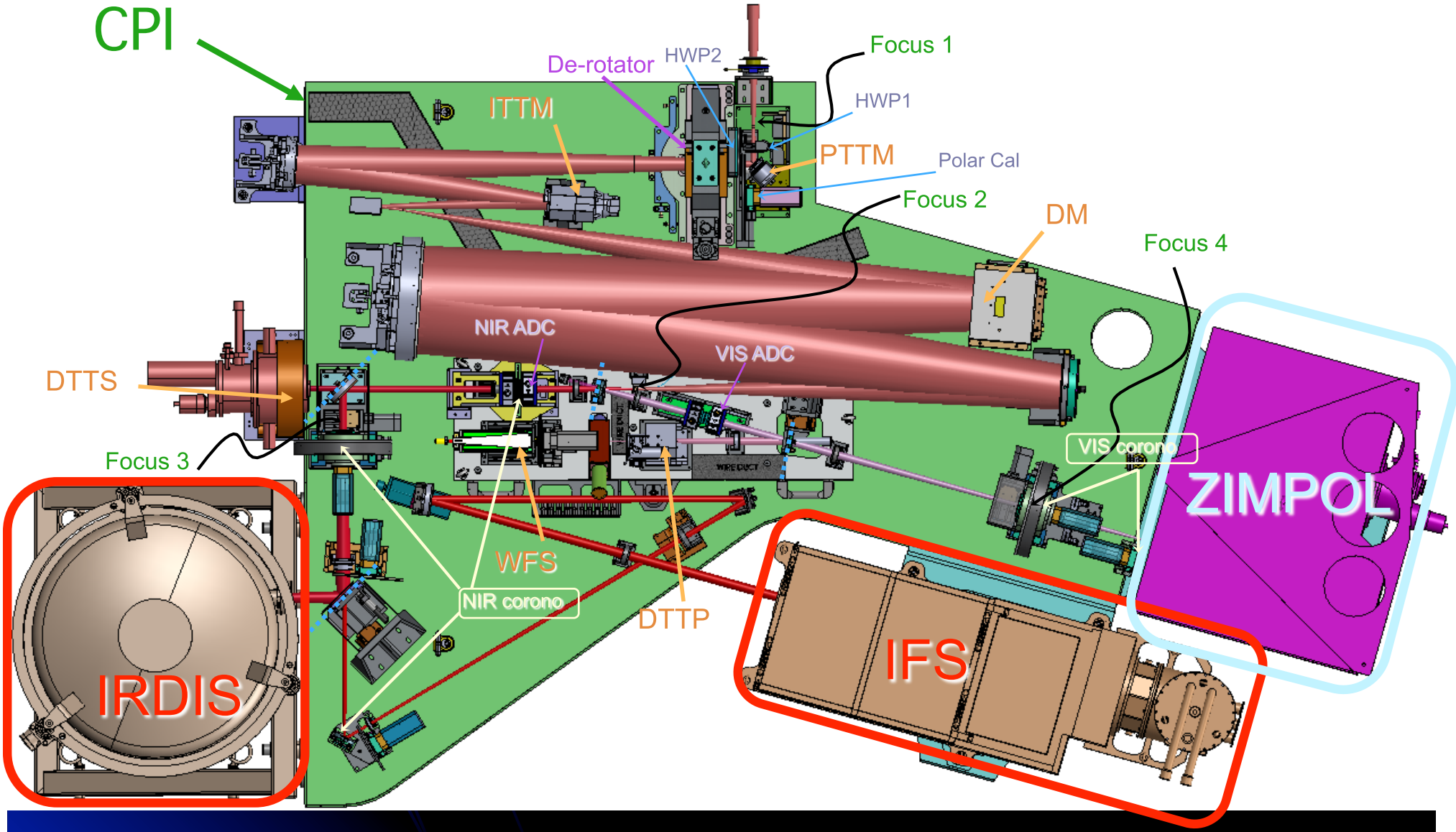


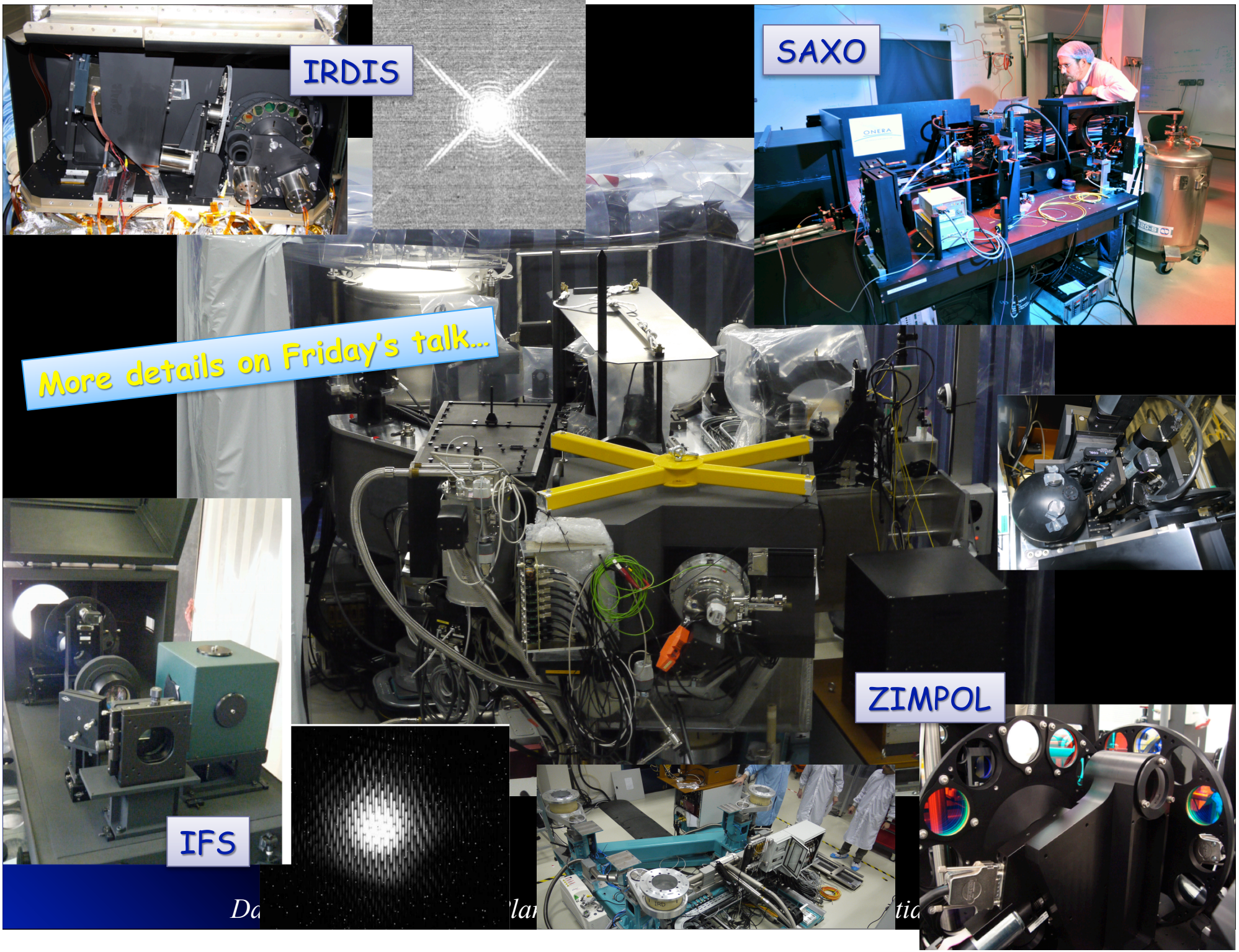
SPHERE Concept overview




Fore optics
WFS
IRDIS
DM
IFS
ZIMPOL

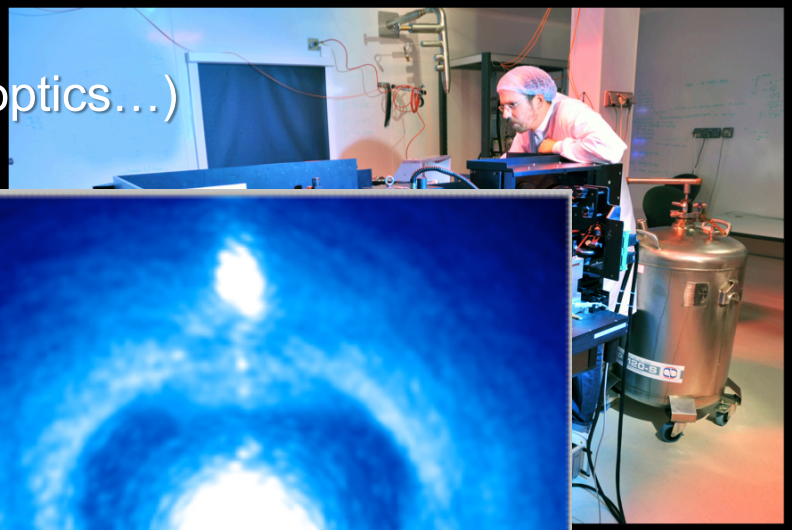
Implementation

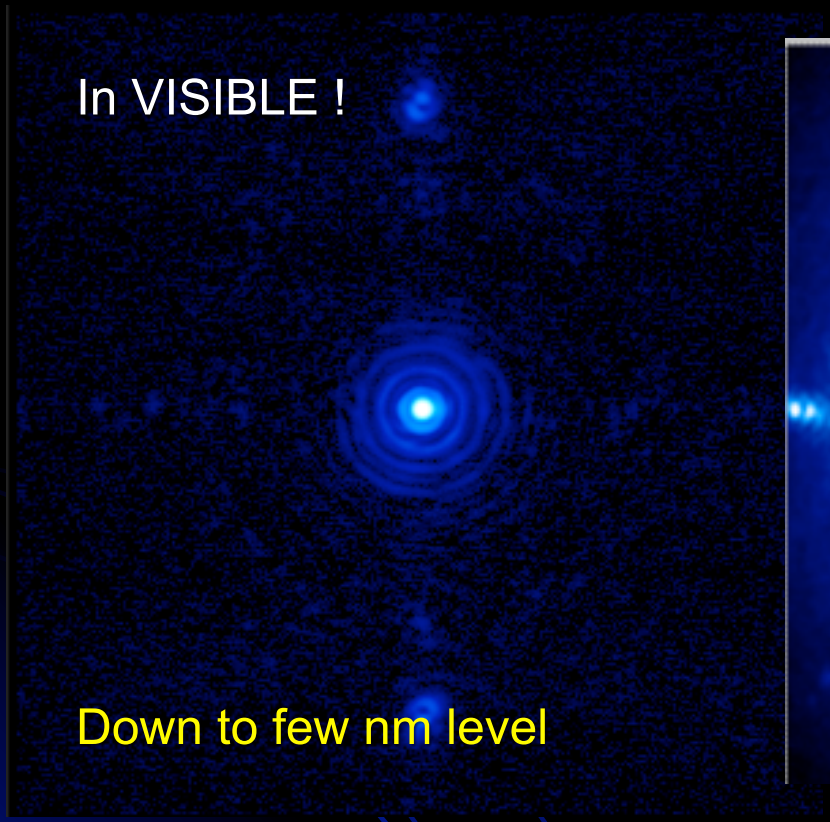


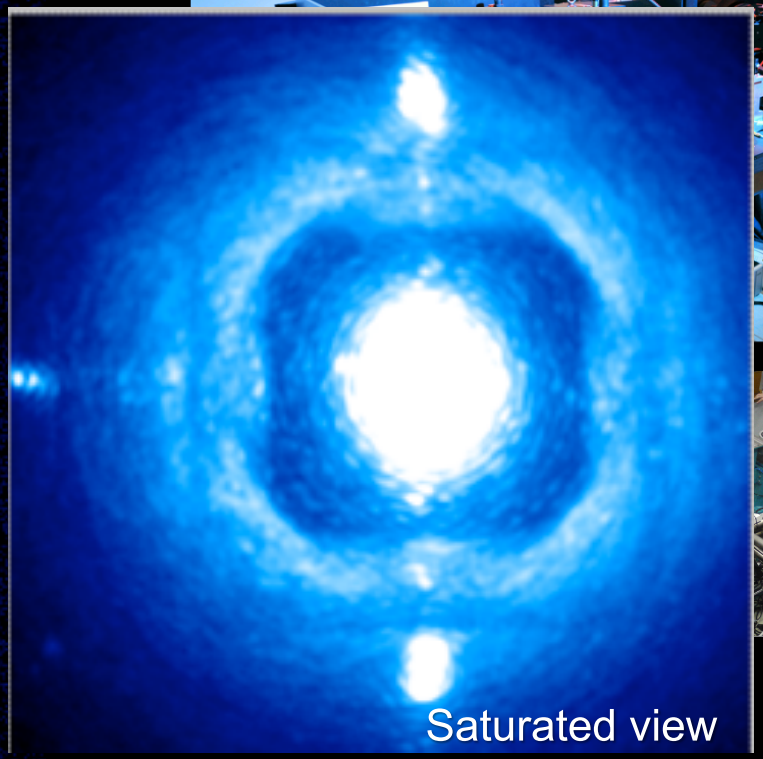

IRDIS
SAXO
More details on Friday's talk…
IFS
ZIMPOL

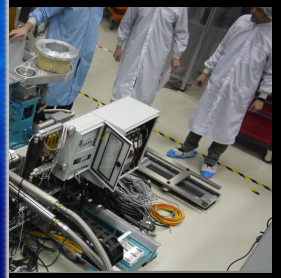
SPHERE: image quality and stability

Testing the accuracy of NCPA measurement
and correction in real life (actually after poor optics…)



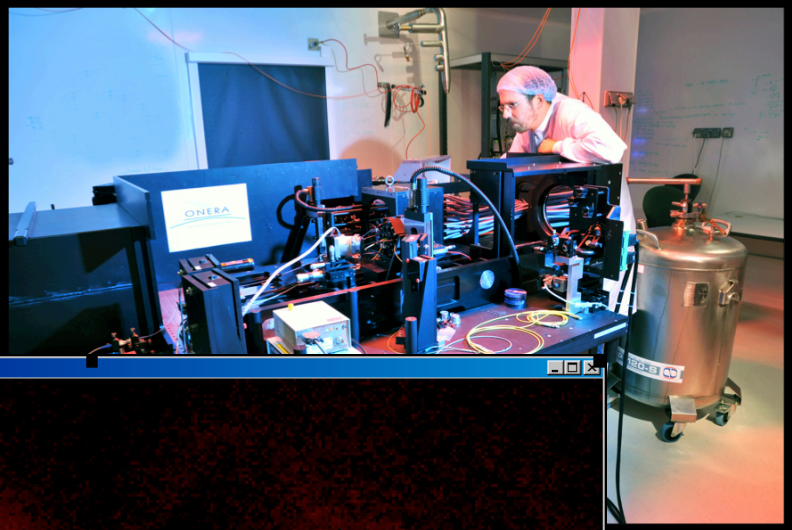


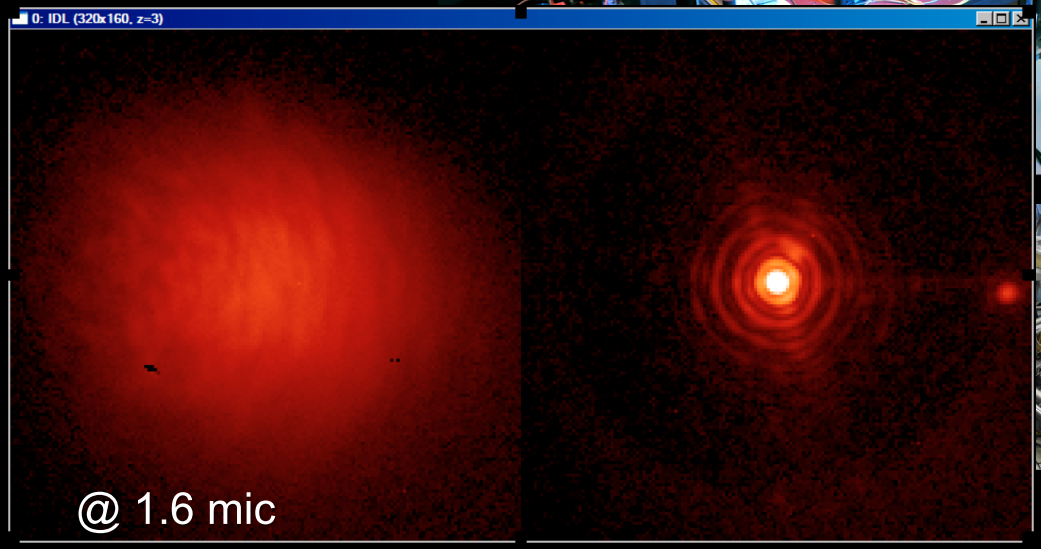


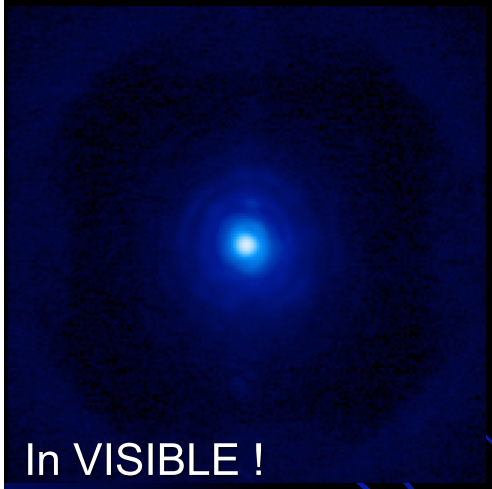


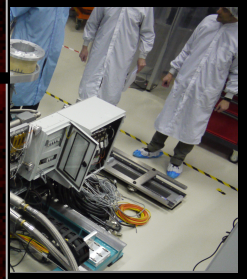
SPHERE: image quality and stability

- Fine slow WFE sensing and correction
- Fast turbulence correction (0.9" seeing)









Additional contributions to high stability and accurate alignement: fixed gravity, tilt-dedicated sensor, pupil servo-loop, vibration damping system, thermal insulation

SPHERE: sub-systems main properties

	ZIMPOL	IRDIS	IFS
FoV	Sq 3.5" (instantaneous) Up to 4" radius (mosaic)	Sq 11"	Sq 1.77"
Spectral Range	0.5 – 0.9 µm	0.95 – 2.32 µm	0.95 – 1.35/1.65 µm
Spectral information	BB, NB	BB, NB Slit spectro: 50/400	50 / 30
Linear Polarisation	Simultaneous on same detector, x 2 arms, exchangeable	Simultaneous dual beam, exchangeable	x

Coronography: no /4Q / Lyot

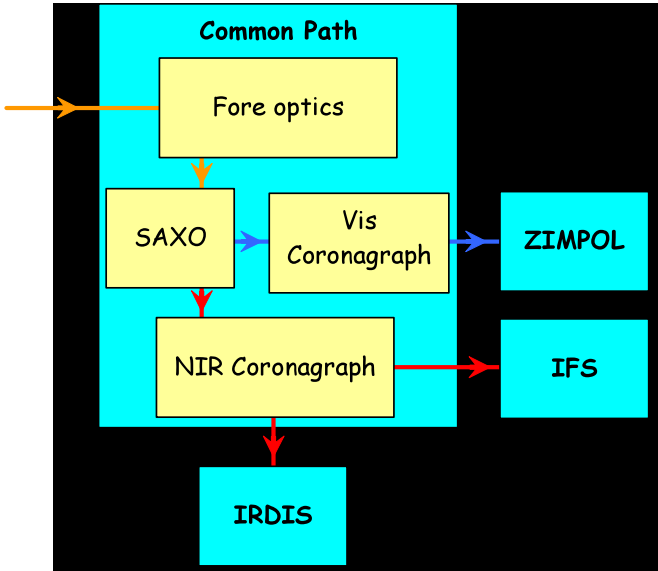
Rotation at Nasmyth:

- Pupil-stab. (instrument fixed wrt tel.)
- Field-stab (slit spectro, long DIT…)
- No rotation: minimize crosstalk…)

AO sensitivity for high contrast: R=9.5 for NIR; R=9 for R; R=7.8 for whole VIS

Separation range where improved contrast: 2 - 20 λ/D, ie 30-300 mas in R, or 80 – 800 mas in H

Mode switching: not VIS and NIR in same night

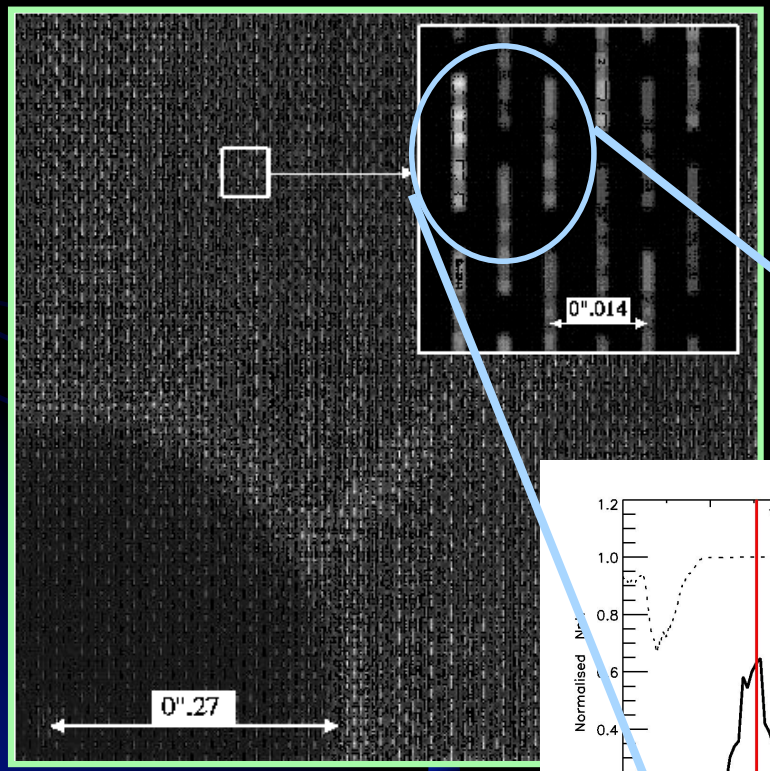


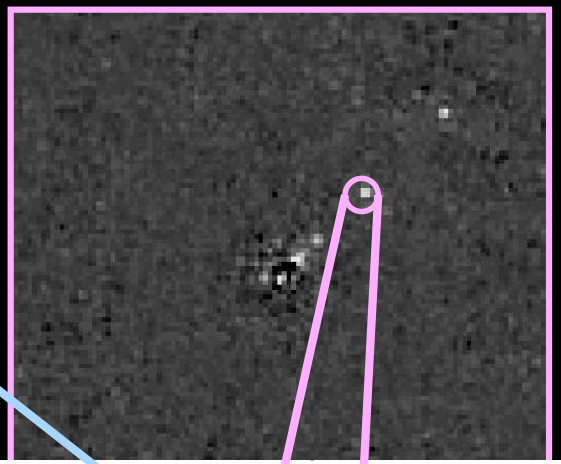
SPHERE in NIR

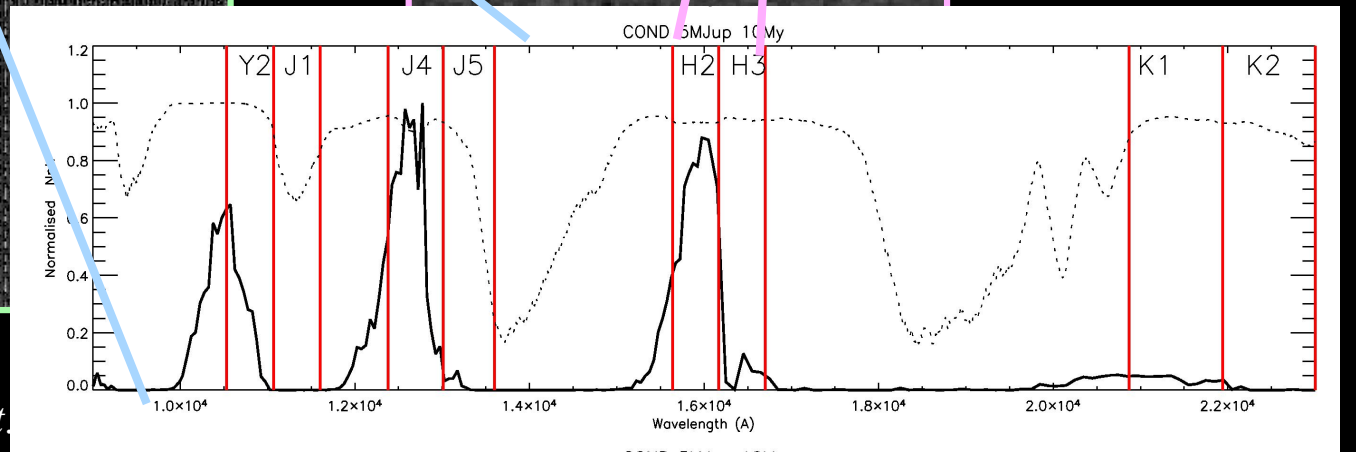
ONE observing mode optimized for identification of low mass companions in large surveys

Simultaneous and complementary use of both imager and IFS for NIR survey search for EGPs

DBI in H + IFS in Y-J

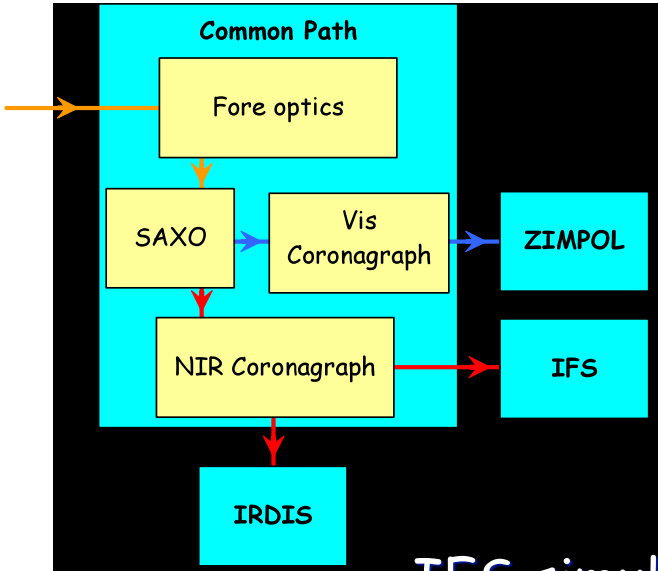






David Mouillet

SPHERE in NIR



Complementary modes in NIR

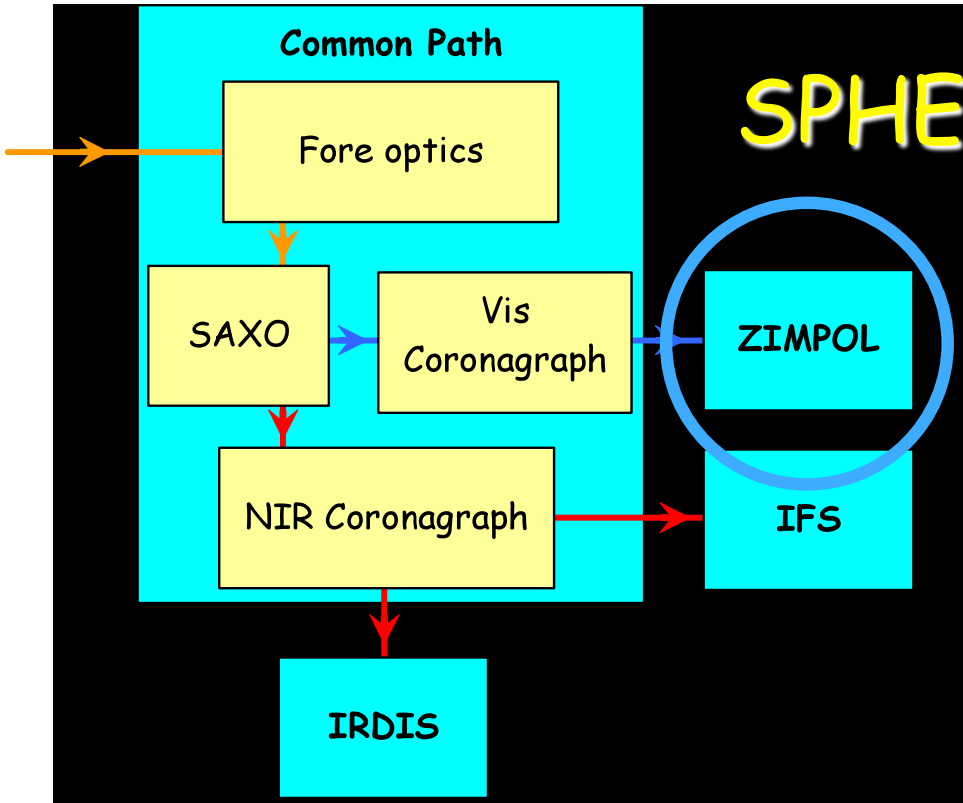
- IFS simultaneously from 0.95 to 1.65
- IRDIS polarimetry

- Various filters: BB, NB, dual band, from Y to Ks

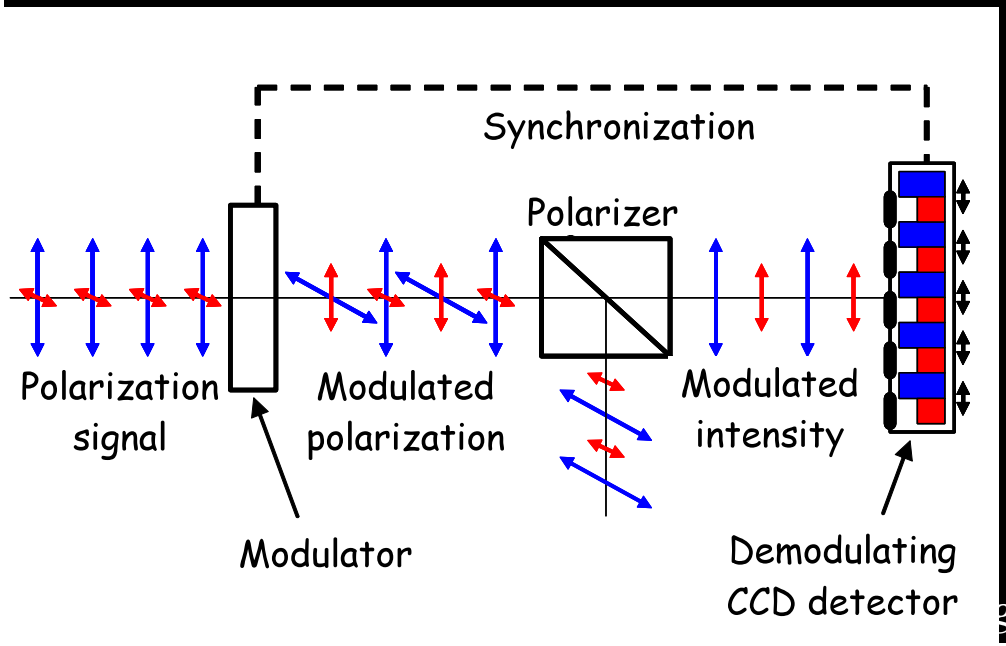
- Slit spectroscopy over the field, up to R = 400

See A. Vigan, on Friday

SPHERE in VISIBLE

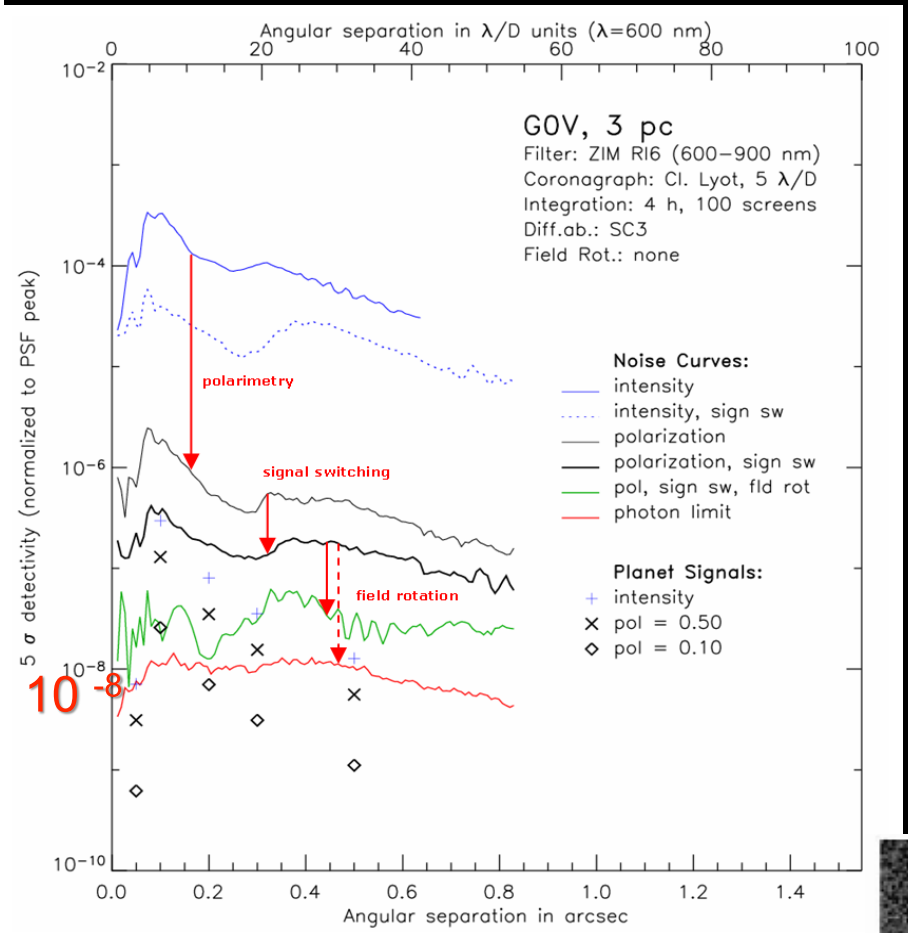


- Polarized reflected light on planets around very nearby stars
- high contrast and high angular resolution on disks, nebulae, ejecta …

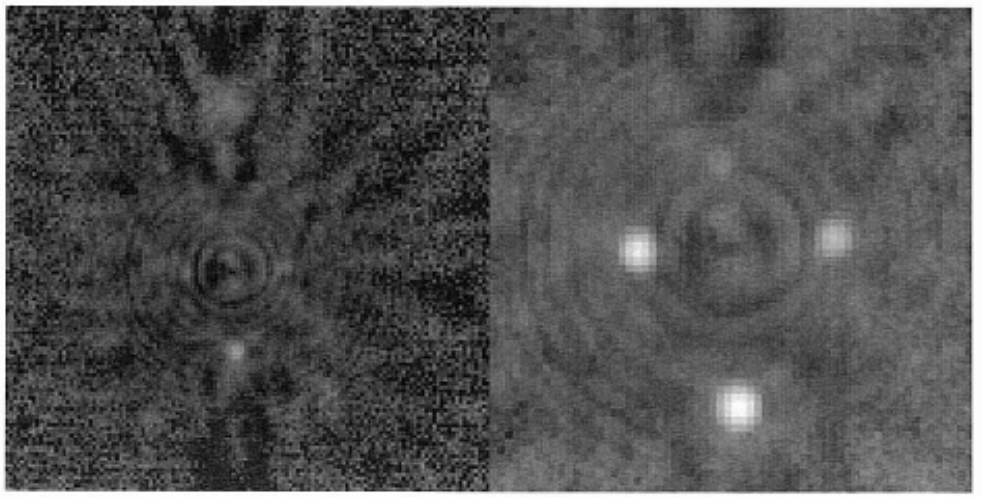


- Visible light (500 to 900 nm)
- Polarimetric precision better than 10^{-5}
  - ✓ Ferro-electric polarization modulator (1 kHz)
  - ✓ Synchronous demodulating CCD
- 3" x 3" FOV on detector
  - ✓ Access to a field of radius 4" by detector x-y stage

SPHERE in VISIBLE



- Diff polar greatly helps for reflected light !! + angular resolution
- Going down to 10^{-8} !!
- Unprecedented direct look into the inner planet around nearest stars
- Great for disk polar imaging
- + any very HAR classical imaging



Planet imagers

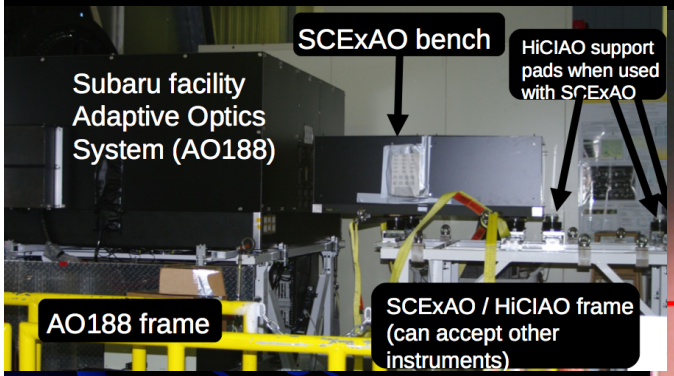
New/Future experiment on sky

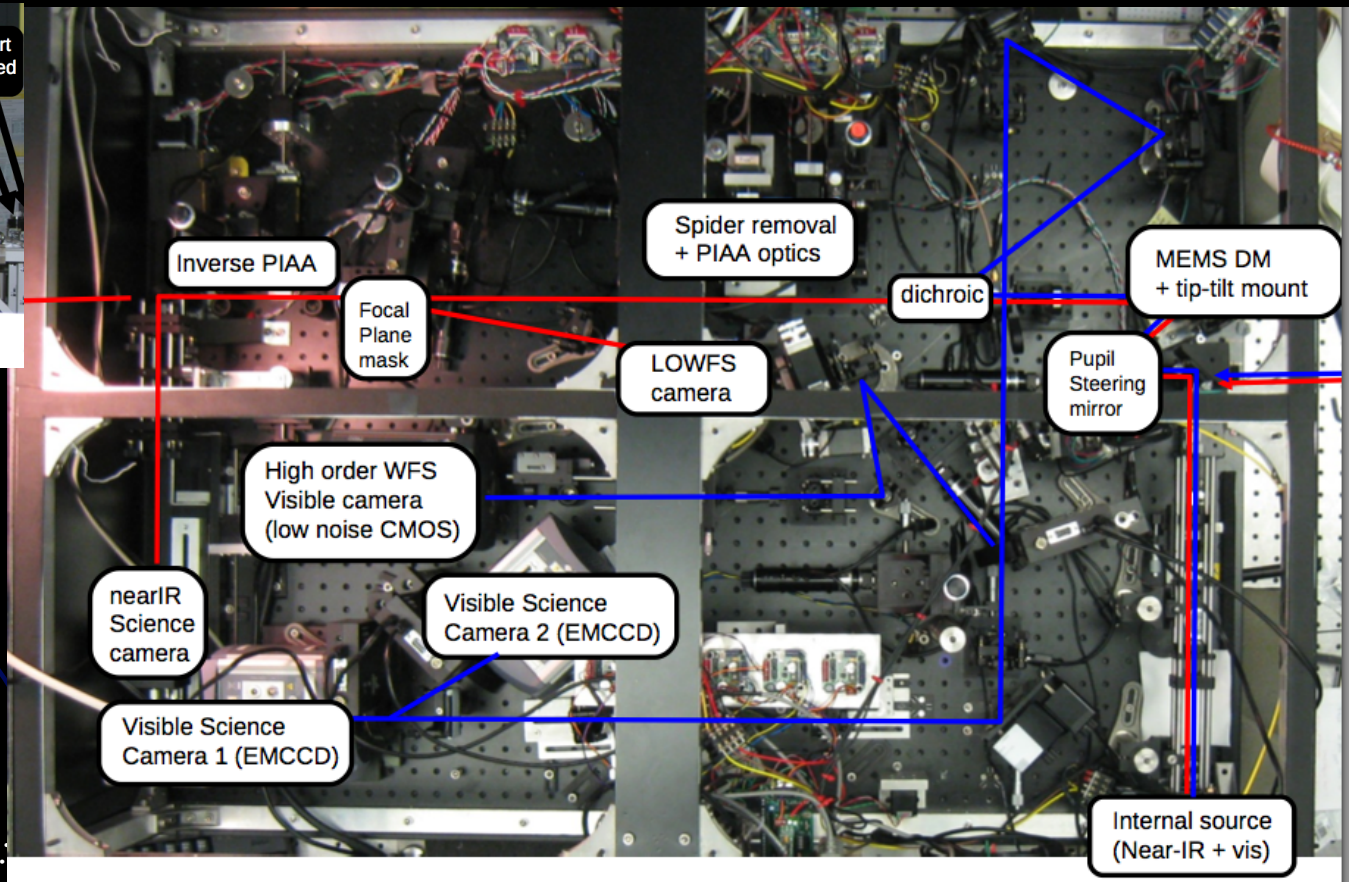
- Palomar
- Subaru / SCExAO / HiCiao (O. Guyon et al)
  - Highly focussed to very low IWA and high contrast
  - High order sensor: lower noise propagation to lower modes
  - Sensing and compensating residual WFE: LOWFS, modulation-supported speckle detection and control
  - Advanced coronagraph design
  - Inc. Visible imaging

Planet imagers

New/Future experiment on sky

- Palomar
- Subaru / SCExAO / HiCiao (O. Guyon et al)

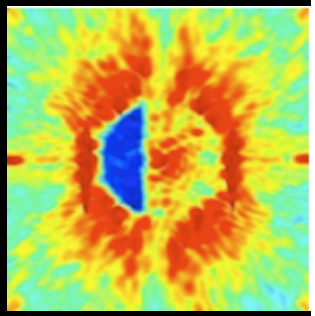




what to expect and prepare next ?

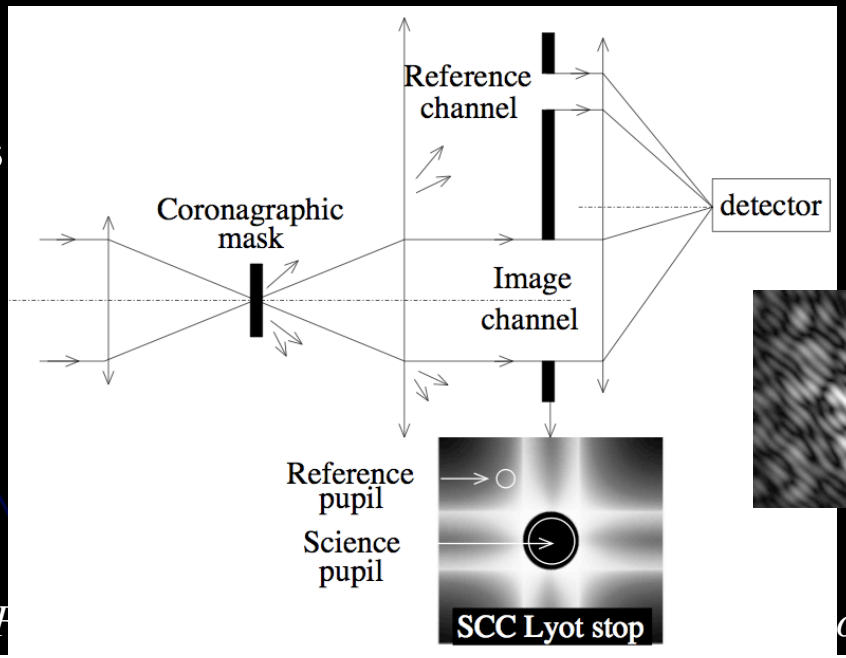
- On-going research on speckle sensing and correction: focal plane sensors
  - Ultimate accuracy ?
  - Tolerance with overlying (zero-mean) turbulence residuals
  - Support of coherent modulation
  - Coherence discrimination star/companion

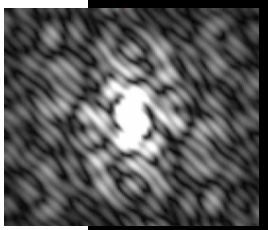
Friday: Galicher et al, Kenworthy et al



Among various approaches
« Self-coherent camera »

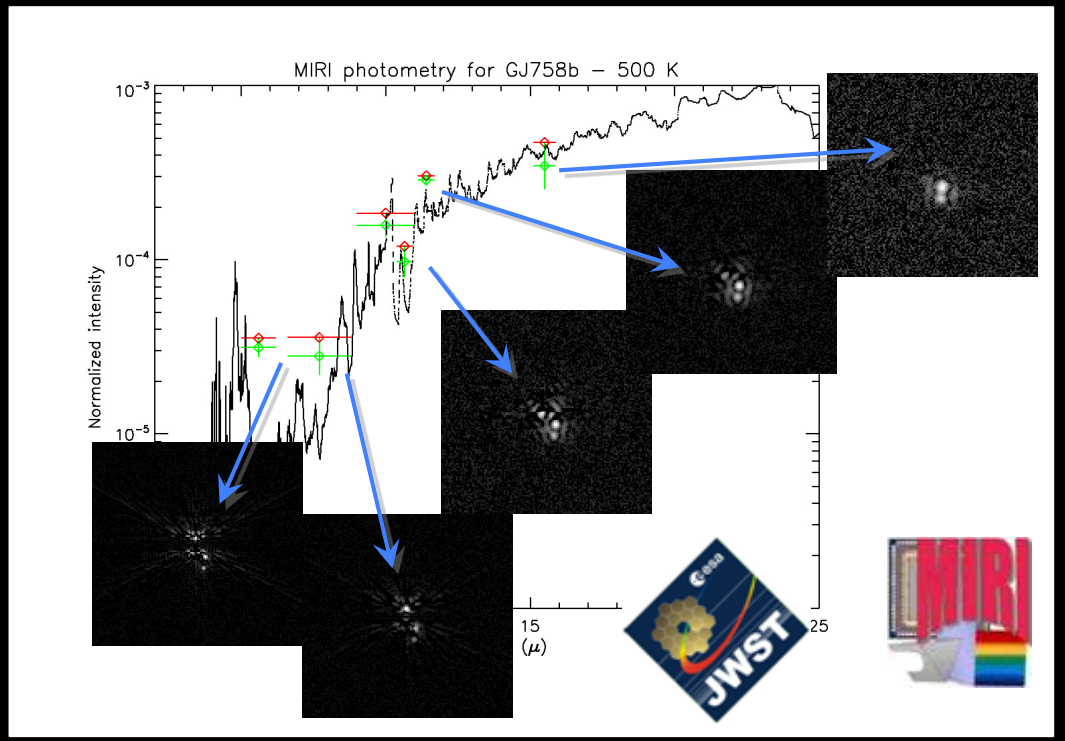
Baudoz et al 2007
Galicher et al 2010





what to expect and prepare next ?

- On-going research on speckle sensing and correction: focal plane sensors
- Direct imaging at longer wavelength … assuming you have large telescope, and small IWA (imaging complementary at larger separation to transits)
  - JWST / MIRI
  - E-ELT / METISS



Lagage, Boccaletti, Ronayette et al

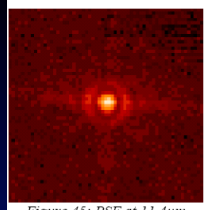


Figure 45: PSF at 11.4μm

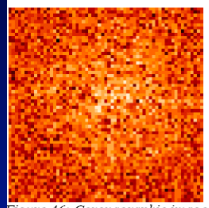


Figure 46: Coronagraphic image at 11.4μm

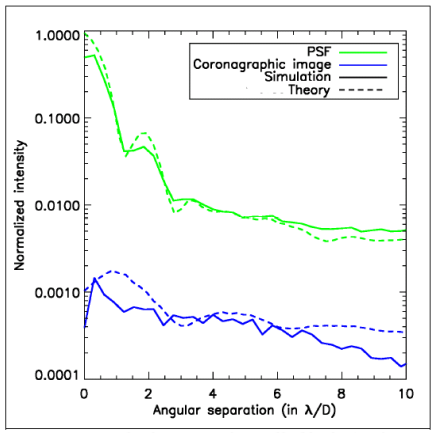


Figure 47: Normalized coronagraphic profile (blue line) and PSF (green line) compared to simulated profiles (doted lines) at 11.4μm

what to expect and prepare next ?

- On-going research on speckle sensing and correction: focal plane sensors
- Direct imaging at longer wavelength … assuming you have large telescope, and small IWA
- Strong motivation for still higher contrast and inner working angle in Visible and NIR
  - Outer planets : there will still be a lot to do !! New detections, lower masses, cooler, characterization, perturbations, high SNR
  - Towards inner planets : complementarity to other planets for complete/finer characterisation
  - From ground (eg E-ELT / EPICS) or space (see Boccaletti, this conf. Friday)
  - To be prepared now

Concluding remarks

- For L' band and/or faint targets: current instruments are better !
- High contrast instrumentation: an incredibly active and exciting research field and performance increase curve
- Performance gain about to come now:
  - On large target samples
  - For a large community, well-prepared on existing programs
  - To probe the essential population of outer giant planets
- A step before later deeper characterization of individual targets (E-ELT, space)