Keck Science Strategic Planning 2035

Keck AO Future Study Group Recommendations

P. Wizinowich & M. Fitzgerald
Keck SSC – Nov. 11, 2021

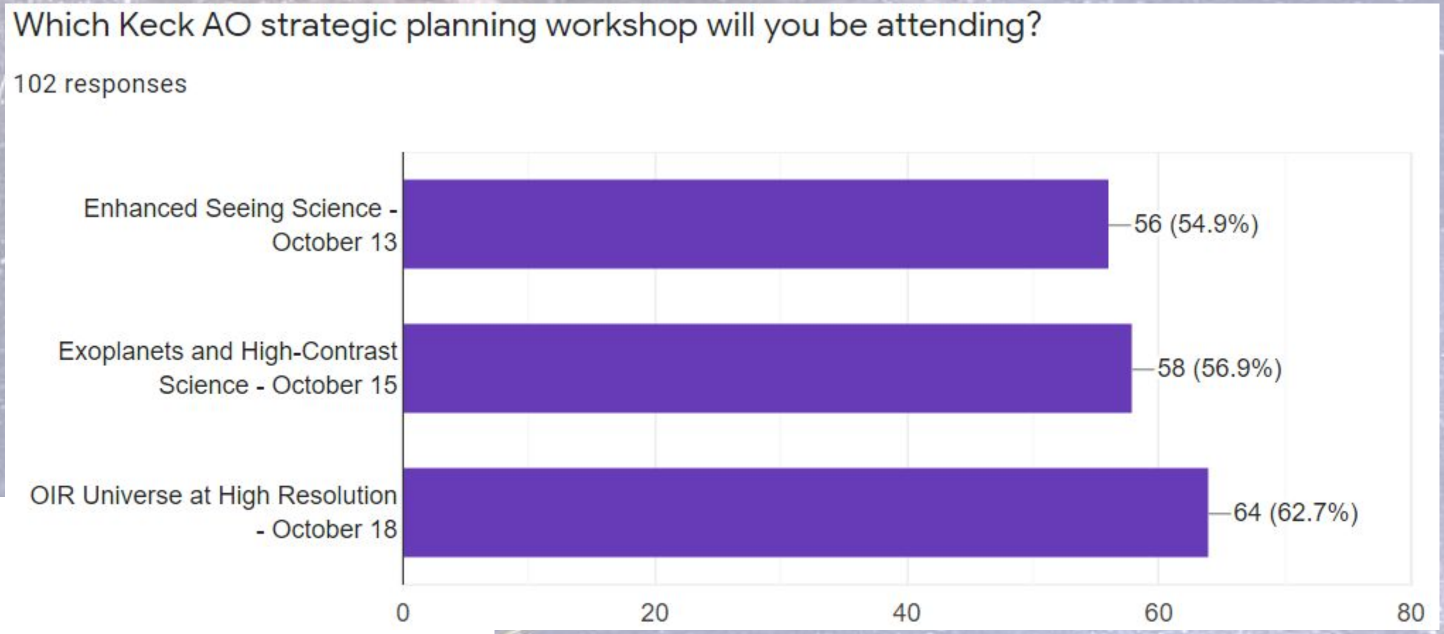
Keck AO Workshops

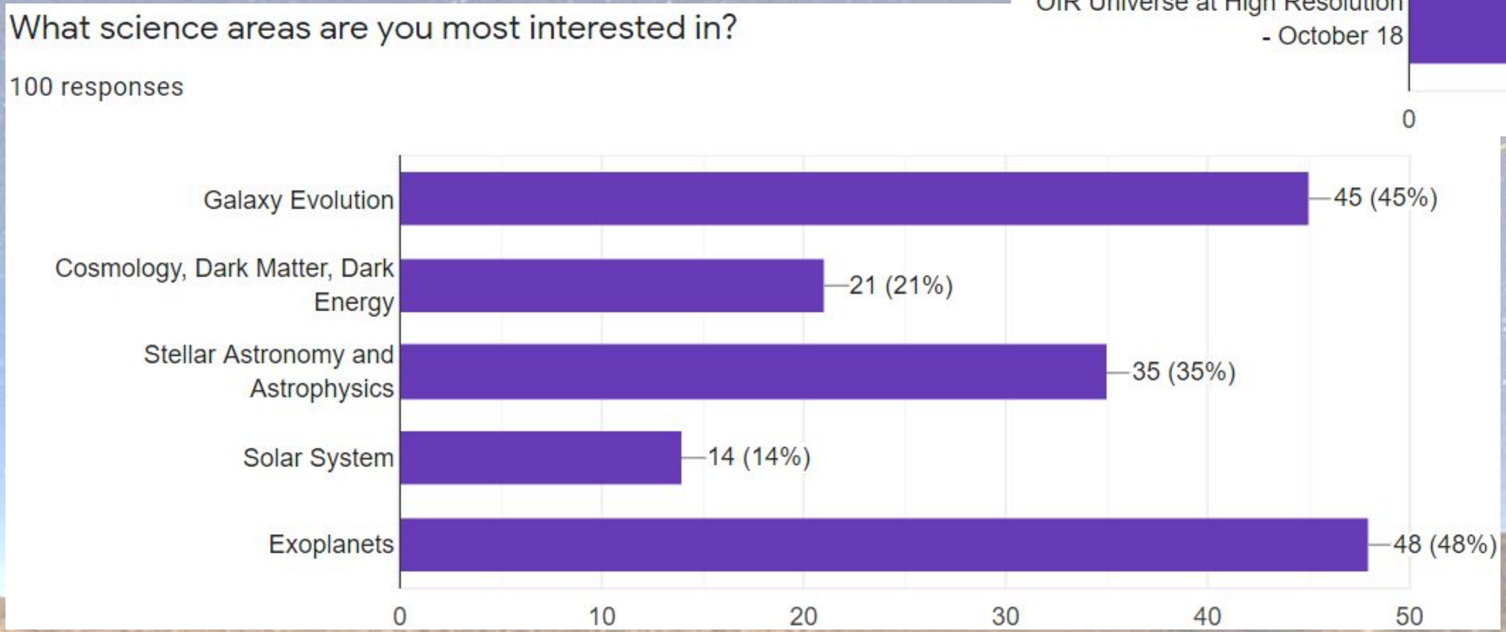
Recommendations are the product of FSG discussion & three FSG-hosted community workshops:

- Enhanced seeing-limited science
- Exoplanet & high contrast science
- OIR Universe at high angular resolution

FSG Membership: Mark Chun (UH), Chris Fassnacht (UCD), Mike Fitzgerald (UCLA, co-chair), Becky Jensen-Clem (UCSC), Katherine de Kleer (CIT), Mike Liu (UH), Jessica Lu (UCB), Jim Lyke (WMKO), Dimitri Mawet (CIT), Peter Wizinowich (WMKO, co-chair), Shelley Wright (UCSD)
Ex-officio: Phil Hinz (UCSC), Sam Ragland (WMKO)

Workshop Registrants



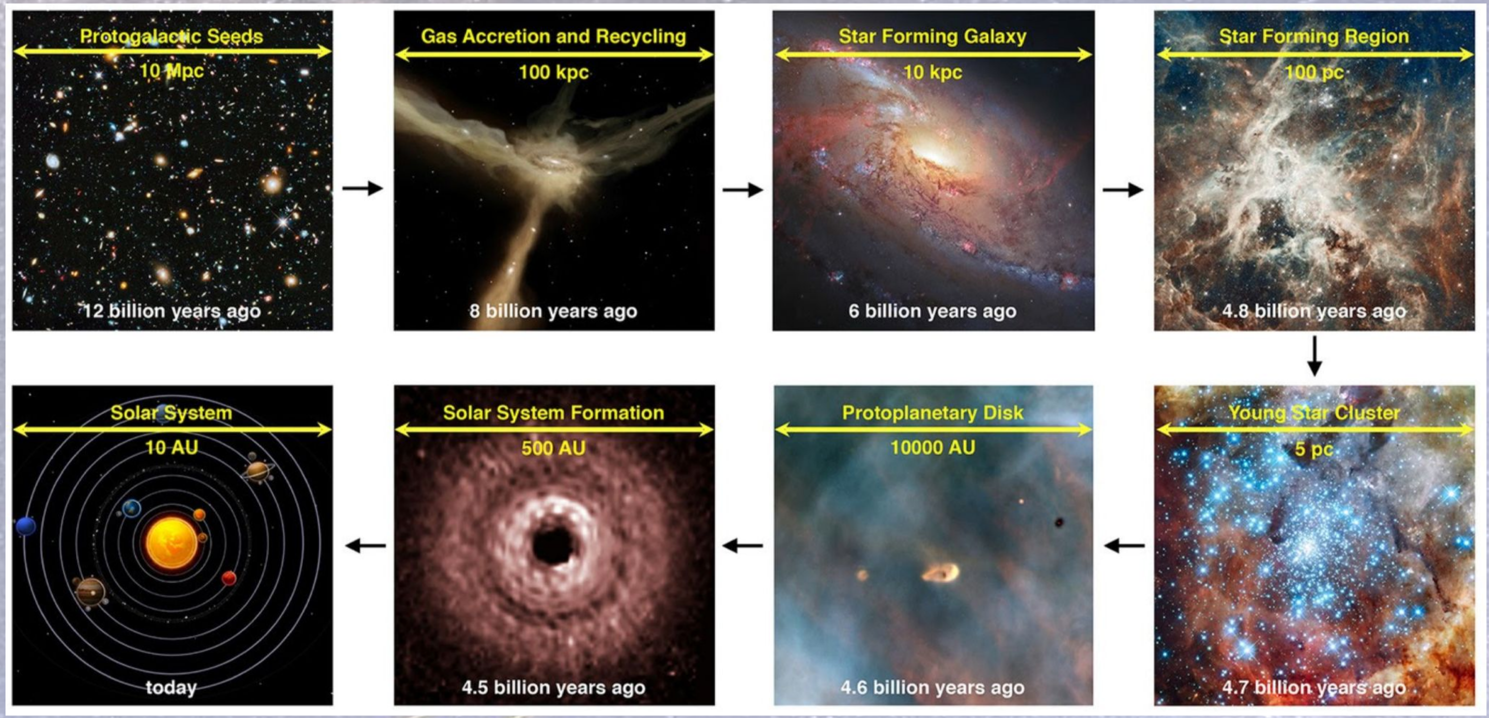


In general ~30 participants in each workshop

Workshop Products

- Products:
  - Summary report with key findings & recommendations
    - White paper (in development for pre-Dec. 1 delivery)
    - This presentation
  - Set of template slides for each science case
    - Enhanced seeing, Exoplanets & high contrast, OIR Universe
  - AO context documents for each workshop
    - Enhanced seeing, Exoplanets & high contrast, OIR Universe

AO Science Landscape in 2035



Known Unknowns:

- dark matter
- dark energy
- compact objects (origins, evolution, populations)
- fundamental physics (gravity, equations of state of dense matter)
- Solar system (habitability of planets and moons, small bodies)
- exoplanets (habitability, formation, populations)

AO Science Landscape in 2035

Unknown Unknowns:

- expanding the gravitational wave window will lead to…
- massive increase in time-domain imaging data will lead to…
- increase in time-domain spectroscopic data will lead to…
- 3-5x improvement in spatial resolution will lead to…

Current & Near-Term Keck AO

Telescope	AO Sys.	Instrument	Type	AO	λ	Details
Keck I	K1AO	OSIRIS	SCAO	N/LGS	0.95-2.4	R=3k; 0.3x1.3" at 20mas to 4.8x6.4"at 100mas
						20x20" at 10 mas
	+KAPA (2024)	Liger (2027)	LTAO	4 LGS	0.8-2.4	R=4-10k; 1.9x1.9" at 14mas to 13x7" at 150mas
						20x20" at 10 mas
Keck II	K2AO	NIRC2	SCAO	N/LGS	0.95-5	10x10" at 10 mas to 40x40" at 40 mas; vortex; SAM
		NIRSPEC			0.95-5.5	R=35k slit
		KPIC+NIRSPEC			2-3.5	Single mode fiber fed; R=35k
		FVC (2022)			0.5-0.95	10" diameter at 6.7 mas. Up to 750 frames/sec
		SCALES (2025)			2-5	R=35-250, 2.15x2.15" at 20mas. R=3-7k, 0.36x0.36" at 20 mas
					1-5	20x20" at 10 mas
	+KPIC2 (2022)	KPIC+NIRSPEC			1.5-3.5	Single mode fiber fed; R=35k
		HISPEC (2025)			0.95-2.5	Single mode fiber fed; R=100k
	+HAKA (2026)	all above			0.5-5	64x64 actuator DM to replace 20x20 DM
		KPIC2+KPF			0.45-0.87	Single mode fiber fed.
		Vis IFS			0.5-1	Under study assuming HAKA funded

Not funded

Operational	Planned

AO Landscape

Telescope	AO Sys.	Instrument	Type	AO	λ	Details
Gemini-N	Altair	NIRI	SCAO	N/LGS	1-5	22x22" at 22 mas; 51x51" at 50 mas
		GNIRS			0.8-5.4	R=1.2-18k slit
		NIFS			0.95-2.4	R=5-6k; 3x3" at 100x40mas
	GNAO (2028)	GIRMOS	GLAO+MOAO	4 LGS	0.95-2.4	4 MOS, R=3-8k, 1x1" at 25 mas to 4x4" at 100 mas
			LTAO			85x85" at 21 mas
	GPI 2.0 (2022)	IFS	ExAO	NGS	0.95-2.4	R=10 & 40 IFU, 2.4x2.4" at 14 mas
		Polarimeter				Dual channel polarimeter
Gemini-S	GeMS	GSAOI	MCAO	5 LGS	0.9-2.4	85x85" at 20mas
LBT	LBTI	LMIRCam	Single tel AO	NGS	1-5	11x11" at 11mas
			Dual tel AO			
	FLAO to SOUL	LUCI	SCAO		0.9-2.4	30x30" at 15mas
			ESM			4x4' at 0.12". Partial (11 mode) correction; Multi slit R=2-8.5k
	ARGOS		GLAO	3xRLGS		4x4' at 0.12". NIR imaging/multi-slit R=2-8.5k
Magellan	MagAO	VisAO	ExAO	NGS	0.6-1.05	8.2x8.2" at 8mas
		CLIO			1-5.3	8x16" at 16mas or 14x28" at 27 mas
	MagAOX (2022)	EMCCD	ExAO	NGS	0.5-1	Dual-EMCCD SDI
		VIS-X				IFS
Palomar	PALM-3000	PHARO	ExAO	NGS	1-2.5	1024x1024pix at 25 or 40mas/pix. R=1.5k slit + grism
		PARVI			1.2-1.8	High contrast, high dispersion (R=100k) RV spectrograph
	SIGHT (2023)	NGPS	Enhanced Seeing	1 RLGS	0.36-2.5	Next Gen Palomar slit Spectrograph; R=4.6k. Narrow-field seeing improvement (BMC 648 actuator); no tip/tilt star.

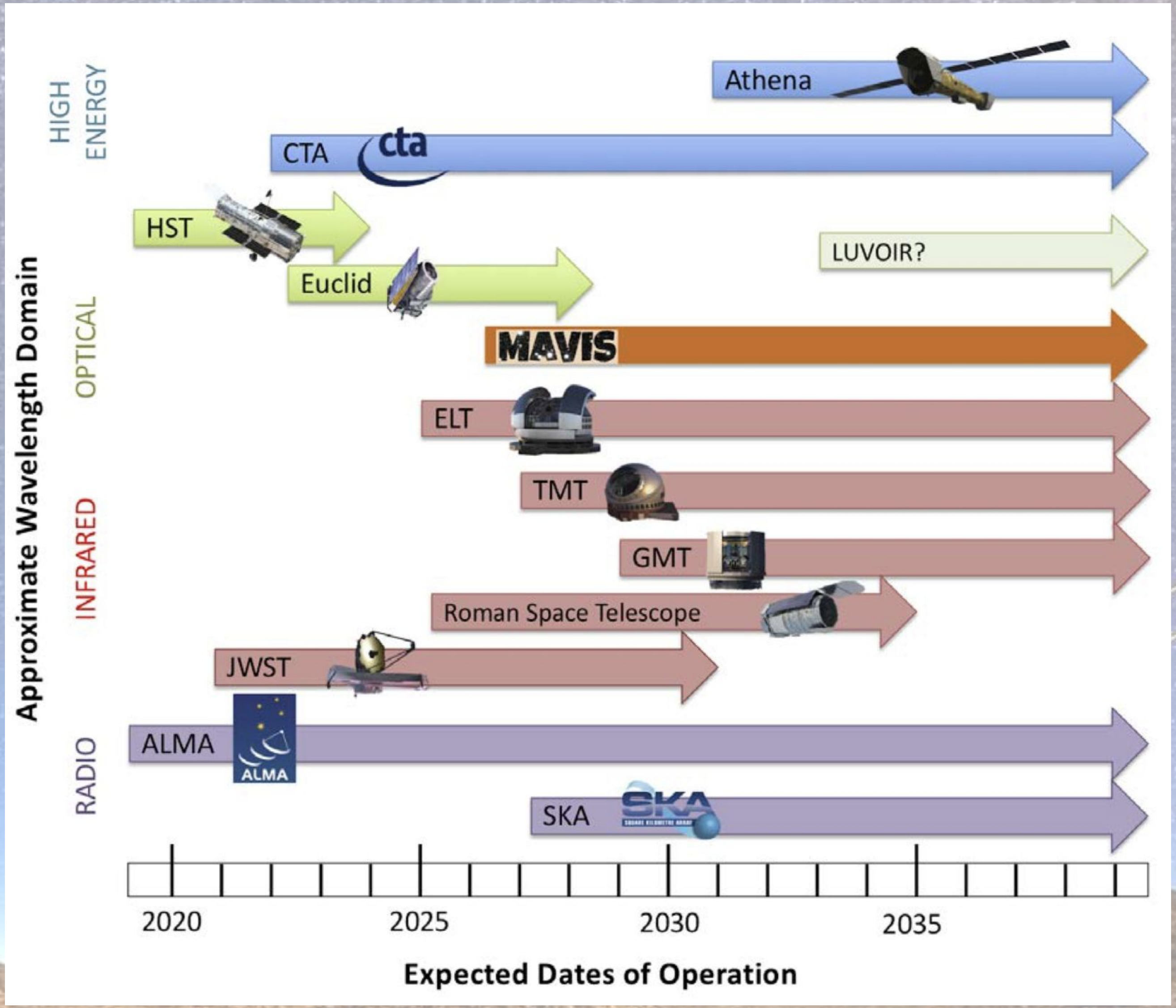
AO Landscape

Telescope	AO Sys.	Instrument	Type	AO	λ	Details
Subaru	AO188	IRCS	SCAO	N/LGS	1-5	Imager 21x21" at 20mas
						Spectrograph R=5-20k; ≥0.15" slit
		IRD			0.97-1.75	MM fibers; R=100k
	AO188 + SCExAO		ExAO	NGS		7 SM fiber in a hexagon; R=100k
		CHARIS			1.1-2.4	IFS R=19-90, 2x2" at 16 mas; spectro-polarimeter mode
		VAMPIRES			0.6-0.8	Aperture mask polarimetric imager. 0.5" at 10mas
	ULT-START		LTAO	4 LGS		Replaces AO-188 with a ALPAO 64x64 DM
	ULTIMATE (2027)	MOIRCS	GLAO	4 LGS	0.9-2.5	Imager 4x7' at 0.12"
						MOS 0.5-3k, 40-60 slits
		WFI				14x14' at 0.1"
		IFS			0.9-1.8	8-13 IFUs; R=0.5-3k; 1.2x1.2" at 0.15"
VLT (UT3)	SPHERE	IFS	ExAO	NGS	0.95-1.65	R=30-50
		IRDIS			0.95-2.32	Classical, dual-band or dual-polariz imager; R=50-350 slit
		ZIMPOL			V-I	Imaging polarimeter
	MACAO	CRIRES+	SCAO	NGS	0.95-5.3	R=40k (0.4" slit) or 80k (0.2" slit)
VLT (UT4)	GALACSI	MUSE IFUs	GLAO	4 LGS	0.48-0.93	60x60" at 0.2"; R=1.8-3.6k; 2x EE gain in 0.2"
			LTAO			7.4x7.4" at 25 mas; R=1.7-3.5k; 1-10% EE in 25 mas
	GRAAL	HAWK-I	GLAO	4 LGS	Y-K	7.5x7.5" at 100mas
	ERIS (2023)	NIX Imager	SCAO		J-M	Coronagraph; SAM; R=900 long slit
		SPIFFIER IFS			J-K	R=5-10k; 25, 100, 250 mas spaxel
	MAVIS (2027)	Imager	MCAO	8 LGS; 3 NGS	V-I	4x4k; 7.3 mas
		MOS			0.37-1	R=5-15k; 3x3" at 25 mas; 6x6" at 50 mas
VLTI	MACAO	GRAVITY	SCAO	NGS	2-2.4	Interferometric imaging & astrometry
	GRAVITY+			N/LGS		

ELTs & Space

Telescope	AO Sys.	Instrument	Type	AO	λ	Details
ELT	HARMONI	IFS	SCAO-LTAO	8 LGS	0.47-2.45	R=3-17k; 0.8x0.6" at 4mas; 6x9" at 30x60mas
	MAORY	MICADO	SCAO+MCAO		0.8-2.45	50x50' 4 mas; 19x19' 1.5 mas; R=20k slit
	METIS	Spectro-imager	SCAO		3-13	10x10" at 5 mas; R=0.4-1.9k slit
						R=100k IFS, 0.6x0.9" at 8mas
GMT	AO	GMACS	GLAO/ASM	6 LGS	0.33-1	7'x6' MOS, R=1k-6k. MANIFEST fiber feed.
		GMTIFS	LTAO		0.9-2.5	R=5-10k IFS; 0.5x0.25" at 6mas to 4x2" at 50mas
						20x20" at 5 mas imager
		GMTNIRS	LTAO		1-5	R=50-100k echelle
TMT	NFIRAOS	IRIS	MCAO	6 LGS	0.84-2.4	34x34" at 4mas
						R=4-10k; 0.5x0.5" at 4mas to 2.3x4.4" at 50mas
		MODHIS			0.95-2.4	Single mode fiber fed; R=100k; 6 to 15 mas
JWST (2022)	NIRCam				0.6-2.3	2x 132x132" fields at 31mas (FWHM 2pix at 2um)
					2.4-5	2x 129x129" at 63mas (FWHM 2pix at 4um)
						R=1.6k at 4um with 63mas
	NIRISS				0.6-5	R=150-700. 133x133" wide field.
					0.8-5	133x133" at 65mas (FWHM 2pix at 3.4um)
	NIRSpec				0.6-5.3	R=0.1-2.7k; 100mas pix; IFS 3x3"
	MIRI				5.6-26	74x113" at 110mas
NGRT (2027)	WFI				0.48-2.0	Imaging 45x23' at 0.11"
					0.75-1.93	Slitless spectroscopy 45x23' at 0.11" R=70-865
	Coronagraph				0.5-0.8	0.15 to 0.66 working angle; R~50

Beyond AO: Capabilities in 2035



Others:

LISA,

Lynx,

Origins, HabEx

ngVLT

Rubin

UltraSAT (UV all-sky)

SPHERE-X

Enhanced Seeing Science Cases

- Science case templates produced for:
  - Galaxy evolution (nearby AGN, mergers, outflows, inflows)
  - Milky Way Dwarf Galaxy abundances & dark matter profiles
  - M31 & satellites
  - Constraints on dark energy & galaxy evolution from deep spec-z datasets enabled by GLAO/FOBOS
  - Supporting Rubin/Roman
  - Expand exoplanet systems accessible for Keck RV study
  - Visible to IR asteroid & KBO characterization (with NIRES)

Key Findings: Enhanced Seeing Science

- 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)
- Broad range of wavelength coverage interest.
  - Go blue, have higher spectral resolution, with wider field, since these are hard for ELT's
  - Optical GLAO could be a differentiating feature compared to Subaru-ULTIMATE
- Many science cases desire the widest field correctable on Keck (20', if possible).
  - Could be a differentiating feature from VLT/AOF/MUSE
- 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

Exoplanets & High Contrast Science Cases

- Science case templates produced for:
  - EPRV discovery for Earth-analogs around Solar-type stars
  - Direct characterization of planets from transits & combined light
  - Follow-up of Roman microlensing events
  - Spectroscopy of exoplanets (0.1<sma<10au) with interferometry
  - Galaxy morphology & merger histories for Galaxies with bright, compact cores
  - Towards smaller planets – high contrast in the visible/NIR
  - Characterization of astrometrically identified exoplanets

Key Findings: Exoplanents & High Contrast

- Strawman configuration of capabilities & instruments in 2035
  - AO-fed EPRV spectroscopy
  - High-performance optical AO
  - Keck playing a role in technology development
  - Instrumentation:
    - Core facility: Moderate FoV, low-R IFU 2-5 μm (SCALES; GAIA follow-up)
    - Fiber-coupling capability

Key Findings: Exoplanents & High Contrast

- Visible wavelength AO (especially in the post-HST era) will enable new science
  - Wavelength coverage & smaller IWA are both compelling
- Keck can play a unique role for both transit spectroscopy and EPRV with AO-coupled red-optical high-R (>~200k) spectrometer
  - Leverage Keck's robust AO; ELTs unlikely to have many cadence programs
- High performance LGS AO will enable both faint *Gaia* follow-up & non-exoplanet cases
- Take a fresh look at interferometry at Keck & Maunakea
- Keck should play a unique role as a technology development platform
  - Opportunities to demonstrate technology required for ELTs & space-based high contrast imaging
- Consider how sky-time can be made available for technology development, while acknowledging tension between engineering & science needs
  - Achieving ambitious high contrast science goals with the TMT requires ambitious technology development at Keck, e.g. 100X contrast improvements by 2030s
- ASM can help in 3-5 μm regime.
  - Some value through increased efficiency. Take advantage of its existence.

OIR Universe Science Cases

- Science case templates produced for:
  - SMBH mergers in the era of NANOGrave & LISA
  - Studying high-z star formation & AGN feedback on galaxy evolution
  - Dark matter mass function determination via gravitational imaging
  - Determining H0 & expansion history via time delay cosmography
  - Stellar chemistry in bulges beyond the Milky way
  - Binary star populations (halo, bulge, Galactic centers)
  - Star & planet formation
  - Origin & evolution of stars in the faintest & lowest mass galaxies
  - Origins, evolutions & demographics of hidden planets & compact objects in the Milky Way
  - Probes of gravity near supermassive black holes
  - Finding intermediate black holes
  - (Cryo)volcanism on outer Solar System moons
  - Geological mapping surveys of small Solar System bodies
  - Solar System small body companion detection
  - Seasonal evolution & storm systems on gas giant planets (+Titan)

Key Findings: OIR Universe Science

- Cadence, time domain & large samples are competitive advantages:
- Shorter wavelengths important for
  - angular resolution
  - spectral features & wavelength coverage (vs ELTs/JWST)
- High sky coverage needed
- Modest corrected fields (~30” radius)
- New science instrumentation needed
  - Visible imager
  - Visible IFU from R = 500 to >10k
- Keck gains insufficient at 3-5 um over ELTs/JWST

Key Findings: Shorter Wavelengths

- Shorter □ higher the angular resolution
  - Structures in AGN, lensed galaxies.
  - Resolving binaries
  - Astrometric precision
  - Structures in disks and planet systems
- Particular spectral features
  - H-alpha (accretion signatures) in star/planet formation.
  - [OIII] ionized gas? Na-doublet
  - Ca triplet
  - Metal-absorption lines for CGM probes.
  - Salt features (720 and 460 nm) in icy Solar System bodies (habitability).
  - Scattered-light (light-echos, debris disks).
  - Optical continuum from inner/hot disks (AGN, planet formation)
- High-energy phenomena and their optical counterparts
  - Quickly finding decaying high-energy phenomena (bright in optical first).
  - Jets

AO in Astro2021 Report (summary)

- #1: "large (20-40 m) telescopes with diffraction-limited adaptive optics"
- "Key capabilities required on the pathway to habitable worlds include the following: Ground-based extremely large telescopes equipped with high-resolution spectroscopy, high performance adaptive optics, and high contrast imaging"
- Foundational Activities: "Expand support for early-stage and basic technology development" through APRA and ATI.
  - "including the pressing need to develop advanced adaptive optics systems in the optical"
- Investment in Mid- and Small-Scale Ground Facilities: "The development of adaptive optics (AO) in the 1990s serves as an excellent case in point, and led to ground-breaking advances such as the direct imaging of exoplanets, and the precise definition of the orbits of stars that determined the gravitational forces near the black hole at the center of the Milky Way"

AO in Astro2021 OIR Panel Report

- "case for continued support of development over the next decade is strong:
- 1. AO/High-Contrast Imaging are key enabling technologies for high science priorities identified by the Exoplanets, Stars, and Galaxies science frontiers panels;
- 2. They play an essential role in boosting the scientific return and efficiency of existing facilities (e.g., Gemini, Keck, Magellan, DKIST) with modest-scale investment throughout the 2020s;
- 3. NSF Mid-scale program opportunities have been identified (e.g., GNAO, GmagAO-X, LIGER) to nurture existing 6–10 m class telescopes.
- 4. Such investments in AO systems development is a key risk mitigation strategy for ELTs, whose full resolution and sensitivity potential can only be realized with AO, and which is recognized as the most important technical risk for both GMT and TMT."

Recommended AO Capabilities

- Use AO to enhance our science community's competitive advantages in cadence, time domain & large samples
- Use Keck AO to support ELT & space missions risk reduction technology demonstrations
- AO in the visible (all three workshops/communities)
  - Drivers: angular resolution &/or wavelength coverage
  - Many different flavors desired (sky coverage, Strehl ratio, FOV, contrast)
  - Keck in visible provides complementary & similar resolution to ELTs in NIR
- Improve overall efficiency through GLAO-enhanced seeing

Consistent with Astro2021 emphasis on AO development.