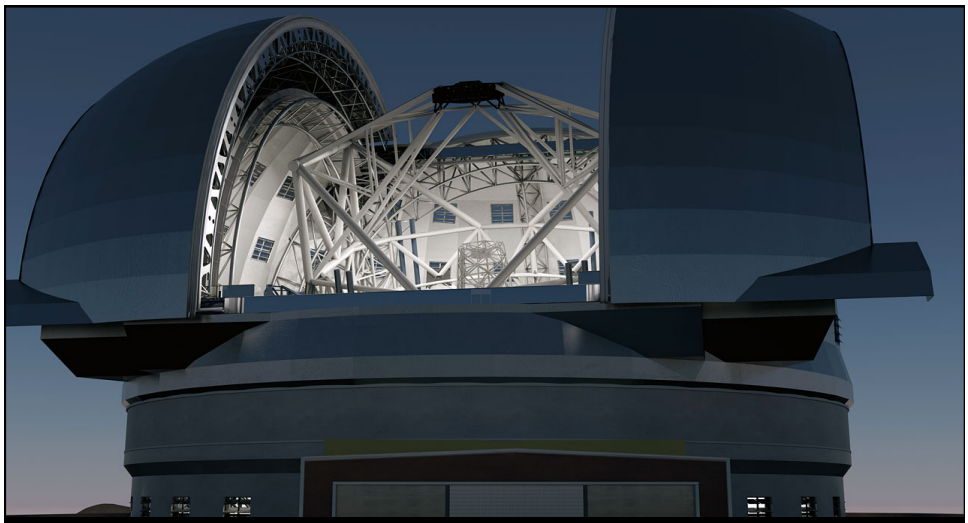


RISE OF A GIANT

The European Extremely Large Telescope

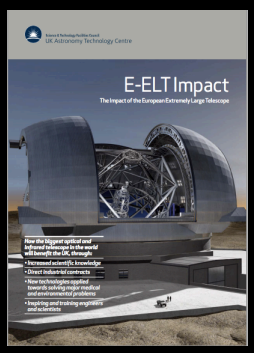
Aprajita Verma
University of Oxford

With thanks to the UK E-ELT Project Team, Adrian Russell (ESO), Joe Liske (ESO)

Big Telescopes, Big Science, Big Questions

Astronomy is still in a state of exploration

Its advance is sometimes limited by current technology, but it also drives new technologies (e.g. WIFI)



By Prof Colin Cunningham & the UK E-ELT team
http://www.roe.ac.uk/elt/E-ELT_Impact.pdf

New large telescopes lead to new & fundamental discoveries

Innovative science, technology, computing & engineering

Inspires & trains next generation of scientists & engineers

The World's Largest Eye on the Sky

A 39.3m diameter, adaptive telescope

0.3-14 μm, 10' diff limited FoV

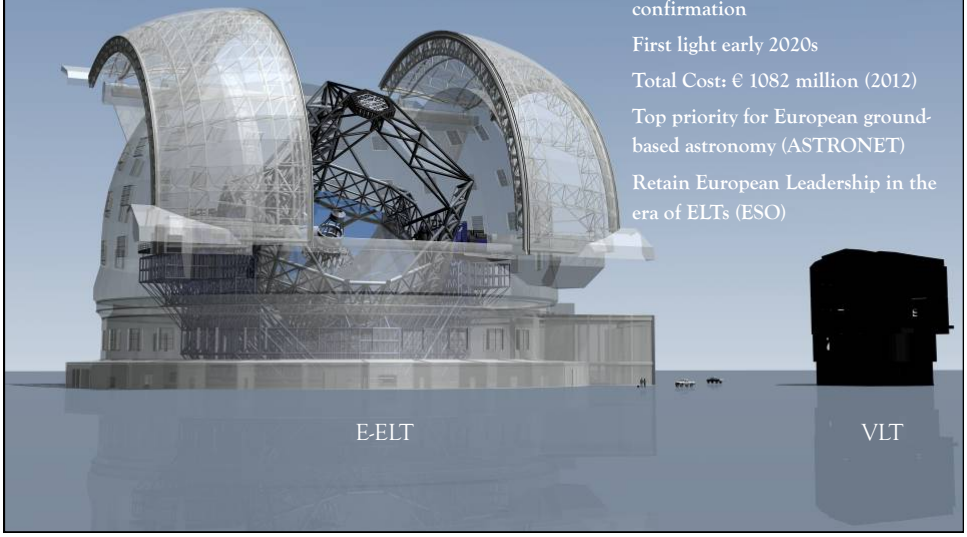
Approval June 2012, subject to confirmation

First light early 2020s

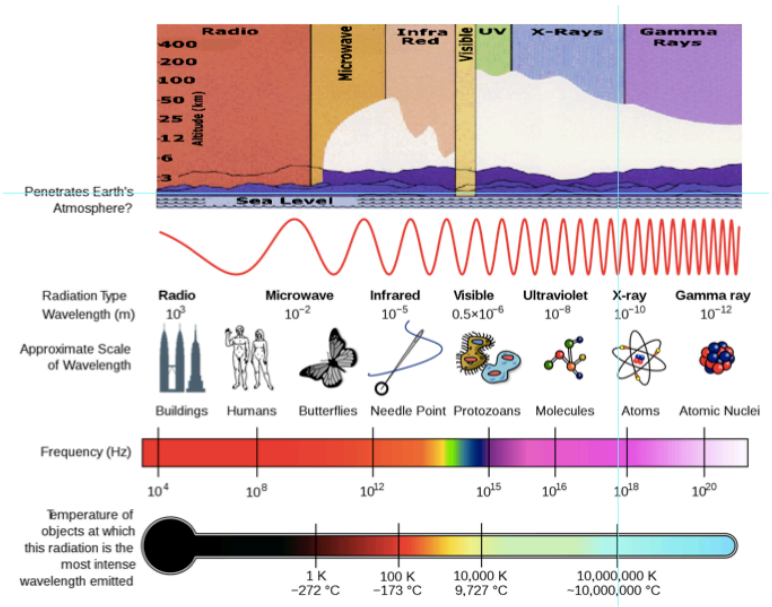
Total Cost: € 1082 million (2012)

Top priority for European ground-based astronomy (ASTRONET)

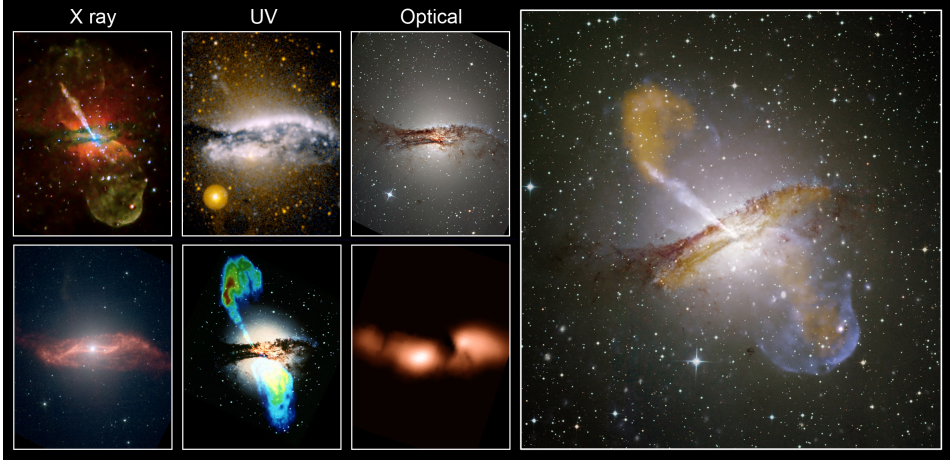
Retain European Leadership in the era of ELTs (ESO)



Multiwavelength Astronomy



Multiwavelength Astronomy



Centaurus A

Synergies with major facilities

Synergies across most areas of astronomy

sensitivity

matching high angular resolutions:

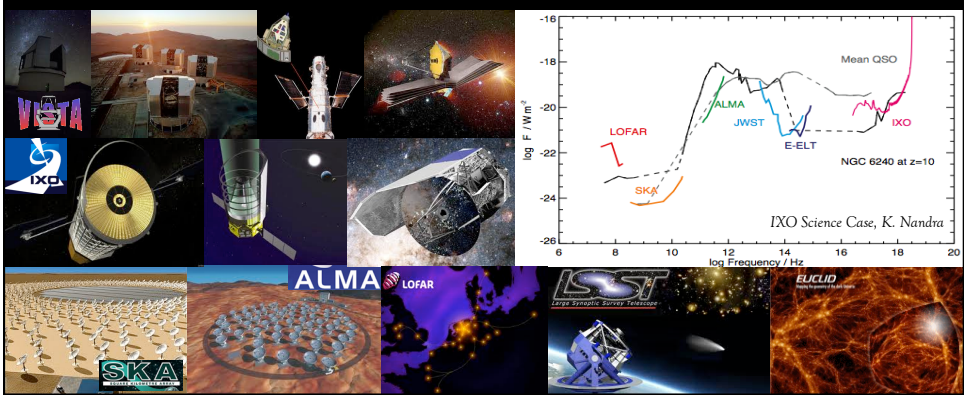
different wavelengths and spectral resolutions (e.g. ALMA)

matching wavelengths:

different angular and/or spectral resolutions (e.g. JWST)

Spectroscopic and high angular resolution follow-up of sources discovered with current 4m-10m telescopes

Opt/NIR telescopes (VLT, Keck, VISTA, PANSTARRS, LSST), HST, Herschel, LOFAR, GAIA, JWST



Telescopic Astronomy: The beginning

1609: birth of modern astronomy

Based on **Lipperhay's magnifying "spy-glass"** 1608

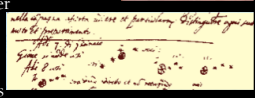
Galileo Galilei supporter Copernican Theory built his own version & turned towards the sky 1609

Excellent lenses achieved 20x magnifications

What did he see?

- Moon – craters & prominences

- Moons of Jupiter



- Phases of Venus

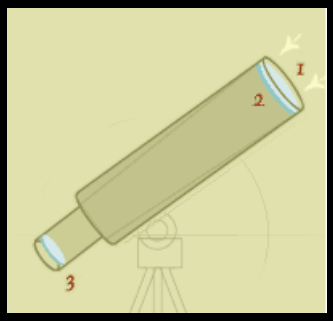
- "Ears" of Saturn

- Sunspots

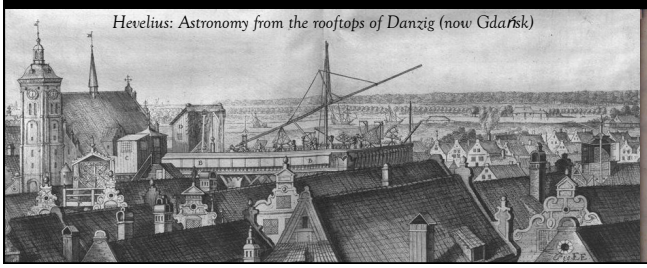
First Giant Telescope!

- Inspirational discoveries based on refracting design
- 1611 **Johannes Kepler** improved design by using convex lens near eye, greater field of view
- **Johannes Hevelius** b. *1611 (Brewer, Councillor, Mayor, telescope & instrument designer!)*
  - 10 new constellations
  - - 3 rooftop telescope
  - 45m telescope 1673
- **Cassini** identified 2 Saturn's moons with large refractors
- **Huygens** 200ft (61m) refractor

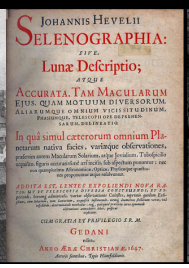
Giant but tricky!



Credit: © WGBH Educational Foundation



Hevelius: Astronomy from the rooftops of Danzig (now Gdańsk)

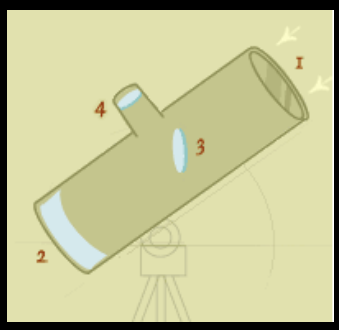


If I have seen further, it is by standing upon the shoulders of Giants

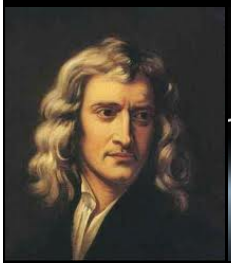
Sir Isaac Newton, in a letter to Robert Hooke, 1675

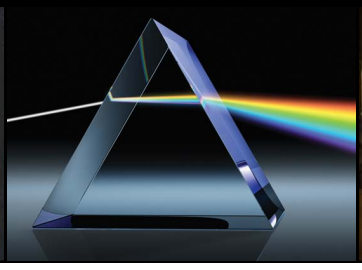
- Cumbersome design and chromatic aberrations overcome by Isaac Newton's reflective telescope design using concave primary mirror + flat secondary mirror
- 1663: James Gregory discusses the reflecting telescope concept in Optica Promota
- 1668: First reflecting telescope made
- 1672: Cassegrain reflector, convex secondary

Modern Astronomy Born



Credit: © WGBH Educational Foundation

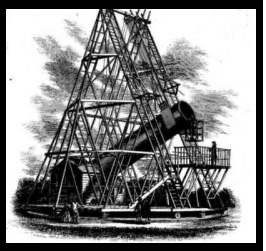




British 19th Century Large Telescopes & Innovators

Sir William Herschel

- Talented musician, astronomer & telescope builder (worked with brother Jakob & sister Caroline)
- Built 400 telescopes during his life
- First casting of large mirror (largest 1.26m primary)

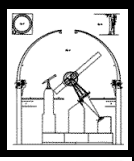


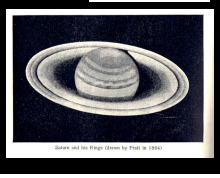
William Lassell

- 9" equatorial reflector was revolutionary (cast iron, roller bearings & precision engineered)
- Followed up by 20ft 24" telescope (Saturn below)
- Tracking: motivated by a desire to observe planets designed a 0.64m reflector discovering Triton, 17 days after Neptune's discovery (1854)
- First to optimise observing sites to atmospheric and dark sky conditions 24" and 48" (1.2m) telescopes in Malta

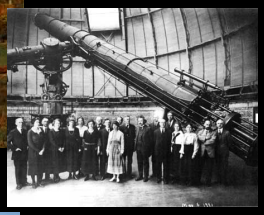
William Parsons, 3rd Earl of Rosse

- Leviathan of Parsonstown 1.83m, remained world's largest telescope until early 20th century (M51 sketch)

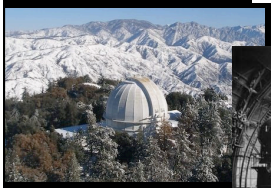


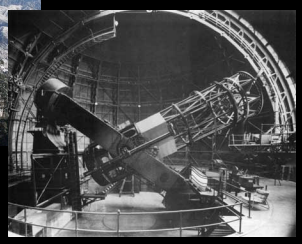


George Ellery Hale

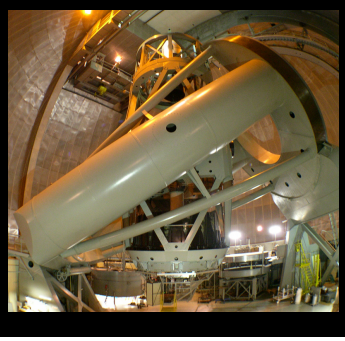


Yerkes Observatory
1895 largest refractor 40"



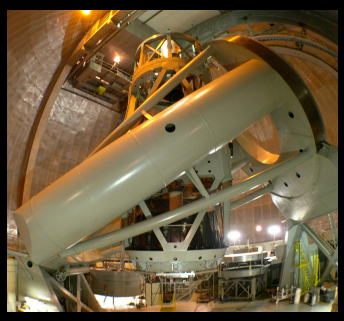


Mt Wilson
1917 100" reflector



Palomar
Observatory
1948 200"
reflector

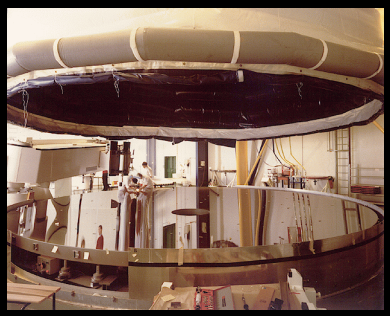
Heavy Glass Mirrors

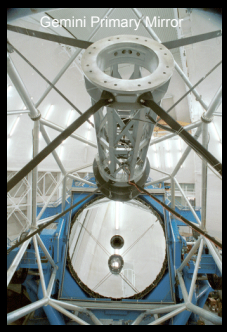


- Palomar Hale 5m mirror remained the largest for several decades
- Heavy, sturdy
- Mirror: 40 tonnes alone!
- Sturdy structural & precision engineering needed to make it move incredibly smoothly (*structure based on battleship engineering!*)

The next generation: Aluminized thin mirrors

- Solution thin layers of aluminium on toughened material that is relatively insensitive to temperature
- Light – manoeuvrable

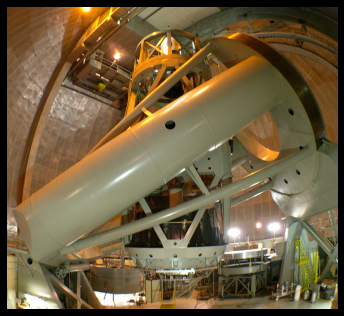




Bigger the better?

Why is mirror size important?

- Collect more light – like pupils dilating in the dark allow to harness more light
- Spatial resolution becomes finer as mirror diameter increases
  - ➢ A deeper, finer view of the Universe
- Spatial resolution becomes coarser with wavelength e.g. radio telescope need larger diameters to resolve fine scales
- Surface alignment 10% wavelength (λ)
  - Technologically challenging
  - Why we've hard large radio telescopes longer than optical ones



An exercise in precision!

VLT mirror

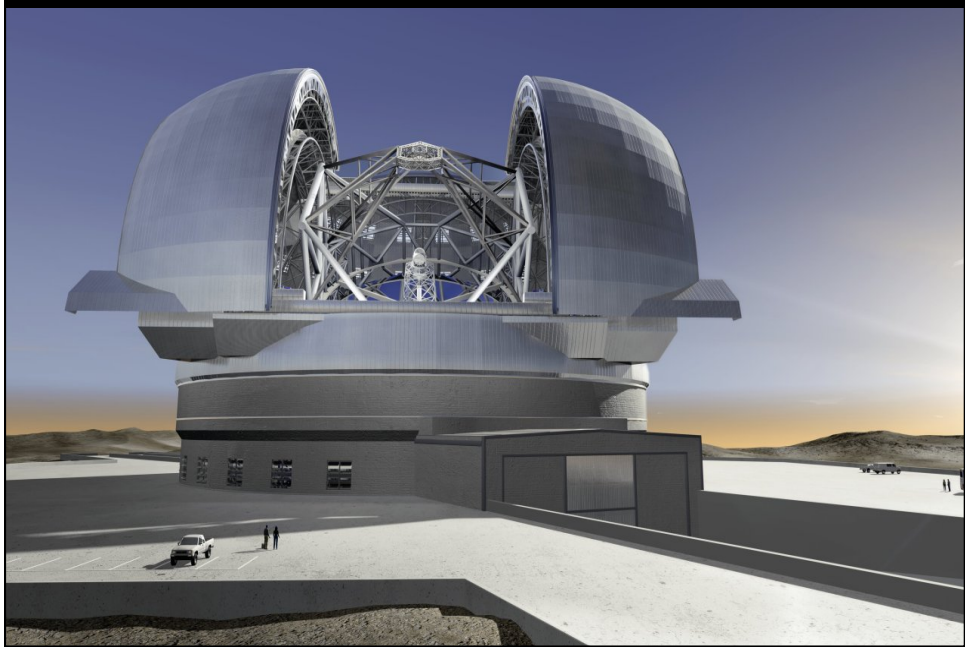
Diameter: 8.2m

Precision of the mirror surface: 0.00005mm

Like a few cm ripples …

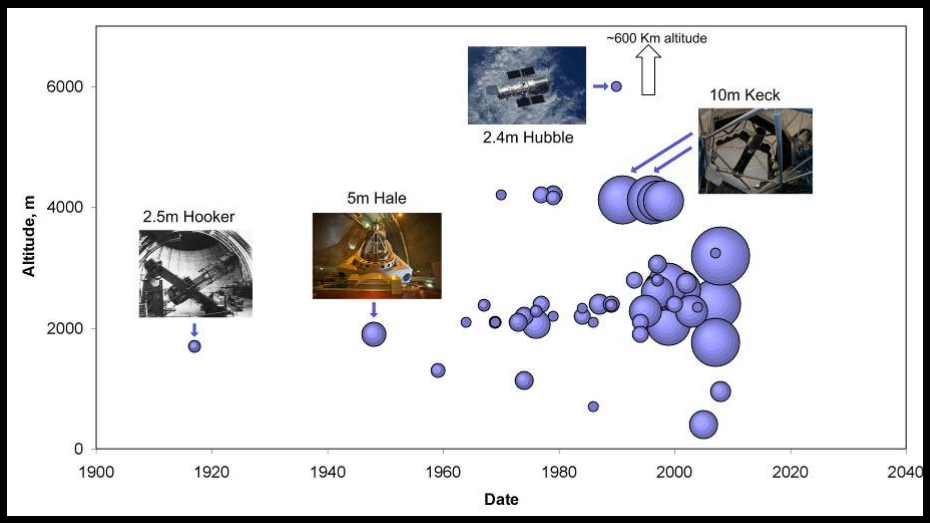
… on the Atlantic ocean!

The E-ELT



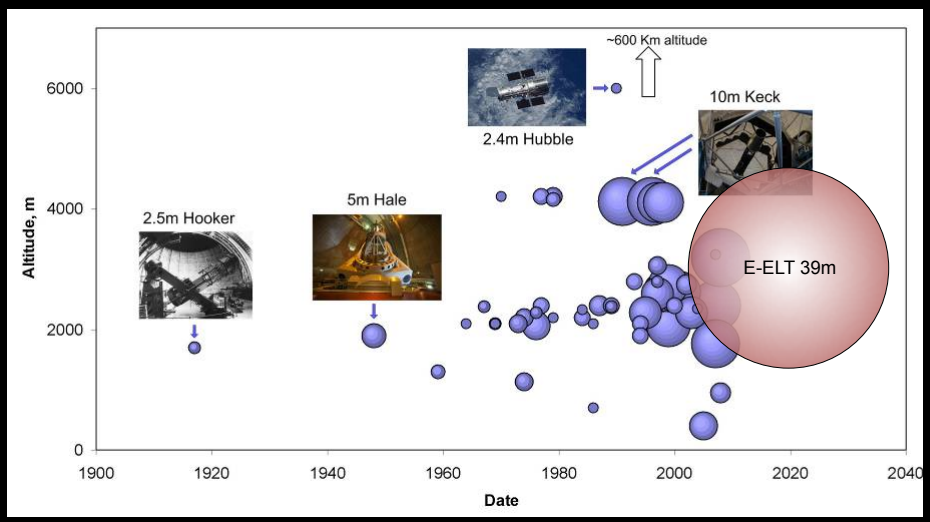
Telescope Mirror Size Progression

2m and more



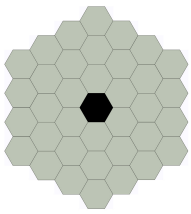
Telescope Mirror Size Progression

2m and more



Making Large Mirrors

- Largest mirror that can be manufactured and polished to the required precision is ~8m in diameter
- How do you build a mirror of 40m?

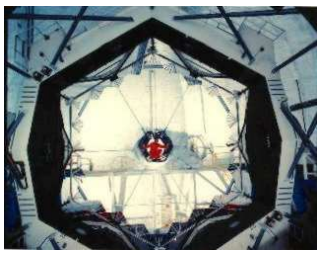


Keck 10 meter

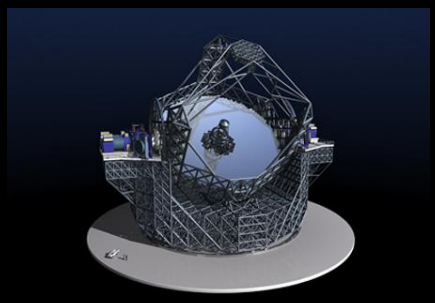
Guido Horn d'Arturo at Bologna Observatory

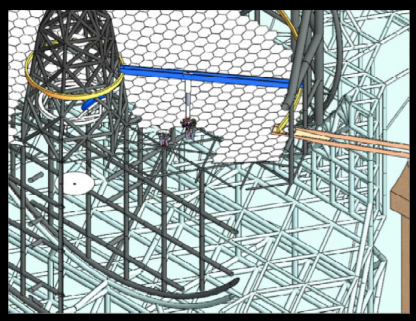
Built between 1935-52

61 segments to form 1.8m diameter mirror

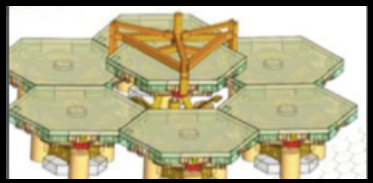


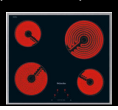
The E-ELT 39.3m primary mirror



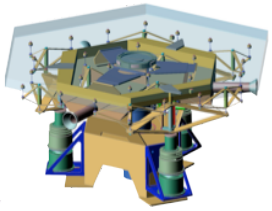


- 798 segments + 133 spares (1/family)
- Hexagonal in shape, 1.4m across
- 1-3 segments will be removed each day for cleaning & recoating
- Low thermal expansion glass (Zerodur) – used in ceramic hob!

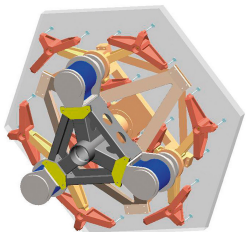


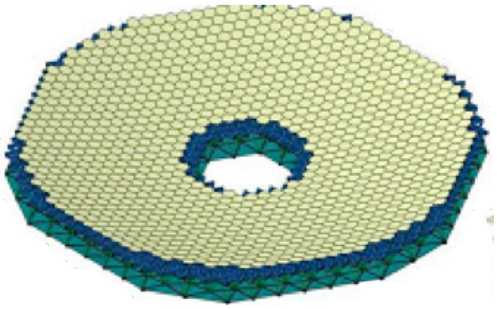


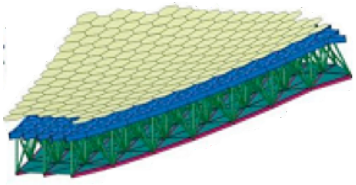
Primary Mirror



- Real-time software, electronics and mechanics
- Maintain the shape and position of the telescope mirrors
- Compensate for changing gravity as telescope moves around the sky
- Compensates for wind shake on the telescope structure







- Partial correction of image wander induced by atmospheric turbulence
- Produces excellent image quality at infrared wavelengths

E-ELT Revised Baseline Design

3-mirror anastigmat
+2 fold mirrors
39m primary
5000 tonnes
Fully adaptive
Diff. lim. over full 10' FoV

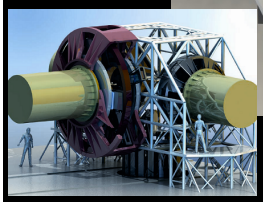
M2: 4.1m convex

M4: 2.5m flat **adaptive** mirror 5790 actuators

M5: 2,6x2.1m flat tip/tilt field-stabilisation mirror

Nasmyth Instrument platforms (size of tennis courts)

Lasers (6)

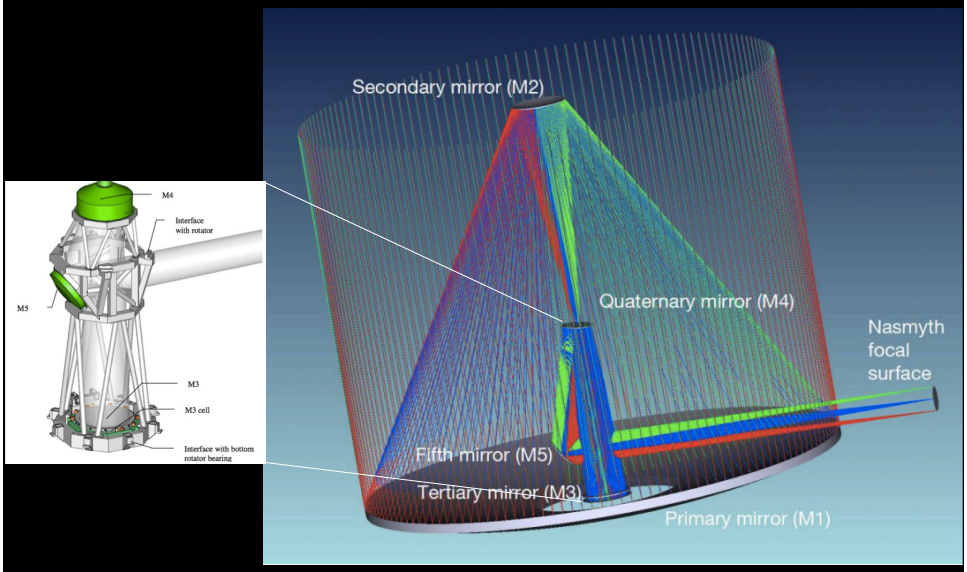


Coudé focus

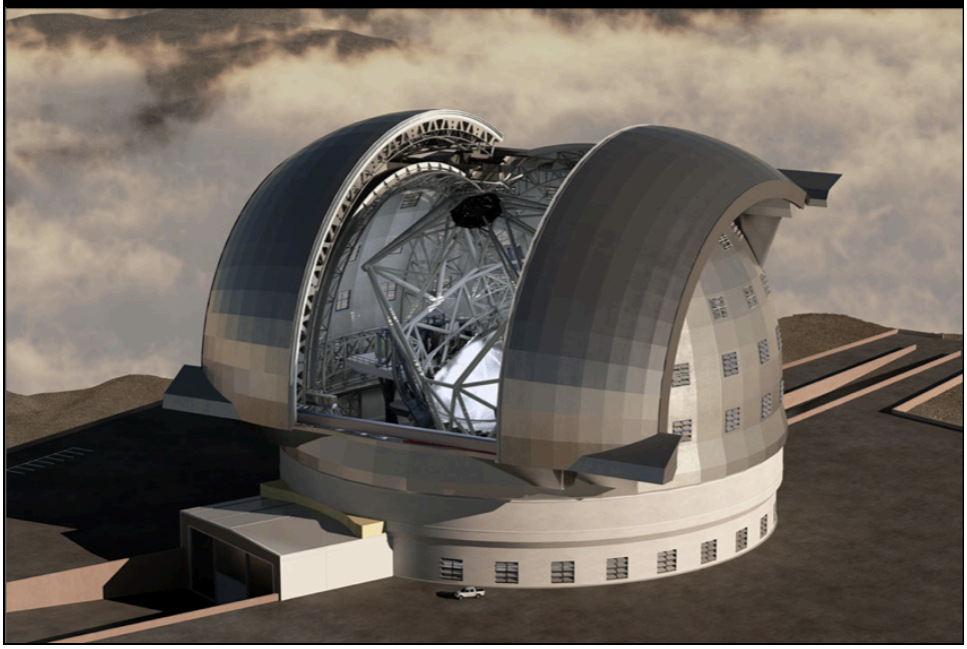
M3: 3.75m Controls f ratio

M1: 39.3m f/0.88 aspheric 11m obstruction 798 segments

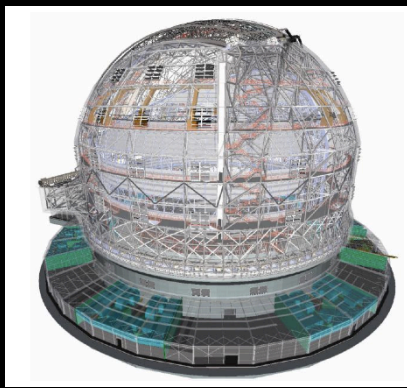
5-mirror design



The Dome

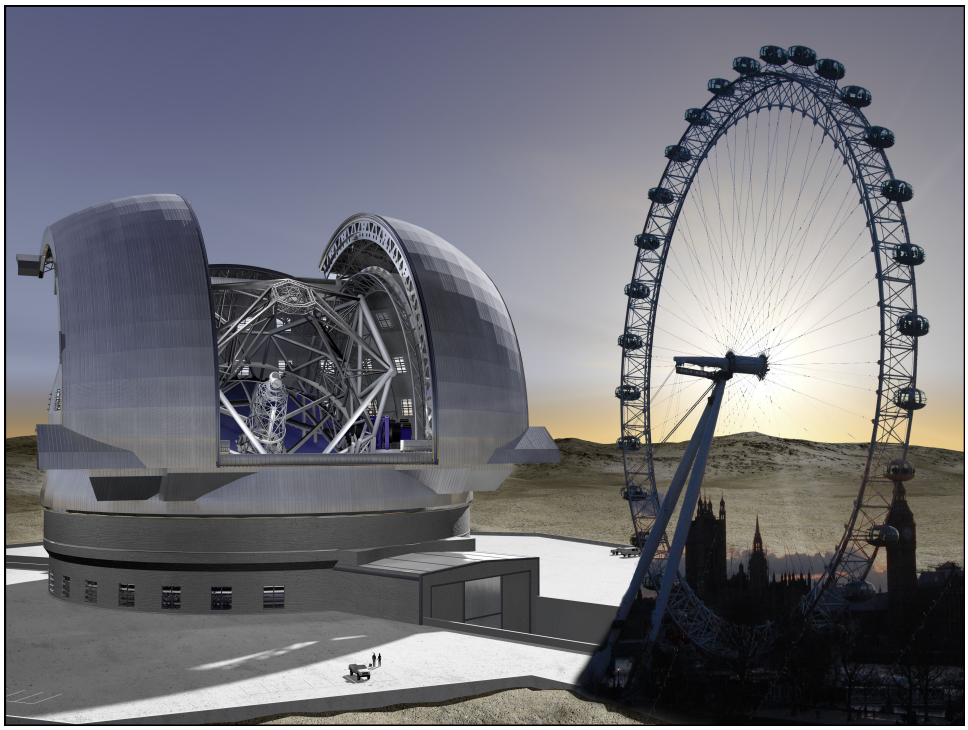


The Dome



- Two dome design studies were carried out, both choosing spherical design
- The E-ELT dome: base of 84m diameter, and 74m high
  - The size of a football stadium

- Fully air-conditioned and wind shielded
- Equipped with several heavy duty cranes and a lifting platform for instruments



Looking for a Site

The Site(s)

Other International ELTs

Thirty Meter Telescope

30m telescope

U. California (10), Caltech, Canada Japan, China, India ($100M)

Construction proposal complete

NSF partnership sought

www.tmt.org

Giant Magellan Telescope

24m diameter (7x 8m segments)

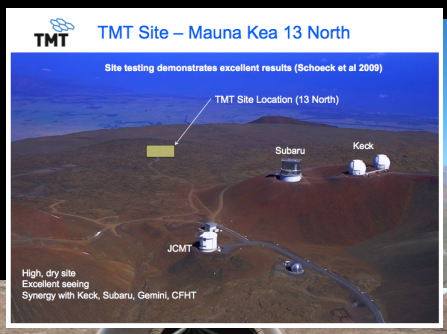
Collaboration of private US universities, Australia (ANU + AAL) + Korea

First mirror polished, 2nd mirror cast

Site blasted (Mar 2012) & levelling

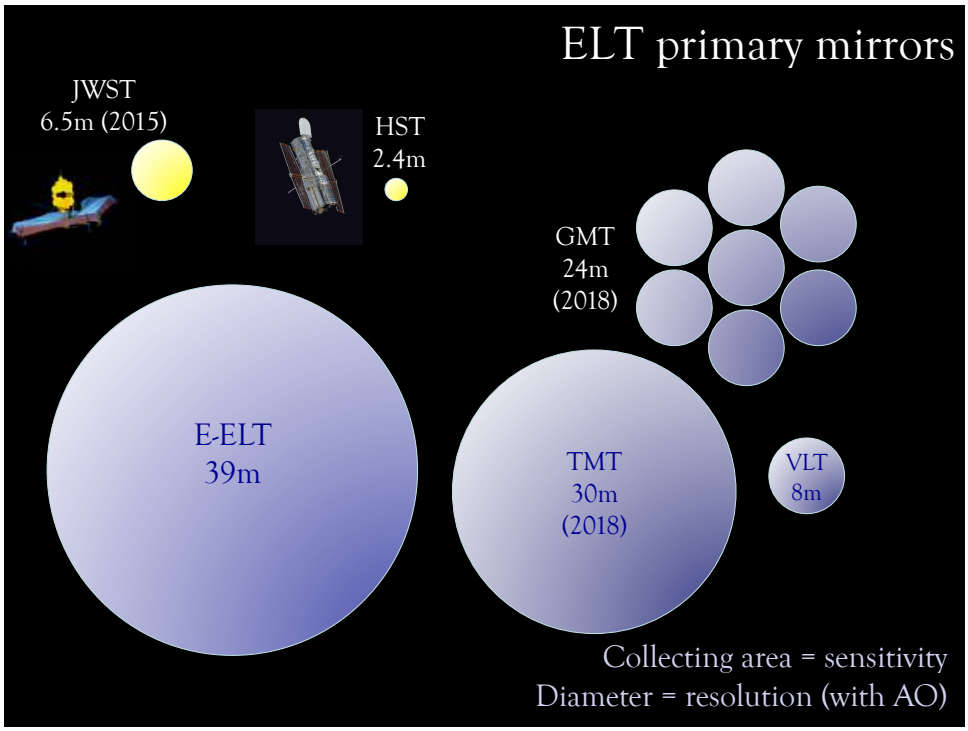
www.gmto.org

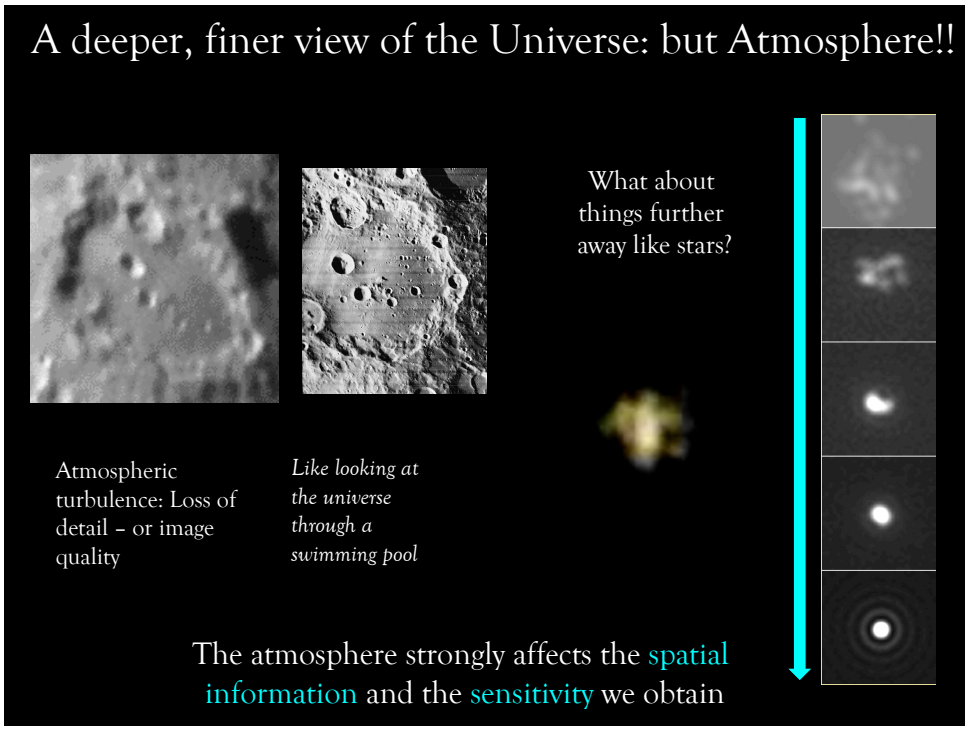
Other International ELTs



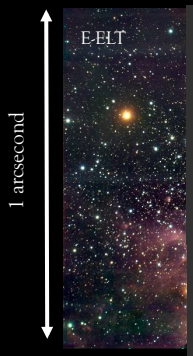
Mauna Kea, Hawaii

Las Campanas, Chile


ELT primary mirrors
JWST
6.5m (2015)
HST
2.4m
GMT
24m
(2018)
E-ELT
39m
TMT
30m
(2018)
VLT
8m
Collecting area = sensitivity
Diameter = resolution (with AO)


A deeper, finer view of the Universe: but Atmosphere!!
What about things further away like stars?
Atmospheric turbulence: Loss of detail – or image quality
Like looking at the universe through a swimming pool
The atmosphere strongly affects the spatial information and the sensitivity we obtain

High quality images from the ground



E-ELT excels in **collecting power** *and* **angular resolution**

39.3m telescope with **Adaptive Optics** will deliver

4.9× better angular resolution (1/D)

510× faster exposure time ($1/D^4$)

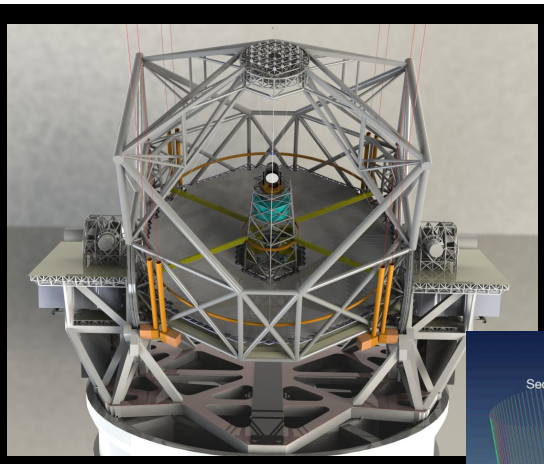
than existing 8m telescopes

Unprecedented sensitivity and angular resolution

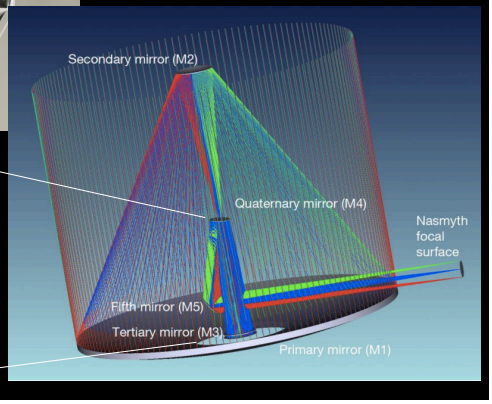
Prepare for the unexpected...!!

Large gain in sensitivity by building an
Extremely Large Telescope with good Adaptive Optics

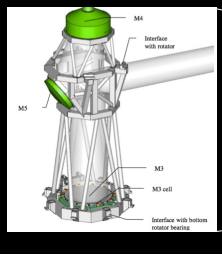
5-mirror design



Laser Guide
star launch
telescopes



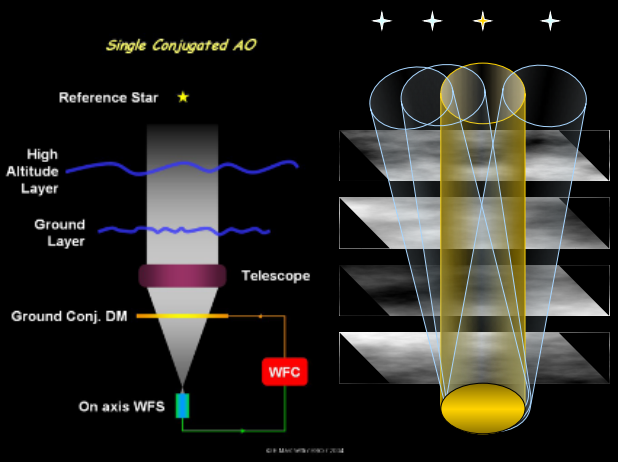
Deformable
mirror with
6000
actuators



Limitations of Basic Astronomical AO

Limited Corrected Field of View

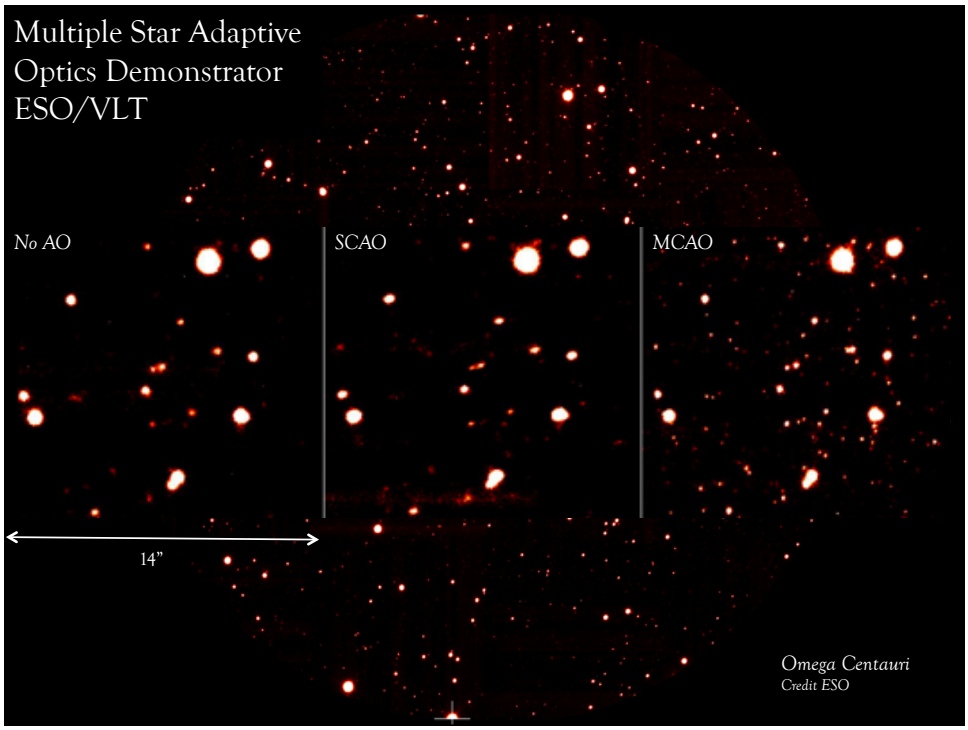
A single deformable mirror can only fully correct turbulence along one line of sight

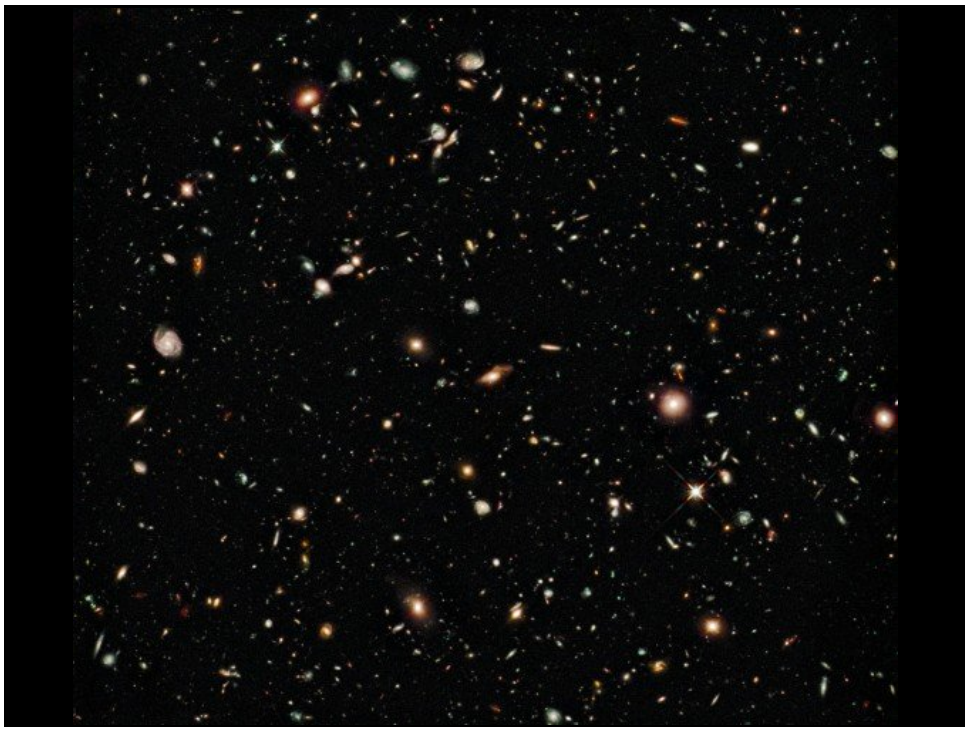


Solution: use multiple deformable mirrors

- Multi Conjugate AO
- Multi Object AO

37



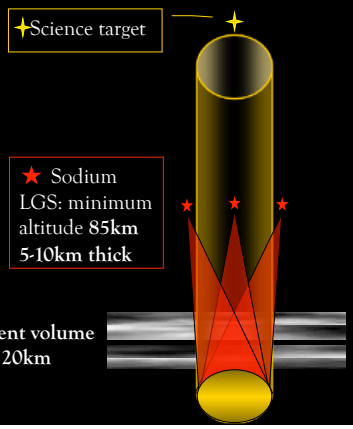


Artificial Stars!

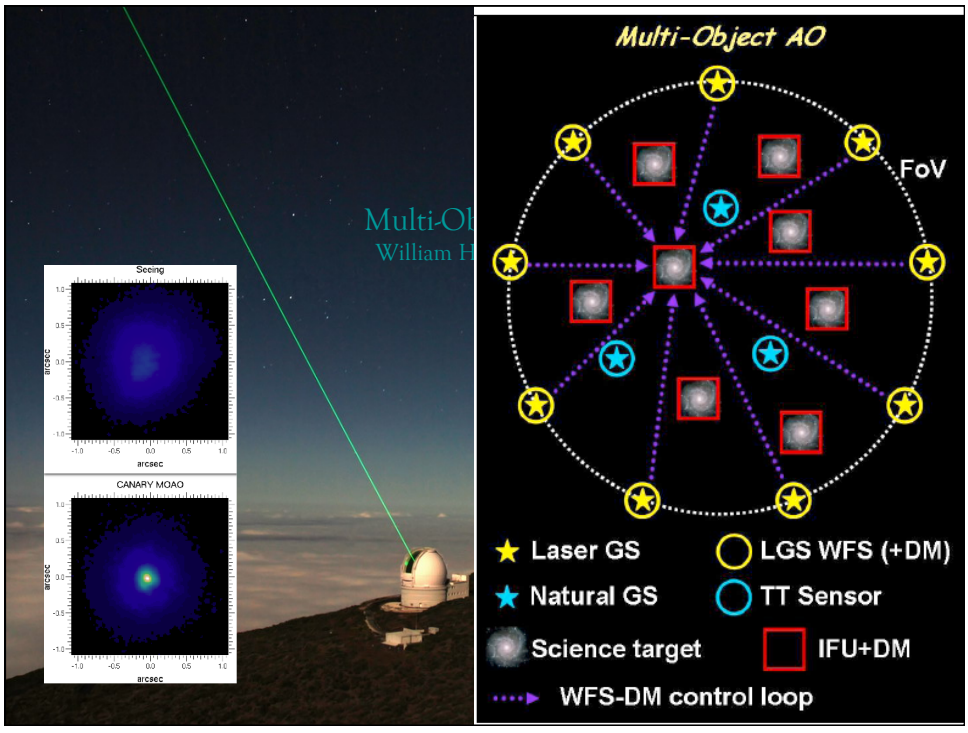
ESO's LGS + VLT
Magellanic Clouds + comet McNaught

Adaptive optics needs a bright reference star
Corrects a patch of sky around the reference
Not always a natural star nearby

Laser excites sodium atoms in the atmosphere to create an artificial star




CANARY
Laser Guide Star
Multi-Object (Stars+Lasers) Adaptive Optics
William Herschel Telescope on La Palma, Canary Islands
E-ELT PATHFINDER
ON-SKY
DEMONSTRATOR
Collaboration: UK & France
Richard Myers (Durham)


Multi-Ol
William H
Seeing
arcsec
CANARY MOAO
arcsec
Multi-Object AO
FoV
Laser GS
Natural GS
Science target
LGS WFS (+DM)
TT Sensor
IFU+DM
WFS-DM control loop

E-ELT First Generation Instruments

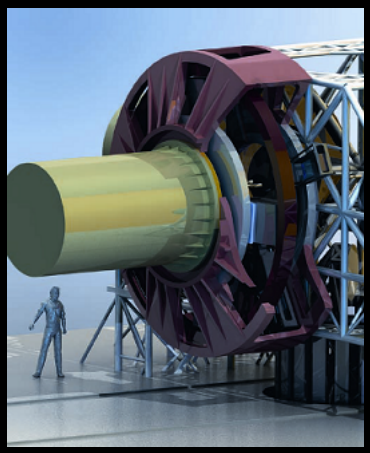
E-ELT instrumentation

Phase-A studies completed (Spring 2010) collaborations with institutes in ESO community

- 8 instruments
- 2 AO modules

Two selected for first light

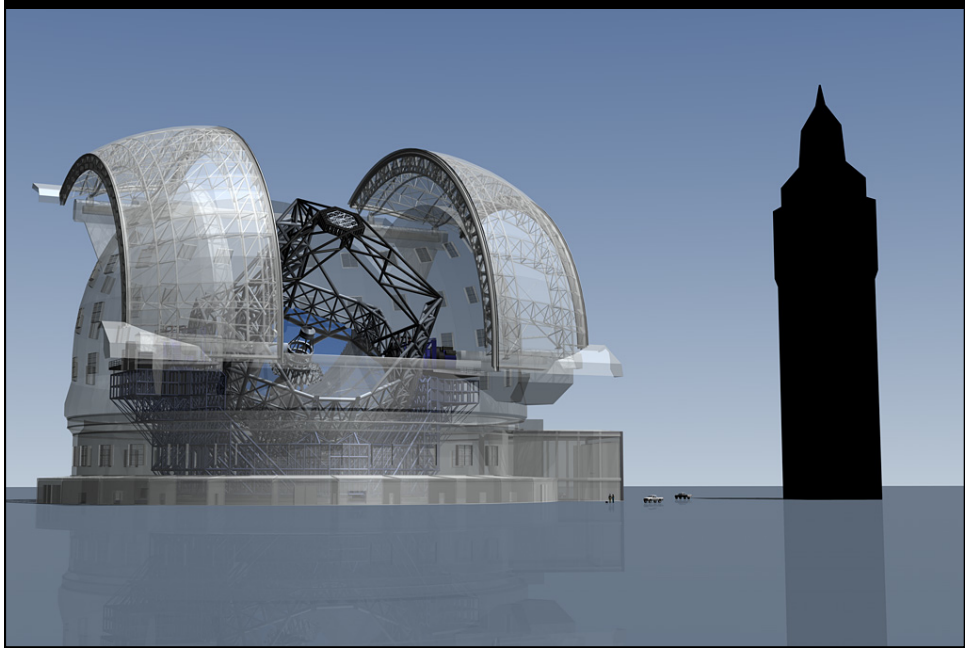
Full instrument suite to be built up over first decade



Phase A Instrument Studies

CODEX	Ultra-high-resolution optical spectrograph Luca Pasquini (ESO) (UK: Martin Haehnelt, Cambridge)	
EAGLE	Multi-IFU, AO-fed near-IR spectrometer Jean-Gabriel Cuby (LAM), Simon Morris (Univ Durham)	
EPICS	XAO imager/spectro-polarimeter for exo-planets Markus Kasper (ESO) (UK: Matthias Tecza, Oxford)	
HARMONI	Diffraction-limited, visible-NIR IFU Niranjan Thatte (Univ Oxford)	✪ ELT-IFU
METIS	Mid-IR (3-14μm) imager & spectrometer Bernhard Brandl (NOVA, Leiden) (UK: Alistair Glasse, ATC)	✪ ELT-MIR
MICADO	Near-IR, high-resolution imaging camera Reinhard Genzel (Max Planck Institute for Extraterrestrial Physics)	✪ ELT-CAM
OPTIMOS	Seeing-limited/GLAO high-multiplex spectrograph Olivier Le Fevre (LAM), Francois Hammer (GEPI), Gavin Dalton (Univ Oxford)	
SIMPLE	Near-IR, high-resolution spectrograph Livia Origlia (INAF, Bologna) (UK: Roberto Maiolino, Cambridge)	
AO-relays	MAORY (MCAO relay) & ATLAS (LTAO relay)	

E-ELT Science Case

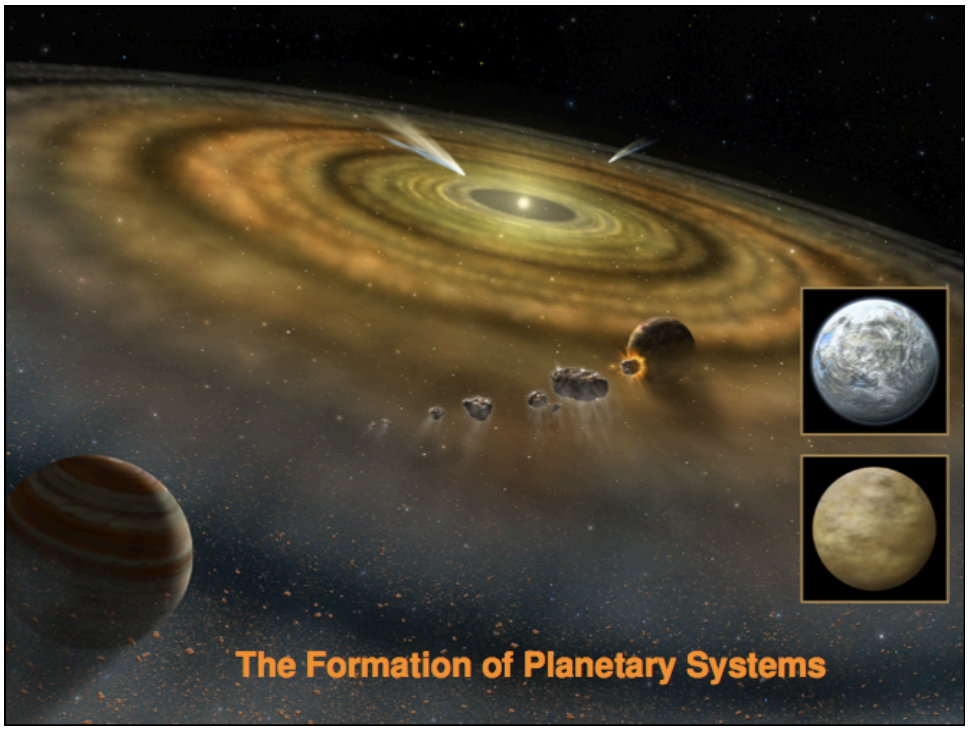


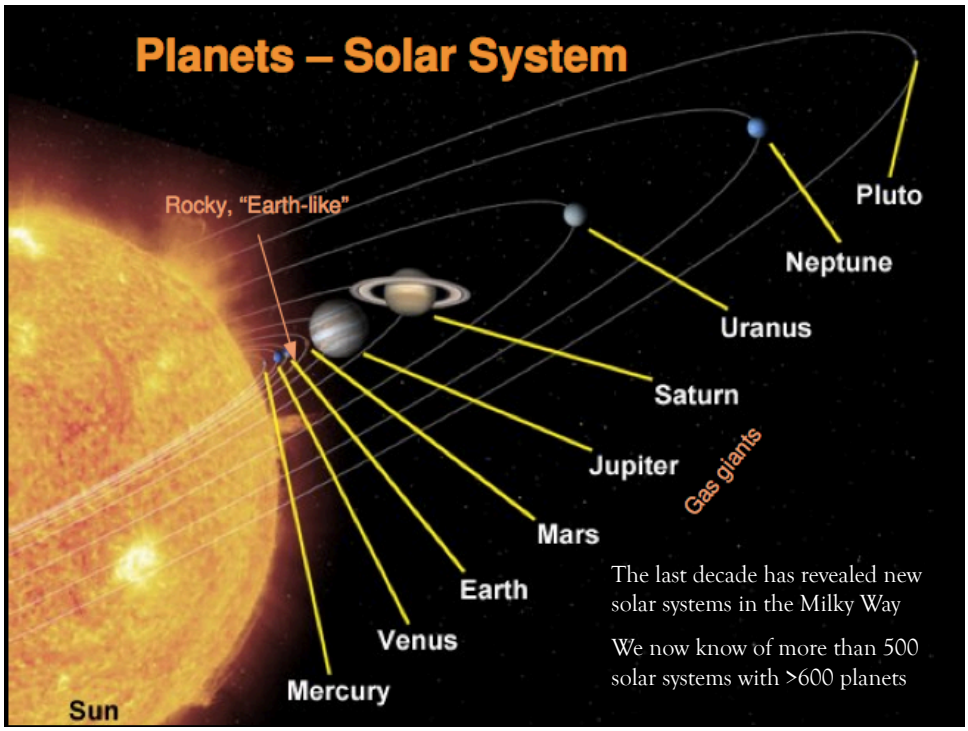
Foundations of the E-ELT Science Case

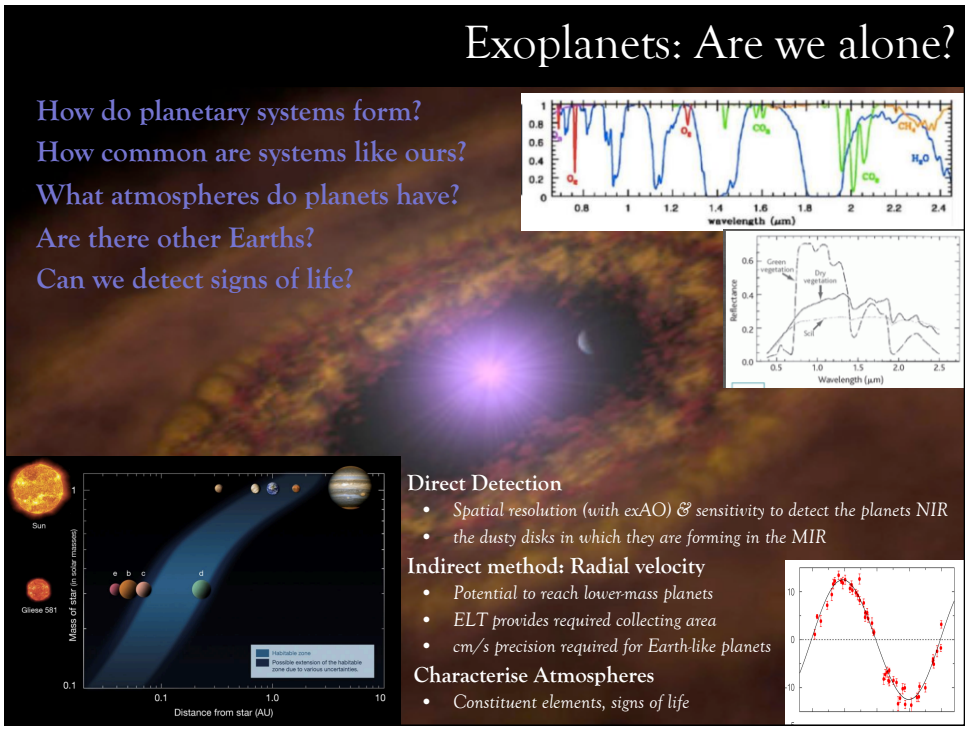
Collecting area = sensitivity
Diameter = resolution (with AO)

Spectacular new science


EAGLE
HARMONI
Galaxies & Cosmology
• Detecting First-light
• The physics of the highest redshift galaxies
• A dynamical measurement of the expansion of the universe
EPICS
Planets & Stars
• From Giant to terrestrial planets: detection, imaging spectral characterisation of their atmospheres
• Circumstellar Disks
CODEX
OPTIMOS DIORAMAS
MICADO
Stars & Galaxies
• Imaging and spectroscopy of extragalactic resolved stellar populations
• The nature of black holes and active galactic nuclei
METIS
OPTIMOS
Extreme Visual Explorer
SIMPLE


The Formation of Planetary Systems

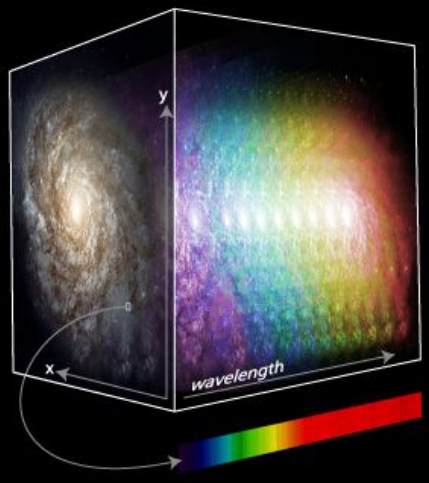

Planets – Solar System
Rocky, "Earth-like"
Pluto
Neptune
Uranus
Saturn
Jupiter
Gas giants
Mars
Earth
Venus
Mercury
Sun
The last decade has revealed new solar systems in the Milky Way
We now know of more than 500 solar systems with >600 planets

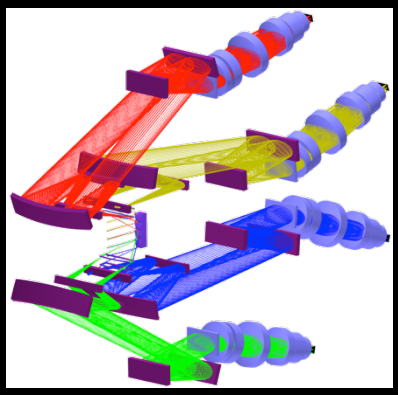

Exoplanets: Are we alone?
How do planetary systems form?
How common are systems like ours?
What atmospheres do planets have?
Are there other Earths?
Can we detect signs of life?
wavelength (μm)
Wavelength (μm)
Reflectance
Green vegetation
Dry vegetation
Soil
Sun
Gliese 581
Mass of star (in solar masses)
Distance from star (AU)
Habitable zone
Possible extension of the habitable zone due to various uncertainties
Direct Detection
Spatial resolution (with exAO) & sensitivity to detect the planets NIR
the dusty disks in which they are forming in the MIR
Indirect method: Radial velocity
Potential to reach lower-mass planets
ELT provides required collecting area
cm/s precision required for Earth-like planets
Characterise Atmospheres
Constituent elements, signs of life

HARMONI

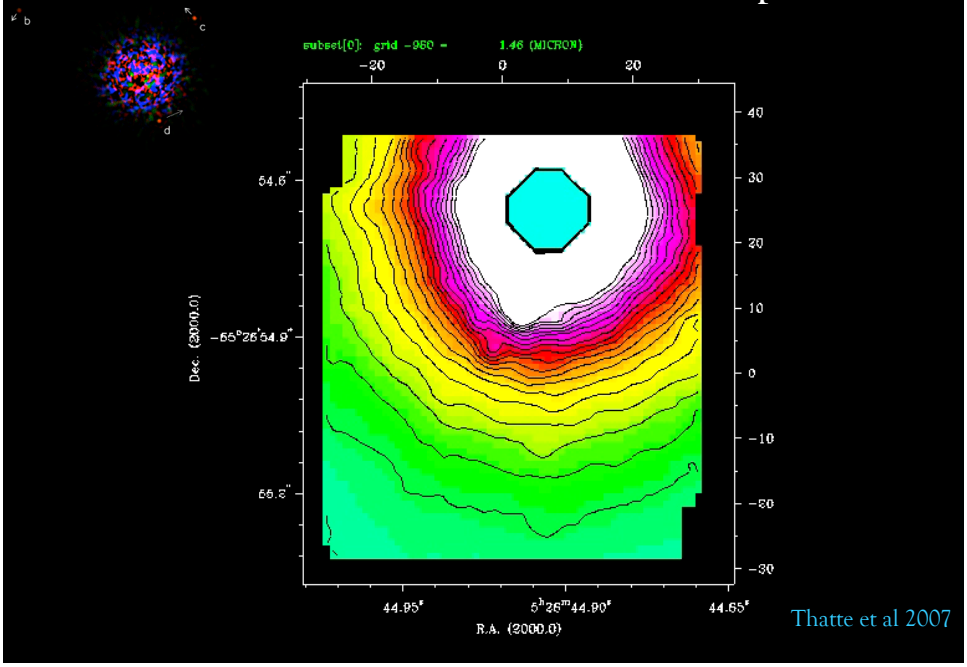
Integral Field Spectrometer

Niranjan Thatte, Matthias Tecza & Fraser Clarke (Oxford)
& consortium partners (UK, France, Spain)





Direct detection of a "Super Earth"



Thatte et al 2007

Black Holes

Black holes believed to reside in the centres of all massive galaxies! Fundamental importance to understand them and their role and influence on galaxy evolution

They come in three size classes

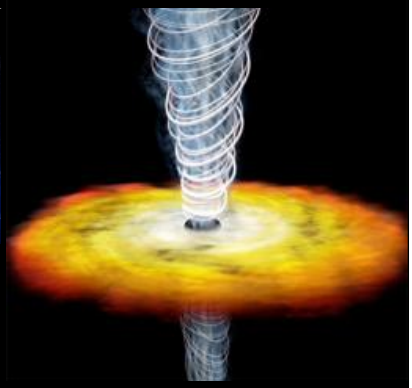
S: Stellar black holes

M/L: in star clusters

XL/XXL: in galaxy centres

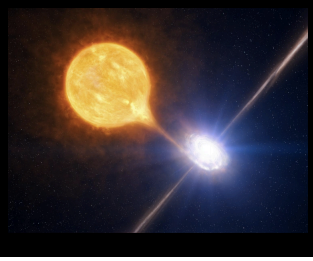
BUT:

Only a few black holes have accurate mass measurements



How common are they?

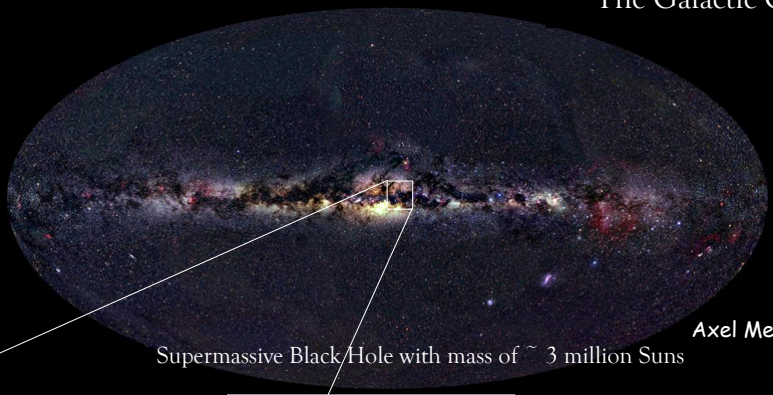
Why do their masses relate to that of host galaxy bulges?



ELT provides resolution track the motions of stars moving under the influence of the central black hole in thousands of galaxies

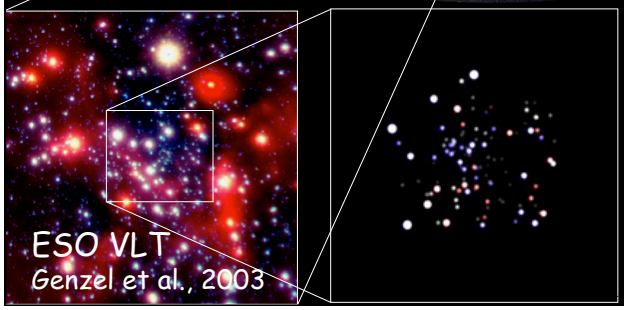
- $10^9 M_\odot$ BHs to 100Mpc
  - statistical samples (and perhaps to high-z..)
- $10^6 M_\odot$ BH @ Virgo distance

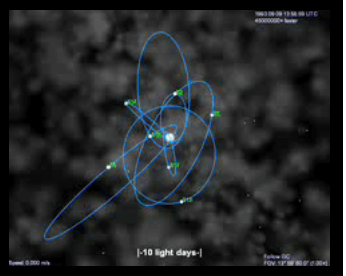
The Galactic Centre



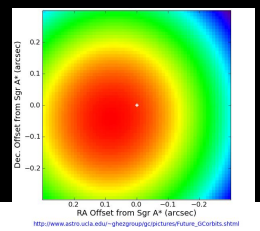
Axel Mellinger

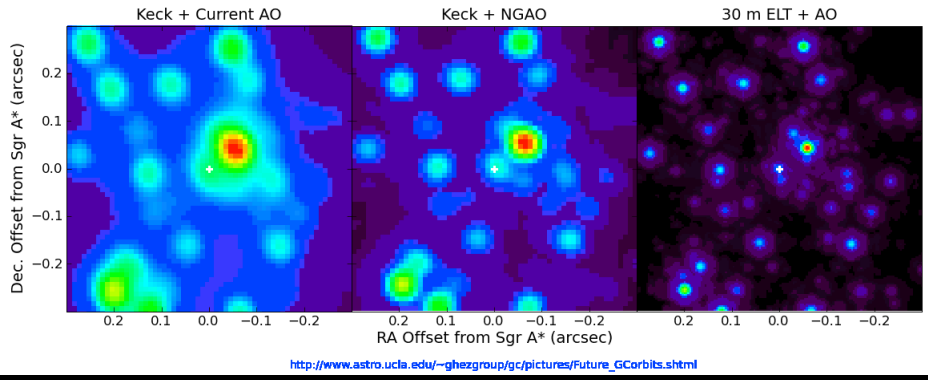
Supermassive Black Hole with mass of ~ 3 million Suns





The Galactic Centre

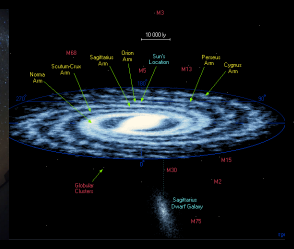


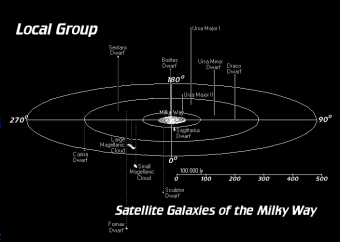


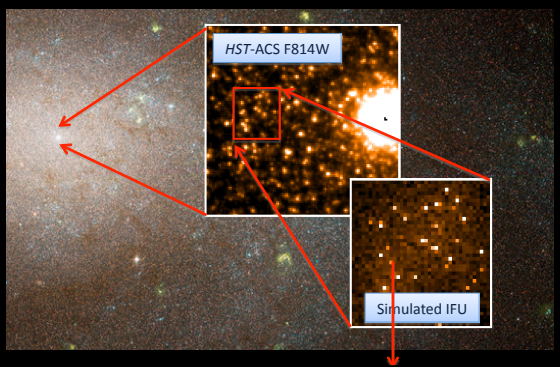
Formation of Galaxies

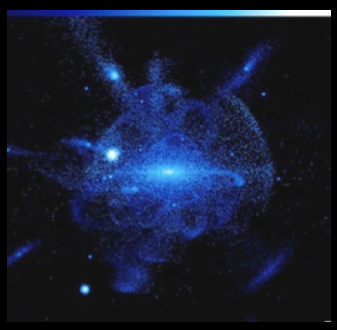
When and how did galaxies form?
How did they build up their stars?
Why are there different types of galaxies?

Galactic Archaeology: How are galaxies built up?

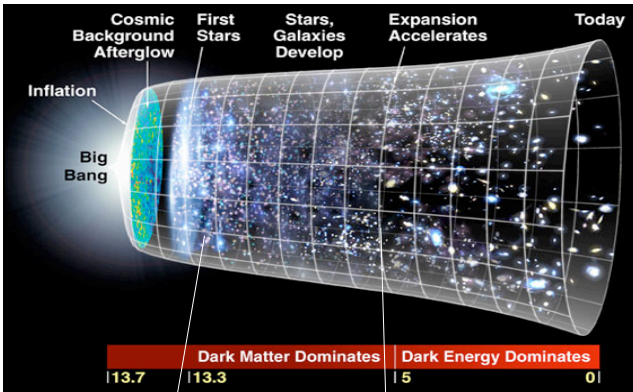


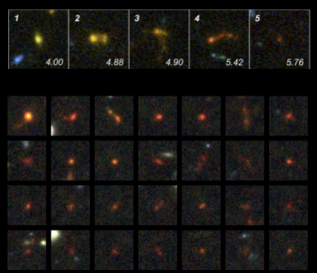


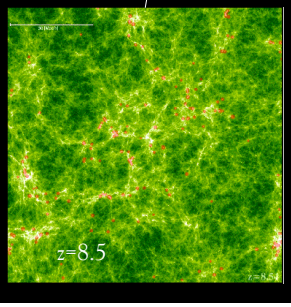


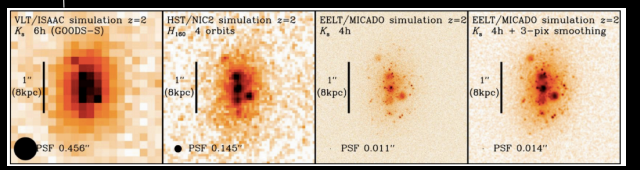


First Galaxies

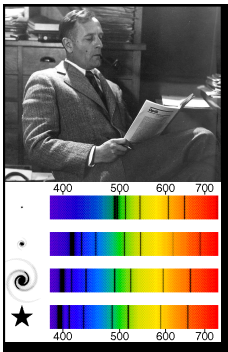


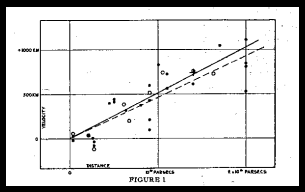


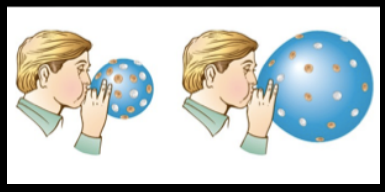




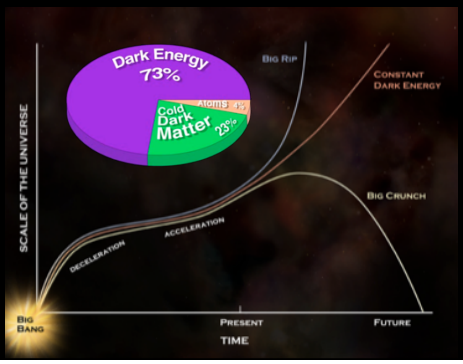
Expansion of the Universe



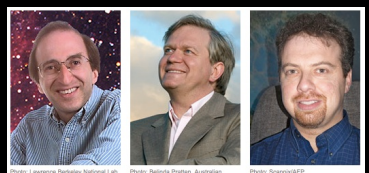




1926: Hubble – the Universe is expanding



1998: the expansion accelerates
(2011 Nobel Prize for Physics)

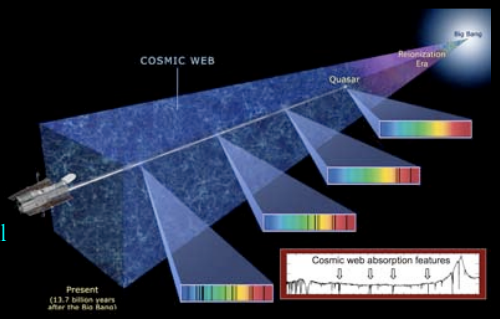


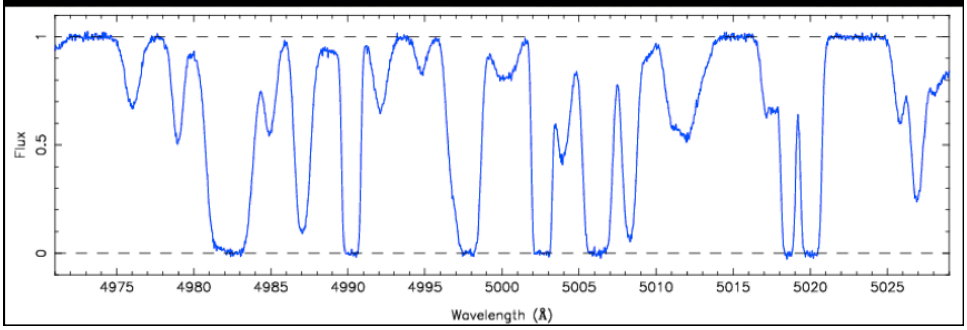
Saul Perlmutter | Brian P. Schmidt | Adam G. Riess

Watching the Universe accelerate in real time

What causes this acceleration?
Called "Dark Energy"
- an unknown form of energy with negative pressure
- our understanding of gravity and general relativity is not right

ELT can measure acceleration **directly**, in real time by measuring redshift





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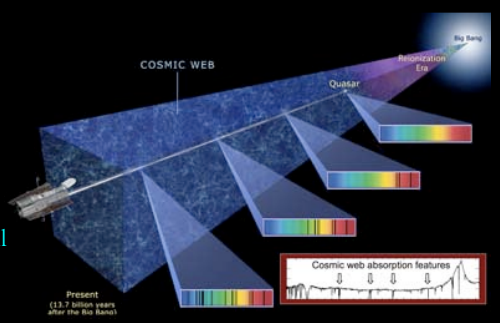

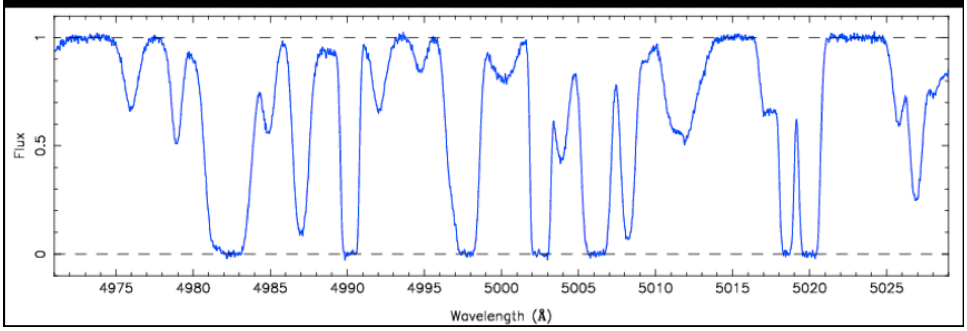

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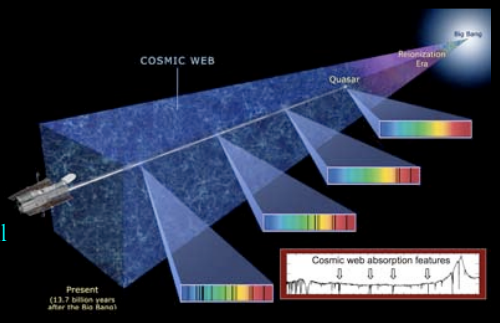
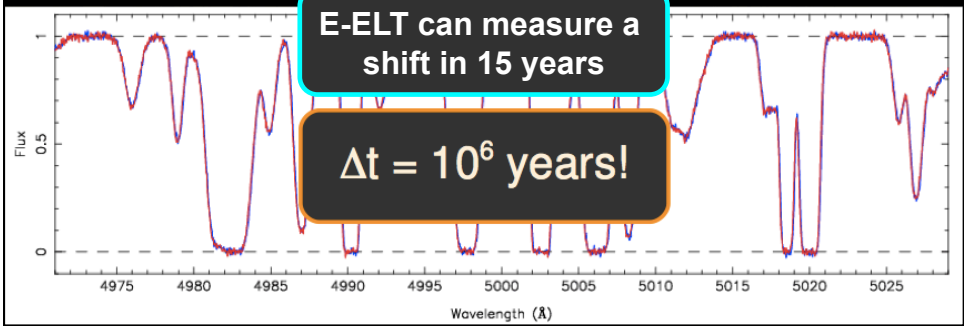
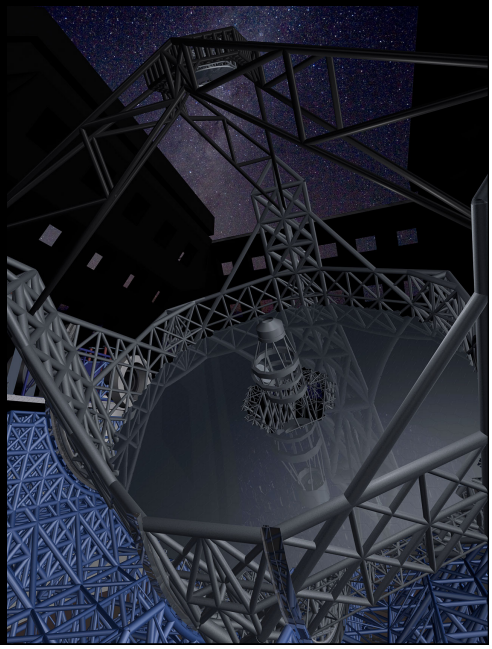




What happens next for the E-ELT?

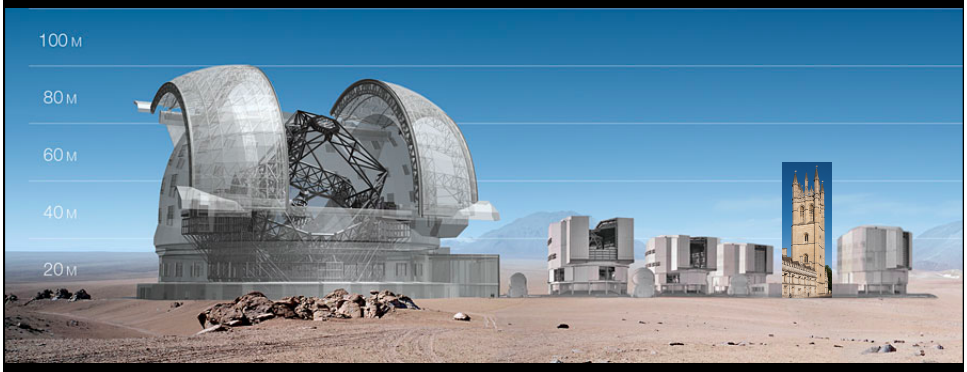
- Chile has donated land for the telescope in return 10% of the observing time
- Preparations for the site & infrastructure are underway
- Program is approved subject to confirmation of funding
- 6 partners confirmed
- 4 partners to confirm in the near future
- 4 preparing finances commitments to the project
- Accession of Brazil



Anticipated Schedule

Start assumed	Jan 2012
AIV Starts	Jan 2020
Technical First Light	Dec 2021
First Instrument	Jun 2022
Observatory Operations	Oct 2022

The European Extremely Large Telescope



The public web pages: **http://www.eso.org/public/astronomy/projects/e-elt.html**
Gallery: **http://www.eso.org/public/images/archive/category/e-elt/**

The science web pages: **http://www.eso.org/sci/facilities/eelt/**
UK Project pages: **http://www.roe.ac.uk/elt/index.html**
Construction Proposal
Full: https://www.eso.org/sci/facilities/eelt/docs/e-elt_constrproposal.pdf
Exec Summary: https://www.eso.org/sci/facilities/eelt/docs/e-elt_executivesummary.pdf
Instrument plan: https://www.eso.org/sci/facilities/eelt/instrumentation/index.html