OWL Instrument Concept Studies

Sandro D’Odorico, on behalf of ESO and Institute Instrument Teams

OUTLINE :

- **Scope and setting up of the studies**
- **Quick presentation of the instrument concepts**
- **Summary of the results and feedback to telescope design**

OWL Instrument Concept Studies

SCOPE

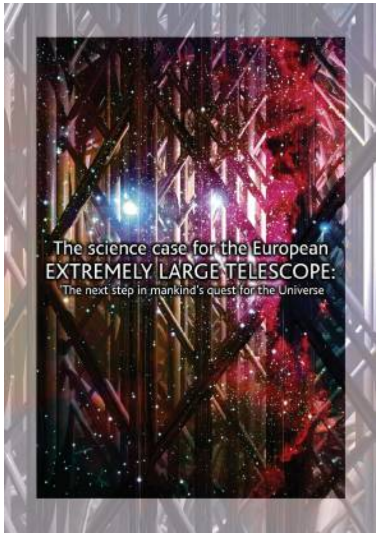
- to support the main OWL science cases with **feasible instrument** concepts
- to verify and optimize the **telescope- instrument interfaces**
- to identify the instrument **enabling technologies** and the **required R&D**

BEWARE !

- ***Do not claim to cover <u>all</u> important science with OWL***
- ***The studies were completed in October 2005 only. Feedback to the telescope design will be taken into account in the next Phase of the project.***

OWL Instrument Concept Studies

SELECTION OF THE INSTRUMENT PACKAGE



The science case for the European
EXTREMELY LARGE TELESCOPE:
The next step in mankind's quest for the Universe

- ❖ Guided by requirements from OPTICON ELT Science Case and the previous work on OWL science
- ❖ Choice of external teams based on previous expertise on VLT or other large telescope instruments and availability at short call
- ❖ 6 led by external P.I., 2 coordinated by ESO

OWL Instrument Concept Studies

SETTING UP OF THE STUDIES

❖ Studies officially launched in 3 and 4Q 2005. All completed by October 2005 (6-12 months)

❖ Steered by dedicated Statement of Work

❖ Supported by:

- ➢ An ESO Instrument Scientist for each study
- ➢ An OWL Telescope Interface Document
- ➢ Exposure Time Calculator
- ➢ Exchanges with telescope design and AO teams

OWL Instrument Concept Studies

→
B-Vis
→
→
→
NIR
→
→
TIR→
Submm
→

INSTRUMENT	Wav. range	Main Capability	P.I. (I.S. at ESO)	INSTITUTES
CODEX	0.4-0.7 µm	High Velocity Accuracy, Visual Spectrograph	L Pasquini (ESO)	ESO, INAF-Ts, Geneve Obs, IoA Cambridge
QuantEYE	0.4-0.8 µm	Photometry at 10^{-3} - 10^{-9} second resolution	C.Barbieri & D.Dravins (R.Fosbury)	Padova Univ. & Lund University
HyTNIC	1.1-1.6 µm	High-contrast diffraction-limited Imager	O.Lardière,V.Borkowski & A.Labeyrie (G.Monnet)	LISE- Collège de France
EPICS	0.6- 1.9µm	Camera-Spectrograph at diffraction limit	N.Hubin,M.Kasper, C.Vèrinaud (ESO)	ESO + ext. experts
MOMFIS	0.8-2.5 µm	Near IR Spectrograph using many deployable IFUs	J.G.Cuby (M.Casali)	CRAL, LAM, OPM
ONIRICA	0.8-2.5 µm	NIR Imaging Camera on a field up to 3 x 3 arcmin	R.Ragazzoni (E.Marchetti)	INAF Arcetri ,Padova, Roma& Heidelberg MPIfA
T-OWL	2.5-20 µm	Thermal, Mid Infrared Imager and Spectrograph	R.Lenzen & B.Brandl (H.U.Käufl)	MPIfA Heid., Leiden, ASTRON, ESO
SCOWL	250-450-850 µm	Imager at Sub-millimeter Wavelengths	B. Dent (R.Siebenmorgen)	ATC

OWL Instrument Concept Studies

The Study Teams were asked to :

Develop high priority science cases to define the requirements to the instrument

↓

Derive an instrument concept and use it to estimate the performance and make the first guesses on volume, mass and cost

↓

Assess performance in the context of present and future key facilities (JWST, ALMA) and as a function of diameter in the range 50-100m

↓

Identify critical components

↓

Identify discrepancies and special requirements to the telescope design

OWL Instrument Concept Studies

Outcome of the Studies:

- **Presentation and discussion of all study reports at ESO on September 27, 2005. They include quantitative science cases and advanced instrument concepts**

- **All Reports delivered to ESO by October 20 .**
  A total of 1200 A4 pages.

- **Available as of last week to the Review Board on the OWL Documentation password-protected web site. Now on CD**

OWL Instrument Concept Studies: CODEX

P.I.: L.Pasquini, coP.I.: S. Cristiani, M.Haehnelt, P.Molaro,F.Pepe & staff of 22 from 4 institutes

PRIMARY SCIENCE GOAL:

To test the cosmological model by measuring the predicted drift in the redshift of distant sources as a function of time

Unique in probing the validity of the dark matter and dark energy concordance model in the redshift range z = 1.5- 4. Based on **Dynamics, not Geometry** (→High Z SNae search and WMAP)

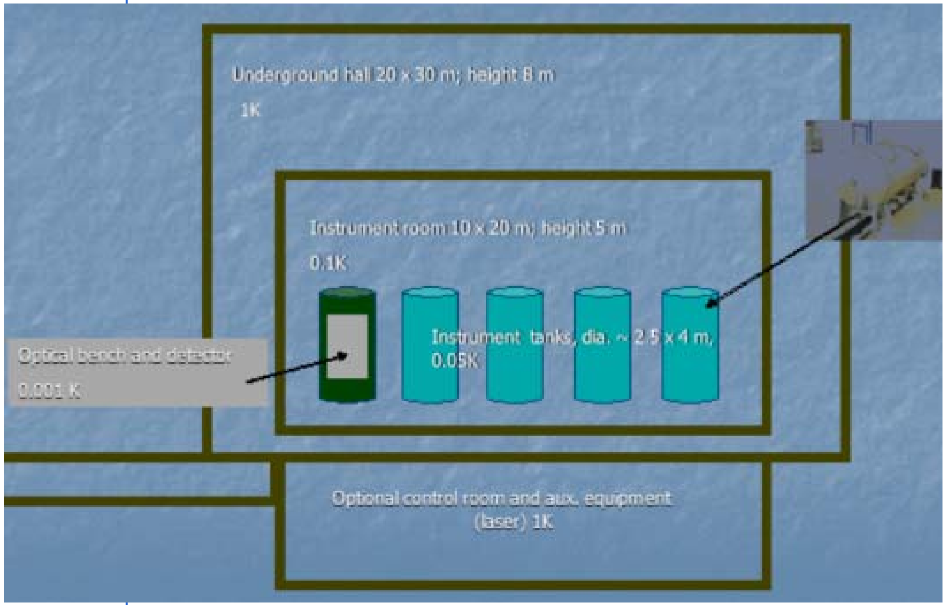
THE METHOD

Exploits OWL huge collecting area and an high resolution spectrograph with a highly accurate and stable wavelength scale to measure the shifts in the Ly α forest and metal systems in the direction of bright QSOs over a large time interval ($\geq$10 years).

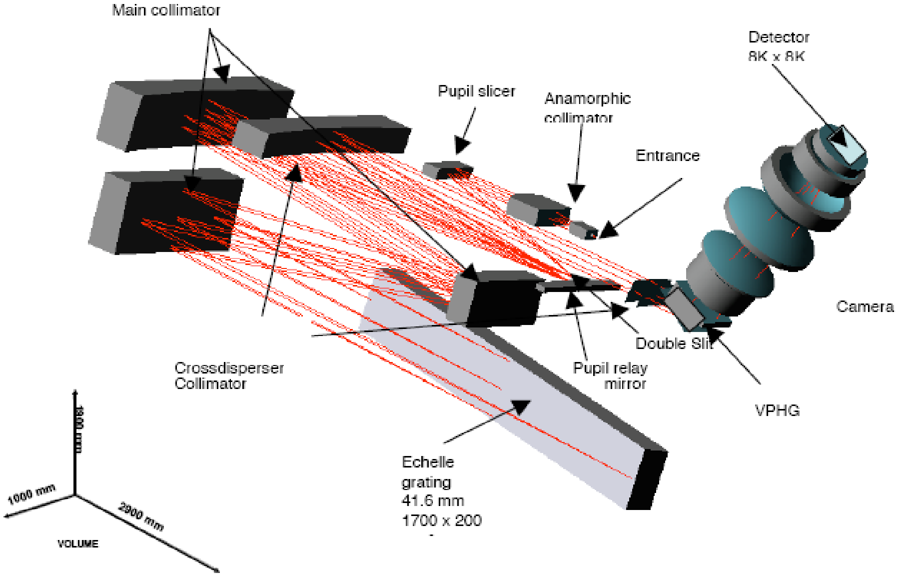
OWL Instrument Concept Studies: CODEX

THE INSTRUMENT :

High Resolution Spectrograph operating in the spectral range:400-680 nm at R = 150000 with a long term stability of 1cm / s from an absolute calibration and stable environment



CODEX Laboratory floor plan (with thermal requirements)



Optical layout of one of the 5 CODEX Unit Spectrograph

OWL Instrument Concept Studies: CODEX

WILL ENABLE CORNUCOPIA OF UNIQUE SCIENCE. Three additional cases studied in the report:

- Cosmological variation of the Fine-Structure Constant: at the accuracy of the OKLO reactor measurement ($D\alpha/\alpha \sim 10^{-8}$)
- Terrestrial planets in extra-solar systems (radial velocity of Earth-mass planets, spectroscopy of planets in transit)
- BB nucleosynthesis by measuring primordial Li7 and Li6/Li7

CHALLENGES: CODEX implies:

- Very large, gravity invariant, thermally stable (0.01 K) laboratory fed by a coude train (fibre)
- Efficient optical design with novel features delivering a manageable 2D spectral format
- Calibration system with absolute reference (Laser comb project)
- Development of a number of advanced optical components

QuantEYE

P.I.s: D. Dravins and C. Barbieri & staff of 11 from 5 institutes

SCIENCE GOAL:

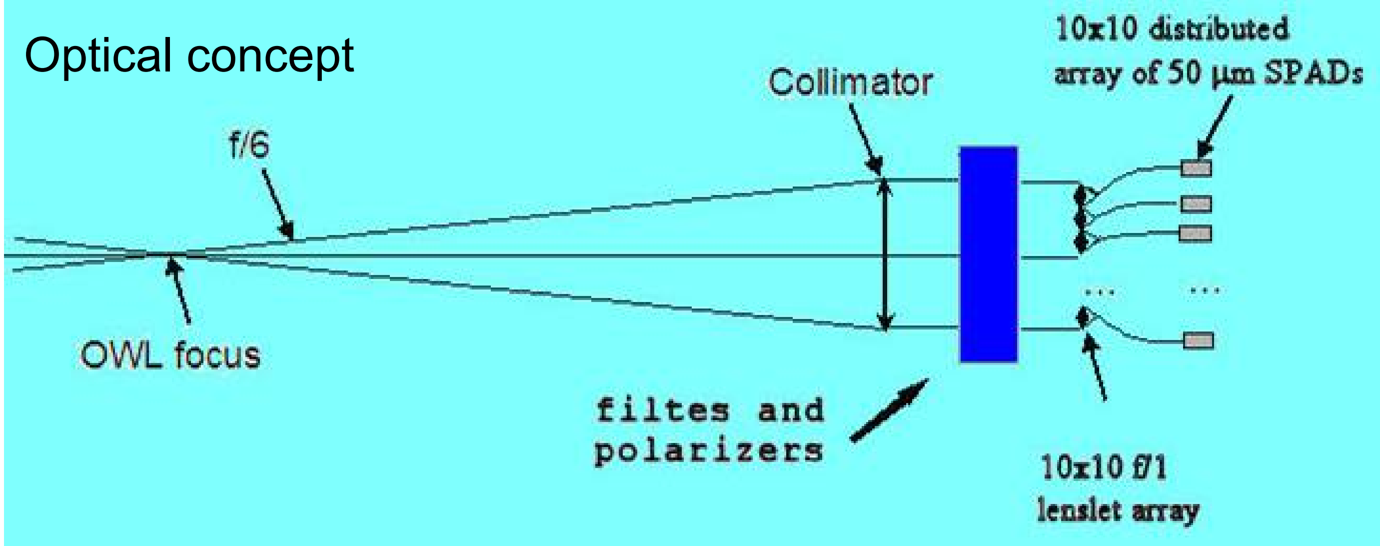
- **To investigate photons and their properties in Astronomy beyond conventional imaging, spectroscopy, polarization, interferometry.**

Open up quantum optics as another information channel from the Universe

- **Proposal focussed on use of the OWL photon collecting power to explore for the first time photon arrival statistics of astrophysical targets at an unexplored time resolution, $<< 10^{-3}$ s**

(Potential targets: Millisecond pulsars ; Variability near black holes ; Surface convection on white dwarfs ; Non-radial oscillations in neutron stars ; Surface structures on neutron-stars ; Photon bubbles in accretion flows ;Free-electron lasers around magnetars ; Astrophysical laser-line emission)

<u>INSTRUMENT CONCEPT</u> : two head, high time resolution (10^{-3} - 10^{-9} s) photometer operating in the Vis-Red bands



The f/6 beam from OWL is collimated and sampled by a 10×10 array of 10x10 mm square section lenses, working at *f*/1 and feeding a 10 x 10 Single Photon Avalanche Diode Array

<u>Optically simple, light instrument. It does not require AO</u>

Advantages of very large telescopes in photon statistics

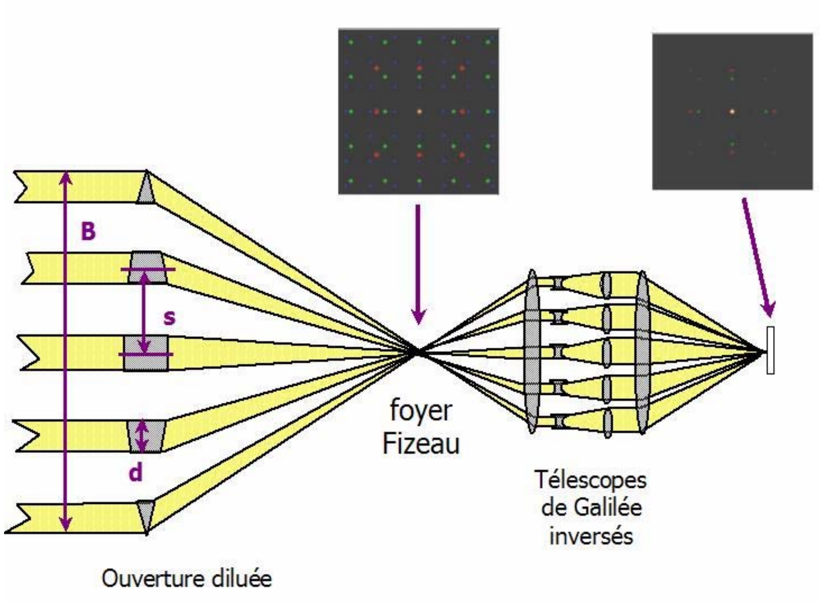
Telescope diameter	Intensity $\langle I \rangle$	Second-order correlation $\langle I^2 \rangle$	Fourth-order photon statistics $\langle I^4 \rangle$
3.6 m	1	1	1
8.2 m	5	27	720
4 x 8.2 m	21	430	185,000
50 m	193	37,000	1,385,000,000
100 m	770	595,000	355,000,000,000

CHALLENGES:

- Reliability of high speed photon counting detectors
- Data handling computer
- Separate source intrinsic phenomena from atmosphere and telescope-instrument effects

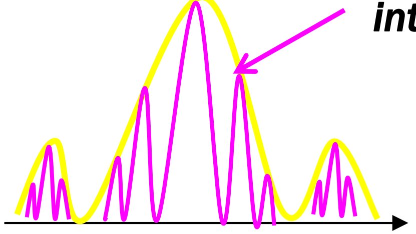
HYPERTELESCOPE CAMERA CONCEPT O. Lardière, V. Borkowski and A. Labeyrie

Hypertelescope is a multi-element imaging interferometric array

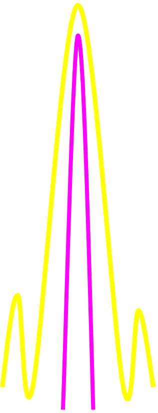


Envelope produced by a single aperture

interferences

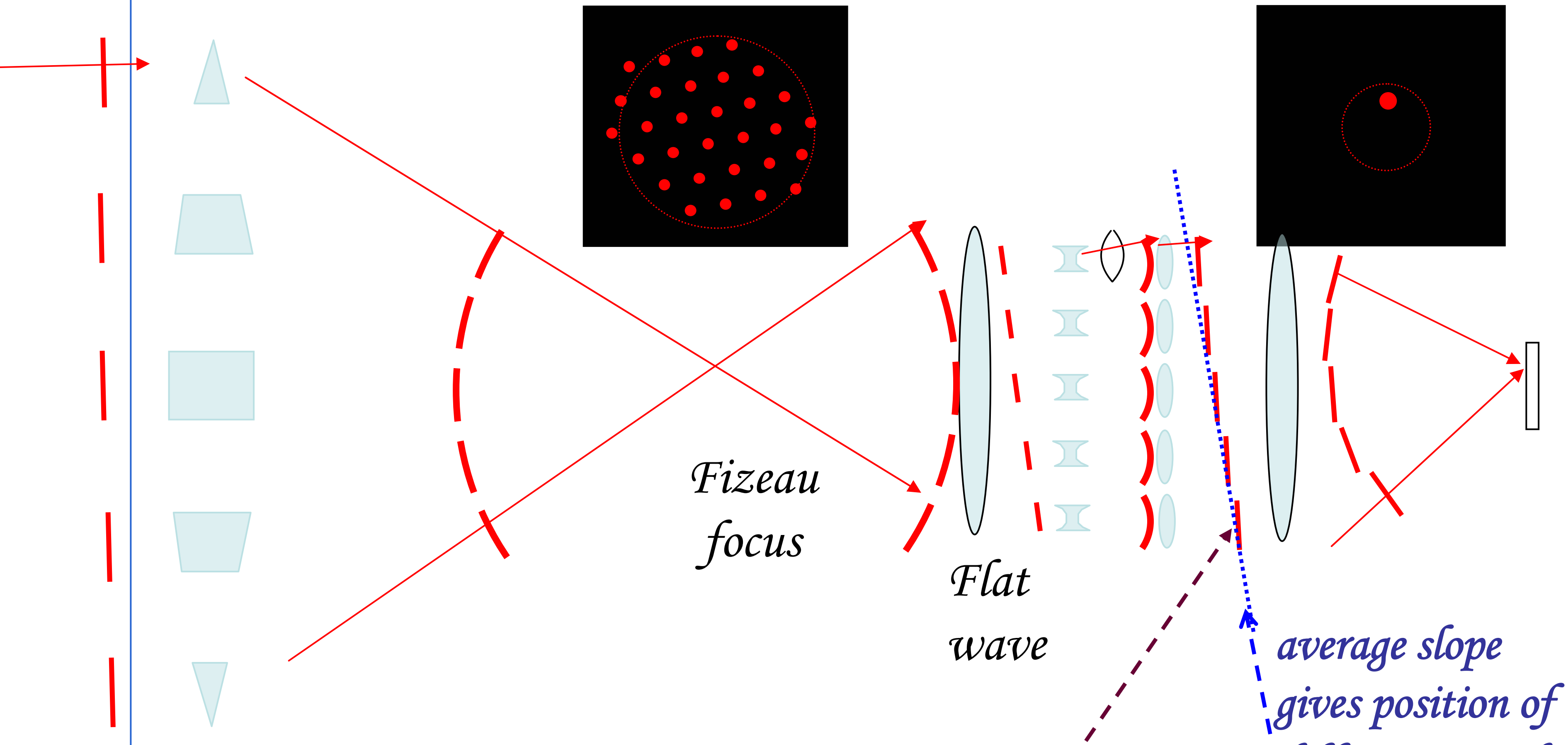


at Fizeau focus



after densification

Optical Concept of Hypertelescope (drawing by A.Labeyrie)



Fizeau focus

Flat wave

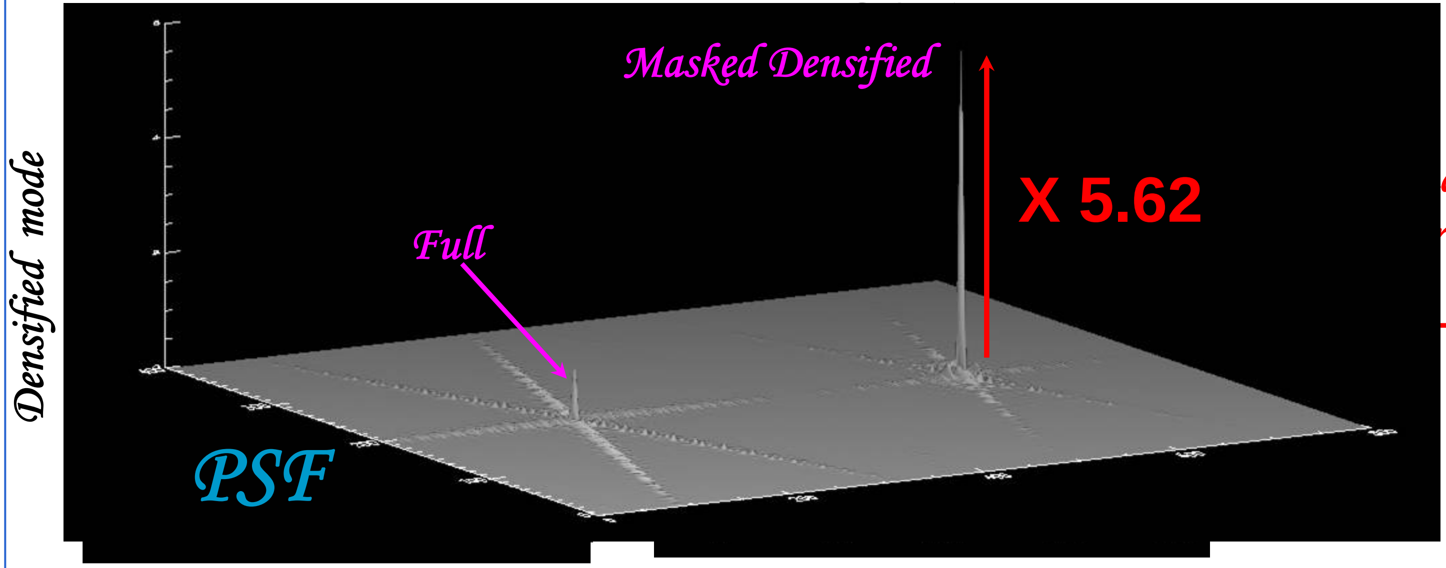
average slope gives position of diffraction peak

Local slope of stair-case wave due to 1 sub-aperture < average slope

- *flat wave becomes stair-case shaped*
- *image is translated in envelope*

4 Pupil Densification Strategies explored by simulations

- **Best result with concentric rings with connection masked**



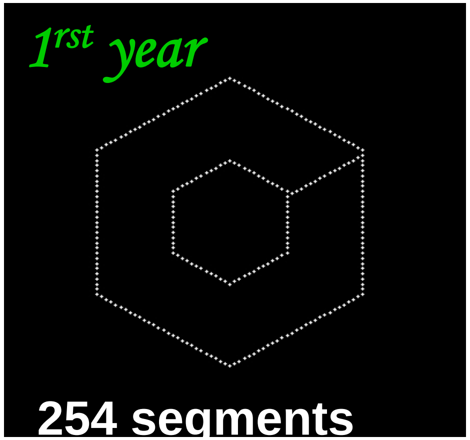
ax gain 5.6
red to Fizeau

Speckle Interferometry observing mode would allow detection of hot Jupiters 10 4 times fainter than their parent stars without AO**

Further explored in the study:

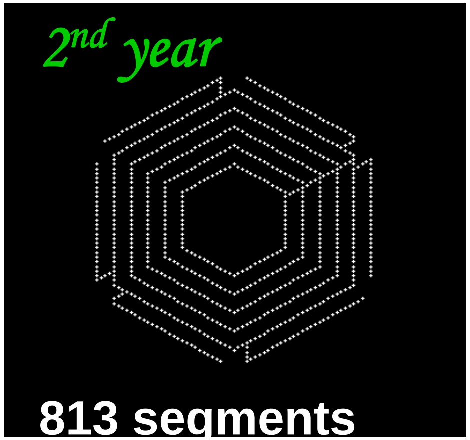
- **Use of Dispersed Speckles Principle to cophase segments during first years of integration**
- **Use of hypertelescope camera in combination with AO and Coronograph**

IMPLEMENTATION STRATEGY: Coexistence of a diluted pupil (High-resolution) with compact pupil (high-dynamic)



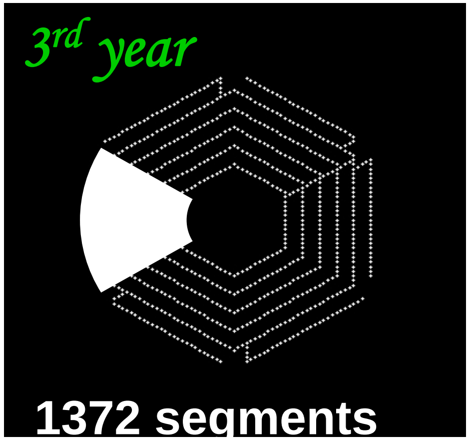
1rst year

254 segments



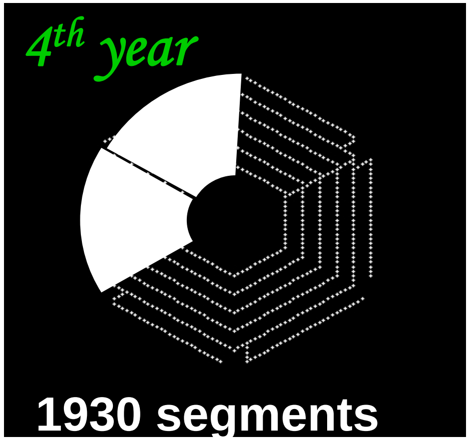
2nd year

813 segments



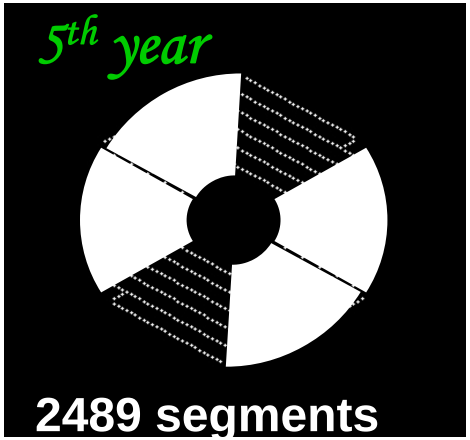
3rd year

1372 segments



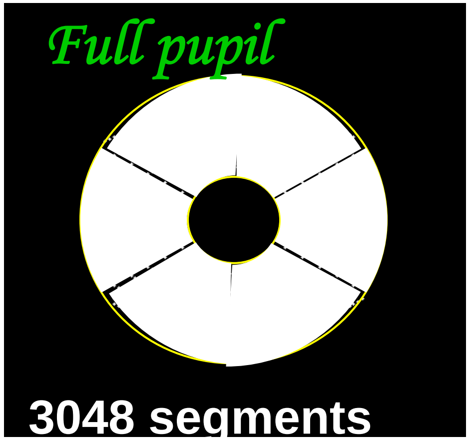
4th year

1930 segments



5th year

2489 segments



Full pupil

3048 segments

OWL Instrument Concept Studies

EPICS

N.Hubin, M.Kasper & C. Verinaud (ESO) + 43 scientists & engineers in 14 institutes

Science goals:

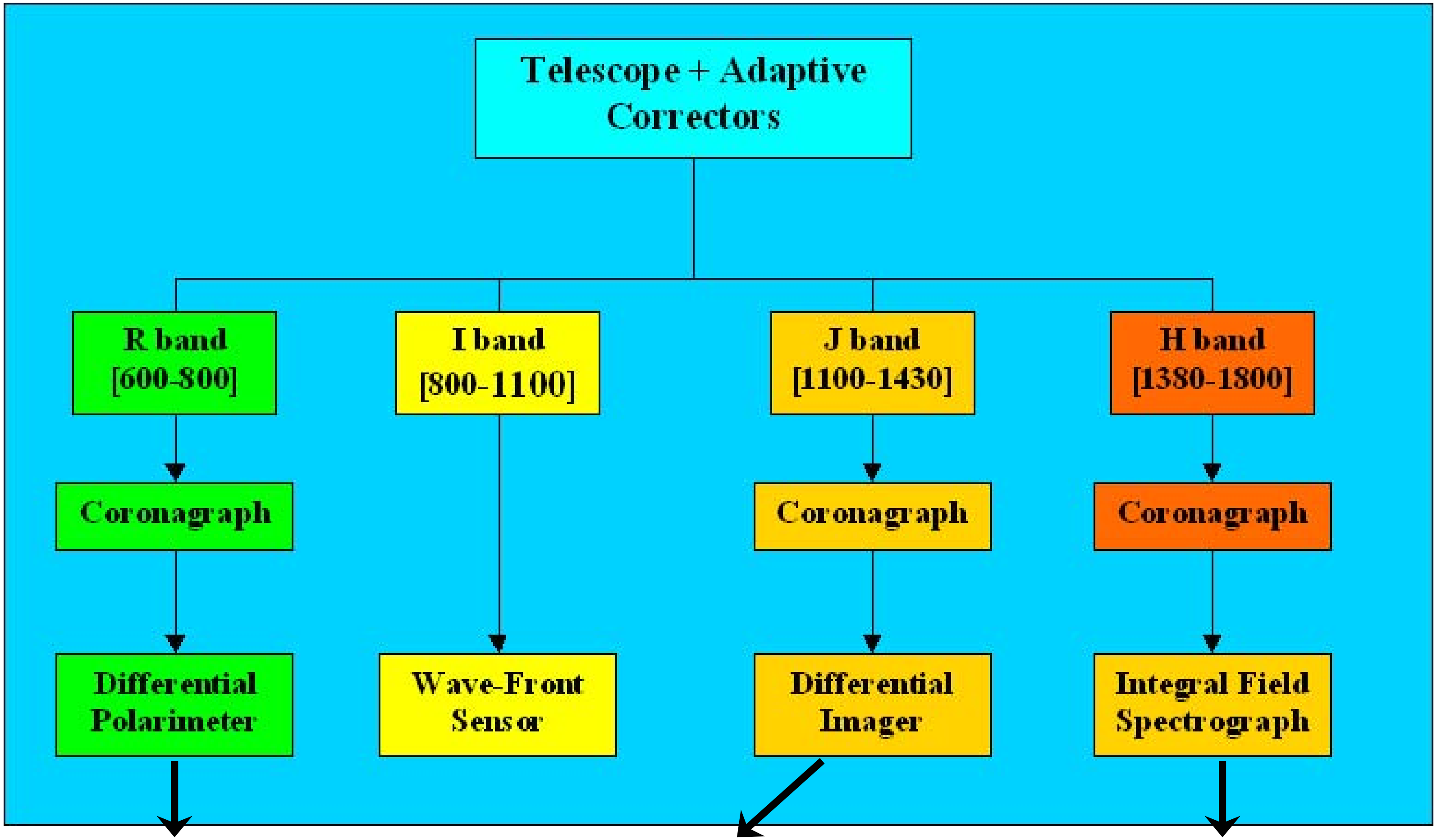
- Primary: Statistics on <u>Rocky Planets in Habitable Zone</u> (HZ) Detection via H2O, CO2, O2
- Secondary: Detection (via CH4) and Characterization of <u>evolved gaseous giant planets</u>

Targets: significant sample of G, K and M stars, ~300 targets (100 for each spectral type)

Top-Level Requirements: Contrast & Angular separation

Star spectral type	Star – Planet Distance (AU)	Star-planet contrast in NIR and VIS	Angular separation (90 deg phase)
G2 at 25 pc m_V=7.0	1.00	**2.21×10^{-10}**	**40 mas**
K2 at 20 pc m_V=8.0	0.51	**8.07×10^{-10}**	**25 mas**
M2 at 15 pc m_V=10.0	0.16	**8.30×10^{-9}**	**15 mas**

EPICS : Differential Imaging based on VLT-PF concepts



Telescope + Adaptive Correctors

R band [600-800]

Coronagraph

Differential Polarimeter

I band [800-1100]

Wave-Front Sensor

J band [1100-1430]

Coronagraph

Differential Imager

H band [1380-1800]

Coronagraph

Integral Field Spectrograph

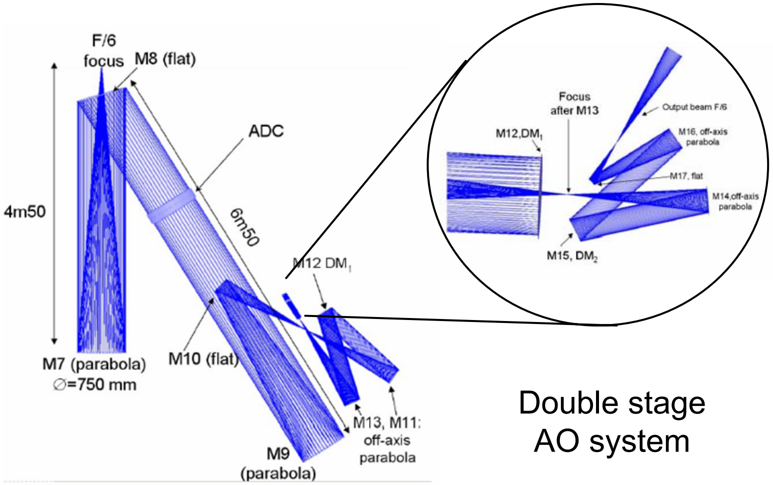
- Polarization detection
- O_2 detection (dedicated spectrum)

- 4 arcsec field
- 4 filters R=15
- Main markers: H_2O, CH_4

- 2 arcsec field
- R=15-30
- Main markers: CO_2,CH_4,H_2O

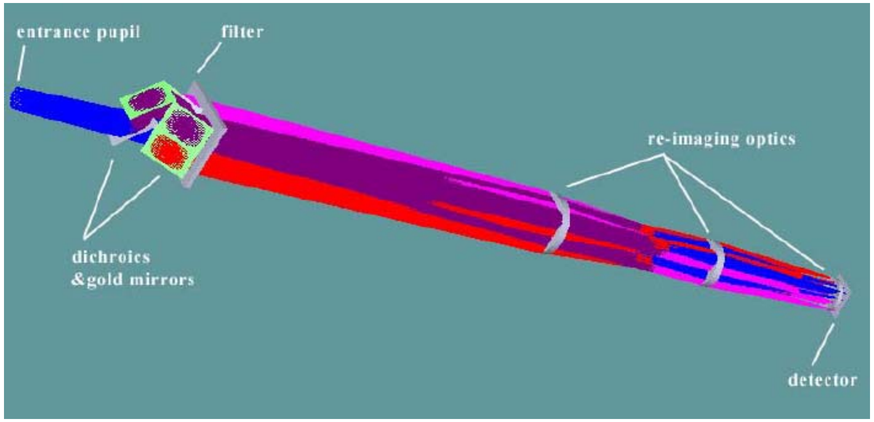
EPICS Sub-systems Conceptual Designs

AO common path optics

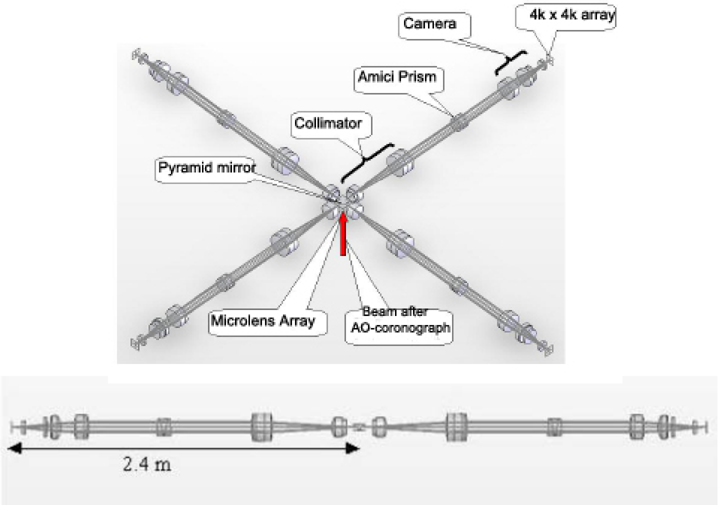


Double stage
AO system

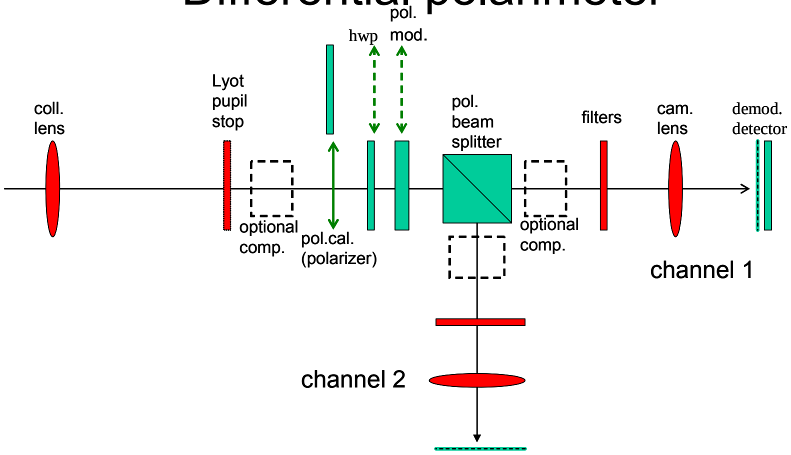
Differential imager



Integral field spectrograph



Differential polarimeter

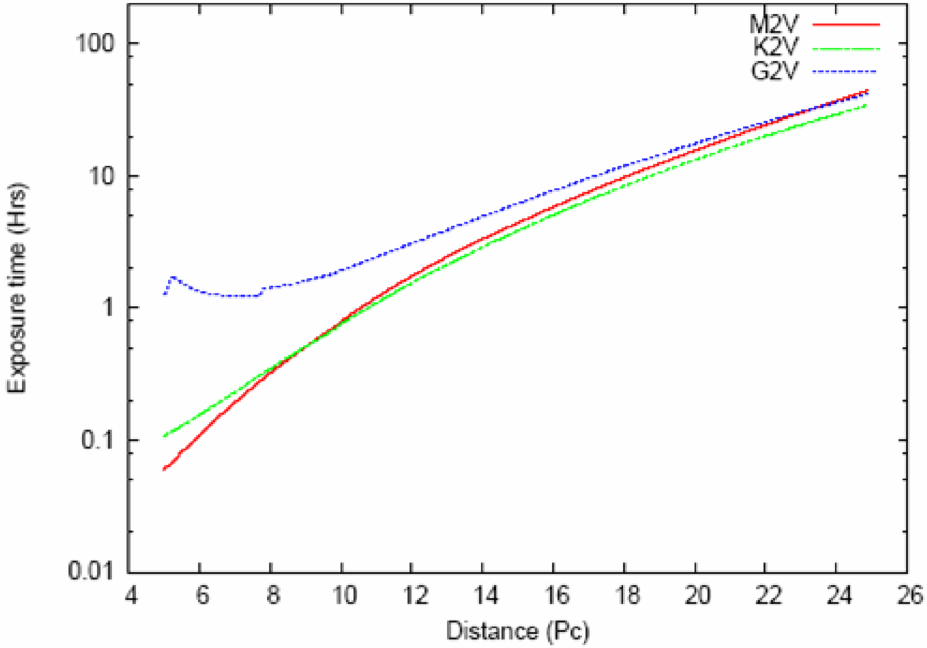


EPICS: Performance in dual imaging, detection at SNR=5

- Conditions: Good seeing: 0.5 arcsec ,16% instrumental transmission, altitude 4000-m (atm. transmission for H_2O and O_2)
- H_2O and CO_2 (if abundance > 10%) detected in a few hours at 10 pc and in 1-2 nights at 25 pc
- O_2 detection possible in follow-up in ~10-200 hours up to 15 pc
- Detection of Earth-like planets by polarization in ~3-50 hours up to 15 pc
- Jupiter-like planets up to 25 pc detected at high SNR (50 σ) in one night.

Time to detect an Earth-like planet in H_2O bands.
λ=1300 nm

Time to detect O_2
in an Earthlike planet.
λ=760 nm



CHALLENGES:

- Single instrument to aim at diffraction-limit at visual wavelengths, although over a very small field
- Very challenging contrast values for Earth –like planets in habitable zone(up to 10^{-10})
- needs ad-hoc X-AO system (3rd generation !) to reach the required high Strehl
- Complex error budget which involved diverse subsystem of telescope and instrument. To be fully explored

OWL Instrument Concept Studies

ONIRICA

P.I.: R. Ragazzoni, & staff
of 14 from 4 institutes

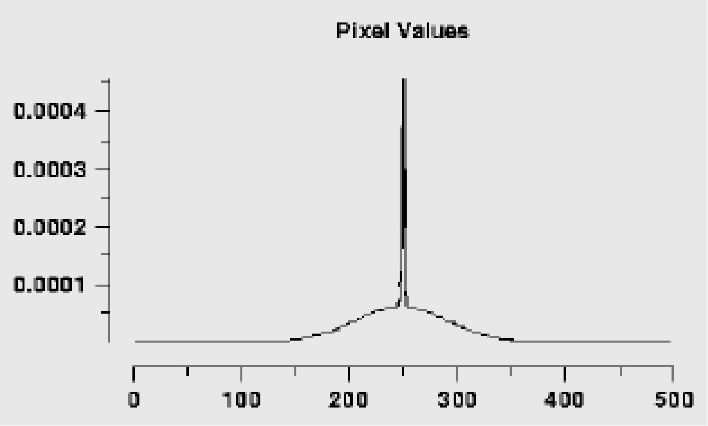
WORKHORSE NIR IMAGER FOR OWL

- COMPETITORS : 6.5m JWST, 30m class telescopes
- REQUIREMENTS: Diffraction-limited to fully realize OWL advantage in observations of stellar objects over space and smaller ground-based telescopes

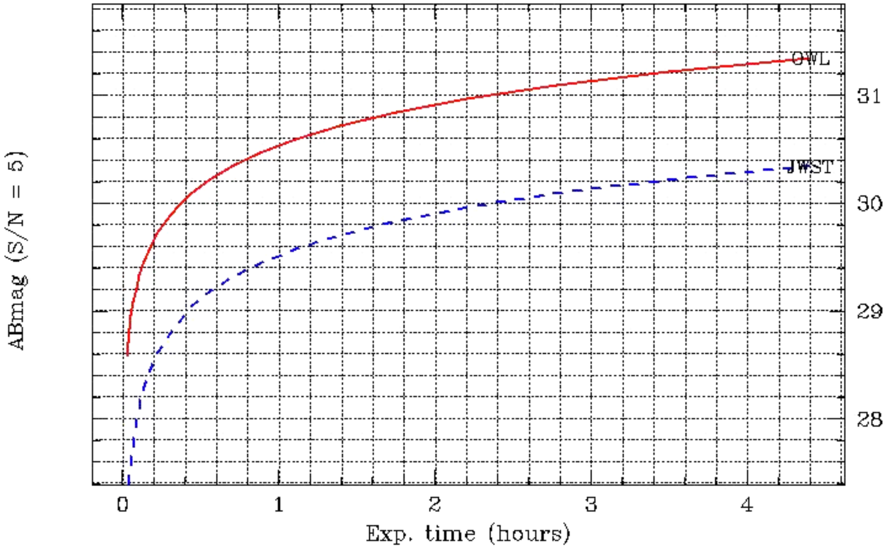
MCAO operating in a different regime that at 8-10m telescope:

h_{lim}	D=8	D=30	D=60	D=100
FoV=2'	14km	51km	103km	171km
FoV=4'	7km	13km	26km	86km
FoV=6'	5km	17km	34km	57km

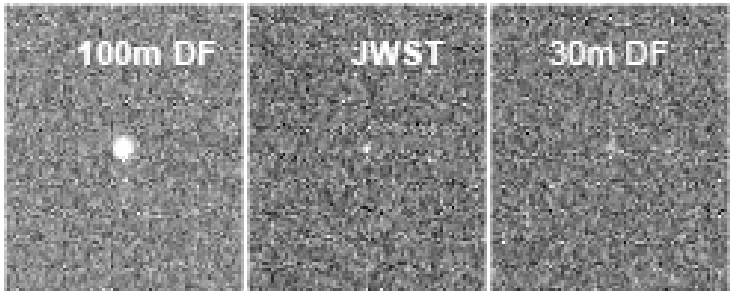
ONIRICA



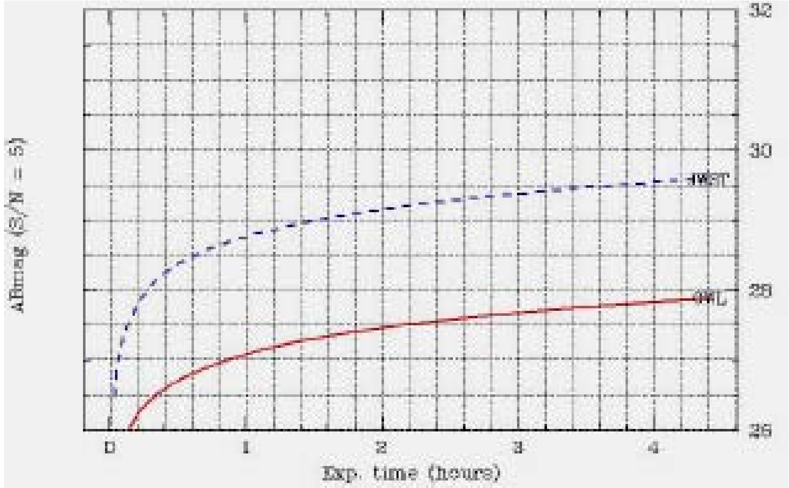
PSF in central field (K band)



ABOVE: Point sources, K-band, Ground (D=100m) vs. Space (D=6.5m); BELOW: Extended (scale length 0.1")



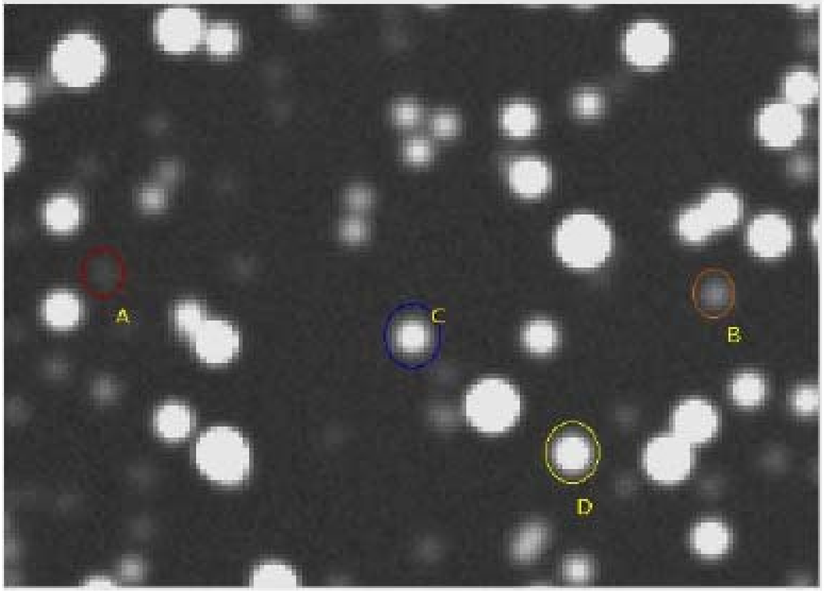
Simulated stellar source (K(AB)=29, 5h exposure)

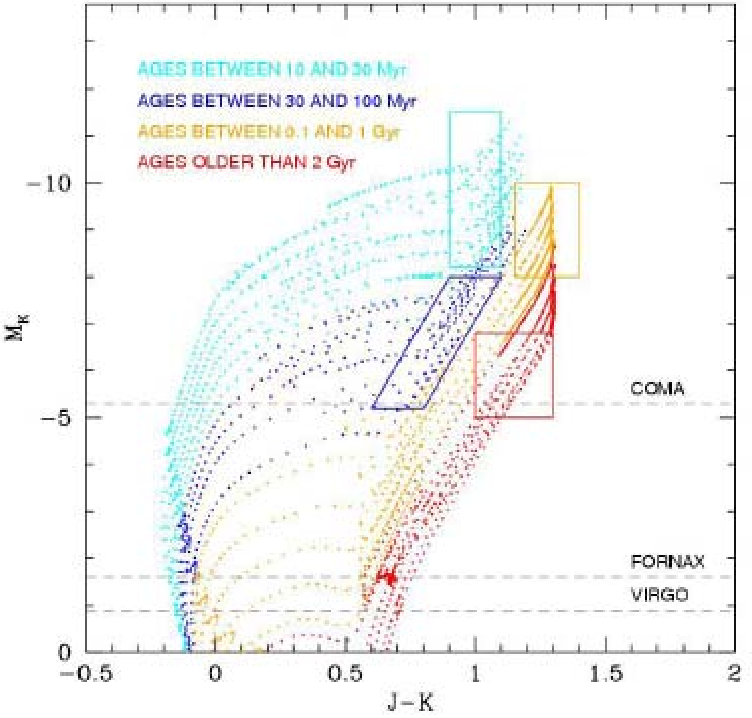


ONIRICA

PRIMARY SCIENCE GOAL:

Study of CMDs in distant ellipticals. Counts in different regions of the diagram lead to the SF history of the galaxy.





Limiting Magnitude Predictions supported by photometric measurements on simulated images in various conditions of crowding

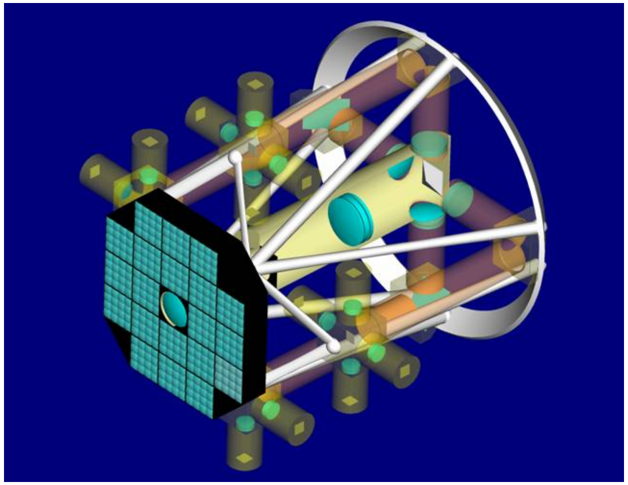
Theoretical CMD. (Girardi et al 2002). ONIRICA limiting magnitudes of K(AB)=30 for different clusters are marked

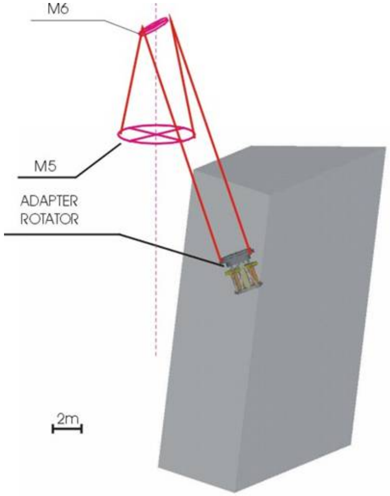
ONIRICA

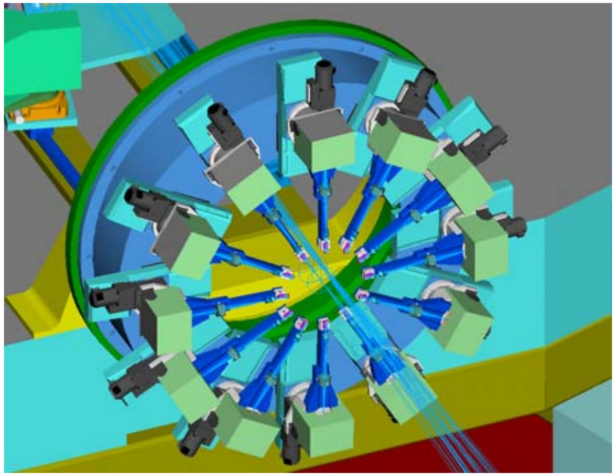
The Instrument Concept: Full MCAO, superb seeing imager

- J,H,K bands
- Combination of a central field up to 1’ diameter sampled close to diffraction limit, with Strehl 30% (MCAO)+ outer field, max 5 ‘ x 5’ , 20-50 mas sampling, “improved seeing” image quality (GLAO)

➢Final choice to be dictated by AO performance limitations, science case, cost (large number of NIR arrays) and instrument complexity







OWL Instrument Concept Studies

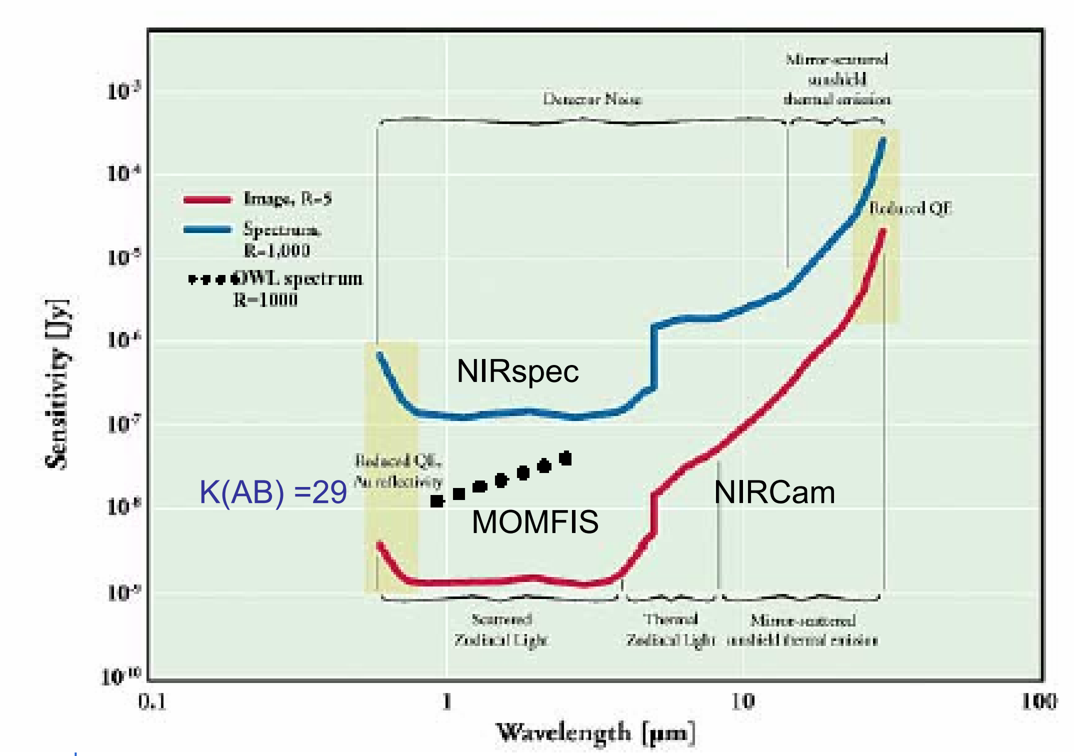
MOMFIS

P.I.: J.G. Cuby & staff of
18 from 5 institutes

LAM LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE
l'Observatoire de Paris GEPI
l'Observatoire de Paris LESIA
ONERA
CRAL Lyon

Main Science Goal : First Galaxies in the Universe

High z (7-10) galaxy surveys using NIR spectroscopy to study/constrain:



- luminosity function
- epoch of re-ionization
- galaxy size evolution
- metallicity of IGM
- star formation history at z>7

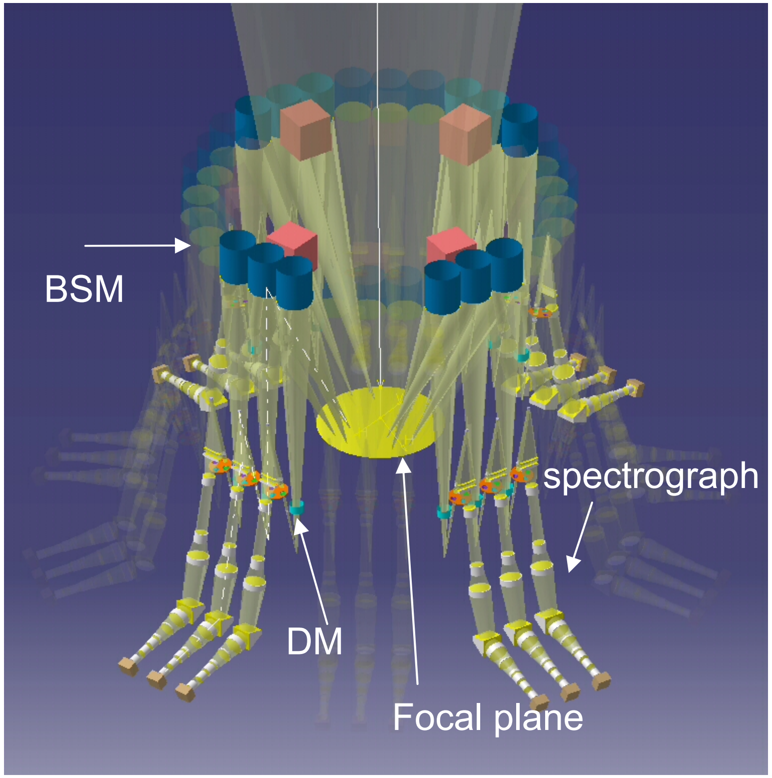
Targets from 30m, JWST, and OWL camera

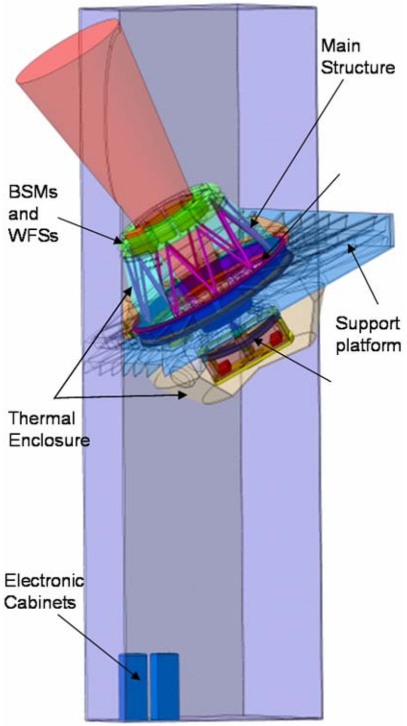
JWST sensitivity for 100 ksec exposure, red curve: imaging, blue curve: spectroscopy at R=1000. Points: MOMFIS spectroscopy

MOMFIS

The Instrument concept

- Multi-IFU (~30) system to pick up targets over a 3’x3’ (5’ x 5’) scientific field
- Image quality: 30% ensquared energy within 50 (30) mas at K,
  sampling 15 mas/pix
- GLAO + instrument MOAO using mini DMs in the light path of each IFU
- Spectroscopy J or H or K in one shot at R~ 4000; Nr. pixels per IFU 30 x30





MOMFIS

CHALLENGES

- **Relies on a distributed MOAO system delivering a decent energy concentration within the IFU pixel (size 10-30 mas). To be demonstrated**
- **Density, brightness, size of high z galaxies to tune number, properties of IFUs**
- **Complex, large, massive instrument with a large number of moving devices requiring very high accuracy.**

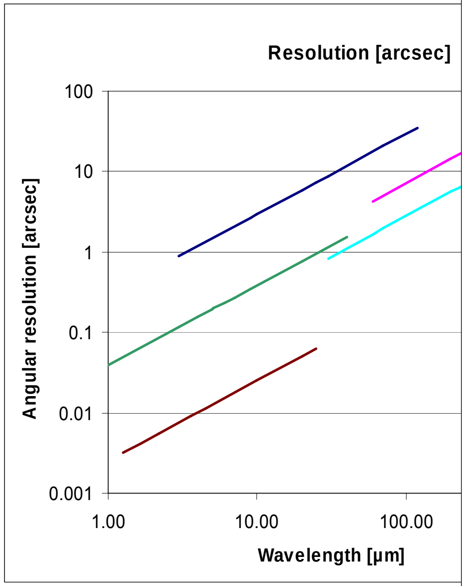
OWL Instrument Concept Studies

T-OWL

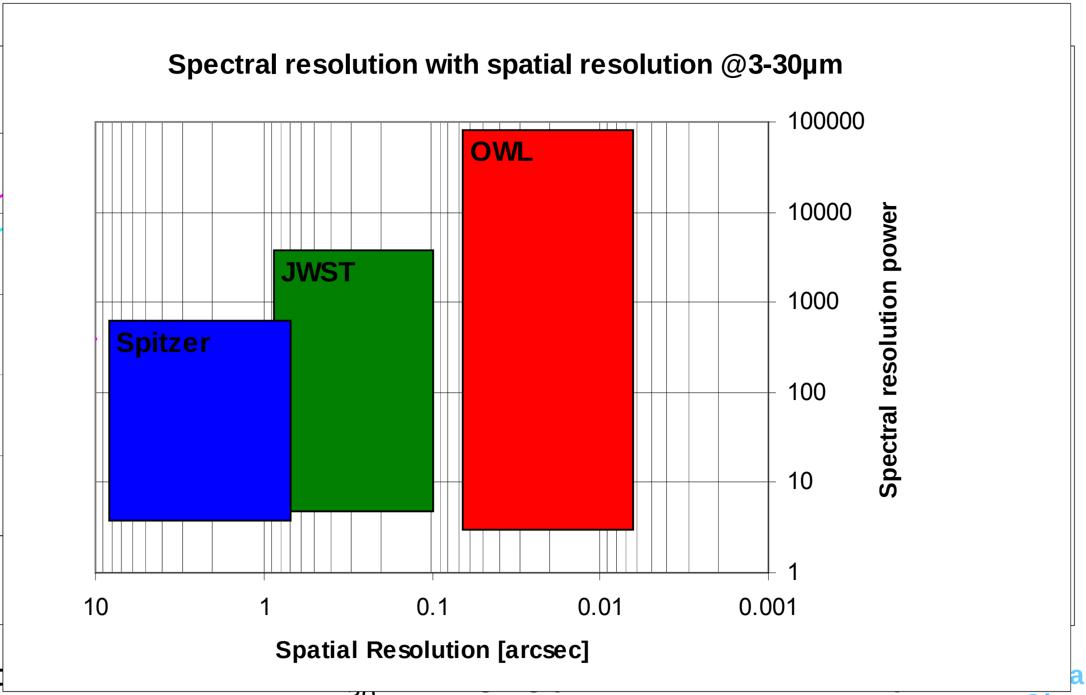
P.I: R. Lenzen, coPI: B.Brandl & staff of 26 in 4 Institutes

WHY A THERMAL INFRARED (3- 20 μM) INSTRUMENT ON THE GROUND IN COMPETITION WITH JWST (MIRI+NIRCAM+NIRSPEC)?

- **Image quality at unique OWL diffraction limit (10-50 milli-arcsec) with very modest AO requirements**
- **For stellar objects in imaging and high resolution spectroscopy superior to JWST and future space missions in atmospheric windows**



Angular Resolut

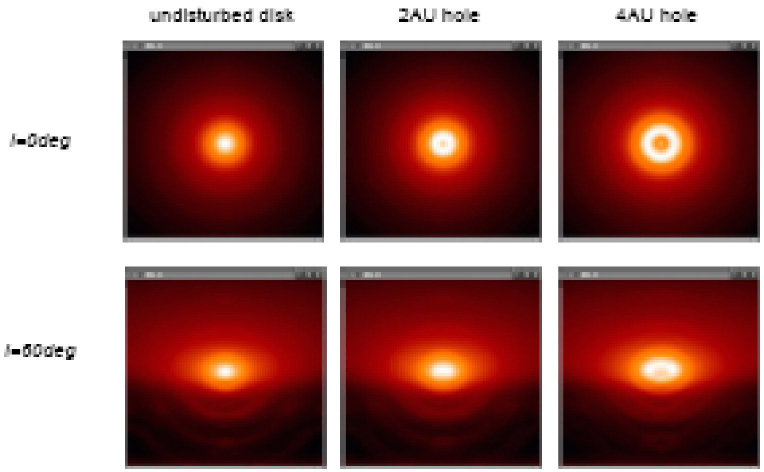


SCIENCE GOALS:

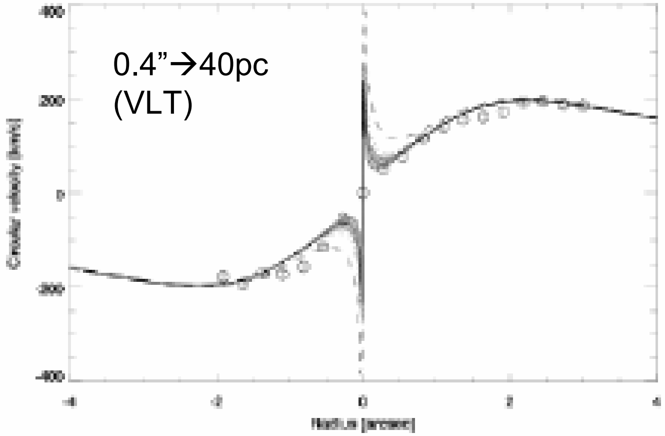
A variety of targets from solar system objects to high redshift AGN

Simulations of dusty circumstellar disks observed with OWL

Probing the masses of BH in dusty AGN



HH star at 140pc. Size of box 40 x40 AU



0.4”→40pc
(VLT)

Fig. 29: [Ne II] velocity map of the starburst/Seyfert galaxy NGC 7582, taken with VLT/VISIR in HR mode (Wold et al. 2005).

OWL Instrument Concept Studies

T-OWL

INSTRUMENT CONCEPT:

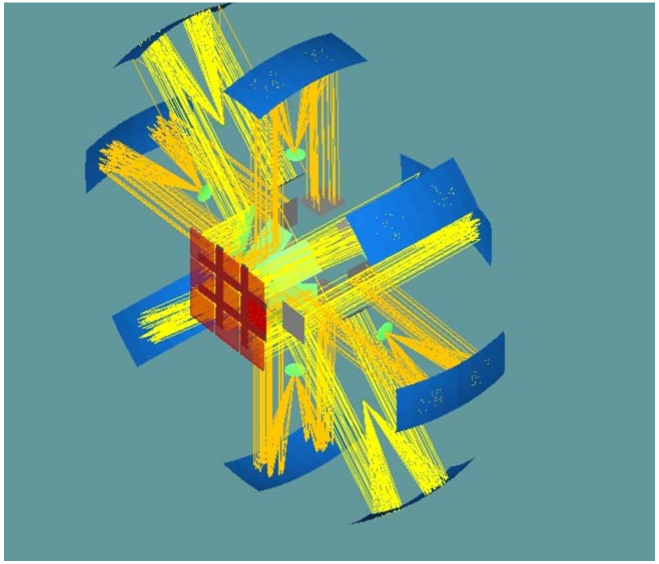
Wavelength Range: 3- 27 μm (two paths splitted by dichroic)

Imaging Pixel Scale: 3.5 mas@ 3-5 μm,
7.0 mas @ 7-14 and 16-25 μm

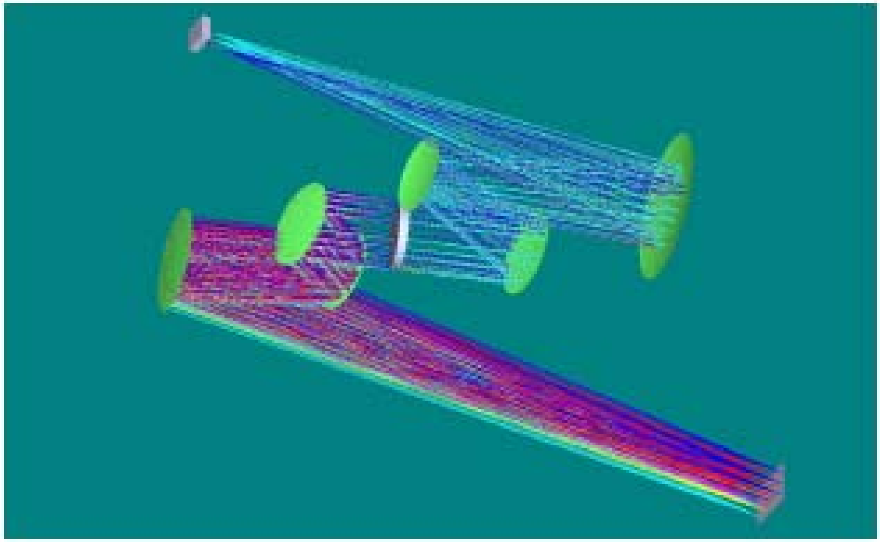
Imager FOV≥ 15x15 arcsec

Detectors: 4 (2k x 2k) InSb (0.9 – 5.4 μm)
4 (1k x1k) Si-As (2-28 μm)

Spectrograph: Modules at R=100000-2000 preliminarily investigated



Splitting of the field over 9 channels



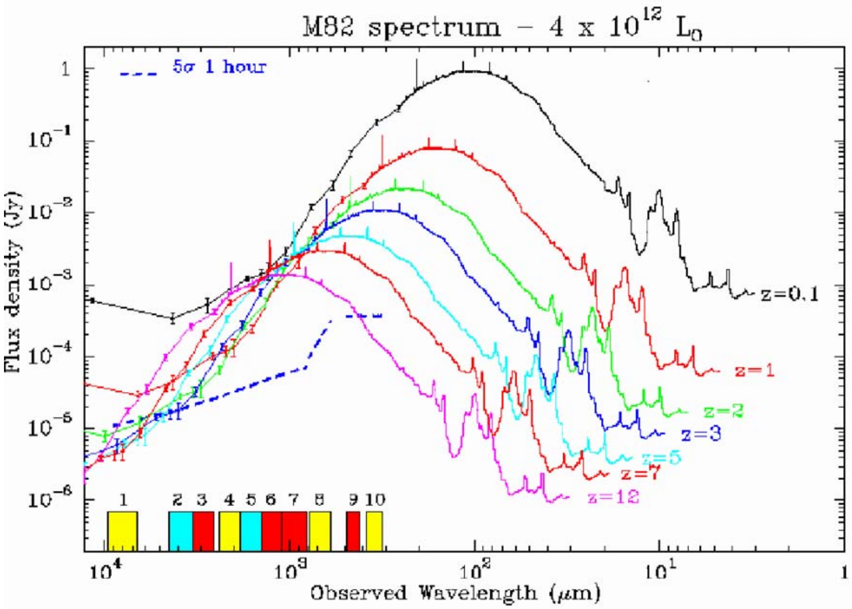
All reflective Imager channel +grism

SCOWL

P.I. : B. Dent & staff of 7 from ATC and ESO

SUB-MM SCIENCE:

Formation processes (planets, stars, galaxies) are hidden in clouds with >100 magnitudes of optical extinction – A survey instrument at OWL makes deep, large-scale mapping projects feasible



Probing the role of luminous , dusty star-forming galaxies in the field and in clusters, in the early universe

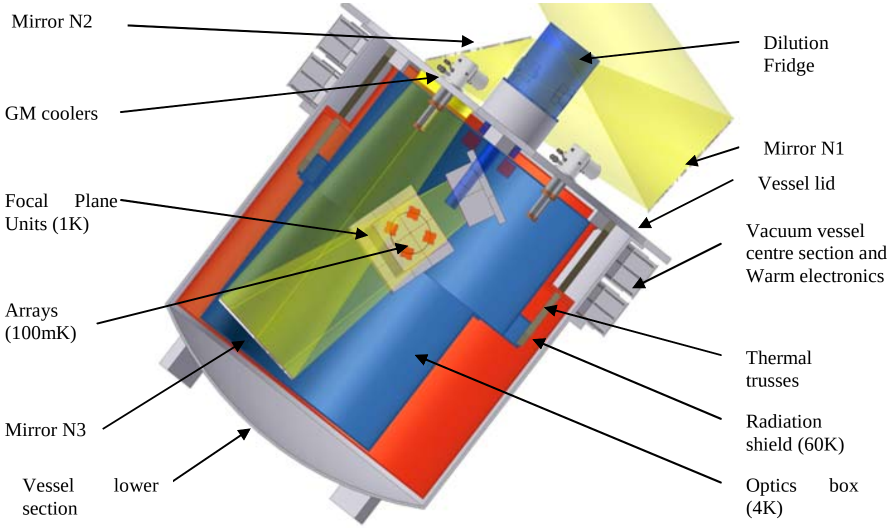
SCUBA-2 at the JCMT will detect mostly massive galaxies, SCOWL can survey large fields for galaxies down to a few L* up to very high redshifts

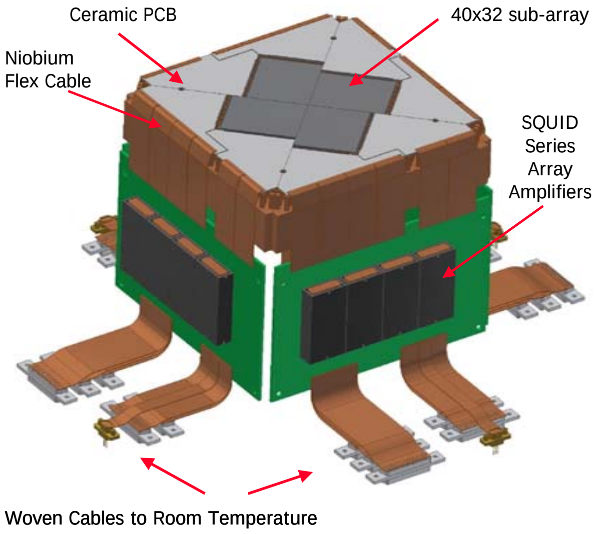
(SCOWL will be able to detect the MW to z~5)

Peak of SED (M82-type): z=0.7-> 170 micron ; z=1.5 ->250 micron ; z=2.5 ->350 micron ; z=4 -> 500 micron

SCOWL

INSTRUMENT CONCEPT : Imager in three simultaneous submillimeter bands (350, 450, 850 μm) at resolution 1 arcsec (DL at 350 nm) over a field of ~2’.5 with a sensitivity of 0.1 mJy

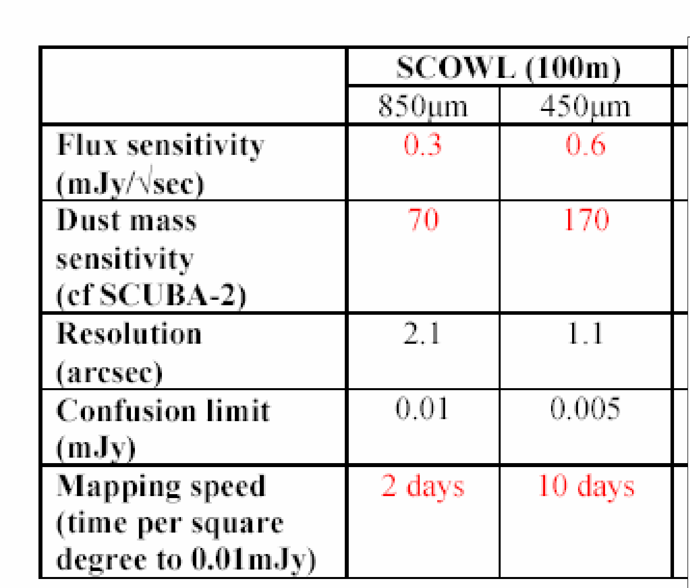




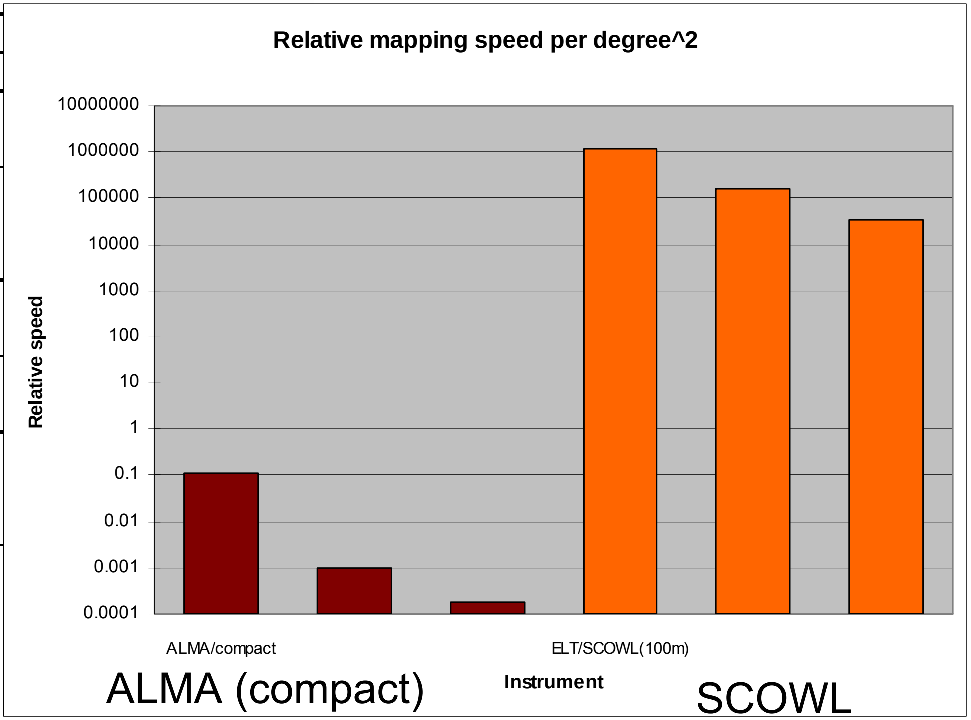
TES detector array unit (x4 per focal plane for SCOWL)

Complementarity to ALMA:

- **Higher point-source sensitivity (factor 20-6); much higher large scale mapping speed.**
- **Much lower resolution and higher confusion limit**

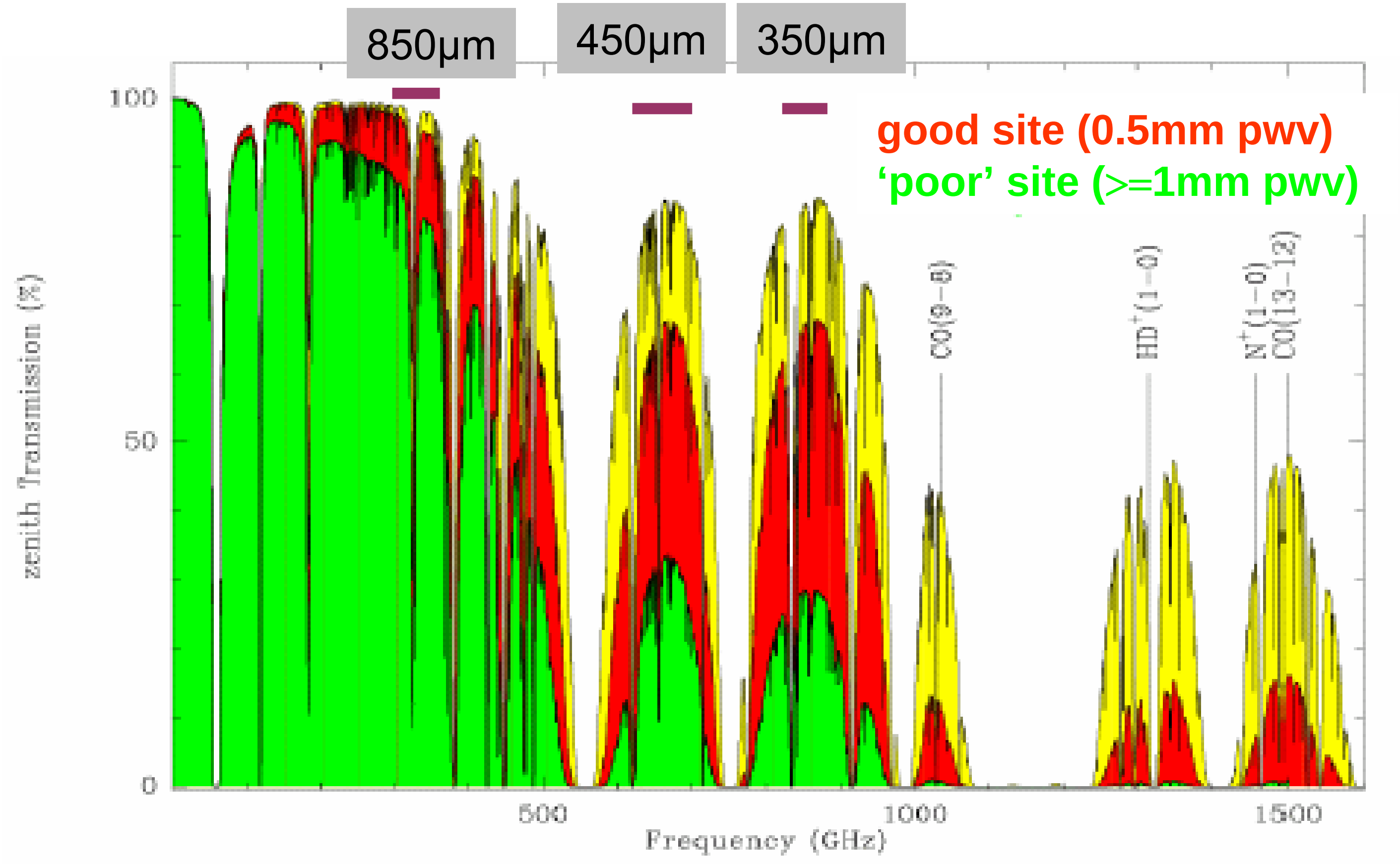


	SCOWL (100m)	
	850µm	450µm
Flux sensitivity (mJy/√sec)	0.3	0.6
Dust mass sensitivity (cf SCUBA-2)	70	170
Resolution (arcsec)	2.1	1.1
Confusion limit (mJy)	0.01	0.005
Mapping speed (time per square degree to 0.01mJy)	2 days	10 days



SPECIAL REQUIREMENTS:

- **High altitude, dry site**
- **Submm seeing dominated by water vapour variations . Tip-Tilt correction driven by water-vapour meter**



OVERVIEW OF THE RESULTS (1):

Instrument Feasibility and Performance

- The studies show that a wide spectrum of OWL instruments can be build and matched to the telescope
- A number of interface problems identified
- The instruments are mainly based on extension of proved technology. R & D, prototyping required for a few specific subsystems only
- Most critical advances required in the area of associated AO.
- Cost of a major instrument appears in the range of 20-30 MEUR + 100-200 FTEs. ~10% of project budget required for the hardware of four instruments

OVERVIEW OF THE RESULTS (2):

Feedback to the telescope design

❖ **SCIENCE :** Studies confirm that an “overwhelming large” D enables unique science thanks to its huge photon collecting power and exquisite diffraction limit

❖ **FOCAL RATIO:** F/6 focal ratio coupled with no focal distance makes cryogenic instruments difficult to build without relay optics

❖ **FOCAL STATIONS:**

External focus required for space-hungry instruments and/or with extreme stability requirements.

Gravity-variant instrument rooms not a bonus for integration, maintenance and operation of largest instruments

OVERVIEW OF THE RESULTS (2):

Feedback to the telescope design (continued)

❖ **DIFFRACTION LIMITED FIELD:** based on the present set of instruments, in the NIR and TIR max field <90” x 90”

❖ **ADAPTER-ROTATOR** Critical co-existence of wavefront sensors for active and adaptive optics and instrument at the adaptor strongly-curved focal plane

❖ **MIRROR COATING:** Desirability of an efficient coating on the mirror train to keep efficiency high and minimize IR emissivity

OVERVIEW OF THE RESULTS (3):

Successful "Call to Arms for an European ELT"

- More than 150 scientist and engineers in over 20 Institutes in 7 ESO member states have contributed to the studies

- Significant increase of the awareness of scientists in Europe to the extraordinary capability of an ELT

- A significant fraction of the design parameter space of the OWL Instrumentation (or of any 50-100 m ELT) now explored

FUTURE WORK

- Instrument Concepts further explored within EU FP6 ELT Design in 2006-7 (7 “Small” Studies launched in Sept 2005, 3 Point Design Studies in 2006)

- Pursue development of a selection of the most critical components & subsystems identified in this phase

- Use feedback from OWL instrument studies in future steps of telescope design