Enhanced Seeing Science: Workshop Products

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Products

1. Context Documents

- Workshop goals
- Decadal priorities
- Primer

2. Science Cases Templates (this document)

- Galaxy Evolution
- Galactic Science
- Cosmology
- Exoplanets & Solar System

3. Summary (this document)

Galaxy Evolution Slides

Overview of Galaxy Evolution Cases Discussed

(Vivian, Claire) Low surface brightness - flows, AGN, connection to cosmic web:

- Resolved Line emission diagnostics - line ratios and dynamics
- CONTINUED ON NEXT SLIDE

(Kevin) Resolved Stellar absorption diagnostics

- How is internal structure of ETGs built up over time? What is the resolved SF assembly/formation history? IMF variation?
- Kinematics and stellar populations (perhaps stacking for the S/N)
- Improved time resolution for “fossil record” of distant stellar populations

(Matt) Spectral followup of high-z grism (e.g., Euclid, JW, Roman) (R~50-100) surveys - MOS or IFUs

- Spectral resolution - 6-8000 (min 3000)
- Wide-field competitiveness compared to narrow fields of ELTs
- Improved efficiency

(Barry) Resolving crowded (detailed) structure in nearby galaxies (e.g., mergers - Antennae Galaxies, quiescent - spirals, ellipticals)

- Young star clusters and globular clusters by merger phase -- Spectral studies of more YSCs and GCs over large FOV (probe lower mass/fainter targets) diagnose age gradients to determine merger phase (e.g. 1st pass, 2nd pass, final coalescence)
- Quiescent galaxies - map the metallicity and measure r_eff of GCs as a function a spatial position to many r_effs - evolutionary history of GCs provides key info on the evolutionary of the host galaxy (absence of blue or red GCs, “blue tilt” seen in ellipticals - more massive blue GCs increase in metallicity, etc). Probe out to earlier epochs (z ~0.05-0.1 for imaging to match what can be done currently - 0.1” ~50-185 pc)

Local-Group Dwarf Galaxies -- Connie?

Galaxy Evolution Science Case (Nearby AGN, Mergers, Outflows, Inflows)

(Vivian/Claire)

- Science questions: relation between mergers and AGNs, when are outflows driven by AGN vs. star formation, low surface brightness inflows from CGM and possibly from cosmic web
    - If we can understand for nearby galaxies, gain insight into what is going on at high z
- Necessary observations:
- Spatially resolved spectroscopy of relatively nearby galaxies (e.g. $z < 0.1$)
- Stellar and gas emission lines and absorption lines for kinematics, excitation, stellar pops
- Connecting outflows/inflows on large galactic scales with the properties close to nucleus
- How do these properties change with z (e.g. between $z\sim0.01$ and $z\sim0.1$)?

Galaxy Evolution Case [Resolved Outflows, AGN, SF at z=0.1]

Requirement	VALUE	COMMENT/JUSTIFICATION
Largest Acceptable FWHM	0.1-0.5”	
PSF Uniformity	Ellipticity and/or delta-FWHM	Need to explore what tolerances we can accept for PSF variations. Note that PSF variability also matters quite a bit: GLAO has been shown to greatly reduce temporal variability of PSFs: a real benefit.
Field of View	~20’	> 100 kpc, connection to the halo. IFU desirable.
Wavelength Coverage	Blue optical - 2.2 microns	The optical and NIR feature a range of diagnostic lines of ionized, neutral, and molecular gases
Simultaneous Bandpass	Optical to NIR	Not critical but would be nice.
Number and types of science targets	~100	All-sky, but some may not be in fields with nearby guide stars
Plate Scale and/or Spectral Resolution	Min R > 3000	Better spectral resolution than, say, Roman would be helpful with line diagnostics and resolved kinematics
Photometric, Astrometric, or RV Precision (or other science metrics)		
Sensitivity (Brightness of object)	Mag or mag/arcsec^2	Tend to bright in nearby universe, but need to reach low surface brightness features

Galaxy Evolution Case [Resolved stellar populations (z~0.2-1) e.g., FOBOS IFUs]

Requirement	VALUE	COMMENT/JUSTIFICATION
Largest Acceptable FWHM	0.4'' at 700 nm	
PSF Uniformity	Ellipticity and/or delta-FWHM	Perhaps not critical if stacking. Would like to have the PSF well characterized per observation (for forward modeling)
Field of View	8' diameter..	
Wavelength Coverage	600-1000 nm.	Would really like to go into near-IR for higher redshift, but would need IR-FOBOS.
Simultaneous Bandpass	600-1000 nm	. Probably makes life easier if GLAO PSF varies from night-to-night.
Number and types of science targets	1000 galaxies	Expect several targets per sq. arcmin, and would like ~1000 galaxies. These would be many-hour integrations to get sufficient S/N.
Plate Scale and/or Spectral Resolution	R~3000	
Photometric, Astrometric, or RV Precision (or other science metrics)		Would like field-wise flux calibration.
Sensitivity (Brightness of object)	Mag or mag/arcsec^2	

Galaxy Evolution Case [Followup of deep surveys]

Requirement	**VALUE**	**COMMENT/JUSTIFICATION**
Largest Acceptable FWHM	0.1-0.5” (specify at what wavelength)	A factor of 2 X improvement in encircled energy over what is currently available with seeing-limited observations will be a game-changer
PSF Uniformity	Ellipticity and/or delta-FWHM	Surveys do not require perfectly uniform sensitivity limits, so a range of ~2X in the FHWM’s across the field would still allow most science goals to be achieved
Field of View	20’	20’ or as large as is feasible for multi-object surveys with a FOBOS-like fiber IFU instrument
Wavelength Coverage	Blue optical - 2.2 microns	Ideally both broad optical and IR coverage: Full optical spectrum from UV cutoff to ~1 micron Full NIR coverage (J, H, K windows) will be essential for studying the key spectral diagnostics in higher redshift galaxies. Most of their light is concentrated into much smaller regions (a few tenths of an arcsecond) than the current MOSFIRE slitlets.
Simultaneous Bandpass	E.g. J-band or 5% bandpass in NIR	For optical spectroscopy, full simultaneous coverage from UV cutoff to 1 micron.
Number and types of science targets		Extragalactic surveys (e.g. JWST, Euclid and Roman slitless grism spectroscopy) are on the threshold of a revolution in deep identifications, identifying tens of thousands of new high-redshift galaxies in typical deep fields around the high-latitutde sky, ranging from several to tens of arcminutes.
Plate Scale and/or Spectral Resolution		Spectral resolution R~3000 minimum The discovery spectra have far too little resolution (R~50--200) to measure veclocities, or separate closely blended key diagnostic emission lines (such as OII and SII doublets for electron density, [NII]/Halpha for abundances). A minimum spectral resolution of ~100 km/sec will allow the kinematics of these high-z galaxies to be studies to be

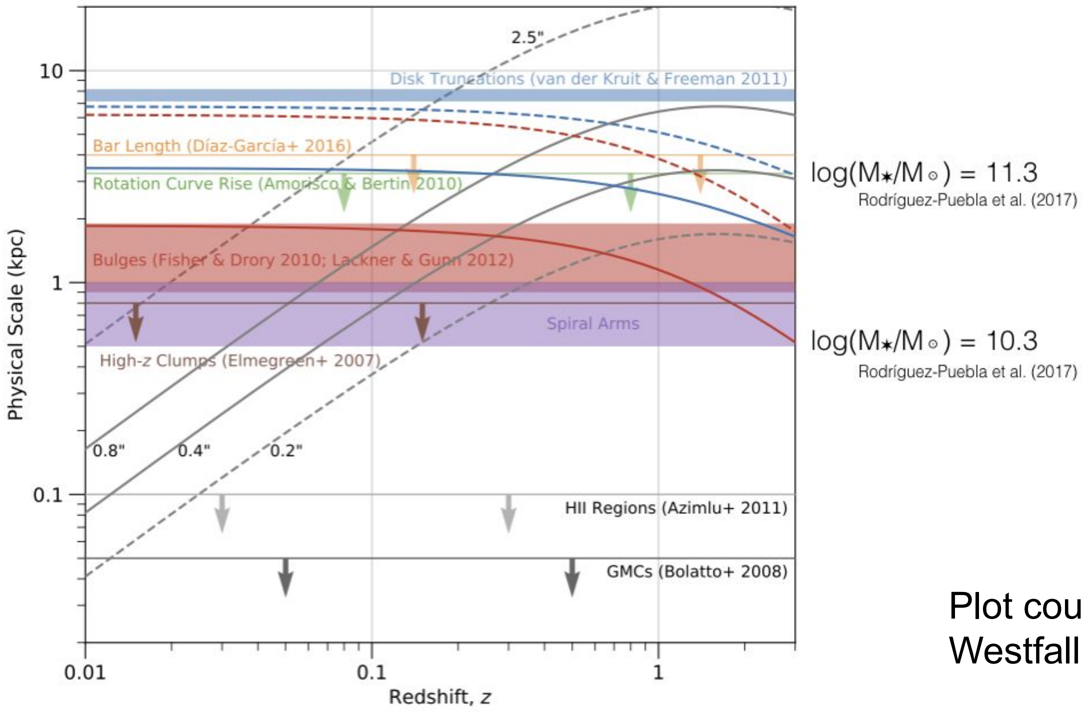
Galaxy Evolution Case [Resolved Structure Galaxies - Young Star Clusters/Globular Clusters Mergers & Quiescent]

Requirement	**VALUE**	**COMMENT/JUSTIFICATION**
Largest Acceptable FWHM	0.4” @V-band	Improve angular resolution to resolve and pick out faintest objects
PSF Uniformity	Ellipticity and/or delta-FWHM	+/-0.1” FWHM
Field of View	4’-20’	to encompass the sizes of the largest galaxies to more efficiently and fully capture the entire object
Wavelength Coverage	Blue optical - 2.2 microns	Blue wavelengths provide critical information on young populations and/or metal-poor. Reddest wavelengths for older and/or metal-rich.
Simultaneous Bandpass	Full filter (e.g. H) for spectra - wide and narrow for imaging	Full “filter” in each spectroscopic setting / imaging - one filter at a time
Number and types of science targets		Resolving Young star clusters & Globular clusters in mergers (or any galaxies). **Spectroscopic diagnostics**: age-date clusters across the entire angular size of the galaxy (map the age gradients in mergers), in non-merging systems get a proper metallicity assessment of the GC population (e.g. blue-tilt seen in ellitICals). Probe fainter levels spectroscopically. **Imaging**: wide-field imaging with FWHM 0.1”-0.3” can catalog and map the young clusters/GCs in mergers - color diagnostics to determine properties in objects too faint for spectroscopy. Use of narrow band filters to provides a “poor” spectral resolution (i.e. H-alpha, Br-gamma, etc). For ellipticals and spirals - more efficiently map the GC populations to many Reff, beyond what can be done with HST (for angular resolution) or seeing-limited wide-field images on 8-10m class telescopes (wide fields but angular resolutions >> 0.5”).
Plate Scale and/or Spectral Resolution		R~1000 min / 0.05”/pix (to make sure you are nyquist sampled at the best angular resolution (0.1”).
Photometric, Astrometric, or RV Precision (or other science metrics)		
Sensitivity (Brightness of object)	Vmag < 22	Current reasonable limits for SL spectroscopy of YSCs or GC is V~22mag. Improved PSF will allow for fainter targets to

Why is this a Keck science case in the 2035 era (vs. ELTs, etc.)?

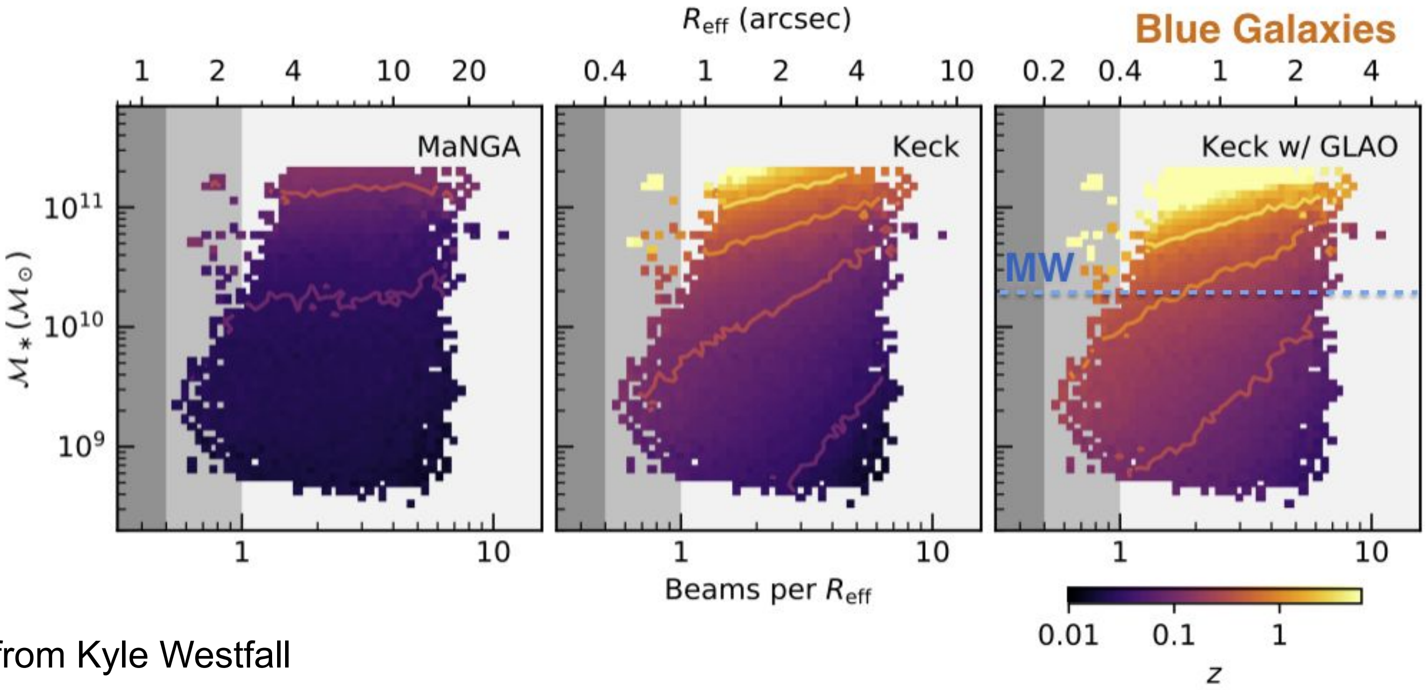
- Can follow up Roman which won't have high enough spectral resolution (see cosmology slides)
  - Also applies to JWST and Euclid
- Multiplex advantage is important for competing with ELT instrumentation (FOV).
- Survey work is complementary advantage to ELT resolution.
  - ELTs won't survey - smaller FOVs and less time available

Reference info on size, structure, mass parameter space



Plot courtesy of Kyle Westfall

Reference info on size, structure, mass parameter space



Plot from Kyle Westfall

Galactic Science Slides

Milky Way Dwarf Galaxy abundances, DM profiles (motivation, visuals, references).

Masses and stellar populations of MW dwarf galaxies

- metallicity distributions, especially for the lowest luminosity, most metal-poor dwarfs
- Identification and characterization of EMP ([Fe/H] < -3) stars
- kinematics to get velocity dispersions, velocity dispersion profiles -> DM mass, DM halo mass profiles

- LF means small gain in sensitivity = many more stars, get velocity dispersion, dispersion profile to get DM mass profile
  - factors of 2 up to an order of magnitude more targets in some dwarfs for modest sensitivity gain
  - lowest mass dwarfs have so few stars current studies are limited to sample size possible to observe with current telescopes and instruments. Know only mean RVs, really want dispersions
    - What is the smallest (lowest-mass) galaxy?
- Higher resolution on more stars to measure abundances, individual elements
  - more stars = abundance spreads -> model chemical evolution
  - bluer is better to get individual elements

Milky Way Dwarf Galaxy abundances, DM profiles

Requirement	VALUE	COMMENT/JUSTIFICATION
Largest Acceptable FWHM	0.35”	0.35” = factor of 2 better than uncorrected seeing ->, R~10,000 on DEIMOS-like spectrograph. Investigate impact on FOBOS apertures Helps selection of targets in crowded fields
PSF Uniformity	Needs to be characterizable	Characterizable: slowly varying across field (quartic?) Not very asymmetric, much less elliptical than 2-1. Detailed simulations probably needed for spectral extraction Azimuth fiber scrambling would help
Field of View	10’	10’ well suited to dwarf galaxies, larger always better (i.e., FOBOS) 5’ not competitive
Wavelength Coverage	3900 to 9000 A	Bluer for stellar pops science, Keck more competitive bluer. Pushing to 3900A critical, bluer is better. Ideal general-case performance would be seeing 0.35” over a 10’ diameter field down to 3900A RVs can use redder wavelengths (but still < 1 micron)
Simultaneous Bandpass	1000s of Angstroms	
Number and types of science targets		resolved stars, RGB and upper MS
Plate Scale and/or Spectral Resolution		R~ 10,000 and 0.35” FWHM seeing would improve capabilities over current instruments
Photometric, Astrometric, or RV Precision (or other science metrics)		<~ 1 km/s
Sensitivity (Brightness of object)	[illegible]	

M31 and satellites (motivation, visuals, references).

Spectroscopy of resolved stars in M31 and its satellites, possibly out to M81/M82

- M31 and its satellites will accessible for the same kind of resolved-star population studies as the LMC,SMC in the current era

Higher resolution = selecting targets in crowded fields, i.e. M31 clusters, dwarfs and RGB stars in the disk

M81/M82 tip-RGB stars would be a stretch goal

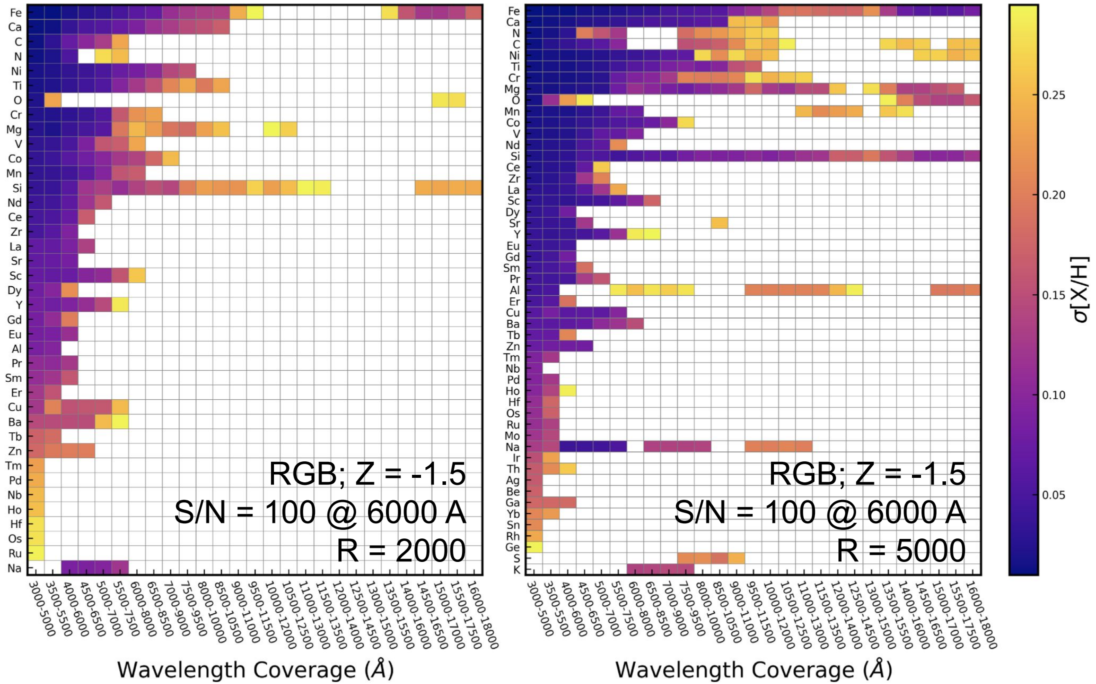
M31 and satellites

Requirement	VALUE	COMMENT/JUSTIFICATION
Largest Acceptable FWHM	0.1-0.5” (specify at what wavelength)	0.2” or better resolves RGBs in the central part of M31 disk
PSF Uniformity	Ellipticity and/or delta-FWHM	much better than 2-1 ellipticity
Field of View	2’-30’	Large as possible (M31 is many degrees)
Wavelength Coverage	3900-9000 A(?)	3900A for resolved stars in the M31 dwarfs M31 disk and bulge science is largely RGBs, so redder is likely to be the main science single-object follow-up spectra of red stars
Simultaneous Bandpass		RVs, kinematics can be in the red, abundances need blue
Number and types of science targets		
Plate Scale and/or Spectral Resolution	trade SN and resolution	Note that this is higher than FOBOS’ design. R~15,000 would be ideal.
Photometric, Astrometric, or RV Precision (or other science metrics)		few km/s in the M31 dwarfs
Sensitivity (Brightness of object)	Mag or mag/arcsec^2	

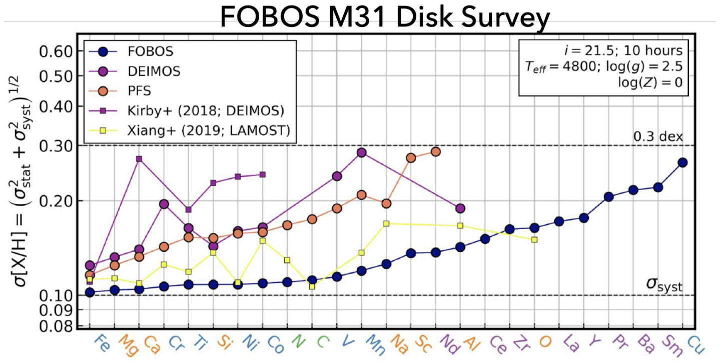
Reference Figures for Chemical Abundance Precision:

Blue spectra are rich in chemical information

Forecasted Abundance Precision vs. Wavelength Coverage



[Sandford+ (2020)]



[Bundy+ (2020)]

- Calculations do not factor in AO improvements
- Calculations assume 1D-LTE models

Why is this a Keck science case in the 2035 era (vs. ELTs, etc.)?

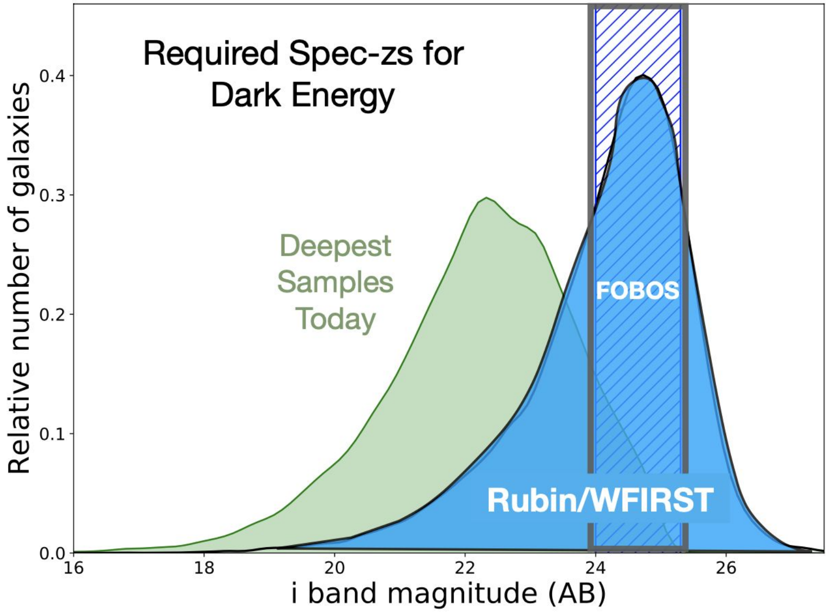
- Field of View and Multiplexing is competitive against ELT's
- Spectra are interesting as complement to space missions
- Imaging is less compelling because of space missions
- Access to blue with multiplexing capabilities can be unique
- [what are blue ELT capabilities?] - WFOS
- E-ELT blue capability should be compared - E-ELT (HIRES, MOSAIC) only down to ~400-450nm?

Cosmology Slides

Constraints on dark energy and galaxy evolution from deep spec-z datasets enabled by GLAO/FOBOS

- Keck can support extremely expensive dark energy missions such as Rubin/Roman in a way no other facility can or will
  - Adds spec-z data needed to ensure robust redshift calibration for dark energy inference from weak lensing
  - Provides a spectroscopic “Rosetta stone” to understand galaxy properties as a function of observed photometry over the full sky
- Deep spec-z training samples (C3R2) currently incomplete at i~24 AB.
  - Unlikely to change by 2035 (Only contenders PFS/MSE etc. but unclear they can achieve depth)
- Rubin/Roman main sample depth peaks at i~25.2 AB
- Factor of 2x in seeing enabled by GLAO + 10m vs. 8m gives Keck a two magnitude advantage for fixed exposure time
- Similar number of fibers but PFS has larger FOV
  - However, FOBOS can use all fibers on galaxies at this depth
- Uniquely deep and complete spectroscopic dataset with FOBOS/GLAO would enable a large range of additional TBD science

Mismatch between current deep spec-z and upcoming imaging surveys



From FOBOS Snowmass LOI

Supporting Rubin/Roman

Requirement	**VALUE**	**COMMENT/JUSTIFICATION**
Largest Acceptable FWHM	0.3'' at 0.4 micron	This is for enhanced sensitivity at Ly-alpha for z~1.5-2 galaxies (big fraction of photometric samples)
PSF Uniformity	<10% non-uniformity	Uniformity needed for keeping maximum light in the fiber. PSF temporal stability is relevant here as well. Overall total ability to gather light from objects across the field of view is the critical item here.
Field of View	20'	Large enough field to select sources carefully - 20' diameter is plenty for source density of ~40/sq arcmin (Rubin)
Wavelength Coverage	0.35 - 2 micron	Ideally longer wavelength coverage as well for sensitivity to rest-frame optical lines, useful for galaxy properties
Simultaneous Bandpass	TBD	
Number and types of science targets	~1e5 faint galaxies	Multiple deep pointings spread across range of R.A. / galactic reddening, ~1.5k galaxies per pointing
Plate Scale and/or Spectral Resolution	R~2000	Sufficient for precision redshifts from emission lines (~5e-4).
Photometric, Astrometric, or RV Precision (or other science metrics)	N/A	
Sensitivity (Brightness of object)	25.5 AB in i band	Matched to Rubin full survey depth

Why is this a Keck science case in the 2035 era (vs. ELTs, etc.)?

- ELTs will not be survey instruments
- Same for JWST
- Space-based telescopes like Roman have grism spectroscopy, but lack the depth, spectral resolution, and wavelength coverage to meet this need
- Keck dataset could be uniquely powerful as an anchor for many different science areas
- Positions Keck well for the ELT era
  - It becomes the spectroscopic survey instrument
  - Can identify the most interesting objects in Rubin/Roman for follow-up with other instrumentation
  - Observations could be coordinated with most interesting sources discovered in Rubin/Roman

Exoplanets and Solar System Slides

Expand the number of exoplanet systems accessible for RV study at Keck

The majority of exoplanets are those of the lowest masses, currently the frontier is the super-Earth/sub-Neptune regime. Bulk densities, which require masses and radii, are the key measurement for understanding their composition, but masses are a critical component of atmospheric modeling. By 2035, we want to be able to measure the masses of super-Earth and even sub-Earth mass objects around nearby (~100 pc) stars.

To realize this science goal we must improve how quickly and how precisely measures the RV of planet-hosting stars by improving the stability and throughput of KPF.

- Without decreasing transmission (no extra optics) we want to tighten the PSF onto the KPF fiber - smaller (0.1”) images mean removing reformatting stage
- This should also improve the line spread function stability, possibly giving a better RV precision.
- This should decrease the integration time needed for each observation - this helps stellar activity and so increases the precision.
- M dwarfs in particular, will benefit from fainter limiting magnitude as M dwarfs are faint at 100 pc!

Simultaneous HiSPEC and KPF observations will also be critical for mitigating stellar activity (the sun shows a 4 m/s signal) as stars are chromatic but exoplanet caused RVs are not.

More efficient and precise RV observations

Requirement	VALUE	COMMENT/JUSTIFICATION
Largest Acceptable FWHM	0.3”	Want better fiber throughput
PSF Uniformity	Stable over time	Temporal Stability is important. Can translate to more stable RV’s
Field of View	tiny	N/A
Wavelength Coverage	0.5-0.9 um	KPF spectral range
Simultaneous Bandpass	0.5-0.9 um	
Number and types of science targets	Want this for all KPF targets.	TESS v~10-11. Kepler would be V~13
Plate Scale and/or Spectral Resolution	R~100,000	
Photometric, Astrometric, or RV Precision (or other science metrics)	10 cm/s	30 cm/s is the current goal
Sensitivity (Brightness of object)	V=10-13	

Why is this a Keck science case in the 2035 era (vs. ELTs, etc.)?

Cadence is important for RV observations
Baseline will also be useful
ELT’s will likely focus on short period as “low hanging”

Multiple RV facilities improve instrumental systematic problems.

Visible to infrared Asteroid and KBO Characterization (Improving the stability and throughput of NIRES)

The composition of an asteroid from reflectance spectra we need 0.5-3 um coverage.
(NIRES would be 0.9-2.4 um)
Going fainter and more stable PSF helps.
m=21-22, we would be able to characterize a fair number of these objects
(currently there are <10 objects KB dwarf planets that can be reached)

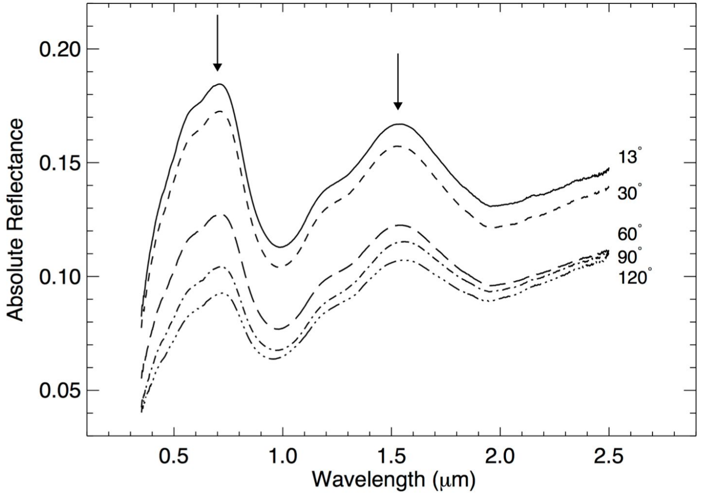


Figure from Reddy et al. (2015)

Visible to infrared low spec. res. Asteroid and Dwarf Planet Characterization

Requirement	VALUE	COMMENT/JUSTIFICATION
Largest Acceptable FWHM	Any improvement helps.	This is really an O/IR science driver.
PSF Uniformity	N/A	
Field of View	Single object	
Wavelength Coverage	0.5-3.3 um	
Simultaneous Bandpass		Important, because objects rotate
Number and types of science targets	Dozens are intriguing.	Numbers increase dramatically beyond m>20 for Dwarf Planets
Plate Scale and/or Spectral Resolution	R~50 is sufficient for seeing vibrational bands.	
Photometric, Astrometric, or RV Precision (or other science metrics)		
Sensitivity (Brightness of object)	Need spectra for V=19-23 objects for comparative planetology	

Why is this a Keck science case in the 2035 era (vs. ELTs, etc.)?

- Non-siderial tracking with ELT’s may not be a priority
- Thermal IR (volcanoes on Io - asteroid minerology) will be competitive until METIS/PSI-Red. Also time-variable so not easy to do with ELT regularly.

Other Ideas

RV’s for very distant star-hosting planets for comparing environments (for example, Andromeda)
RV’s of dwarf planets for satellites
Volcanoes on exoplanets
Tomography of exoplanets
Rings around exoplanets

Enhanced Seeing Science Summary

General comment about seeing improvement science (Claire)

- Our dirty little secret: Much of our data is not used in publications because the seeing was too bad.
- Even if all wide-field AO does is to turn the bottom half of the seeing distribution into median seeing, it could be ~ a factor of two improvement in science output from MWKO
- From a science point of view, this is like waving a magic wand and making our two telescopes into four telescopes (!)
- <u>Let's not forget this</u>
    - It would be worth looking into some statistics for MK seeing and ground layer strength

Technical Requirements

1. **Resolution (FWHM, PSF shape)**
- GalEvol: Drivers: sensitivity gain over seeing limited, resolving structure/objects - better than nominal seeing conditions.
- MW: factor of x2 better than seeing limited to gain in resolution and resolve crowded fields, ~0.35”, M31: < 0.2” to resolve central regions, resolving crowded fields.
- Cos/LLS: want sensitivity gains over PFS/Subaru, 0.3” at 0.4um, temporal stability of PSF
- Exoplanets/SS: <0.3” (fiber throughput) - sensitivity gain, <0.1” would increase TP of instrument (no reformatting)

2. **Uniformity (time, field)**
- MW/M31: ellipticities<< 2:1, “characterizable”
- Cos/LLS: 10% non-uniformity - discussion (Matt/Dan) could deal with worse
- Exo/SS: temporal stability is important

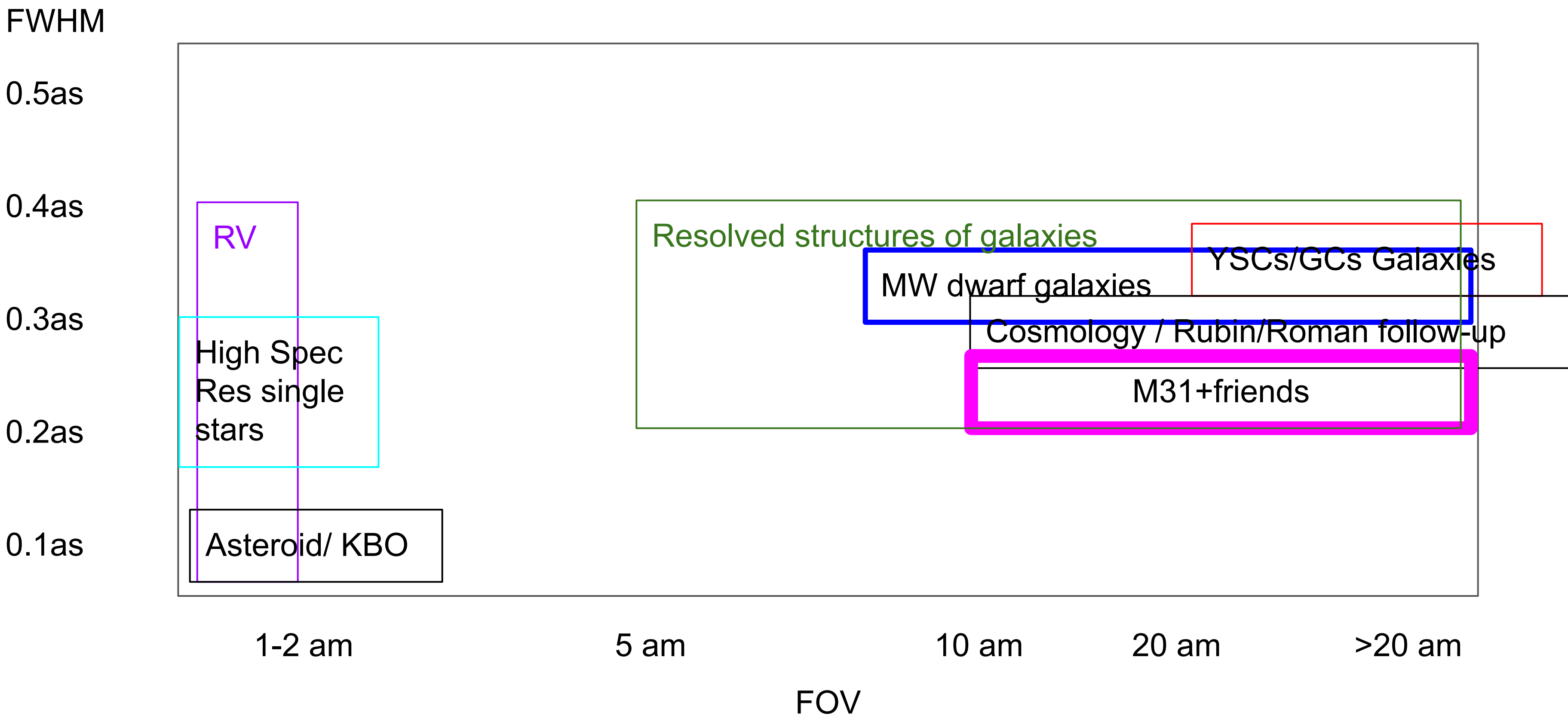
3. **Field of view**
- GalEvol: 8am to 20am
- MW: 10’ matched to nearby dwarf galaxies. 5’ is NOT competitive. M31: as large as possible 30’
- Cos/LLS: 20am is large enough
- Exo/SS: RV: tiny

4. **Wavelength coverage (resolution, field, simultaneous bandpass/spectral resolution)**
- GalEvol: Blue visible to NIR (JHK)
- MW: At least down to 390nm but bluer is better. RVs up to 1micron, M31 390-out to 900nm
- Cos/LLS: 0.35-2 um
- Exo/SS: 0.5-0.9um, Asteroid/dwarf planet out to 3.3um

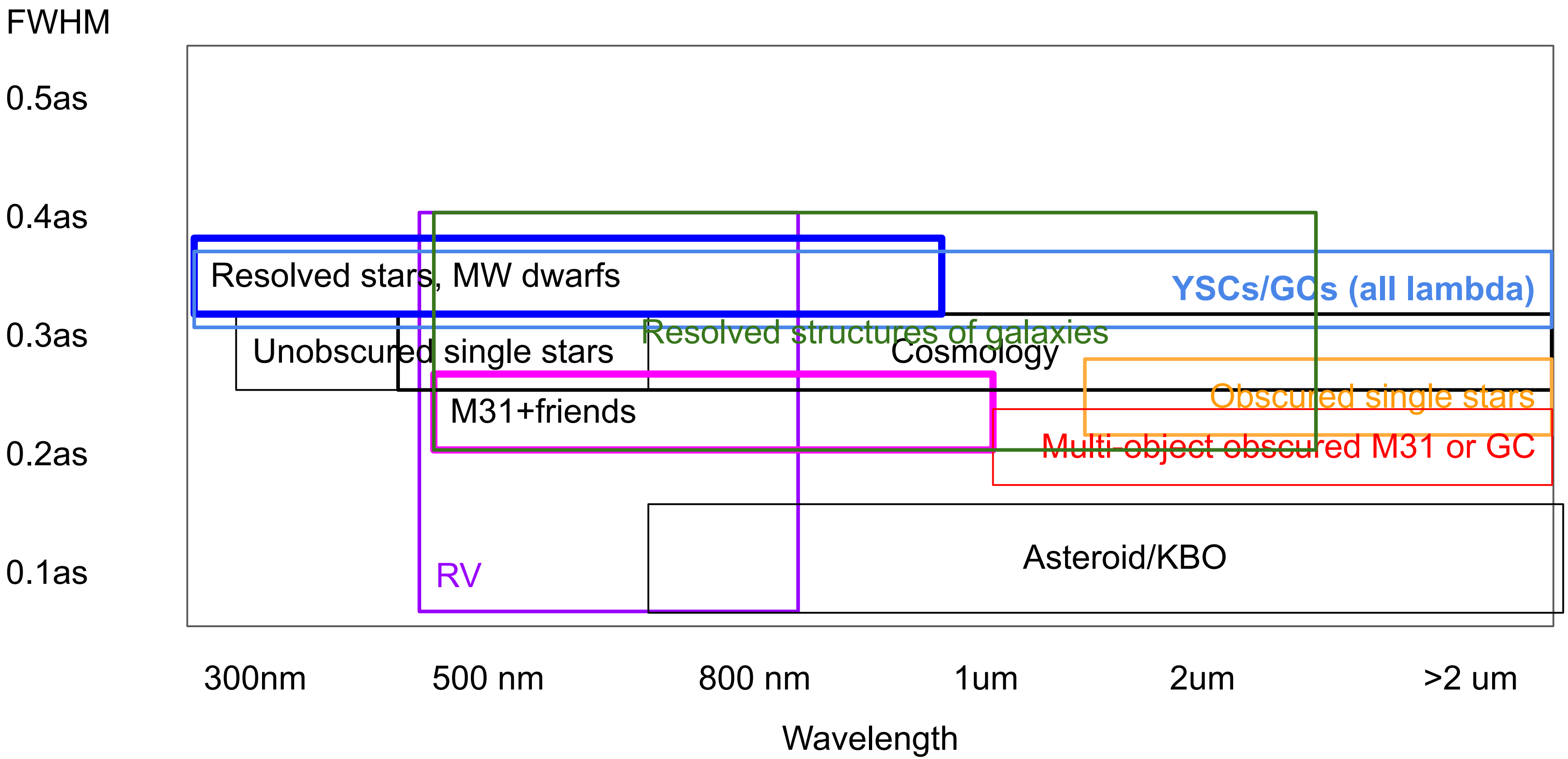
5. **Science target (number, density, brightnesses)**
- GalEvol: 100s to 1000s
- Cos/LLS: survey toRubin depth so 10k faint objects to get large enough sample
- Dwarf planets - dozens

6. **Photometric, astrometric, or RV precision, or other science metric**
- GalEvol: SpecRes of R>3000 for dynamics, line diagnostics, and metallicities (synergy with future space missions), multiple IFUs to exploit the spatial resolution.
- MW: Resolutions <~ 1km/s, R~10k, M31: few km/s - Discussion of higher R, NIR enabled by the sensitivity gains (FOBOS high res)
- Cos/LLS: R~2000
- Exo/SS: R~100,000 (10cm/s), Asteroid R~50

Resolution v. Field



Resolution v. Wavelength



VLT GLAO performance (at 2 different airmasses)

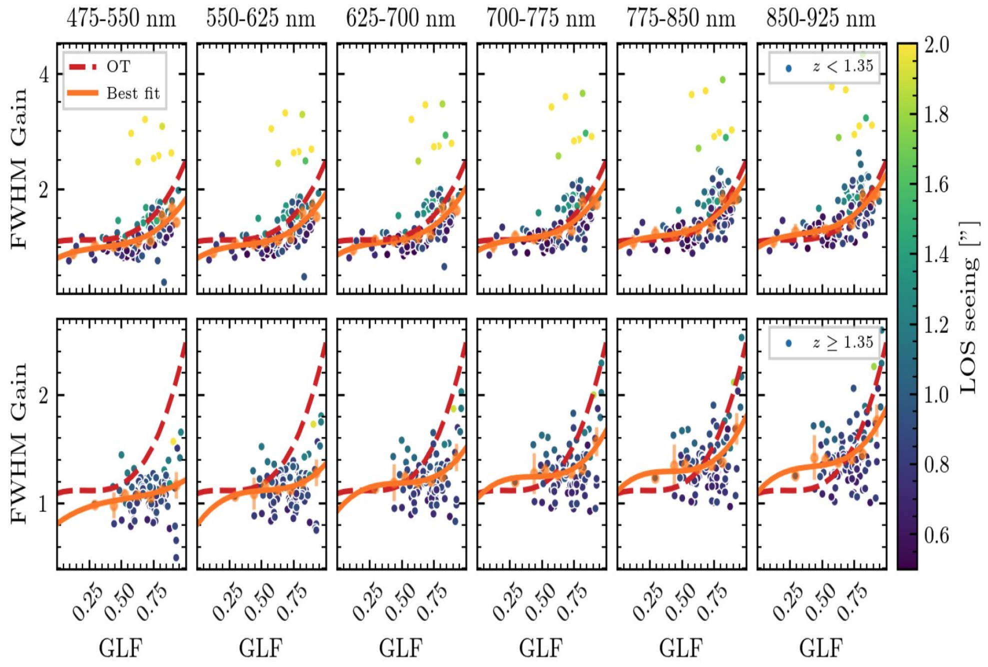
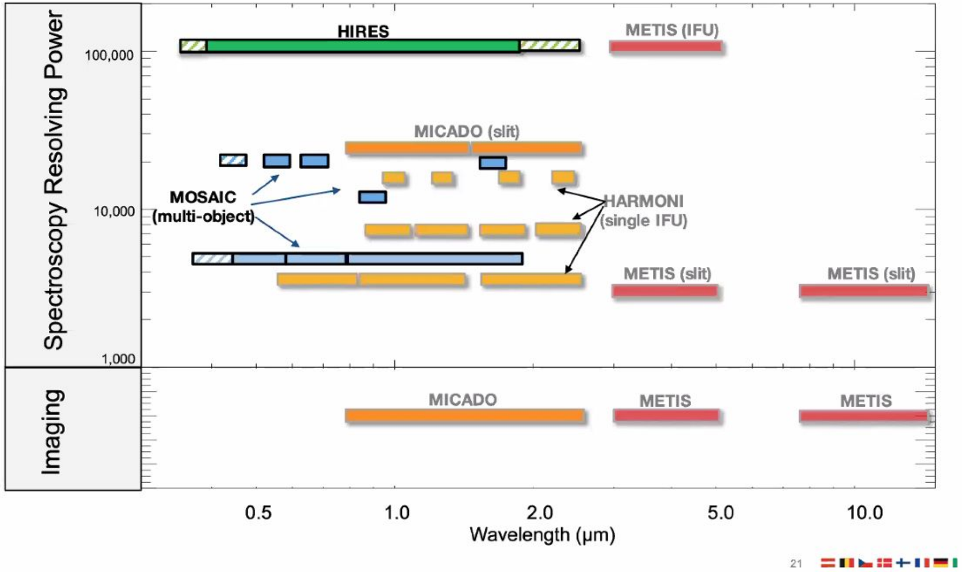


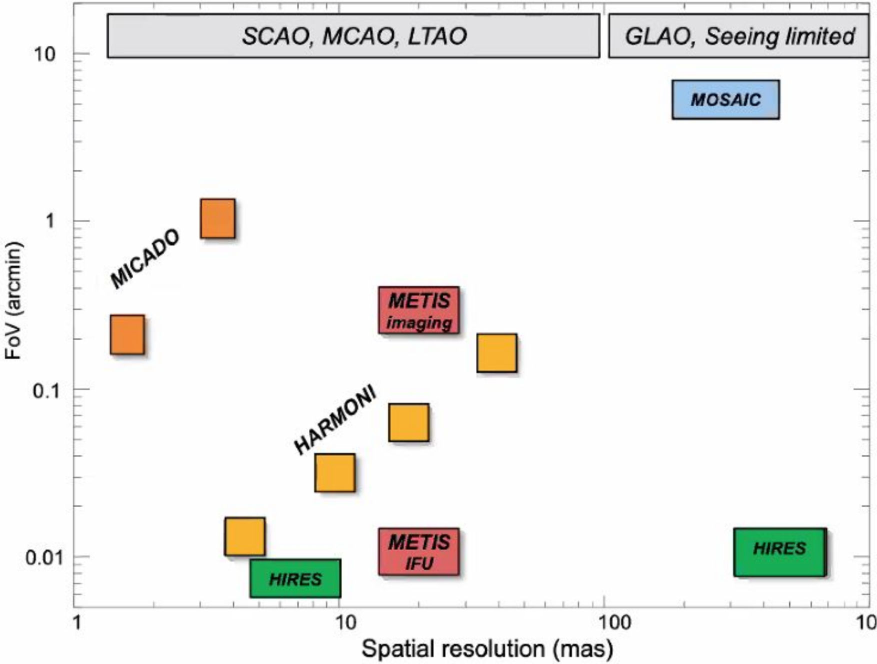
Figure 9. Gain in image quality as function of GLF in six wavelength bins for low- ($z < 1.35$, top row) and high-airmass ($z \geq 1.35$, bottom row) observations. The colour-coding is the same as in Fig. 7. The dashed red line corresponds to the predicted gain that is used in the ETC and OT in operations, while the orange line is a polynomial fit to the binned data in each wavelength slice.

- Horizontal axis: ground layer fraction
- Vertical axis: gain factor in FWHM
- Yellow and green points: worst seeing
- Dark blue points: best seeing
- Solid orange line: best fit
- Note significant gain in worst seeing even at 500 nm

Hartke et al. 2020 (I think)

ELT Capabilities





From the ELT workshop's overview talk
https://elt2020.web.ox.ac.uk/programme

Goals for 2035

Be the most efficient facility (most usable nights, best PSF, best scheduling, broadest spectral coverage for RV)

Large surveys

Focus on large multiplexing capability (like FOBOS)

Go blue, have higher spectral resolution, with wider field, since these are hard for ELT’s

Define synoptic and/or large time need type programs.

Use Roman/Rubin or other facilities as leverage for Keck observations. Observe with spectral resolutions and wavelength ranges that are complementary to those on Roman, JWST