

Detectors for Astronomy and Astrophysics : towards a Roadmap

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SCOPE

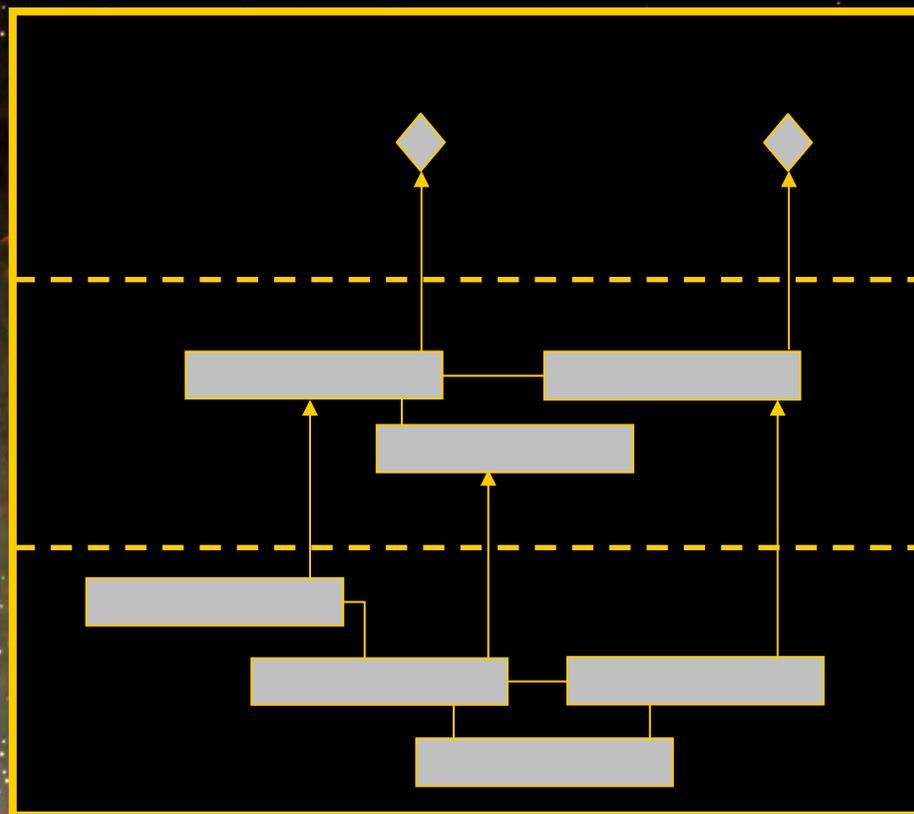
- Astronomy & Astrophysics
- Not Solar System or Particle Astrophysics
- X-ray to submm
- Space & Ground-based

Technology Planning: Roadmap

Science Goals

Facility, Mission or Instrument

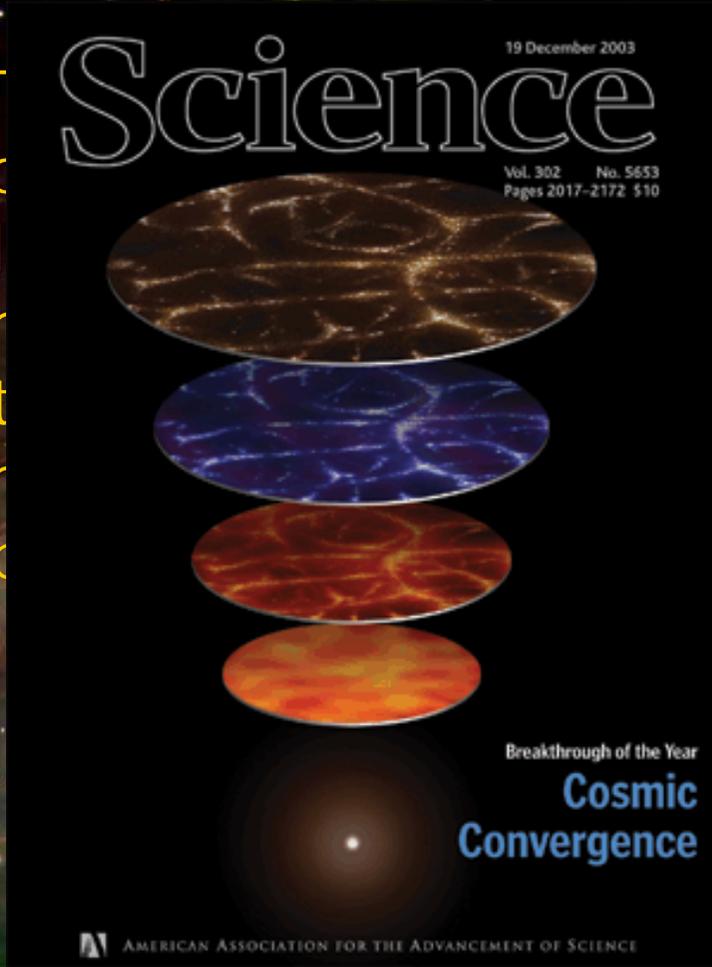
Technology



Major Science Drivers

- Cosmology
- Dark Energy, Dark Matter
- Extreme Astrophysics
- Star and Planet Formation
- Astrobiology & Exoplanets

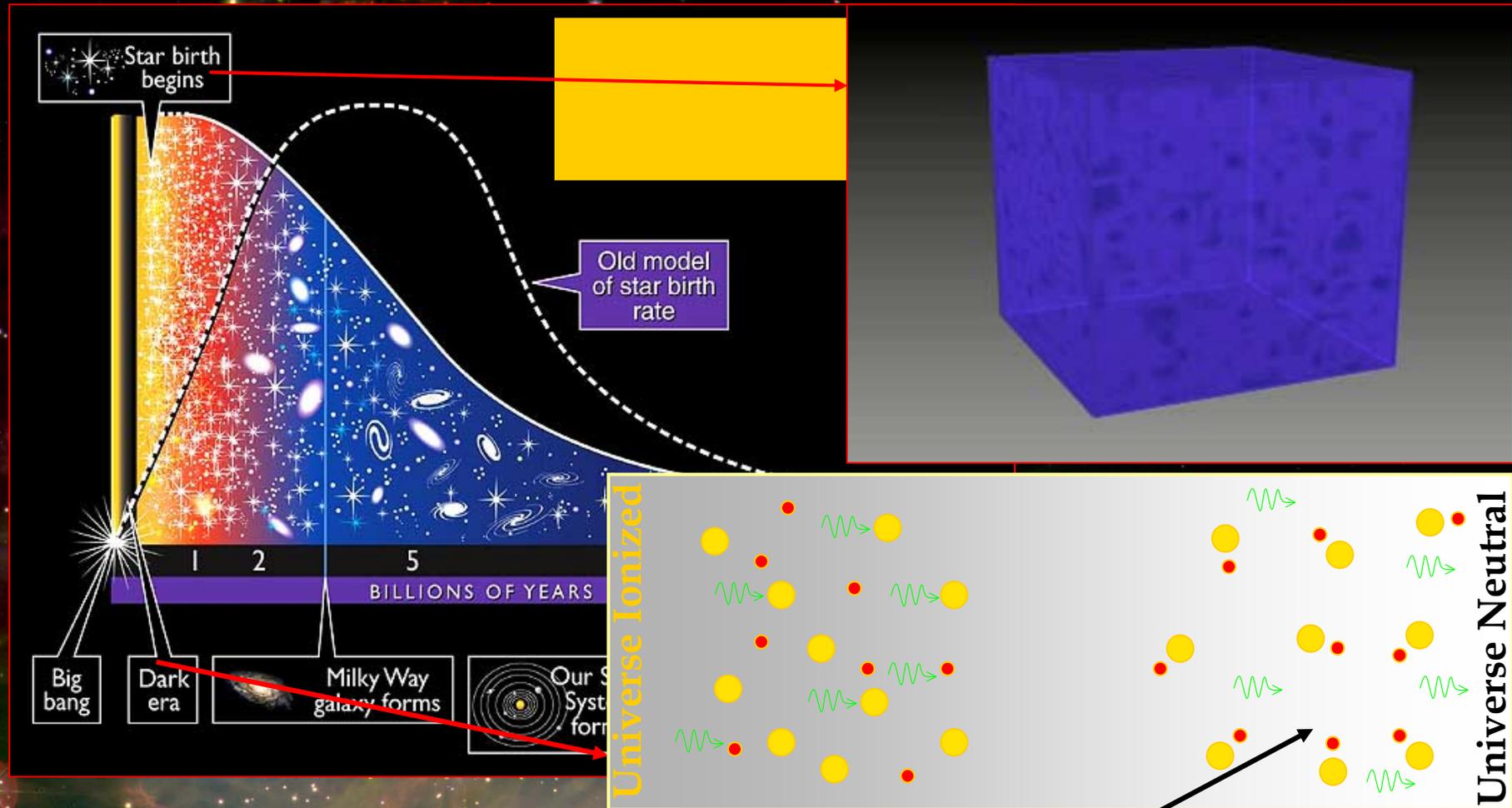
Origins of Galaxies and structure of the Universe



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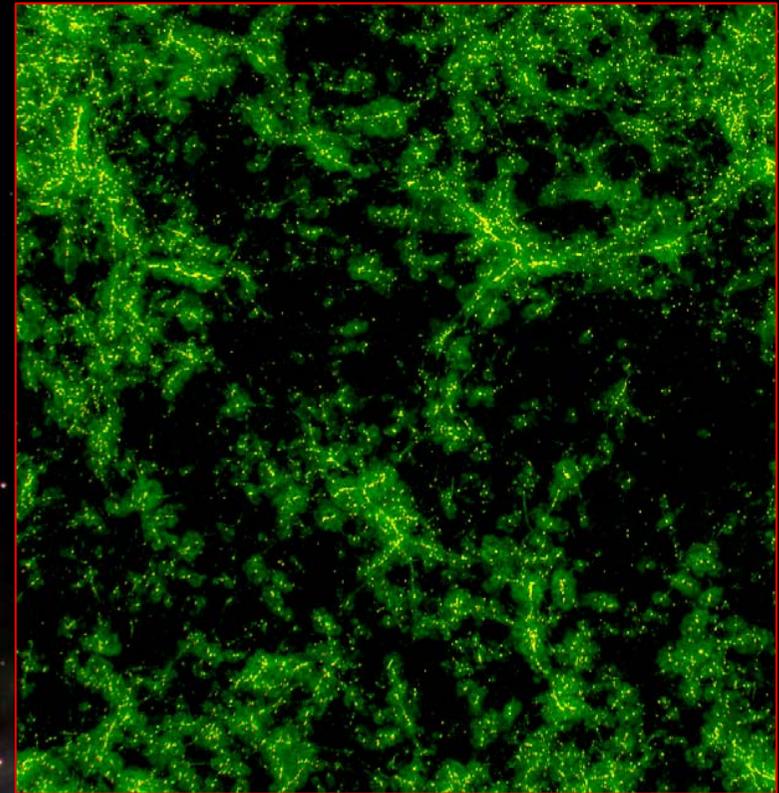
Key Epochs in the Early Universe



Photons from this scattering surface are what we now see as the Cosmic Microwave Background (CMB)

"First Light" in a Dark Universe

- Using current and/or next-gen telescopes, we will, for the first time, detect the first luminous objects in the universe – the "First Light"
- The light from these distant objects is red shifted to $1-2 \mu\text{m}$, hence the need for large format, low noise, NIR detectors in the future



**Simulation of an Ultra Deep
NIR Image of the First Stars**

Planet Finding & Astrobiology

- Challenge:
 - All exo-planets found so far are gas giants
 - Find earth-like planets
 - Search for bio-markers

THE PROBLEM:

Speckle illustration from ESO VLT-PF study

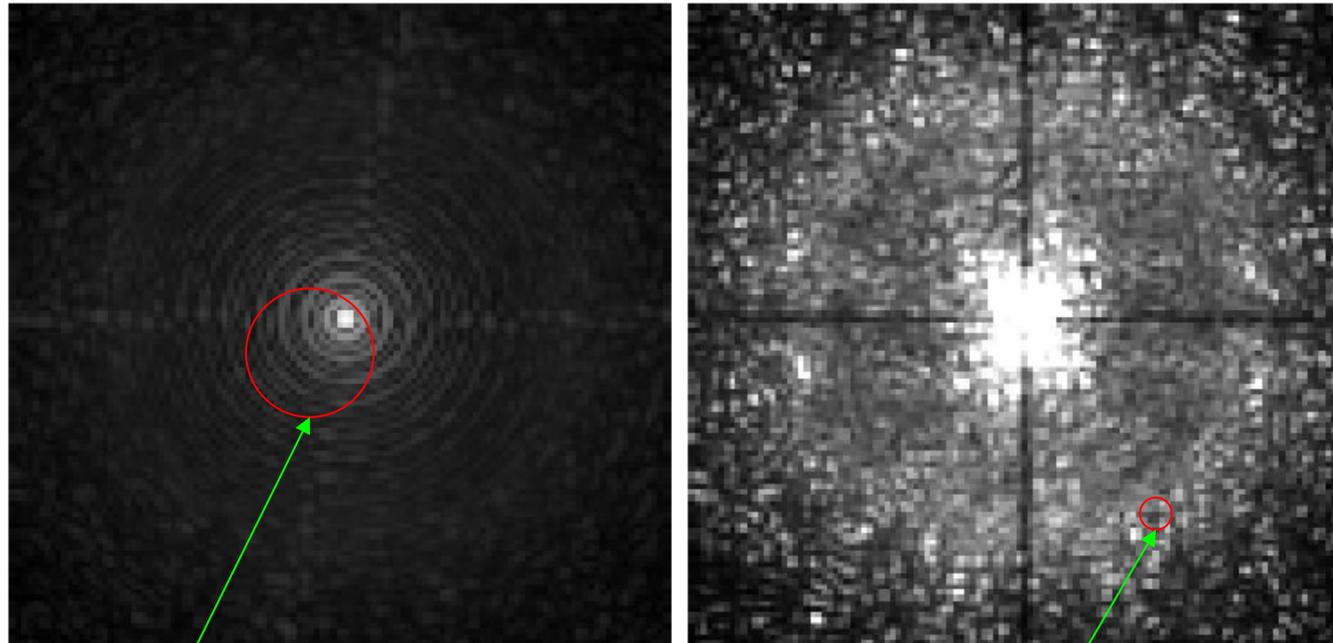


Figure 14: AO corrected bright star image before (left) and after (right) a 4Q mask coronagraph. PSF image is represented with a non linear (0.1 power law) gray scale. Coronagraphic image gray scale is linear, with white corresponding to 5.E-05 of PSF maximum.

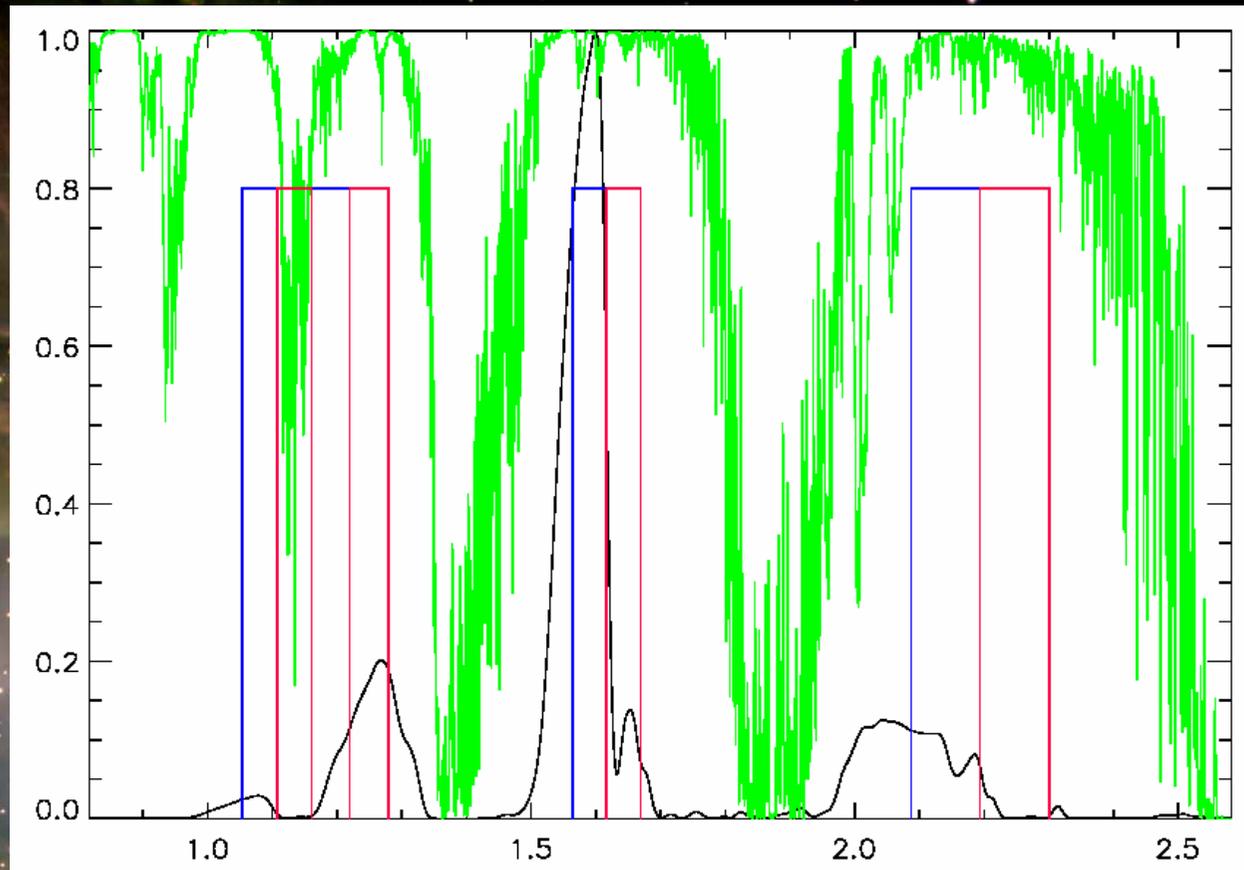
> 10^{10} photons

< 10 photons

A solution: Differential Imaging

- Use property of planet that is different from that of star to identify planet photons
 - Wavelength splitting
 - Polarisation splitting
- Form two (or more) images, obtain difference image

Filters for Differential Imaging - Jovian Planets



Differential imaging challenges

- High Strehl ratio image (superb WF) required => (very) High Order Adaptive Optics
- Opto-mechanical stability, incl. temperature
- Extremely low lateral chromaticity
 - in common path optics, atmospheric dispersion
 - < 1mas at coronagraph for VLT
- High rejection of coherent (stellar) radiation
 - coronagraph design, (&/or interferometry)
 - stringent demands on fore-optics
- Extremely low differential path WF error
- Detector stability, performance, innovation

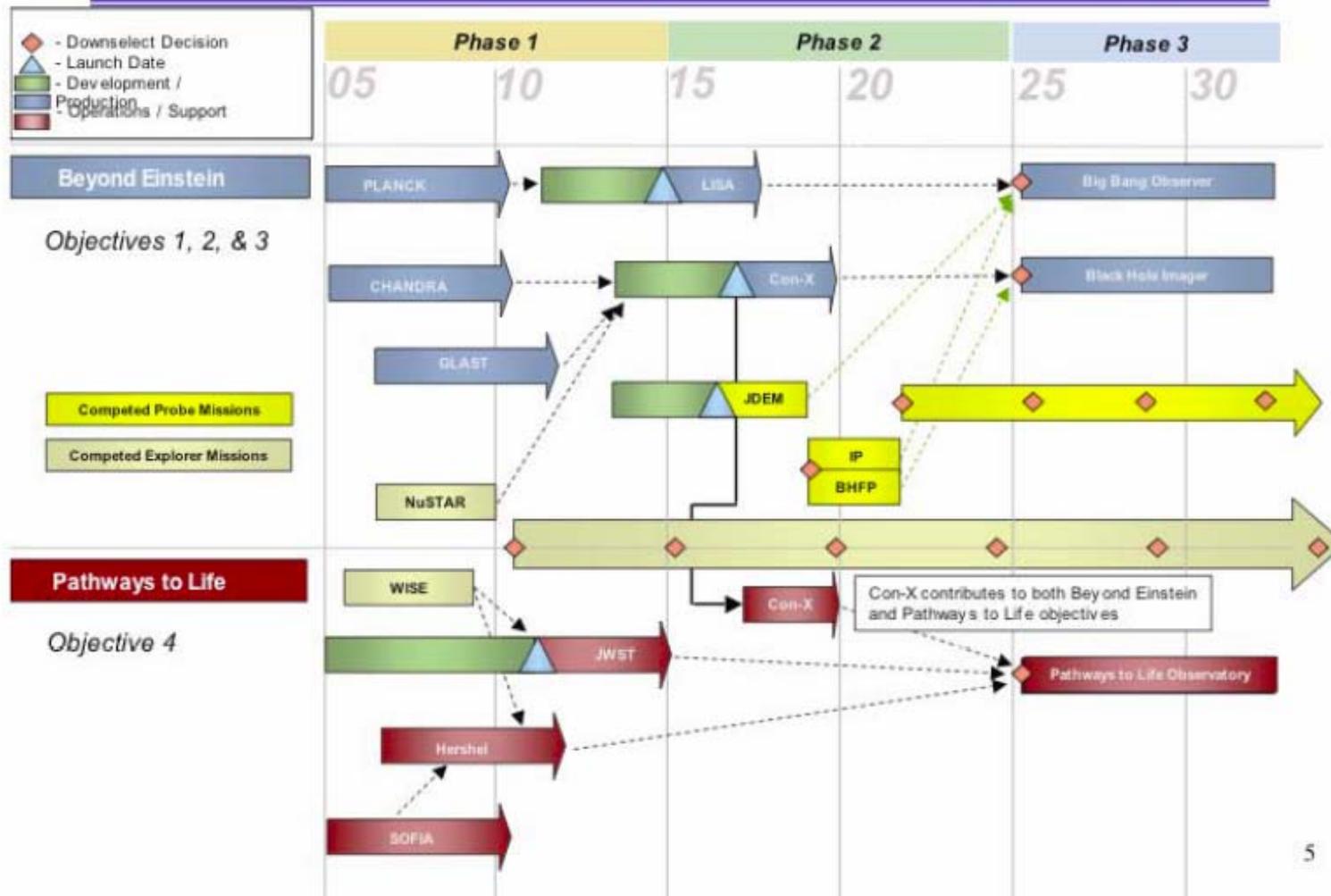
Possible Solution: dual /multi band / spectroscopic detectors

- Goal: Eliminate dichroic-split optics
- QinetiQ: Multi Band capability - up to 4 spectral bands in each pixel using optimised different layers for each waveband: New-process HgCdTe
- Superconducting Tunnel Junctions, Transition Edge Superconductors, Kinetic Inductance Devices: spectral information....

Facilities, Missions and Instruments: SPACE

- JWST
- DARWIN / TPF
- GAIA
- XEUS
- FAR-IR

Universe Exploration Timeline



Detector Technology for Space

- Larger visible mosaics for flight applications
 - ≥ 1 Gpixel, CCD or CMOS (CMOS offer operational advantages)
- Larger near-IR mosaics for flight applications
 - State of the art is JWST: mosaic sizes will increase
- Increased emphasis on mid-IR, far-IR and sub-mm.
 - Next major frontier for flight detectors
 - Technology development is required for the Far-IR missions

Facilities, Missions and Instruments: Ground-based Projects

- Next generation instruments for ESO Very Large Telescope (VLT)
- Gemini next generation instruments
- ESO VLT Interferometer
- Magdelana Ridge Observatory Interferometer
- Extremely Large Telescopes
- Large Submm Telescope

Technology requirements: Science Detectors

- Imaging
- Fringe counting
- Fast detectors
 - Photon counting
 - High time resolution astronomy
- Spectroscopy
 - Energy sensitive detectors
 - Heterodyne receivers

Engineering detectors

- Guiding
- Adaptive Optics
 - Wavefront sensors

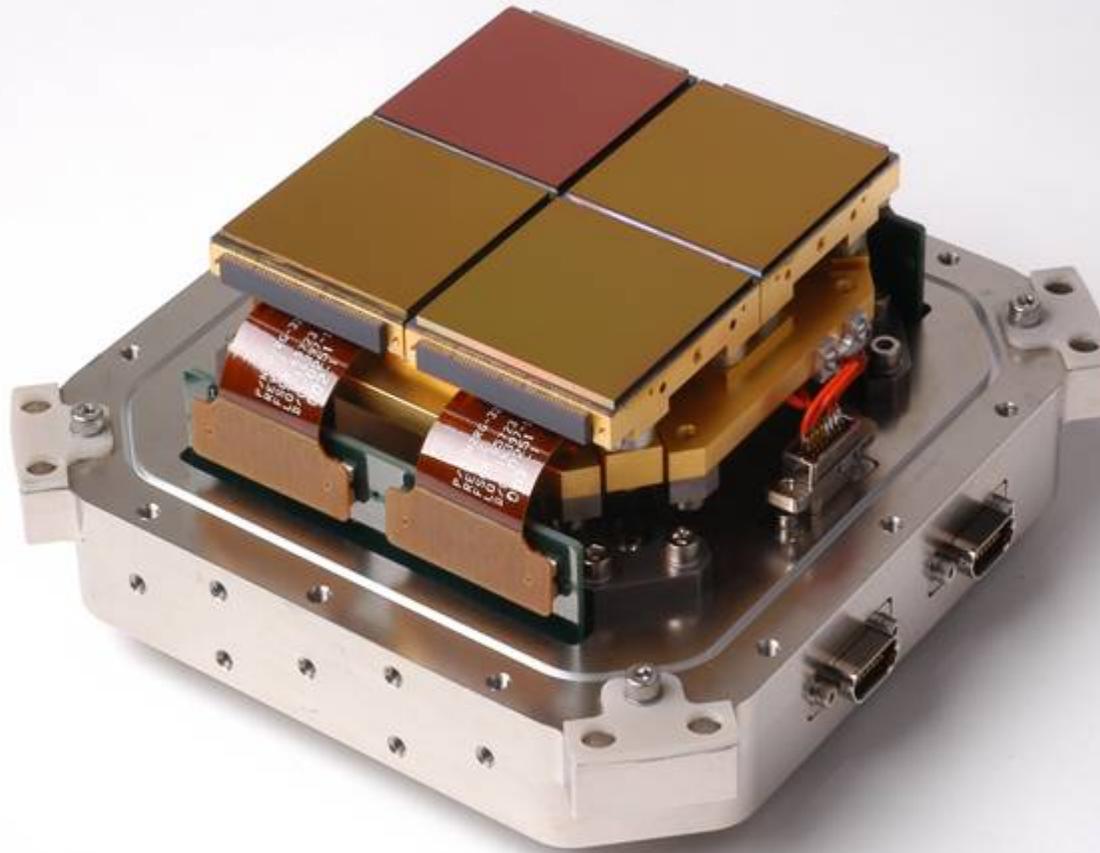
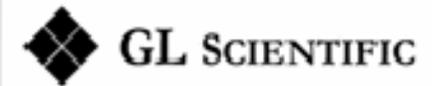
Wavelength Range

- X-ray - space
- UV - space
- Visible - space/ground
- Near IR - space/ground
- Mid IR - space/ground/air
- Far IR - space/air
- Submm - space/ground/air

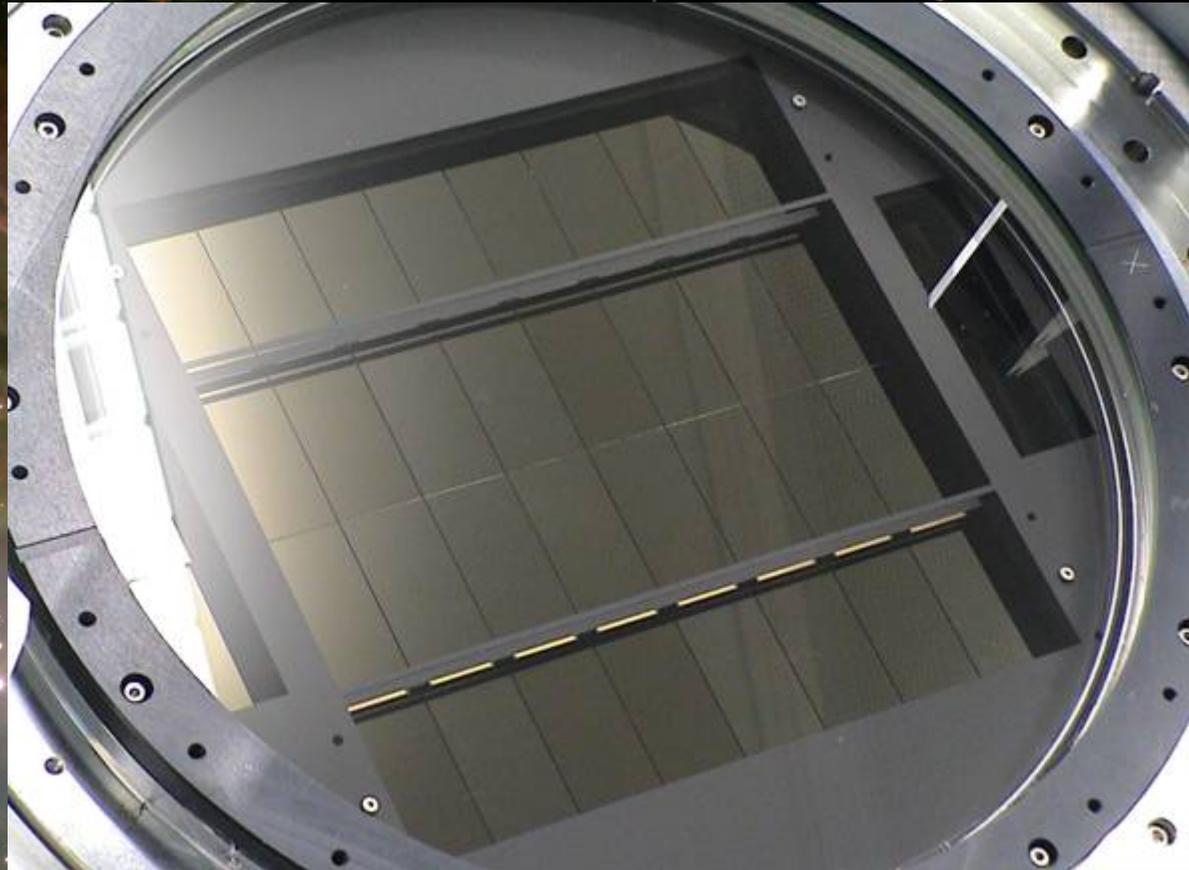
Detector Technologies

- CCDs
- Microchannel plates
- Avalanche Photodiodes
- DEPFET
- CMOS
- Quantum Well Devices
- Superconducting
 - TES
 - STJ
 - KIDs
- Hybrid Devices:
 - Hybrid HgCdTe
 - Hybrid SiAs
 - Hybrid InSb
 - Hybrid Silicon
 - HgCdTe on Silicon
 - Active Pixels

NIR - ESO: HAWK Mosaic Package



Visible - CFHT: MEGACAM

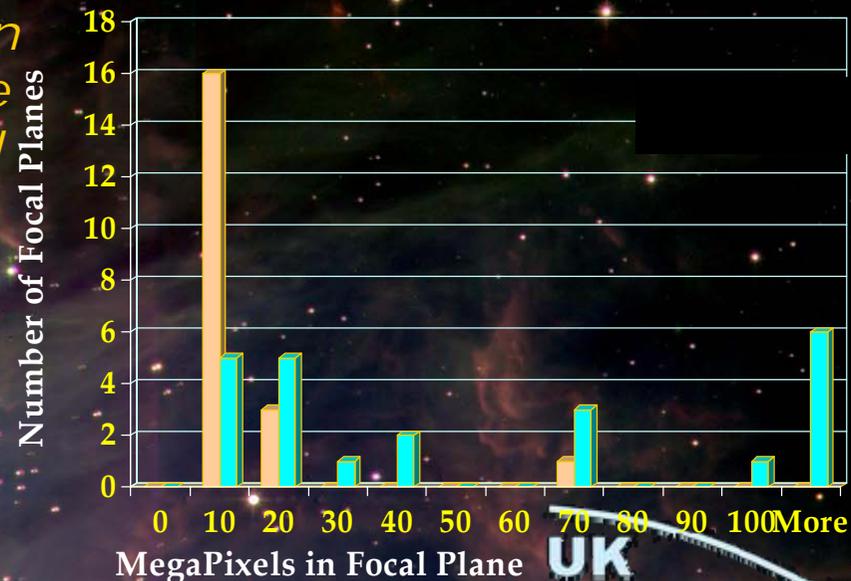
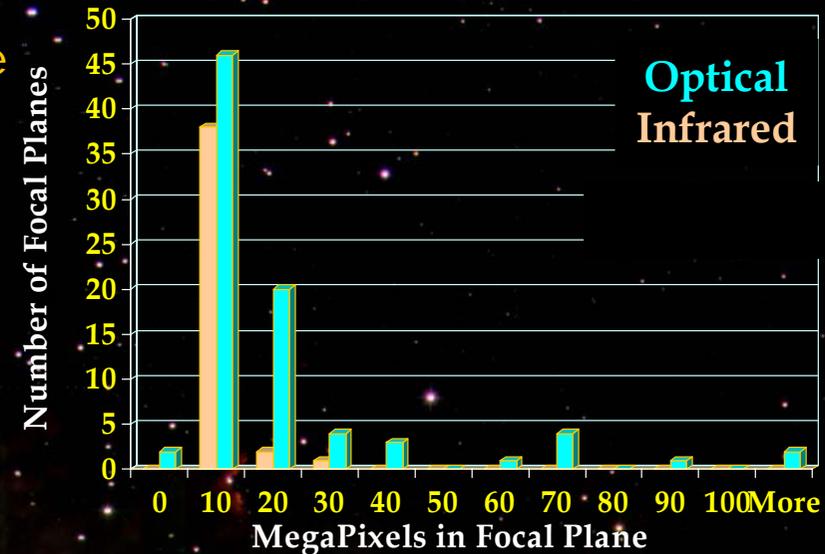


Critical Issues

- Performance:
 - Quantum Efficiency
 - Read-out noise
 - Dark current
 - Pixel size
 - Flatfield
 - Close -packing
 - Flatness of mosaics
 - Dynamic range
 - Wire count
 - Temperature
 - Thermal load
 - Reliability
 - Radiation Hardness
 - Read-out electronics
- Supply Chain
 - Cost
 - ITAR – International Trade in Arms Regulations

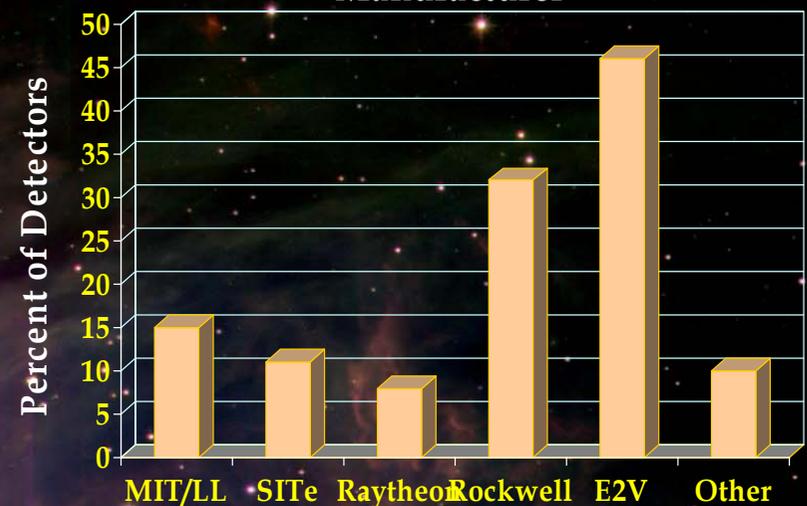
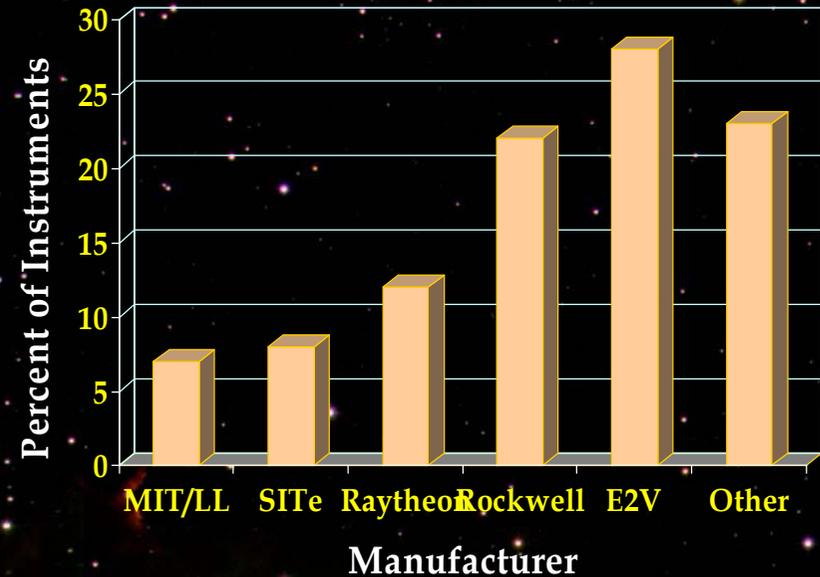
Ground-based: Total Pixel "Inventory", Now and Tomorrow...

- The future looks similar to the present in the infrared with most instruments having modest size focal planes
- At visible wavelengths we expect many more large focal planes
- *The future market includes ~7.7Gpixels of science grade detectors, >90% of which is in the form of CCDs in the future "More" category (>100 Mpixel focal planes)*
- Lack of planned IR large format focal planes due to lack of money... or arrays to costly!

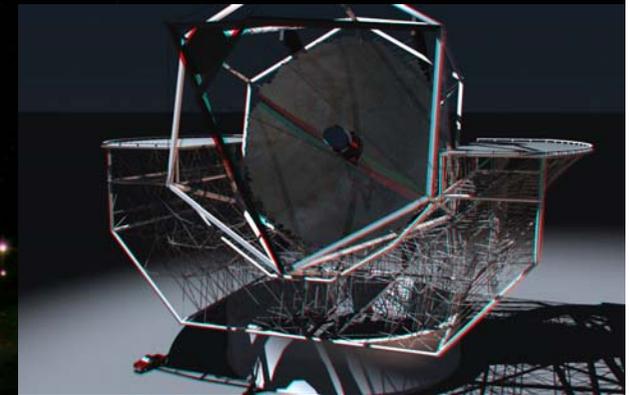
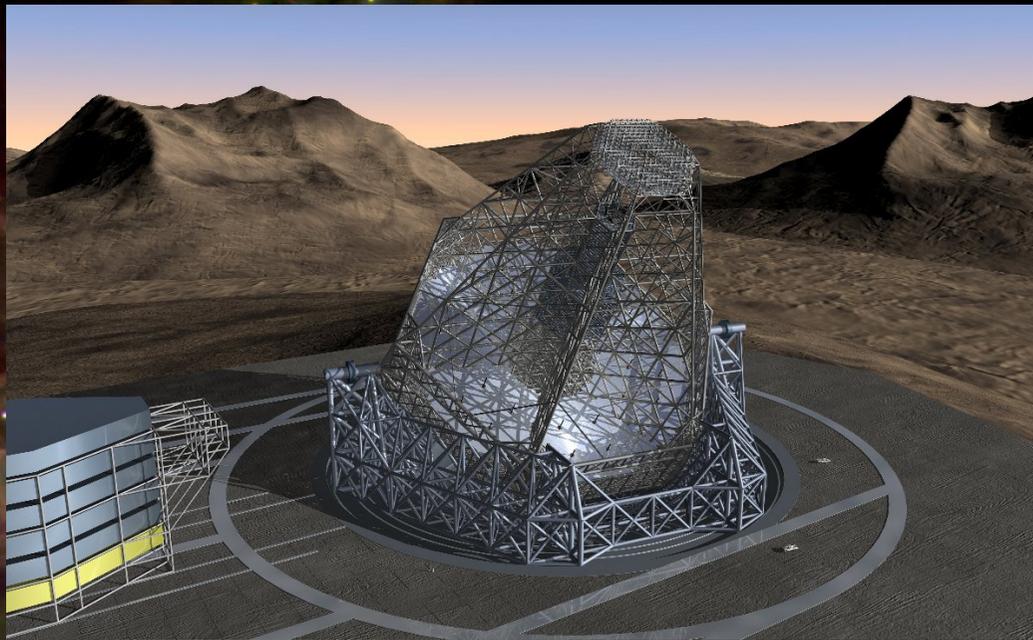


Current Market Share by Manufacturer

- Top histogram shows dominant manufacturers used in various instruments
 - Effectively assumes 1 detector per instrument
 - "Others" in many cases are one-off devices in specialized instruments which together account for ~20% of all instruments
- Bottom plot tallies all detectors sampled in survey so is a true "head count" of detectors in use



Example: ELT IR detectors



Spatial resolution

0.6 arcsec



Limiting
mag in 10^h :
 $V=38$

- Full AO: 1.0 mas at V
i.e. 40 × Hubble
Space Telescope

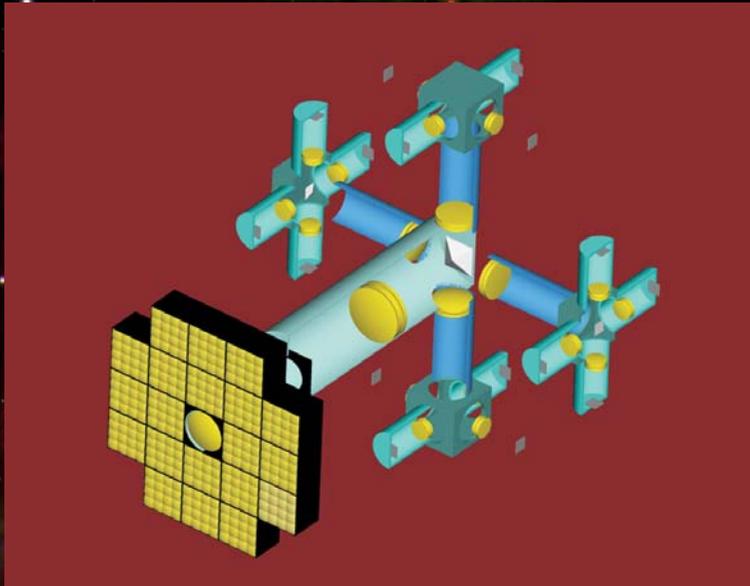
100m ELT

Cost?

- 1mas nyquist sampling at $2\mu\text{m}$
- 2 arcmin diffraction limited field
- 120,000 x 120,000 pixels
- 2048x2048 HgCdTe arrays
 - VISTA cost \$300k each
- Total 3600 arrays
 - \$1080M – more than telescope!

Large-Field NIR Camera

Concept Study carried out by INAF-Arcetri and MPIfA Heidelberg (P.I. R. Ragazzoni)



- J,H,K; central field (30-60 arcsec diameter sampled at \sim diffraction limit); outer field 3-6 arcmin. Choice dictated by AO performance, science case, cost and complexity.

- MCAO using 2-3 DM for the central part, GLAO for the outer part

Detector Requirements

- Central field of 30" sampled at 1mas (Nyquist at K) \rightarrow 15 x 15 (2K x 2K) Hg Cd Te arrays (or 8 x 8 (4K x 4K), 12 μ m pixels)
- Outer field (e.g. 3' x 3') with a 10mas sampling \rightarrow 9 x 9 (2K x 2K) Hg Cd Te arrays

Cost?

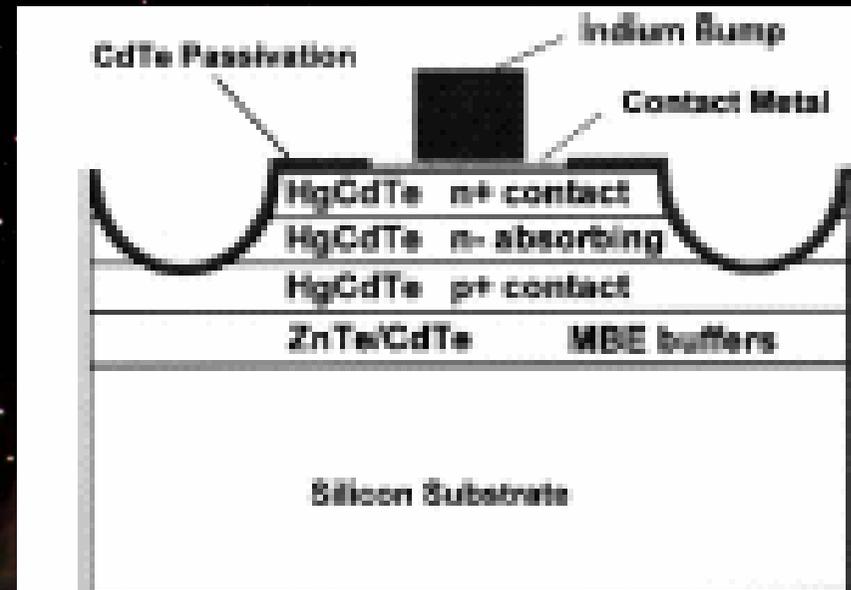
- Now down to 306 arrays
- \$92M – will come down in these quantities
- But still 2-3 FTEs per array
- Move away from hybrid arrays?

IR Detector Technology



HgCdTe on Si IR Detectors

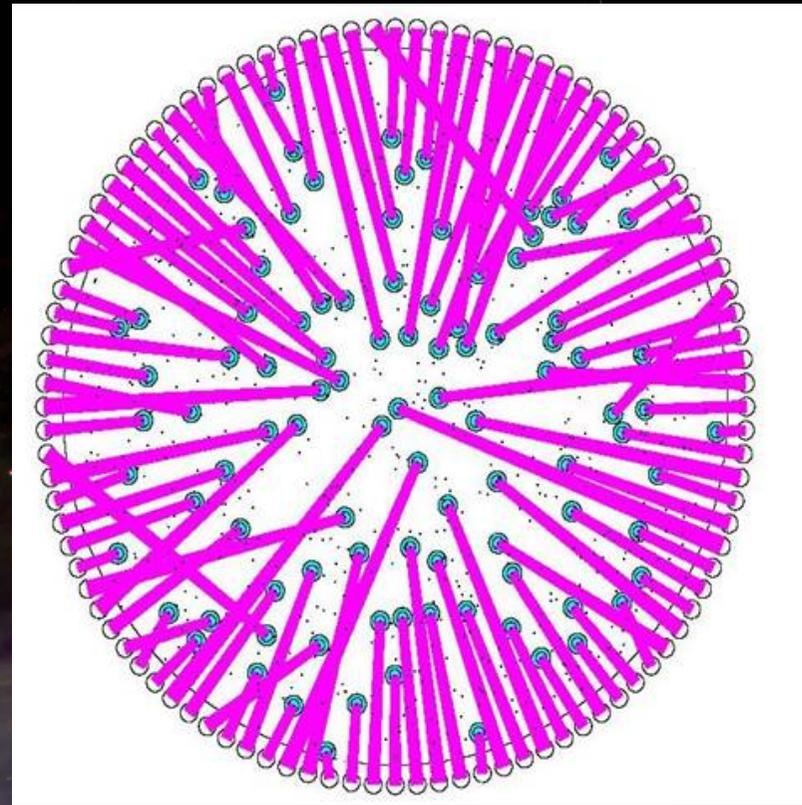
- The QUEST group at QinetiQ, Malvern, have recently demonstrated the successful growth of HgCdTe *directly* onto the silicon read out circuit itself using Metal Organic Vapour Phase Epitaxy (MOVPE).
- Could dramatically drive down their manufacturing cost compared with hybrid bump-bonded arrays



1. A cross-section of a MET device. The ZnTe and CdTe layers are grown by MBE and the Hg_{1-x}Cd_xTe layers grown by MOVPE.

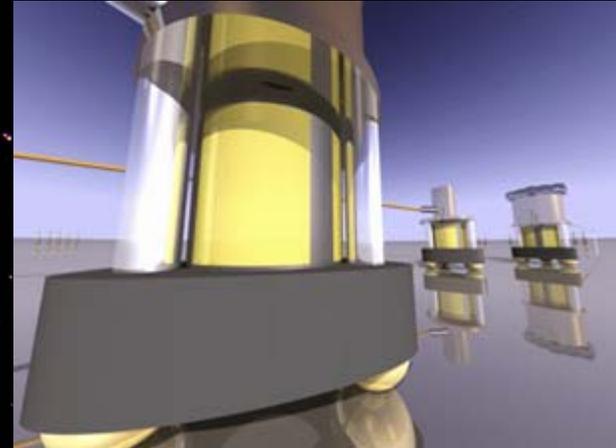
Smart Focal Planes?

- We have only looked at imaging – spectroscopy multiplies problem by at least 1000!
- If we are investigating objects where we know positions, then we don't need to image the whole field

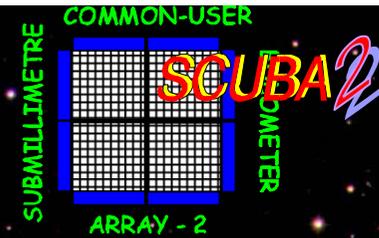


Starbugs

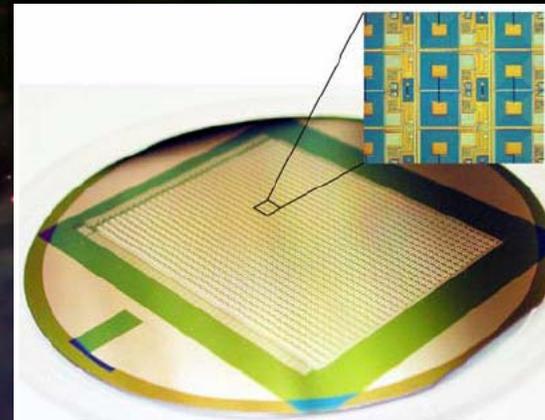
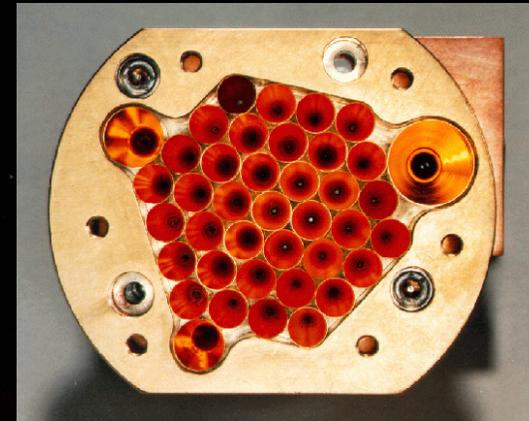
- Under development at AAO
- Self-propelling 'bugs' patrol the focal plane
- Status: cryo-testing underway



Example 2 : submm arrays

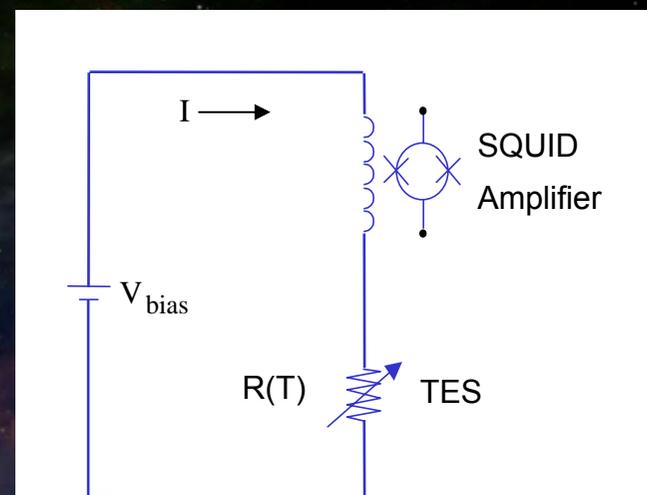
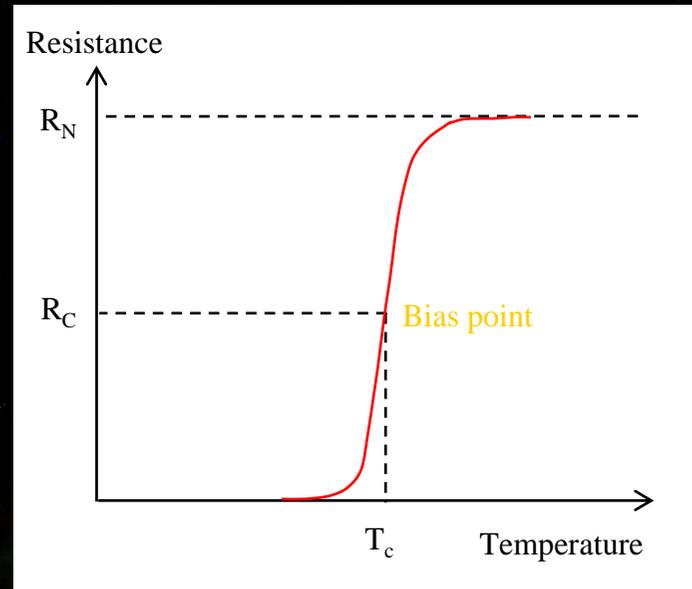


- SCUBA – arrays built from discrete bolometers and horns
- SCUBA 2 – ‘CCD’ like superconducting bolometer arrays

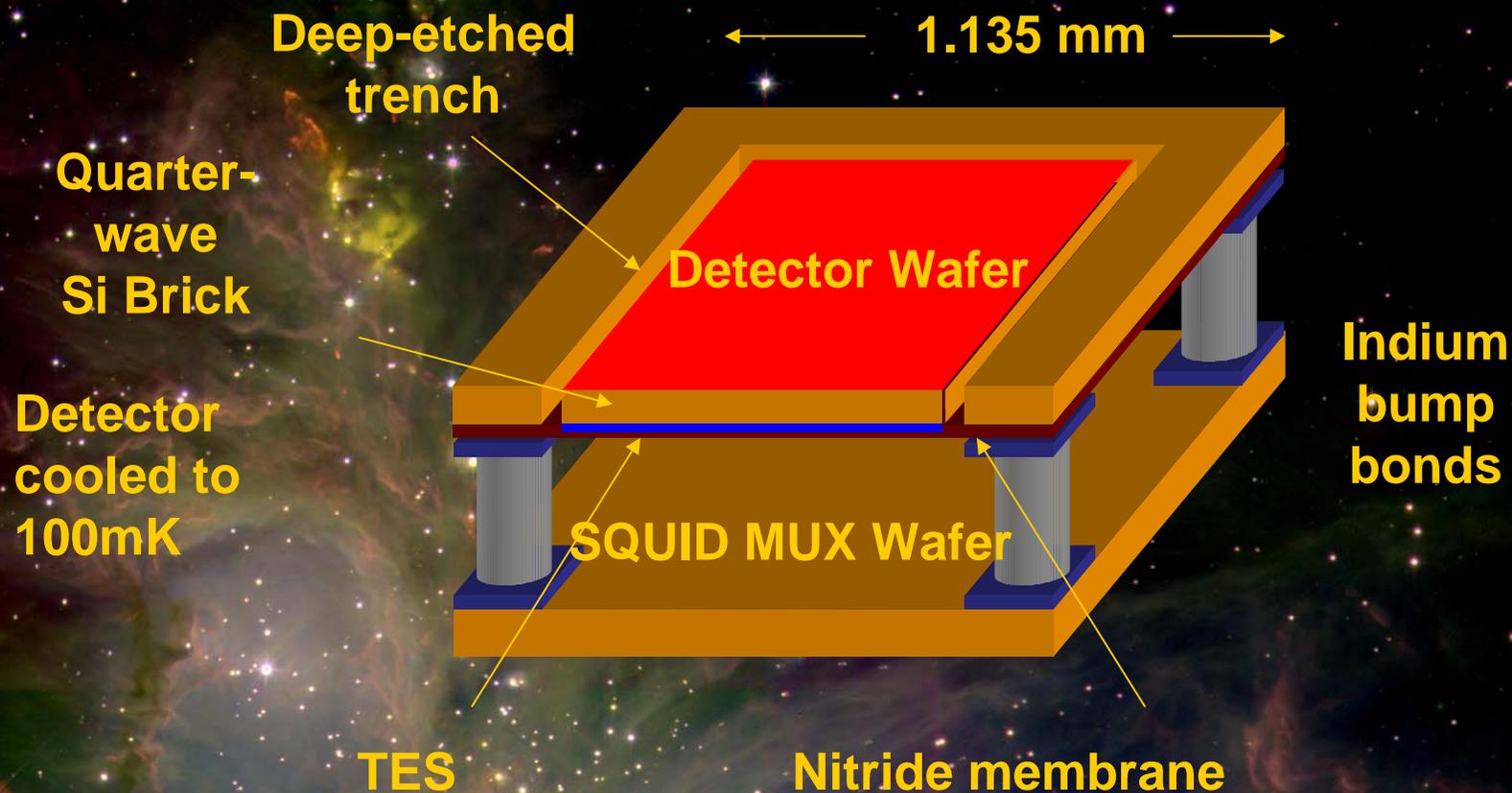


Transition Edge Superconducting detectors

- Voltage-biased on normal-superconducting transition – thermal feedback keeps constant bias point
- Resistance is a very steep dependence on temperature in transition region
- Thin films of Mo/Cu – tuned transition temperature by proximity effect
- Film held at constant voltage bias - change in resistance results in a change in current through the film
- Low noise, low power ($\sim 1\text{nW}$) SQUID ammeter readout

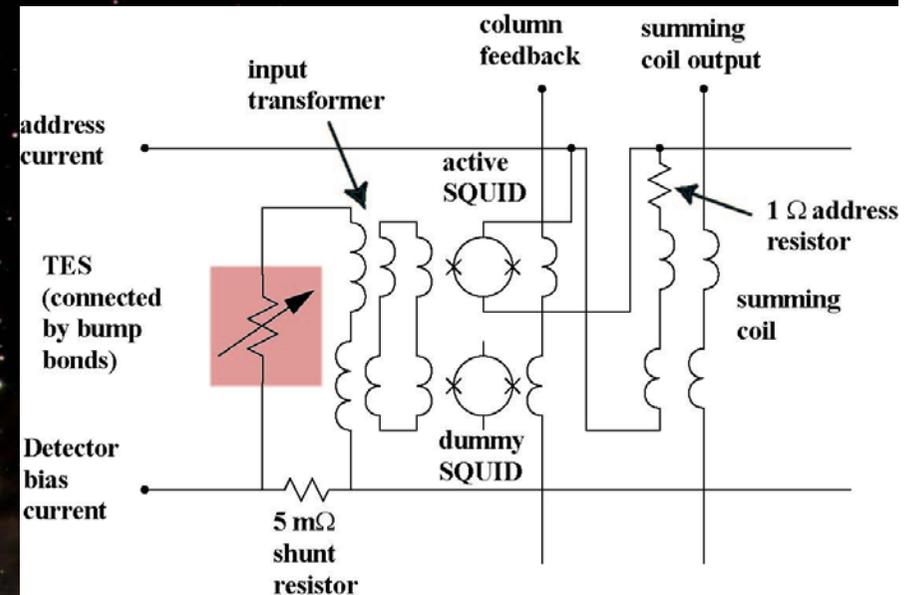


Pixel geometry



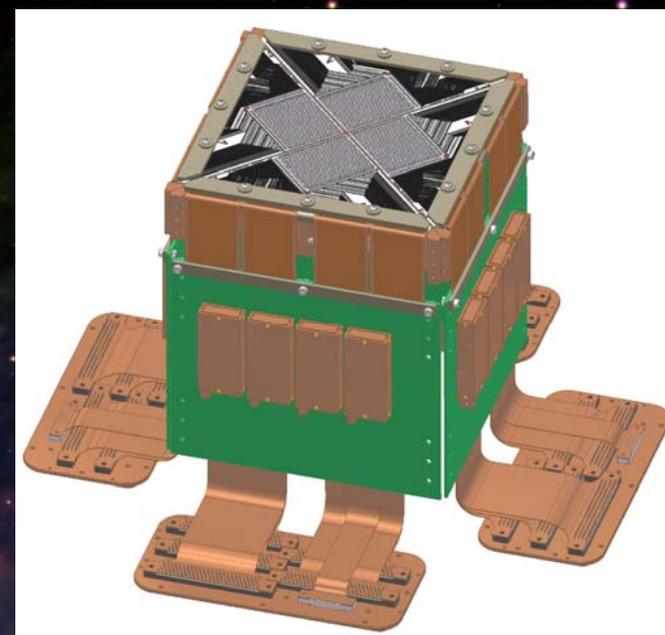
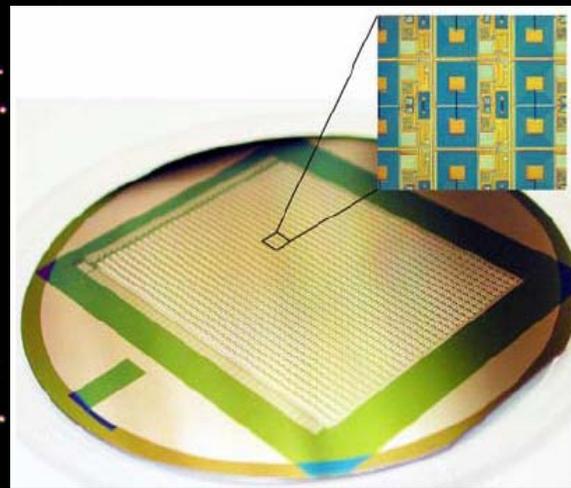
Multiplexing

- Time division multiplexing based on SQUID amplifier
- Mux is formed by columns of SQUIDS connected in series
- Address line turns on each row of SQUIDS



SCUBA-2 focal planes

- 4 × 1280 pixel sub-arrays in each focal plane
- 100mK operation using liquid cryogen-free dilution refrigerator

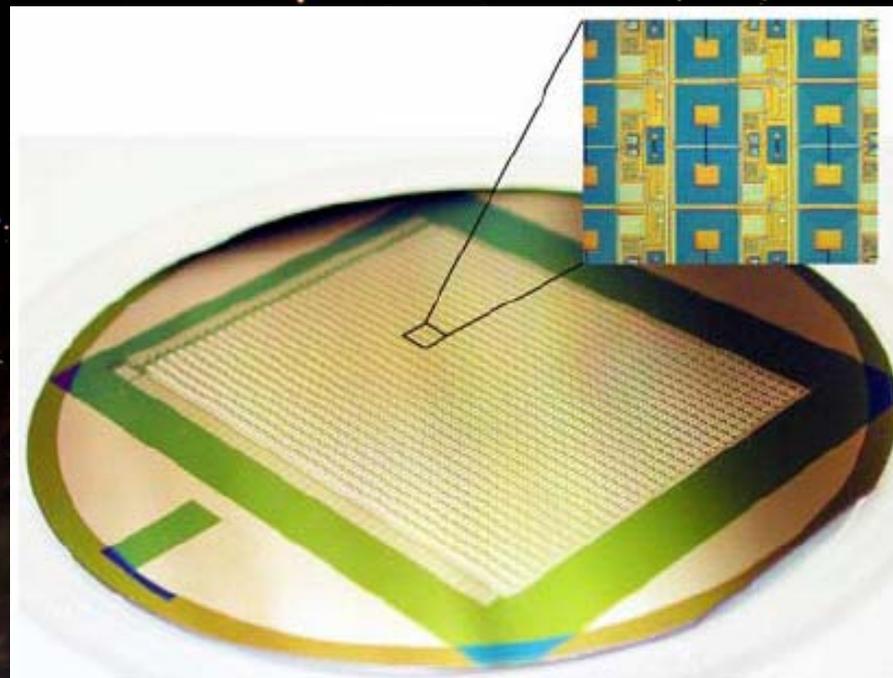
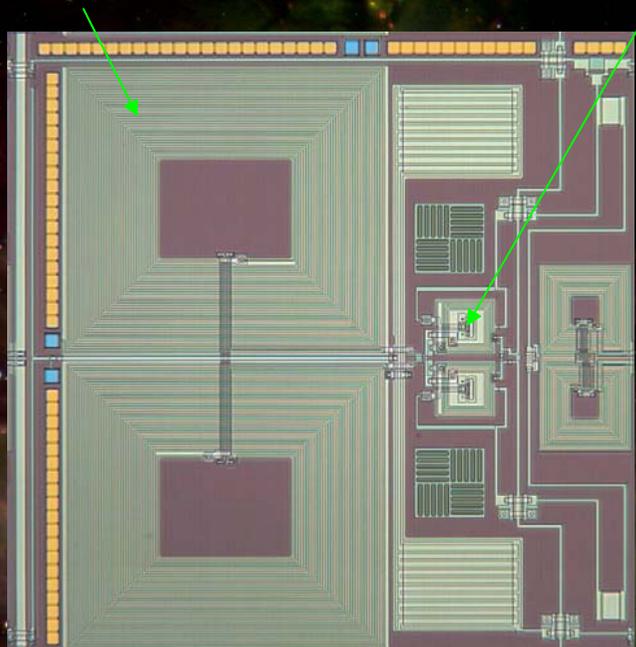


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In-focal-plane multiplexers

Input transformer

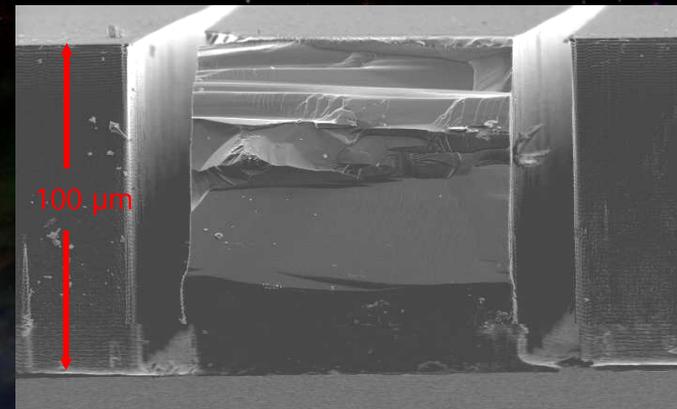
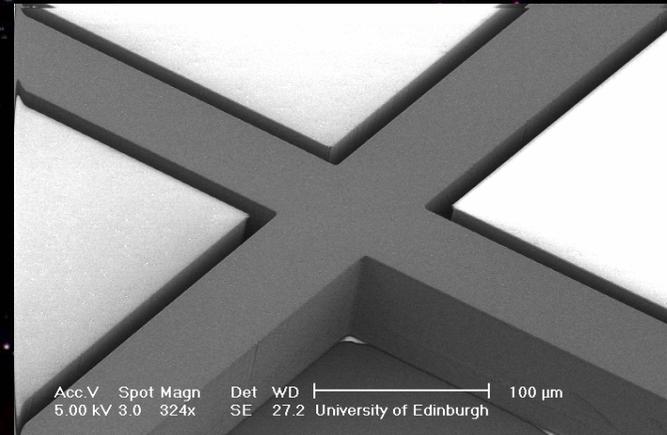
Active SQUID



A full-sized (32 × 40 pixel) multiplexer wafer with detail of the layout shown in the insets.

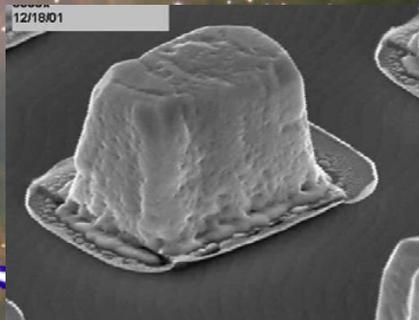
Detector fabrication process

**Bump bonding
mux to detector**



**Deep etching to isolate
detector pixels.**

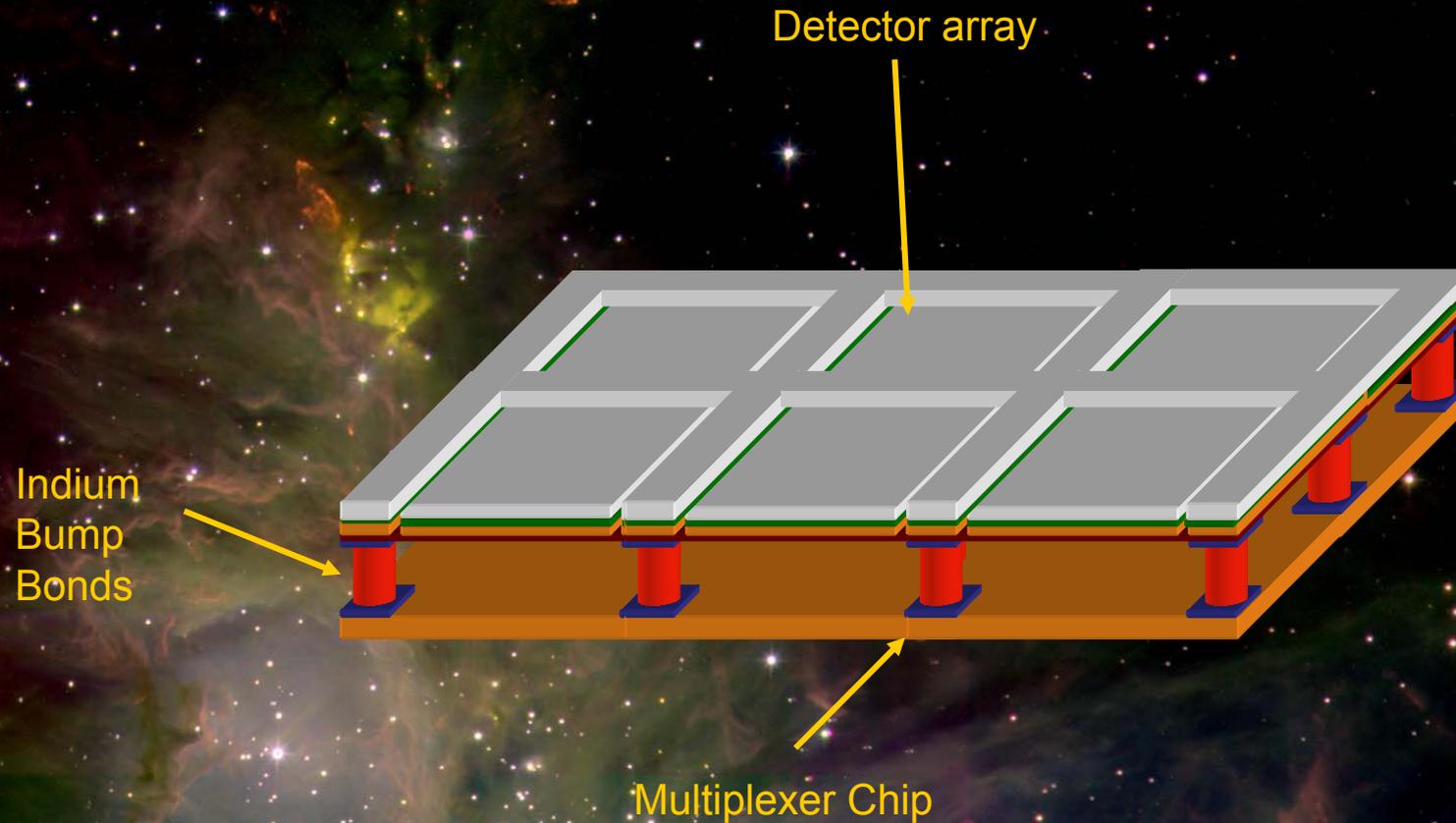
Raytheon
Vision Systems



PPARC

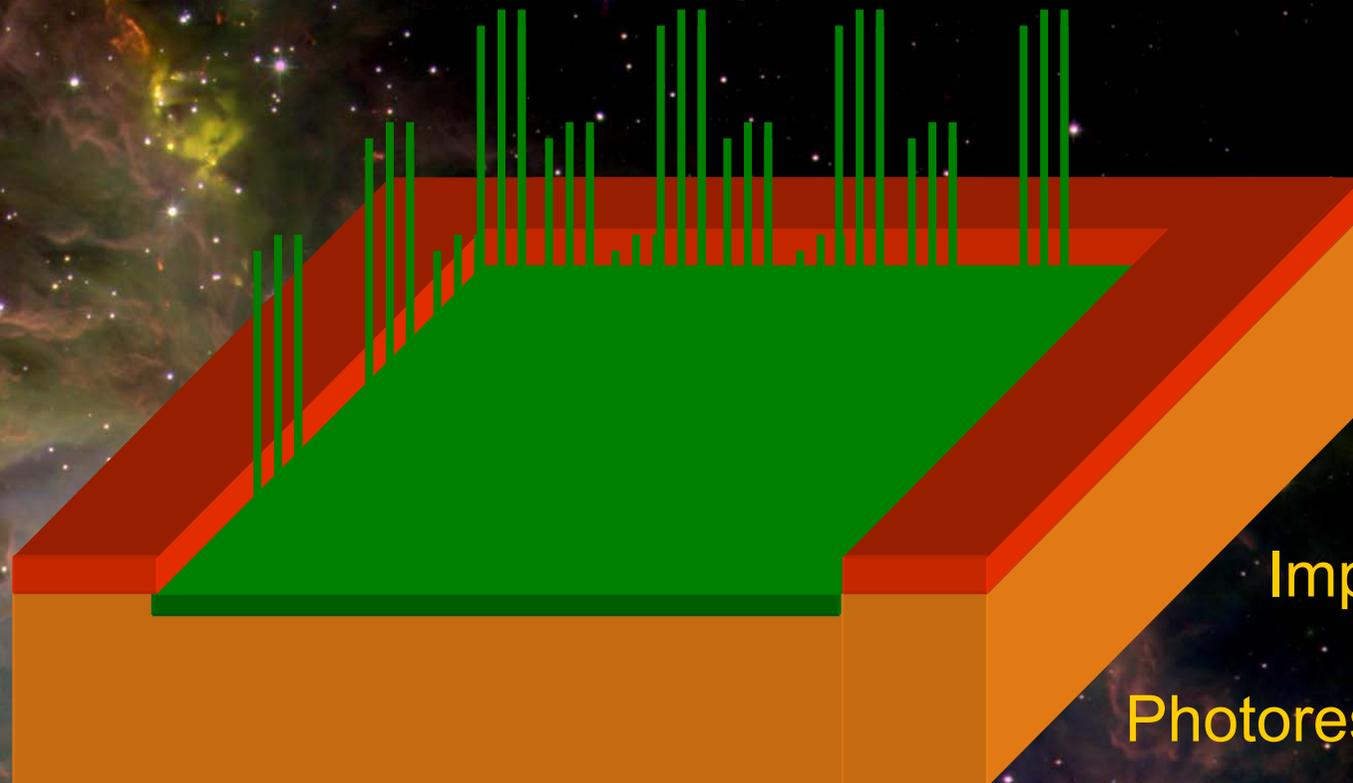
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Pixel Structure



Process sequence for detector

Bottom Wafer



Implantation

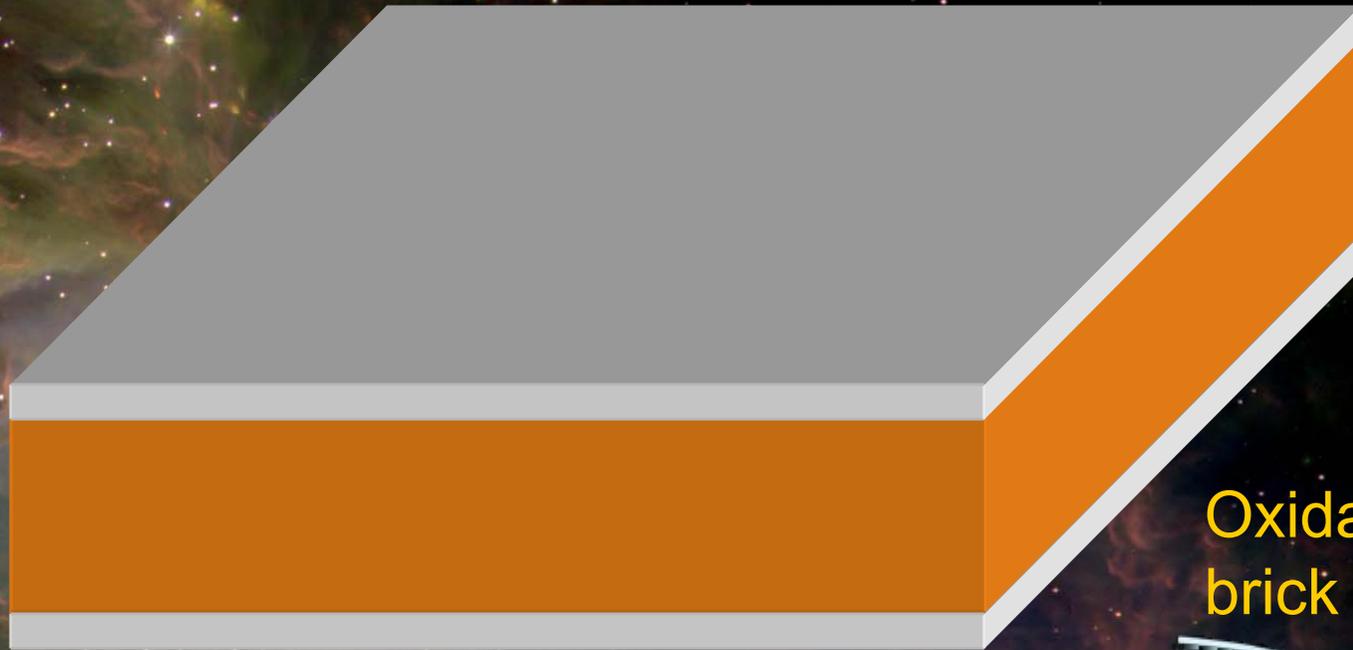
Photoresist mask



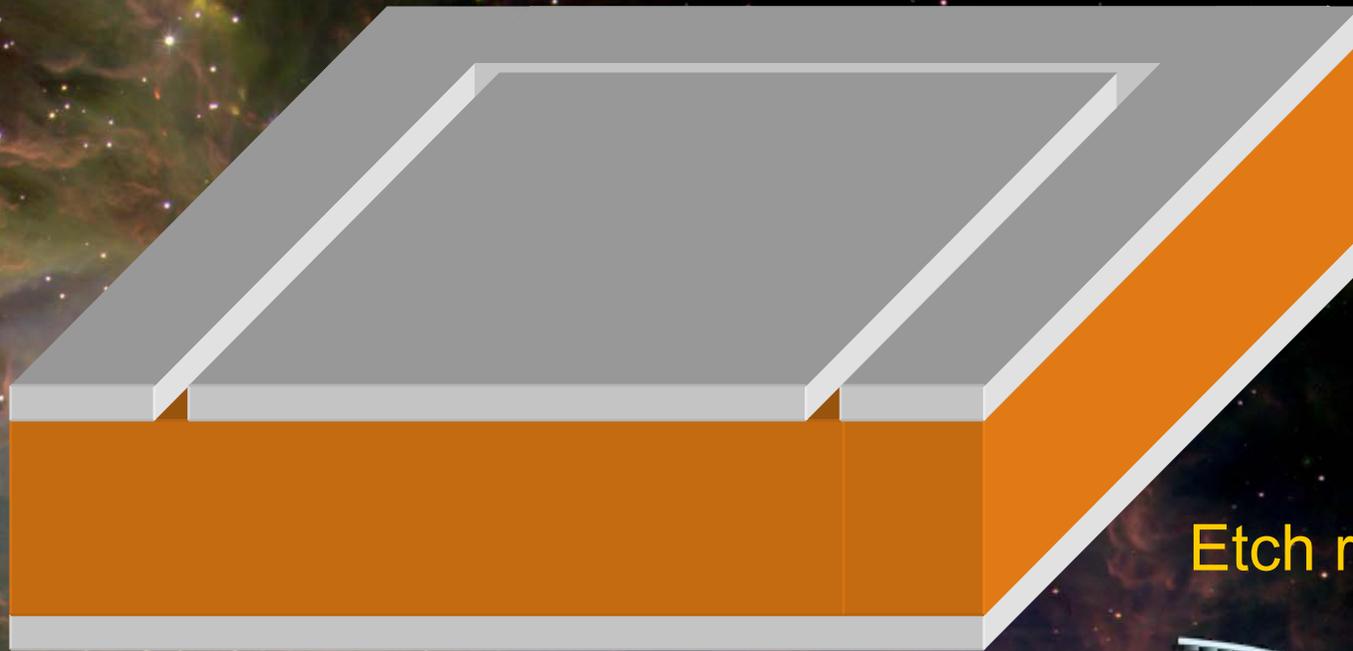
Screen Oxidation

Photoresist strip

Top Wafer



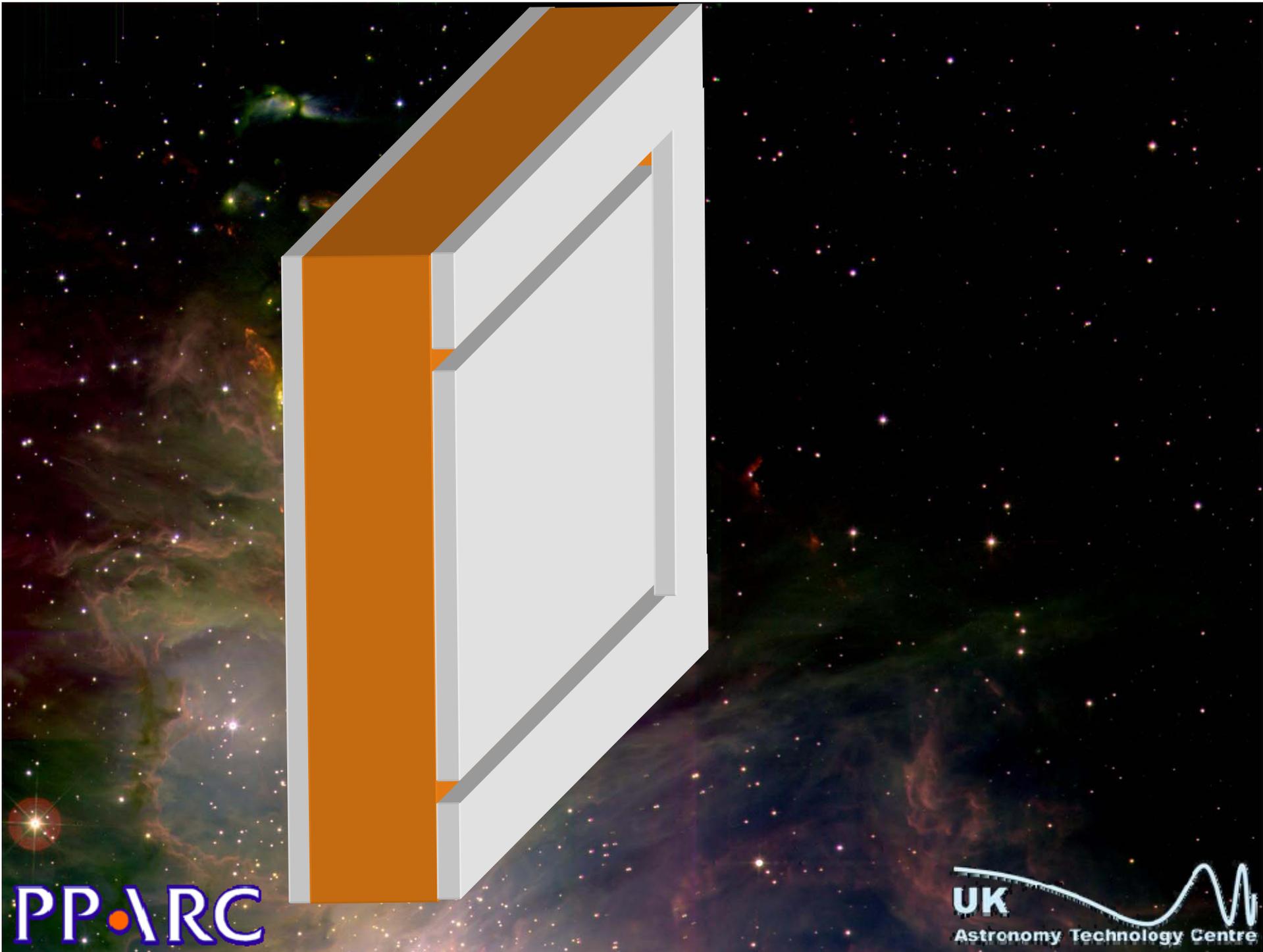
Oxidation for Si
brick etching



Etch racetracks

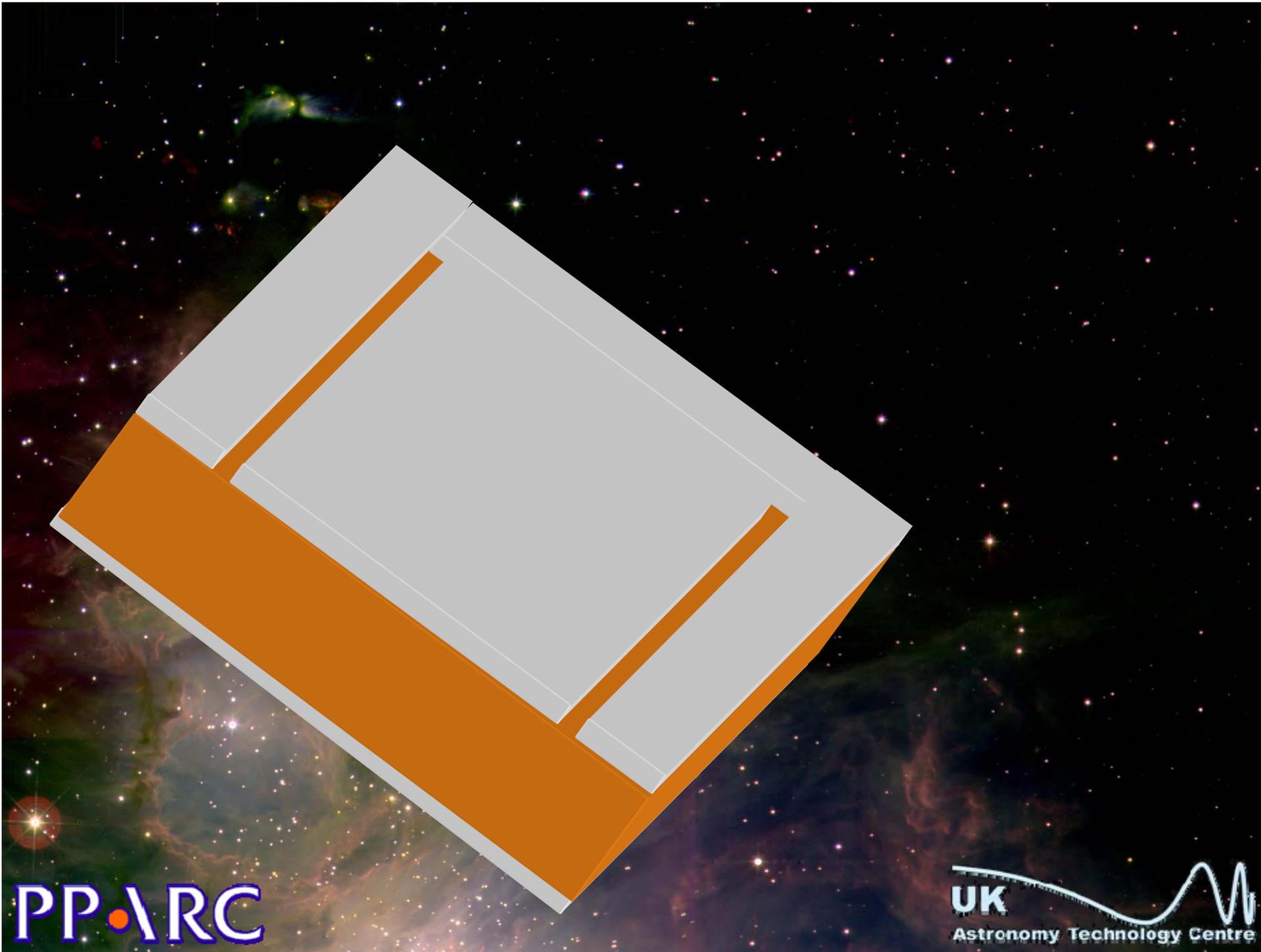
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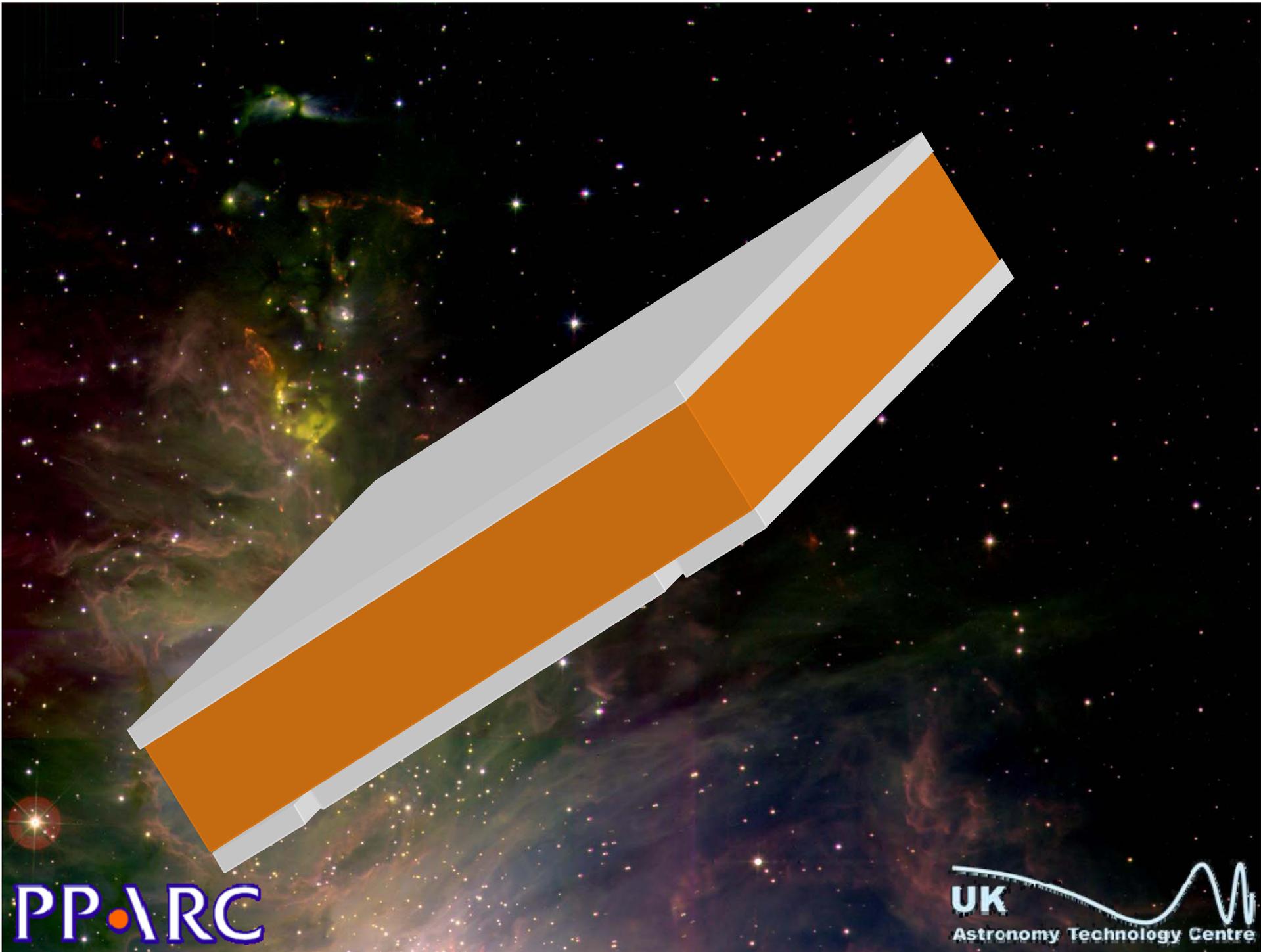
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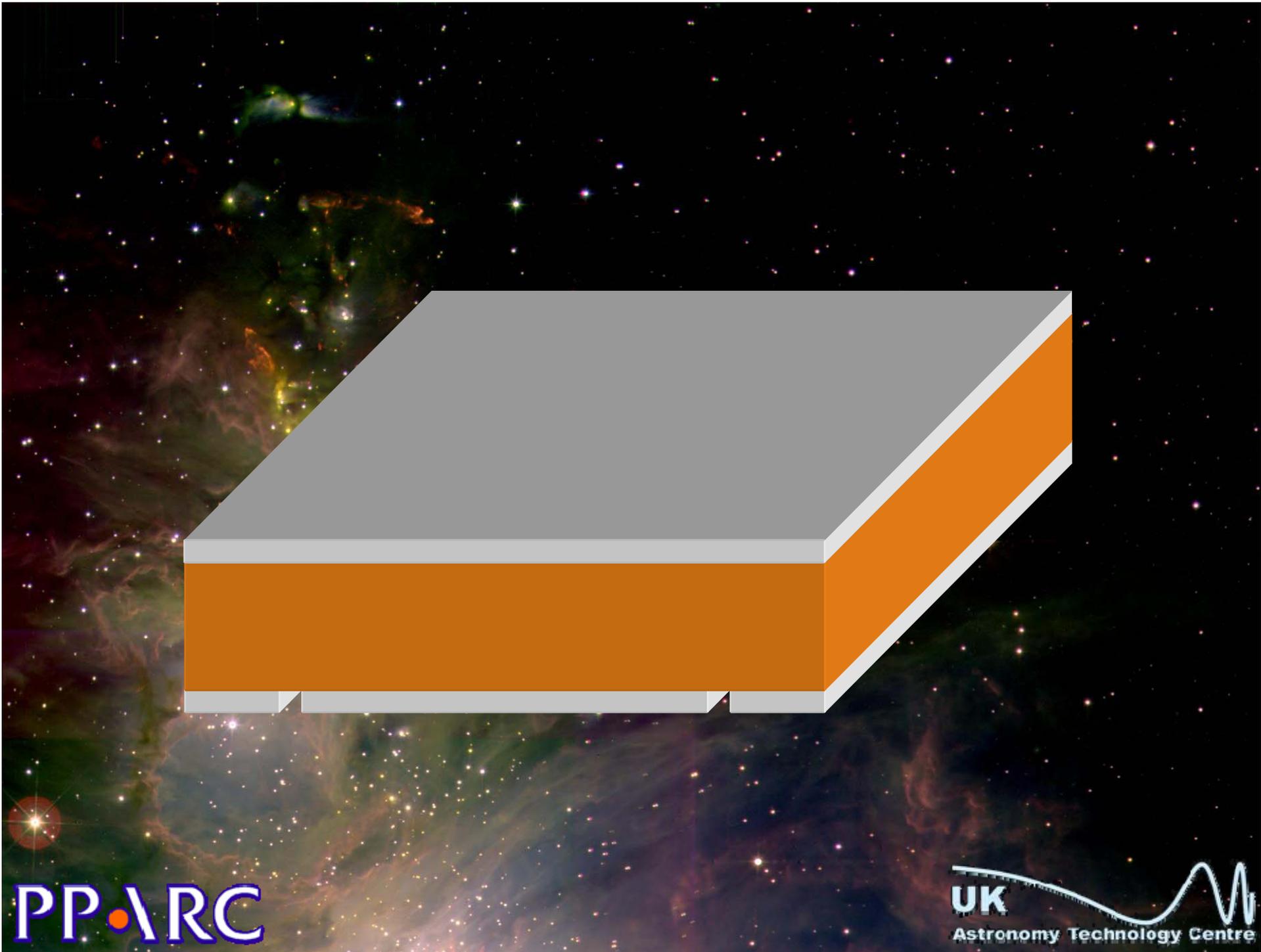
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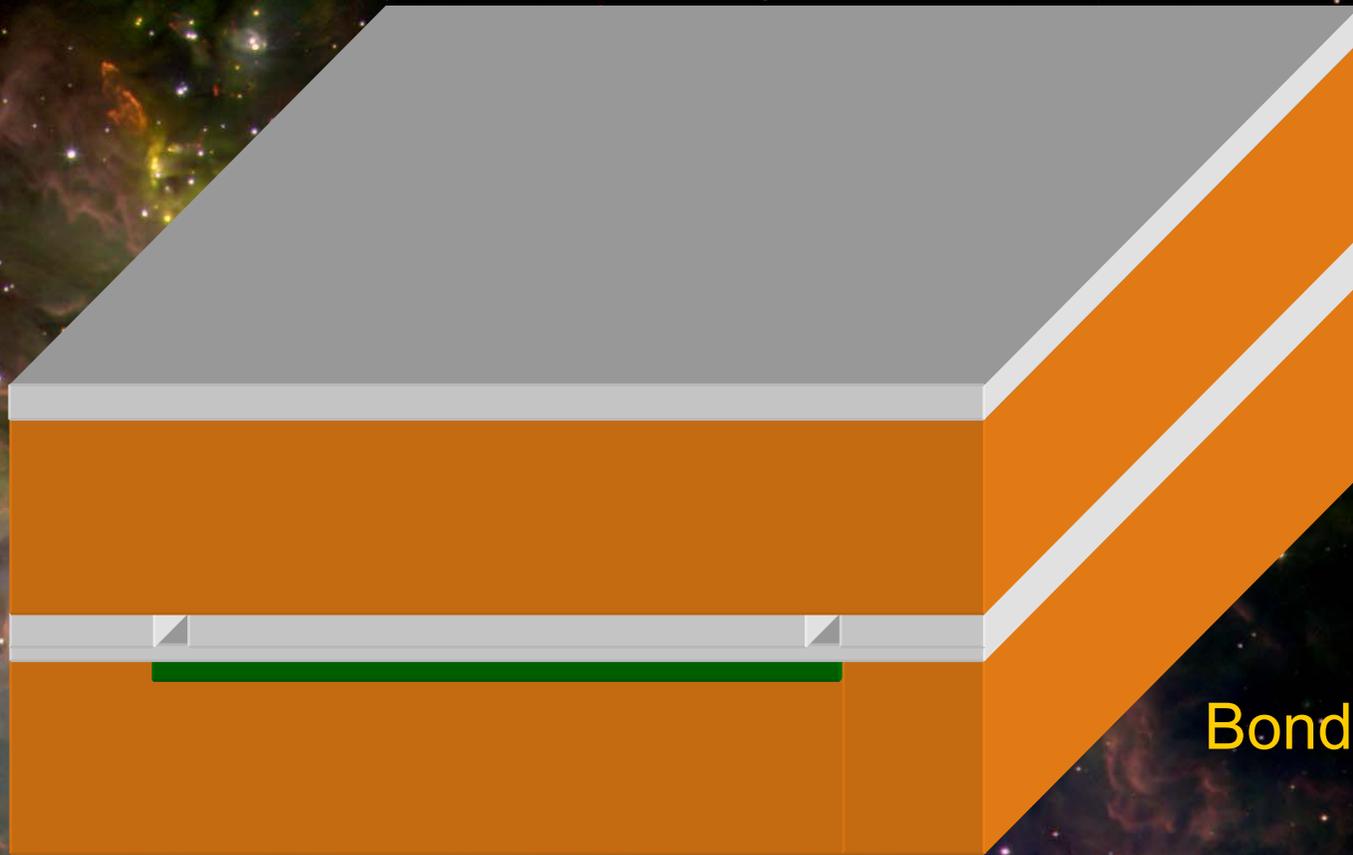
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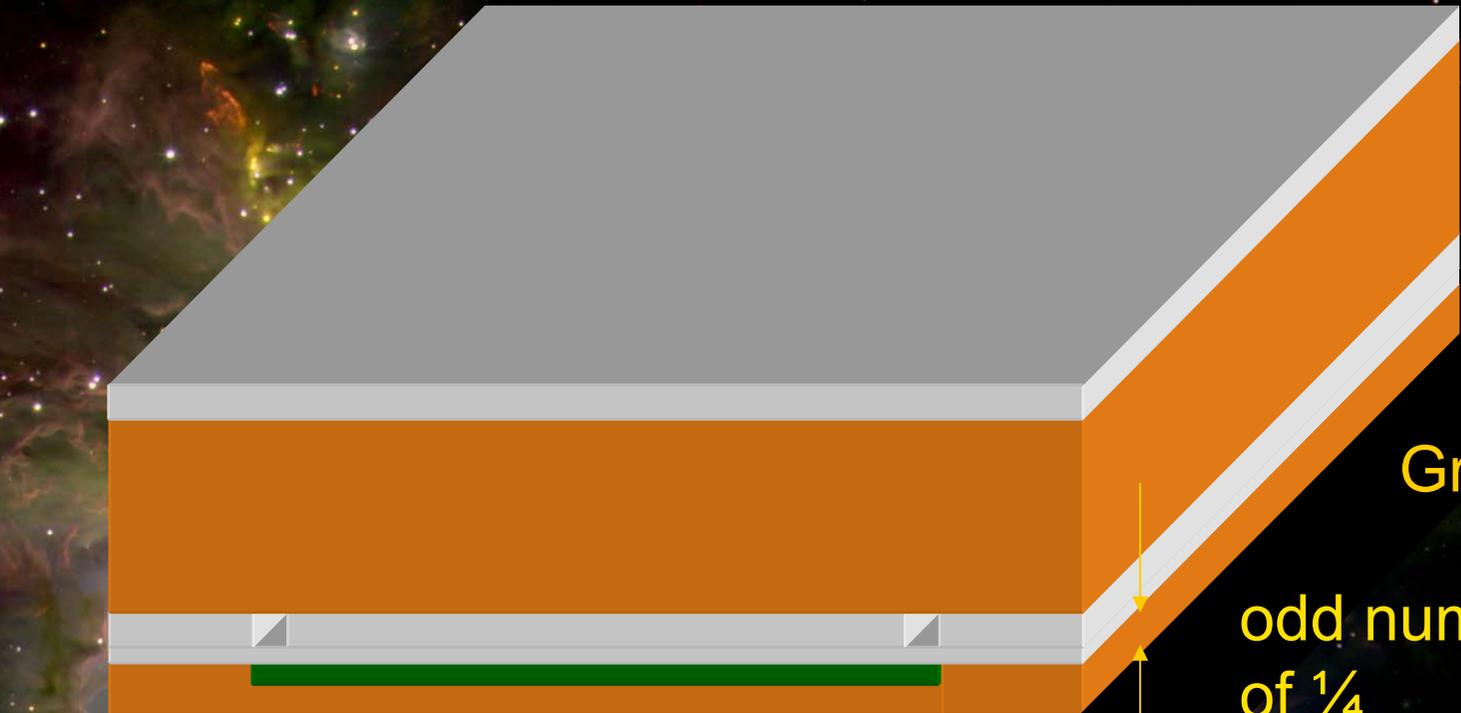


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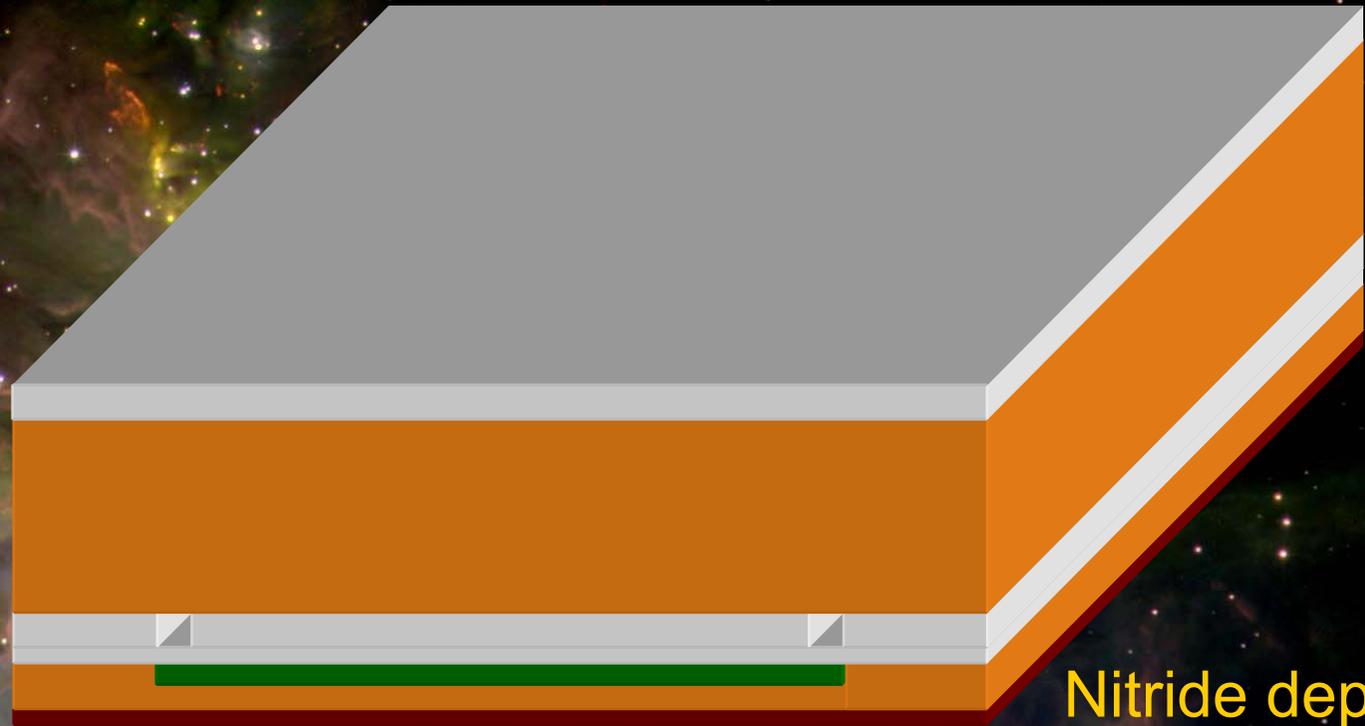


Bond wafers

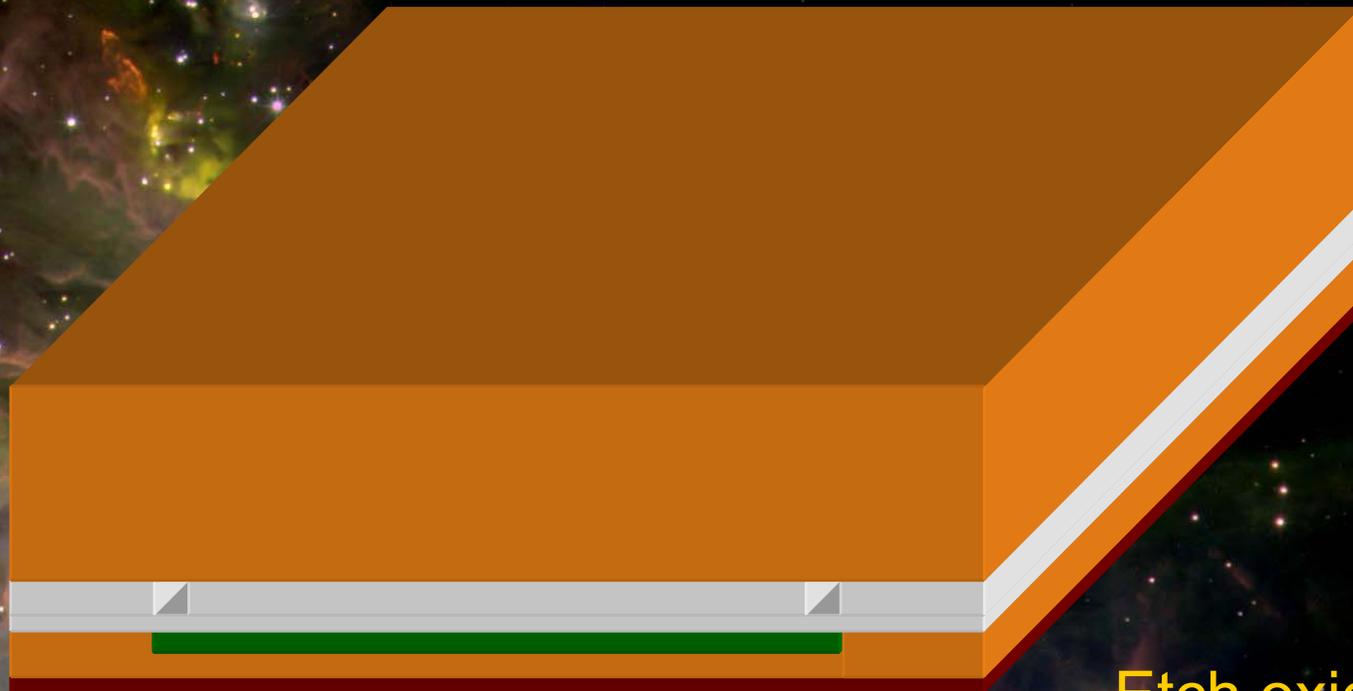


Grind back

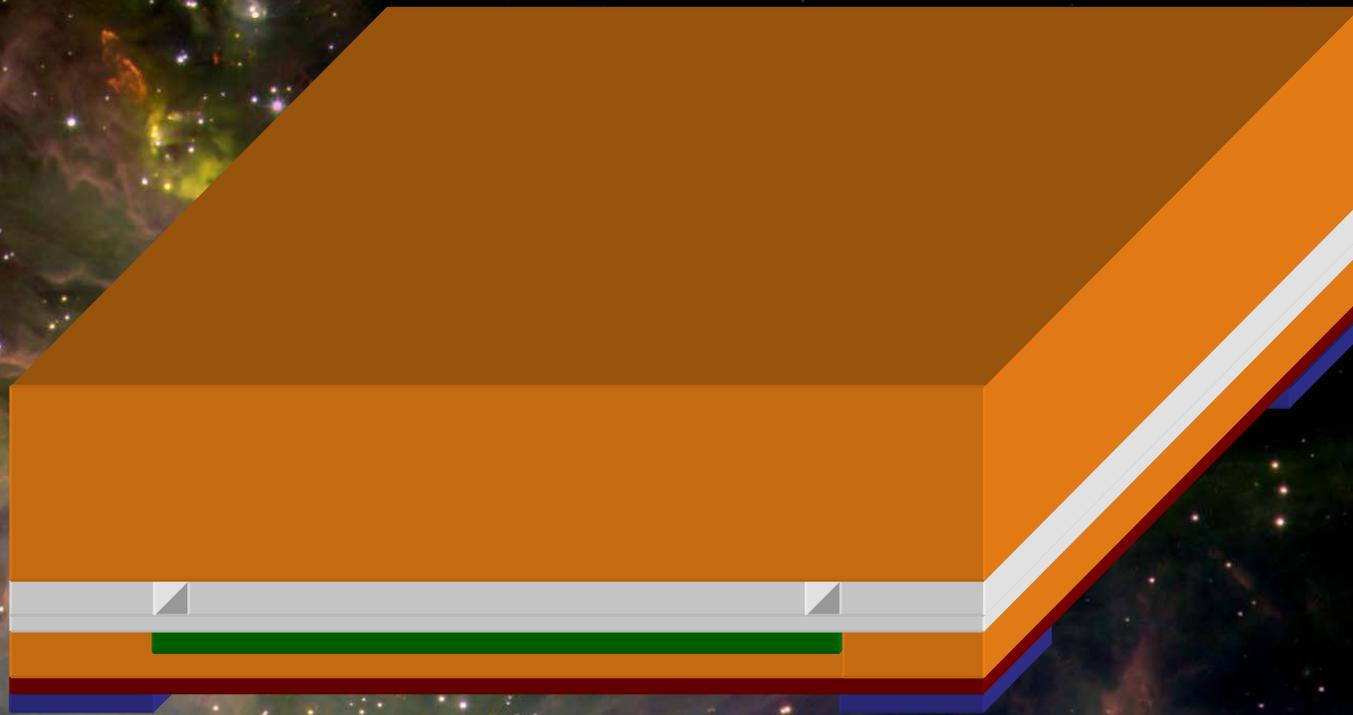
odd number
of $\frac{1}{4}$
wavelengths



Nitride deposition

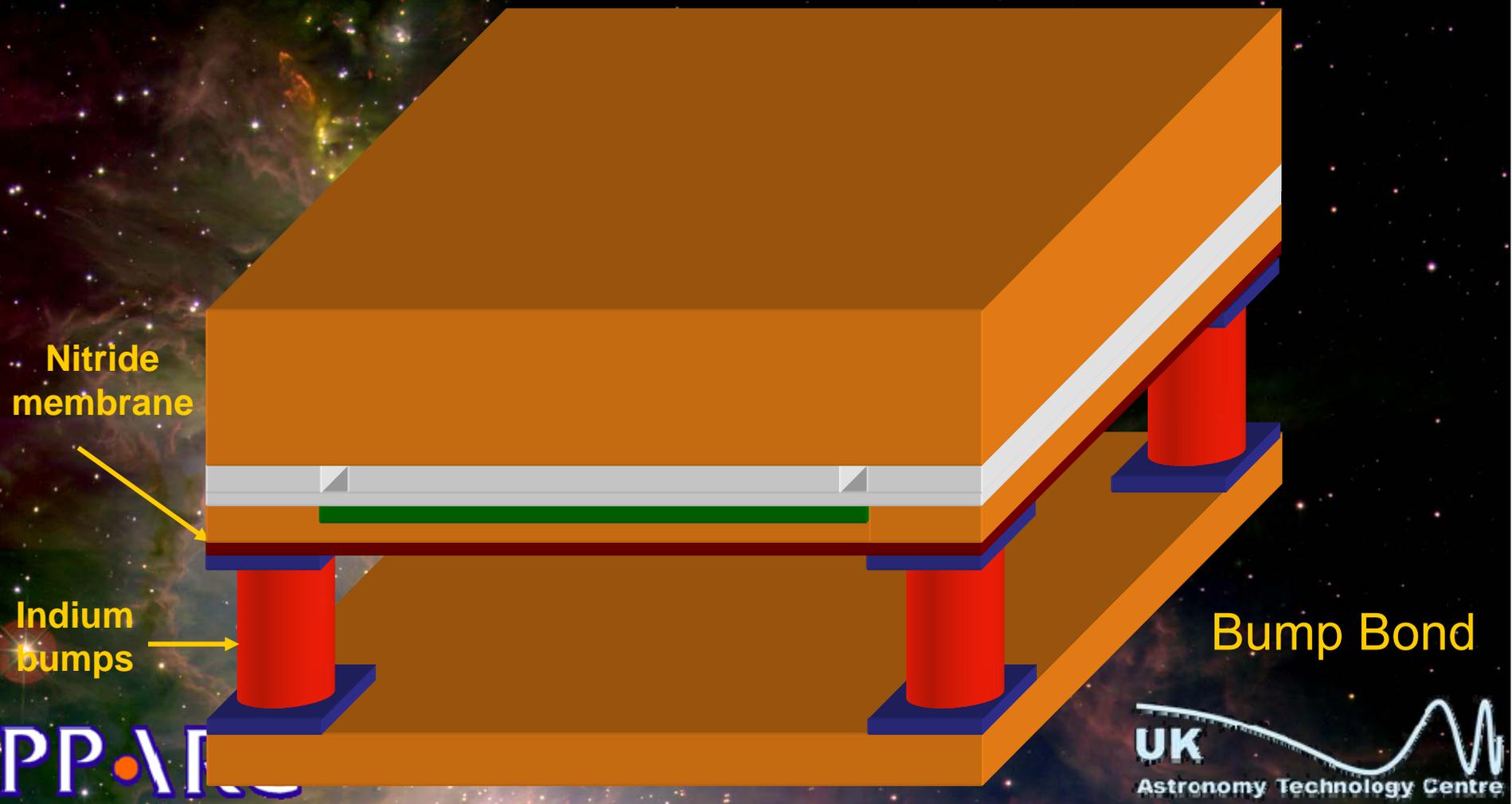


Etch oxide mask



Bond pads, TES and interconnect

Process sequence for hybridised detector/mux pair

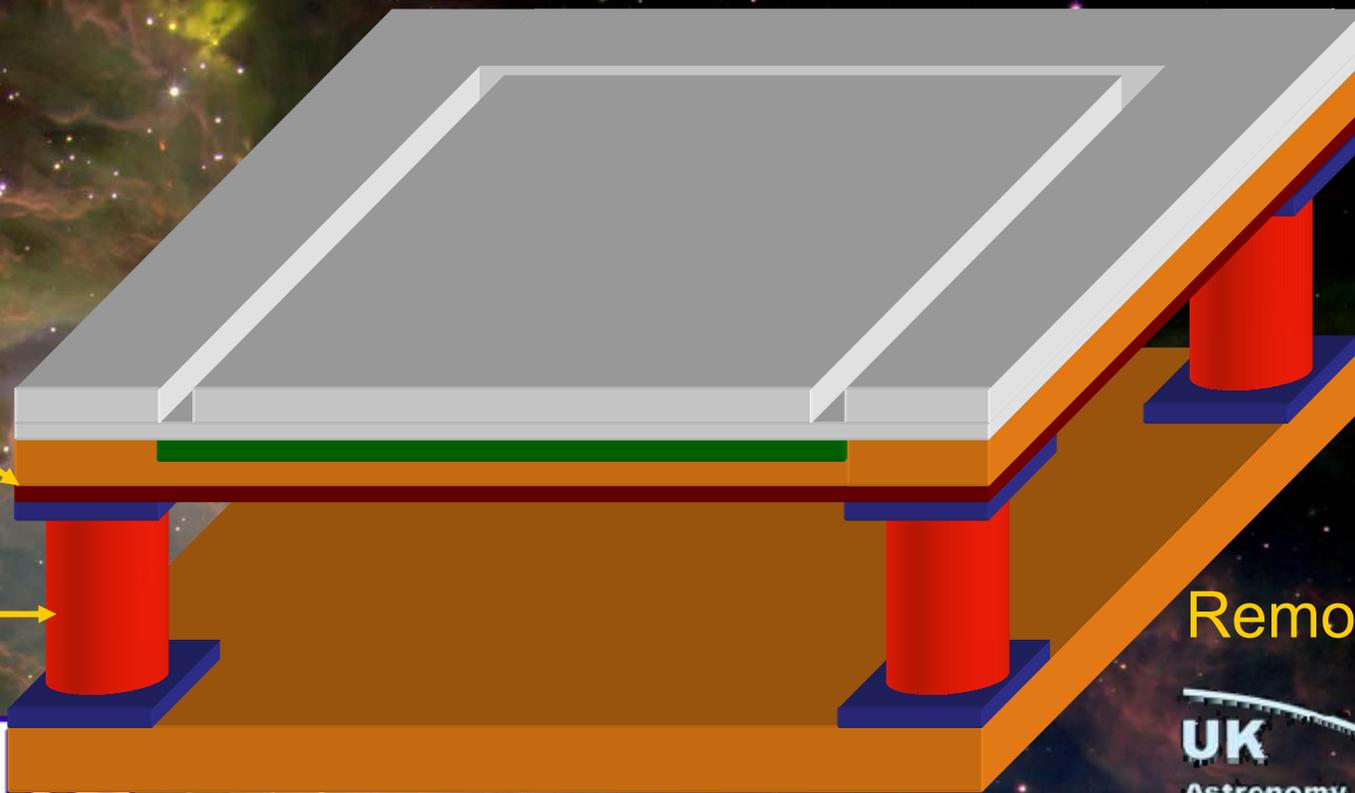


Process sequence for detector/mux pair

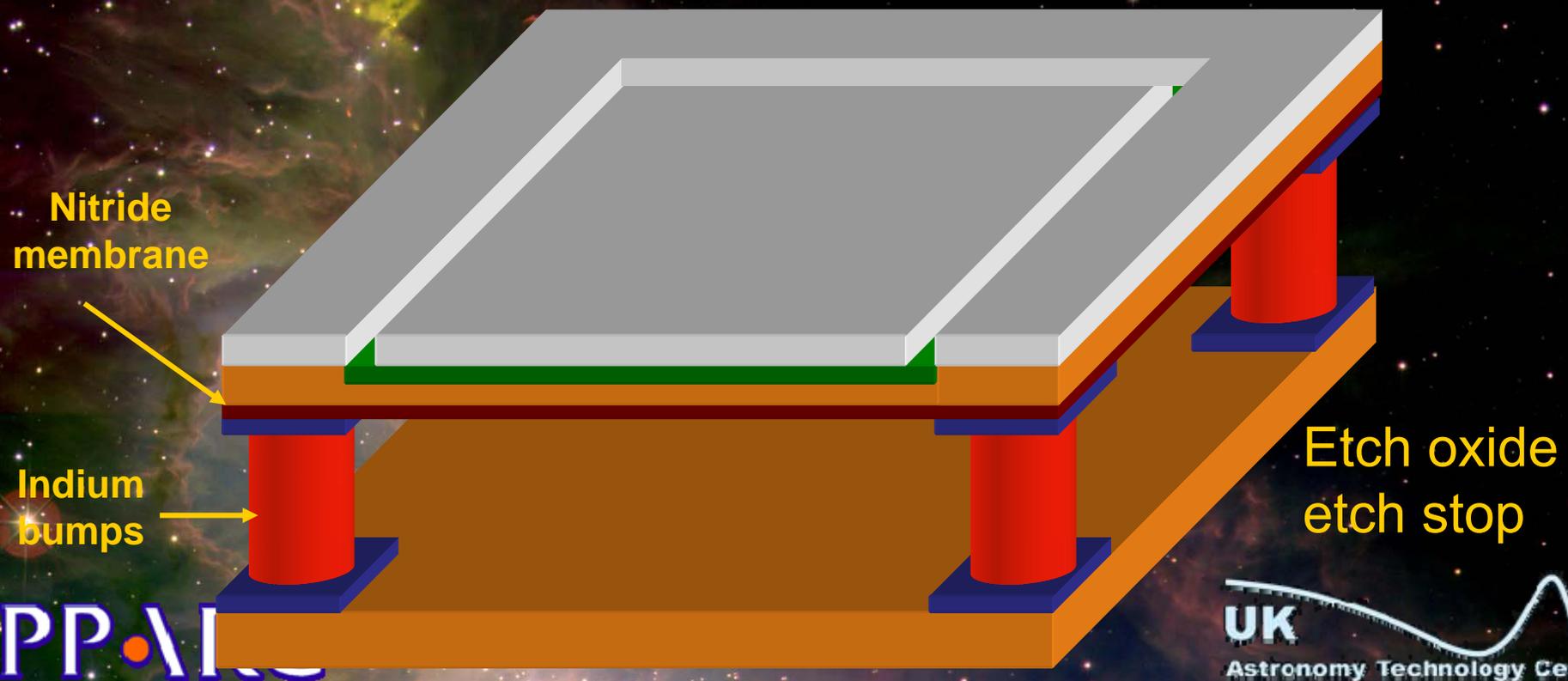
Nitride membrane

Indium bumps

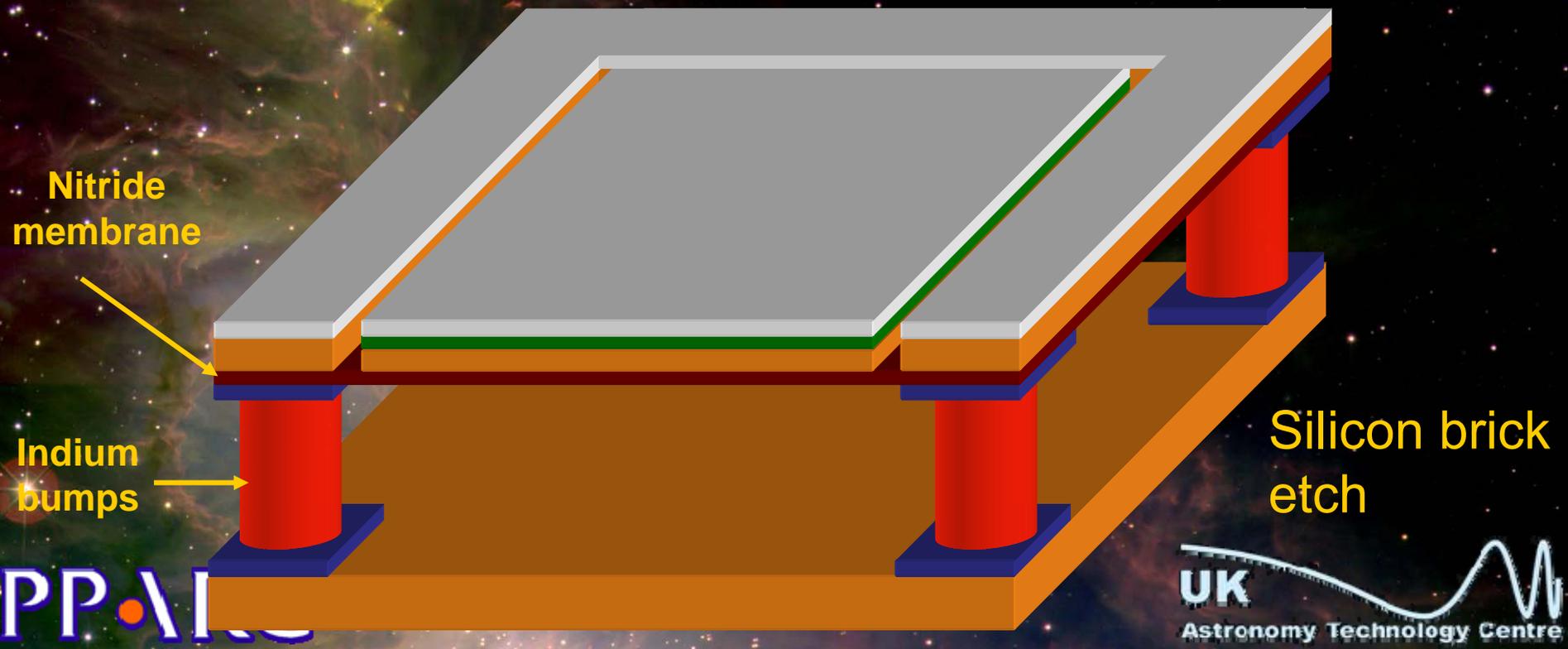
Remove handle



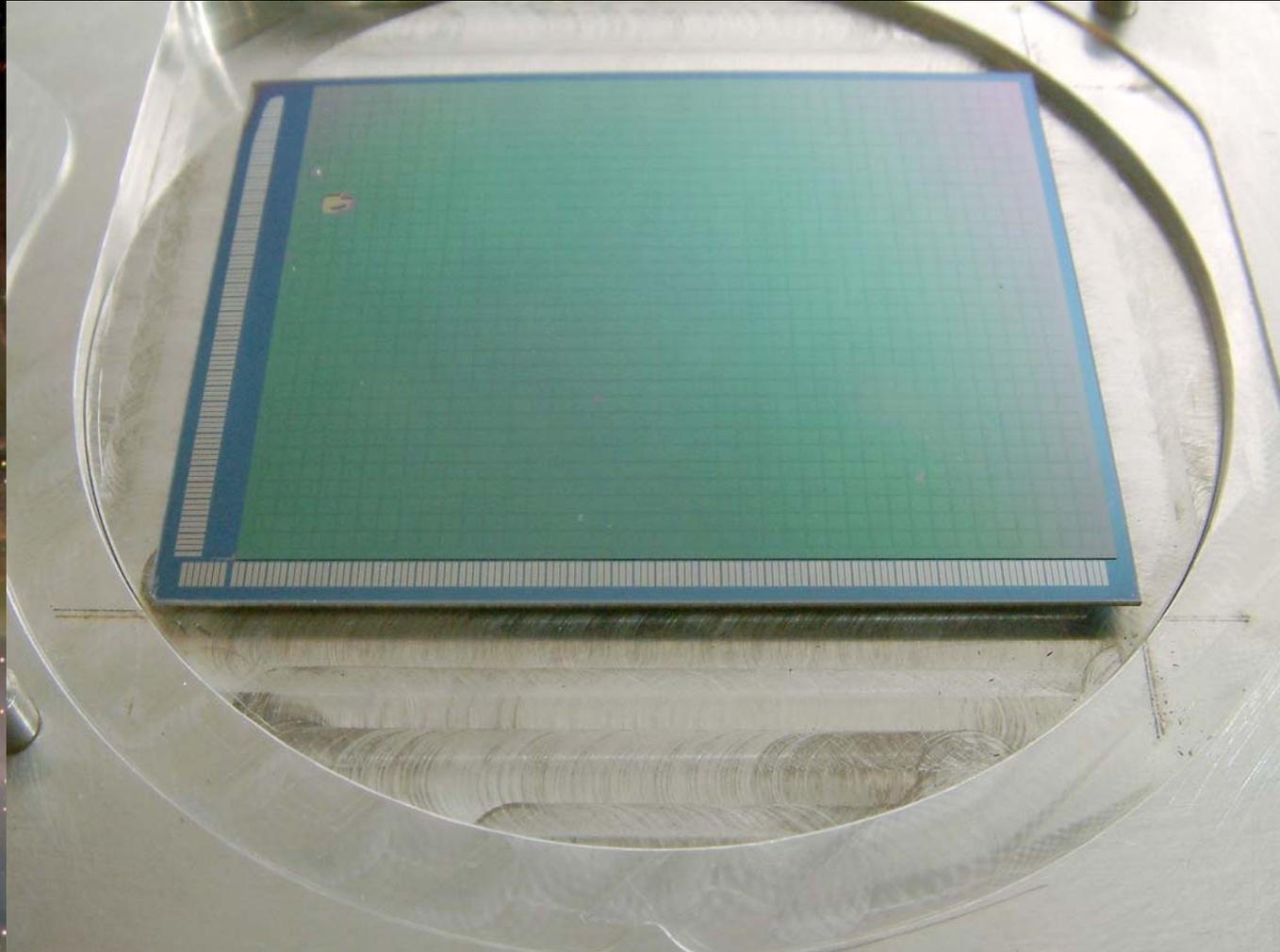
Process sequence for detector/mux pair



Process sequence for detector/mux pair



Completed sub-array



Next Generation Submm detectors

- SCOWL
- Large Submm Telescope
- Far IR Space Missions
- At least 4x SCUBA 2 pixels
- Issues:
 - Dilution refrigerator
 - Wire count
- Solutions?
 - Frequency division mux
 - CMOS mux
 - Kinetic Inductance Devices



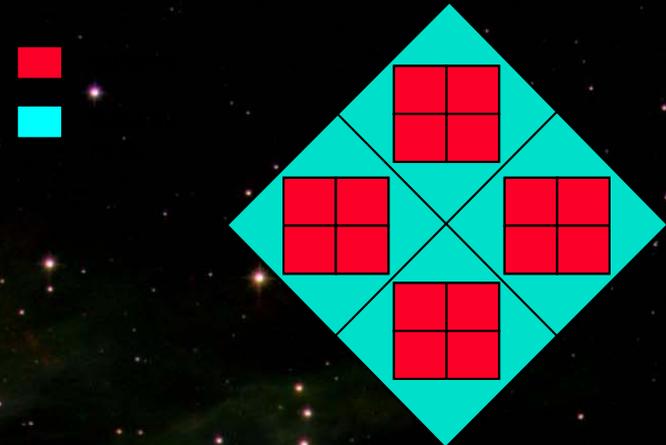
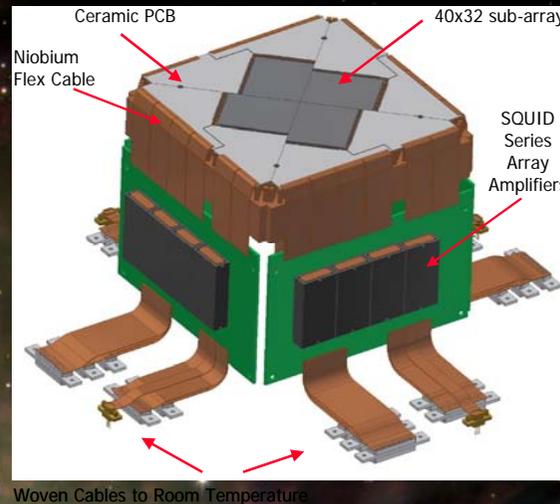
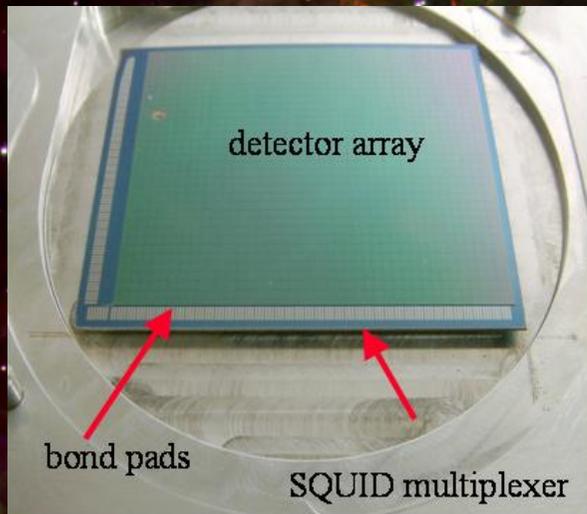
SCOWL (SCUBA at OWL)

Concept Study carried out by ATC (P.I. I. Egan)



Imager in the 350 and 450 μm bands (850 μm desirable)

FOV 2 x 2 arcmin, Surveyer for ALMA targets Resolution <2 arcsec



4 SCUBA 2 TES Detectors (20480 pix)

Transition Edge Sensors hybridized to a Superconducting Quantum Interference Design (SQUID) time-division multiplexer

Contrast with Particle Physics Detector Development

- Range of development mechanisms
 - Industry based > Academic based
- IR detectors coming from Defence-based industry – but now 50% of Rockwell IR business in Astronomy
- Submm detectors developed by research labs and Universities – more like PP detectors
- Should we take this approach for ELT detectors?

Mechanisms for joint detector development



Consortia

- Example 2kx4k CCDs developed by E2V
- Opticon FP6 programme > Adaptive Optics detectors
- Big projects
 - JWST
 - XEUS
 - ELT
- Global Tech Dev programme?
Lobby companies, maximise order size

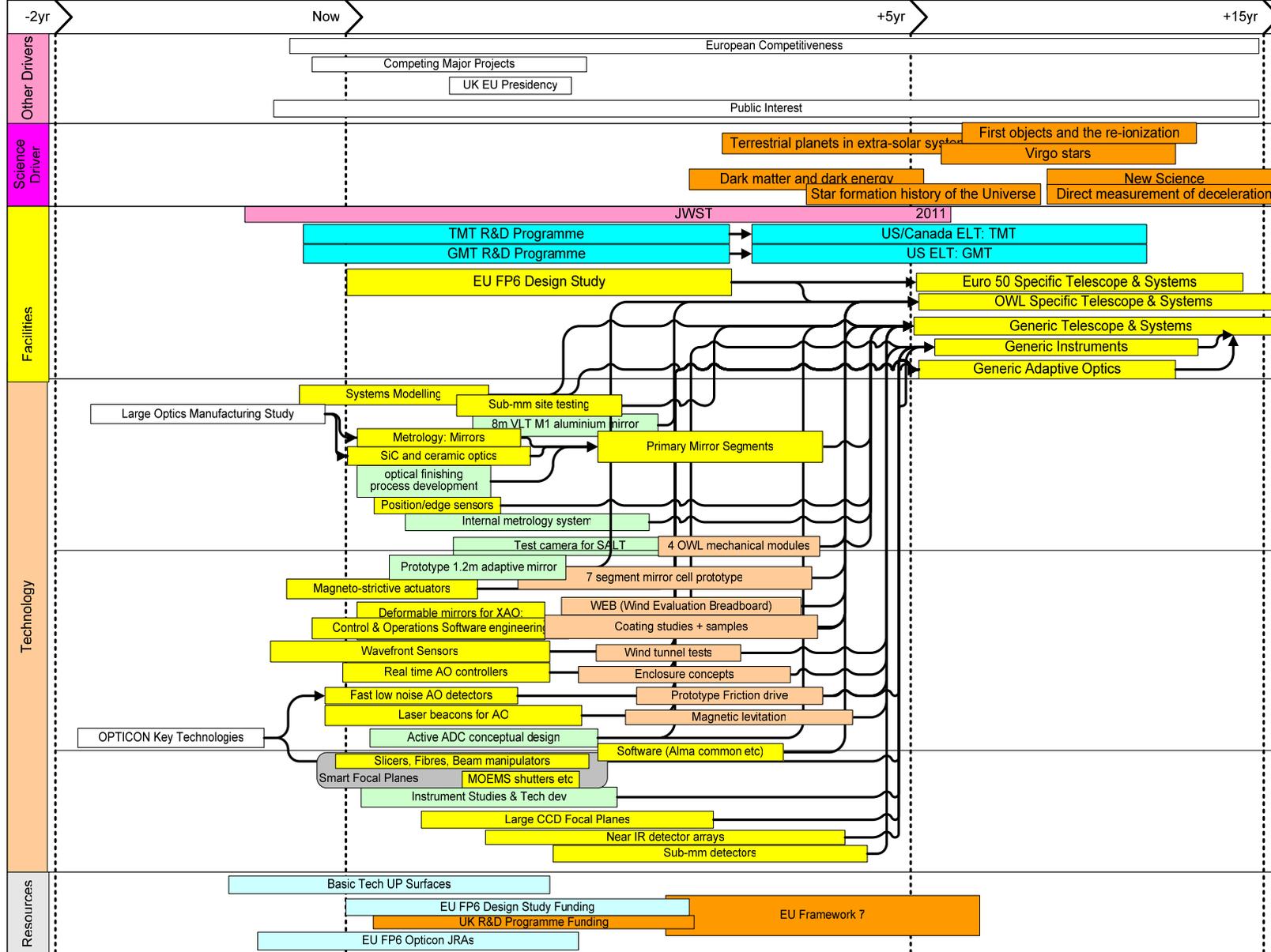
Next step: Develop European Roadmap for Detectors for Astronomy ?



- Using Opticon Key Technology Network
- Coordinated by UK
- Include ESA & ESO
- More on Space Missions in Andrew Holland's Talk

UK ELT Technology Roadmap

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