A cryogenic material property database - why bother?

Invited talk given at the SUPA annual meeting, Strathclyde University, 14th June 2006

Adam Woodcraft

SUPA

http://woodcraft.lowtemp.org/

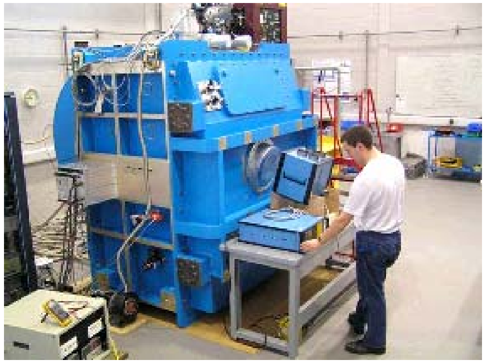
What is TEOPS?

•**T**echnology for **E**xperimental and **O**bservational **P**hysics in **S**cotland

•“Spans the areas of particle physics, astrophysics and astronomy with a common theme of leading edge technology”

•Collaboration between ATC Detector Development group and Glasgow University IGR and Experimental Particle Physics groups

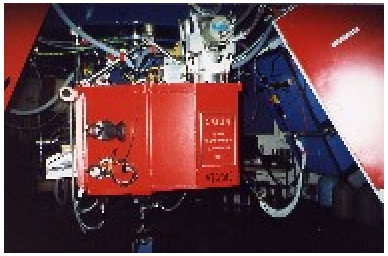
Commonality



•Significant areas of commonality: some examples:

- Cryogenics
  - The ATC has decades of experience in constructing reliable and robust instruments operating at cryogenic temperatures (as low as 4 K and even below 100 mK)

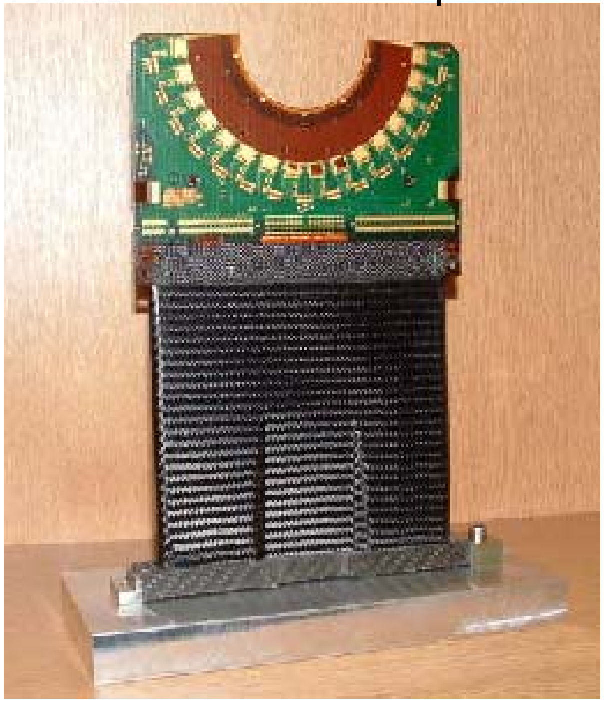
- Cryogenic operation is now of interest for future generations of both gravitational wave detectors and colliders for particle physics



Commonality

- New materials
  - e.g. silicon-carbide being looked for use in both astronomical instruments and in gravitational wave detectors

LHC module using carbon fibre mount – Si-C considered as replacement



Si-C lightweighted telescope mirror (courtesy M. Krodel)

Commonality

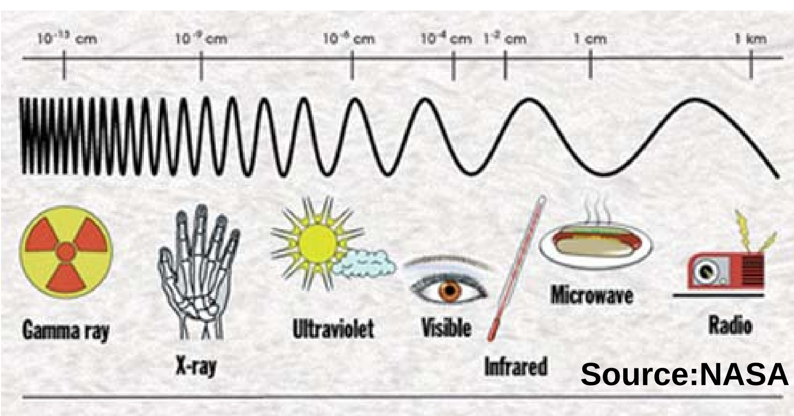
- Particle physics detector groups have experience in constructing detectors on an “industrial” scale
  - will be required in astronomy as telescopes increase in size (and number of telescopes in the case of arrays)

CERN ATLAS detector

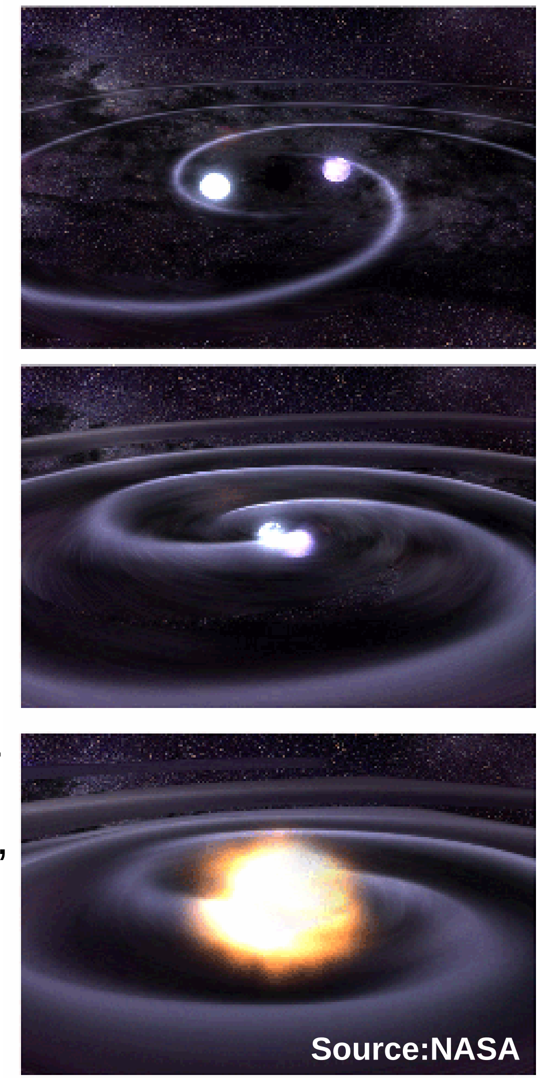
Further commonality

• Commonality not just in technology, but also in the resulting science

- Gravitational wave detection is astronomy, albeit unconventional ("multi-messenger" astronomy; going outside e/m spectrum)



Orbiting white dwarf stars discovered by X-ray emission should be 'bright' source of gravitational waves



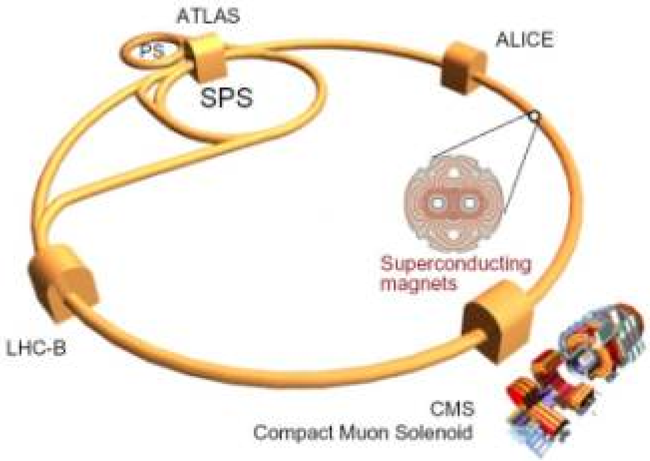
Further commonality

• Commonality not just in technology, but also in the resulting science

  • Particle physics and cosmology are converging (e.g. dark matter: can look for astronomical evidence, try to detect, or try to produce in accelerators)

X-ray image of Abell 2029 tracing dark matter distribution (NASA)

CRESST dark matter detector



LHC

How will we exploit this?

- Creation of two SUPA Advanced Fellowships each based both in Edinburgh and Glasgow
    - Both fellows now in post (just)

- Setting up facilities shared between the three groups

- Setting up web site to make researchers in each group aware of facilities and expertise available in other groups

- Setting up joint techniques seminar series

- Exploring collaborations between TEOPS and other SUPA themes as well as external institutions

Cryogenic material properties

- Today we’ve had talks on table-top fusion, particle physics...
  - Why should a scientist spend time on constructing a database of material properties at cryogenic temperatures?

  - “Because it isn’t there”

The need for data

- Good engineering requires reliable data
- This is mostly missing at cryogenic temperatures
- Making measurements:
  - is much harder (and expensive) than at room temperature
  - Need cryostat
    - no access to experiment when cold to alter/repair
    - warm-up and cool-down time-consuming
    - can't see what's going on
    - need to get things right first time

The need for data

- Good engineering requires reliable data
- This is mostly missing at cryogenic temperatures
- Making measurements:
    - is much harder (and expensive) than at room temperature
    - Need cryostat
        - no access to experiment when cold to alter/repair
        - warm-up and cool-down time-consuming
        - can’t see what’s going on
        - need to get things right first time
        - experiment might as well be in orbit...

The need for data

- Sample to sample variation often much larger than at room temperature
    - Partly down to physics of materials
    - But also because most materials (e.g. alloys) aren't designed to be used at low temperatures - lack of reproducibility at 1 K is not considered a problem

    - Therefore measuring one sample is often insufficient

- Some case studies….

Gravitational wave detectors

- Sources of fundamental noise:
  - photon (shot) noise
  - seismic noise
  - thermal noise
    - Essential to reduce for 3rd generation detectors
    - achieve with high Q suspension & mirrors and cooling to cryogenic temperatures

- Moving to next generation is likely to require changes to new materials to achieve required sensitivity

- So we need to know Q factor and other properties of candidate materials at cryogenic temperatures
  - Most information required does not exist

Gravitational wave detectors

- Silicon is a promising material
    - High thermal conductivity (to conduct away heat from laser power)
    - Low thermal expansion (to reduce deformation of mirror surface)

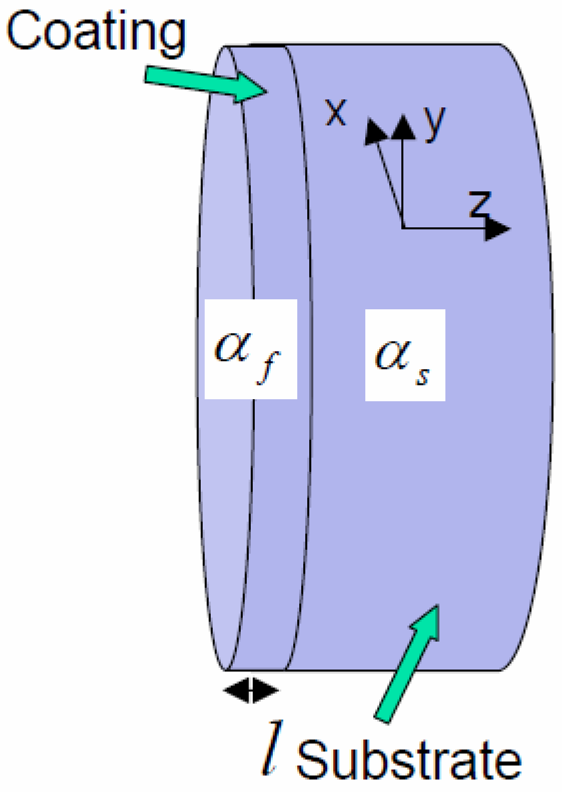
Gravitational wave detectors

- Properties will depend on doping; large phase space to examine, largely unexplored
  - elastic moduli
  - thermal conductivity
  - thermal expansion
  - heat capacity (determines cool-down times)
    - all as a function of temperature

Gravitational wave detectors

- Also need to investigate the effect of optical coatings
  - Thermal noise depends on relative thermal and elastic properties of coating and substrate

  - Need to know
    - expansion coefficient
    - thermal conductivity
    - Young’s modulus
    - Possion ratio



Particle physics

- An important current goal is to increase the radiation hardness of detectors; required to cope with increases in luminosity
    - Need improvement of factor of 10 in radiation resistance for Super LHC (2015+)
    - Cryogenic operation is being studied as a way to achieve this
    - This requires measurements of the electrical properties of irradiated silicon across a range of temperatures

- Properties of other materials used in cryogenic parts of instruments are less critical but still important…

Material data

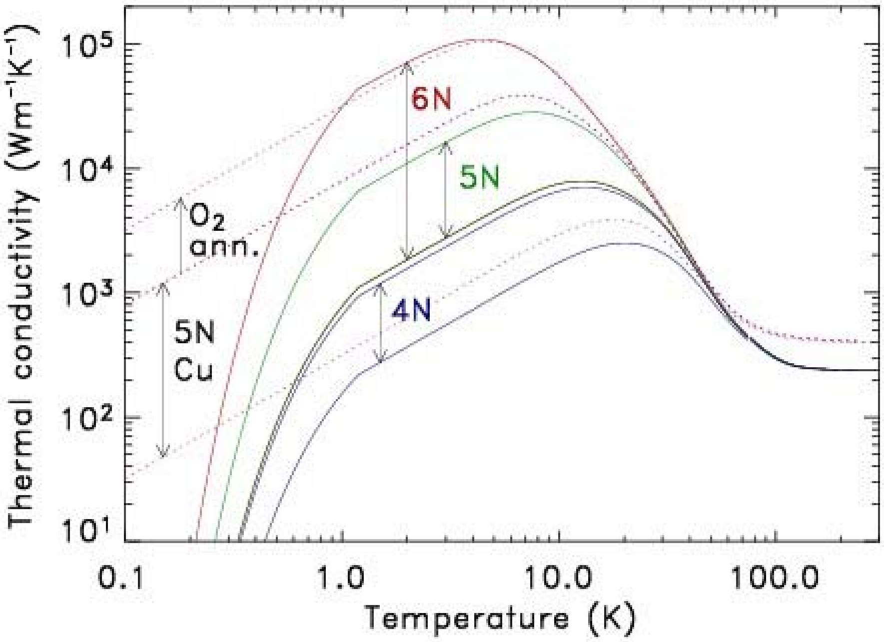
- Cryogenic instruments and experiments have been constructed and used for decades

- Still a lack of important material property data...
  - Often measured on an ad-hoc basis during instrument development
  - Adds risk:
    - May take longer than expected to make measurements
    - Chosen material may be found to be unsuitable, forcing further unscheduled research
    - Often time is too short to do a good measurement
    - Inexperience and lack of appropriate facilities often leads to poor measurements and false conclusions

Example

- A (nameless) group wanted to choose between pure aluminium and copper for a thermal link
- One sample each of 5N purity Al and Cu was measured

- But there is a huge sample to sample variation!
  - This wasn't a good way to choose between the materials



Thermal conductivity ranges for aluminium of different purities

Example

- A (nameless) group wanted to choose between pure aluminium and copper for a thermal link
- One sample each of 5N purity Al and Cu was measured
- But there is a huge sample to sample variation!
  - This wasn’t a good way to choose between the materials
  - The information they needed did exist, but not in an accessible form (i.e. a critical evaluation)
- A good material property database would have avoided this error.
- Also, measurements are often seriously in error, sometimes in ways that would be obvious with appropriate experience
- Material property measurements need to be decoupled from instrument development!

Astronomy (SCUBA-2)

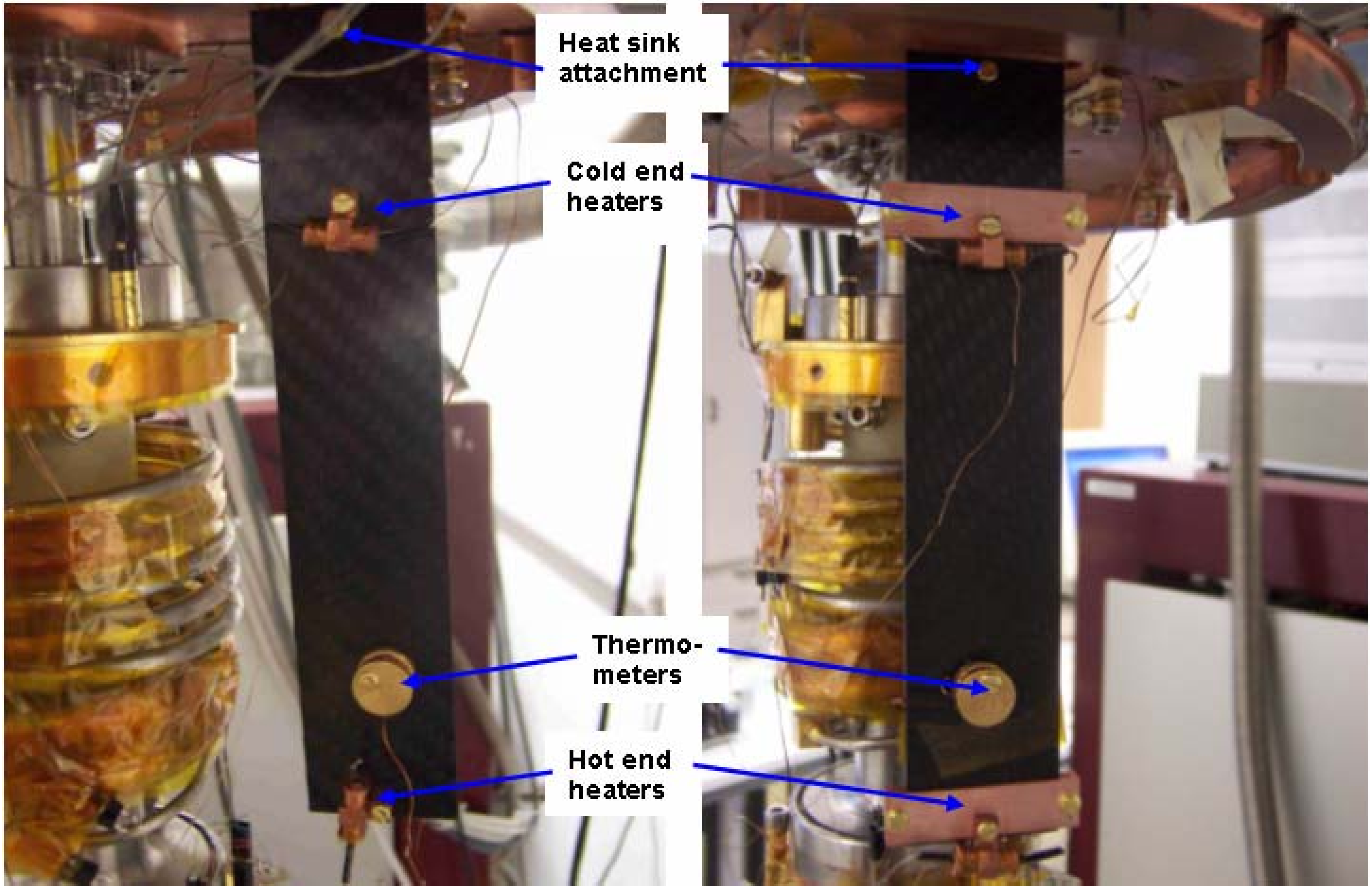
- SCUBA-2 (sub-mm astronomical instrument under construction at ATC)
  - Had to measure thermal conductivity of:
    - CFRP supports
    - Welds between various types of aluminium
    - Pure copper for thermal straps
    - Bolted thermal joints

- Insufficient time to measure *all* materials used; had to rely on extrapolation and large safety margins in some cases.

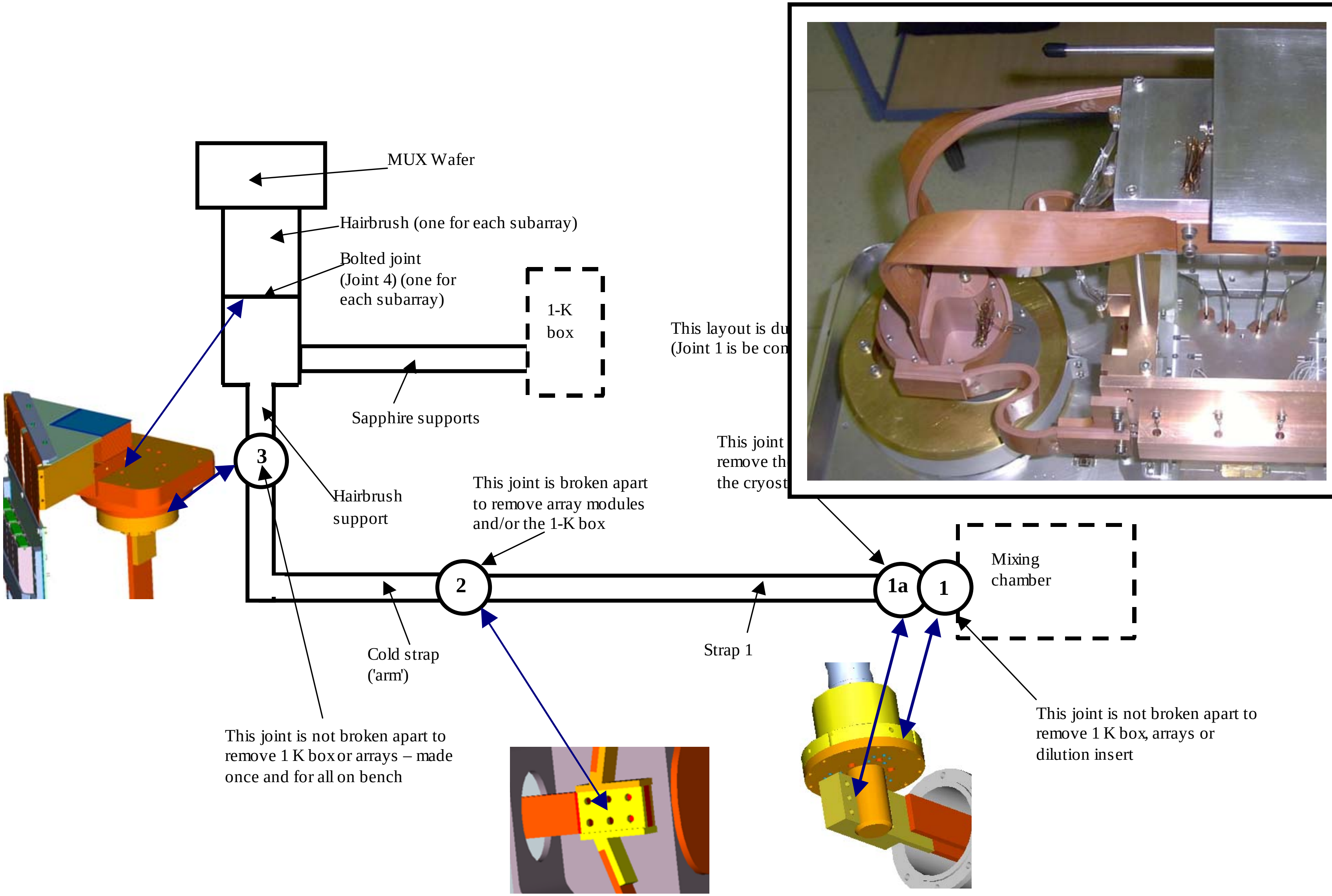
- Design also compromised by need to use well characterised materials despite better choices *probably* being available (who knows?)
- Better information would have led to cheaper and faster construction

CFRP supports

- Measured in detector development testbed



SCUBA-2 strap system



Unexplored territory

- In astronomy, particle physics and gravitational wave physics, new discoveries come about by building better detectors e.g.
  - gravitational wave spectrum completely unexplored
  - sub-mm astronomy – so far only area about size of full moon has been mapped to any depth
  - particle physics – go to increasing energy ranges

- But we already have cryostats and there is still much to be learnt about materials at low temperatures, despite having had the equipment needed for decades!

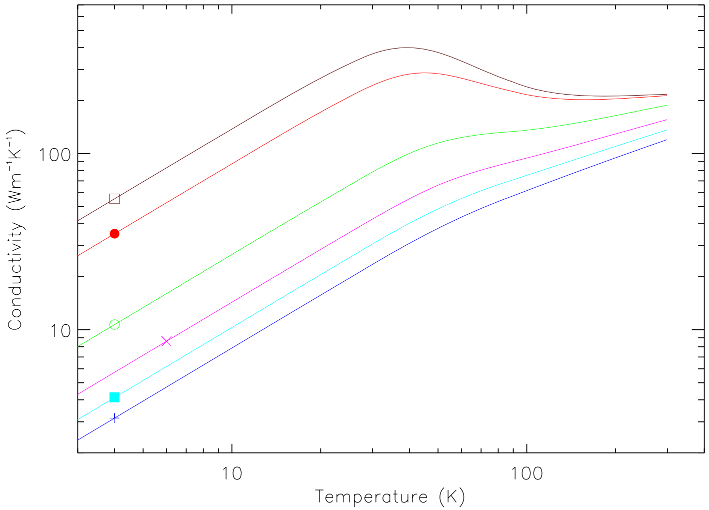
- Worse (or better?) – still much to be found from existing data

Example

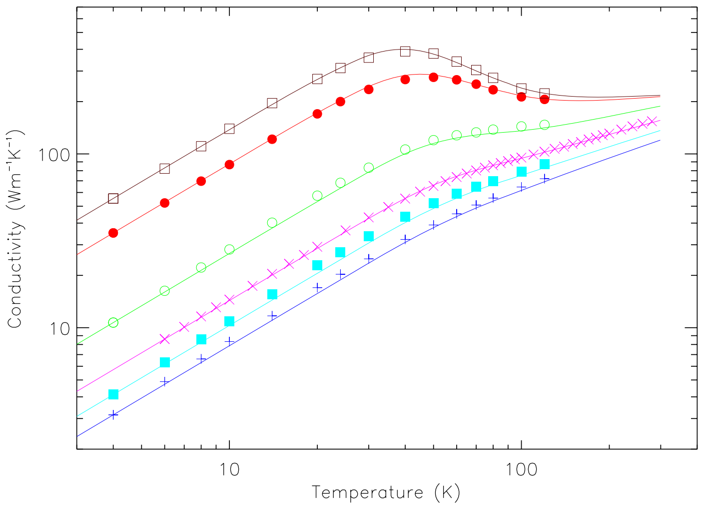
- Method to predict aluminum alloy conductivity from a measurement at a single temperature
- Work carried out for instruments under development

- Much of the data I used was obtained in the 60's!

Predict from single point…



Remaining measurements agree



Timeliness

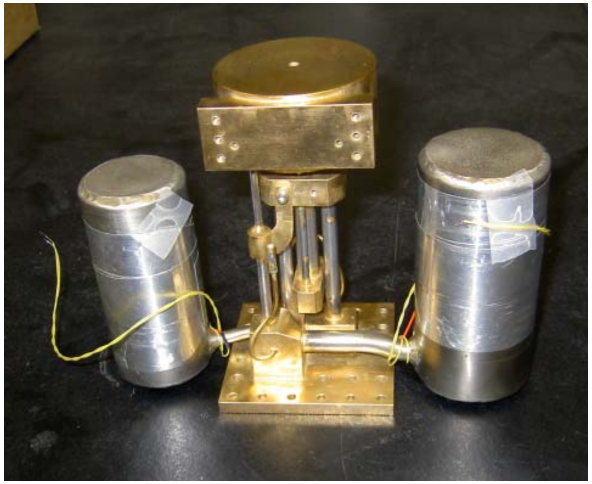
- Instruments requiring cryogenic temperatures are moving out of the lab

- Traditionally the need for frequent helium transfers has limited the use of cryogenics outside the lab
    - Only used in very limited cased e.g. MRI scanners

Timeliness

•Pulse tube coolers make 'turn-key' operation below 4 K possible without need for helium transfers or experience in cryogenics

- Closed cycle ^3He fridges, dilution fridges and continuous ADRs make temperatures down to 100 mK and below possible in a similar manner



Timeliness

- Examples:
    - Superconducting electronics for mobile phone base stations
    - Passive Terahertz detectors for security applications
    - X-ray microcalorimeter for materials analysis (e.g. semiconductor industry)
    - Superconducting computers
    - Things we haven’t even though of yet…

- But reliable engineering data is needed!

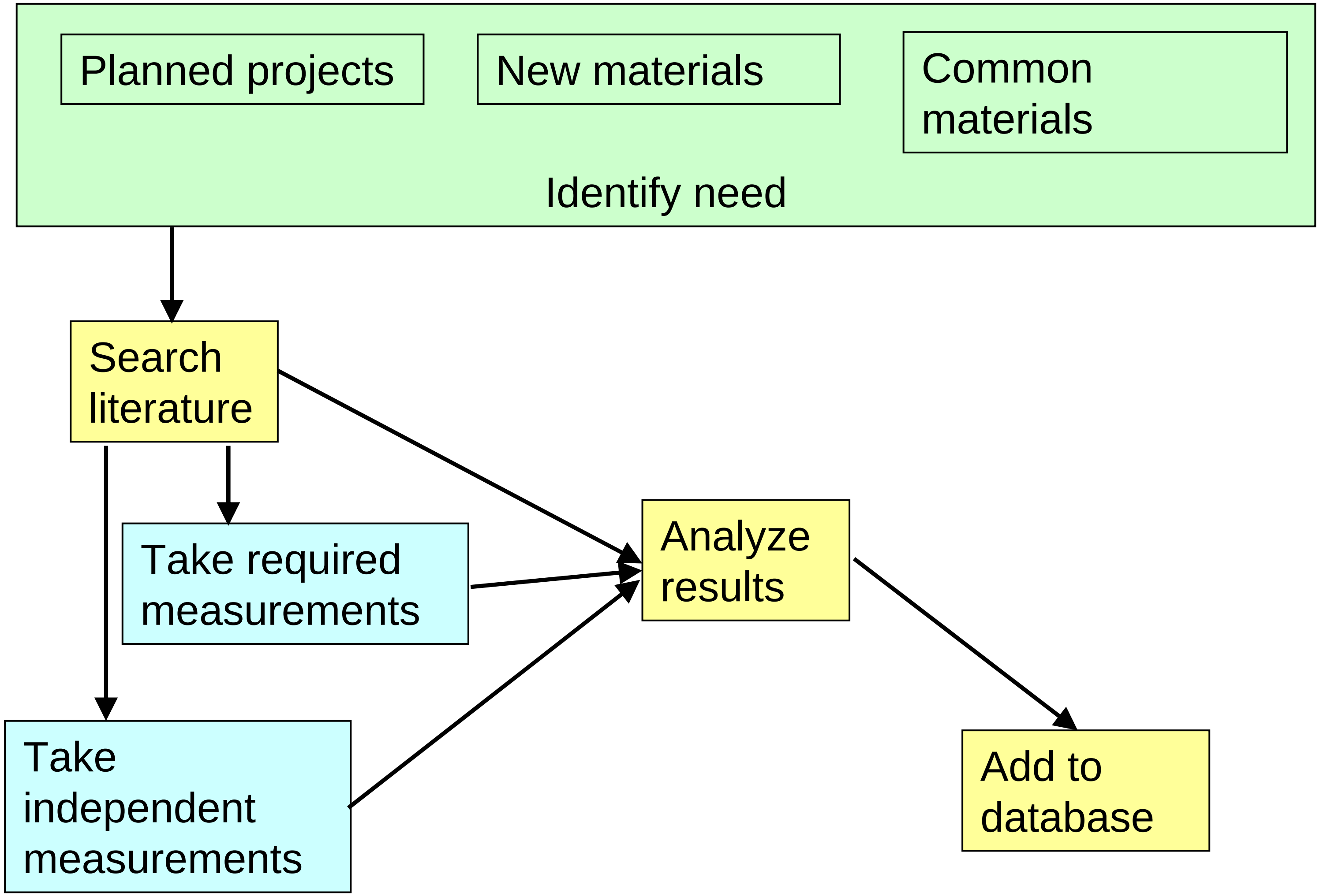
Wider picture

- So as well as the immediate needs of SUPA, we want to look at the wider picture
- Looking at setting up a co-ordinated network of institutions to carry out and critically examine the results of material property measurements
    - Perhaps a network of groups with overlapping specialities, so measurements can be confirmed by independent measurements

- European (Framework 7) funding?

- Cryogenic heritage of the ATC makes it an obvious location for work of this type

Wider picture



Conclusions

- The three SUPA TEOPS groups have specific needs for material property information
  - We will set up a flexible test facility that will be able to obtain this information
  - We will also be looking to collaborate with other groups with a need for material property information

- The world needs a good database of cryogenic material property measurements
  - This requires a critical analysis of existing data as well as new measurements
  - Now is the time to start doing something about it!

- *Thanks to* Calum Torrie, Shiela Rowan, Jim Hough, Stuart Reid, Colin Cunningham, Val O'Shea

IGR

SUPA Scottish Universities Physics Alliance

UK Astronomy Technology Centre

University of Glasgow