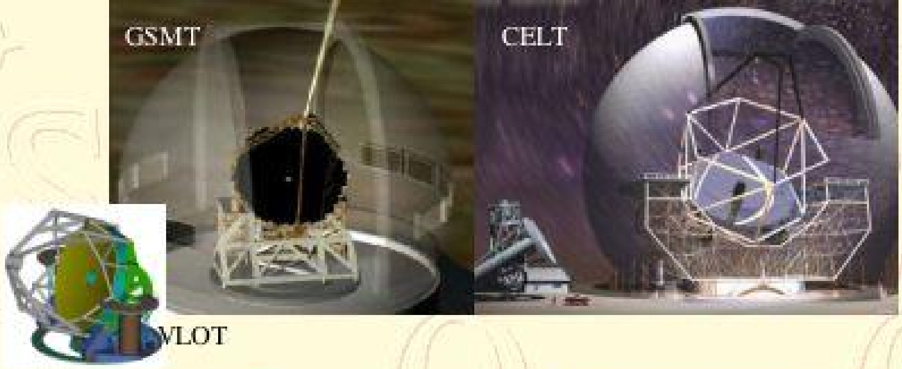
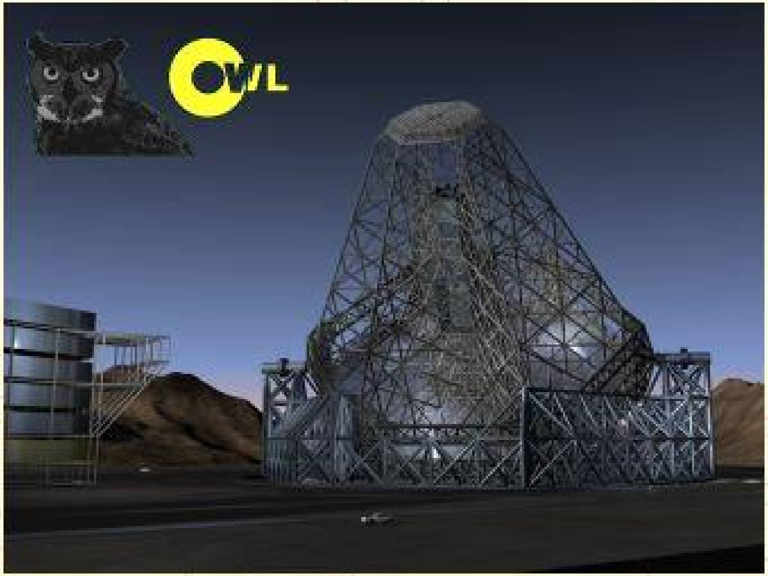
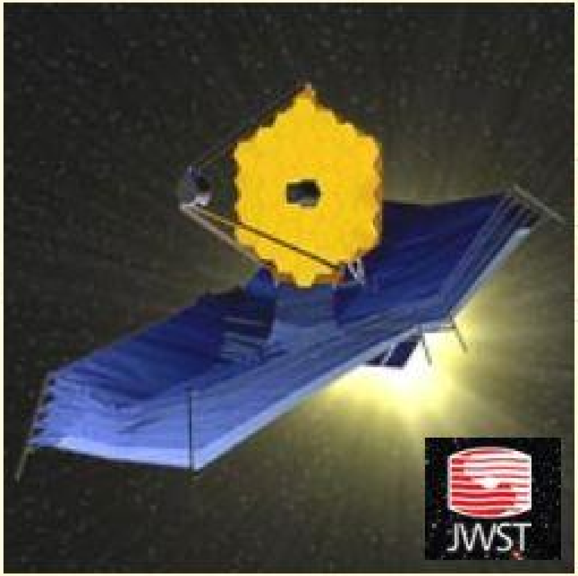


Future OIR telescopes





Roberto Gilmozzi, ESO

Exploring the cosmic frontier:

Astrophysical instruments for the 21st century

Berlin, 18-21 May 2004

Acknowledgements

- Nino Panagia, STScI
- Matt Mountain, Gemini
- Larry Stepp, Gemini
- Philippe Dierickx, ESO
- The OWLers, ESO
- Roland Bacon, Lyon
- The OPTICON ELT science WG

Context: II decade, III millennium AD

- **"Maturity" of current generation**
  - VLT, Keck, Gemini, Subaru, HET, GTC, SALT, ...
  - AO → λ/D performance, 2nd gen instruments
- **Interferometry**
  - "Faint object" regime (K~20), astrometry (μas)
- **ALMA**
  - mm, sub-mm "equivalent" of optical facilities
- **New ground-based telescopes**
  - 30 to 100m diameter, λ/D ~ mas
  - OWL, CELT+GSMT=TMT, GMT, ...
- **New space telescopes**
  - JWST, XEUS, TPF/Darwin precursors…

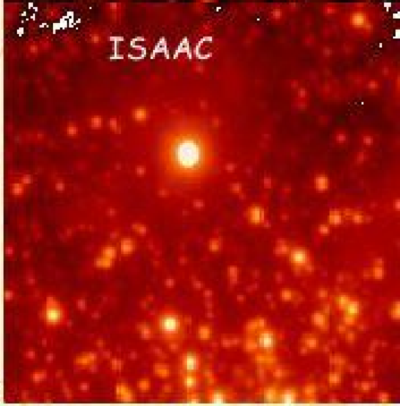
Enhancing the parameters

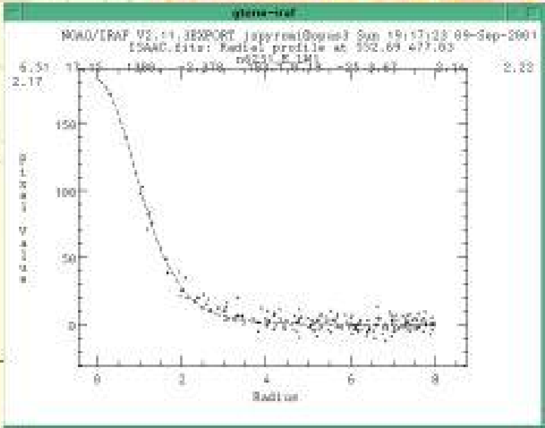
- Area
- Image quality
- Field of view
- Wavelength coverage/resolution
- Synergy space/ground (e.g. IR, FoV, λ/D)

- What's the best way to sample the parameter space?
- **Science driven**
  - (eg FOV_{VLT} *vs* FOV_{Gemini})

Evolution of existing facilities

- **AO "puberty"**
  - Single NGS/LGS systems
  - Limited field of view
- **MCAO infancy**
  - Multiple NGS/LGS systems
  - (Wide) field of view
- **Next generation instruments**
  - Falcon (micro-mirrors)
  - Planet finders
  - Super-MOS/IFU (eg MUSE)

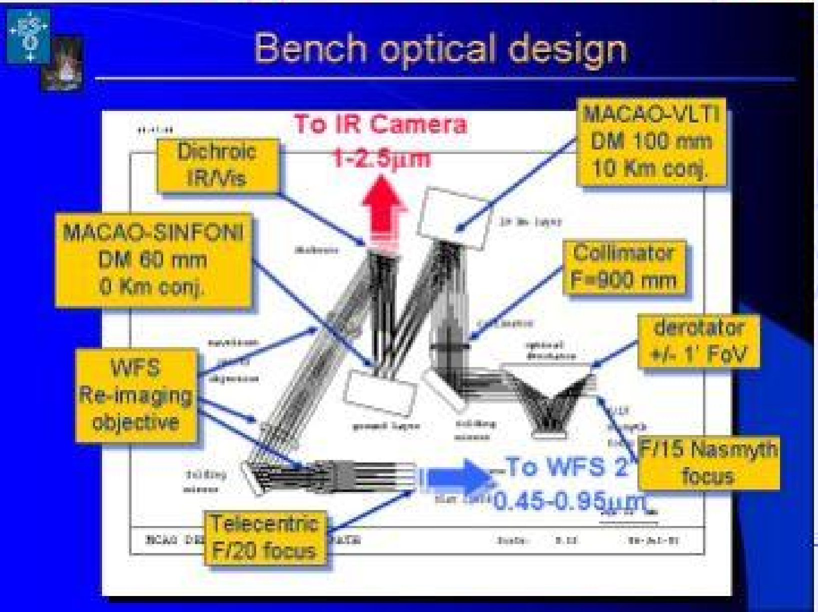




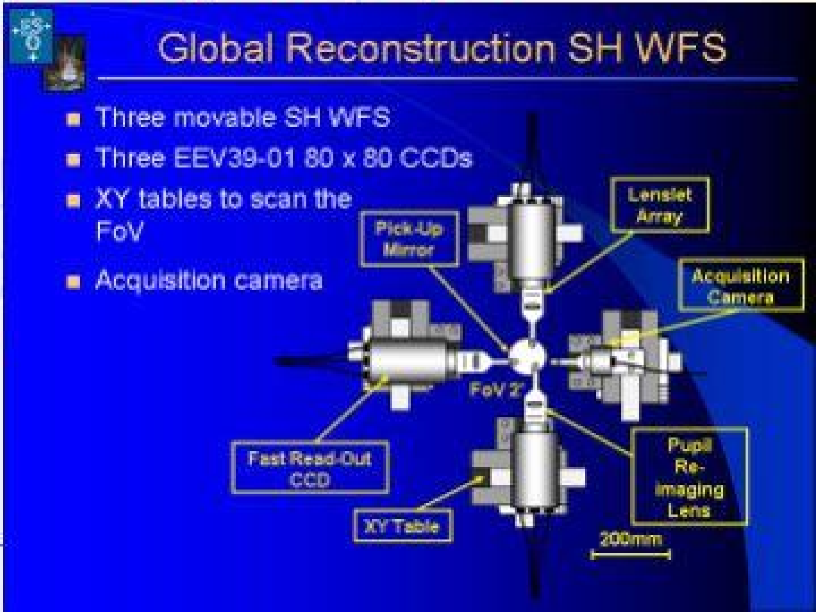
MAD?

MCAO Adaptive Optics Demonstrator at ESO

- Enabling experiment for 2nd gen instr (& OWL)
- Many other instruments being developed



Bench optical design



Global Reconstruction SH WFS

- Three movable SH WFS
- Three EEV39-01 80 x 80 CCDs
- XY tables to scan the FoV
- Acquisition camera

Evolution of ex
facilities

- AO "puberty"
  - Single NGS/LGS systems
  - Limited field of view
- MCAO infancy
  - Multiple NGS/LGS systems
  - (Wide) field of view
- Next generation instruments
  - Falcon (micro-mirrors)
  - Planet finders
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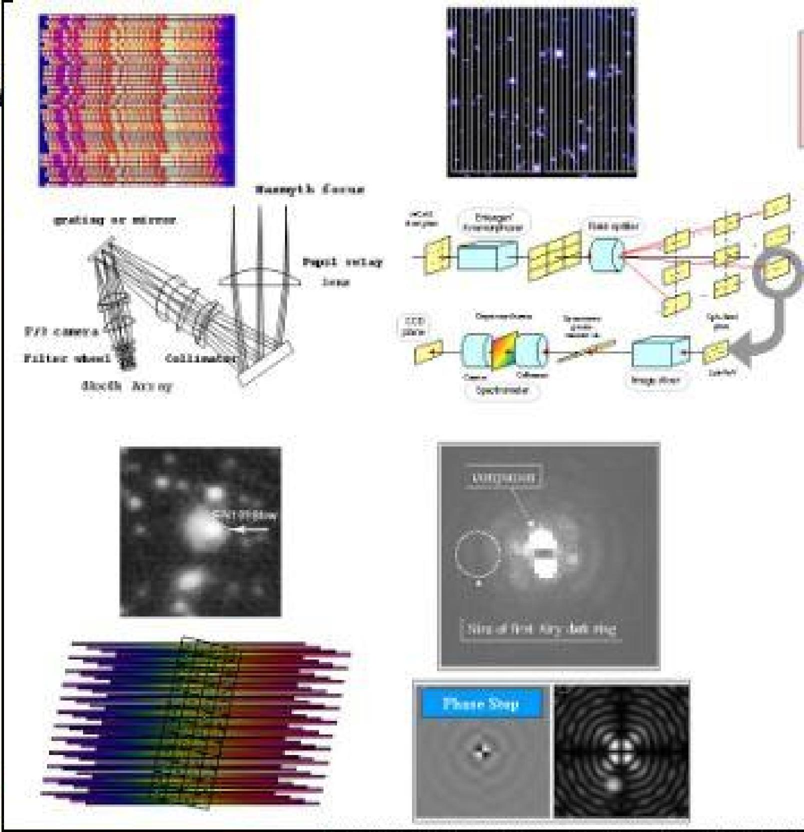
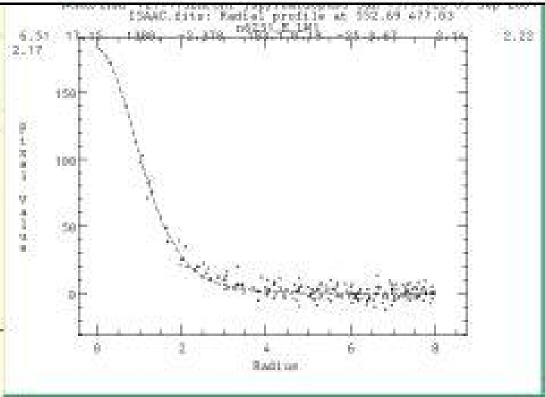
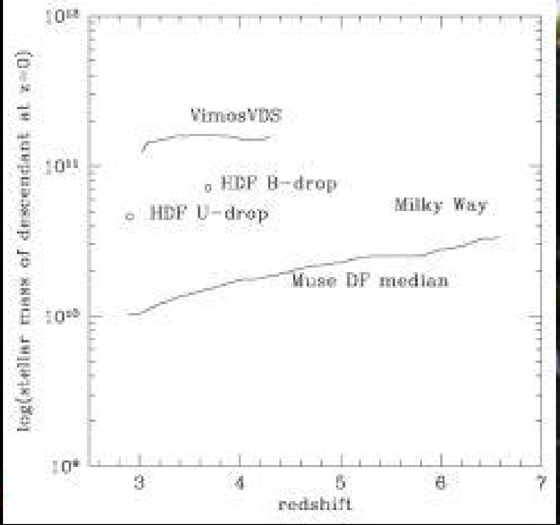




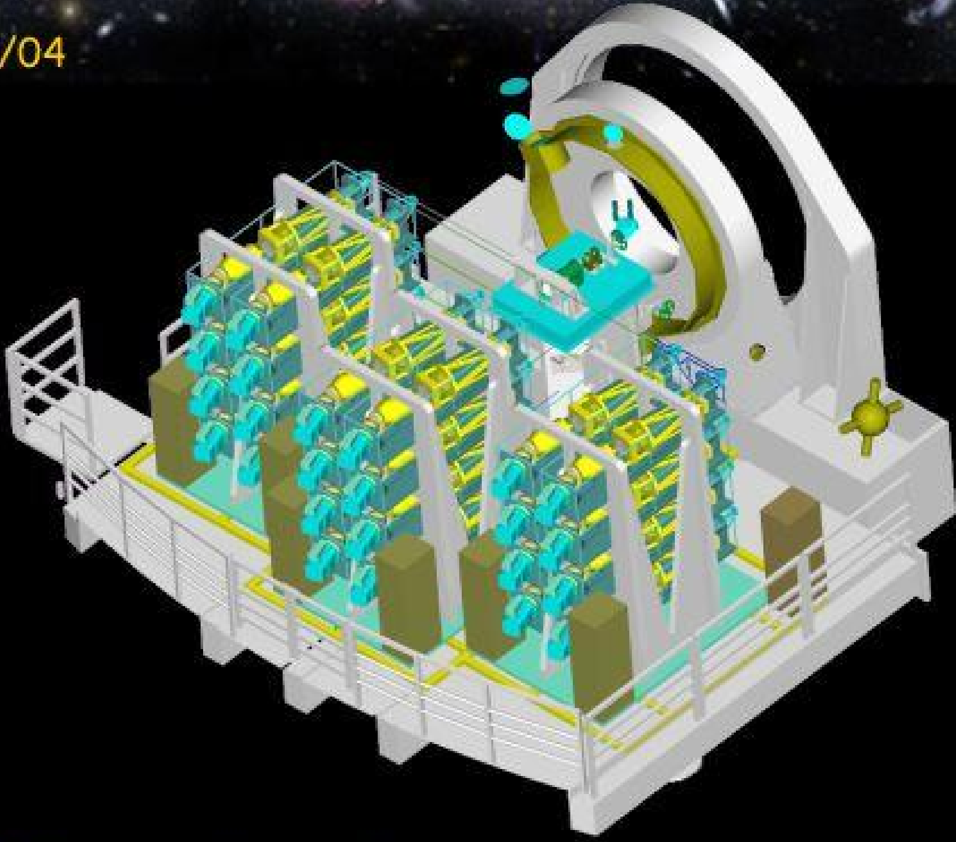
3D deep field: the goal

- Comprehensive study of the faint galaxy population over a wide range of redshift
  - Wide range of redshift for Lyα
    - Z=2.8-6.7
    - Vol 2.2 10^6 Mpc^3 (SF 200 $arcmin^2$)
  - Faint
    - Progenitor of MW type galaxies up to z=6.7
  - Comprehensive
    - Detection, statistics (luminosity function, clustering), star formation history, diffuse ionized gas, interaction with IGM, spatial information, nuclear activity, …



MUSE

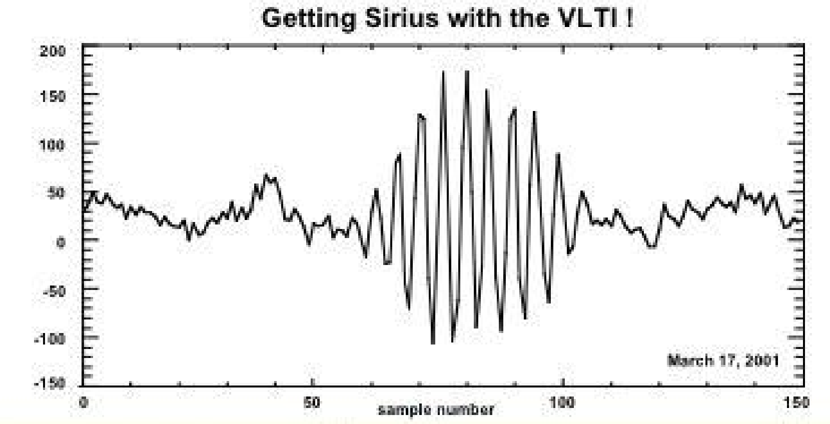
STC 57th - 23/04/04



MUSE: II generation *and* precursor to OWL instruments

ESO Leiden Lyon Oxford Potsdam Toulouse Zurich

Interferometry

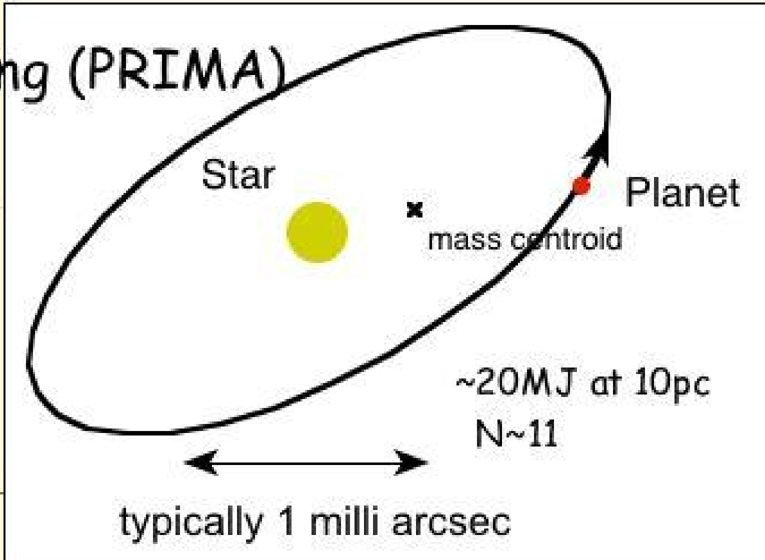


Two methods for imaging:

- Three telescope measurements of closure phase (AMBER)
- Phase referenced imaging (PRIMA)

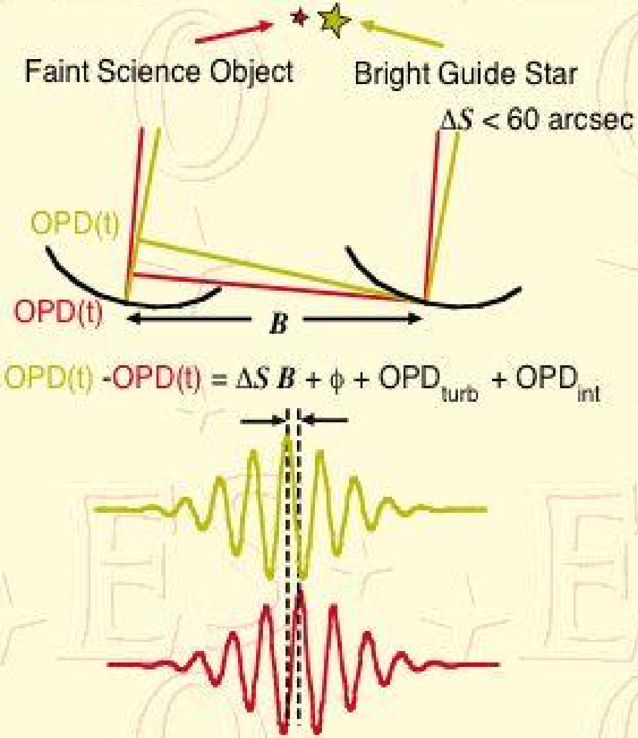
⇒ μas astrometry

⇒ faint object imaging



PRIMA – the VLTI dual feed facility

- Tracking the fringes on the guide star
    - Fringes of science object are stablised
- PRIMA picks two stars in the Coudé, feeds it into the Delay Lines
- $\mathrm{OPD}_{\mathrm{int}}$ measured with laser metrology
- $\mathrm{OPD}_{\mathrm{turb}}$ averaged by long integration
- $\Delta S\, B + \phi$ determined by interferometric instruments
- ΔS gives the astrometry, ϕ the imaging



The OIR future

- JWST
- TMT
- OWL
- other projects

James E. Webb

- NASA’s second administrator (1961-1968)
- Guided NASA to the Moon
- Initiated vigorous science program

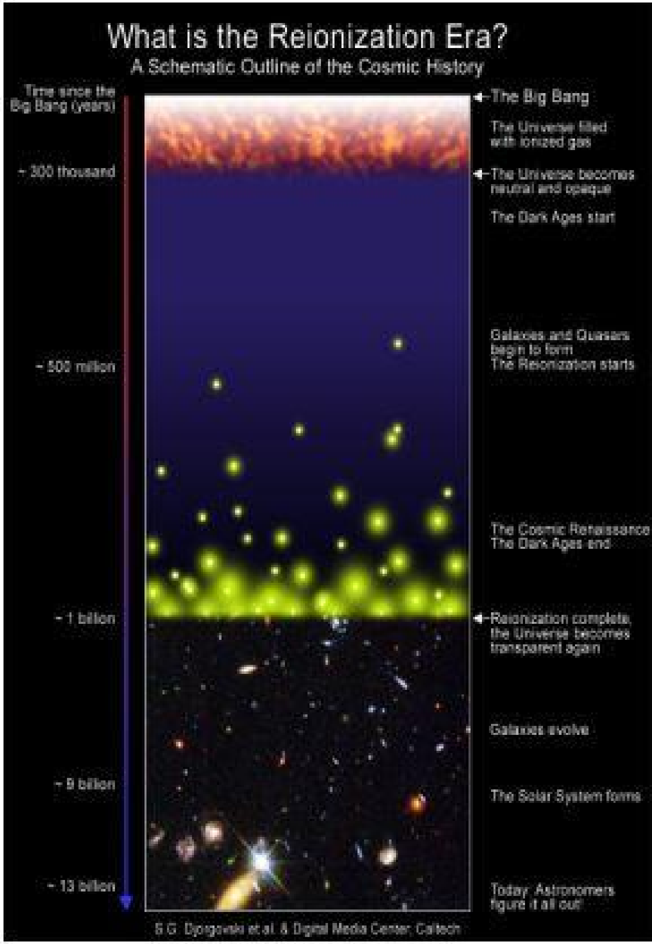
The Quest for Origins

Four Major Science Themes

- **End of the Dark Ages**
    - Determine the space density, energy source, and physical characteristics of the first luminous objects from $z \sim 20$ up to the epoch of reionization.
- **Assembly of Galaxies**
    - Understand the structural and chemical evolution of galaxies, AGN and the intergalactic gas and their interplay from the epoch of reionization to $z \sim 1$.
- **Formation of Stars and Stellar Systems**
    - Unravel the birth and early evolution of stars, from infall onto dust-enshrouded proto-stars to the genesis of planetary systems.
- **Planetary Systems and the Conditions for Life.**
    - Determine the physical and chemical properties of planetary systems, including our own, and investigate their potential for life.

End of the Dark Ages

- Characteristics of first luminous objects
  - Proto-galaxies
  - Supernovae
  - Black holes
  - Large scale structure
- Reionization of the Universe
  - Primary source of UV flux
  - Multiple epochs?



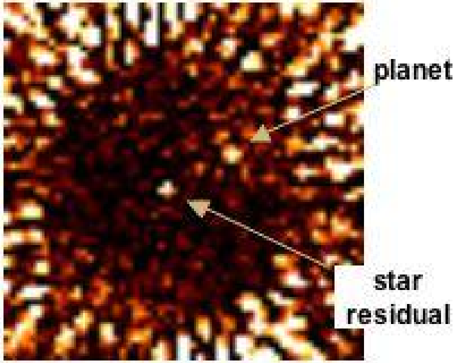
What is the Reionization Era?

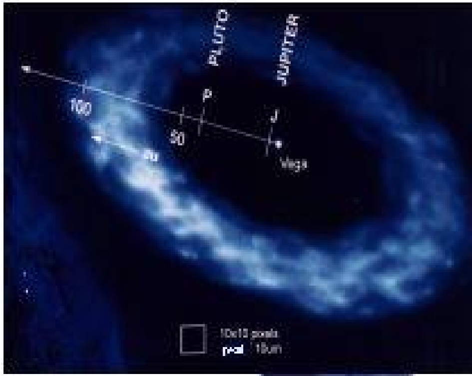
A Schematic Outline of the Cosmic History

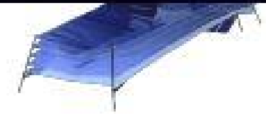
S.G. Djorgovski et al. & Digital Media Center, Caltech

Planetary Systems and the Origins of Life

- Formation of planets
  - How and how many are formed
  - Properties of planets and circum-stellar disks
  - Properties of outer Solar System bodies and relation to other planetary systems
- Potential for life
  - Source of life supporting elements (water & organics)
  - Habitable planetary evolutionary pathways and the evidence in our Solar System

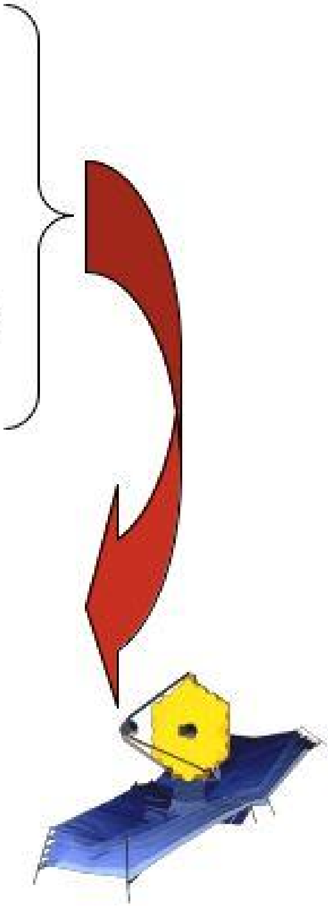






Why a Space Telescope?

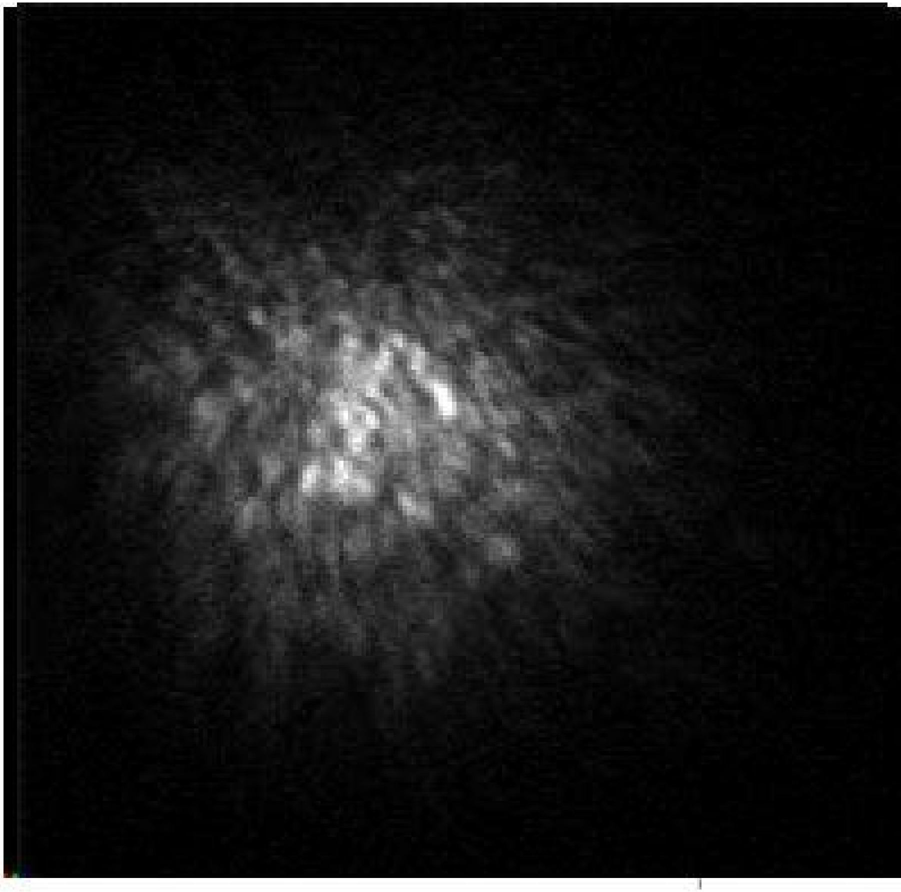
- High spatial resolution
- PSF stable over large field of view
- Not limited to atmospheric windows
- Low, stable background
- Continues access to certain fraction of the sky (no day/night limits)



- Accurate, high sensitivity access to near- and mid-infrared

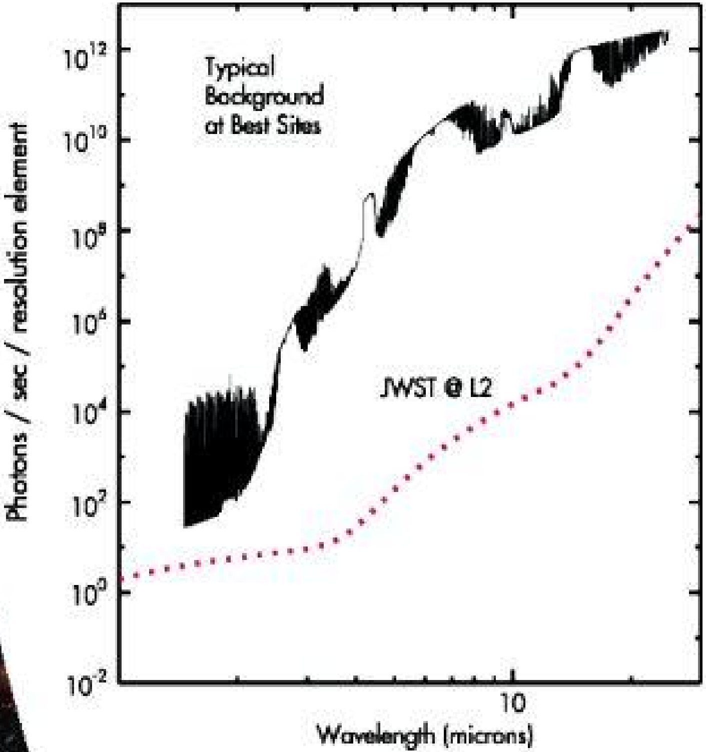
High Spatial Resolution

- Not limited by atmospheric blur
- Stable over large field of view
- Stable over extended periods of time



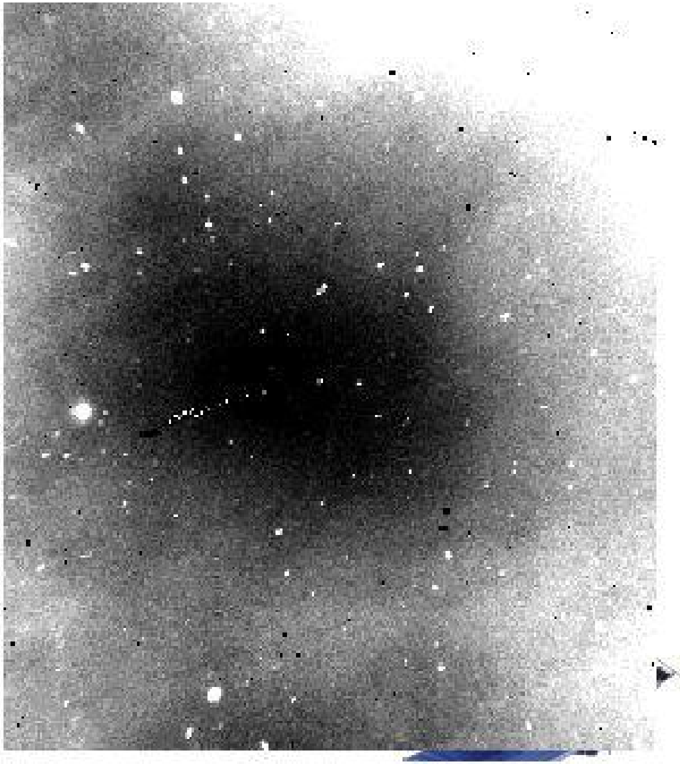
The Background Advantage

Low



Predicted JWST background

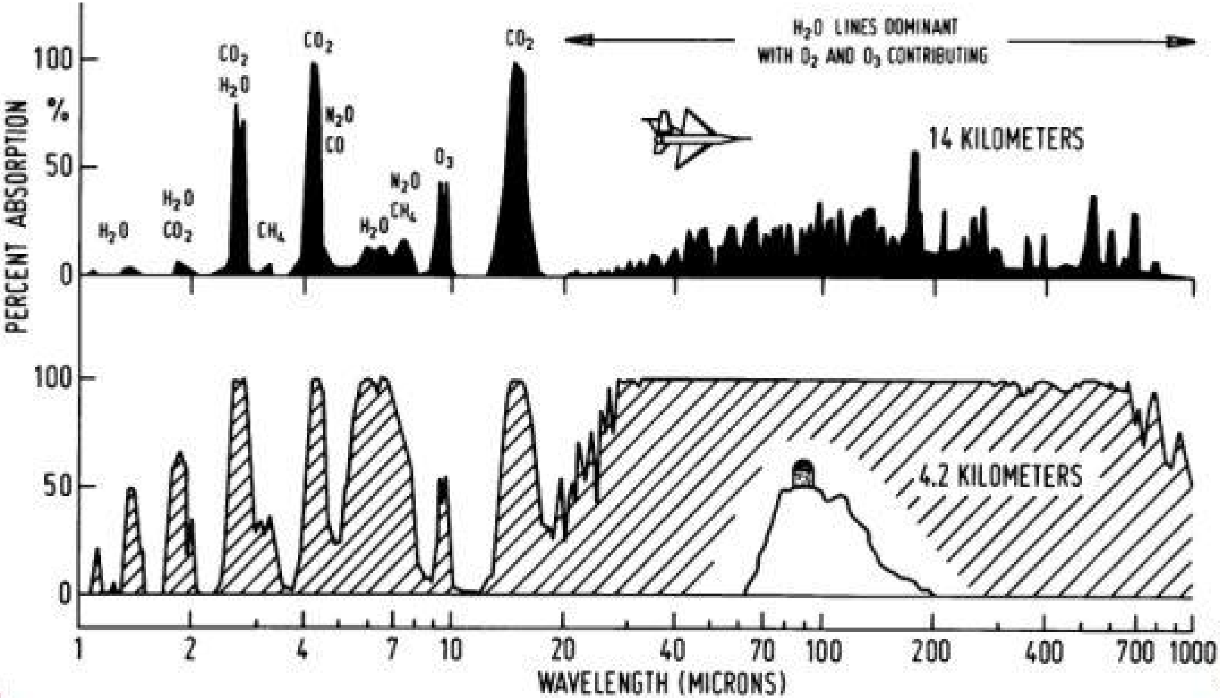
Stable



An H-band look through the atmosphere on a clear night

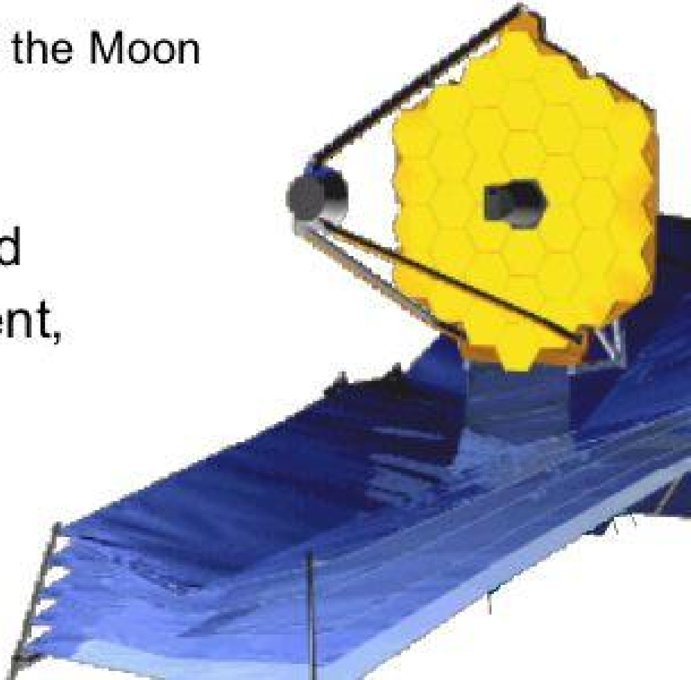
Wavelength Access

- Space not limited to atmospheric windows

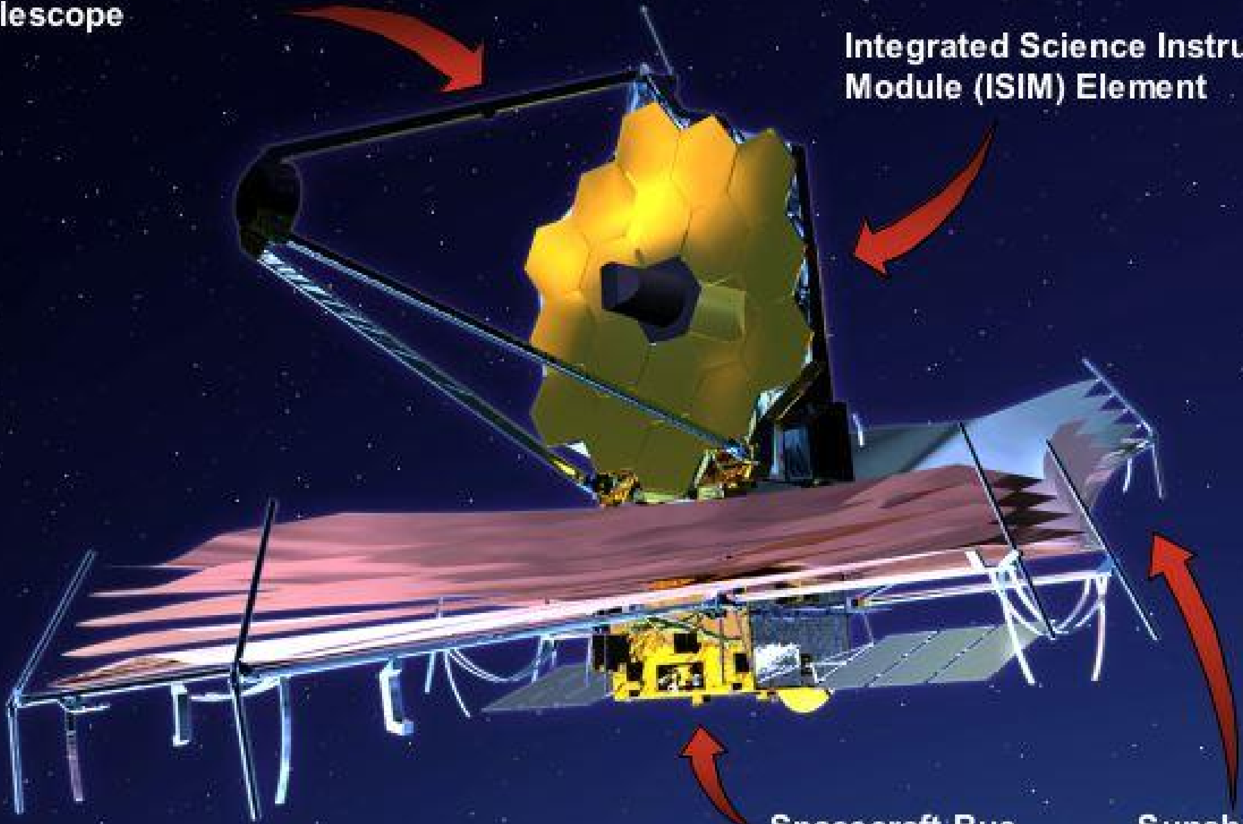


The JWST Telescope

- 6-m class mirror (25 m^2 area)
- 18 segments made of Beryllium
- Wave front sensing for alignment
- 0.6 - 28 micron wavelength range
- Operating at Earth-Sun L2
  - 1.5 million km from Earth past the Moon
- Large sunshade
  - about size of tennis court
- Folded to fit in launch shroud
- 5 year operations requirement,
  - 10 year goal



JWST Main Elements



Optical Telescope Element

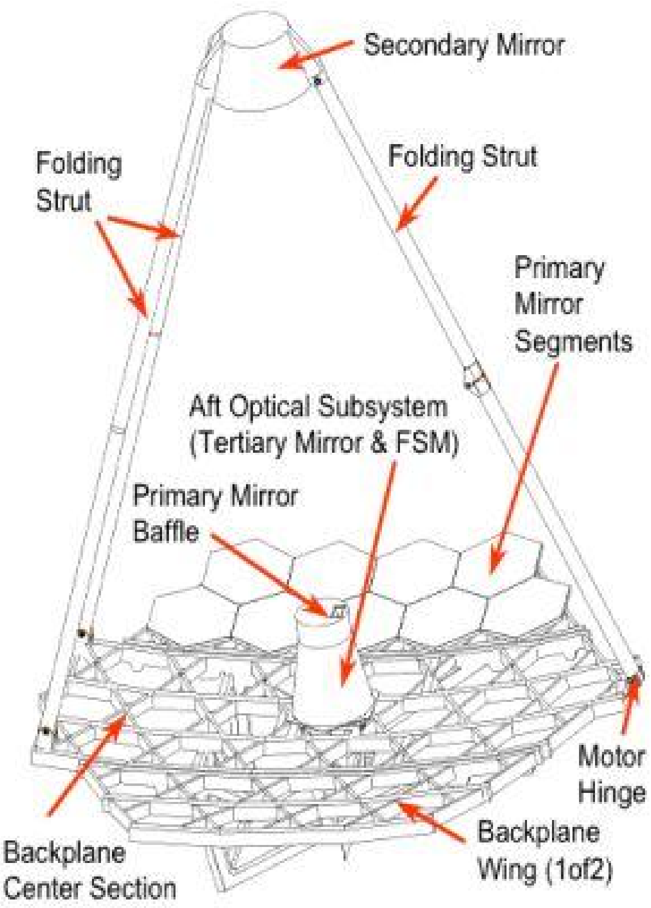
Integrated Science Instrument Module (ISIM) Element

Spacecraft Bus

Sunshield

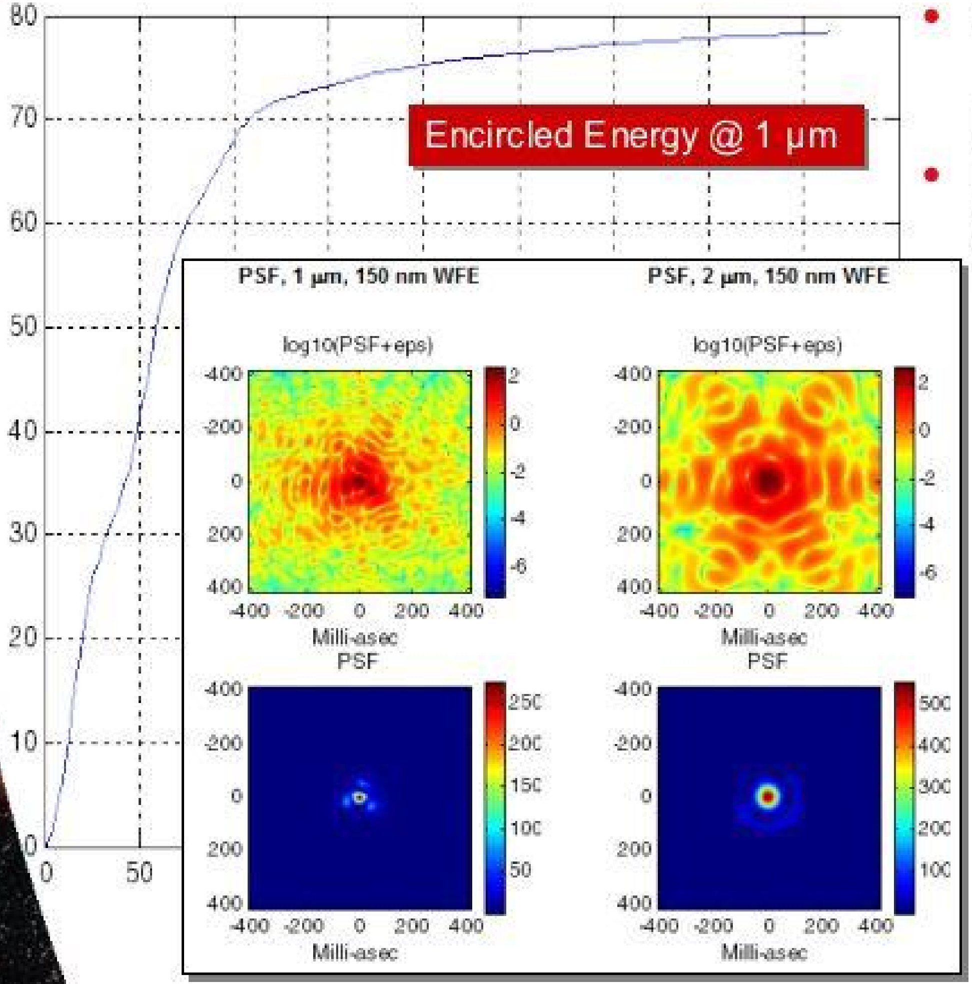
Spacecraft Element

Optical Telescope Element



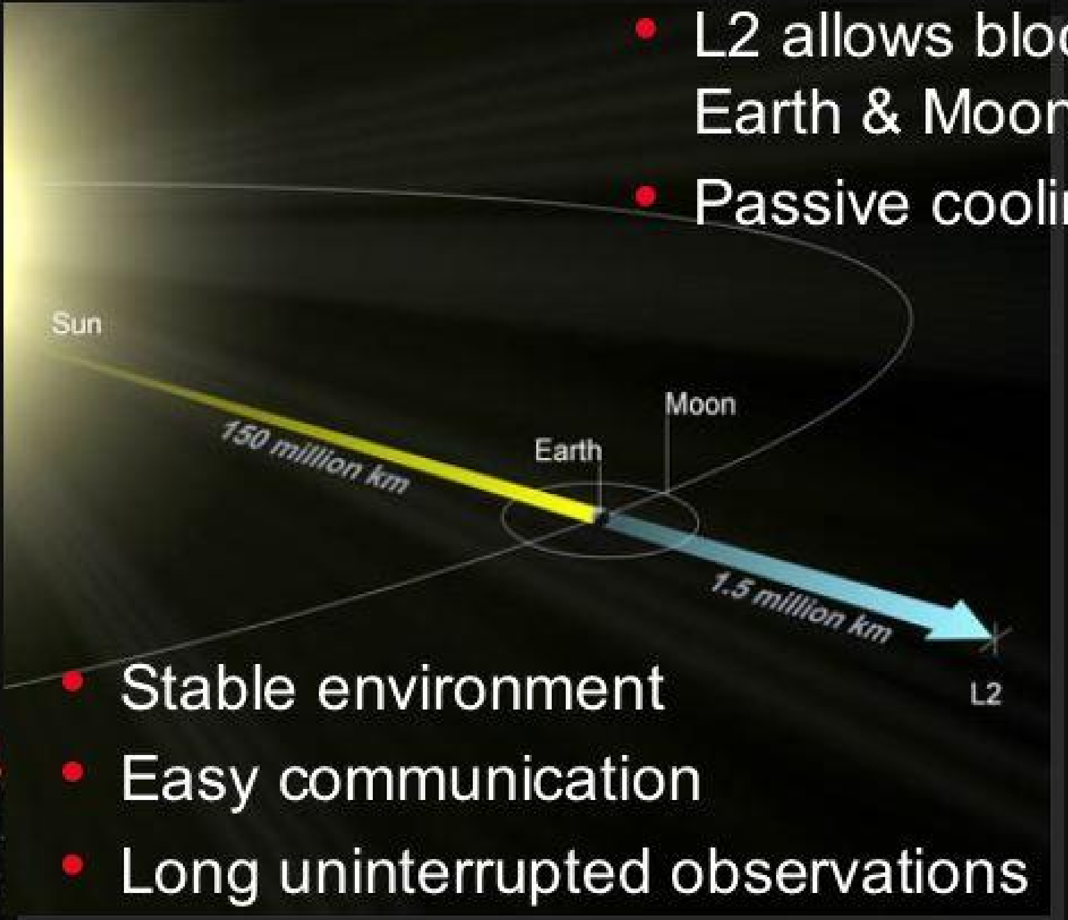
- 18 Beryllium segments ~1.3 m flat-to-flat
- Each segment has 7 degrees of freedom: 6 for position, 1 for radius of curvature
- Secondary on hexapod for 6 degrees of freedom
- Fine Steering Mirror (FSM) for guiding and offsets

Image Quality

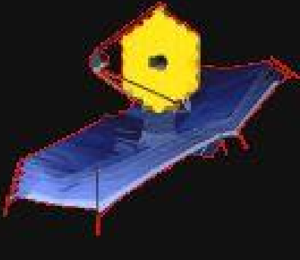


- Encircled energy at 1 µm >74% at 0.15" radius
- Diffraction limited at 2 µm with a Strehl ratio ≥0.8.

JWST Will Operate at Sun-Earth L2

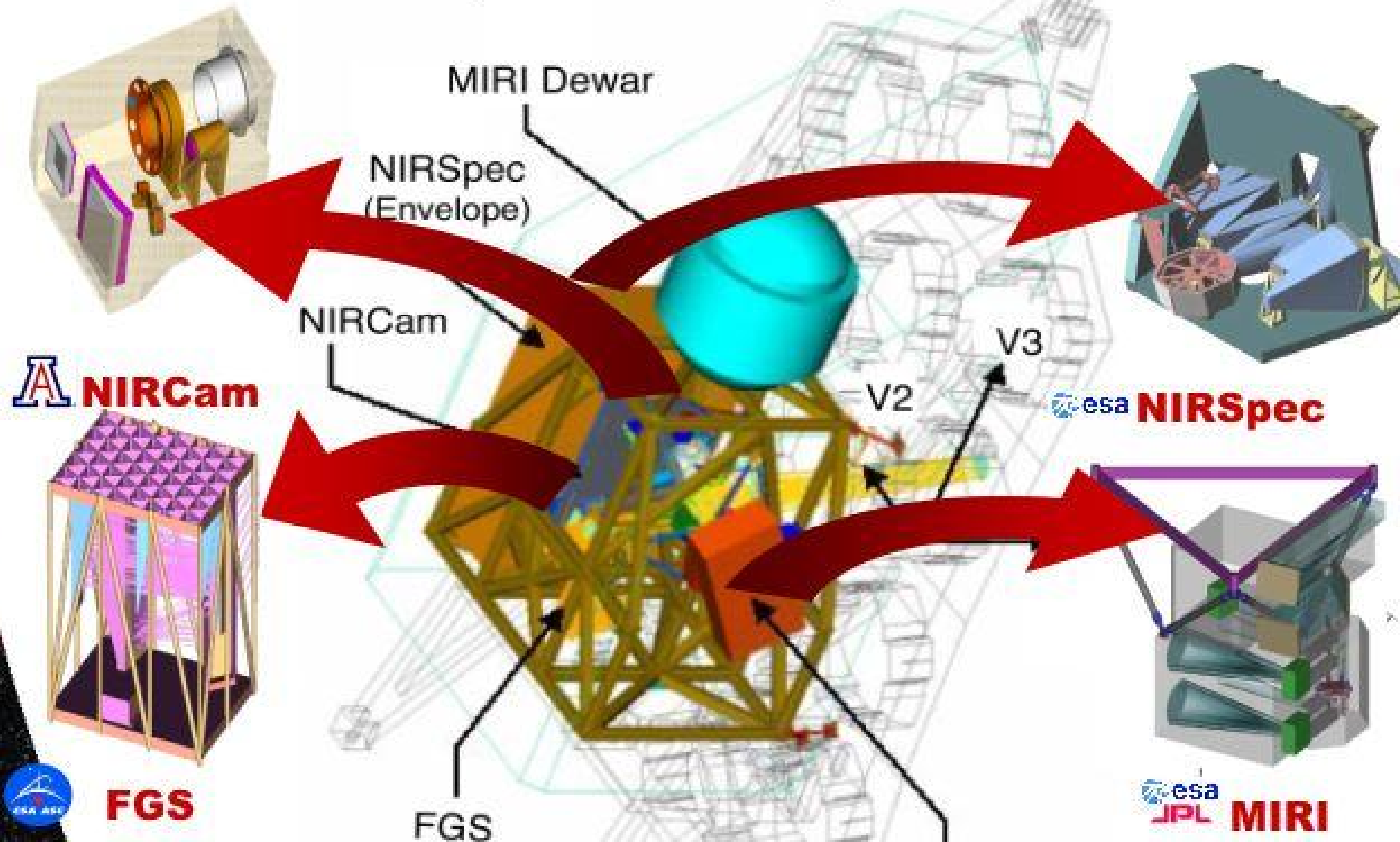


- L2 allows blocking Sun, Earth & Moon light
- Passive cooling to ~50K
- Stable environment
- Easy communication
- Long uninterrupted observations



Integrated Science Instrument Module (ISIM)

- Shared hard- and software for instruments reduces development and operations costs



Near-Infrared Camera (NIRCam)

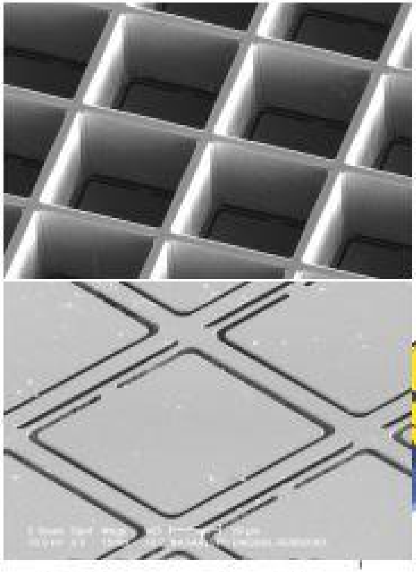
- PI Marcia Rieke (University of Arizona)
  - LOCKHEED MARTIN industrial partner
- Sensitivity from 0.6 - 5 µm
  - 8 broad-band and 8 medium-band filters
- Two identical modules with 2.16x2.16 arcmin FOV
- Each module dichroic separation in two arms
  - Short: 0.6-2.3 µm, four 2k x 2k detectors, 0.0317 arcsec/pixel
  - Long: 2.4-5 µm, one 2k x 2k detector, 0.0648 arcsec/pixel
  - ROCKWELL SCIENTIFIC HgCdTe detectors
- Diffraction limited at 2 & 4 µm
- Coronagraphs in all modules
- Support wavefront sensing

NIRCam Science Goals

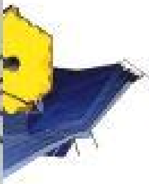
- First light
- Galaxy formation
- Dark matter
- Supernovae searches
- Young stars
- Kuiper Belt Objects
- Stellar populations
- Initial Mass Functions
- Planet properties

Near-IR Spectrograph (NIRSpec)

- PI: Peter Jacobson
- Multi-Object Spectroscopy
  - MEMS Micro-shutter arrays
  - Two 2k x 2k HgCdTe arrays
  - 3.4' x 3.4' FOV
- R~1000 Mode
  - 3 gratings cover $1.0 < \lambda < 5.0$ µm
- R~3000 Long-slit Mode
- R~100 Prism
  - $0.6 < \lambda < 5.0$ µm in one exposure

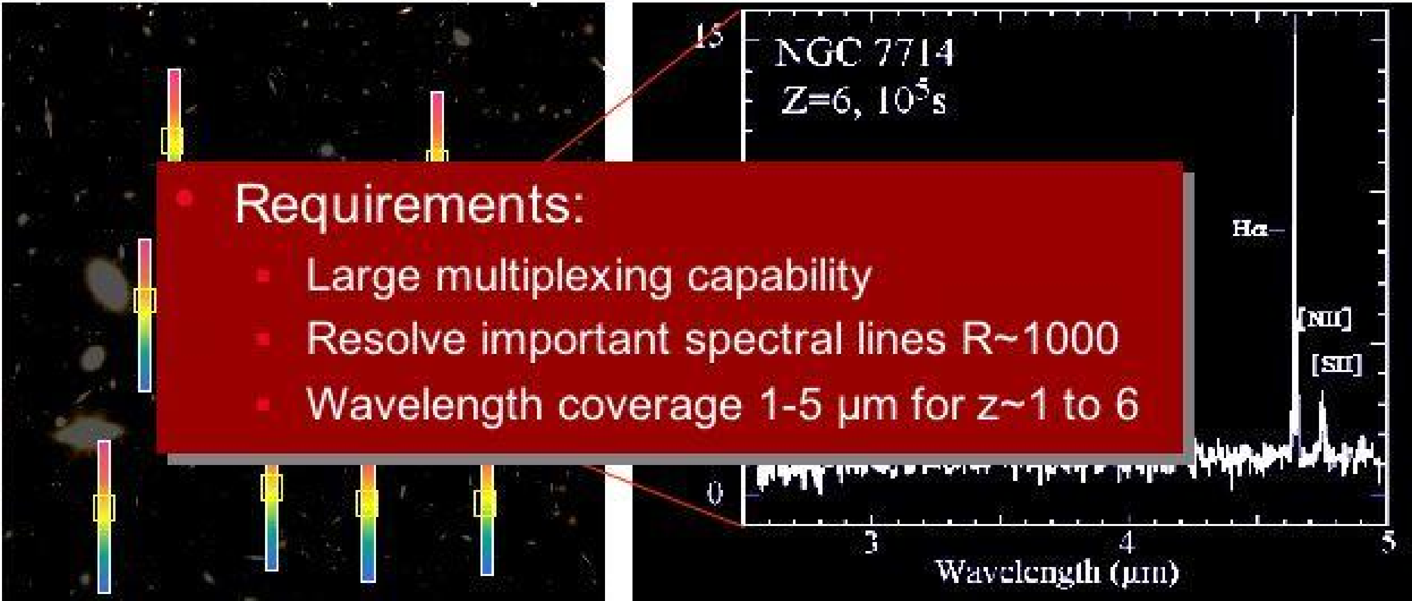


Micro-shutters



NIRSpec Science: Galaxy Evolution

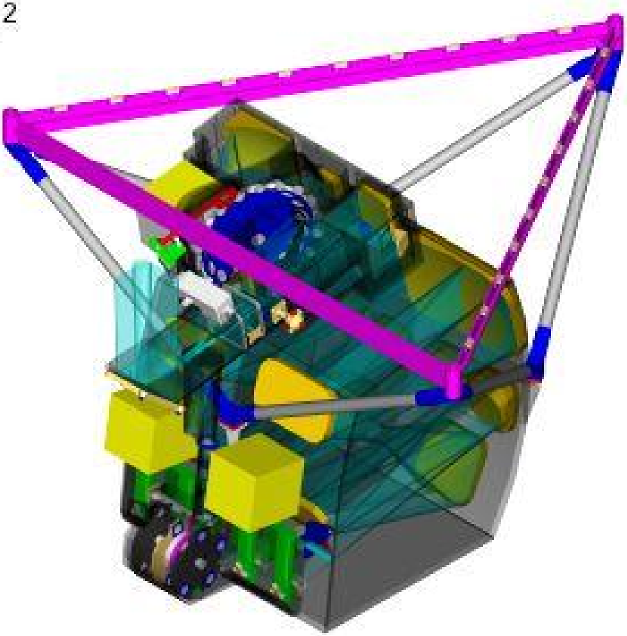
- Origins of galaxy morphology
- How did the heavy elements form?
- Hierarchical formation and scaling relations
- Relation to ULIRGs and AGN



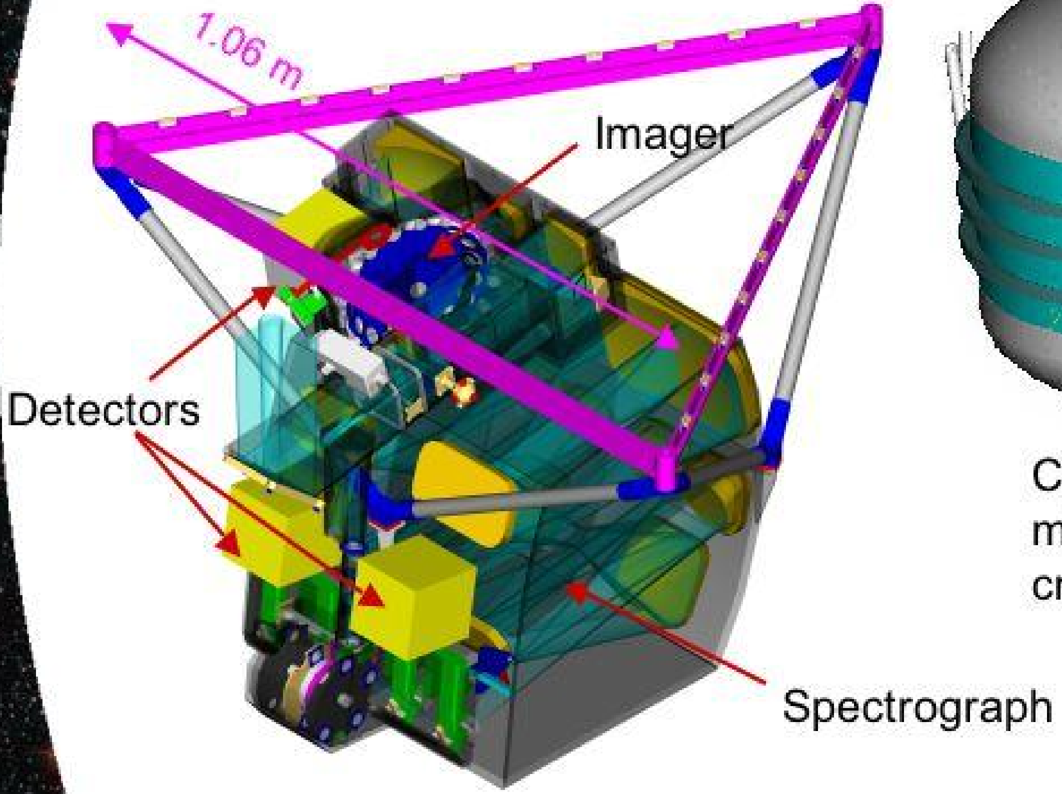
- Requirements:
  - Large multiplexing capability
  - Resolve important spectral lines R~1000
  - Wavelength coverage 1-5 μm for z~1 to 6

Mid-Infrared Instrument (MIRI)

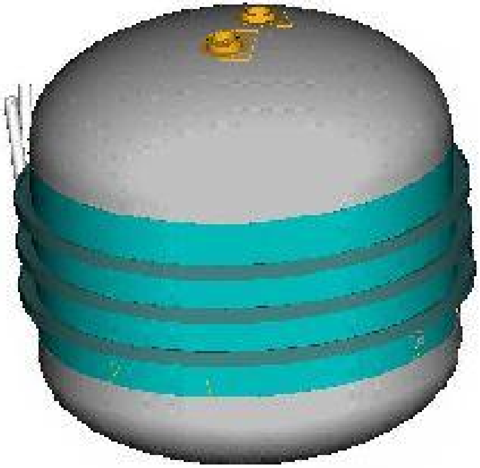
- Science Leads:
  - George Rieke (Univ. of Arizona)
  - Gillian Wright (UK ATC)
- Broad- and Medium-band Imaging, 12 filters
  - 5 < λ < 27 µm
  - Diffraction limited sampling at 7 µm, 0.11 arcsec/pixel
  - FOV 1.88' x 1.27' = 2.29 arcmin^2
  - Strehl ratio ≥0.8
- R~3000 Integral Field
  - 3" x 3.9" to 6.7" x 7.7" FOVs
  - 4 channels, two detectors
    - 5 < λ < 10 µm
    - 10 < λ < 27 µm
- R~100 Slit
  - 5 < λ < 10 µm
- Coronagraphs



MIRI design



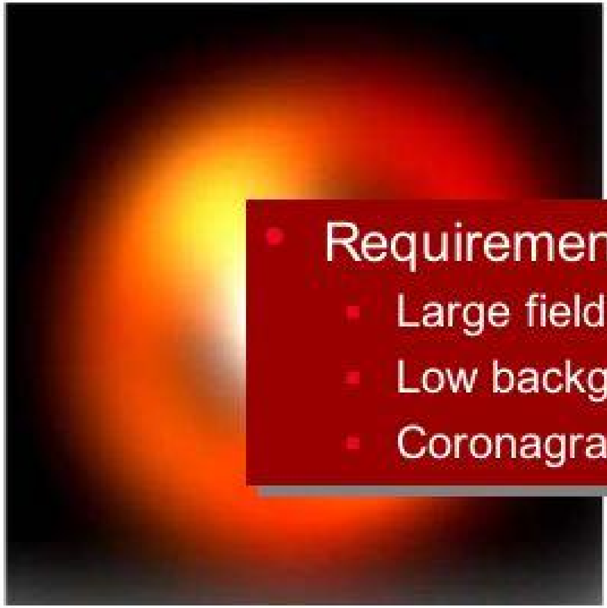
Optics Module concept
developed by European
Consortium



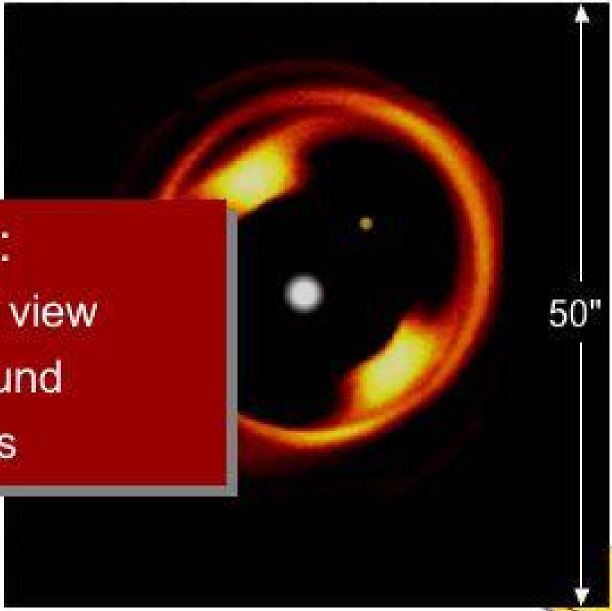
Cryostat provides
minimum 5 year
cryogenic lifetime

MIRI Science: Extrasolar planets and disks

- Simulation of the effect of a planet on the Vega dust disk (Wilner et al. 2002).



SIRTF

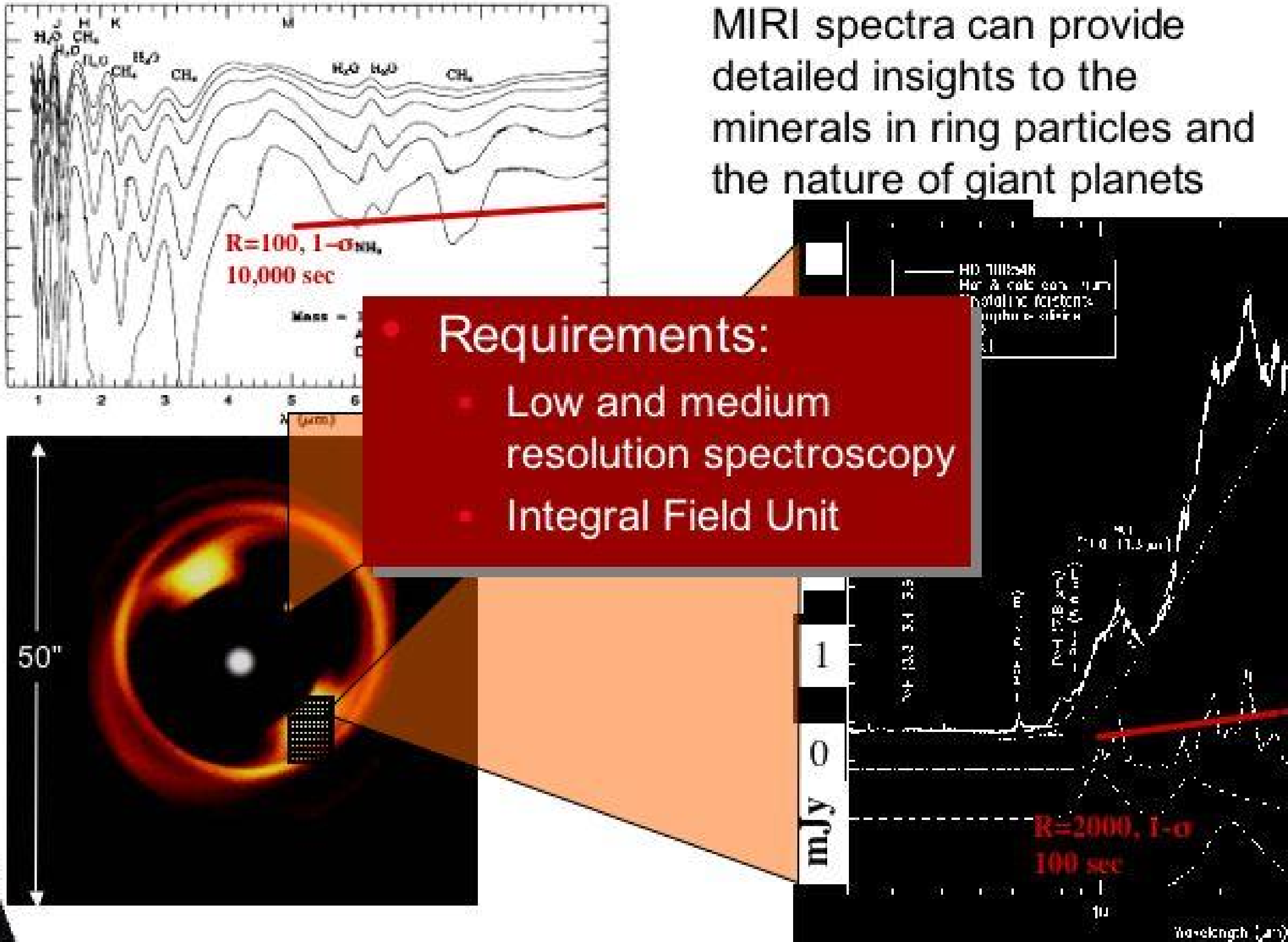


JWST

- Requirements:
  - Large field of view
  - Low background
  - Coronagraphs

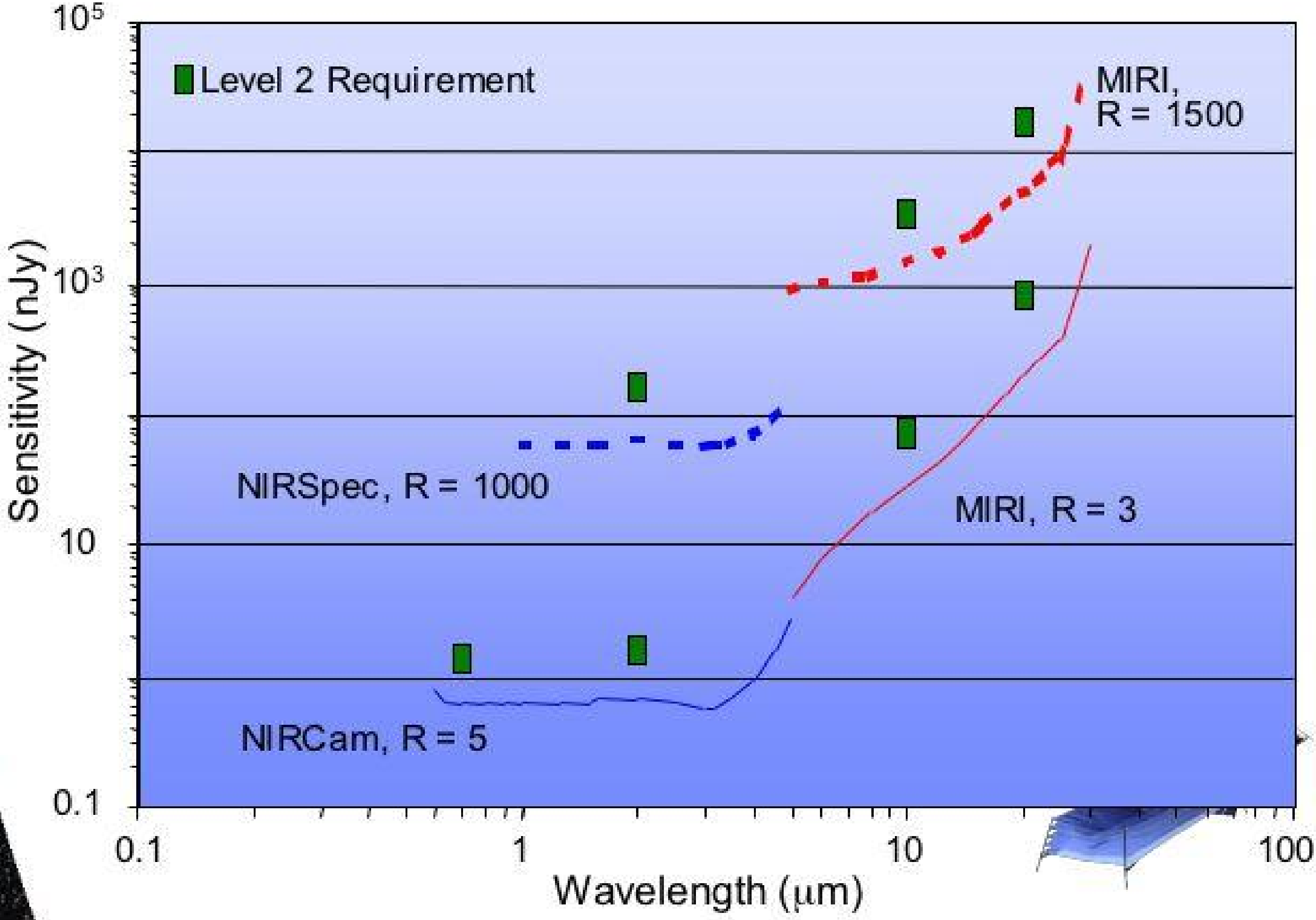
MIRI Science: Spectral Diagnostics

MIRI spectra can provide detailed insights to the minerals in ring particles and the nature of giant planets



- Requirements:
  - Low and medium resolution spectroscopy
  - Integral Field Unit

Sensitivity predictions

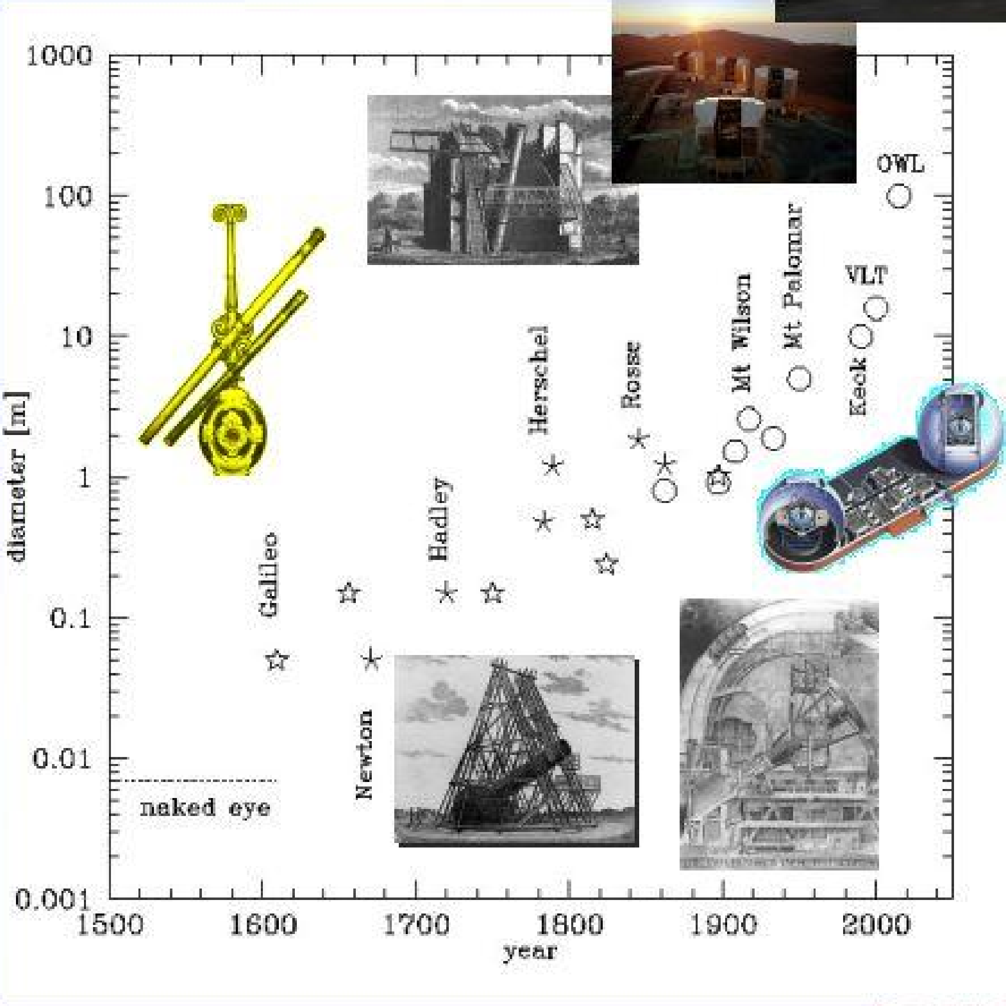


Development Schedule

- 2003-2005 Detailed design and budgeting
  - Set requirements and modify designs to meet them
  - Continue development of critical technologies
  - Start procuring long lead items
- 2006-2008 Development
  - Integrate, test, and calibrate instruments
  - Fabricate and test mirror segments
- 2009-2011 Integrate and test
  - Integrate instruments in ISIM at GSFC
  - Integrate observatory at NGST
  - End-to-end ambient and cryogenic vacuum testing
- 2011-2012 Launch, commissioning, operations
  - Ariane V launch August 2011
  - Commissioning in first 6 months
  - Call for proposals

Telescope growth since Galileo

- Telescope size has been driven by the available technology. The glass was the limiting factor.
- In the 1980's we designed and started constructing the 8-10m class telescopes. That was the technological limit.
- Today, advances in fabrication and control technologies allow primary mirrors of 100-m to be built for reasonable costs and with competitive schedules.



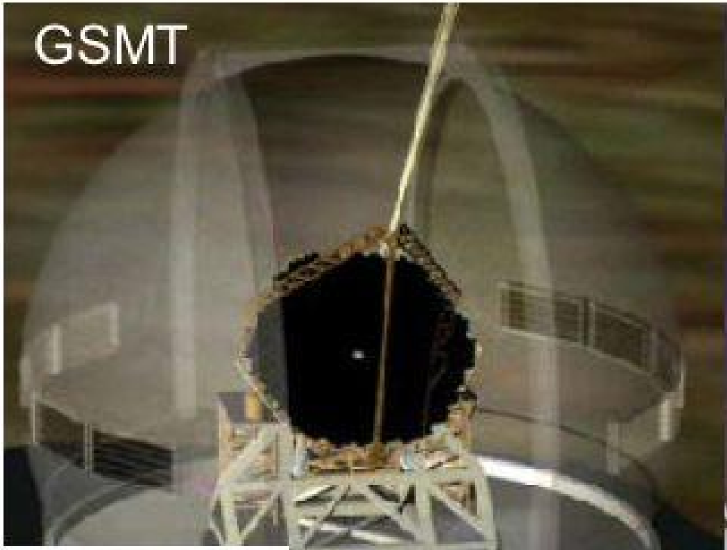
Not easy to predict how fast technology develops

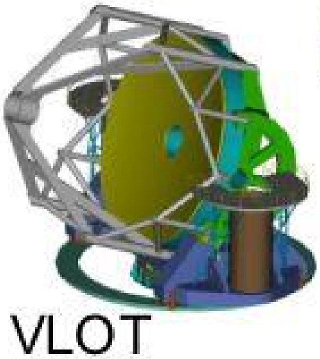
- 1943
  - ⇨ Thomas Watson, chairman of IBM:

    “I think there is a world for maybe five computers”
- 1981
  - ⇨ Bill Gates, founder of Microsoft:

    “640K ought to be enough for anybody”

TMT: A partnership of CELT, AURA & ACURA
Status and Technical Requirements





Design & Development Phase (DDP)

TMT

Thirty Meter Telescope

Science cases Examples

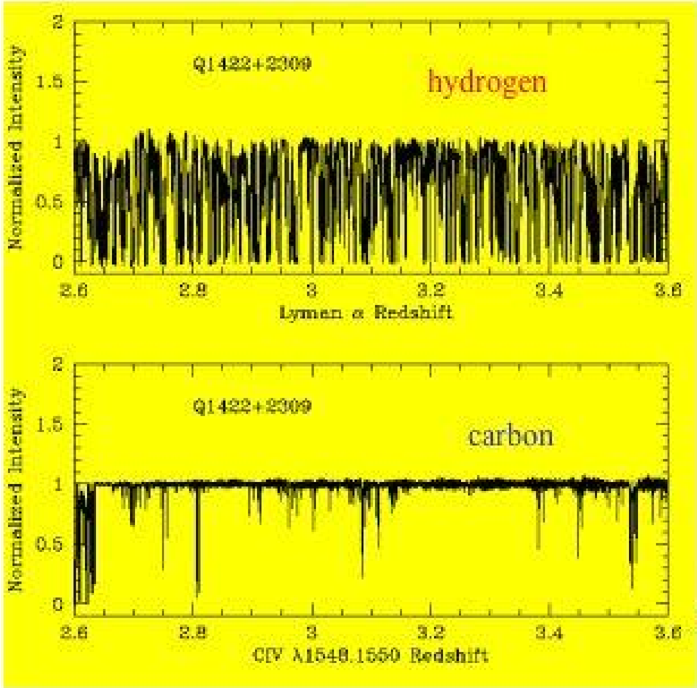
- Spectral studies of Solar System objects
- Extra-solar planets
  - Extend searches to lower L/M
  - Spectroscopic studies of ESP atmospheres
  - Direct detection
- Star formation
- Chemical Evolution/star formation histories of galaxies to 20Mpc
- Black hole demographics
- Evolution of galaxies and the IGM from z=1-5

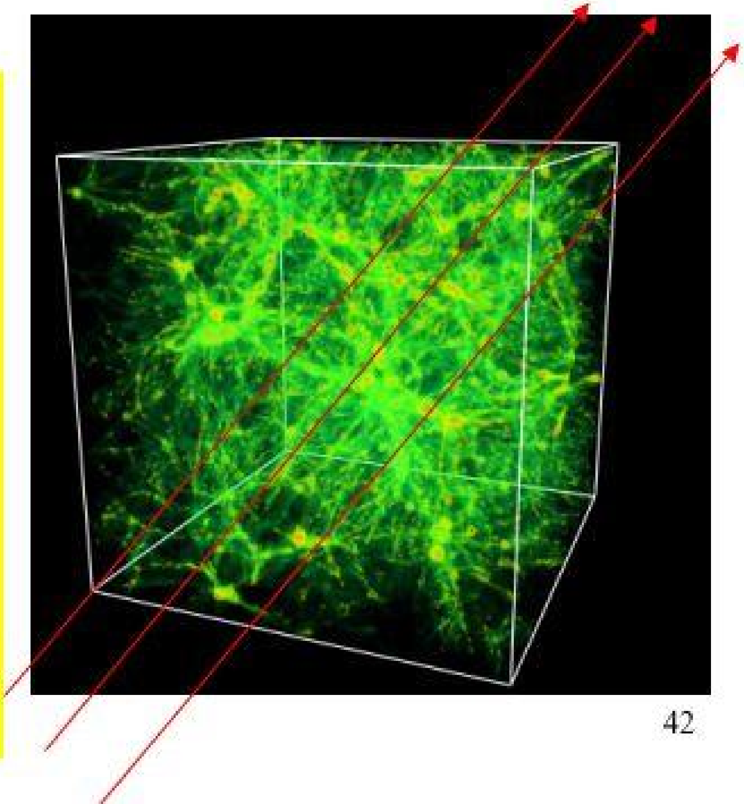
- Seeing-limited optical/near-IR spectroscopy of faint objects over wide fields (0.3-2.5 microns)
  - Much of the highest-impact Keck science to date has been in this area.
  - This capability provides much of the synergy with other observatories working at other wavelengths.
- Near-IR diffraction-limited imaging and spectroscopy (1-2.5 microns)
  - Science applications from the nearest star-forming region to the most distant galaxies.
  - Raw sensitivity competitive even with NGST for imaging (but with 5 times the spatial resolution).
  - New dimension is spectroscopy. R>5000 allows astrophysics– kinematics, chemistry, measurement of physical properties
- Thermal-IR diffraction limited imaging and spectroscopy
  - Spatial resolution coupled with high spectral resolution complements the sensitivity of SIRTF, NGST
  - Similar spatial resolution to ALMA, at shorter wavelengths.

Example: Baryonic Structure at High Redshift

The 3-D Structure of the diffuse IGM can be probed using "tomography" via multiple sightlines through the survey volume

Keck/HIRES





Progress with the TMT Partnership

- AURA & ACURA sign agreements with CELT (Jun 03)
- Caltech/UC raise $35M from Moore Foundation and form CELT Corporation
    - Sept-Dec'03
- AURA Submits ELT technology study to NSF
    - $17.5M for TMT
    - $17.5M for alternative technology approaches
- Canada (ACURA) submits proposal to CFI to join CELT as major partner
    - Jun 03, positive decision (Mar 04)
- TMT Board and governance established (June 03 -)
    - Project Office in Pasadena (ready summer 04)
    - Science Requirements complete (under change control Jul 04)
    - Working Groups established (Site, AO, Instruments, Integ. Modeling)
    - Gary Sanders becomes TMT Project Manager (April 04)
    - Partners agree integrated plan for $70M Design and Development Phase (DDP) April' 04

Goals of Design Development Phase

(2003-2007)

- Develop requirements: science and operations
- Design observatory: facility, initial AO and instruments
- Assess & mitigate risks
- Establish schedule: construction, I&T, commissioning
- Understand cost versus scientific performance
- Establish costs: construction, operations, development
- Select and acquire site
- Develop operational plan & construction proposals

Science Requirements Document

Merger of 4 community efforts!

SAC Co-Chairs : Steidel, Bolte, Carlberg, Strom

Project Scientist: Nelson

Science-Based Observatory Priorities (in order)

1. diffraction-limited imaging at near-IR wavelengths (combines aperture and angular resolution)
2. wide-field seeing-limited UV/optical multi-object spectroscopy ("workhorse" capability, AO impractical in short-term)
3. high resolution spectroscopy at near-IR and mid-IR wavelengths (diffraction-limited)

Later (ExAO, Hi-res UV/opt, GLAO, Mid-IR imaging)

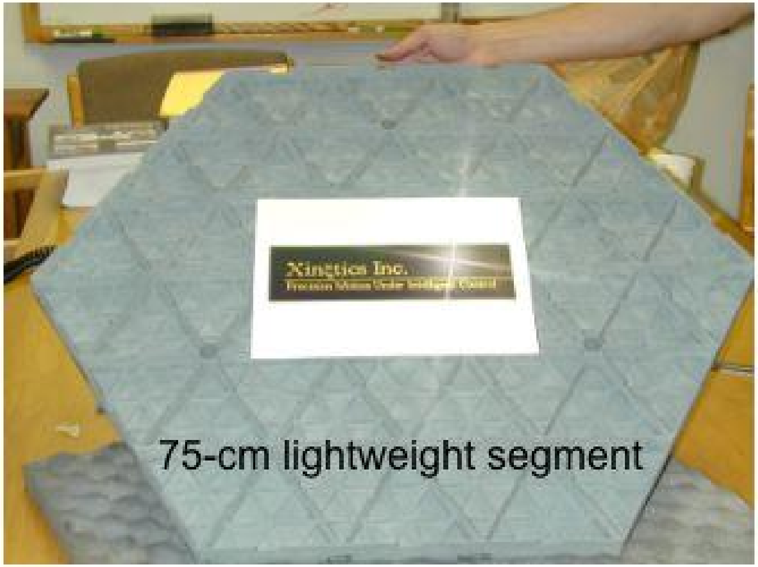
Risk Mitigation

Technical area	Uncertainties	Potential impact	Mitigation strategy
Optics	Segment costs and schedule, control bandwidths, secondary fabrication	Significant project delay and cost increase, degraded science	Prototype segments, vendor development, dynamic modeling
Optics active control	Actuator and edge sensor cost and reliability, phasing instrumentation	Poor performance, high maintenance costs	Prototype and life-cycle test
Dynamics	Effect of wind buffeting on the image quality produced by the telescope	Reduction in seeing-limited and diffraction-limited science	Wind modeling used to iterate design
Adaptive optics	Availability of components, performance level upon completion	Loss/delay of diffraction-limited science, cost increase	Vendor development, modeling, model validation
Instruments	Optical performance, availability of critical components,	Reduction in science return, cost increase	Modeling, vendor development, component prototyping
Site testing & acquisition	Parameters of the various sites	Reduced science, in critical path of project	Vigorous site testing campaign
Operations	Maintenance requirements, software requirements	Increased cost, loss of observing time due to failures	Design, analysis, modeling
Enclosure	Cost and local turbulence environment (dome seeing)	High cost, adverse wind disturbances, increased operational needs	Design, wind modeling, tunnel prototyping, and vendor iteration

Example of Key Development Areas - Optics

- Investigate advanced structural approaches
- Stressed-mirror polishing on CP machine
- Alternate segment materials: SiC


3.66 m CP machine by CEBA Corp.



75-cm lightweight segment

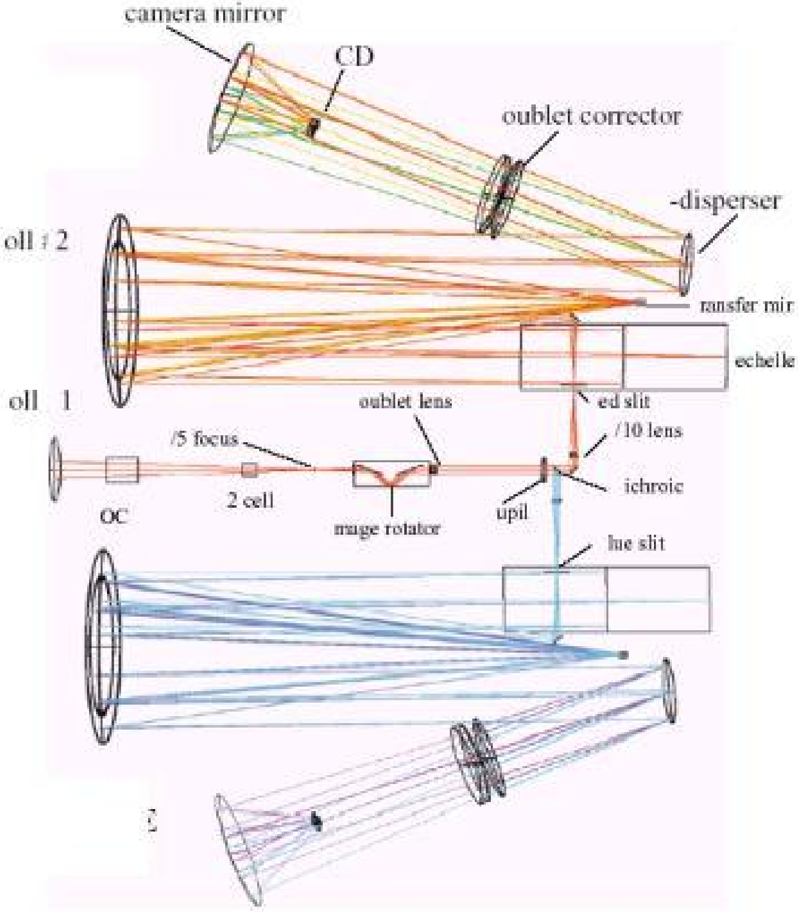
TMT AO Systems

	Wavelength	Science (SRD v12)	Complexity	Priority
MCAO Multi-Conjugate	0.8-2.5μ	•Dark ages •Early galaxies, AGNs •Nearby galaxies resolved star pop. and nuclei •Galactic Center •Star forming regions	•Multi Lasers •Multi DMs	1st light
MIRAO Mid IR	7-28μ	•Star forming regions, protoplanetary disks •Characterize planetary systems; AGNs	•Cryogenic •Adaptive Secondary	1st light
ExAO Extreme	1-2.5μ	•Exo planet imaging	•MEMS •Calibration •Tel. Stability	2nd gen
GLAO Wide Field	0.7-2.5μ	•Large sample galaxy spectra	•Optical design •Deployable IFUs	2nd gen
MOAO Multi-Object	1-5μ?	•Galaxy chemistry? •Star forming chemistry?	•Deployable AO •MEMS? •dIFUs?	2nd gen

Instruments: challenges in optics & manufacture

Science Requirements defines the need for:

- wide field seeing-limited optical spectroscopy
- deployable integral field units for near-IR AO-fed multi-object spectroscopy
- mosaics of high performance IR detectors
- large optical elements, cryogenic VPH gratings
- high performance optical coatings



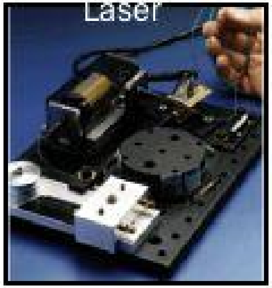
CELT MTHR concept: Steve Vogt//Keith Taylor

Investment in key technologies with field/laboratory tests

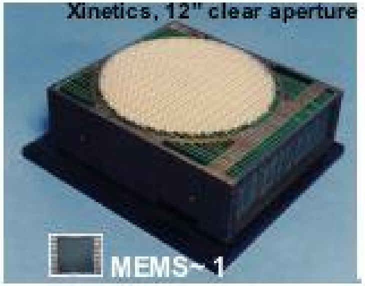
High risk technologies

- High Power Lasers
- Deformable Mirrors
- Low noise Detectors
- Complex Instruments
- System design

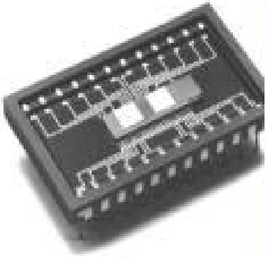
Prototype Laser



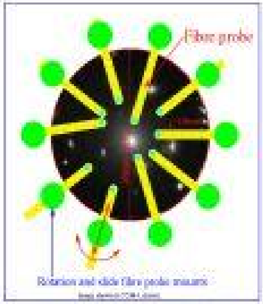
Next generation DM



Next generation detectors

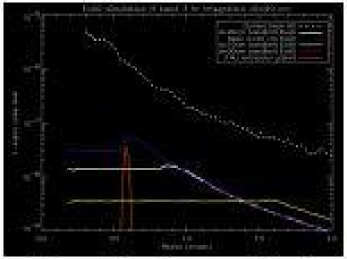


instruments



Palomar test-bed system

Optical AO



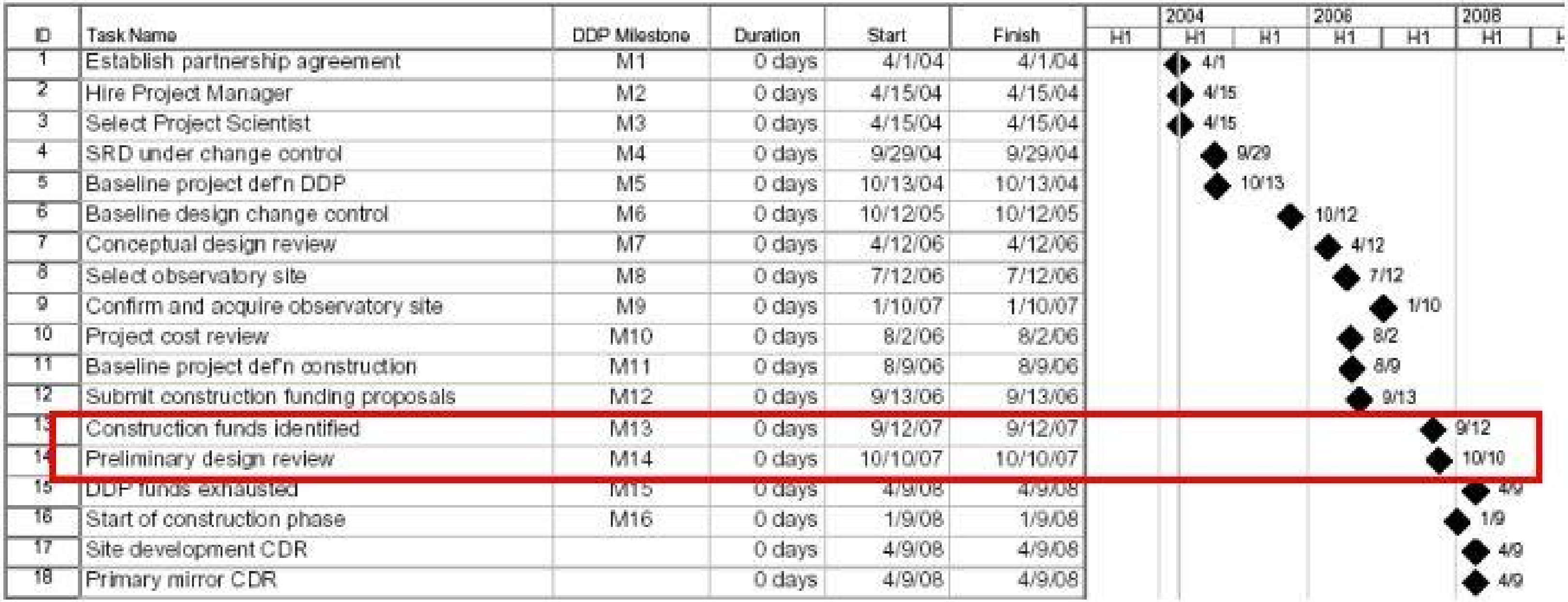
Planet finders on Keck

Goal: high risk items costed and demonstrated before construction begins

Proposed funding in TMT DDP plan

• Systems Engineering	$3.7M
• Telescope design	$4.1M
• Optics	$9.5M
• Facilities	$4.6M
• Adaptive Optics (models, components, on-sky tests)	$11.7M
• Instrumentation (concept studies, prototypes)	$10.2M
• Site Testing (3 Chilean, M Kea, S P Martir)	$4.1M
• Software	$2.7M
• Science oversight	$1.6M
• Management, staffing and project office	$8.6M
TOTAL (incl contingencies)	**$70.0M**

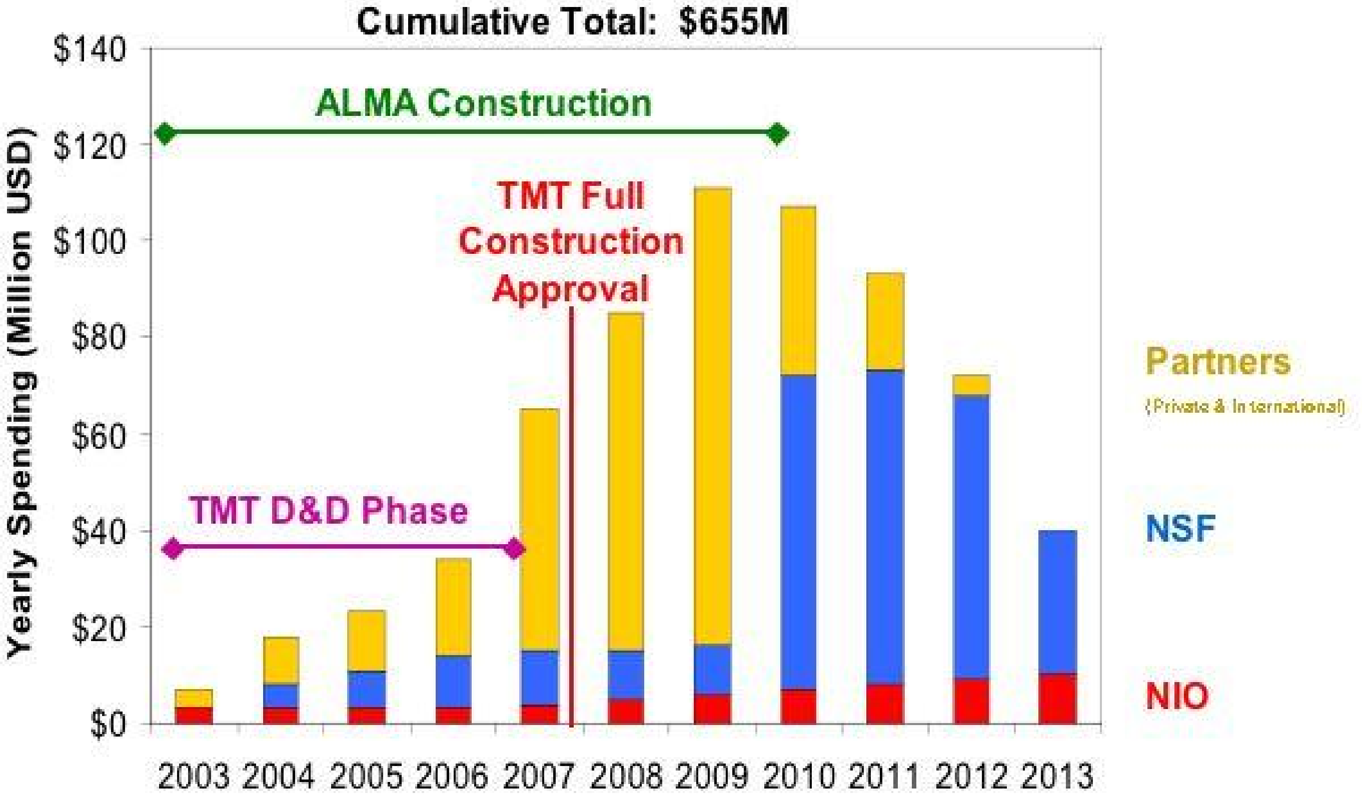
Preliminary TMT Schedule



ID	Task Name	DDP Milestone	Duration	Start	Finish
1	Establish partnership agreement	M1	0 days	4/1/04	4/1/04
2	Hire Project Manager	M2	0 days	4/15/04	4/15/04
3	Select Project Scientist	M3	0 days	4/15/04	4/15/04
4	SRD under change control	M4	0 days	9/29/04	9/29/04
5	Baseline project def'n DDP	M5	0 days	10/13/04	10/13/04
6	Baseline design change control	M6	0 days	10/12/05	10/12/05
7	Conceptual design review	M7	0 days	4/12/06	4/12/06
8	Select observatory site	M8	0 days	7/12/06	7/12/06
9	Confirm and acquire observatory site	M9	0 days	1/10/07	1/10/07
10	Project cost review	M10	0 days	8/2/06	8/2/06
11	Baseline project def'n construction	M11	0 days	8/9/06	8/9/06
12	Submit construction funding proposals	M12	0 days	9/13/06	9/13/06
13	Construction funds identified	M13	0 days	9/12/07	9/12/07
14	Preliminary design review	M14	0 days	10/10/07	10/10/07
15	DDP funds exhausted	M15	0 days	4/9/08	4/9/08
16	Start of construction phase	M16	0 days	1/9/08	1/9/08
17	Site development CDR		0 days	4/9/08	4/9/08
18	Primary mirror CDR		0 days	4/9/08	4/9/08

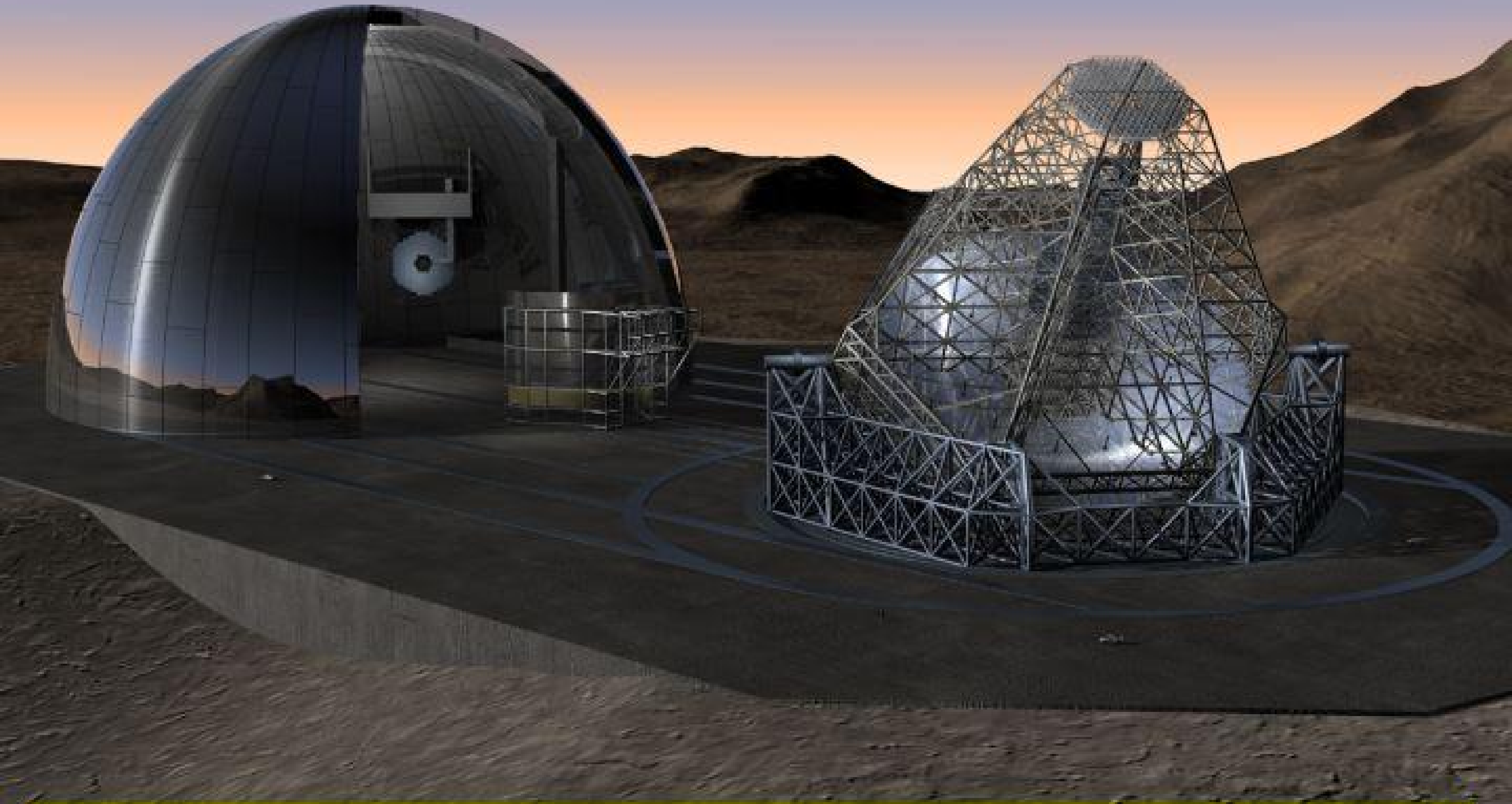
To maintain schedule, aiming to match likely CELT private and possible Canadian capital funds by late 2007, with Public NSF funds completing project as ALMA comes on-line.

Required TMT Funding Profile



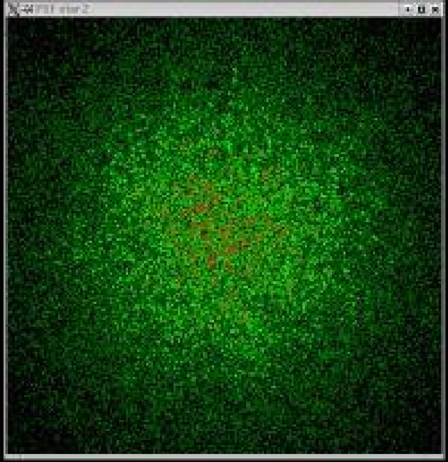
A combination of public and private funds are required to deliver a TMT in the 2012-2013 timeframe

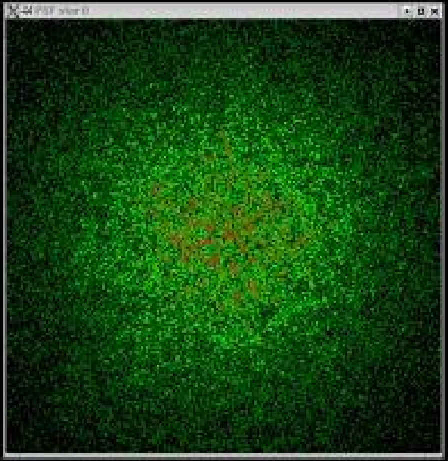
OWL

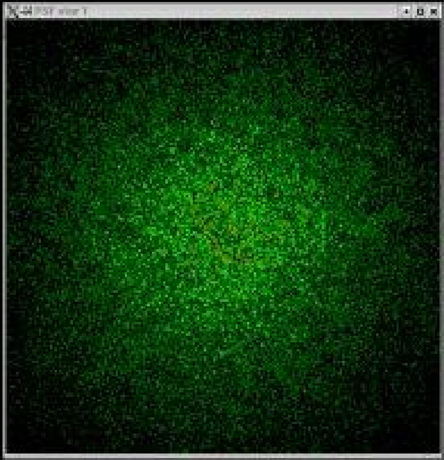


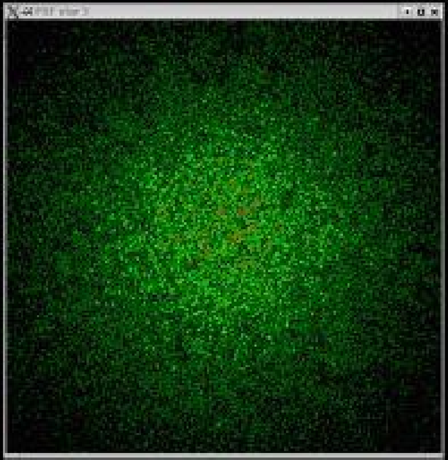
10 Dec 2003: Council declares that pursuing an ELT is an urgent priority for ESO

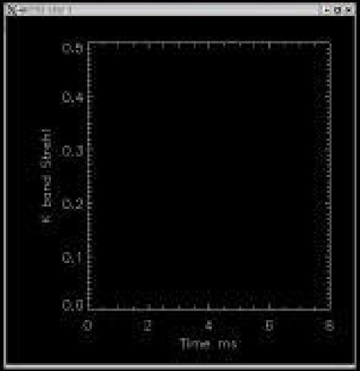
MCAO simulation

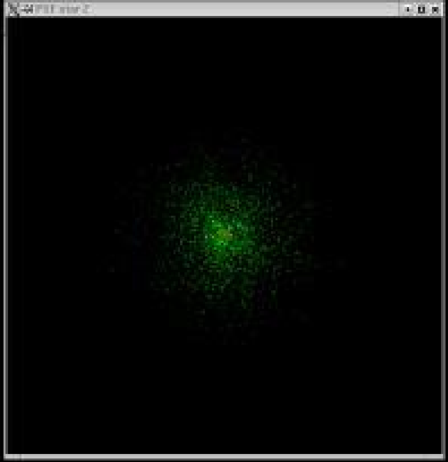








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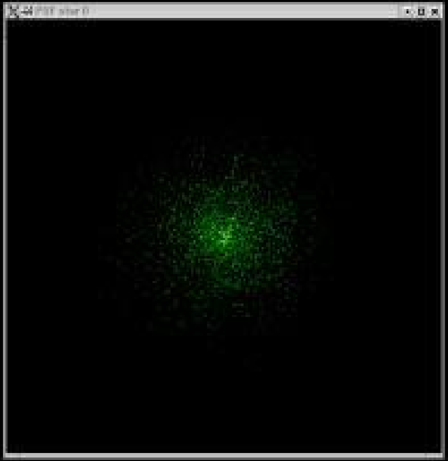
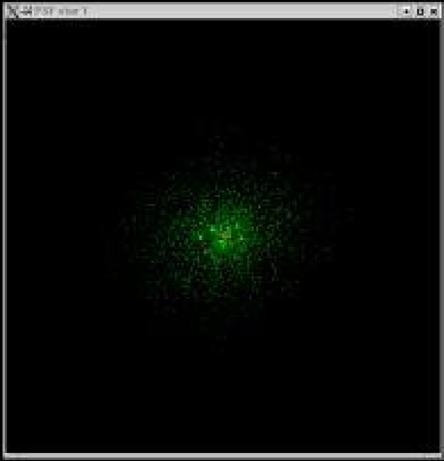
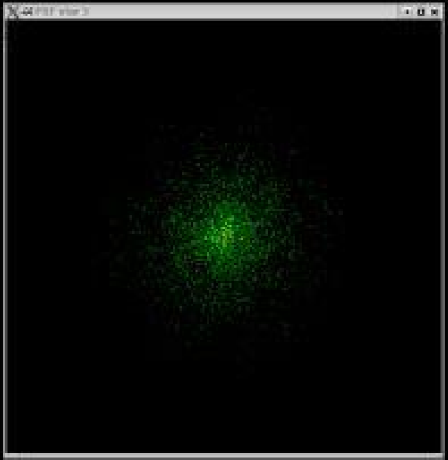
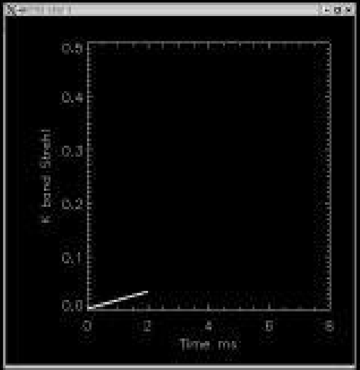

PSF star 0


PSF star 1


PSF star 3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K band Strehl
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2
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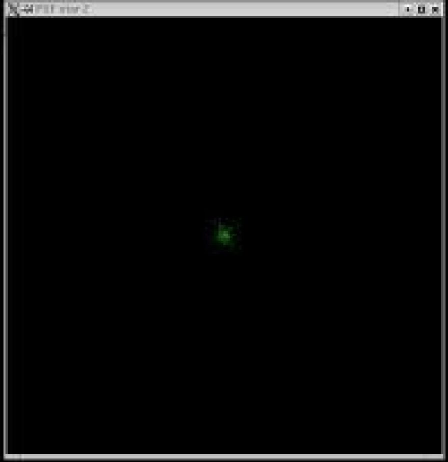
6
8
Time, ms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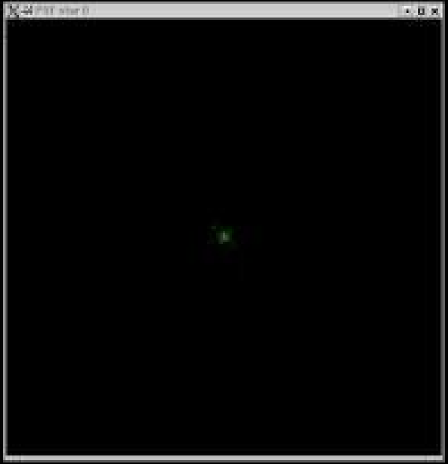
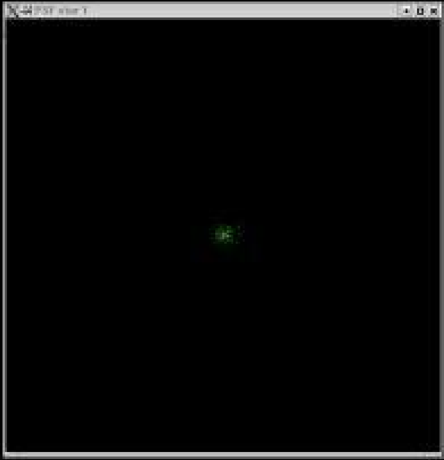

PSF star 0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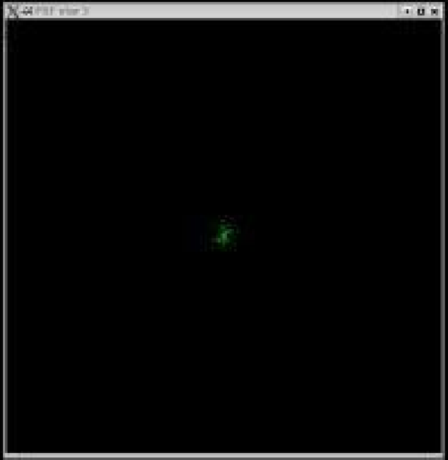
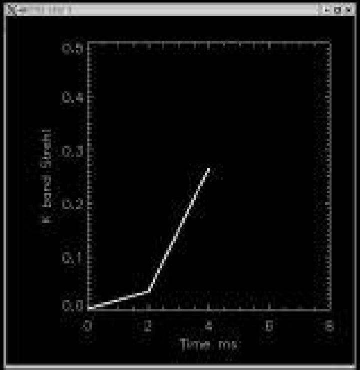

PSF star 3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K band Strehl
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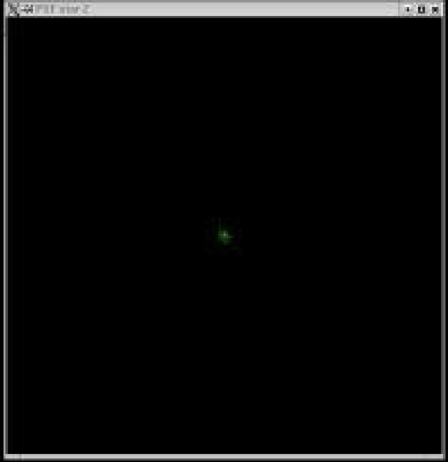
Time, ms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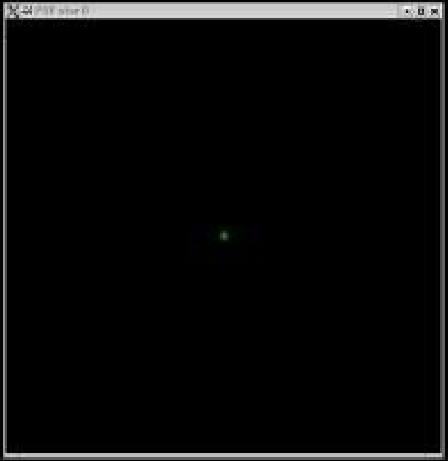
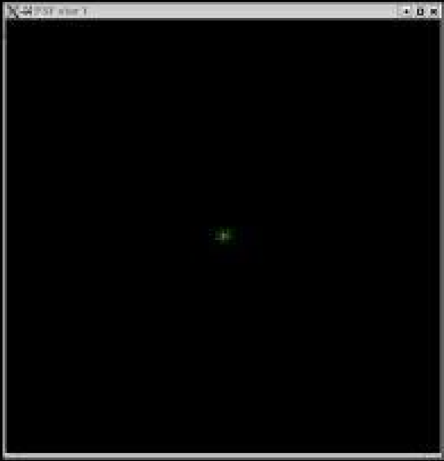
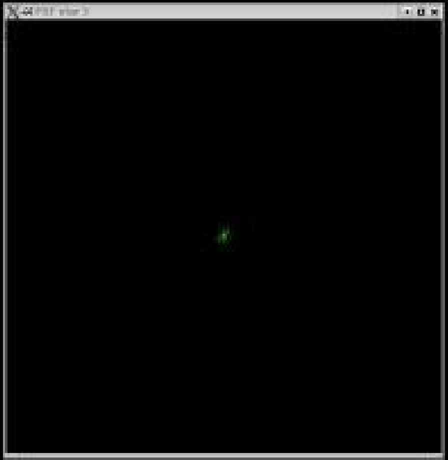
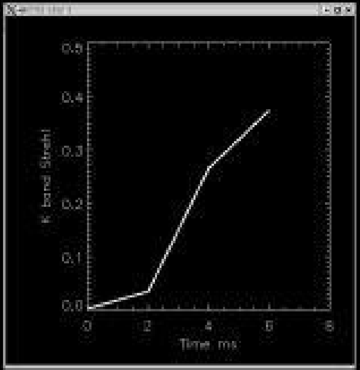

PSF star 0


PSF star 1


PSF star 3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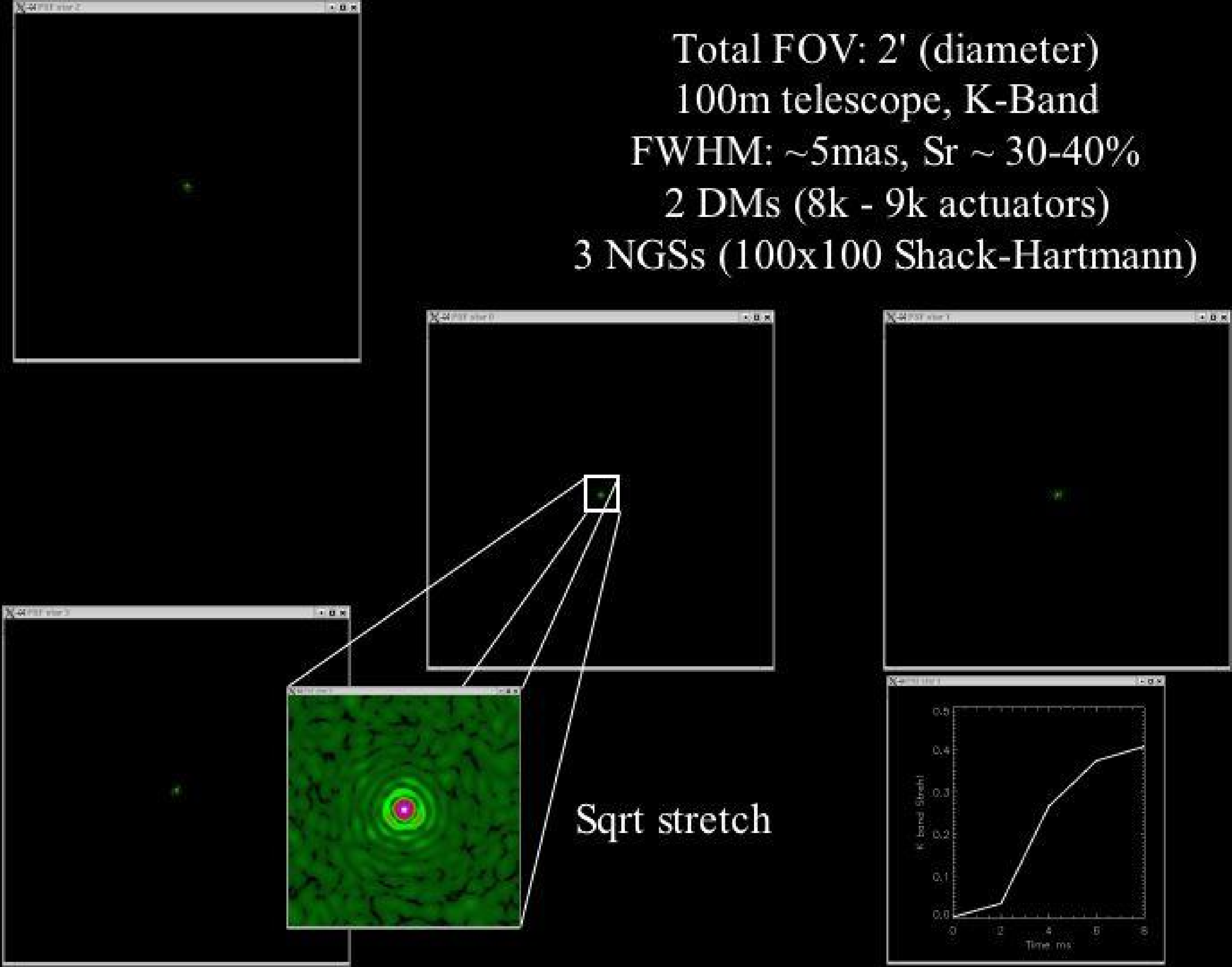
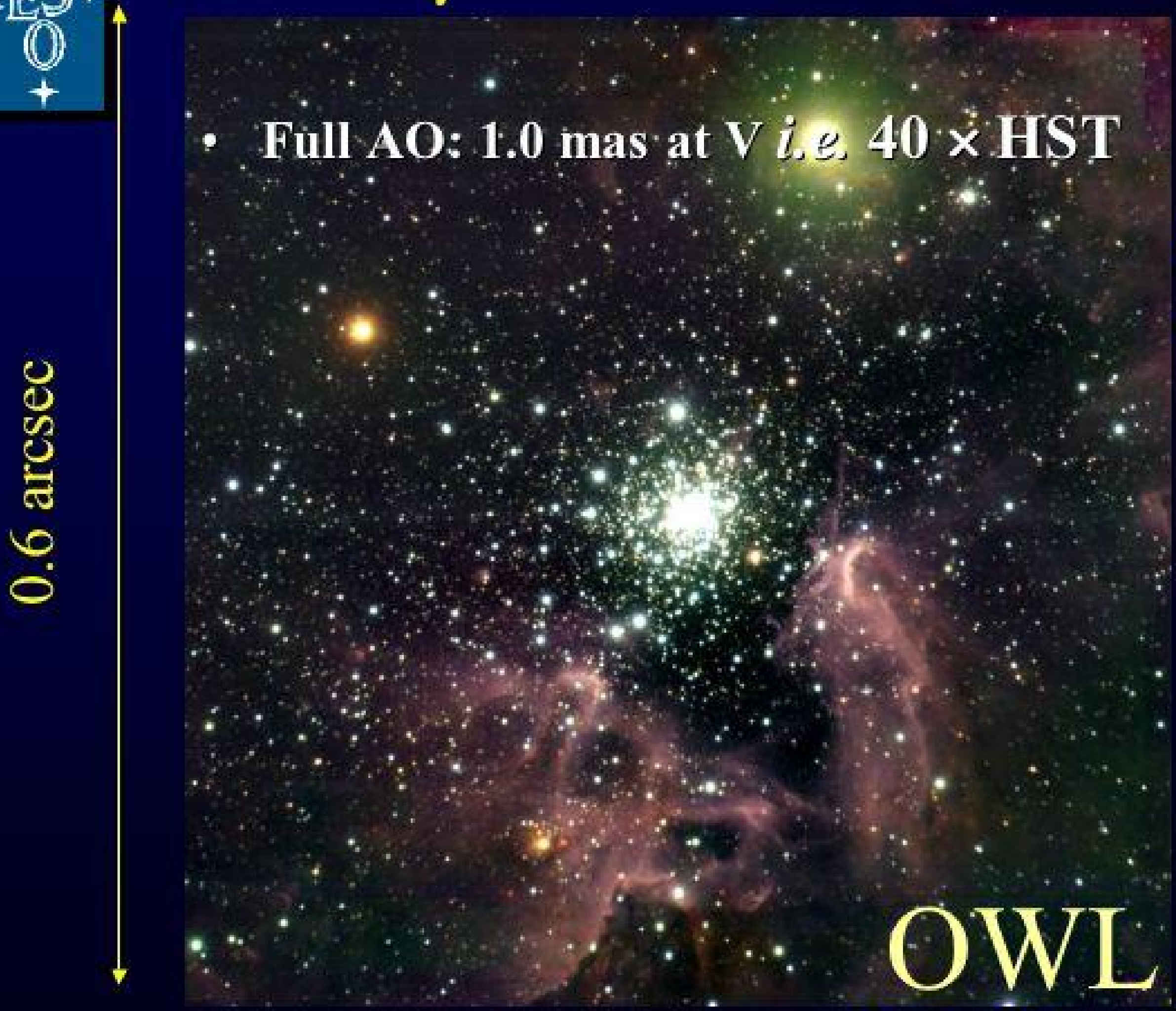
0.4
0.3
0.2
0.1
0.0
0
2
4
6
8
K band Strehl
Time, ms

Total FOV: 2' (diameter)
100m telescope, K-Band
FWHM: ~5mas, Sr ~ 30-40%
2 DMs (8k - 9k actuators)
3 NGSs (100x100 Shack-Hartmann)



Sqrt stretch

The spatial resolution challenge



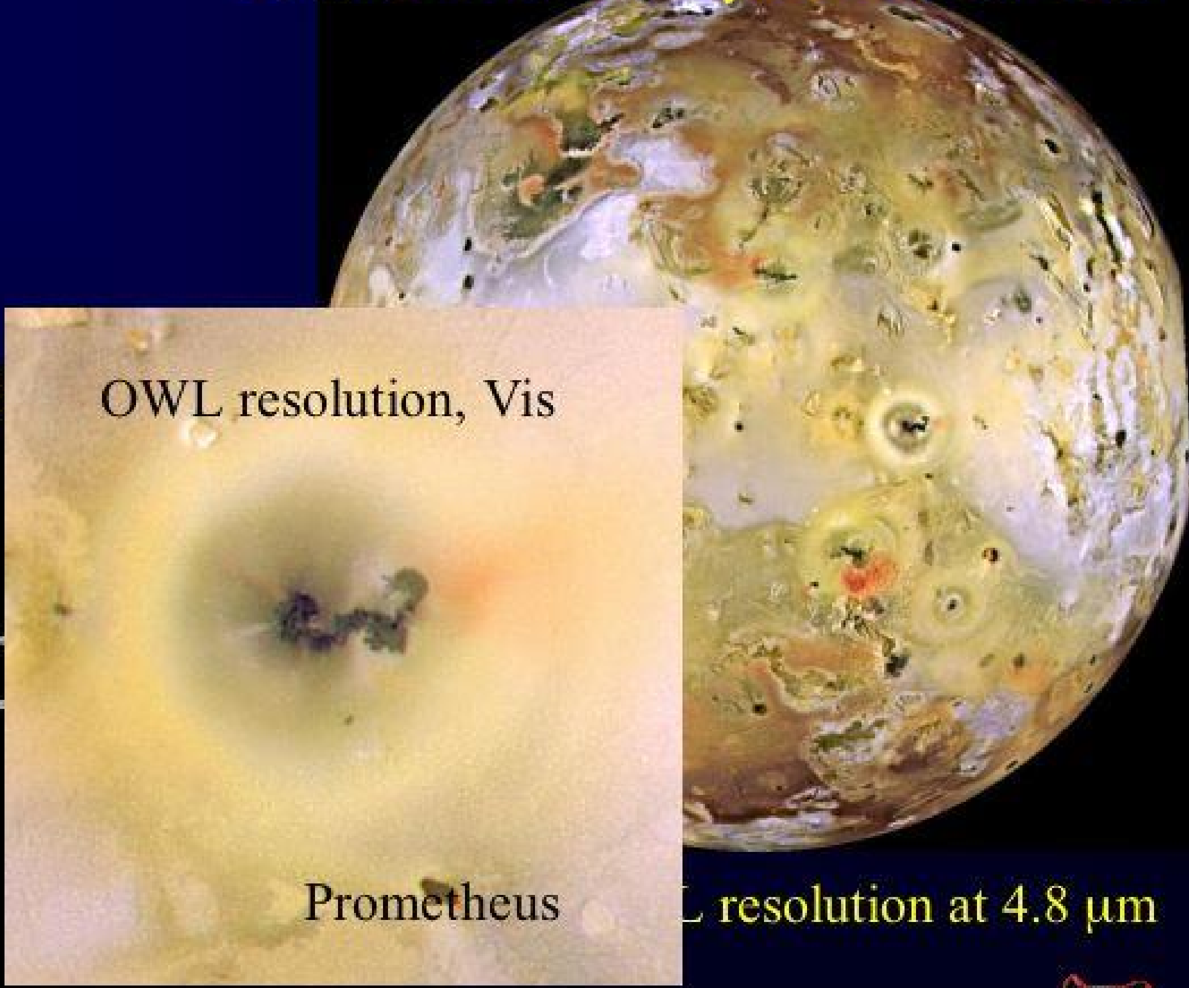
- Full AO: 1.0 mas at V *i.e.* 40 × HST

Limiting mag in 10^h: V=38

Sensitivity and Field-of-view

A flotilla of spacecrafts…

4.8 μm ground



L resolution at 4.8 μm

Exo-earths: strong dependence on D

- Accessible volume $\propto D^3$

  30m: 20 G stars (*)

  60m: 165 G stars

  100m: 750 G stars

- Sensitivity

  Science case $\propto D^4$

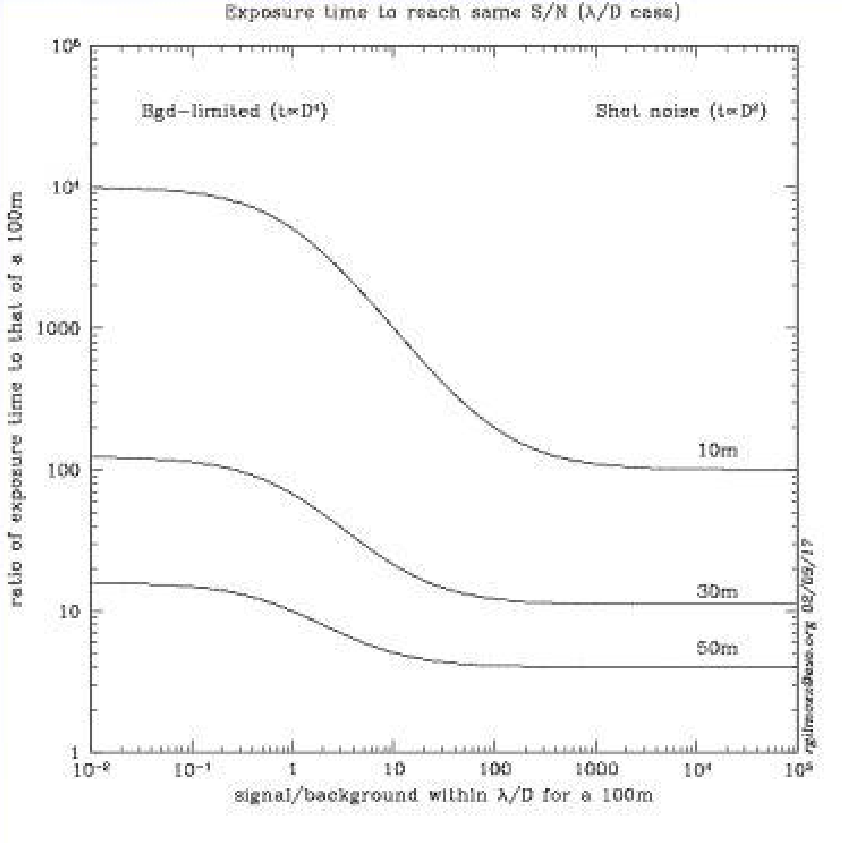
  → **to reach same S/N:**

  $t_{30m} = 120 \times t_{100m}$

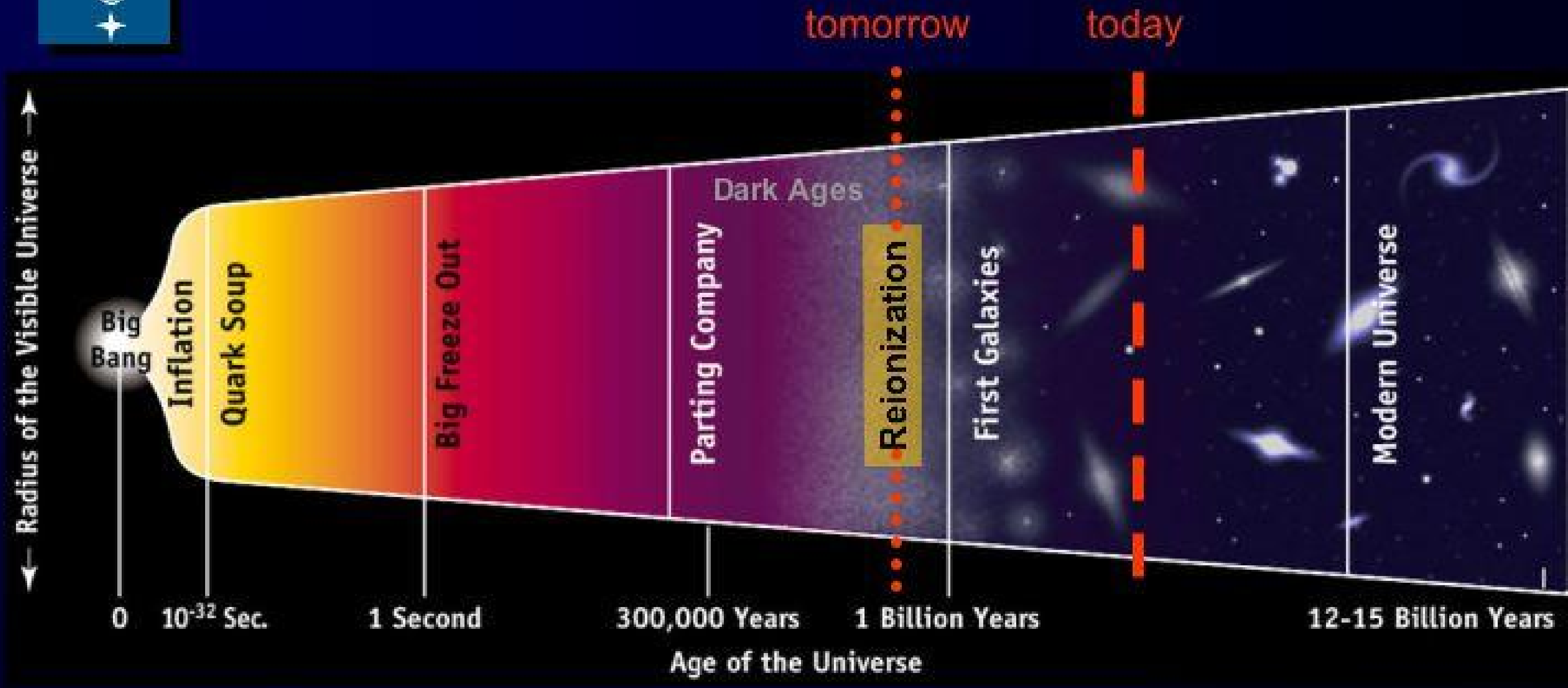
- Spectroscopy

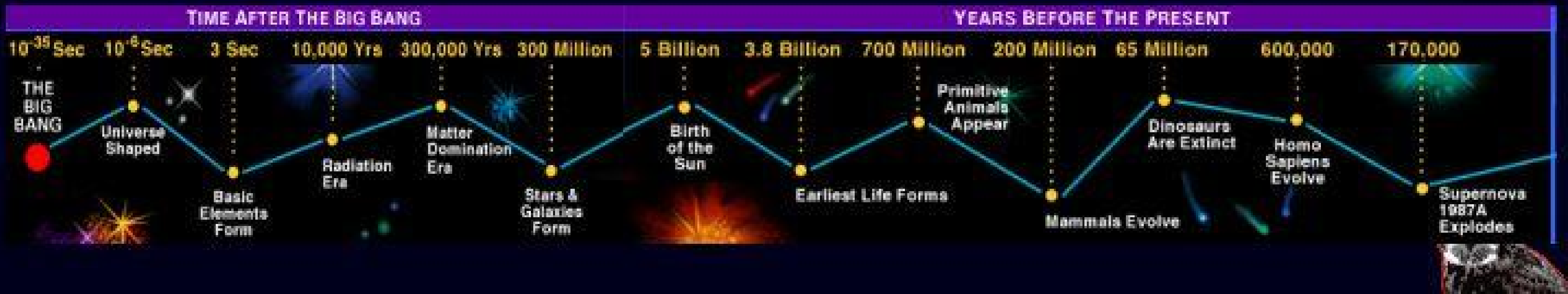
  $D \gtrsim 80m$

(*) $\forall\ d_{min} = 5\ \lambda/D$



Extreme imaging





Measure of cosmic parameters with primary distance indicators

- Note: NOT H_NOT ☺

- Complex SNe Ia calibration
  - ⇨ Derived + calibrated standard candles
  - ⇨ Phillips relationship (1993):

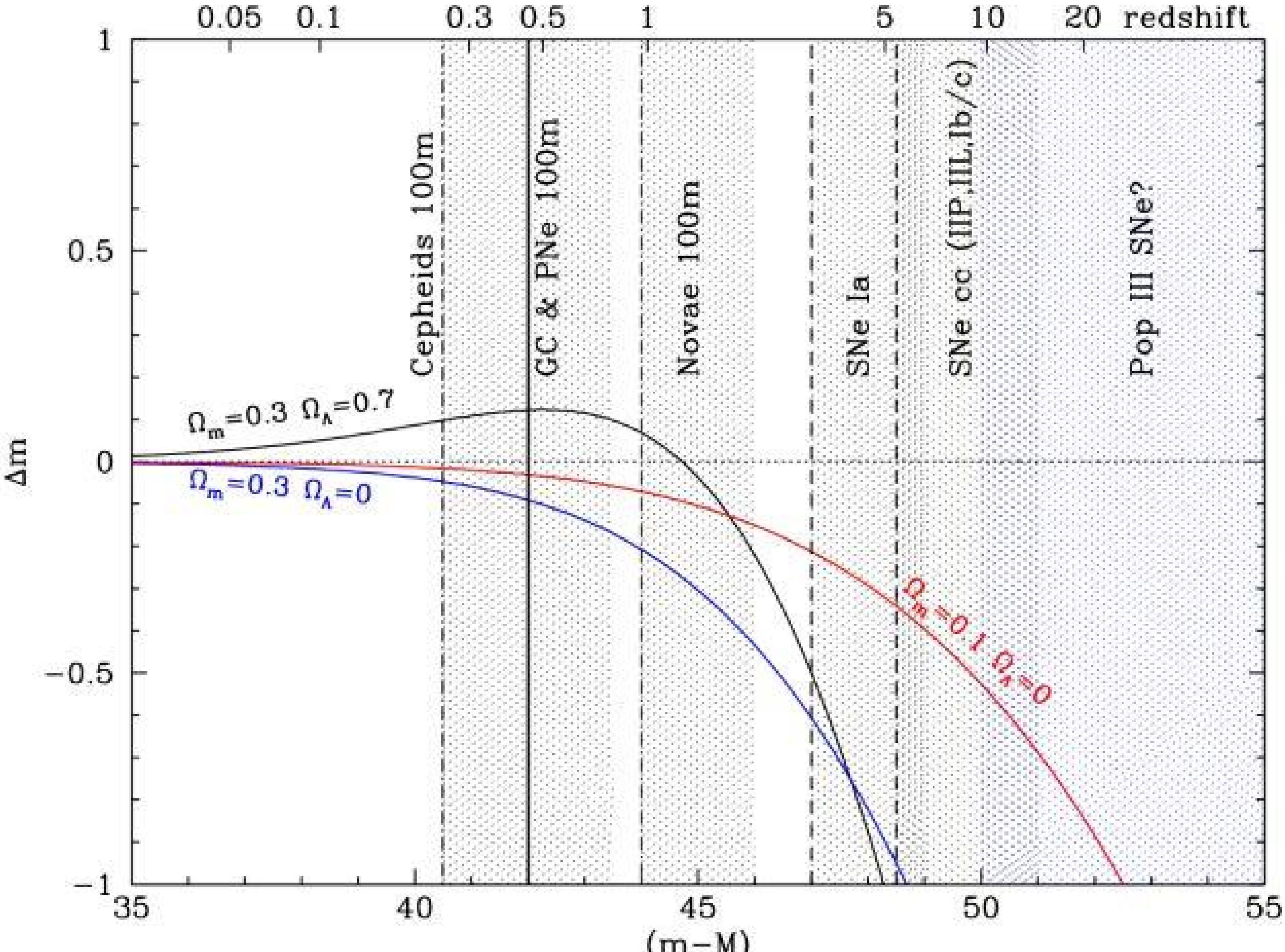
    Empirical relation M_{max} *vs* rate of decline

    Difficult to calibrate at high z
  - ⇨ Progenitors: single or double degenerate?

- OWL provides several alternatives

Cosmological parameters *cont'd*

- Disentangling models at $z \sim 1$
  - **Domain of <u>primary</u> indicators:**
    - **Cepheids**: P-L
      - (direct SFR; analog to HST@Virgo)
    - **Globular Clusters**: turnover mag of LF
    - **Bright PNe**: cutoff mag of LF
    - **Novae**: MMRD
      - (visible in *all* galaxy types)


0.05
0.1
0.3
0.5
1
5
10
20
redshift
Cepheids 100m
GC & PNe 100m
Novae 100m
SNe Ia
SNe cc (IIP,IIL,Ib/c)
Pop III SNe?
Ω_m=0.3 Ω_Λ=0.7
Ω_m=0.3 Ω_Λ=0
Ω_m=0.1 Ω_Λ=0
Δm
1
0.5
0
−0.5
−1
35
40
45
50
55
(m−M)

Other cosmological issues *cont'd*

- Re-ionization epoch
  - **WMAP sets re-ionization at z ~ 10-20**
  - **Who re-ionizes the universe?**
    - The usual suspects
      - First QSOs
      - Pop III stars
      - Primordial SNe
      - GRBs
      - ?

Probing the Nature of the Re-Ionization Sources

10^5s OWL exposures

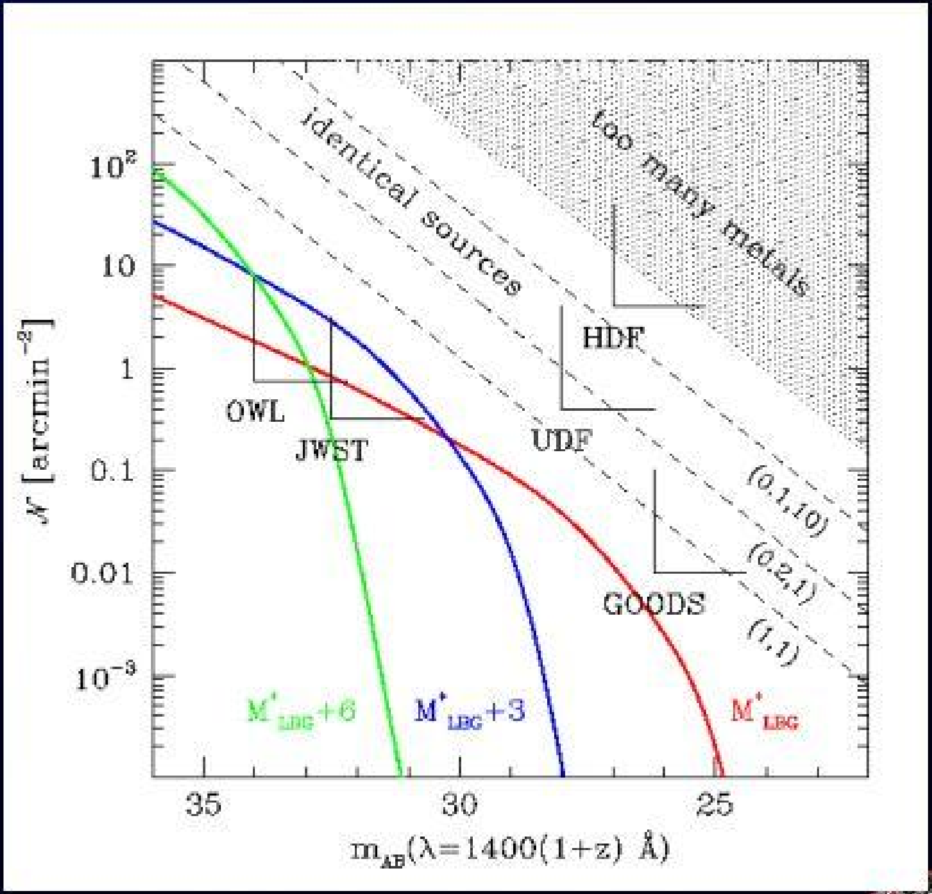
will be enough

to detect and

characterize

the sources

of re-ionization



Adapted from Stiavelli, Fall & Panagia, 2003, ApJ, in press

Primordial Stellar Populations

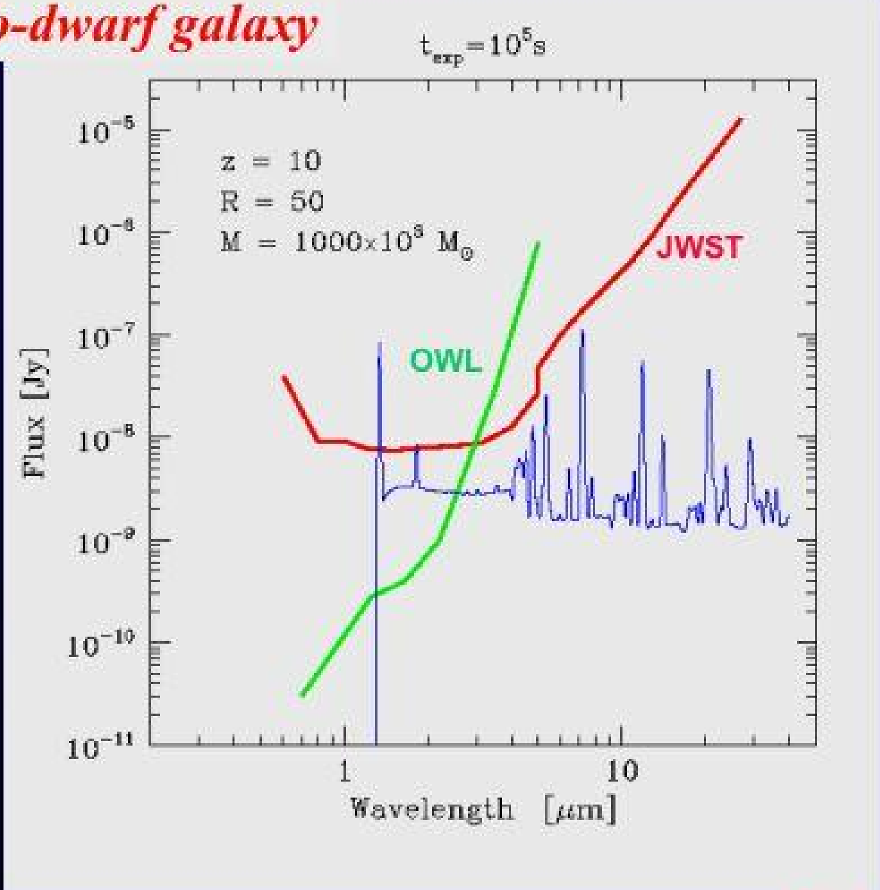
- Primordial stars (aka *population III stars*) form before re-ionization, say, at $z=10-20$
- They are *hot* and *massive*, and may form preferentially in *dwarf-galaxy class* overdensities $\Rightarrow M \approx 10^6\text{-}10^7\ M_\odot$
- Their spectra are characterized by *strong emission lines of H and He* and *strong nebular continuum*

Primordial Stellar Populations *cont'd*

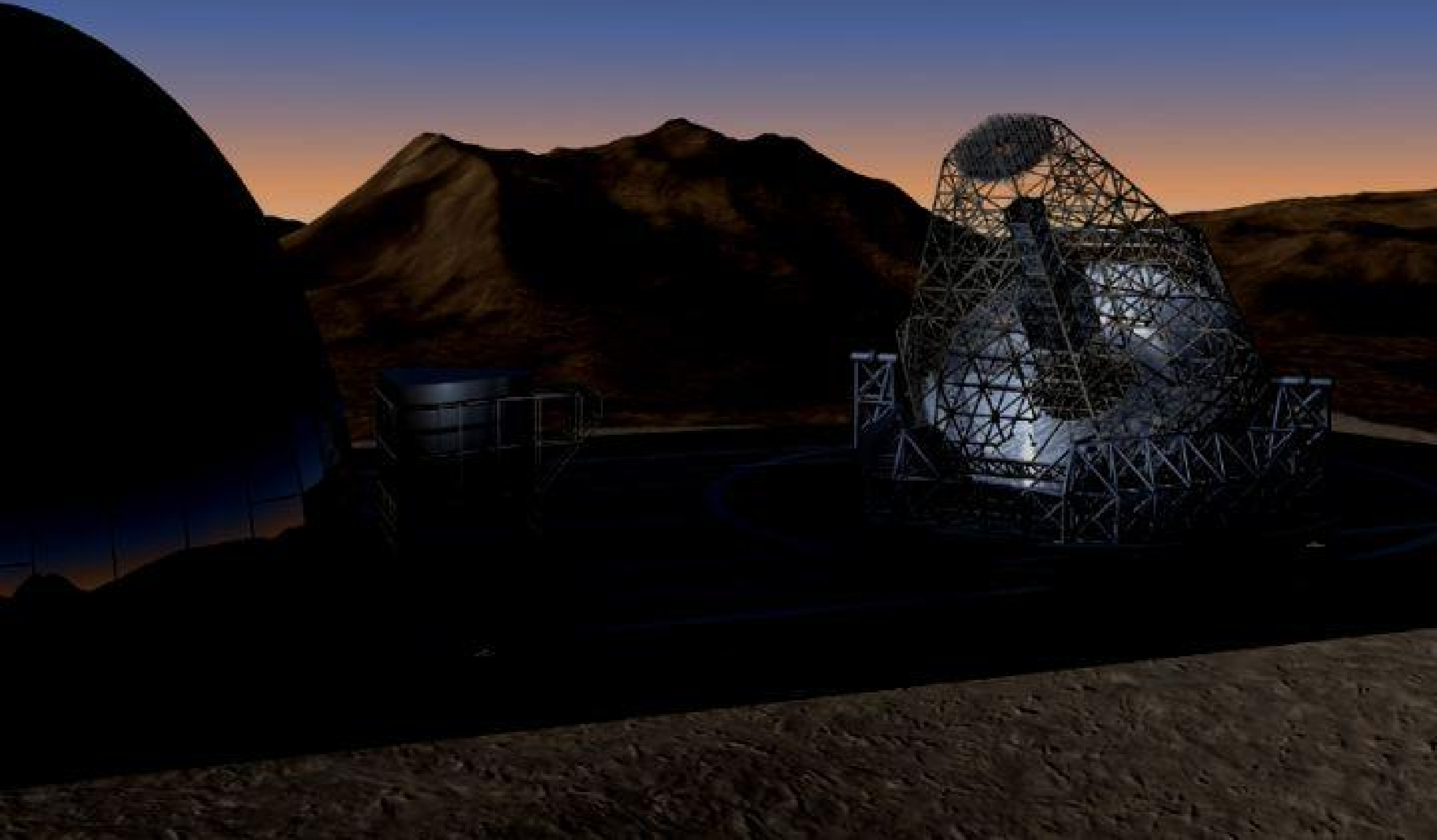
A typical proto-dwarf galaxy

Both continuum and line spectrum can accurately be studied with OWL at high z

Thus detecting and characterizing the first-light objects in the Universe



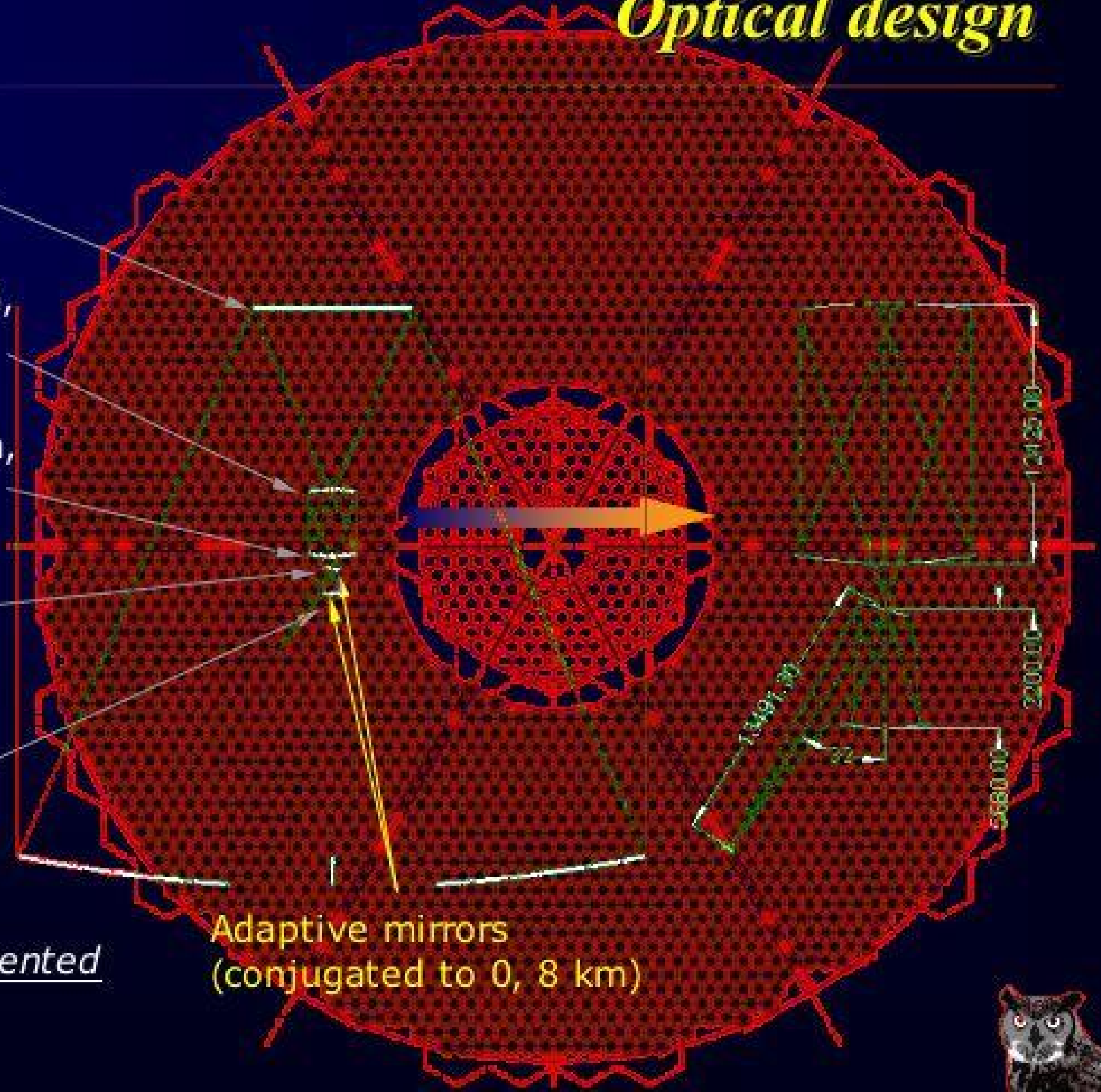
Design status



Design status

Optics	6-mirror, f/7.5, ~6,900 m≤ collecting area, near-circular outer rim
M1	Spherical dia. 100m, f/1.25
M2	Flat, dia. 25.6 m
Corrector	4 elements, dia. 8, 8, 3.5, 2m
FOV	10 arc min. seeing -limited; 6 focal stations (rotation of M6) > 2 arc min.diffr action -limited (vis.)
Stability	*Very low sensitivity to external disturbances (gravity, thermal, wind)*
Structure	2.1 Hz eigenfrequency, 14,200 tons moving mass; Standard steel beams, serially produced joints;
Kinematics	Distributed low -cost friction d rives, self -adjusting; Relaxed dimensional tolerances
Control	Multi-stage, distributed wavefront control: phasing, pre -setting, field stabilization, focusing, fine centering, dual conjugates active optics, adaptive optics

Optical design



M2 - Flat, 25.6-m, *segmented*

M4 - Aspheric, 8.1-m, thin *active* meniscus

M3 - Aspheric, 8.2-m, thin *active* meniscus

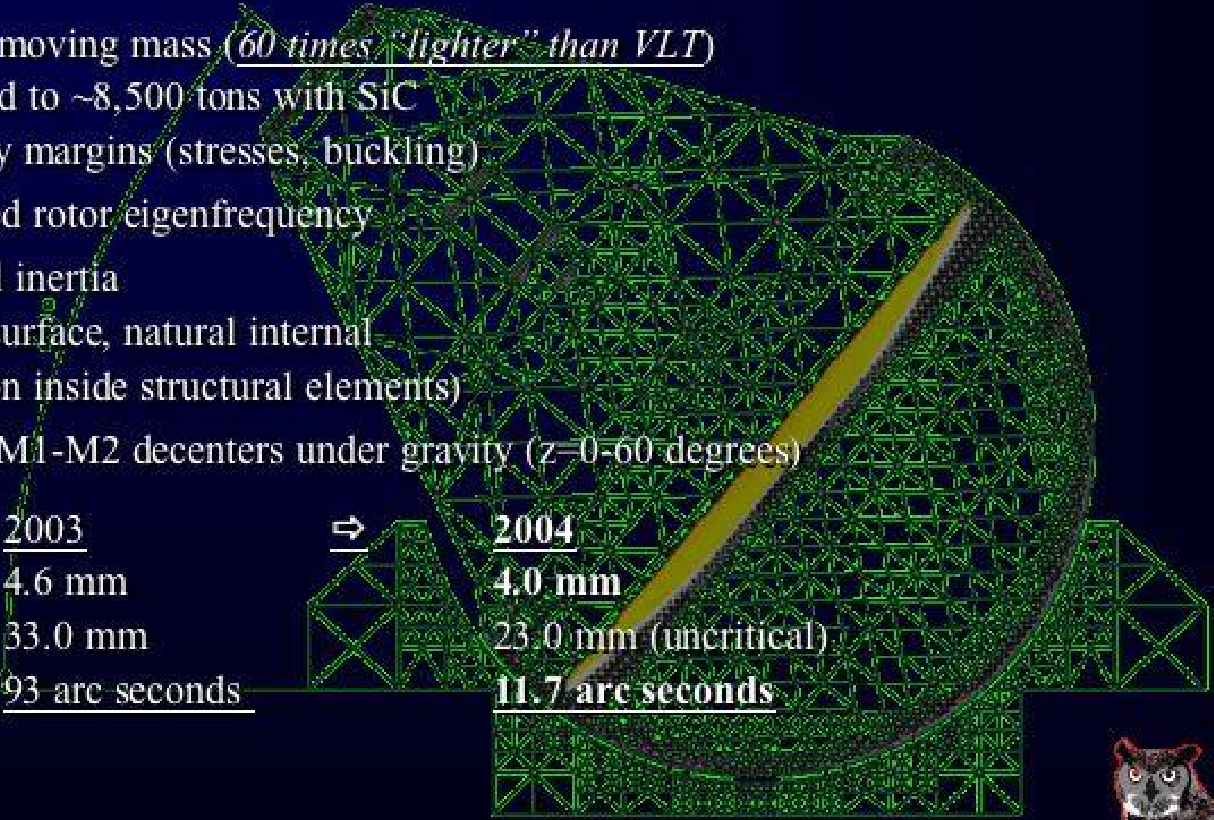
M6 - Flat, 2.2-m, Exit pupil, *field stabilization*

M5 - Aspheric, 3.5-m, *focusing*

M1 - Spherical, 100-m, f/1.25, *segmented*

Adaptive mirrors (conjugated to 0, 8 km)

Optomechanics



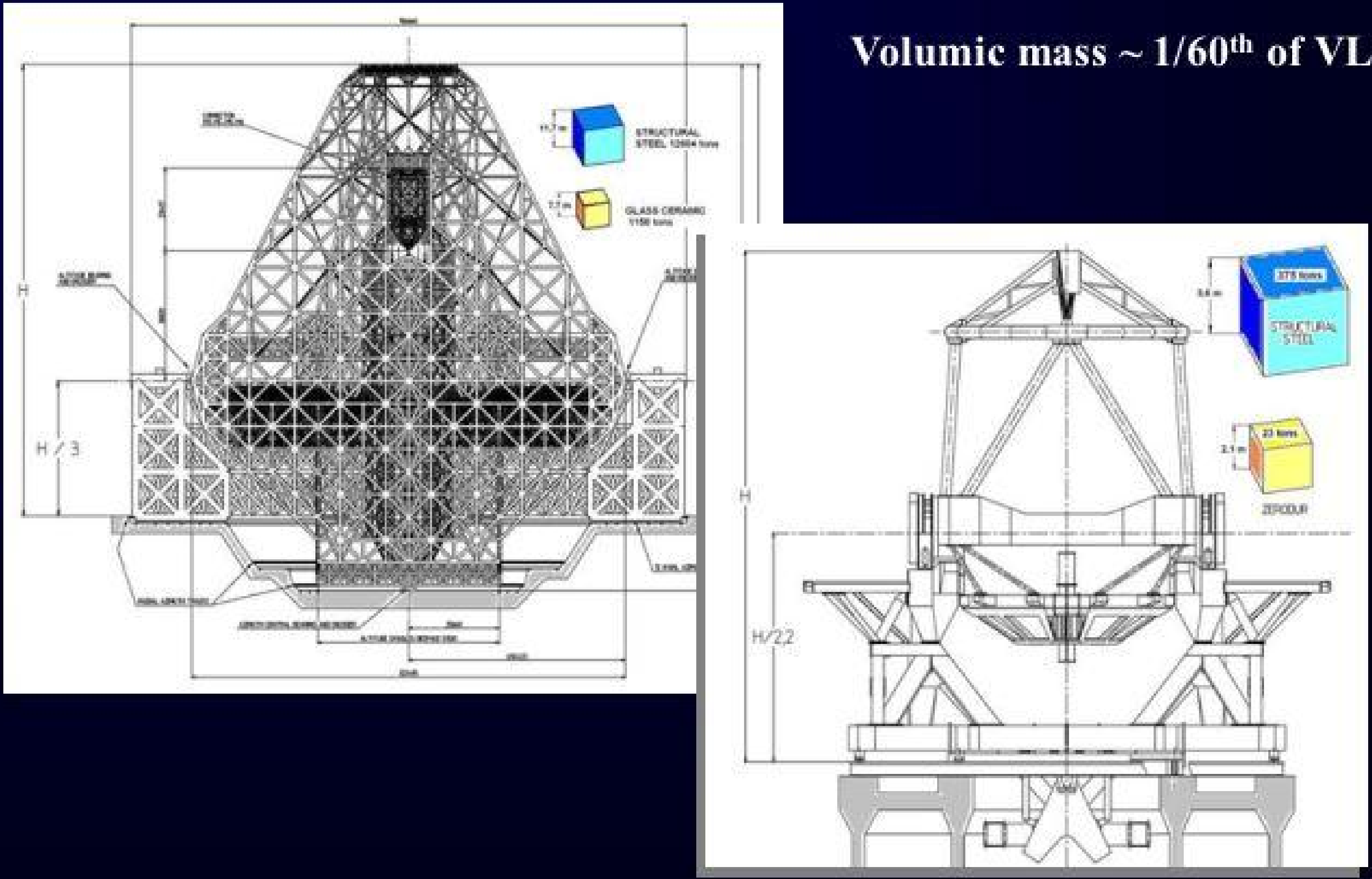
Fractal design - Low-cost, lightweight steel structure

- 14,200 tons moving mass (*60 times "lighter" than VLT*)
  Mass reduced to ~8,500 tons with SiC
  Ample safety margins (stresses, buckling)
- 2.1 Hz locked rotor eigenfrequency
- Low thermal inertia
  (developed surface, natural internal
  air circulation inside structural elements)
- Differential M1-M2 decenters under gravity (z=0-60 degrees)

	2003	⇨	2004
Piston	4.6 mm		**4.0 mm**
Lateral	33.0 mm		23.0 mm (uncritical)
Tilt	93 arc seconds		**11.7 arc seconds**

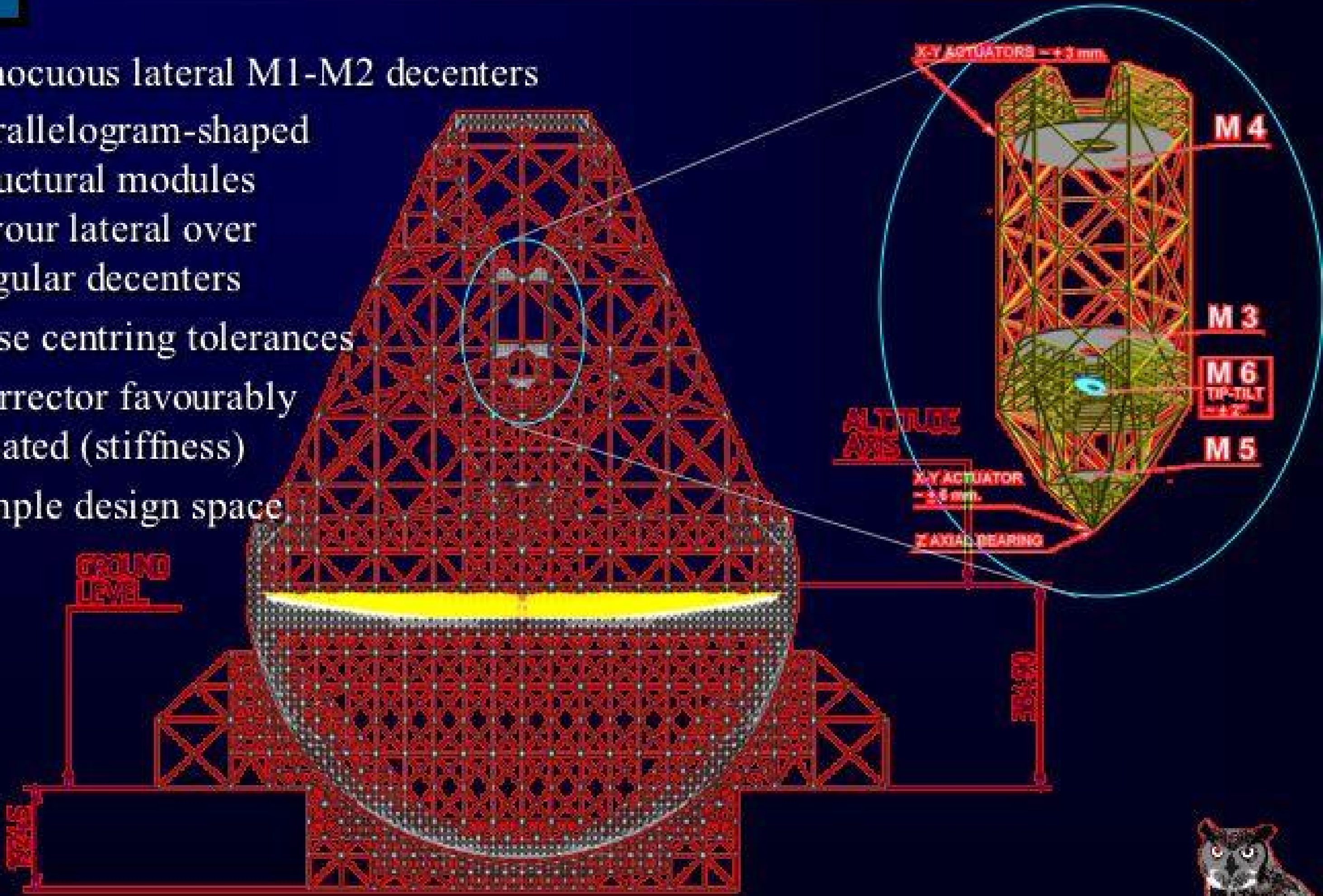
Lightweight ???

Volumic mass ~ 1/60th of VLT



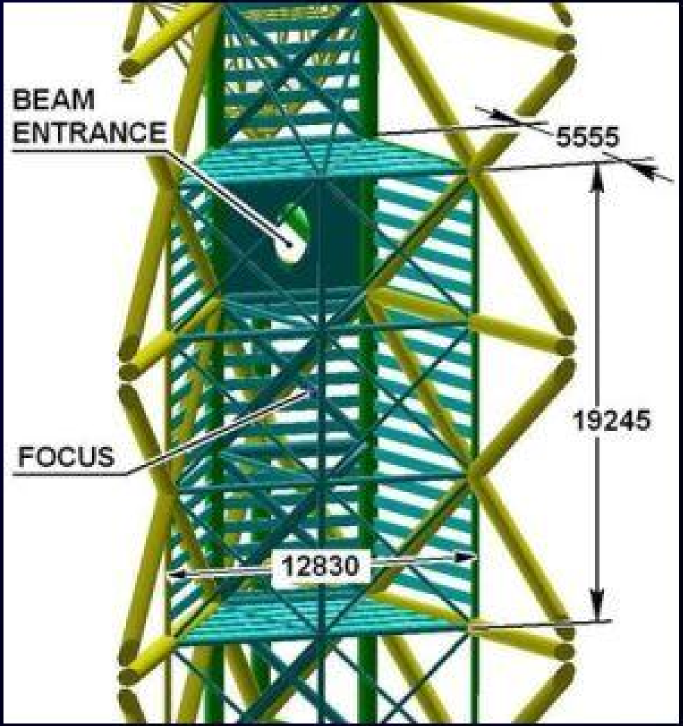
Reducing sensitivity by design

- Innocuous lateral M1-M2 decenters
- Parallelogram-shaped structural modules favour lateral over angular decenters
- Lose centring tolerances
- Corrector favourably located (stiffness)
- Ample design space



Instrument racks

- 6 focal stations; switch by rotating M6 about telescope axis.
- Local insulation & air conditioning
- Issue: needs rigid connection with corrector (TBC).
- Issue: available instrument mass



Piston, Tip, and Tilt: Examples

Piston only

X – tilts
same signs

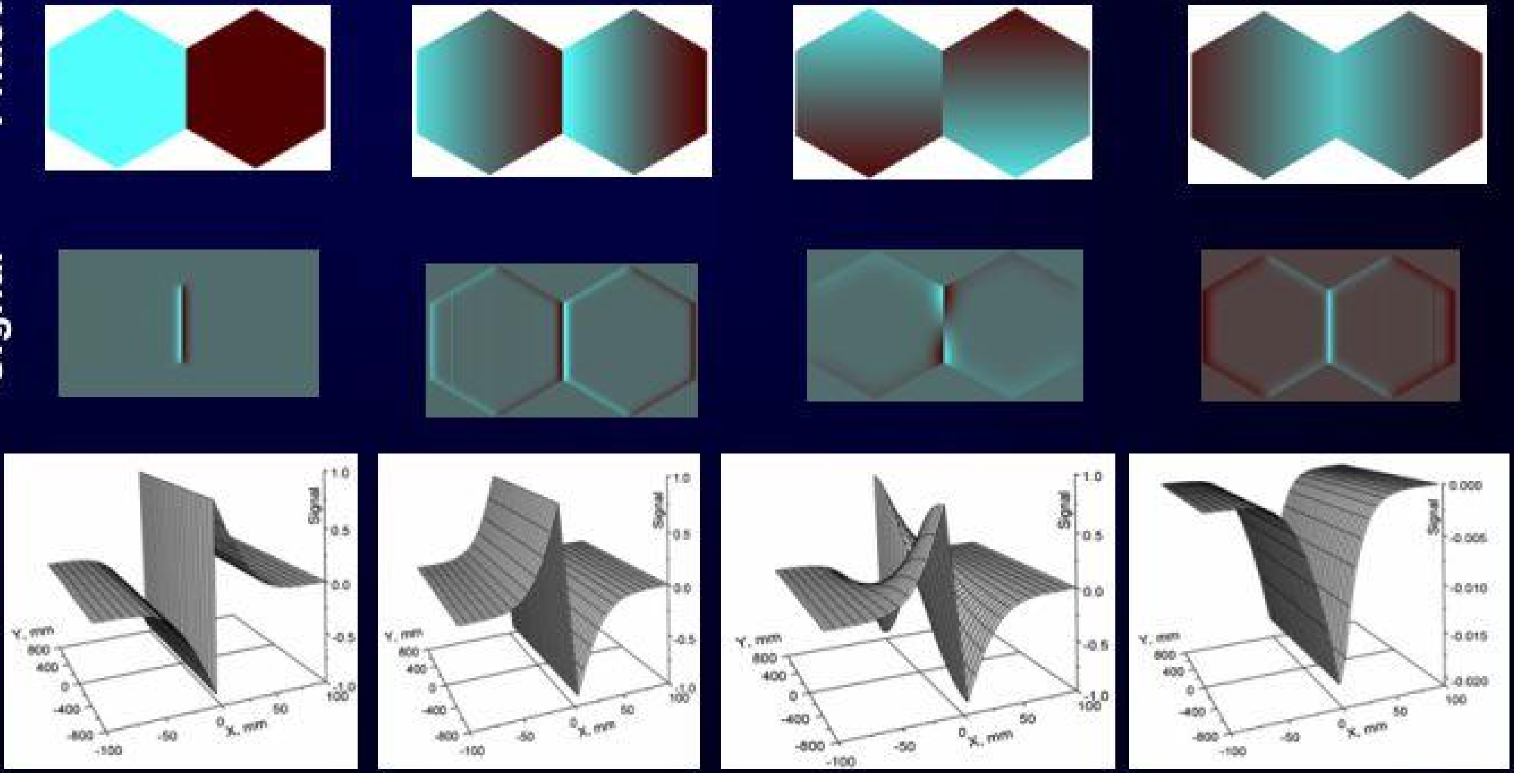
Y – tilts
opposite signs

X – tilts
opposite signs

Phase

Signal

Features



Antisymmetry
axis Y

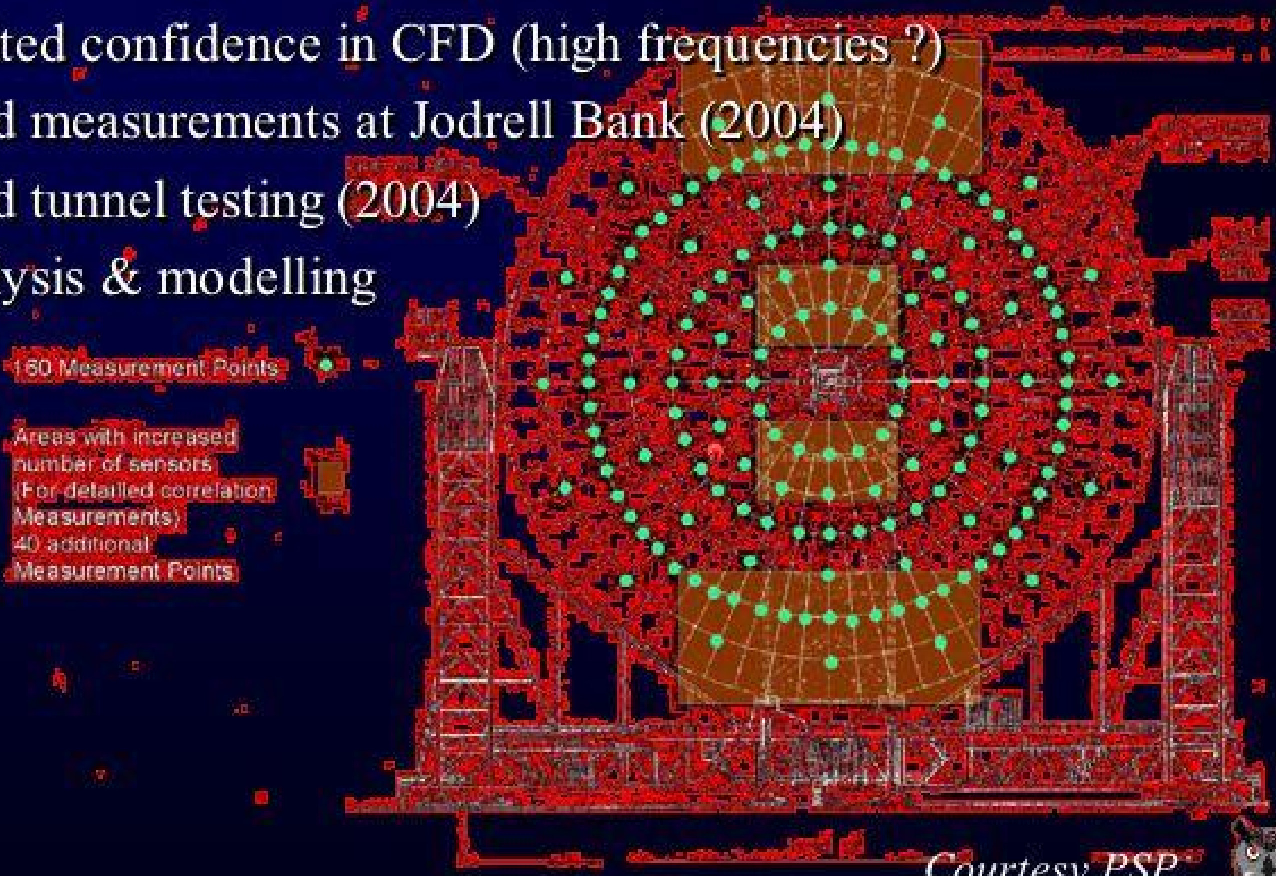
Antisymmetry
axis Y

Antisymmetry
axis X

Symmetry
axis Y

Wind

- Limited confidence in CFD (high frequencies ?)
- Wind measurements at Jodrell Bank (2004)
- Wind tunnel testing (2004)
- Analysis & modelling



160 Measurement Points

Areas with increased
number of sensors
(For detailed correlation
Measurements)
40 additional
Measurement Points

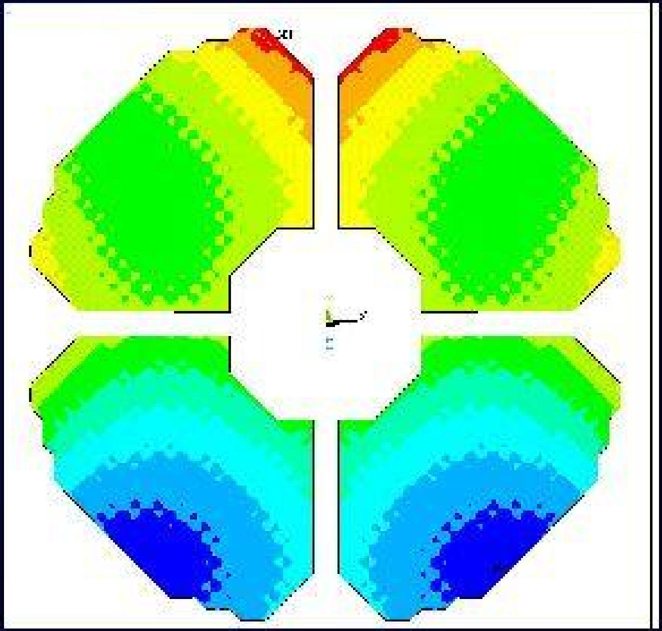
Courtesy PSP

Telescope performance (wind)

OWL under wind load.

The following two quasi static wind load cases have been evaluated:

1. Telescope in zenith configuration, wind load applied on full telescope, wind speed of **10 m/s**, conservative drag coefficient values used, which generates maximum tilt and decenter.
2. Telescope in 60° from zenith position, wind load applied only on M1 and M2, wind speed of **10 m/s**, conservative drag coefficient values used, which generates the maximum piston.



Maximum mean displacements out of both load cases

Mirror	Piston (uz)	Tilt (rotx)	Decenter (uy)
	[mm]	[arcsec]	[mm]
M1	-0.216	0.420	-0.129
M2	-0.336	1.680	-1.132

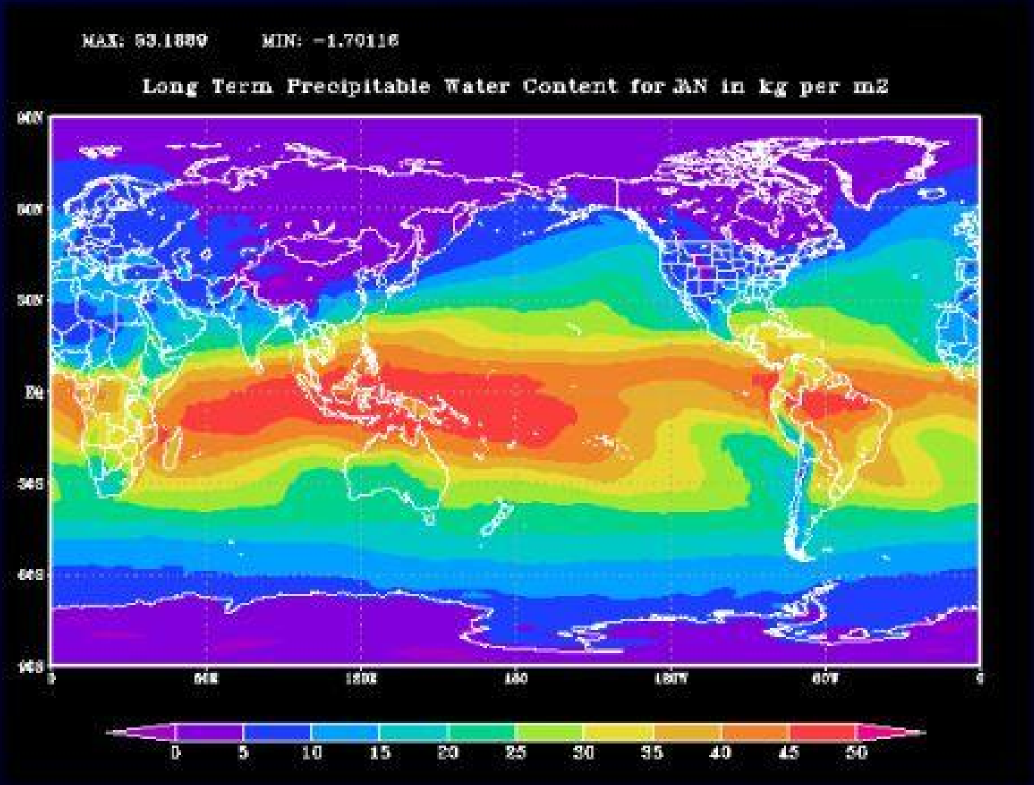
Adaptive Optics

	Today	2008	2015	2019
IR Deformable Mirrors	LBT (JWST)	Prototype	OWL 1st Gen.	2nd Gen.
Diameter	**1-m (2-m)**	**0.3-m**	**2-m**	**4-m**
Actuator spacing	**30 mm**	**15 mm**	**10-15 mm**	**10 mm**
XAO corrector				Moems/Pzt
Detector	256x256 ?		512x512	1kx1k
AO real time control			*Almost OK*	
Reference stars	NGS (LGS)		NGS	NGS / LGS

- High sky coverage in the near-IR (better filling of metapupil)
- LGS needed ~2018; lower number of LGS,
- Cone effect requires novel approaches e.g. PIGS (Ragazzoni et al)

Site characterization

NCEP / NCAR PRECIPITABLE WATER CONTENT 1948-2001



FRIOWL, University of Fribourg

Cost estimate (capital investment)

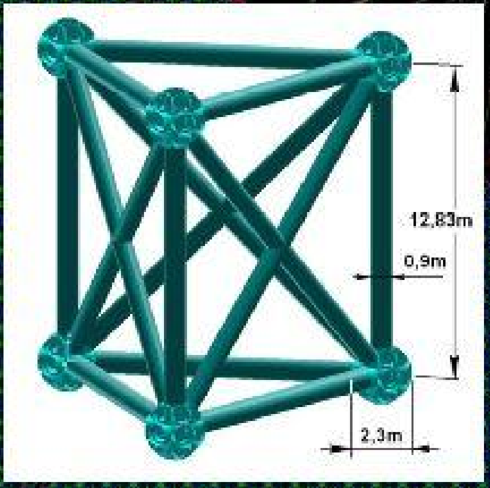
SUMMARY	MEuros	
OPTICS	**406**	
Primary & secondary mirror units		355.2
M3 unit		14.4
M4 unit		21.4
M5 temporary unit		5.3
M6 temporary unit		10.1
ADAPTIVE OPTICS	**110**	
M5/M6 design & prototypes		10
M6 AO unit		25
M5 AO unit		35
XAO units		20
LGS		20

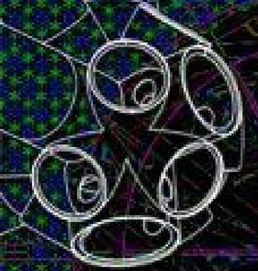
MECHANICS	**185**	
Azimuth		53.8
Elevation		34.9
Cable wraps		5.0
Azimuth bogies (incl. motors)		14.7
Altitude Bogies & bearings		5.7
Mirror shields		15.0
Adapters		6.0
Erection		50.0
CONTROL SYSTEMS (*)	**17**	
Telescope Control System		5.0
M1 Control System		8.0
M2 Control System		2.0
Active optics Control System		2.0
CIVIL WORKS	**170**	
Enclosure		40.4
Technical facilities		35.0
		25.0
		70.0
		50
		938.9
stems		

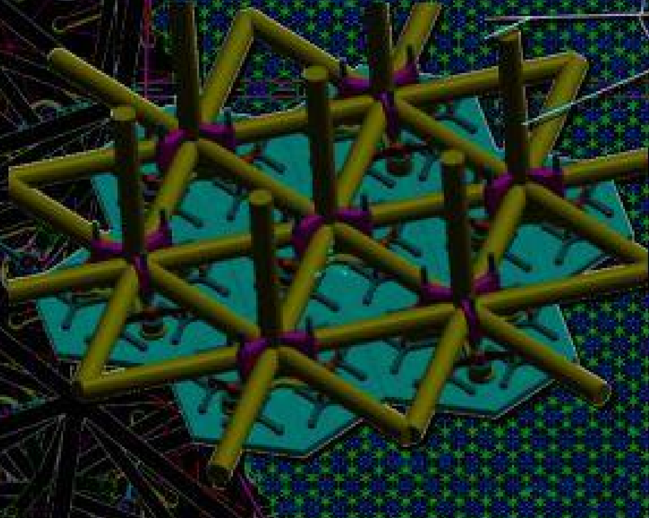
Total cost: 1.2 B€

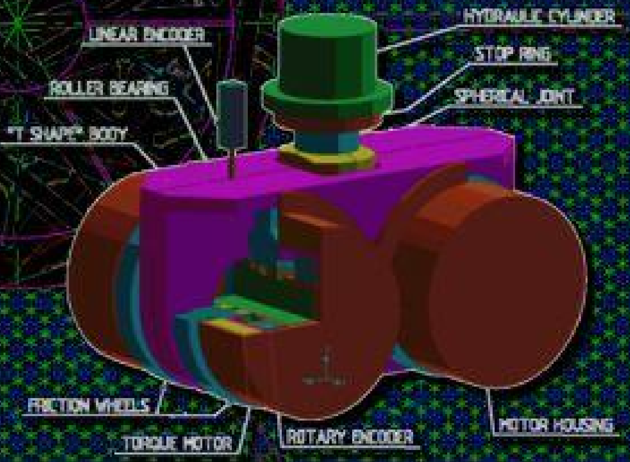
Including manpower and 16% contingency

- Optimized geometry (interface optics-mechanics)
- All parts fitting in 40-ft containers
- 1.6-m all-identical segments (~3000 units), single optical reference for polishing
- 12.8-m standard structural modules (integer multiple of segment size)
- Friction drive (bogies), hydraulic connection



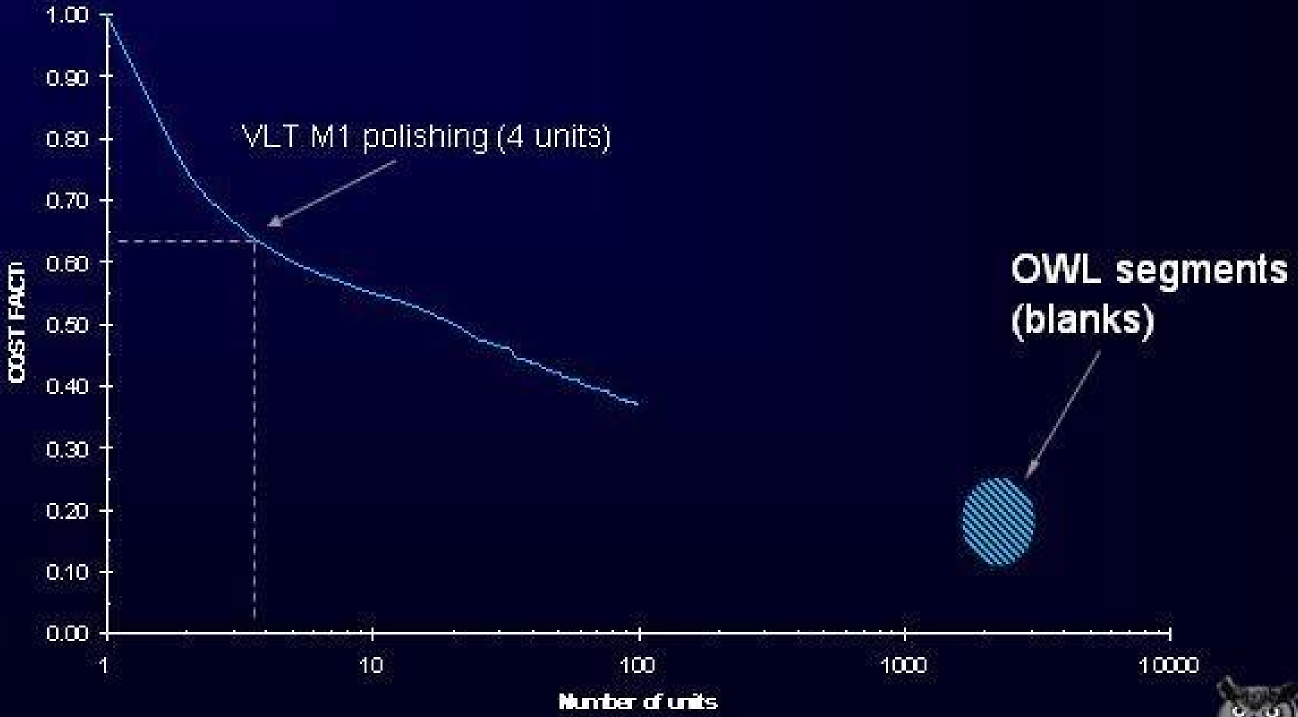






Cost vs quantity

Industrial data
Applies to conceptually simple items
(e.g. segments, structural nodes)



VLT M1 polishing (4 units)

OWL segments
(blanks)

International collaborations

- Pan-European technology development study submitted to FP6 (design independent)
  - ⇨ Foster industrial readiness to build an ELT
- AURA-ESO collaboration on key technology developments
  - ⇨ Segmented mirror fabrication
  - ⇨ Adaptive optics
  - ⇨ Instruments and detectors
  - ⇨ Site selection
  - ⇨ Science case
- Generally open exchange amongst all involved
  - ⇨ e.g. Europe, US, Canada, Japan, Australia, China, ….

Optical Fabrication

- Emphasis on substrates:
  - ⇨ Silicon Carbide for segments
    - Lighter, stiffer, cheaper ?
    - 4 blanks already in production (ESO contract)
    - Technology still uncertain for segmented apertures (bimetallic effects ?)
  - ⇨ Aluminium for large mirrors
    - 1.8-m mirrors produced under ESO contract in 1992
    - Verify their ageing
- Coatings (study + samples)

Critical issues

- Adaptive Optics
  - Necessary to remove the effects of atmospheric turbulence in order to achieve the *diffraction limit*
    - Spatial resolution = 1.22 λ/D (D=100m would resolve 2m on the Moon)
- Detectors
  - Sampling at λ/D needs many pixels!
- Site evaluation
  - Site needs to be chosen before final design
- System engineering
  - Cannot be stressed enough
- New materials
  - For optics, mechanics etc

Critical issues cont'd - Cost

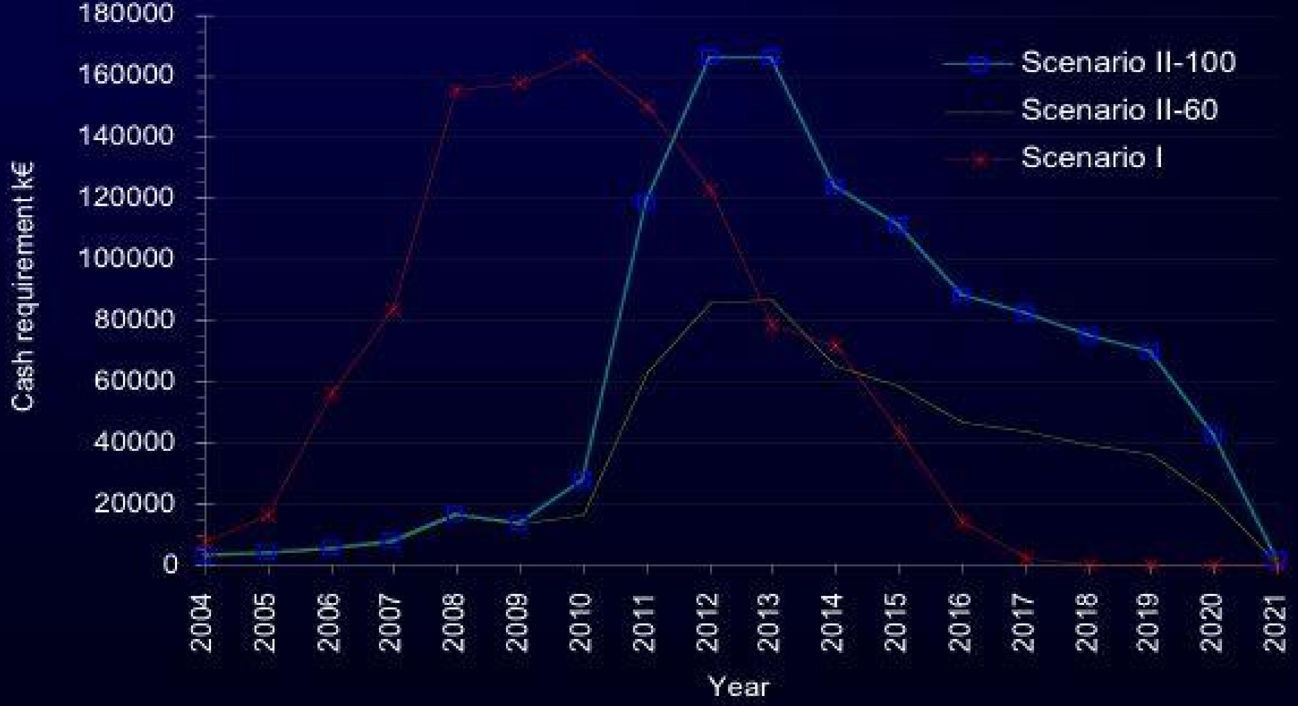
- Break the historical $D^{2.6}$ cost law
  - ⇨ Innovative designs
  - ⇨ Industrial involvement
    - * To determine early in the process what is feasible
  - ⇨ "New" concepts (e.g. serialized production)
    - * New to the art of telescope making, that is
  - ⇨ "Built-in" maintenance concepts
    - * Running a facility with a goal of ~3% of capital per year
- Constrain budget to a "reasonable" total
  - ⇨ e.g. $\text{cost}_{OWL,100m} < \text{cost}_{JWST,6m} < \text{cost}_{HST,2.4m}$
- Make design scalable where possible

OWL's design philosophy

- Science requirements drive size
  - Exoearths
  - Virgo or bust
  - Cosmology
- R&D only where necessary: use proven solutions
- Mass production of identical elements
  - Primary & secondary mirrors
  - Mechanics
  - Supports
- Involved Industry from the start
- Grow a telescope (and AO!)
  - Science capable before reaching full size

Possible scenarii

Scenario	Telescope diameter	Phase B starts	Phase C/D starts	Start of science (partially filled)	Full completion
I	100-m	2004	2006	2012 (50-m dia.)	2016
II-100	100-m	2006	2010	2017 (60-m dia.)	2021
II-60	60-m	2006	2010	2016 (40-m dia.)	2020



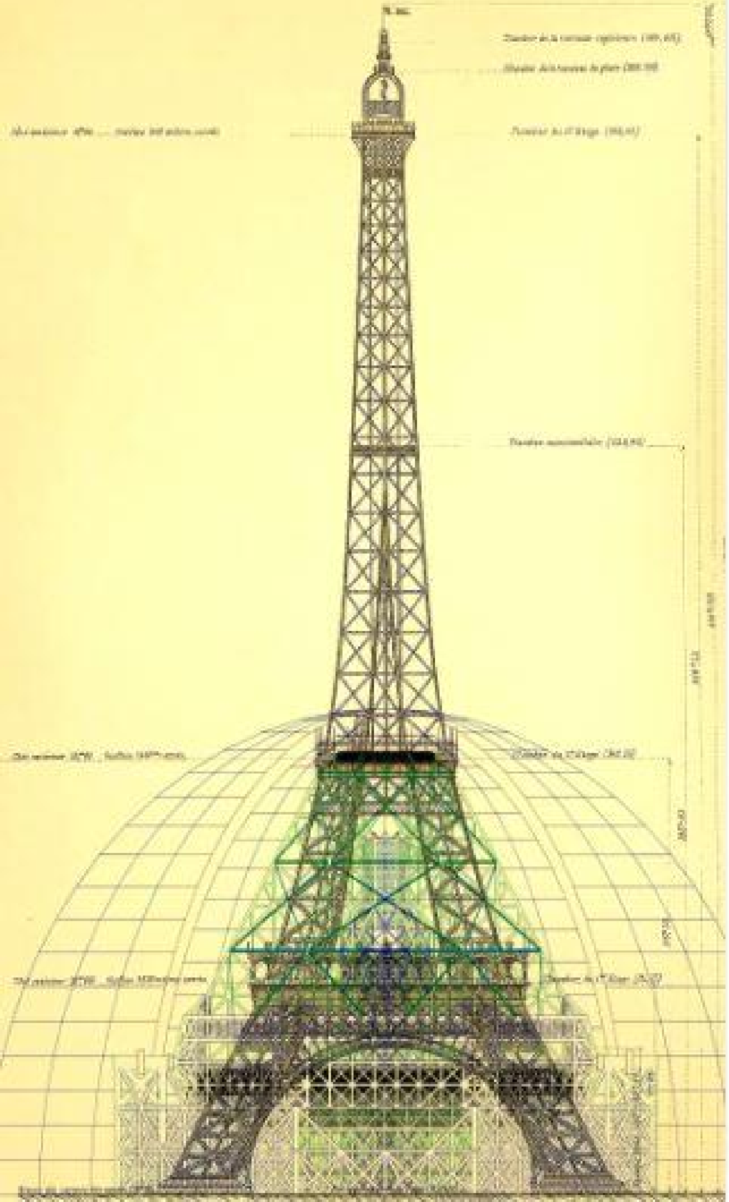
Schedule estimate

Grow-a-telescope - Main optics no longer on critical path

- Critical path: structure & enclosure; can be sped up:
  - Standard parts ⇨ multiple supply & integration lines possible.
  - Large scale, structure as its own scaffolding.
  - 4-5 years from start of contract possible; could be sped up.
    (Eiffel tower: 26 months; SIAT Zeppelin enclosure: 18 months)
- Sub-critical path: M3 & M4 mirrors (8-m): ~4 years, incompressible
- After first light & commissioning:
  - routine segment integration;
  - significant time for science once all functions have been commissioned

Gradual implementation (5.5 years, conservative)

First light (T_0)	provisional, low cost M5 & M6 units ⇨ 50-m seeing limited, engineering time, telescope commissioning;	
T_0+16 months	Integrate adaptive M6 (2m) ⇨ IR AO	**60-m science**
T_0+32 months	Integrate adaptive M5 (3.5m) ⇨ IR MCAO	**80-m science**
T_0+66 months	Integrate X-AO	**100-m science**



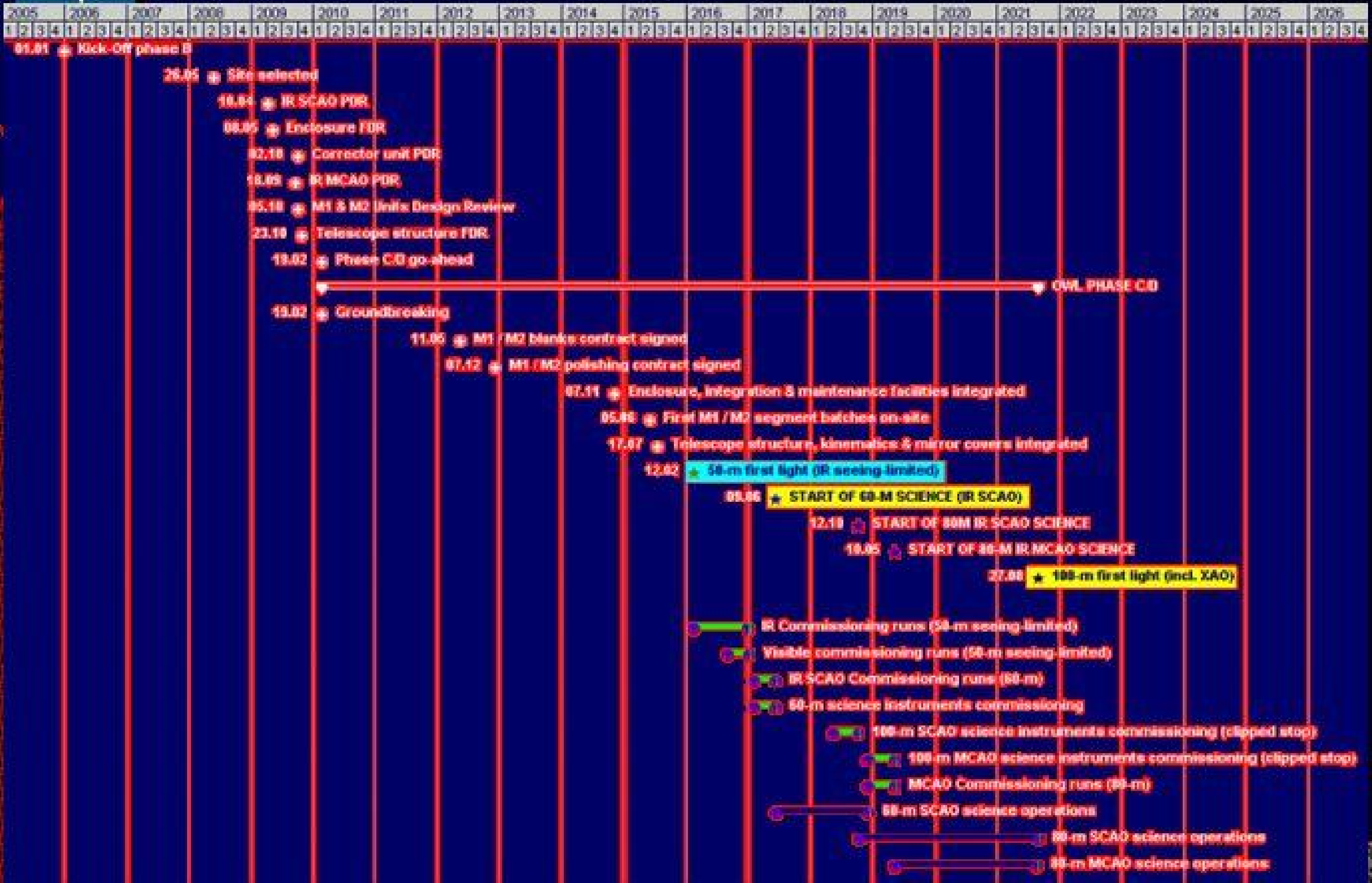
mai 1888

juillet 1888

septembre 1888

mai 1889

Schedule estimate



01.01 Kick-Off phase B

26.05 Site selected

10.04 IR SCAO PDR

08.05 Enclosure FDR

02.10 Corrector unit PDR

18.09 IR MCAO PDR

05.10 M1 & M2 Units Design Review

23.10 Telescope structure FDR

19.02 Phase C/D go-ahead

OWL PHASE C/D

19.02 Groundbreaking

11.06 M1 / M2 blanks contract signed

07.12 M1 / M2 polishing contract signed

07.11 Enclosure, integration & maintenance facilities integrated

05.08 First M1 / M2 segment batches on-site

17.07 Telescope structure, kinematics & mirror covers integrated

12.02 ★ 50-m first light (IR seeing-limited)

05.06 ★ START OF 60-M SCIENCE (IR SCAO)

12.10 ☆ START OF 80M IR SCAO SCIENCE

10.05 ☆ START OF 80-M IR MCAO SCIENCE

27.08 ★ 100-m first light (incl. XAO)

IR Commissioning runs (50-m seeing-limited)

Visible commissioning runs (50-m seeing-limited)

IR SCAO Commissioning runs (60-m)

60-m science instruments commissioning

100-m SCAO science instruments commissioning (clipped stop)

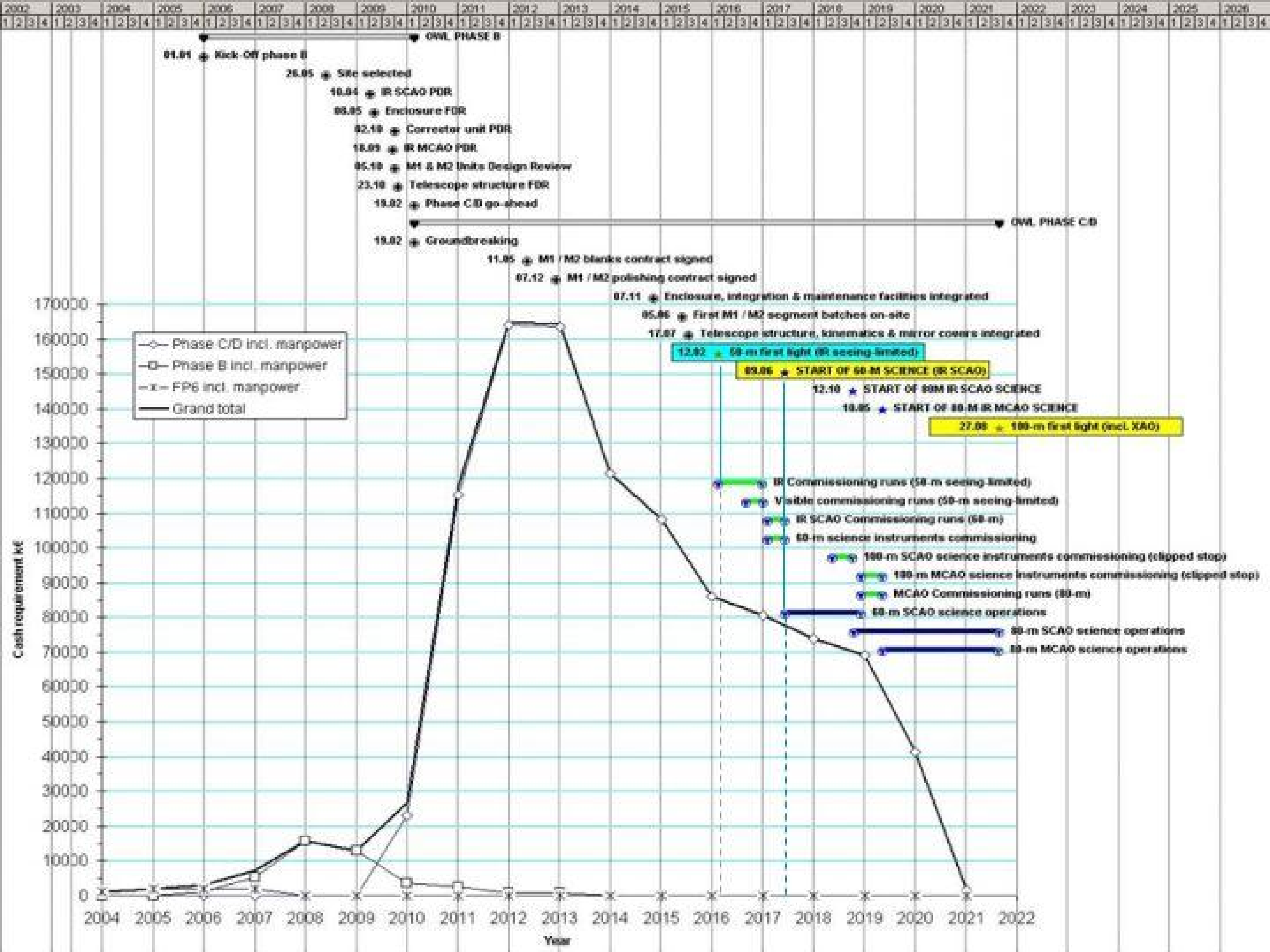
100-m MCAO science instruments commissioning (clipped stop)

MCAO Commissioning runs (80-m)

60-m SCAO science operations

80-m SCAO science operations

80-m MCAO science operations


2002
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1 2 3 4
OWL PHASE B
01.01 Kick-Off phase B
26.05 Site selected
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IR Commissioning runs (60-m seeing-limited)
Visible commissioning runs (60-m seeing-limited)
IR SCAO Commissioning runs (60-m)
60-m science instruments commissioning
100-m SCAO science instruments commissioning (clipped stop)
100-m MCAO science instruments commissioning (clipped stop)
MCAO Commissioning runs (80-m)
60-m SCAO science operations
80-m SCAO science operations
80-m MCAO science operations
Phase C/D incl. manpower
Phase B incl. manpower
FP6 incl. manpower
Grand total
Cash requirement k€
170000
160000
150000
140000
130000
120000
110000
100000
90000
80000
70000
60000
50000
40000
30000
20000
10000
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2004
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2014
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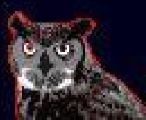
2018
2019
2020
2021
2022
Year

Challenges

- Financing
  - 940 M€ over 15 years
- Science case
  - The ideas of today need to advance to the telescope of tomorrow. Unprecedented potential for new discoveries
- Multi-Conjugated adaptive optics (*go / no go* milestone)
  - MCAO with thousands of degrees of freedom
  - Some OWL advantages over the 30/50-m class telescopes.
    - No strong dependence on laser guide stars. Field of view advantage of OWL's design over classical telescope design
  - MCAO demonstrator on VLT (first light 2004)
    - Will give us the first heads-up on how much of the 110 M€ AO-budget line is needed.

The industries that built VLT do not see show stoppers for OWL.



Challenges: Adaptive Optics

- Toughest challenge
- Gradual implementation
- Technology closer than anticipated for the first stage of deployment
- Ample R&D time in plan
- Sky coverage
  - ⇨ Much larger thanks to diameter (& optical design!)
  - ⇨ No dependence on LGSs for IR
  - ⇨ (For exo-earths sky coverage is 100%!)

OWL status

- Phase A well under way
  - Feasibility of optomecanics demonstrated
  - Science case being consolidated with community
  - Detailed design/fabrication/integration plans available
- Substantial science capability before completion
  - Progressive implementation of AO
    - 60-m with IR AO in 2017, 80-m with MCAO in 2019
  - With Extreme Adaptive Optics: 1 mas at V=37-38
- OWL's design approach:
  - Optics and mechanics mass produced
    - at "reasonable" cost ($\approx 2 \times$ VLT) – less than space experiments
  - Cost law $\propto D^{1.3}$ for 60m < D < 130m (classical law: $D^{2.6}$)
- Feedback from Industry
  - They want to be part of this.
  - They think we can go faster.

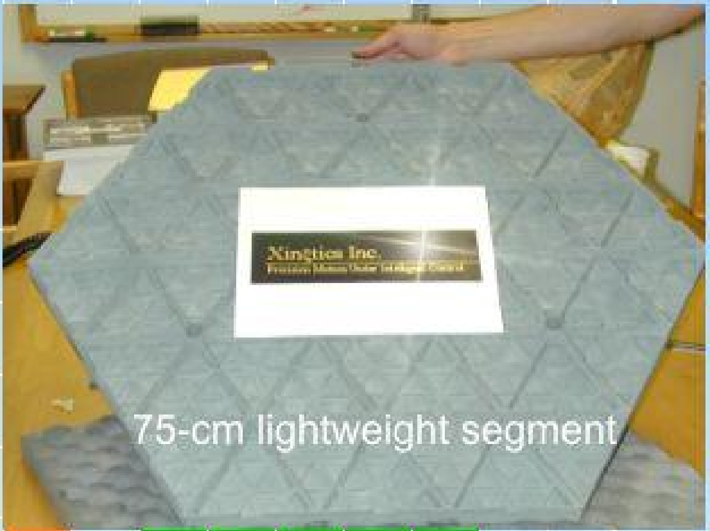
First operation support astronomers recruited

[(if time) OTHER PROJECTS]

Required Technology Developments:
Telescope & Optics

🟩 Required Development

🟧 Possibly Required



75-cm lightweight segment

Lightweight 1-m to 2-m segments									
Large numbers of aspheric segments									
Fab & test of large aspheric segments									
Active/adaptive structure									
Fab & testing of large, convex M2s	🟧		🟩	🟩	🟩	🟩	🟩		
High-reflectivity durable coatings	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Efficient segment co-phasing systems	🟩				🟩	🟩	🟩	🟩	🟩
Large, fast tip-tilt-piston mirrors			🟧			🟩	🟩	🟧	🟩

Required Technology Developments:

Telescope & Optics

🟩 Required Development

🟧 Possibly Required

	LAT	M20	HDRT	LPT	VLOT	CELT	GSMT	E50	OWL
Lightweight 1-m to 2-m segments	🟩				🟩	🟩	🟩	🟩	🟩
Large numbers of aspheric segments	🟩				🟩	🟩	🟩	🟩	
Fab & test of large aspheric segments		🟩	🟩	🟩					
Active/adaptive structure	🟩	🟧	🟩	🟩	🟧	🟩	🟩	🟩	🟩
Fab & testing of large, convex M2s	🟧		🟩	🟩	🟩	🟩	🟩		
High-reflectivity durable coatings	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Efficient segment co-phasing systems	🟩				🟩	🟩	🟩	🟩	🟩
Large, fast tip-tilt-piston mirrors			🟧			🟩	🟩	🟧	🟩

Required Technology Developments:
Adaptive Optics

🟩 Required Development

🟧 Possibly Required

	LAT	M20	HDRT	LPT	VLOT	CELT	GSMT	E50	OWL
Improved analysis & simulation	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Large adaptive mirrors	🟩	🟩			🟧	🟧	🟩	🟩	🟩
MOEMS deformable mirrors for EXAO	🟧	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
MCAO system designs	🟩	🟩	🟧	🟩	🟧	🟩	🟩	🟩	🟩
Laser guidestar beacons	🟩	🟩	🟧	🟧	🟩	🟩	🟩	🟩	🟧
Large-format, fast, low noise detectors	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Wavefront rec. & fast signal processors	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Site testing of C_N^2 distribution	🟩	🟩	🟧	🟧	🟧	🟩	🟩	🟧	🟩

Required Technology Developments:
Instruments

- Affordable large near-IR detectors
- Affordable large mid-IR detectors
- Advanced image slicers for IFUs
- Fiber positioners
- MOEMS slit masks for multi-object spectroscopy
- Large-format volume-phase holographic gratings
- Large-format immersed silicon gratings
- Large lenses & filters

Conclusions (actually, questions)

- **A bolometric view of the Universe seems to be the integrated outcome (goal?) of future projects.**
  - Should we try to plan synergies in advance?
- **AO brings "cheap" λ/D in ground optical, NIR**
  - Should we consider *only* the ground for these $\lambda\lambda$?

controversial question…

- **All 2010-2020 instruments want to find planets**
  - Is there a "best approach"?
- **A ground 70m+ could find exo-earths**
  - Should we invest now to have one asap?
  - Should it be alternative or complementary to space?
  - Could we accelerate the follow up missions (e.g. TPI)?
- **Giant Optical Devices* designs**
  - Should we converge to a collaborative unified effort?

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