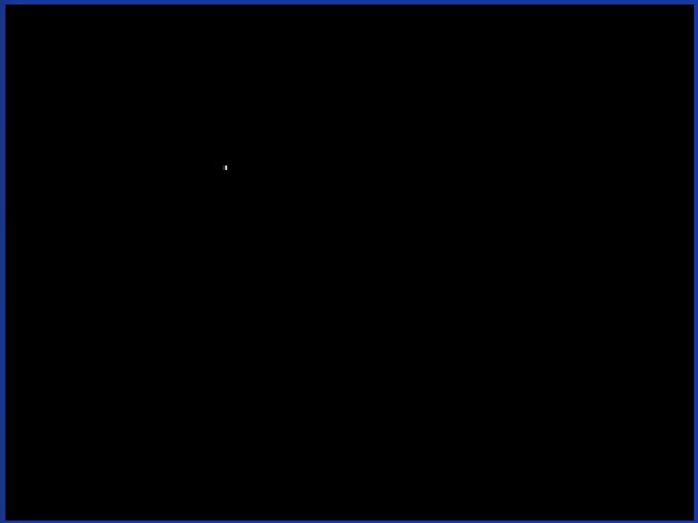
SOFIA – 2.5m IR telescope at 13,000m



Herschel – 3.5m FIR telescope at 1.5 m Km

First light

2009!

Future Technologies for Telescopes and Instruments

Colin Cunningham

Director, UK Extremely Large Telescope Programme

Science & Technology Facilities Council

UK Astronomy Technology Centre

Royal Observatory Edinburgh

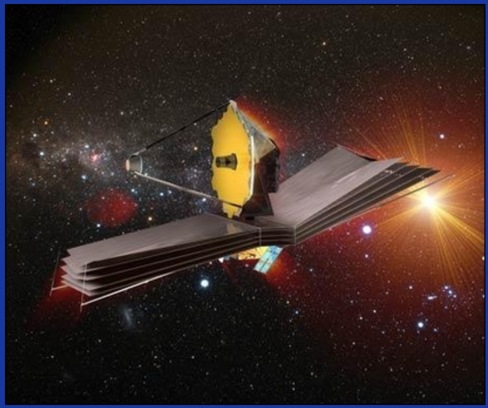
400 Years of Astronomical Telescopes

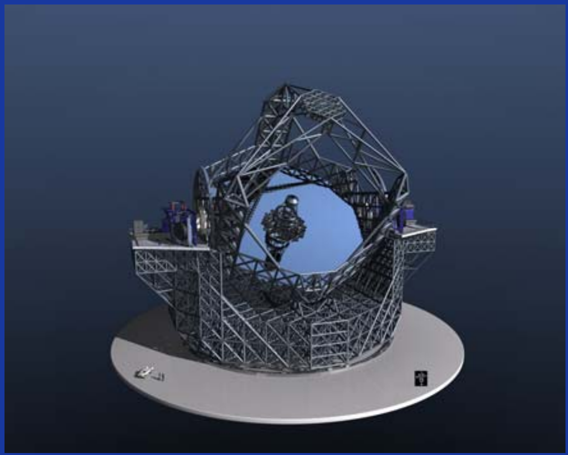
A Review of History, Science and Technology

Sterrewacht Leiden

Scope of talk

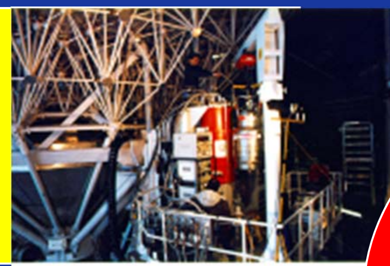
- Innovation in Optical/IR Astronomy – ground & space
    - Science Drive and Technology Push
    - Disruptive Technologies
    - Gestation Periods for new technology to be adopted
- Survey of current ideas for new technology for telescopes and instruments
- Where might we go in next 50 years?





Why do we need Technology Development in Astronomy?

Open New Parameter Space > New Science



Disruptive Technology – changes how we do things

Reduce cost- make New Science affordable

Reduce time to reach Science Goal

Reduce Risk

Disruptive Technology

A new technology that has a serious impact on the status quo and changes the way people have been dealing with something, perhaps for decades

Disruptive Technology

A new technology that has a serious impact on the status quo and changes the way people have been dealing with something, perhaps for decades

Credit: LSST Corp.

Which Technologies have changed how we do astronomy?

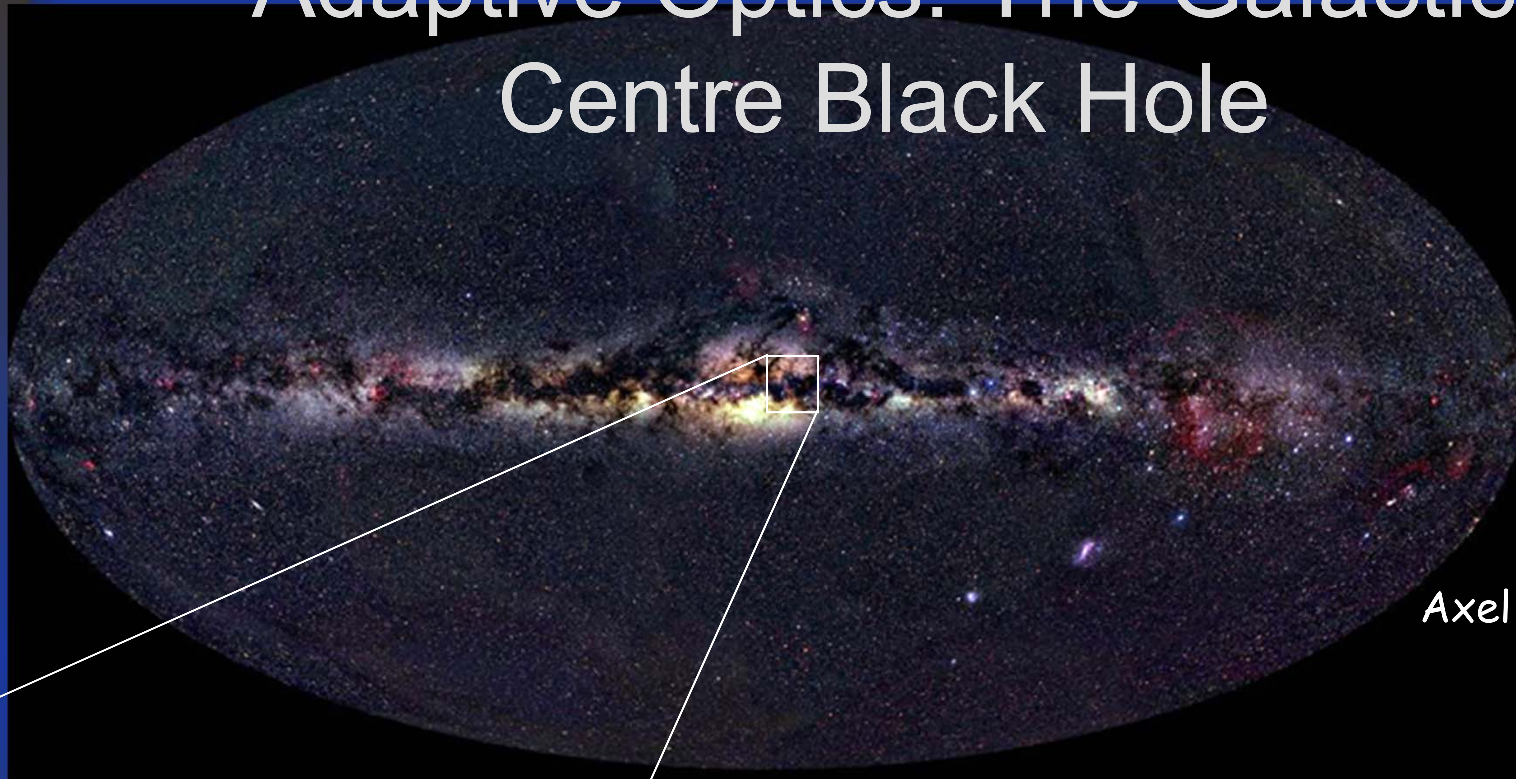
- Lens > Galileo's Telescope
- Metal mirrors > Herschel's Telescope
- Silver on glass mirrors > Foucault's Telescope
- Go up a mountain >Tenerife, Lick Obs
- Pyrex Glass Mirror & Ship engineering > Hale 200" Telescope
- Electronic Detectors: CCDs & IR Arrays
- Space Telescopes > HST
- Segmented Mirrors > Keck
- Active optics > VLT, Gemini Subaru



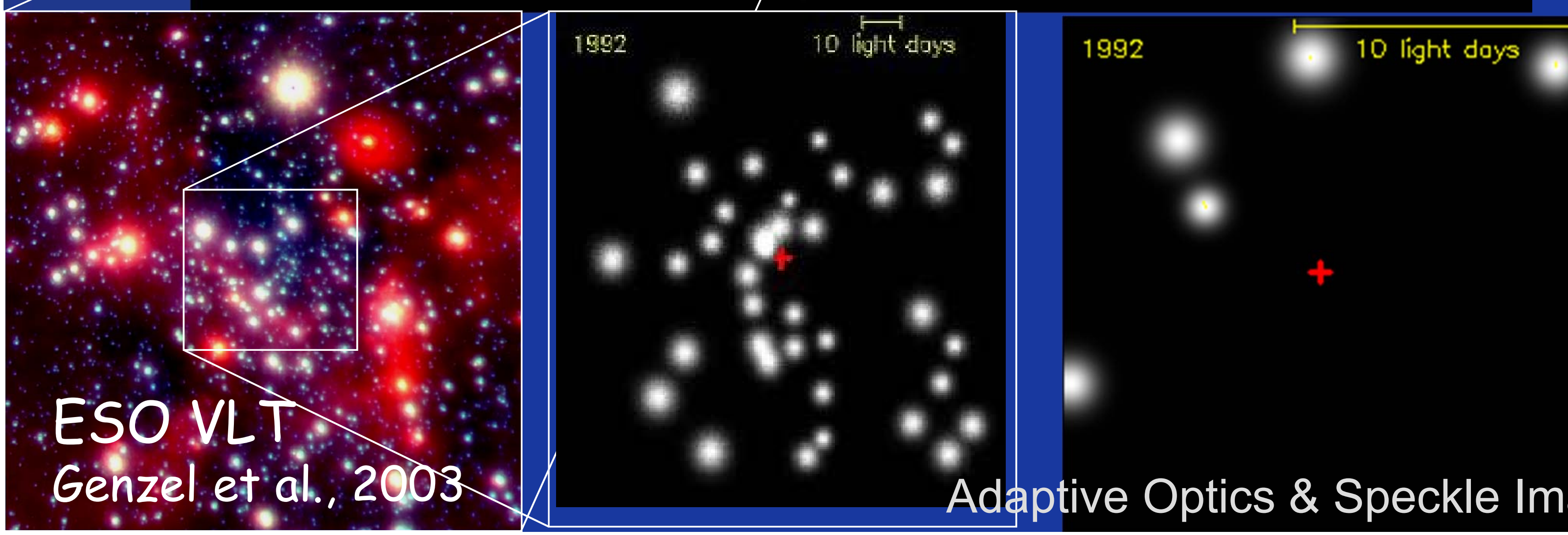





Adaptive Optics: The Galactic Centre Black Hole



Axel Mellinger



What will the Disruptive Technologies of the future be?

?

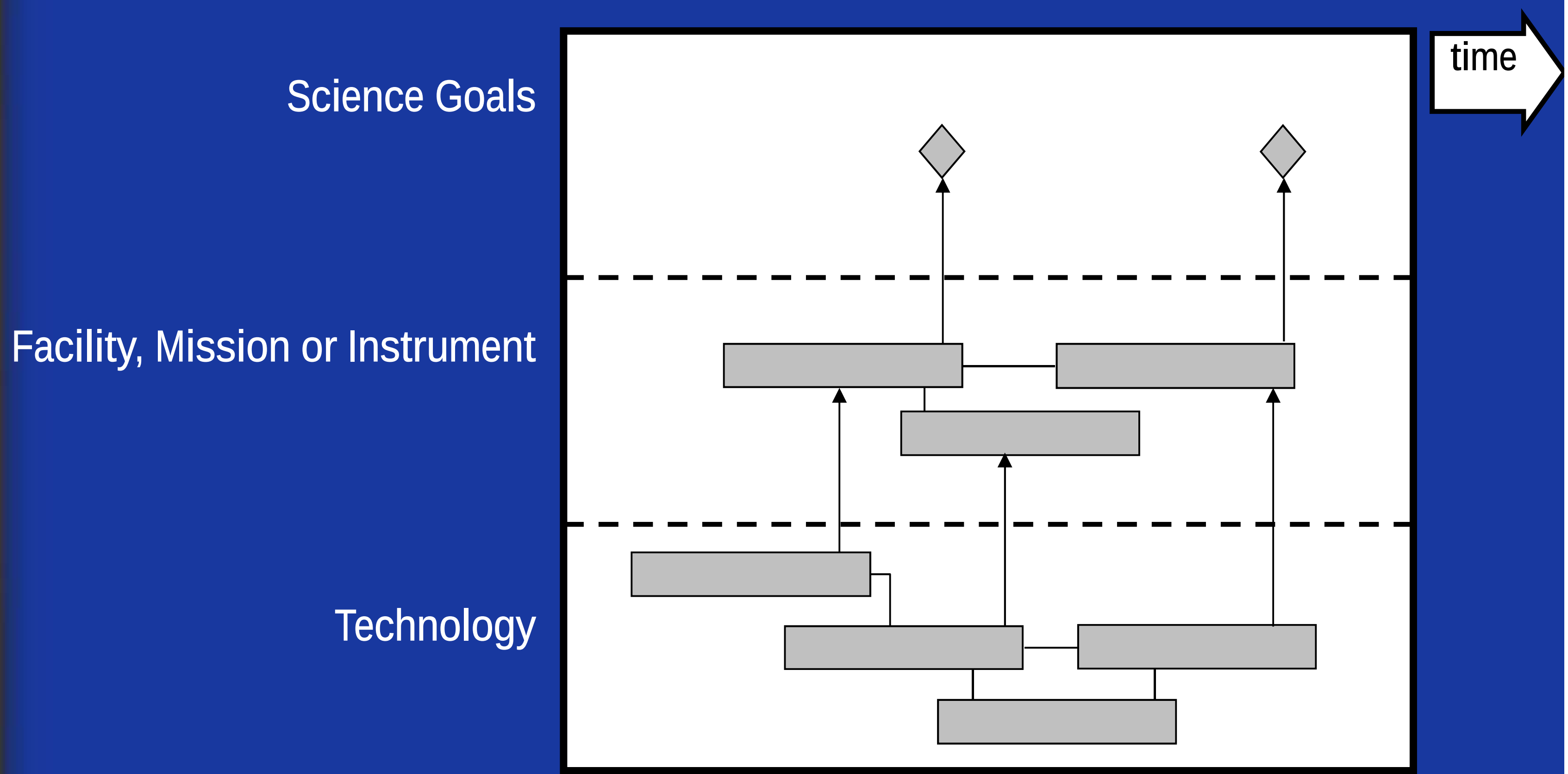
By definition – impossible to answer!

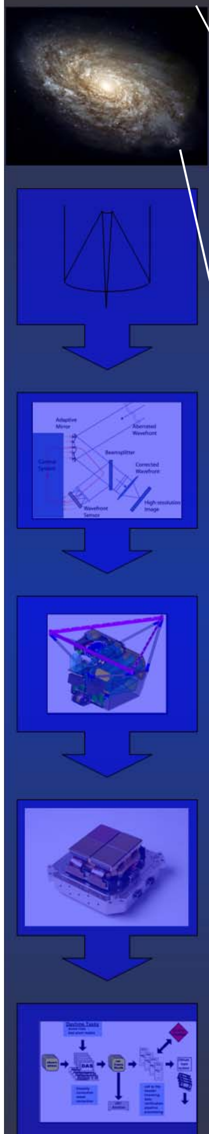
"If you can look into the seeds of time, and say which grain will grow and which will not, speak then unto me"

William Shakespeare

(Macbeth)

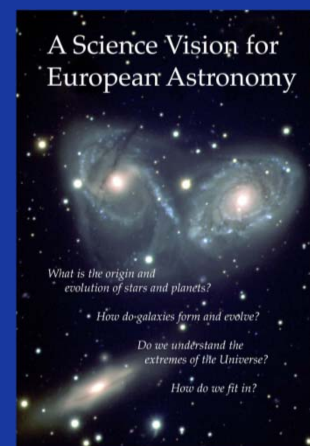
Technology Planning: Roadmap





Science Drivers

- NASA 2006 Strategic Plan
  - Discover the origin, structure, evolution, and destiny of the universe, and search for Earth-like planets
- ESA 2008 Cosmic Vision
  - What are the conditions for life and planetary formation**?**
  - How did the Universe begin and what is it made of?
- ASTRONET 2008 European Science Vision
  - The Extremes of the Universe
    - What is Dark Matter & Dark Energy?
  - Galaxy Formation & Evolution
    - How were galaxies assembled?
    - How did our Galaxy form?
    - How do galaxies form and evolve?
  - Origins and evolution of stars and planets
    - Where are most of the metals throughout cosmic time?
  - How do we and the solar system fit in?



Science Needs Drive Technology Requirements

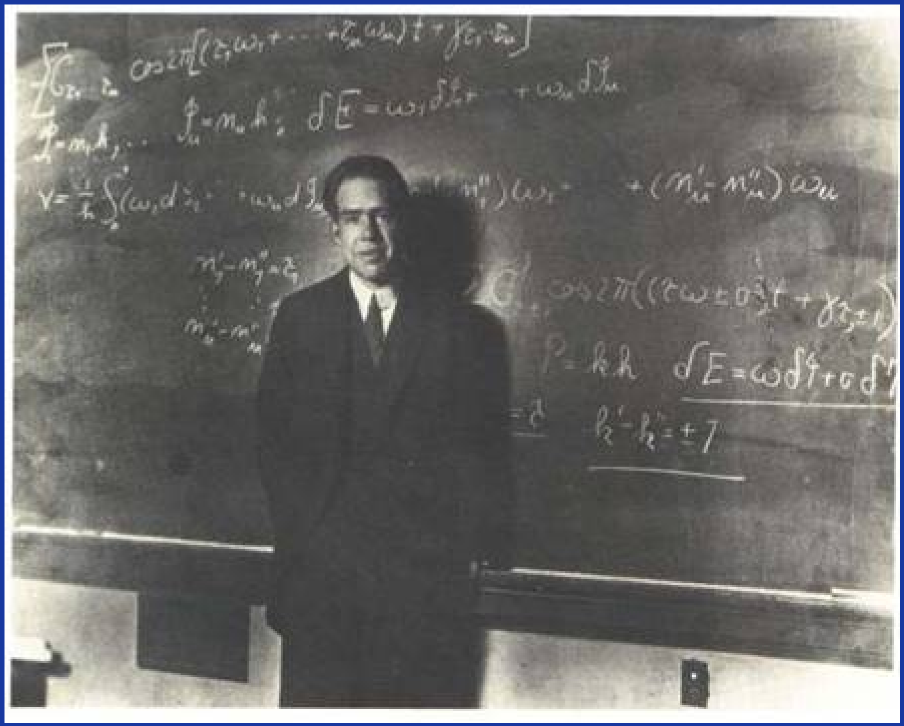
- Is it is simple as this?
- Can we define science needs, then facility requirements, then decide what technology should be developed and when?
- Probably yes, for evolutionary developments
- Or is it often much more iterative?
  - Disruptive technologies push us into new parameter space or observing methods
    - Detectors
    - Computing
    - Photonics?

Political Drivers

- Why do governments spend money on astronomy?
  – Gain or maintain World standing in science
  – Feed Industry
  – Inspire people into science and technology
- Organisational agenda: SIRTF/Spitzer & NASA
- We don't succeed without taking care of these issues

Predicting the next 50 years

"Prediction is very difficult, especially if it's about the future." Nils Bohr



Or was it Yogi Berra?

"It's tough to make predictions, especially about the future"

Prediction from 100 yrs ago

Edward Pickering 1909 POPULAR SCIENCE MONTHLY

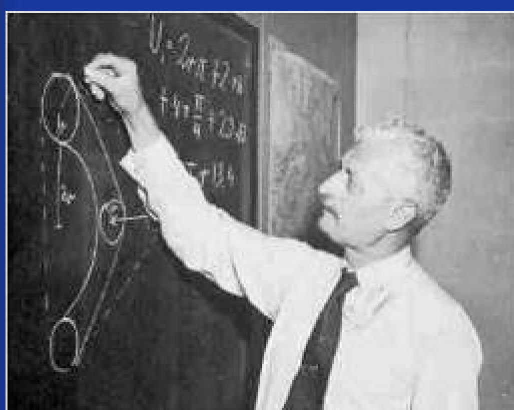
- 'Have we at length reached the limit in size?.... It is more than doubtful, however, whether a further increase in size is a great advantage. Much more depends on other conditions, especially those of climate, the kind of work to be done and, more than all, the man behind the gun'
- Other predictions:
- 1) Service Observing at 2 Large observatories at +30 deg and -30 deg, with central data reduction centre
- 2) Determining stellar distances
  - Differential absorption in interstellar medium
  - Variations in speed of light with wavelength !!!
  - 'If we could determine our motion with reference to the ether, we should have a fixed line of reference to which all other motions could be referred'

Prediction from 50 yrs ago

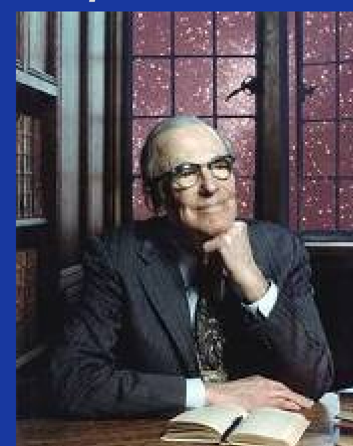
Henry King, 1955

The History of the Telescope (pub Griffin)

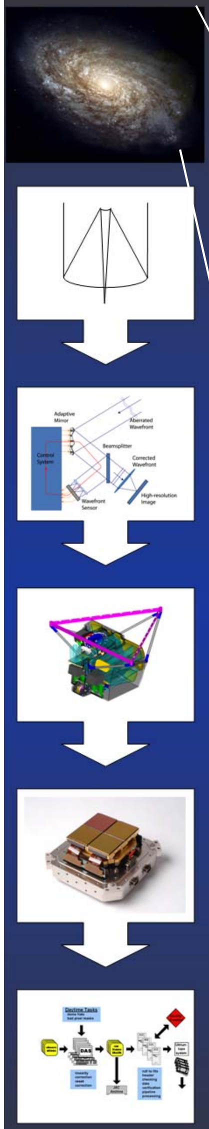
'Thus we return to the old problem of escaping from the damaging optical effects of the earth's atmosphere – and there is no escape as yet….in the future, when interplanetary travel becomes possible, observing stations and, ultimately, observatories may be established in space'



- Observatory in space was proposed in 1923 by Hermann Oberth
- Lyman Spitzer described benefits of a space telescope in 1946



What can we measure ?



I N F O R M A T I O N

We can also measure or collect:

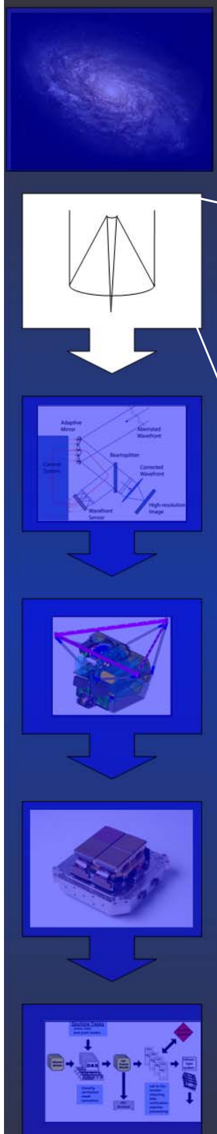
- Neutrinos
- Gravitational Waves
- Cosmic rays (particles)
- Meteorites

Probe the Universe by collecting photons:

- Photon emission
- Absorption
- Eclipses
- Gravitational lensing
- Angles - astrometry
- Doppler shift > dynamics of galaxies > Dark Matter
- Measure properties of E-M radiation::
  - Intensity
    - Spatial
    - Temporal
  - Wavelength (Energy)
  - Amplitude & Phase
  - Polarisation
  - Orbital Angular Momentum?

c. Miles Padgett

Telescopes



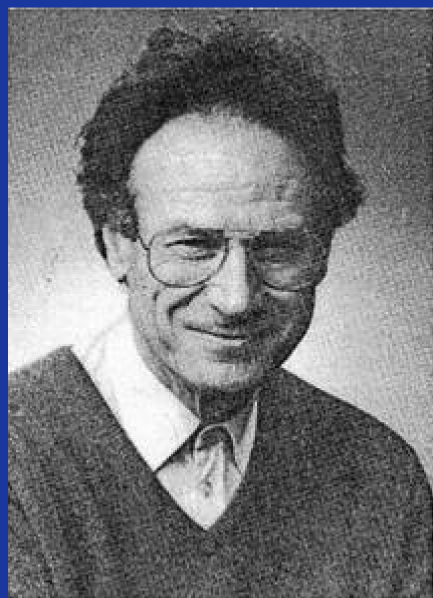
What does the telescope structure do?

Example: Gemini Telescope

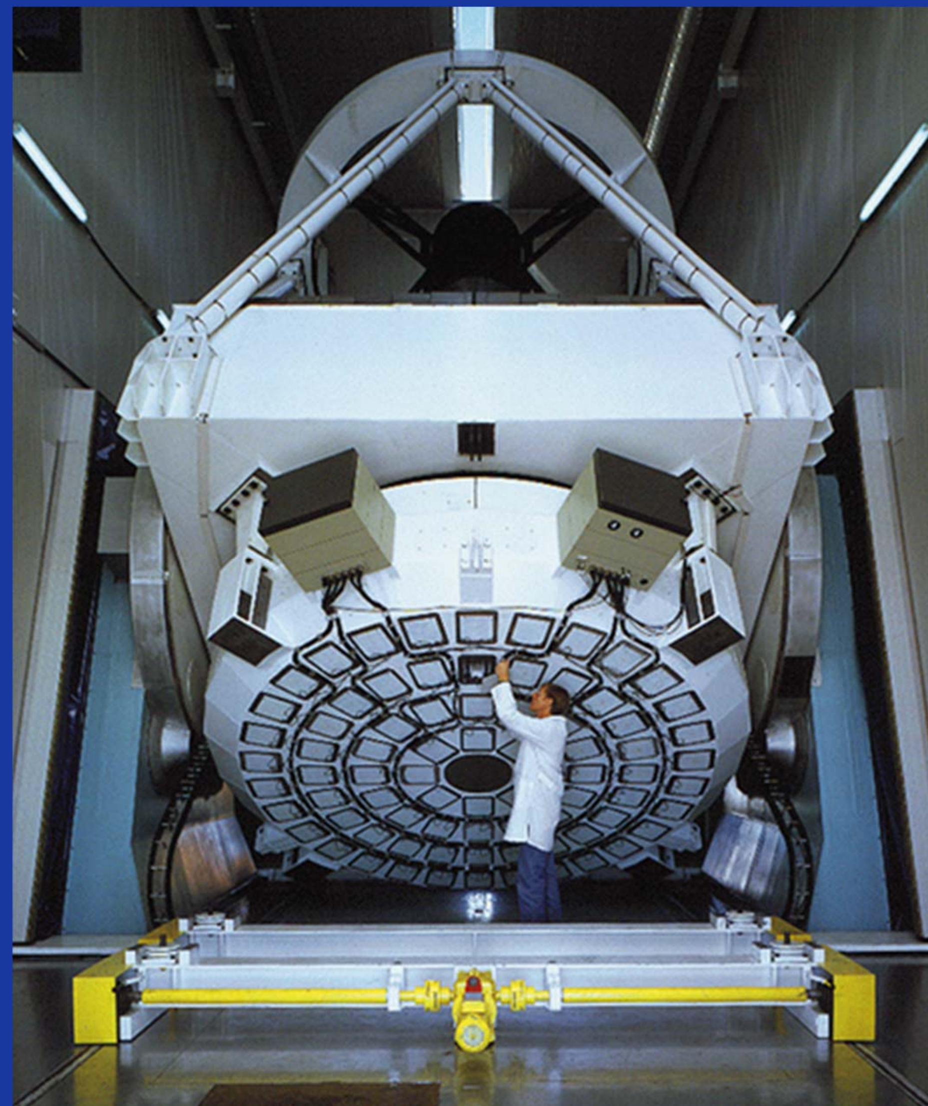
17g of aluminium or silver supported by 380 tons of structure!

How about making the structure ‘smart’ ?

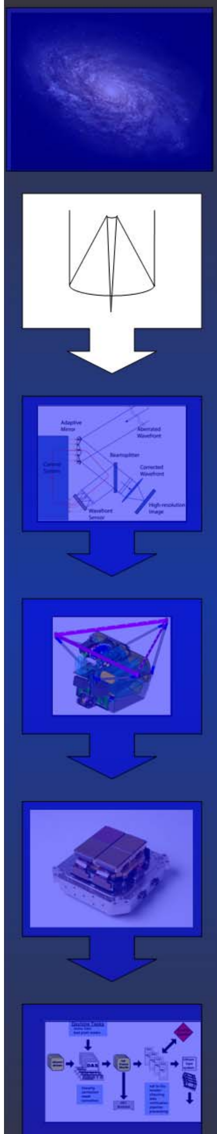
Ray Wilson & Active Optics

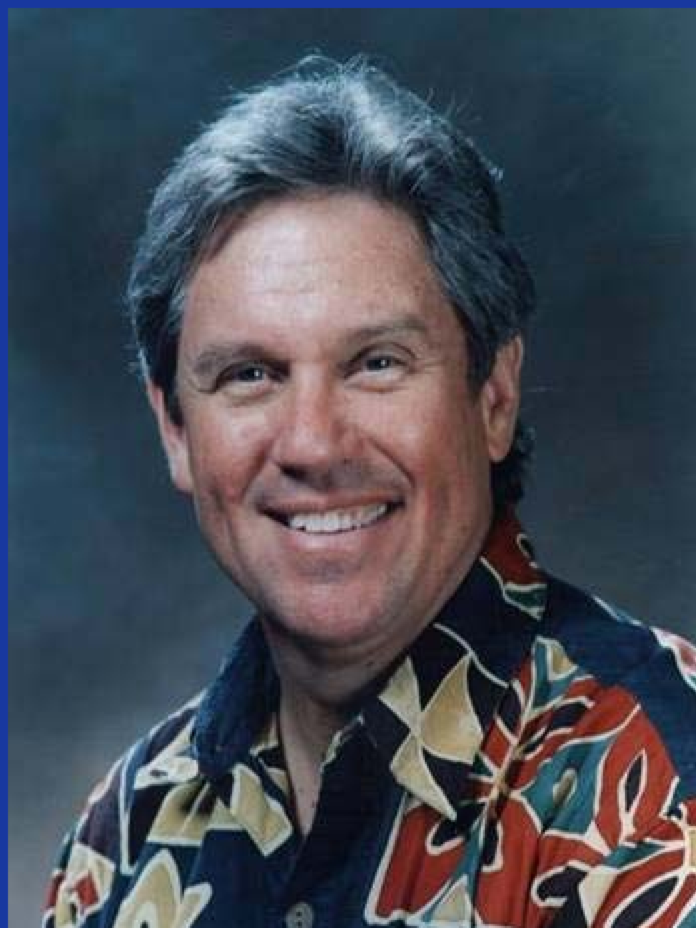


- •Active Optics
  - •Thin Mirror
  - •Wavefront Sensing
  - •Actuators
- •New Technology Telescope>
  - •VLT
  - •Subaru
  - •Gemini



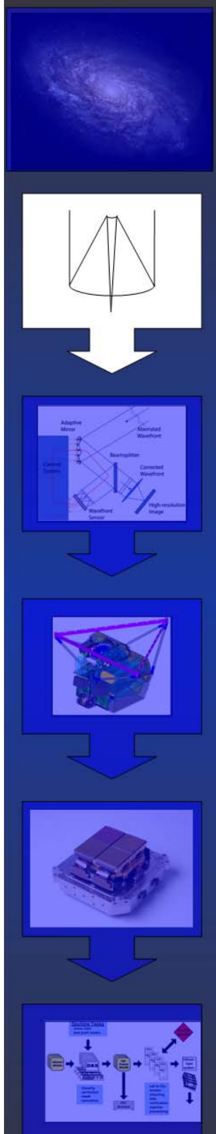
Jerry Nelson & Segmented Telescopes





10m Keck Telescopes: 36 Segments

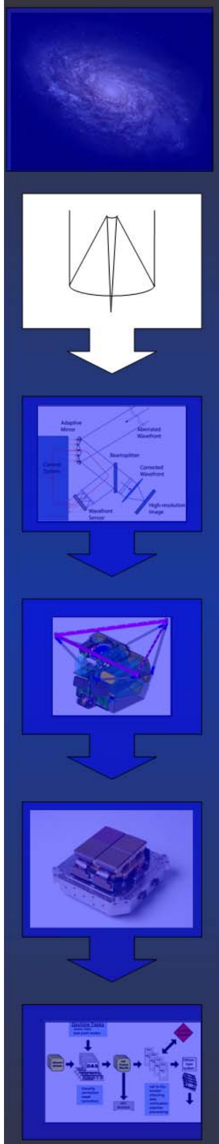
©Russ Underwood/W.M. Keck Observatory

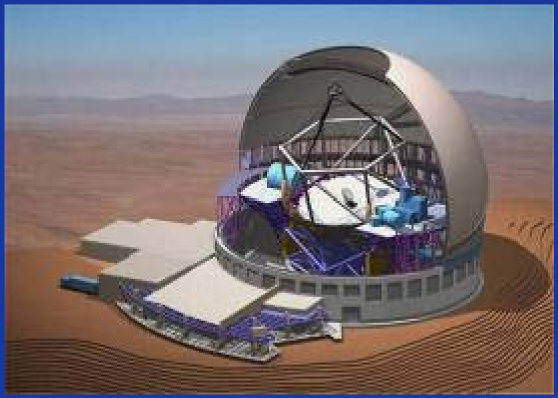


Segmented Mirrors

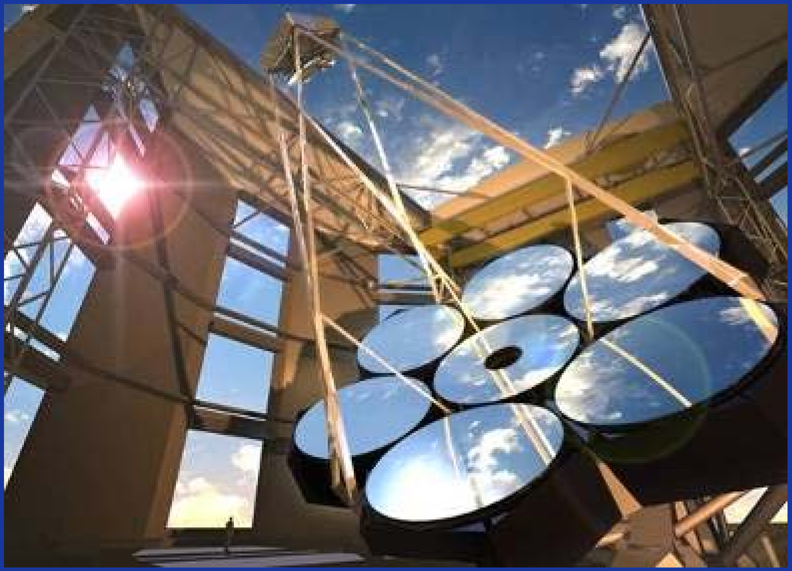
- Not new!
- Guido Horn d'Arturo at Bologna Observatory
- Built between 1935-52
- 61 segments to form 1.8m diameter mirror

Enables next step: bigger telescopes!

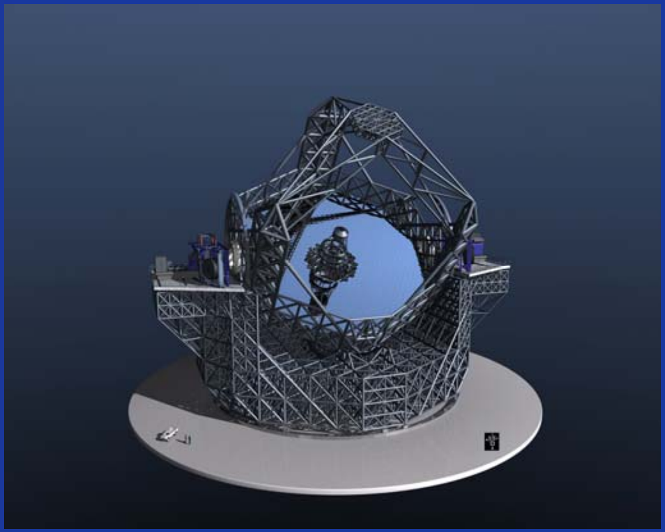




Thirty-Meter Telescope Project

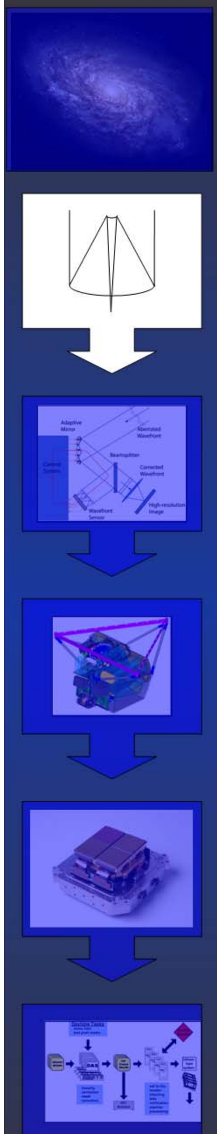


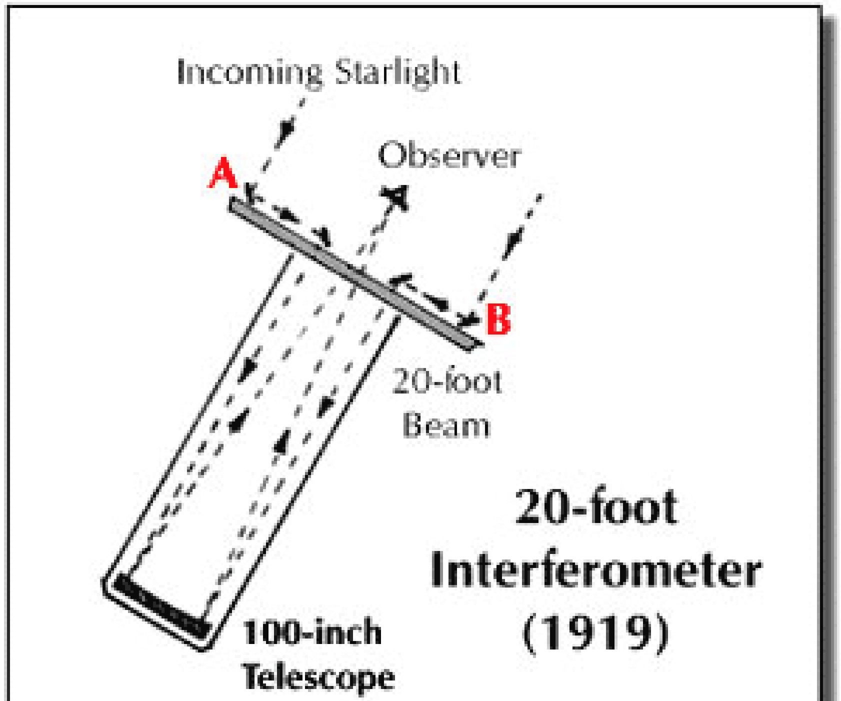
Giant Magellan Telescope - Carnegie Observatories.
Artwork by **Todd Mason**



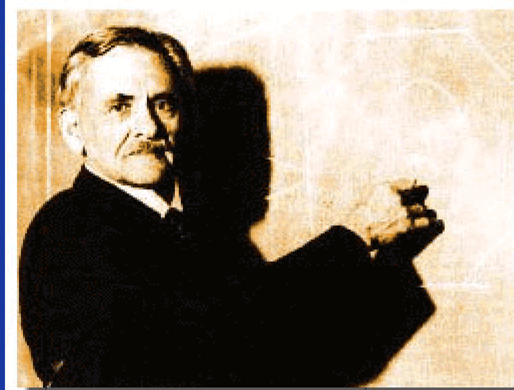
European Extremely Large Telescope

Increase apparent D: Interferometers

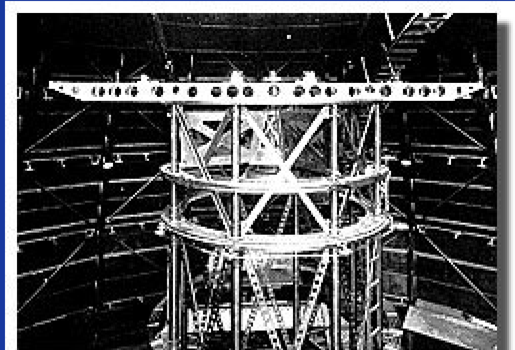




Small mirrors on the 20-foot beam directed light into the telescope. The effective diameter of the telescope has now become the distance between mirror A and B.



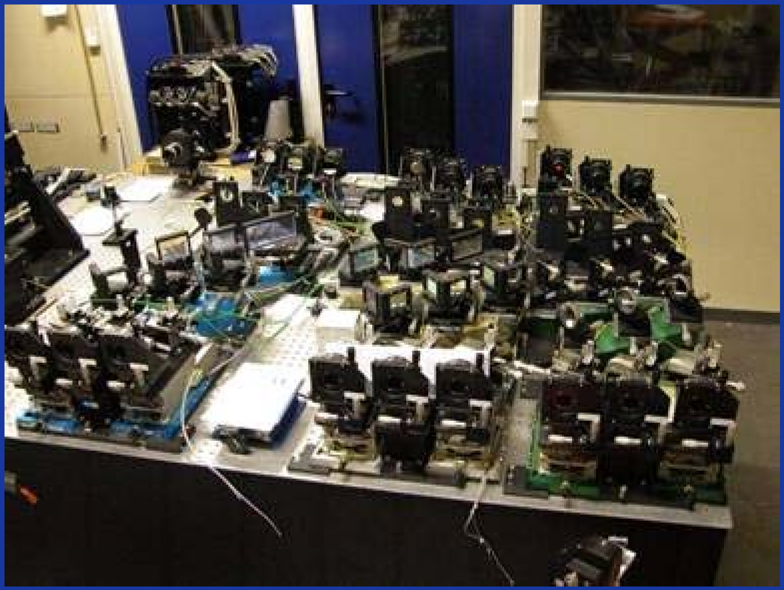
Albert Michelson



The 20-foot beam on top of the 100-inch Hooker Telescope on Mt. Wilson in Southern California.

Interferometers : Novel technologies

- Instruments are complex and large
- So integrated optics are attractive

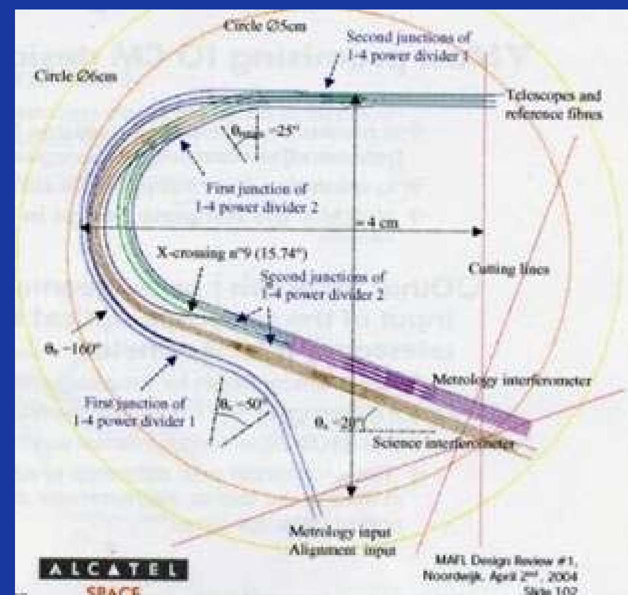


VLTI AMBER, Grenoble

Full integrated instrument:
Multi Aperture Fibre Linked Project

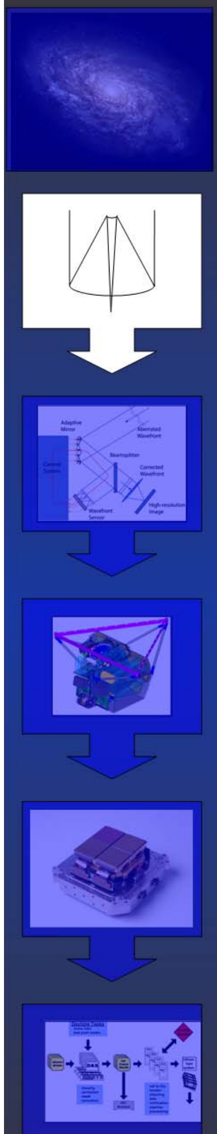
An integrated instrument that includes most of the optical functions required to control a three-arm interferometer:

- ✓ **coherent transport including modal filtering**
- ✓ **metrology system**
- ✓ **3-channel beam combiner**



ESA Alcatel Space, IMEP, GeeO, IRCOM

SPACE: Sputnik Changed Everything!



This geopolitical earthquake fundamentally changed the way we look at science and science funding


"All the News That's Fit to Print"

The New York Times.

LATE CITY EDITION

SOVIET FIRES EARTH SATELLITE INTO SPACE; IT IS CIRCLING THE GLOBE AT 18,000 M. P. H.; SPHERE TRACKED IN 4 CROSSINGS OVER U.S.

HOFFA IS ELECTED TEAMSTERS HEAD; WARNS OF BATTLE

COURSE RECORDED

Navy Picks Up Radio Signals—A Report Sighting Device

560 MILES HIGH

Visible With Simple Binoculars, Moscow Statement Says

Device Is 8 Times Heavier Than One Planned by U.S.

FAUBUS COMPARES HIS STAND TO LEE'S

ARGENTINA TAKES EMERGENCY STEPS

SATELLITE SIGNAL BROADCAST HERE

Ex-Premier Mollet Accepts Bid To Form a New French Cabinet

City Sifts Charge That Schupler, Brooklyn Councilman, Sold a Job

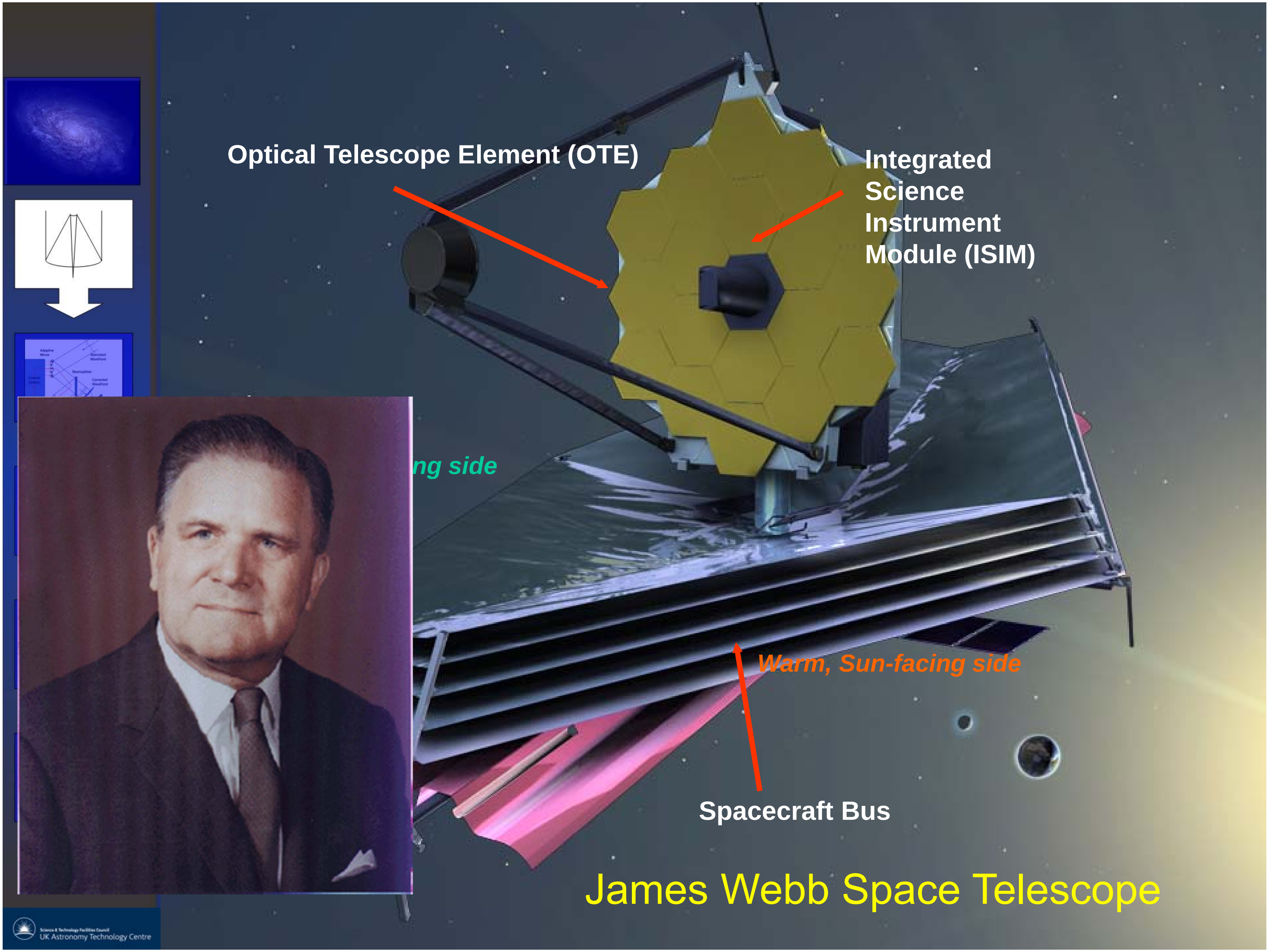
Warsaw Crushes New Protest; Clubs, Tear Gas Rout Students

1957 *NY Times* front page

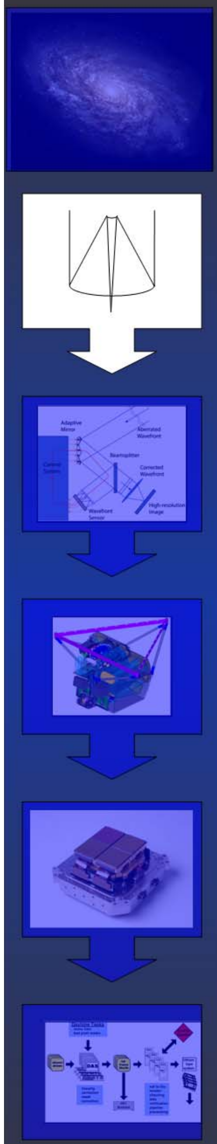
Jim Crocker, Lockheed Martin

Launched 1990

Fixed 1993


Optical Telescope Element (OTE)
Integrated Science Instrument Module (ISIM)
ng side
Warm, Sun-facing side
Spacecraft Bus
James Webb Space Telescope
UK Astronomy Technology Centre

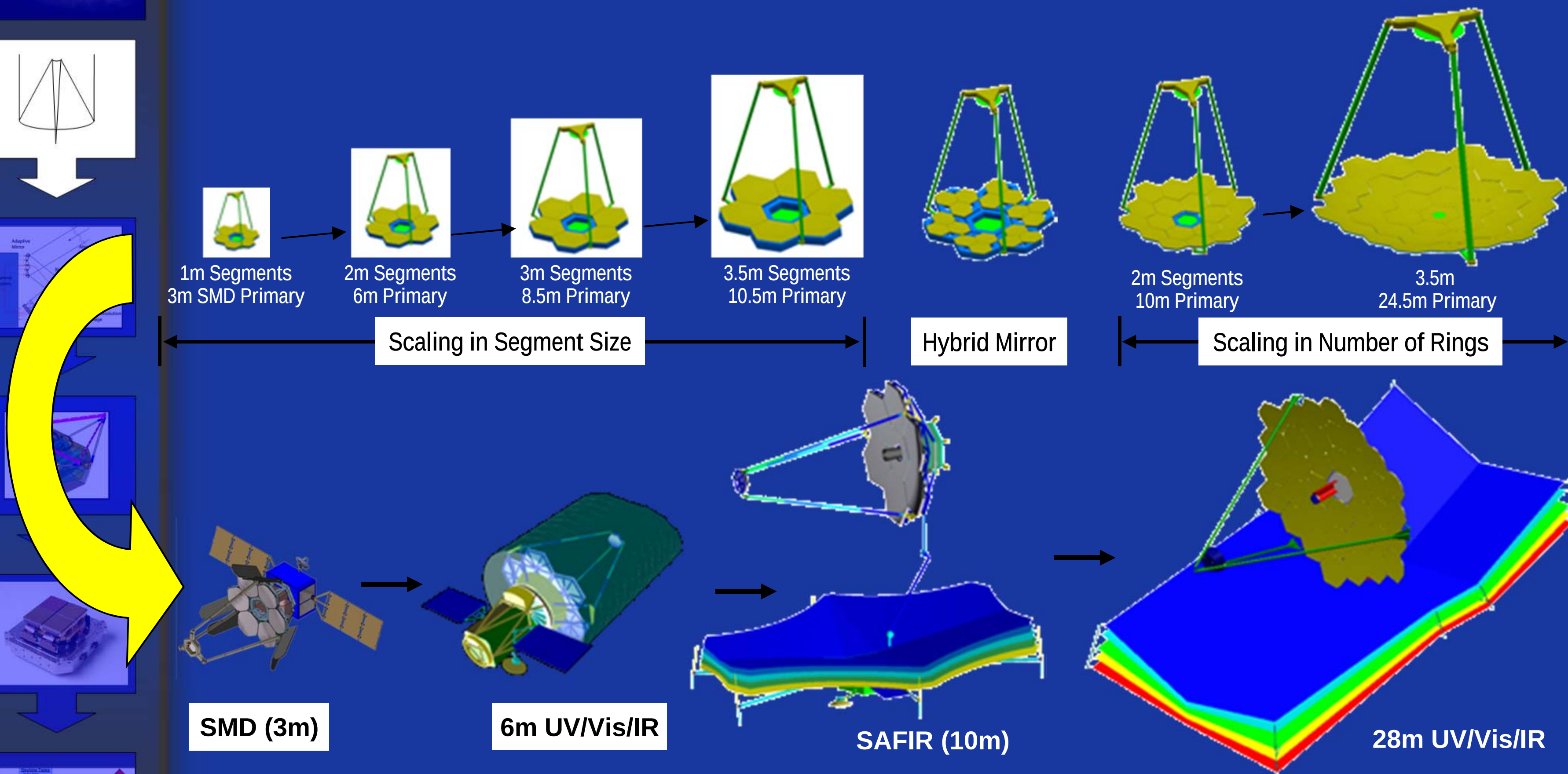
Possible Next Steps for Space Telescopes



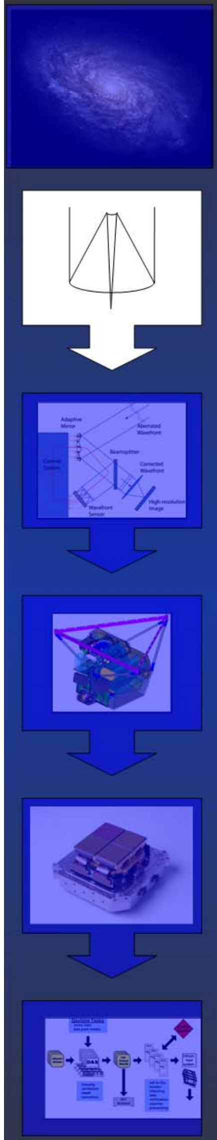
- Larger filled aperture telescopes
  - Using ARES V launcher
  - Could launch 8m monolithic mirror
- Robotic assembly of giant telescopes
- Nulling Interferometers
  - ESO: Darwin
  - NASA: Terrestrial Planet Finder

Courtesy of Jack Frassanito & Associates and Dr. Harley Thronson

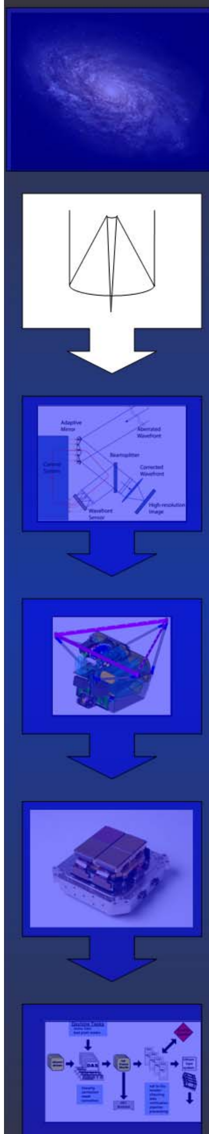
Scaling to Very Large Apertures



ARES V & 8m monolithic Telescope



Harley Thronson, NASA

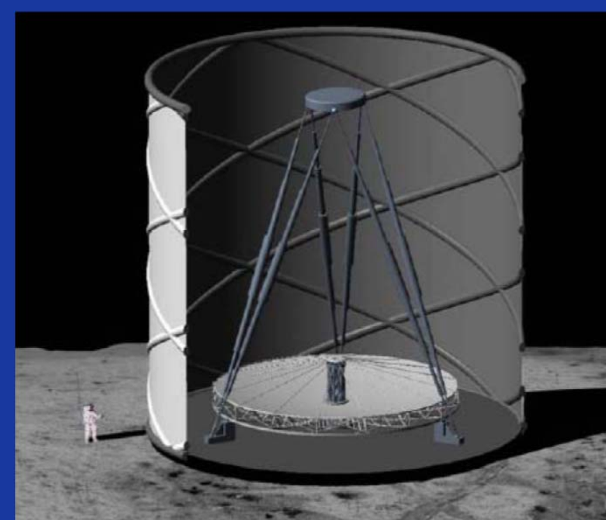


Lunar Telescopes

Roger Angel: Liquid Mirror:

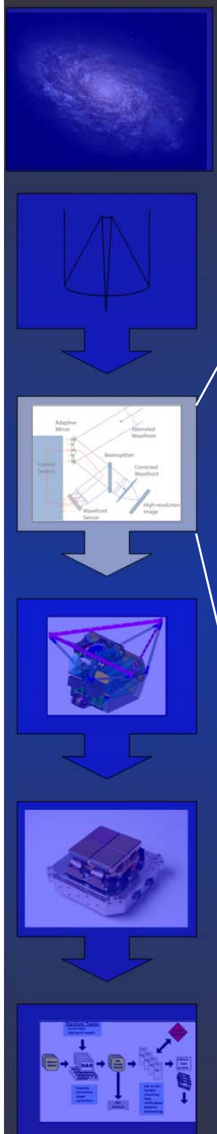
- Metal coated, low viscosity liquid
- Superconducting mag-lev bearing
- Inflating sun-shield

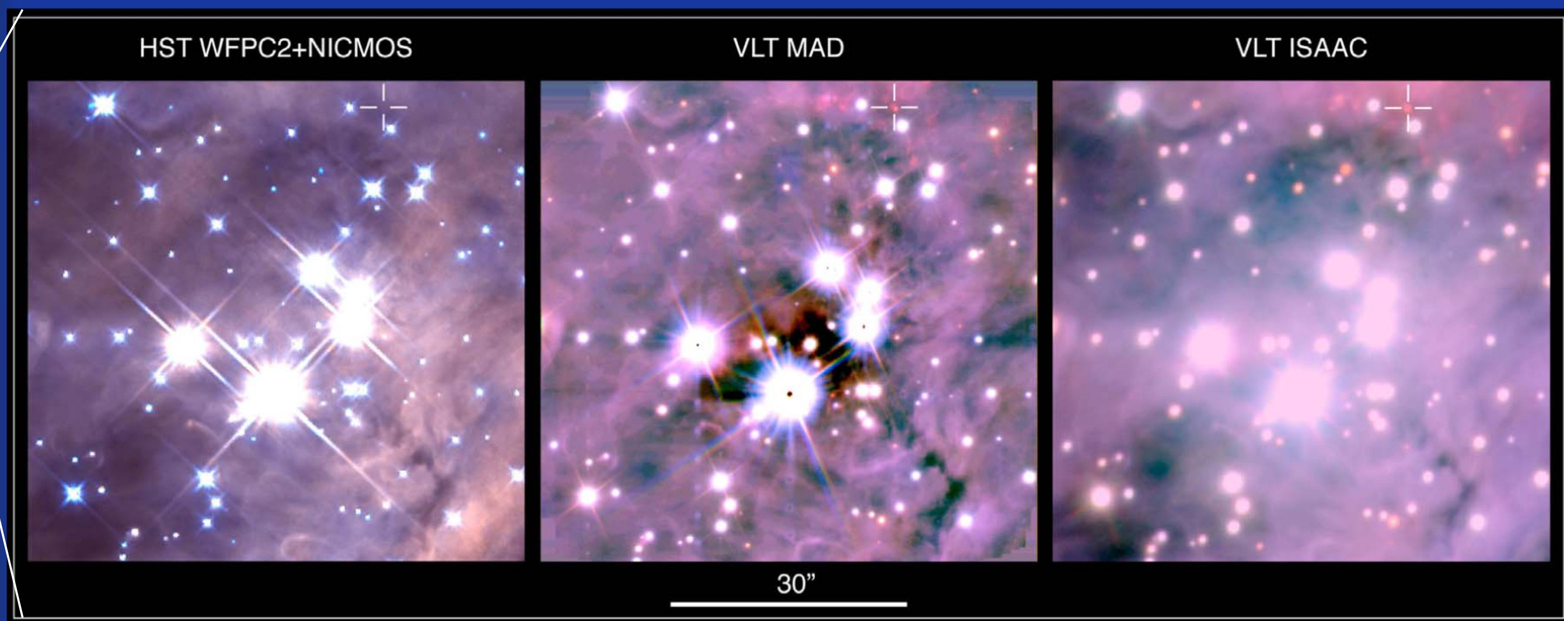
Peter Chen of Goddard has ideas for a spun cast moon dust & carbon nanotube composite mirror!



Roger Angel, Dan Eisenstein, Suresh Sivanandam, Simon P. Worden, Jim Burge, Ermanno Borra, Clément Gosselin, Omar Seddiki, Paul Hickson, Ki Bui Ma, Bernard Foing, Jean-Luc Josset, Simon Thibault, Paul Van Susante

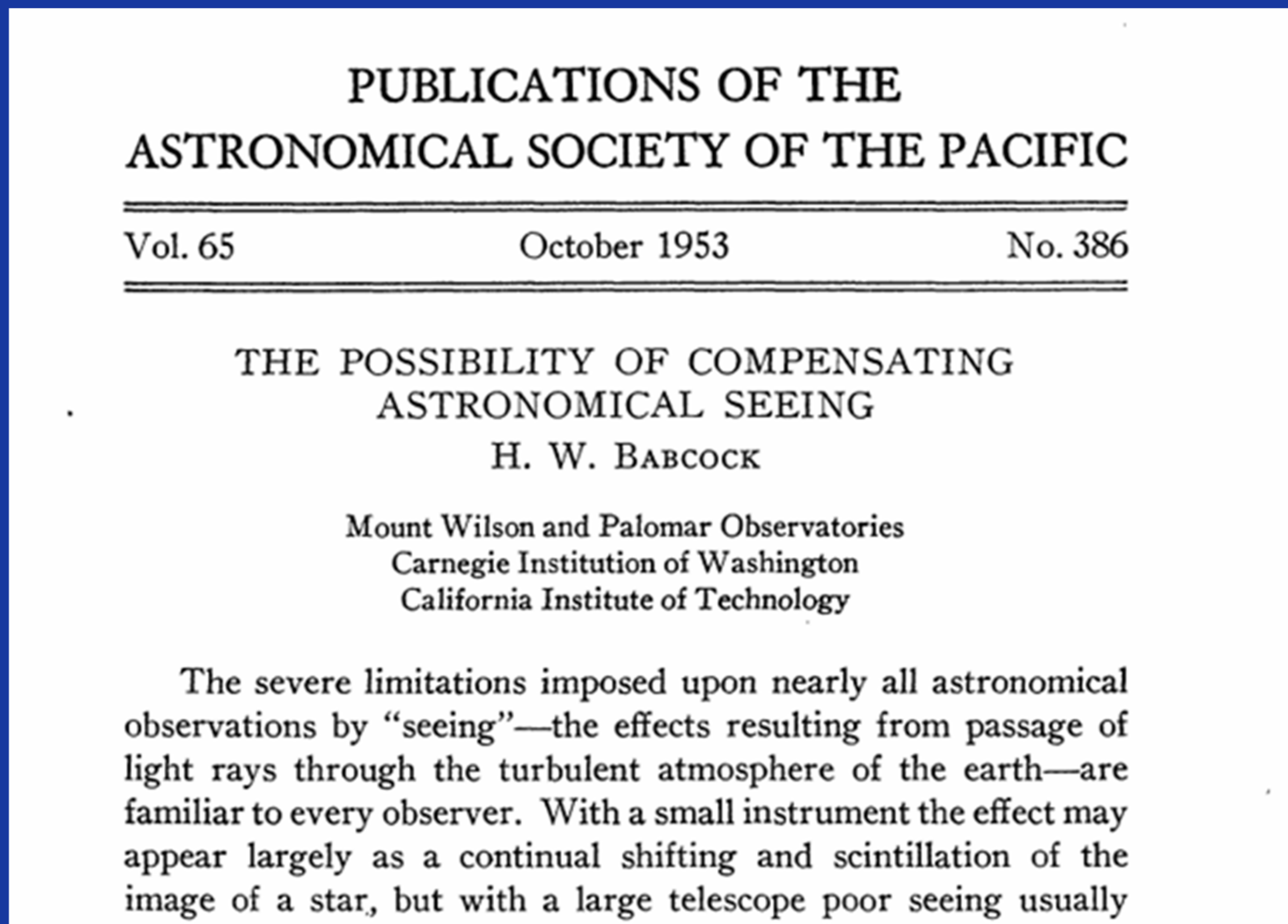
Adaptive Optics
MCAO Demonstrator





Hubble Space Telescope | VLT with MAD | VLT with no AO

Origin



PUBLICATIONS OF THE
ASTRONOMICAL SOCIETY OF THE PACIFIC

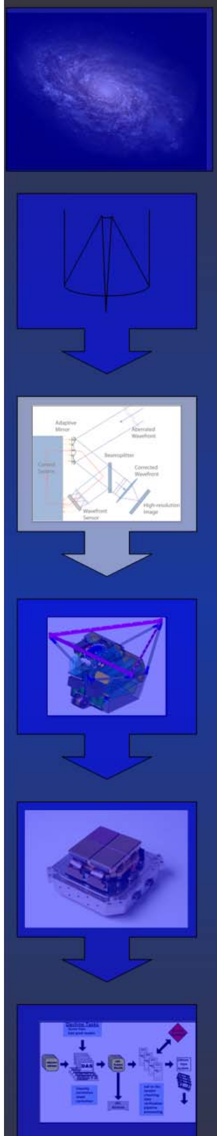
Vol. 65 October 1953 No. 386

THE POSSIBILITY OF COMPENSATING ASTRONOMICAL SEEING

H. W. Babcock

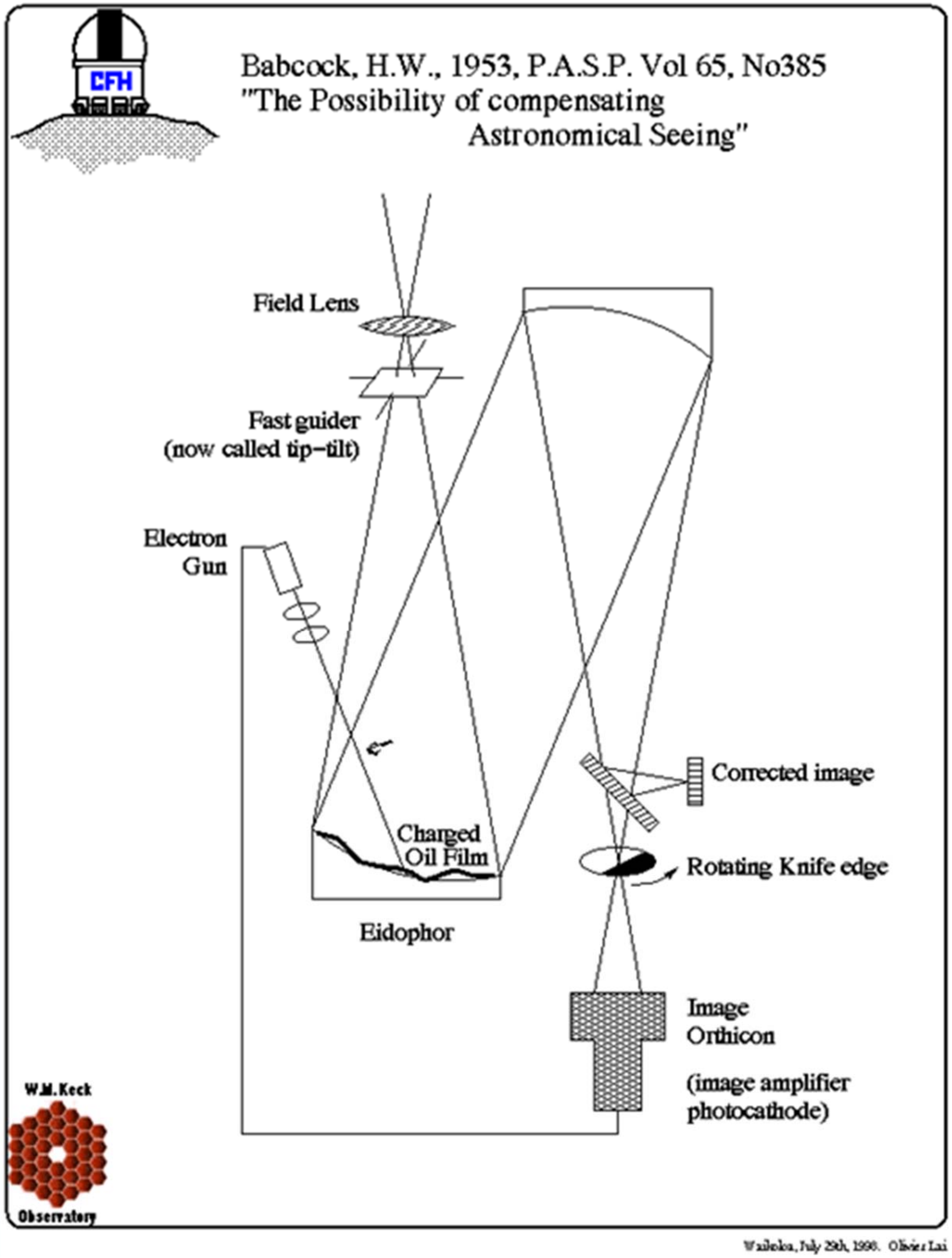
Mount Wilson and Palomar Observatories
Carnegie Institution of Washington
California Institute of Technology

The severe limitations imposed upon nearly all astronomical observations by "seeing"—the effects resulting from passage of light rays through the turbulent atmosphere of the earth—are familiar to every observer. With a small instrument the effect may appear largely as a continual shifting and scintillation of the image of a star, but with a large telescope poor seeing usually

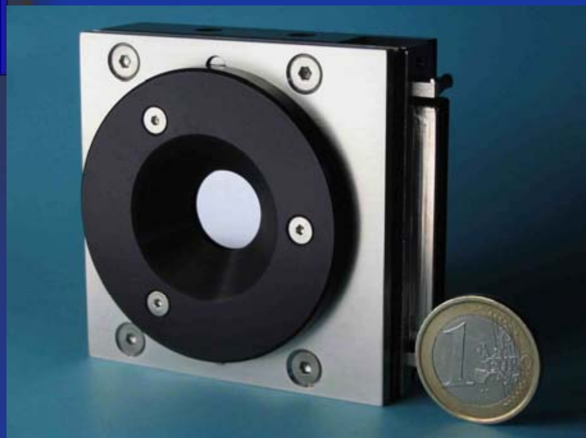


55 Years of Adaptive Optics

First Proposed by Horace Babcock



Critical Technology: High density Deformable Mirrors

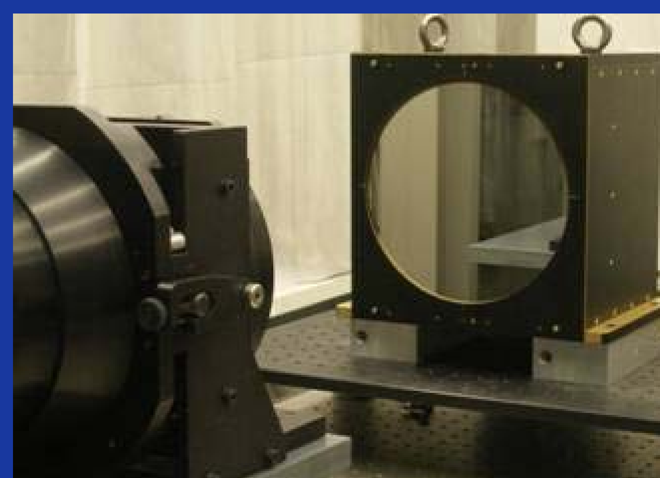


Magnetic DM

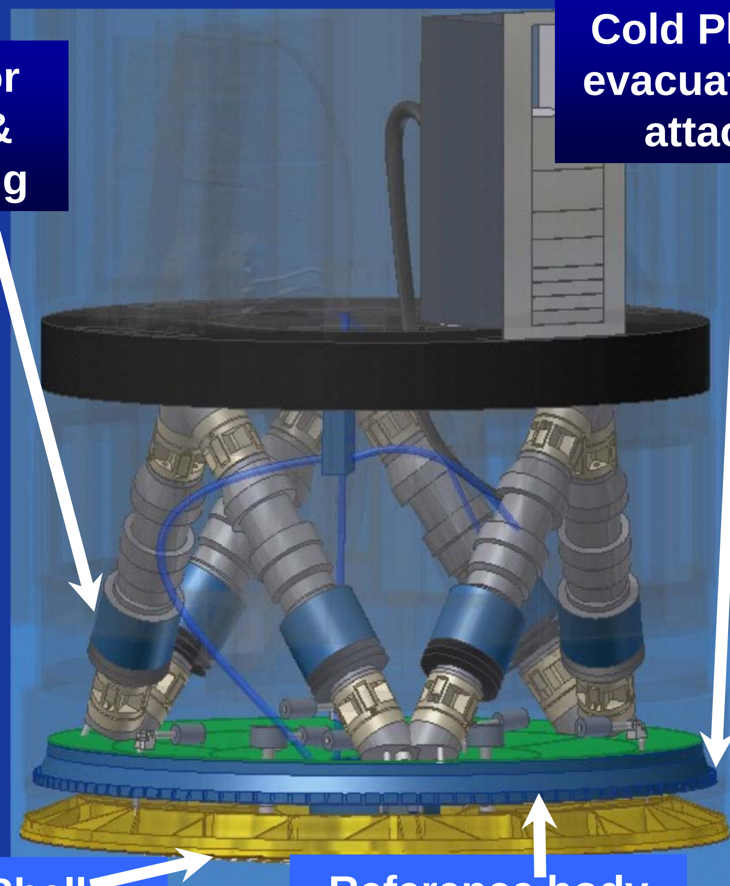
- Integration of MEMS and micro-mechanics
- Presently 52 actuators
- Large stroke: up to 100 µm
- Pitch 2mm
- Best flat better than 5 nm
- Aiming to 50 > 100^2 actuators

CILAS Piezo Stack DM

- 41x41 = 1370 actuators,
- 4.5 mm pitch
- 9µm stroke DM



Critical Technology: Large Adaptive Mirrors



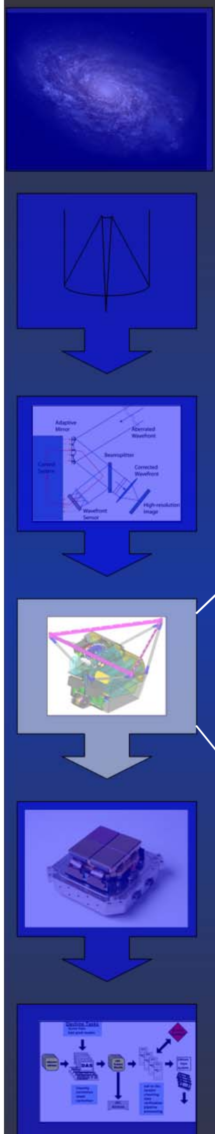
Voice coil force actuators
with capacitive position feedback

New Materials may help!

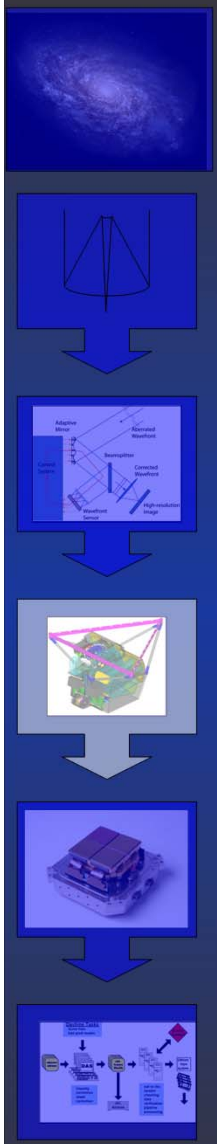
VLT
- 1.1 m Convex
- 1170 actuators
- 29 mm pitch
- 1 ms response
- Stroke <100 μm

European ELT
- 2.5 m Flat
- 5000 actuators
- 30-50 mm pitch
- 1 ms response
- Stroke 25-90 μm

Instruments



VISTA 64 Mpixel IR Camera



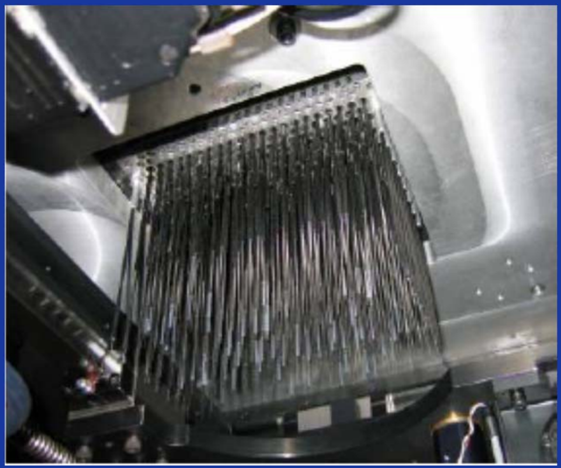
Instruments

- What are the fundamental measurements we do in optical/IR astronomy?
  - Measure intensity and energy of electromagnetic radiation – photons

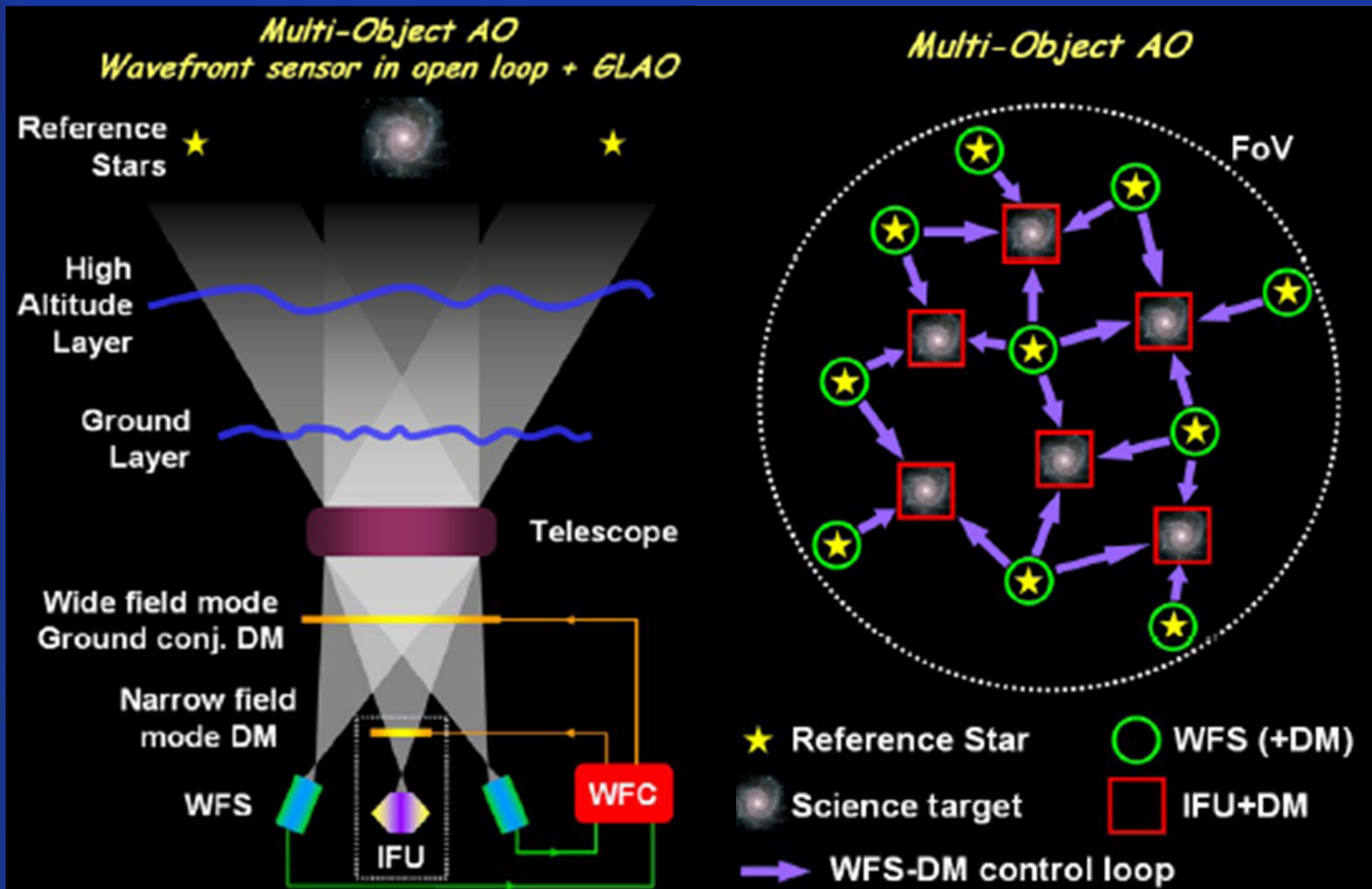
    (And sometimes the amplitude & phase)
  - Divide spectrum up in space or time by dispersion, filtering, Fourier Transform, Fabry-Perot
  - Spatially sample an appropriate field of view
  - **Sounds easy!**

Novel Technologies: Smart Focal Planes

- Make best use of available wide FoV by multiobject and integral field spectroscopy
- Provide alternative to fibre systems for cryogenic infrared instruments

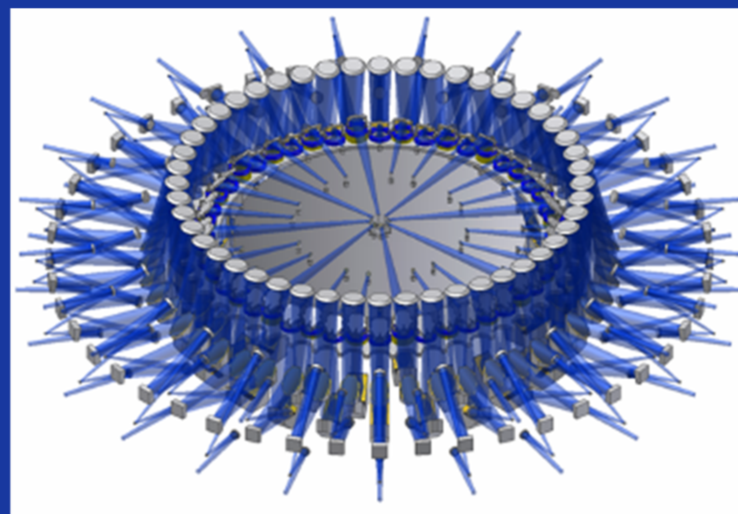


Multi Object Adaptive Optics



Object Selection

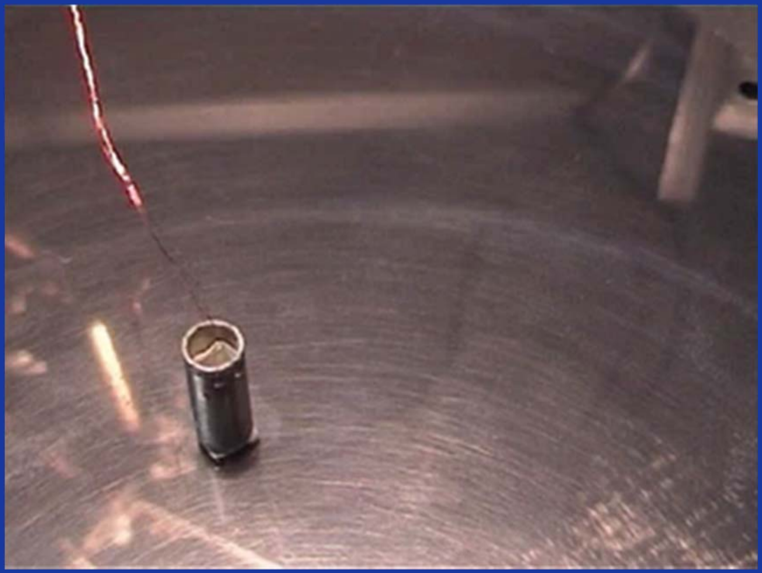
- Options:
  - Pickoffs feeding Integral Field Units and spectrometers
  - Slit exchangers or reconfigurable slits
  - Fibre positioners



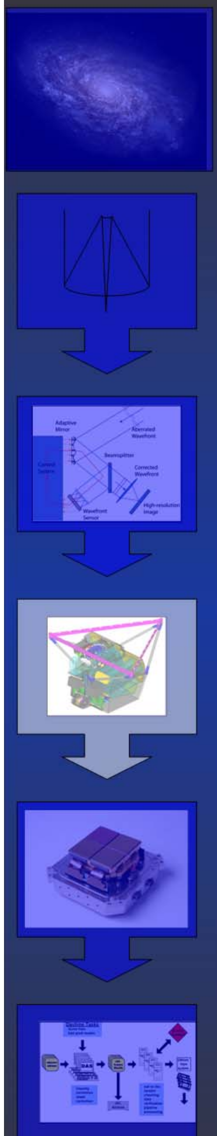
- EAGLE Multi object, multi IFU spectrometer for E-ELT
- Built in Multi Object AO

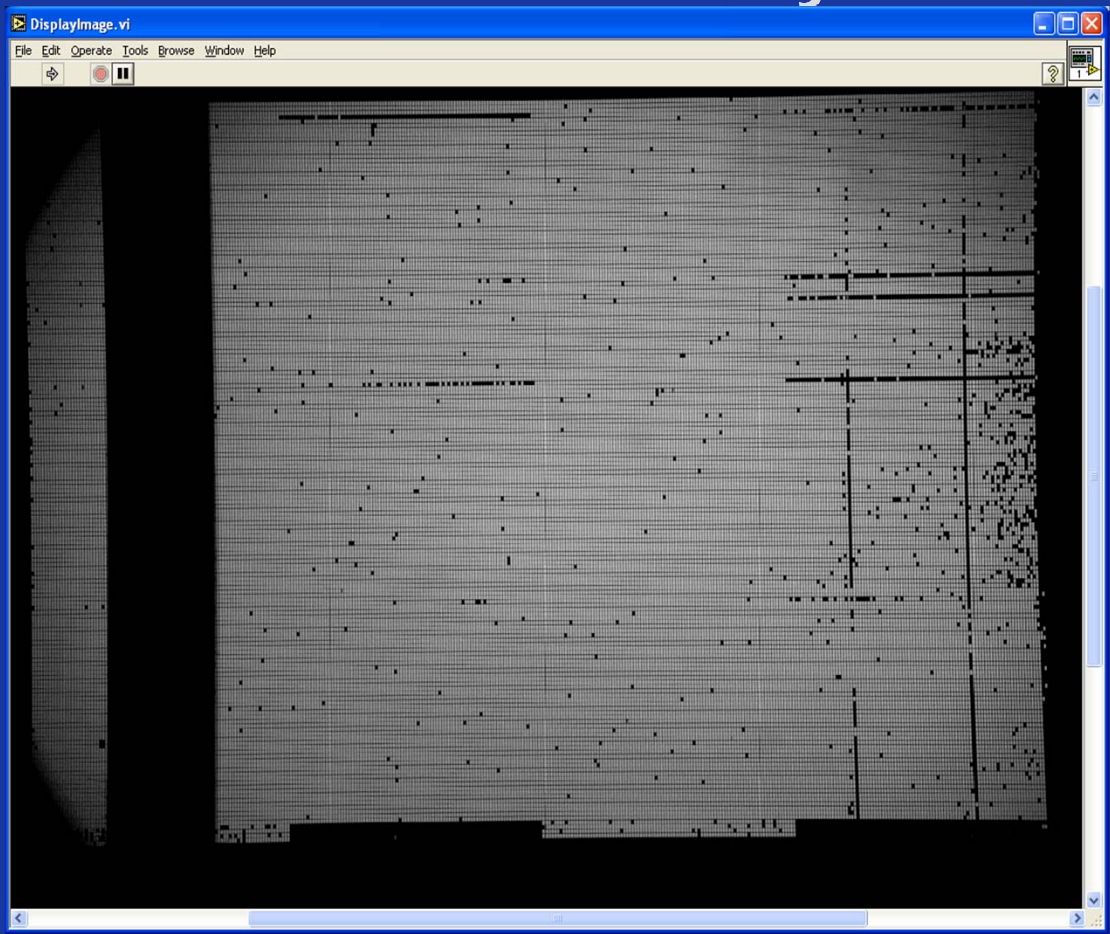
  (UK ATC, Durham, LAM, Meudon, ONERA)

Starbugs & Starpicker

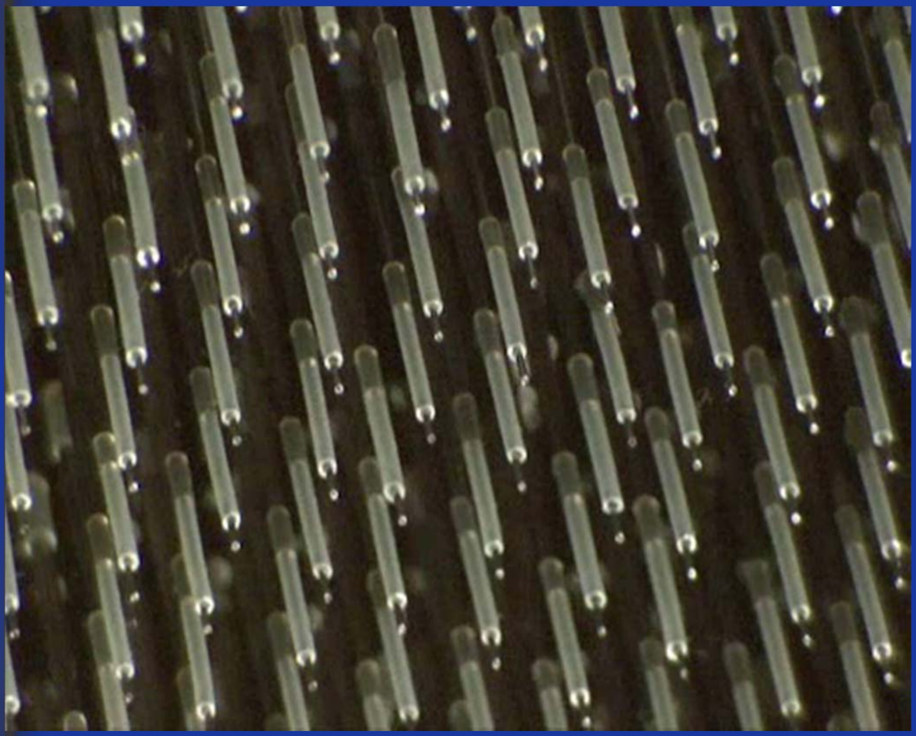


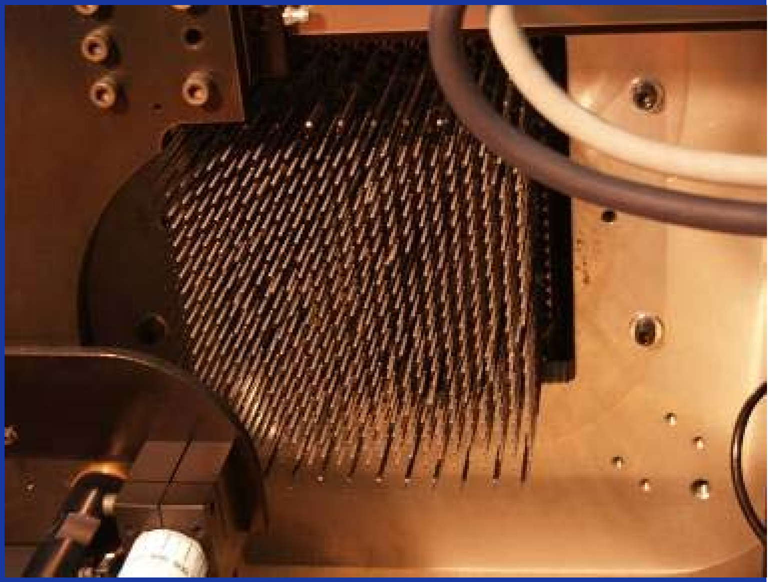
Programmable Slit Spectrometers: MOEMS Shutter arrays



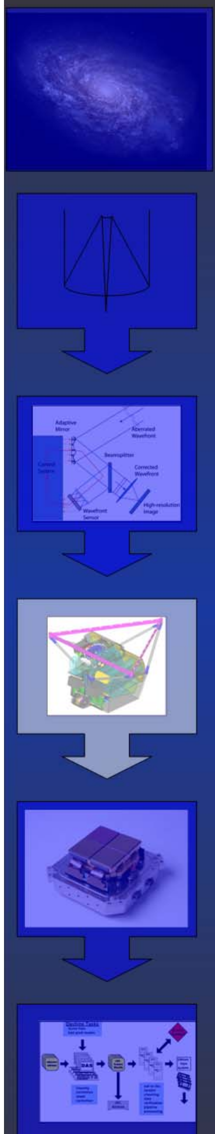


FMOS Echidna: Under testing for SUBARU





Smart Focal plane with 480 fibres.



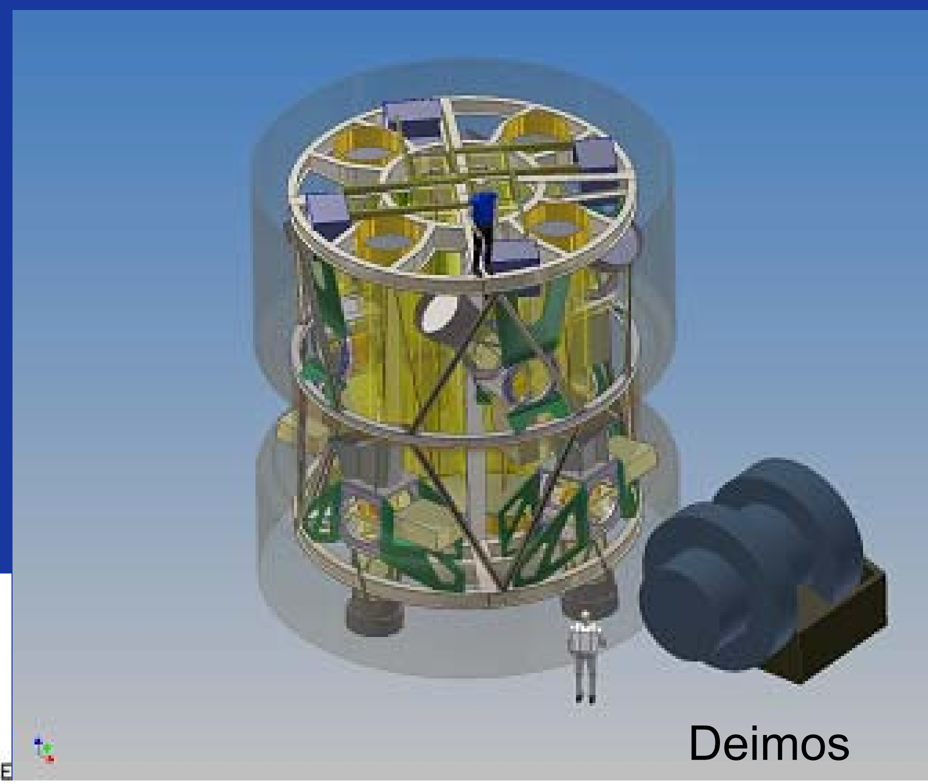
Size of seeing-limited ELT instruments!

WFOS Wide Field Optical Spectrograph

– 8m diam x 10m high

– Size of an 8m telescope!

TMT
THIRTY METER TELESCOPE



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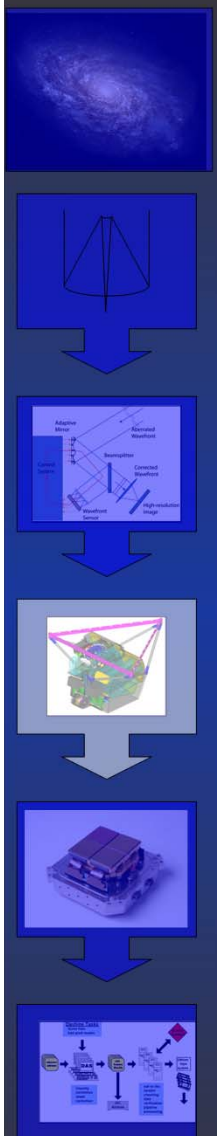
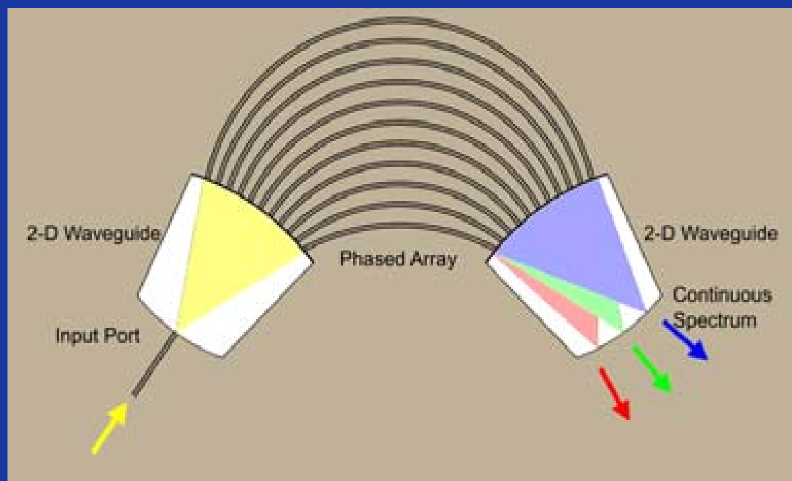


Photonic devices

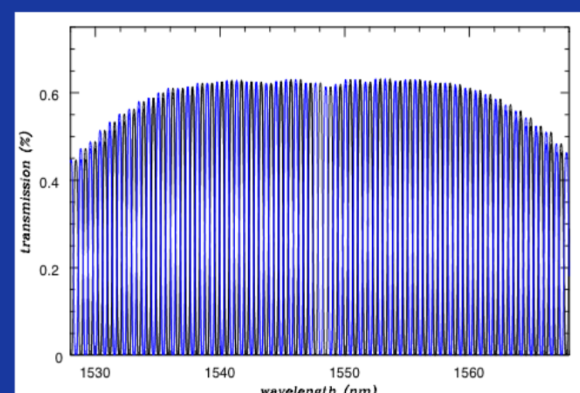
- Devices developed for communications and industrial instrumentation are being investigated for Astronomy:
  - Bragg Gratings
  - Photonic (crystal) fibres
  - Waveguide Beam combiners
- These technologies could be combined with an integrated detector to make compact integrated spectrometers, with built-in OH suppression
- Could we build 1000 spectrometers with integrated detectors to build compact & cheaper multi-object instruments?
- Move them around the focal plane on miniature robots

Example: Array Wave Guide devices

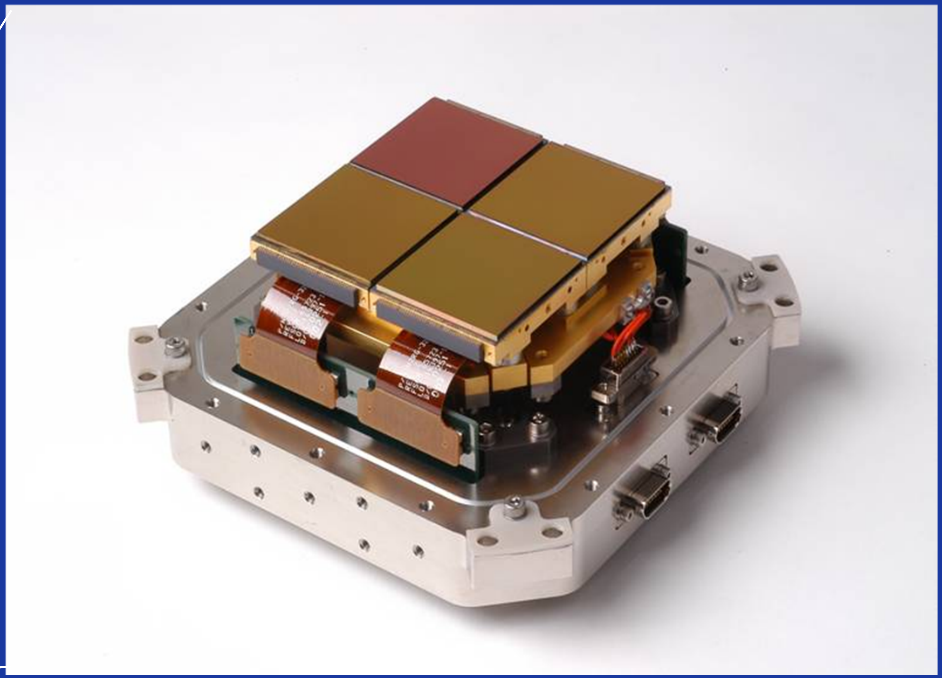


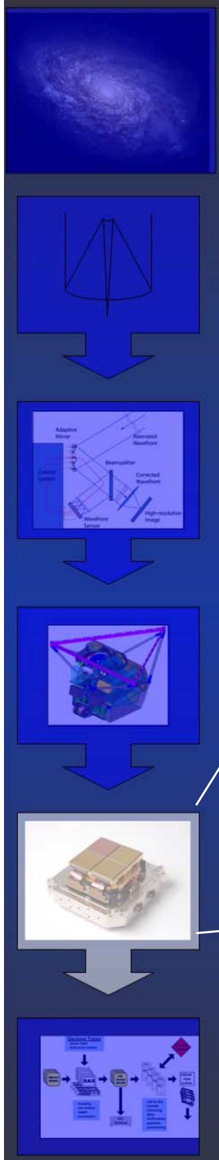
7.5 cm, R=4000

AAO Newsletter Aug 07
Instruments without optics: an integrated photonic spectrograph (Joss Bland-Hawthorn & Anthony Horton)



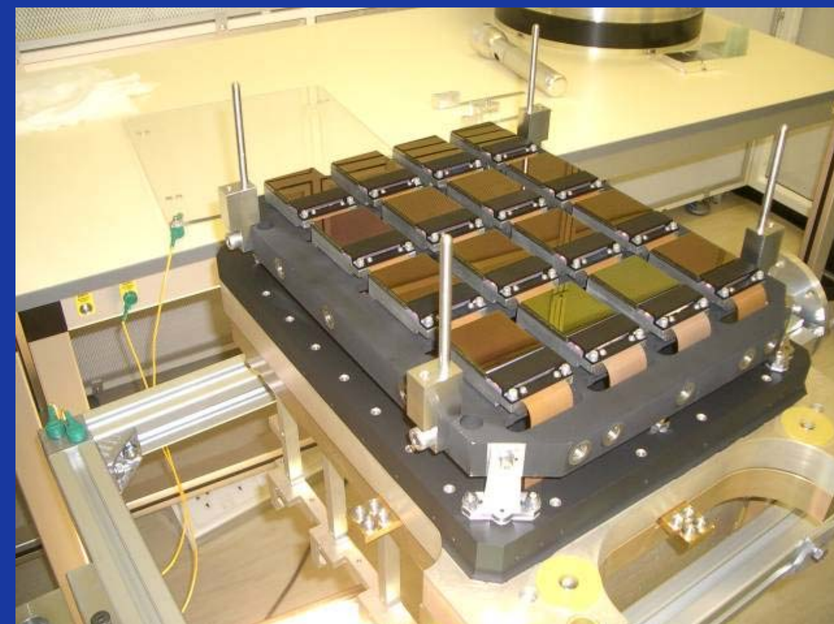
Detectors





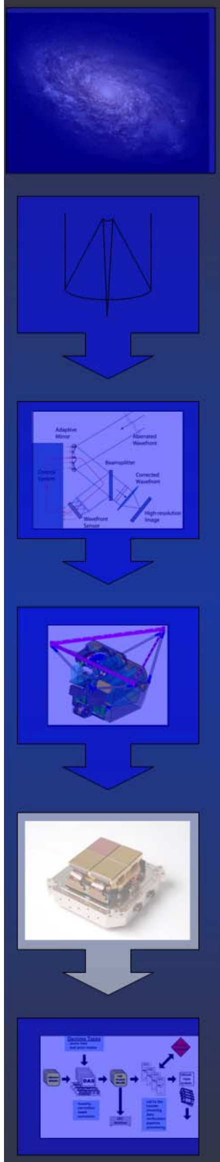
Detectors

- Needs:
  - Bigger, cheaper, better!
- E-ELT will need 60 -100 2kx2k IR arrays
- Lower noise would be good!
- James Webb Space Telescope shows how IR detector performance can be pushed by astronomy
  - But at high cost



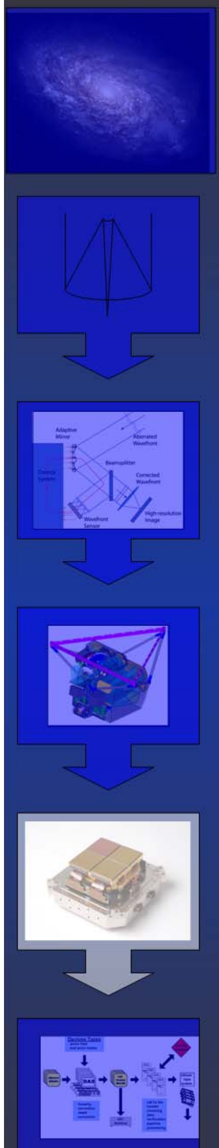
16 2kx2k Raytheon Arrays in VISTA

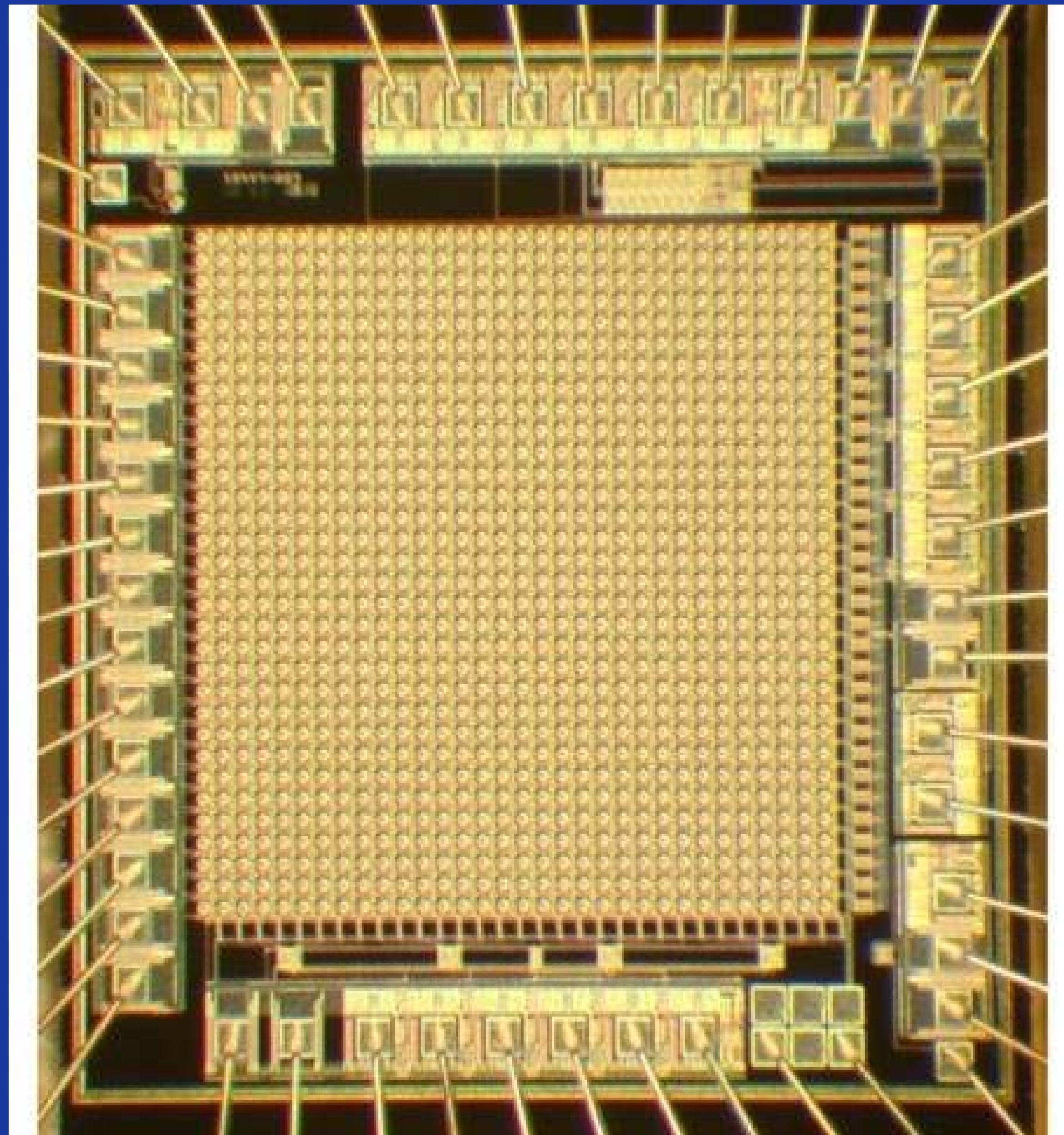
High time resolution



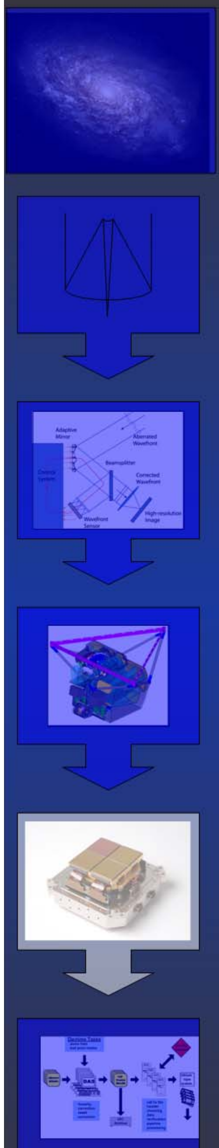
- **On timescales of milliseconds**
  - study the optical emission from pulsars.
  - optical analogue of the kilohertz quasi-periodic oscillations and related small-scale accretion phenomena found in X-ray binary stars (XRBs)

Accretion processes in an XRB. Artwork by Catrina Liljegren, *Bild & Form*, Lund; ©Dainis Dravins, Lund Observatory.



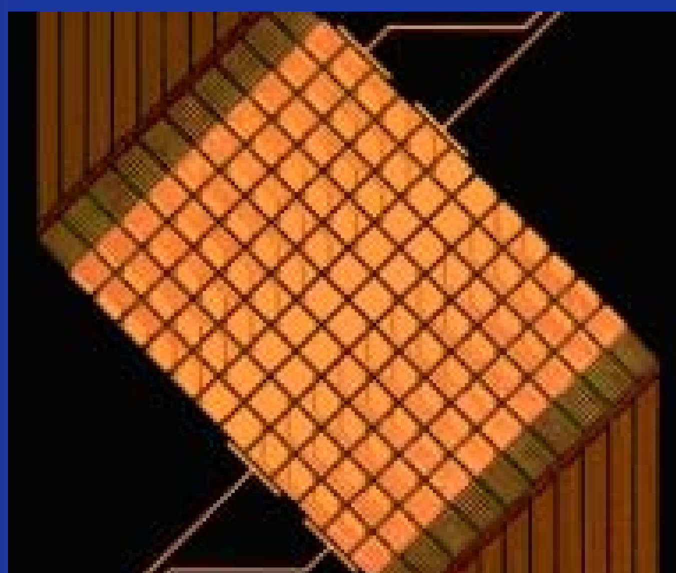


32x32 Single Photon Silicon Avalanche Diode Array
Quantum Architecture Group, *L'Ecole Polytechnique Fédérale de Lausanne*



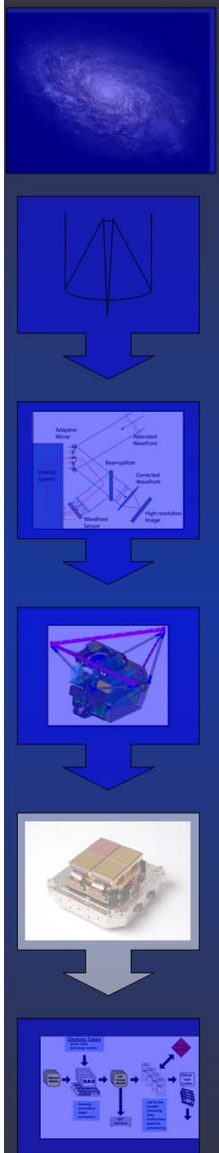
Energy resolving detectors

- Superconducting Tunnel Junctions
- ESA's S-CAM

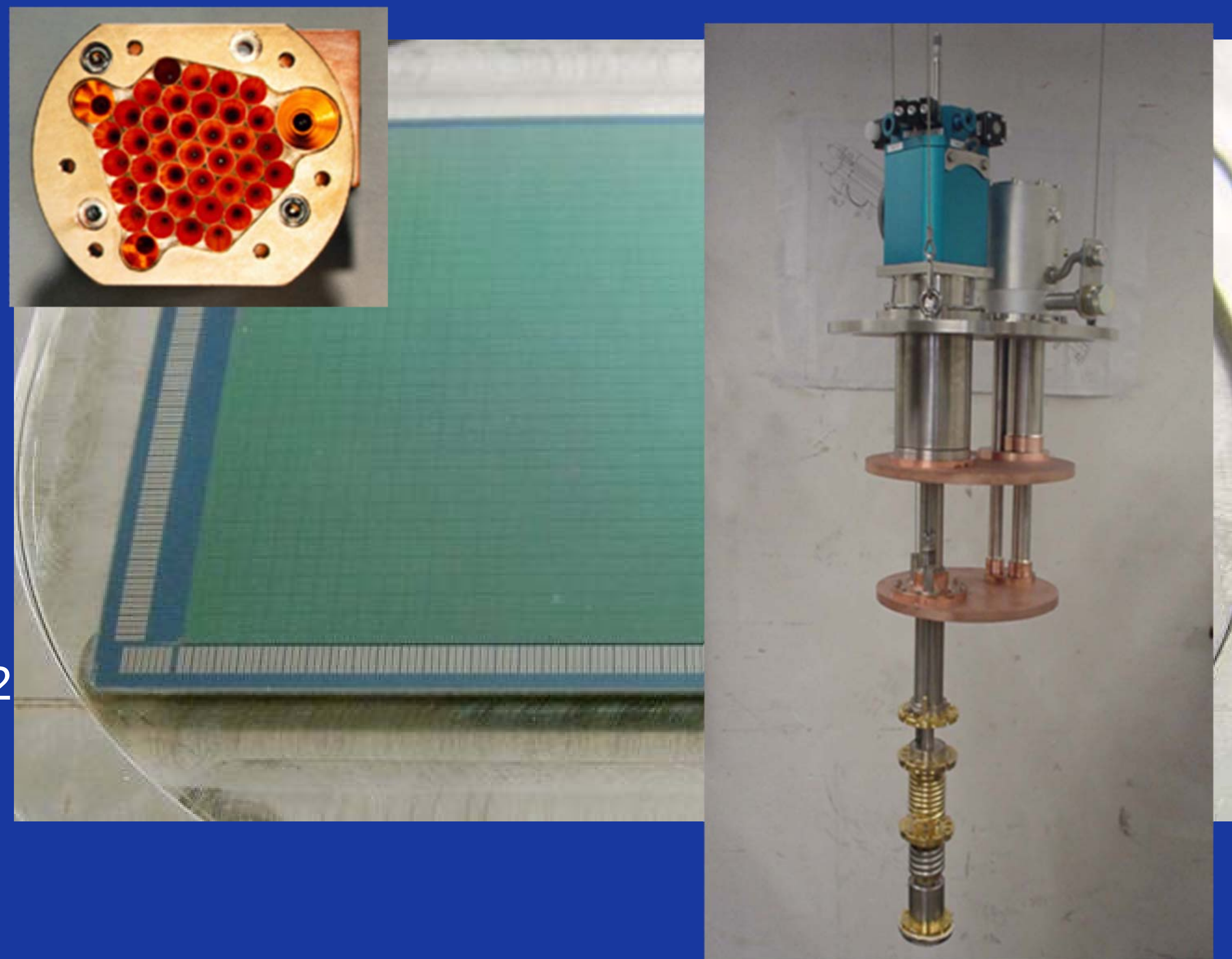


Detector	12x10 Ta/Al STJs
Pixel size	33 x 33 μm^2
Fill factor	76%
Plate scale	0.8"/pixel
FOV	11"x9"
Pass band	330-745 nm
Maximum detection efficiency (@500nm)	30%
$\lambda/\Delta\lambda$ @ λ=500nm	8-11
Event time resolution	~5 μs
Operating temperature	285 mK

Transition Edge Superconducting Detector Arrays

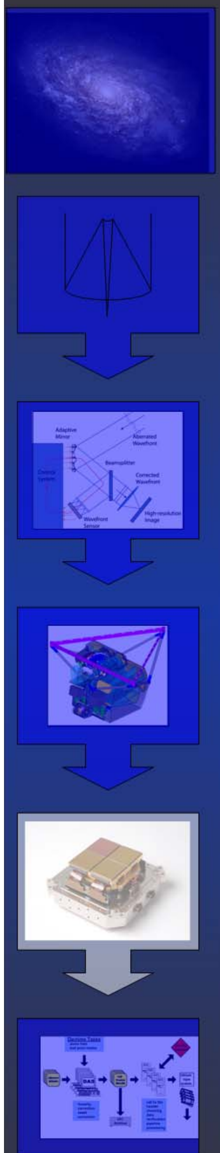


SCUBA
850µm array
(same pixel scale)



Completed
40   32
(1280) pixel
array
for SCUBA 2

UK ATC, NIST, U of Edinburgh &
Cardiff



Other novel detectors….

- Quantum dots
- Quantum Well Interference Photodetector (QWIPs)
- Quantum Well Intrasub-band Photodetector (QWISP)
- Carbon nano-tubes?
  - Bolometers or photodetectors
- Kinetic Inductance Devices
- Single Electron transistors
- Smart Active pixels

Science & Technology Facilities Council
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Key Technologies for Optical/IR Astronomy

- Next 5-15 years – my view:
  - Formation flying
  - Heavy Launch Vehicles
  - Large and small high-density deformable mirrors
  - Laser Guide Stars
  - Smart Focal Planes
  - OH sky line suppression devices
  - Fast detectors
  - Lower noise (and cheaper!) NIR detectors
  - Free-form aspheric optics
  - Lightweight mirrors
  - Photonic Fibres
  - Laser Comb calibration sources
  - IR optimised fibres
  - Photonic beam combiners
- What are the priorities & what can we afford to develop?
  - Should be driven by science & facility needs
  - And what we can get from developments outside astronomy

What will the Disruptive Technologies of the future be?

?

By definition – impossible to answer!

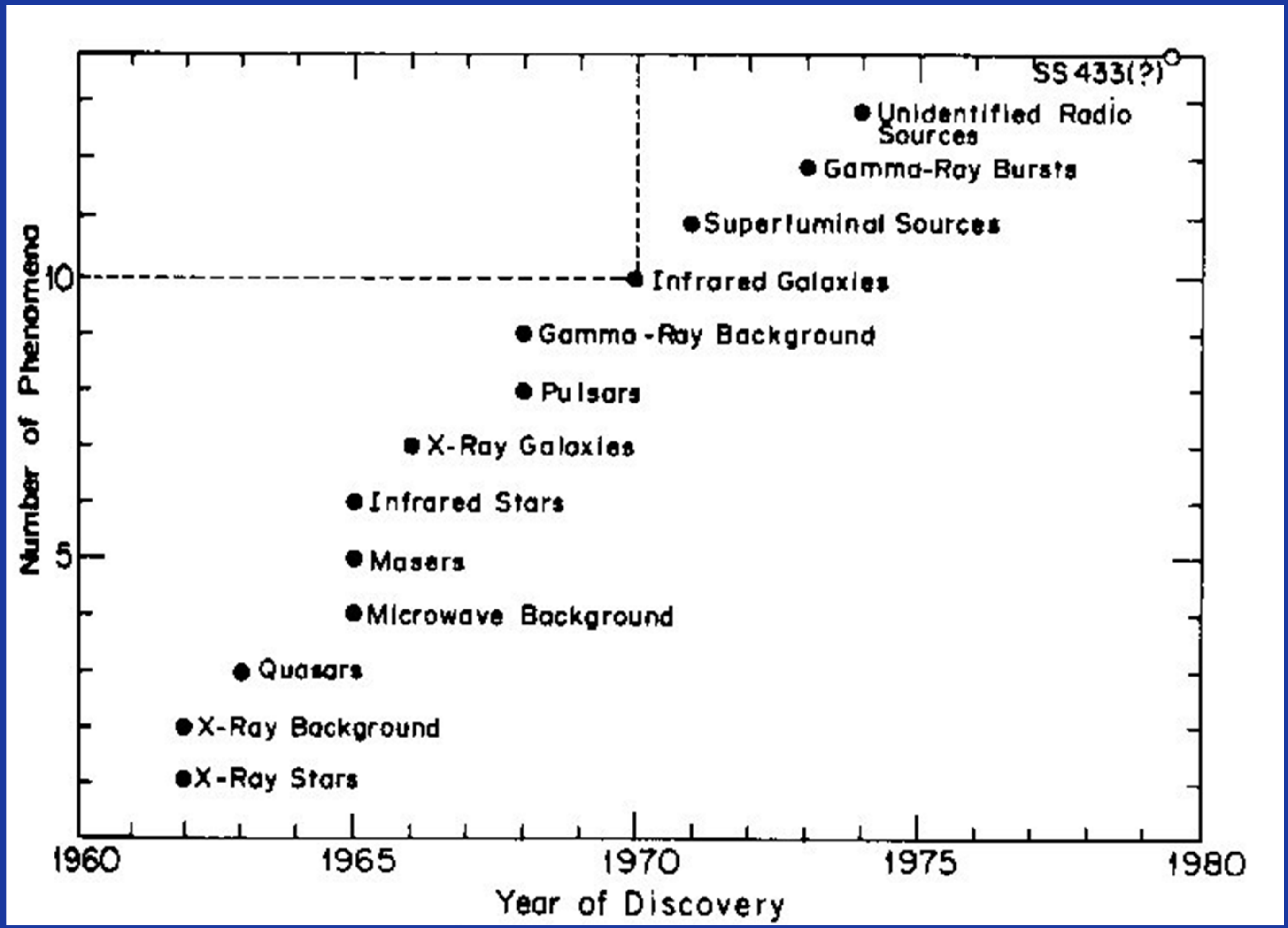
Let's try anyway!

- Photonics:
  - OH Suppression Devices – big improvements in ground–based NIR sensitivity
  - Swarms of Robotic Micro-Spectrometers
- Energy Sensitive Detectors
  - No dispersion elements
- Robotic Assembly of Space Telescopes
  - Very large aperture
  - Interferometers

Where will the new parameter space be, when we have JWST, ELTs & Space interferometers?

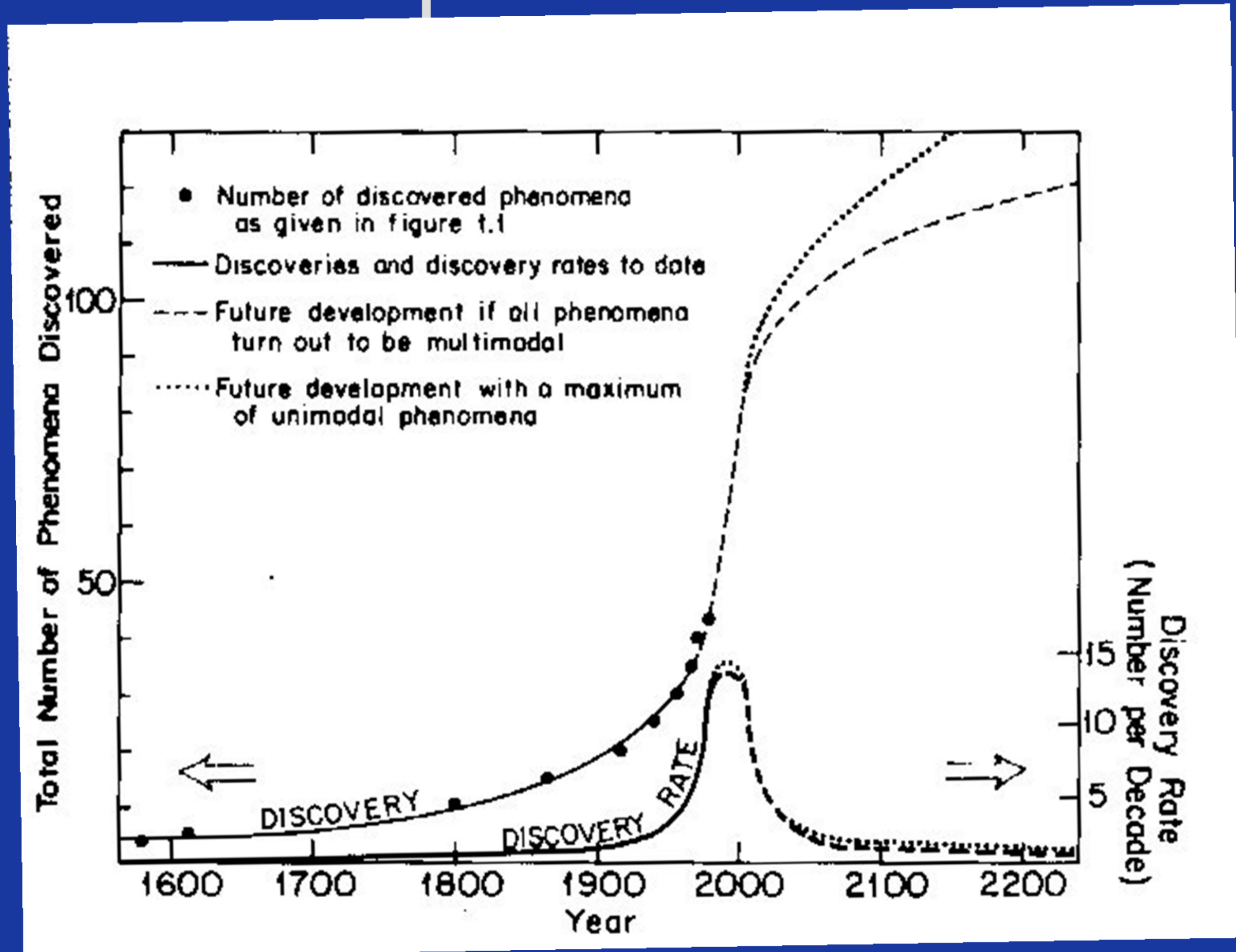
- Will it be:
  - More sensitivity
    - Bigger, colder telescopes
  - Higher spatial resolution
    - Interferometry
    - Larger Aperture
    - Better adaptive optics
  - High contrast imaging & spectroscopy
  - High time resolution
  - Wider field…
- Where will the balance be: Space/Ground?
- 'Wide Field Surveys and Astronomical Discovery Space' Andy Lawrence (Astronomy & Geophysics, 2007)
  - *Most parameter space is full, or too expensive to extend, except high time resolution and neutrinos!*
- See Martin Harwit's *Cosmic Discovery* from 1981

Martin Harwit's prediction in 1981



Cosmic Discovery, 1981

Martin Harwit's discovery rate prediction



Where will Astronomy be in 50 years: 450th anniversary of Lipperhey?

Astronomical Telescopes and Instruments in 2058 ?

- Will we have run out of astronomical discoveries to be made at affordable cost?
  - Is there a law of diminishing returns?
- Or will we have:
  - Nano engineered membrane telescopes
  - Swarms of robotic integrated photometers
  - Interferometers with integrated photonic instruments using detectors measuring intensity, energy and polarisation?
  - Or a liquid mirror telescope on the moon?
- Or a larger version of what we are planning now?
  - ELTs up to 100m – OWL-like?
    - On a cold/high site – Antarctica?
    - With instruments like today's ?
  - 15 – 25 m segmented space telescopes
- Radio Arrays take over – SKA ?
- Or will discovery space not be from Electromagnetic Wave detection but with Gravitational Wave or Neutrino observatories?

Economic and Resource Impacts

- Will the Golden Age of Astronomy be over – due to resource crises, global warming, financial meltdown?
- Will governments, the public and benefactors run out of patience with investment in bigger and bigger facilities?
  - Are we already seeing such a fatigue in space missions – and particle physics?
- But what about the ambitions of China and India?
  - at present these are mostly aimed at non-astronomy space projects

Let’s be optimistic! New York Times – 2057


The New York Times

$6.59

Vol XIIVCCMM, No 1005100 NEW YORK, November 13, 2057

New Eden Planet Found

Astronomers say they have found a new planet in orbit around a star light years from Earth. The planet is so similar to Earth, it is being called “New Eden.”

The discovery ipsum dolor sit amet, consetetur sadipscing elitr, sed diam nonumy eirmod tempor invidunt ut labore et dolore magna aliquyam erat, sed diam voluptua.

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NASA

Planet hunters say the system has many similarities to our own.

Behind the Great Discovery

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100 Years after Sputnik

Jim Crocker, Lockheed Martin

LOCKHEED MARTIN

Science & Technology Facilities Council
UK Astronomy Technology Centre

Ares V and 8m Monolithic Telescope

Harley Thronson, and NASA Future In-Space Operations working group