GMT

Sharp Images and Wide Fields

The scientific power of GMTIFS and MANIFEST on GMT

Lecture 1

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USP/IAG Advanced School on Astrophysics

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Introduction

Aims

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- Explain why sharp imaging (i.e. adaptive optics) and wide fields (i.e. MOS & IFS) are important for GMT
- Show how the science goals and instrument constraints interact – the real history of how instruments are built and what science they do
- Examine the two types of science outcomes:
  - the ‘extrapolated’ science based on current knowledge and the expected capabilities of the instrument
  - the ‘discovery space’ science opened up by exploring with the instrument’s new capabilities

Structure

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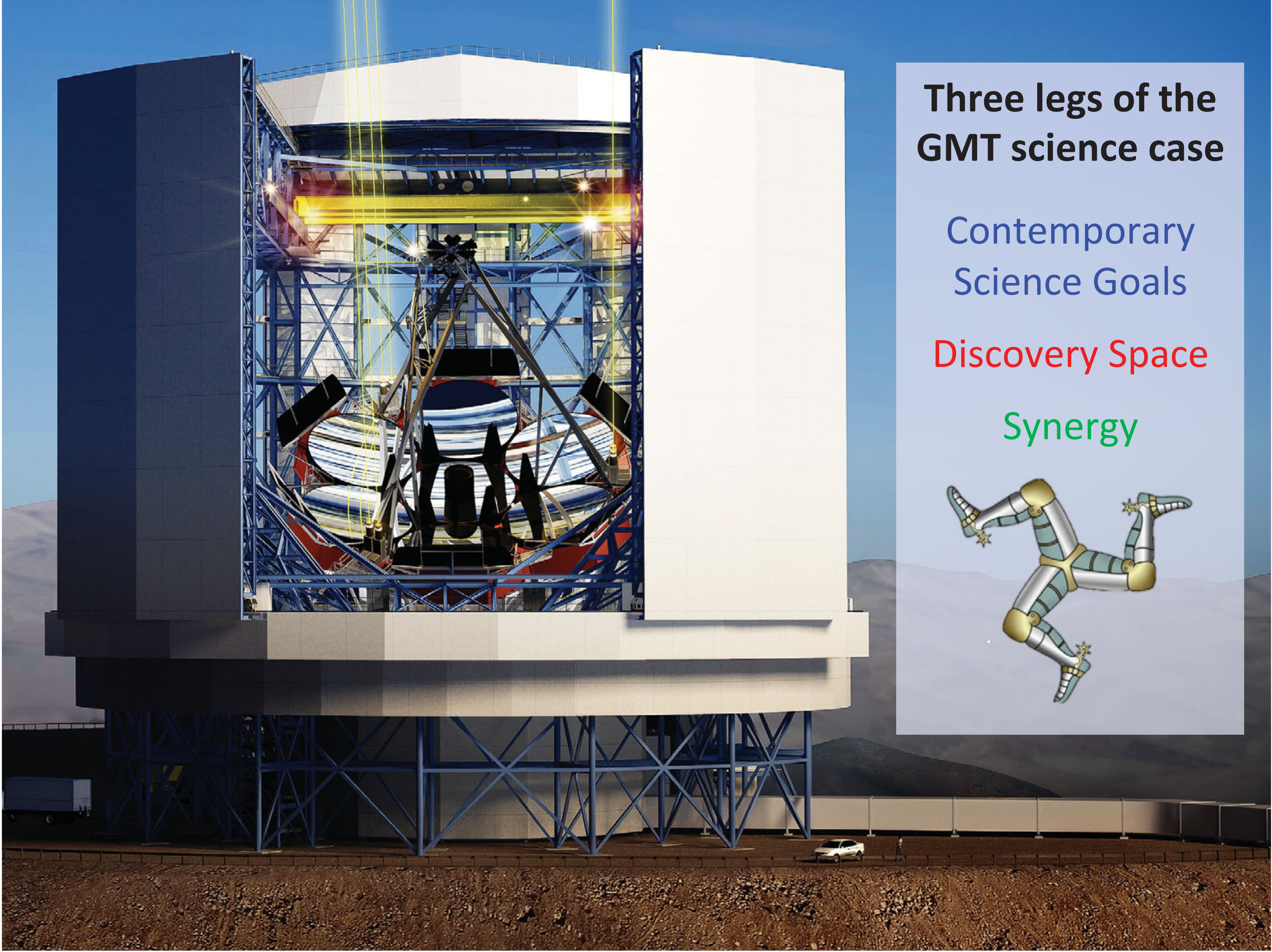
- ❑ Lecture 1 – Sharp Images and Wide Fields
- ❑ Lecture 2 – The GMT Integral Field Spectrograph
- ❑ Lecture 3 – The MANIFEST fibre facility

Outline of Lecture 1

- Introduction
- Sharp images ⇒ adaptive optics
- Wide fields ⇒ MOS + IFS
- The GMT instrument suite
- GMTIFS science
- MANIFEST science
- Summary


Three legs of the GMT science case
Contemporary Science Goals
Discovery Space
Synergy

Telescopes are getting larger

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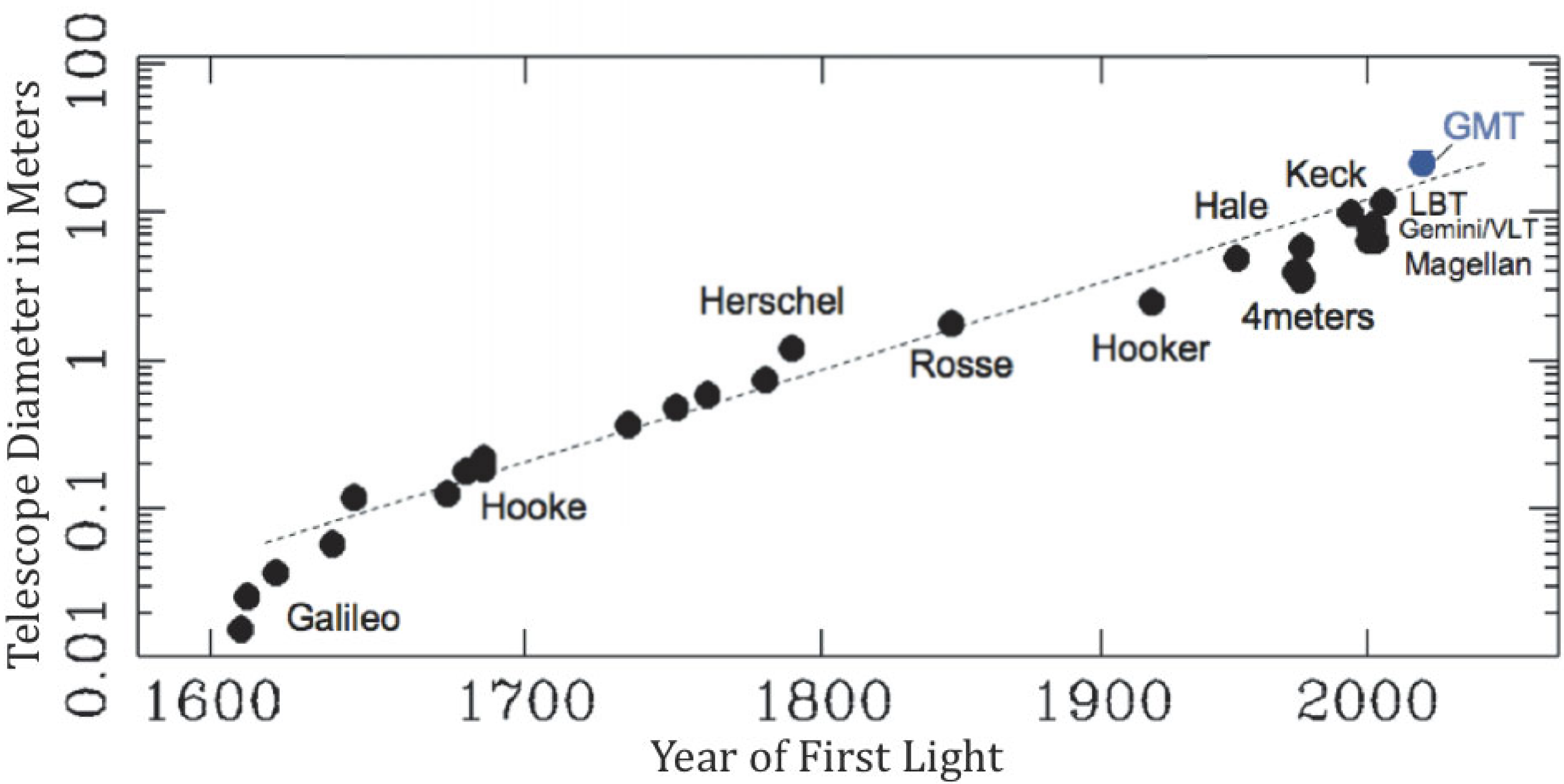
Doubling time for telescope apertures is ~35 years



GMT concept evolution

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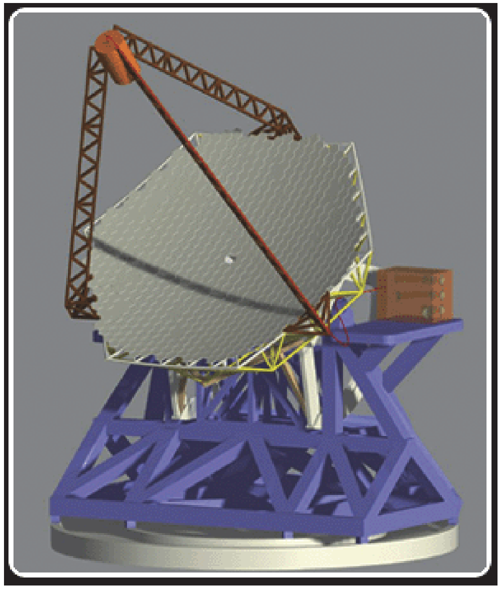
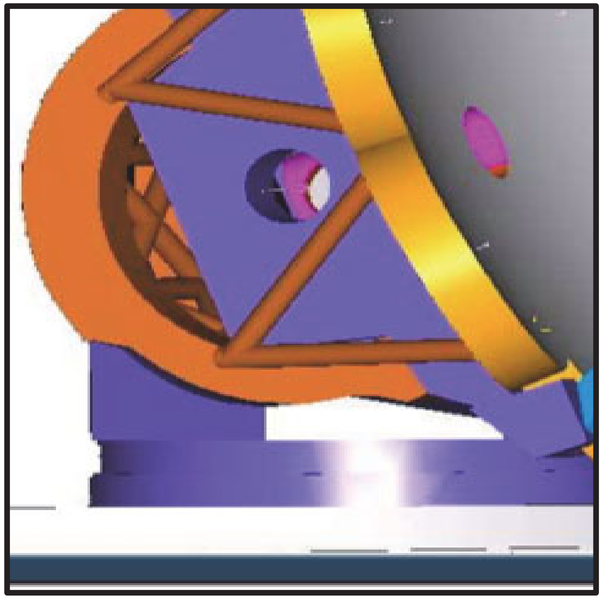
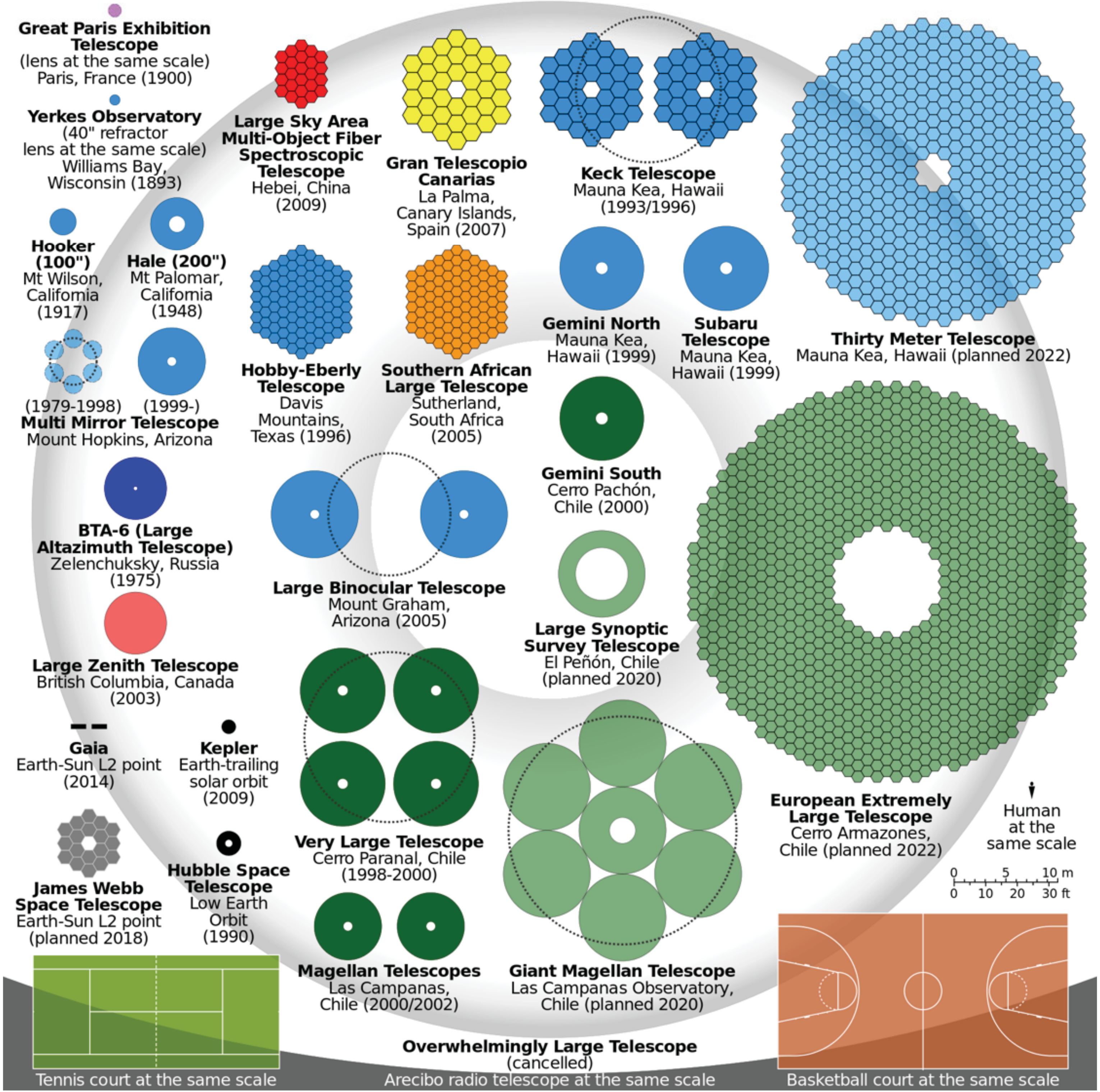
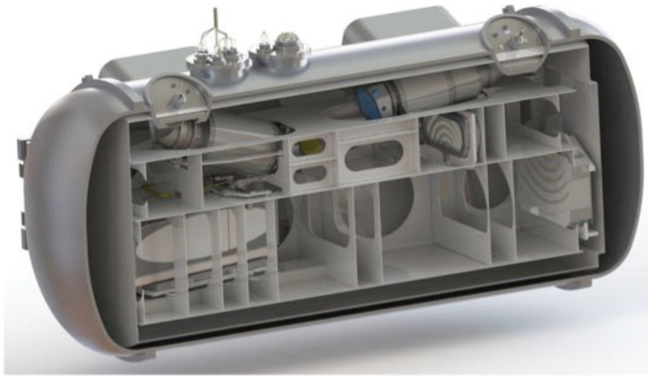
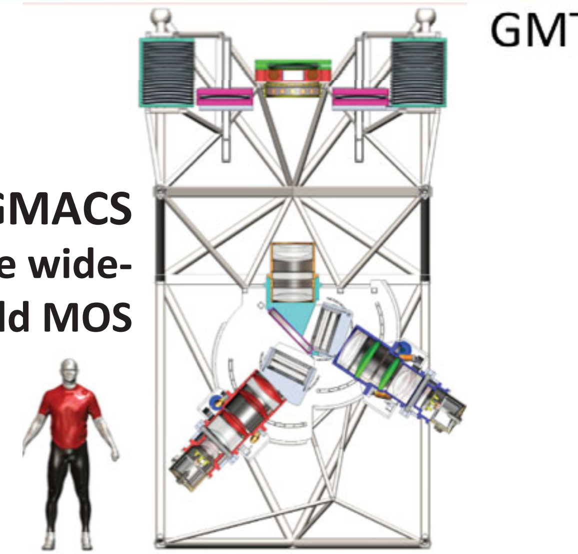
Giant Segmented Mirror Telescope	20/20 Telescope (20-metre by 2020)	Giant Magellan Telescope
		
2000	2002	2005


Great Paris Exhibition Telescope
(lens at the same scale)
Paris, France (1900)
Yerkes Observatory
(40" refractor
lens at the same scale)
Williams Bay, Wisconsin (1893)
Hooker (100")
Mt Wilson, California (1917)
Hale (200")
Mt Palomar, California (1948)
(1979-1998)
(1999-)
Multi Mirror Telescope
Mount Hopkins, Arizona
BTA-6 (Large Altazimuth Telescope)
Zelenchuksky, Russia (1975)
Large Zenith Telescope
British Columbia, Canada (2003)
Gaia
Earth-Sun L2 point (2014)
Kepler
Earth-trailing solar orbit (2009)
James Webb Space Telescope
Earth-Sun L2 point (planned 2018)
Hubble Space Telescope
Low Earth Orbit (1990)
Large Sky Area Multi-Object Fiber Spectroscopic Telescope
Hebei, China (2009)
Gran Telescopio Canarias
La Palma, Canary Islands, Spain (2007)
Keck Telescope
Mauna Kea, Hawaii (1993/1996)
Thirty Meter Telescope
Mauna Kea, Hawaii (planned 2022)
Hobby-Eberly Telescope
Davis Mountains, Texas (1996)
Southern African Large Telescope
Sutherland, South Africa (2005)
Gemini North
Mauna Kea, Hawaii (1999)
Subaru Telescope
Mauna Kea, Hawaii (1999)
Gemini South
Cerro Pachón, Chile (2000)
Large Binocular Telescope
Mount Graham, Arizona (2005)
Large Synoptic Survey Telescope
El Peñón, Chile (planned 2020)
European Extremely Large Telescope
Cerro Armazones, Chile (planned 2022)
Human at the same scale
0 5 10 m
0 10 20 30 ft
Very Large Telescope
Cerro Paranal, Chile (1998-2000)
Magellan Telescopes
Las Campanas, Chile (2000/2002)
Giant Magellan Telescope
Las Campanas Observatory, Chile (planned 2020)
Overwhelmingly Large Telescope
(cancelled)
Tennis court at the same scale
Arecibo radio telescope at the same scale
Basketball court at the same scale

First-generation GMT instruments

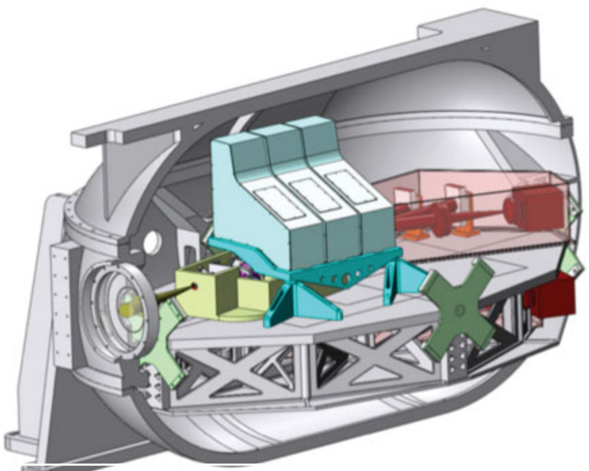


G-CLEF
high-resolution echelle



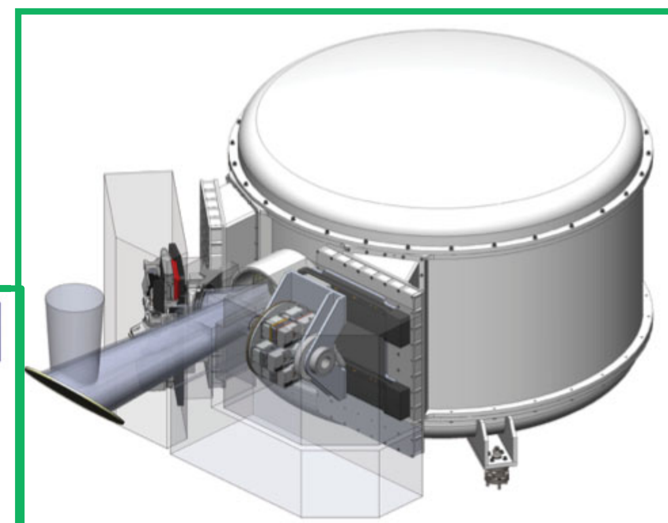
GMACS
visible wide-field MOS

MANIFEST
facility fibre system



GMTNIRS
AO-fed 1-5 micron echelle

GMTIFS
AO-fed IFU spectrograph and imager



Sharp images ⇒ adaptive optics

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- Adaptive optics is the key technology for sharper imaging – ranging from better-than-natural-seeing to nearly-diffraction-limited – on large telescopes
- How does adaptive optics (AO) work? The basic principles and techniques
- Types of adaptive optics…
  - LTAO = laser tomography adaptive optics
  - MCAO = multi-conjugate adaptive optics
  - MOAO = multi-object adaptive optics
  - GLAO = ground-layer adaptive optics

Credits: Claire Max & Francois Rigaut

Why is adaptive optics needed?

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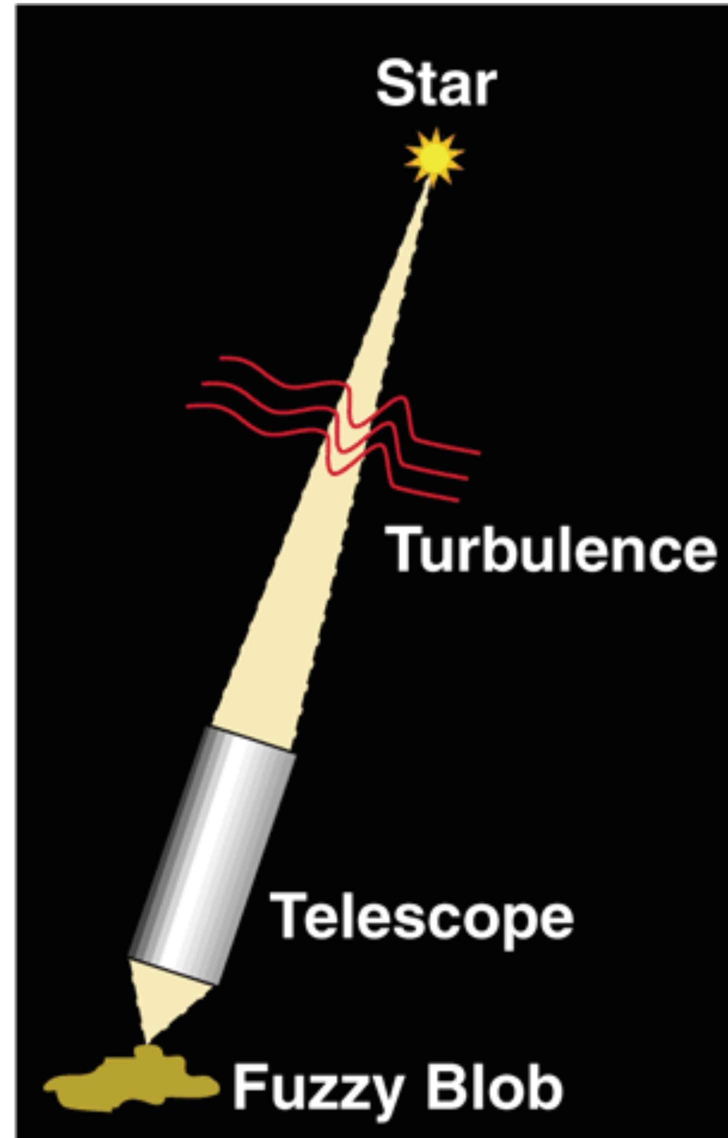
- Turbulence in earth's atmosphere makes stars twinkle
- Turbulence spreads out light; makes it a blob rather than a point
- This blob is a lot larger than the ideal Point Spread Function (PSF), which is limited only by the size of the telescope
- Even the largest ground-based astronomical telescopes have no better resolution than a ~25cm telescope!



Atmospheric wavefront distortion

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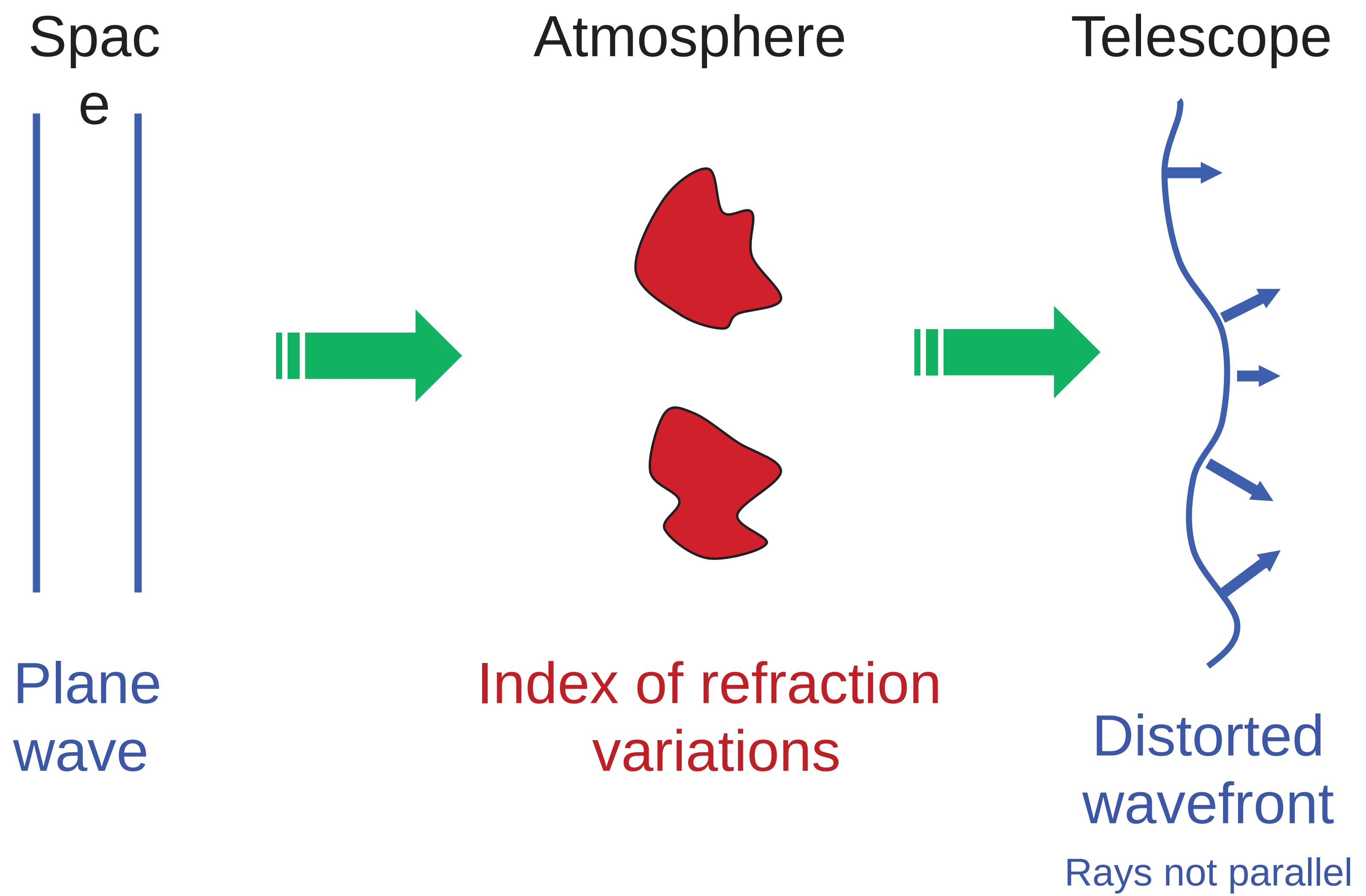

Optical effects of turbulence

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- Temperature fluctuations in small patches of air cause changes in index of refraction (like many little lenses)
- Light rays are refracted many times (by small amounts)
- When they reach telescope they are no longer parallel and so the rays cannot be focused to a point

Parallel light rays

Light rays affected by turbulence

Images of a bright star

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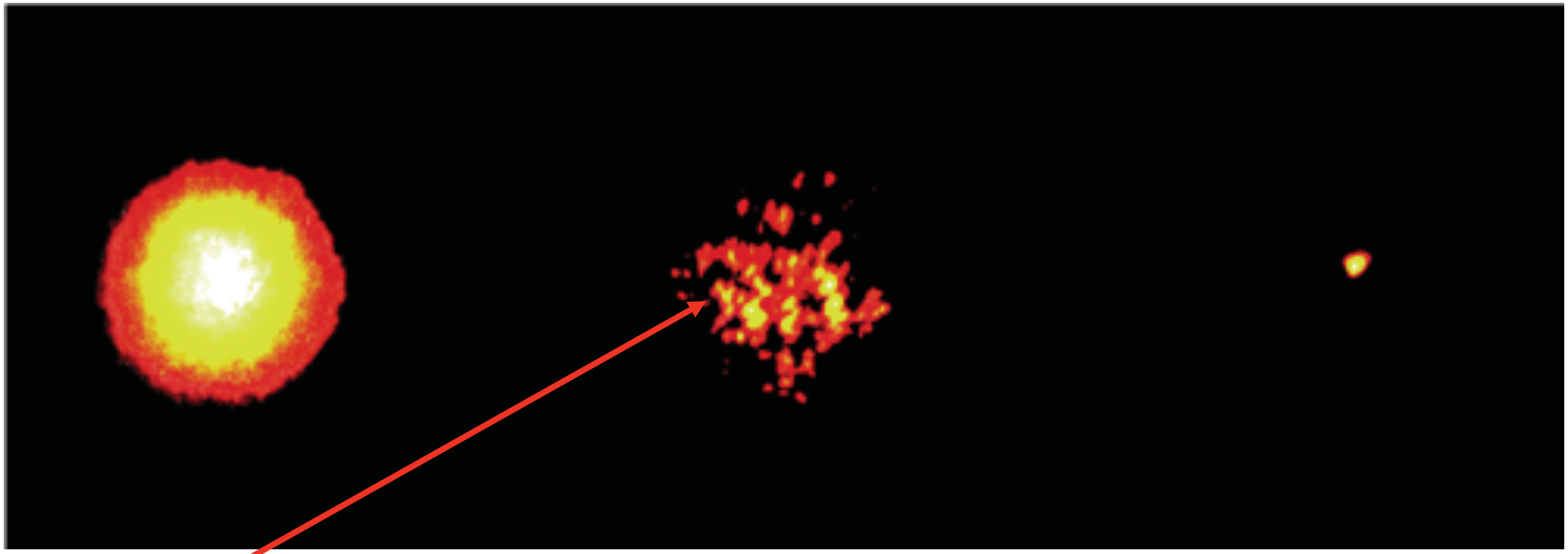
1-metre telescope



Speckles (each is at diffraction limit of telescope)

Turbulence is dynamic

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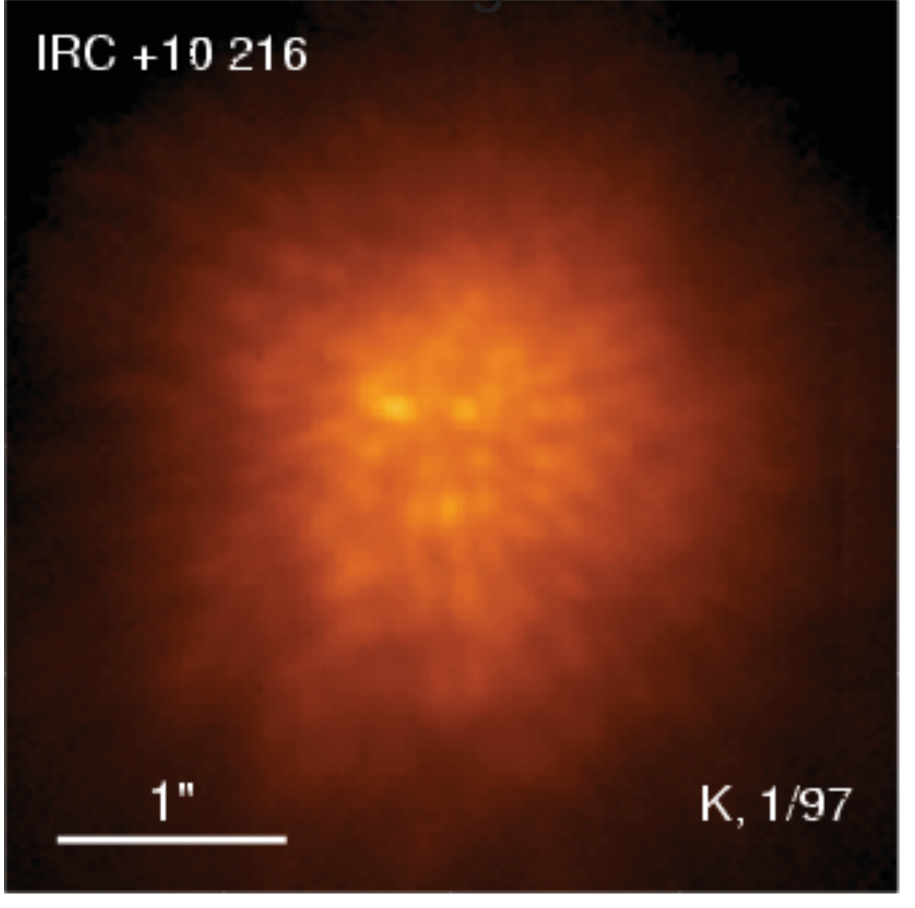
Speckle images: sequence of short snapshot of a star image

Image is spread out into speckles

Image centroid jumps around (image motion)



The origins of turbulence

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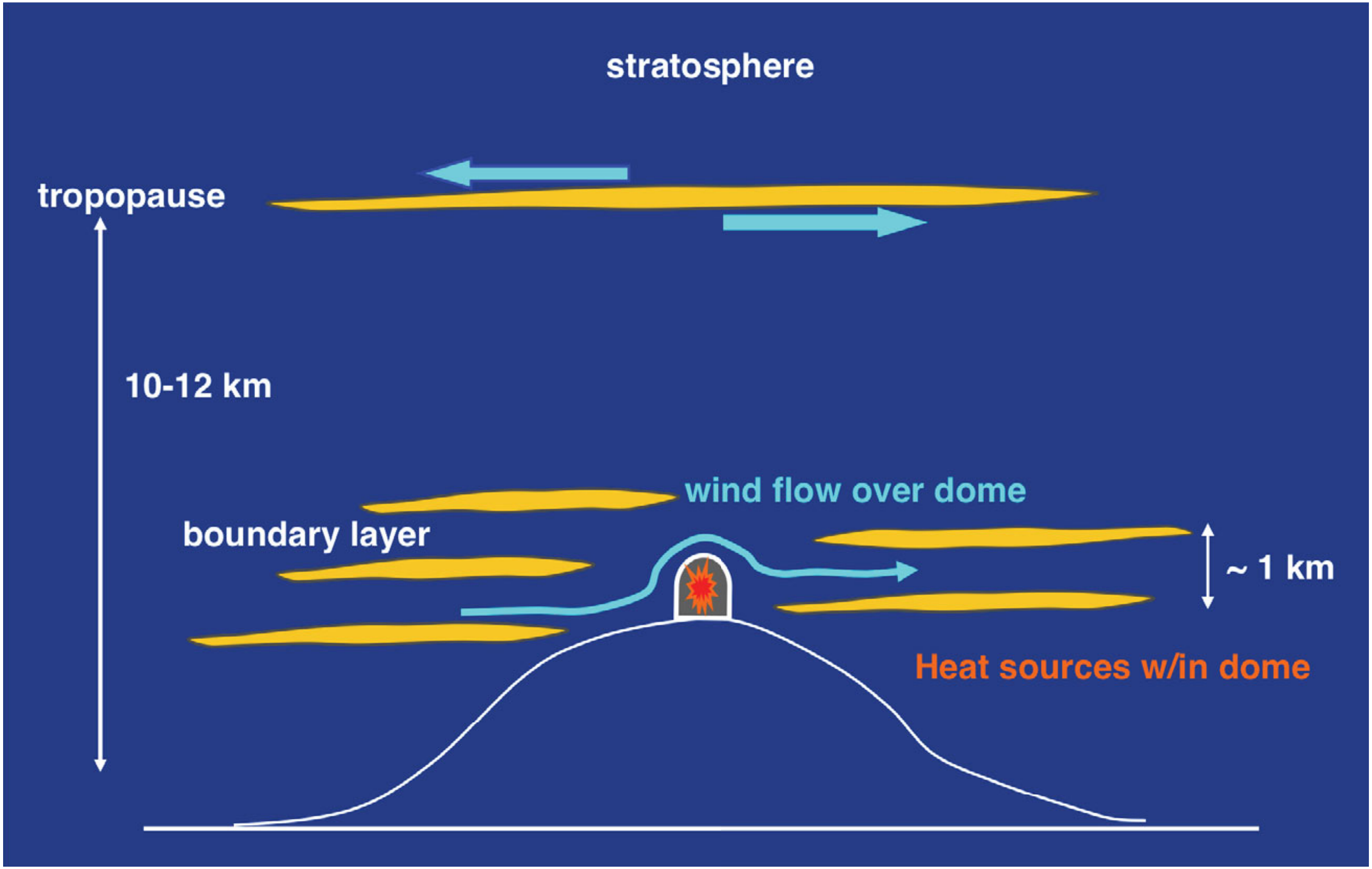

A perfect telescope image

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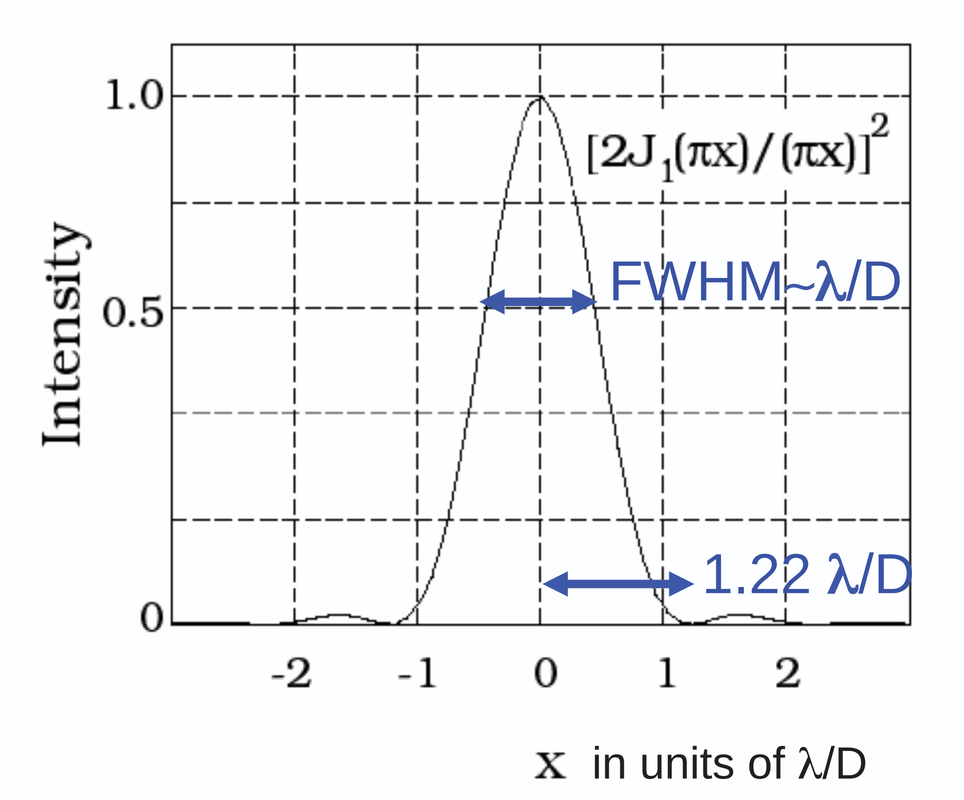

- Point Spread Function (PSF) = intensity profile of point source
- With no turbulence, FWHM is diffraction limit $\theta \sim \lambda/D$
- Example:
  - ▶ $\lambda / D = 0.02''$ for $\lambda = 1\mu m$, $D = 10m$
- With turbulence, image size is much larger (typically 0.5–2”); this is ‘natural seeing’

Turbulence is characterized by r_0

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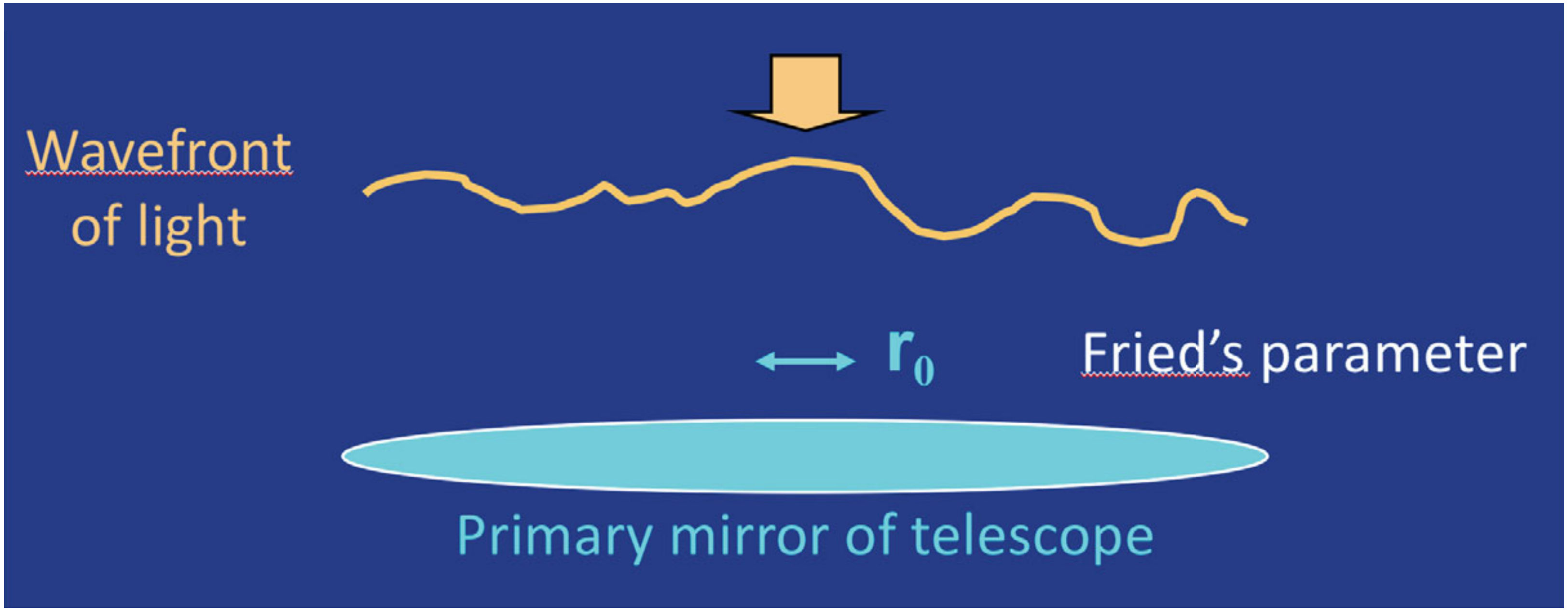

- Coherence length r_0 = distance over which optical phase distortion has mean square value of 1 rad^2 ($r_0 \sim$ 15–30 cm at good observing sites)
- Remember: r_0 = 10 cm ⇔ FWHM = 1″ at λ = 0.5 μm
- The larger the coherence length the better the seeing

Effect of turbulence on image size

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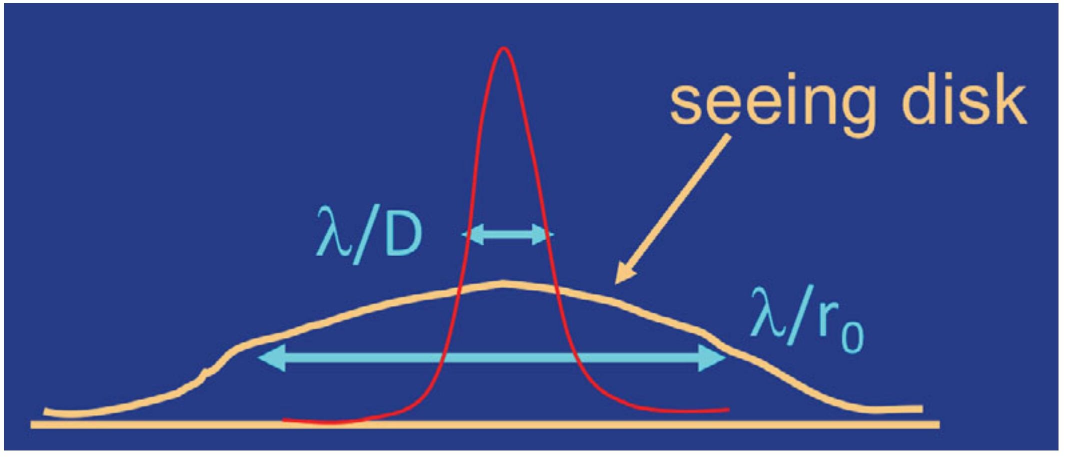
- If telescope diameter D >> r_0 , image size of a point source is λ/r_0 >> λ/D



- r_0 is the diameter of the circular pupil for which the diffraction-limited image and the seeing-limited image have the same angular resolution
- $r_0 \approx$ 25cm at a good site – so any telescope larger than this has no better spatial resolution!
- For GMT, diffraction limit is ~100x sharper than natural seeing!

How does adaptive optics help?

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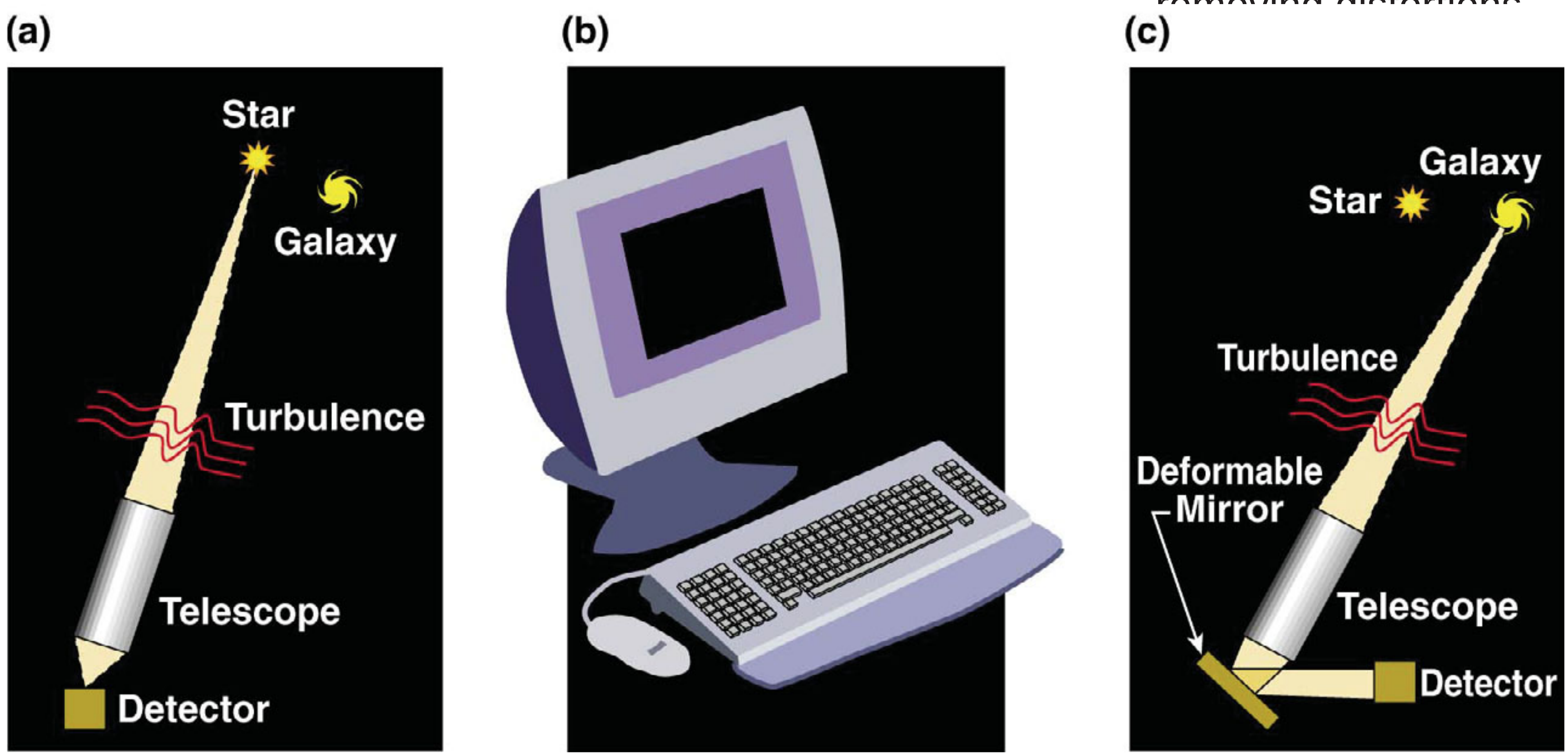
Measure details of blurring from “guide star” near the object you want to observe

Compute the shape to apply to a deformable mirror to correct the blurring

Light from the guide star and real star is reflected from deformable mirror, removing distortions



Effect of adaptive optics

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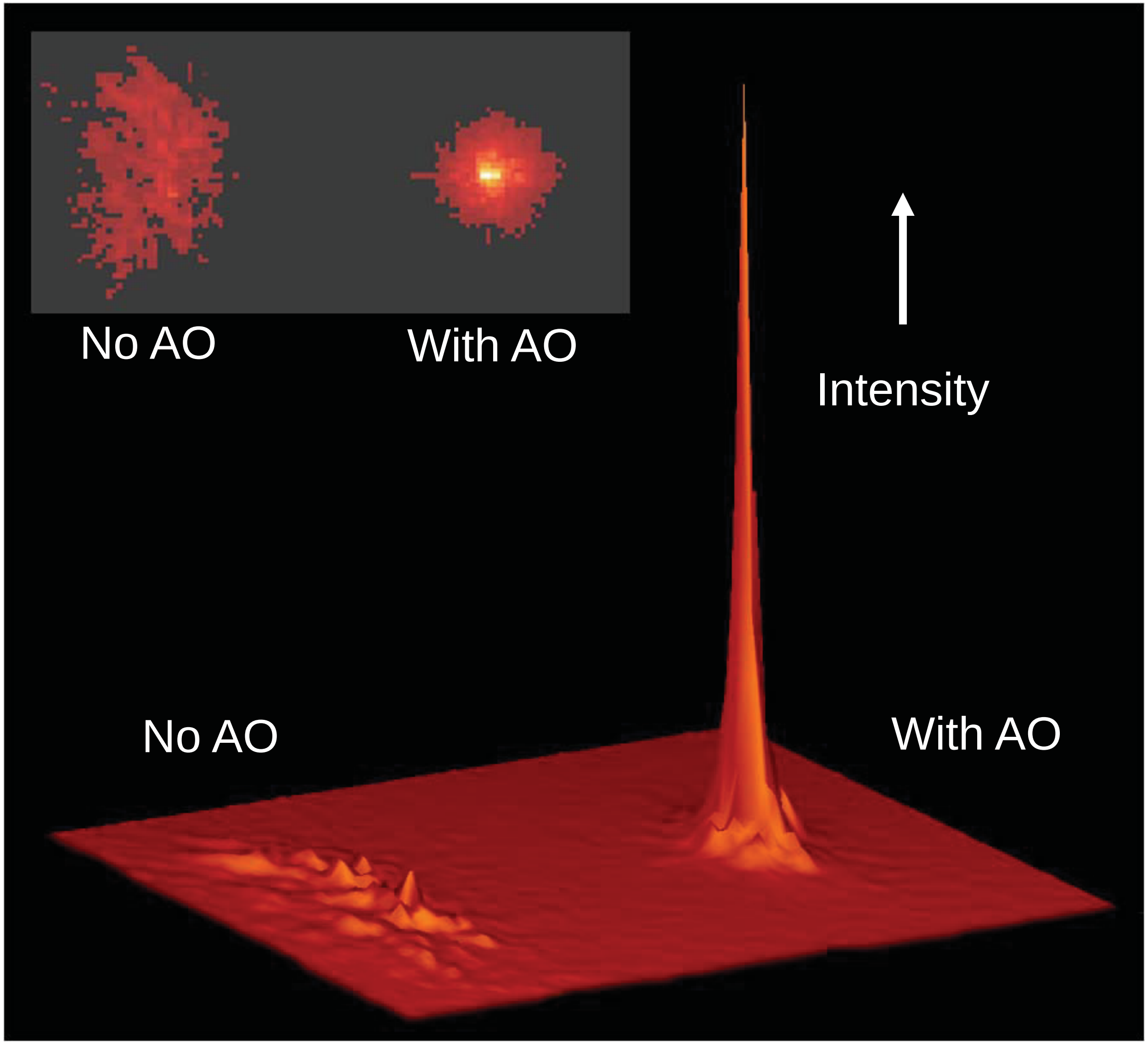

Adaptive optics increases peak intensity of a point source

AO PSF has a core and a halo

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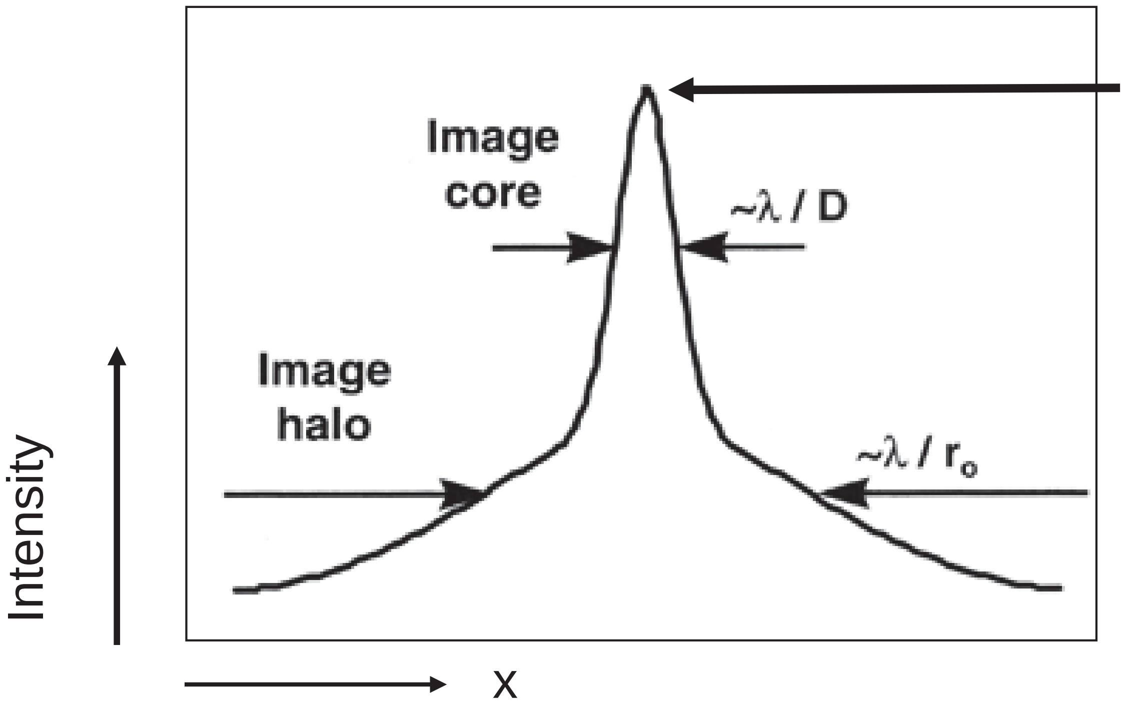

Strehl ratio is ratio of peak intensity of point source to that produced by a 'perfect' optical system

- When AO system is performing well, more energy in core and less in halo
- When AO system is stressed (e.g. by poor seeing), the halo (with diameter ~ λ/r_0) contains a larger fraction of the energy
- The ratio between the diffraction-limited core and the natural-seeing halo varies with conditions and performance of the AO system

AO images of binary star

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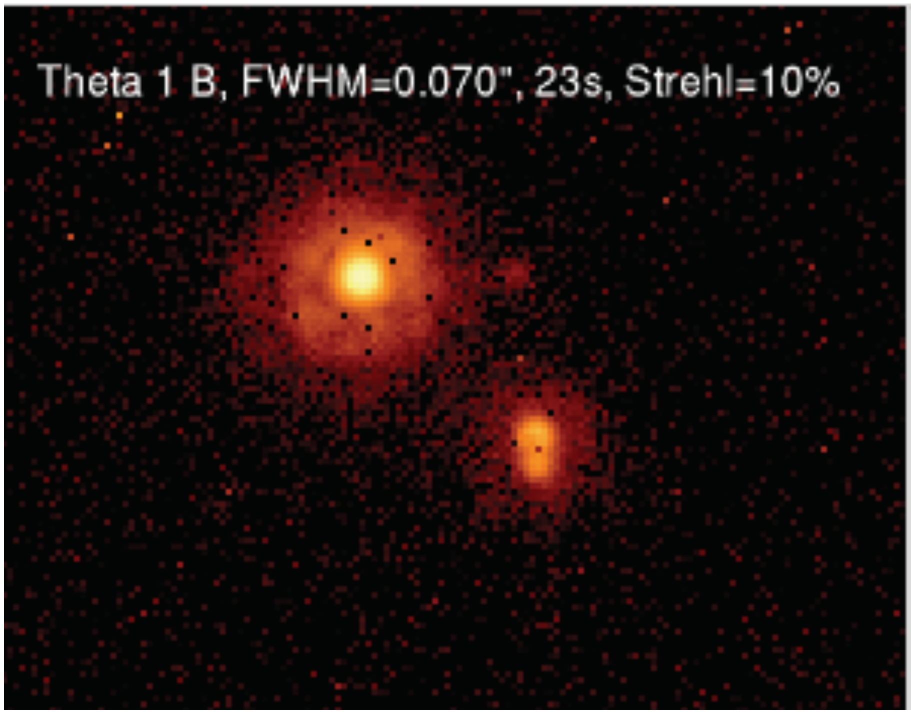
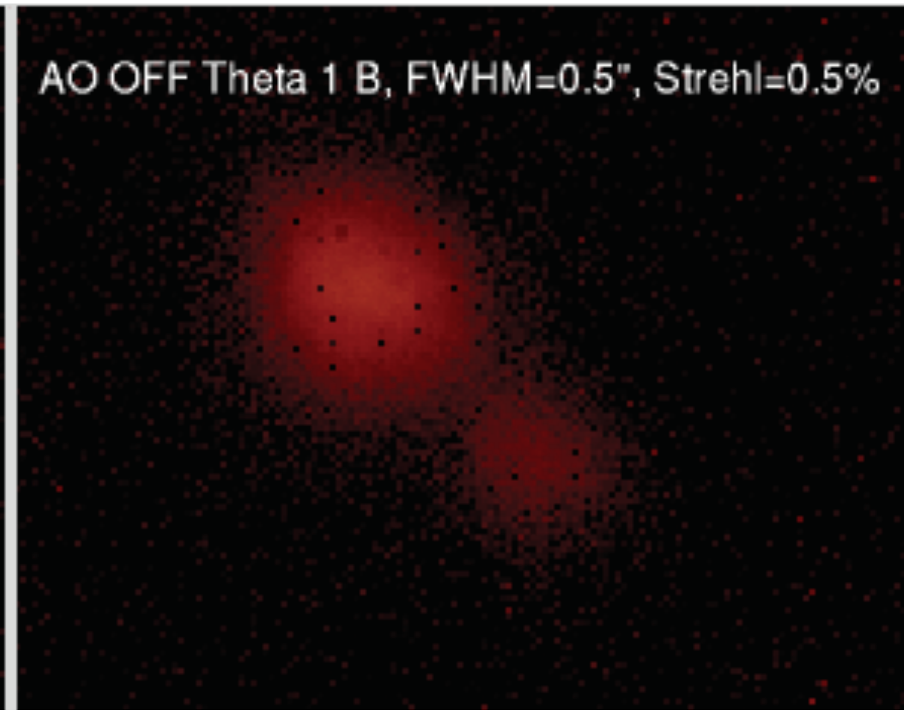


With adaptive optics



No adaptive optics

Schematic adaptive optics system

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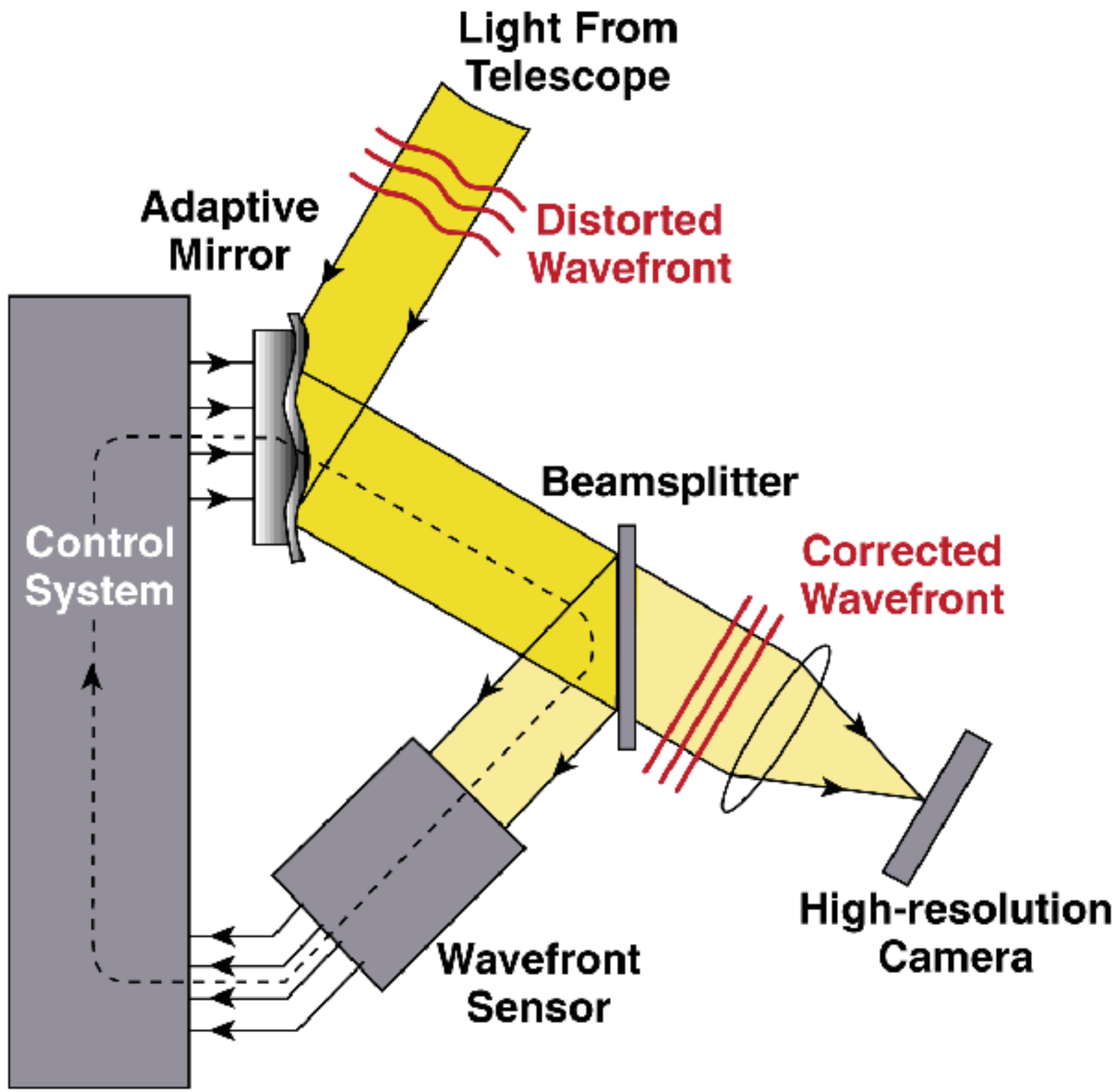
AO operates in a feedback loop: the next cycle corrects the (small) errors of the last cycle



Deformable mirror

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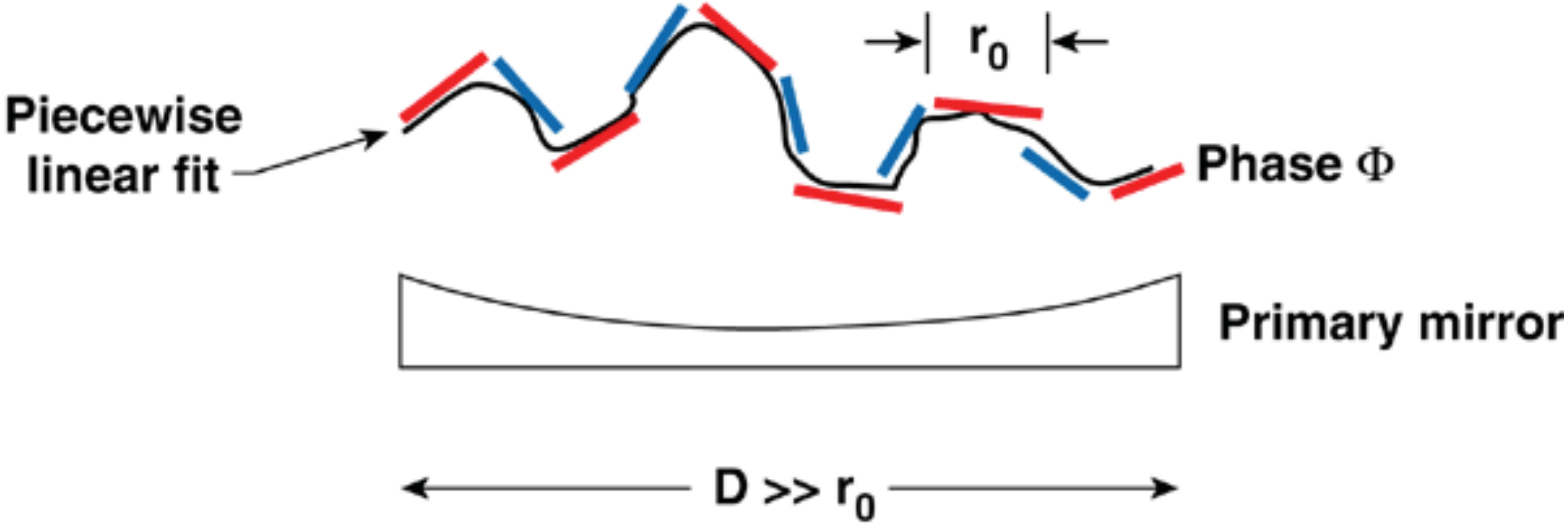

- Real deformable mirrors have smooth surfaces
- In practice, a small deformable mirror with a thin bendable face sheet is used
- Placed after the main telescope mirror

Example AO applications

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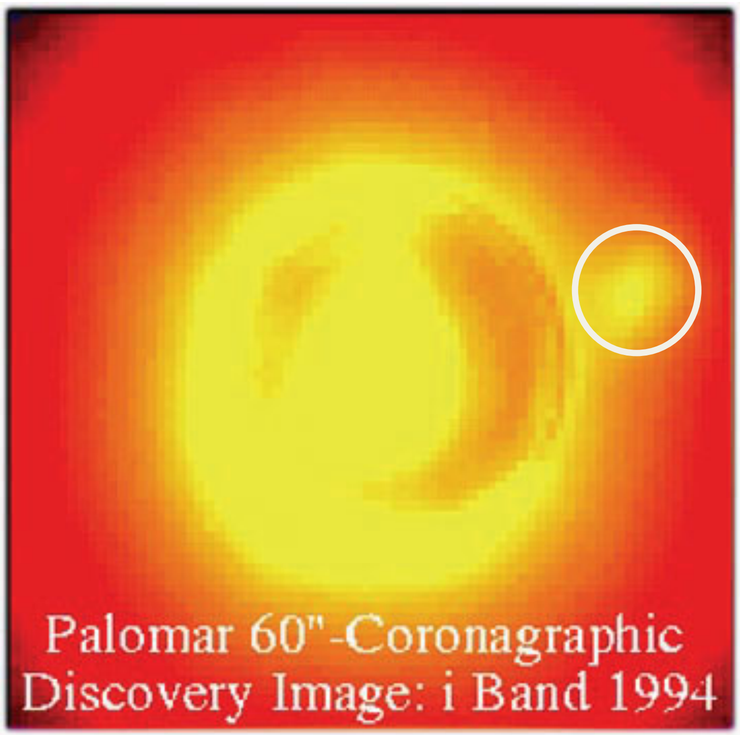
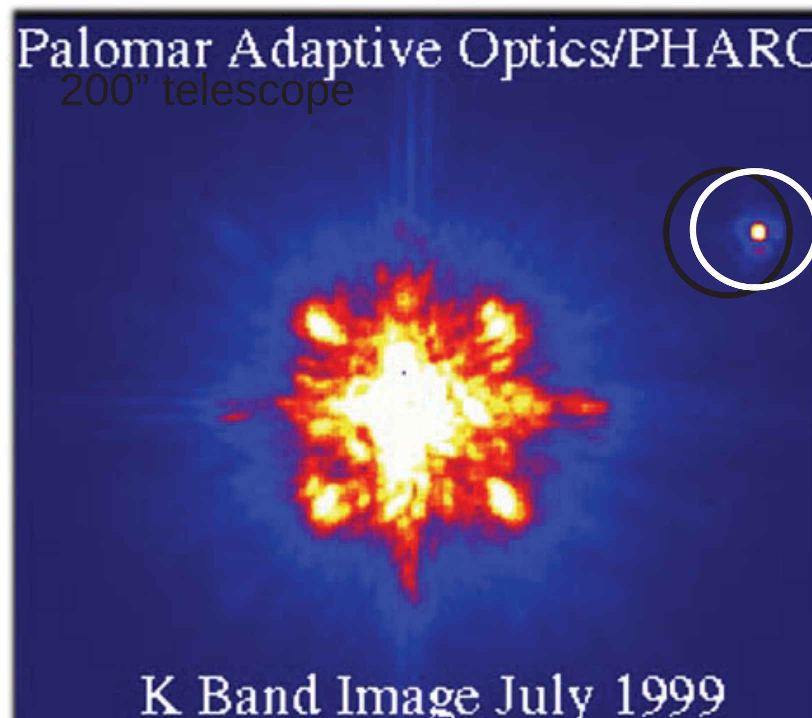
Finding faint companions around bright stars:
two images from Palomar of a brown dwarf companion to GL 105



No AO



With AO

Example AO applications

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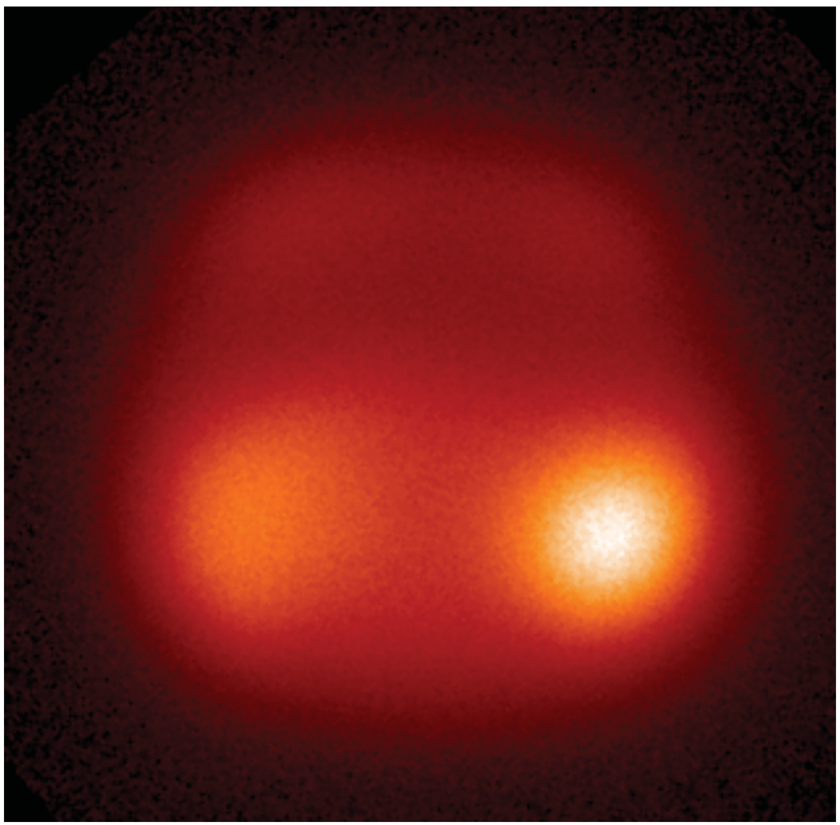
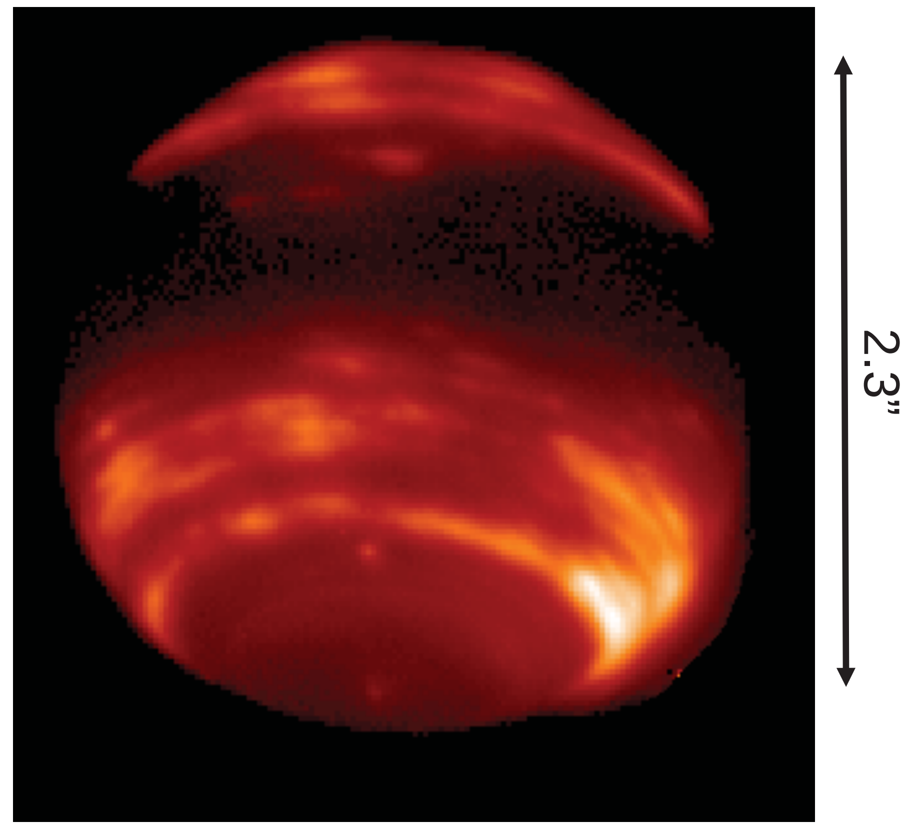
Infrared images of Neptune (1.65 μm)



No AO



With AO

Example AO applications

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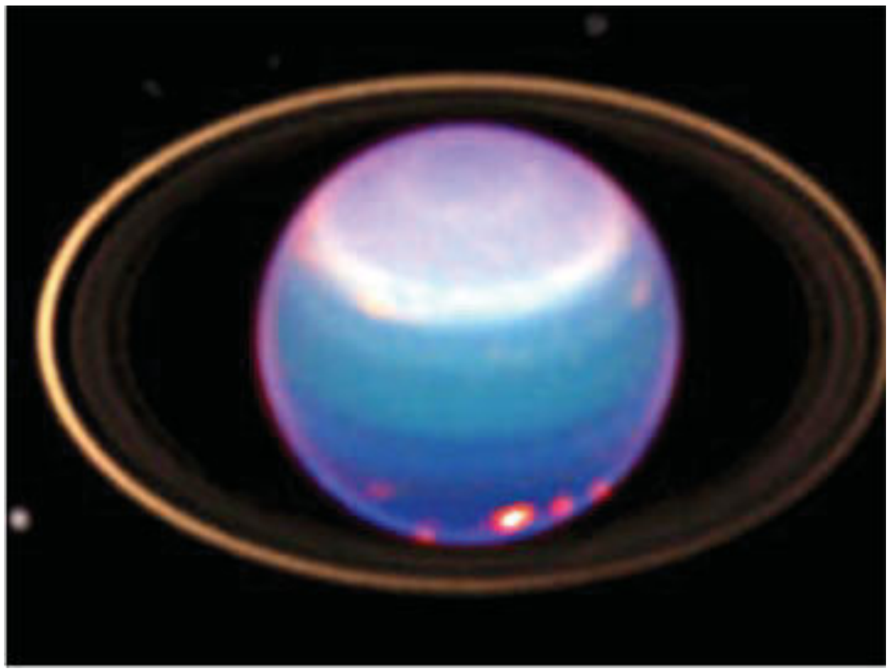
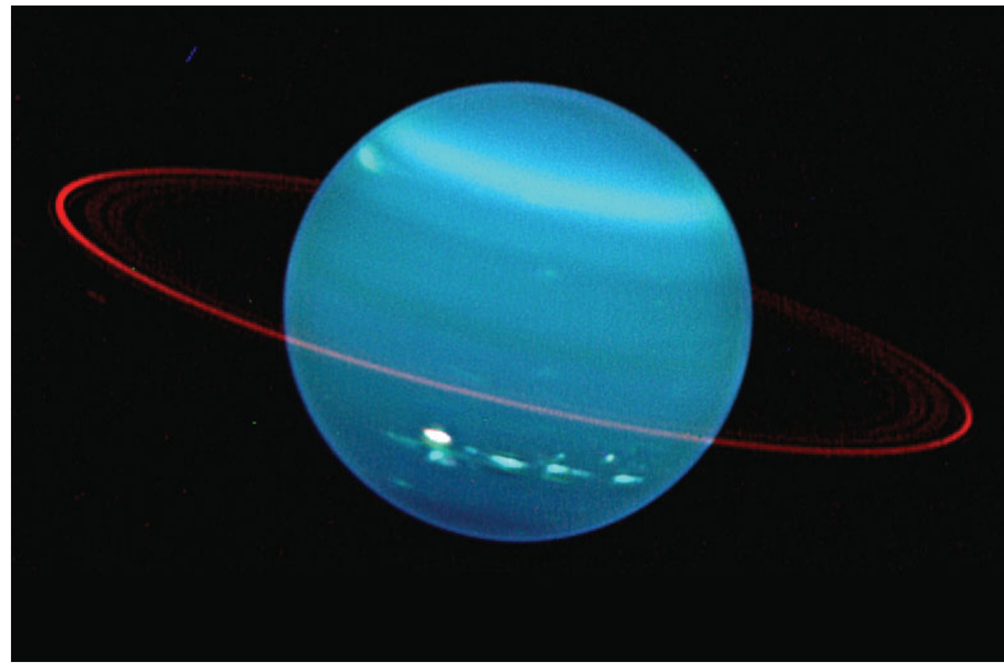
Uranus with Hubble Space Telescope and Keck AO



HST, visible



Keck with AO, near-infrared

With AO in the infrared, Keck as about the same resolution as HST

Limitations of single-star AO

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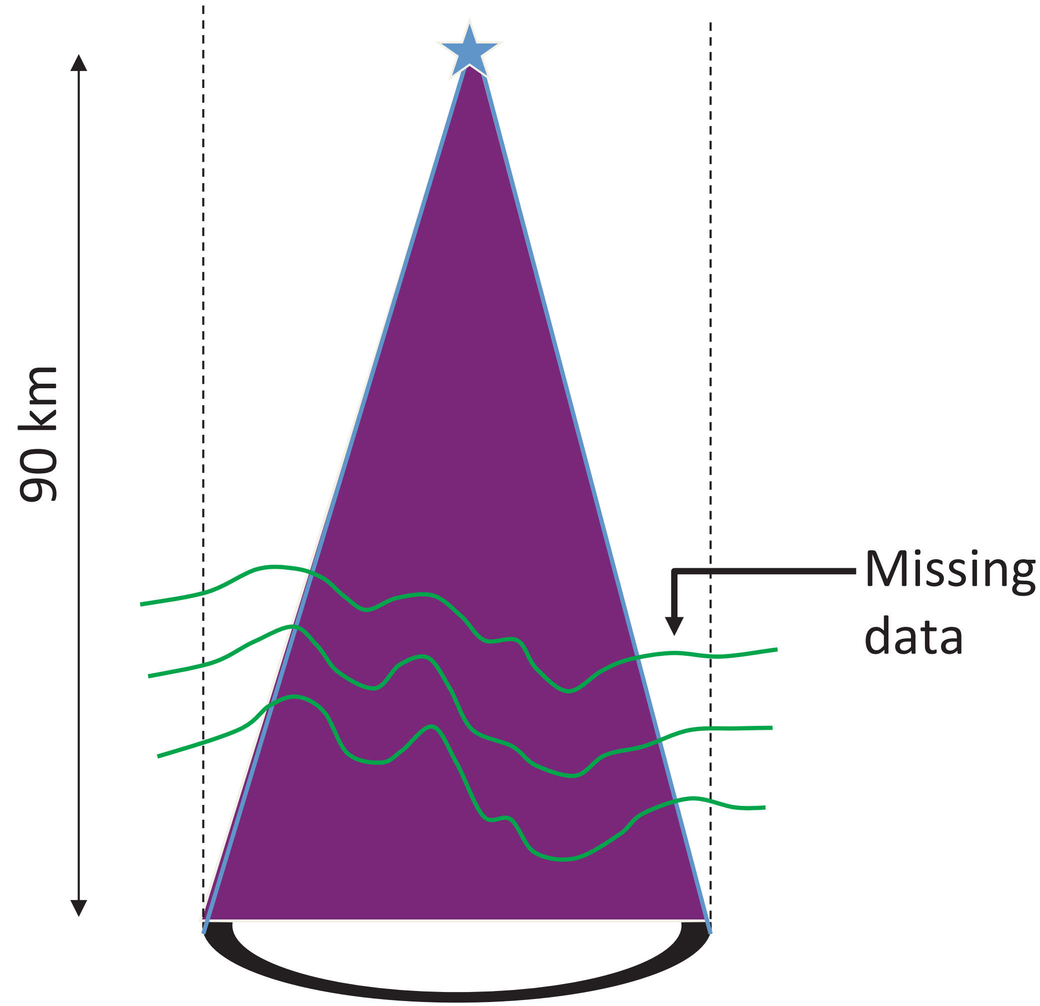
Single guide-star AO can only correct a narrow field of view due to the *cone effect*



AO tomography

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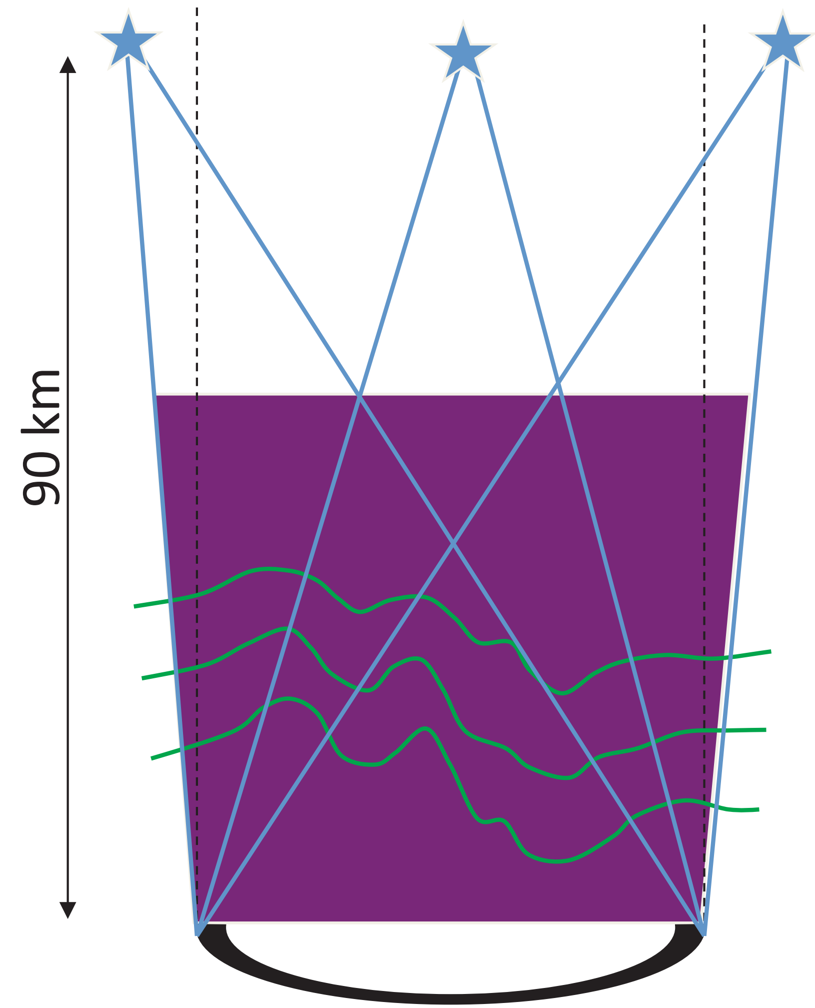
Using multiple guide-stars, tomographic AO allows reconstruction of the turbulence in the entire cylinder of atmosphere above the telescope



AO configurations – SCAO, LTAO

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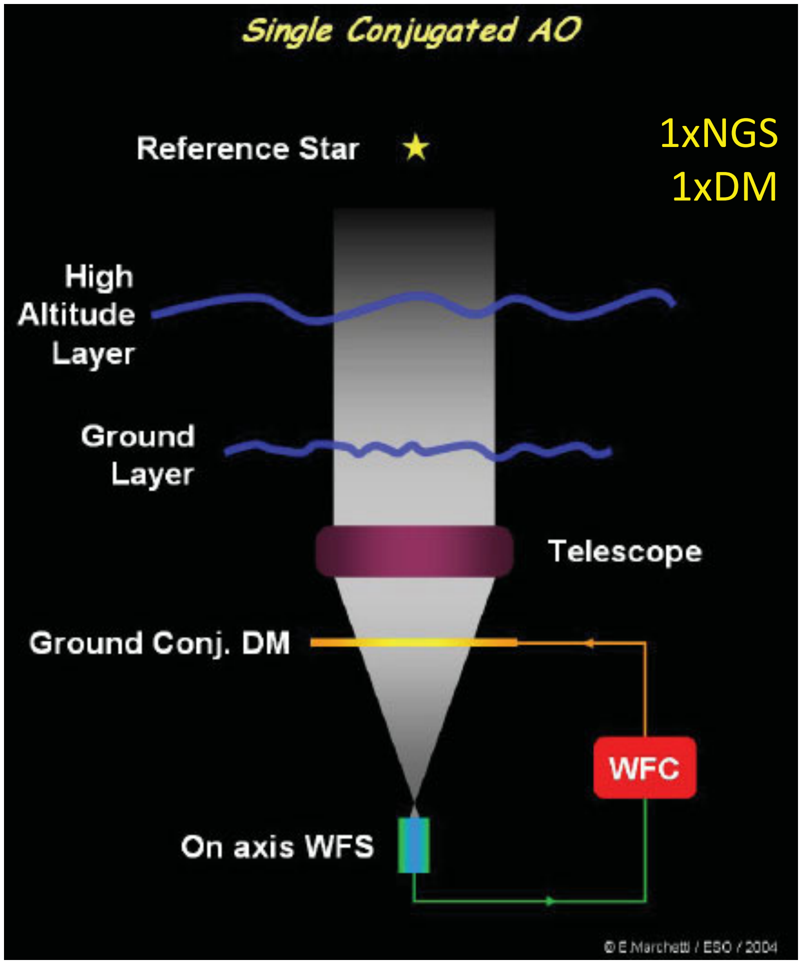

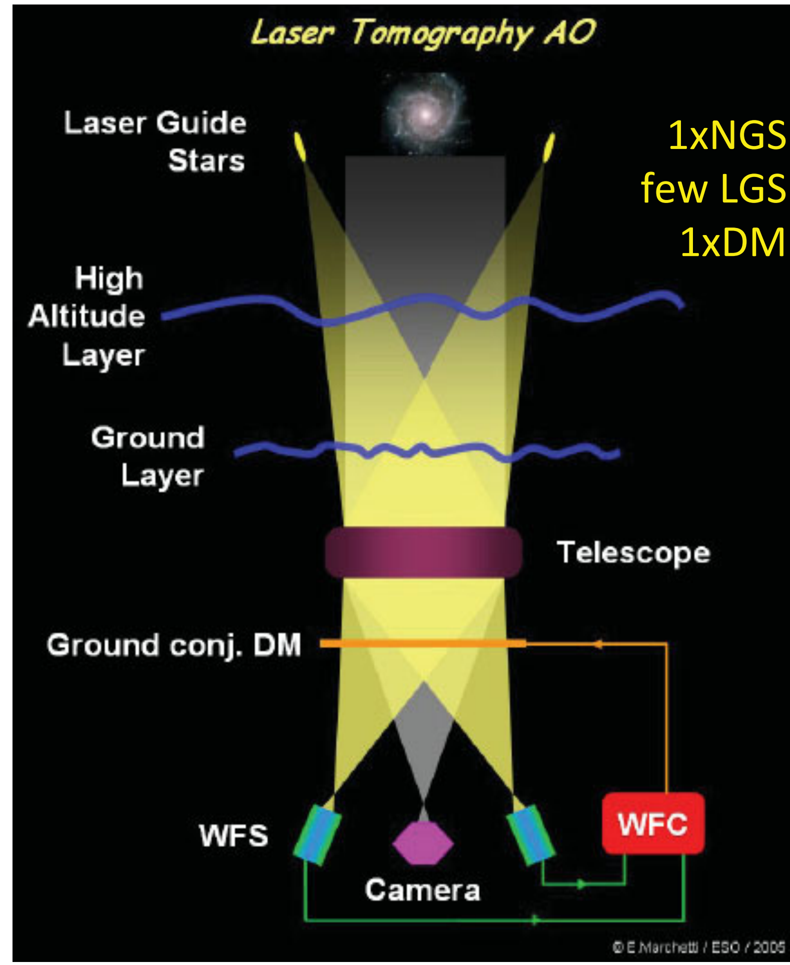

SCAO partially corrects a narrow field; suffers from cone effect

LTAO fixes the cone effect and better corrects a narrow field

AO configurations – MCAO

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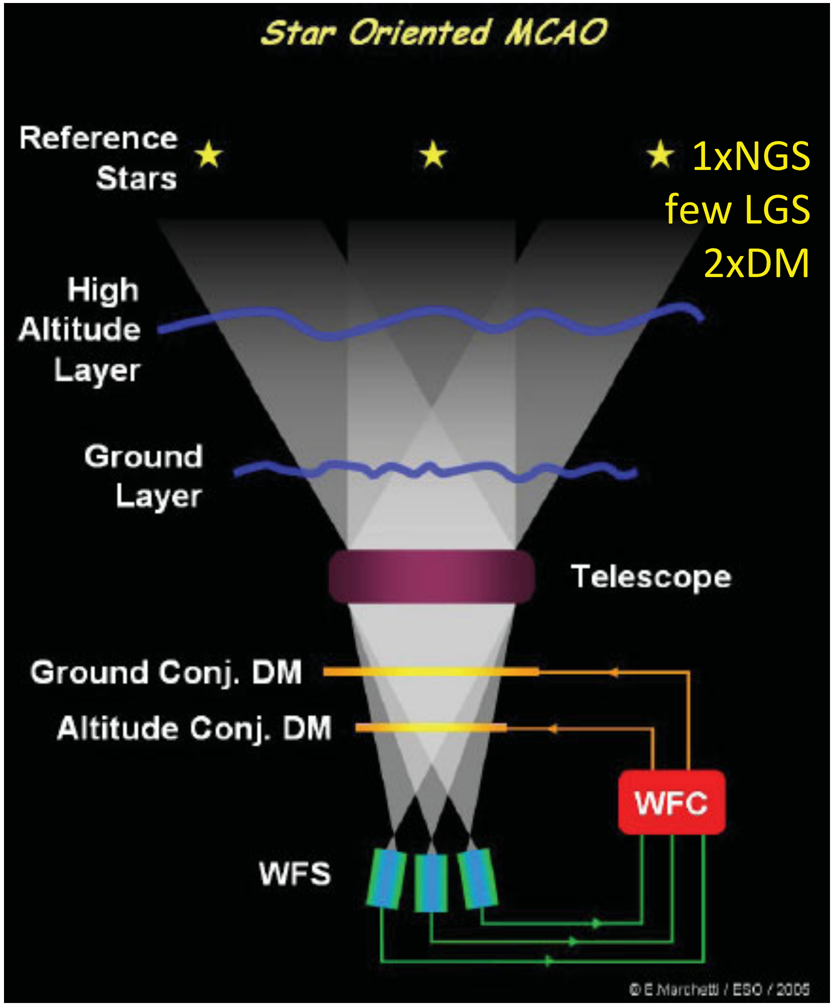

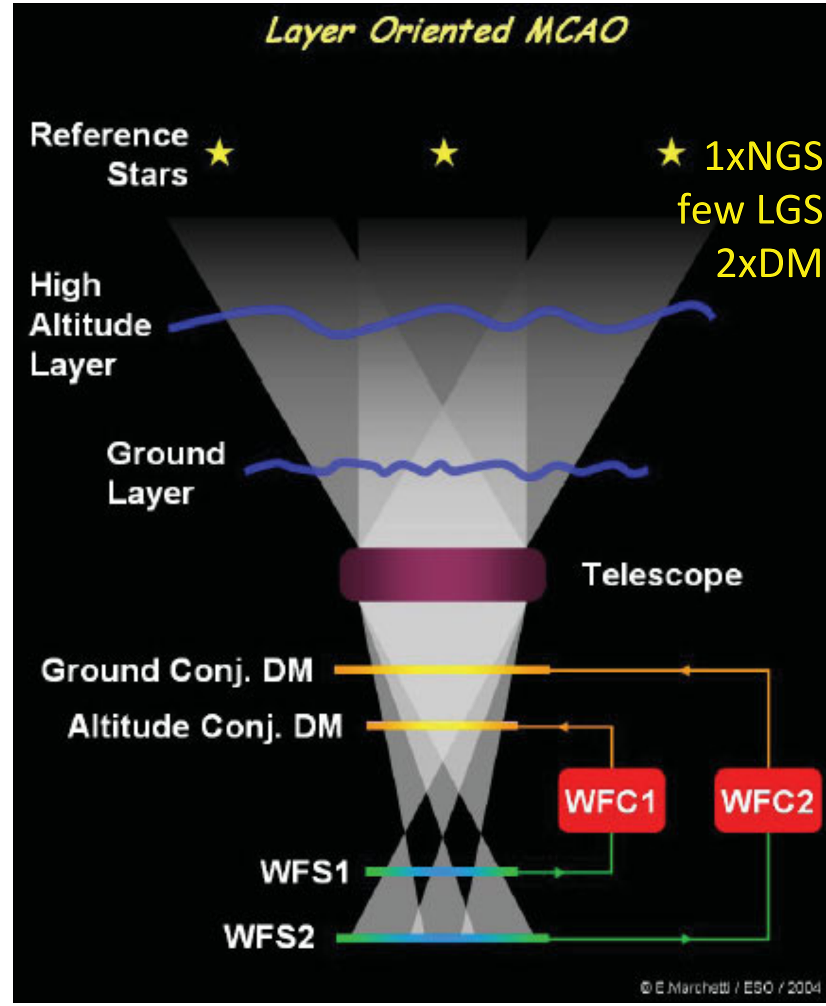

MCAO provides correction over a wide field, at a penalty in peak Strehl

AO configurations – MOAO, GLAO

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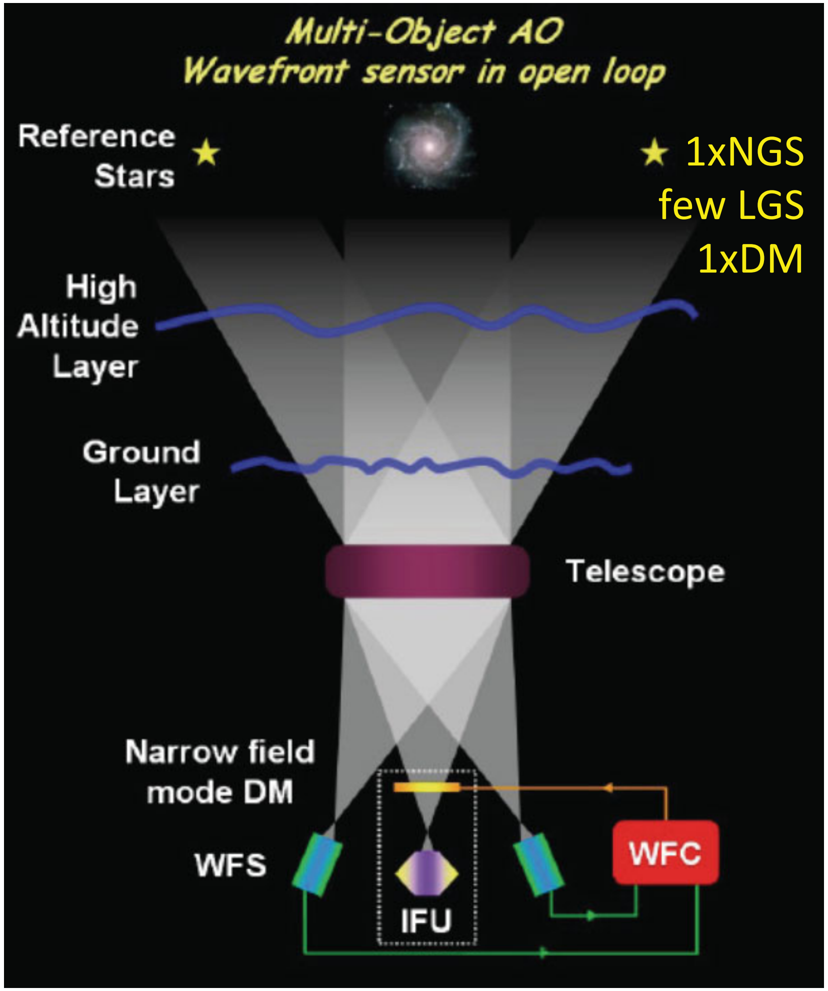
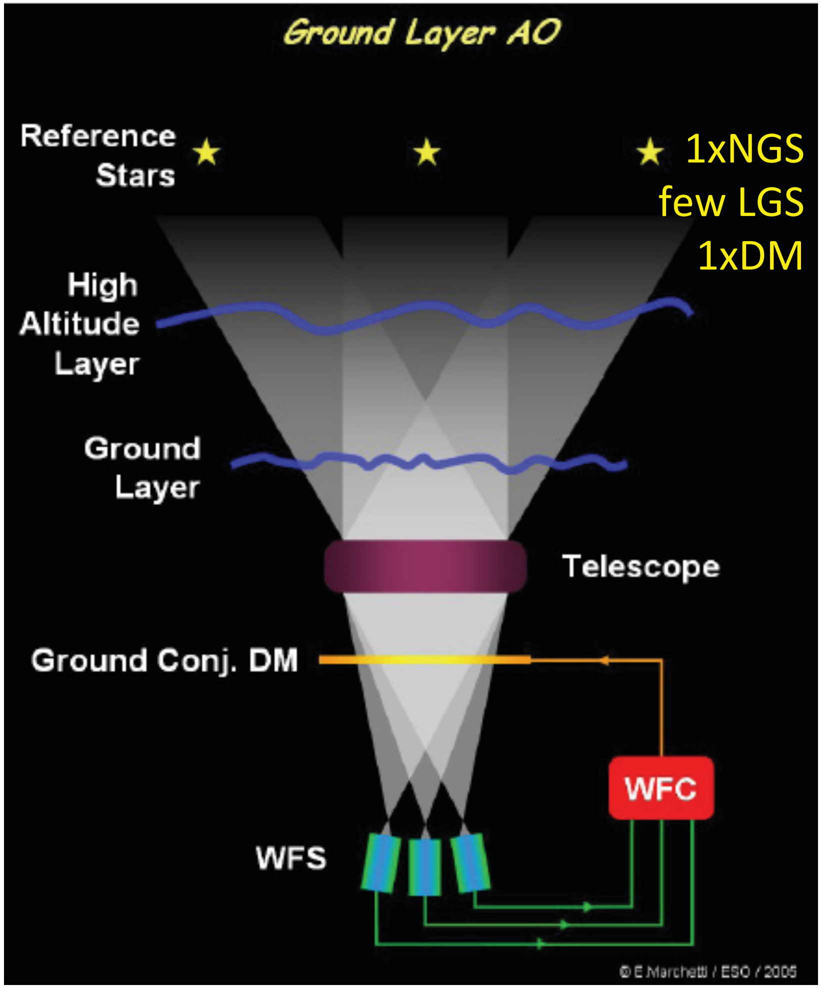


MOAO corrects a narrow field of view at multiple locations over a wide field of regard (open loop)



GLAO provides modest correction over a very wide field of view

GLAO on GMT

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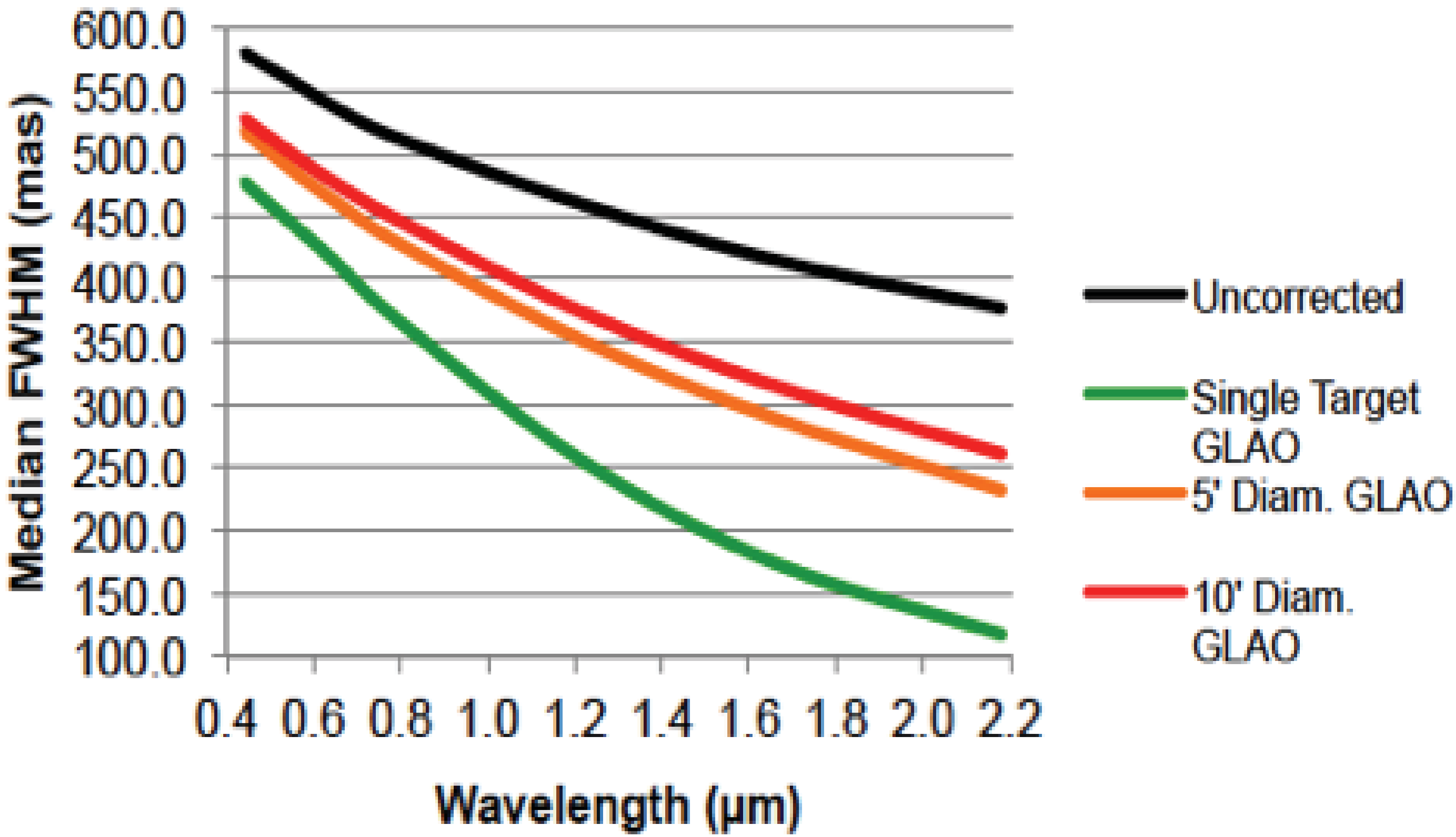

Wide fields ⇒ MOS + IFS

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- MOS = Multi-Object Spectroscopy
  - Spectroscopy of many objects over a wide field of view
  - Imaging MOS images the focal plane and uses slits to isolate targets of interest
  - Fibre MOS collects light from targets of interest using optical fibres
- IFS = Integral-Field Spectroscopy
  - Spatially-resolved spectroscopy or imaging spectroscopy
  - Obtains a spectrum for each image pixel
- Multi-IFS = multi-object IFS
  - MOS with IFS of each object!

How important is MOS/IFS for ELTs?

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- How critical are multi-object spectroscopy & integral-field spectroscopy in the ELT era?
- ESO 2015 community polling asked "What are the 3 most important capabilities for your research after 2020?"
- 40% of responses put some form of MOS or IFS facility as top 3 priorities (~80% O/NIR)
- Even with some polling biases it is clear that optical & NIR MOS/IFS are a top priority (see ESO Messenger #161, pp6-14)

Messenger #161, p9, Figs 3&4

ELTs+MOS: high multiplex, modest field

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- Multi-object spectroscopy (MOS) is most potent for science programs needing to observe either or both of…
  - Large numbers of targets per field (high multiplex)
  - Large areas of sky (wide field)
  - Survey metric: AΩ = product of aperture (m^2) and field of view (deg^2)
  - Other factors: multiplex, seeing/PSF (sky background)
- ELTs can access very large numbers of targets per field, but giant apertures mean relatively modest fields of view, and hence modest AΩ
  - GMT+MANIFEST: 368m^2 aperture, 314 $arcmin^2$ FoV ⇒AΩ = 32 m^2 deg^2 [==1]
  - TMT+WFOS: 655m^2 aperture, 25 $arcmin^2$ FoV ⇒ AΩ = 4.5 m^2 deg^2 [=1/6]
  - (E-ELT+MOSAIC: 978m^2 aperture, 32 $arcmin^2$ FoV ⇒ AΩ = 8.7 m^2 deg^2) [=1/4]
  - [cf. Subaru+PFS: 52.8m^2 aperture, 1.33 deg^2 FoV ⇒ AΩ = 70 m^2 deg^2] [>2]
  - [cf. UKST+Taipan: 1.9m^2 aperture, 28.3 deg^2 FoV ⇒ AΩ = 54 m^2 deg^2] [>1.5]
  - *AΩ is not everything, even for MOS*, as the last two examples indicate!

ELTs+IFS: a natural combination

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- Integral field spectroscopy (IFS) usually suffers from *photon starvation* — specifically, in galaxies…
  - Surface brightness (SB) profiles decline rapidly with radius
  - Cosmological surface brightness dimming ⇒ $SB \propto (1+z)^{-4}$
  - In consequence it is challenging to do spatially resolved spectroscopy of galaxies either far out in radius or far back in time
- ELTs offer significant gains in two ways…
  - As *big light buckets,* they offer D^2 light-grasp gains
  - With *adaptive optics,* they offer up to D^2 gains via smaller PSFs
- How do ELTs' smaller PSFs help for extended sources?
  - To the extent galaxy SB profiles are *smooth* there is of course no gain
  - But in fact the SB distribution in galaxies is generally *structured*, and at least partially unresolved (even by ELTs)
- For integral field spectroscopy, *ELTs offer gains of* D^2 *to* D^4

ELT integral field spectrographs

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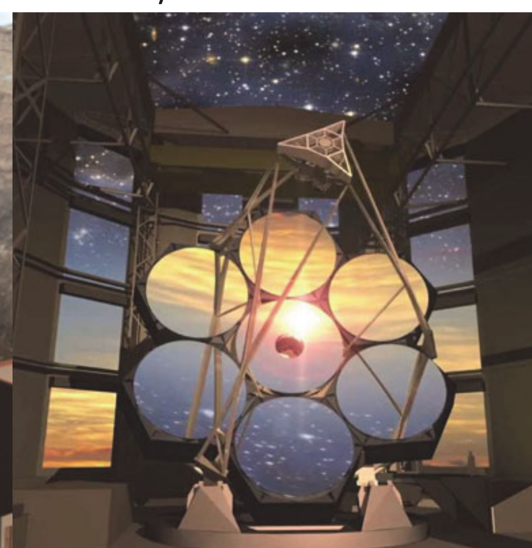
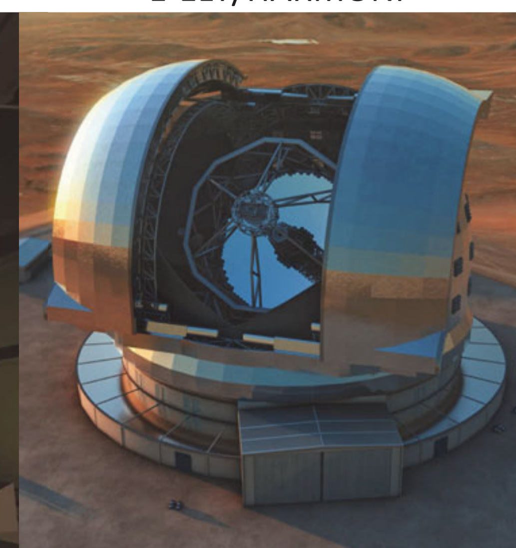
- All three ELTs have first-generation IFS instruments:
  - E-ELT (39m) – HARMONI
  - TMT (30m) – IRIS
  - GMT (25m) – GMTIFS & MANIFEST+GMACS

TMT/IRIS

GMT/GMTIFS+MANIFEST

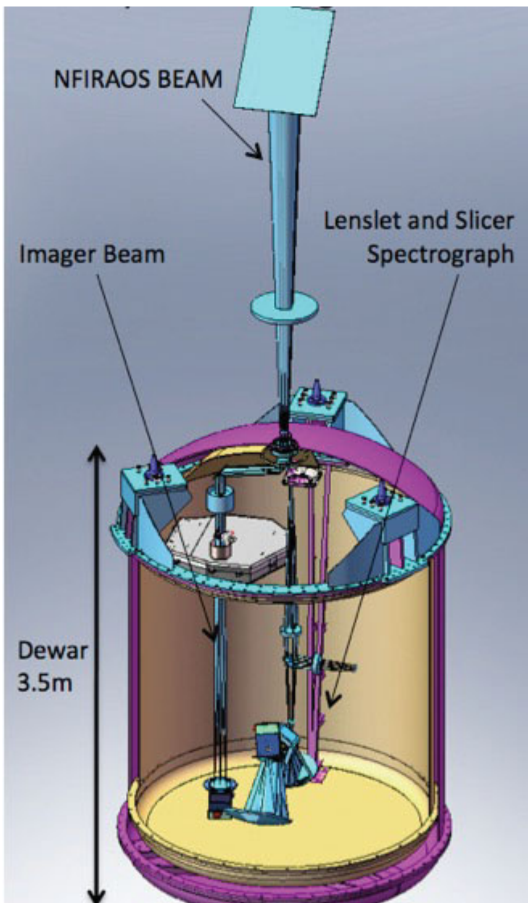


E-ELT/HARMONI



TMT + IRIS

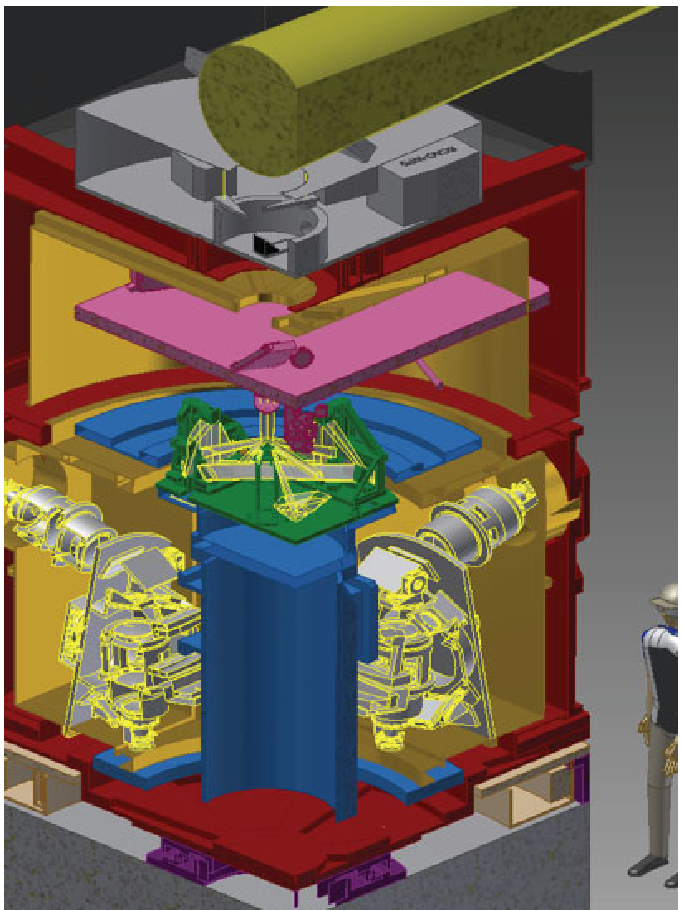
- IRIS is a NIR (0.85-2.5 μm) instrument on the TMT combining an integral field spectrograph (R~4000) and imager (17"x17")



Wavelength coverage	0.8–2.5 μm; multiple gratings (shared by lenslet and slicer)
Spectral Resolution	R=4000; potential R=8000
Spatial Scales	Lenslet: 4 mas, 9 mas Slicer: 25 mas, 50 mas
Field Size	BB=Broadband, NB=Narrowband 4mas: 0.064"x0.512"(BB); 0.458"x0.512"(NB) 9mas: 0.144"x1.152"(BB); 1.008"x1.152"(NB) 25mas: 1.1"x2.275"; 50mas: 2.2"x4.55"
Image Quality	Wavefront error less than 30 nm; coarser scales (25/50mas) may deviate
Filters	Broadband filters (Y, Z, J, H, K), Narrowband (5 % bandpass) filters, and specialized filters (< 1% bandpass)
Detector	4096 x 4096 Teledyne Hawaii-4RG + ASIC; 15 μm pixels, long-wavelength cutoff @2.5 μm; low charge persistence; highest QE

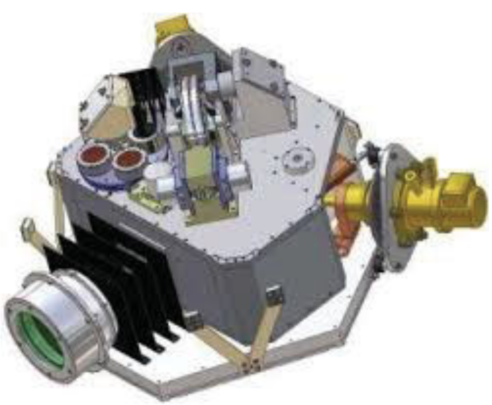
E-ELT + HARMONI

GMT



- HARMONI is an integral field spectrograph…
  - Spectral range from 0.47 µm to 2.45 µm
  - Resolving powers from R~500 to R~20000
  - 32000 (NIR), 8000 (VIS) spaxels in √2:1 field
  - Spaxel scales optimized from ultra-sensitive (coarse: 0.06"x0.03") to diffraction-limited in NIR (fine: 0.004"x0.004")
  - High throughput (35% average)
  - Variety of AO modes: GLAO, LTAO, SCAO
  - In seeing-limited conditions, offers a gain of ~25x in speed relative to MUSE on the VLT
  - Provides similar angular resolution to ALMA and comparable sensitivity to JWST

GMT + GMTIFS



- GMTIFS is an AO-corrected integral field spectrograph, that builds on ANU's experience in building NIFS for Gemini and WiFeS for the ANU 2.3m, and also a high-Strehl AO imager that builds on ANU's experience in building GSAOI for Gemini
- GMTIFS works in near-infrared (1–2.5 µm) with LTAO & NGSAO
- As a small-area, AO-corrected, integral-field spectrograph…
  - Spectral resolutions: R = 5,000 & 10,000 (Δv = 60 & 30 km/s)
  - Range of spatial sampling and fields of view:

Spaxel size (mas)	6×6	12×12	25×25	50×50
Field of view (")	0.54×0.27	1.08×0.54	2.25×1.13	4.5×2.25

- As a narrow-field, AO-corrected, imaging camera…
  - 5 mas/pixel, 20.4"× 20.4" FOV
- Other features…
  - AO-corrected NIR On-Instrument Wave-Front Sensor (180" diameter field)
  - Internal flat-field and wavelength calibration

GMTIFS science drivers

GMT

- Planets and their Formation
  - Imaging of exoplanets
  - Radial velocity searches for exoplanets
  - Structure and dynamics of proto-planetary debris disks
  - Star formation and initial mass function
- Stellar Populations and Chemical Evolution
  - Crowded population imaging
  - Chemistry of halo giants in Local Group galaxies
- Assembly of Galaxies
  - Mass evolution
  - Chemical evolution
  - IGM tomography
- First Light & Reionization
  - The reionization era
  - First Light
- Black Holes
  - Mass determinations
- Dark Energy
  - BAO at z > 4
  - Supernovae at z > 1

E-ELT + HARMONI science drivers

GMT

Session 2: Transients
Overview of transient science with the E-ELT/HARMONI
Superluminous Supernovae: progenitor scenario and distance probes from current days to the E-ELT era
Distant Type Ia Supernovae with HARMONI

DAY 2: Tuesday 30th June 2015

Session 3: Stellar Evolution I
Stellar evolution in the light of spectroscopy
Massive stars in the Local Universe
Surveying star forming regions in the E-ELT era
Resolved Stellar Populations with HARMONI
Coffee
Session 4: Stellar Evolution II
Ultrafaint dwarfs - relics from before reionization
Resolving stellar populations with crowded field 3D spectroscopy
RSGs
Chemo-dynamics of galaxies from resolved stellar populations with HARMONI
Lunch
TMT
TMT-IRIS
Session 5: Galaxy Formation & Evolution I
Galaxy evolution at the peak epoch of cosmic star formation
Observations of U/LIRGs-like systems with HARMONI
Tracing kinematic (mis)alignments in CALIFA interacting galaxies: A local-Universe yardstick for high-z mergers
Tea
Session 6: Galaxy Formation & Evolution II
Stars' turbulent birth in galactic collisions.
Galacitc Winds of low mass galaxies
Disentangling the chemical and physical properties of metal-poor star-forming galaxies with high-resolution emission line imaging
3D kinematics of intermediate redshift galaxies

DAY 3: Wednesday 1st July

GMT
The Giant Magellan Telescope Integral Field Spectrograph
Session 7: Solar System
The Contribution of HARMONI for Solar System Studies
The main belt to the Kuiper belt: simulating HARMONI observations in the solar system
Coffee
Session 9: Black Holes & AGN
Supermassive Black Holes in Galactic Nuclei
Black holes with HARMONI
Intermediate-mass black holes with HARMONI
Lunch
Session 10: Galaxy Formation & Evolution III
Galaxy formation and evolution from the perspective of nearby galaxies
The diffuse ISM and diffuse interstellar bands observed with HARMONI
Spatially resolved studies of Diffuse Interstellar Bands beyond the Local Group
Molecular gas in center of the Galaxy, from SPIFFI to HARMONI
JWST
NIRSpec: the first slit-based MOS spectrograph in space
Tea
Session 10: Galaxy Formation & Evolution IV
Cosmological Simulations of Galaxy Formation
Simulation-based integral field spectroscopy studies of high-z galaxies with E-ELT/HARMONI
From cusp to core dark matter haloes
Conference Photo
Conference Dinner

DAY 4: Thursday 2nd July 2015

Session 11: Exoplanets & Disks
Direct detection of extra-solar planets and debris disks
Spectral characterization of exoplanets with HARMONI: estimation of the achievable contrast levels.
Disk Review & METIS
Preparing for HARMONI: Lessons learned from early SPHERE observations
Coffee
Session 12: Galaxy Formation & Evolution V
Resolved observations of high z galaxies using strong lensing
IFU studies of high-z star-forming galaxies through cosmic telescope: ELT science in 2015!
Metallicity gradients and resolved chemical abundances in high-z lensed galaxies
Lunch
Session 13: Galaxy Formation & Evolution VI
Absorption line spectroscopy of the first passive galaxies
Integral Field Unit Observations of High Redshift Dusty Quasars

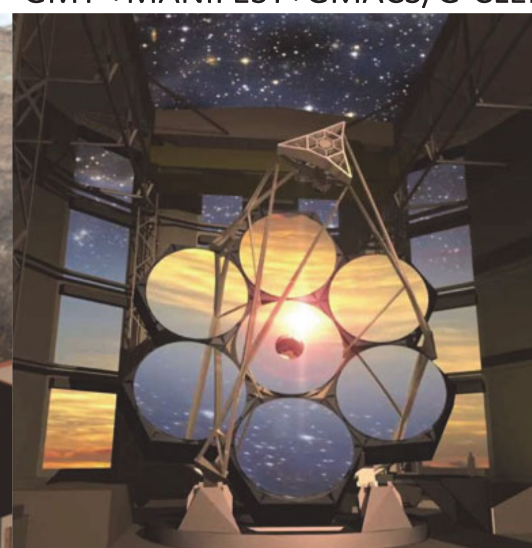
ELT Multi-Object Spectrographs

GMT

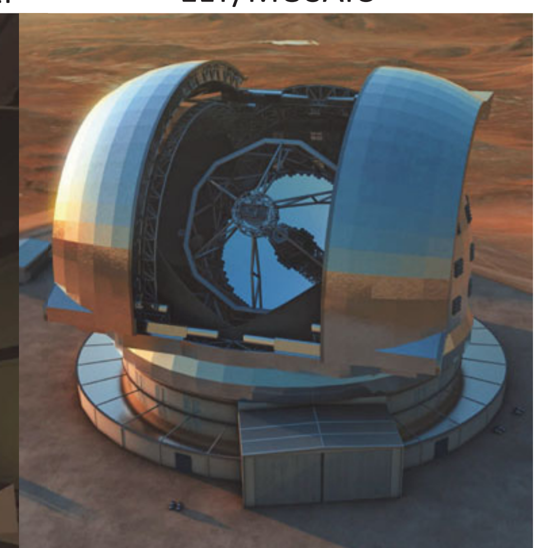
- Both GMT and TMT have first–generation MOS instruments, while the E-ELT has a possible second-generation MOS:
  - GMT (25m) – GMACS (imaging MOS) &
    MANIFEST+GMACS/G-CLEF (fibre MOS)
  - TMT (30m) – WFOS (MOBIE)
  - E-ELT (39m) – ELT-MOS (MOSAIC)

TMT/WFOS

GMT +MANIFEST+GMACS/G-CLEF



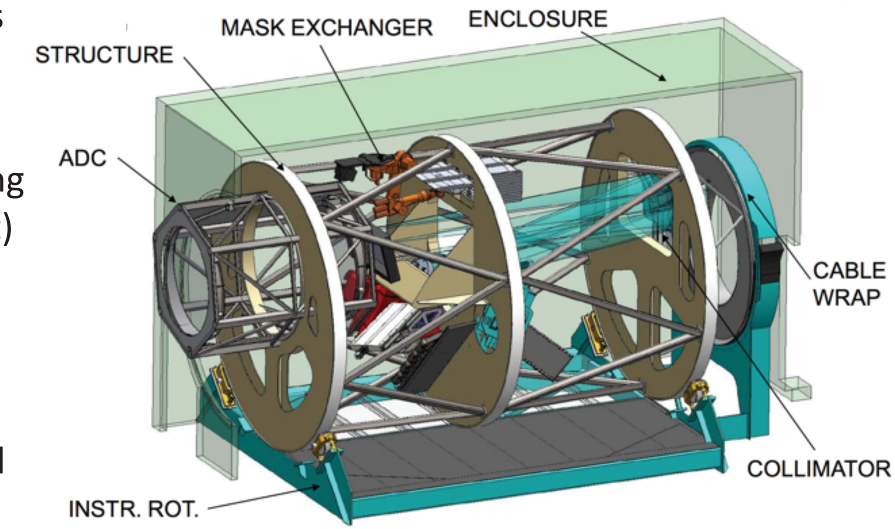
ELT/MOSAIC

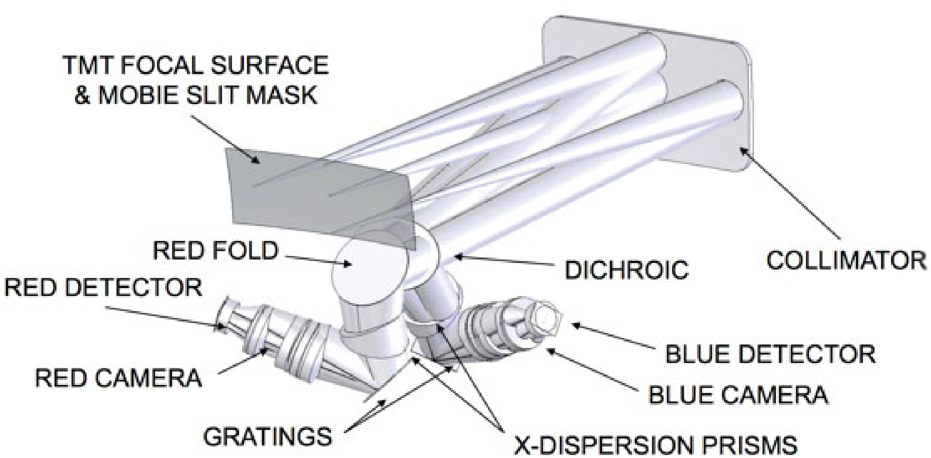


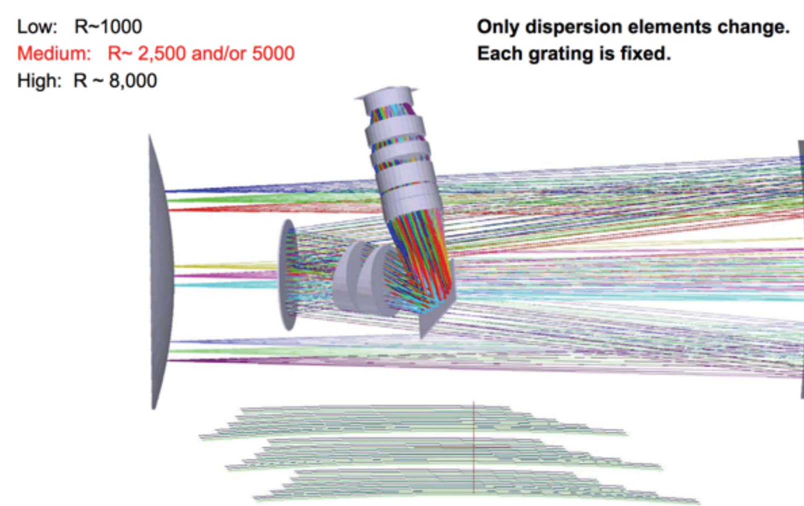
TMT + WFOS

GMT

- TMT's Wide Field Optical Spectrometer (WFOS) is realised as the Mutli-Object Broadband Imaging Echellette (MOBIE) instrument
- MOBIE provides NUV/optical (0.3–1.1 µm) imaging and spectroscopy at R=1000-8000 (for a 0.75" slit) over a 25 arcmin^2 FoV
- Focal plane masks offer single-object long-slit & multi-object short-slits (multiplex of a few 100)
- MOBIE will include an ADC and operate in natural seeing (uncorrected images)
- Red & blue arms; imaging & 3 spectroscopic modes



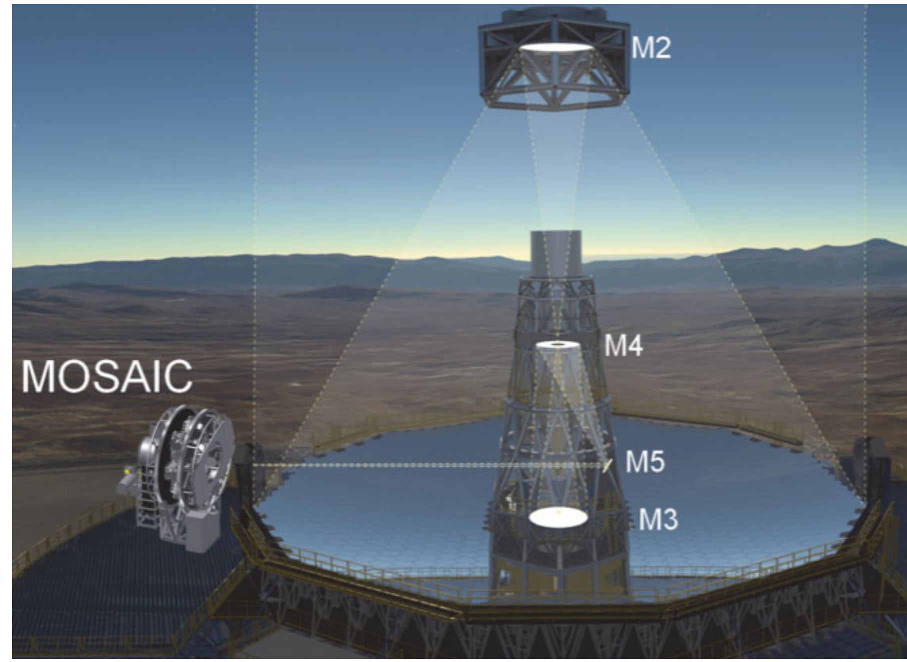




E-ELT + MOSAIC

GMT

- MOSAIC is a *potential* second-generation instrument for E-ELT
- MOSAIC has 3 operating modes
  - a high multiplex mode (HMM) covering the visible and NIR
  - a high definition mode (HDM) that will provide spatially resolved observations in the near-infrared
  - a multi light bucket integral field mode for the inter-galactic medium mode (IGM)



- HMM-visible: 0.4-0.8μm, 200 objects, R=5000/15000, 32 arcmin^2 FoV, seeing-limited or GLAO
- HMM-infrared: 0.8-1.8μm, 100 objects, R=5000/15000, 32 arcmin^2 FoV
- HDM: 0.8-1.8μm, R=5000, 10 IFUs each 2”x2” FoV @ 0.75mas, requires MOAO

GMT+MANIFEST - full-field MOS & IFS

GMT

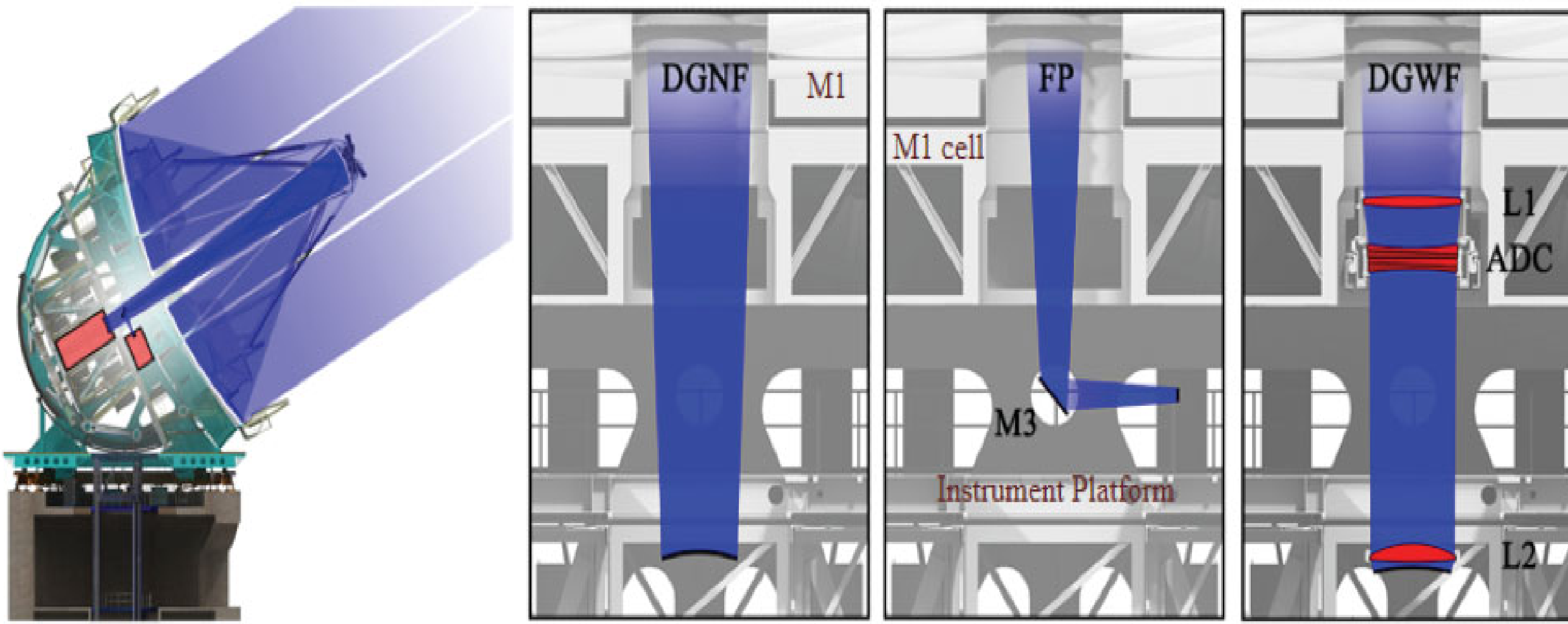
- MANIFEST is a versatile fibre feed and positioner servicing *all* of GMT's natural-seeing and GLAO spectrographs (GMACS, G-CLEF at first, and NIRMOS in future)
- MANIFEST is not an instrument per se, it is a facility for spectrographs (MANIFEST maximizes use of the focal plane, just as AO maximizes the image quality)
- MANIFEST offers a range of advantages, including…
  - ① increased fields of view for all instruments
  - ② multiple deployable IFUs in a variety of sizes
  - ③ increased spectral resolution (factor 3-8) via image-slicing
  - ④ efficient detector packing, both spectrally and spatially
  - ⑤ feed narrow spectrograph field from fibres with wide FOV
  - ⑥ simultaneous observations with multiple instruments
  - ⑦ feed spectrographs at gravity-invariant locations
  - ⑧ potentially, OH sky-line suppression in the near-infrared

The GMT instrument suite

GMT instrument focal stations

GMT

The GMT light path (blue) and instrument focal stations



GMT = the complete telescope

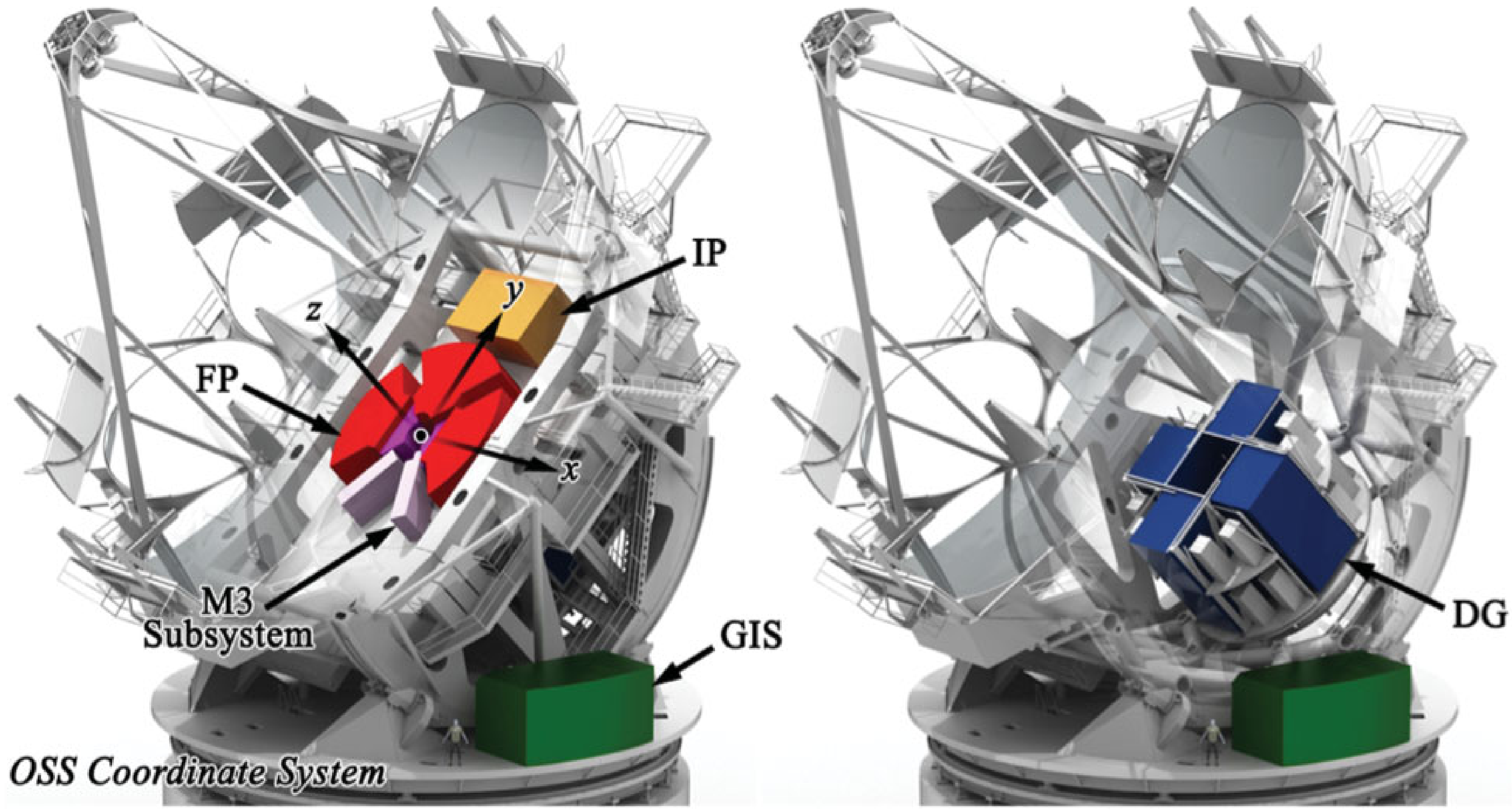
DGNF = direct Gregorian narrow focus (no corrector)
MANIFEST-narrow

FP = one of 3 folded ports
GMTIFS

DGWF = direct Gregorian with wide field corrector (red)
MANIFEST-wide

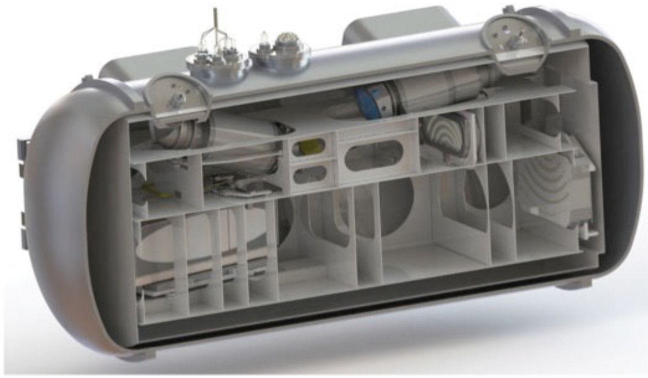
Instrument locations

GMT



A cutaway view of the GMT's focal stations showing. The red, blue, and green rectangular boxes indicate the volumes available to instruments at the folded ports (FP), direct Gregorian (DG), and gravity invariant station (GIS) mounting locations, and additional instrument space on the fixed instrument platform (IP).

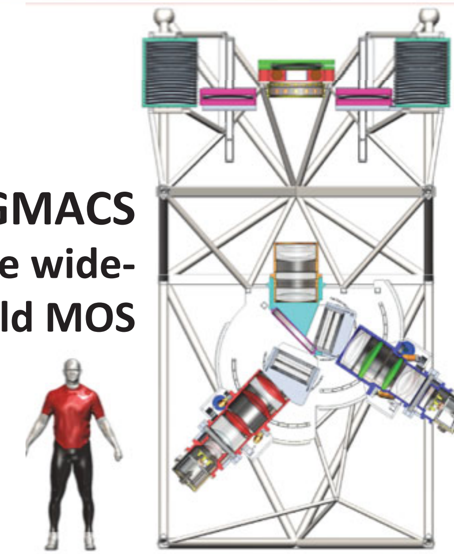
First-generation GMT instruments



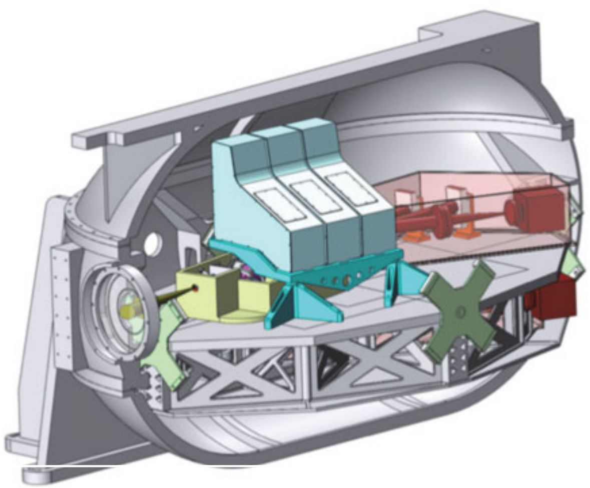
G-CLEF
high-resolution
echelle

GMT

GMACS
visible wide-
field MOS

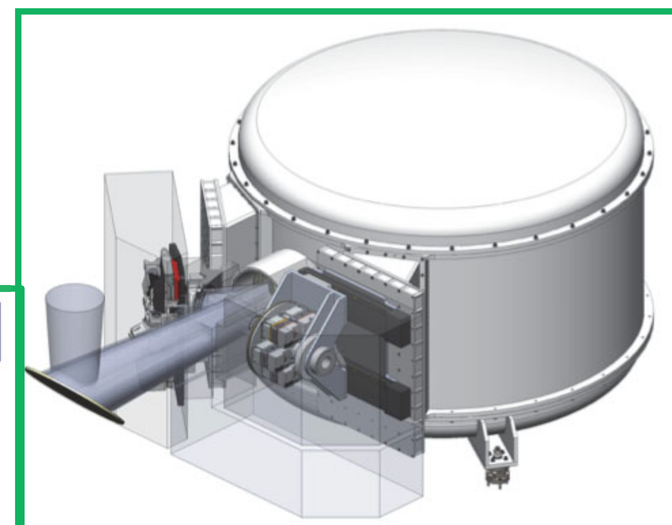


MANIFEST
facility fibre
system



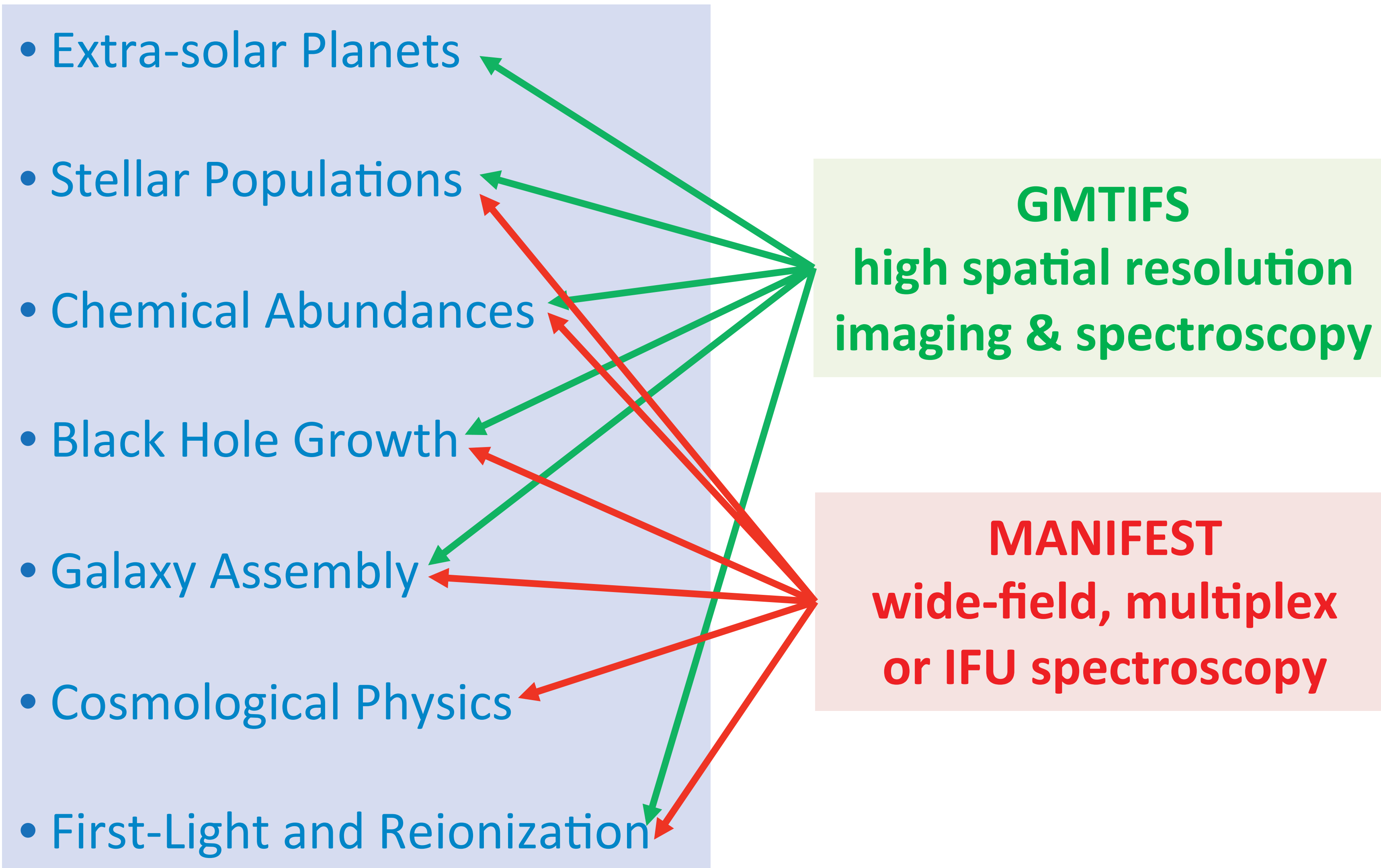
GMTNIRS
AO-fed 1-5 micron echelle

GMTIFS
AO-fed IFU
spectrograph
and imager



GMT science ↔ GMT instruments

GMT



GMTIFS science

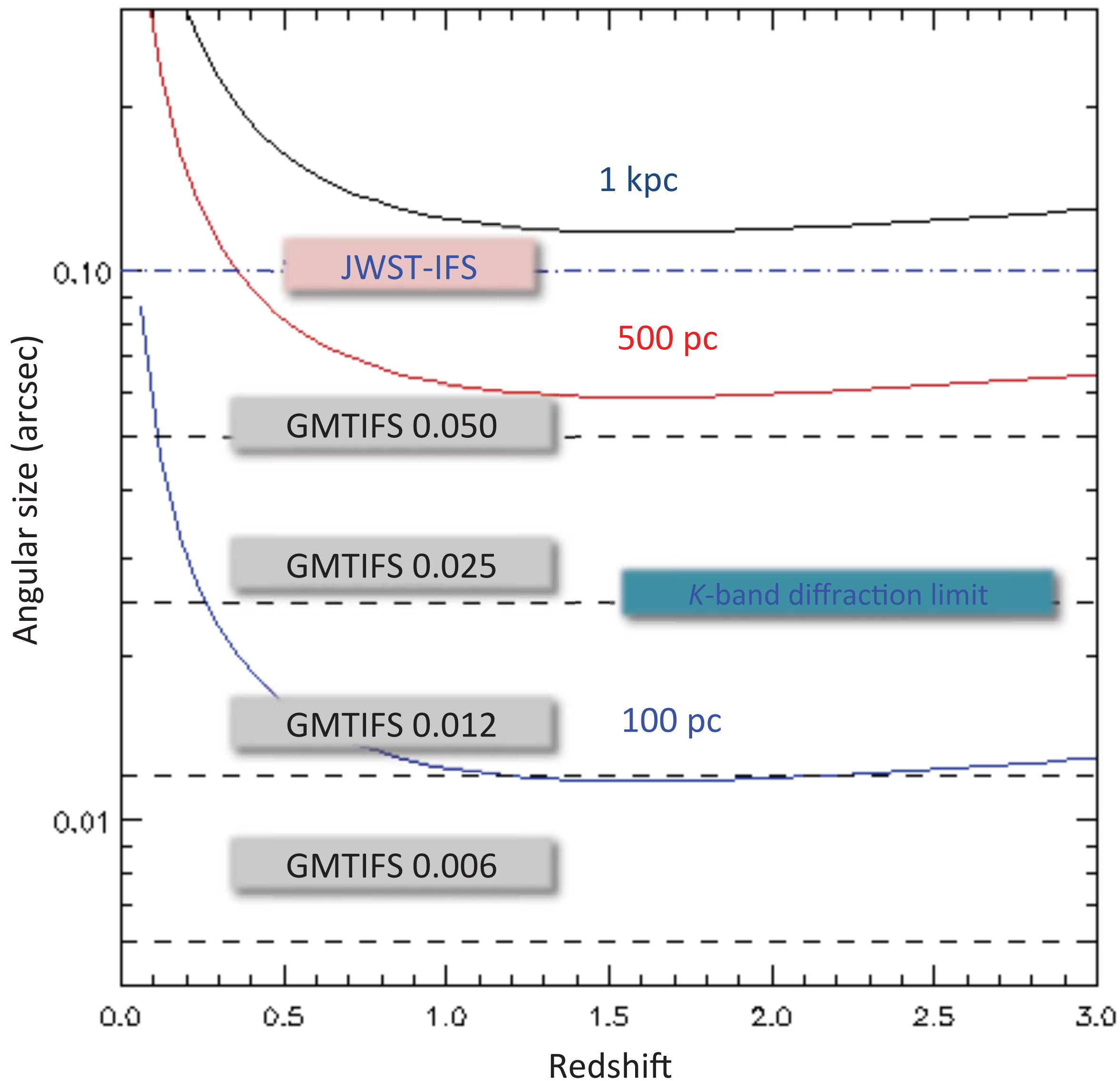
GMTIFS science & technical reqs

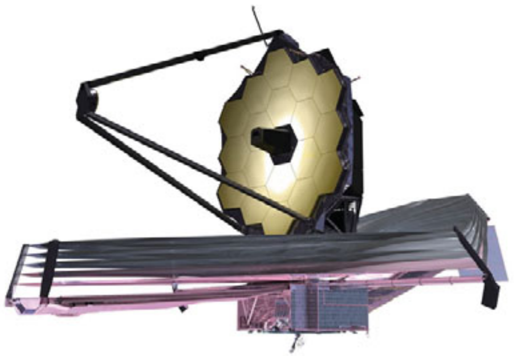
GMT

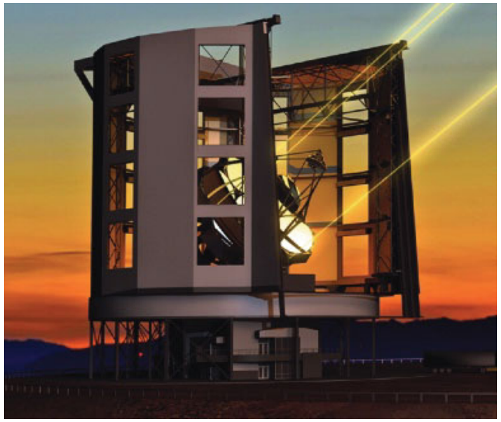
Science Application	λ range	λ/Δλ	Notes
Internal structure and dynamics of distant galaxies	1-2.5 μm	5,000	Kinematics, line widths, abundances, star formation rates [LTAO coarse pitch]
Black hole masses and AGN physics	1-2.5 μm	5,000	Emission line kinematics, bulge velocity dispersions, line ratios [LTAO fine pitch]
Young stellar objects	1-2.5 μm	5,000	Outflows, line profiles, excitation levels [LTAO fine pitch]
IMF in dense star clusters	1-2.5 μm	5,000	Line indices, velocities [LTAO fine pitch]
SNe and GRB spectroscopy	1-2.5 μm	5,000	SNe and GRB redshifts, SNe physics, reionization studies [LTAO coarse pitch]
Technical Parameter	**Requirement**	**Goal**	**Notes**
Wavelength range	1-2.5 μm	0.9-2.5 μm	
Spectral resolution	R > 3,000	R > 5,000	Resolution for fine spatial scale
Spatial resolution element fine pitch	≤ 10 mas	–	
Spatial resolution element coarse pitch	≥ 30 mas	50 mas	
Field of view fine pitch	1 arcsec^2	1" x 1"	
Field of view coarse pitch	7 arcsec^2	3" x 3"	
Image quality	Diffraction-limited	–	
Throughput	≥ 20%	–	Exclusive of atmosphere, telescope, and slit losses
Imaging mode	–	Full LTAO field	Optional

Spatial resolution is key

GMT



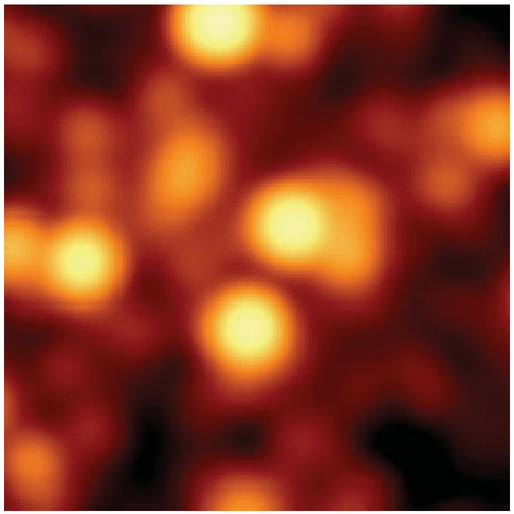




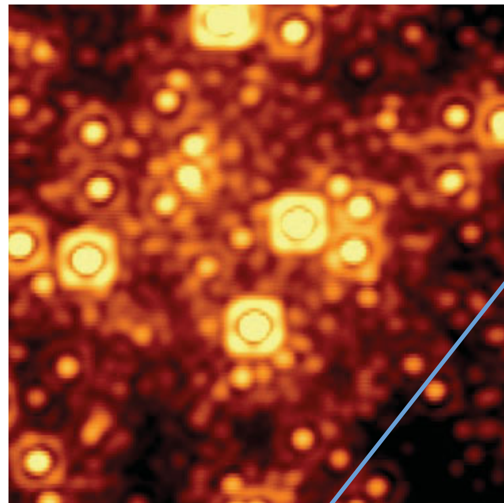
GMT image simulations

GMT

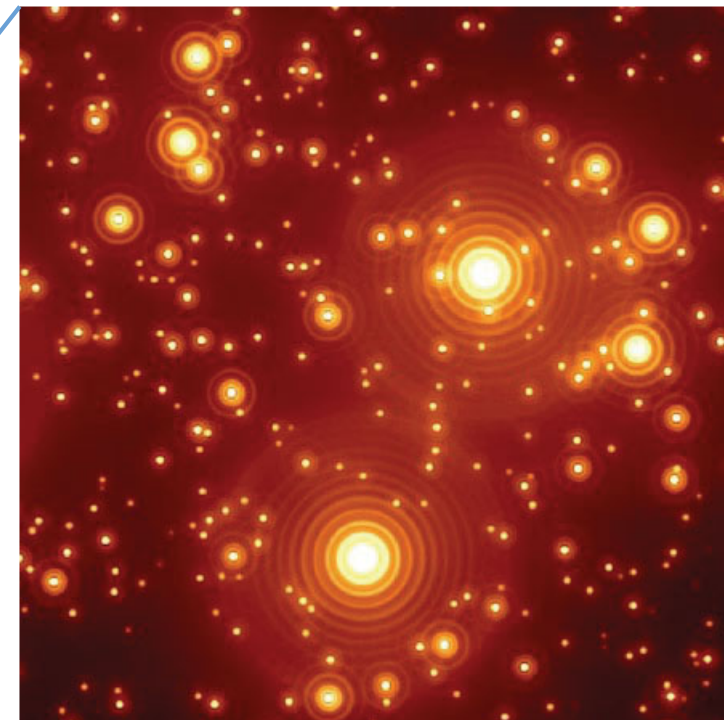
Natural Seeing 0.6”



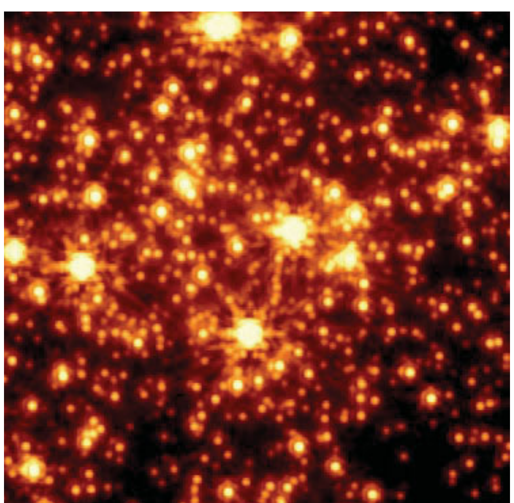
HST/NICMOS



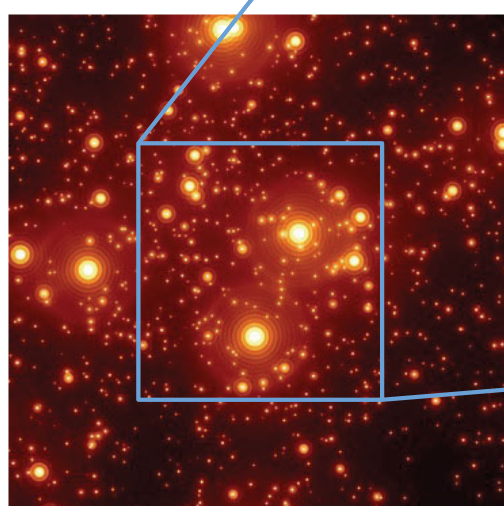
GMT Strehl: 80%



JWST NIRCAM

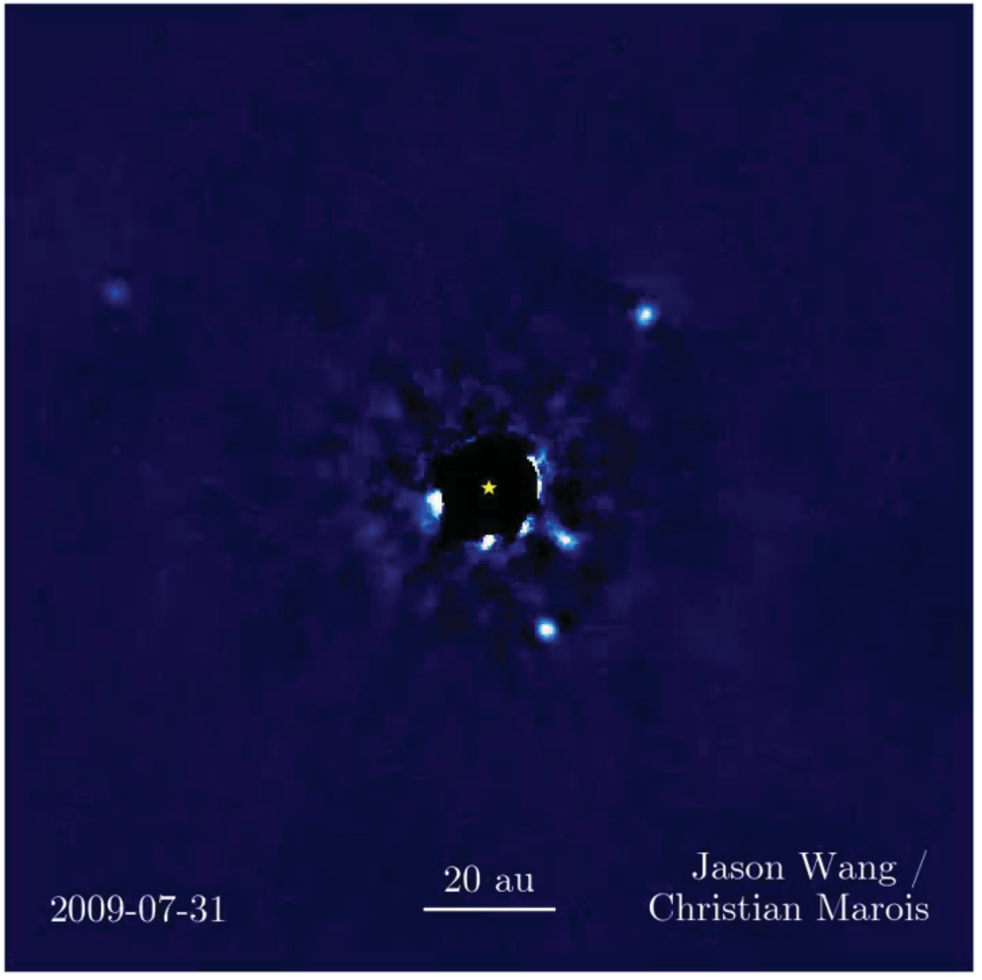


GMT Strehl: 80%



Imaging other planetary systems

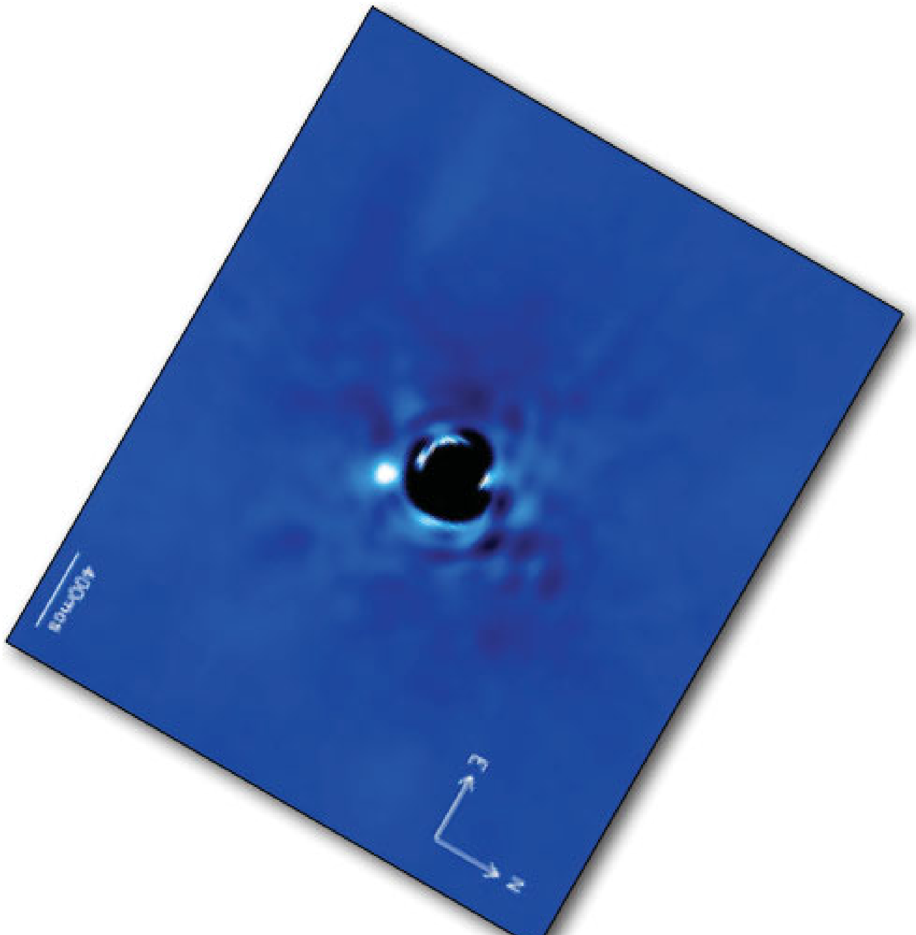
GMT



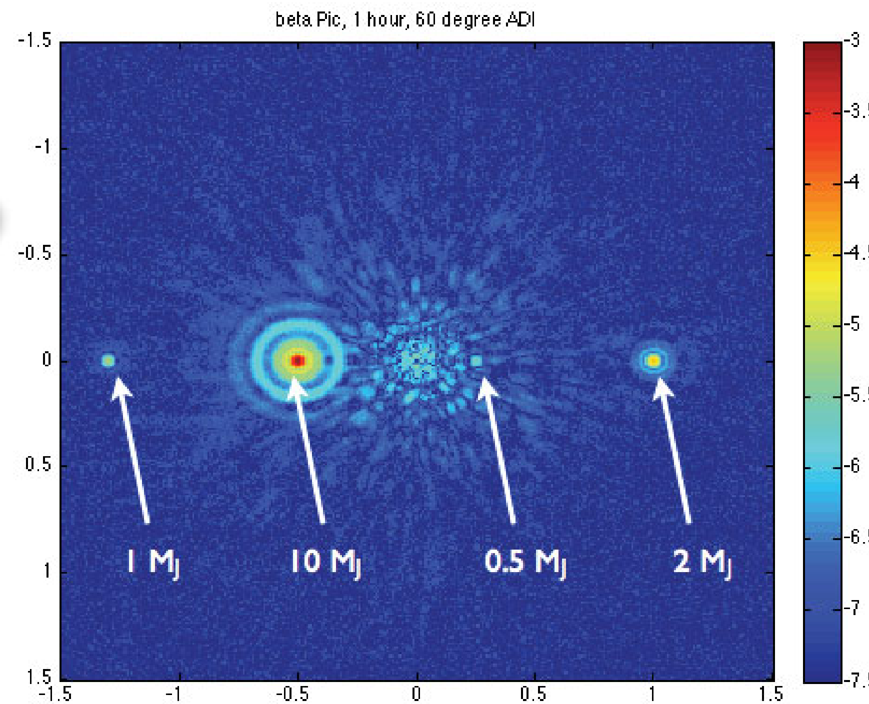
GMT imaging of exoplanets

GMT

GMT will image giant planets to 150pc and Earth-like planets within 10pc



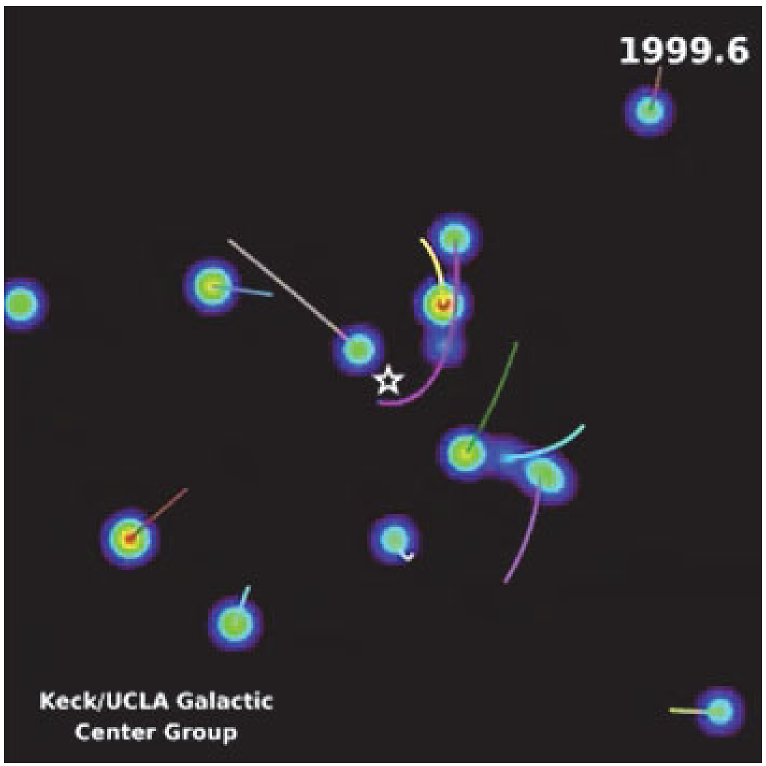
VLT L' observation

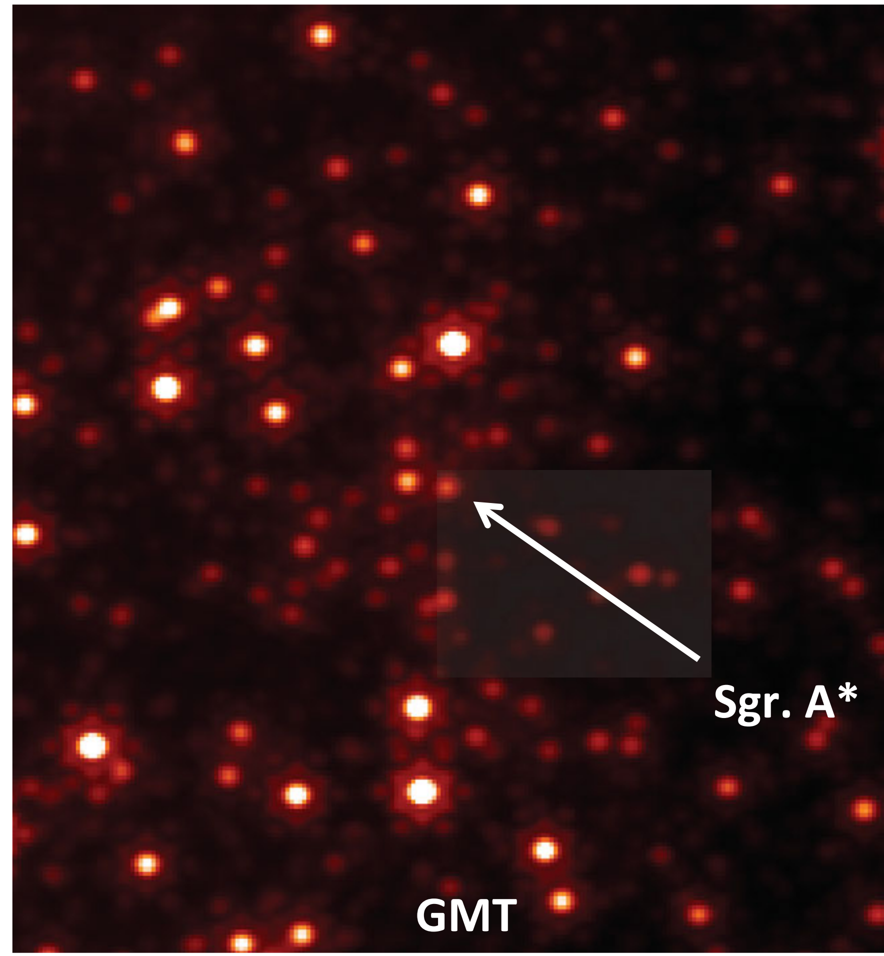


GMT L' simulation

Weighing the Milky Way's black hole

GMT

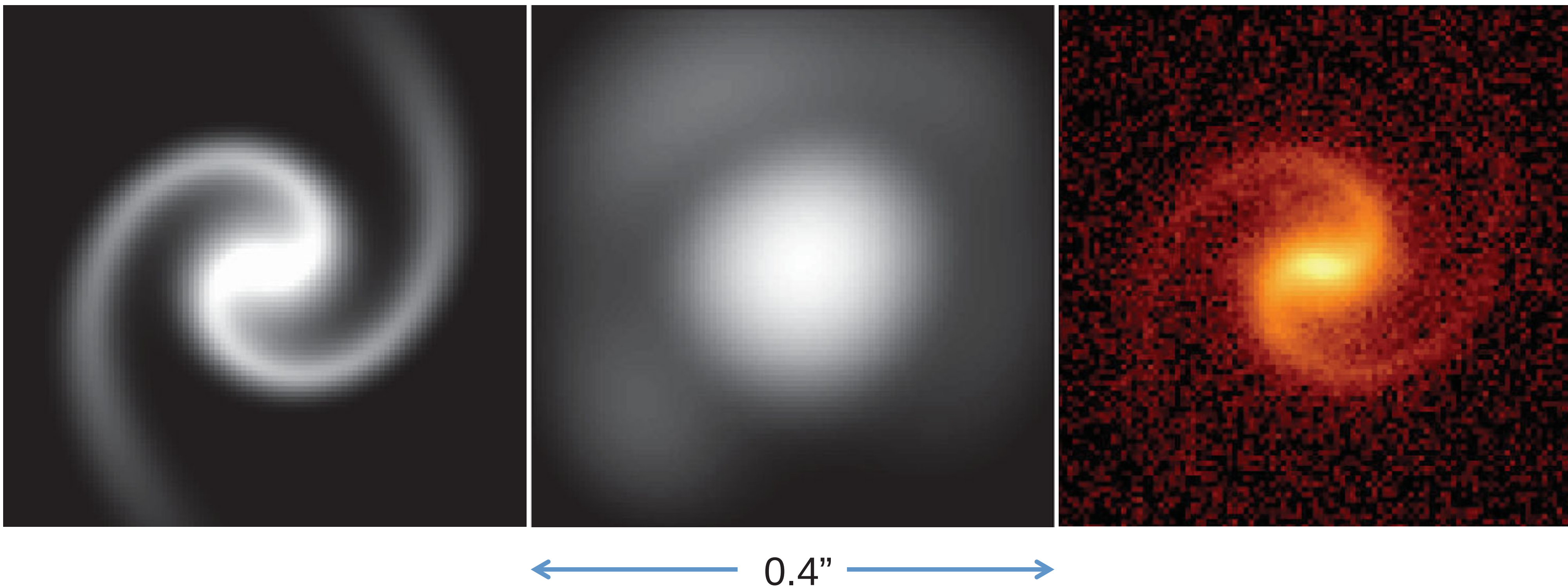




Galaxies at peak star formation

GMT

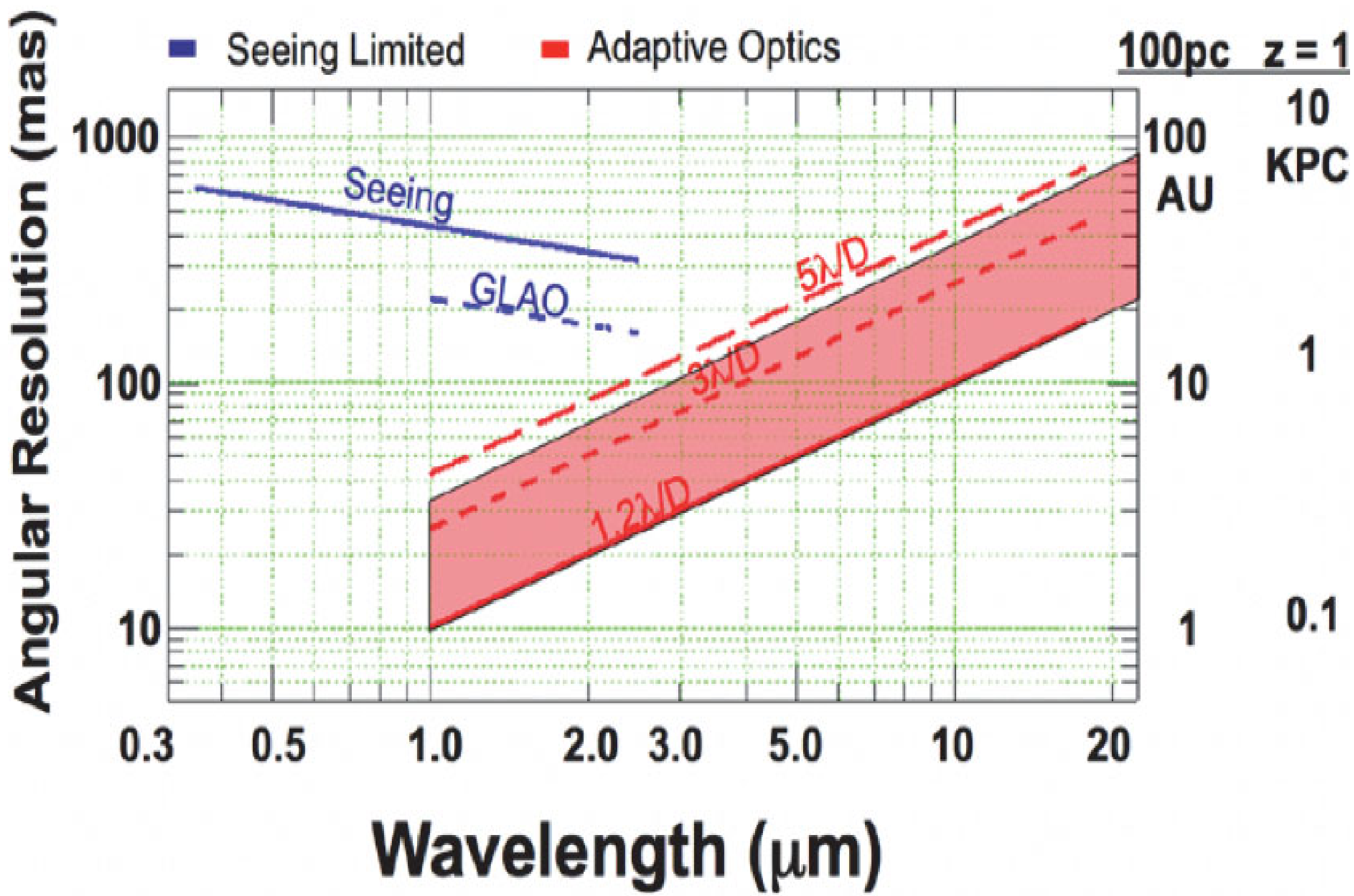
Model | HST NIC2 J-band | GMT H-band, Strehl=0.8



GMT gains in angular resolution

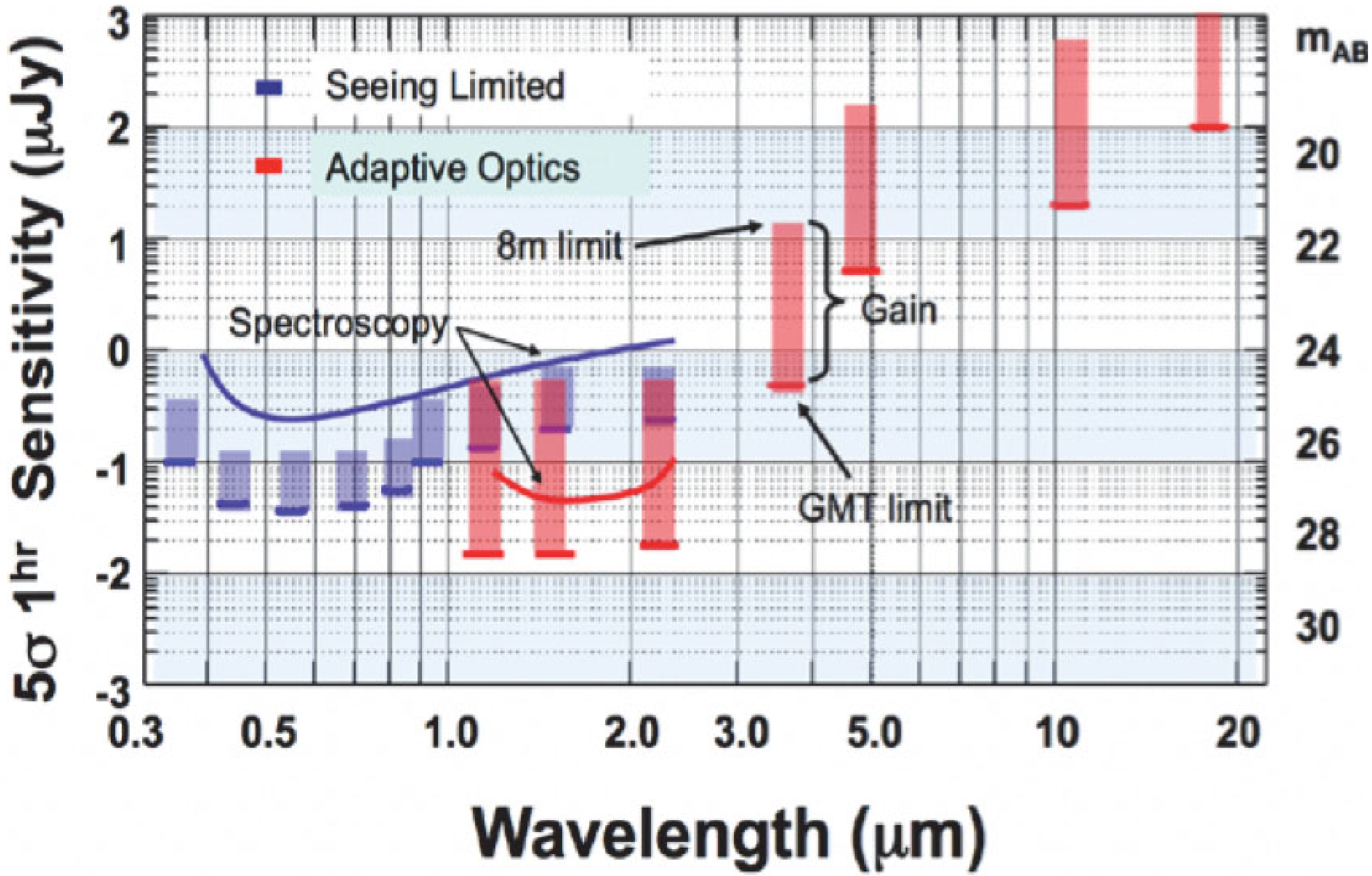
GMT

The gains in angular resolution of GMT+AO relative to 8m+AO – top of range is 8m diffraction limit and bottom is GMT diffraction limit (defined by 1.2λ/D Rayleigh criterion); dashed lines show GMT's 3 and 5 λ/D resolution for contrast limited cases (e.g. exoplanet around bright star); seeing-limited and GLAO resolutions do not scale with aperture



GMT gains in sensitivity

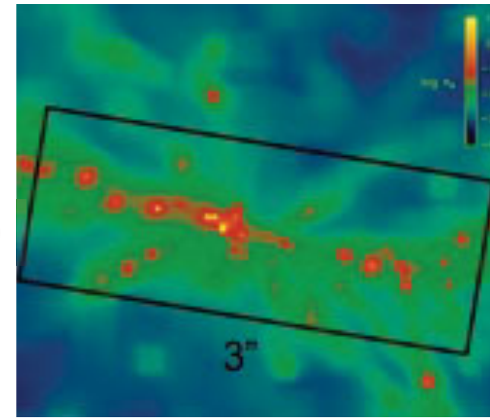
GMT's imaging sensitivity relative to that of an 8m telescope for a 5σ detection in one hour – top of range is 8m sensitivity and bottom of range is GMT sensitivity for natural seeing and adaptive optics; also spectroscopic sensitivity curves

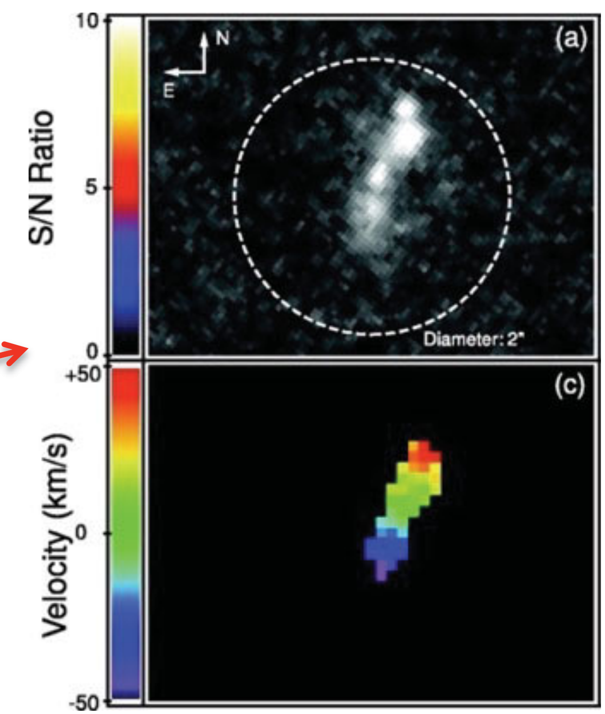


First light & high-redshift galaxies

GMT

- **First Light:** ELTs with AO and IFS will be able to identify and characterize the first galaxies and (potentially) individual Population III stars, as in this simulation of a forming galaxy at z=12.5 *[Dense hydrogen gas (orange) shows the Pop III stars forming; overlay is 1"x3" field (3.6x11 kpc), close to the TMT+IRIS 0.025" slicer scale]*





- **High-z galaxy dynamics and morphologies:** ELTs with AO and IFS will be able to trace galaxy formation and mass assembly over the redshift range $1 < z < 5$ using Hα, Hβ, [OIII] etc. to map the 2D dynamics of galaxies during the peak epoch of star formation and AGN accretion

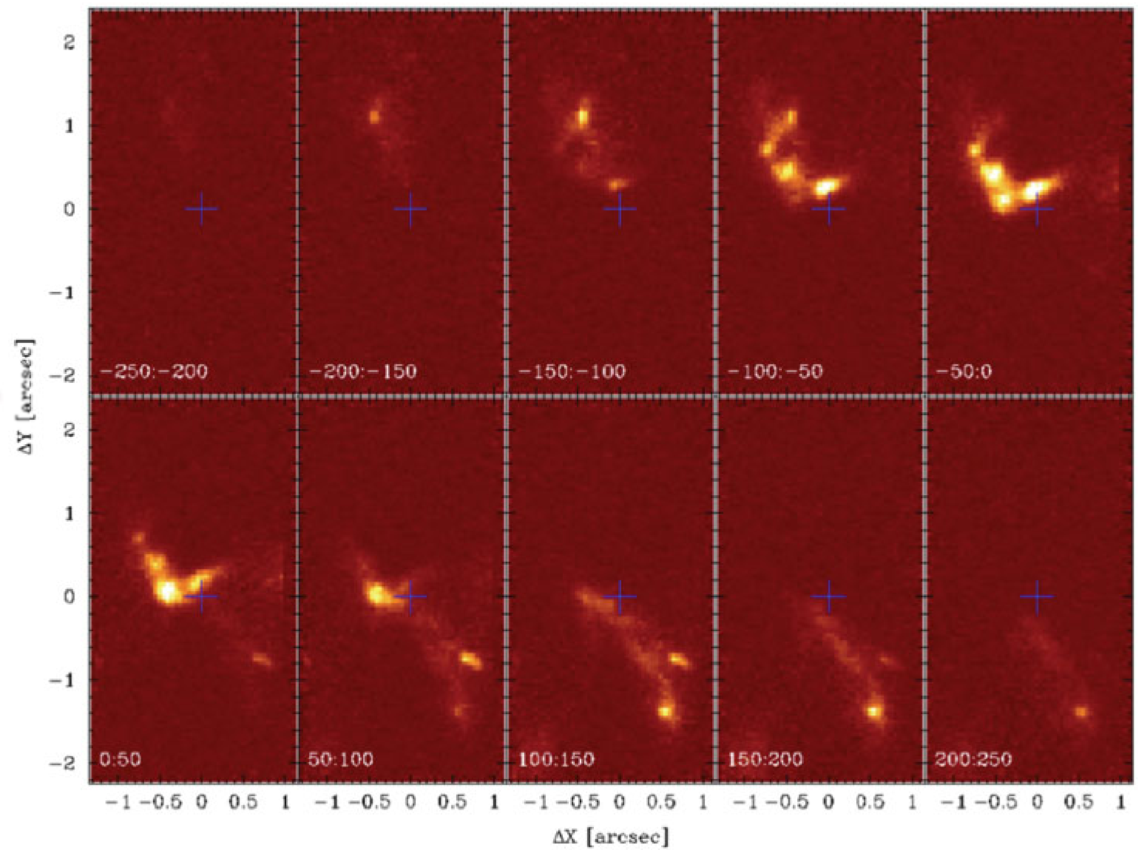
Dynamics of high-redshift galaxies

GMT

Simulated GMT +GMTIFS velocity channel maps from observation of a z=1.5 galaxy

An ordered velocity field of +/-200 km/s imposed on a HUDF *i*-band ACS image

Simulation assumes 50 mas spaxels and a total line flux of 1.1×10^{-16} erg cm^{-2} s^{-1} observed over 12 hours (9 hour source + 3 hour sky)



MANIFEST science

GMT

MANIFEST science & technical reqs

GMT

Mode a = visible, single fibers or IFU bundles, low resolution spectroscopy

Mode b = NIR, single fibers, low resolution spectroscopy

Mode c = visible, single fibers, high-resolution spectroscopy

Science Application	λ range	λ/Δλ	Mode	Notes
Star formation and chemical evolution in galaxies	400-1000 μm	~2000	a, b	Abundances, stellar populations and ages, star formation rates
Massive galaxy assembly	500-1000 μm	~3000	b	Stellar ages, stellar populations, velocity dispersions, rotation curves
Chemical tagging of Milky Way structures	320-1000 μm	~50000	c	Abundance and kinematic studies of tidal streams
Dark matter distributions	400-800 μm	~5000	a	Dynamics of clusters, planetary nebulae, resolved stellar populations
Evolution of galaxy clustering	400-900 μm	~2000	a	Large-scale galaxy surveys
Tomography of the IGM	400-900 μm	~2000 & ~10000	a, c	Galaxy surveys and IGM tomography with faint background sources
Technical Parameter	**Requirement**	**Goal**	**Notes**	
Wavelength range	400-900 nm	320-1100 nm 1-1.6 μm	Two sets of fibers may be needed to address visible and near-IR	
Patrol field	20' diameter	–	Should reach full extent of corrected field	
Positioning accuracy	0.1" RMS	–		
Setup time	≤ 8 min	–	Should not add more than 25% overhead to observation for most applications	
Throughput	≥ 60%	≥ 80%	Includes coupling and transmission losses; excludes input losses, telescope and atmosphere	
Multiplex factor	> 150	–	Feed for optical low-resolution spectrograph	
Multiplex factor	> 10	–	Feed for optical high-resolution spectrograph	
Multiplex factor	> 100	–	Feed for near-IR spectrograph	

GMCS instrument requirements

GMT

Science Application	λ range (nm)	λ/Δλ	Notes
Star formation and chemical evolution in galaxies	400-1000	~2000	Abundances, stellar populations and ages, star formation rates [slit MOS]
Massive galaxy assembly	500-1000	~3000	Stellar ages, stellar populations, velocity dispersions, rotation curves [slit MOS]
Dark matter distributions	400-800	~5000	Dynamics of clusters, PNe, resolved stellar populations [slit MOS]
Evolution of galaxy clustering	400-900	2000	Large scale galaxy surveys [fiber MOS]
Tomography of the IGM	400-900	2000 & 10000	Large galaxy surveys, IGM tomography with faint background sources [slit and fiber MOS]
Technical Parameter	**Requirement**	**Goal**	**Notes**
Wavelength range	320-980	320-1000	
Spectral resolution	≥ 1000 (at 600 nm)	–	Baseline: 0.7″ slit widths
Multiplex factor	> 100	–	For slit-fed mode
Field of view [slit-fed]	35 arcmin^2	45 arcmin^2	
Field of view [fiber-fed]	20′ diameter	–	
Field of view [imaging]	35 arcmin^2	45 arcmin^2	Imaging capability is desired only if it does not compromise spectrograph performance
Image quality	0.24″ at 10′ field radius	0.16″ at 10′ field radius	Should not degrade images from telescope and site by more than 5%
Velocity stability	< 0.1	–	Flexure in units of spectral resolution element in one hour of observation
Throughput	≥ 25% 500-800 nm	≥ 35% at blaze peak	Exclusive of atmosphere, telescope, and slit losses

G-CLEF instrument requirements

GMT

Science Application	λ range	λ/Δλ	Notes
Stellar abundance studies	320-1090 nm	≥40,000	e.g. extreme metal poor stars [single object mode]
Line profile studies	320-1000 nm	~100k	e.g. isotopic studies, atmospheric physics [single object mode]
Exoplanet atmospheres	380-650 nm	~50k	Transit spectroscopy [single object mode]
IGM abundances and dynamics	450-1000 nm	30-50k	Line profile studies [single object mode]
Reionization of the IGM	800-1000 nm	10-30k	Gunn-Peterson effect [single object mode]
Stellar dynamics in resolved populations	400-950 nm	–	Single or few orders, precision velocities [fiber feed]
IGM tomography	320-600 nm	~20k	Faint background sources over a 20-arcminute diameter field [fiber feed]
Technical Parameter	**Requirement**	**Goal**	**Notes**
Wavelength range	400-950 nm	320-1100 nm	He I 10830 coverage desired, but not required
Spectral resolution	RΦ ≥ 30,000	–	Baseline 'resolution-slit size' product for 0.7″ slit width
Image quality	< 0.25″	< 0.15″	FWHM broad-band, absent seeing
Slit length	≥ 3″	–	Should allow simultaneous sky sampling when observing point sources
Velocity stability	≤ 100 m/s	–	Precision velocity work is the subject of a separate instrument request
Throughput	≥ 20%; 400-900 nm	≥ 30%; 400-900 nm	Exclusive of slit losses, ADC, telescope and atmosphere

Galactic archaeology

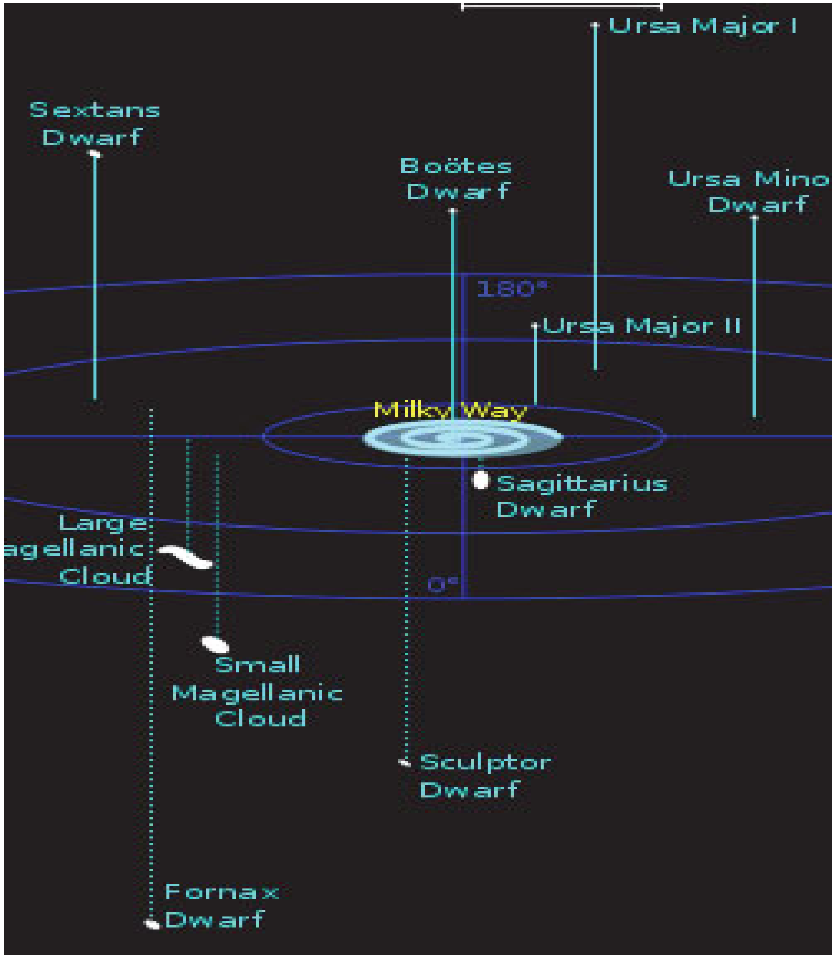
GMT

- Galactic archaeology collects detailed information for large numbers of individual stars in our Galaxy and its satellites to study the universal processes of galaxy formation and evolution in fine detail
  - initial mass function for stars and star clusters across Galactic history
  - track chemical evolution through high-dimensional abundance space
  - quantify effects of various processes responsible for radial migration
- GMT will be in a powerful position in this field
  - With GMACS and G-CLEF, GMT is the only ELT to have low- and high-resolution spectroscopy across the optical waveband at first-light
  - With MANIFEST, GMT offers wide-field multi-object spectroscopy with both GMACS and G-CLEF
- Opportunities include:
  - Understanding the origins of Galactic extremely metal-poor stars
  - Full membership identification and self-enrichment histories for newly discovered low-mass Galactic satellites
- Galactic archaeology results have major ramifications for fields ranging from nuclear astrophysics to galaxy formation

Dwarf galaxies and stellar streams

GMT

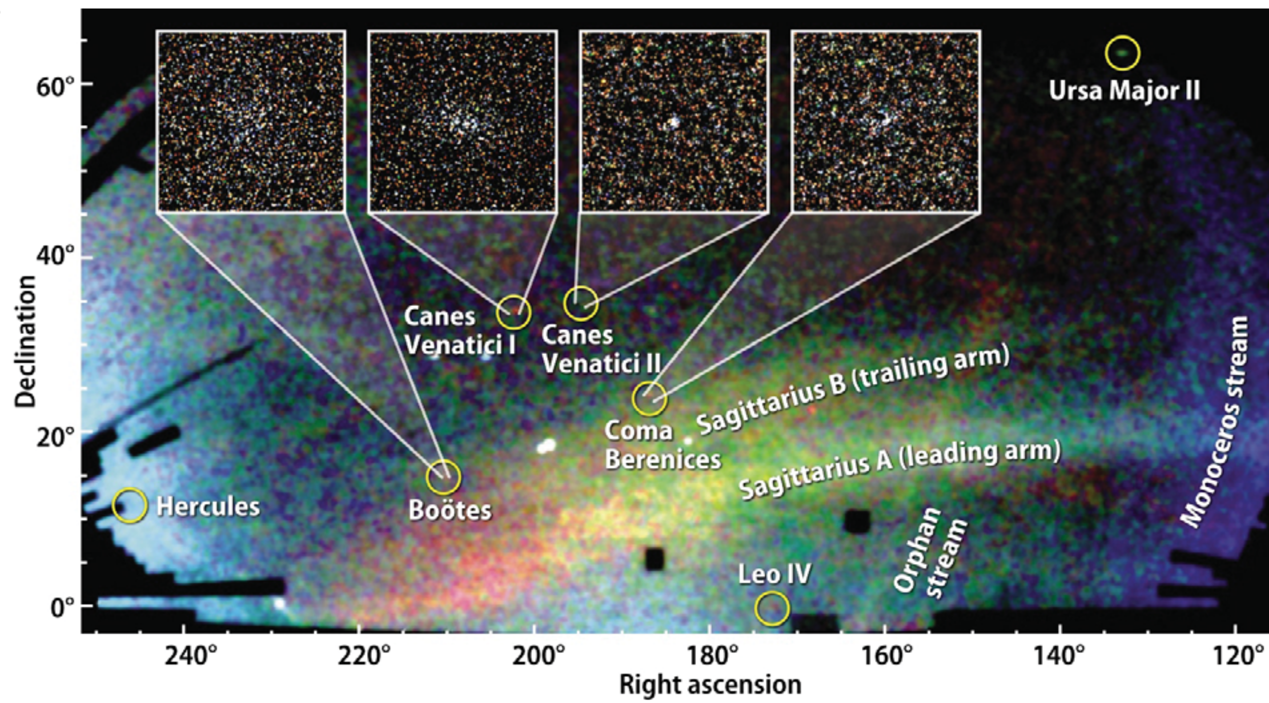
- Large-scale imaging projects like DES & Pan-STARRS are finding new low-mass Galactic satellite galaxies and stellar streams; LSST will identify many more
- These objects represent galaxy formation and evolution in the lowest-mass regime and in the lowest-density environments
- GMACS+MANIFEST will obtain low-resolution spectra for hundreds of stars simultaneously over a 20' field of view
- This gives high-quality (SNR~80) spectra for stars brighter than the main-sequence turnoff in ultrafaint dwarfs out to 100 kpc in 2 hr, and in 10 min for dwarfs at 40 kpc
- Enables quick, confident assessment of membership and kinematics, fundamental stellar parameters, and allows a subset of elemental abundance & potentially ages to be measured for these key objects



Near-field cosmology

GMT

- Near-field cosmology is the study of the formation history of all components of the Local Group to understand, in detail, its assembly and the physical conditions and processes operating at earlier cosmic epochs (Freeman & Bland-Hawthorn 2002)
- GMACS+MANIFEST's wide field-of-view and multi-object spectroscopy can efficiently characterize metallicities & velocities for large numbers of stars in Local Group streams
- Chemical fingerprints link individual stars to their birth cluster and enable reconstructions of disrupted galaxies



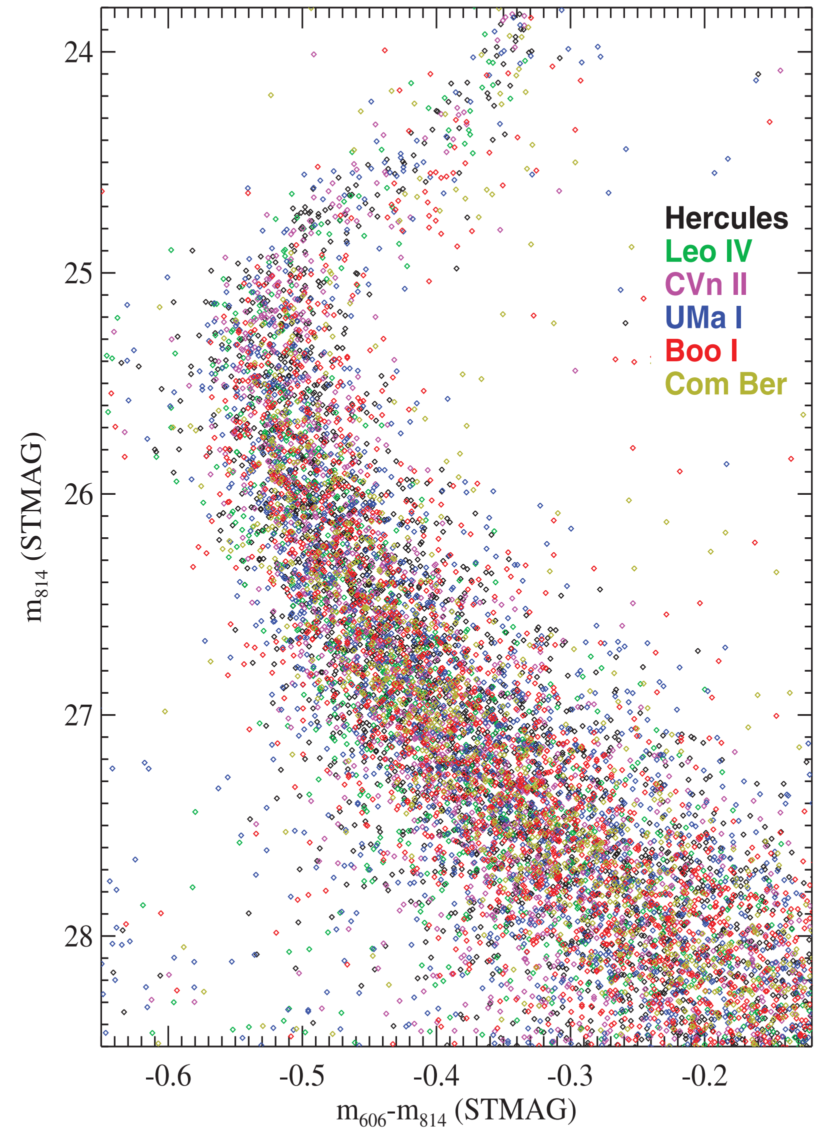
Credit: Vasily Belokurov, SDSS-II

- These disrupted galaxies can be compared to surviving systems to understand how mergers & tidal debris contributed to the assembly of the Milky Way and Local Group

Near-field cosmology

GMT

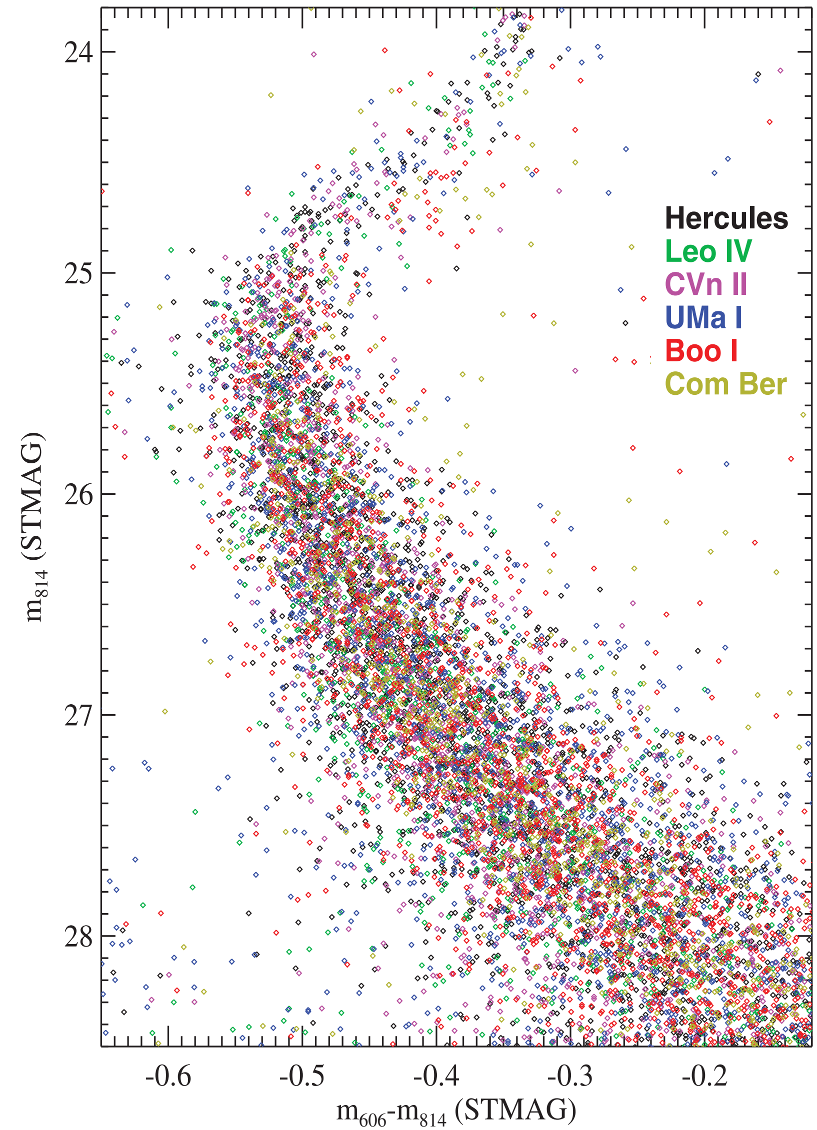
- The faintest known galaxies in the Local Group are all gas-poor with uniformly old stellar populations, reflecting the physical conditions in the early universe; studies of such systems in the near field will reveal how the earliest galaxies formed
- Low-metallicity [Fe/H] < -3] stars in ultra-faint dwarf galaxies contain signatures of the first supernova explosions and early chemical enrichment of these tiny galaxies
- For nearby systems like Segue I, GMT could obtain chemical abundances for every known member star, yielding a full picture of the star formation and chemical enrichment history of one of the earliest galaxies, and a window into the earliest epochs of star formation



Near-field cosmology

GMT

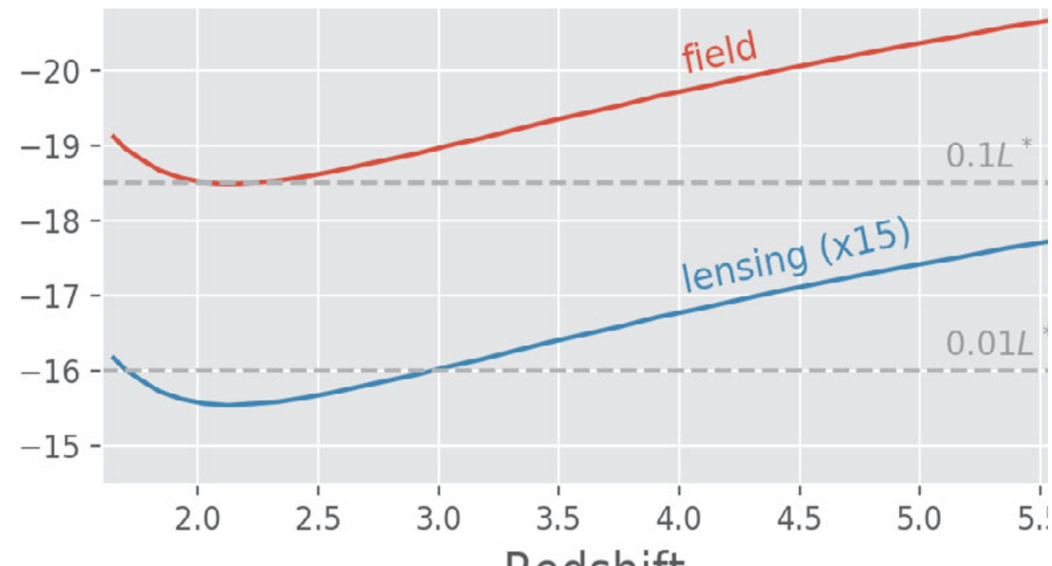
- LSST will discover hundreds of ultra-faint galaxies to well beyond the virial radius of the Milky Way or M31
- JWST will provide star formation histories based on resolved colour-magnitude diagrams in ultra-faint systems throughout the Local Group
- Building on LSST and JWST, GMT spectroscopic observations will give detailed dynamical and chemical maps of nearby galaxies beyond the edge of the Milky Way's dark matter halo
- Studying the fossilized remains of tens or hundreds of Local Group galaxies will provide a rich and detailed picture of the first phases of galaxy formation that is unobtainable by any other method



Surveying galaxy formation

GMT

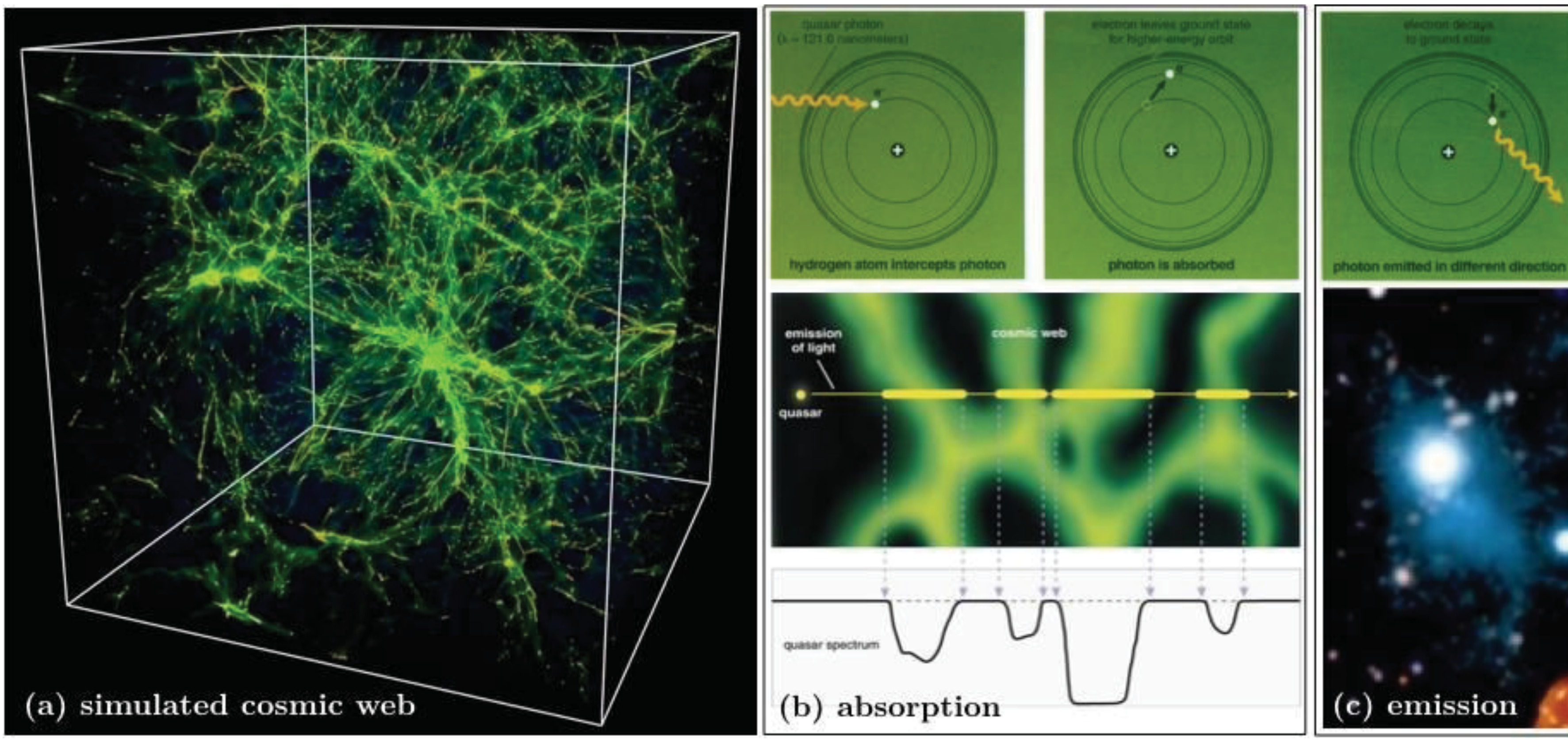
- GMACS+MANIFEST is well-matched to the source density (few arcmin^{-2}) of high-redshift, low-mass, low-luminosity (<L*) galaxies
- An 8 hour integration with GMACS+MANIFEST gives a S/N=5 detection of the rest-frame UV continuum for 0.1 (0.5) L* galaxies at z=2 (z=5.5)
- In a few x 10 nights, GMT could survey ~10^4 low-mass galaxies at 2<z<5, mapping the physical properties of the ISM and stellar components of young galaxies over a long time baseline to track star formation activity during the first few billion years to its peak around z~2



The faintest absolute magnitude reached by GMACS at 5σ/pixel in 8 hours at each redshift. GMACS(+MANIFEST) provides medium-resolution rest-frame UV spectra of sub-L galaxies at 1.5<z<5.6; with gravitational lensing, UV spectra ~0.01L* galaxies at z~2 can be obtained*

Mapping the cosmic web

GMT

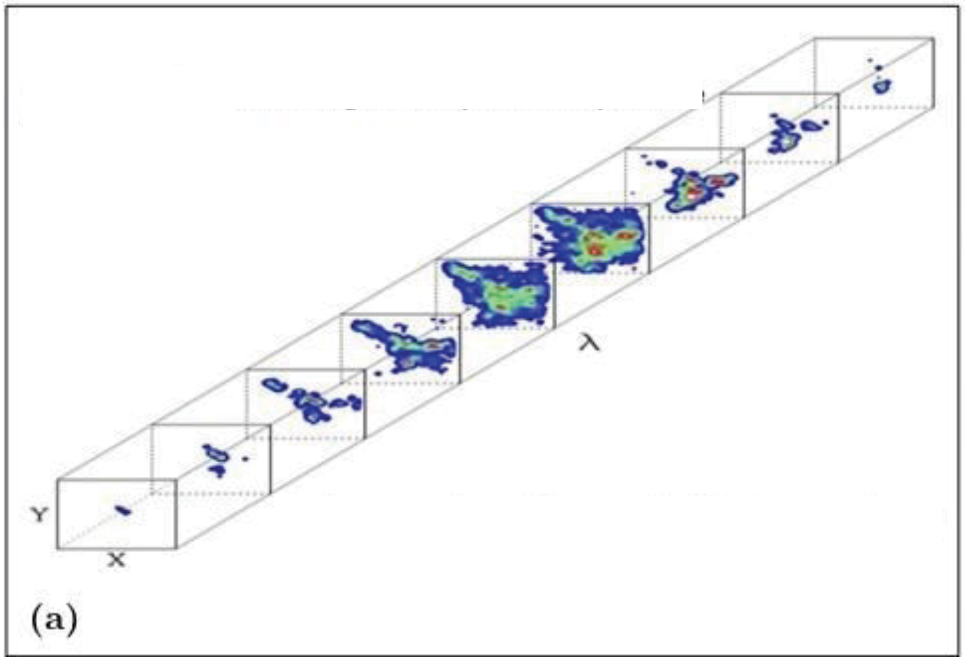


The universe has ~12x as much matter in diffuse gas as in stars. GMT will map the 'cosmic web' of diffuse gas by emission from gas excited by light from nearby stars and by absorption of light from background objects passing through gas. Observations of stars, gas near galaxy disks (mainly in emission), and warm or hot gas far from disks (in absorption) offer complementary views of matter in different physical states and stages of the gas transport cycle in and out of galaxies

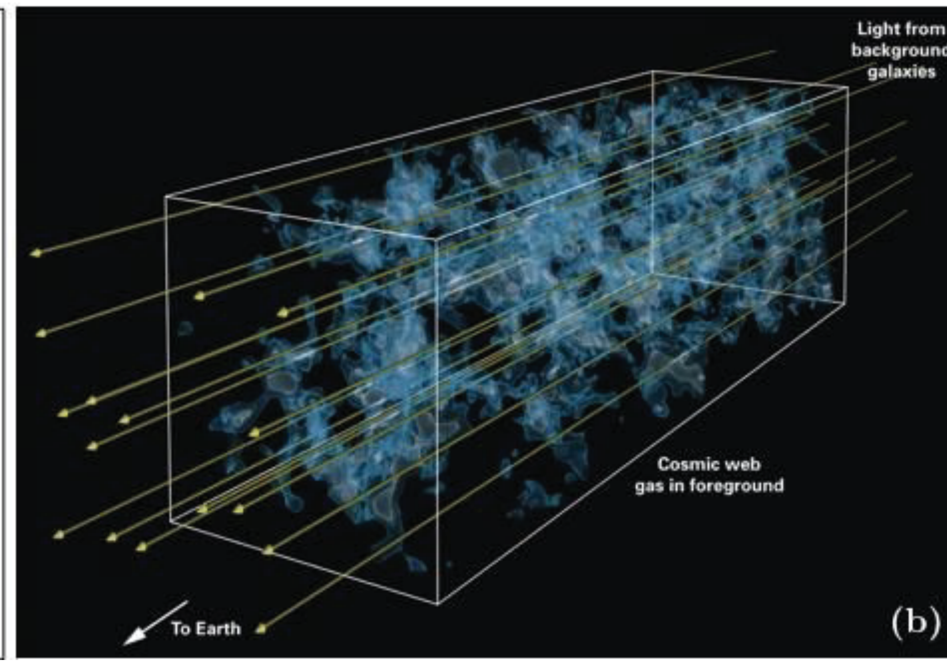
Mapping the cosmic web

GMT

3D views of the cosmic web…



…in emission (Kollmeier++ 2010)

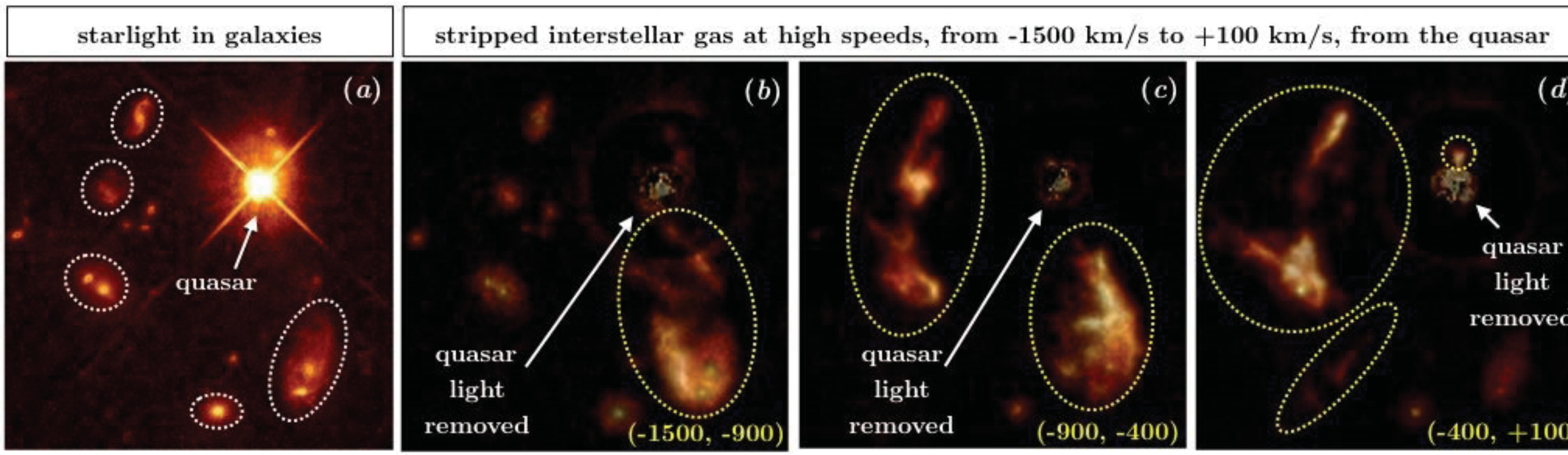


…in absorption using a large sample of background galaxies (Lee++ 2014,2017)

Mapping gas flows in emission

GMT

- ❑ Gas flowing in and out of star-forming regions can be imaged in line emission using an integral field spectrograph, and the 3D density and velocity fields can be reconstructed by tracing line-emitting gas in both spatial and spectral directions

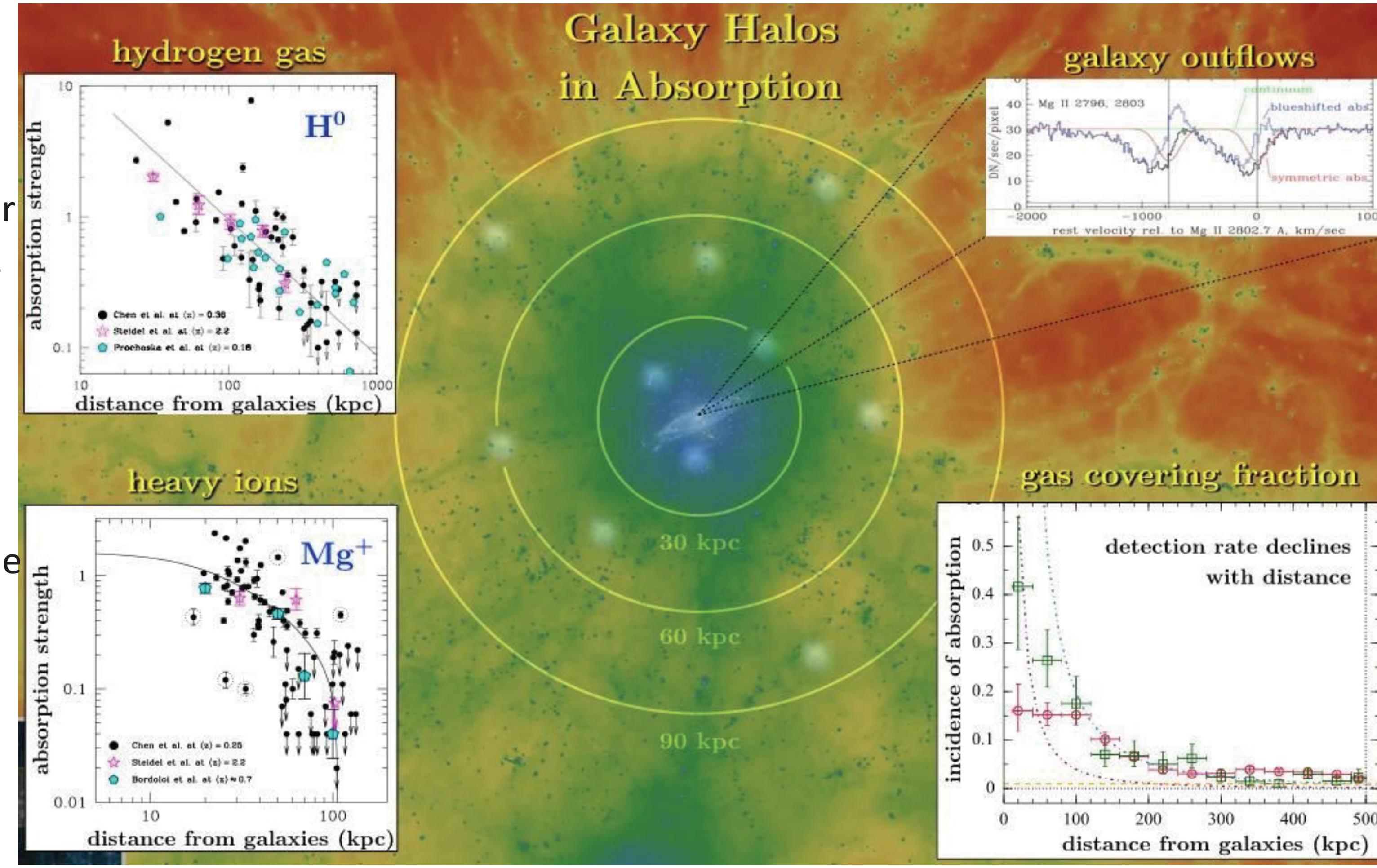


- ❑ The relative strengths of common lines such as [OII], [OIII] and Hβ constrain the underlying gas density, relative motion, metallicity, and temperature
- ❑ 3D data cubes can be turned into mass flow rates in and out of galaxies, plus the spatial variations in the chemical enrichment level and in ionizing radiation field
- ❑ The large wide-field optical IFU of MANIFEST and the GMACS medium resolution spectrograph offer 5-7x the survey speed of Keck or the VLT for such studies

Mapping gas flows in absorption

GMT

- Rest-UV galaxy spectra provide many strong absorption lines in the interstellar medium (ISM) & circumgalactic medium (CGM)
- Absorption spectra of background objects probe the spatial distribution of hydrogen gas and heavy ions & the covering fraction of each gas species with distance



- Absorption spectroscopy of the galaxy can characterize outflowing gas rates and velocities from the observed absorption-line profiles

Pop III stars & metal-free galaxies

GMT

- Surveying galaxies at z~6-10 with a NIRMOS-like near-infrared MOS will allow the first systematic search for galaxies with populations of metal-free stars
- While galaxy formation is well underway at z~6, the metal enrichment from star formation is local and gradual, leaving chemically-pristine gas in large volumes
- Semi-analytic models and numerical simulations suggest that Pop III stars can still form in under-dense regions at z~6, 1 Gyr after the Big Bang (e.g. Xu++ 2016)
- If the Pop III IMF is favours very high-mass stars, the strong EUV radiation will power nebular He II λ1640 emission, while the lack of metals results in weak emission from C and O emission lines (Schaerer 2002)
- Near-infrared spectrographs on GMT (such as the proposed NIRMOS instrument) can characterize the strength of He II & metal lines in galaxies at redshifts z~6-10
- Since the Pop III phase is likely very short (~10 Myr), such metal-free galaxies are rare, so it will be necessary to observe 1000s of z>6 galaxies over a ~1 deg^2 field
- NIRMOS will be effective at finding rare objects in the under-dense regions where Pop III galaxies are expected; deep spectroscopic follow-up of Pop III galaxy candidates will offer precious insight into metal-free stellar populations

Pop III stars & metal-free galaxies

GMT

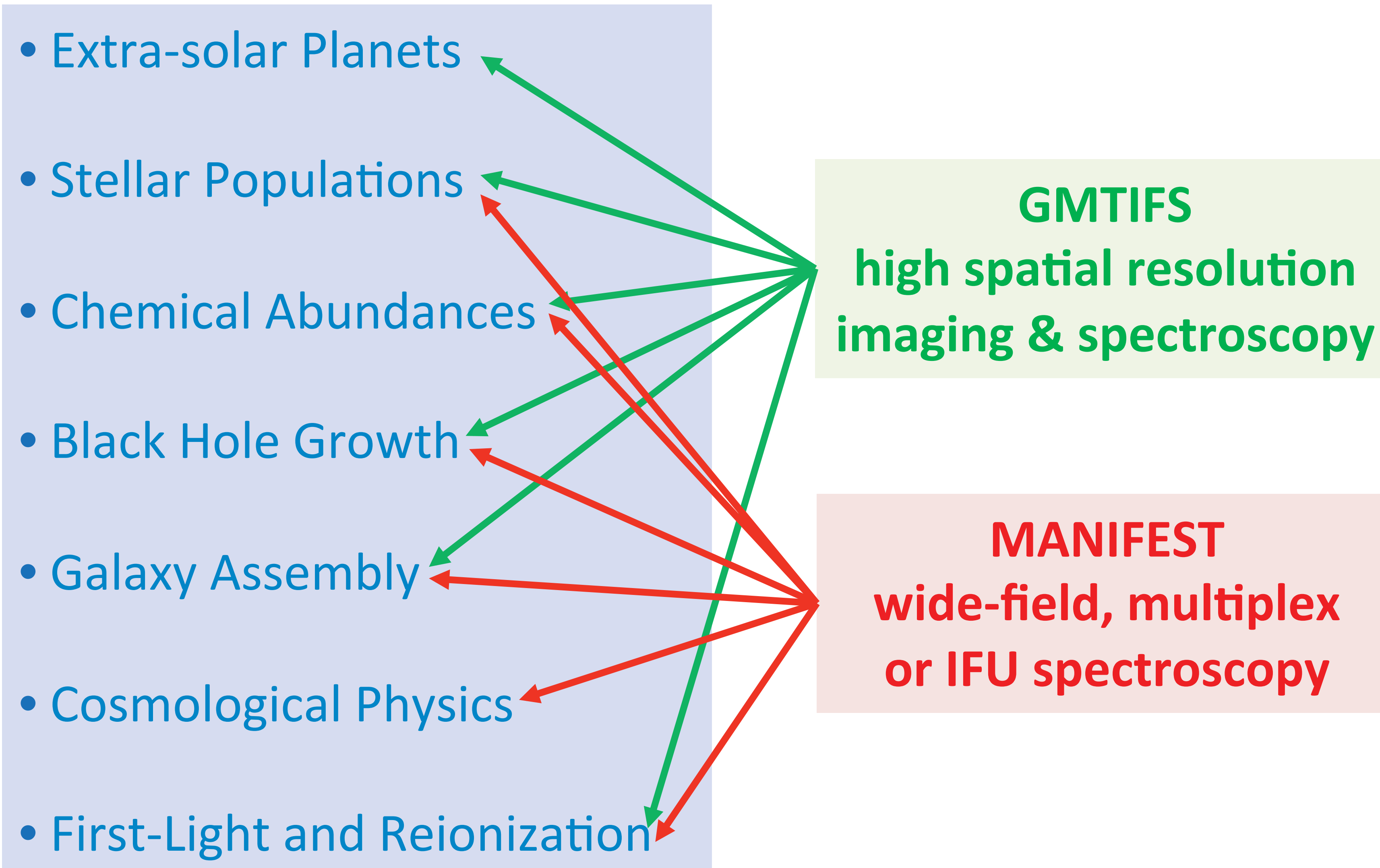
- Since faint z~6-10 objects have higher surface densities (~1 $arcmin^{-2}$ at H~28 AB mag), GMT+NIRMOS will provide a significant multiplexing and sensitivity advantage, allowing large spectroscopic samples to be constructed at z~6-10
- NIRMOS+MANIFEST can target galaxies over a 20' (i.e. 7 Mpc diameter) field and follow up z>6 galaxies identified in the large areas surveyed by WFIRST
- Note: this is nearly impossible with JWST given its much smaller field of view
- Present luminosity function estimates predict there will be ~300 z=6-10 galaxies in the MANIFEST field to the WFIRST/HLS depth; this number increases by ~10x at the m~29 limit expected over ~1 deg^2 from GO programs with WFIRST
- Thanks to its unique wide field capabilities, GMT requires only ~10 different pointings to cover the full square degree – *no other planned or existing spectroscopic facility can effectively target z>6 galaxies over such an area*
- Spectrographs on the other ELTs have fields of view that are too small (requiring over 500 pointings) and current 8-10m class telescopes are not sensitive enough to detect faint emission lines from m~26-29 galaxies in the reionization era

Summary

GMT

GMT science ↔ GMT instruments

GMT



Synergy with other telescopes

GMT

GMT will leverage the potential of world-wide astronomy facilities in the 2020s & beyond

ptical/infrared – High spatial resolution – sensitivity