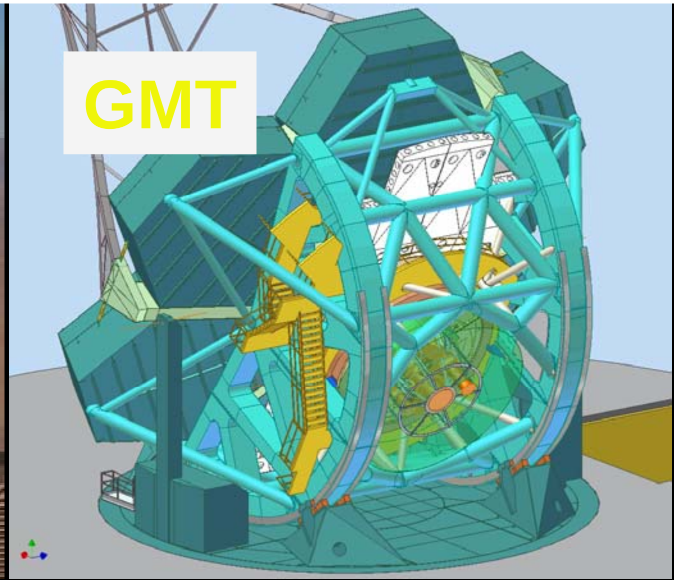

Telescopes and Instrumentation of the Future

Betsy Barton

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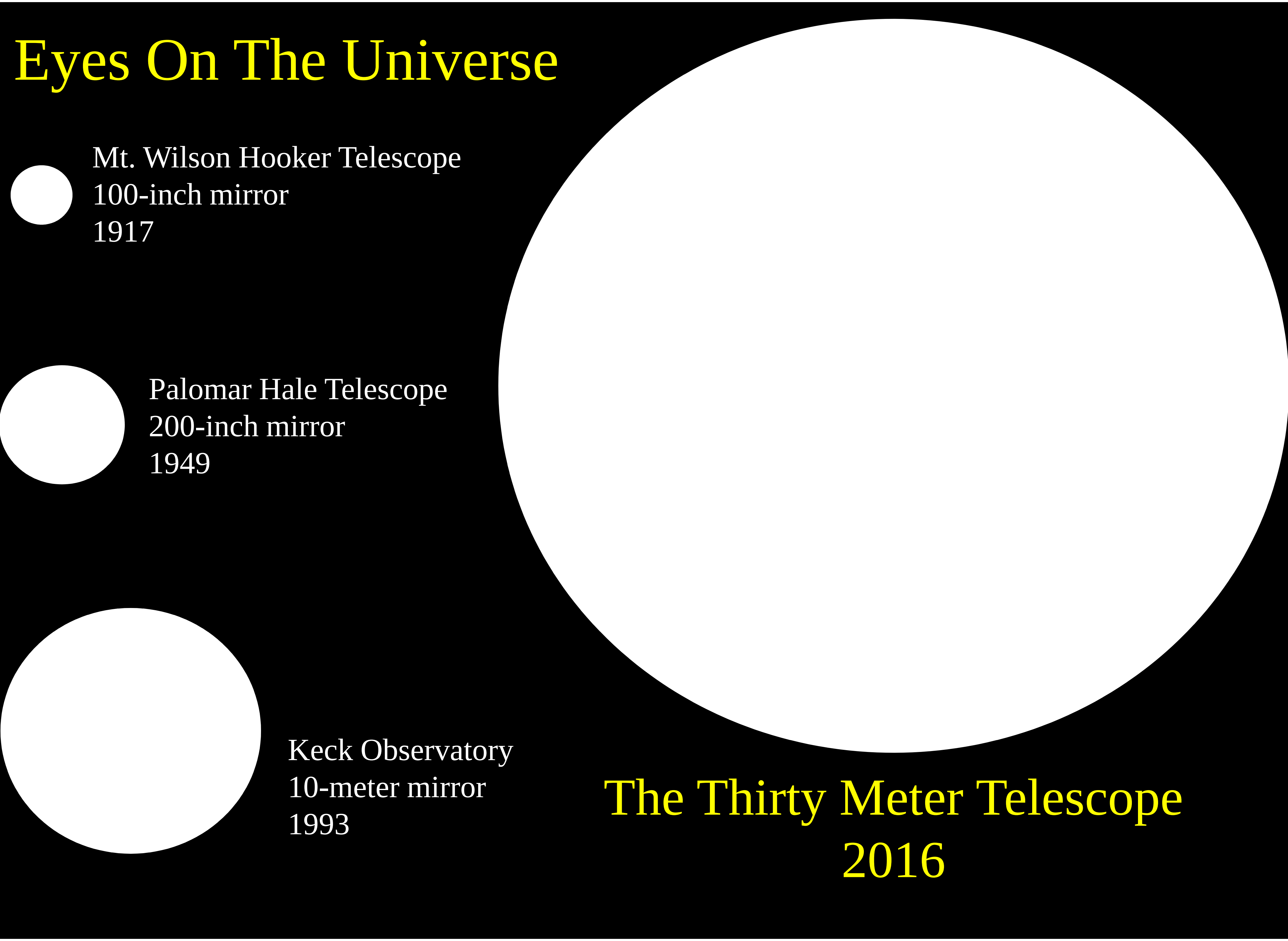
Grateful acknowledgements to…

- **Jerry Nelson (UC Santa Cruz), Project Scientist, the Thirty Meter Telescope Project**
  - **David Silva (TMT/AURA)**
  - **The Science Advisory Committee**
  - **Authors of the Detailed Science Case and Construction Proposal**
- **Steve Schectman and Patrick McCarthy (Observatories of the Carnegie Institution of Washington), The Giant Magellan Telescope Project**
  - **Scott Kenyon (Smithsonian Astrophysical Observatory)**
  - **Members of the GMT Science Working Group**
- **The Large Synoptic Survey Telescope Project and its web site**

Outline

- A basic introduction to the projects
  - TMT (Thirty Meter Telescope)
  - GMT (Giant Magellan Telescope)
  - LSST (Large Synoptic Survey Telescope)
- Selected key science the facilities will address:
  - "First light" in the Universe: the origins of galaxies
  - How do planets form?
  - Dark Energy and Dark Matter, the Cosmic Web


Eyes On The Universe
Mt. Wilson Hooker Telescope
100-inch mirror
1917
Palomar Hale Telescope
200-inch mirror
1949
Keck Observatory
10-meter mirror
1993
The Thirty Meter Telescope
2016

Why Bigger is Better: Primary Mirror Size

- **Light-gathering power (~D^2)**
- **Resolution:**
  - **Best possible image quality is 1.22 λ/D**
  - **Atmospheric turbulence limits this capacity**
  - **Adaptive Optics technology corrects atmosphere**
- **Types of observations:**
  - **D^2 regime: resolved sources, or without the use of adaptive optics**
  - **D^4 regime: unresolved sources in the background-limited regime with adaptive optics**
  - **D^6 regime (rare): with adaptive optics in extremely crowded star fields, where the crowding limits the accuracy of flux measurements**

Primer on adaptive optics technology

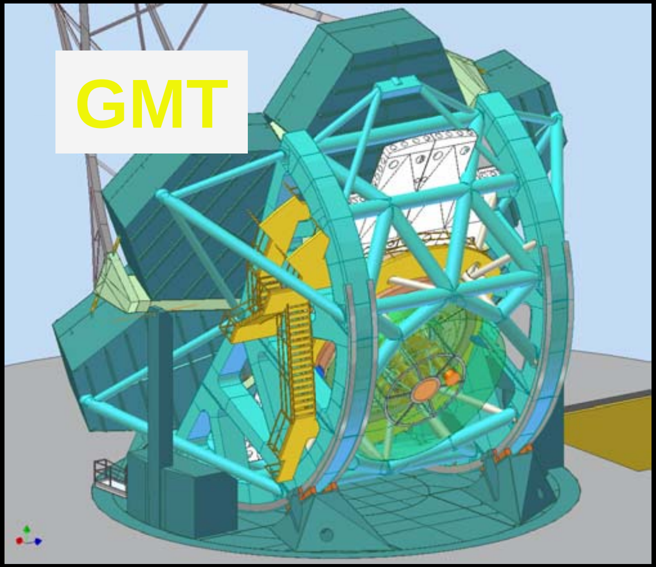
- Correct for turbulence in real time on ms timescales
- Observe reference source(s)
  - Natural guide stars
  - Laser guide stars
- Theoretically possible to achieve diffraction limit
  - In practice, achieve diffraction limited “core” plus much larger “halo” for a star
- Works better at longer wavelengths
  - currently almost non-functional in the optical
  - works best around 2 μm
- Works for a limited field size (arcseconds to arcminutes)
- Will be more complex for a next-generation large telescopes
  - Larger number of turbulent cells above the primary mirror

Current-generation ground-based optical and infrared telescopes

- Keck telescopes
  - University of California and Caltech
  - twin 10-meter segmented primaries, Mauna Kea, Hawaii
- Gemini telescopes
  - US National, UK, Canada, Australia, Chile
  - Twin 8-meter telescopes in Chile, Mauna Kea
- The Very Large Telescopes (VLTs)
  - European Space Observatory
  - Four 8-meter telescopes on Cerro Paranal in Chile
- Newer 10-meter segmented primaries

Thirty Meter Telescope

- 30m segmented primary mirror
- Moderate field of view
- Broad instrument suite to observe the faint, the fuzzy, and the small
- Emphasis on adaptive optics, near-infrared

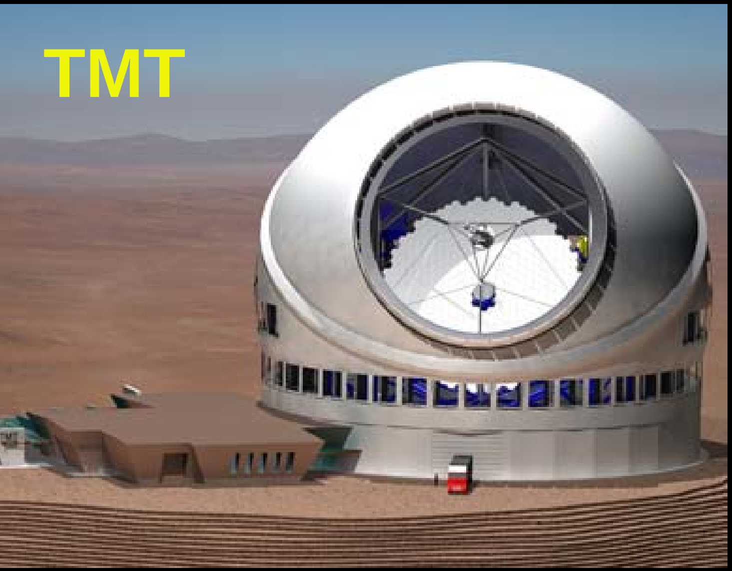


Giant Magellan Telescope

- 7x8.4 = 25m primary mirror
- Moderate field
- Broad instrument suite
- Some emphasis on wide surveys

Large Synoptic Survey Telescope

- 8m primary mirror
- Focused optical imaging telescope
- Huge field-of-view imaging camera to survey the sky every few nights

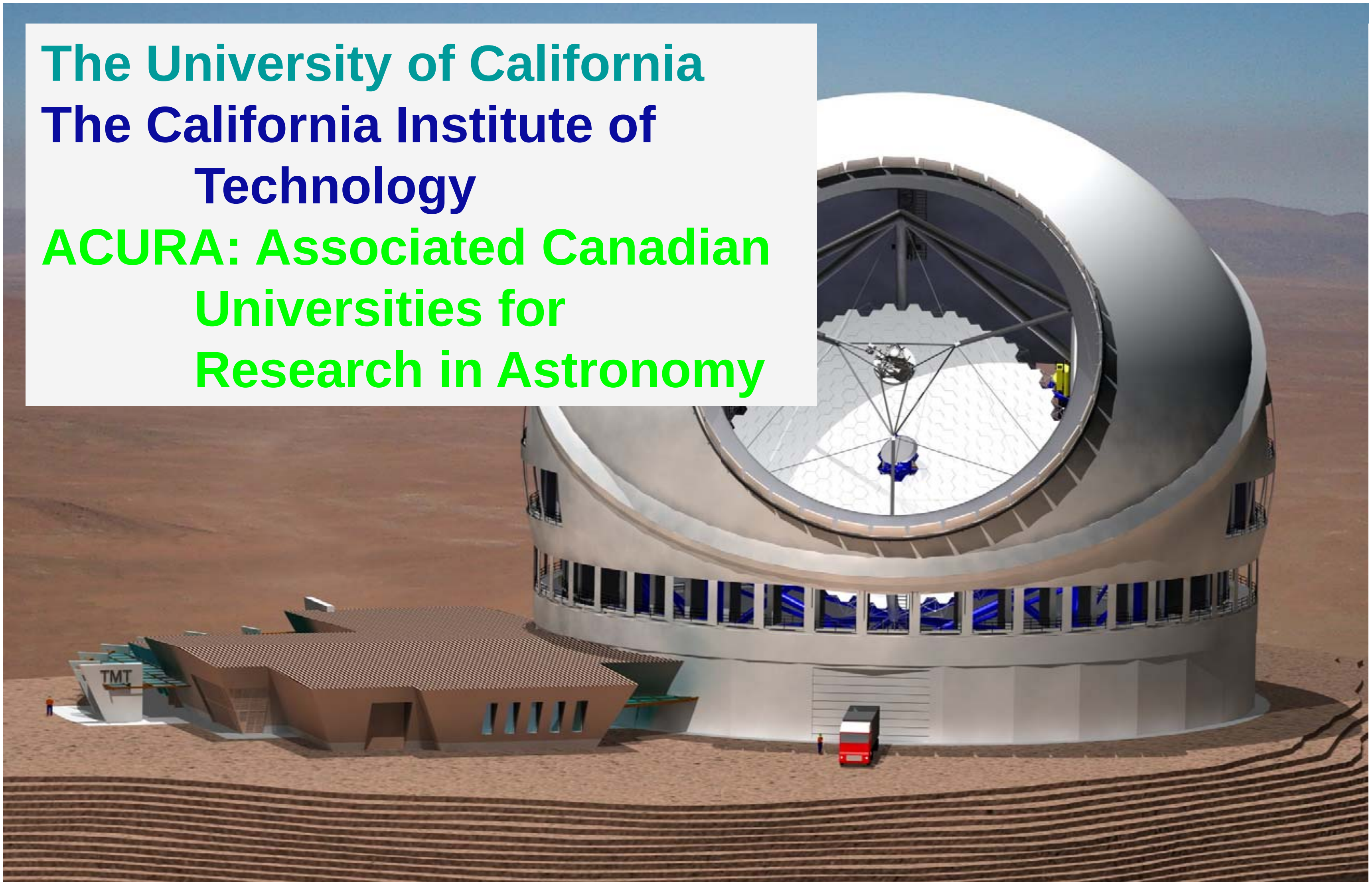


Slide courtesy of J. Nelson.

TMT
THIRTY METER TELESCOPE

Summit Support Facilities and Telescope Enclosure

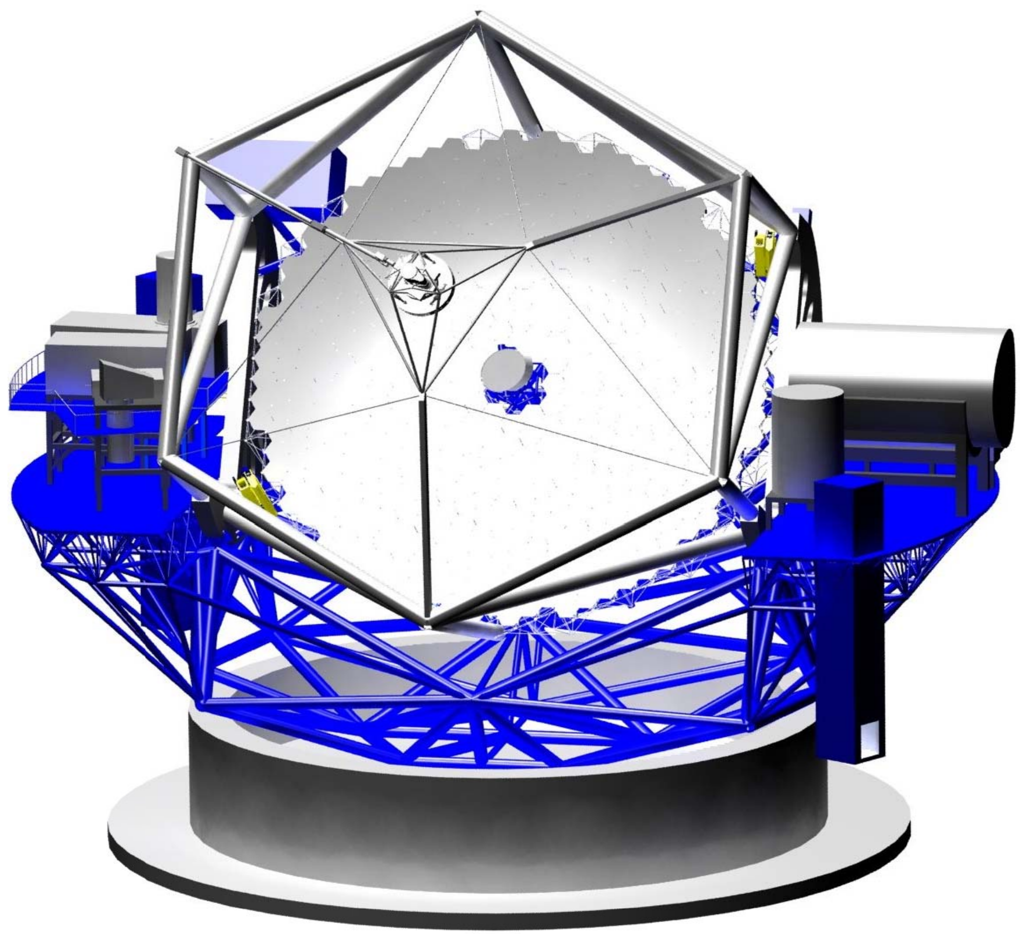
The University of California
The California Institute of Technology
ACURA: Associated Canadian Universities for Research in Astronomy



Slide courtesy of J. Nelson.

Telescope Design

- Ritchey-Chretien optical design
  - f/15 output focal ratio
  - 15 arc min FOV
- D = 30 m, f/1 primary
  - 492 1.42m segments
- 3.05 m convex secondary
- Articulated tertiary
  - Elevation axis 3.5m above primary
- Nasmyth-mounted instrumentation

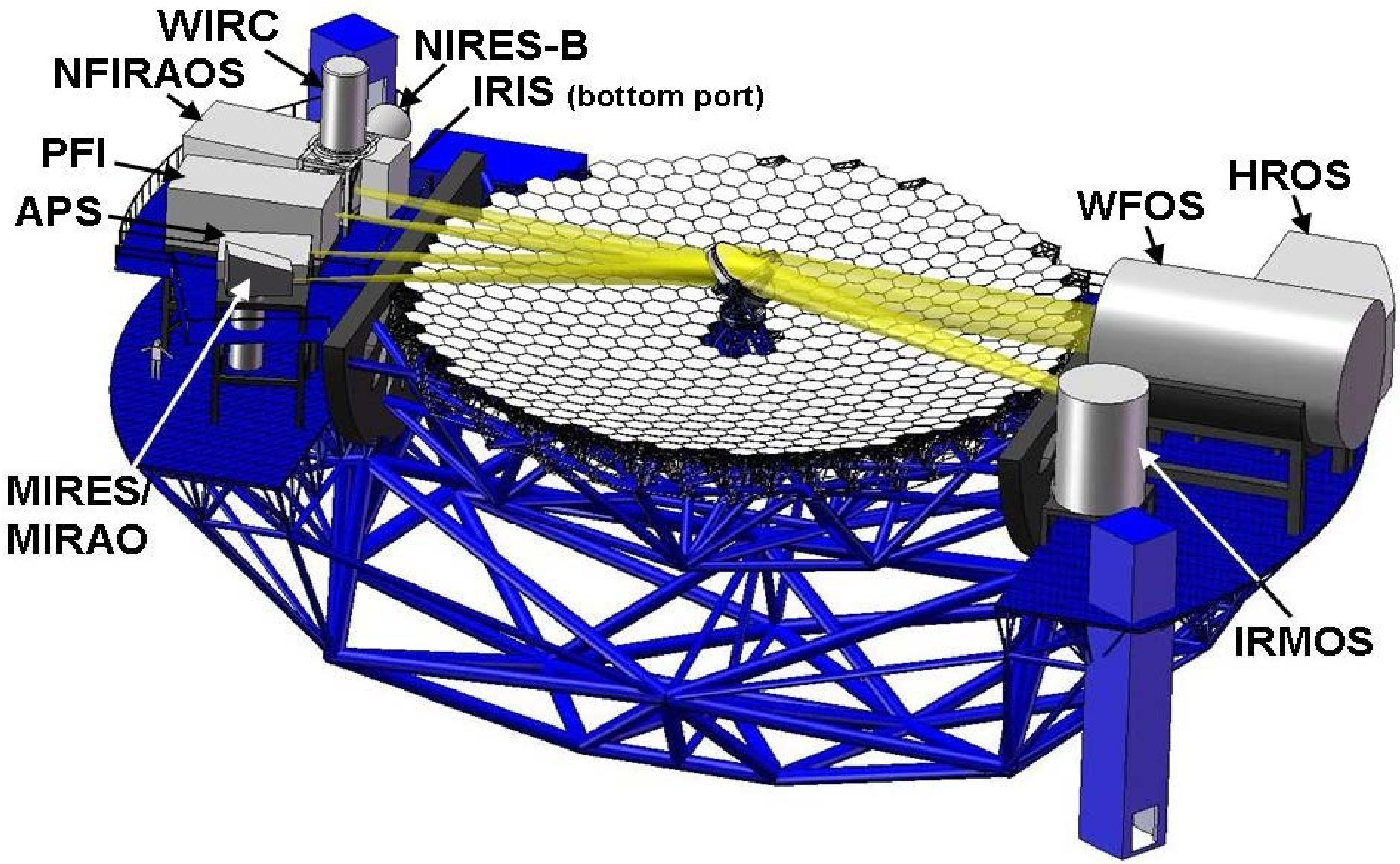


Slide courtesy of J. Nelson.

TMT
THIRTY METER TELESCOPE

Nasmyth Configuration Supports Full Instrument Suite

- Platform 7 m below elevation axis
- Articulated M3 – facilitates quick instrument change
- Addressable regions: -28° to 6° and 174° to 208° for small FOV



TMT Earliest-light Instrumentation

- NFIRAOS - facility Adaptive Optics (AO) system
- IRIS - versatile near-infrared Imager/spectrograph
  - Samples diffraction limit from high-order adaptive optics
  - 3” field-of-view spectrograph, 15” imager
- IRMS - near-infrared multi-object spectrograph
  - Works with AO (but can function without it)
- WFOS - optical multi-object spectrograph
  - Seeing-limited
  - Up to 14 arcminute field-of-view

Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

Major Project Milestones

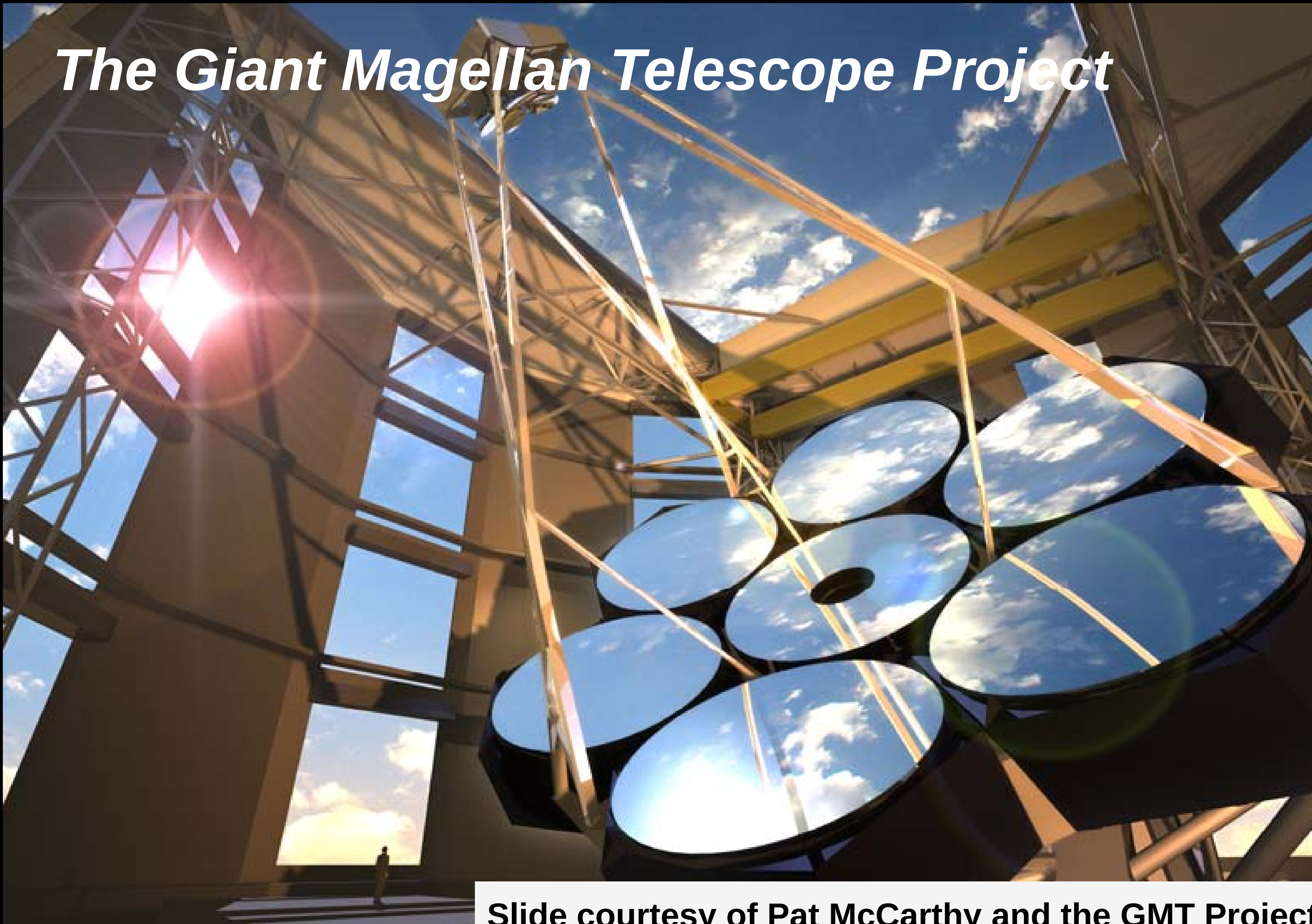
According to our current *technically-paced* TMT Schedule:

- April 2009: TMT Construction Phase Begins
  - Start of RTC Hardware Procurement Contract
- …
- April 2016: "First light" on a client science instrument of the TMT facility AO system
  - Closed loop LGS AO
  - All telescope primary mirror segments phased

Changes are possible as we develop a *funding-paced* schedule:

- First $300M in construction funding has already been committed by the Moore Foundation, Caltech, and the University of California starting this year

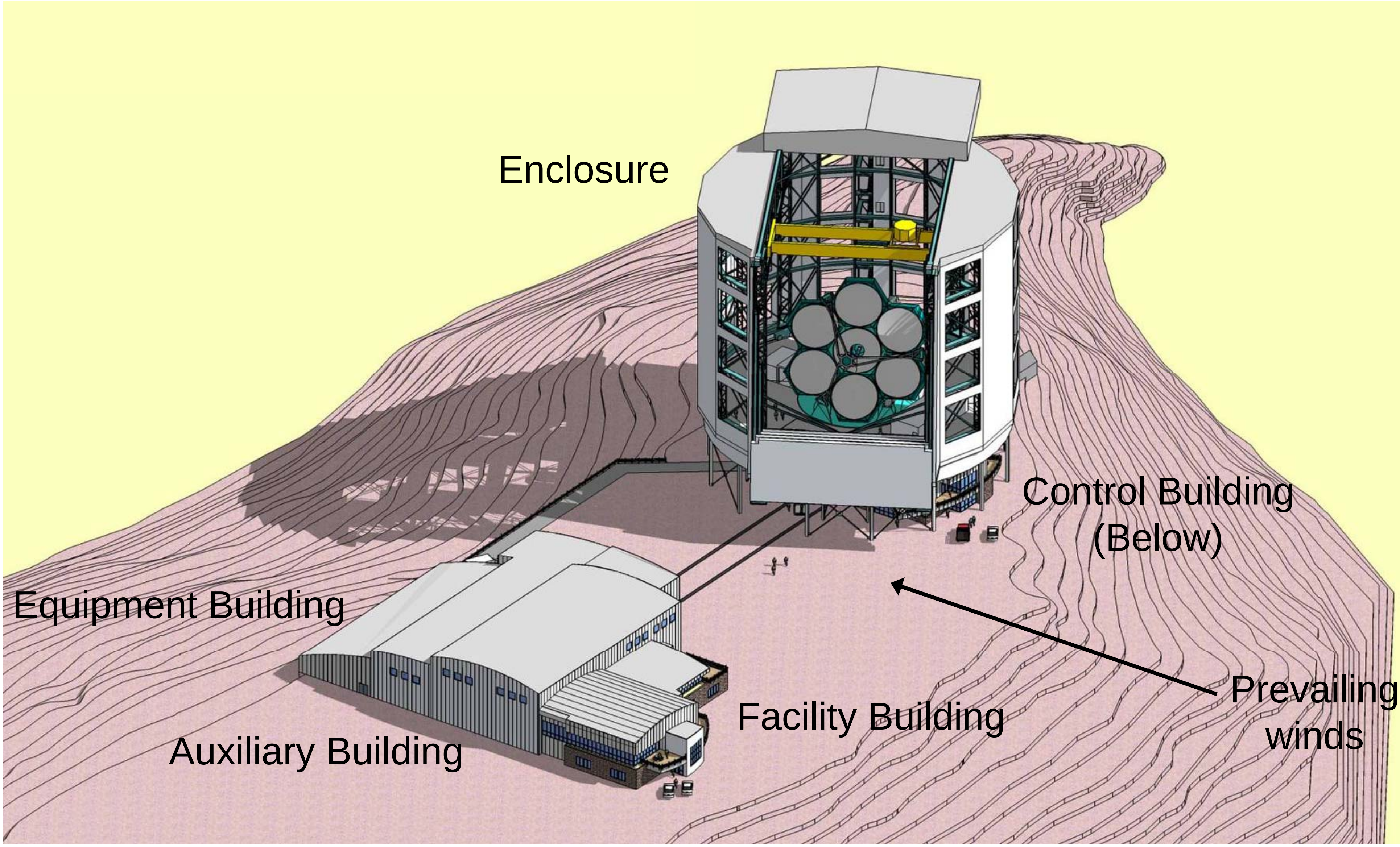
The Giant Magellan Telescope Project



Slide courtesy of Pat McCarthy and the GMT Project.

Slide courtesy of Pat McCarthy and the GMT Project.

Site Layout on Campanas Peak



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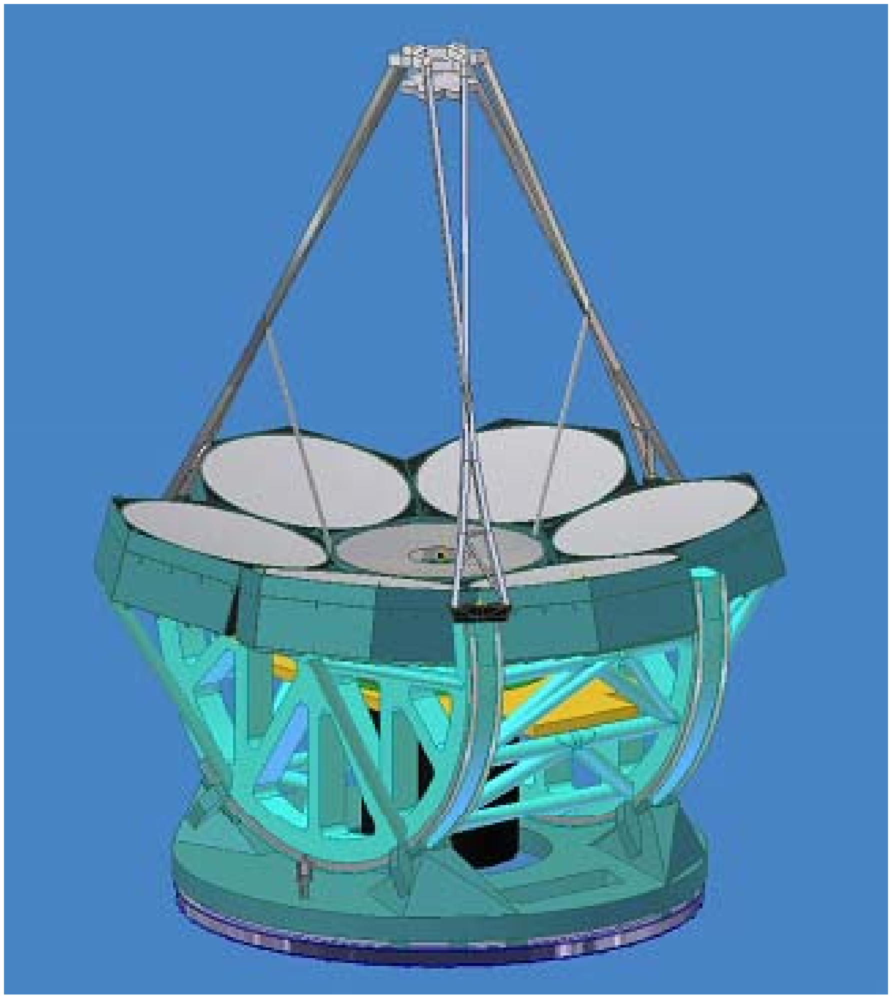
GMT Institutions



Carnegie Institution of Washington

Harvard University

Smithsonian Astrophysical Observatory

University of Arizona

University of Texas at Austin

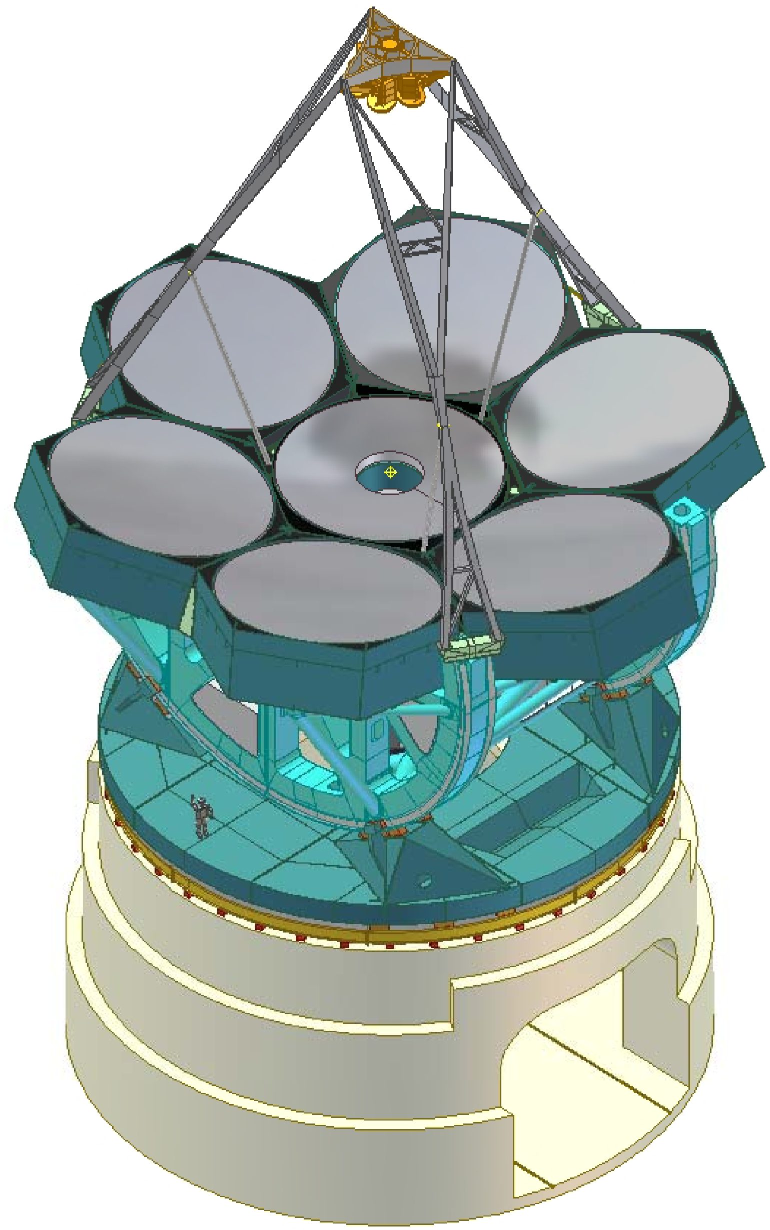
Texas A&M University

Australian National University

Slide courtesy of Steve Schectman and the GMT Project.

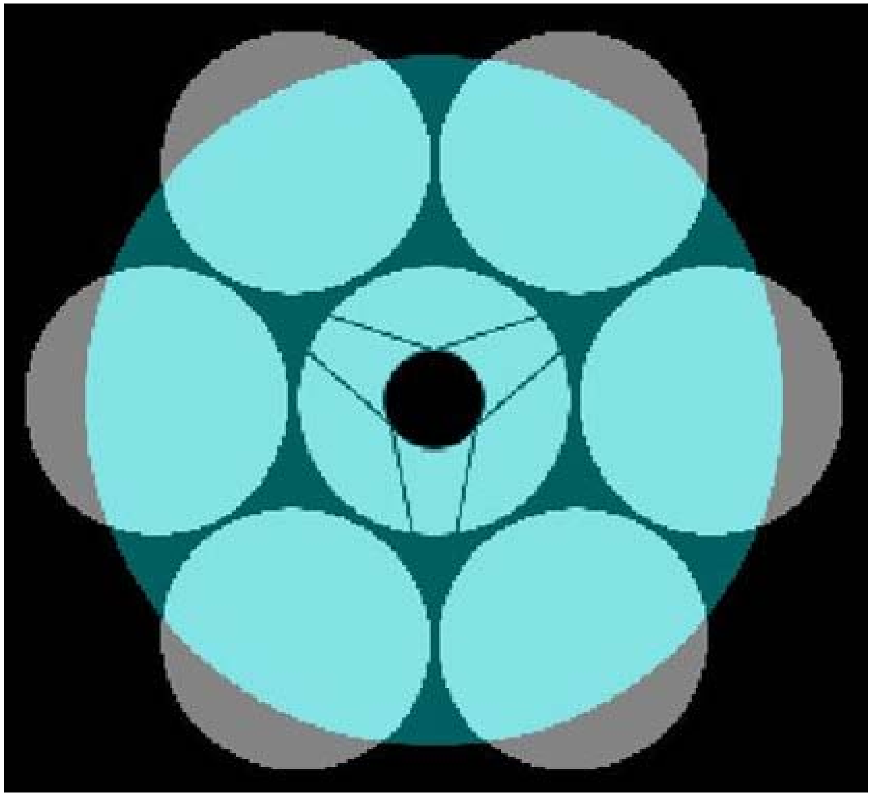
Overview

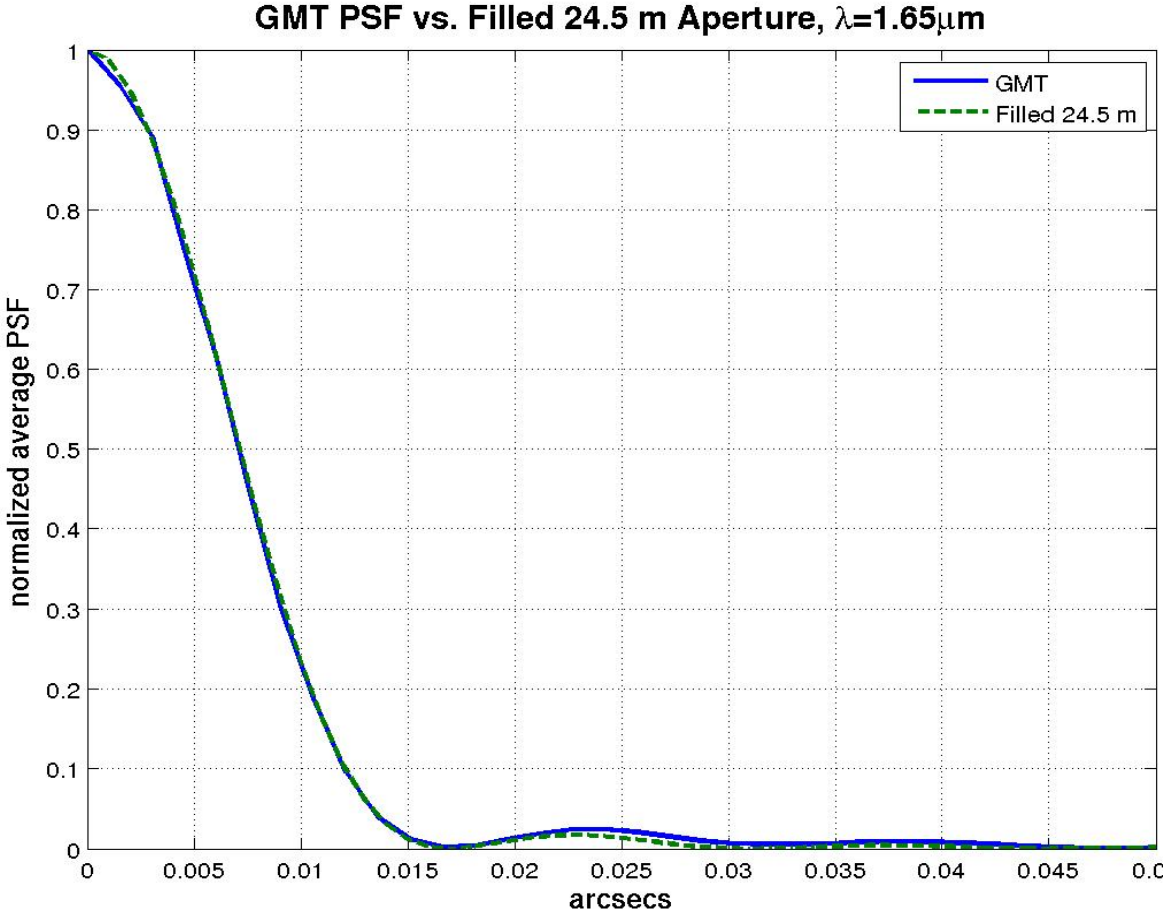
- Seven 8.4m cast borosilicate primary mirror segments, f/0.7
- Segmented secondary mirror with f/8 Gregorian Focus
- 20´ "Wide-Field" mode w/corrector
- Multiple AO modes
- Instruments mount behind primary



Slide courtesy of Steve Schectman and the GMT Project.

FAQ: How Big Is It?





Full Diameter: 25.4 m

Circular aperture 21.9 m

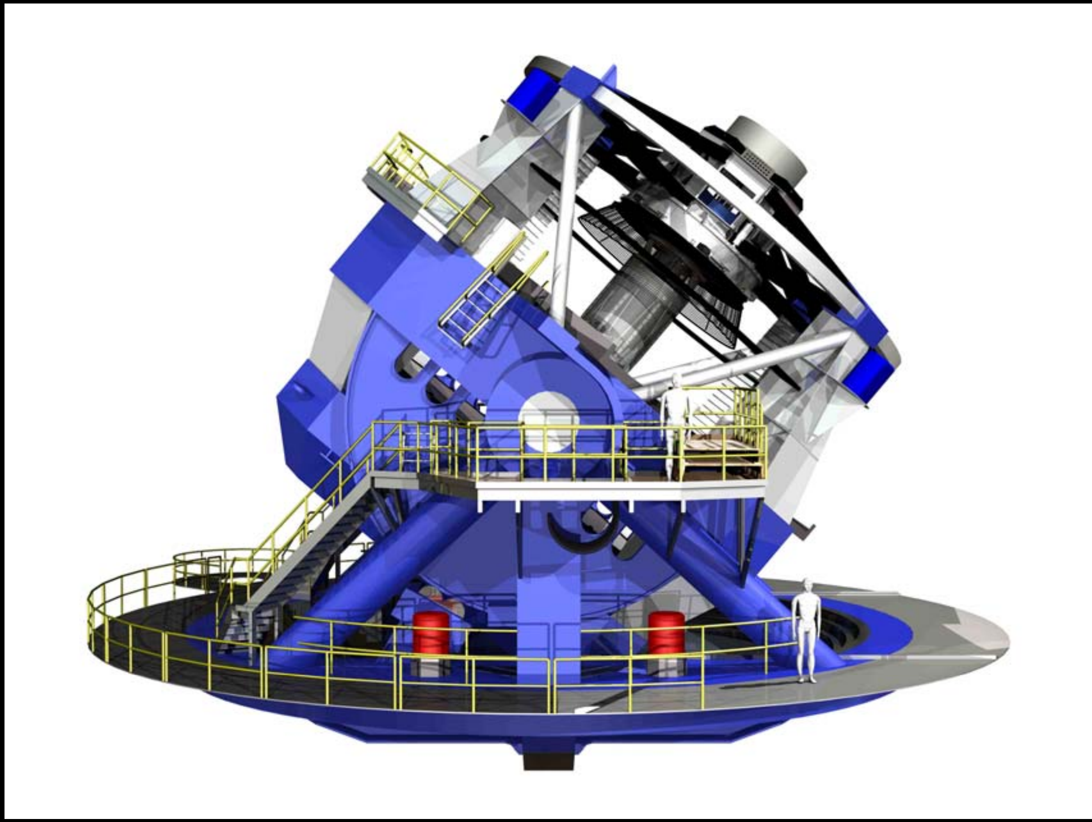
Diffraction limit 24.5 m

66% in central diffraction peak

- (84% for perfect filled aperture)
- (72% for Hubble ST)

LSST: The Large Synoptic Survey Telescope

- 8.4 meter primary mirror
- Dedicated, GIANT science camera
  - 3.5 degree field of view, 3.2 Gpixel camera
  - Optical wavelengths (0.32-1.06 nm)
  - 5 active filters
  - 15-second exposures (all night)
  - 15 TBytes/night



Slide based on information and graphics from the LSST web site.

The LSST Partnership

- **Director, J. Anthony Tyson (UC Davis)**
- **Large consortium, including:**
  - **University of California, Davis**
  - **University of Arizona**
  - **The Research Corporation**
  - **The University of Washington**
  - **The National Optical Astronomy Observatory**
  - **California Institute of Technology**
  - **University of California, Irvine**

- **Nominal first-light: 2014**

Slide based on information and graphics from the LSST web site.

Large Synoptic Survey Telescope

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The LSST Partnership

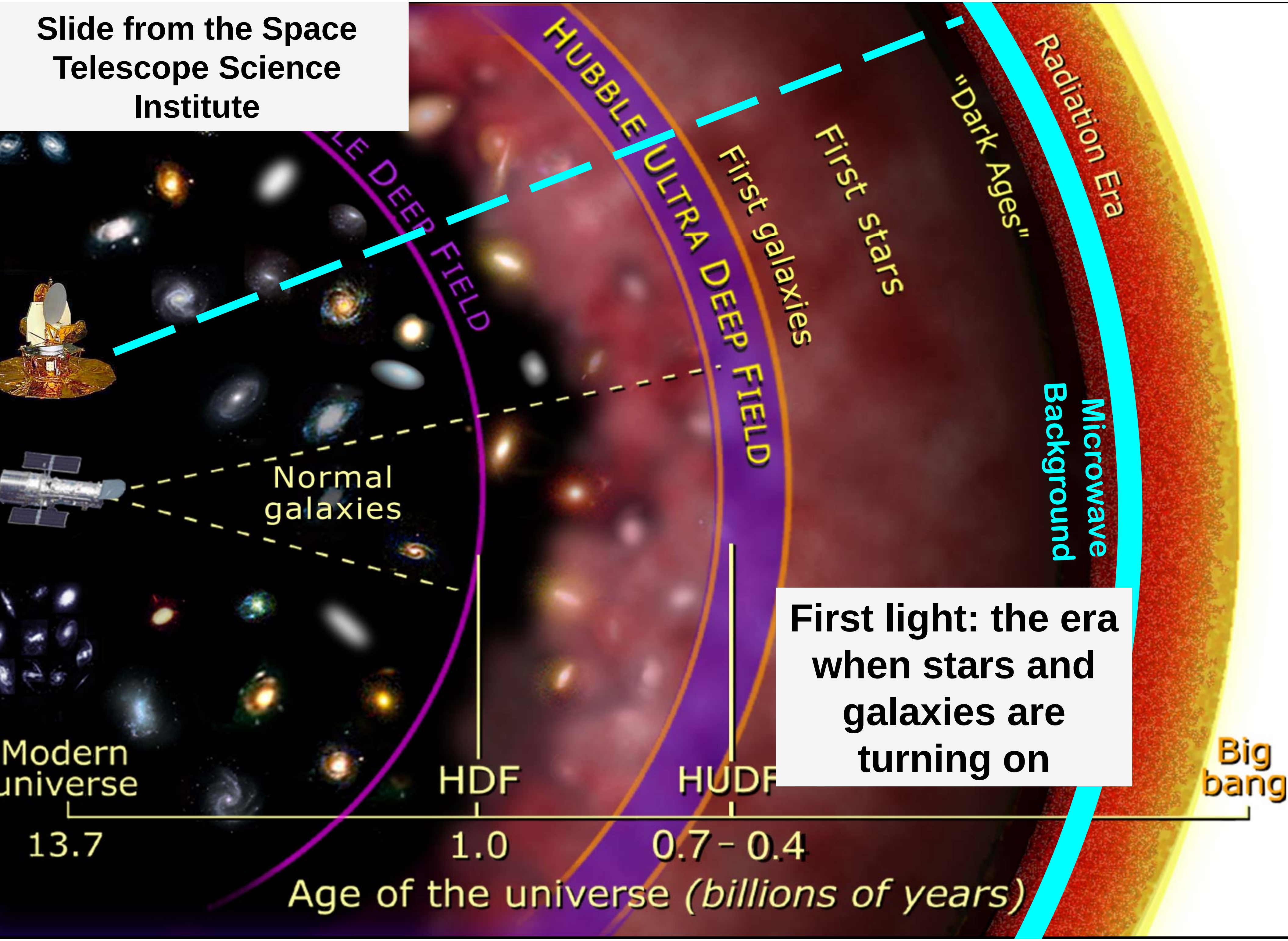
Institutional Members	Representative
Brookhaven National Laboratory (BNL)	Samuel Aronson
California Institute of Technology	George Helou
Carnegie Mellon University	Fred Gilman
Columbia University	Michael H. Shaevitz
Google, Inc.	Rob Pike
Harvard-Smithsonian Center for Astrophysics	Christopher Stubbs
Johns Hopkins University	Alexander Szalay
Las Cumbres Observatory, Inc.	Wayne Rosing
Lawrence Livermore National Laboratory (LLNL)	William H. Goldstein
National Optical Astronomy Observatory*	Sidney Wolff
Penn State University	Daniel J. Larson/Don Schneider
Princeton University	Michael Strauss
Purdue University	Ian Shipsey
Research Corporation*	John P. Schaefer
Stanford Linear Accelerator Center	Jonathan Dorfan
Stanford University -Kavli Institute for Particle Astrophysics and Cosmology	Roger Blanford
The University of Arizona*	Peter A. Strittmatter
University of California at Davis	Barry M. Klein
University of California at Irvine	David Kirkby
University of Illinois at Champaign-Urbana	Richard Crutcher
University of Pennsylvania	Bhuvnesh Jain
University of Pittsburgh	Jeffrey Newman
University of Washington*	Craig J. Hogan

Slide based on information and graphics from the LSST web site.

Science highlights from the future…

- First light and the end of the cosmic "dark ages"
- Exoplanets: what are out there and how do they form?
- Constraining Dark Matter and Dark Energy and the Cosmic Web

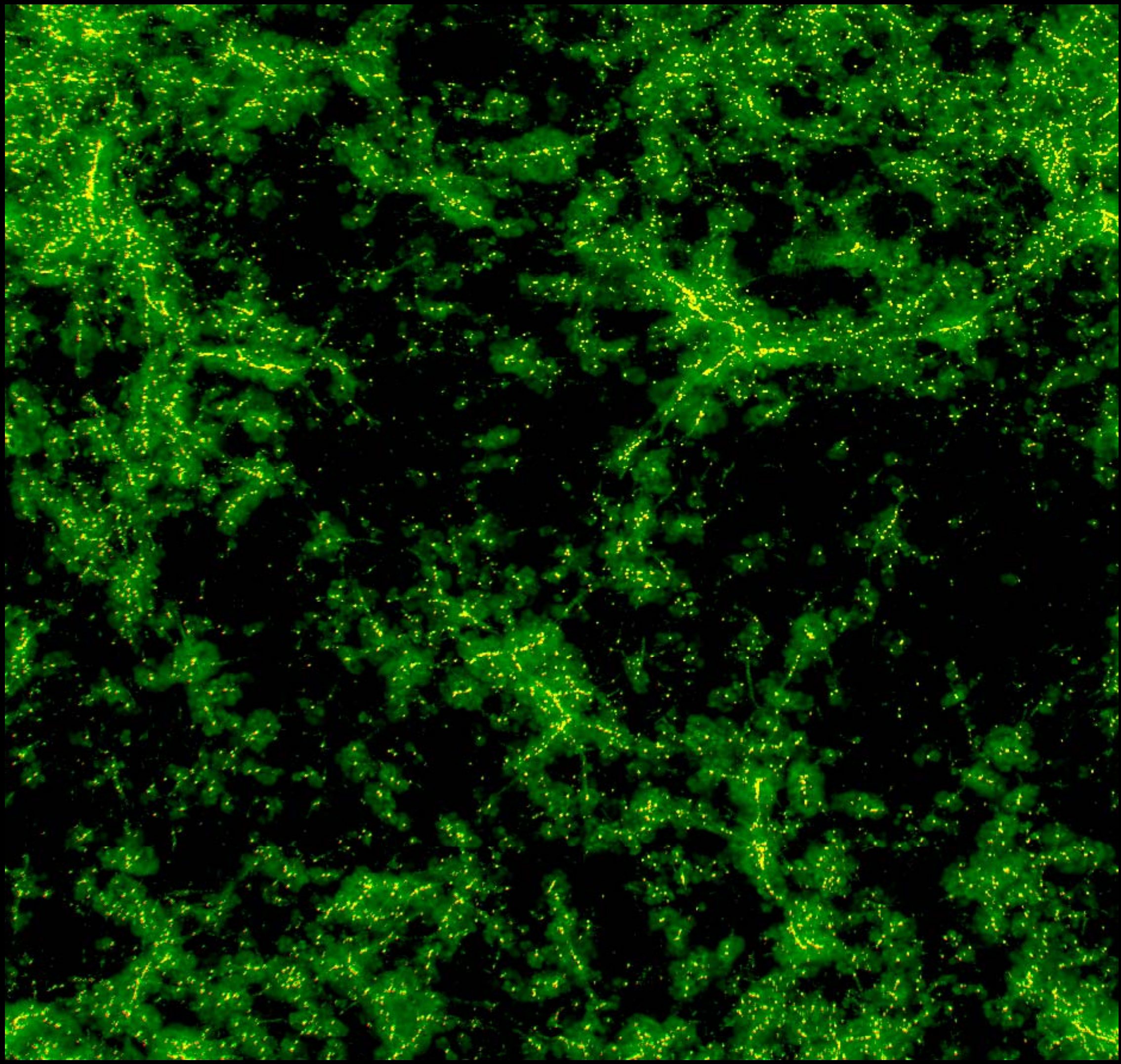
Slide from the Space Telescope Science Institute



First light: the era when stars and galaxies are turning on

Searching for the first stars

- At early epochs (z > 7 or ~13 billion years ago), galaxies were small and star formation rates were low
- These tiny galaxies merged to form bigger ones
- All light is redshifted at least into the near-infrared



Computer simulation of Springel & Hernquist

TMT
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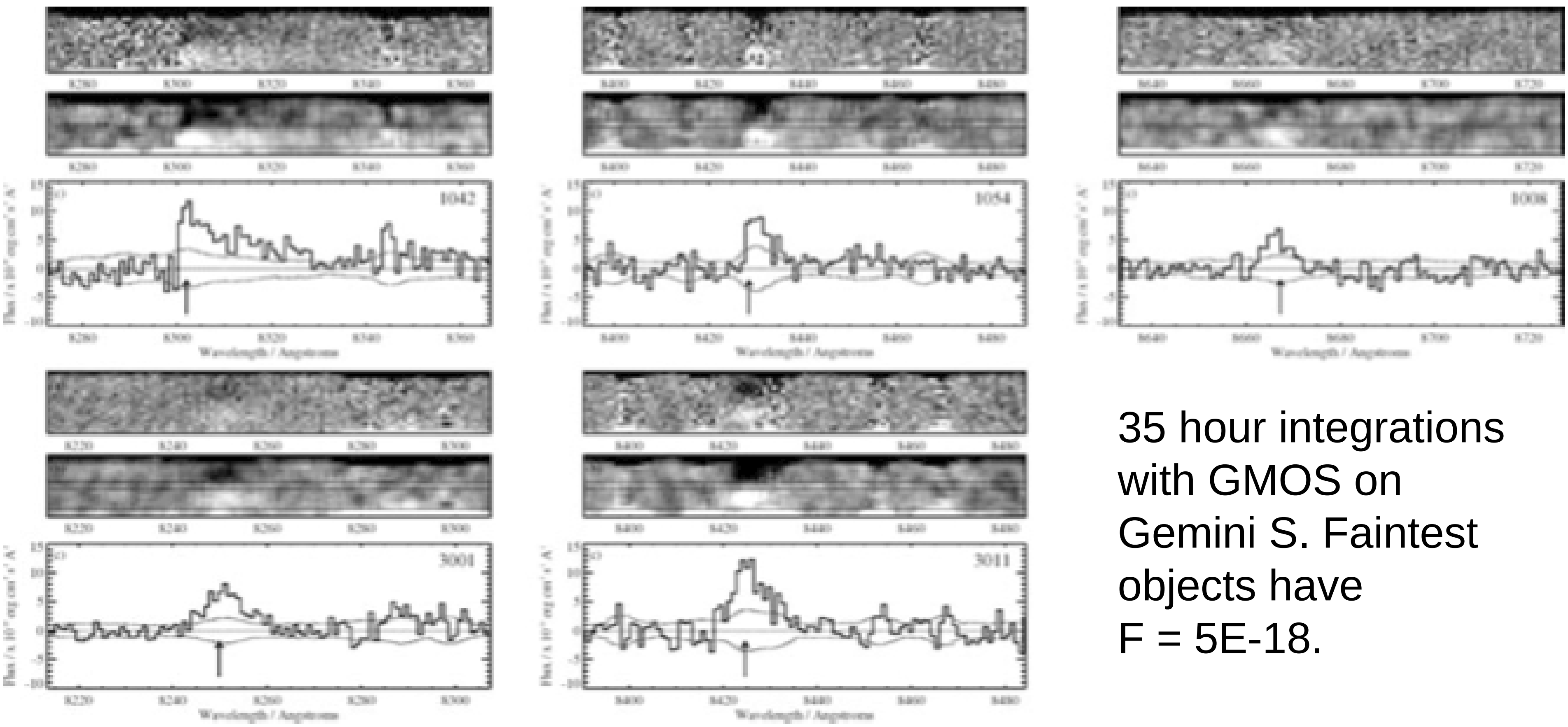
Observations constraining reionization, early star formation

- ***Wilkinson Microwave Anisotropy Probe (WMAP)*:**
  - **Reionization began at 7 < z < 20 (Bennett et al. 2003; Spergel et al. 2007; depending on history)**
- **Becker et al. (2001); Fan et al. (2002):**
  - **Gunn-Peterson troughs in distant quasar spectra**
  - **Reionization ended near z ~ 6**
- **Fan et al. (2001):**
  - **Extrapolated quasar luminosity function not enough to reionize the universe**
- **Yan et al. (2005), Mobasher et al. (2005) and many others:**
  - **Spitzer shows galaxies at z > 6 that are several hundred Myr old**
- **The epoch of pristine (metal-free, “Population III”) star formation remains to be found!!!**

Slide courtesy of Pat McCarthy and the GMT Project.

GMT

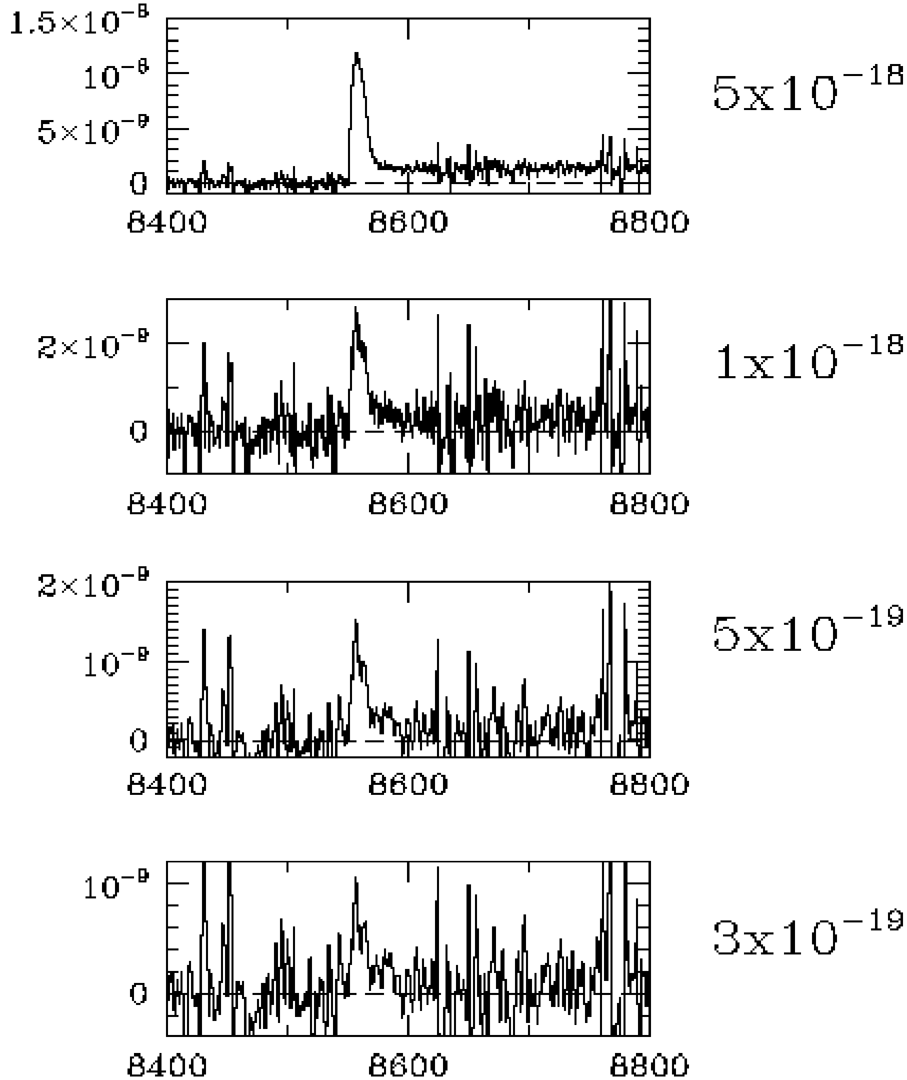
Current State of the Art: Lyα Luminosity Function at z ~ 6



35 hour integrations with GMOS on Gemini S. Faintest objects have F = 5E-18.

Stanway et al. 2006.

GMT and the Lyα Luminosity Function at z ~ 6



500 km/s FWHM

W_λ = 100Å

30hr integration with GMACS using 0.5” slits in 0.5” seeing

30% throughput

Gemini sky spectrum

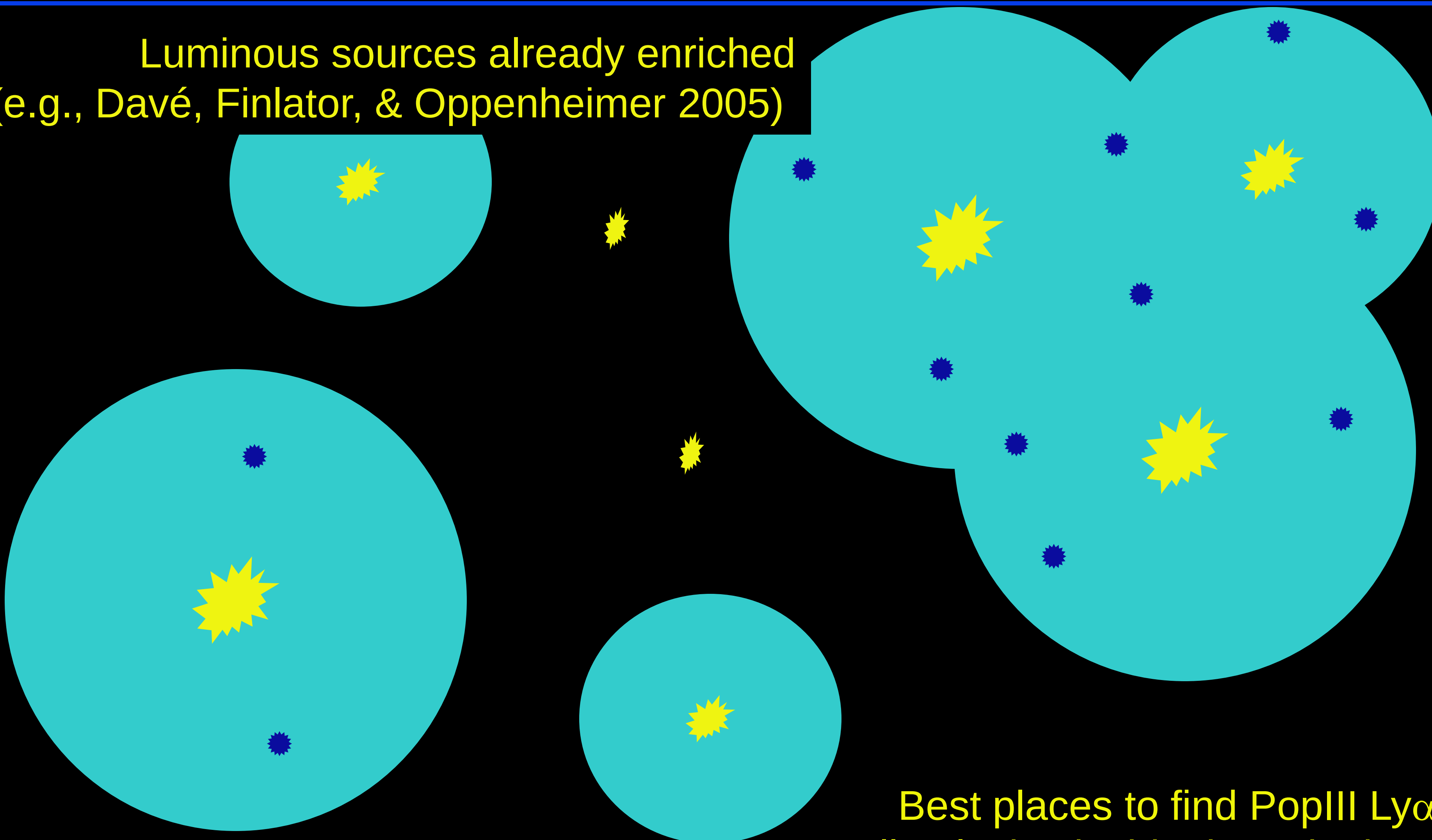
Nod & Shuffle sky rejection

R = 5000 rebinned to

R = 1200, Gaussian smoothing

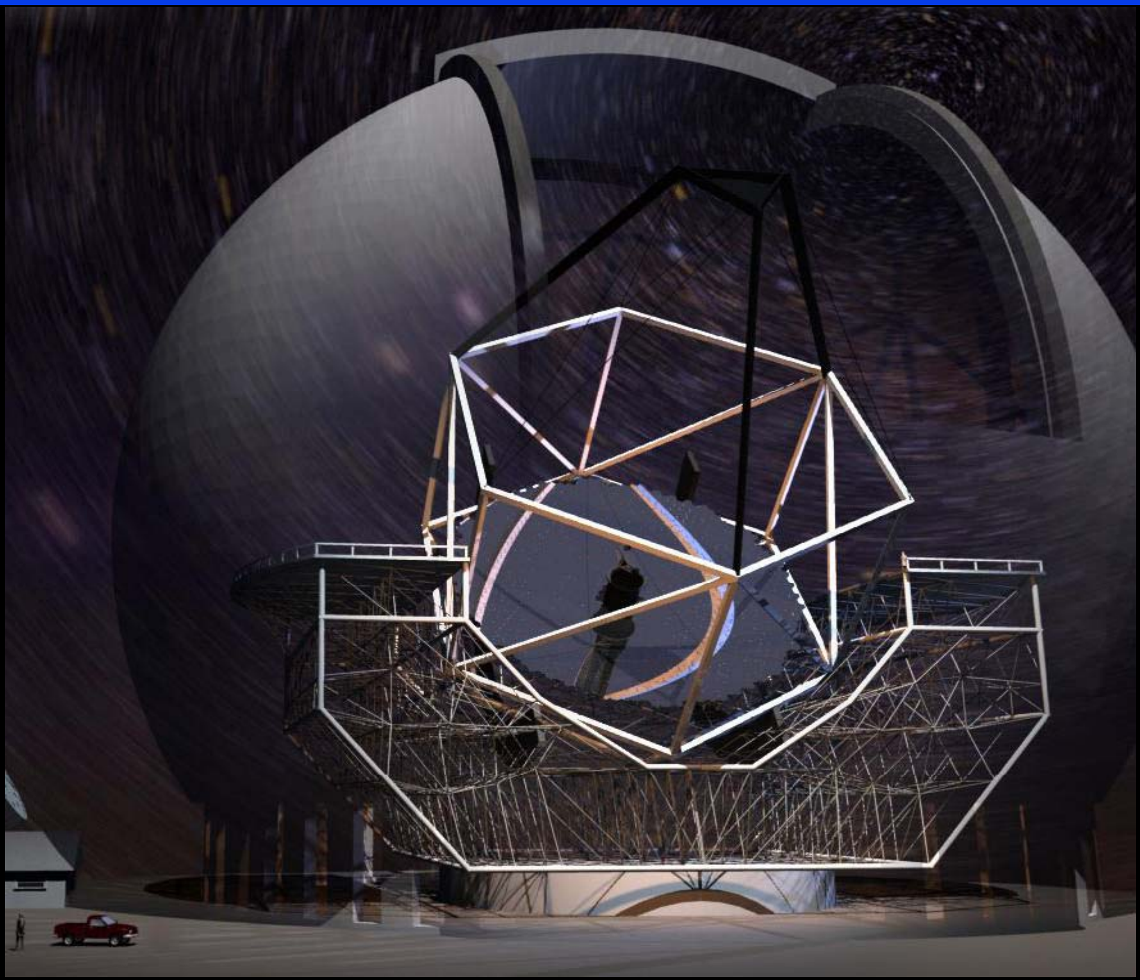
Penetrating the Early, Neutral IGM with ionized bubbles

Luminous sources already enriched
(e.g., Davé, Finlator, & Oppenheimer 2005)



Best places to find PopIII Lyα may be
small galaxies inside these ionized bubbles

Plans for first-light science in the future



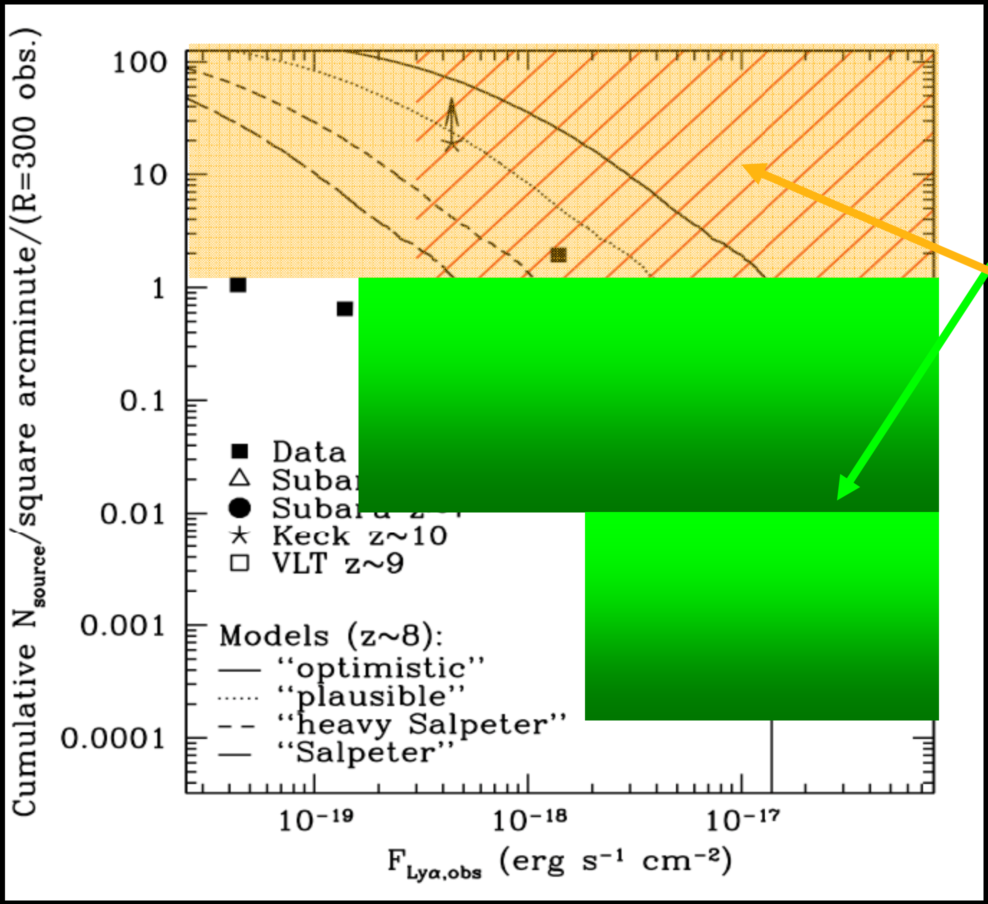
Thirty Meter Telescope

TMT first-light IR instruments that will tackle first light:

- **IRMS: 2 arcminute field-of-view IR MOS behind AO**
- **IRIS: IR, 15-arcsecond fov imager/0.26-3.2 arcsecond IFU**

"First light" parameter space and changes in the Big Telescope era

Number detectable in a given observation



Flux of objects (unknown)

Blind surveys in the 10^{-19} regime; lensed surveys in the 10^{-20} regime

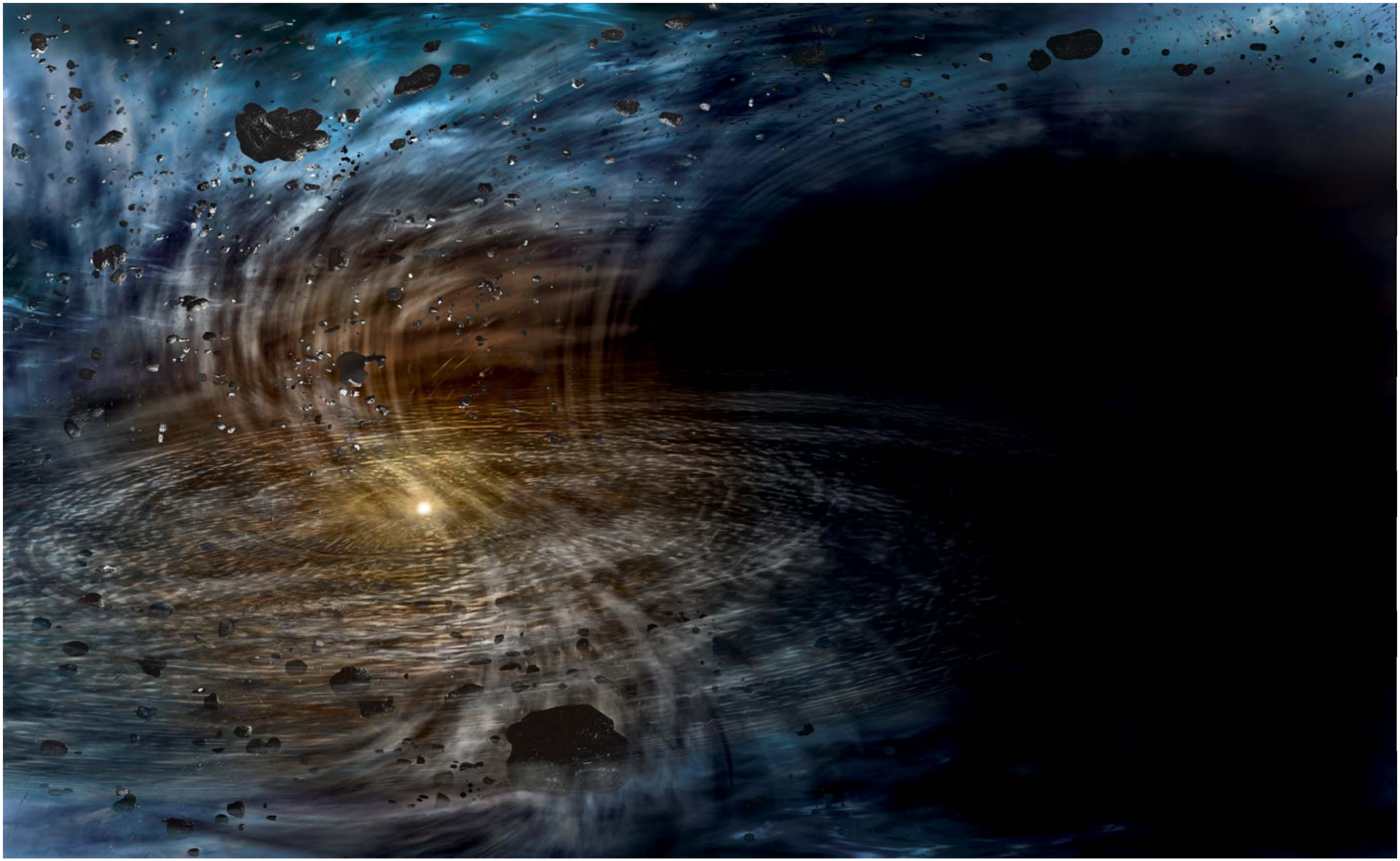
TMT and/or GMT will fill in essentially all of the remaining discovery parameter space.

What can we hope to understand with ELTs and AO?

- **When did galaxies assemble and “turn on”?**
  - **Luminosity functions to z=20 and even beyond (JWST + Lyman α searches with ELTs?)**
  - **Keys are sensitivity and wide field**
- **When did Population III (metal-free) stars form?**
  - **Other spectral features like HeII with ELTs**
  - **Key is extreme sensitivity**
- **How did reionization proceed? (Topology, rate, effects.)**
  - **Maps for Mpc-scale clustering (e.g., Mesinger & Furlanetto 2007; ELTs?)**
  - **Keys are sensitivity and wide field**

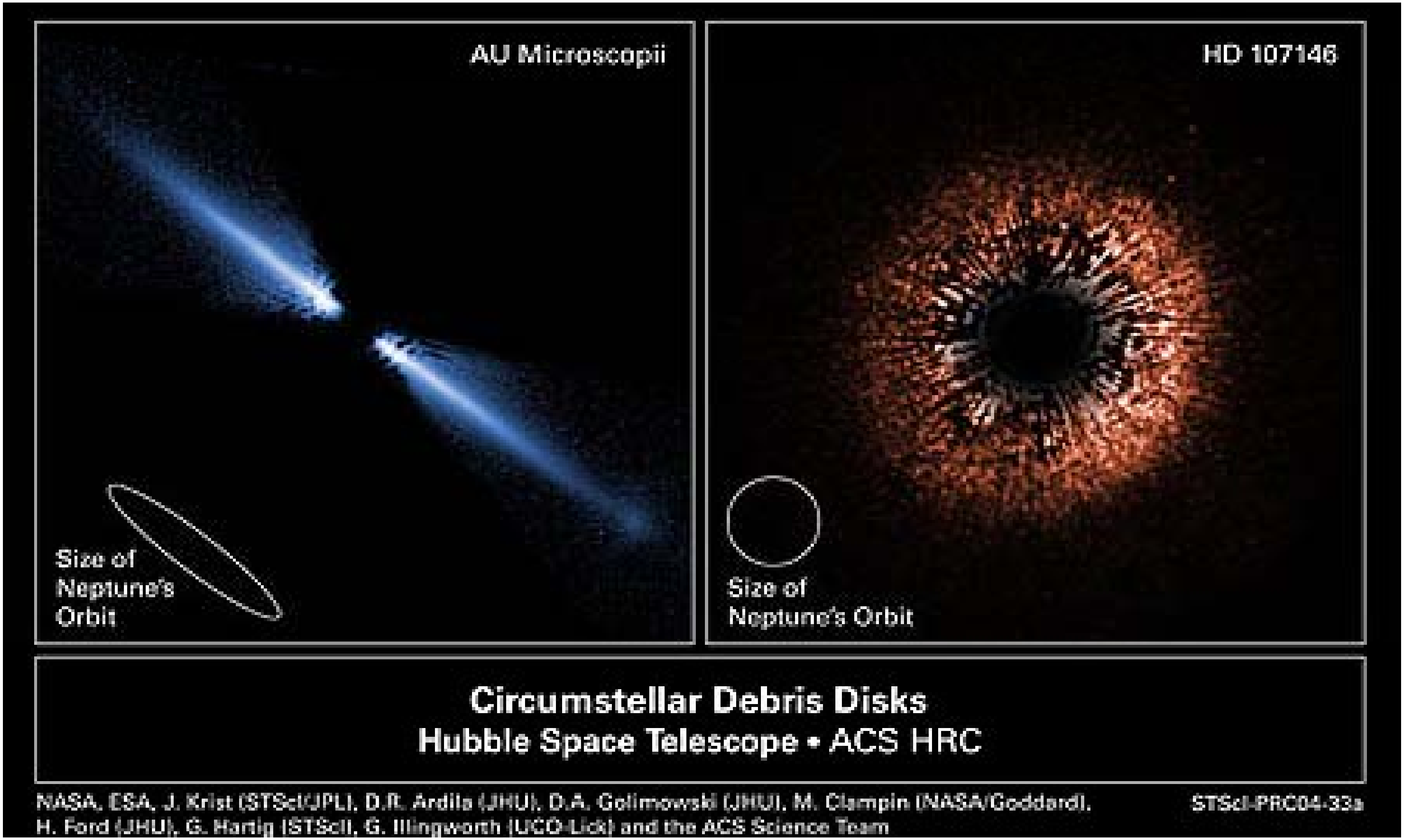
Slide courtesy of the GMT project and Scott Kenyon.

Planets Form in Disks

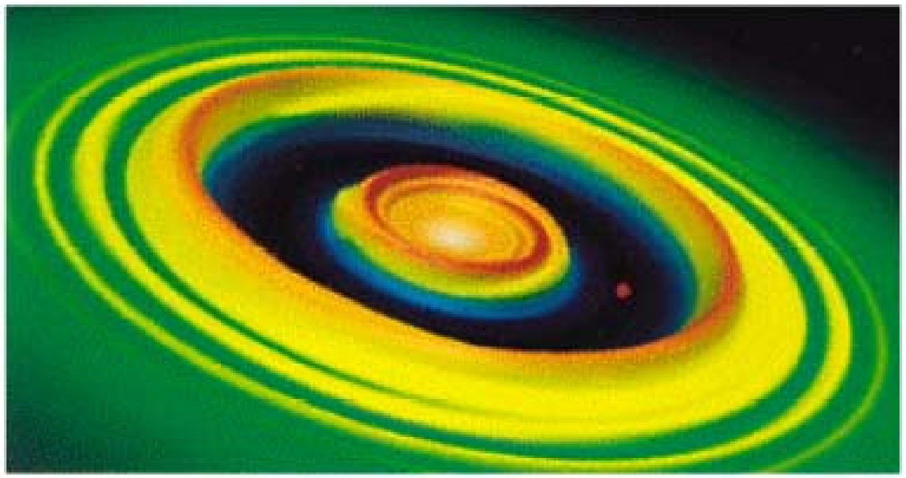


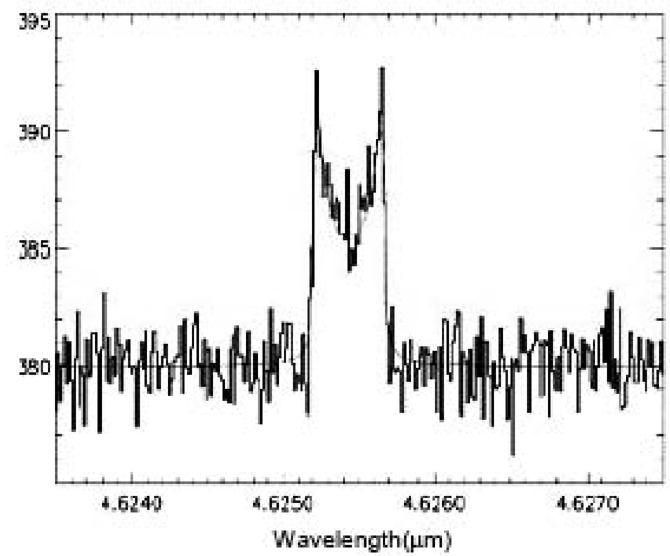
Slide courtesy of the GMT project and Scott Kenyon.

AU Mic and HD 107146



The dynamical effects of a new gas giant on a disk



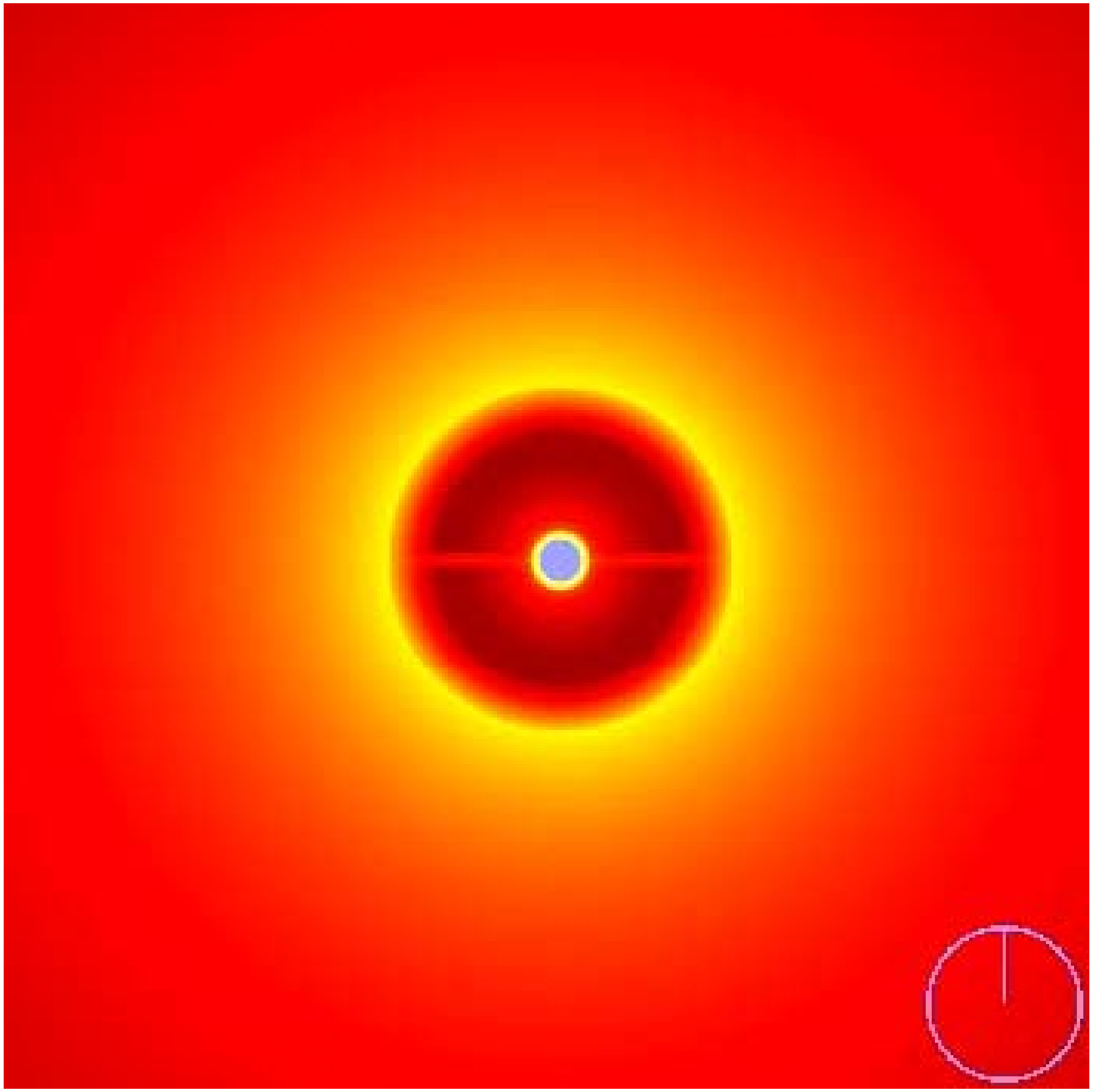


G. Bryden (Caltech) **J. Najita (NOAO)**

- **planet opens a gap in the disk (*left*),**
- **gap introduces a spectral signature in carbon monoxide (simulated with TMT, *right)***
- **horn separation indicates the star/planet separation**

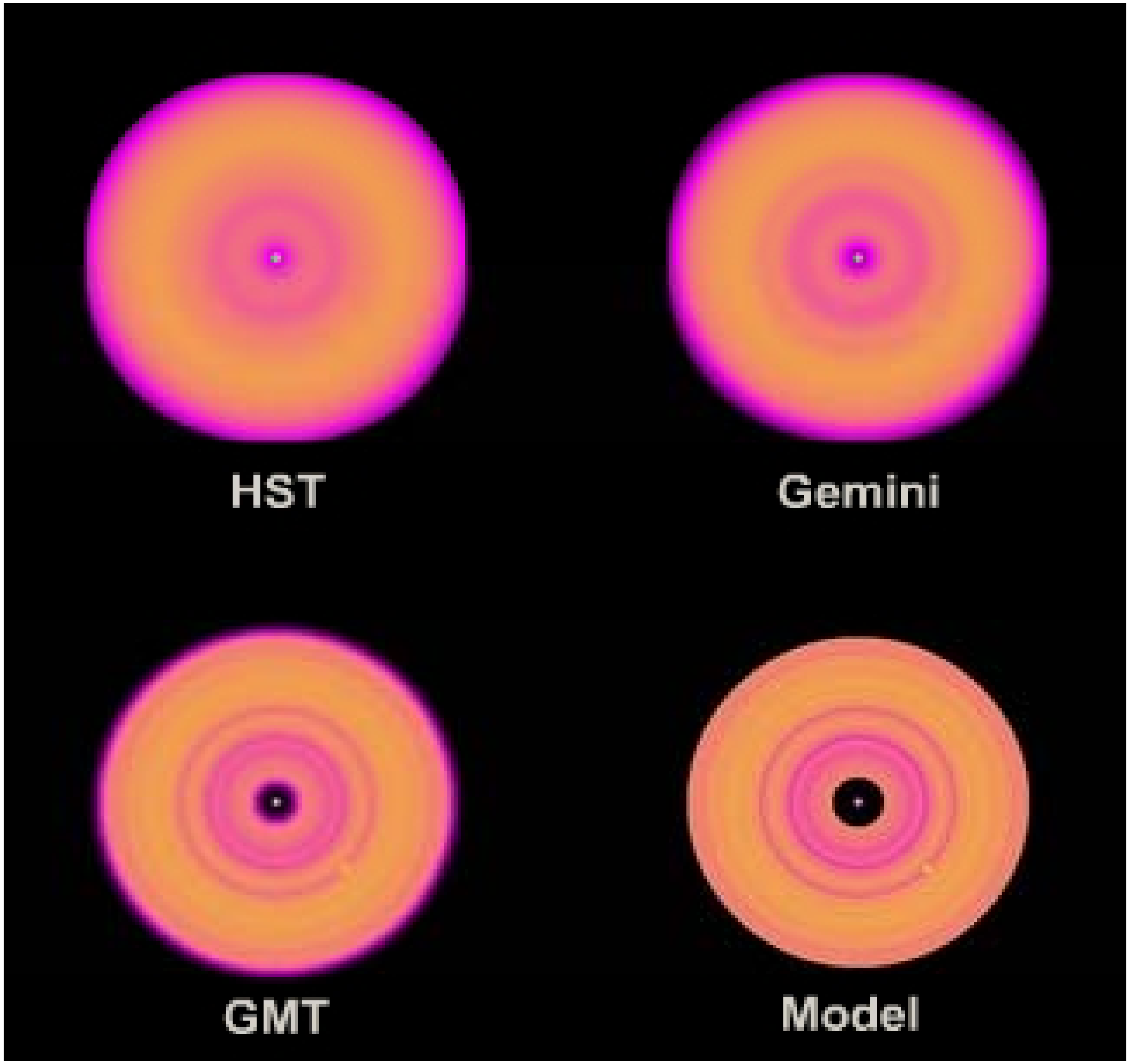
Slide courtesy of the GMT project and Scott Kenyon.

Debris Disk: GMT View

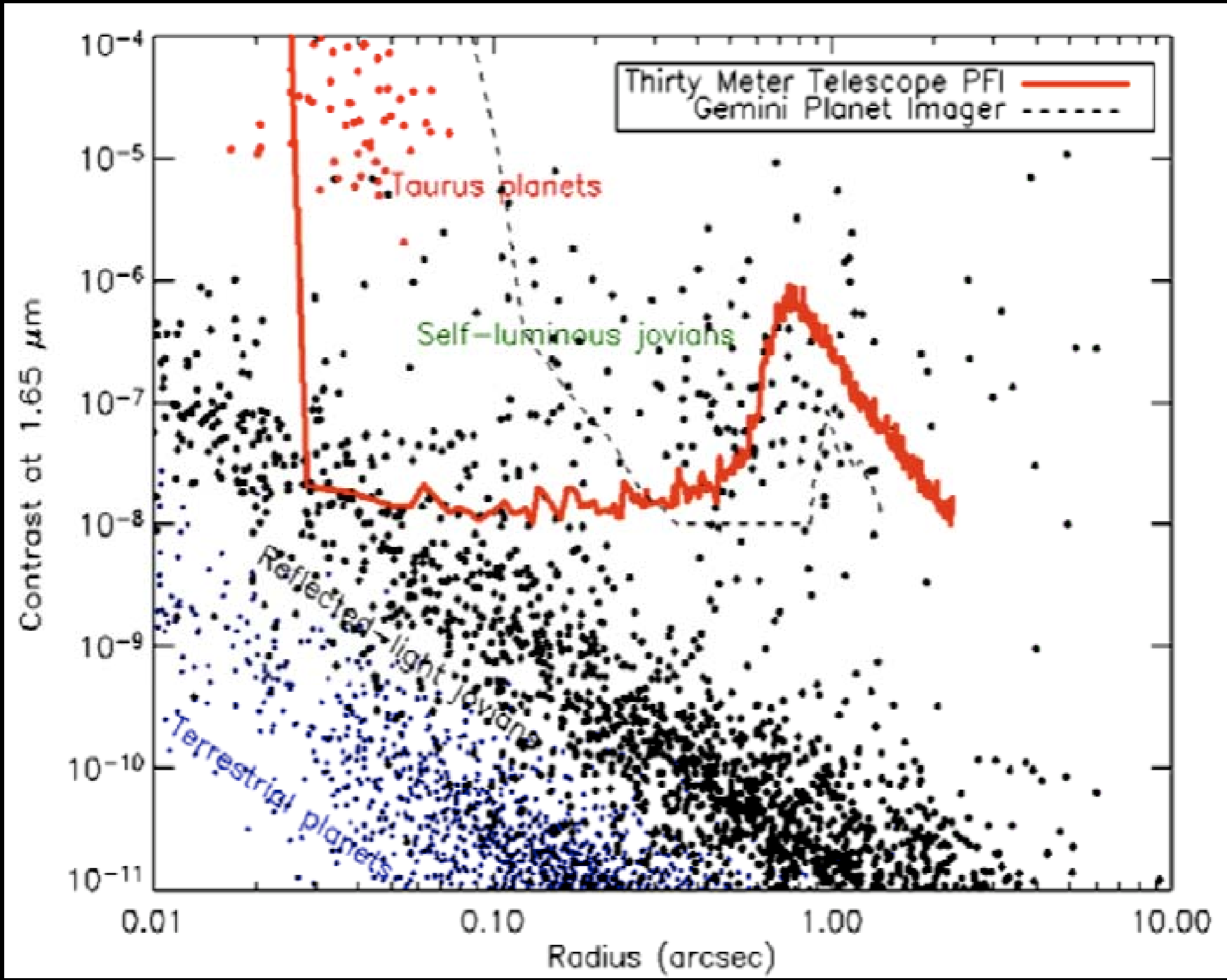


Slide courtesy of the GMT project and Scott Kenyon.

Planets in Debris Disks

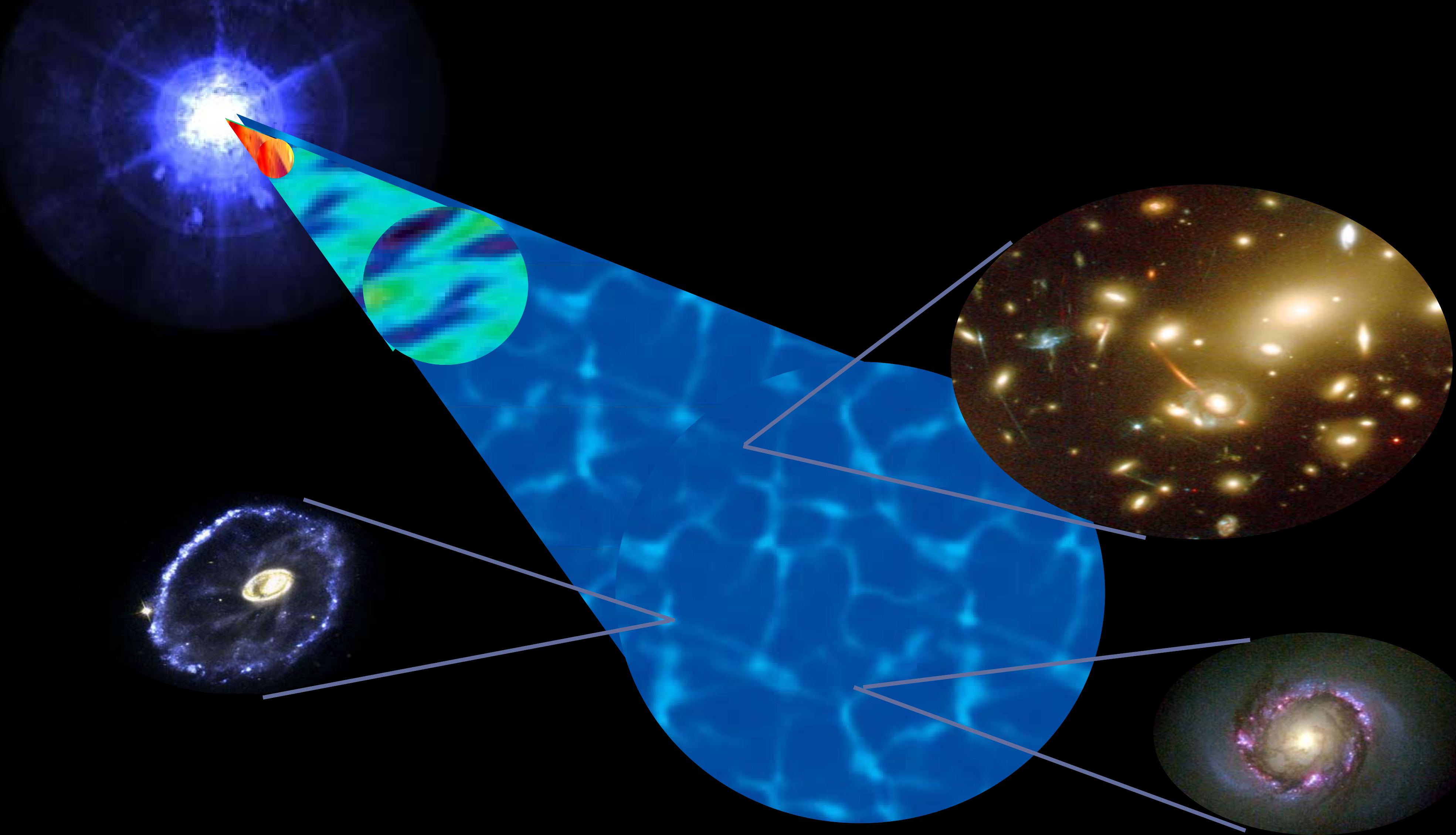


Exoplanet imaging



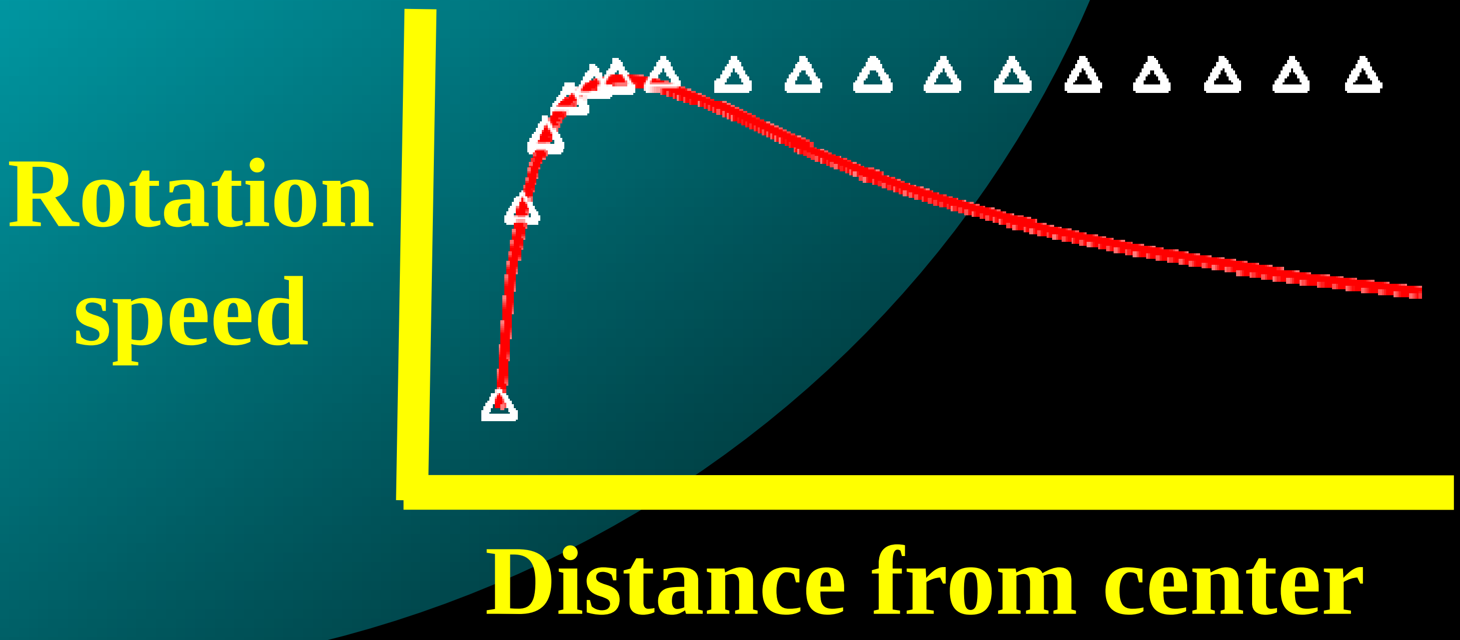
- **Adaptive optics plus large telescopes will enable imaging observations of Jupiter-like planets seen in reflected light**

The Dark Side of the Universe

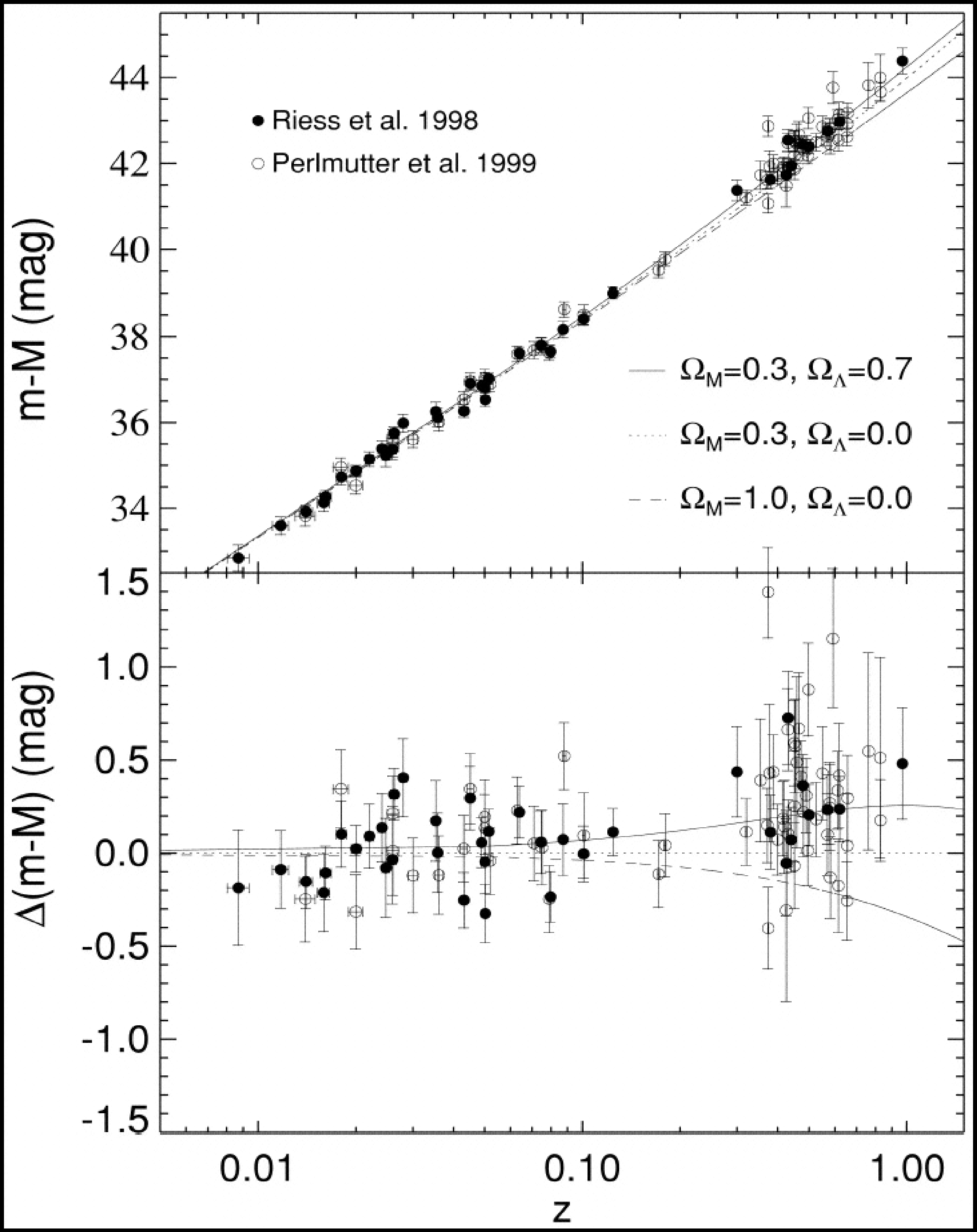


Dark Matter

Rubin



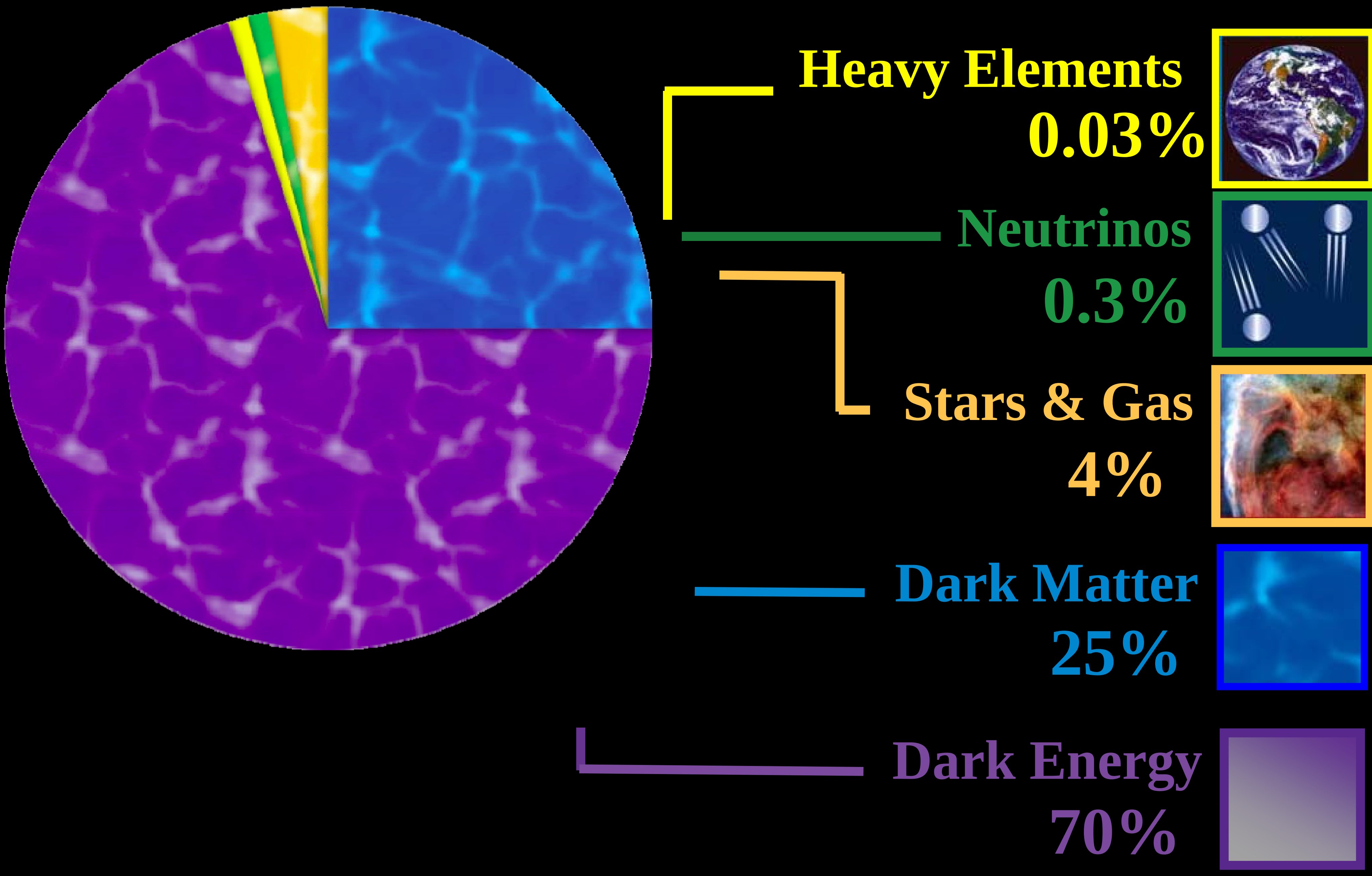
Evidence for Dark Matter in Galaxy Clusters


Riess et al. 1998
Perlmutter et al. 1999
m-M (mag)
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
Δ(m-M) (mag)
z

Λ

is not 0!!

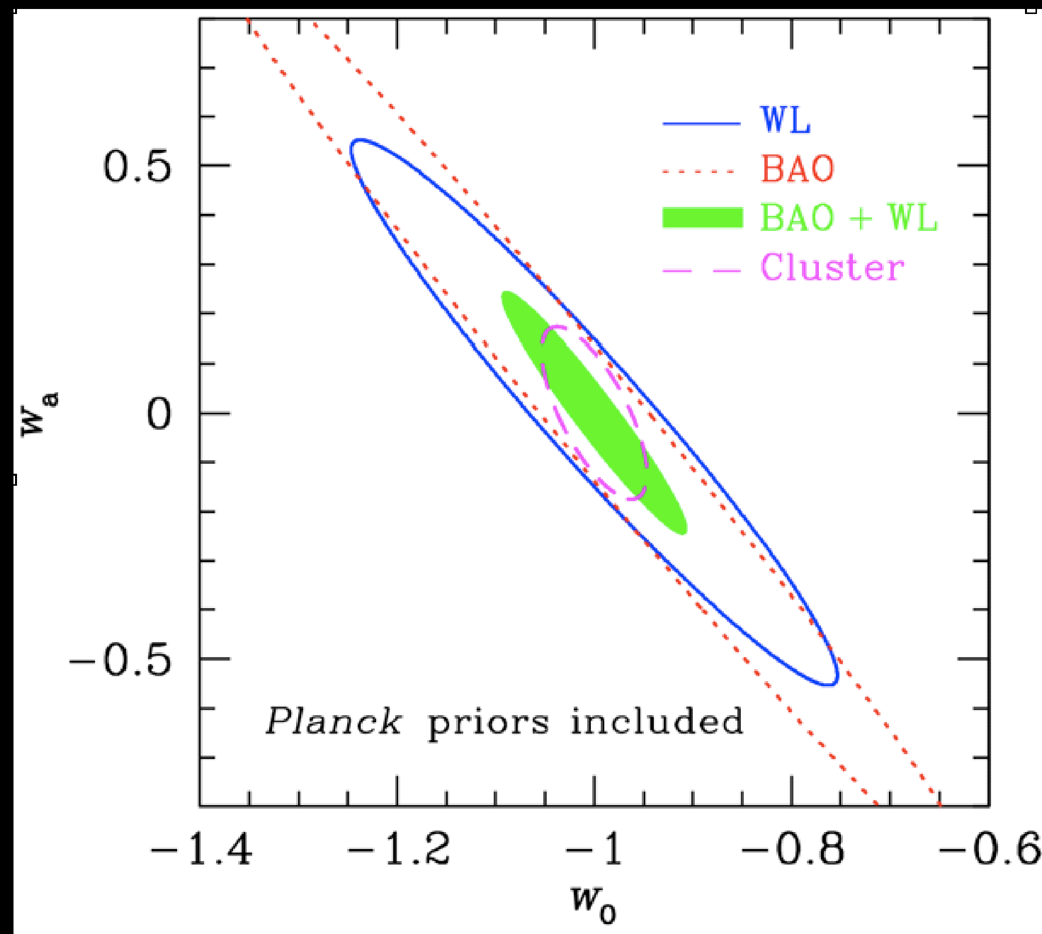
Composition of the Cosmos



Probing Dark Energy with a wide field of view

Large Synoptic Survey Telescope

- **Multiple probes to approach the problem:**
  - **Cosmic shear**
  - **Baryon acoustic oscillations**
  - **Supernovae**
  - **Galaxy cluster counting**



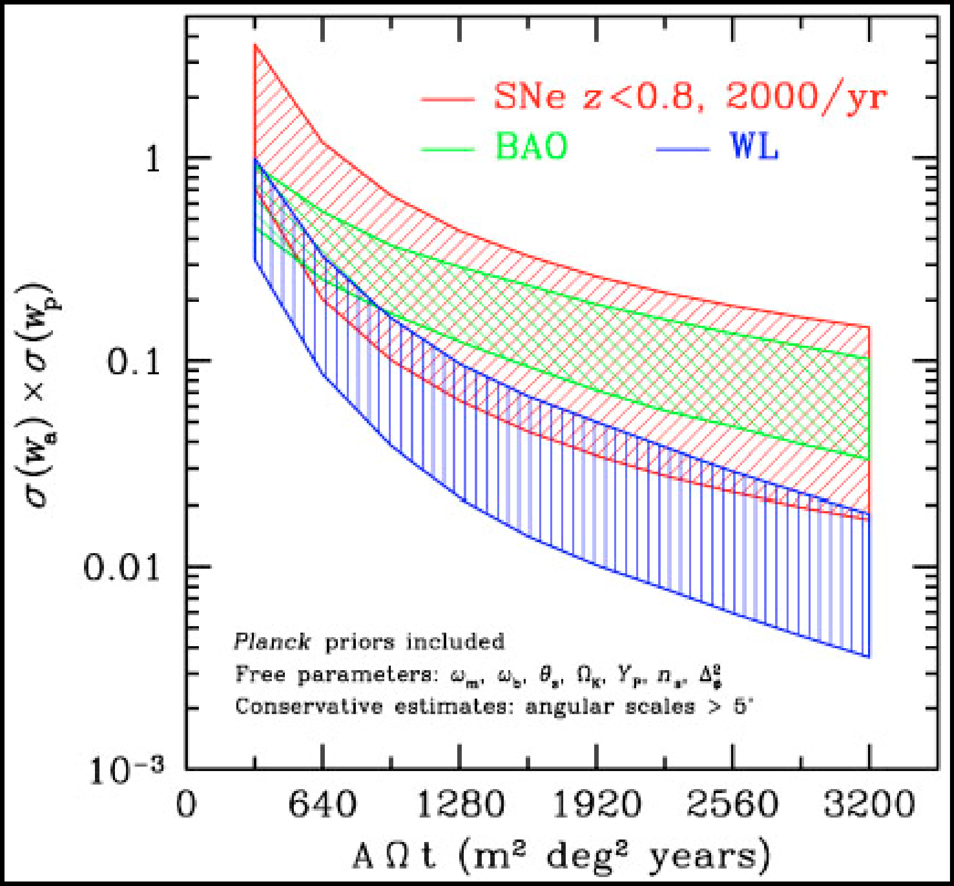
(Equation of state where $w=w_0+w_a(1-a)$, a= scale factor.)

Slide based on information and graphics from the LSST web site.

Probing Dark Energy with a wide field of view

Large Synoptic Survey Telescope

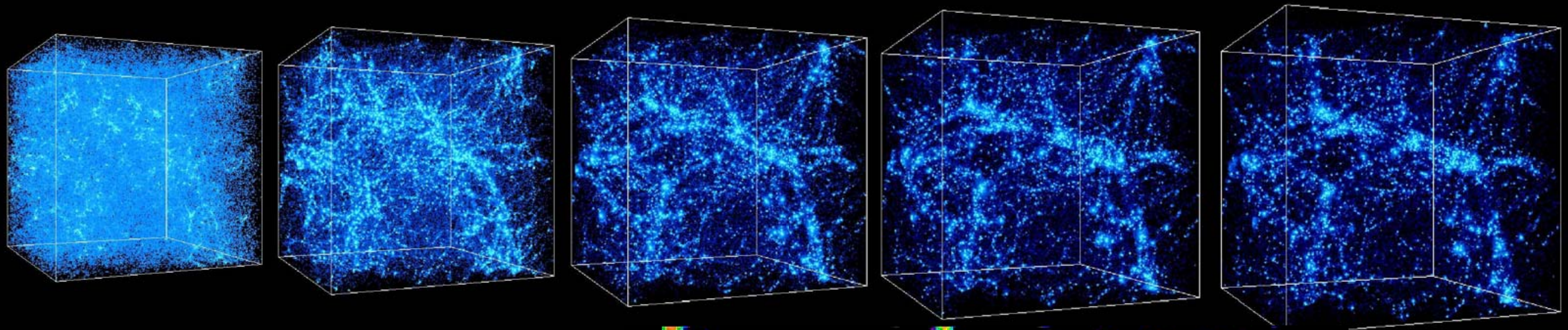
- The primary methods require the combination of a large telescope (A), a large field of view (Ω), and long/deep observations (t)
- LSST is specifically designed to provide this combination



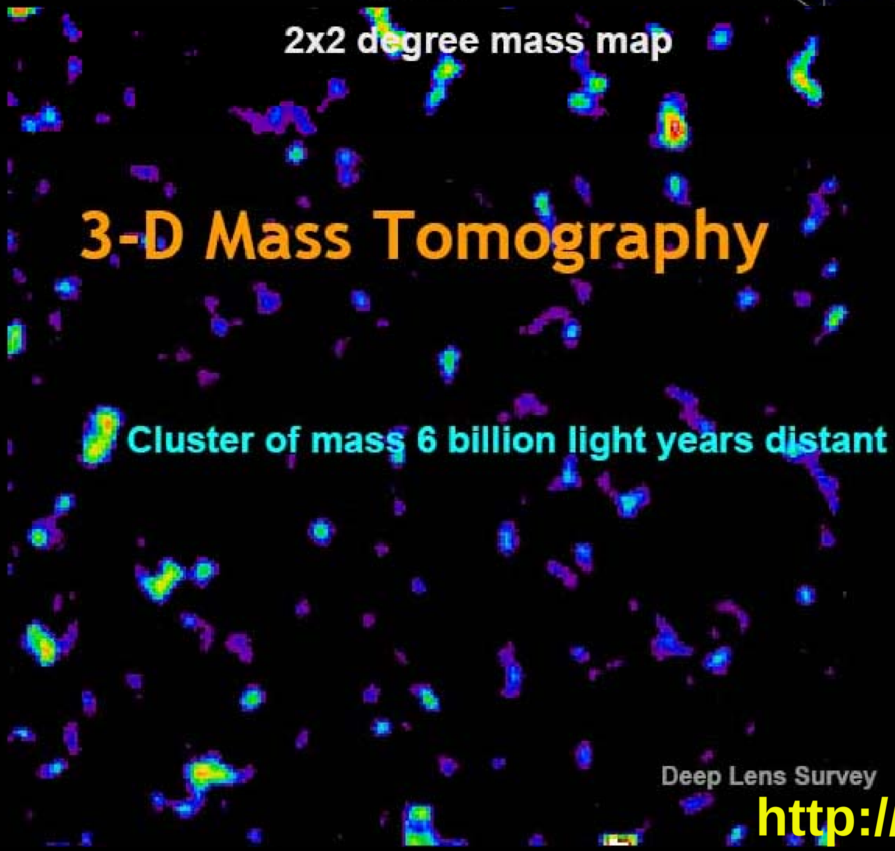
(Equation of state where $w=w_0+w_a(1-a)$, a= scale factor.)

Slide based on information and graphics from the LSST web site.

Computer Simulations of Galaxy Formation



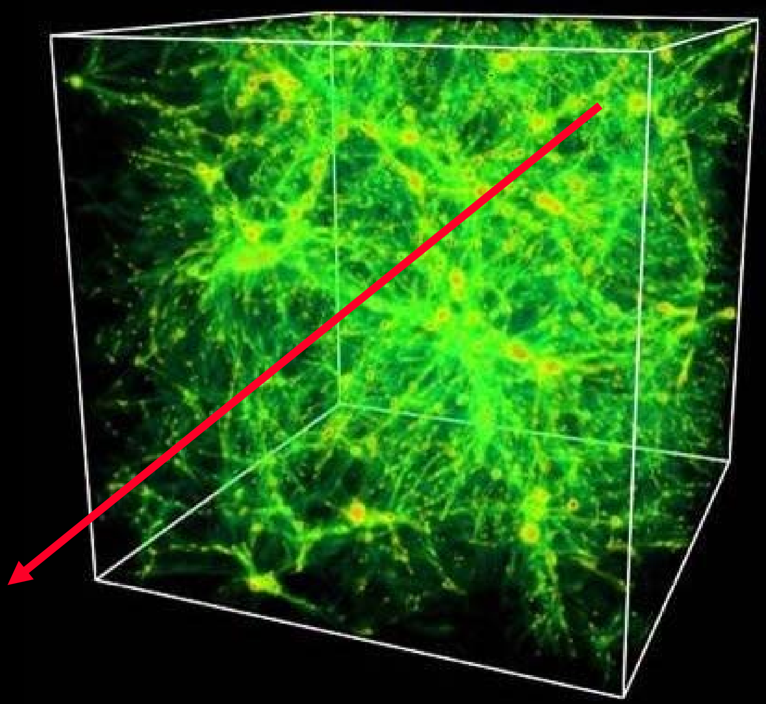
Simulations were performed at the National Center for Supercomputer Applications by Andrey Kravtsov (The University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov.



http://www.lsst.org

Probing the Cosmic Web

- **TMT and GMT will probe the cosmic web with:**
  - **Deep redshift surveys**
  - **Line-of-sight measurements through the intergalactic medium using background quasars and galaxies**



Synergy for the New Telescopes

- LSST is an 8-m, wide-field imager that images the entire sky every 3 nights
- TMT and GMT are giant (30 and 25-meter) telescopes that focus on detailed observations in smaller fields
- LSST will provide a giant imaging survey
- The big telescopes will provide:
  - The only ground-based infrared capability to study extremely distant objects
  - The only spectroscopic capability for physical diagnostics
  - Follow-up of detected objects
  - Calibration/checking for LSST "photometric redshifts"

To find out more…

- **TMT:** **http://www.tmt.org**
- **GMT:** **http://www.gmto.org**
- **LSST:** **http://www.lsst.org**

TMT
THIRTY METER TELESCOPE

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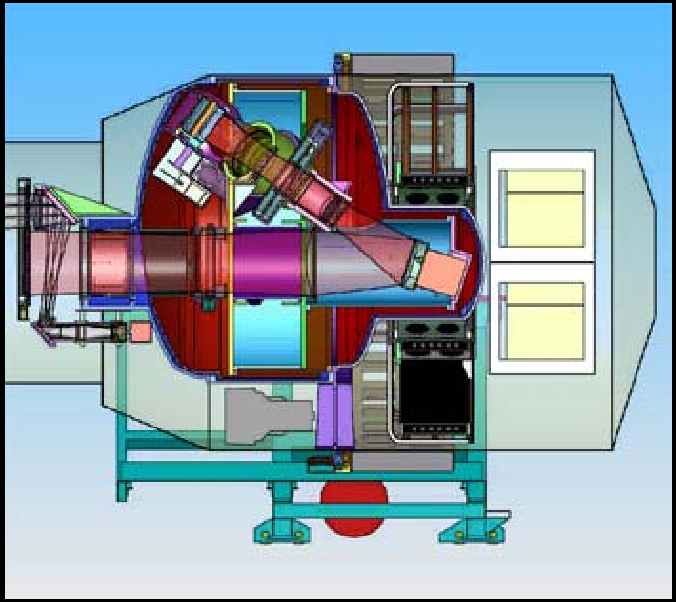
IRIS

- 128 x 128 “pixel” IFU
- 0.8-2.5 μm requirement, 0.6-5.0 μm goal
- 4 plate scales: 4, 10, 25, 50 mas
- 4 fields of view: 0.26, 0.64, 1.60, 3.20 arcsec
- Full Y, J, H, or K coverage at once
- R ~ 4000

See earlier presentation by Anna Moore.

IRMS

- "Little Sister" to Keck/MOSFIRE
- 0.95-2.45 μm
- All of Y, J, H, or K at once
- 2 arcminute field of view
- 46 reconfigurable cryogenic slits
- <= 60-80 mas arcsecond sampling
- 80% energy in 2x2 pixels
- R ~ 4660



WFOS

- 0.31-1.0 μm requirement; 0.3-1.5 μm goal
- Seeing-limited
- R ~ 4000; possible higher-dispersion mode
- 8-10-arcminute field

Slide courtesy of J. Nelson.

Requirements Summary

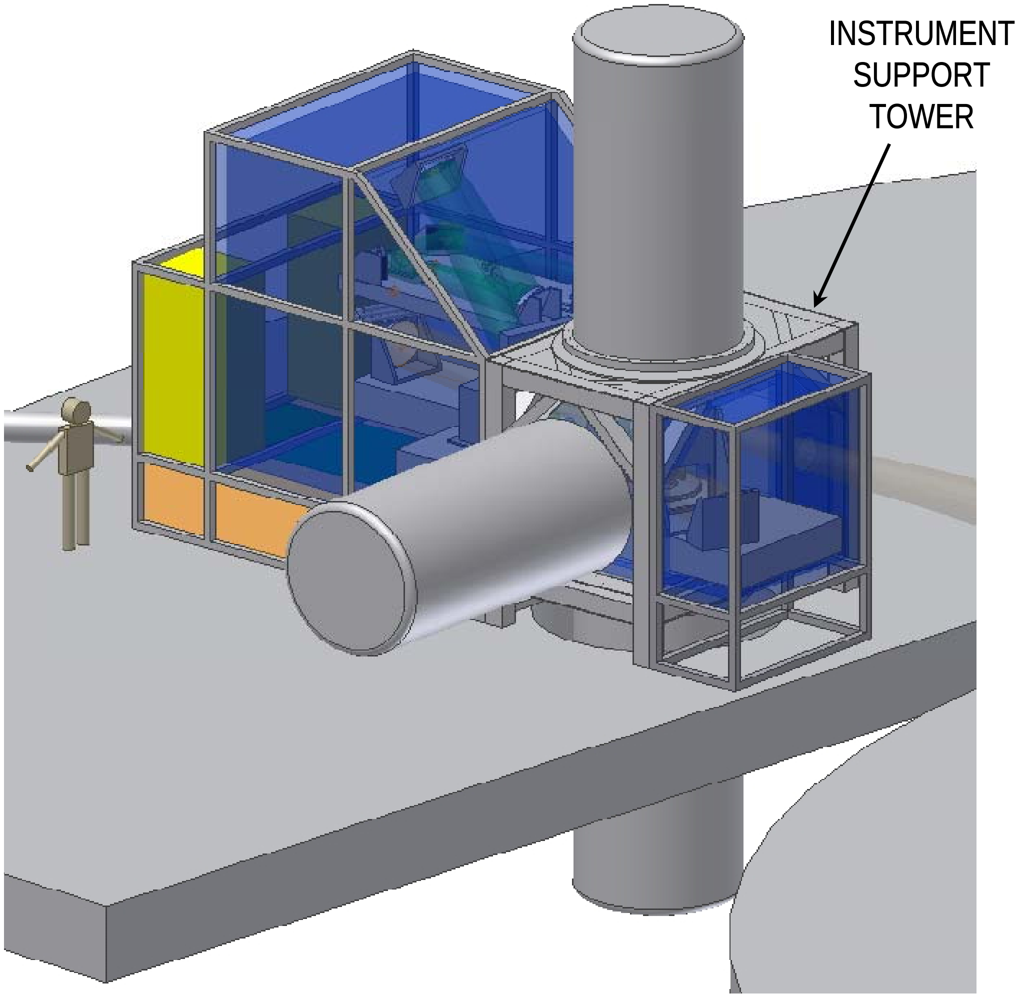
- Science wavelength range is 1.0 - 2.5 um
  - NFIRAOS will work down to 0.8 um with reduced performance
- WFS wavelength range is 0.589, 0.6 - 1.0 um
- NFIRAOS FOV is 2 arcmin
- 6 LGS will be arranged with a central star and five in a 35” radius pentagon
- Optical design will support an upgrade with WFE (including telescope and instrument) < 133 nm RMS
- Operating temperature is -30 deg C
- DM conjugate altitudes are 12 km and 0 km

Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

Structural Design Background

- At CoDR, only the vertical (upper and lower) instruments were to be supported by NFIRAOS, via an "instrument support tower" placed on the Nasmyth platform
  – The lateral instrument was to have been supported from the Nasmyth platform
- The lateral instrument, an instrument calibration unit and possibly a turbulence simulator, have been added to the equipment that will be supported by NFIRAOS
  – An additional 7+ T



Slide courtesy of J. Nelson.

NFIRAOS Performance Requirements for Early Light

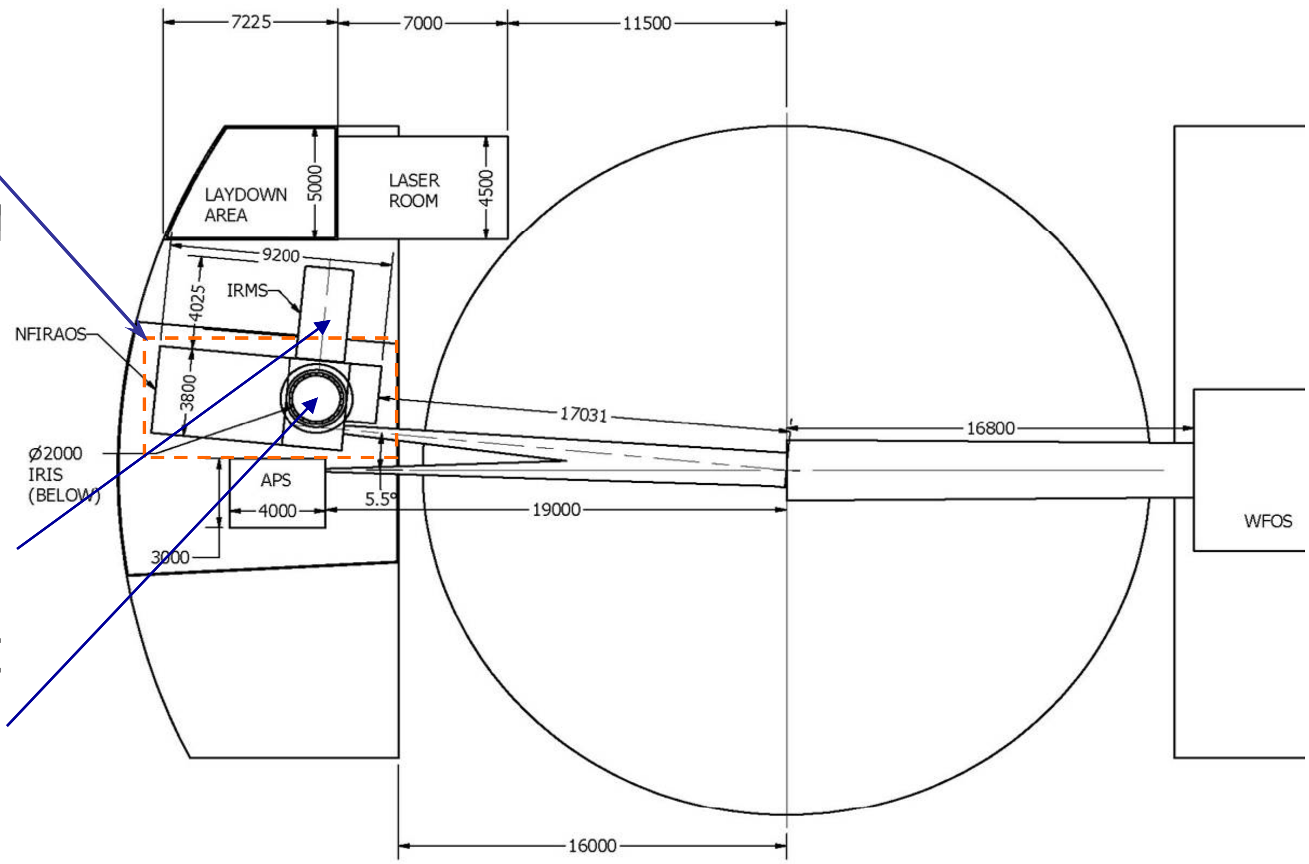
- High throughput in I, J, H, and K spectral bands (0.8-2.4 μm) with very low emission
- 50% sky coverage with < 2 mas jitter at the Galactic pole
- Diffraction-limited near IR image quality on a 10-30” FoV
  – IRIS (additional instruments at a later date)
- High enclosed energy within 160 mas spectrometer slits on a 2’ FoV
  – IRMS
- Excellent photometric and astrometric accuracy
- High observing efficiency, with a minimum of downtime and night-time calibration

Slide courtesy of J. Nelson.

TMT
THIRTY METER TELESCOPE

TMT Nasmyth Layout at Early Light

- NFIRAOS (Narrow Field IR AO System) located on –X Nasmyth Platform
- Early light instruments IRMS (side mounted) and IRIS (bottom)



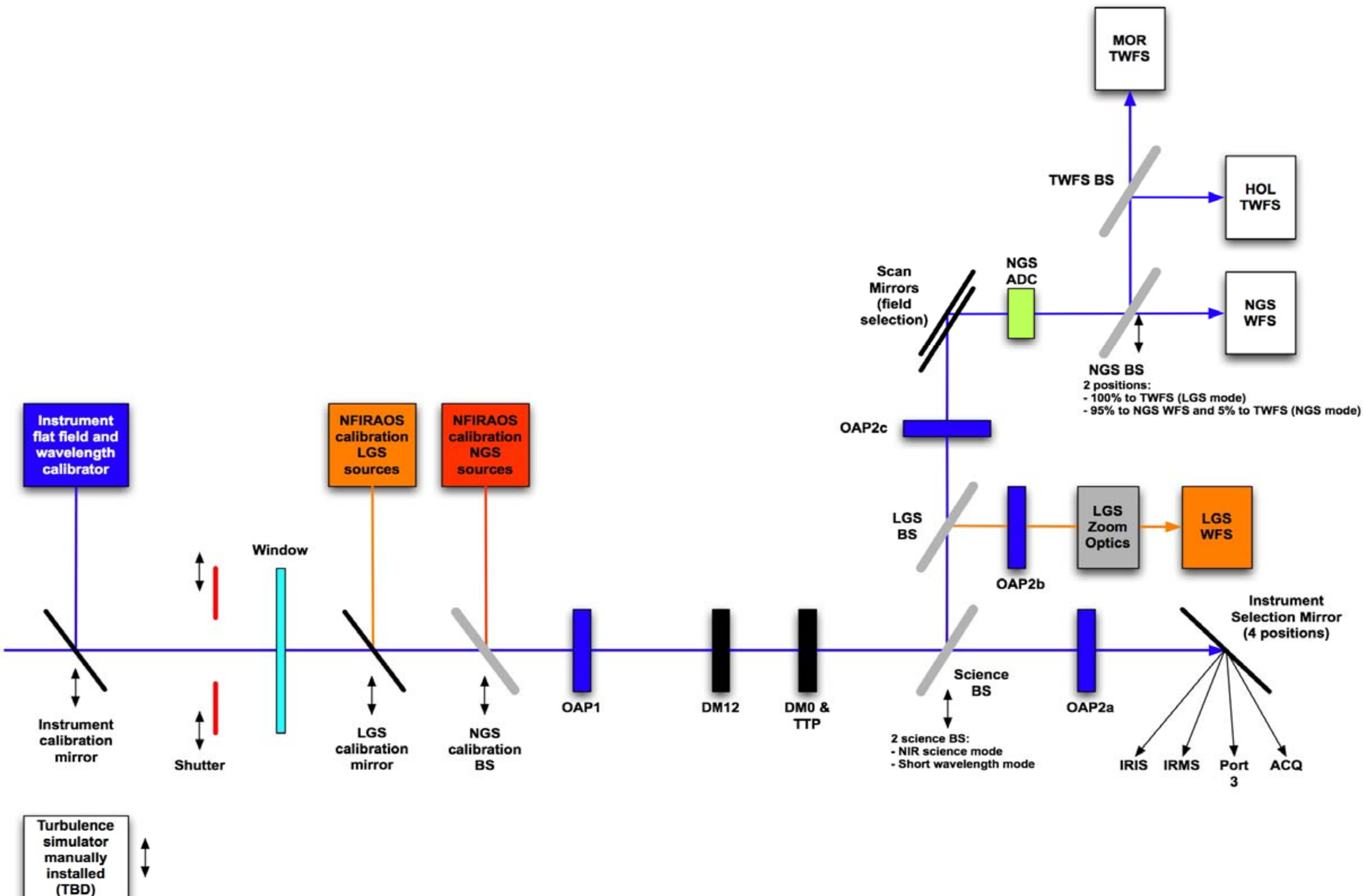
Ref: OAD, Fig. 5

[HIA NFIRAOS Design Team]

Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

NFIRAOS Optical Path Schematic



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TMT
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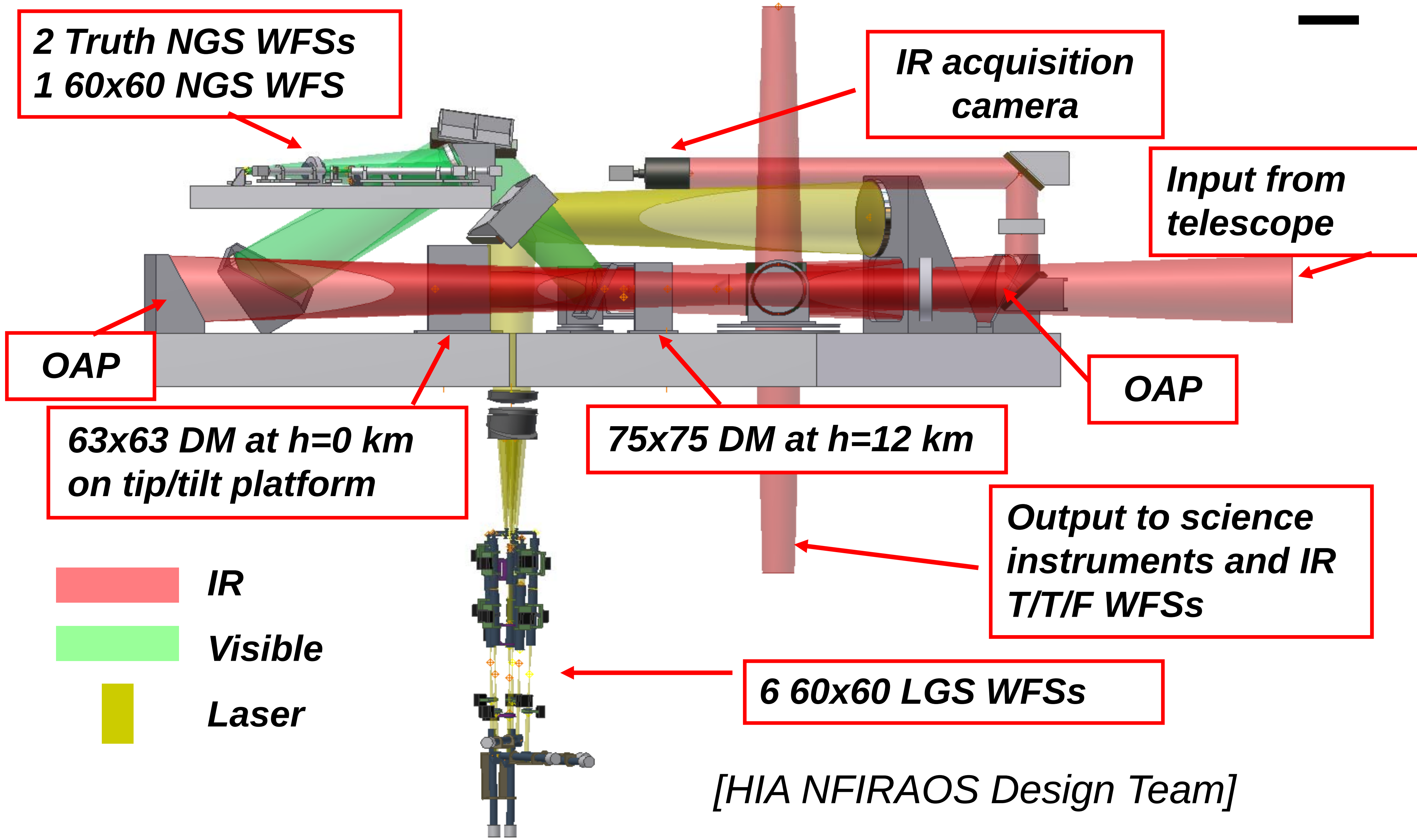
NFIRAOS
Latest Optomechanic Layout

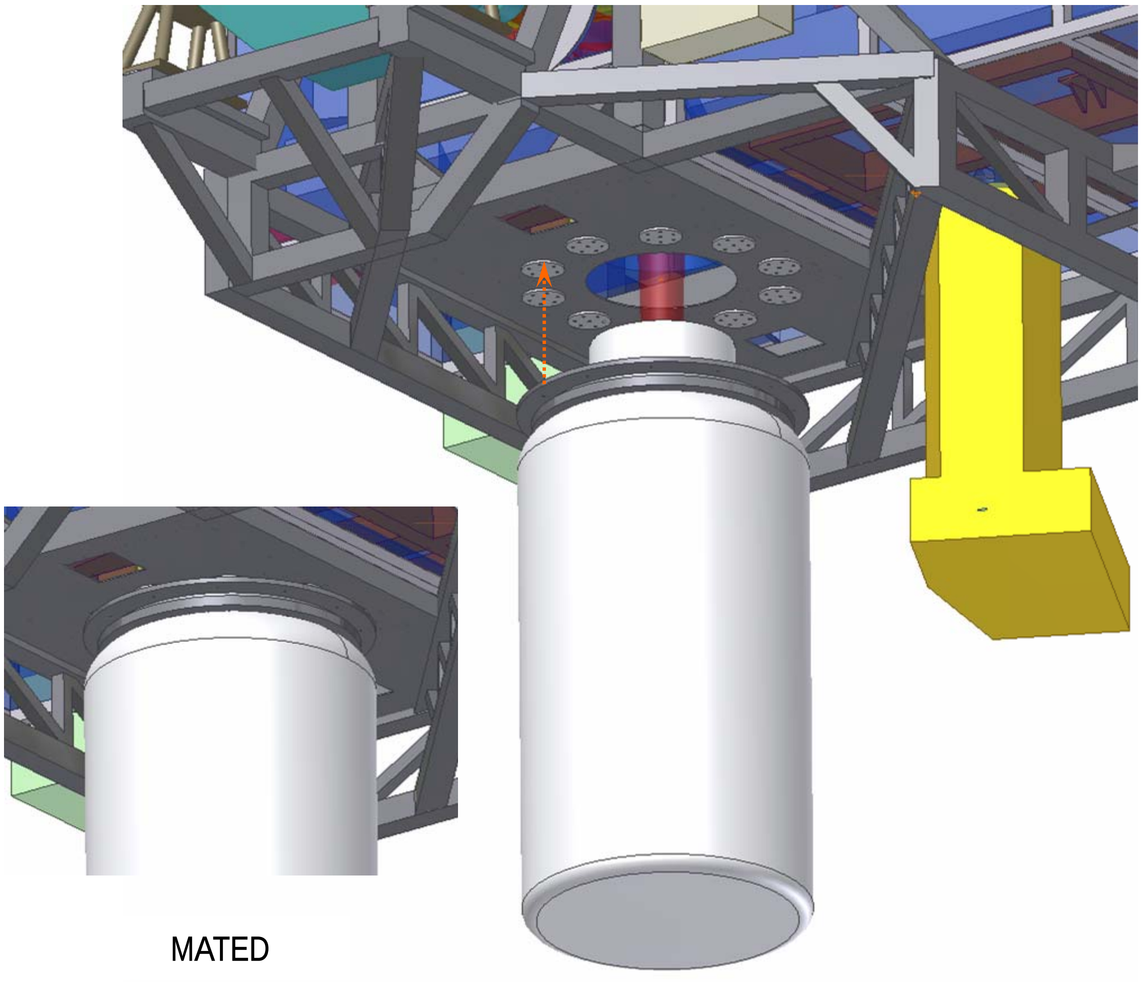


[HIA NFIRAOS Design Team]

Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

Vertical Instrument Interfaces



- Array of ten unit interfaces inscribed within 2m diameter circle concentric on optical axis
- Instrument teams will design and install locational features in selected positions
- Remaining positions used to bolt the instrument to NFIRAOS
- Upper and lower instrument interfaces will be identical

Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

WFOS layout

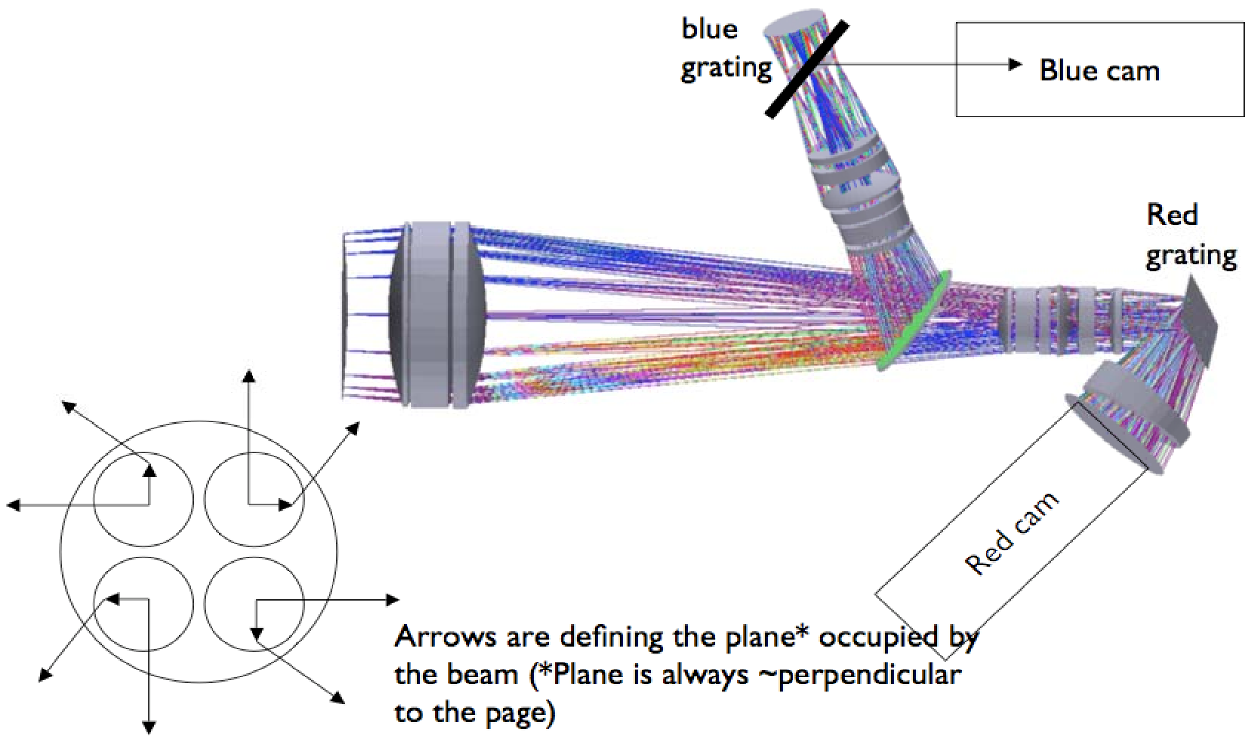
340-1100 nm

7 arcmin/barre

Red, blue arms

R~ 5000

Layout strategy (or something similar):



Slide courtesy of J. Nelson.

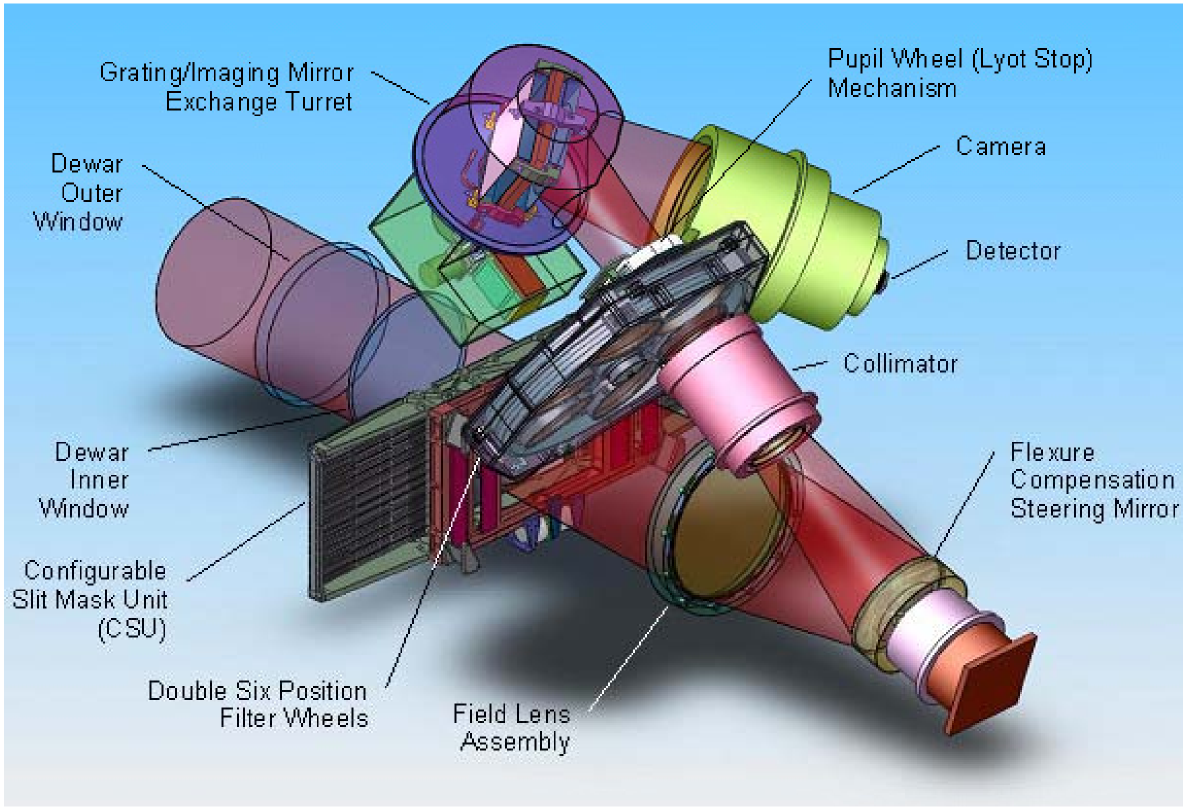
TMT
THIRTY METER TELESCOPE

INSTRUMENT	λ (μm)	FOV / SL	*R*	SCIENCE CASE
Near-IR diffraction-limited (DL) spectrometer and imager (IRIS)	0.8 Š 2.5	10″×10″ (imaging) 0″.7,1″.6 or 4″.5 (IFU)	4000	1) Assembly of galaxies at high z 2) Black holes/AGNs/Galactic Center 3) Resolved stellar populations in crowded fields 4) Astrometry
Wide-Field Optical Spectrometer (WFOS)	0.31 Š 1.0	92.4 $arcmin^2$/ 1300″	150 - 7500	1. IGM structure and composition at 2 < z < 6 2. Stellar populations, chemistry and energetics o of z > 1.5 galaxies
Deployable multi-IFU, near-DL, near-IR Spectrometer (IRMOS)	0.8 Š 2.5	5′ patrol field 2″ per IFU	2000 - 10000	1) First Light 2) Epoch of Peak Galaxy Building 3) JWST followups
Mid-IR Echelle Spectrometer and Imager (MIRES)	4.5 - 25	3″	5000 Š 100000	. Origin of Stellar Masses 2. Accretion and outflows around protostars 3. Evolution of gas in protoplanetary disks
Extreme AO Imager (PFI)	1.1- 2.4	2″.2 × 2″.2	70 Š 500	1 Direct detection and spectroscopic characterization of exoplanets
High-Resolution Optical Spectrometer (HROS)	0.31 Š 1.0	20″	30000 Š 100000	2 Doppler searches for exoplanets 3 Stellar abundance studies in Local Group 4 ISM abundances/kinematics 5 IGM characterization to z~6
MCAO Imager (WIRC)	0.8 - 5	30″× 30″	5 - 100	1. Galactic Center Astrometry 2. Resolved Stellar Populations out to 10 Mpc
Near-IR, DL Echelle (NIRES)	1 Š 5	2″	5000 Š 30000	3. IGM z > 7 , Gamma-ray bursts 4. Local group abundances 5. Abundances, chemistry and kinematics of stars and planet-forming disks 6. Doppler detection of terrestrial planets around low-mass stars

Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

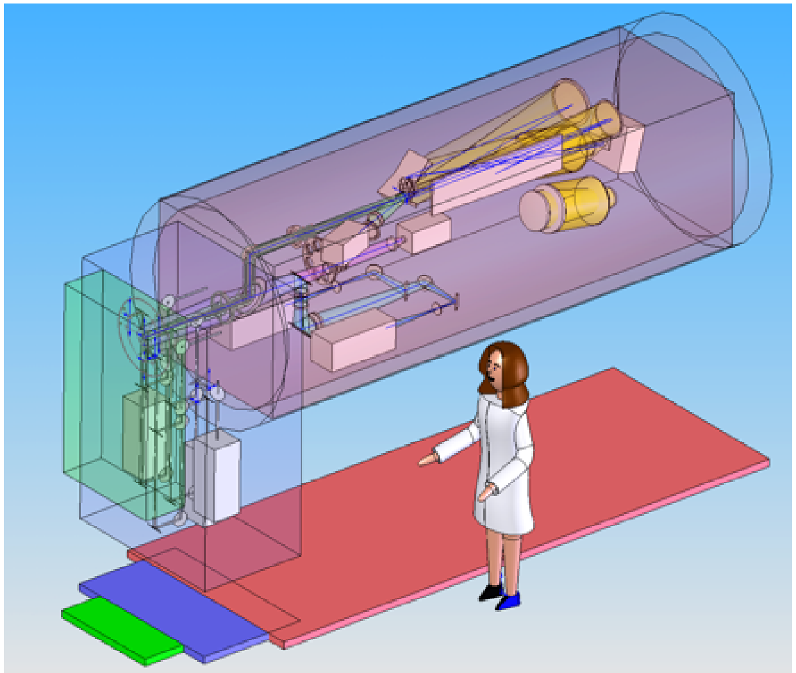
IRMS/MOSFIRE basic design



Slide courtesy of J. Nelson.

THIRTY METER TELESCOPE

MIRES basic design



Slide courtesy of J. Nelson.

IRMS Sky Coverage Overview

- NFIRAOS optimized for 120” IRMS field of view
- RoN of 0,5,10,15,20