Science and Technology Facilities Council

Characterising Neutrons for Neutrino Experiments

Neutron Flux Measurements with Multi-Foil Activation at ISIS

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6th June 2023

KING'S College LONDON

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UKRI Science and Technology Facilities Council

Background Overview

Super-Kamiokande, Neutron Multiplicity, Neutrons in Simulations, Motivations

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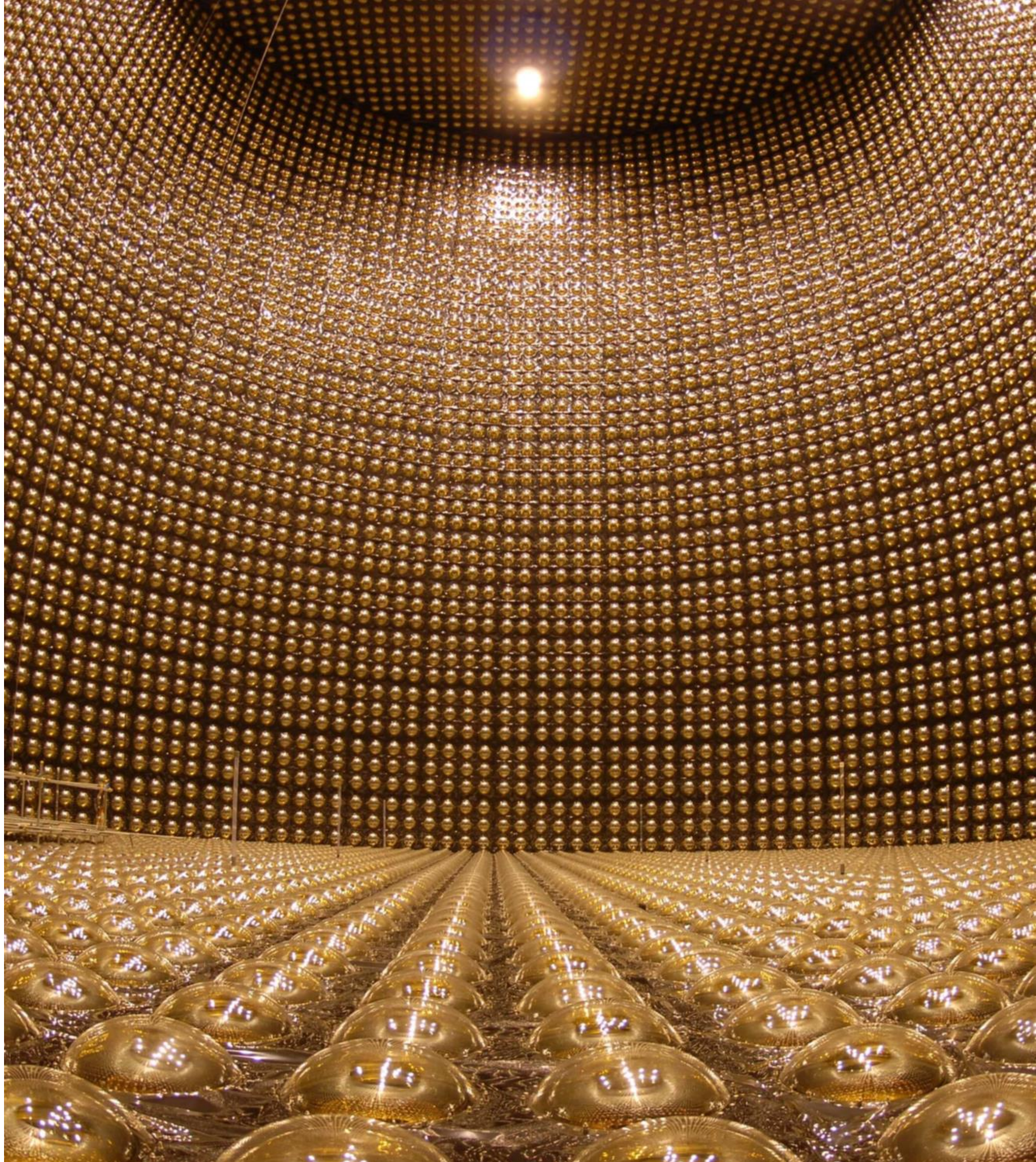
Super-Kamiokande

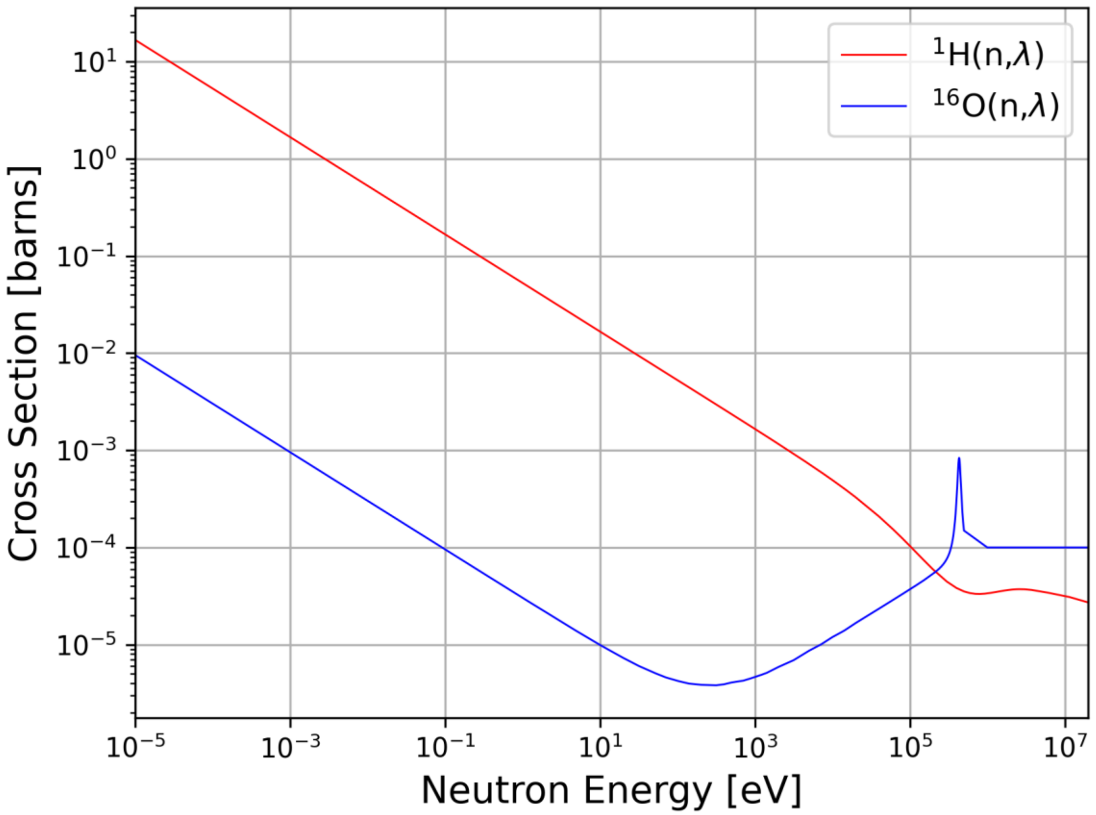
- Nobel Prize winning Water-Cherenkov neutrino detector in Japan
- To be succeeded by Hyper-Kamiokande in late 2027
- Many physics goals including proton decay searches, solar/atmospheric neutrino studies and keeping watch for supernovae
- **Main disadvantage of Water-Cherenkov detectors is that they are not sensitive to neutrons to aid anti-neutrino identification**



Neutron Tagging

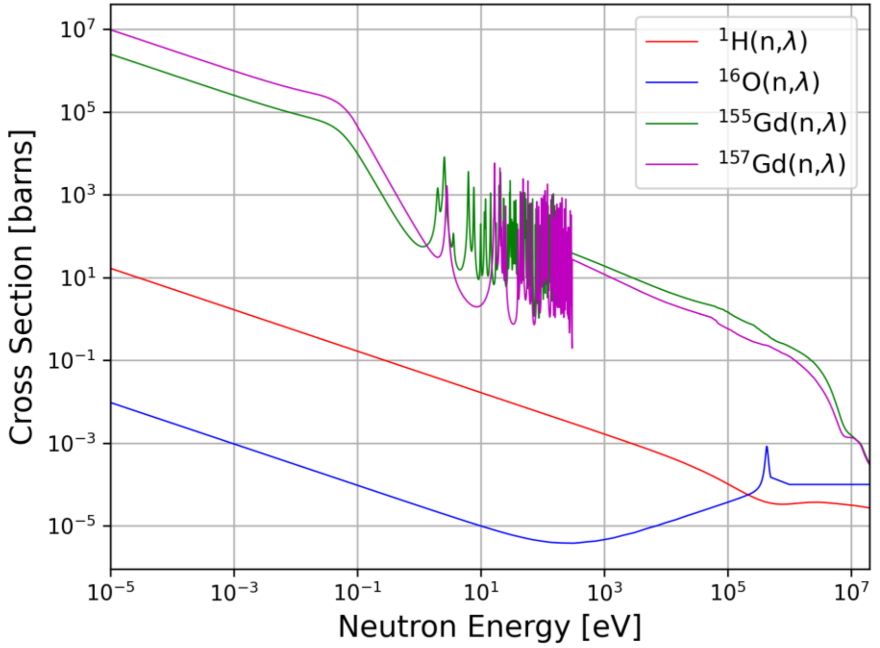
- In pure water, neutrons are primarily captured on hydrogen
- Average neutron capture time is ~200 μs and produces a 2.2 MeV gamma, which is close to the detection threshold
- SK4 (late 2008~) implemented a neutron tagging trigger system
- Neutron tagging was difficult due to the large time difference to the delayed signal and the lack of detectable light

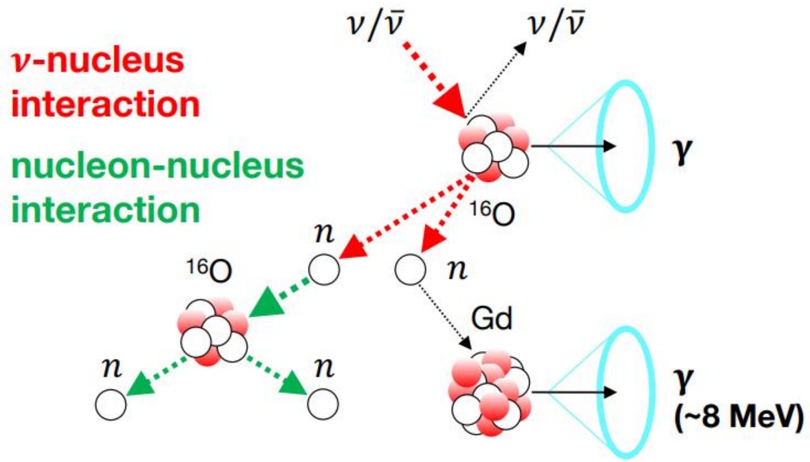
Neutron capture cross sections on H and O



Gadolinium Loading

- Gadolinium has a very large neutron capture cross section
- Neutron capture time is ~20 μs and the resulting gammas are ~8 MeV which produce sufficient light for detection





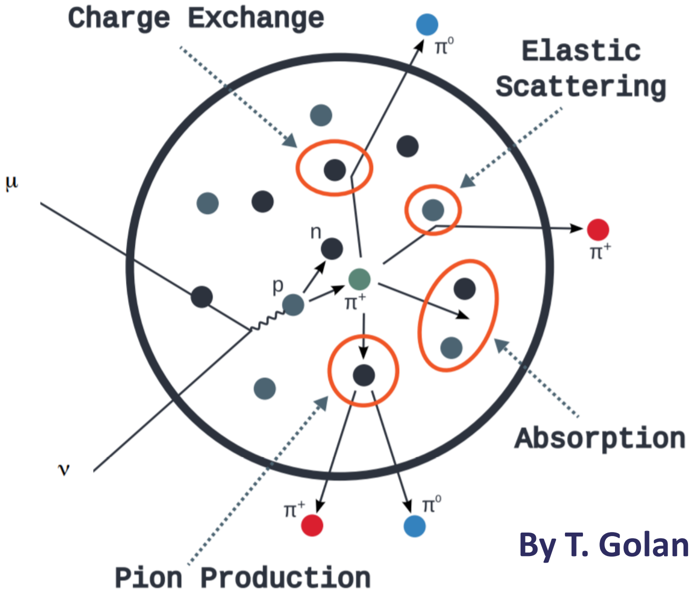
- Super-K has been loaded with gadolinium sulphate
- To use this neutron information correctly in analyses, we must first accurately predict neutron multiplicity

Neutron Multiplicity

Data and simulation do **not** agree

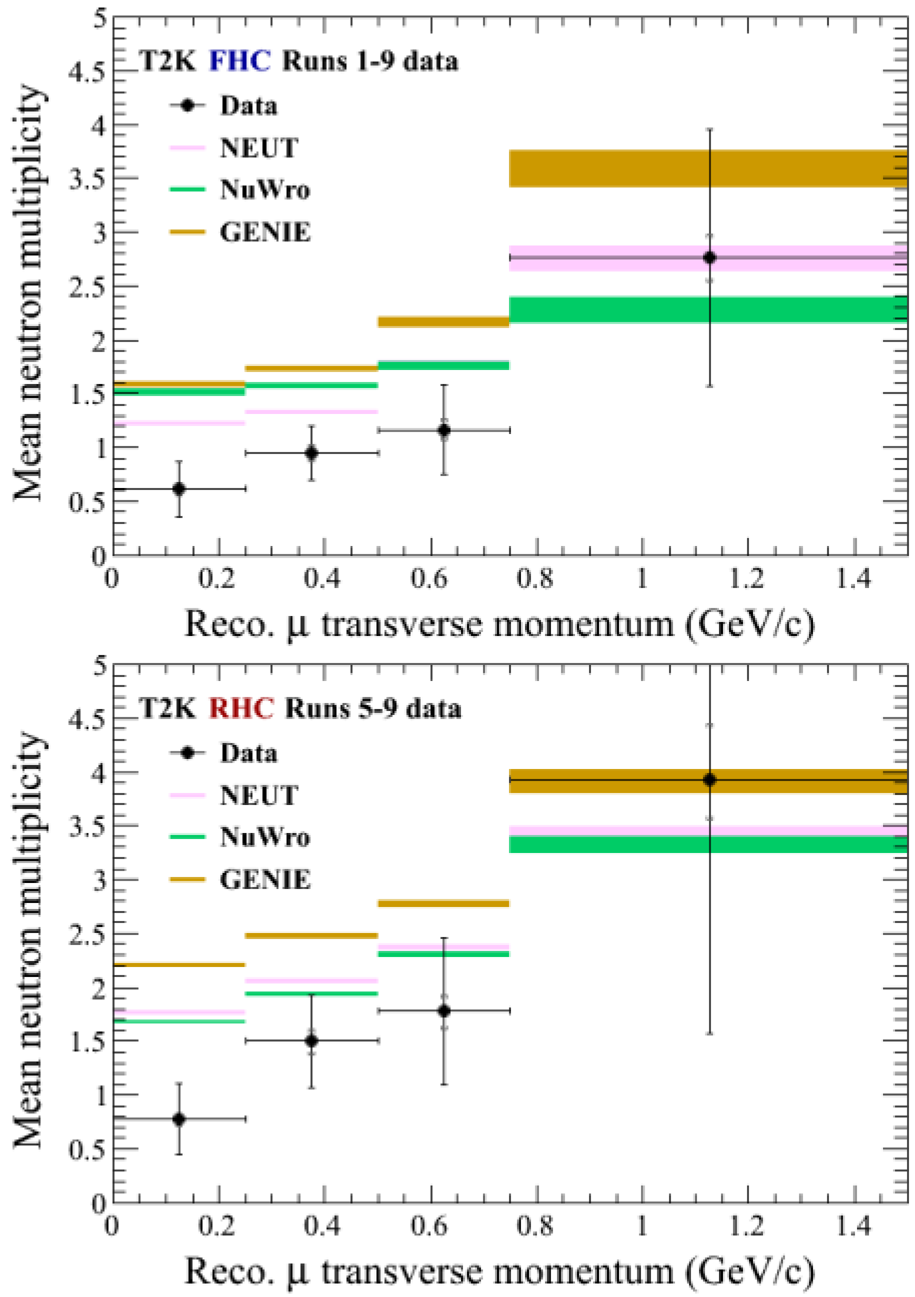
Potentially a result of various problems in simulations:

- Number of neutrons at the neutrino vertex;
- Final state interactions:



By T. Golan

- **Modelling of neutron propagation**

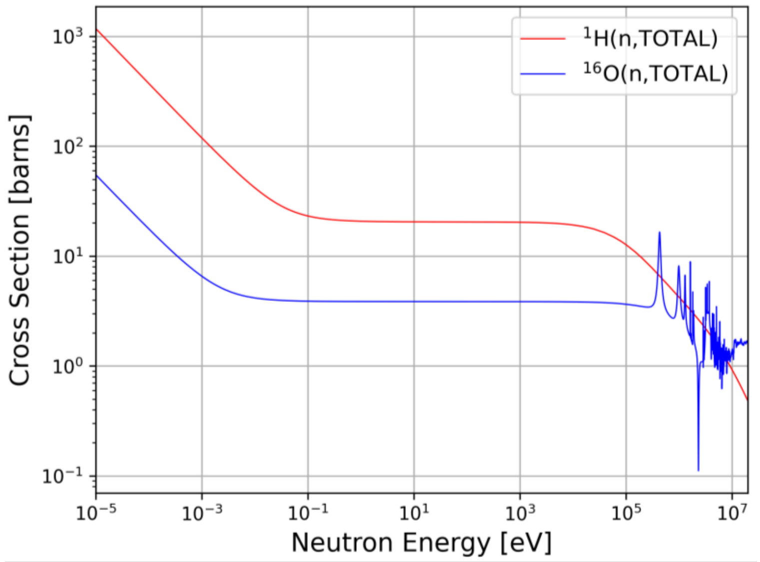


From Akutsu-san's thesis

Neutrons in Geant4

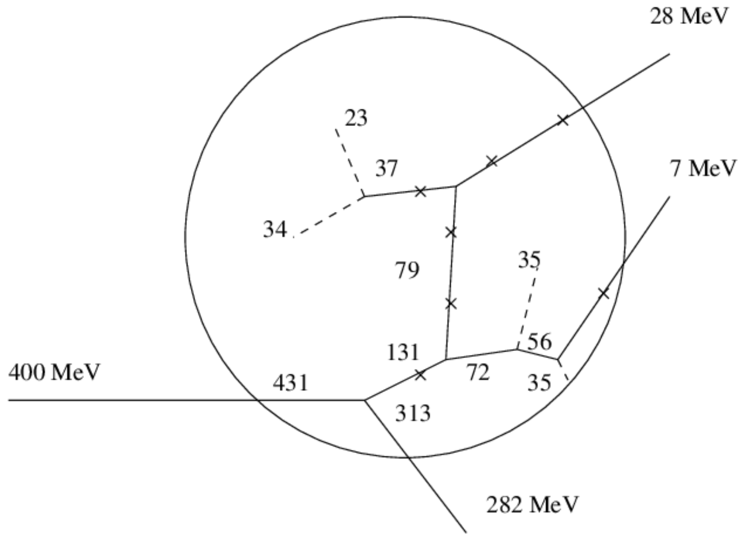
The way a neutron is simulated depends on its energy:

<20 MeV



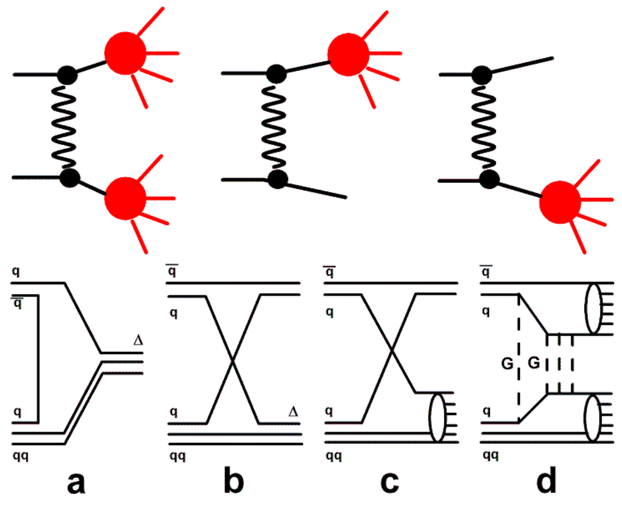
High precision models using cross section data libraries

20 MeV~6 GeV (or higher)



Intranuclear cascade models e.g.: Bertini (pictured), Binary, INCL++

3 GeV~100 TeV



Fragmentation models e.g.: Fritiof (pictured), QGSP

Notes: upper limit of intranuclear cascade can be changed

Nuclear Data Libraries

In the high precision models, Geant4 uses G4NDL which is a custom nuclear data library:

- As of G4NDL-4.6: based on JEFF-3.3
- Until G4NDL-4.5: based on ENDF/B-VII

Several other libraries are available in Geant4 format for neutrons

Each library can lead to a different result..

Cross Section Library
ENDF/B-VII (2011)
ENDF-VIII (2018)
JEFF-3.3 (2018)
JENDL-4.0u (2016)
BROND-3.1 (2016)
CENDL-3.1 (2009)

Various libraries available in Geant4

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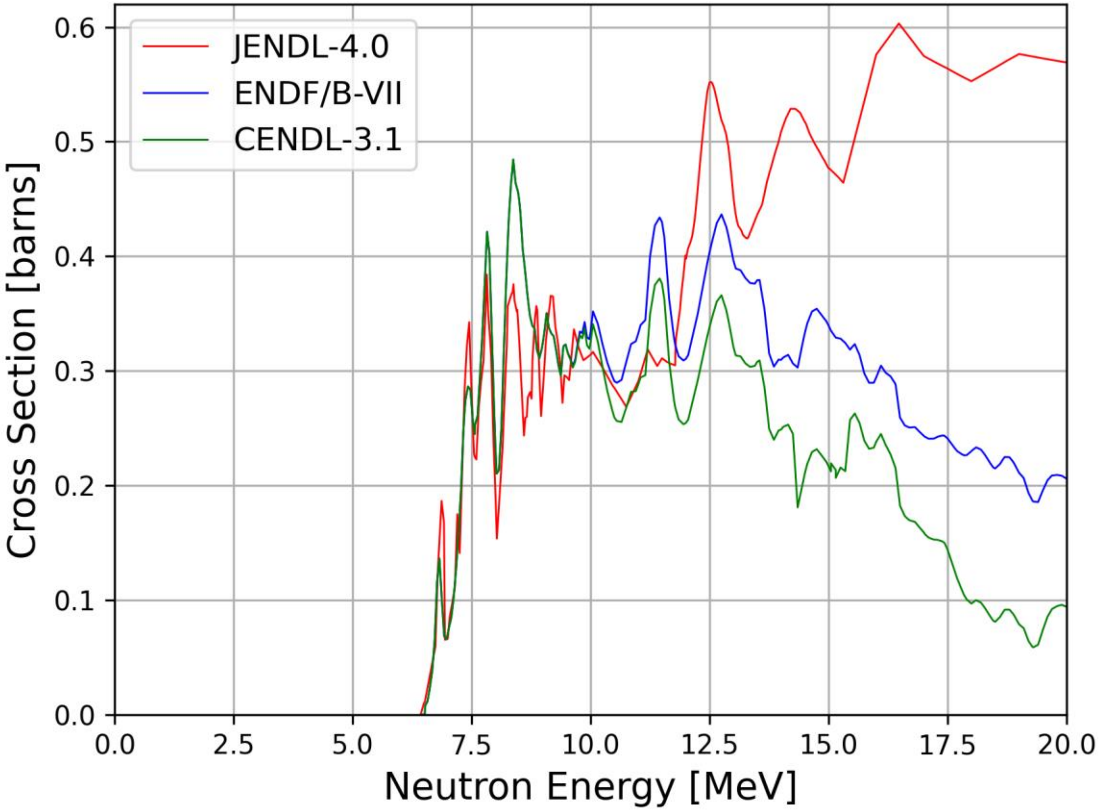
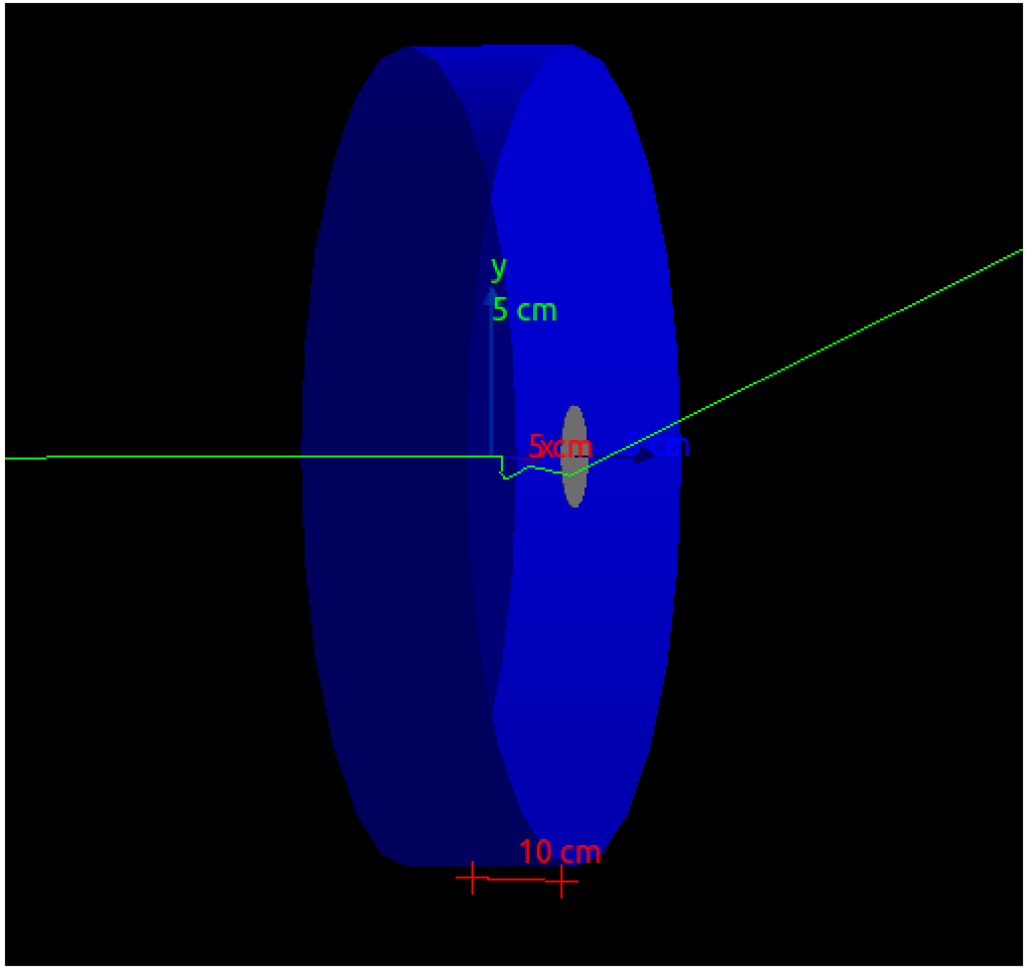
Each library can lead to a different result…

Example: total inelastic cross section on ^{16}O



Example: Effect of Libraries

- Simulation geometry: a cylindrical volume of water with a small cylindrical *neutron detector* attached to the centre of one face
- A neutron beam (E^{-1} flux between 0~20 MeV) is generated incoming from the opposite face
- Different nuclear data libraries (i.e., the cross sections in the 0~20 MeV range) are used and the neutrons passing the *detector* are recorded
- **This is resemblant of the experiment we plan to study neutron-water cross section**



Example: Effect of Libraries

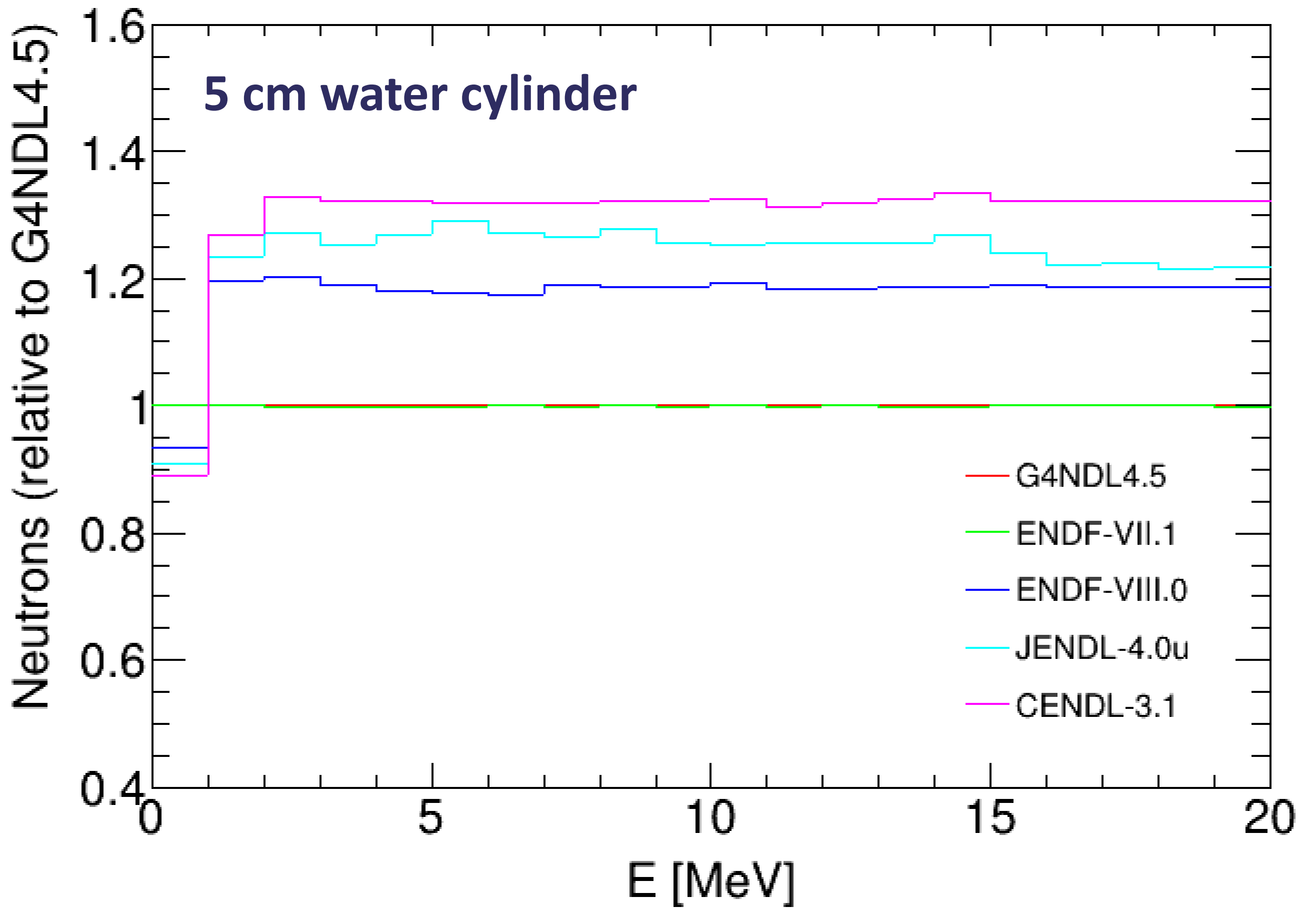
Different libraries lead to different results!

We are planning an experiment to study:

- which library best agrees with data
- how well >20 MeV models agree with data

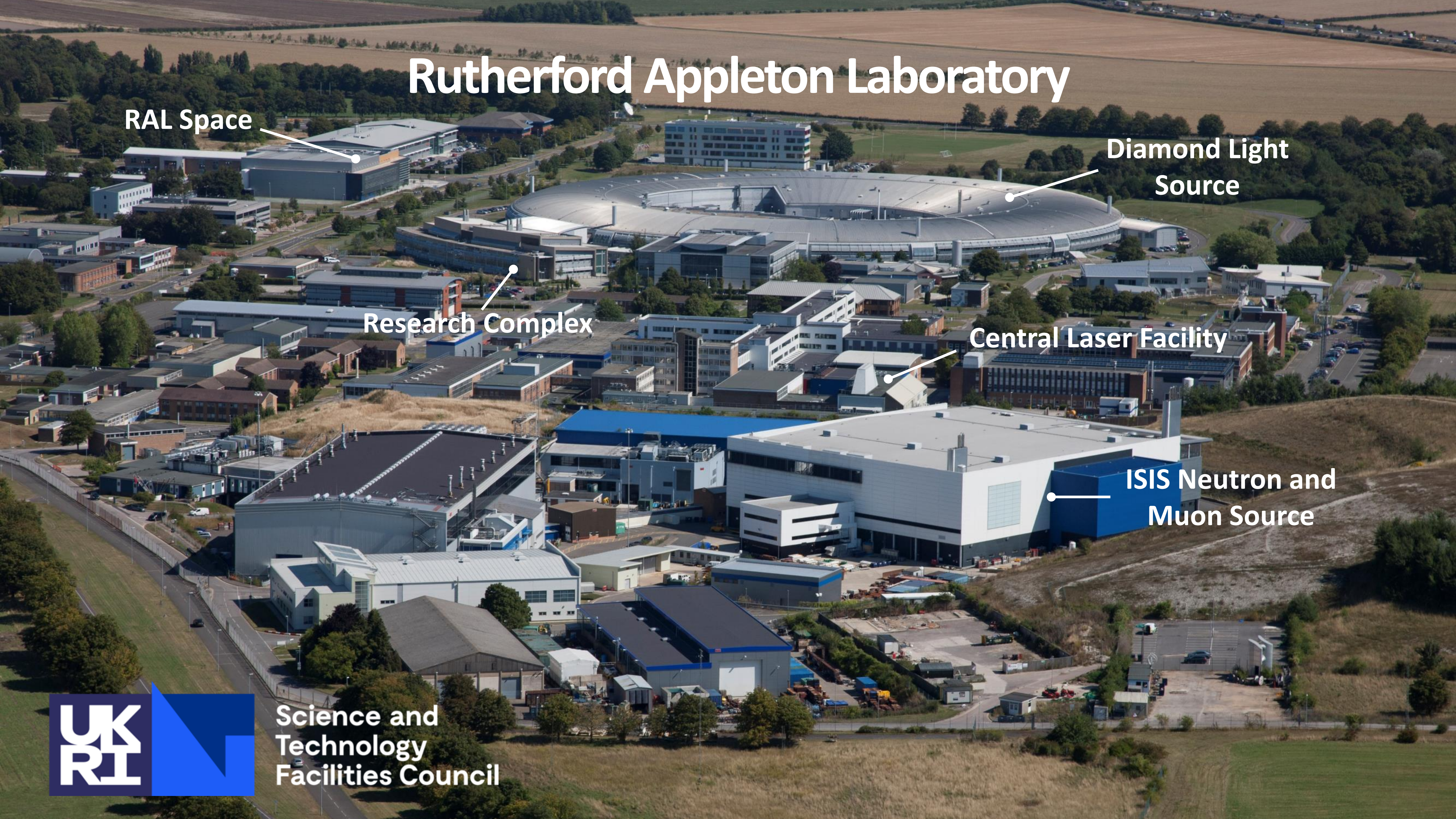
and make a **neutron-water total cross section measurement up to 100 MeV**

By comparing data to simulations, we hope to study the inelastic cross sections also



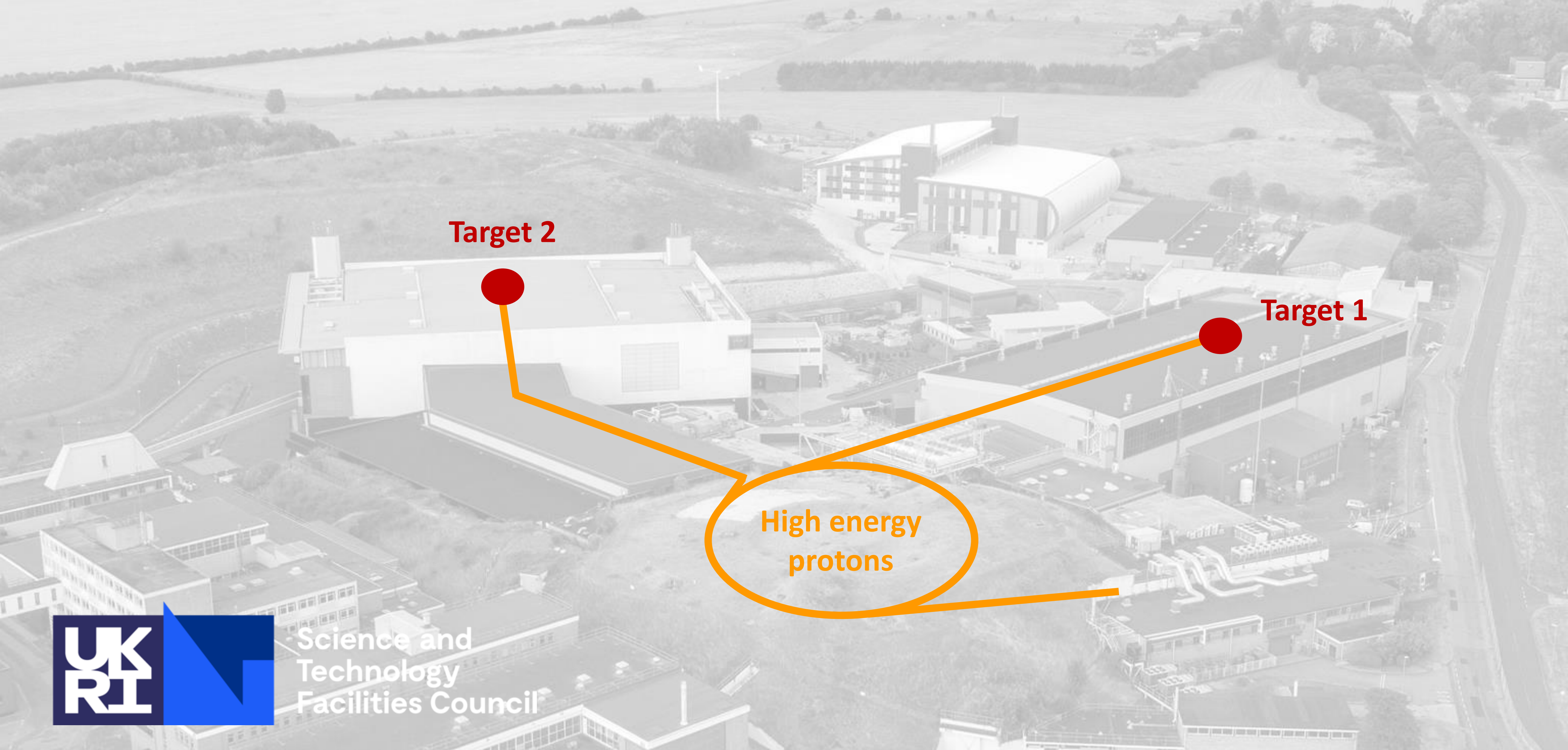
ISIS Neutron Source

Rutherford Appleton Laboratory, ISIS Neutron Source, ChipIr Beamline, Neutron Induced Errors


Rutherford Appleton Laboratory
RAL Space
Diamond Light Source
Research Complex
Central Laser Facility
ISIS Neutron and Muon Source
UKRI
Science and Technology Facilities Council


ISIS Neutron and Muon Source
Target Station 2
Target Station 1
Science and
Technology
Facilities Council

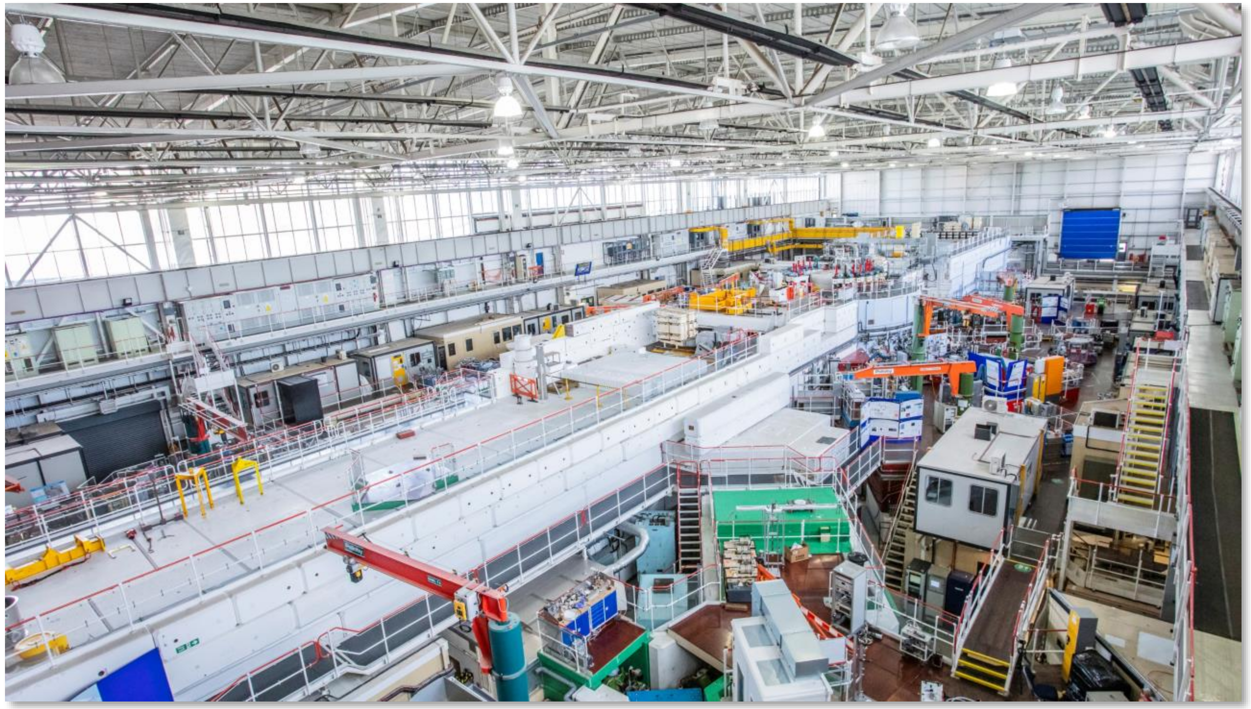
Accelerator driven neutron source



UKRI Science and Technology Facilities Council

Target Station 1

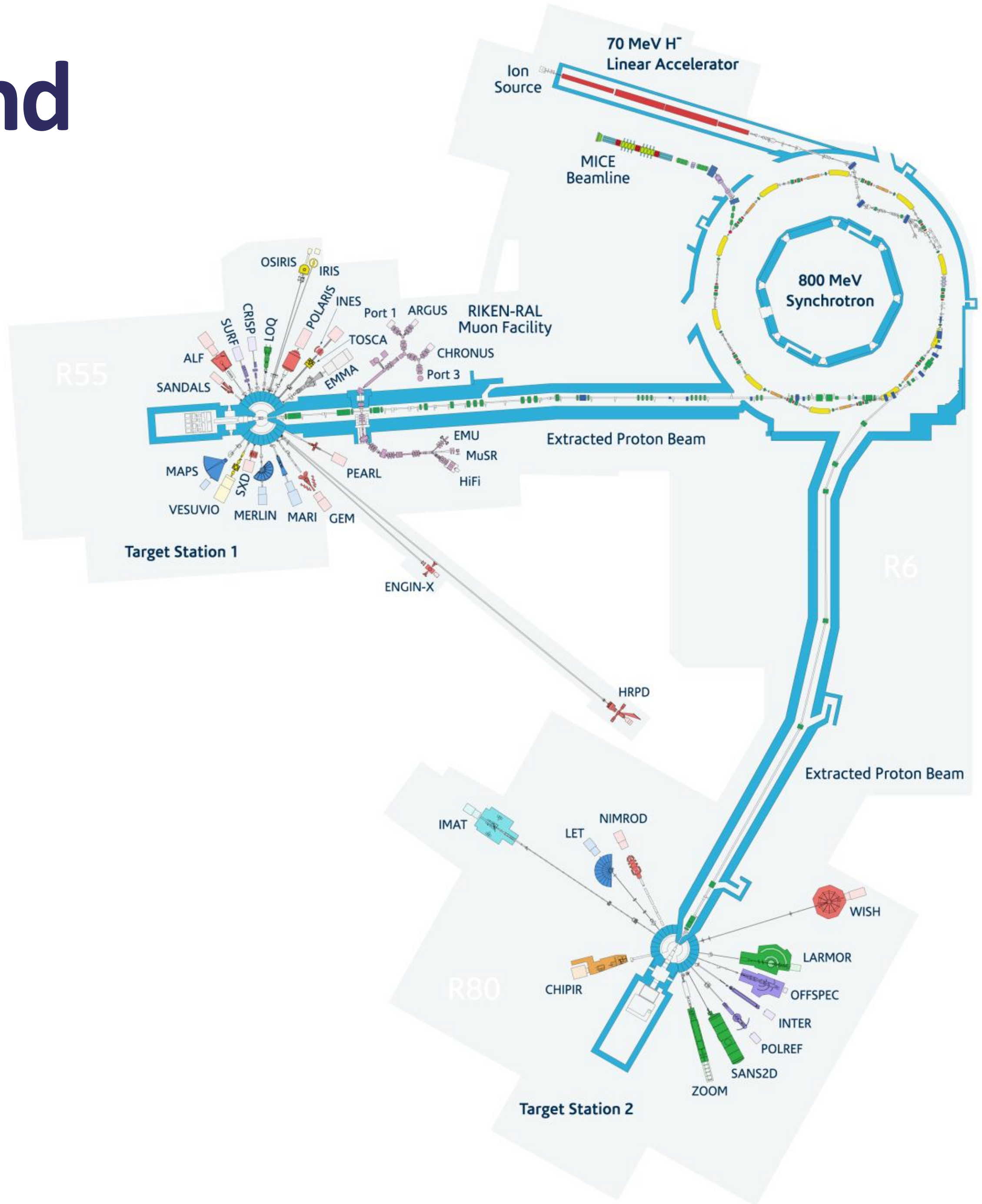
- Originates from 1985 – the very first neutron spallation source in the world
- Produces 20 neutron beams and 5 muon beams
- Sheet carbon target to produce muons, plated tungsten target to produce neutrons



Target Station 2

- Completed in 2011 – low-power and low-repetition rate source optimised for long wavelength neutrons
- Produces over 10 neutron beams
- Single block tungsten target to produce neutrons with maximised efficiency

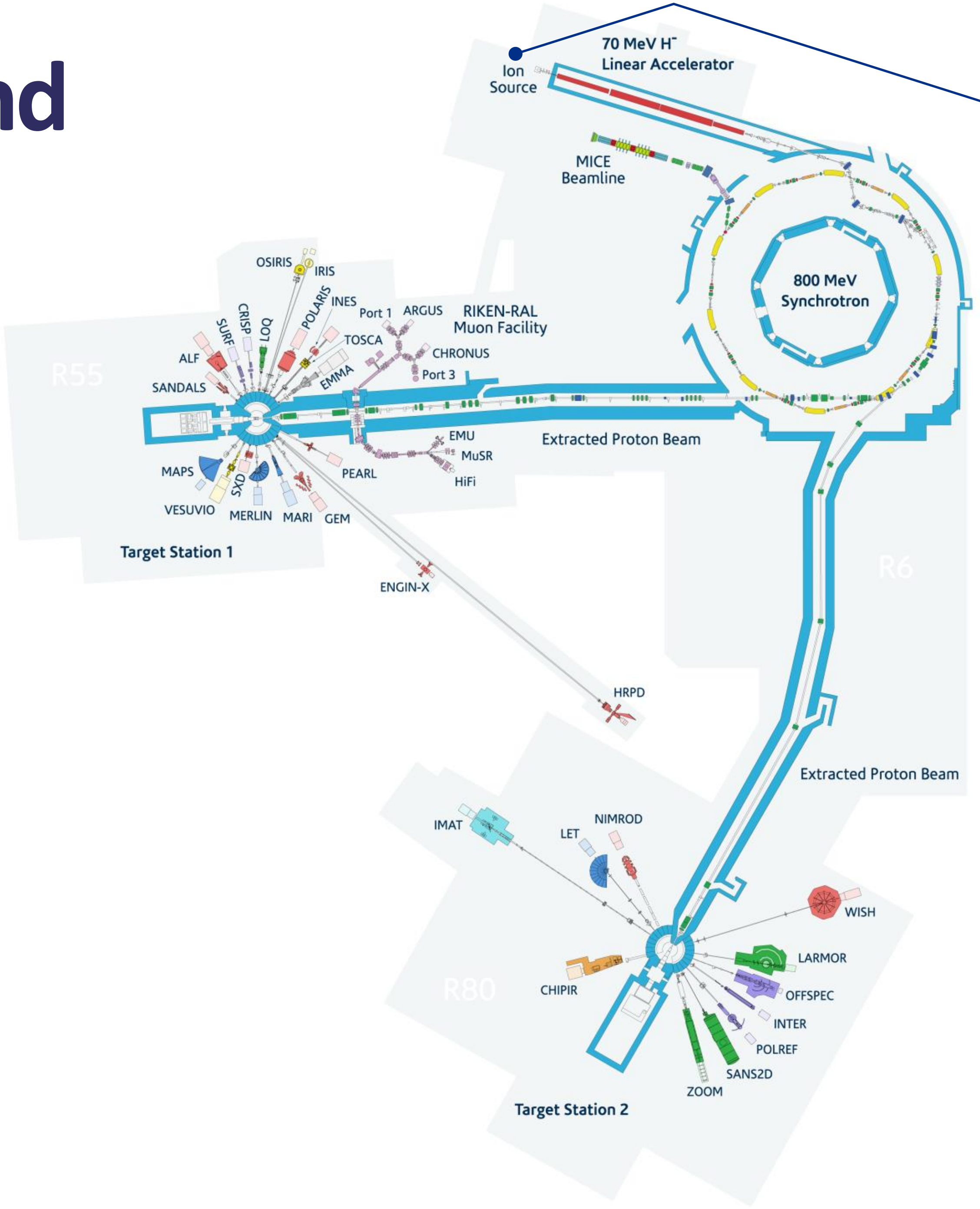
ISIS Neutron and Muon Source



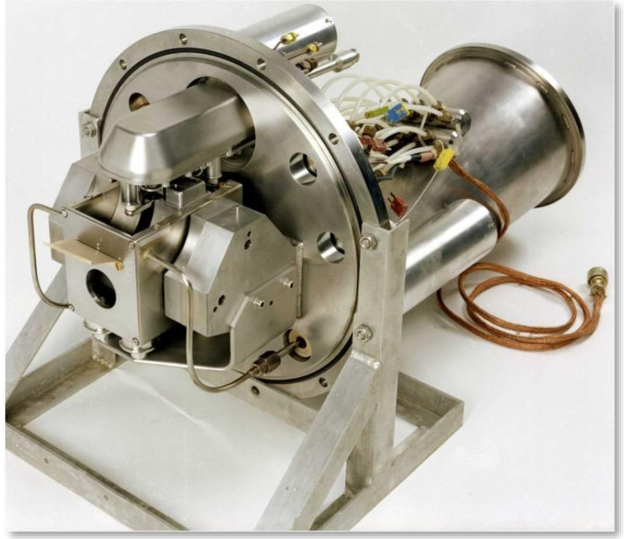
Types of Instrument at ISIS

- Diffractometer
- Reflectometer
- Small Angle Scattering
- Indirect Spectrometer
- Direct Spectrometer
- Muon Spectrometer/Instrument
- Chip Irradiation
- Imaging and Diffraction

ISIS Neutron and Muon Source



1) Hydrogen gas is first fed into the ion source to produce negative H ions



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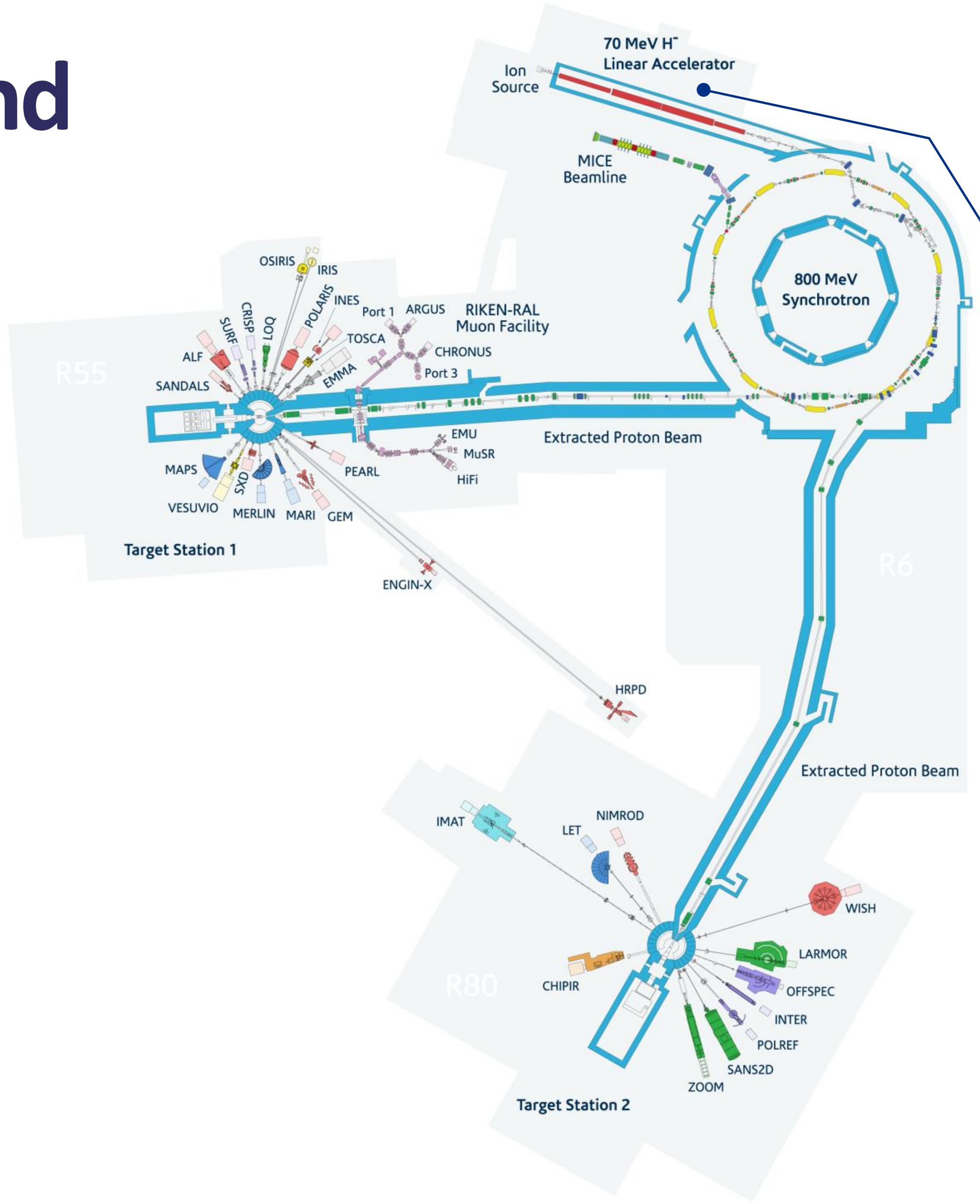

2) The ions enter a 4-tank drift-tube linac and are accelerated from 35 keV to 70 MeV

Types of Instrument at ISIS

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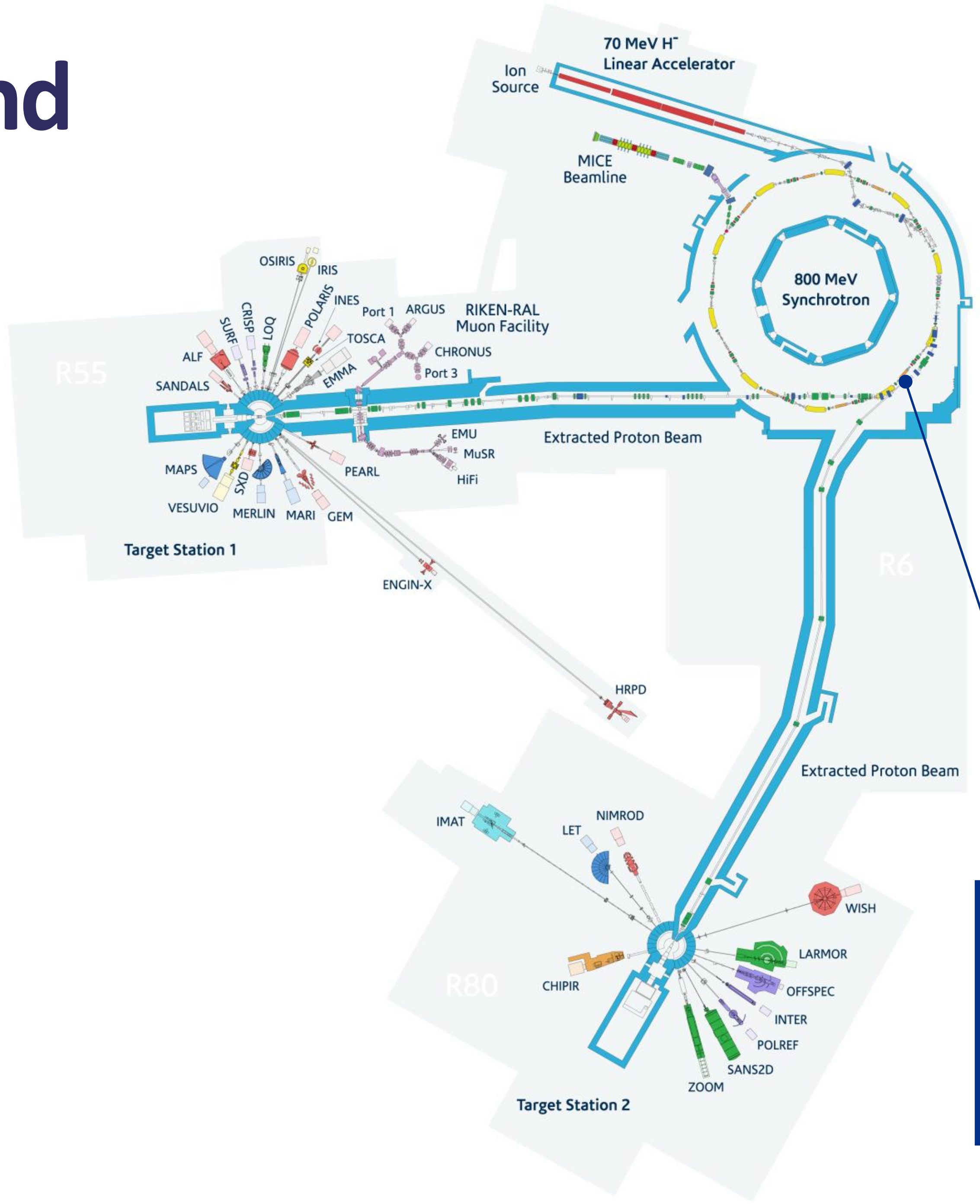

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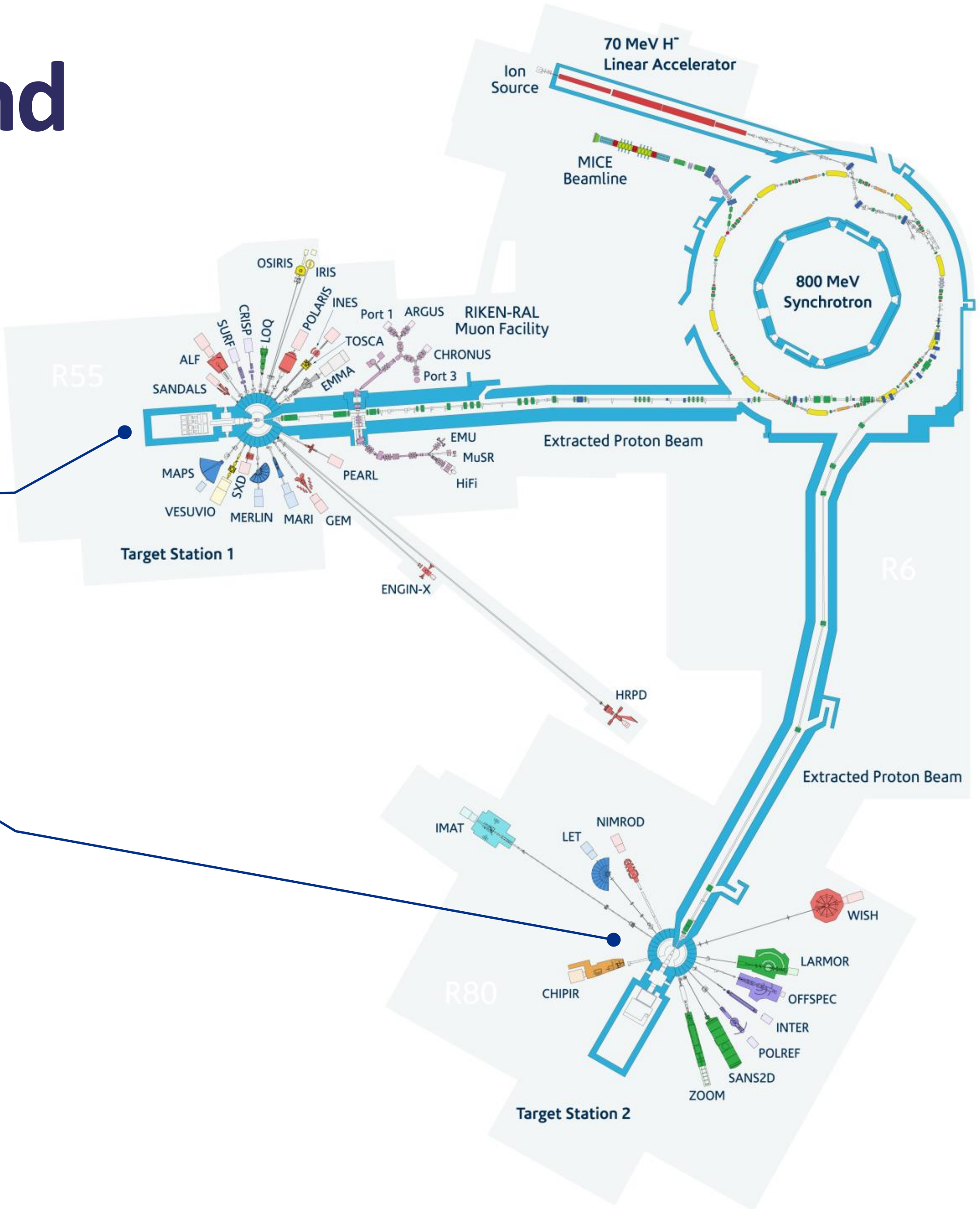
3) After passing a stripping foil, the resulting protons are accumulated and then accelerated to 800 MeV in the synchrotron

ISIS Neutron and Muon Source



4) The protons are extracted onto two tungsten-based target stations, producing many neutrons via spallation

Types of Instrument at ISIS

- Diffractometer
- Reflectometer
- Small Angle Scattering
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- Direct Spectrometer
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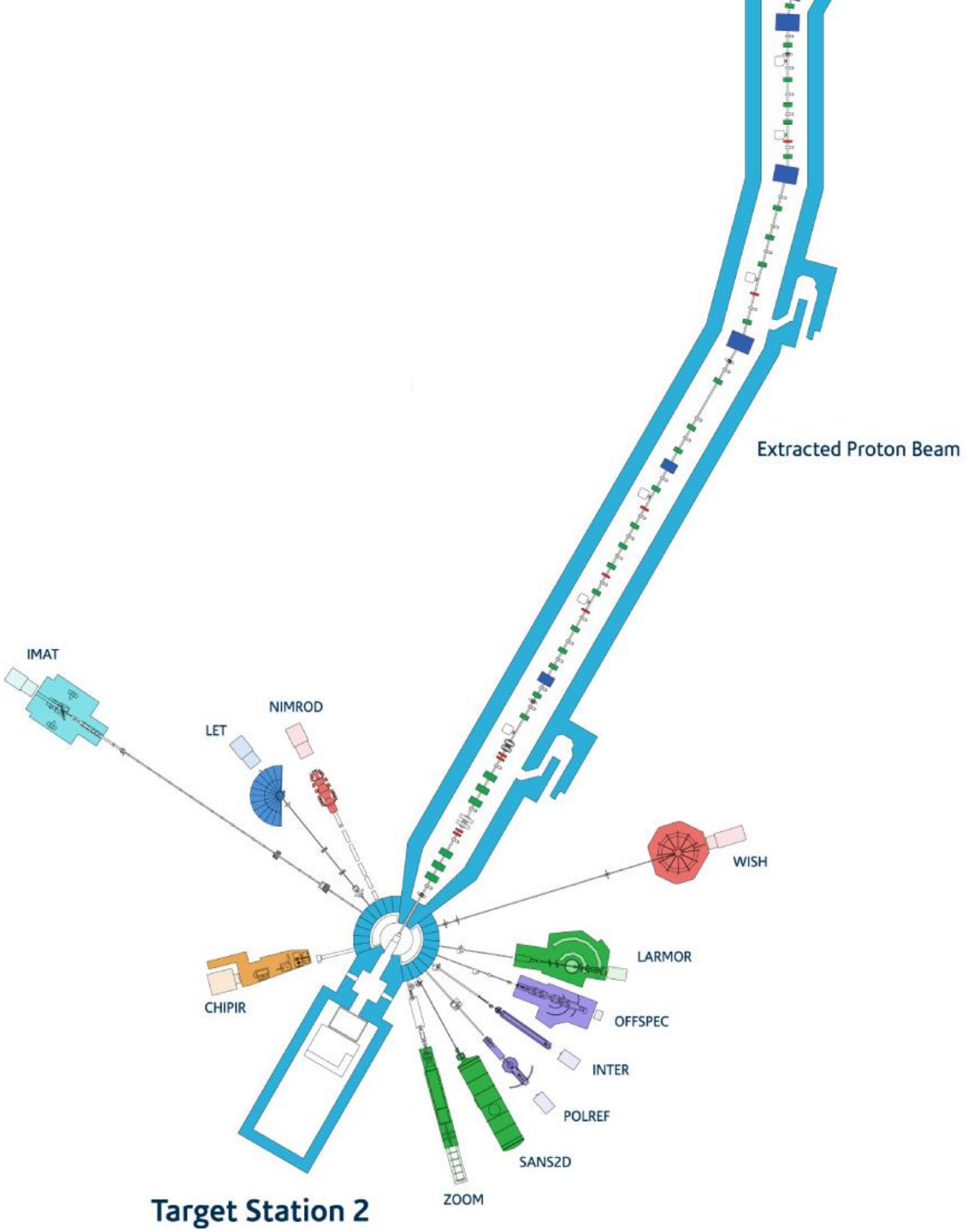
Target Station 2

- Receives one in five proton pulses from the synchrotron
- Proton beam energy deposit is about 40 kW
- Each proton produces about 15-20 neutrons, resulting in around 10^{15} neutrons per second
- The target is surrounded by beryllium with holes that lead into the various beamlines
- Moderators (water, liquid methane, liquid hydrogen) slow the neutrons down to useable energies



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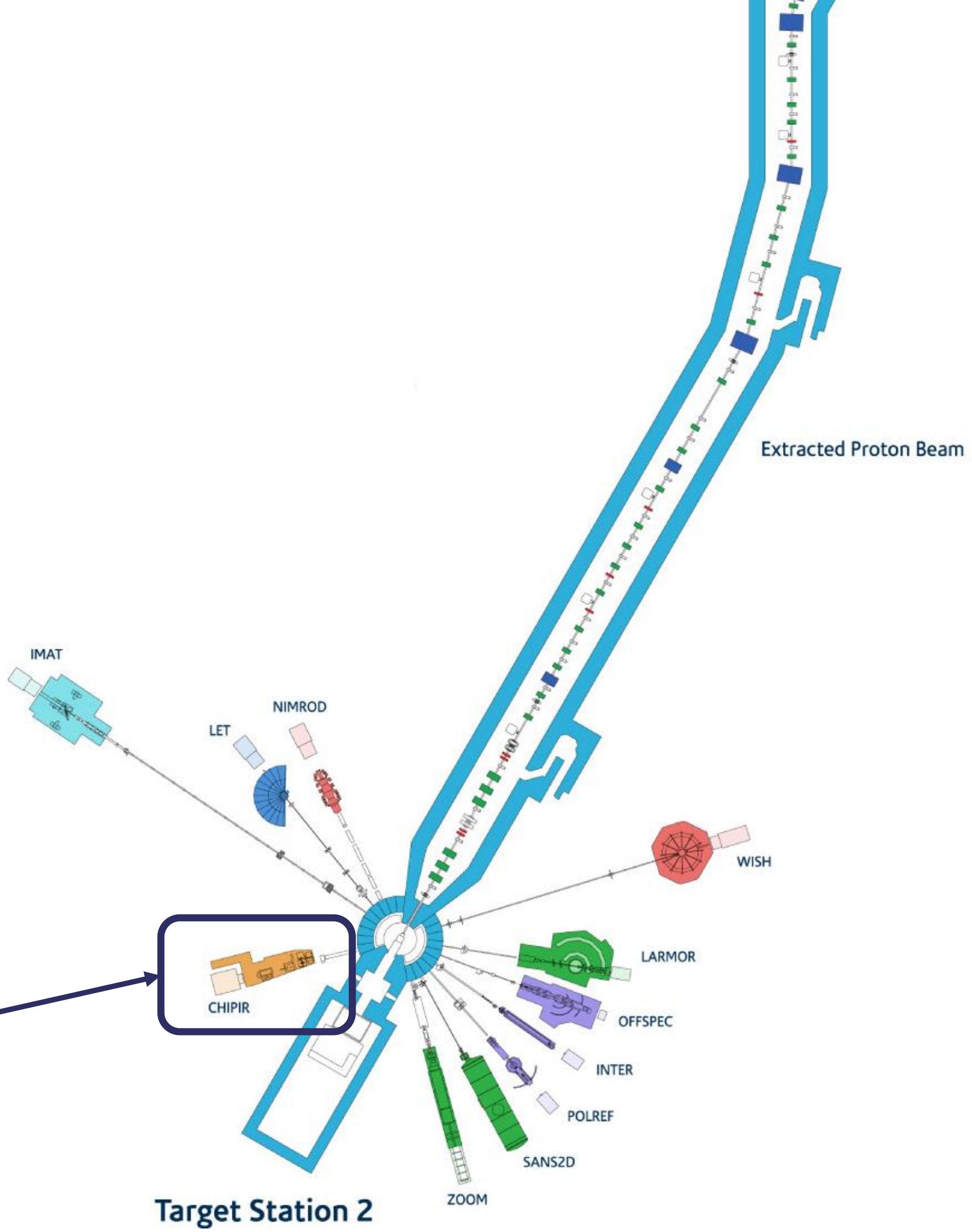
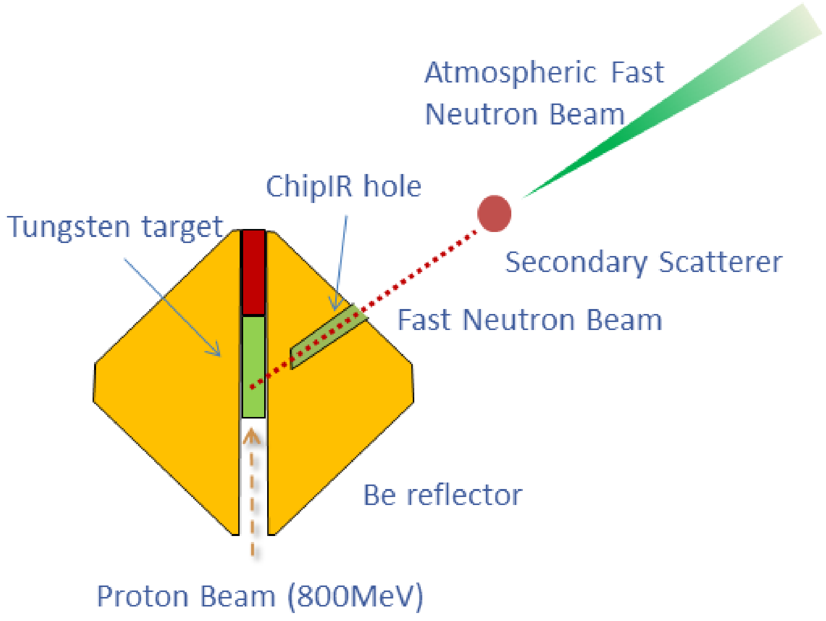
- The target is surrounded by beryllium with holes that lead into the various beamlines
- Moderators (water, liquid methane, liquid hydrogen) slow the neutrons down to useable energies…but one beamline is slightly different



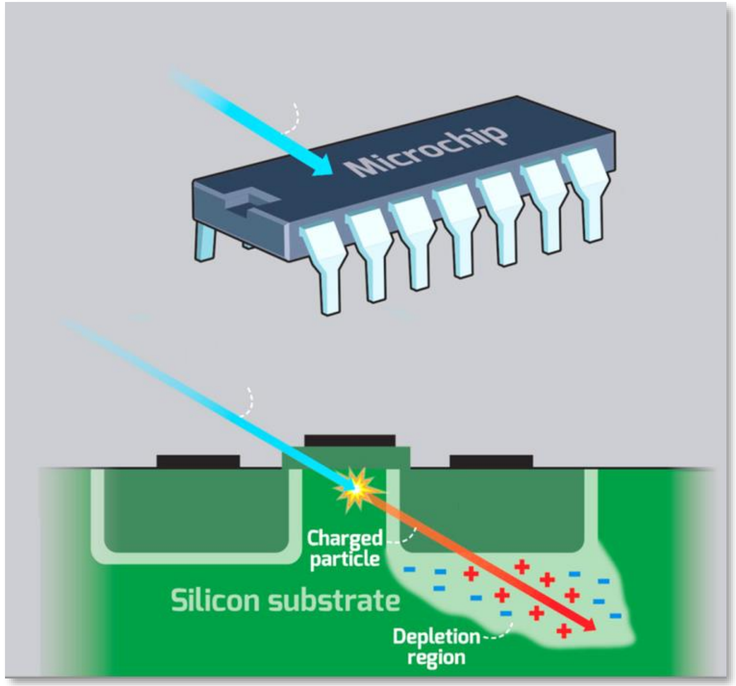
ChipIr

ChipIr is a fast neutron beamline in Target Station 2 that produces an intense atmospheric like fast neutron flux up to 800 MeV



Single Event Effect

Single Event Effect (SEE) - a highly energetic particle strikes sensitive regions of an electronic device, disrupting its correct operation



Can have various results such as a: **burnout**, **gate rupture, latch-up** or **bit-error**

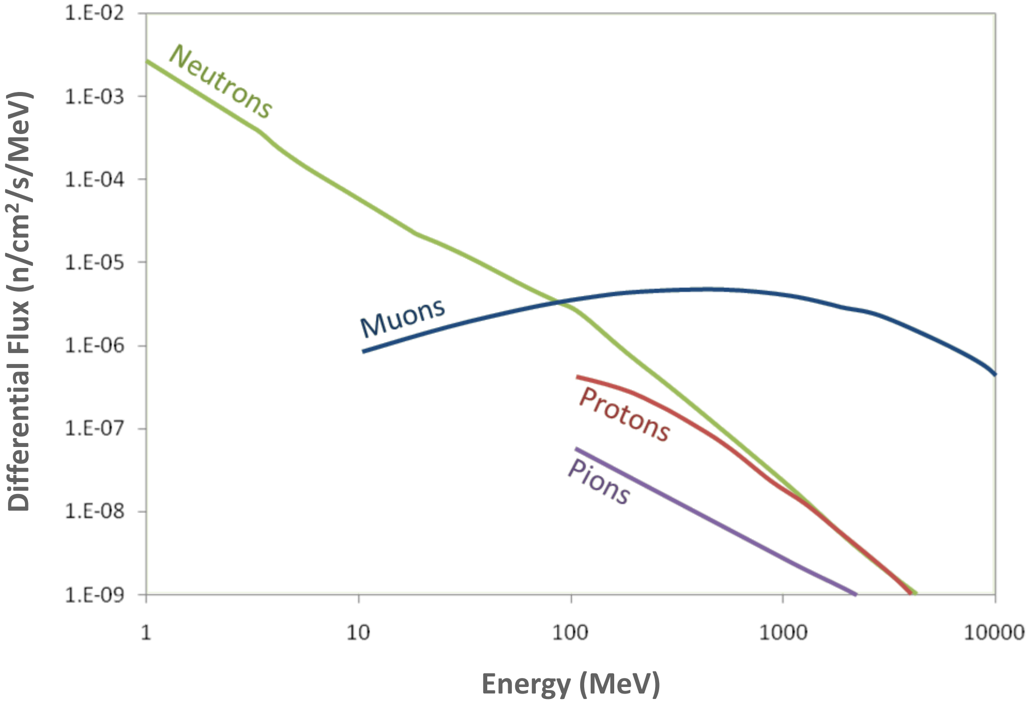
1	0	0	0	1	1	0	0	1	1	0	1

↑ Bit-Error

0	0	0	0	1	1	0	0	1	1	0	1

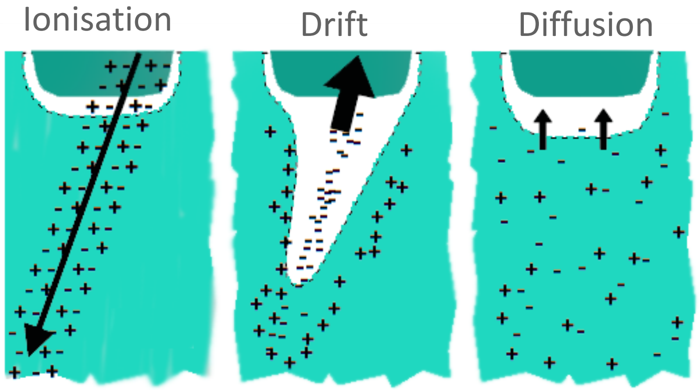
Cosmic Ray Induced Errors

These energetic particles are from cosmic ray induced cascades



Neutrons with energies >1 MeV can produce charged ions in silicon via scattering

If the ions then travel through a sensitive node in the silicon, their energy deposit creates ionisation trails of electron-hole pairs, inducing a **SEE**



Neutrons are the dominant contributor at ground level

Real Incident: Qantas Aircraft

On October 2008, a Qantas aircraft from Singapore to Perth suffered the effects of potential SEE.

Whilst the aircraft was at **11,000 meters**, one of the aircraft systems started giving spurious spikes on all flight parameters to other systems.

Two minutes later, the aircraft pitched down losing an altitude of **210 meters over 23 seconds** and briefly did not respond to any commands from the pilot.

Three minutes later, a second pitch down occurred, and the aircraft further lost **120 meters in 15 seconds**.

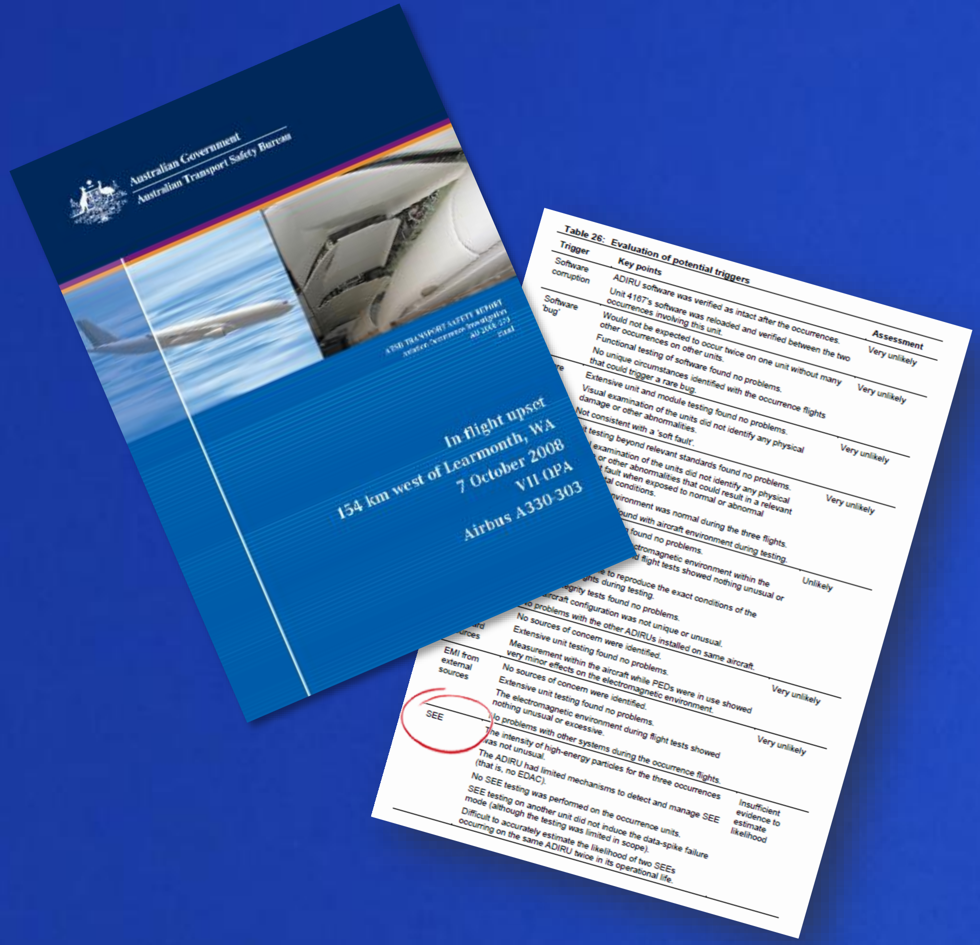
ATSB TRANSPORT SAFETY REPORT
Aviation Occurrence Investigation
AO-2008-070 - Final (2011)

Real Incident: Qantas Aircraft

Plane made emergency landing, fortunately no fatalities!

ATSB TRANSPORT SAFETY REPORT
Aviation Occurrence Investigation
AO-2008-070 - Final (2011)

Real Incident: Qantas Aircraft



"…..the investigation identified SEE [Single-Event-Effects] as an ongoing risk for airborne equipment."

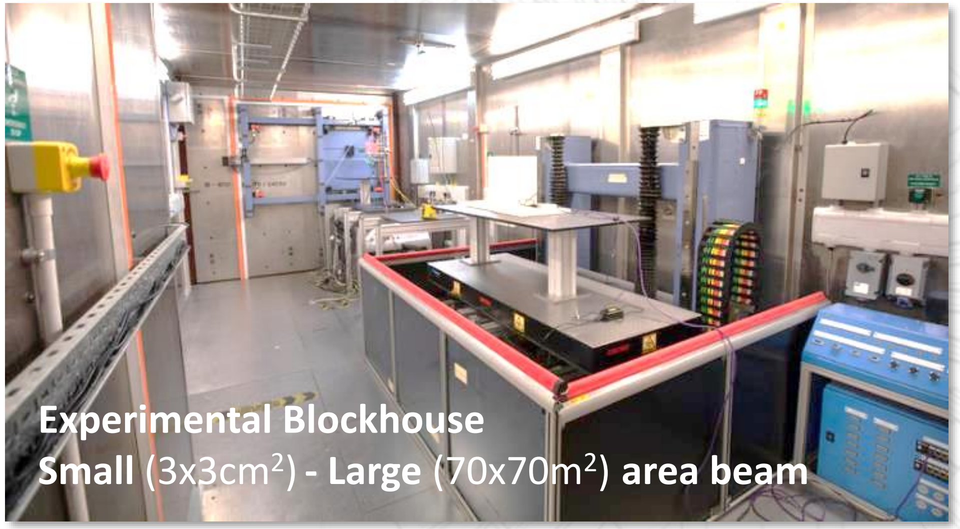
"There were significant logistical difficulties in obtaining access to appropriate test facilities….."

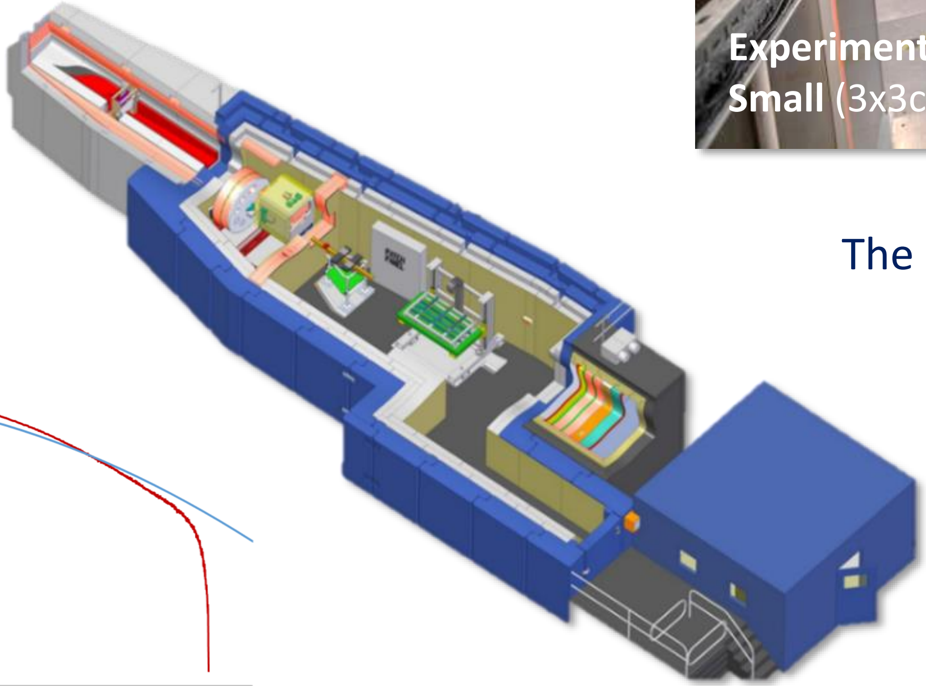
ATSB TRANSPORT SAFETY REPORT
Aviation Occurrence Investigation
AO-2008-070 - Final (2011)

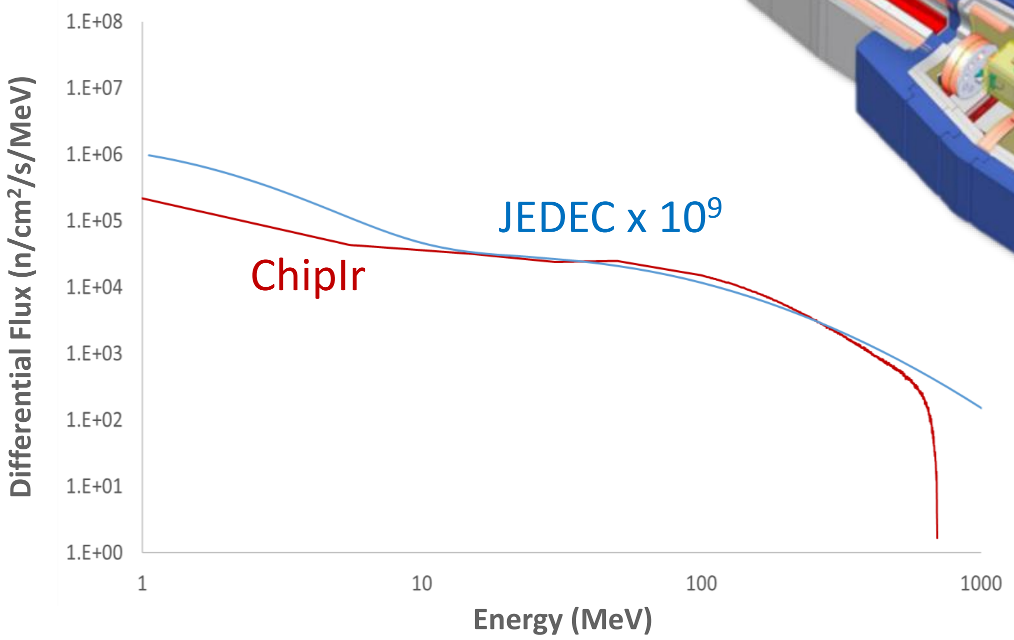
ChipIr

In 2017 ISIS commissioned ChipIr

- Fast atmospheric neutron spectrum
- High flux for accelerated testing
- Large beam (for systems) and small beam (for devices)







The calibrated flux on the instrument is

5.4×10^6 n $cm^{-2}s^{-1}$ (>10MeV)

	>10 MeV Flux (cm^{-2} s^{-1})
ChipIr	5.4 $\times 10^6$
LANSCE	1-2$\times 10^6$
TRIUMF	2.6$\times 10^6$
RCNP	5.4 $\times 10^5$

JEDEC STANDARD – JESD89A Measurement and Reporting of Alpha Particle and Terrestrial Cosmic Ray-Induced Soft Errors in Semiconductor Devices, Sept 2021

Accelerated Testing

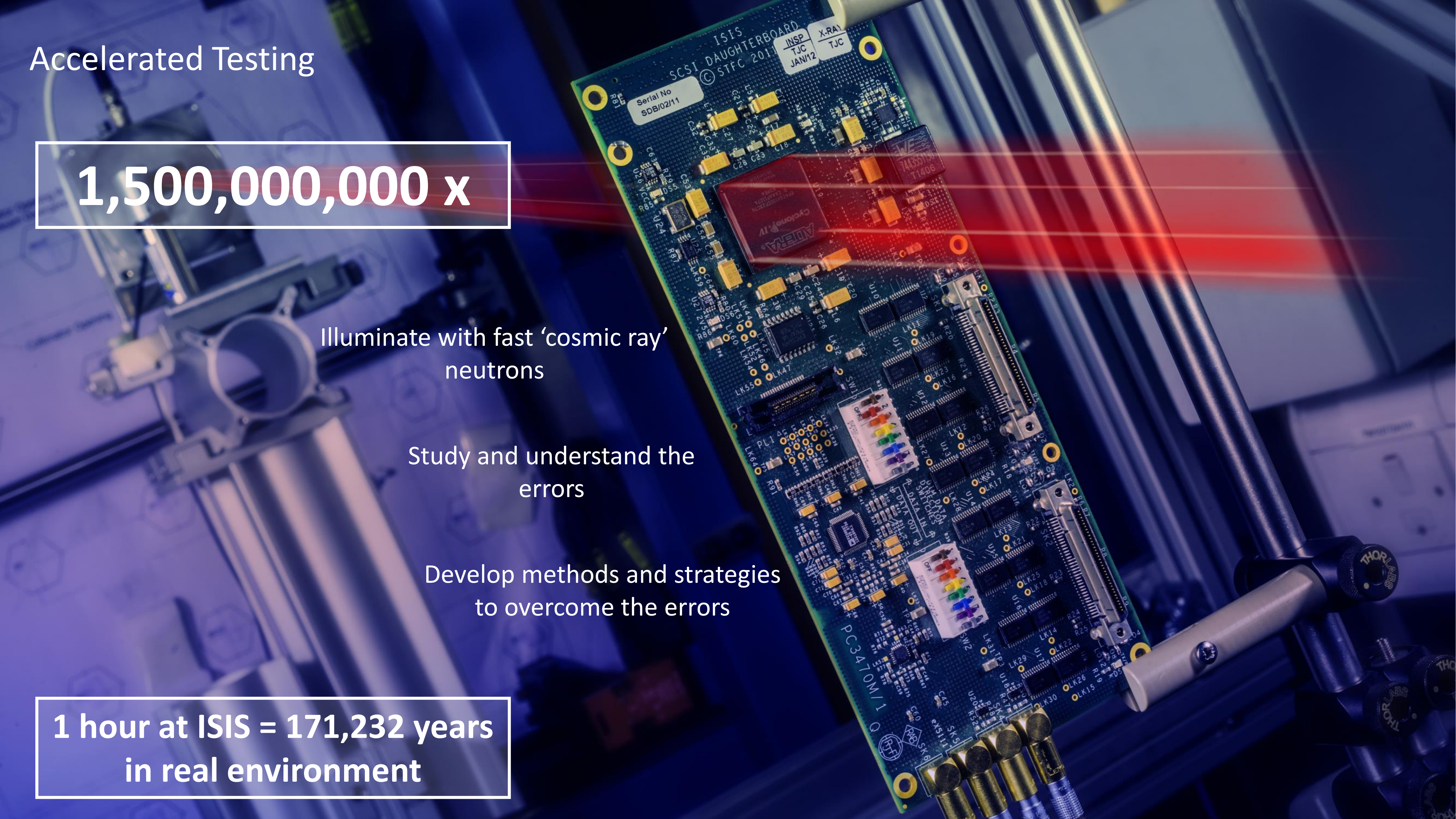
1,500,000,000 x

Illuminate with fast ‘cosmic ray’ neutrons

Study and understand the errors

Develop methods and strategies to overcome the errors

1 hour at ISIS = 171,232 years in real environment



Major areas of current commercial research

1. **Driverless cars** Autonomous systems
2. **Internet**: Device and system level for communication infrastructures
3. **High power devices** for renewable energy applications and automotive
4. **Aerospace** applications

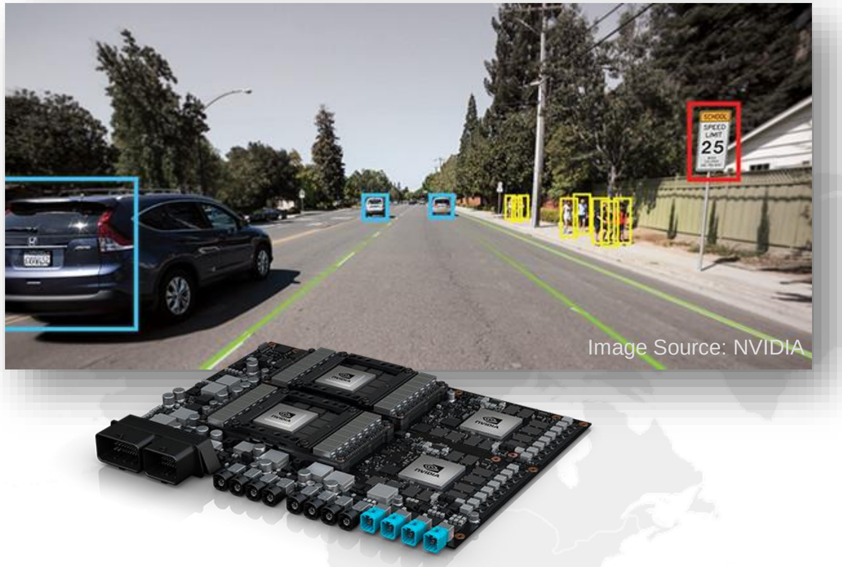


Image Source: NVIDIA

Image Source: Infineon

Image Source: Cobham

Science and Technology Facilities Council

Neutron Flux Measurements

Fast Neutron Activation, Neutron Flux Measurement, ChipIr Flux Results

King's College London

Fast Neutron Activation

1) Activate samples through irradiation

Activation foils: elements of known purity e.g., Bi, Au, Ni, Co, Sc, Lu etc.

Fast Neutron Activation

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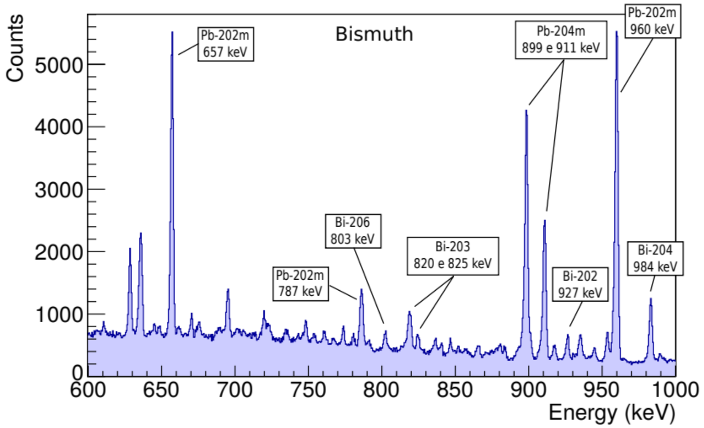
2) Measure sample activities in a HPGe



Fast Neutron Activation

1) Activate samples through irradiation

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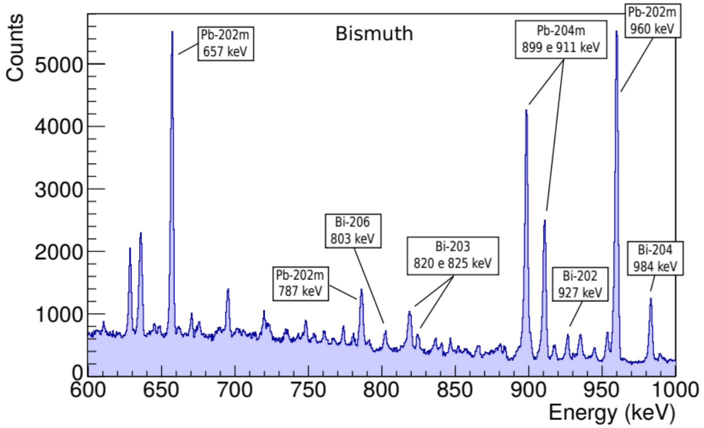


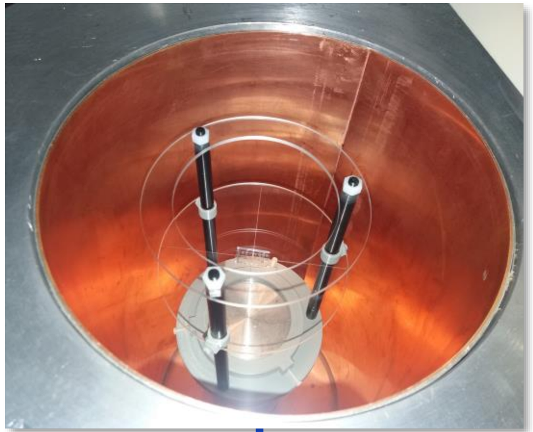
3) Unfold from the activation rate into the neutron flux

Bayesian-unfolding **T**oolkit for **M**ulti-foil **A**ctivation with **N**eutrons

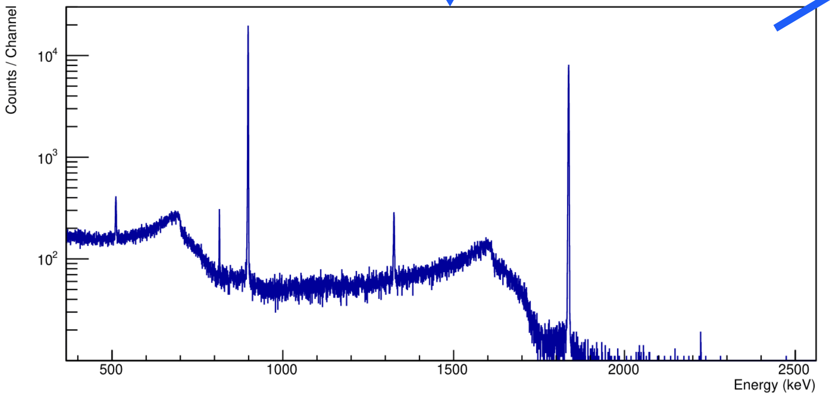
https://github.com/davidechiesa/batman

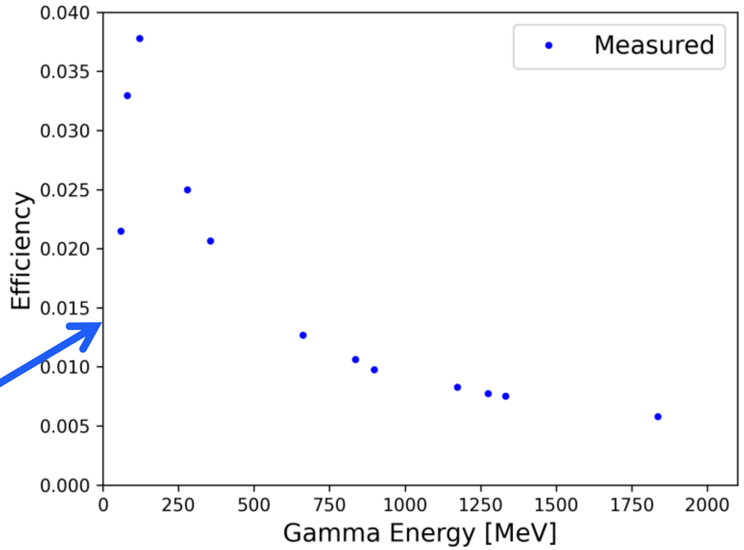
HPGe Detector

Point source measurements



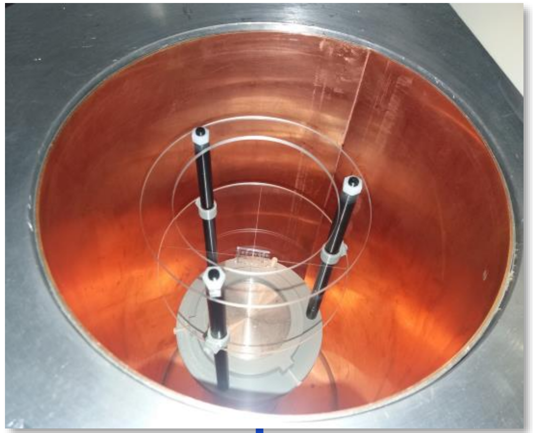
Measured data



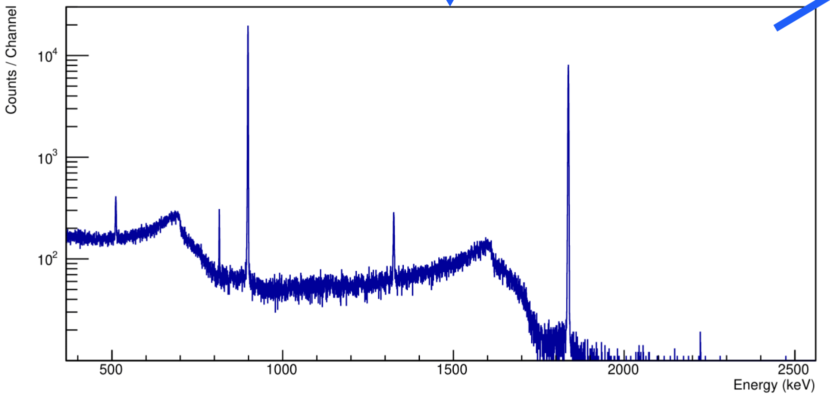


HPGe Detector

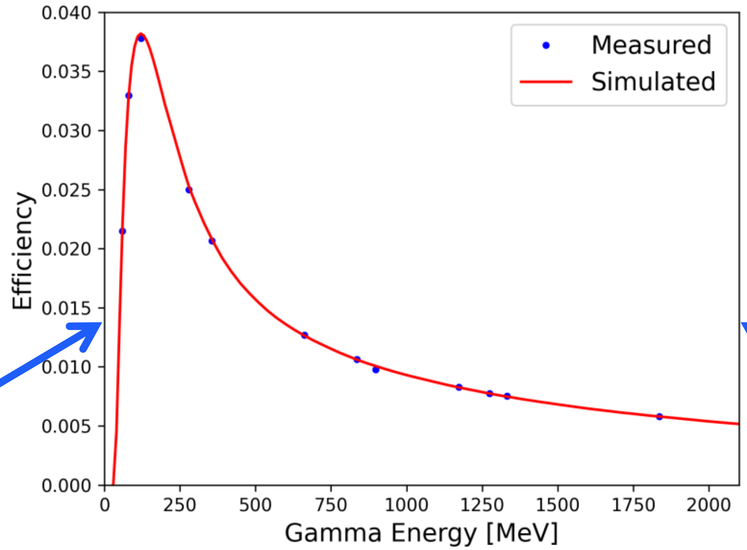
Point source measurements



Measured data

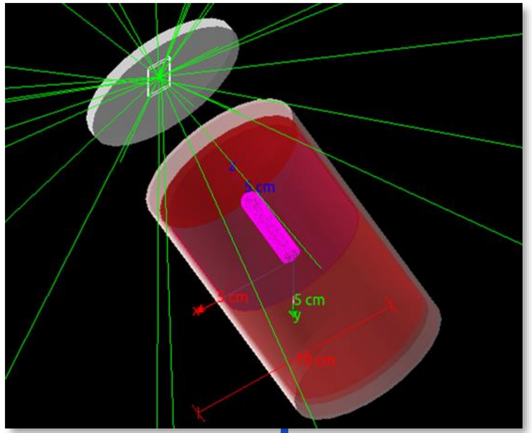


Point source data calibrates simulation

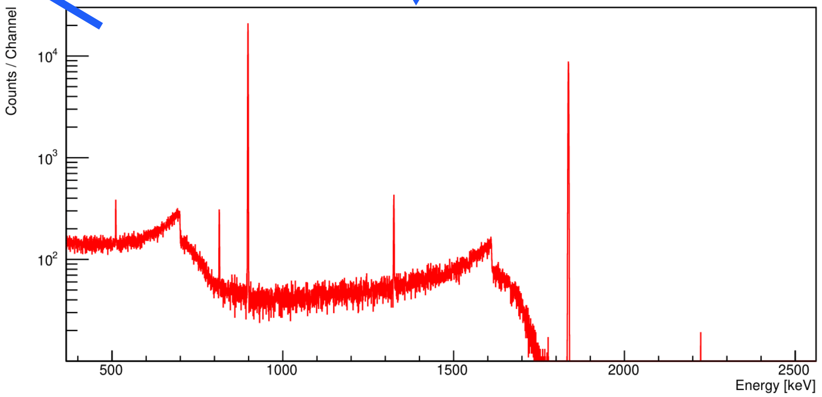


Simulation predicts foil efficiencies

Geant4 simulations



Simulated data

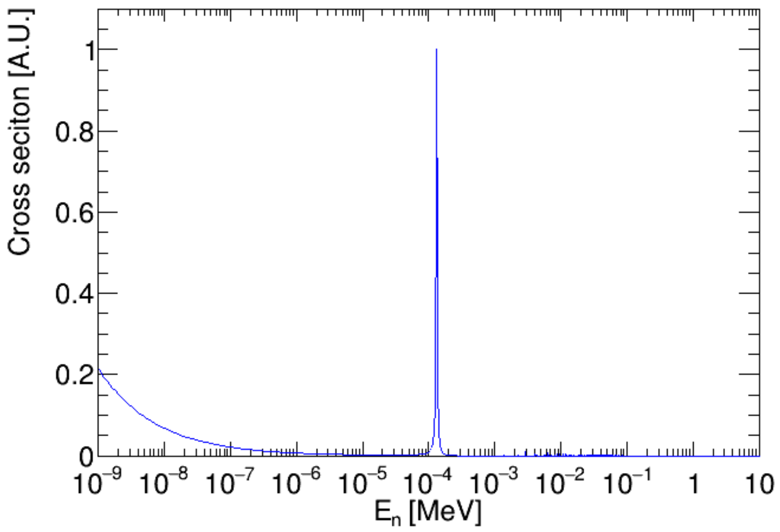


Neutron Flux Measurement

If the neutron flux spectrum shape is known...

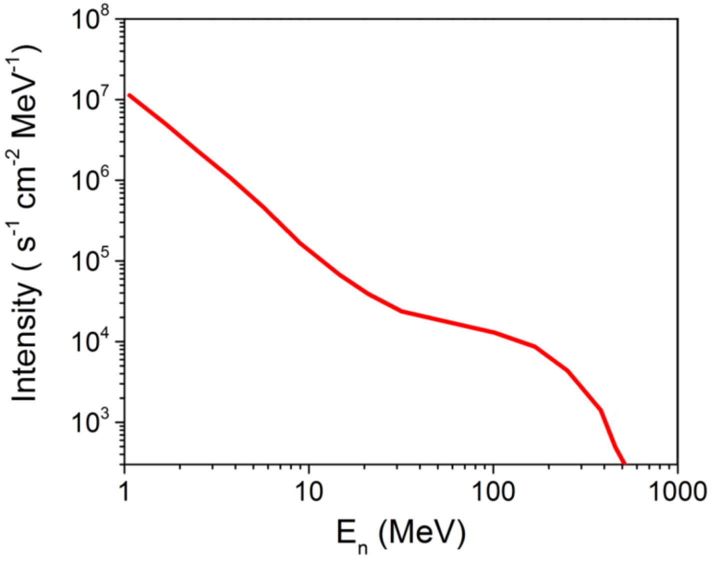
- only need to measure rate of 1 reaction
- reaction rate can normalise the shape, giving the final spectrum

Any activation reaction:



Cross section gives total flux φ

φ **normalises shape**

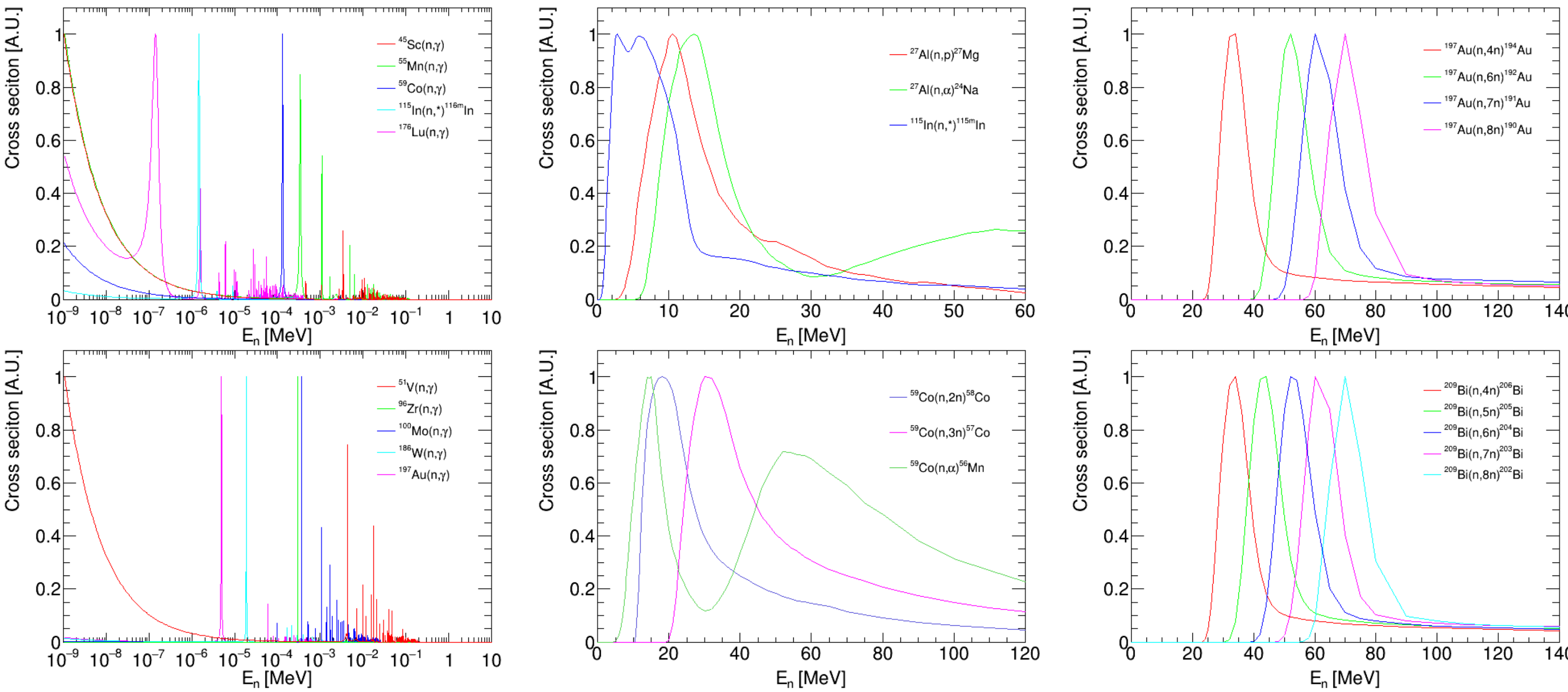


But we generally don't know the neutron flux spectrum shape well...

Neutron Flux Measurement

If the neutron flux spectrum shape is **not known...**

- can no longer use total flux from one reaction
- can instead use **multiple reactions** and normalise with **differential flux** in each bin

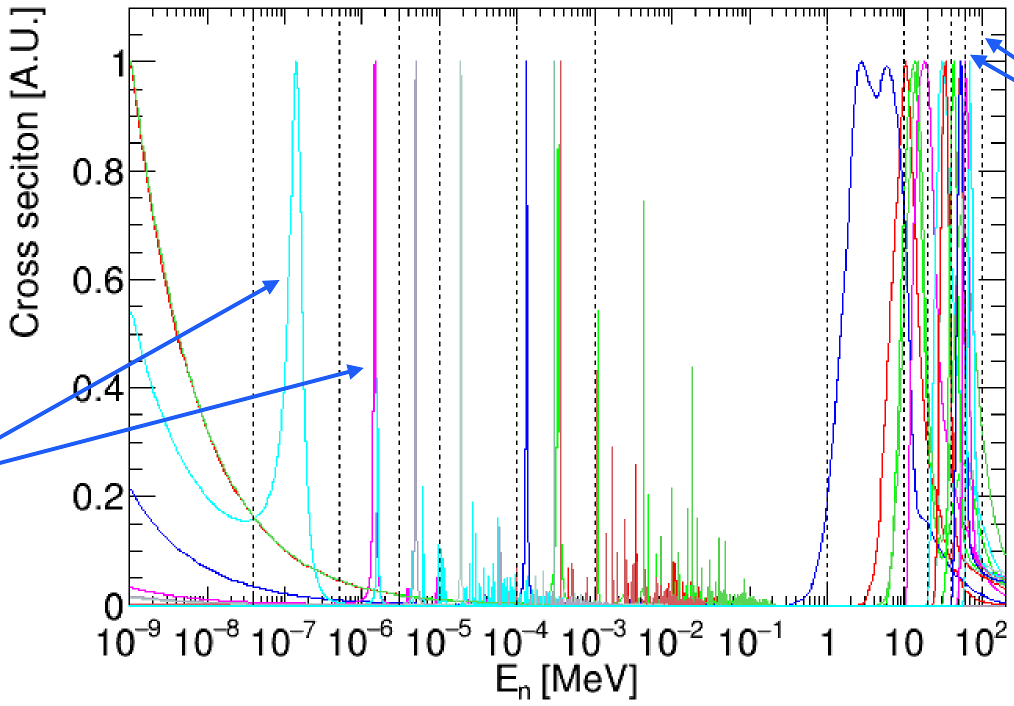


Neutron Flux Measurement

If the neutron flux spectrum shape is **not known**...

- can no longer use total flux from one reaction
- can instead use **multiple reactions** and normalise with **differential flux** in each bin

Cross sections correspond to the activation rates R_j



Dashed lines show bins of flux groups ϕ_i

BaTMAN

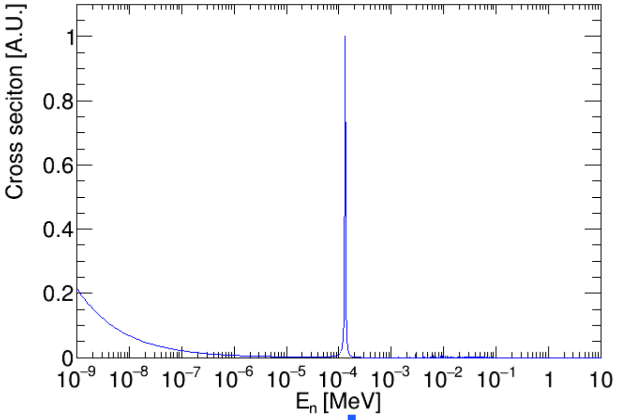
Bayesian-unfolding Toolkit for Multi-foil Activation with Neutrons

Neutron flux unfolding concept:

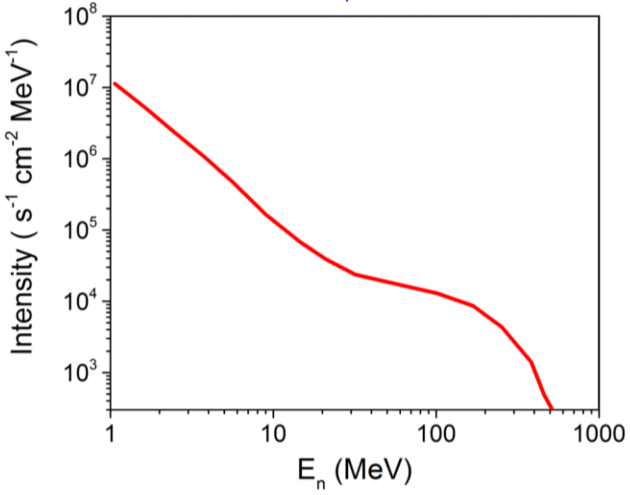
- Activation rate R is related to the neutron flux φ

$$R = N \int \sigma(E)\varphi(E)dE$$

Neutron activation reaction:



φ normalises shape



BaTMAN

Bayesian-unfolding Toolkit for Multi-foil Activation with Neutrons

Neutron flux unfolding concept:

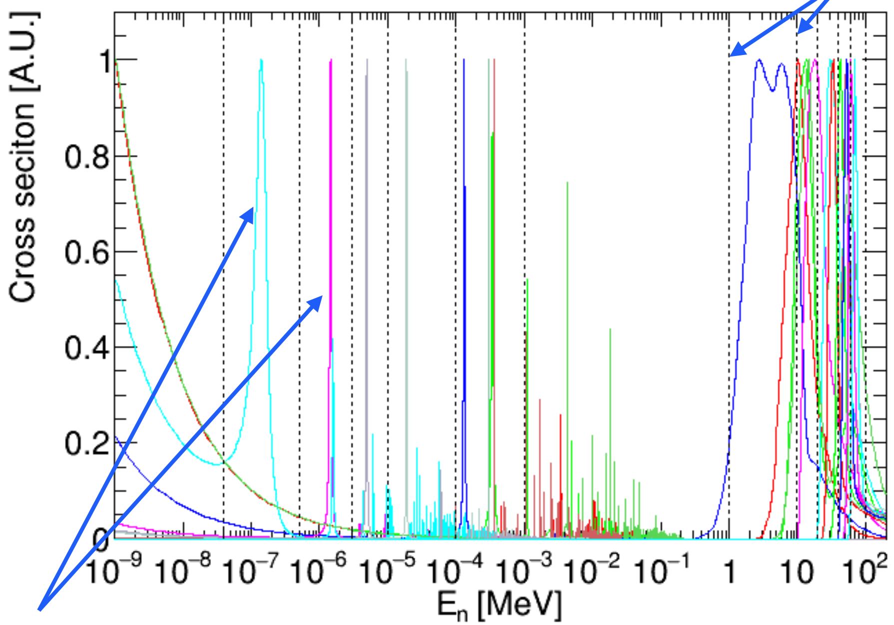
- Activation rate R is related to the neutron flux φ

$$R = N\int \sigma(E)\varphi(E)dE \rightarrow R_j = N_j\sum_{i=1}^{n}\sigma_{ij}\phi_i$$

- Introduce multiple reactions and divide them into flux groups ϕ_i

$$\phi_i = \int_{E_i}^{E_{i+1}} \varphi(E)dE$$

Dashed lines show bins of flux groups ϕ_i



Cross sections correspond to the activation rates R_j

BaTMAN

Bayesian-unfolding Toolkit for Multi-foil Activation with Neutrons

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$$R = N\int \sigma(E)\varphi(E)dE \rightarrow R_j = N_j \sum_{i=1}^{n} \sigma_{ij}\phi_i$$

- Introduce multiple reactions and divide them into flux groups ϕ_i

$$\phi_i = \int_{E_i}^{E_{i+1}} \varphi(E)dE$$

- System of linear equations with unknown variables ϕ_i, solvable by sampling the joint posterior $\mathrm{P}(\phi_i|R_j, \sigma_{ij})$

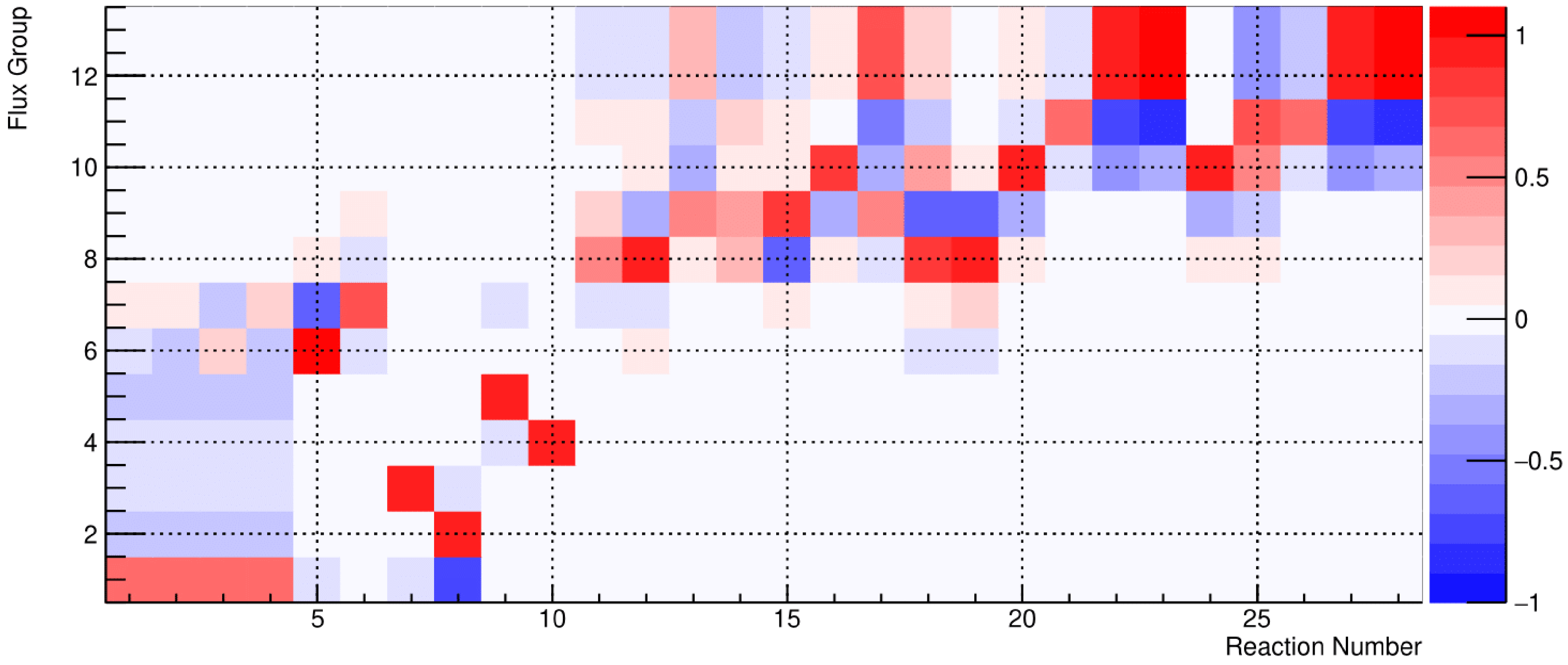
BaTMAN parameterises this statistical mode
JAGS solves the model via MCMC simulation

Paper: https://doi.org/10.1016/j.nima.2018.06.016

BaTMAN

Bayesian-unfolding Toolkit for Multi-foil Activation with Neutrons

In this way, the flux groups are intentionally correlated with activation reactions:

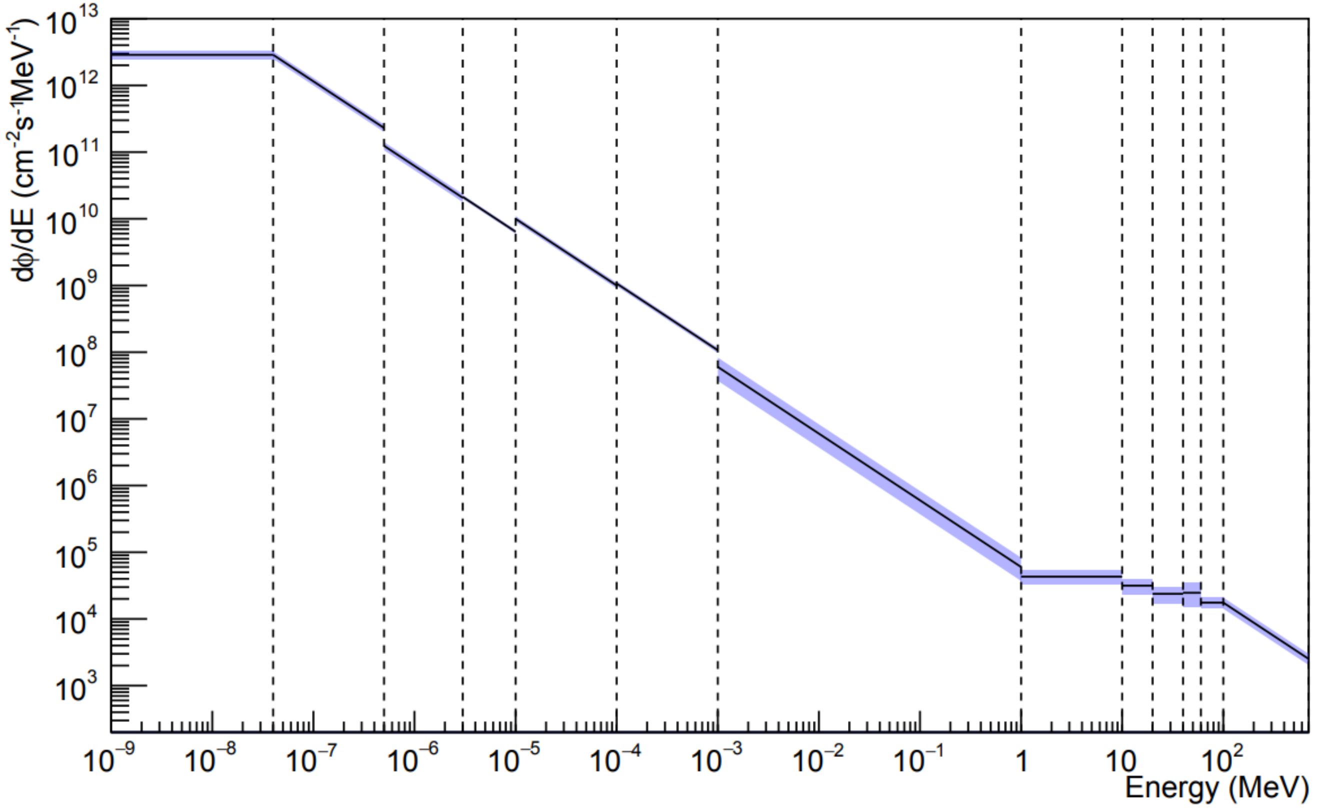


Results for ChipIr Flux

- The result of the unfolding is the **integral fluxes in each group**, and the shape within each bin is still unknown

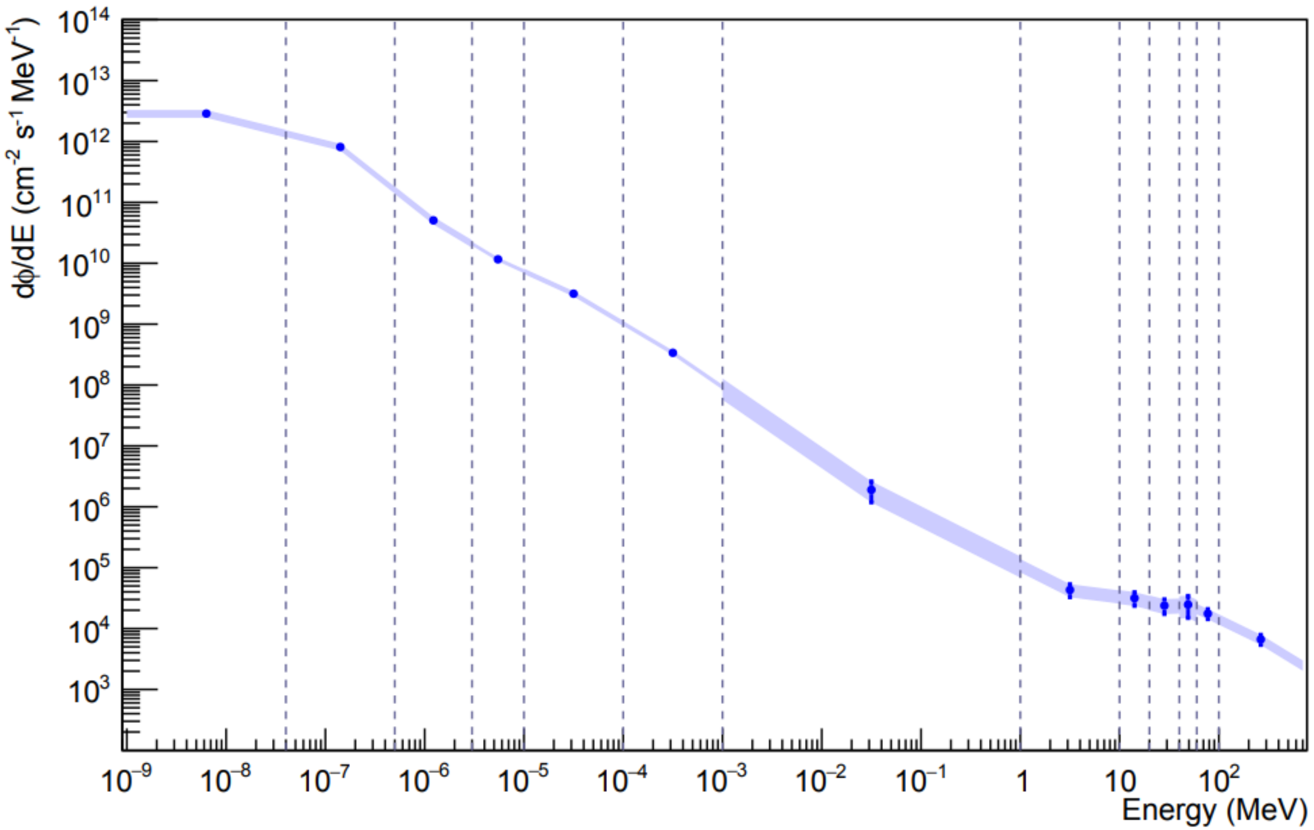
- The quality of the result depends on the number of bins and the corresponding reactions, i.e., more provides a clearer picture of the spectra

- Continuity is **not** assumed...



Results for ChipIr Flux

- The result of the unfolding is the **integral fluxes in each group**, and the shape within each bin is still unknown
- The quality of the result depends on the number of bins and the corresponding reactions, i.e., more provides a clearer picture of the spectra
- Continuity is **not** assumed, but we can impose it in an interpolation that preserves the unfolded integrals

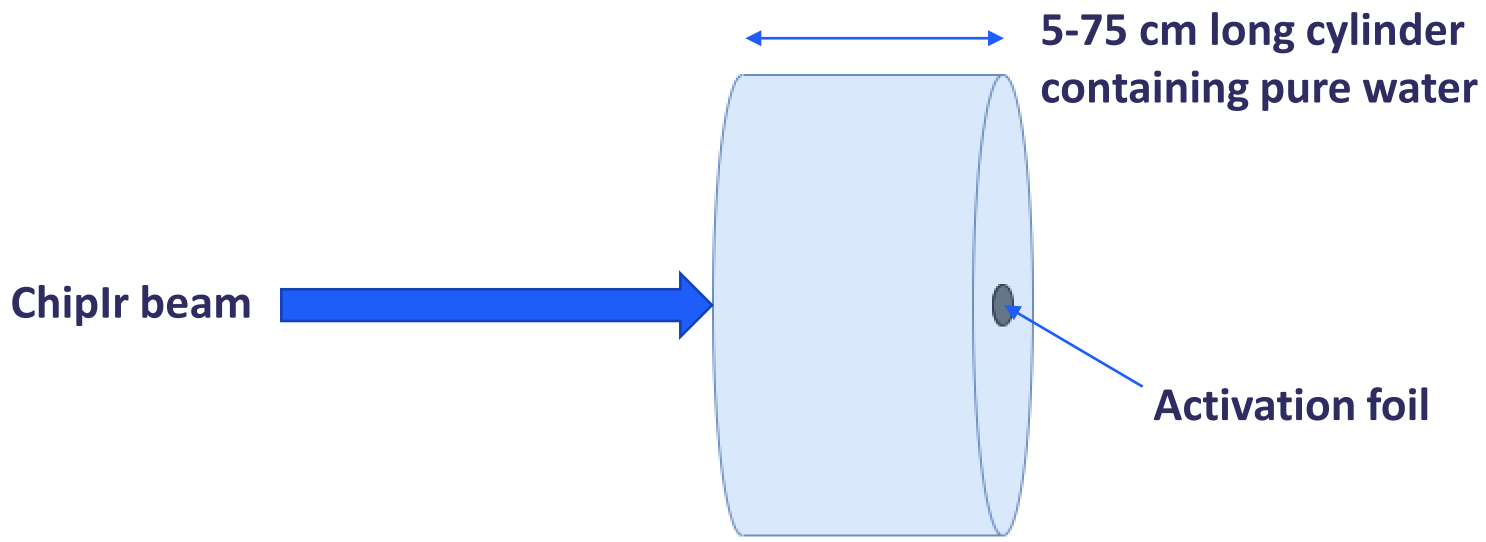


Plans

Neutron-Water Cross Section Experiment

Neutron-Water Cross Section Experiment

Plan: to measure changes in activation rates due to varying volumes of water



By measuring changes in activation rates and adapting the method used to measure the flux, **we can extract neutron-water total cross sections up to at least 100 MeV**

Experiment on schedule to start on 27th June!

Neutron-Water Cross Section Measurement

Activation rate **with** water:

$$R' = N \int \varphi'(\sigma_{water}, E)\sigma(E)dE$$

$$\frac{R'}{R} = \frac{\int \varphi'(\sigma_{water}, E)\sigma(E)dE}{\int \varphi(E)\sigma(E)dE}$$

Activation rate **without** water:

$$R = N \int \varphi(E)\sigma(E)dE$$

Neutron-Water Cross Section Measurement

$$\frac{{R_j}'}{R_j} = \frac{\sum_{i=1}^{n} \sigma_{ij} {\phi'}_i \, (\sigma_{water})}{\sum_{i=1}^{n} \sigma_{ij} \phi_i}$$

First we group this into energy bins i as before such that we can use multiple reactions j.

Neutron-Water Cross Section Measurement

$$\frac{R_j'}{R_j} = \frac{\sum_{i=1}^{n} \sigma_{ij} \phi'_i \, (\sigma_{water})}{\sum_{i=1}^{n} \sigma_{ij} \phi_i}$$

The activation rates (radioisotopes produced per unit time) of the foils for reaction j with and without water. This is what we **measure**.

Neutron-Water Cross Section Measurement

$$\frac{R_j{}'}{R_j} = \frac{\sum_{i=1}^{n} \sigma_{ij} \phi'{}_i\,(\sigma_{water})}{\sum_{i=1}^{n} \sigma_{ij} \phi_i}$$

The corresponding activation reaction cross section in energy bin i. We obtain these from TENDL, which are cross sections predicted by TALYS Nuclear Model.

Neutron-Water Cross Section Measurement

$$\frac{R_j{}'}{R_j} = \frac{\sum_{i=1}^{n} \sigma_{ij} \phi'{}_i \left(\sigma_{water}\right)}{\sum_{i=1}^{n} \sigma_{ij} \phi_i}$$

The unmoderated original neutron flux in bin energy bin i. We can use BaTMAN to measure its integral value and simulation to vary its shape.

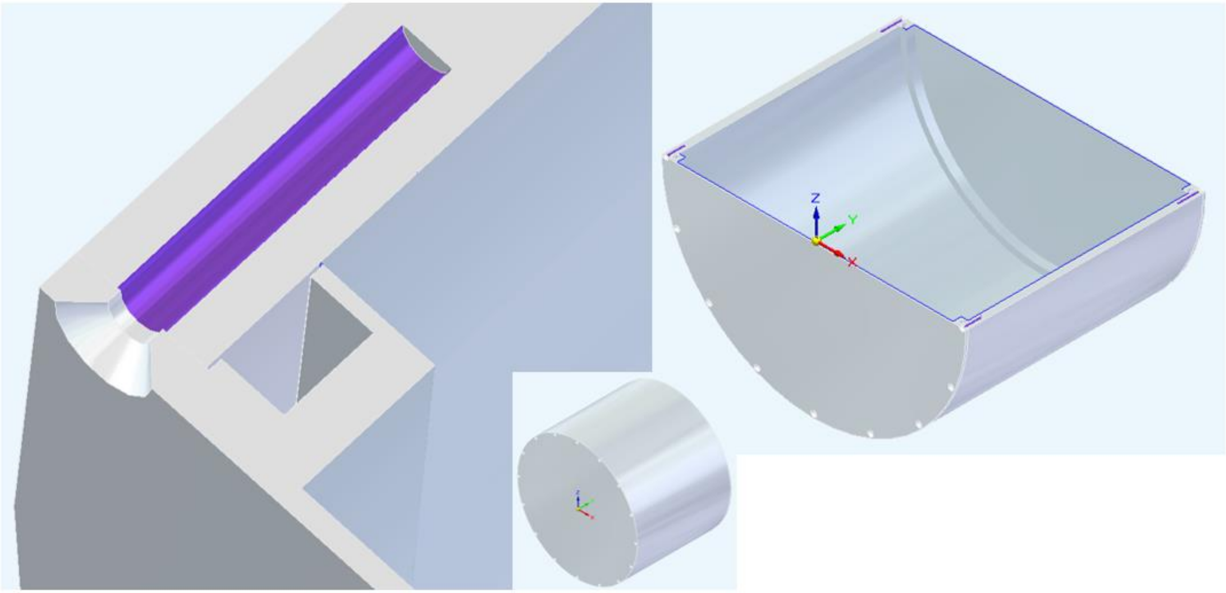
Neutron-Water Cross Section Measurement

$$\frac{R_j{}'}{R_j} = \frac{\sum_{i=1}^{n} \sigma_{ij} \phi'_i\,(\sigma_{water})}{\sum_{i=1}^{n} \sigma_{ij} \phi_i}$$

The moderated neutron flux in bin energy bin i and is a consequence of the total cross section on water. Using ϕ_i as input into simulations, we can find σ_{water} that leads to the ϕ'_i for the equality to hold.

Neutron-Water Cross Sections Study

Cylindrical aluminium containers for the water currently being constructed



Aluminium advantages:

- Strong so walls can be very thin (~1 mm)
- Does not become too radioactive
- Contains neither oxygen nor hydrogen

Multiple containers of 5 cm, 10 cm and 20 cm to be used

Experiment on schedule to start on 27th June!

Summary

- Fast neutrons in simulations are a known problem and we consistently observe discrepancies with measurements
- Using instruments at the ISIS Neutron Source, we've devised a neutron activation analysis method to measure neutron fluxes over the wide range from a few eV to a few hundred MeV
- Adapting this, we now intend to measure fast neutron-water cross sections up to at least 100 MeV using the ChipIr beam
- We also have several other instruments including a DT generator, a DD generator, AmBe sources, lanthanum bromide scintillators, silicon detectors, sRAM detectors, many other beamlines etc.
- **I'm a 2nd year PhD student! We are still actively thinking of other methods we can try. If you have any ideas or would like to get involved, please do contact us!**

:(

Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you.

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Stop code: CRITICAL_PROCESS_DIED

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Questions?

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Thank you

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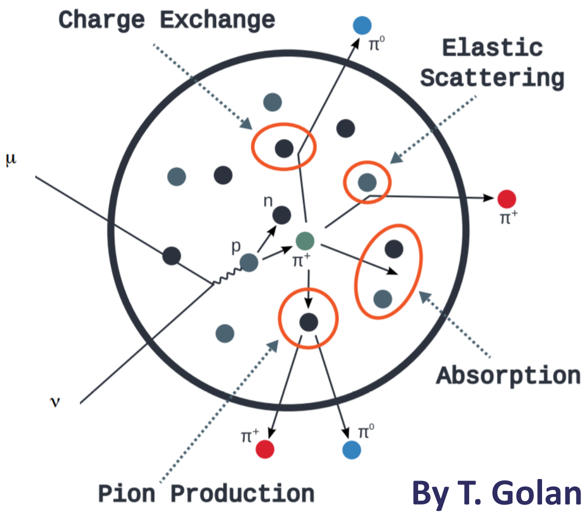
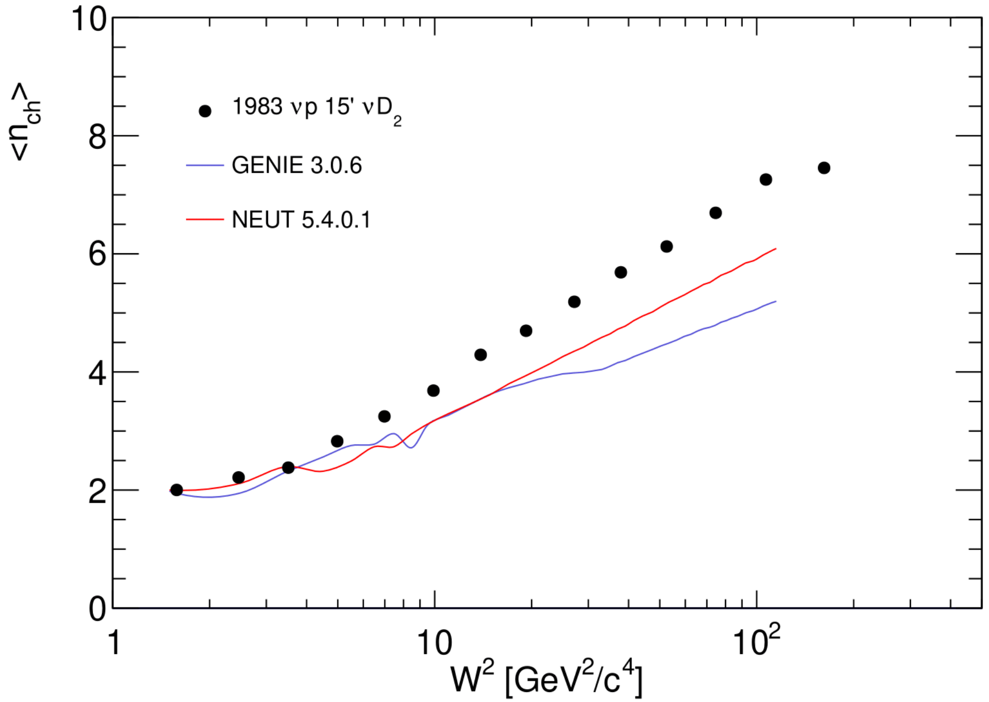
Event Generators

- Neutrino event generators simulate neutrino-nucleus interactions
- Super-K uses NEUT, others also exist such as GENIE and NuWro
- Nuclear effects are a known problem:



By T. Golan

- In nature, interaction types are also not discretely split and may be a combination of multiple, most notably in the shallow inelastic scattering region



Charged hadron multiplicities predicted by generators have poor agreement with data

However, it is also important to have more data to compare with