SCIENCE WITH

HARMONI
A near-infrared & visible integral field spectrograph for the E-ELT

Niranjan Thatte

University of Oxford

HARMONI Consortium

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

David Lunney, Hermine Schnetler, David Montgomery, Derek Ives

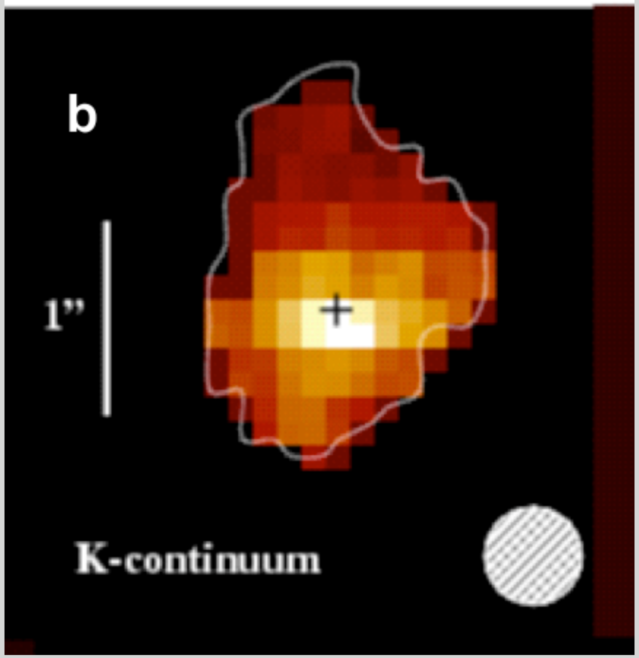
Roland Bacon
Alban Remillieux

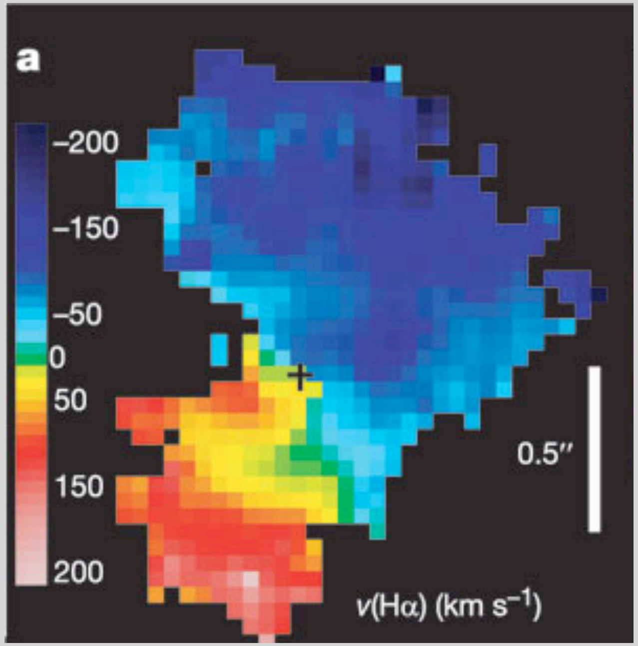
Fernando Gago Rodríguez
Felix Gracia Temich
Fabio Tenegui

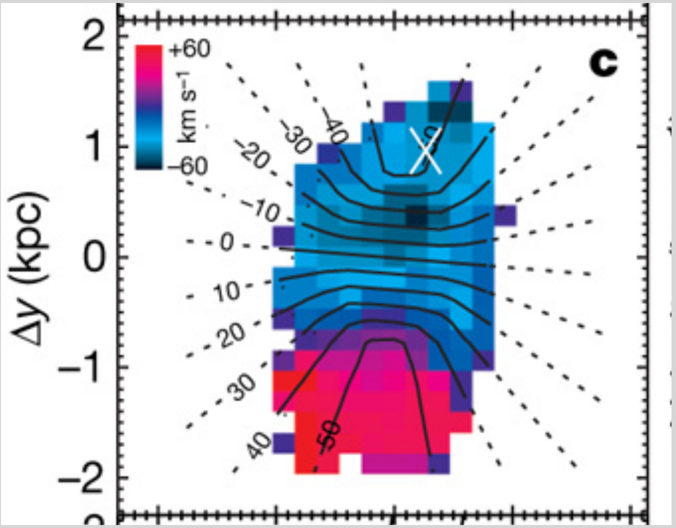
Santiago Arribas
Adolfo García Marín

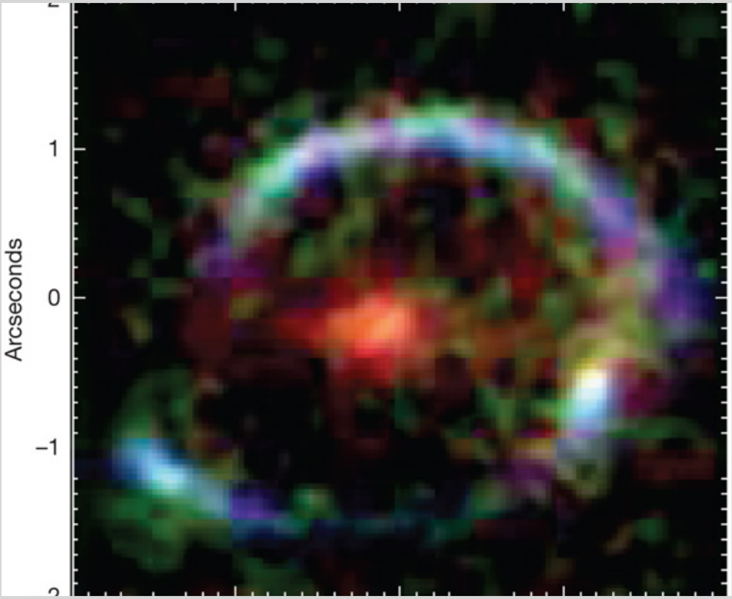
Why Use an IFS?

- Scanning techniques are a very inefficient use of telescope time.
- Slit diffraction results in light loss for diffraction limited slit sizes
- Positioning object in slit difficult for faint / emission line targets, wide slits lead to slit effect
- Atmospheric dispersion causes object to stray out of slit, adding to light loss
- Inhomogeneous data cube due to varying transmission, seeing, AO performance
- Inadequate PSF knowledge for post-analysis
- 1D kinematics often leads to incorrect interpretation.

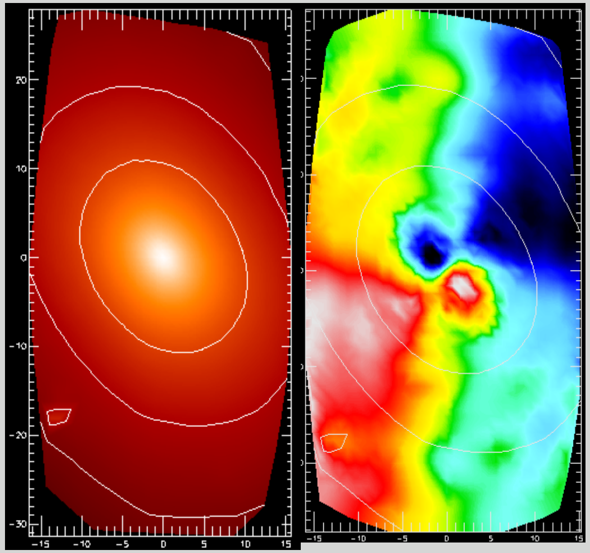

b
1"
K-continuum

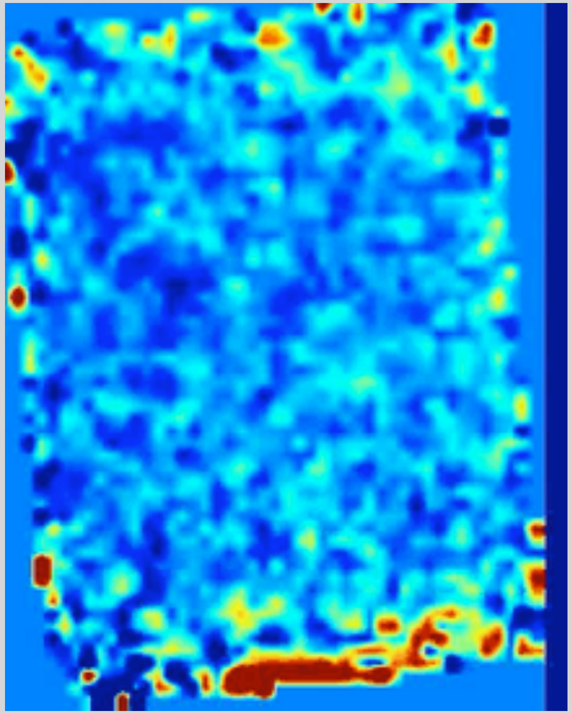

a
−200
−150
−50
0
50
150
200
0.5"
v(Hα) (km s−1)


c
Δy (kpc)
+60
km s−1
−60


Arcseconds

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.
- The D^4 sensitivity gain offered by E-ELT + LTAO will define a new era of observational astrophysics. HARMONI will exploit this gain by efficiently gathering information in the most complete way.
- 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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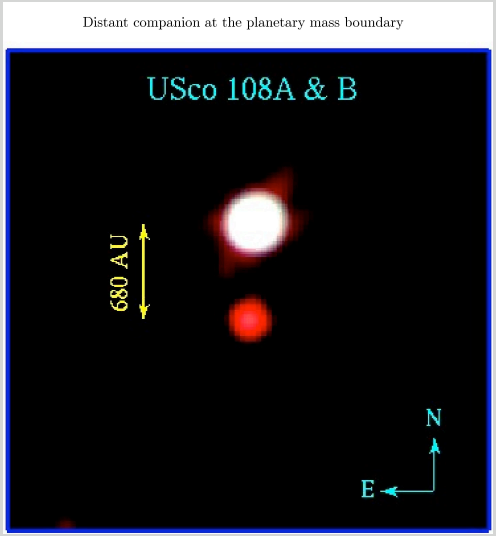
WHAT CAN HARMONI DO?

- Spectral coverage from red visible to near-infrared naturally emphasizes cool objects, highly extincted regions and high z targets.
- Prominent science areas
  - Planetary science
  - Circumstellar disks
  - Star forming regions
  - Stellar populations, IMF & Galactic archaeology
  - Black Holes and Galaxy Cores
  - GRBs
  - High redshift galaxies (1<z<10)

Summary of scientific cases

M/L(age) for brown dwarfs & planetary mass objects

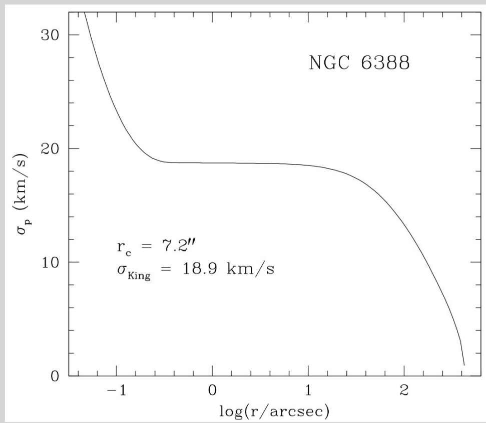
- mass & age determined for cool sub-stellar objects <u>in young clusters.</u>
- HARMONI can simultaneously image & measure velocities for low mass companions.



Requires: diffraction limited, R= 1000 & 10,000 spectra @ λ = 1- 2.2μ.

IMBHs in globular clusters: $10^2 - 10^5$ $M_\odot$

- 0.1 pc SoI resolved by HARMONI
- simultaneous imaging & velocities for individual stars

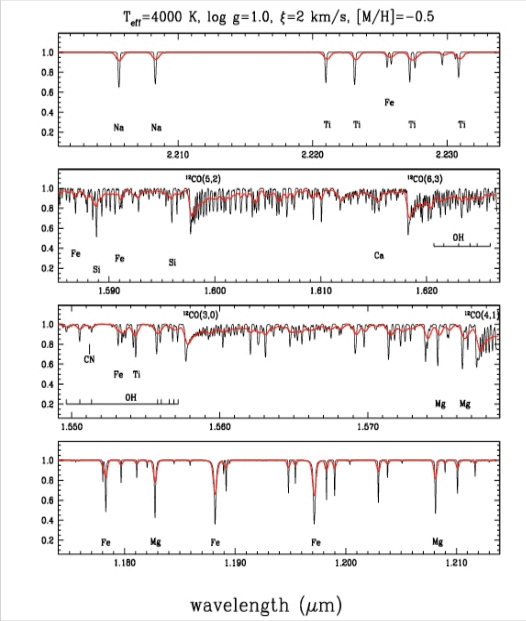


Requires : diffraction limited, R>10,000 spectra PSF measurement

Summary of scientific cases

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

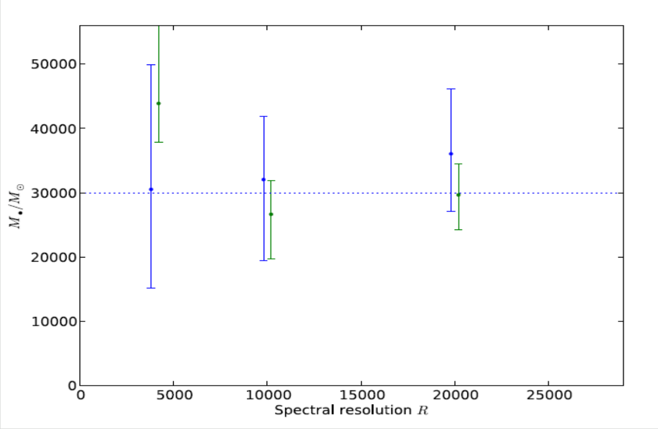
- kinematics & abundances of RG & MS stars in the MW.
- CNO abundances in luminous RGs in galaxies several Mpc distant.
- Integrated light studies.



Requires: R= 4000 & 20,000 spectra, 20mas & 100 mas spaxels @ λ 0.6 - 1.0 & 1.0 - 2.5μ.

Galaxy Cores, Black hole & AGN physics

- Masses for black holes & NSC in low mass galaxies
- Ionised gas distribution & velocities
- Connection between star formation & AGN

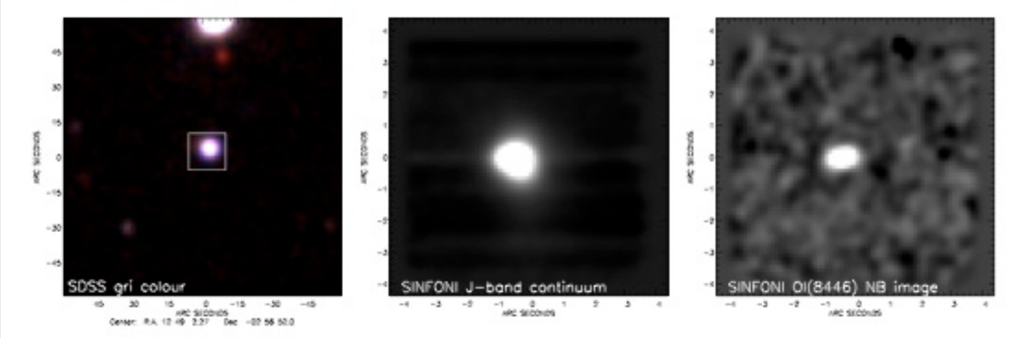


Requires : diffraction limited, R = 4,000 spectra @ λ 0.6 - 2.5μ simultaneously. 10mas spaxels. PSF measurement.

Summary of scientific cases

Evolution of $M_{\bullet}$- M_{bulge} relation

- σ measurements for qso hosts from z=2 to today.
- R_e & I_e from reconstructed images ⇒ FP

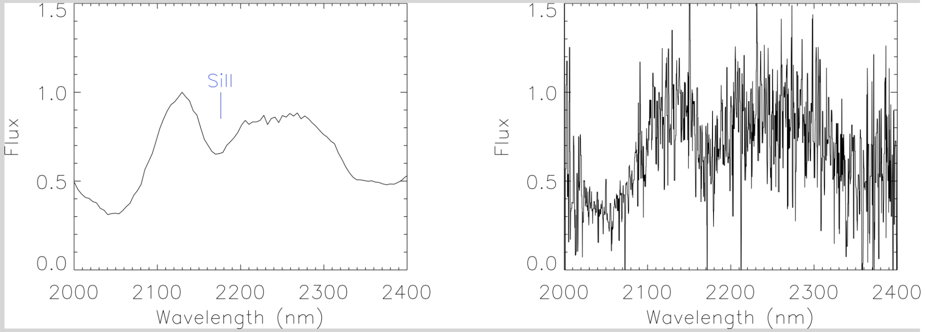


Requires: R > 500 spectra, min FOV = 4" optimum 7-8"
PSF measurement from BLR lines. 40mas spaxels @ λ 1.0 - 2.5μ.

Type Ia Supernovae

- HARMONI + JWST will measure w(z) to z=4
- Confirms SNae types & constrains evolution

Requires : R > 1,000 spectra
@ λ 0.8 - 2.5μ simultaneously. FOV 2".



Summary of scientific cases

High-z Ultra-luminous IR Galaxies

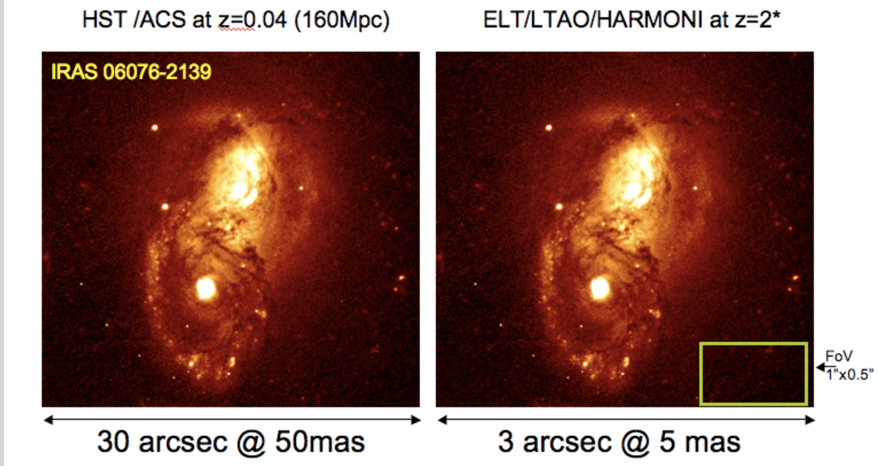
- AGN, star formation & merging in this enigmatic class
- Measure rotation, flows, masses, dust content, stellar pops & FP
- Survey 50 Spitzer candidates 1<z<2.5.

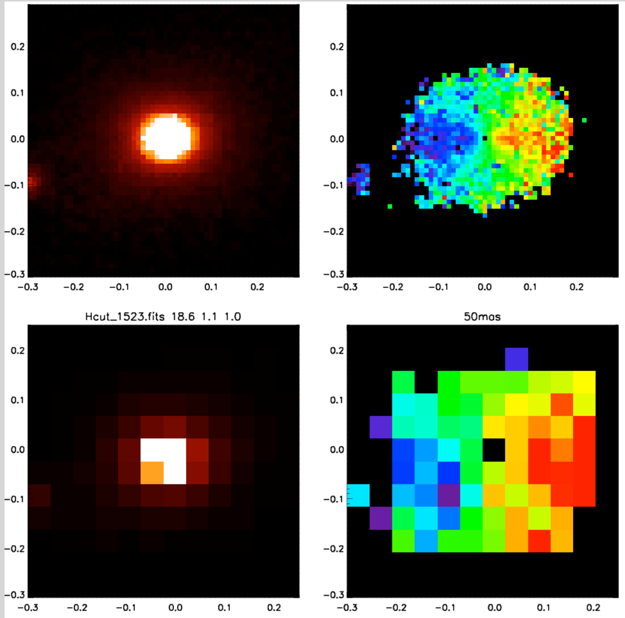
Requires: diffraction limited R > 4000 spectra, spaxels 5-40mas. @ λ 0.5 - 2.5μ.

The Physics of High Redshift Galaxies z=2-5

- Size & luminosity distribution of HII regions
- HII regions as tracers of SFH, mass & mergers
- Measure abundances for individual SF regions

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”.





Summary of scientific cases

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".

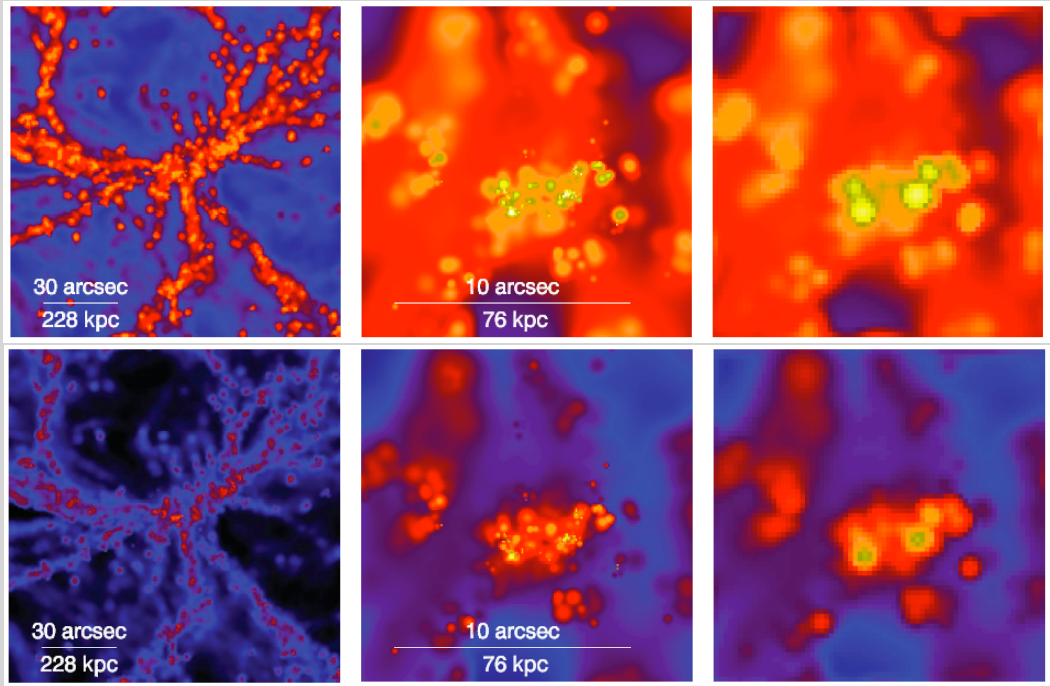
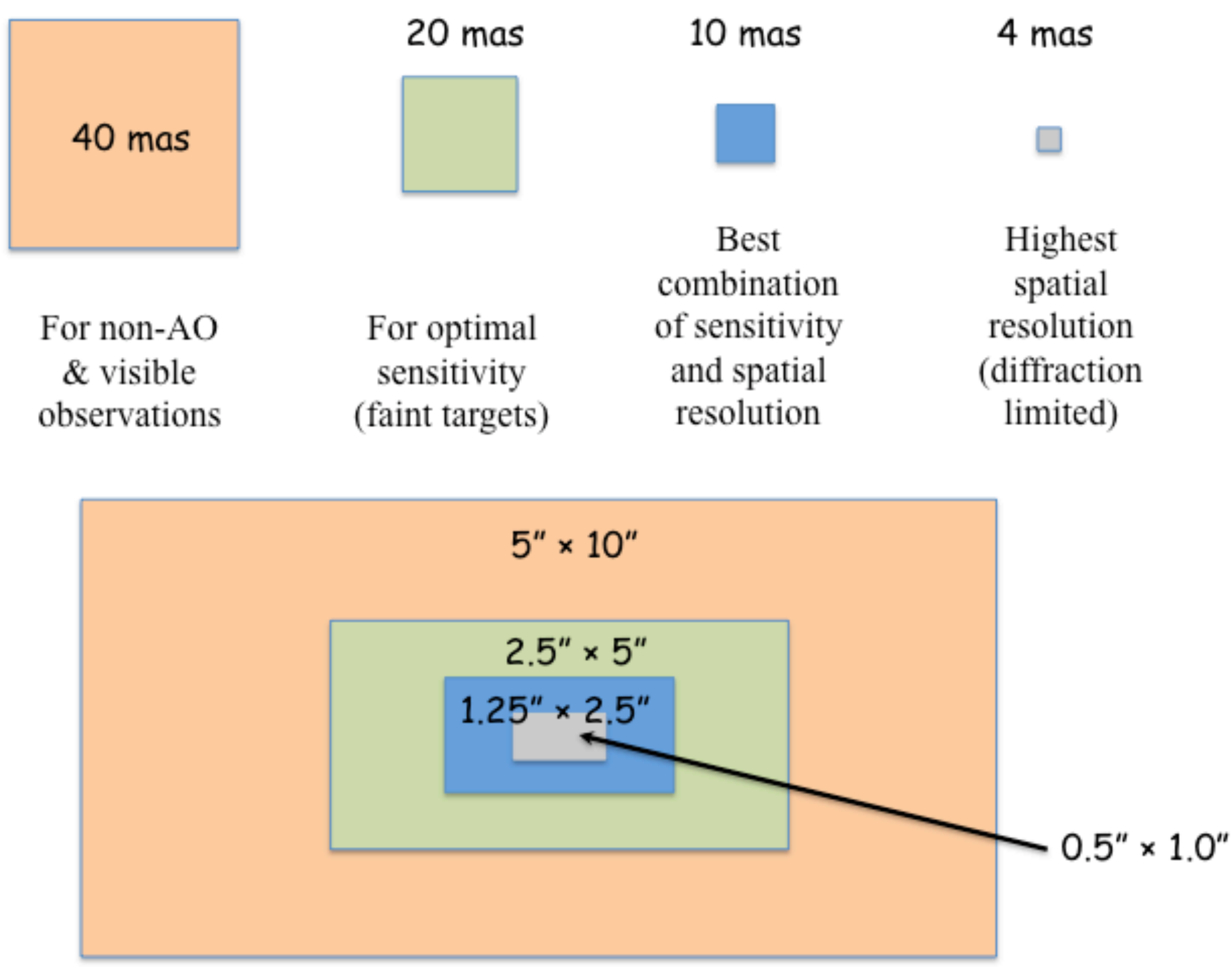


Figure 3 from Yang et al. 2006, showing the cooling of Lyα (top) and HeIIλ1640 (bottom) for an 11Mpc simulation at z~3. Lyα is more diffuse whereas HeII appears as compact points sources, this suggest HeII is a promising tracer of concentrations of dark matter.

Exo-Planet Science

- HARMONI + SCAO + simple Lyot Coronagraph + spectral deconvolution can be a versatile tool for characterization of exo-planets detected by other experiments.
- Work with SINFONI shows this is feasible. Spectral characteristics of gas giants will provide Teff, surface gravity, thus resolving mass-age-luminosity degeneracy.
- Small inner working angle key benefit of E-ELT.



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Instrument Requirements

- HARMONI will have four spaxel scales of: 4, 10, 20 and 40 mas/spaxel
  - Pre-optics including a Scale changer
- HARMONI will have an instantaneous FoV of: ≈128x256 = 32,768 spaxels.
  - FoV = 10.0" x 5.0", 5.0" x 2.5", 2.5" x 1.25", 1.0" x 5.0"
  - 8 spectrographs, each with 4k spectra
- HARMONI will cover the wavelength range from 0.82—2.4μm as a minimum requirement, with a goal of including the I, R, and V bands
  - Reflective optics were possible
- HARMONI shall operate at resolving powers of R≈4000, R≈10000, and R≈20000
  - Grating exchange mechanism
- HARMONI's thermal background at the detector in the H and K bands shall be less than 20% of that from the telescope (M1-M5), with a goal of being less than 10% of that from the telescope.
  - Fully cryogenic instrument
- HARMONI's image quality, considering pre-optics, the slicer, and the spectrograph, shall not to degrade by more than 20% the FWHM of the diffraction-limited core of the PSF delivered by the AO module in the bands from I to K (goal 10%).
  - HARMONI PSF with Strehl ratio ≥ 73%, almost diffraction limited, even in the I band!

Sensitivity

- Point source (AB mag) and surface brightness (AB mag / arcsec2) sensitivity for S:N of 5 in 5 hours on the E-ELT.
- R and H bands as a representative of visible and near-infrared.
- LTAO, 0.8" seeing, airmass = 1
- Standard E-ELT spectroscopic ETC parameters.

HARMONI Sensitivity

Point Source

Spectral Resolution	4mas		10mas		20mas		40mas	
	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}	R_{AB}	H_{AB}
4000	24.15	27.10	24.75	27.32	25.05	27.34	25.30	26.95
10000	23.2	26.35	23.87	26.72	24.35	26.80	24.70	26.45
20000	22.45	25.70	23.20	26.20	23.70	26.35	24.20	26.05

Extended Source

4000	18.80	18.05	20.55	19.40	21.75	20.3	22.55	21.00
10000	17.85	17.25	19.70	18.75	21.05	19.75	21.95	20.45
20000	17.10	16.55	19.00	18.20	20.45	19.31	21.45	20.05

A Workhorse Instrument

HARMONI is designed to provide high throughput and optimal sampling for a range of resolutions delivered by the E-ELT+AO

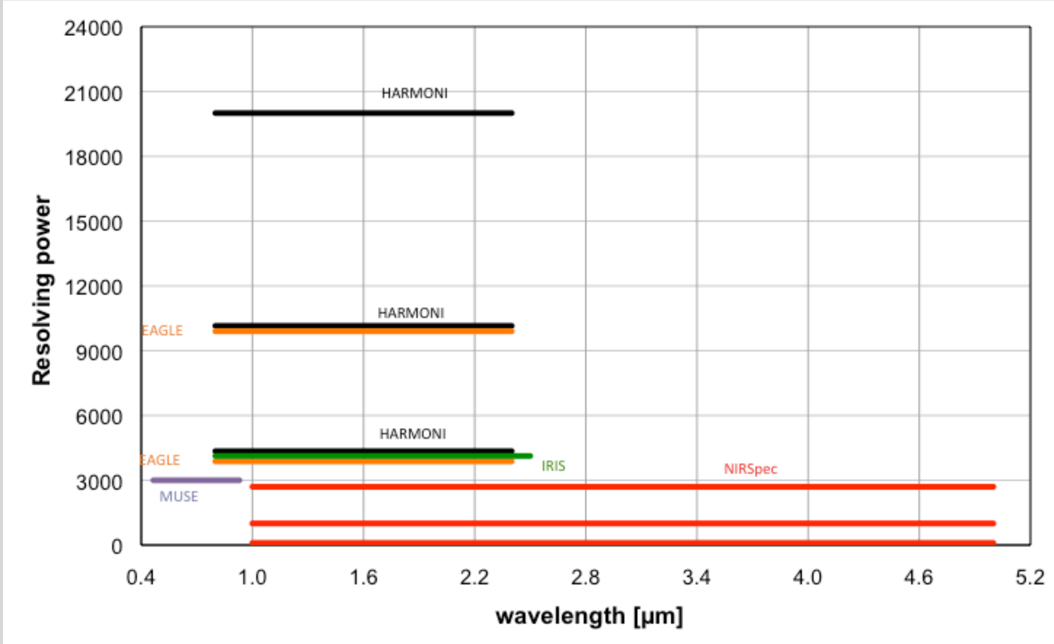
- no AO – suitable for first light, visible wavelengths, moderate seeing conditions
- SCAO – targets bright enough for NGS AO, e.g. exo-planet characterization, solar system objects.
- GLAO – full use of the adaptive telescope, × 2 gain in FWHM, >2 in sensitivity, full sky coverage, all wavelengths
- LTAO – exploiting the diffraction limit, primarily near-infrared, good sky coverage, detailed kinematic studies.

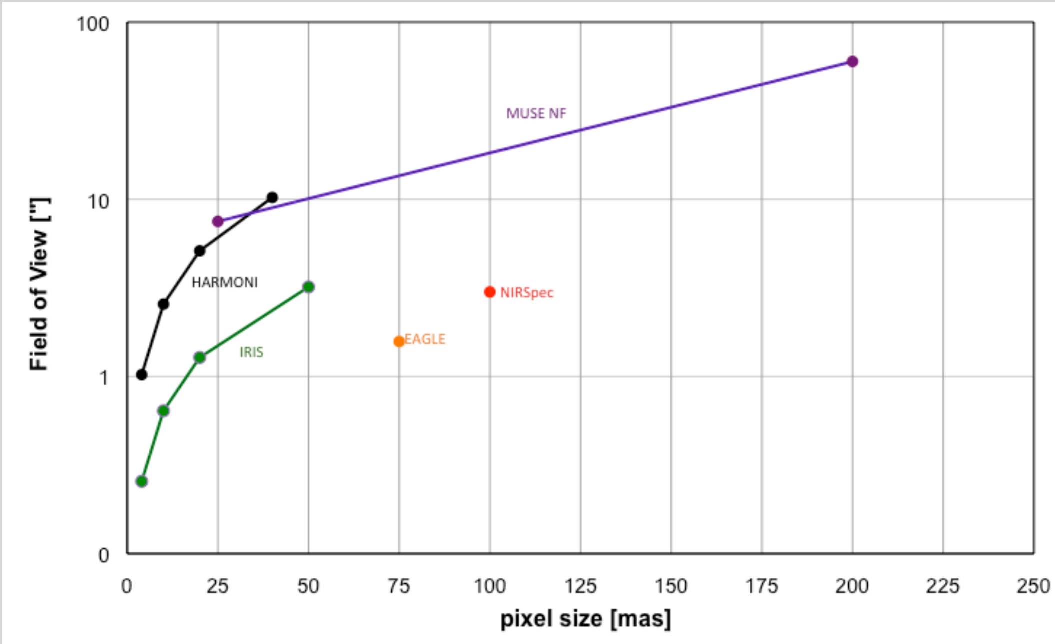
A Workhorse Instrument

- HARMONI can efficiently operate in modest seeing conditions, or at times when conditions are unsuitable for LGS propagation
- At red visible wavelengths, where AO gain is modest, can still exploit E-ELT advantage of a factor of 25 in speed (compared to MUSE).
- Higher spectral resolution modes can deliver unique science in periods when the adaptive capabilities of the telescope cannot be fully exploited.

Discovery Space

- E-ELT science cannot be predicted
- Important to cover a large parameter space
- Synergies and competitiveness





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