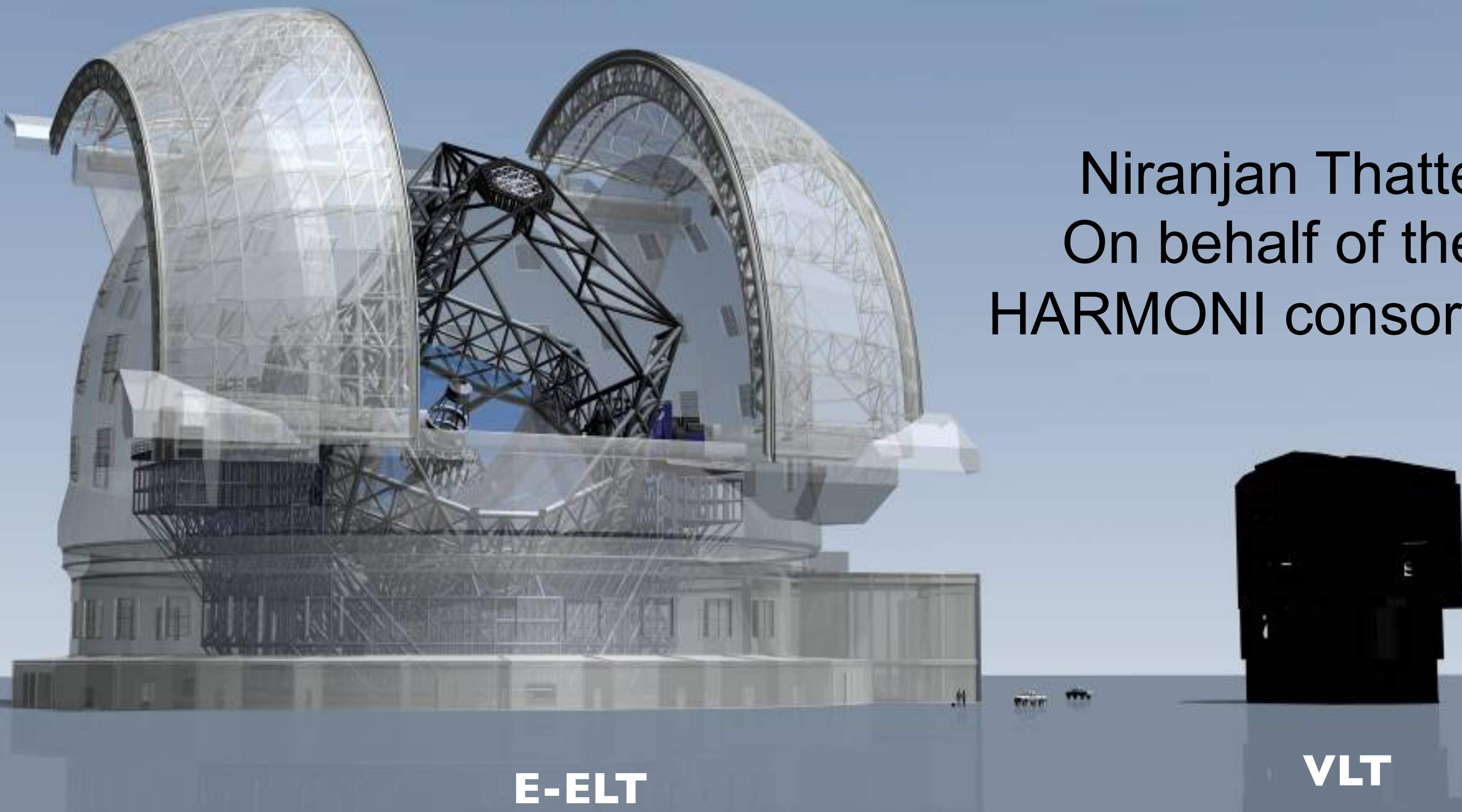
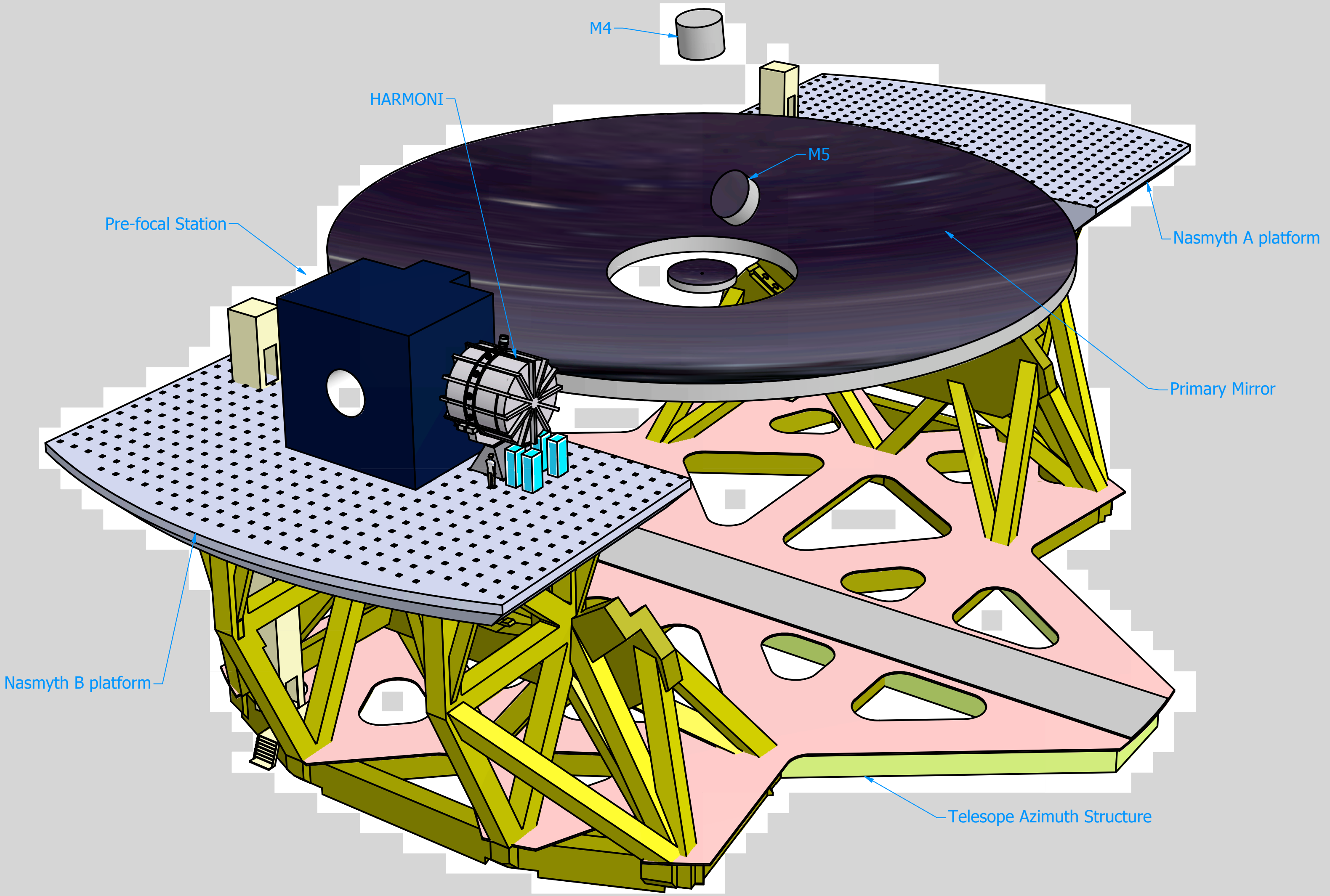
HARMONI – the first light integral field spectrograph for the E-ELT

Niranjan Thatte
On behalf of the
HARMONI consortium



Special thanks to M. Tecza, F. Clarke, D. Montgomery

HARMONI AT THE E-ELT



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HARMONI Consortium

Niranjan Thatte, Matthias Tecza, Fraser Clarke, Roger Davies, Tim Goodsall, David Freeman, James Lynn, Harry Smith.

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Santiago Arribas
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Fernando Gago Rodríguez
Anna Fragoso, Felix Gracia
Javier Fuentes, Dario Sosa,
Evencio Mediavilla

Roland Bacon
Alban Remillieux
Johan Kosmalski
Arlette Pecontal

A Single Field Wide Band Spectrograph

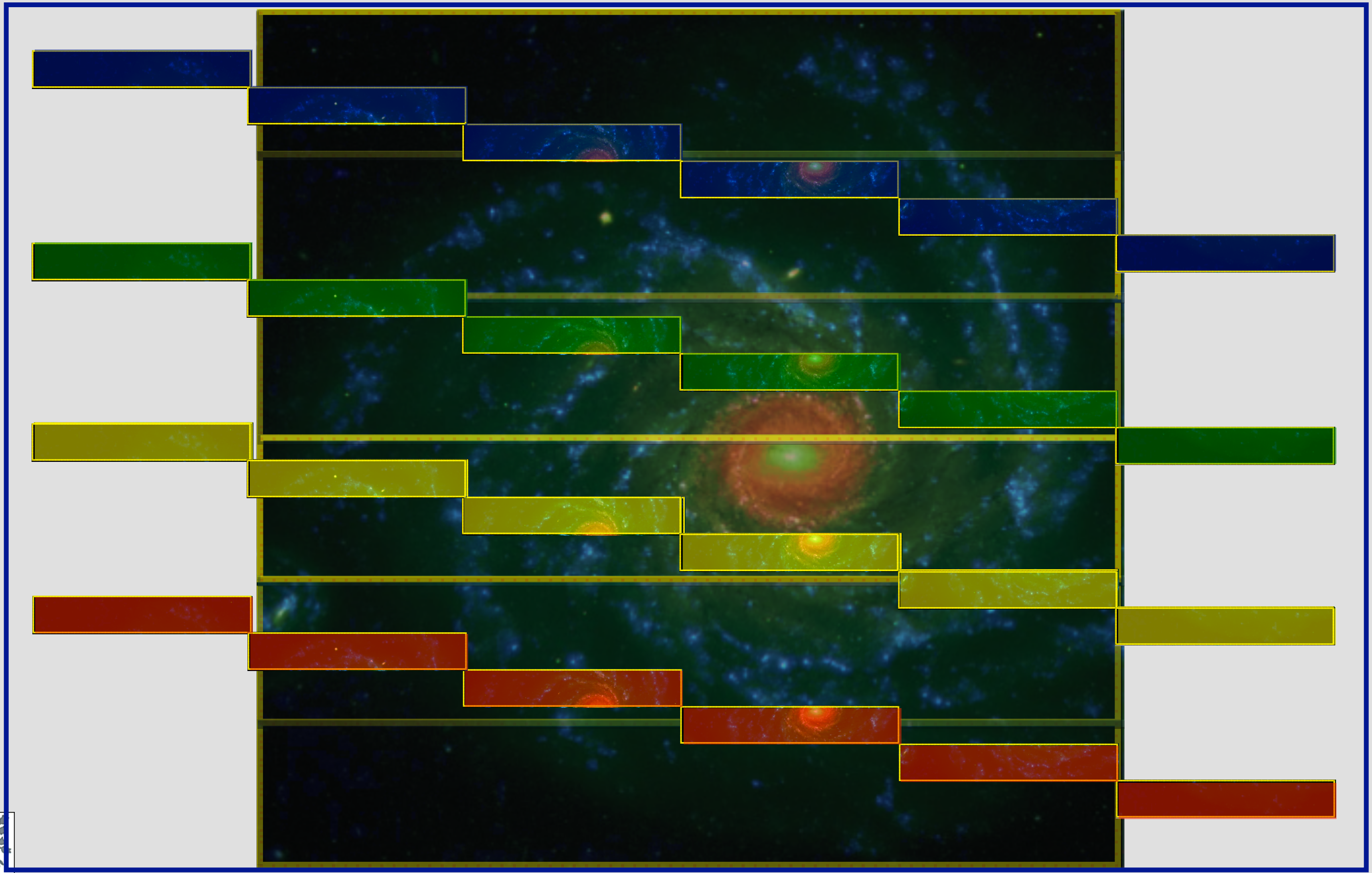
✧ A near infrared integral field spectrograph covering the 0.8 − 2.4 μm wavelength range, with simultaneous coverage of at least one band at a time. R~4000 to work between the OH lines

✧ Range of spatial resolutions from diff. limited to seeing

✧ Possible extension to visible wavelengths and higher spectral resolution

✧ High throughput (>35%), low thermal background (optimized for K band operation), low scattered light

Slicing the Image



Design Drivers

◆ Spatially resolved detailed studies of astrophysical sources – physical, chemical, dynamical & kinematics; ultra-sensitive observations of point sources.

◆ Easy to operate and calibrate

◆ Feasibility for 1st light instrument => simple, reliable, based on proven concepts, can be built with today's technology. Large amount of expertise in consortium

◆ Workhorse instrument – wide range of science programs, all AO modes, range of spatial & spectral resolutions

40 mas

For extended sources & optimal FoV

20 mas

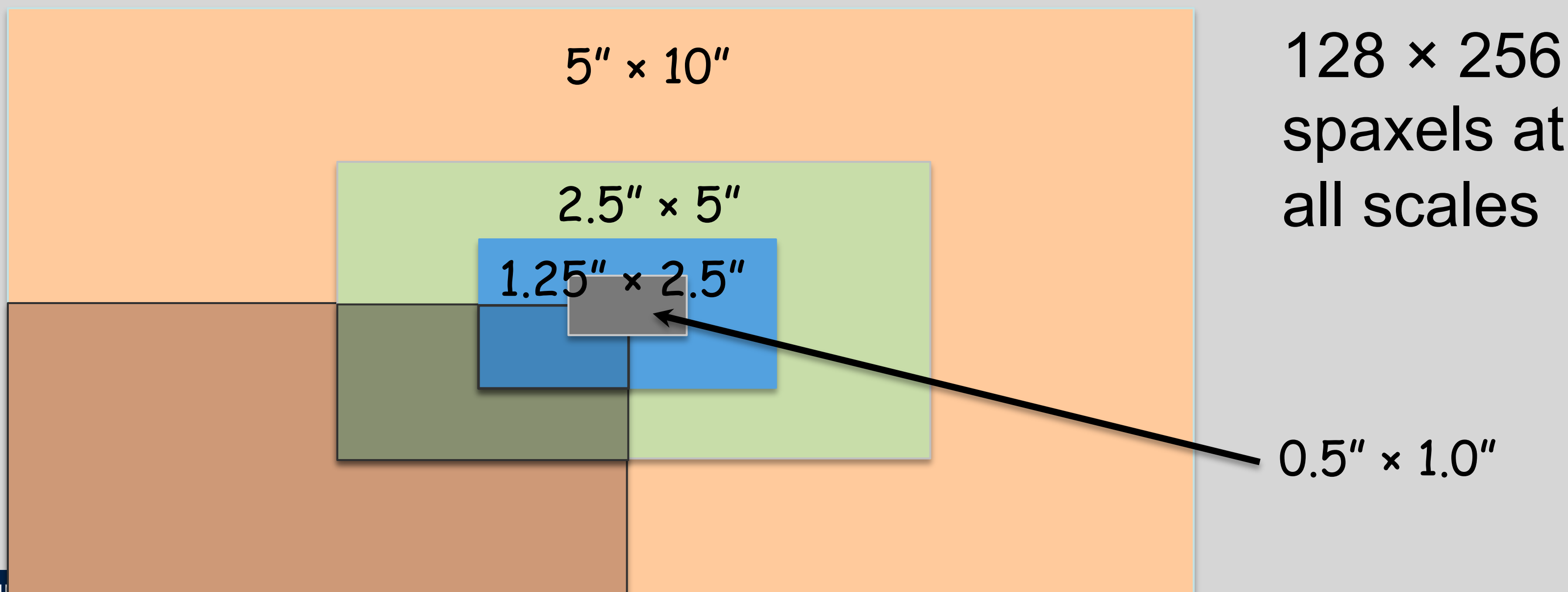
For optimal sensitivity (faint targets)

10 mas

Best combination of sensitivity and spatial resolution

4 mas

Highest spatial resolution (diffraction limited)



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Wavelength Ranges & Resolving Powers

Bands	R
V+R, I+z+J, H+K	~4000
V, R, I+z, J, H, K	~10000
Z, J_high, H_high, K_high	~20000

- Exploring adding simultaneous V-K coverage at R~500-1000
- Re-assessing the need for high spectral resolving power at visible wavelengths (< 0.8 micron)

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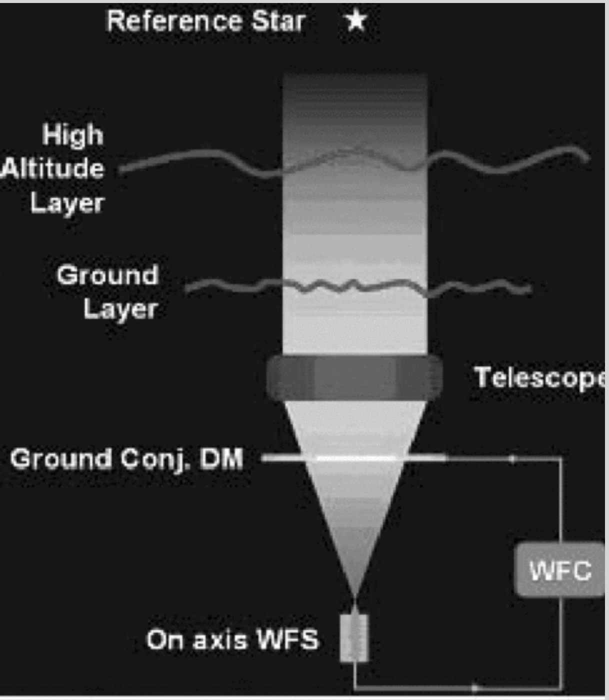
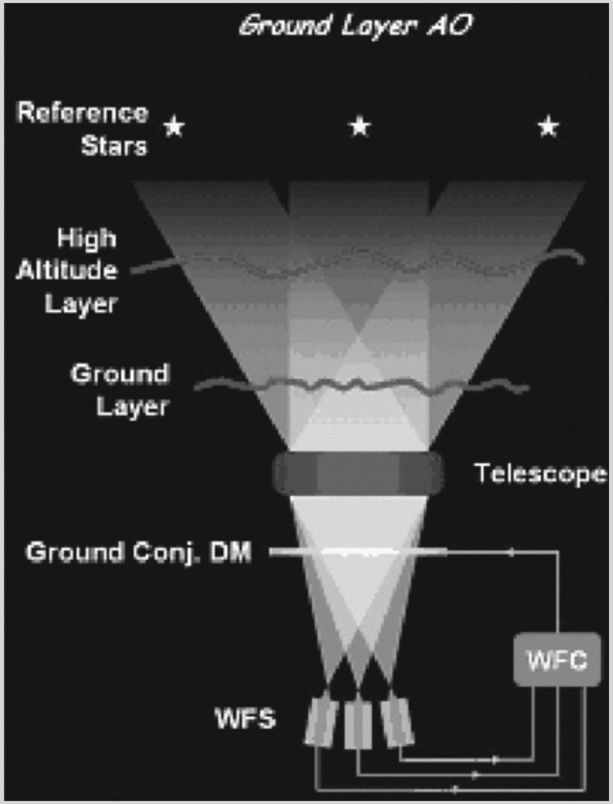
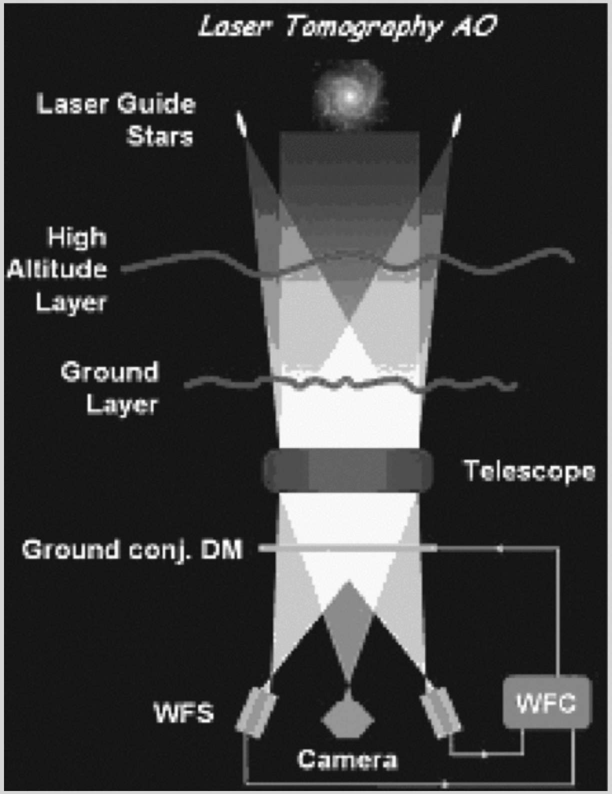
Different Flavours of AO



SCAO



GLAO



LTAO

Or even degraded GLAO (NGS only) !!!

Science Case & Requirements

Contributors: Roger Davies, Matthias Tecza, Santiago Arribas, Roland, Bacon, Fraser Clarke, Luis Colina, Eric Emsellem, Tim Goodsall, Isobel Hook, Matt Jarvis, Andrew Levan, John Magorrian, Livia Origlia, Rafael Rebolo, Dimitra Rigopoulou, Mark Swinbank, Nial Tanvir, Niranjan Thatte, Eline Tolstoy, Aprajita Verma.

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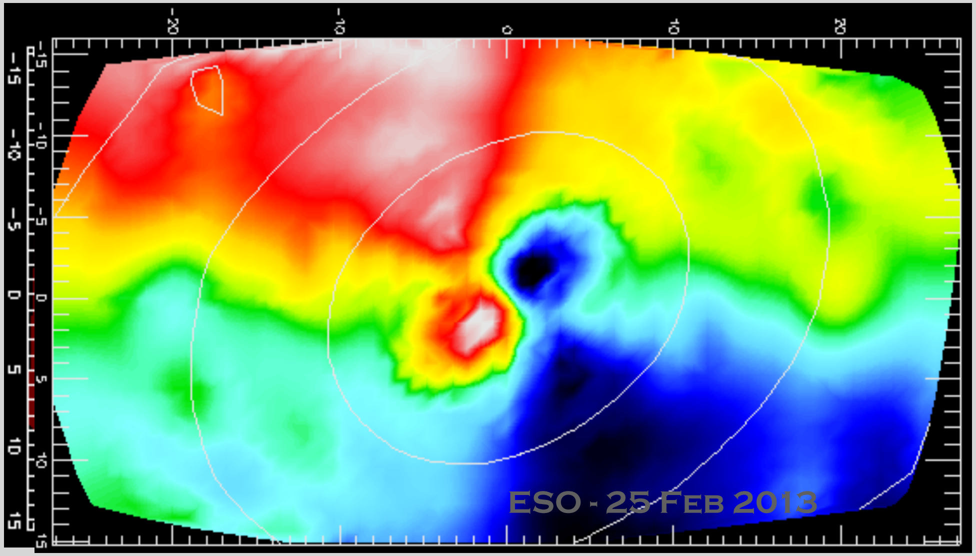
Scientific motivation

- At the fine scale of E-ELT + HARMONI working in the diffraction limit there is enormous value in being able to reconstruct where, in a complex image, a spectrum arises.
- Using AO in the infrared conditions change rapidly so that a simultaneous recording of all positions and wavelengths removes ambiguities.
- At high z there are many more morphologically complex, low mass objects. Fine angular resolution and high spectral resolution are needed.
- IFU records PSF from observations (if FoV contains a point source eg. quasar BLR).



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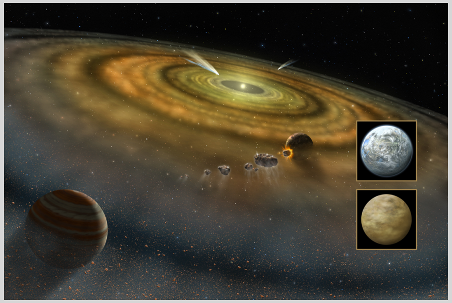
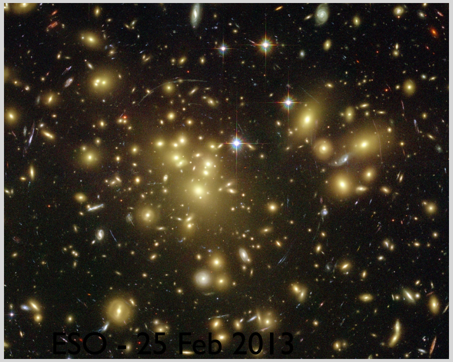
Contemporary Science

Planets & Stars



Stars & Galaxies

Galaxies & Cosmology



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High-z Ultra-luminous IR Galaxies

Survey 50 Spitzer candidate ULIRGs 1<z<2.5

Detect & characterise nuclear disks & rings

Measure shocks, winds, interaction with IGM

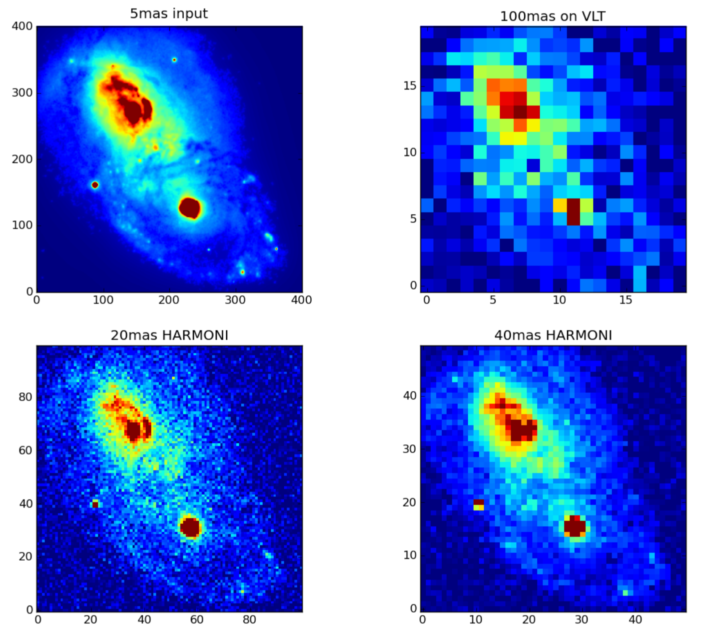
Measure dynamical masses

Measure rotation (kinematics), chemical composition (fraction of heavy metals)

Modes of star formation

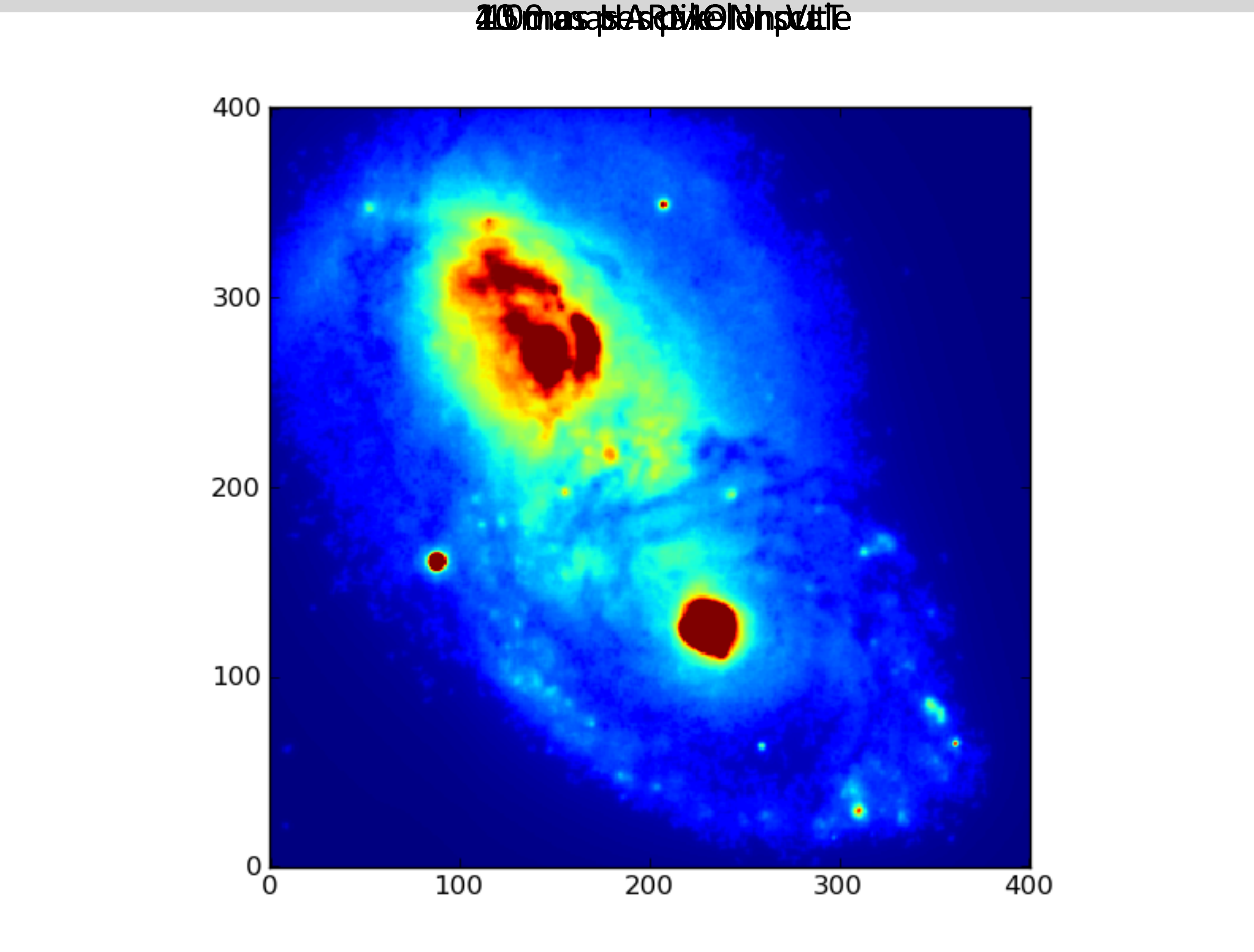
Distribution of dust

Hα in z=2 ULIRG



Requires: diffraction limited R > 4000 spectra, spaxels 5-40mas. @ λ 0.5 - 2.5μ.

Compromise between sensitivity & resolution

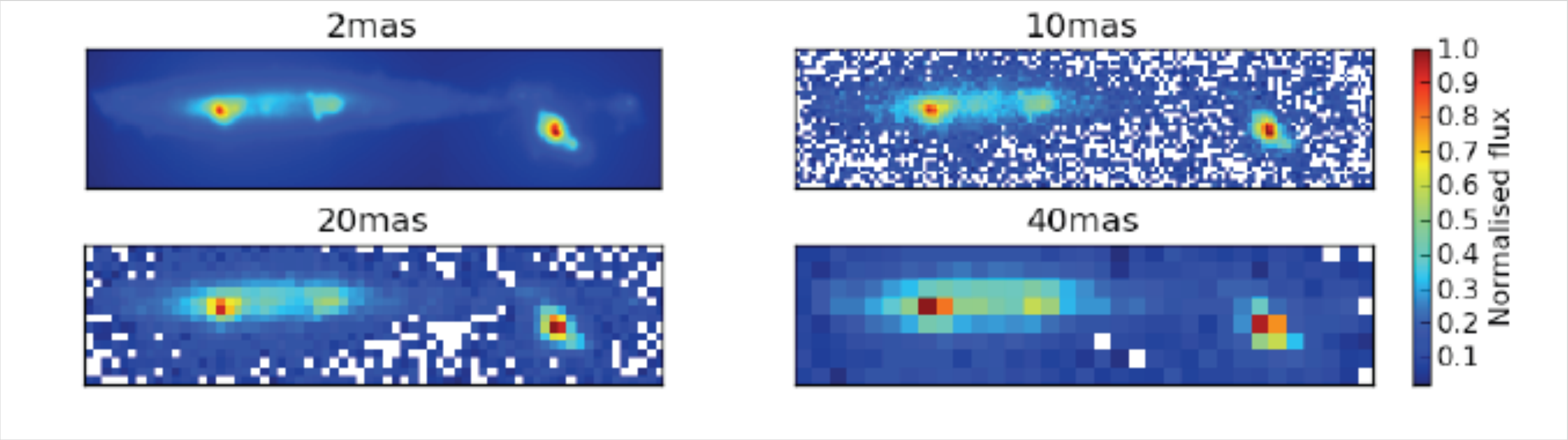


D^4 gain!

The Physics of High Redshift Galaxies z=2-5

Aim: measure the size, velocity & luminosity distribution of HII regions

- HII regions as tracers of SFH, mass & mergers
- Reddening free estimate of star formation rate
- **Measure abundances for individual SF regions**
- Explore HII kinematics as diagnostic of disk settling.



Requires : R > 4,000 – 20,000 spectra
@ λ J+H & H+K simultaneously.
4 - 40mas spaxels FOV 0.5 x 1.0"; 5 x 10".

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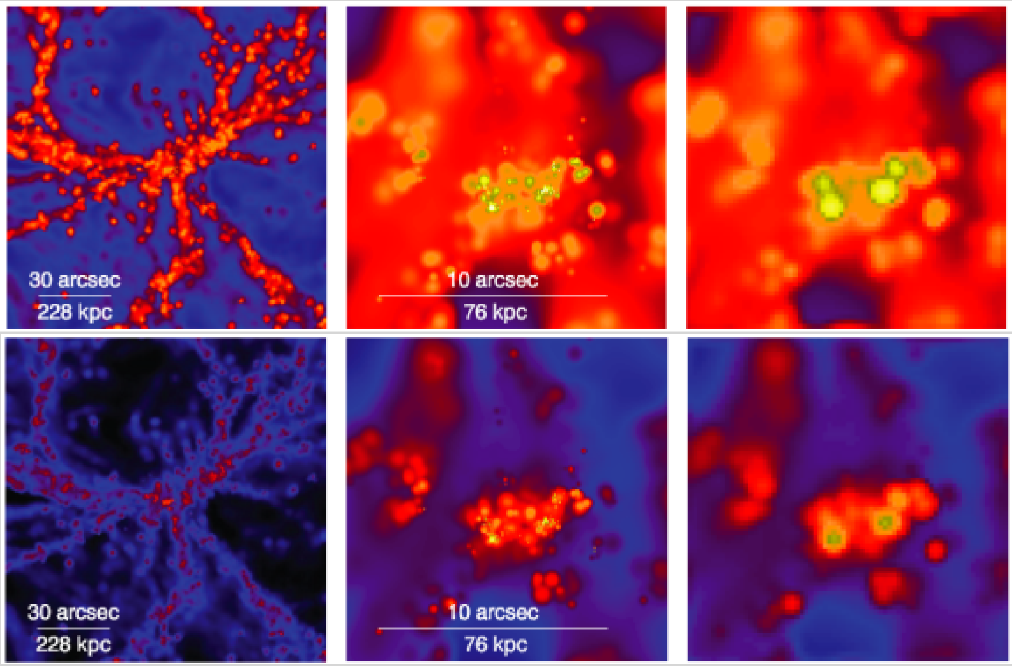
FROM FIRST LIGHT TO THE EARLIEST GALAXIES

- The HARMONI Deep Field
- Detecting the formation of MW like galaxies at z=10.
- Pop III - the first stars
- Detect first enrichment of IGM
- What re-ionised the Universe?



Requires: R ~ 5000 spectra, @ λ 0.8 - 2.5μ.
4 - 40mas spaxels;
FOV 0.5 x 1.0"; 5 x 10".

Figure 3 from Yang et al. 2006, showing the cooling of Lyα (top) and HeIIλ1640 (bottom) for an 11Mpc simulation at z~3. Lyα is more diffuse whereas HeII appears as compact points sources, this suggest HeII is a promising tracer of concentrations of dark matter.

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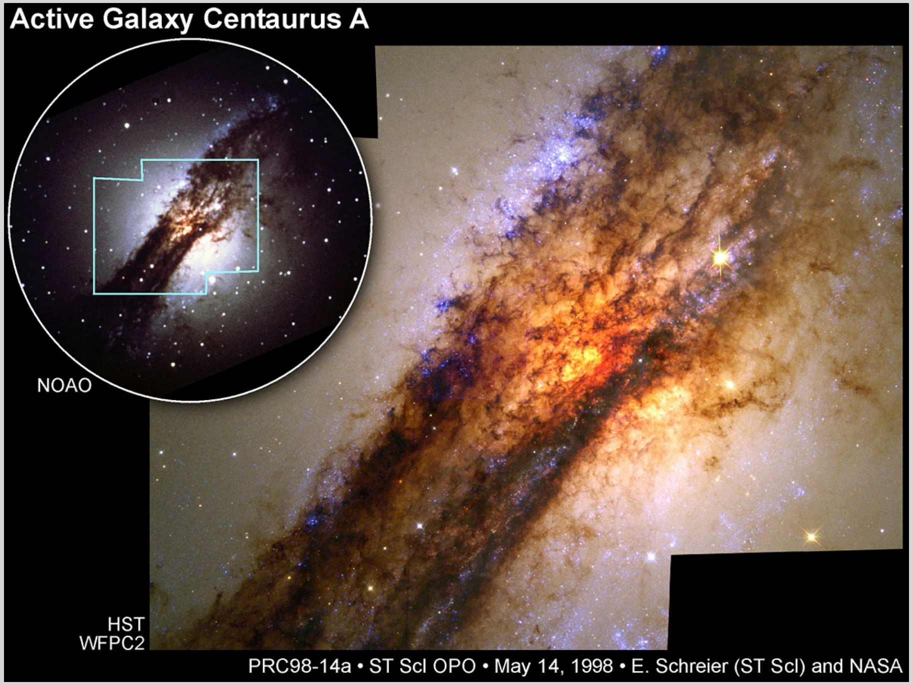
Stars & Galaxies

Imaging and spectroscopy of extragalactic resolved stellar populations



Studies of black holes and active galactic nuclei (AGN)

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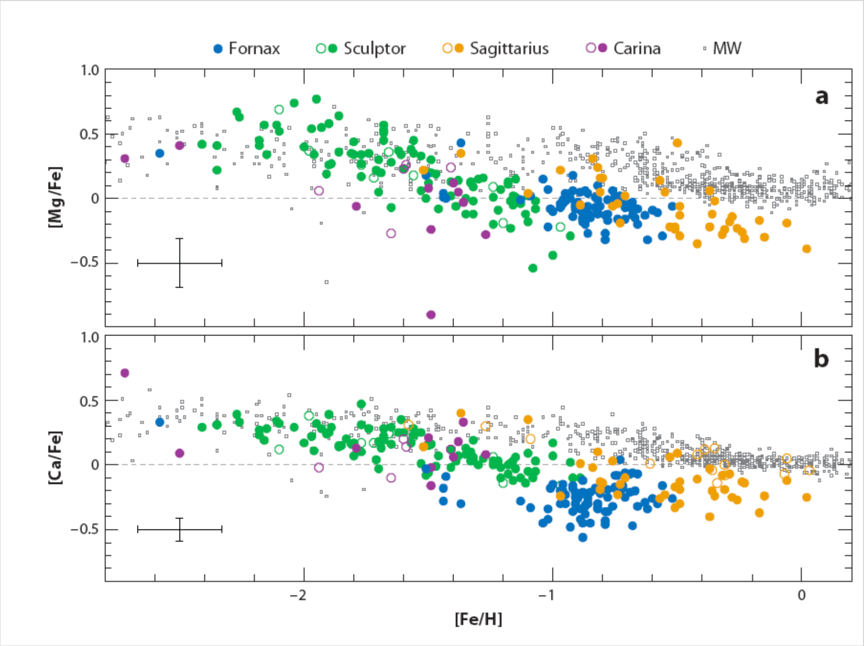
Stellar Populations: star formation history, chemical & dynamical evolution.

Measure the line of sight velocities and heavy element content of individual stars in local group, Fornax and Virgo clusters, so as to be able to decompose the stellar populations into thick disk, thin disk, bulge and halo.



This takes stellar population studies into a completely unexplored realm.

Need to investigate further whether this is best done in the visible or near-IR: nearly all elements have near-IR lines, although not as well understood (r and s process excluded – but is this crucial at 1st light?)

Requires: R= 9000 & 20,000 spectra, 20mas spaxels @ λ 0.6 - 1.0 & 1.0 - 2.5μ.

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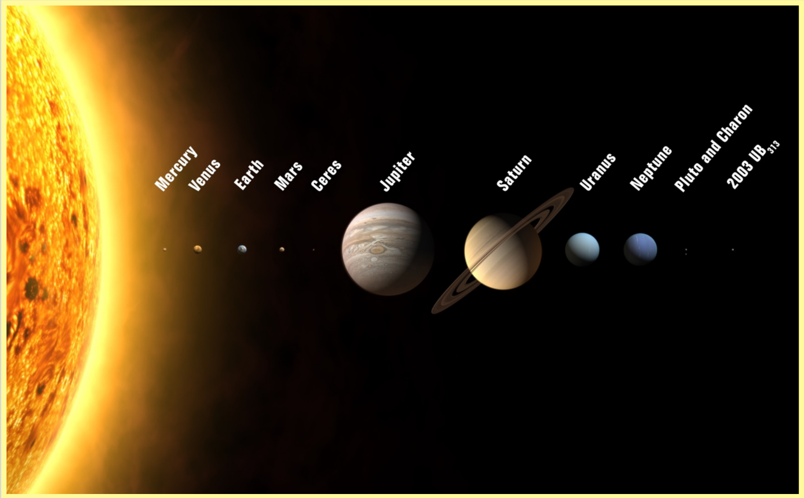
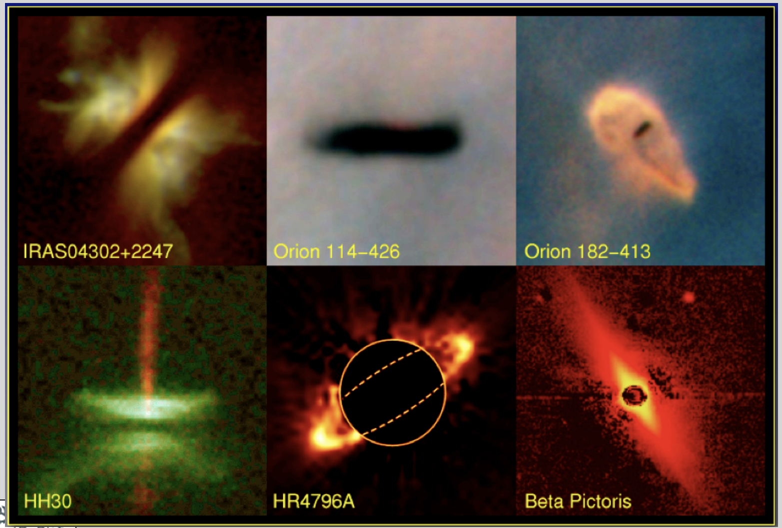
Planets & Stars



From giant to terrestrial exo-planets:

- Direct detection via high-contrast imaging
- Indirect detection via radial velocity variations



Circumstellar disks

Young stellar clusters and the initial mass function

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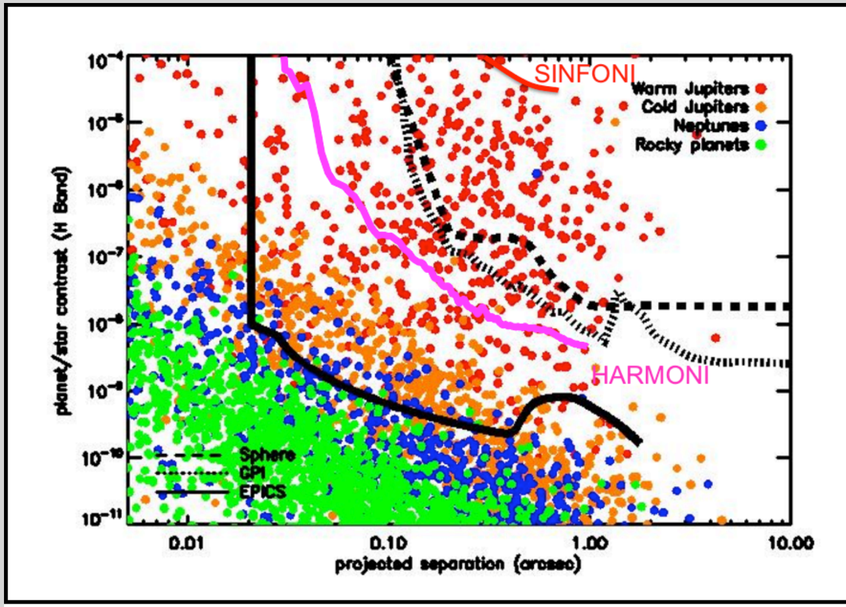
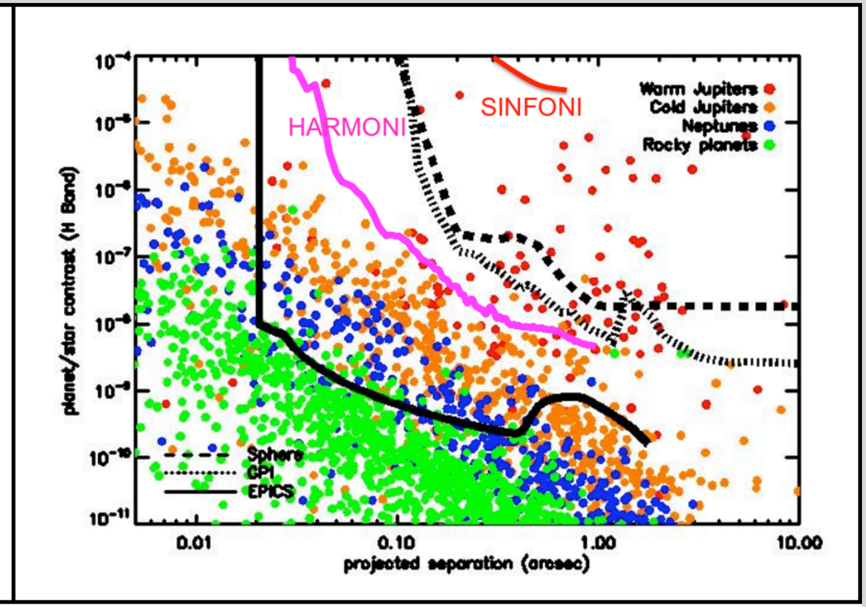
High Contrast Science – Characterising Exo-solar Planets

Aim: *follow-up spectroscopy of candidate exo-solar planets seen by VLT*

- Spectral lines provide measure of surface gravity
- Combine with other techniques to get density, temperature and luminosity.
- **Clues to atmospheric composition** – constrain models



Young stars



Nearby stars

Requires : R > 4,000 – 20,000 spectra @ I+z+J, H+K simultaneously. 4 mas spaxels, FOV 0.5 x 1.0"; SCAO.

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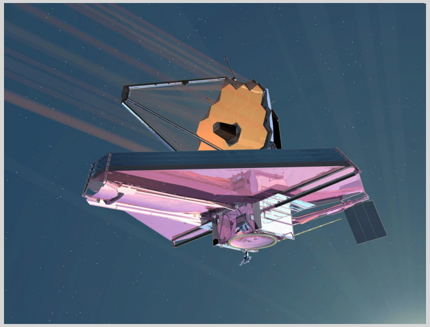
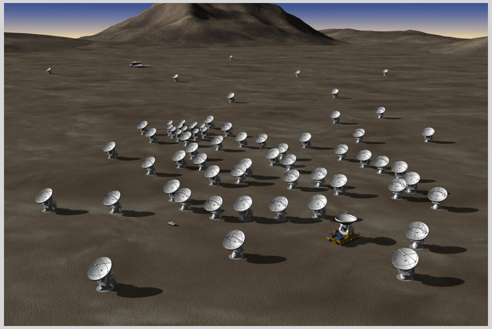
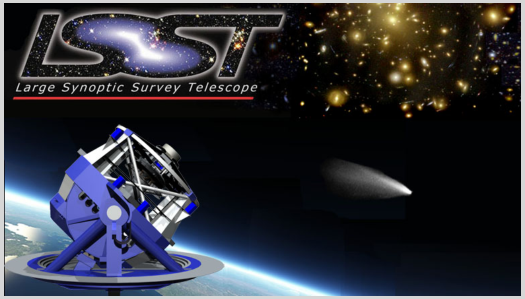
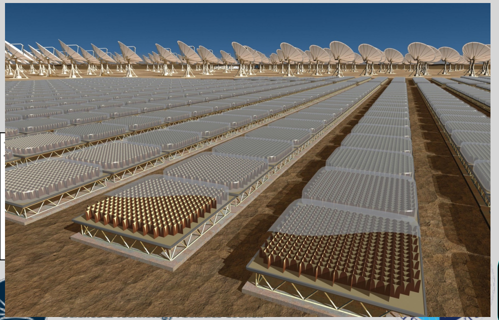
Synergy with Large Facilities

- The 8-10m class Telescopes (VLT/I, ...)
- The JWST
- ALMA
- LSST
- SKA / SKA Pathfinders
- ...









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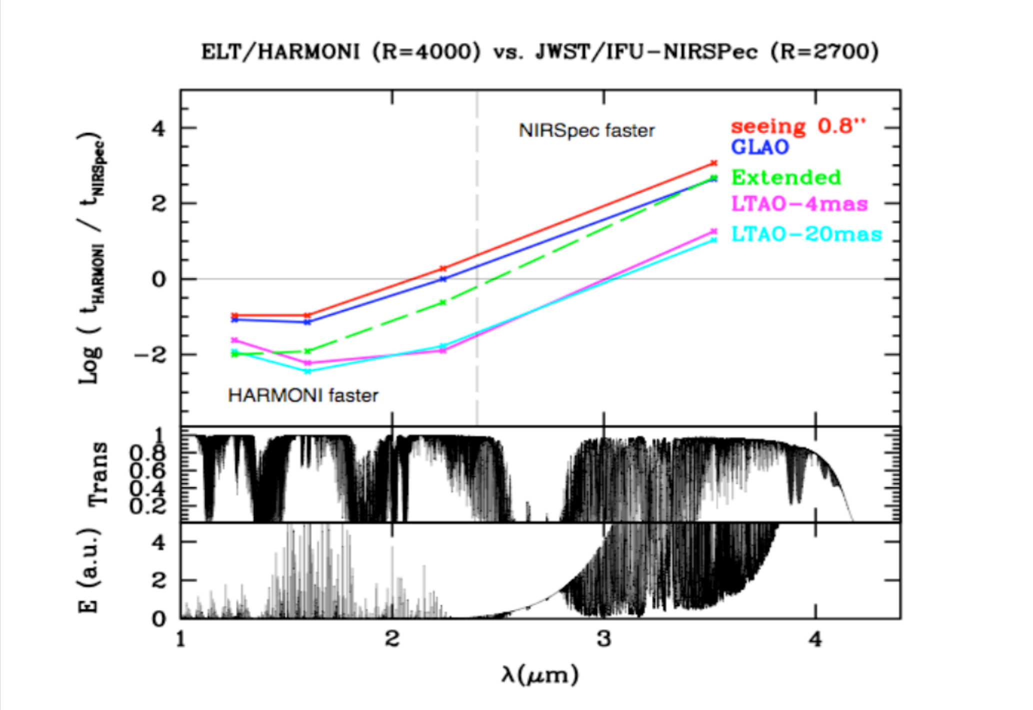
HARMONI vs. JWST NIRSpec



- At J & H E-ELT + HARMONI even in natural seeing HARMONI is 10× faster.
- Using LTAO and for extended sources the advantage rise to × 100.
- At K-band the advantage is retained with LTAO. With GLAO & natural seeing the two facilities are comparable, HARMONI wins at the blue end of K.
- Note that both NIRSpec and HARMONI offer other, less comparable capabilites where they have a greater advantage.

Field of View: shape

- High precision sky subtraction is essential ⇒ nodding-on-IFU
- Half integration time cf. offset sky measurements.

⇒ 2:1 aspect ratio for FoV

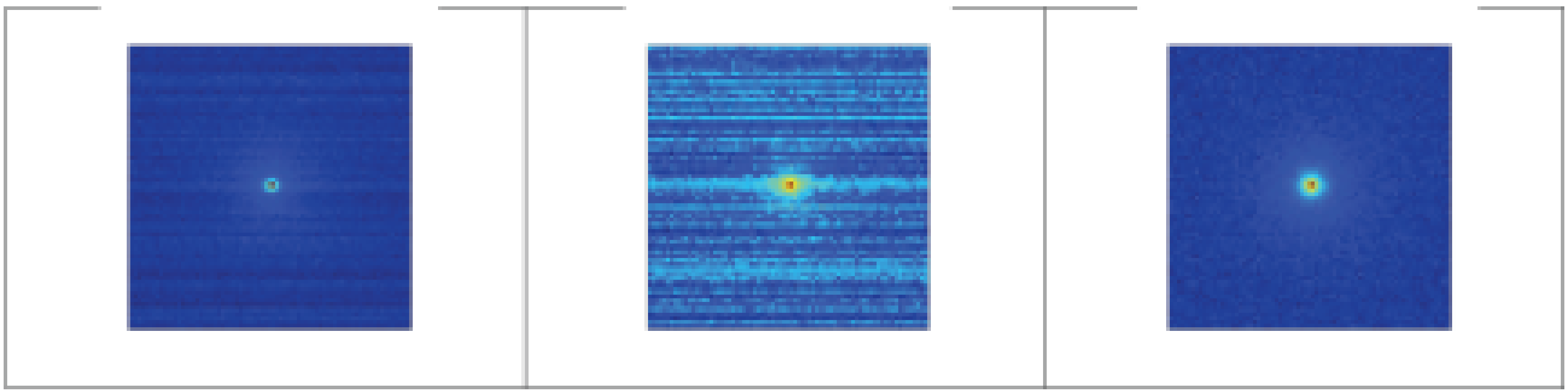


Figure 4: Median data cubes for K band observations of a 20th mag z~2 galaxy. The galaxy has an exponential profile with a 2kpc half light radius, and is "observed" with the 20 mas spaxel scale. The images show half the HARMONI FoV: raw data cube (left), sky derived from periphery of FoV, with 0.5% flat fielding error (centre) and nodding based sky subtraction (right)

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Field of View: size & sampling

- Variable sky & PSF ⇒ advantage to avoid mosaicing
- Typical single objects at z>1 ⇒ 128 x 20mas for short dimension of IFU
- Large objects (QSO hosts) or diffuse emission & stellar pops studies ⇒ largest possible FoV

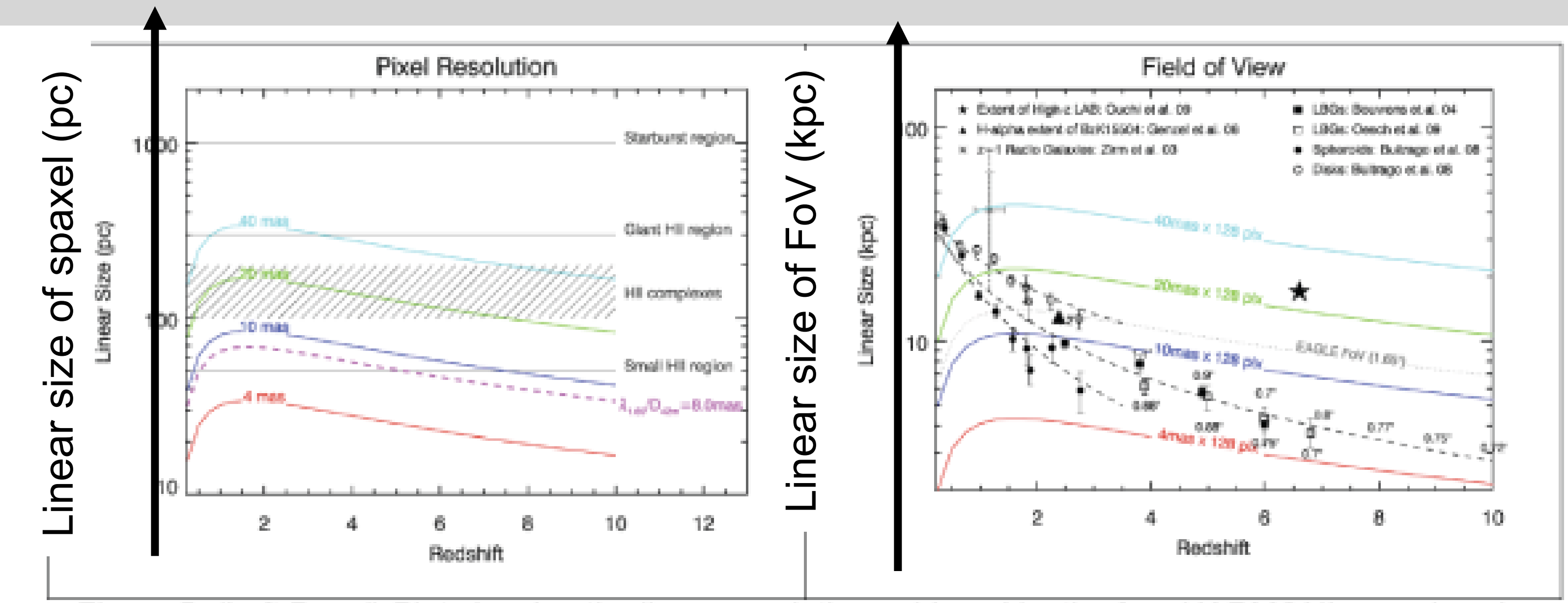

Figure 5: (Left Panel) Plot showing the linear resolution achieved by the four HARMONI spaxel scales as a function of z. Overplotted are typical sizes of HII regions and complexes. (Right Panel) Plot showing the linear size of HARMONI's FoV with each of the 4 spaxel scales. Overplotted are measured median extents for samples of local & high redshift galaxies. The extent corresponds to $2.5 \times D_{NL}$ so that the entire object fits within the FoV.

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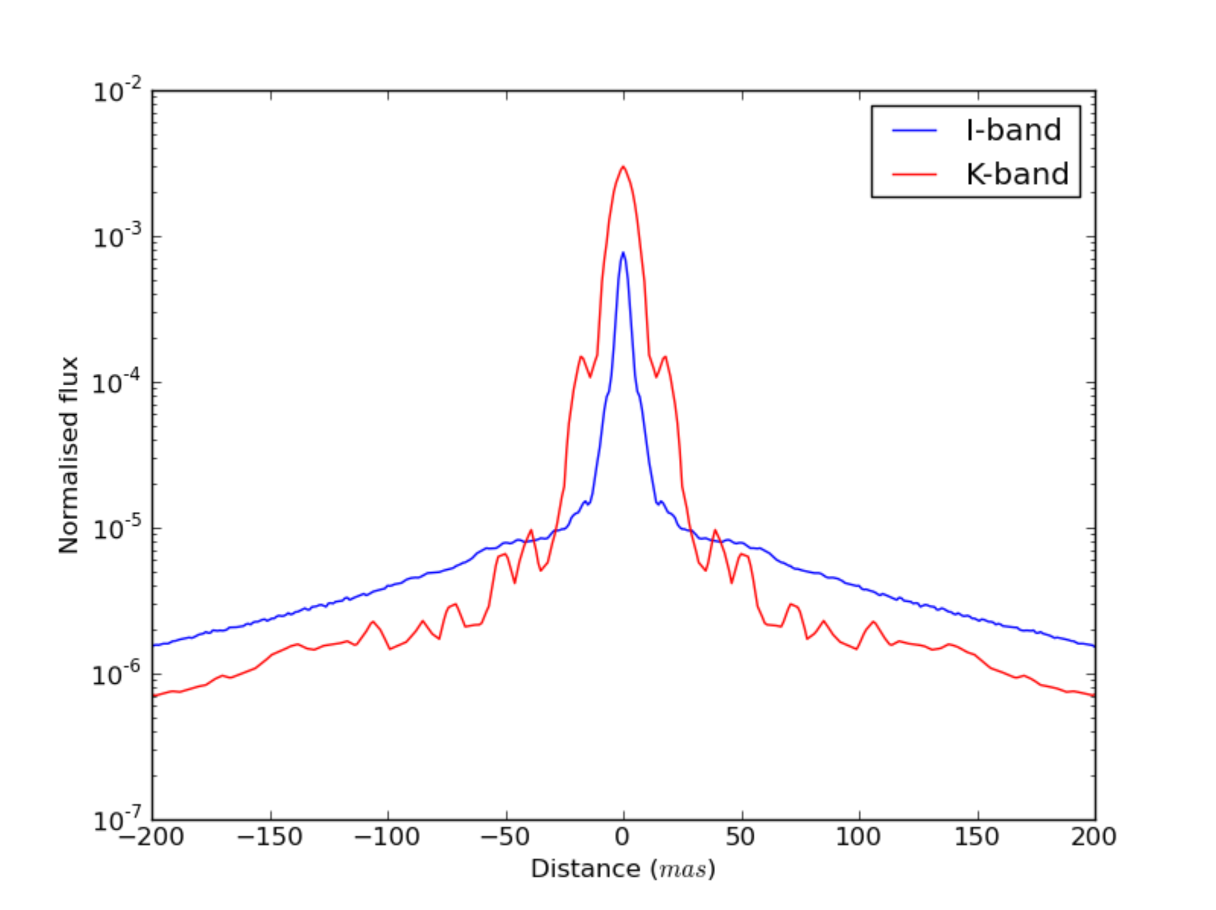
PSF Halo at the E-ELT

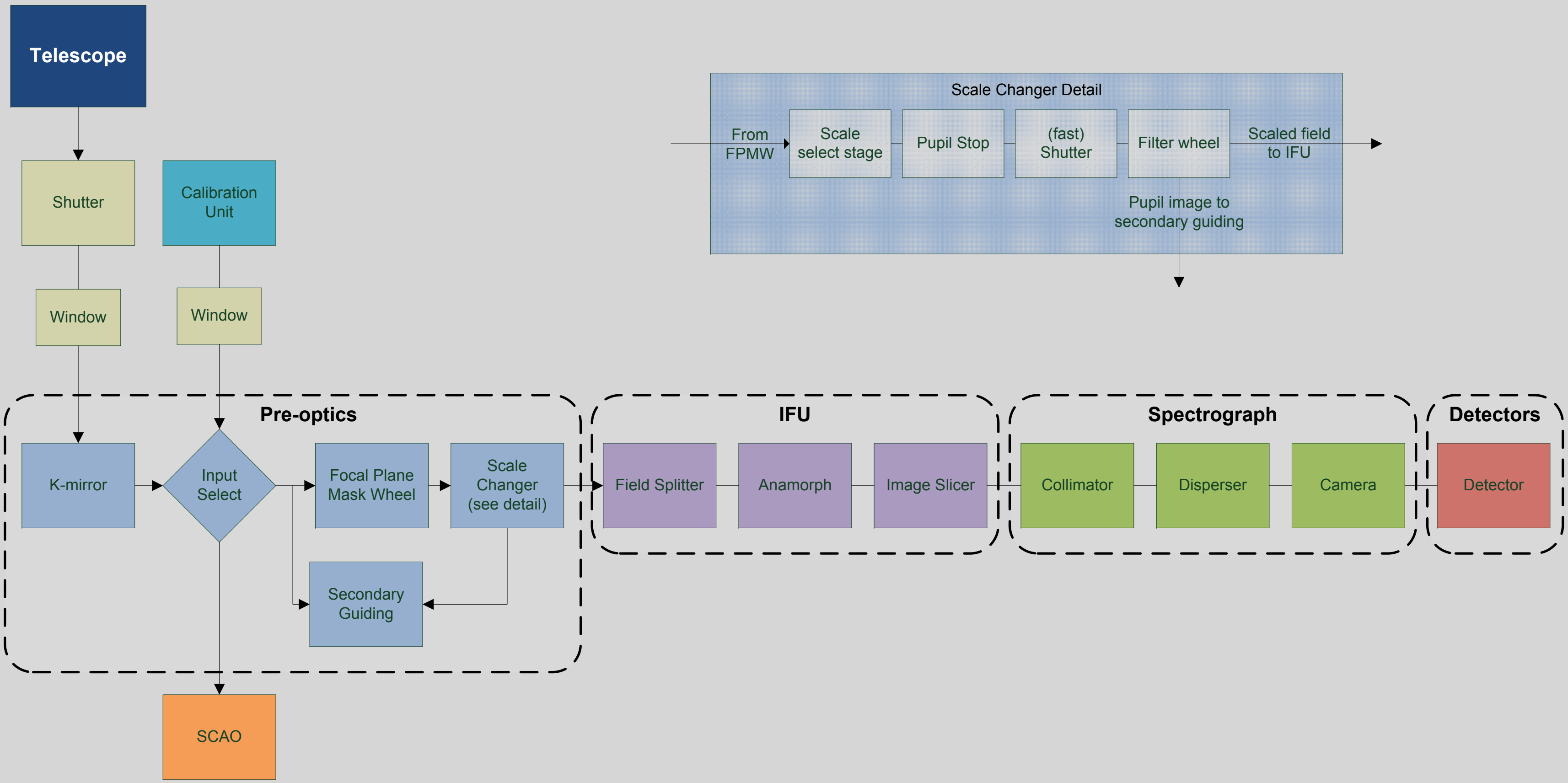


Sensitivity

Spectral Resolution	4 mas		10 mas		20 mas		40 mas	
	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}
	Point source (mag)							
4000	24.2	26.6	25.3	27.4	25.3	27.4	25.4	27.0
10000	23.2	25.6	24.4	27.1	25.0	26.7	25.0	26.4
20000	22.5	25.4	23.5	26.6	24.1	26.5	24.4	26.1
	Extended source (mag / sq. arcsec)							
4000	19.2	18.2	21.0	19.3	21.9	20.3	22.7	21.1
10000	18.2	17.8	20.1	18.9	21.5	19.8	22.3	20.6
20000	17.5	16.7	19.5	18.5	21.0	19.4	22.2	20.3

- 20 mas spaxels provide best sensitivity for point sources
- 40 mas spaxels best for extended sources

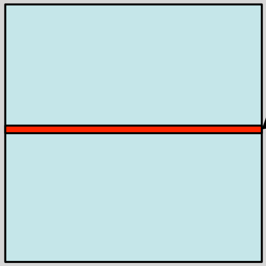
Modular Construction



New Develoments - Spectrographs

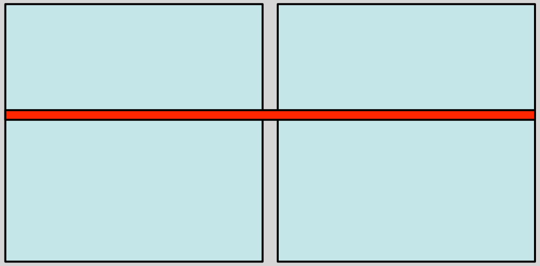
- Number of infra-red (0.8 -2.45 micron) spectrographs reduced from 8 to 4.
  - Spectrograph camera now illuminates two 4k^2 detectors side-by-side, so that spectrum length is 4k pixels, and slit length is 8k detector pixels for each spectrograph
  - Each spectrograph input slit twice as long
- New layout for spectrographs to achieve most compact cryostat geometry has 4 input slits forming a square (see images on next slide).

Spectrographs



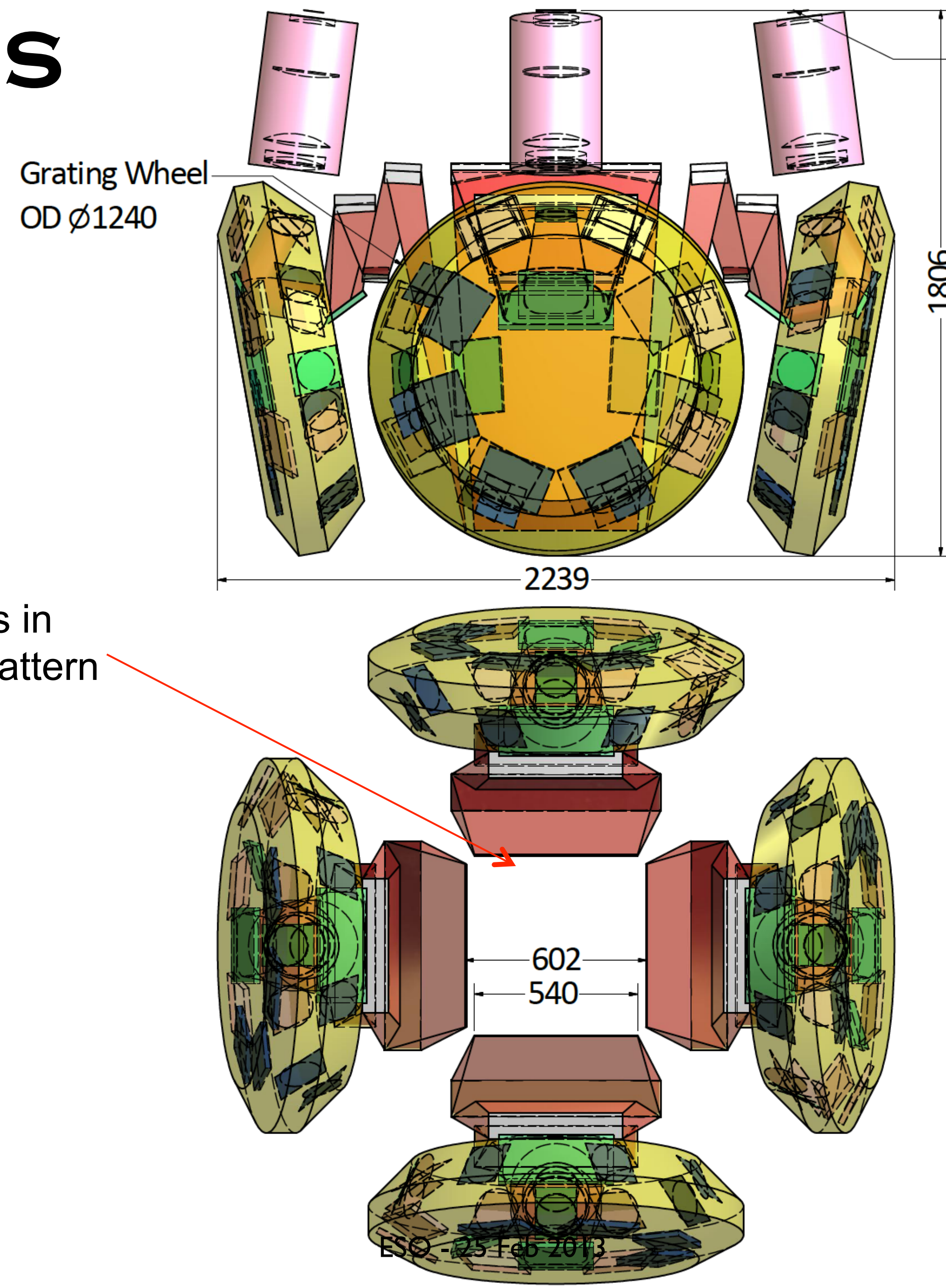
Slit projected on to the detector

Phase A spectrograph feeds a single 4k^2 detector



New design feeds two 4k^2 detectors side-by-side, with a very small gap.

Input slits in square pattern



New Developments – under consideration

- Fixed spectral format visible cameras covering full FoV, enabling CCD detectors and effective blocking of Na laser light
- Low R mode using a prism disperser in near-IR + visible camera to get 0.47 to 2.45 micron coverage in a single exposure
- SCAO mode to maximise Strehl for bright reference stars (factor of 2 over LTAO!) and de-risk diffraction limited operations

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