EUROPEAN SPALLATION SOURCE

Detectors for Spallation Sources

- Neutron Scattering Science
- How to design
- Detectors for the ESS
- Summary

Richard Hall-Wilton

Detector Group Leader

NDRA2016

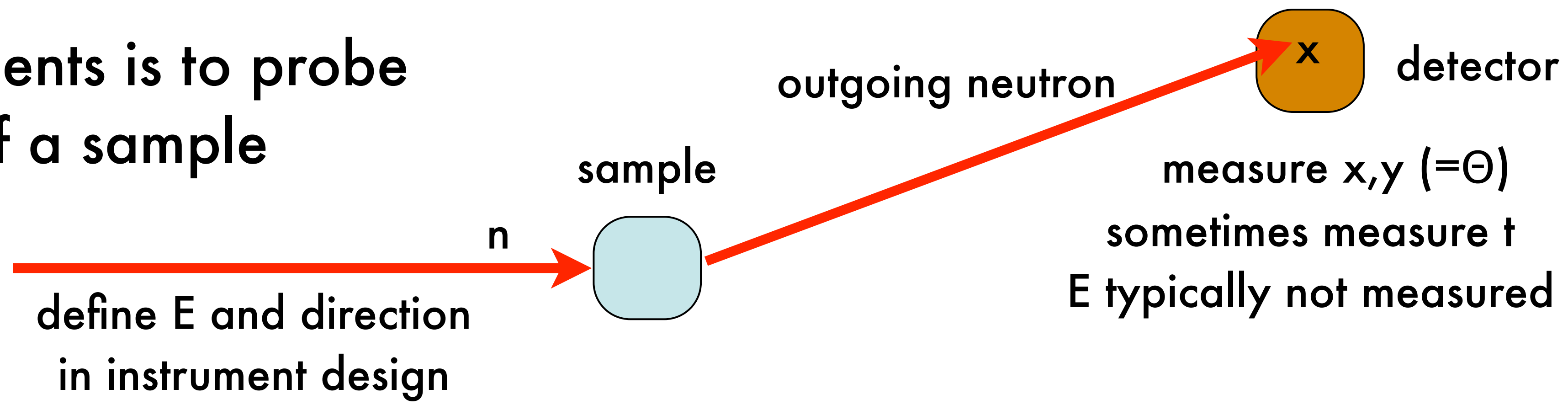
What I am going to talk about

- What is needed?
  - Always design to science goals (but not too closely)
- How to select based on the requirements
  - What can happen to a neutron?
  - Triangle of data/simulation/analytical calculation
  - Rate, dynamic range and noise
  - Resolution
  - Efficiency
  - Background
- Requirements for the European Spallation Source
- Specific examples
- Summary and a few observations

Try and work through as an example of how detector geometries are selected

Why?

- The purpose of the instruments is to probe with neutrons some aspect of a sample



- Very generically, this can be divided into elastic and inelastic categories
  - elastic: gives information on where atoms are
  - inelastic: gives information on what atoms do (ie move)
- This is measuring the cross sections:

elastic

$$\frac{d\sigma}{d\Omega}(\lambda, 2\theta, \psi)$$

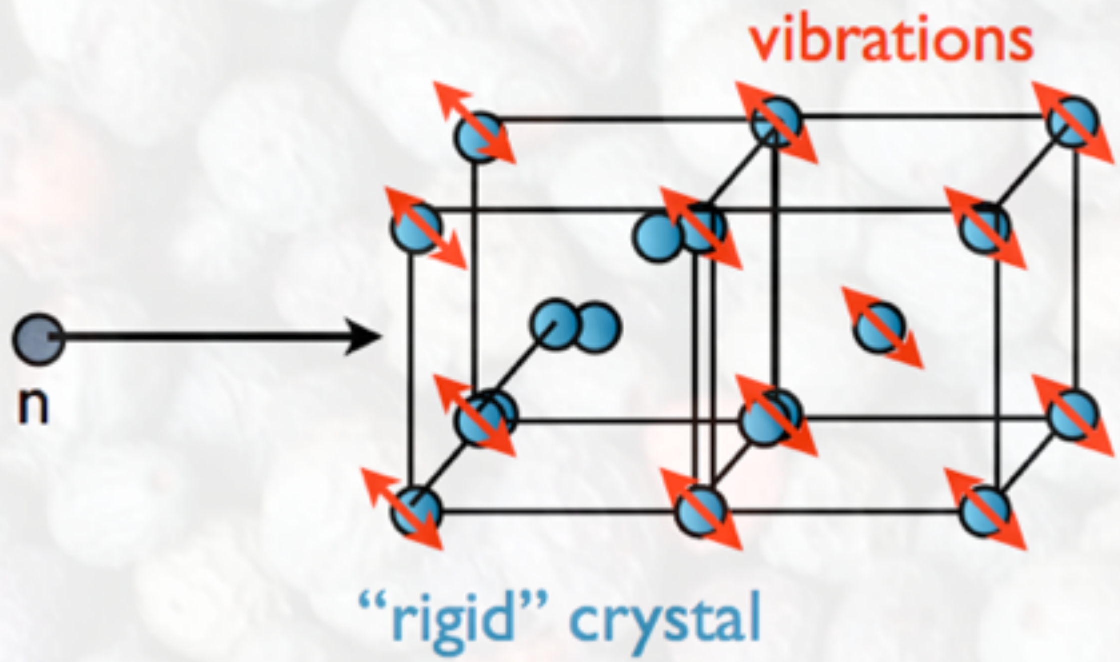
- cross section / scattering probability into a solid angle, as a function of wavelength, scattering angle and aximuthal angle

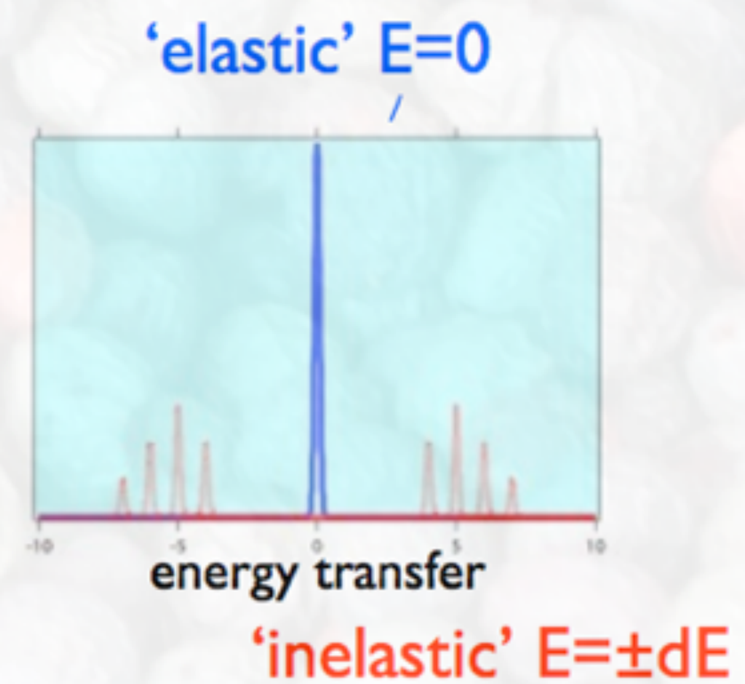
inelastic

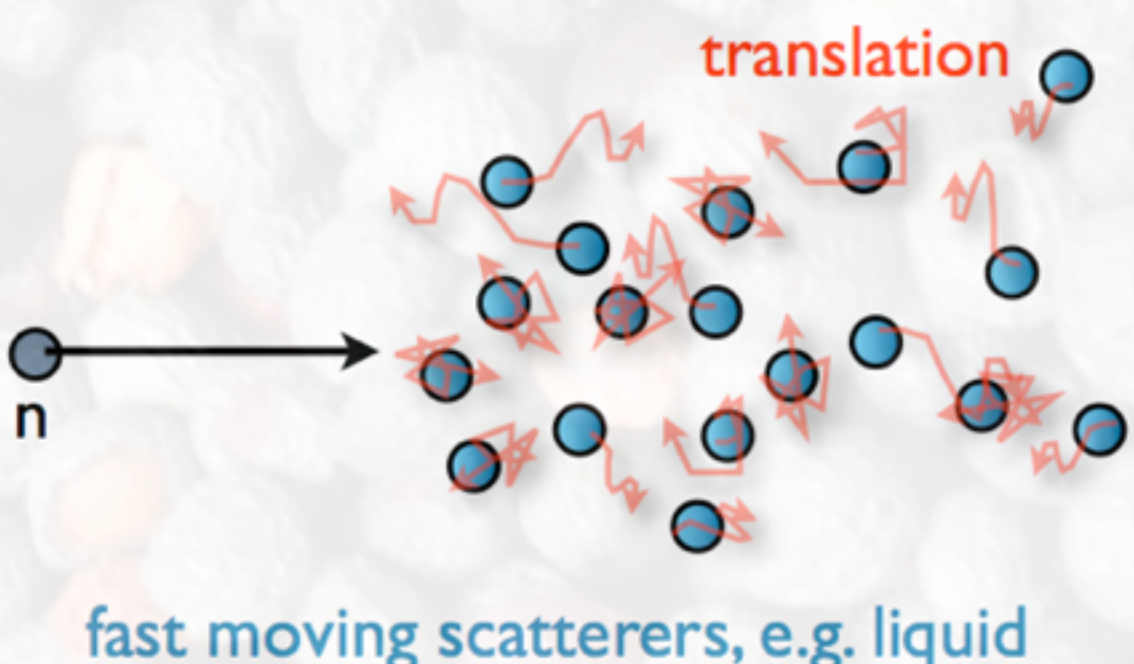
$$\frac{d^2\sigma}{d\Omega dE}(\lambda_{in}, \lambda_{sc}, 2\theta, \psi)$$

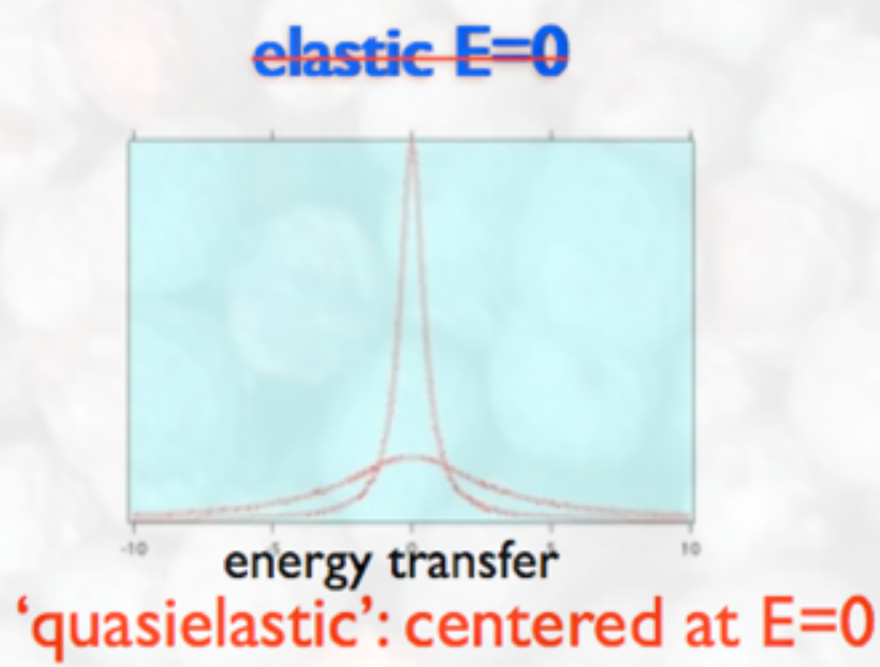
- double differential cross section / scattering probability into a solid angle, as a function of wavelength, scattered wavelength scattering angle and aximuthal angle

Elastic vs Inelastic





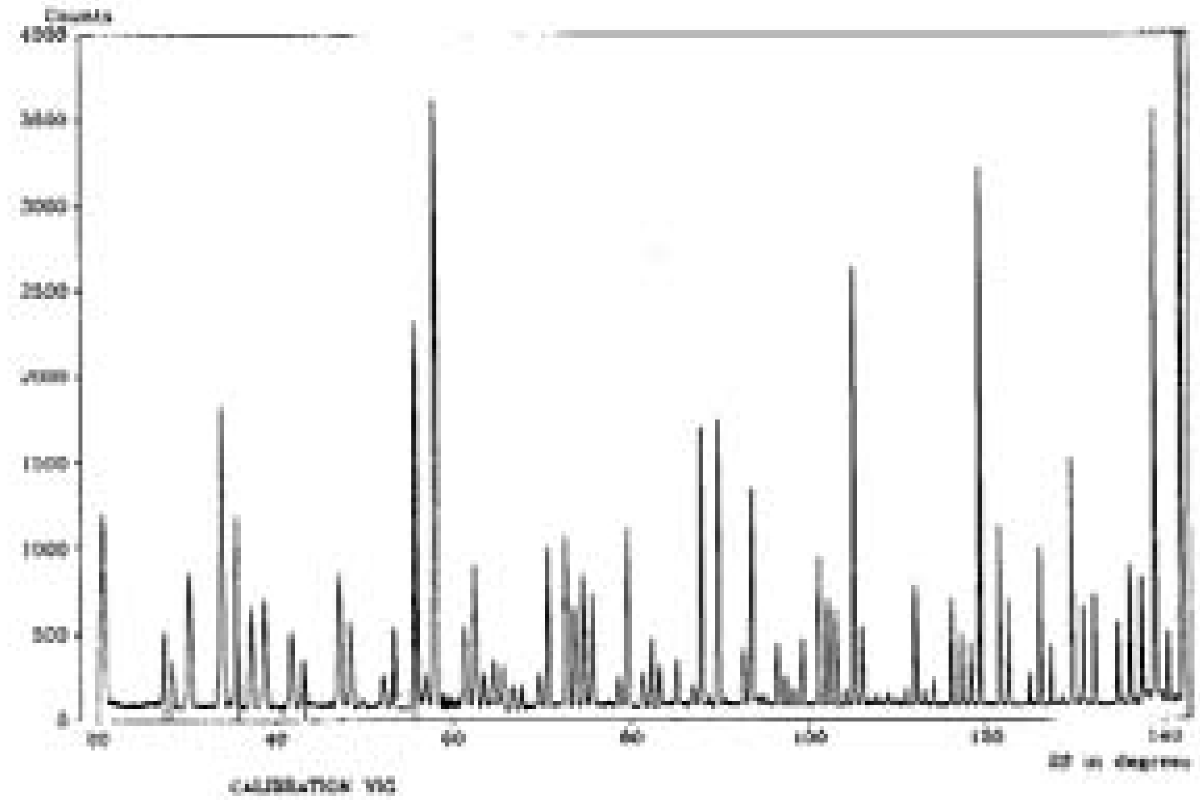




Andrew Jackson

Detectors are tools

Basically, in some form,
you want to measure
Bragg's equation



$$n\lambda = 2d\sin\theta$$

Define the neutron wavelength with your instrument design

Detectors allow you to measure theta

It means that you can calculate "d"

Therefore the detector should be designed to give you the most appropriate measurement of scattering angle for a instrument class

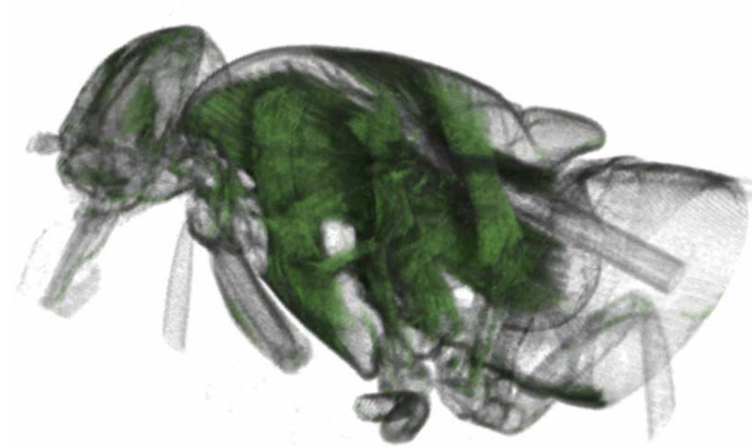
"horses for courses "

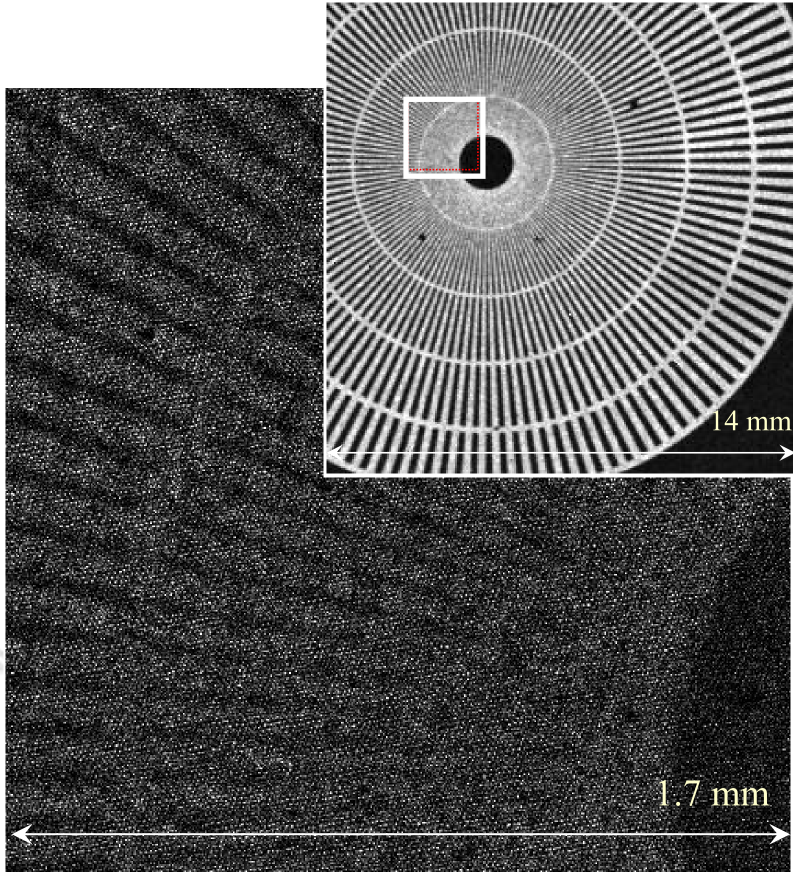
What do the detectors need to measure?

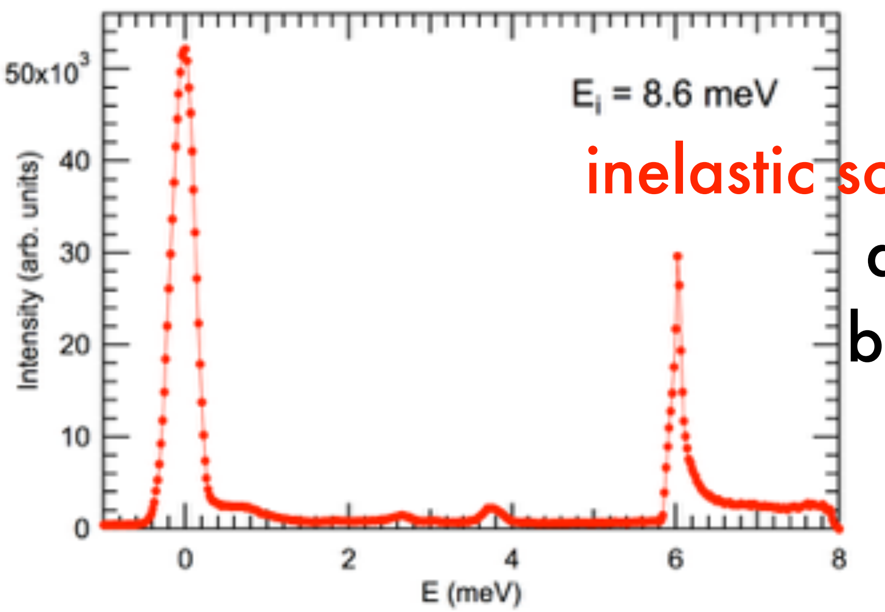
- Neutron Scattering for materials science comprise a great variety of instruments as tools for studying materials
- High efficiency is expected
- Each has its own "figure of merit"

"horses for courses "

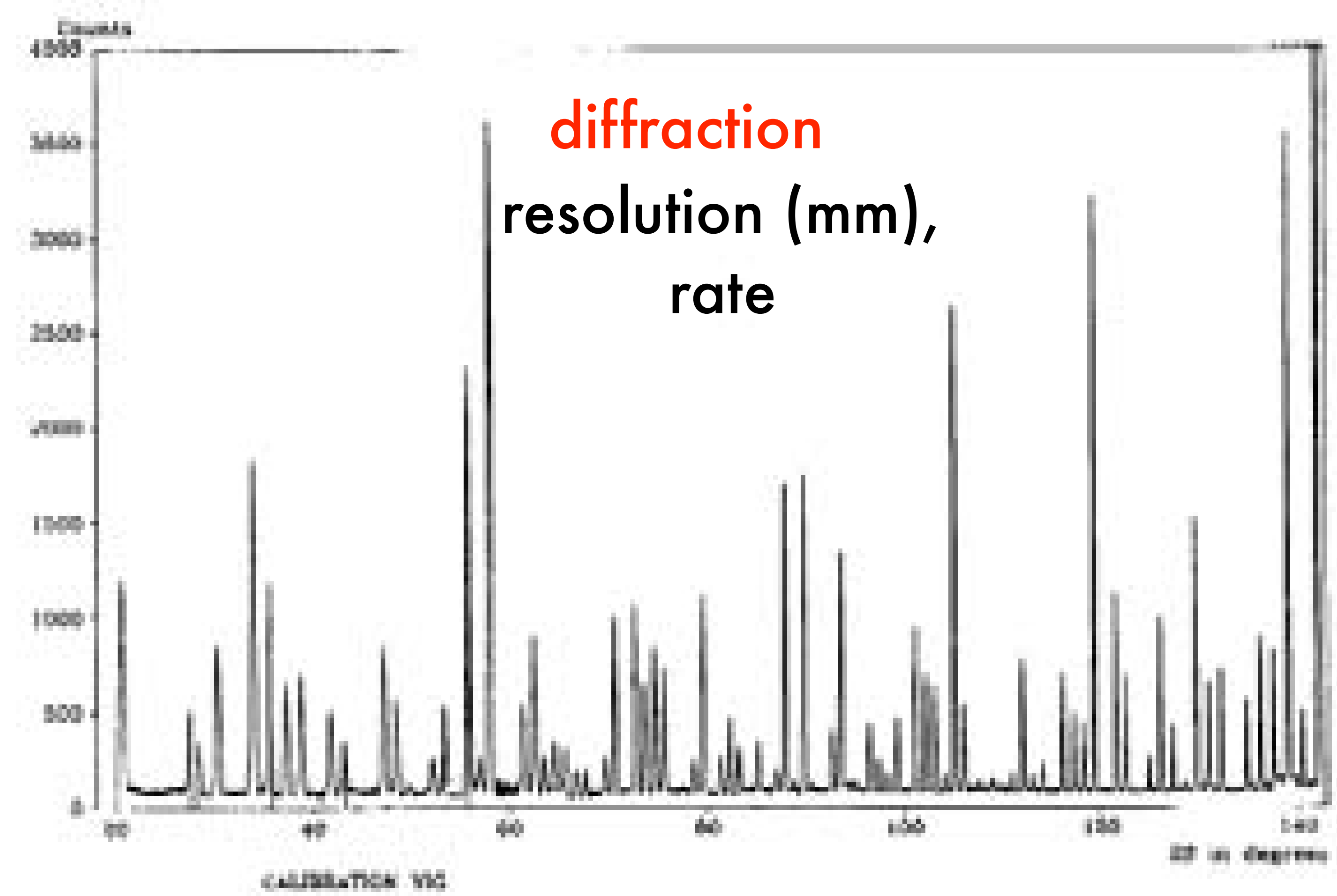
imaging
resolution (<100um),
rate



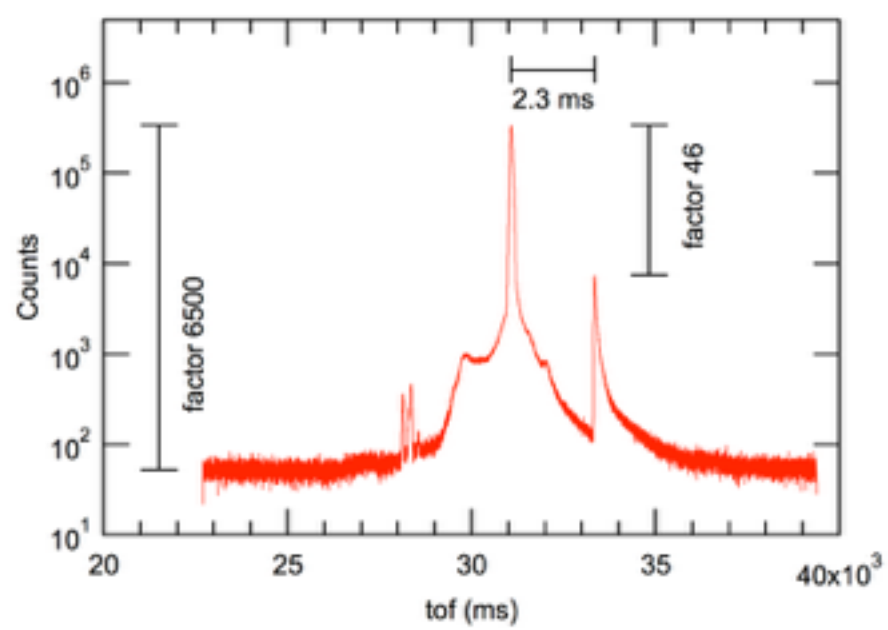




inelastic scattering
area, cost,
background



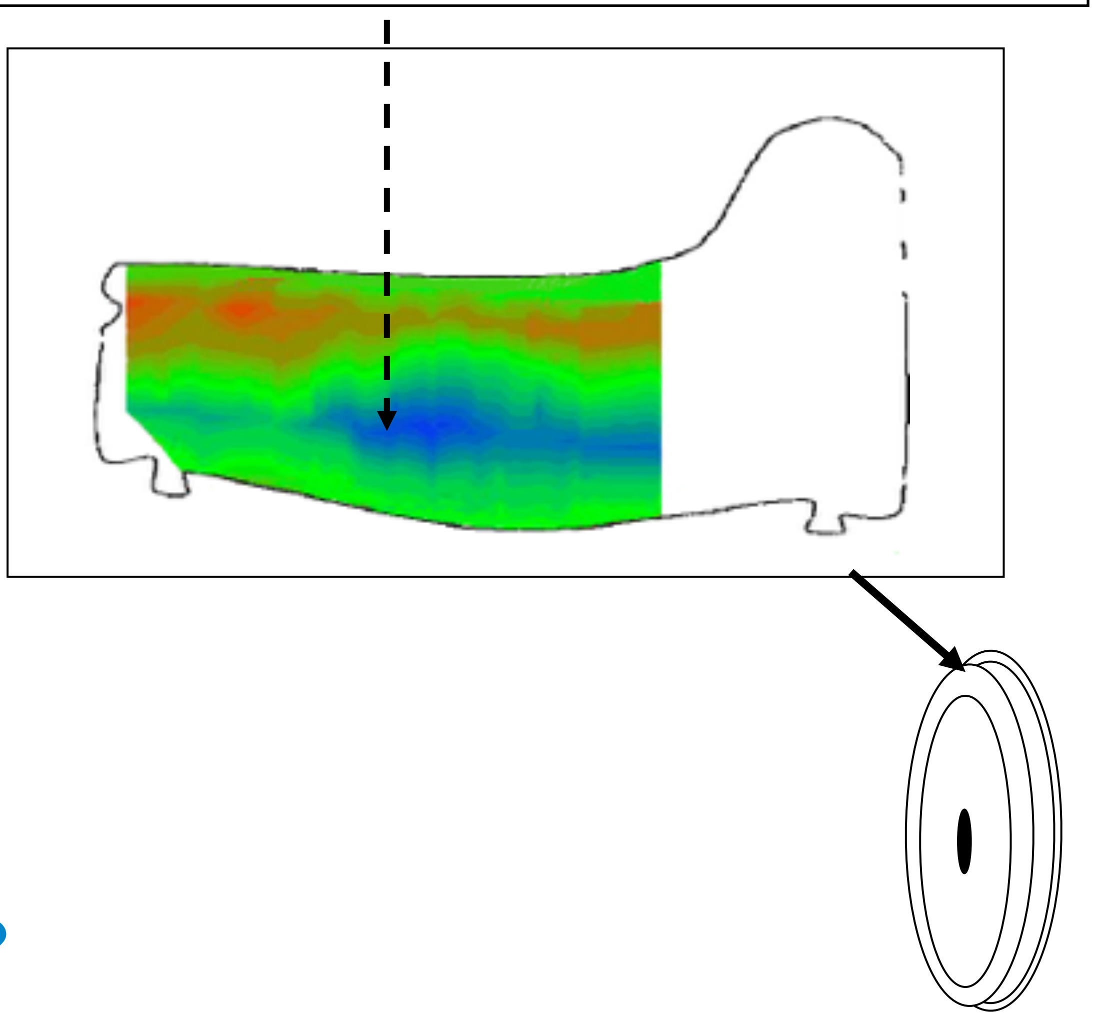
diffraction
resolution (mm),
rate



Neutron can see deep inside matter…

ICE accident, Eschede

Neutrons see **(tensile) stress** inside bulky metal parts that caused wheel failure: **standard engineering theory of plastic deformation stresses in error in the 1990s!!**

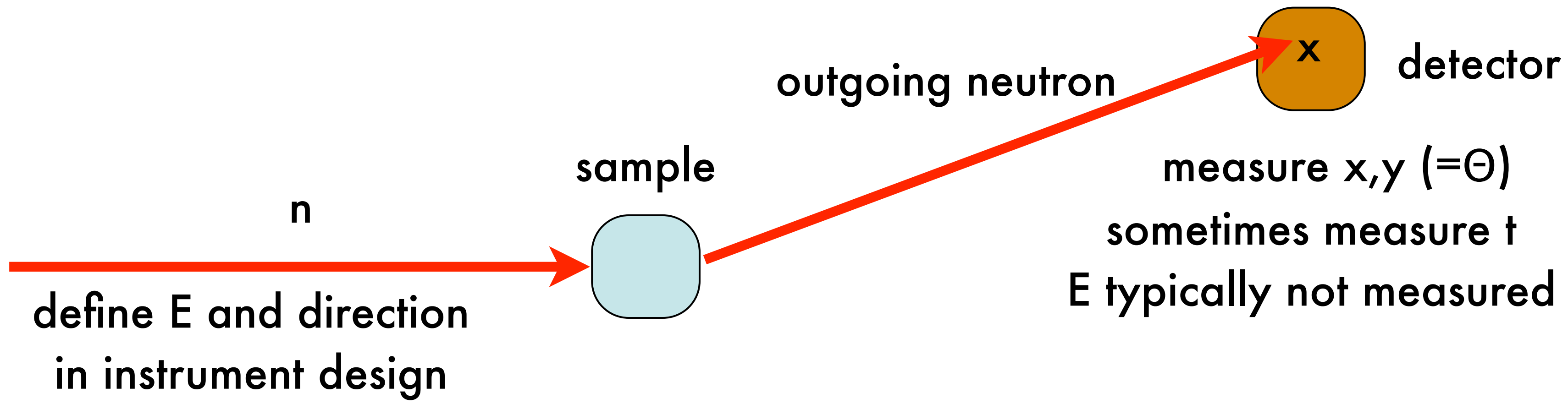


Knowledge based society??
Safety philosophy?
Industrial / proprietary use

Detector Requirements

- How to define the requirements
    - What can happen to a neutron?
    - Triangle: data/simulation/analytical.
    - Rate
    - Resolution
    - Efficiency
    - Background

Neutron Detectors - what information do you get?



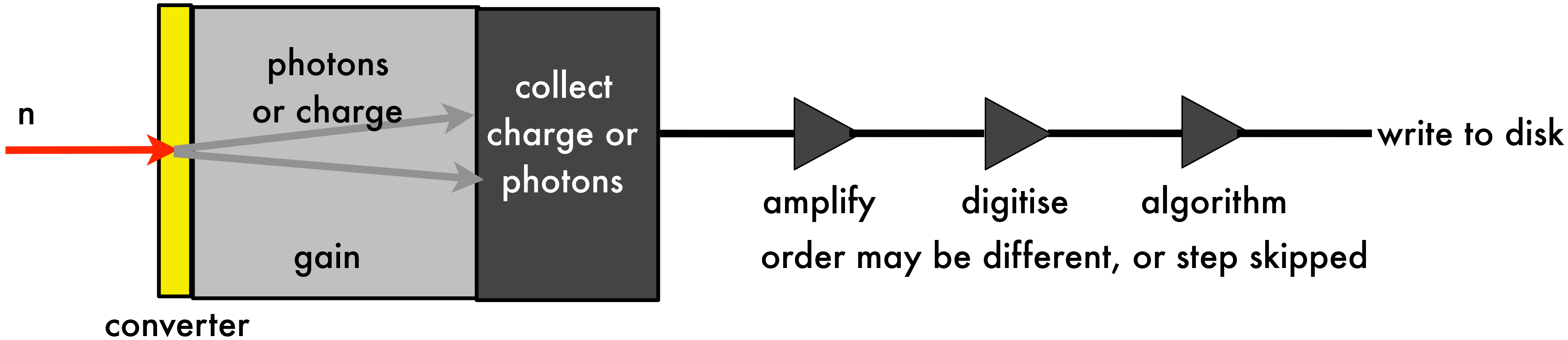
- Scattering angle measured through x,y position of the neutron detected
- Time of detection often used
  - It is vital to have good time resolution for instruments at spallation sources
- Energy typically not measured
  - In some ways, the holy grail to have a good energy measurement of the neutron?
- Detector needs to be adapted to the expectations for that instrument
  - Not one design fits all

Cost is always a limiting factor in the design of detectors
Schedule will determine what you can do about it

Detectors - what do we mean? An analogy ...

Basic Principles of Neutron Detectors

- Need to produce a measurable electric signal
- Not possible to directly detect slow neutrons - energy is too low
- Need to use nuclear reactions to convert neutrons into charged particles
- Then indirectly detect the charged particles in a charged particle detector
- Amplify, digitise, process as needed.
- Store data on disk



Isotopes Suitable as Cold and Thermal Neutron Convertors

Mittuniversitetet MID SWEDEN UNIVERSITY

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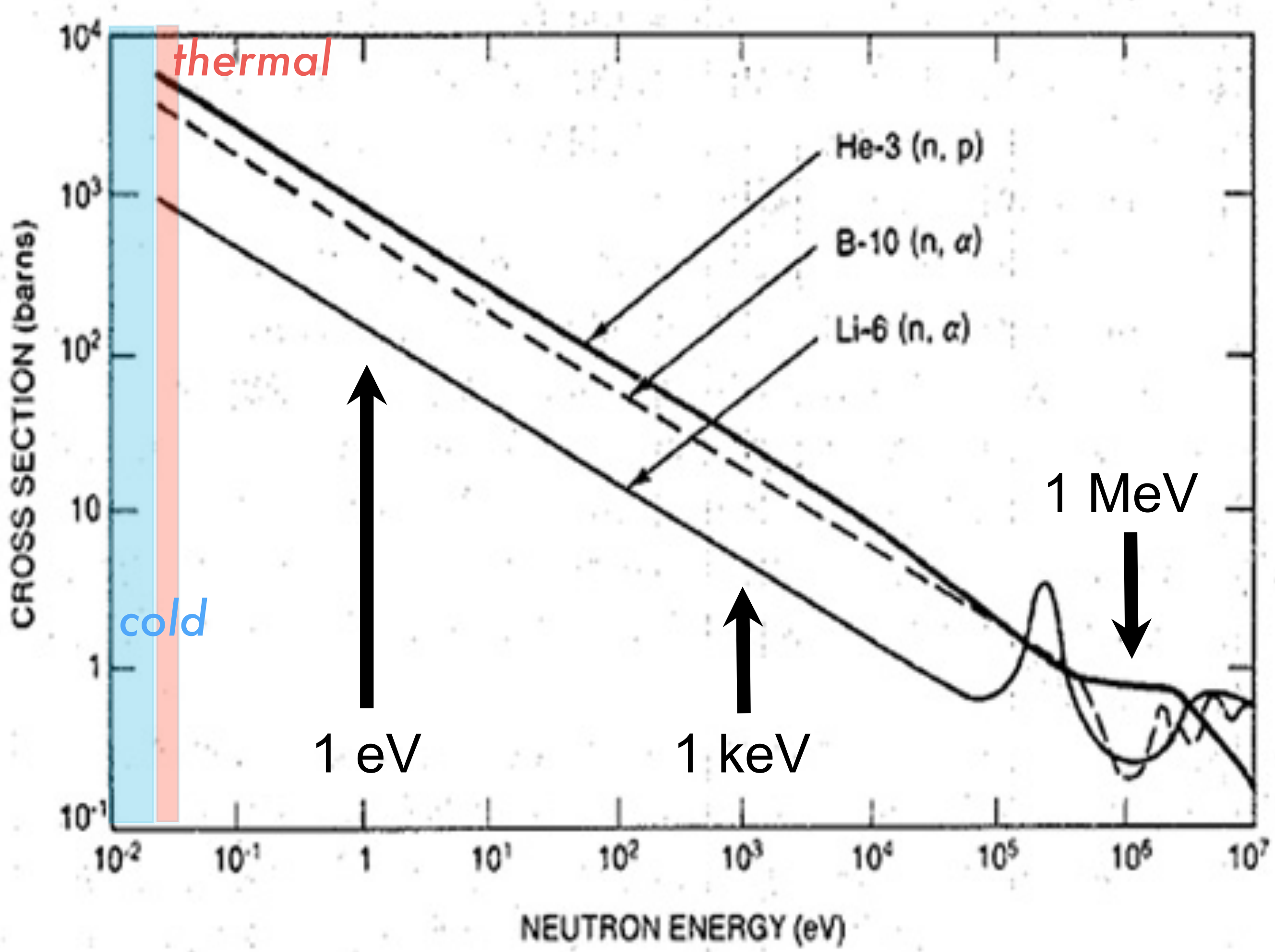
reaction	energy	particle	energy	particle	energy
n (^{3}He, p) ^{3}H	+0.77 MeV	p	0.57 MeV	^{3}H	0.19 MeV
n (^{6}Li, α) ^{3}H	+4.79 MeV	α	2.05 MeV	^{3}H	2.74 MeV
93 % n (^{10}B, α)^{7}Li	+2.3 MeV + γ (0.48MeV)	α	1.47 MeV	^{7}Li	0.83 MeV
7 % n (^{10}B, α) ^{7}Li	+2.79 MeV	α	1.77 MeV	^{7}Li	1.01 MeV
n (^{235}U, Lfi) Hfi	+ ~ 100 MeV	Lfi	< = 80 MeV	Hfi	< = 60 MeV
n (^{157} Gd, Gd) e^{-}	+ < = 0.182 MeV	conversion electron			0.07 to 0.182 MeV

Table 1: Commonly used isotopes for thermal neutron detection, reaction products and their kinetic energies.

- Only a few isotopes with sufficient interaction cross section
- To be useful in a detector application, reaction products need to be easily detectable

- In region of interest, cross sections scale roughly as 1/v
- G. Breit, E.Wiegner, Phys. Rev., Vol. 49, 519, (1936)

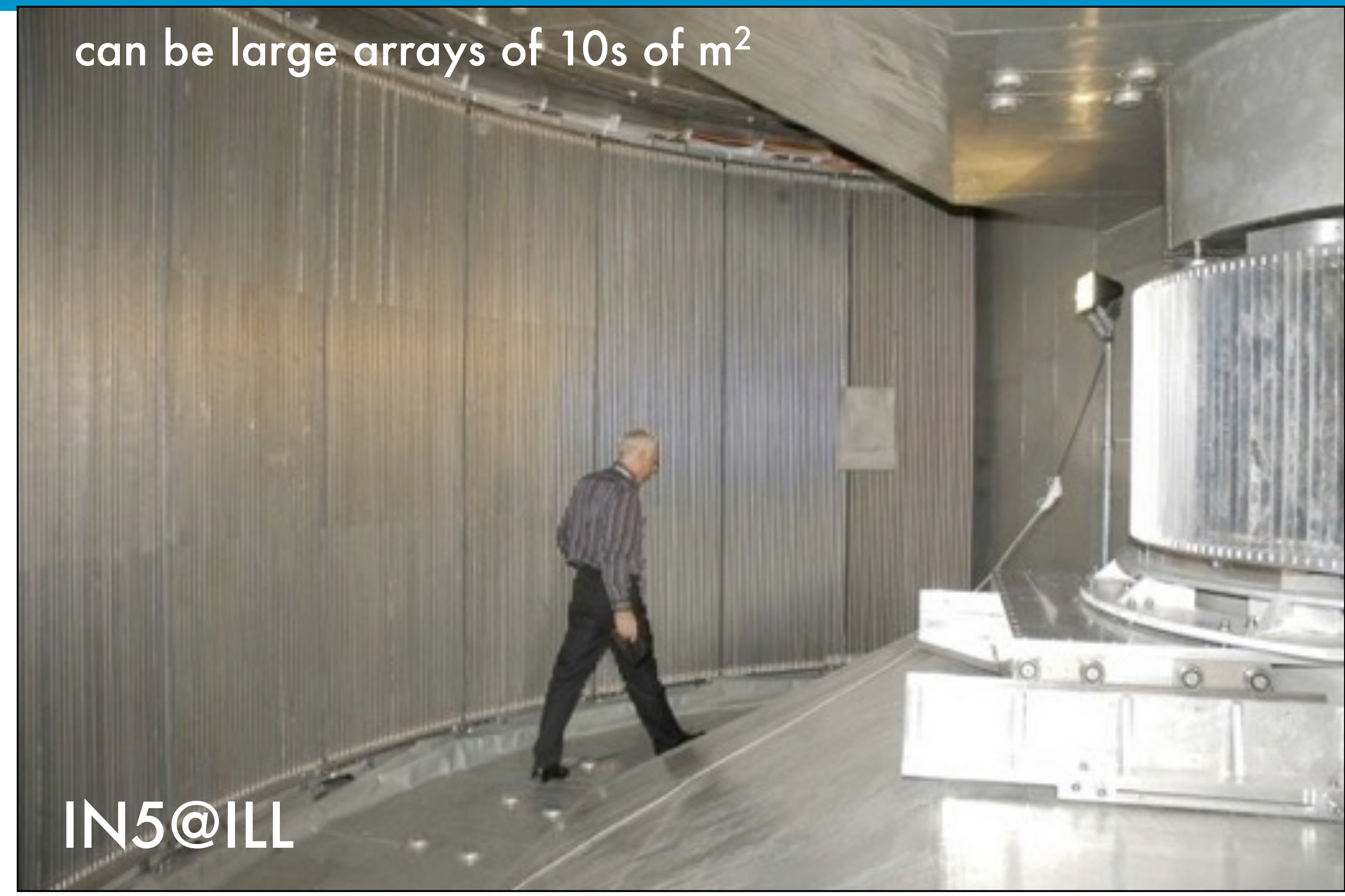
- Presently >80% of neutron detectors worldwide are Helium-3 based



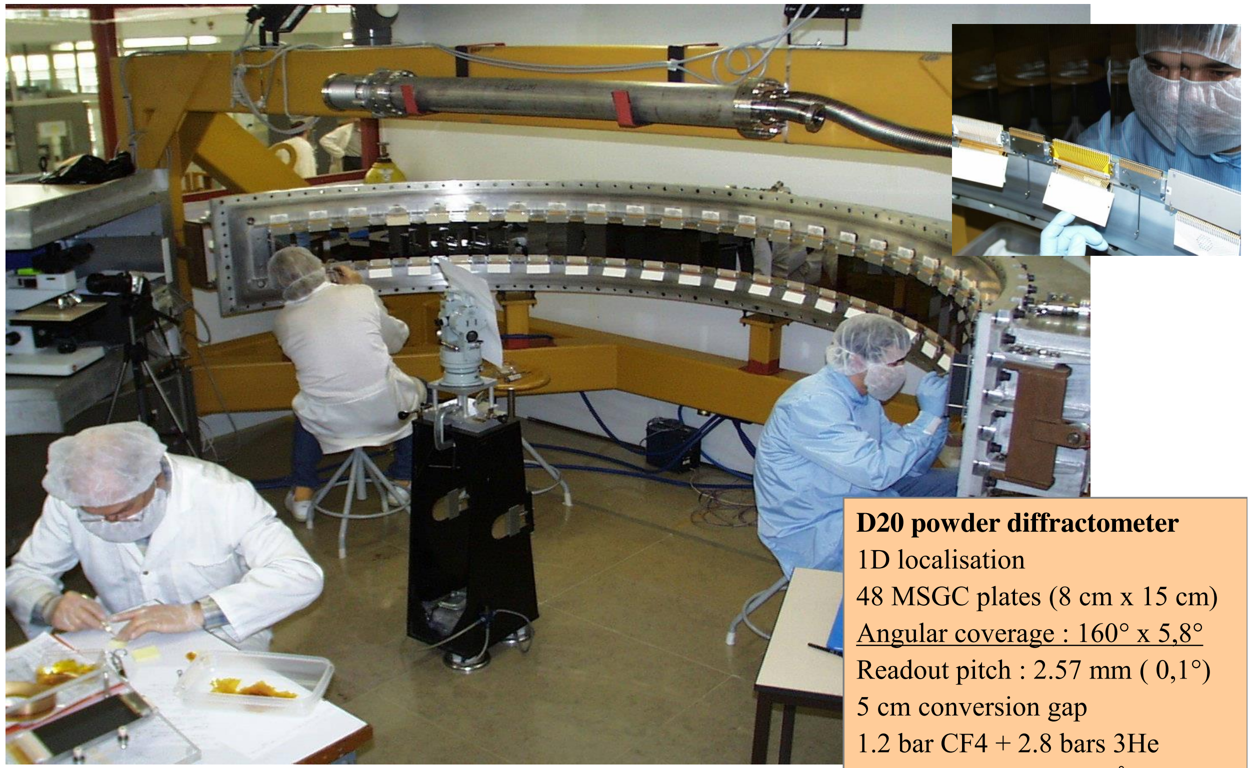
(ILL Blue Book)

State of the Art of Neutron Detectors

- Helium-3 Tubes most common
- Typically 3-20 bar Helium-3
- 8mm-50mm diameter common
- Using a resistive wire, position resolution along the wire of ca. 1% possible



Curved 1D MSGC for the D20 Powder Diffractometer (2000)



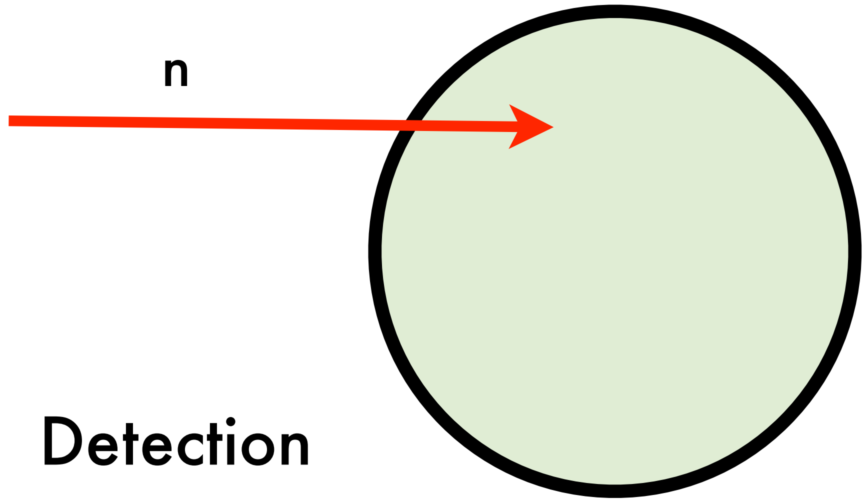
D20 powder diffractometer
1D localisation
48 MSGC plates (8 cm x 15 cm)
Angular coverage : 160° x 5,8°
Readout pitch : 2.57 mm (0,1°)
5 cm conversion gap
1.2 bar CF_4 + 2.8 bars ^3He
Efficiency 60% @ 0.8 Å

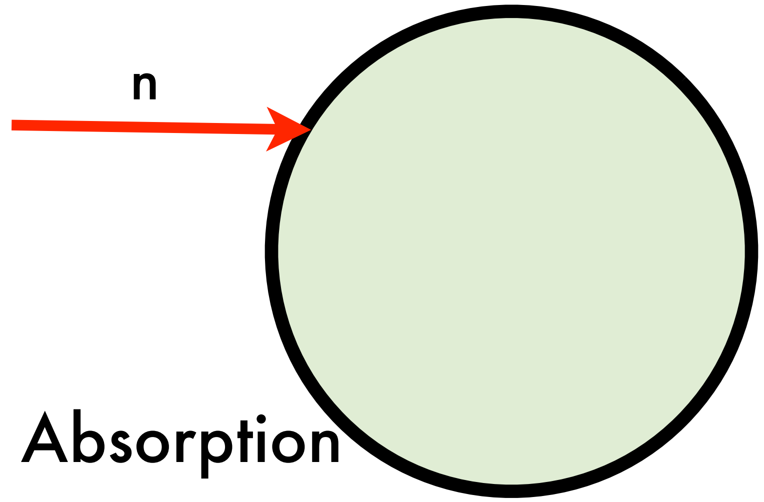
- First micro pattern gaseous detectors was MSGC invented by A Oed at the ILL in 1988
- Rate and resolution advantages
- Helium-3 MSGCs in operation

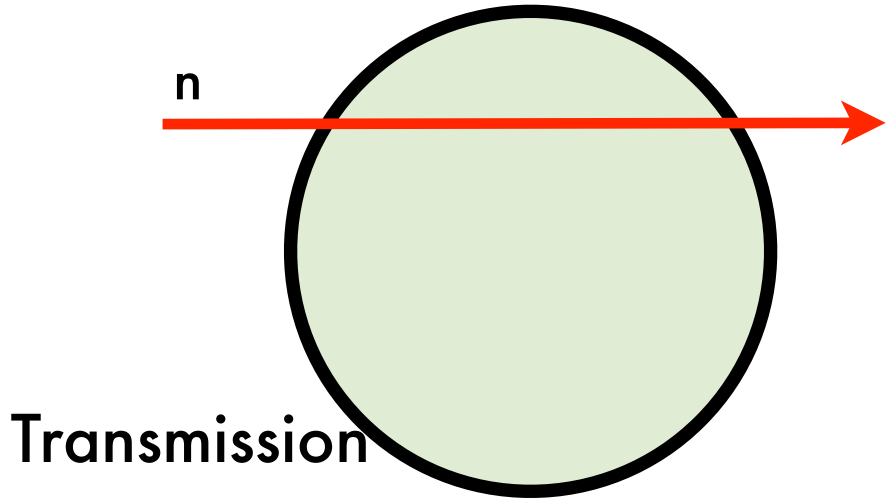
What can happen to a neutron?

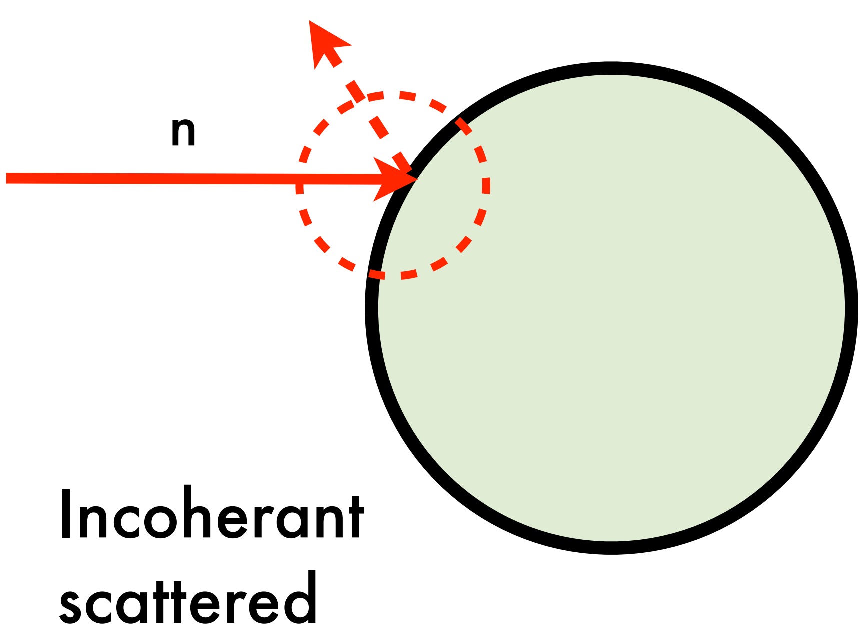
- Detection.
- Absorption.
- Transmission.
- Incoherant scattering
- Diffractive Scattering

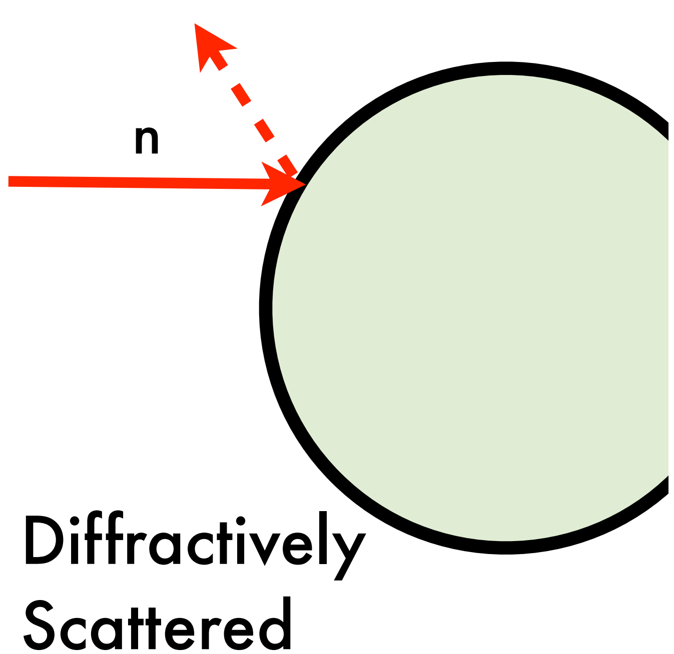
eg on a generic He-3 tube

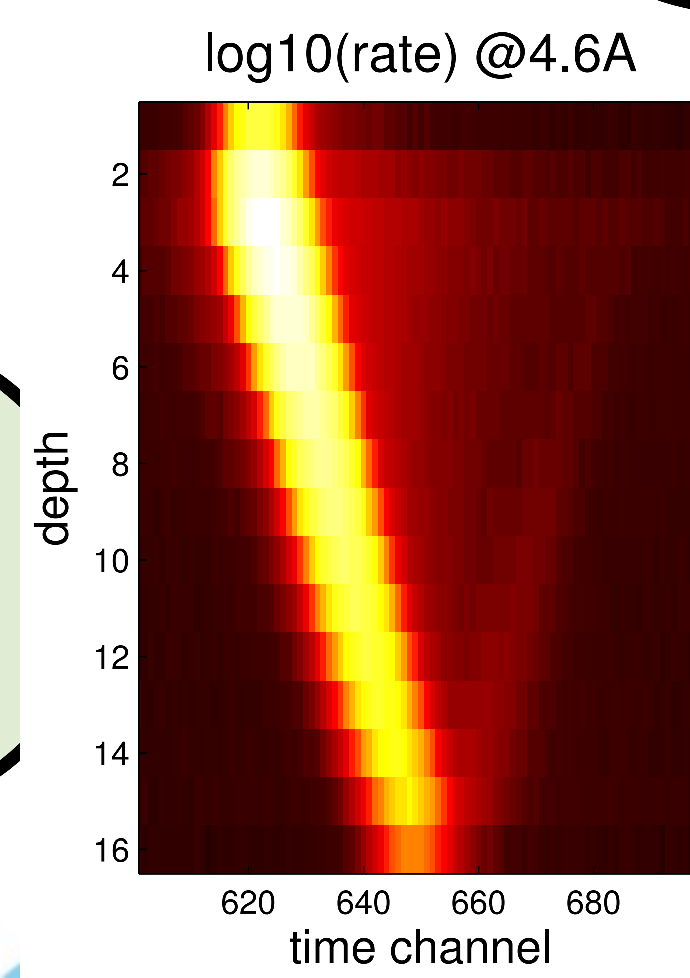












ILL-ESS-LiU Collaboration

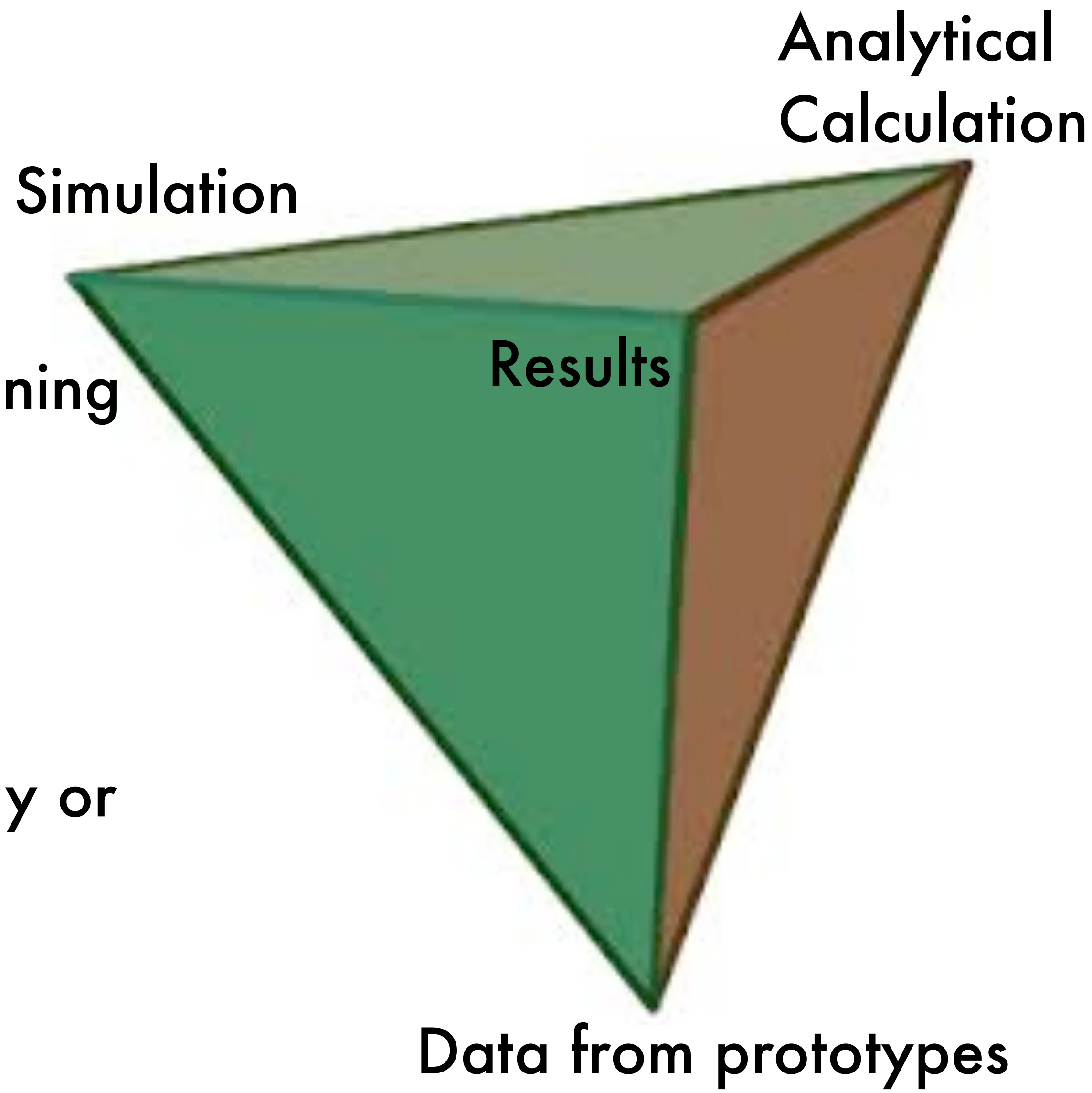
Calculation, Simulation, Data and All That

- As you have heard, simulation is a very powerful tool
- ... but the computer will always lie to you ...

- Data from prototype tests is golden
- Lack of ability to trigger independently on the neutron means some degree of arbitrariness in defining the measurement
- Checking that your measured data is correct is complicated

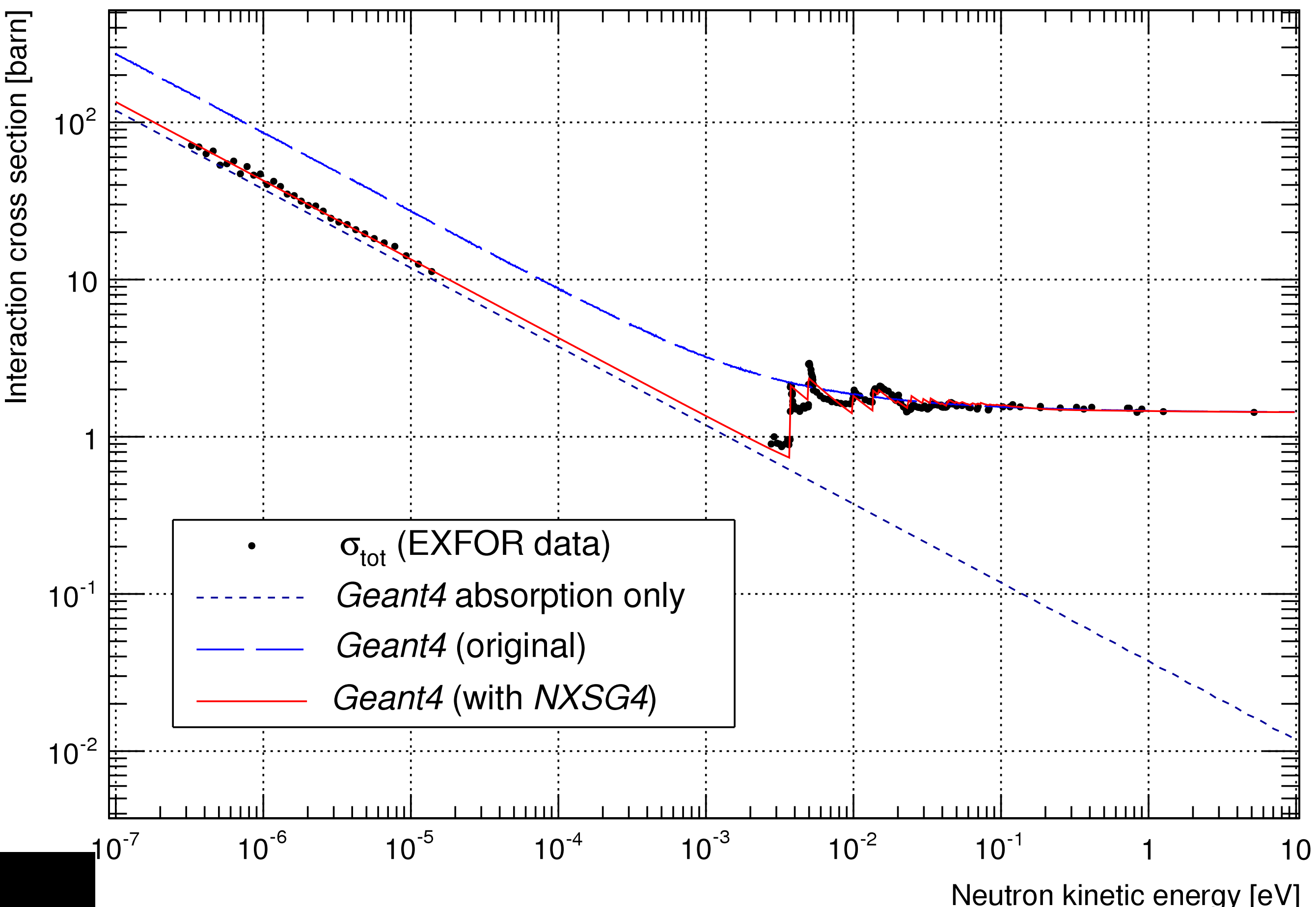
- Additionally, always try and calculate analytically or "back of envelope" what your expectation is
- (Or at least upper and lower limits)

- Use all 3 of these together to understand the performance of your prototypes
- Expect "features" and non-agreement and investigate them
- Iterative

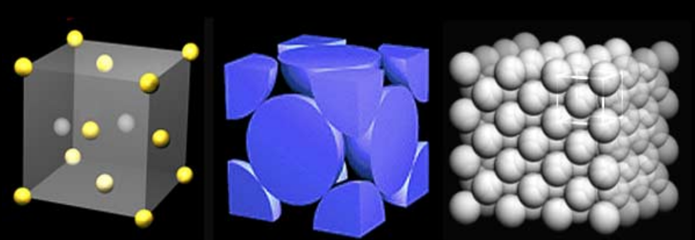


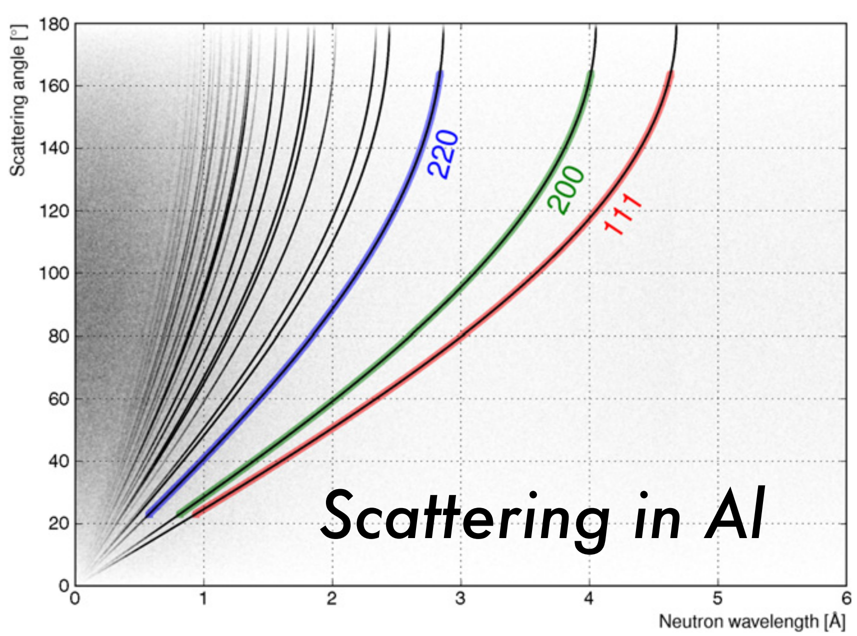
Neutron diffraction in polycrystalline materials: Add-on for GEANT4

- GEANT4 is an invaluable simulation tool
- However, thermal/cold neutrons not well validated
- No support for crystal diffraction
- A new plugin NXSG4 allows neutron diffraction in polycrystalline materials
- Based upon nxs library, used in McStas, Vitess
- Using simple unit cell parameters, only low energy neutron scattering is overriden. All other GEANT4 capability retained.




```
(tkittel@localhost data)> cat Al.nxs
space_group = 225
lattice_a = 4.049
lattice_b = 4.049
lattice_c = 4.049
lattice_alpha = 90
lattice_beta  = 90
lattice_gamma = 90
[atoms]
add_atom = Al 3.449 0.008 0.23 26.98 429.0 0.0 0.0 0.0
```





- Available at http://cern.ch/nxsg4
- **J. Comp Phys Comm 189 (2015) 114**

Simulation of Neutron Scattering in Crystalline Materials

Risø DTU
National Laboratory for Sustainable Energy

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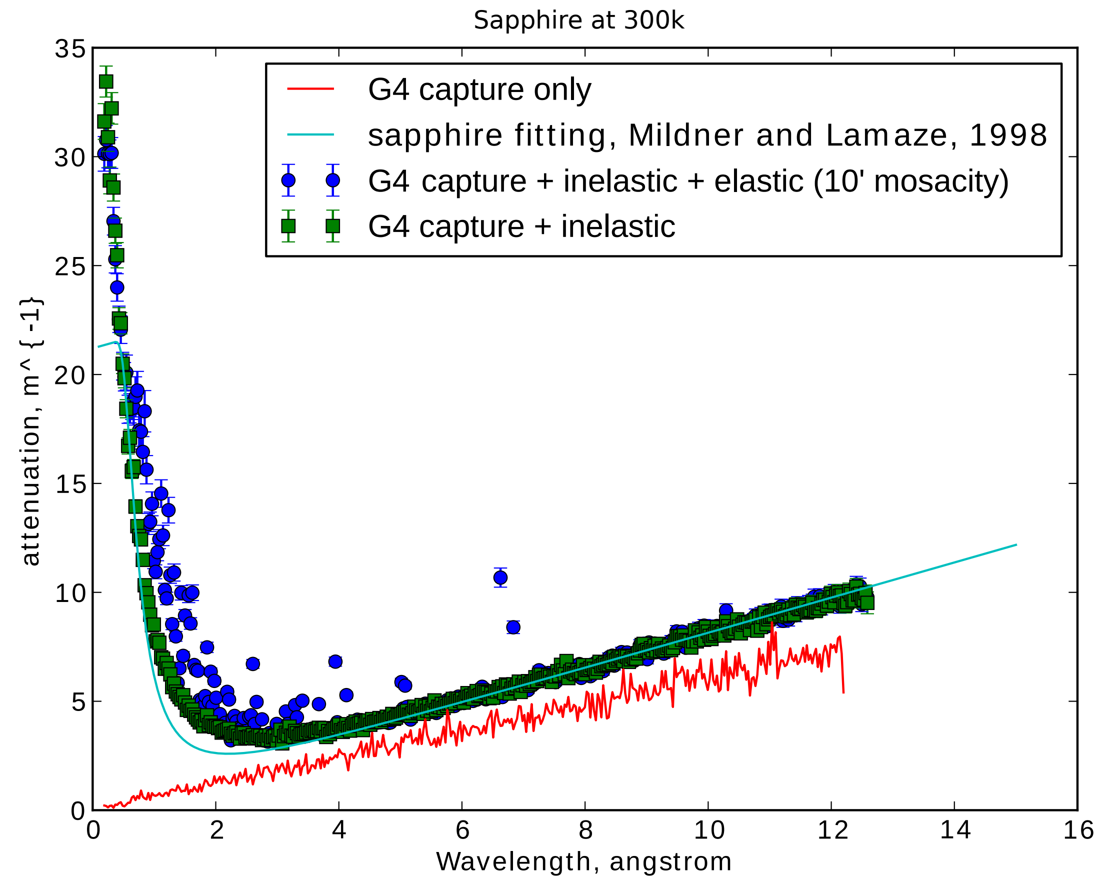
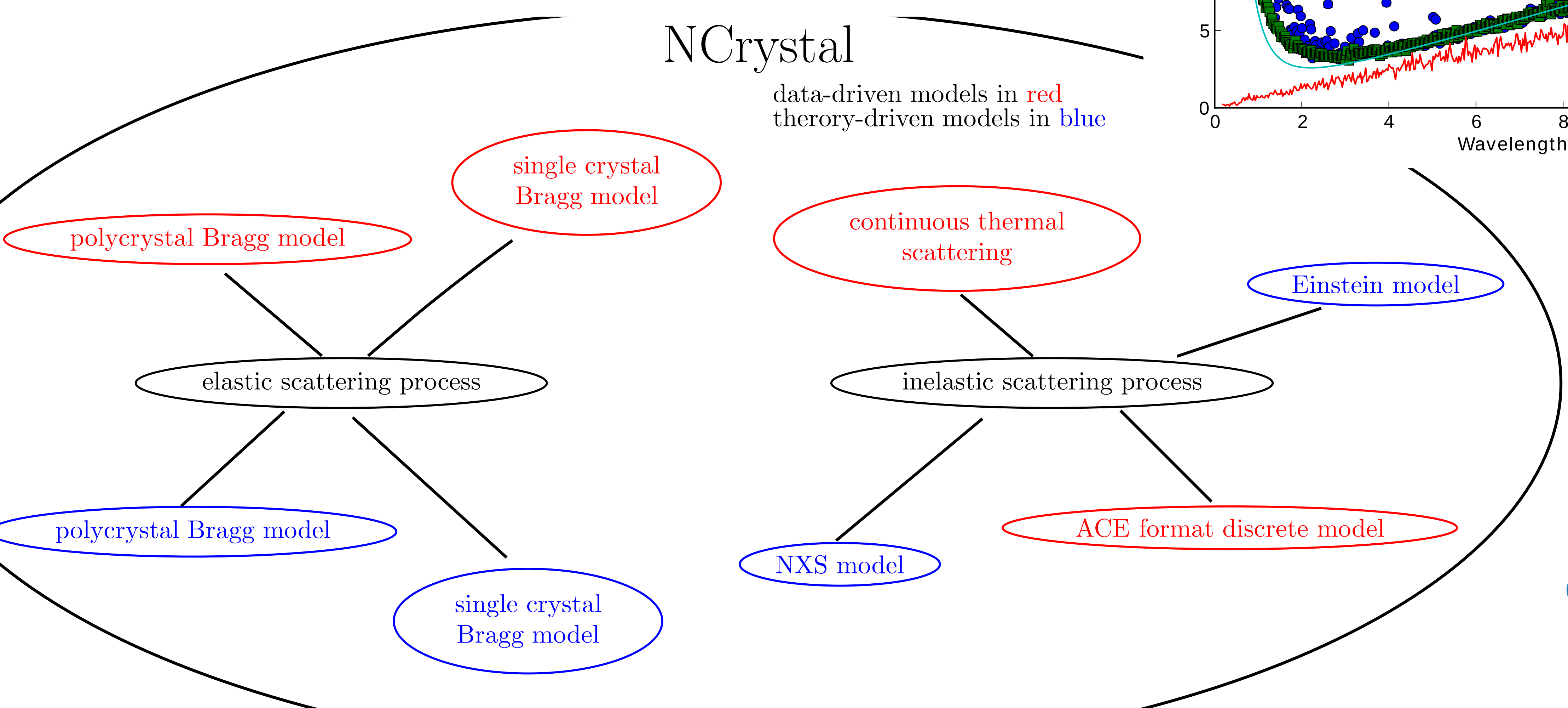
- “NCrystal" models physics of thermal neutron transport in poly- and single-crystalline materials
- Interface to MC models: GEANT4, MCNP, McStas

The scattering physics in NCrystal is a combination of the inelastic and elastic scattering processes. The double differential cross section describes the likelihood of a neutron being scattered into a small solid angle $d\Omega$ with final energy between E' and $E' + dE'$. It can be expressed as

$$\frac{\partial^2\sigma}{\partial E'\partial\Omega} = \frac{\partial^2\sigma_{in}}{\partial E'\partial\Omega} + \frac{\partial^2\sigma_{el}}{\partial E'\partial\Omega}$$





Extension under development

Definitions and Standards

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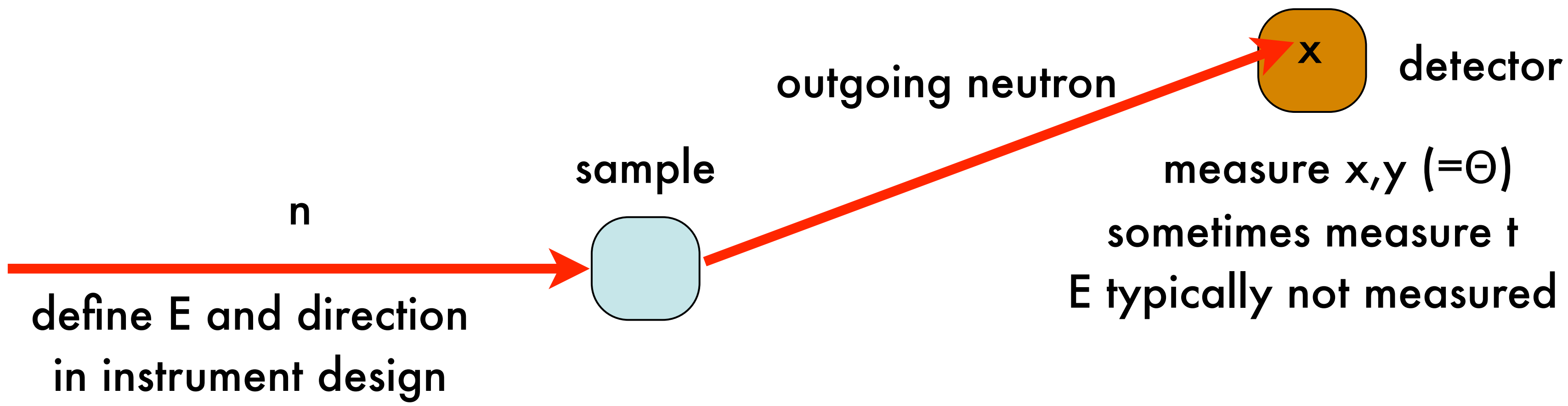
Definitions of Performance



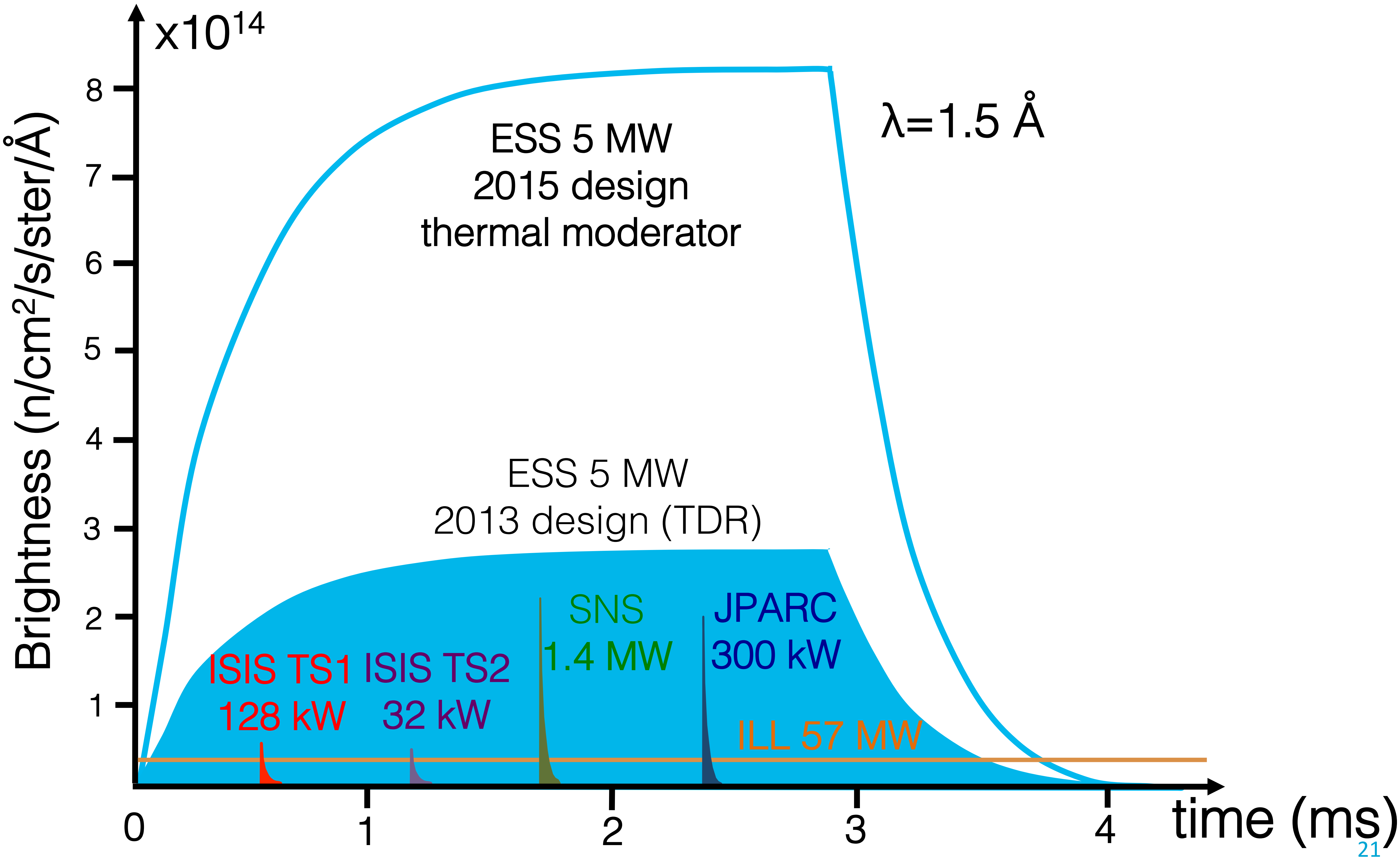
- Position/angular resolution: how well the position of detection is measured
- Time resolution: how well the time-of-arrival of the neutron is measured
- Efficiency: probability that a given neutron will be detected
- Noise: rate of fake hits
- Dynamic range: the "headroom" between noise and maximum rate
- Rate capability: the maximum rate of neutrons that can be detected either locally or globally
- (In-)Scattering: fraction of neutrons scattered from somewhere they shouldn't have (sample or instrument)
- Gamma rejection: fraction of gamma's that are falsely identified as a neutron
- A detector will often be described solely in terms of efficiency and resolution, whereas the scientific performance may be be determined by S/N, background, scattering, gamma sensitivity

Rate

- Rate is the number of neutrons incident per unit time
- For ESS, rate is a key issues for many instruments designs
- Three numbers of interest for assessing a detector choice:
    - Global rate: rate (Hz) over a larger area: detector unit or m^2
    - Local rate: rate over a smaller (channel/pixel): Hz/ca. mm^2
    - Local instantaneous rate: hits during a small interval of time over a smaller (channel/pixel): hits/100us-ms/ca. mm^2
    - The relevant size of the unit depends upon the details of the detection process

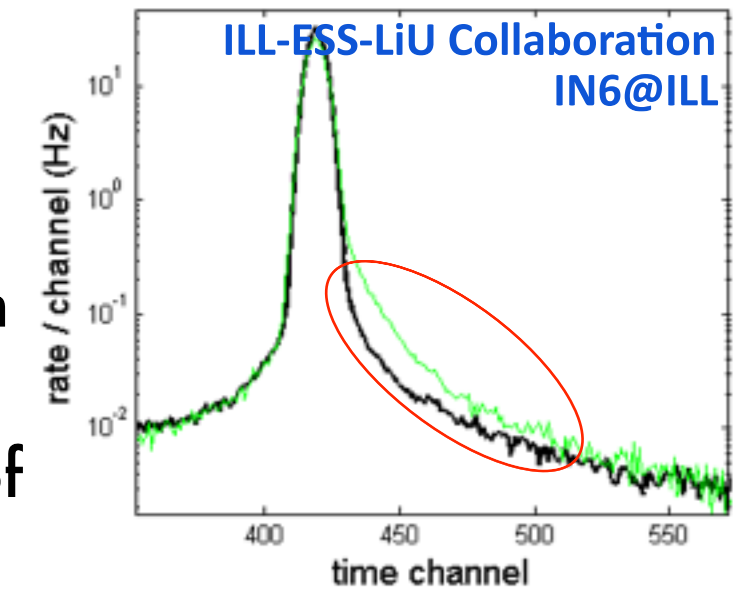
- Details of the detector system as a whole are important
- Even if the detection process can handle the rate, it might be that bottlenecks occur further on
- Important to keep in mind for the electronics and readout design of the detector

Challenge for Rate

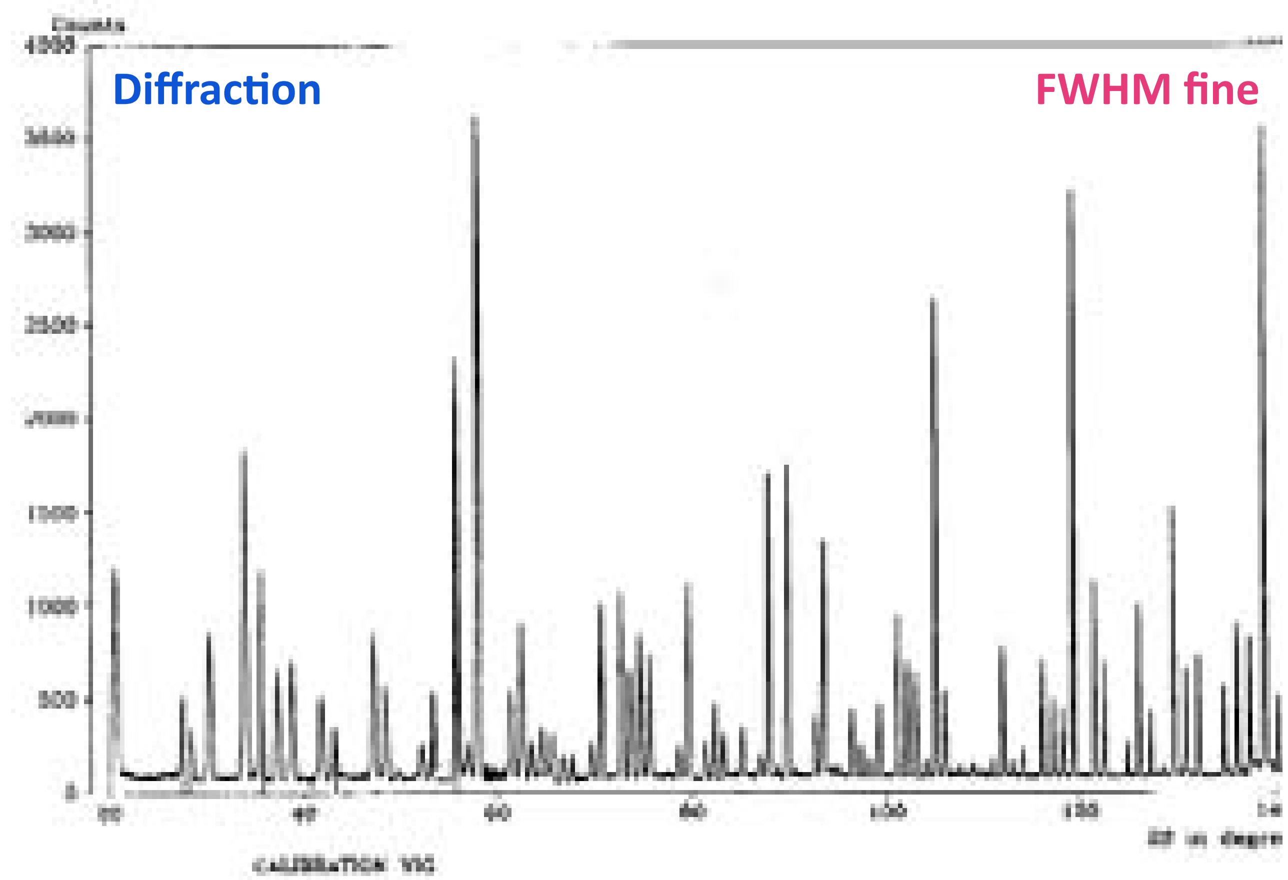


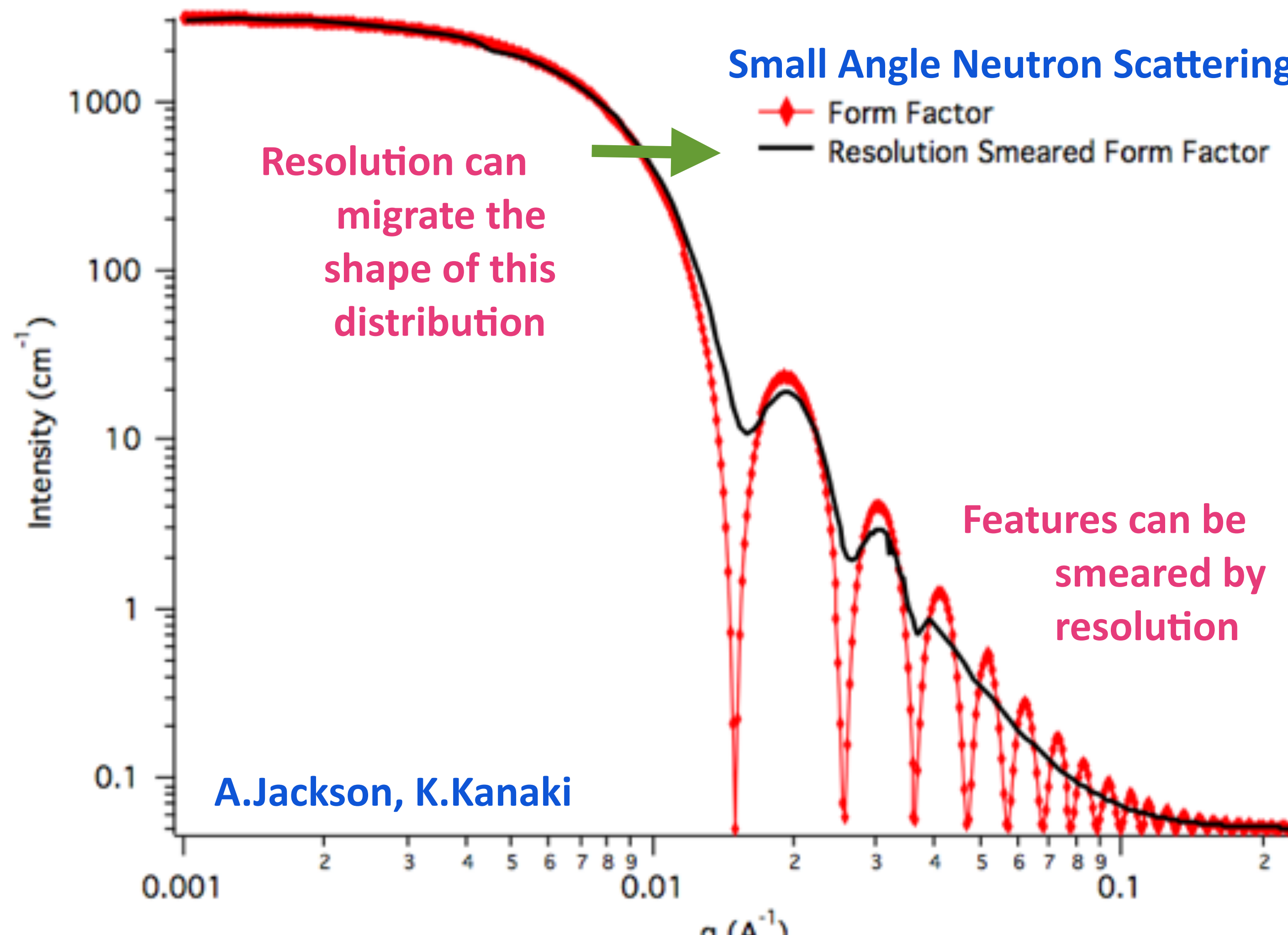
Position Resolution

- The position resolution is the distribution of the measured position of the neutron compared to the true position of the neutron
- Typically simply quoted as a Full-Width-Half-Maximum or width of a Gaussian fit
- However, the details of this distribution are important depending upon the application
- In particular be careful of quickly falling distributions: resolution can smear out features, and change the measurements from the plot



example of smearing from Al scattering





Efficiency

- Efficiency is the fraction of neutrons detected compared to the true number of neutrons
- Typically this is quoted as a point-like efficiency, at the most efficient point in the detector, also in the most efficient configuration of the detector
- Important to quote efficiency at the working point, and explain why the working point is there
- Additionally, whilst the point peak efficiency is a useful number, probably more useful:
  - global efficiency = detected neutrons into solid angle of interest / true number of neutrons into solid angle of interest
  - The solid angle of interest is that subtended by the detector system from the scattering sample
  - This then takes into account dead material (absorption and scattering), non–active areas, etc etc
- As the wavelength dependence of the efficiency is high, need a well-defined wavelength of the neutrons to make the measurement - not moderated radioactive sources
- Lastly, neutron efficiency typically is measured with respect to a "reference detector"
  - Clearly the understanding of this detector needs to be excellent
  - Need to understand possible systematic effects
  - eg background on both detectors needs to known and corrected for
  - Using an additional detector / method highly desirable to reduce errors
  - Uncertainty evaluation

He-3 Efficiency

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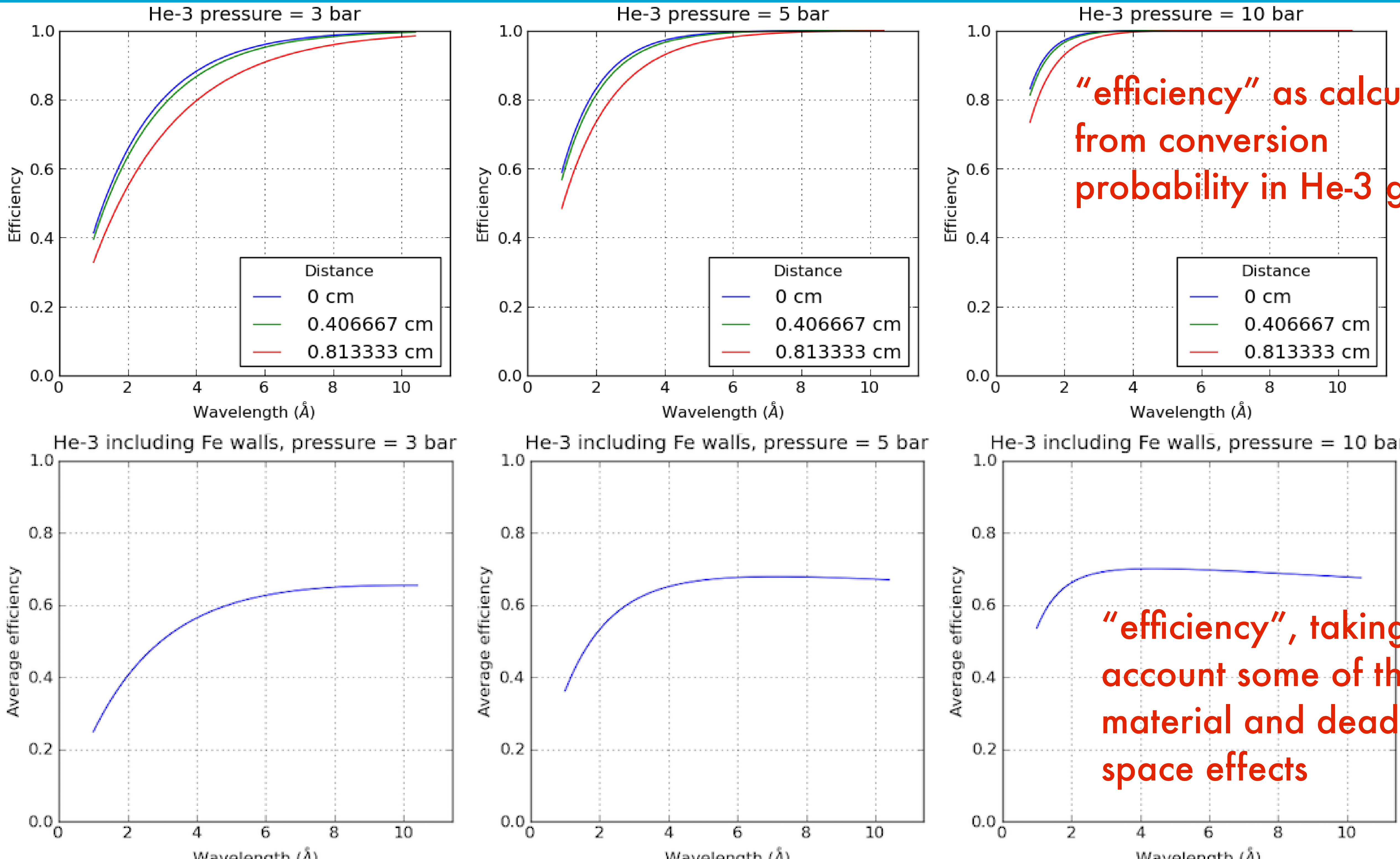
Example of typical large area application:



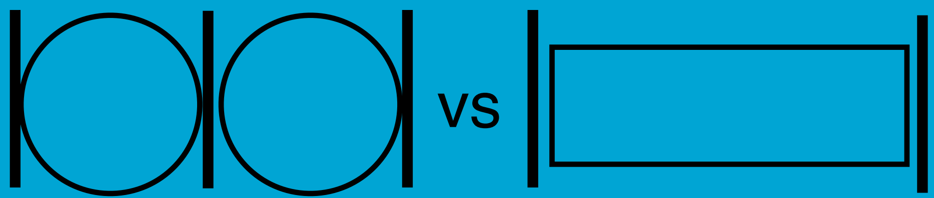
"efficiency" as calculated from conversion probability in He-3 gas

"efficiency", taking into account some of the material and dead space effects

Important to compare like-with-like, in particular when looking at different technologies

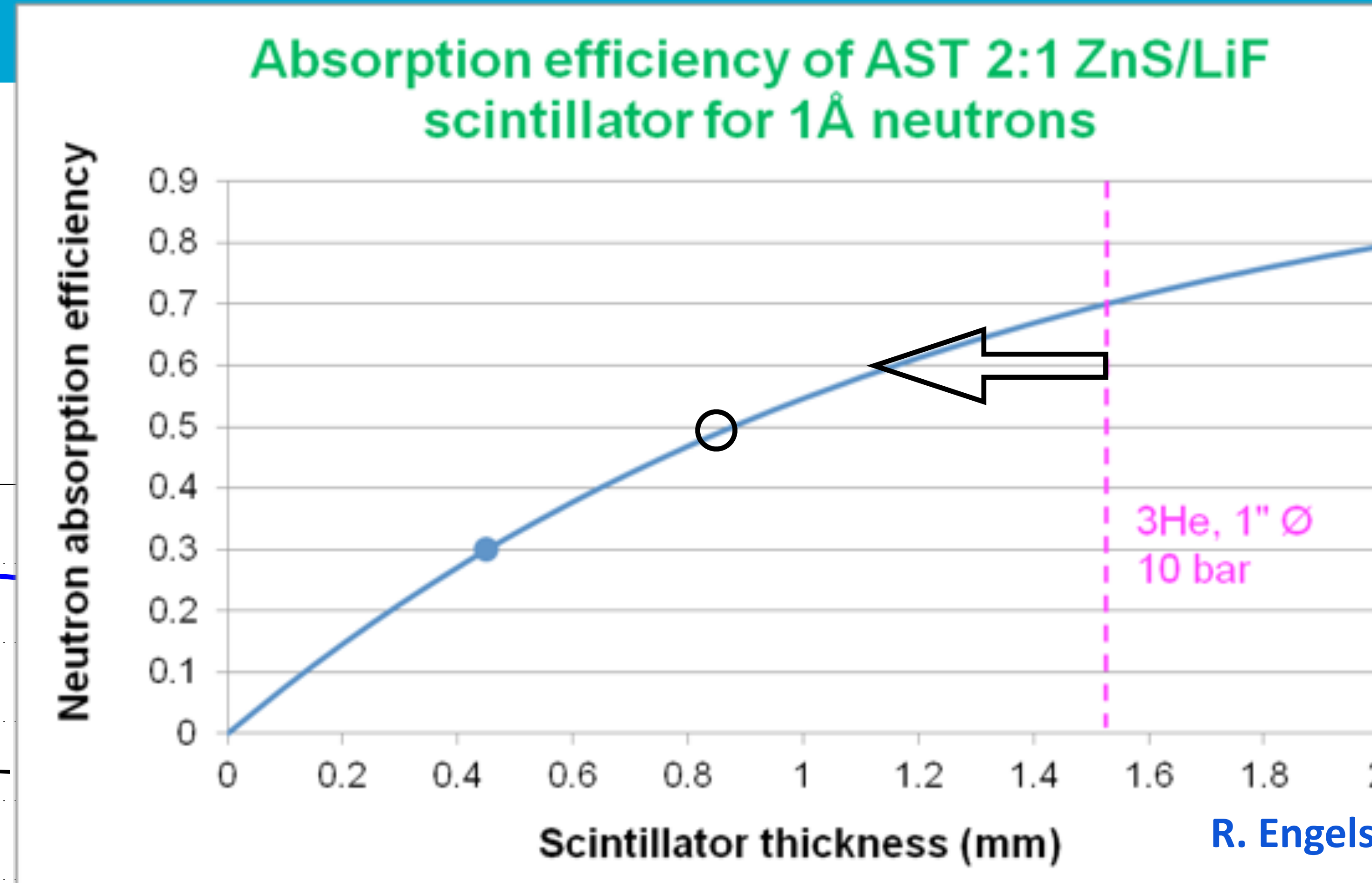
Quality and Standards:Detection Efficiency

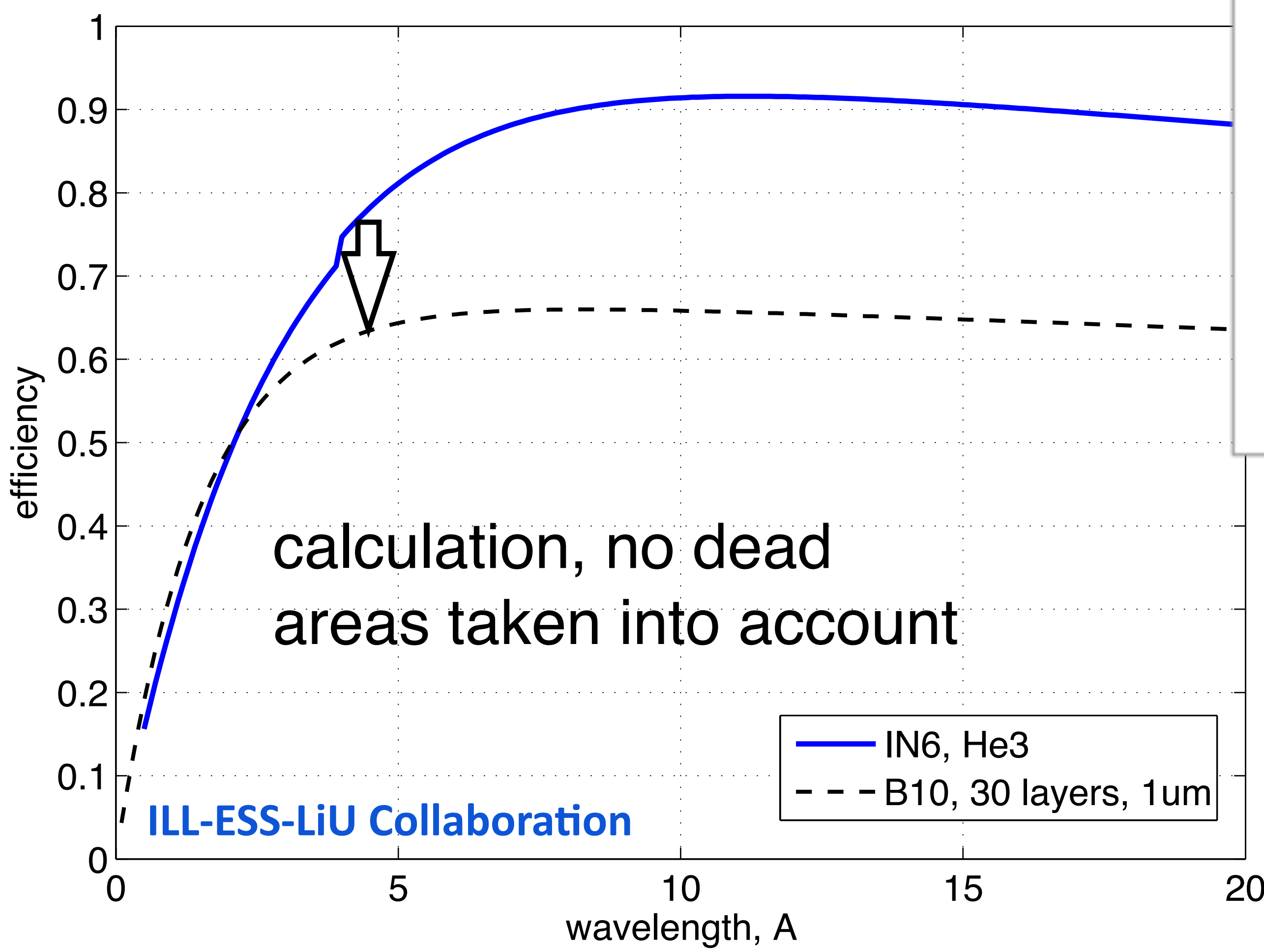
cartoon:



"boundary conditions matter"

- Helium-3 is the gold standard, in particular in terms of detection efficiency
- However, efficiency numbers have rarely compared like-with-like





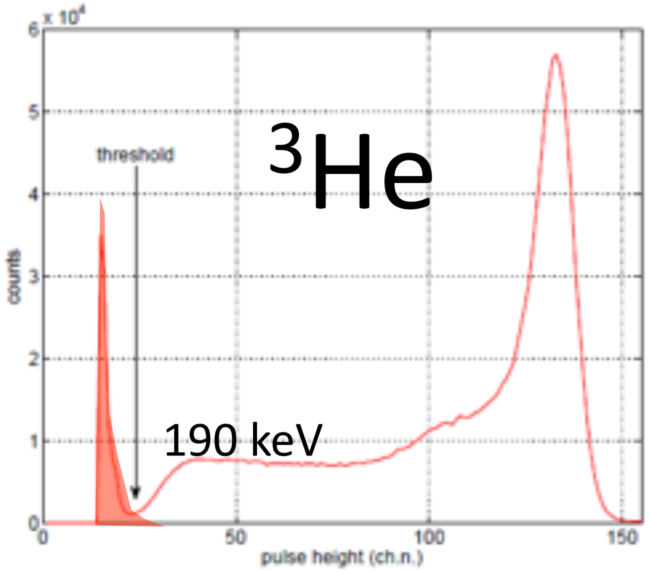
- Arrow indicate effect of dead regions into account with He-3 tubes
- Alternate technologies starting to approach raw efficiency numbers
- There is a need to compare like-with-like for the detailed instrument operating conditions
- Gamma rejection is a similar issue

Standards definition key part of ensuring best cost/quality detectors

compare like-with-like

Especially necessary with commercial suppliers, to define what we want measured

Background - Gamma Sensitivity



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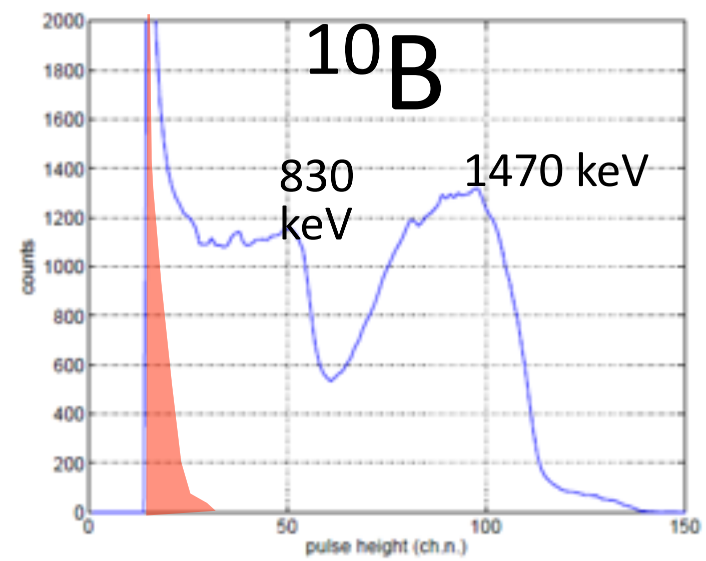

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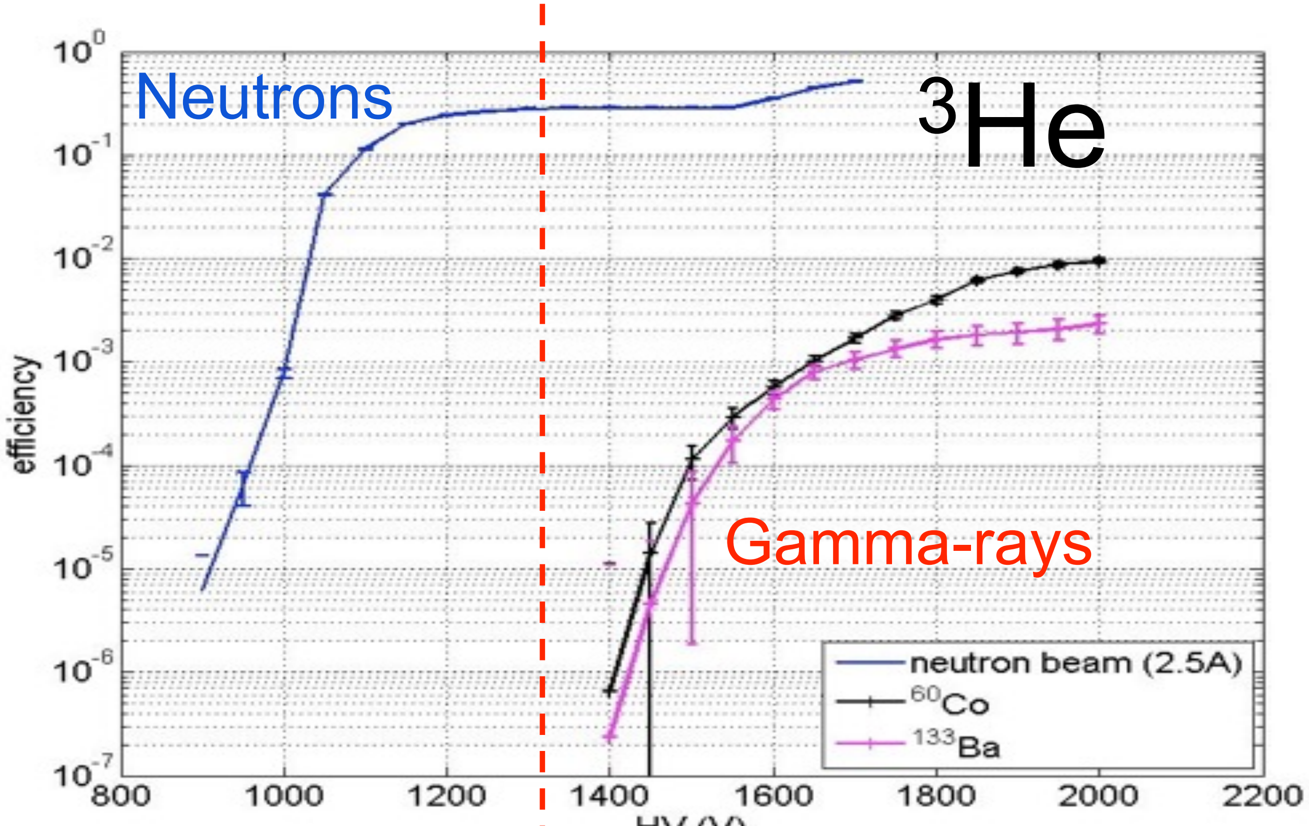
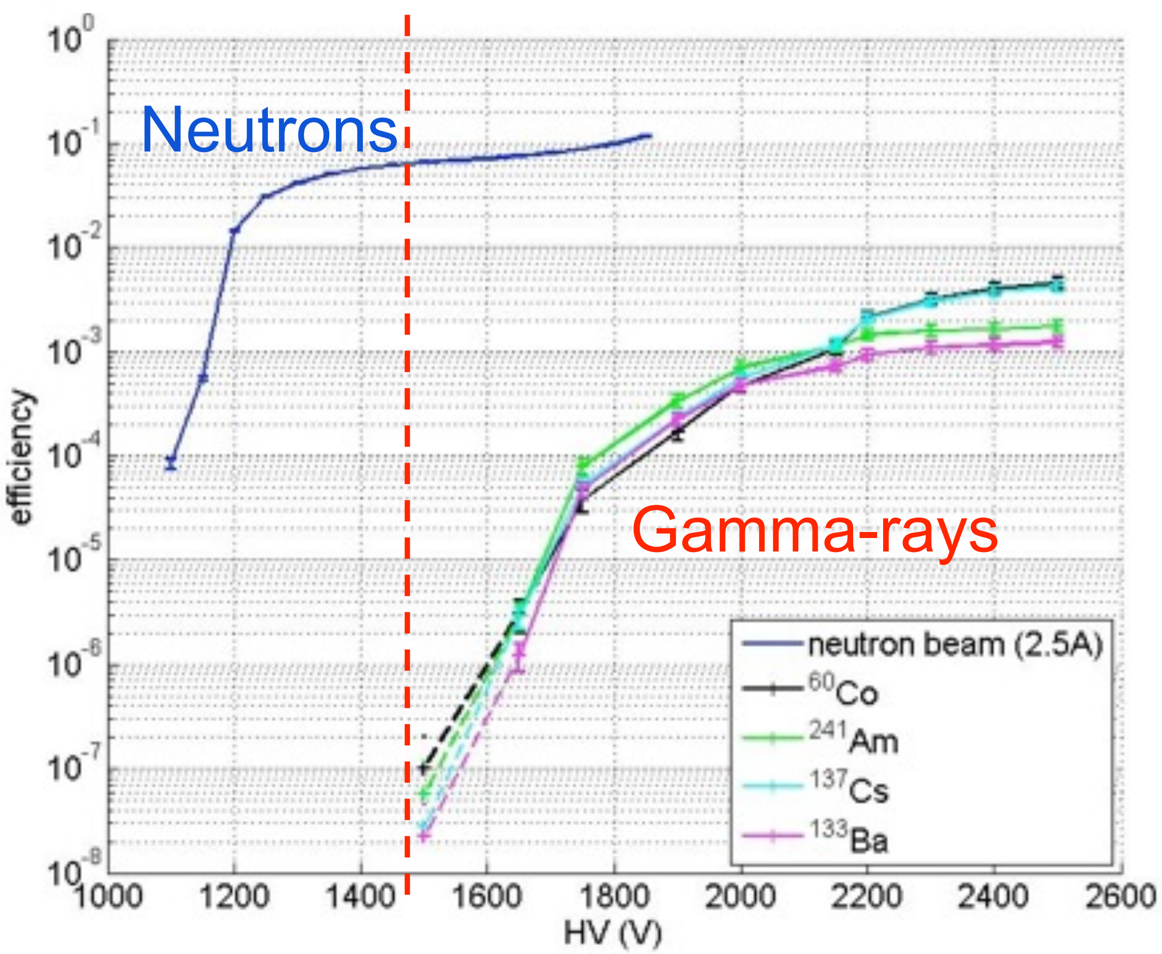




JINST 8 (2013) 10025

Quality and Standards: Gamma Sensitivity

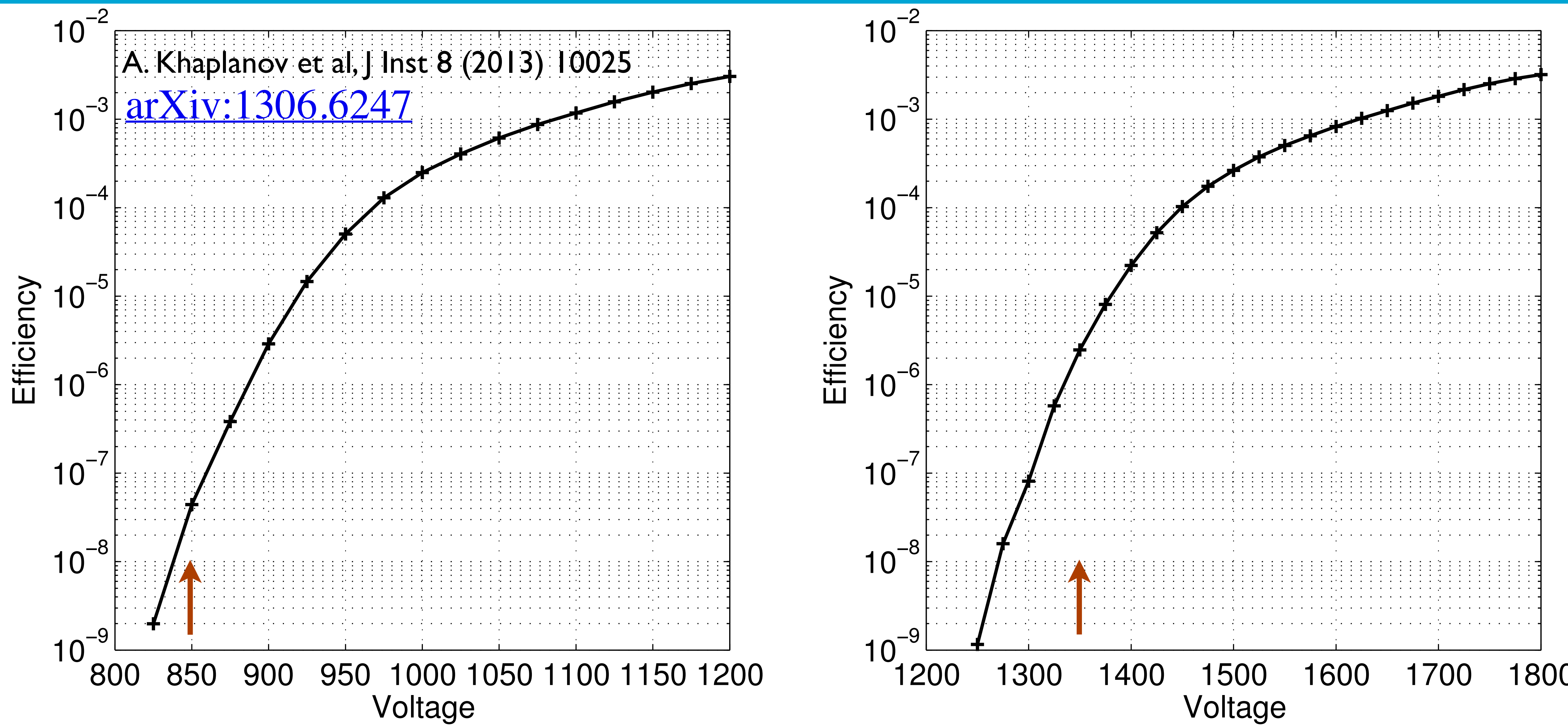
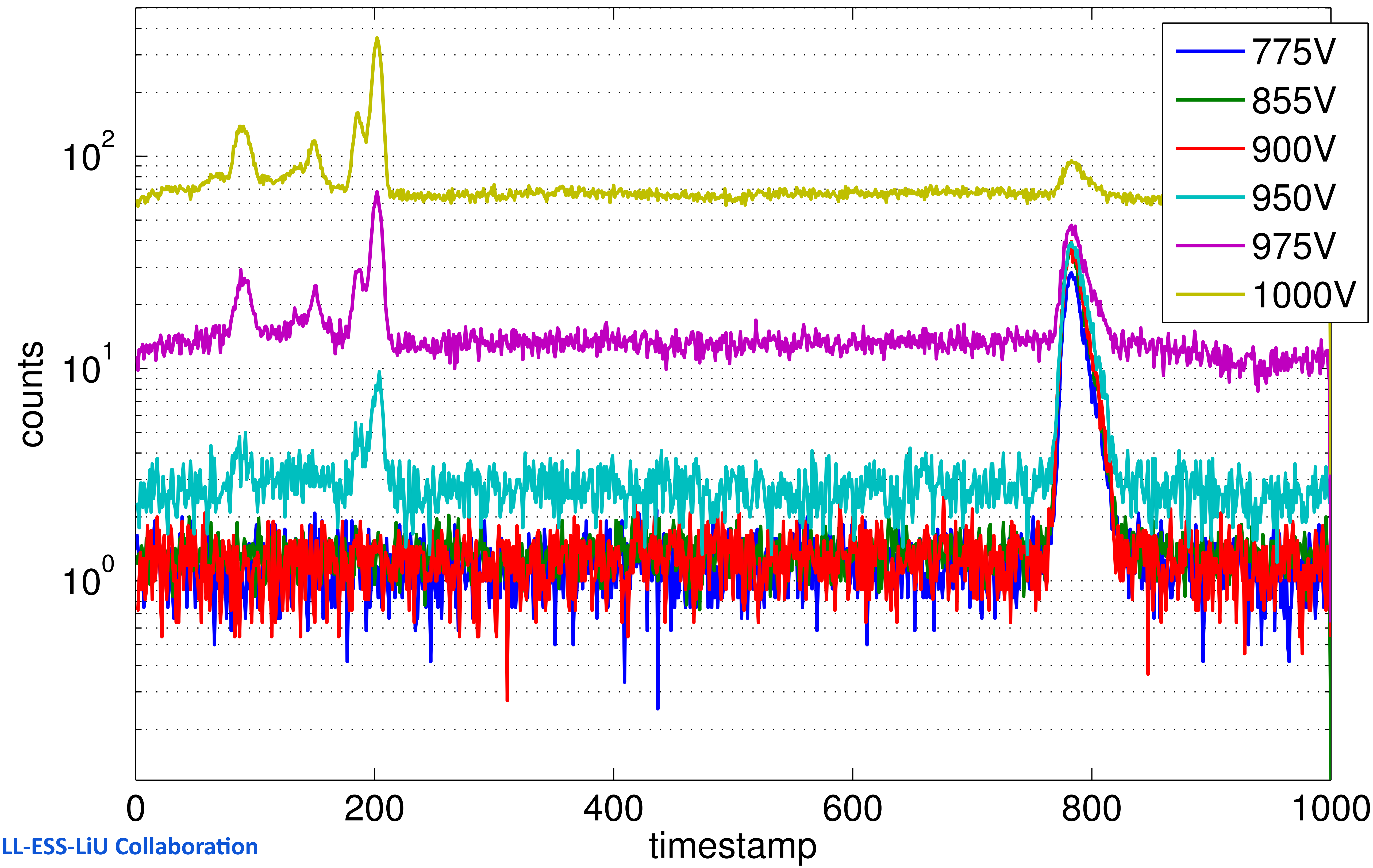


Figure 8: Plateau measurement with the Multi-Grid ^{10}B detector (left) and a Multi-Tube ^{3}He detector (right) with a strong ^{137}Cs source.

Quote gamma sensitivity at same working point as detection efficiency

Working on standards definition for other backgrounds and beam monitors

Turning a neutron detector into a gamma detector



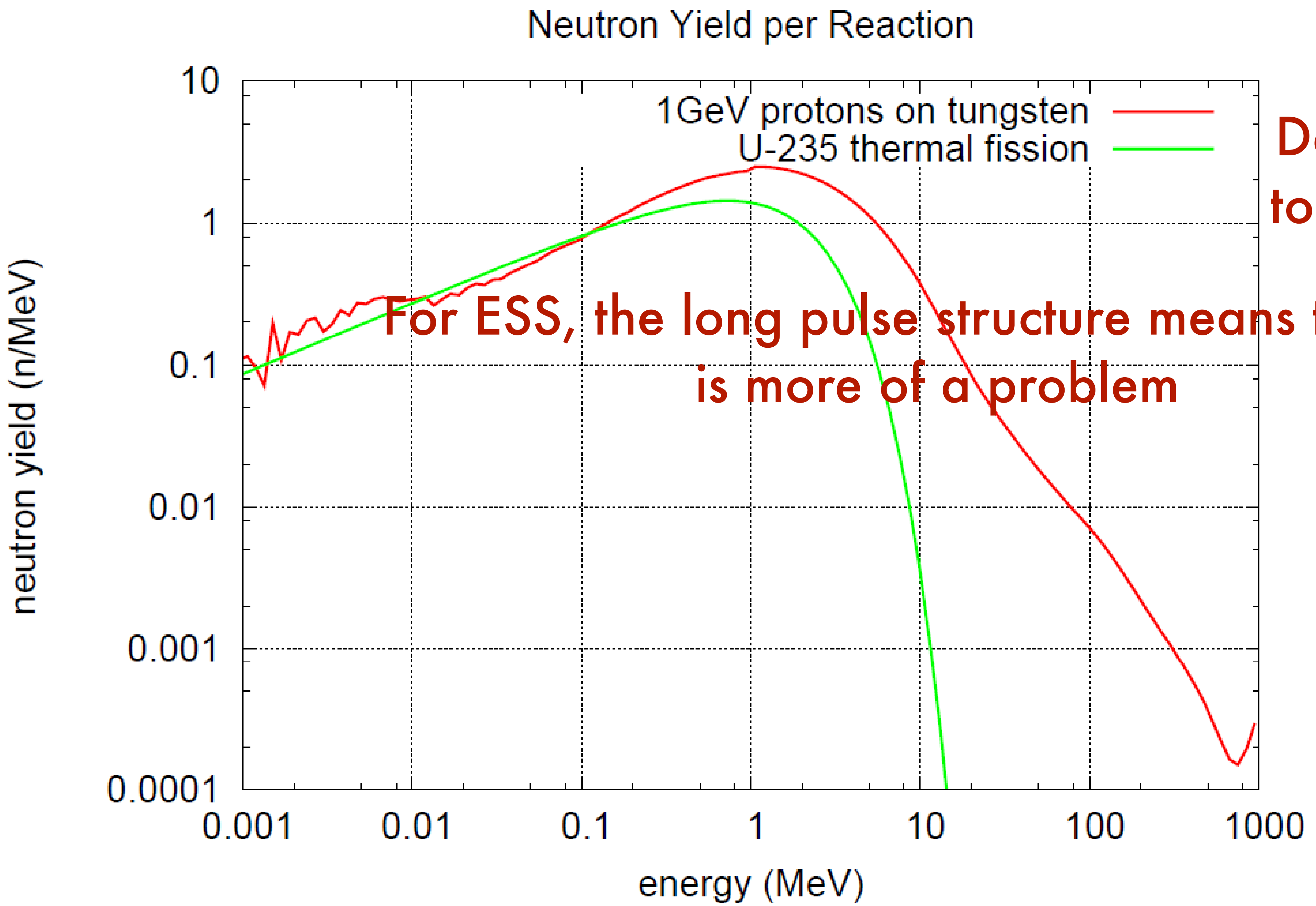
ILL-ESS-LiU Collaboration

fast neutrons are a menace for spallation sources

Why are we here today?

Fission and Spallation Neutron Spectra

For ESS, good control of backgrounds is going to be an indicator of success



Detector insensitive to backgrounds are a good start

For ESS, the long pulse structure means that this is more of a problem

(thanks to Ken Herwig)

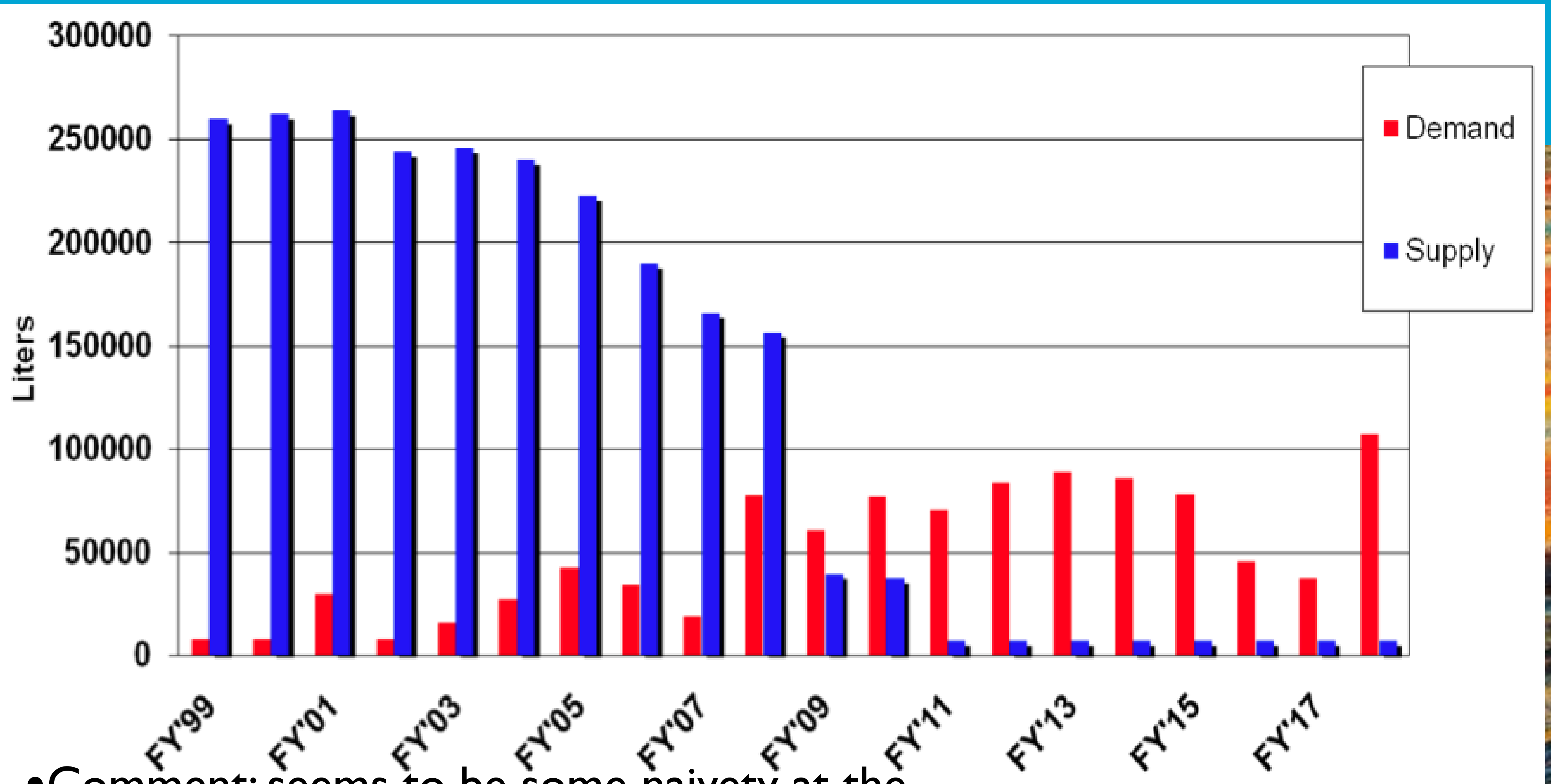
Courtesy – Franz Gallmeier

Detectors for the European Spallation Source

- Context
- Instruments at the European Spallation Source
- Requirements for the Instruments
- Detector design and developments to fulfill those requirements ESS requirements

The ESS Site

Helium-3 Crisis

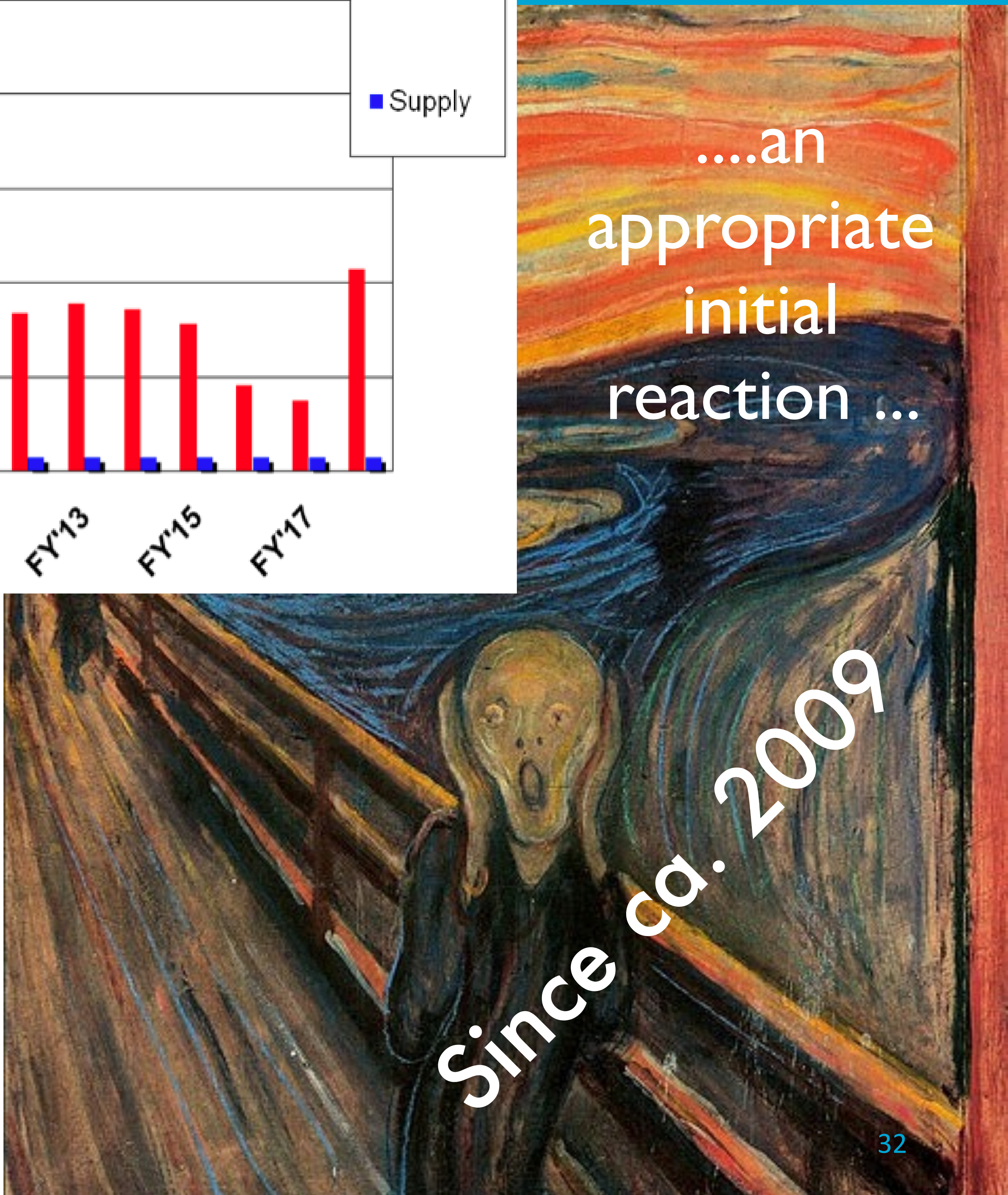


- Comment: seems to be some naivety at the moment as stocks are being emptied rapidly

Aside … maybe He-3 detectors are anyway not what is needed for ESS? eg rate, resolution reaching the limit …

Crisis or opportunity … ?

For almost all instrument classes, detectors are a limitation on performance



….an appropriate initial reaction …

Since ca. 2009

Schedule …

- 5 years until first neutrons …

Instruments and their Requirements

Science Drivers for the Reference Instrument Suite from the Technical Design Report

EUROPEAN SPALLATION SOURCE

Instrument	Science drivers
Multi-Purpose Imaging	life sciences, soft condensed matter, magnetism & superconductivity, engineering & geo-sciences, archeology & heritage conservation
General-Purpose SANS	magnetism & superconductivity, soft condensed matter, chemistry of materials, energy research
Broadband SANS	soft condensed matter, life sciences
Surface Scattering	soft condensed matter, life sciences, chemistry of materials, magnetism & superconductivity
Horizontal Reflectometer	soft condensed matter, life sciences, chemistry of materials
Vertical Reflectometer	magnetism & superconductivity, chemistry of materials, energy research, soft condensed matter
Thermal Powder Diffractometer	chemistry of materials, energy research, engineering & geo-sciences, magnetism & superconductivity
Bispectral Power Diffractometer	magnetism & superconductivity, chemistry of materials, energy research, engineering & geo-sciences
Pulsed Monochromatic Powder Diffractometer	chemistry of materials, energy research, magnetism & superconductivity
Materials Science Diffractometer	engineering & geo-sciences, chemistry of materials
Extreme Conditions Instrument	energy research, magnetism & superconductivity, chemistry of materials
Single-Crystal Magnetism Diffractometer	magnetism & superconductivity, chemistry of materials
Macromolecular Diffractometer	life sciences, magnetism & superconductivity
Cold Chopper Spectrometer	life sciences, chemistry of materials, magnetism & superconductivity
Bispectral Chopper Spectrometer	life sciences, soft condensed matter, chemistry of materials, magnetism & superconductivity
Thermal Chopper Spectrometer	chemistry of materials, energy research, magnetism & superconductivity
Cold Crystal-Analyser Spectrometer	chemistry of materials, energy research, magnetism & superconductivity, engineering & geo-sciences
Vibrational Spectroscopy	chemistry of materials, energy research, magnetism & superconductivity
Backscattering Spectrometer	life sciences, soft condensed matter, chemistry of materials
High-Resolution Spin-Echo	life sciences, soft condensed matter, chemistry of materials, energy research
Wide-Angle Spin-Echo	energy research, magnetism & superconductivity, life sciences, soft condensed matter
Fundamental & Particle Physics	fundamental & particle physics

- life sciences
- soft condensed matter
- chemistry of materials
- energy research
- magnetism & superconductivity
- engineering & geo-sciences
- archeology & heritage conservation
- fundamental & particle physics

What can be done with this brightness

Instrument Design	Implications for Detectors
Smaller samples	Better Resolution (position and time) Channel count
Higher flux, shorter experiments	Rate capability and data volume
More detailed studies	Lower background, lower S:B Larger dynamic range
Multiple methods on 1 instrument Larger solid angle coverage	Larger area coverage Lower cost of detectors

Also: scarcity of Helium-3 …

Developments required for detectors for new Instruments

Collaborations

Everyone should play to their strengths

Mittuniversitetet
MID SWEDEN UNIVERSITY

ESS Partners on Detectors

EUROPEAN SPALLATION SOURCE

CERN

SNS
SPALLATION NEUTRON SOURCE

LINKÖPING UNIVERSITY

ESS bilbao

LUNDS UNIVERSITET

UNIVERSITAS BERGENSIS

Science & Technology Facilities Council

Science & Technology Facilities Council
ISIS

BNC
Budapest Neutron Centre

wigner

Consiglio Nazionale Ricerche

IFP

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

INFN
Istituto Nazionale di Fisica Nucleare

JCNS
Jülich Centre for Neutron Science

DENEX
Detektoren für Neutronen GmbH
Stöteroggestraße 71 | 21339 Lüneburg
Tel.: +49 (0) 4131/248932

I E A P

CDT GmbH
CASCADE Detector Technologies

FZU

Helmholtz-Zentrum Geesthacht
Zentrum für Material- und Küstenforschung

UNIVERSITY OF MALTA
L-Università ta' Malta

Risø DTU
National Laboratory for Sustainable Energy

ideas

COSYLAB

IFE
Institute for Energy Technology

JÜLICH
FORSCHUNGSZENTRUM

Mittuniversitetet
MID SWEDEN UNIVERSITY

icnd.org {

FRM II
Forschungs-Neutronenquelle
Heinz Maier-Leibnitz

HZB Helmholtz Zentrum Berlin

ISIS

J-PARC

NEUTRON SCIENCES

}

INTERNATIONAL COLLABORATION FOR THE DEVELOPMENT OF NEUTRON DETECTORS

Scope: Detector Requirements for Instruments

Instrument	Detector Area [m^2]	Wavelength Range [Å]	Time Resolution [μs]	Resolution [mm]
Multi-Purpose Imaging	0.5	1-20	1	0.001 - 0.5
General Purpose Polarised SANS	5	4-20	100	10
Broad-Band Small Sample SANS	14	2-20	100	1
Surface Scattering	5	4-20	100	10
Horizontal Reflectometer	0.5	5-30	100	1
Vertical Reflectometer	0.5	5-30	100	1
Thermal Powder Diffractometer	20	0.6-6	<10	2x2
Bi-Spectral Powder Diffractometer	20	0.8-10	<10	2.5x2.5
Pulsed Monochromatic Powder Diffractometer	4	0.6-5	<100	2 x 5
Material Science & Engineering Diffractometer	10	0.5-5	10	2
Extreme Conditions Instrument	10	1-10	<10	3x5
Single Crystal Magnetism Diffractometer	6	0.8-10	100	2.5x2.5
Macromolecular Diffractometer	1	1.5-3.3	1000	0.2
Cold Chopper Spectrometer	80	1 -20	10	10
Bi-Spectral Chopper Spectrometer	50	0.8-20	10	10
Thermal Chopper Spectrometer	50	0.6-4	10	10
Cold Crystal-Analyser Spectrometer	1	2-8	<10	5-10
Vibrational Spectroscopy	1	0.4-5	<10	10
Backscattering Spectrometer	0.3	2-8	<10	10
High-Resolution Spin Echo	0.3	4-25	100	10
Wide-Angle Spin Echo	3	2-15	100	10
Fundamental & Particle Physics	0.5	5-30	1	0.1
Total	**282.6**			

Estimates from TDR

Table 2.5: Estimated detector requirements for the 22 reference instruments in terms of detector area, typical wavelength range of measurements and desired spatial and time resolution.

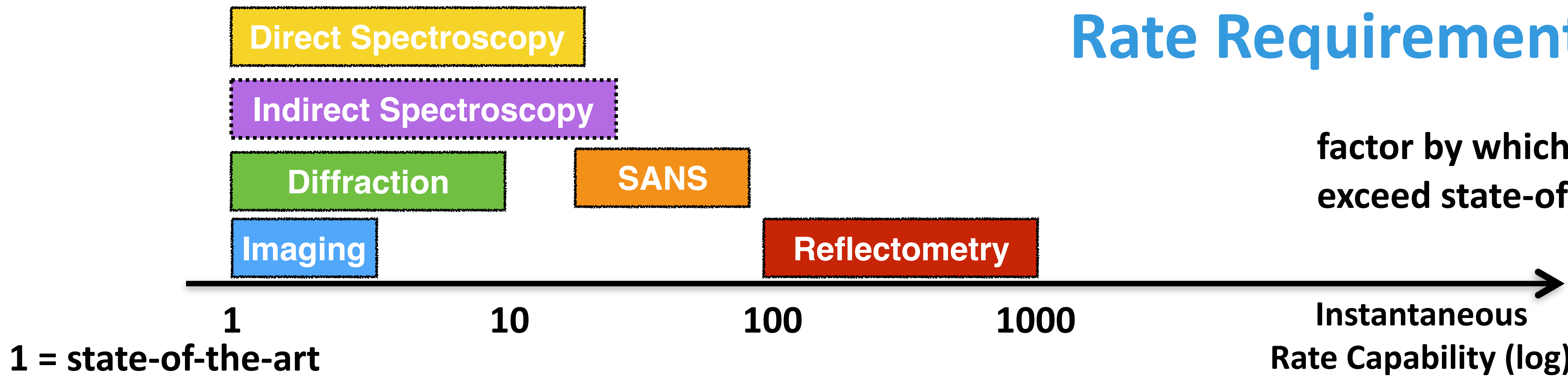
- Specifications very varied
- Typically superior to what is presently state-of-the-art at existing sources
- In many cases, instrument performance dominated by S:B rather than raw specifications here

COST!

RATE!

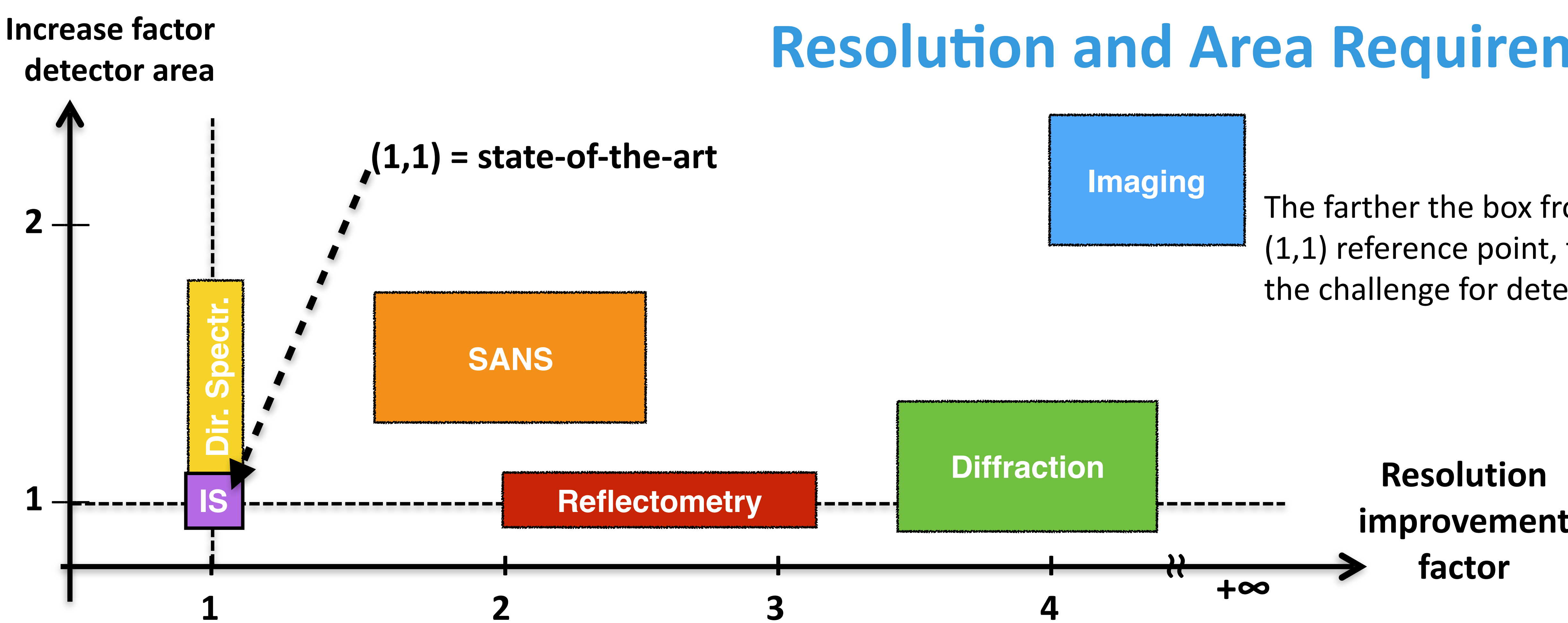
Requirements Challenge for Detectors for ESS: *beyond detector present state-of-the art*

Rate Requirements



factor by which requirements exceed state-of-the-art

Resolution and Area Requirements

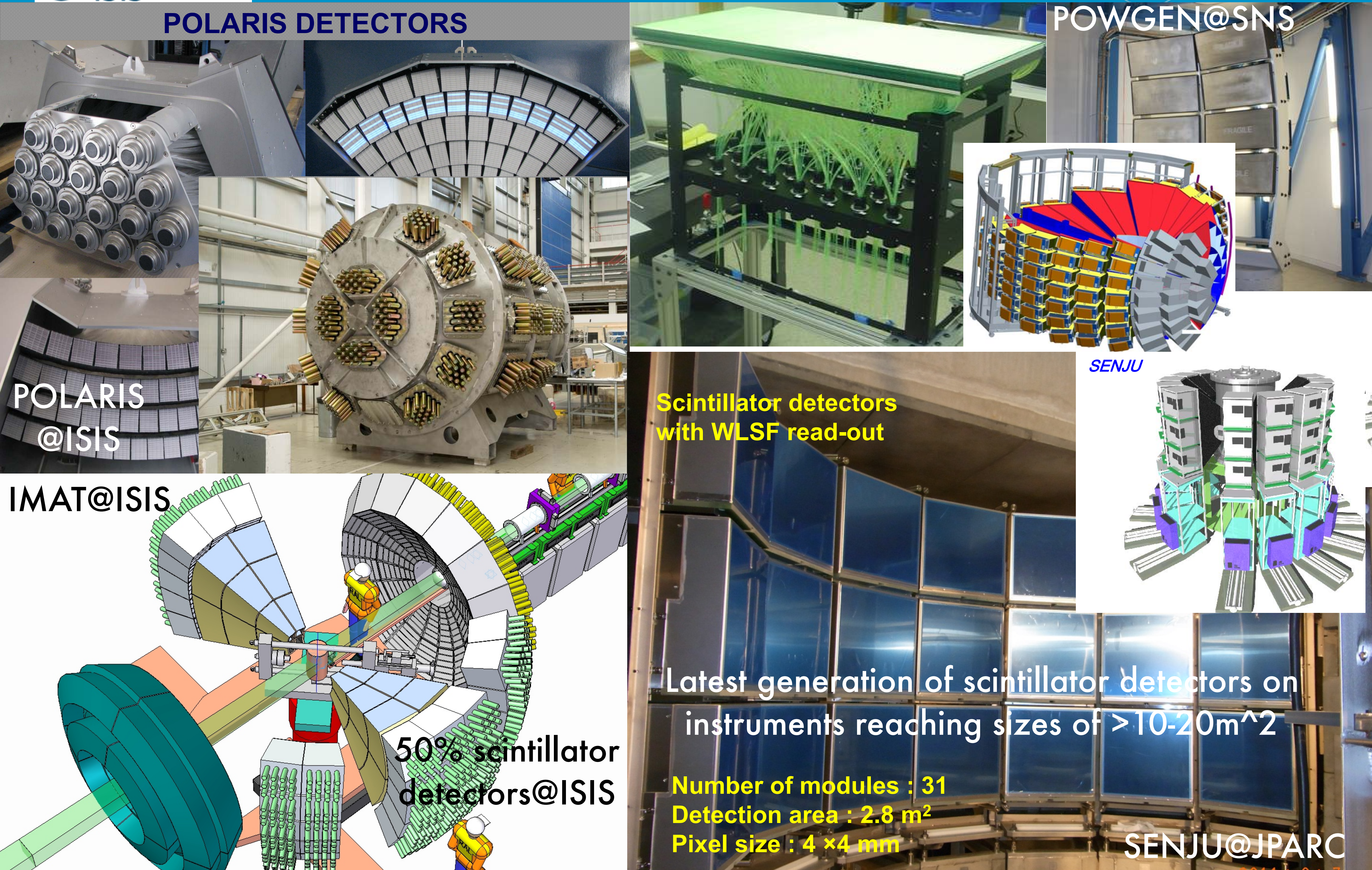


The farther the box from the (1,1) reference point, the bigger the challenge for detectors.

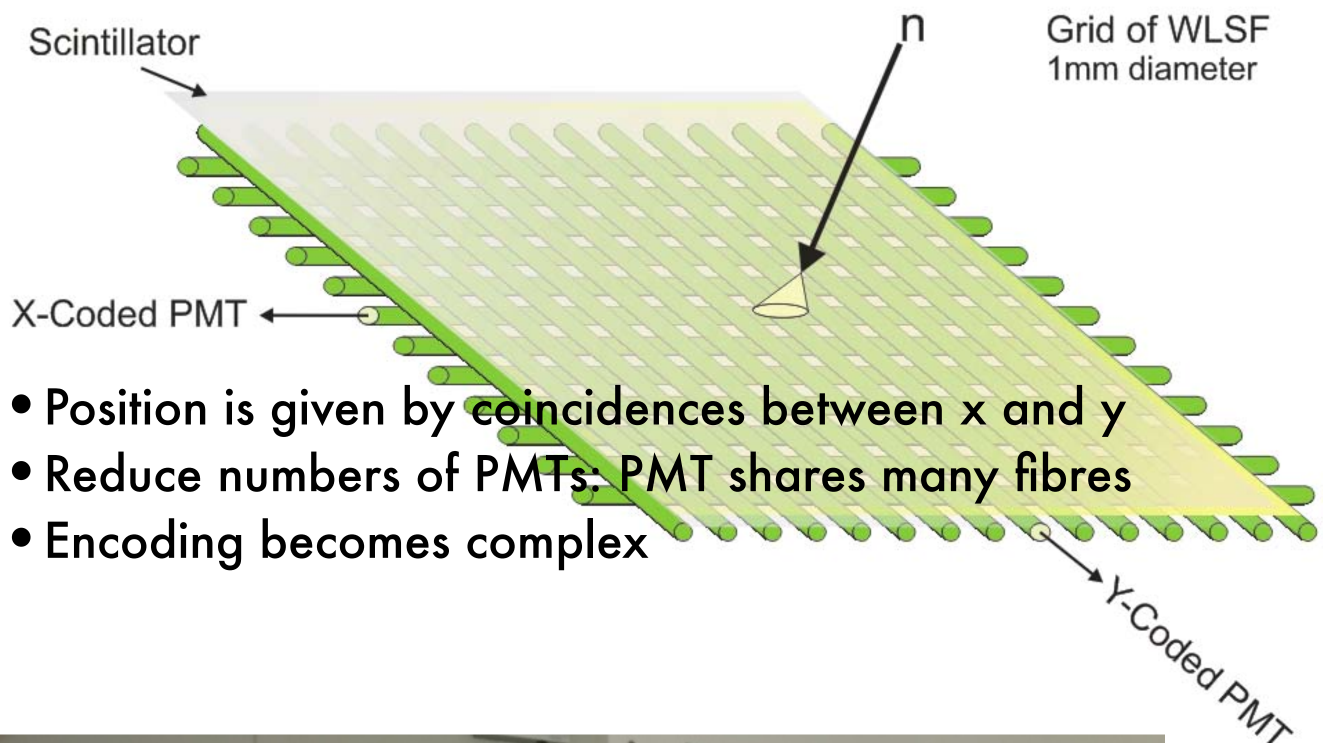
Detectors for ESS: strategy update for 16 instruments

Instrument class	Instrument sub-class	Instrument	Key requirements for detectors	Preferred detector technology	Ongoing developments (funding source)
Large-scale structures	Small Angle Scattering	SKADI	Pixel size, count-rate	Scintillators	SonDe (EU SonDe)
		LOKI		10B-based	BandGem
	Reflectometry	FREIA	Pixel size, count-rate	10B-based	MultiBlade (EU BrightnESS)
		ESTIA			
Diffraction	Powder diffraction	DREAM	Pixel size, count-rate	10B-based	Jalousie
		HEIMDAL		Scintillators/10B-based	
	Single-crystal diffraction	MAGIC	Pixel size, count-rate	10B-based	Jalousie
		NMX	Pixel size, large area	Gd-based	GdGEM uTPC(EU BrightnESS)
Engineering	Strain scanning	BEER	Pixel size, count-rate	10B-based	AmCLD, A1CLD
	Imaging and tomography	ODIN	Pixel size	Scintillators, MCP, wire chambers	
Spectroscopy	Direct geometry	C-SPEC	Large area (^{3}He-gas unaffordable)	10B-based	MultiGrid (EU BrightnESS)
		T-REX			
		VOR			
	Indirect geometry	BIFROST	Count-rate	3He-based	
		MIRACLES			
		VESPA	Count-rate	3He-based	
SPIN-ECHO	Spin-echo	tbd	tbd	3He-based/10B-based	

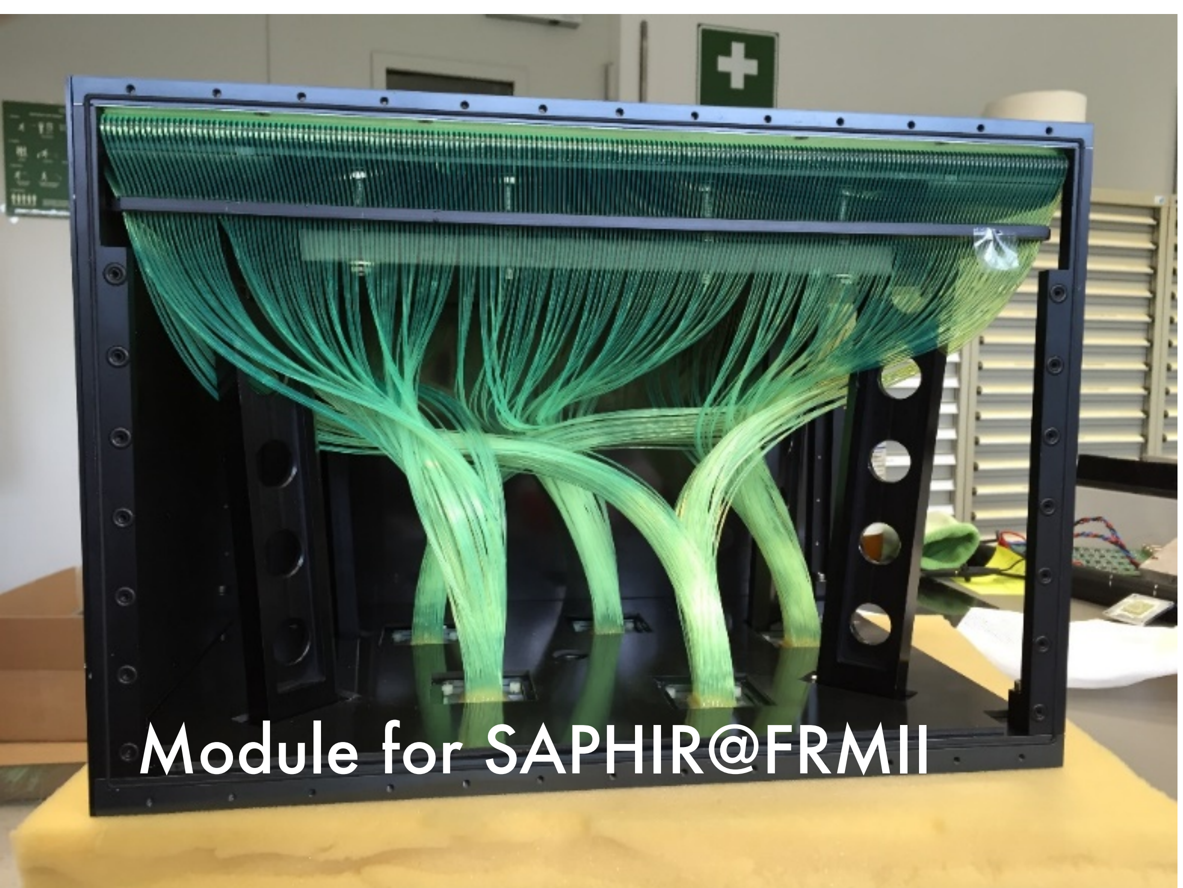
Scintillator Neutron Detectors

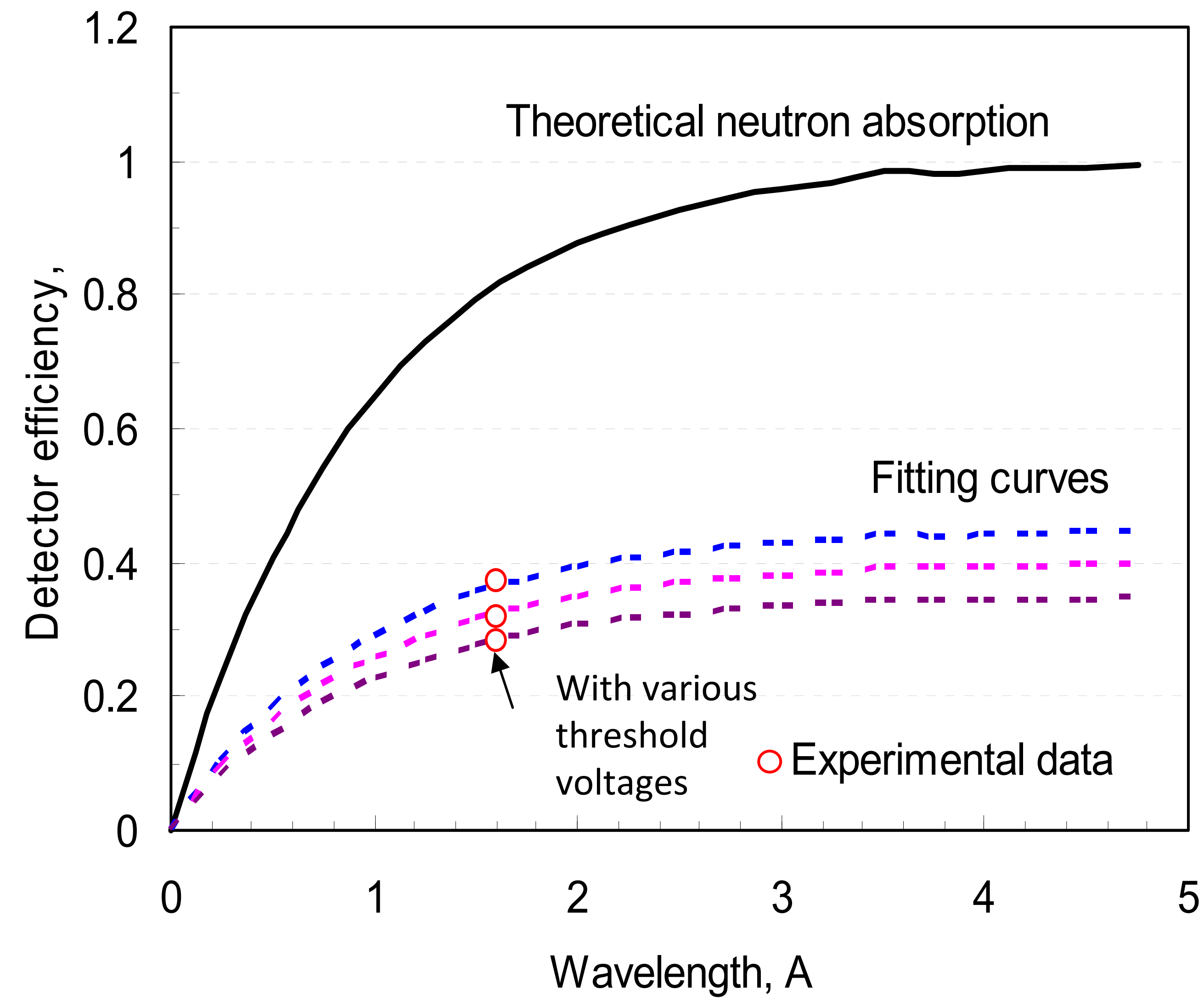


Neutron Scintillator Detectors



- Position is given by coincidences between x and y
- Reduce numbers of PMTs: PMT shares many fibres
- Encoding becomes complex



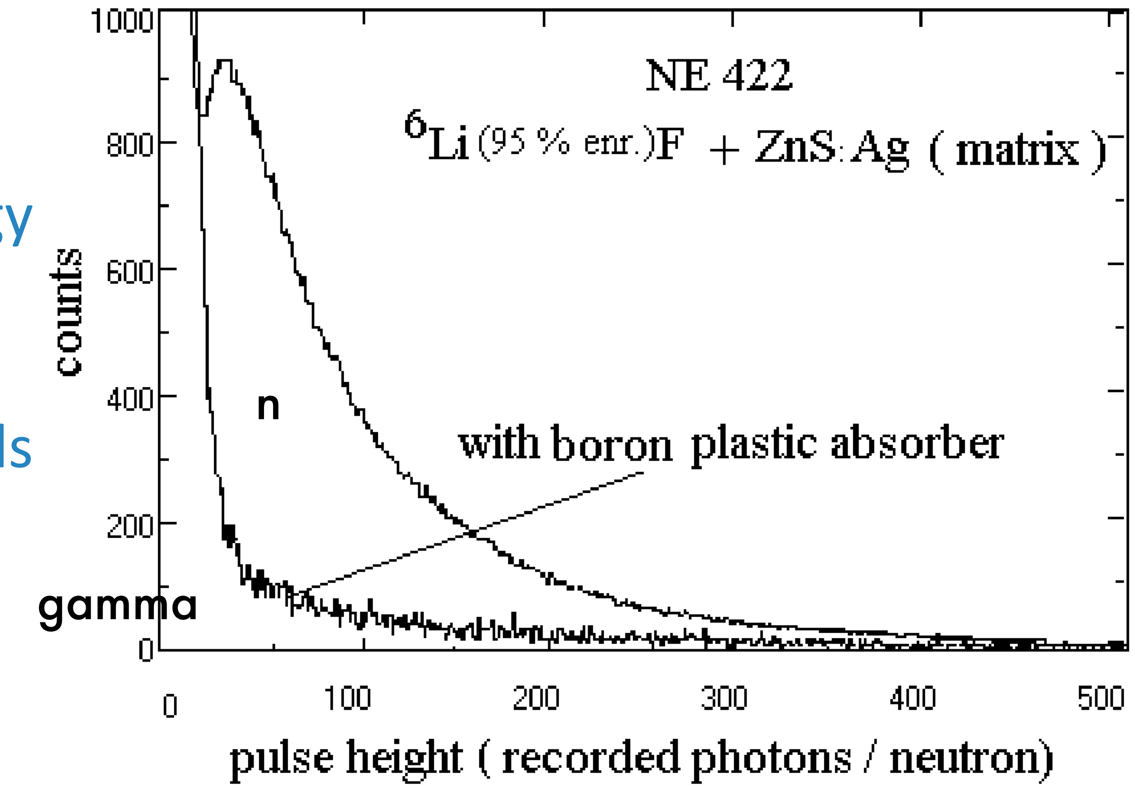


- Scintillator typically used: ^{6}Li embedded in ZnS
- Scintillator detectors tend to be used for more thermal neutrons
- Efficiencies of 30-40% for thermal neutrons
- 2D position resolutions of few mm possible

Neutron Scintillator Detectors

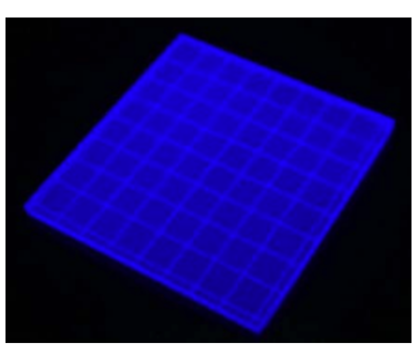
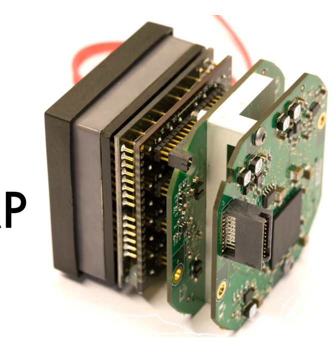
SoNDe

- Now pushing the limits of scintillator detector technology
  - Gamma/n pulse shape discrimination
  - Scintillation decay time (secondary >10us for ZnS)
- Big improvements need novel better scintillator materials or improvement in rate capability



Develop a high-resolution neutron detector technique for enabling the construction of position-sensitive neutron detectors for high flux sources.

- high-flux capability for handling the peak-flux of up-to-date spallation sources (x 20 over current detectors)
- high-resolution of 3 mm by single-pixel technique, below by interpolation
- high detection efficiency of up to 80 %

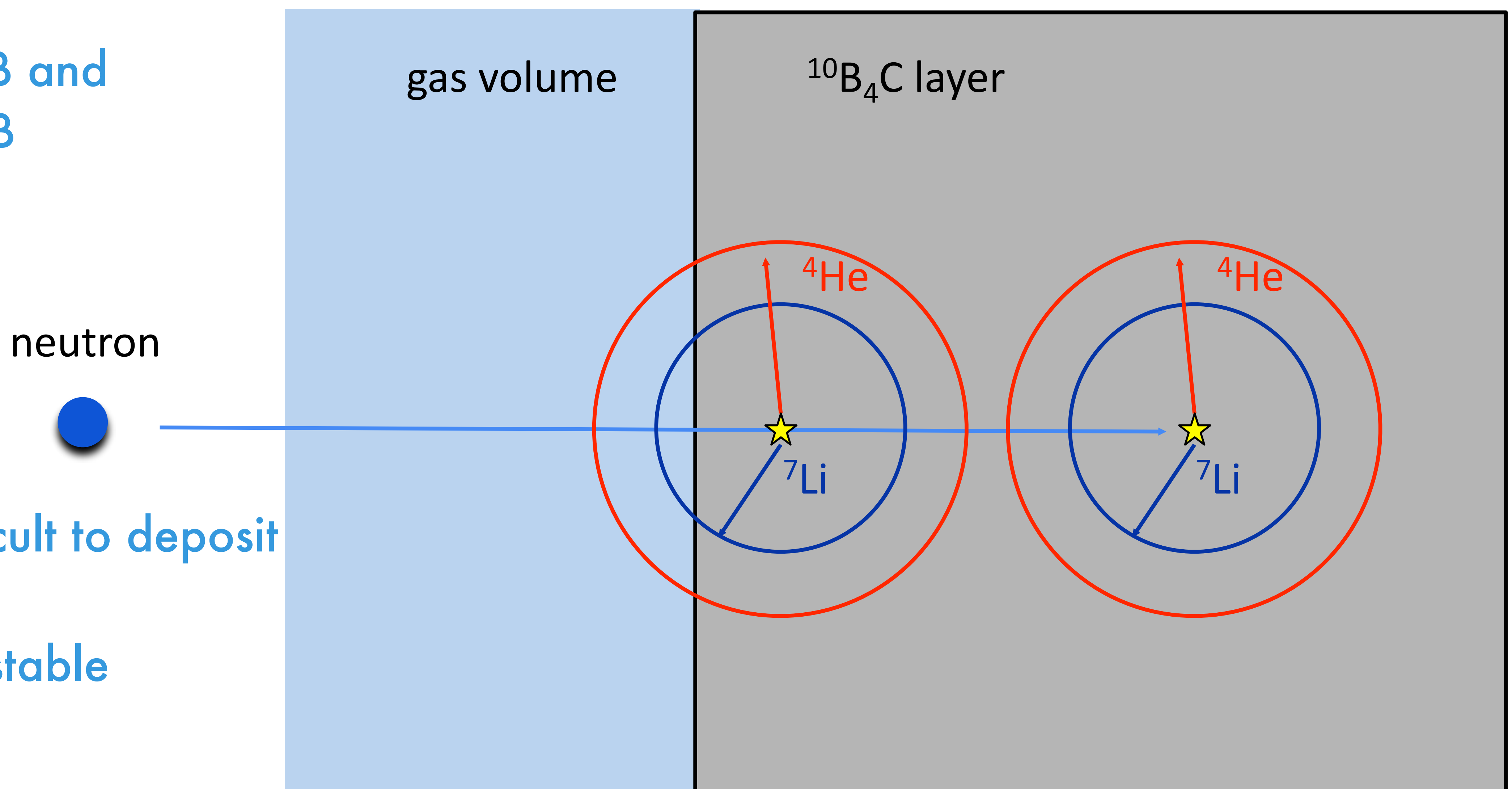
Grooved Li glass  + MA-PMT  + IDEAS ROSMAP 

^{10}Boron-based Thin Film Gaseous Detectors

$$
\begin{aligned}
{}^{10}B + n \rightarrow {}^{7}Li^{*} + {}^{4}He &\rightarrow {}^{7}Li + {}^{4}He + 0.48MeV\,\gamma\text{-ray} + 2.3\ \ MeV \quad (94\%) \\
&\rightarrow {}^{7}Li + {}^{4}He \qquad\qquad\qquad\qquad + 2.79\,MeV \quad (6\%)
\end{aligned}
$$

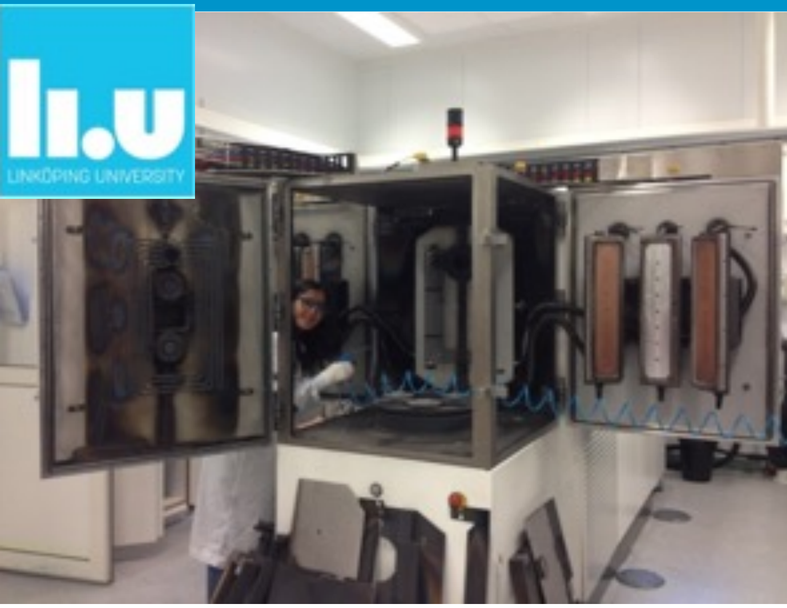
Efficiency limited at ~5% (2.5Å) for a single layer

- ^{nat}B contains
  80 at.% ^{11}B and
  20 at.% ^{10}B



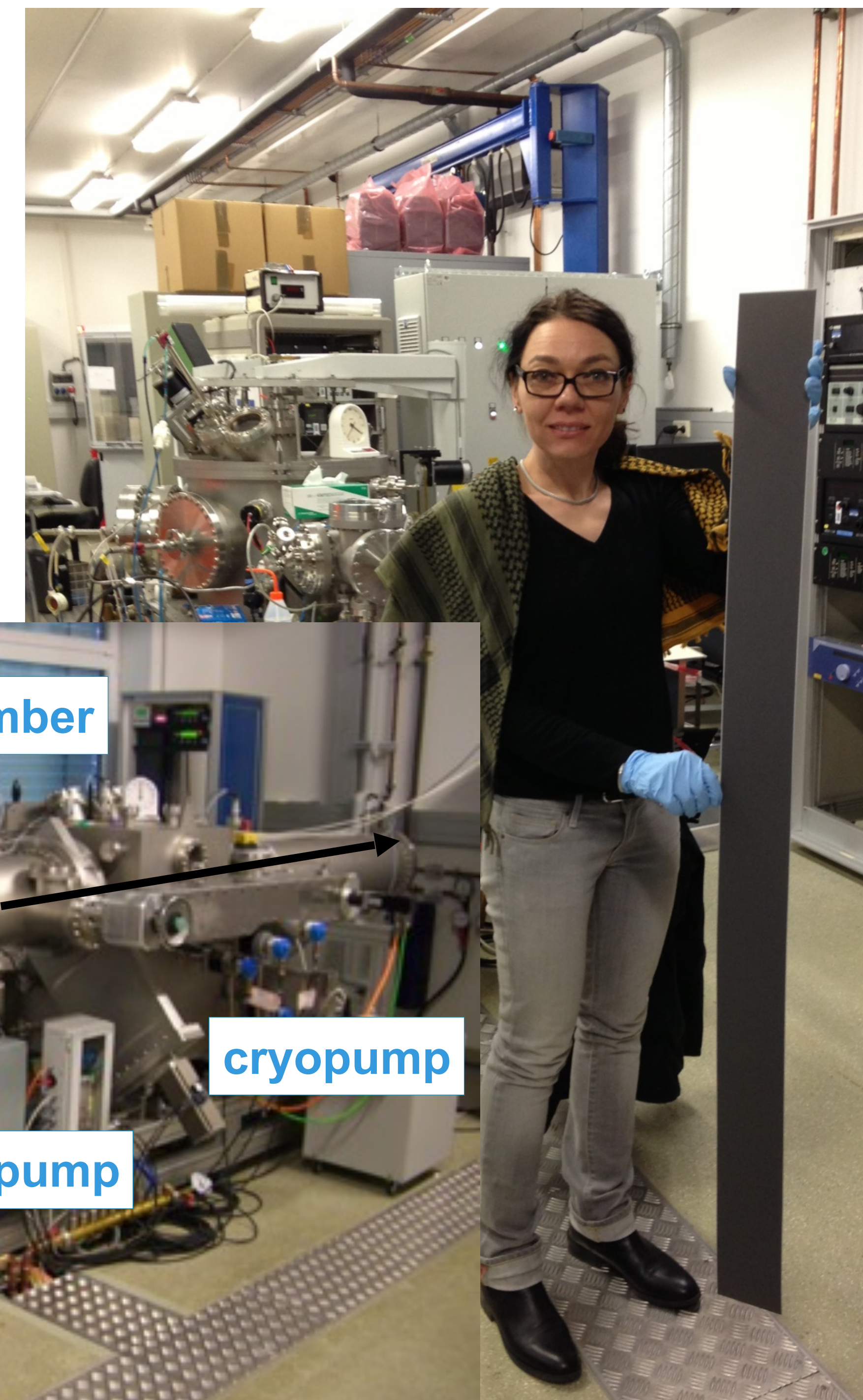
- Boron is difficult to deposit
- Use $^{10}B_4C$
- Conductive, stable

$^{10}B_4C$ Thin Film Coatings

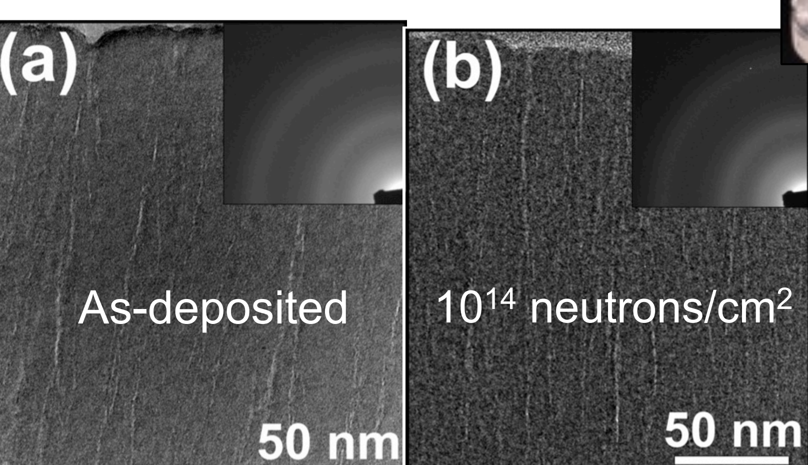


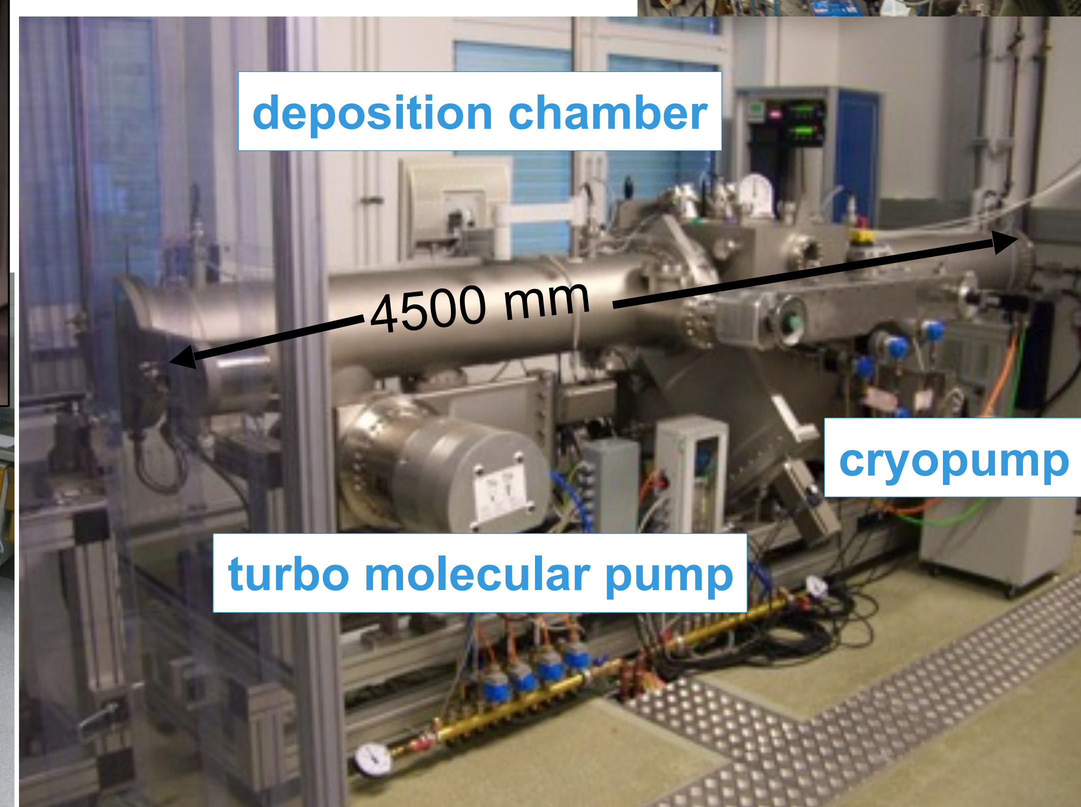
- A number of groups have shown it is possible to deposit large areas of high quality Boron Carbide cheaply
- PVD Magnetron Sputtering
- Deposition parameters highly adaptable
- A very interdisciplinary effort

Helmholtz-Zentrum Geesthacht
Centre for Materials and Coastal Research



- ESS-Linkoping Deposition Facility
- Industrial Coating Machine
- Capacity: >1000m^2/year coated with $^{10}B_4C$





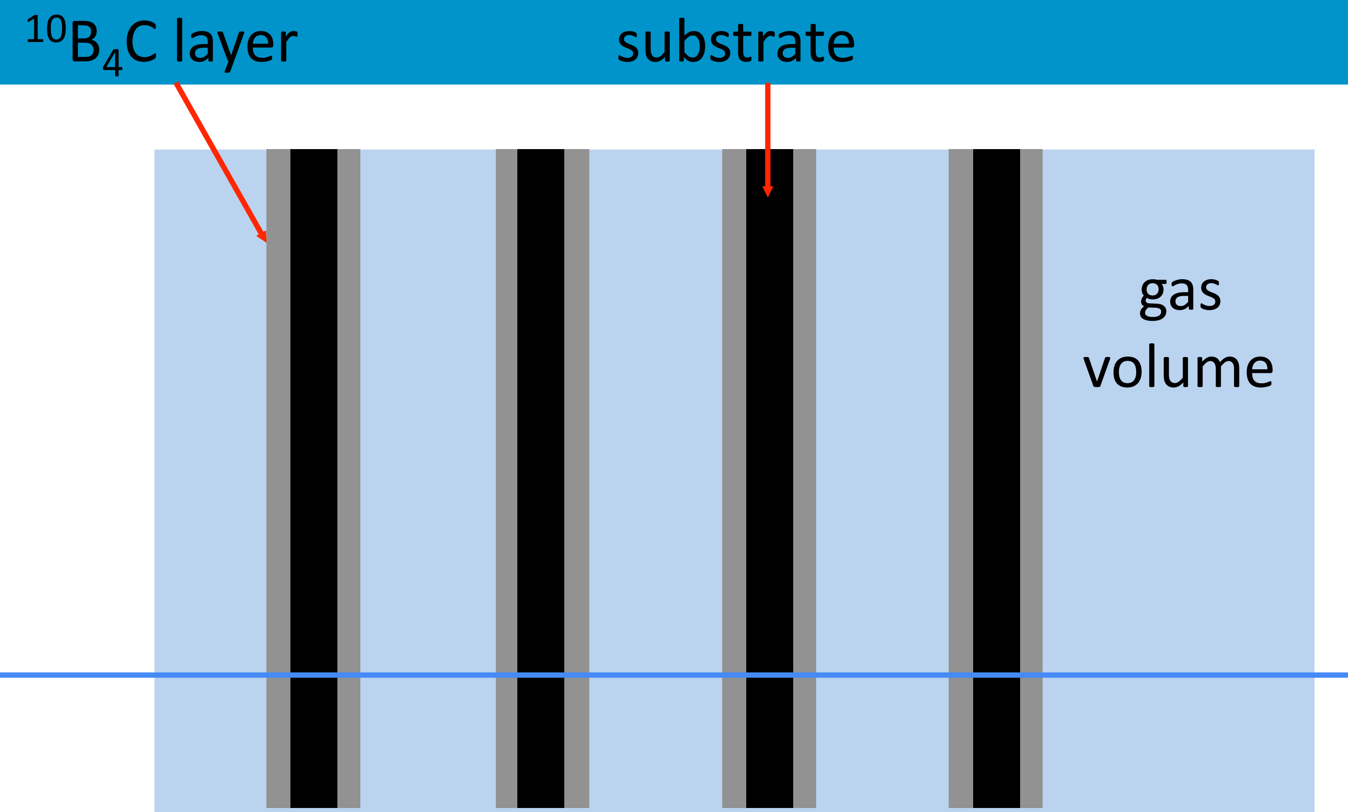
Enhancing the efficiency of ^{10}B-based Neutron Detectors

Mittuniversitetet MID SWEDEN UNIVERSITY

ess EUROPEAN SPALLATION SOURCE

1 Multi layer

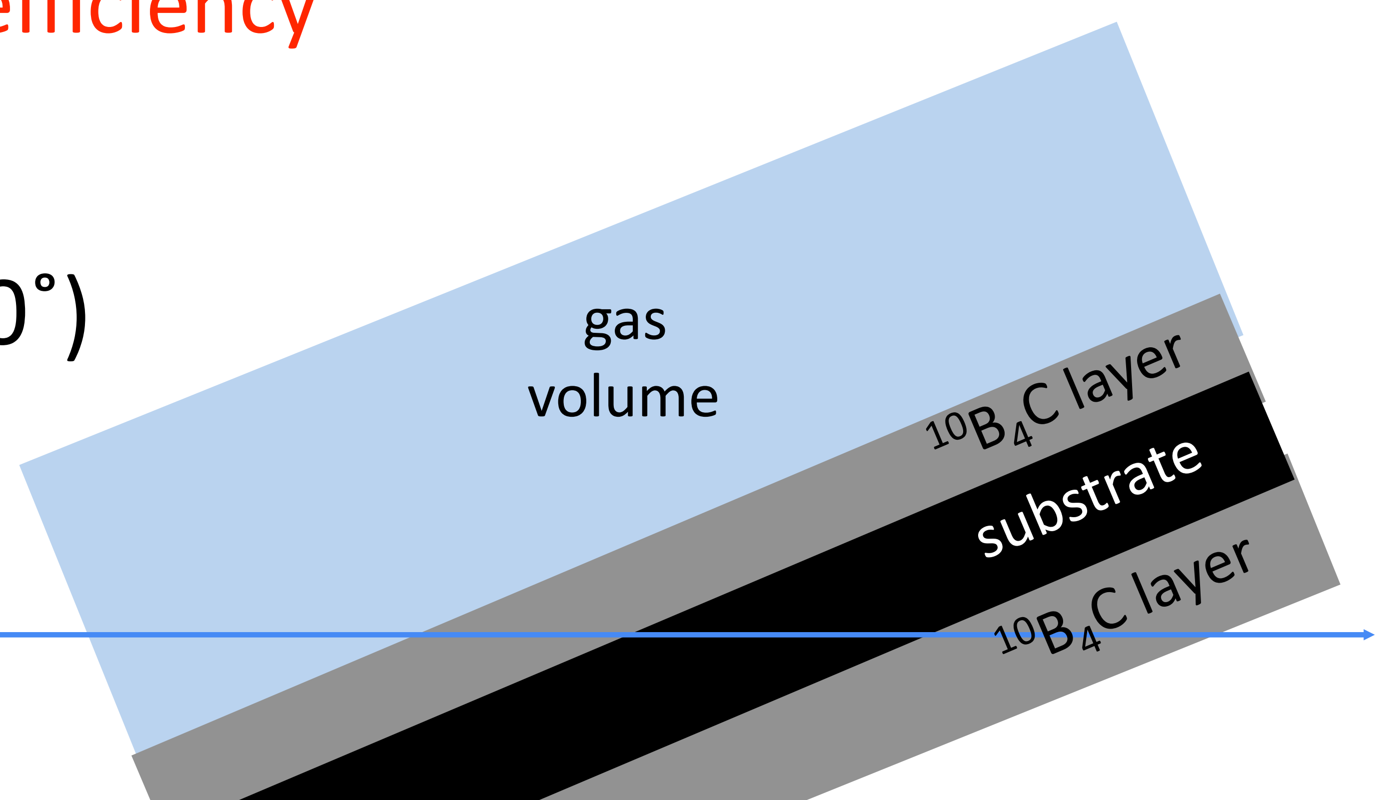
neutron



Generic approaches to improve efficiency

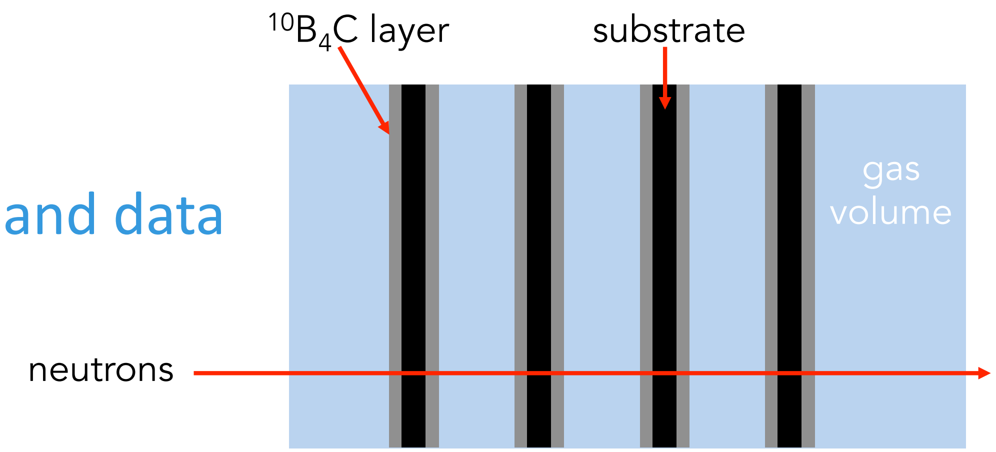
2 Grazing angle (<10˚)

neutron



Efficiency of ^{10}B Detectors: Perpendicular Geometry

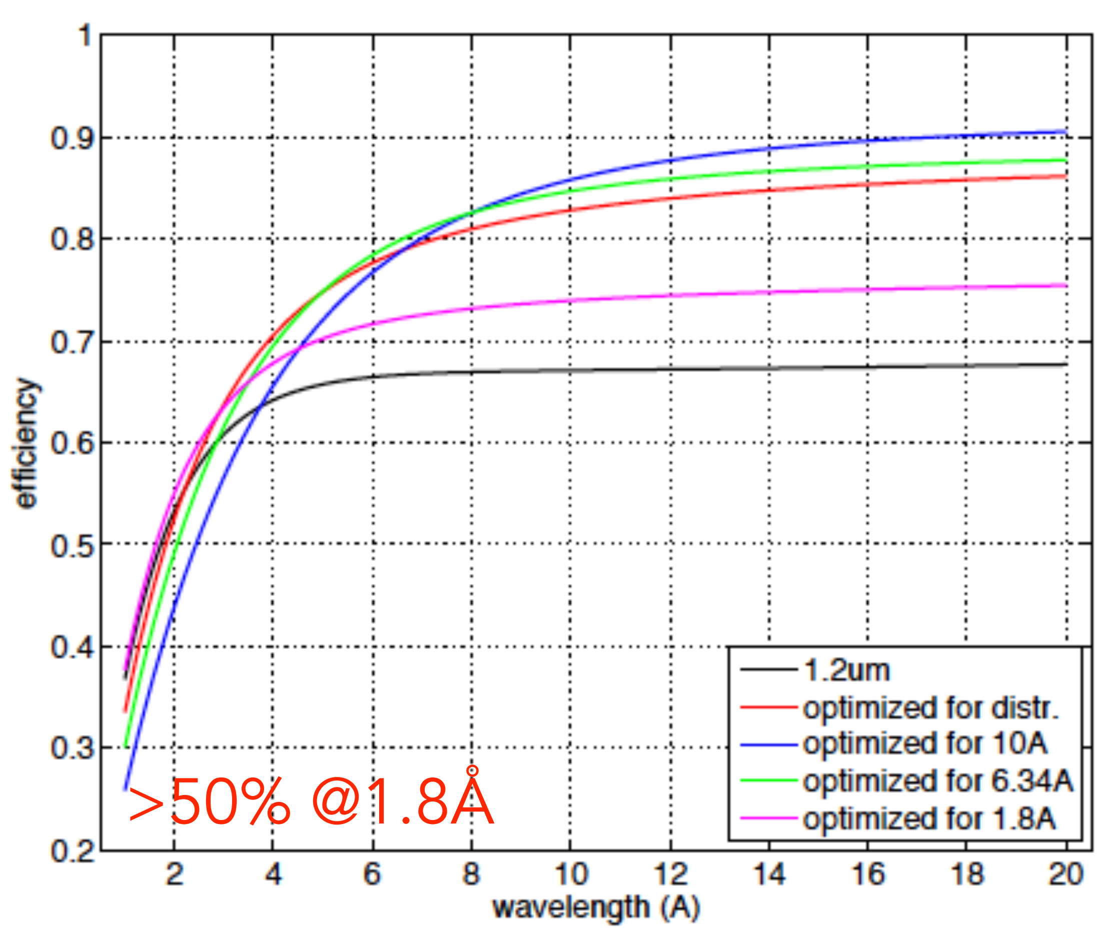
- Single layer is only ca.5%
- Calculations done by many groups
- Analytical calculations extensively verified with prototypes and data
- Details matter: just like for ^{3}He



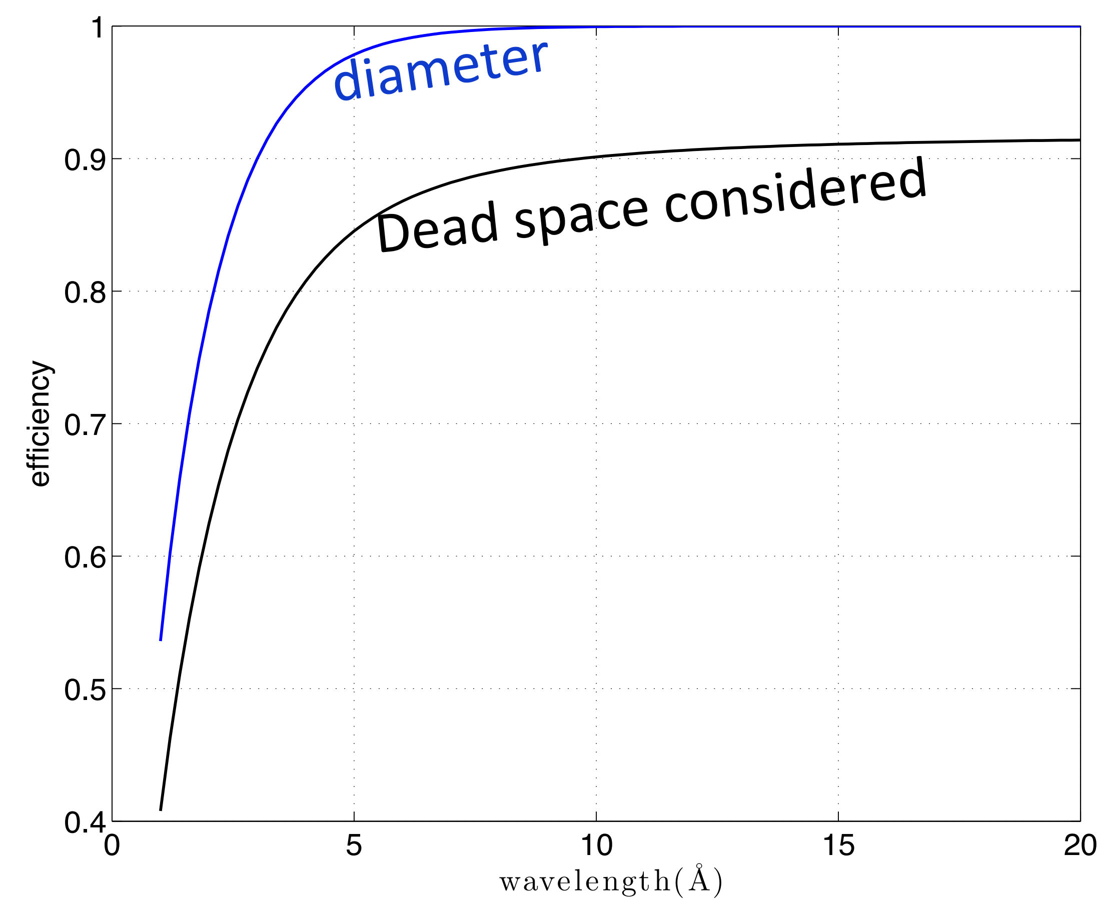
- Multilayer configuration (example):

JINST 8 (2013) P04020

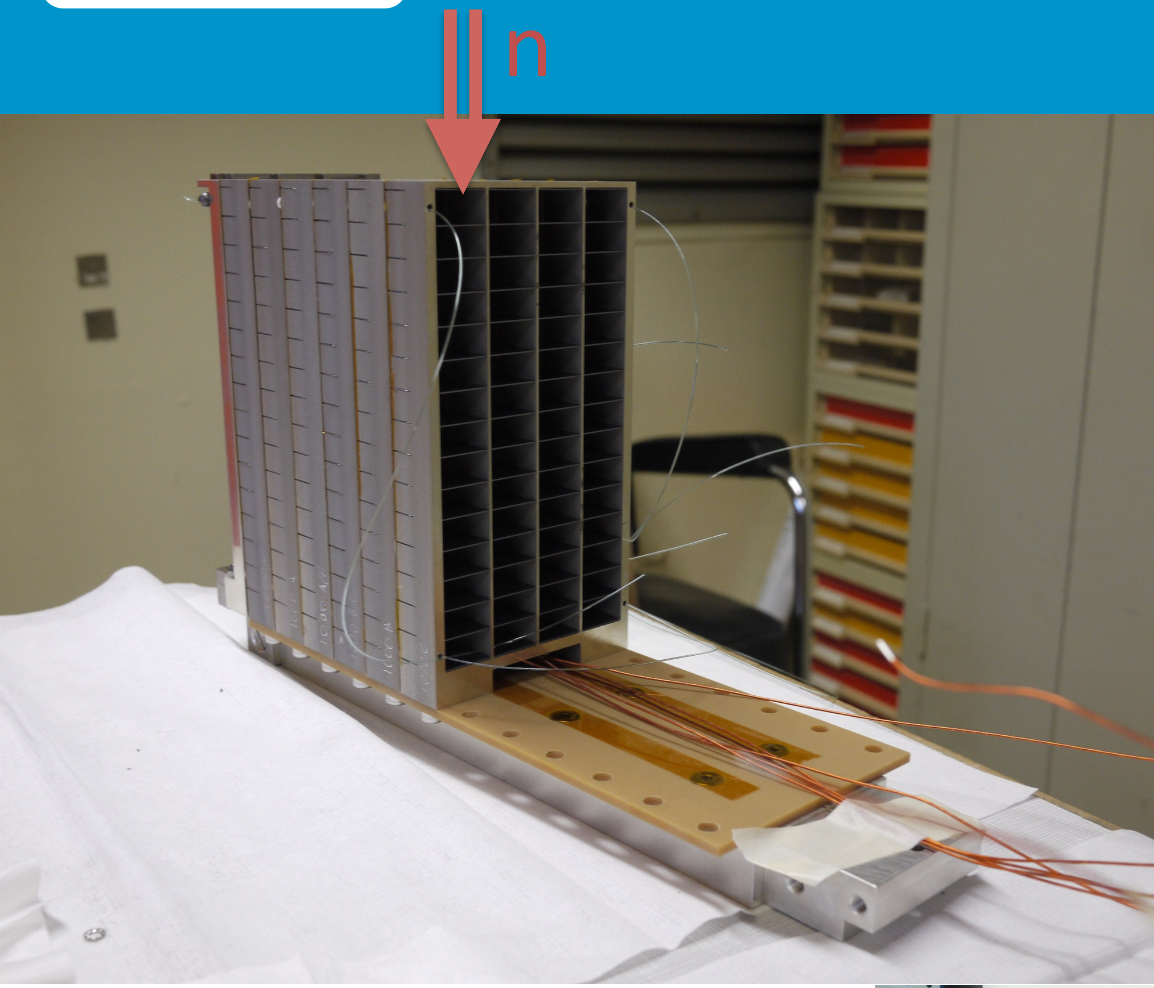
Multi-Grid

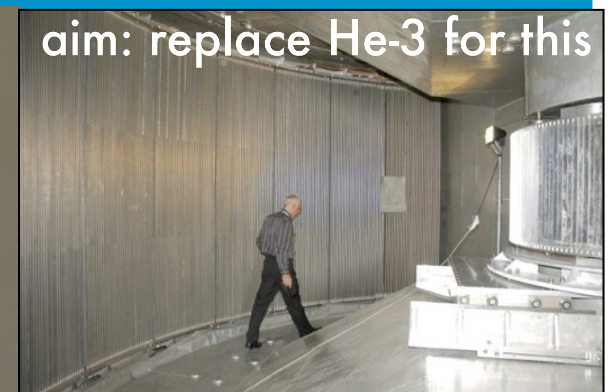


^{3}He tubes – 1 inch – 4.75 bar

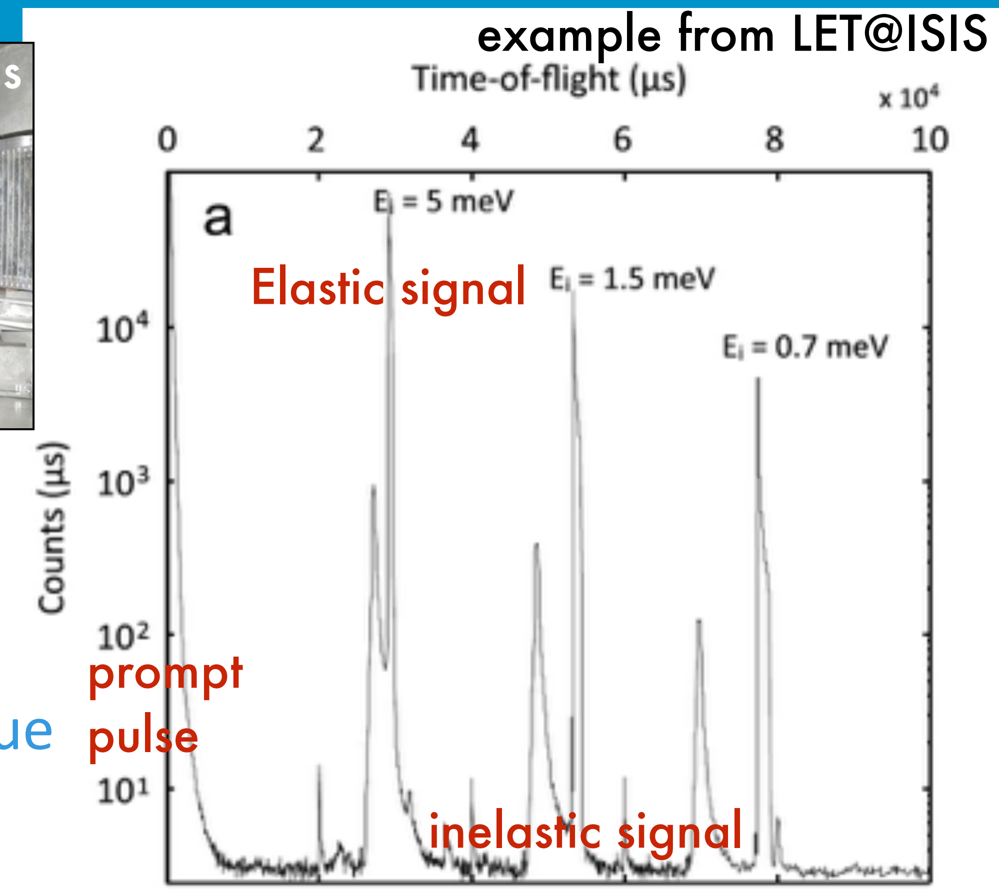


Multi-Grid Detector Design

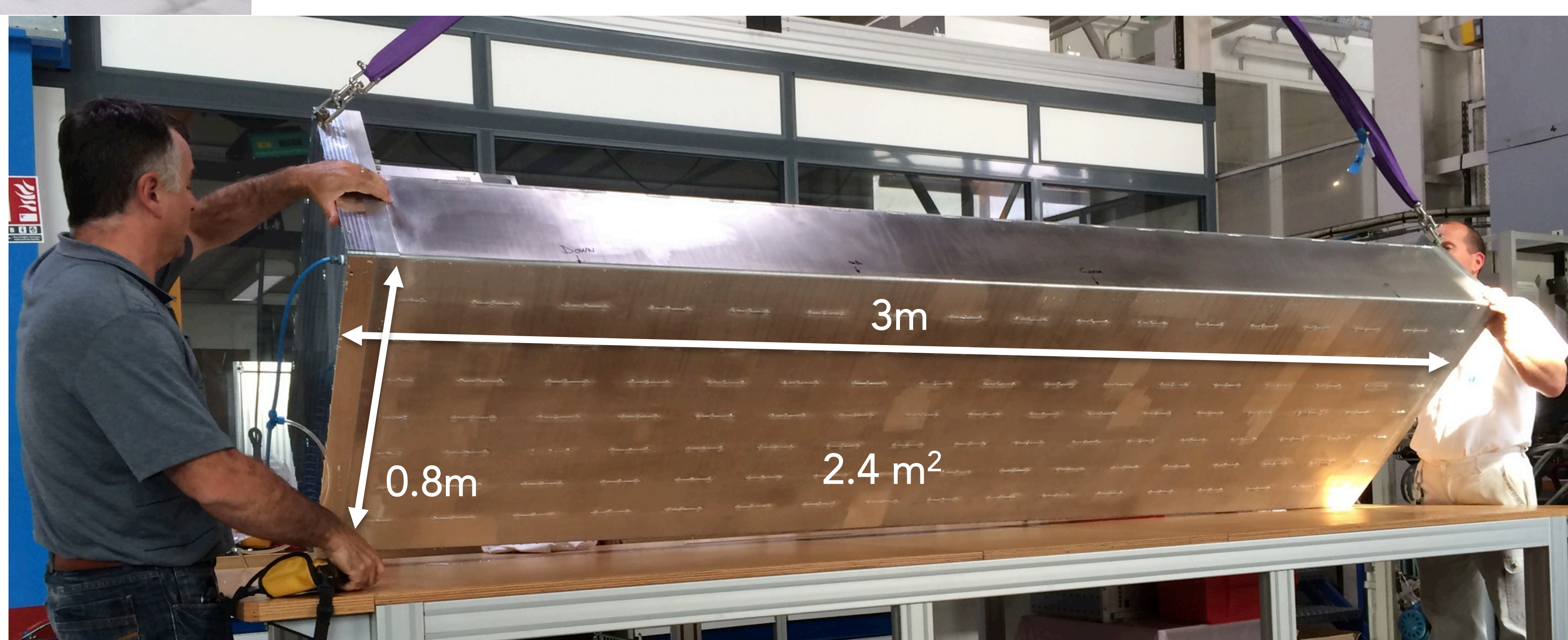




- Very background sensitive technique



- Designed as replacement for He-3 tubes for largest area detectors
- Cheap and modular design
- Possible to build large area detectors again
- 20-50m^2 envisaged for ESS



(slide from B. Guerard)

CLUSTER OF RESEARCH INFRASTRUCTURES FOR SYNERGIES IN PHYSICS

CRISP

Participants: ESS, ILL, LiU

$^{10}B_4C$ thin film Multi-Grid detectors

The goal of the CRISP / WP15 work package is to show that the Multi-Grid concept + B_4C thin film converters is an alternative to ^3He for large area detectors

96 Grids and **60** wires readout individually

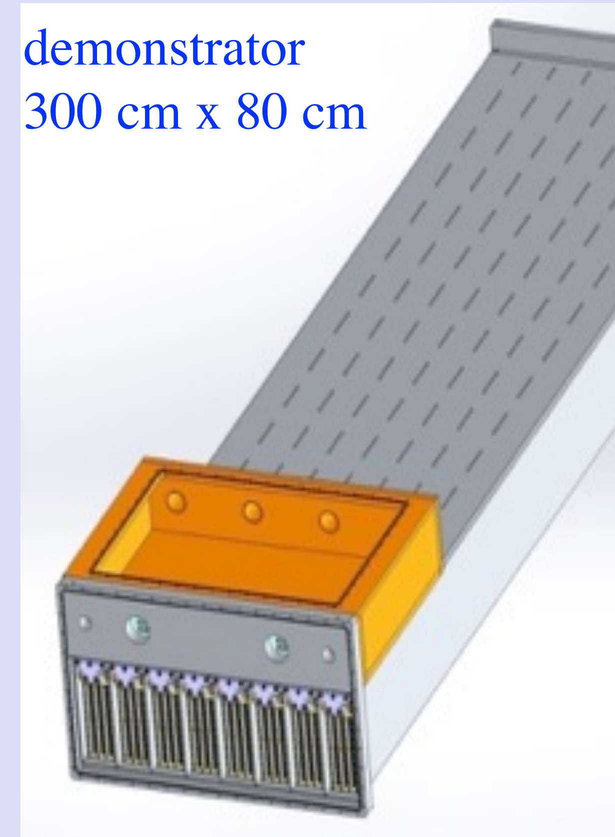
- 50% efficiency measured @2.5 Å
- B_4C coating process validated
- Film characterization
- Simulation of the detector
- Centre Of Gravity localization in Y
- Gamma sensitivity measured
- Ar-CO_2 & CF_4 tested at [0.2 - 1] Bar

Where we were last year

- 96 grids and 360 wires
- Grids of same Y connected by 3 → **32** channels
- Wires X_n & X_{n+1} connected with resistors → **24** channels

- Measurements on IN6
- Background observed, solved
- back scattering measured
- Electronics validated
- Demonstrator in fabrication

What has been achieved since then



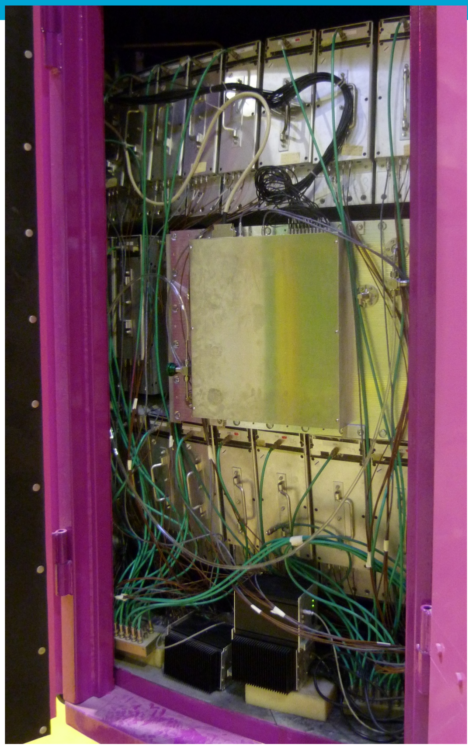
1024 grids/ 512 wires
- **256** x (4Grids) cath channels
- Wires X_n & X_{n+1} connected with resistors → **32** channels

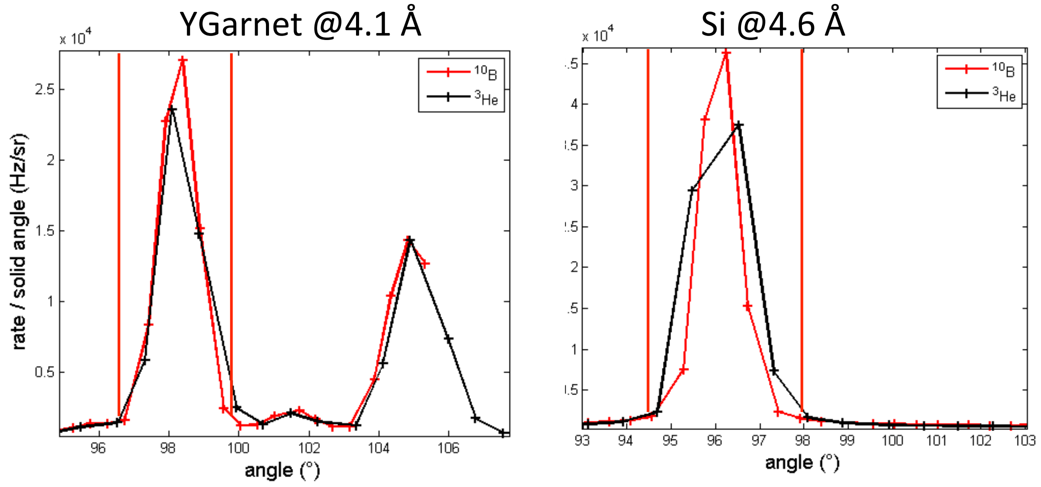
- Pressure vessel tested
- Mass production of B_4C (70 m^2 !) and detector components
- real detector operational

Where we want to be next year

Multigrid Design: IN6 Demonstrator

IN6 Demonstrator



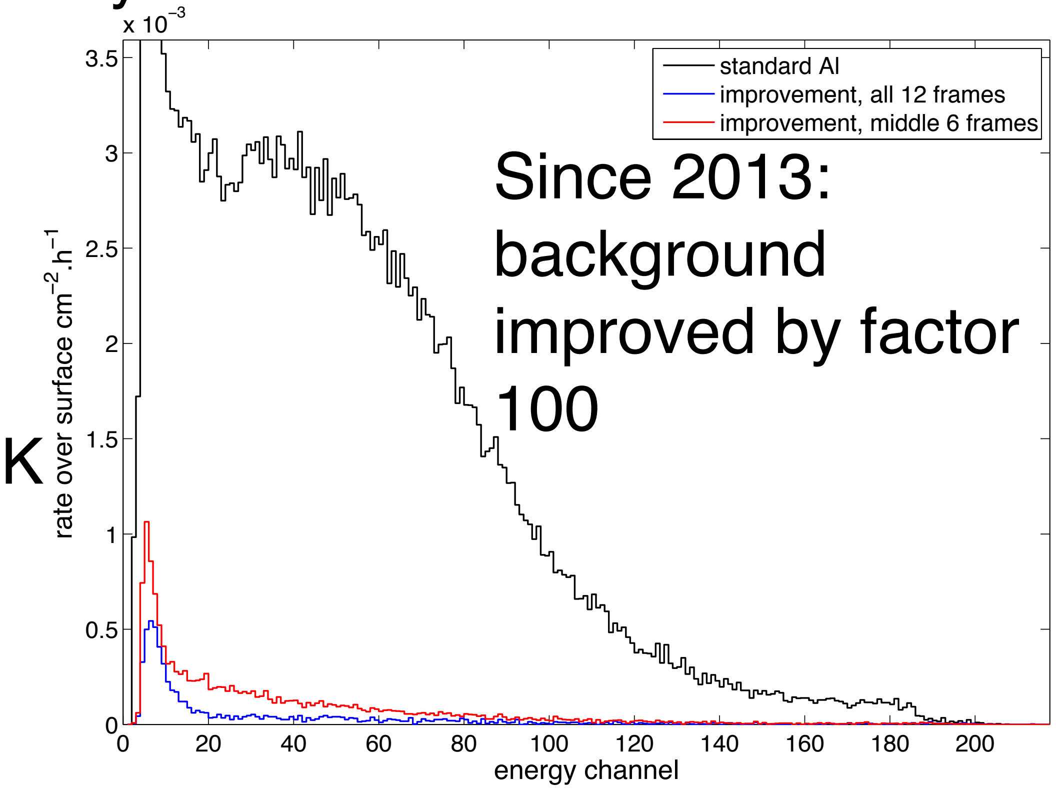


Ratio of integrated rates in Bragg peaks :

- 4.1 Å : rate(^{10}B) / rate(^{3}He) = 1.08
- 4.6 Å : rate(^{10}B) / rate(^{3}He) = 0.97

- Performance basically matches Helium-3

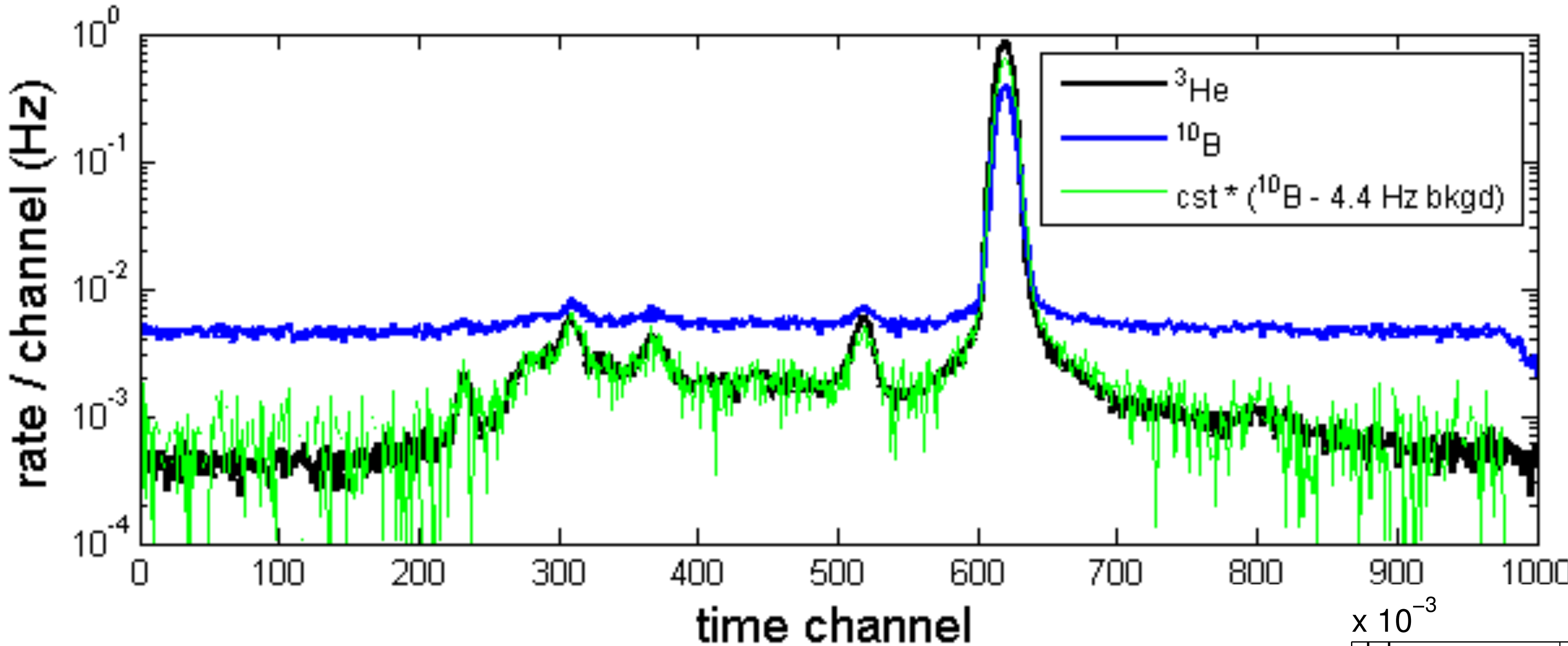
- Efficiency - OK
- Data - OK
- Scattering - OK
- Gamma rej - OK
- t resolution - OK
- x,y resolution - OK



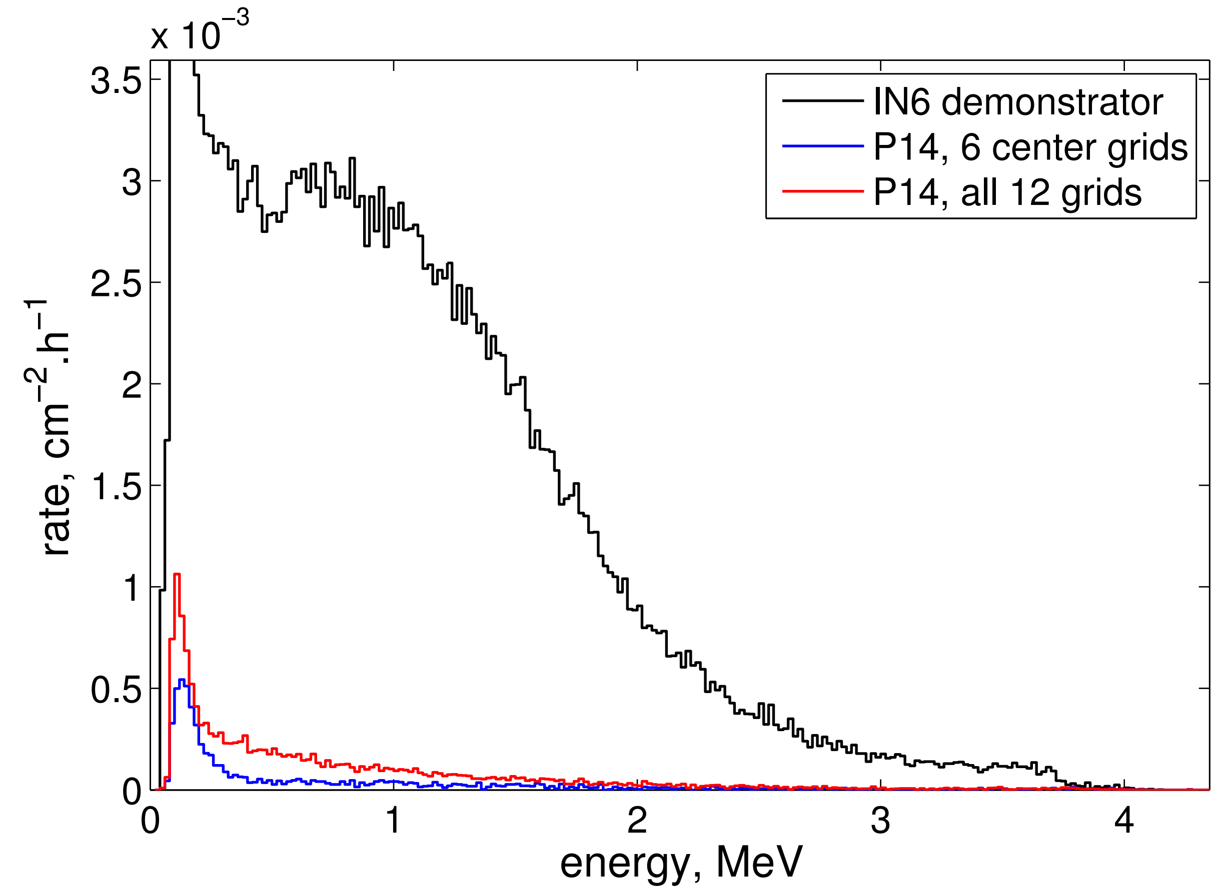
Since 2013: background improved by factor 100

- background from alpha's in Al seen
- Plating or ultrapure Al solves it: now ok

Background from natural radioactivity in Aluminium

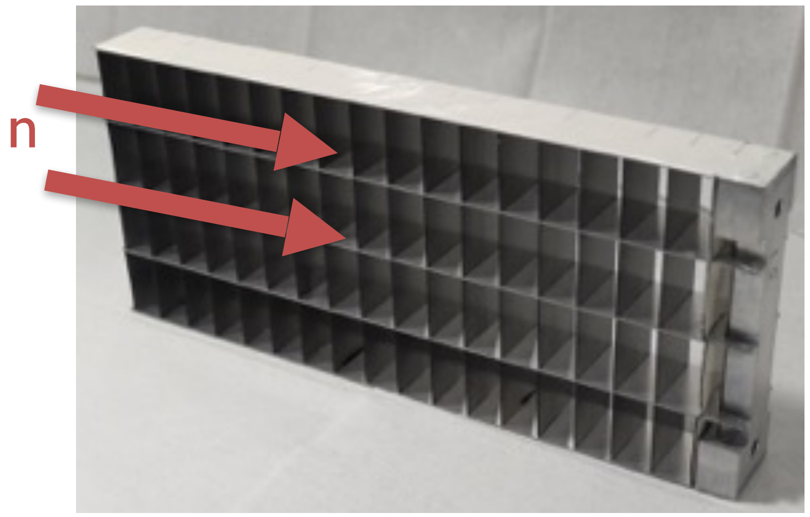


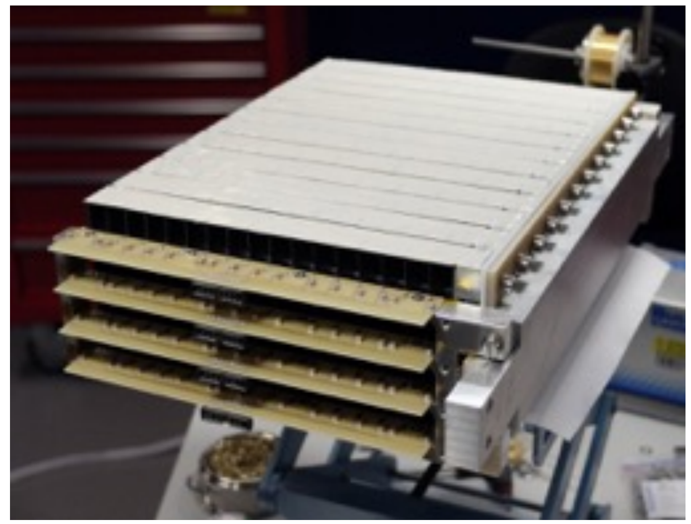
- Side-by-side test of prototype on IN6 instrument at ILL
- Performance matched He-3 except constant background level

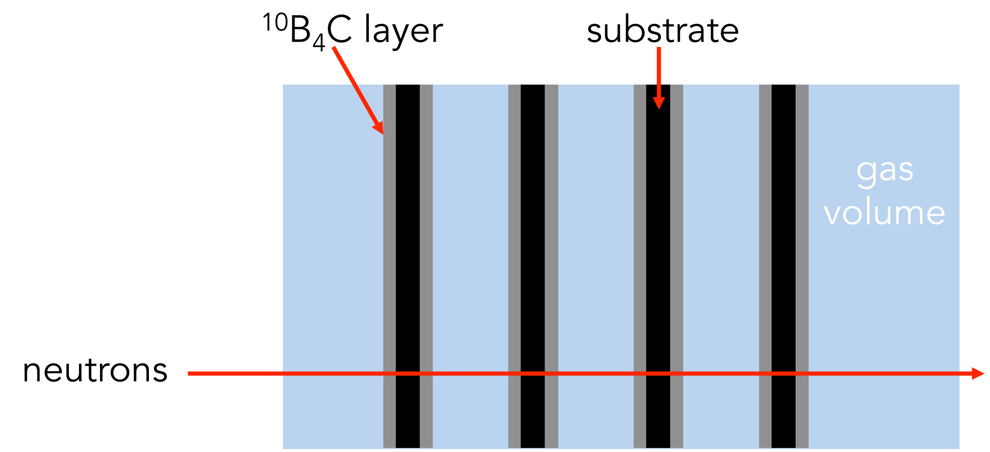


- Source: natural alpha radioactivity in Aluminium
- By using ultrapure- or Nickel-plated- Aluminium removed this background

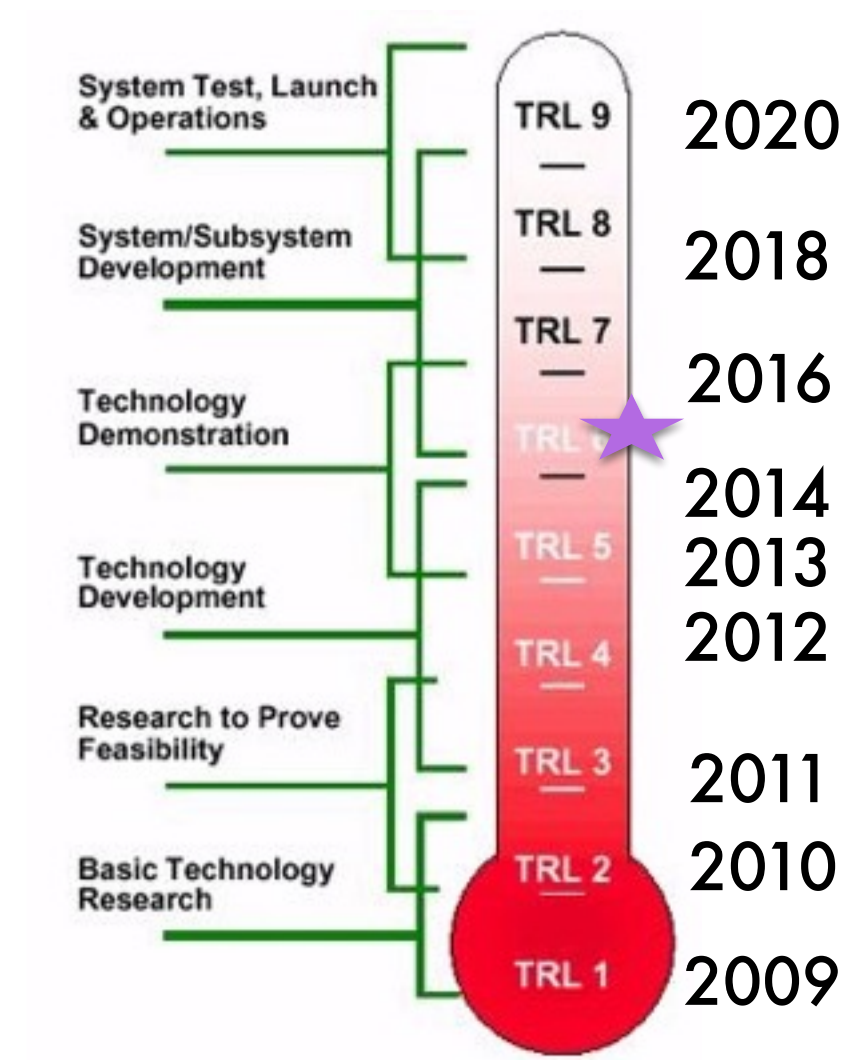
Large Area Detectors:
Multi-Grid Design



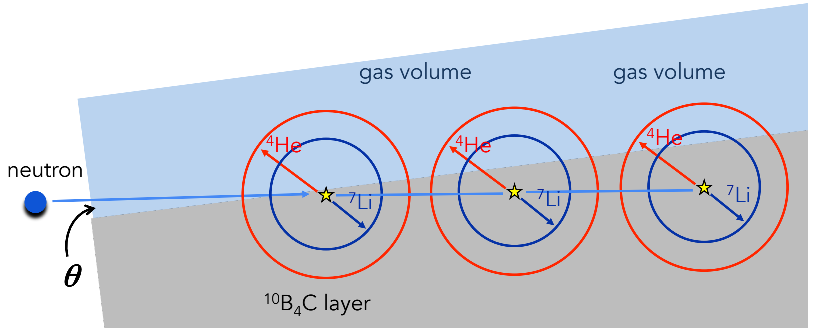


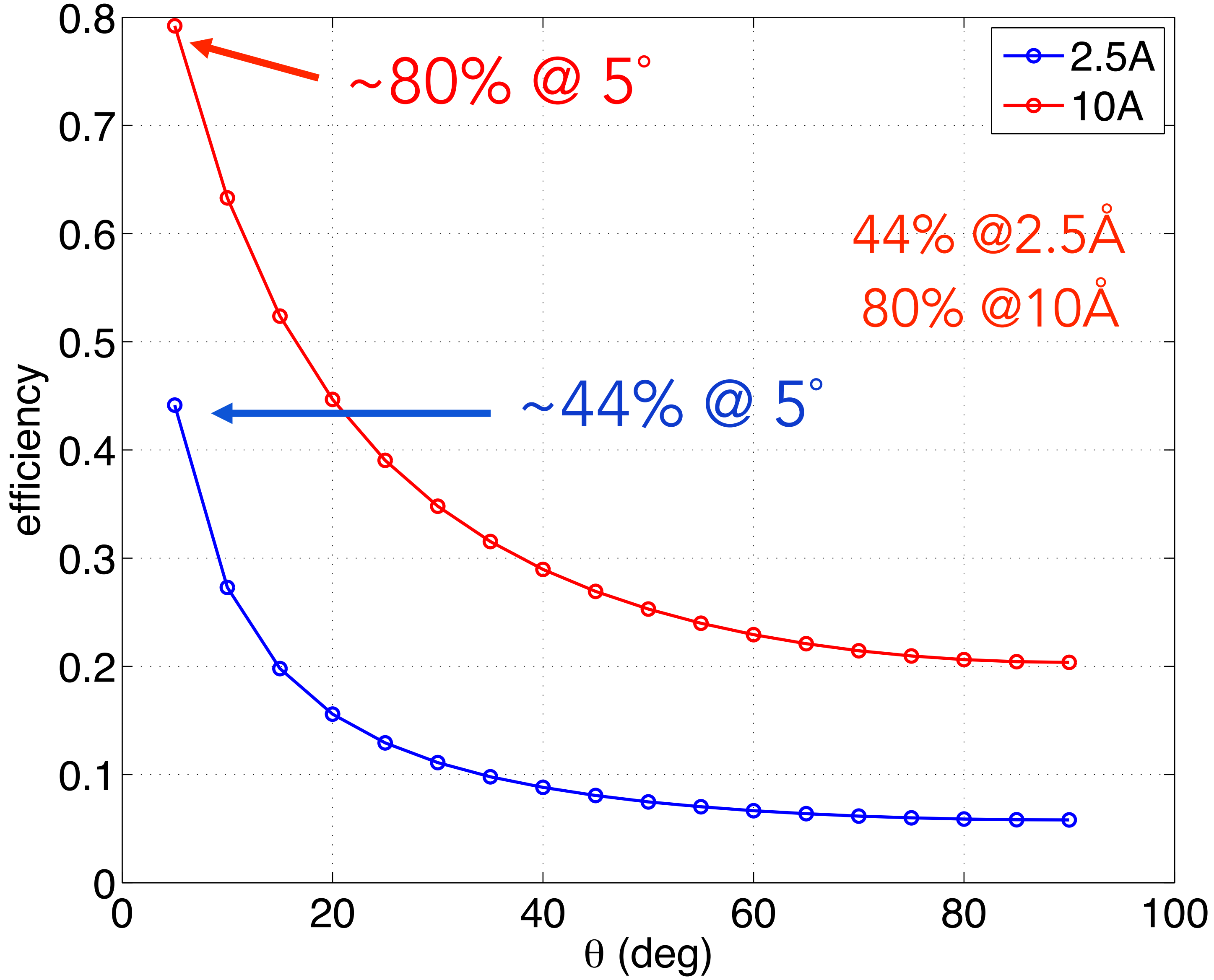


Technology Demonstrators of Scientific Performance planned for: CNCS@SNS and TOFTOF@FRMII



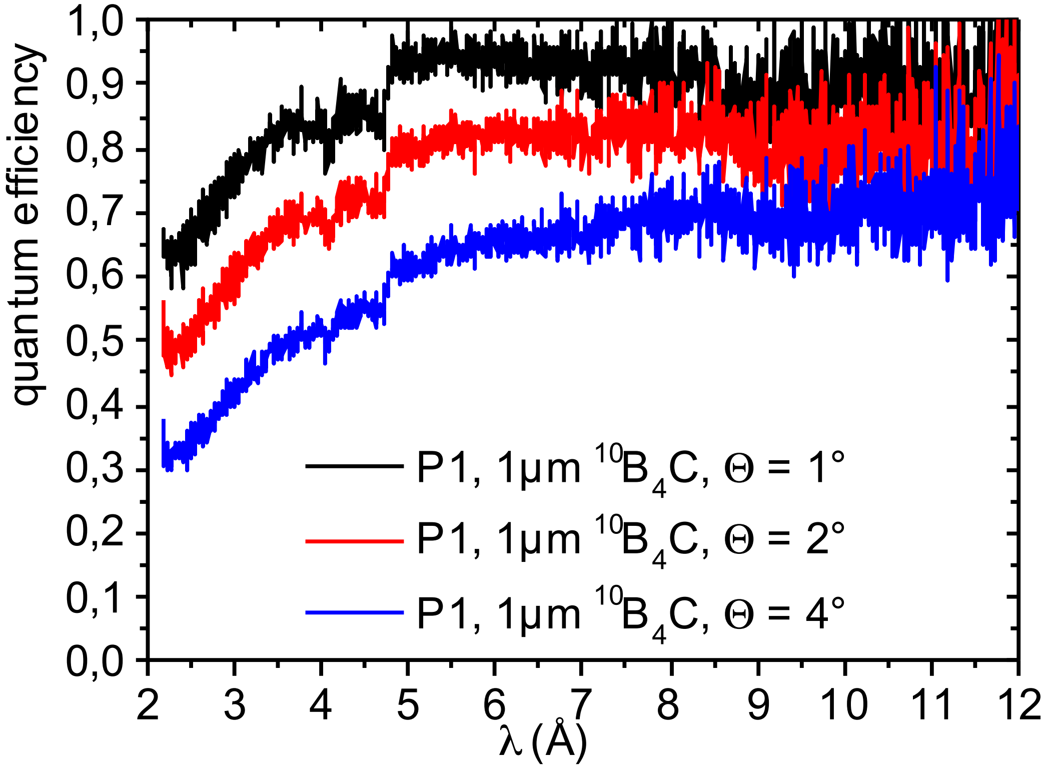
Efficiency of ^{10}Boron Detectors: Inclined Configuration

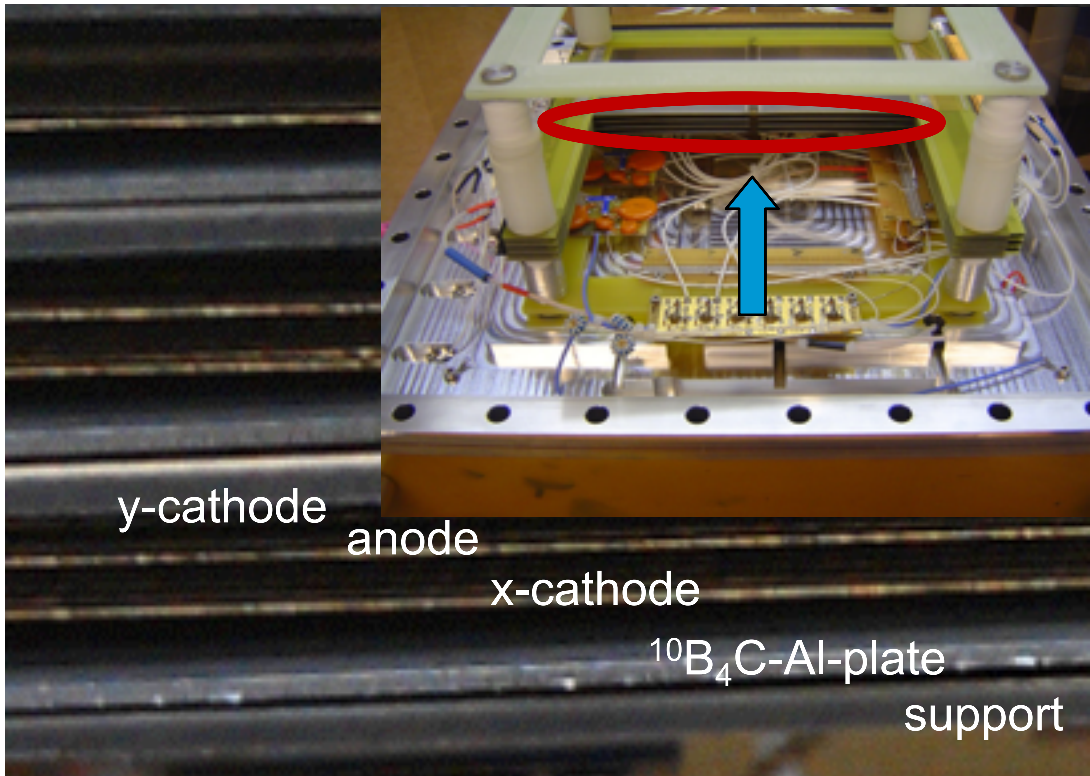




F. Piscitelli, PhD Thesis, U.Perugia (2014)

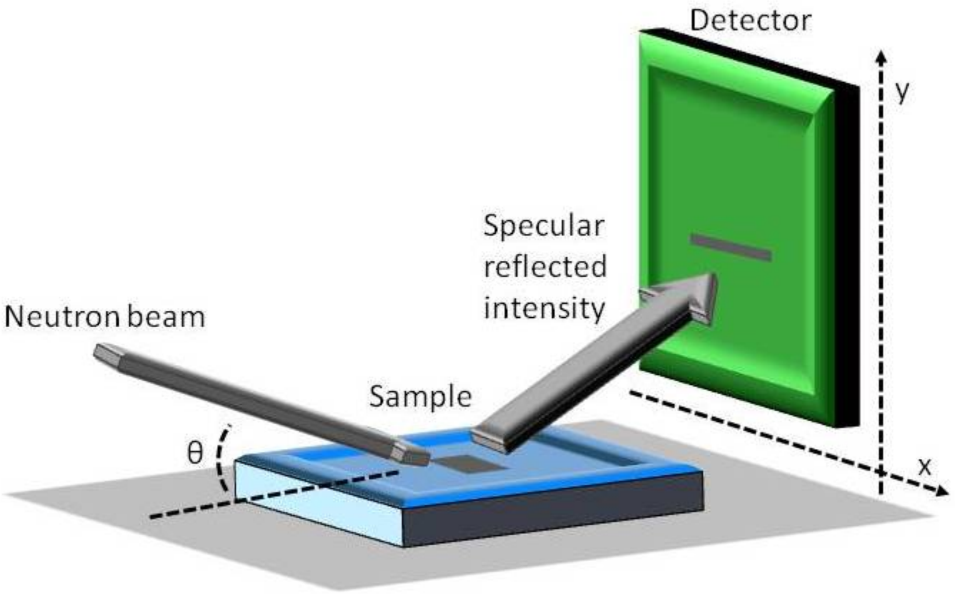
smaller inclined angles: higher efficiency

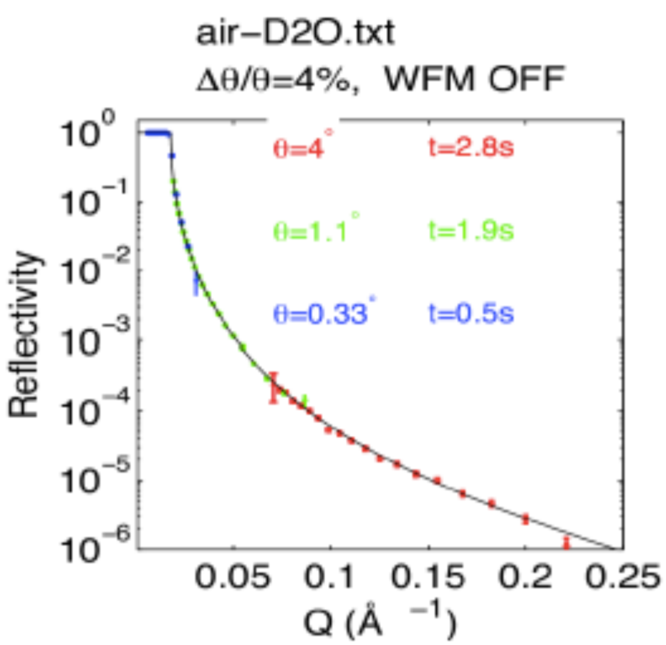




Neutron Reflectometry: A Rate Challenge

- Rate requirements is high:
  - Intensity of new sources
  - Time structure of pulse
  - Advanced design instruments





ESS requirements

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1} mm^{-2})$
500×500	$[\leq 0.5, 2] \times 2$	$[5, 100] \cdot 10^5$	$[5, 300] \cdot 10^2$

x10 x100

The state of the art

area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1} mm^{-2})$
500×500	1×2	$100 \cdot 10^5$	300

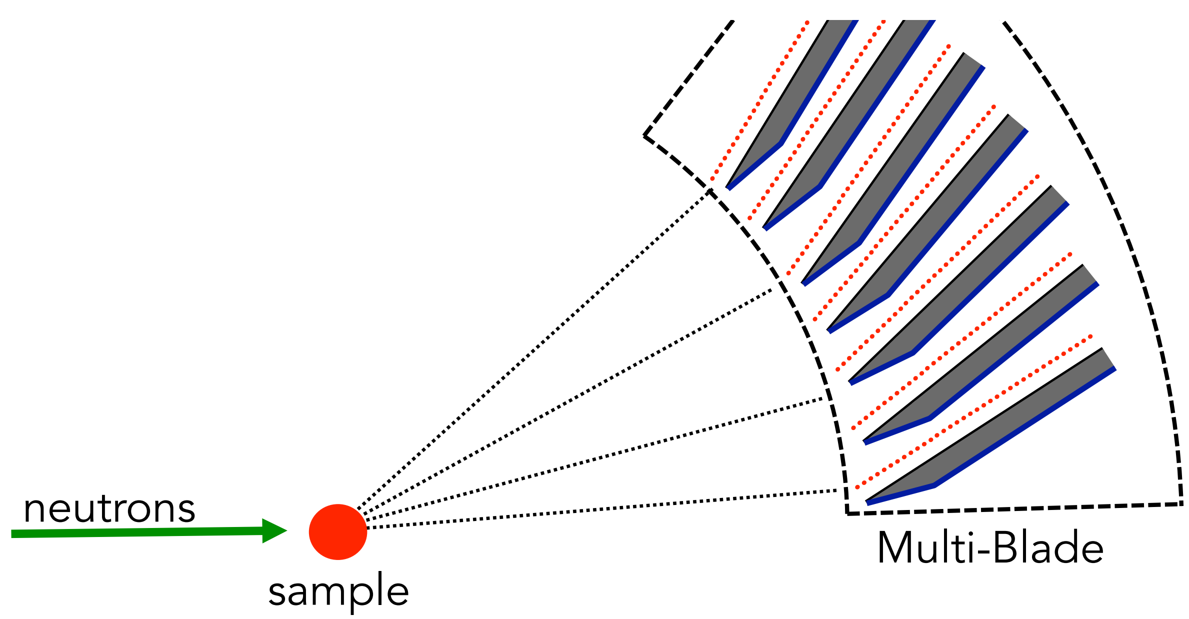
^{3}He technology

x1 x10

Multi-Blade

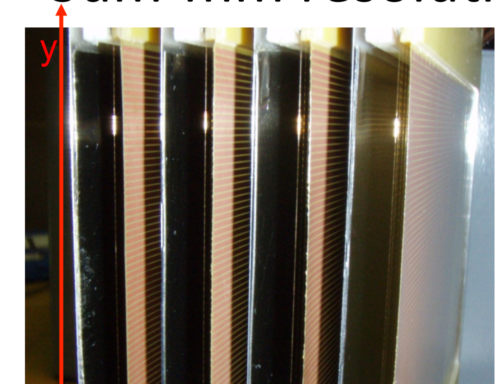
area $(mm \times mm)$	spatial resolution $(mm \times mm)$	global rate (s^{-1})	local rate $(s^{-1} mm^{-2})$
	0.3 x 4		>1000

^{10}B technology



Multi-blade design:

- High rate capability
- Sum-mm resolution



Multi-Blade Design

BrightnESS

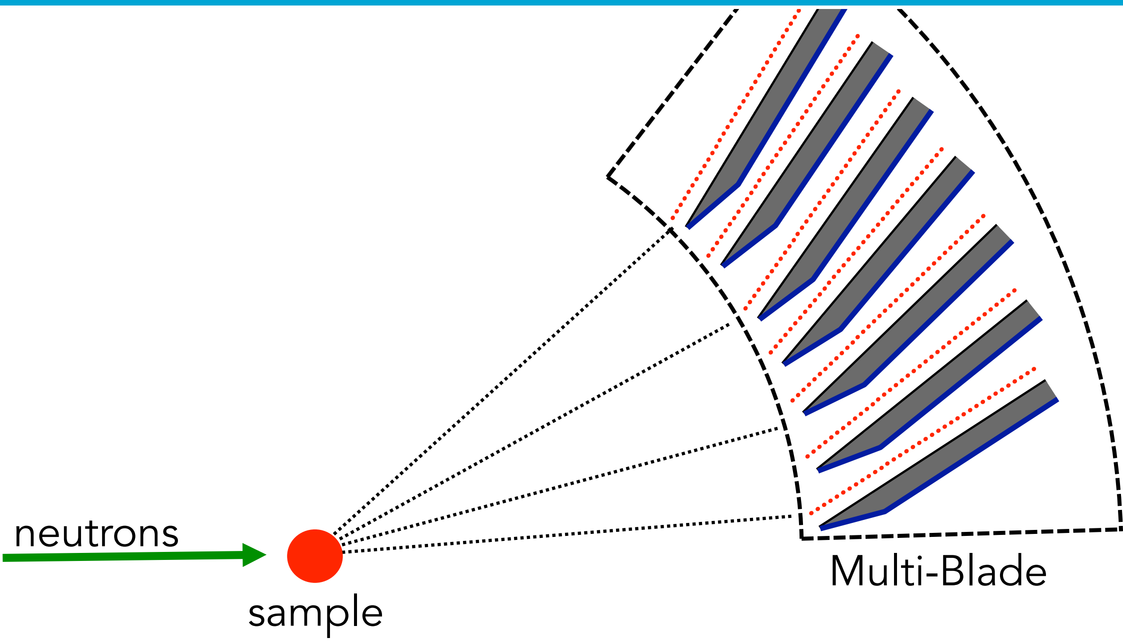
EUROPEAN SPALLATION SOURCE

LUND UNIVERSITY

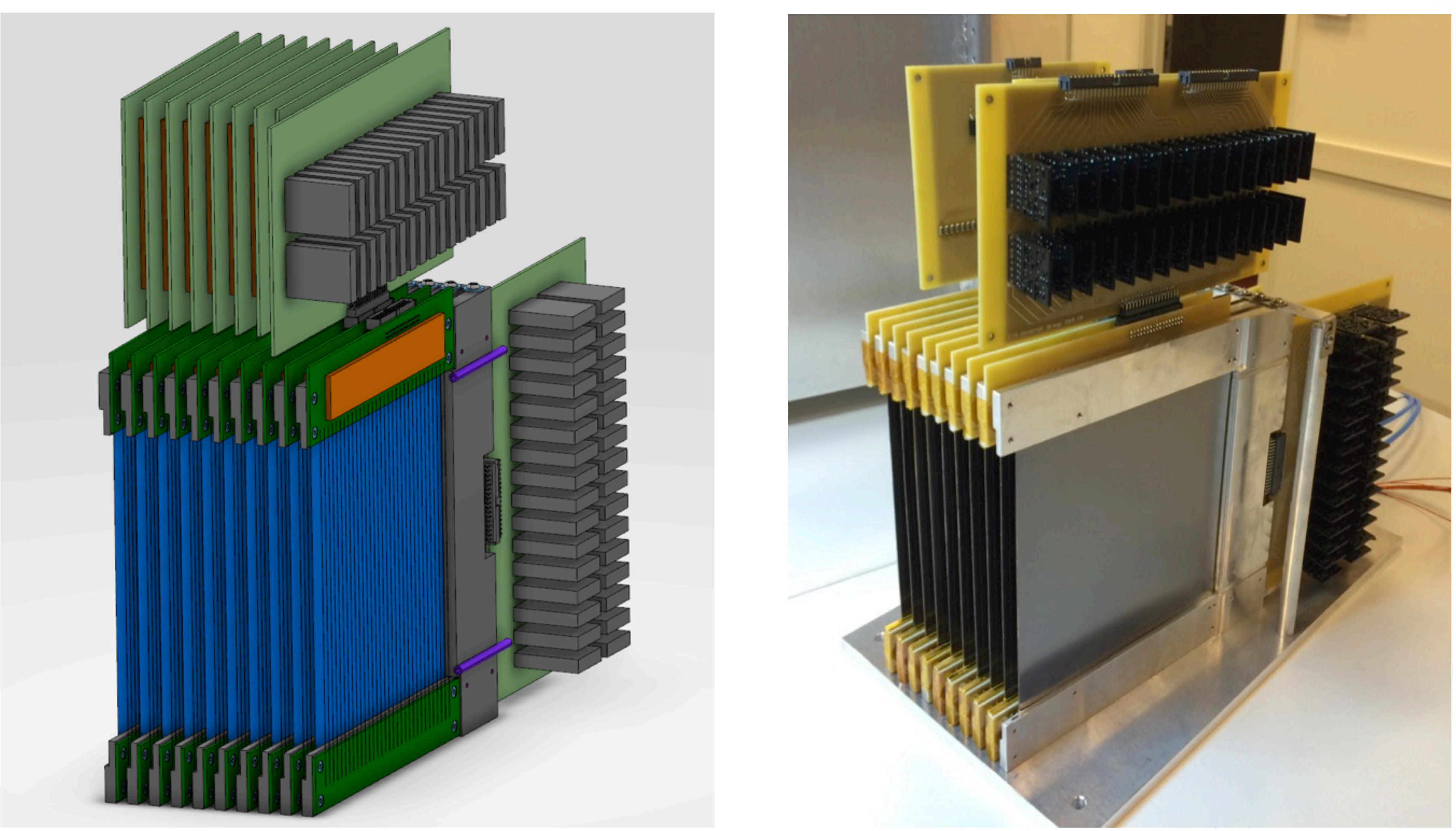
Wigner Research Institute

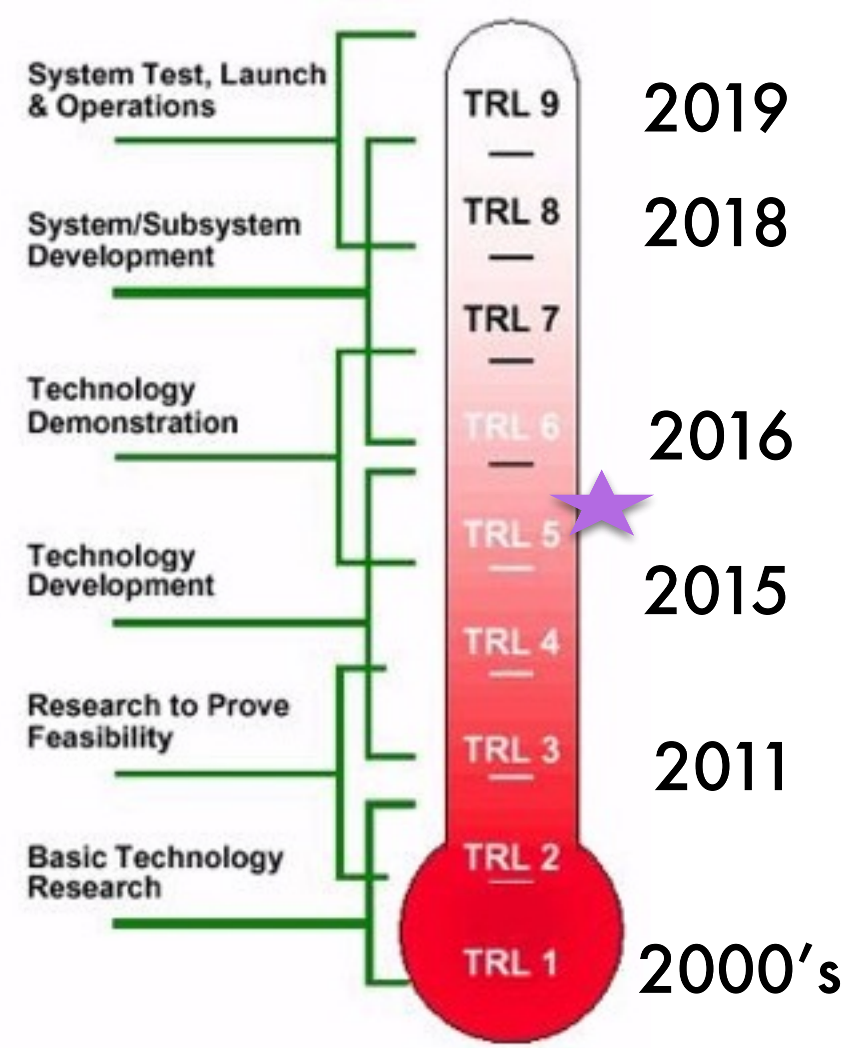
BNC

Budapest Neutron Centre

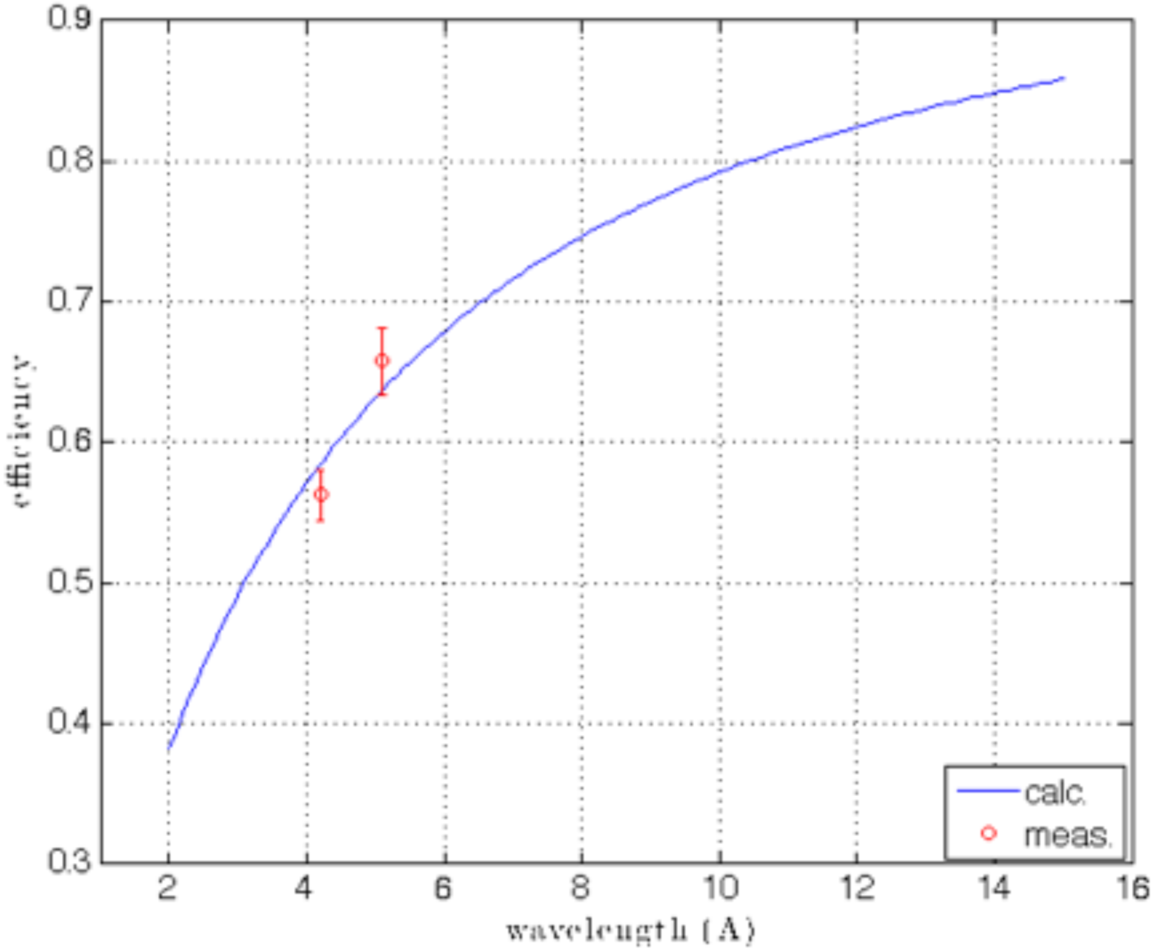


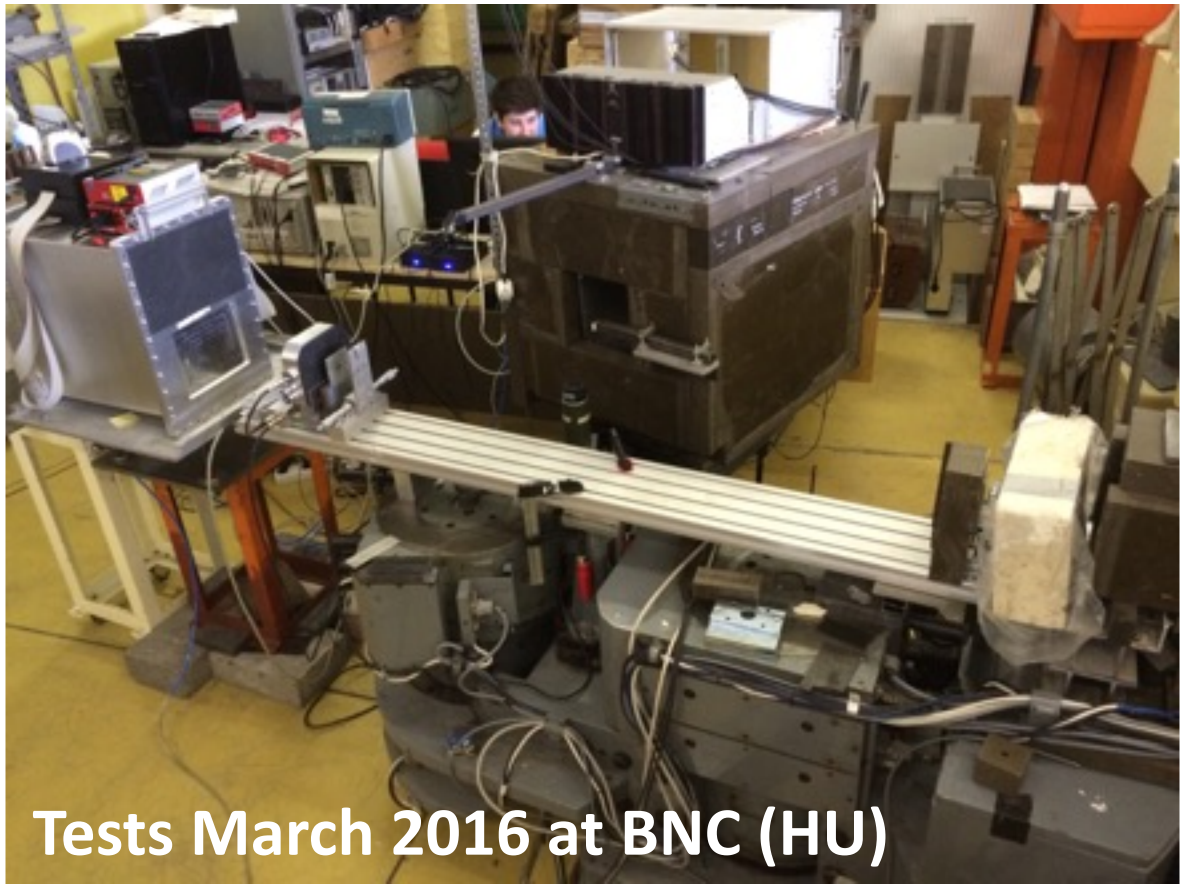
- Design simple: *"KISS"*
- Modular
- Cheap
- Make design available
- *"Open Source Hardware"*

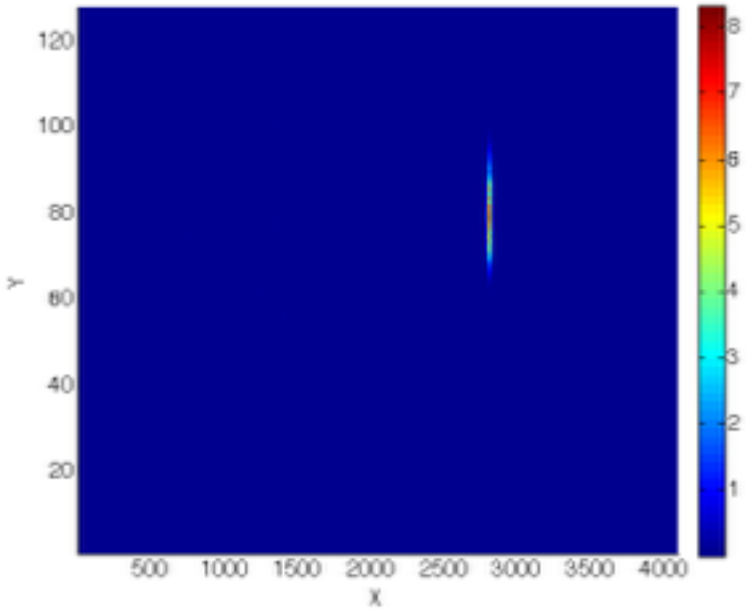




Multi-Blade Design



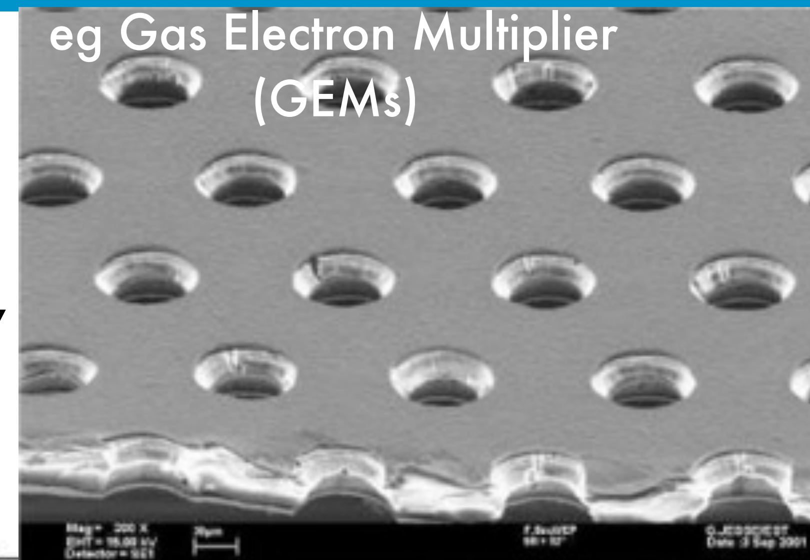


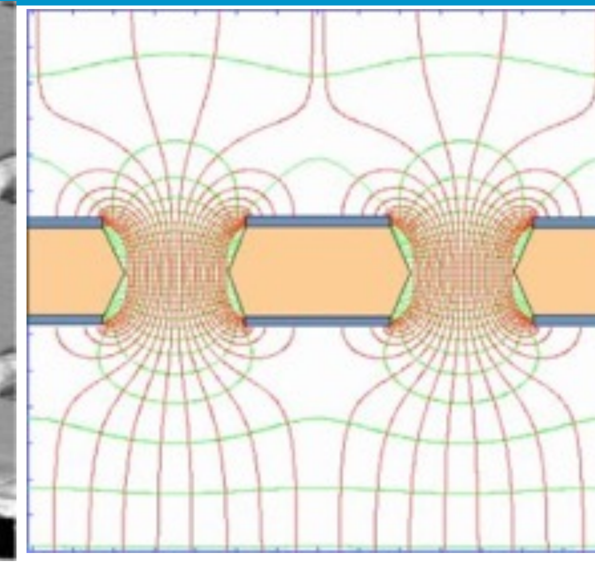


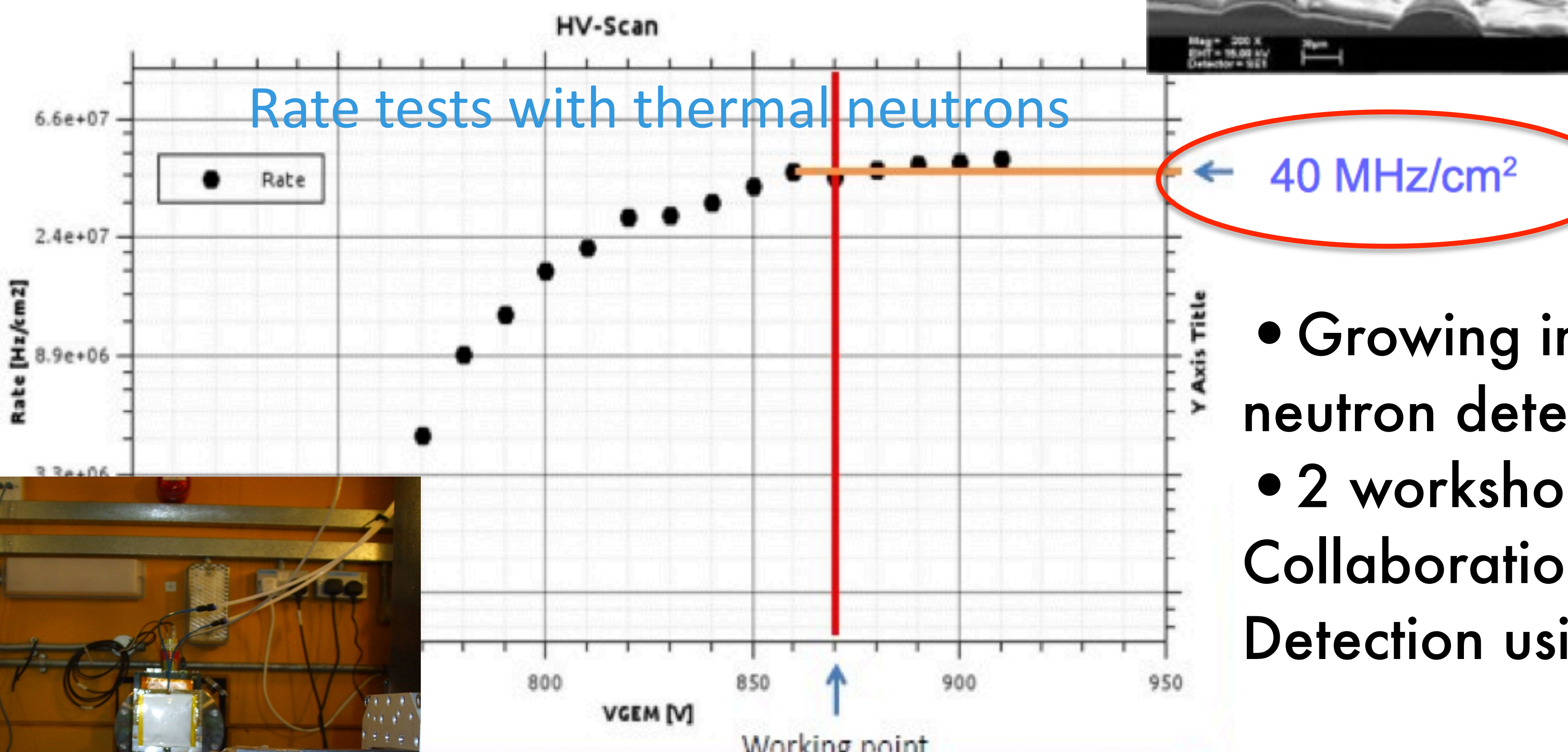
- Counting rate capability: no saturation observed up to 22kHz/mm^2
- ca. 0.4mm x resolution
- Further tests later in year, including scientific demonstration on reflectometry instruments

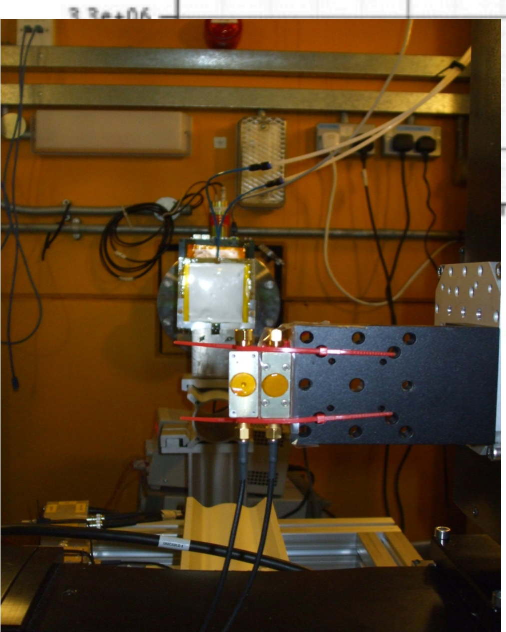
Micropattern Gaseous Detectors

- Field started by A Oed at the ILL with the micro-strip gas chamber (MSGC) in 1988
- Now widespread: many variants
- Potentially very good resolution and very high rate capability









- Growing interest for applications for neutron detection
- 2 workshops organised by CERN RD51 Collaboration (with HEPTECH) on Neutron Detection using MPGDs

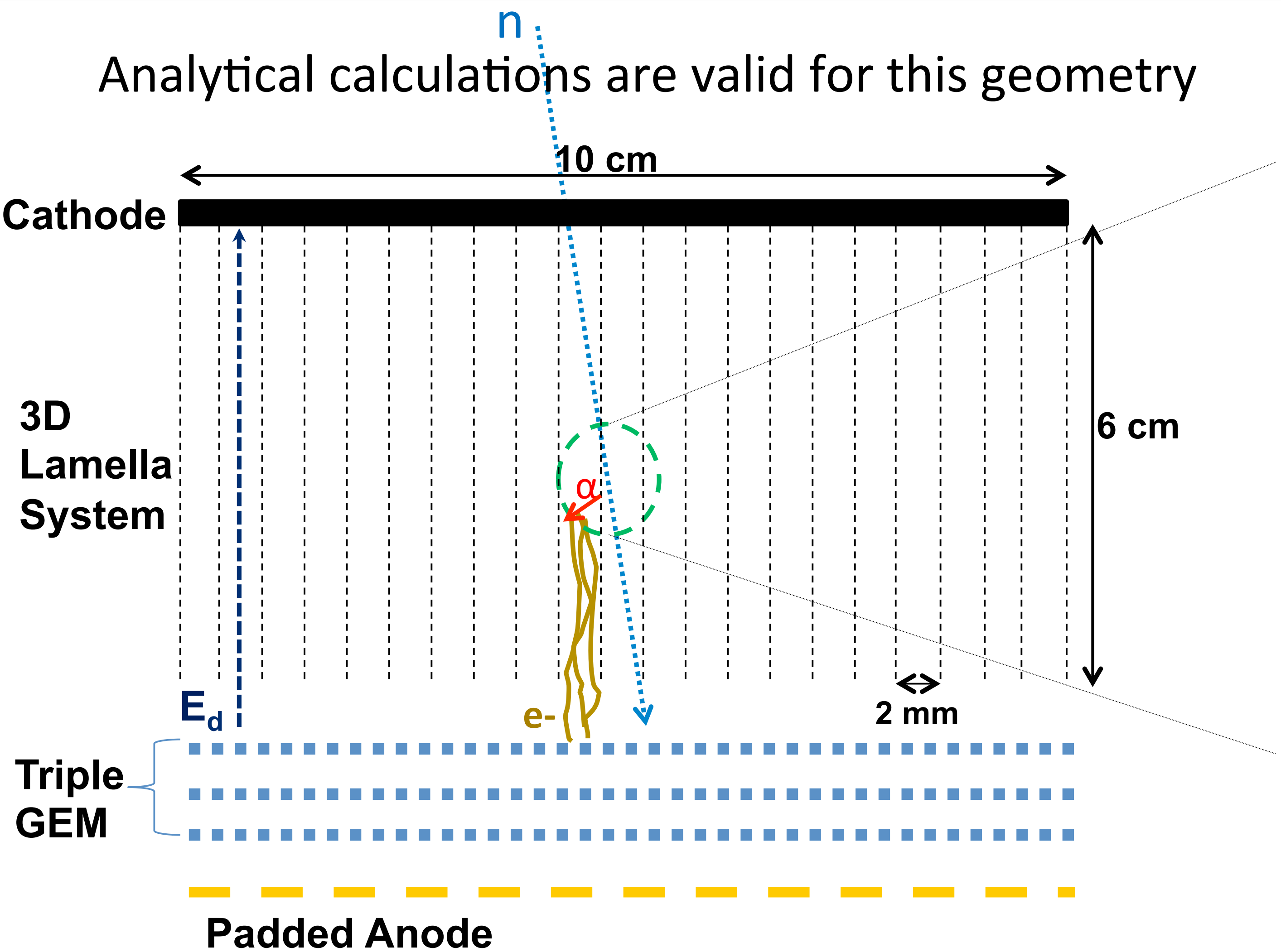
Summary of 1st workshop for MPGDs for neutron detection: arXiv:1410.0107

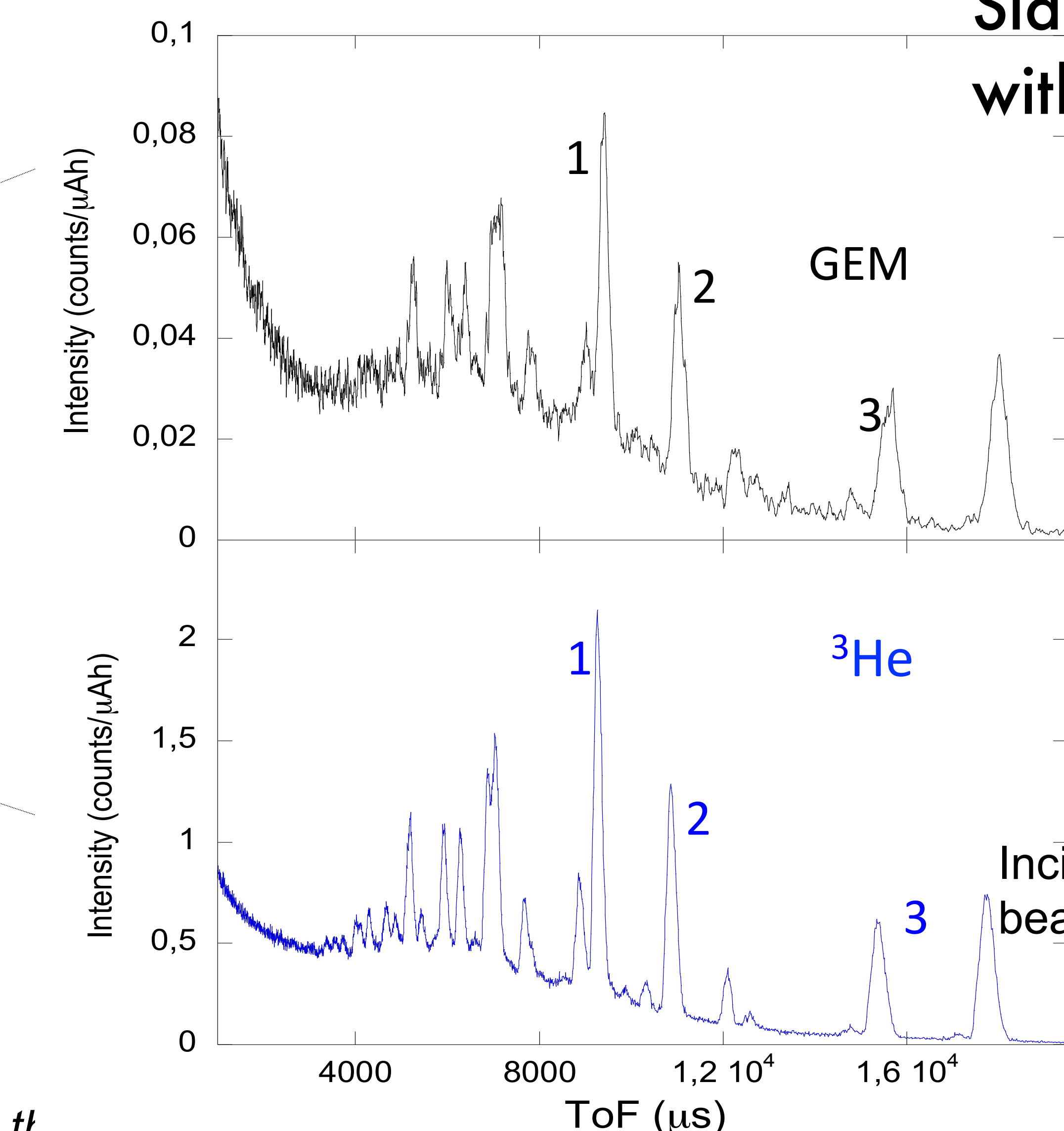
2nd Workshop: https://indico.cern.ch/event/365380/

BANDGEM Detector

Side-by-side with He-3

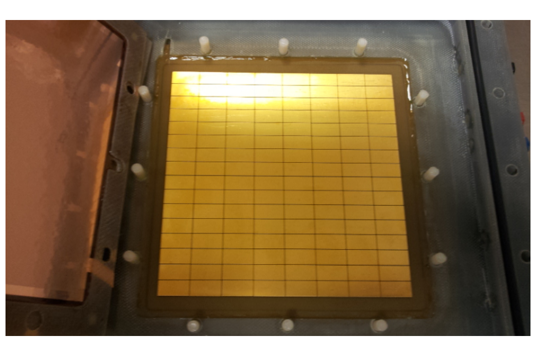
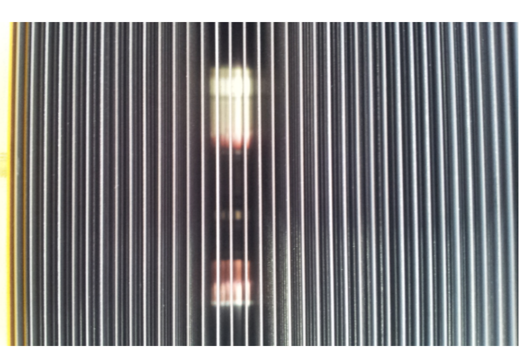
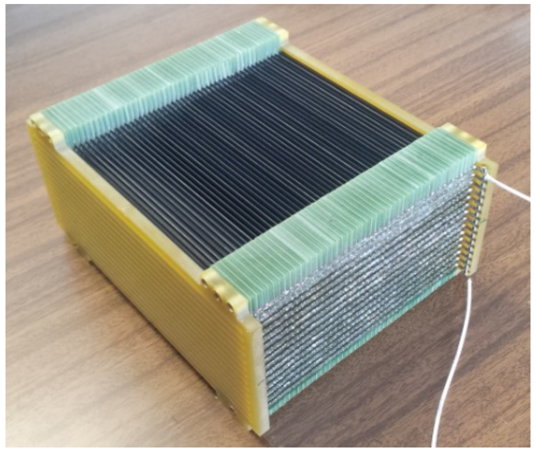
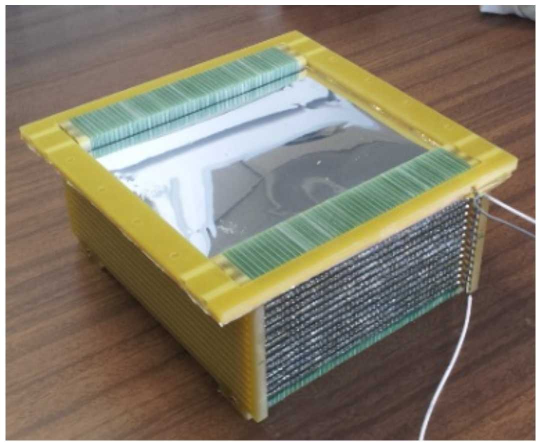
Analytical calculations are valid for this geometry



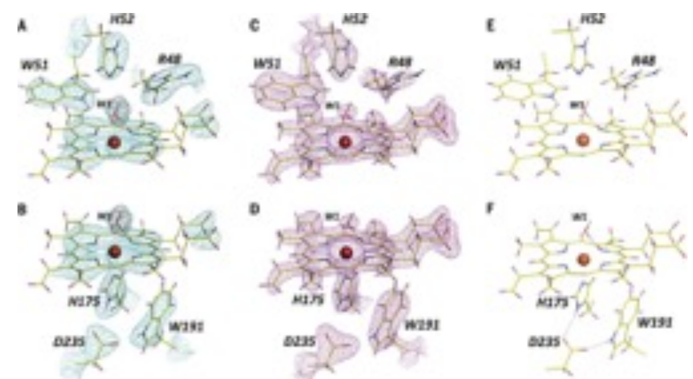


Alumina lamellae coated on both sides with $^{10}B_4C$

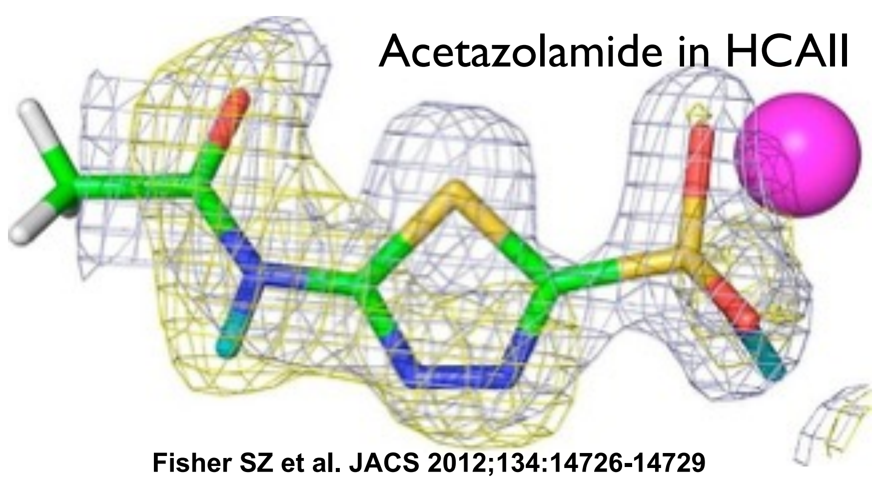
Using low θ values (few degs) the path of the neutron inside tl
B_4C is increased → Higher efficiency when detector is inclined

Where are hydrogens important?



Casadei CM et al. Science 2014;345:193-197

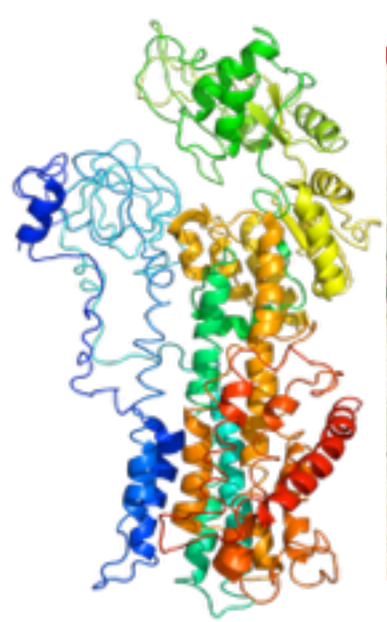


Fisher SZ et al. JACS 2012;134:14726-14729

Enzyme mechanisms → **Drug design**

Protein-ligand interactions → **Drug design**

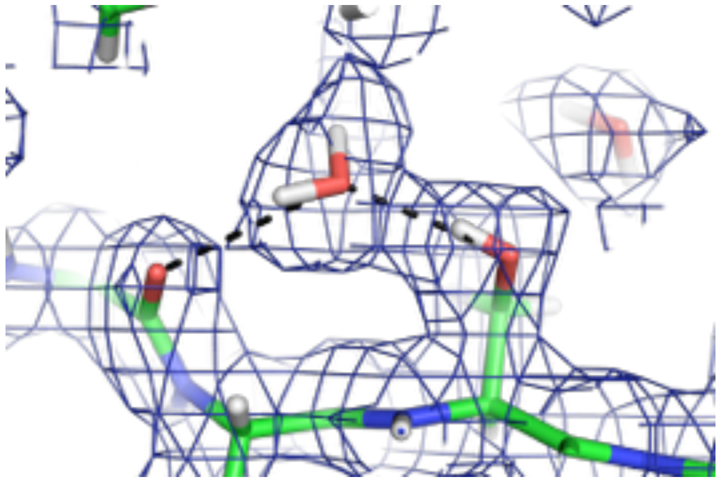
Proton transport across → **Drug design**



Neutron Macromolecular Crystallography

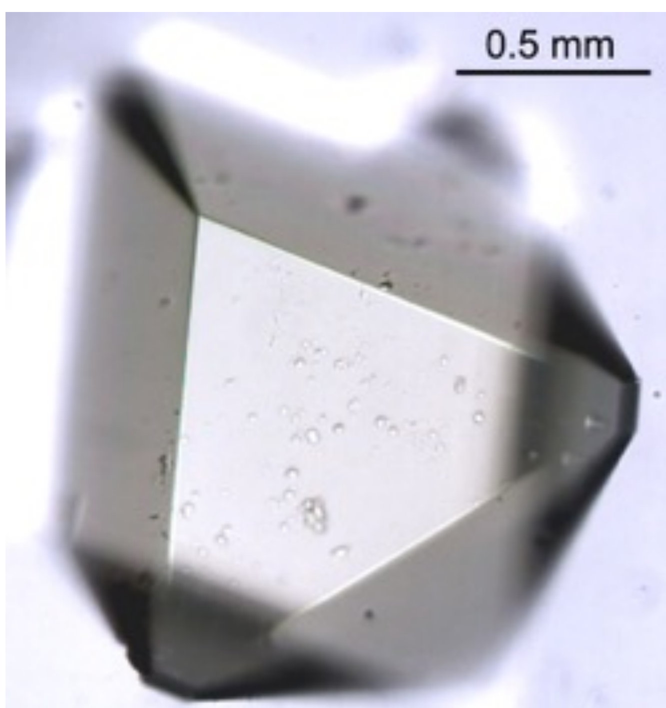
Mittuniversitetet MID SWEDEN UNIVERSITY

EUROPEAN SPALLATION SOURCE



X-Ray structures: >100 000
Neutron Structures <100
A huge opportunity?

☺ Hydrogens are visible
☺ No radiation damage
☹ Large crystals needed
☹ Data collection takes weeks
☹ Few instruments available

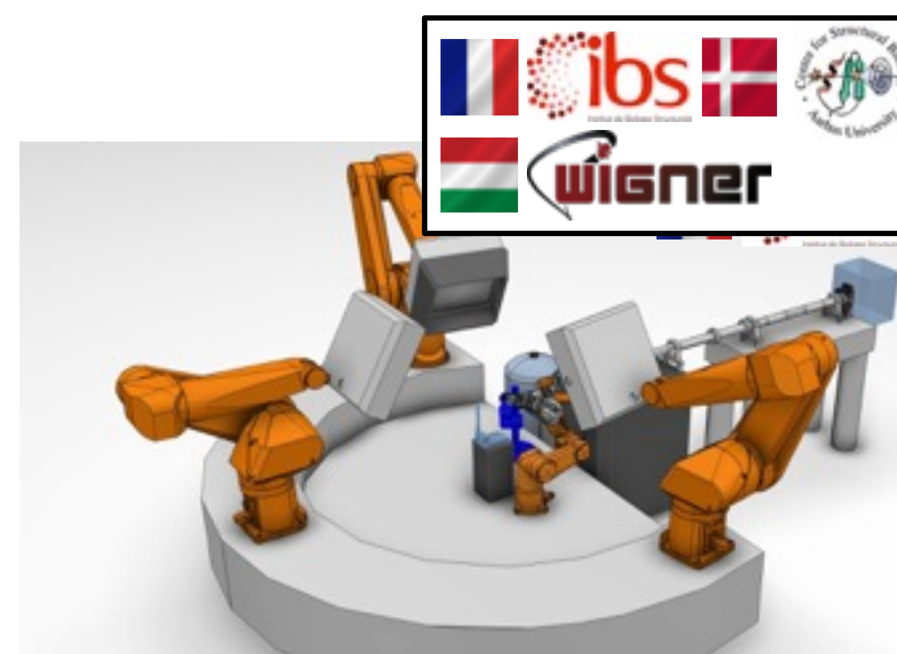


Oksanen, E *et al. J. R. Soc. Interface* **2009**, *6 Suppl 5*, S599-610.

Key advantages of ESS:

- Macromolecular Diffractometer
- Smaller crystals needed (200 µm vs. 1 mm)
- Data collection faster (days vs. weeks)
- Larger unit cells possible (300 Å vs. 150 Å)

NMX Instrument



Bovine heart

cytochrome c oxidase

$P2_12_12_1$

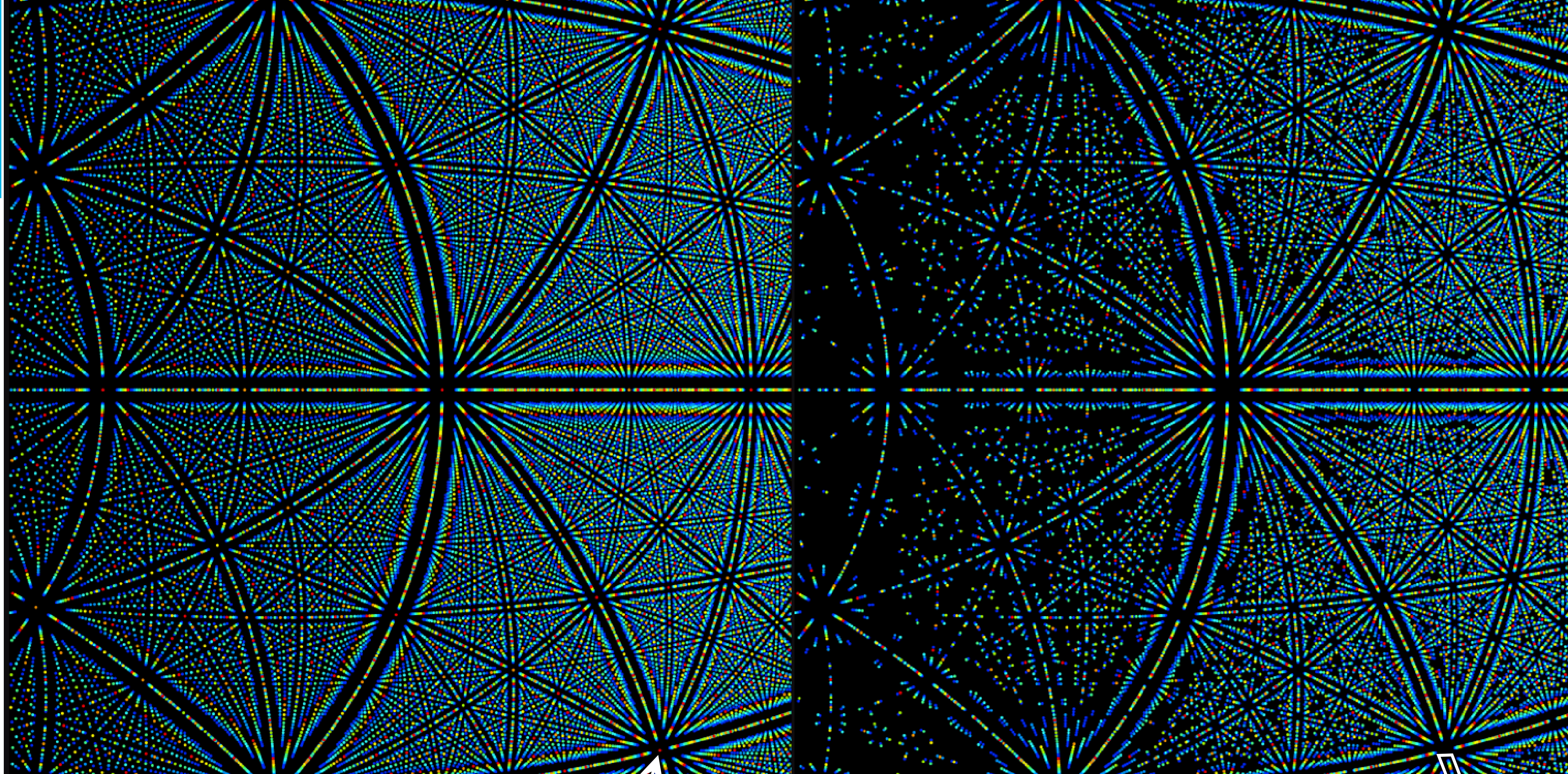
a = 182.59 Å

b = 205.40 Å

c = 178.25 A

Detector distance 1 m

<<1mm spatial resolution to be able to integrate intensities



All reflections

14 28 42 (3.409 Å, 134.4 ms) 21 35 49 (2.809 Å, 110.8 ms)
15 29 43 (3.309 Å, 130.5 ms) 22 36 50 (2.739 Å, 108.0 ms)
16 30 44 (3.215 Å, 126.8 ms) 23 37 51 (2.672 Å, 105.4 ms)
17 31 45 (3.124 Å, 123.2 ms) 24 38 52 (2.608 Å, 102.9 ms)
18 32 46 (3.040 Å, 119.9 ms) 25 39 53 (2.548 Å, 100.5 ms)
19 33 47 (2.959 Å, 116.7 ms) 26 40 54 (2.489 Å, 98.2 ms)
20 34 48 (2.882 Å, 113.6 ms)

Spatial overlaps only

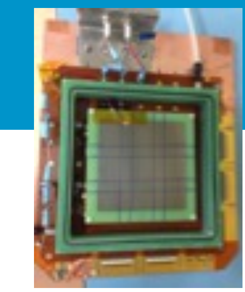
27 53 79 (1.812 Å, 71.4 ms)
22 43 64 (2.236 Å, 88.2 ms)
18 35 52 (2.752 Å, 108.5 ms)
17 33 49 (2.920 Å, 115.1 ms)
19 37 55 (2.602 Å, 102.6 ms)
15 29 43 (3.327 Å, 131.2 ms)
27 52 77 (1.856 Å, 96.4 ms)
26 50 74 (1.933 Å, 76.2 ms)
24 46 68 (2.103 Å, 82.9 ms)
22 42 62 (2.306 Å, 90.9 ms)
21 40 59 (2.424 Å, 95.6 ms)
20 38 56 (2.553 Å, 100.7 ms)
28 53 78 (1.833 Å, 72.3 ms)

- 1.800 to 2.019 Angstroms
- 2.019 to 2.237 Angstroms
- 2.237 to 2.456 Angstroms
- 2.456 to 2.675 Angstroms
- 2.675 to 2.894 Angstroms
- 2.894 to 3.112 Angstroms
- 3.112 to 3.331 Angstroms
- 3.331 to 3.550 Angstroms

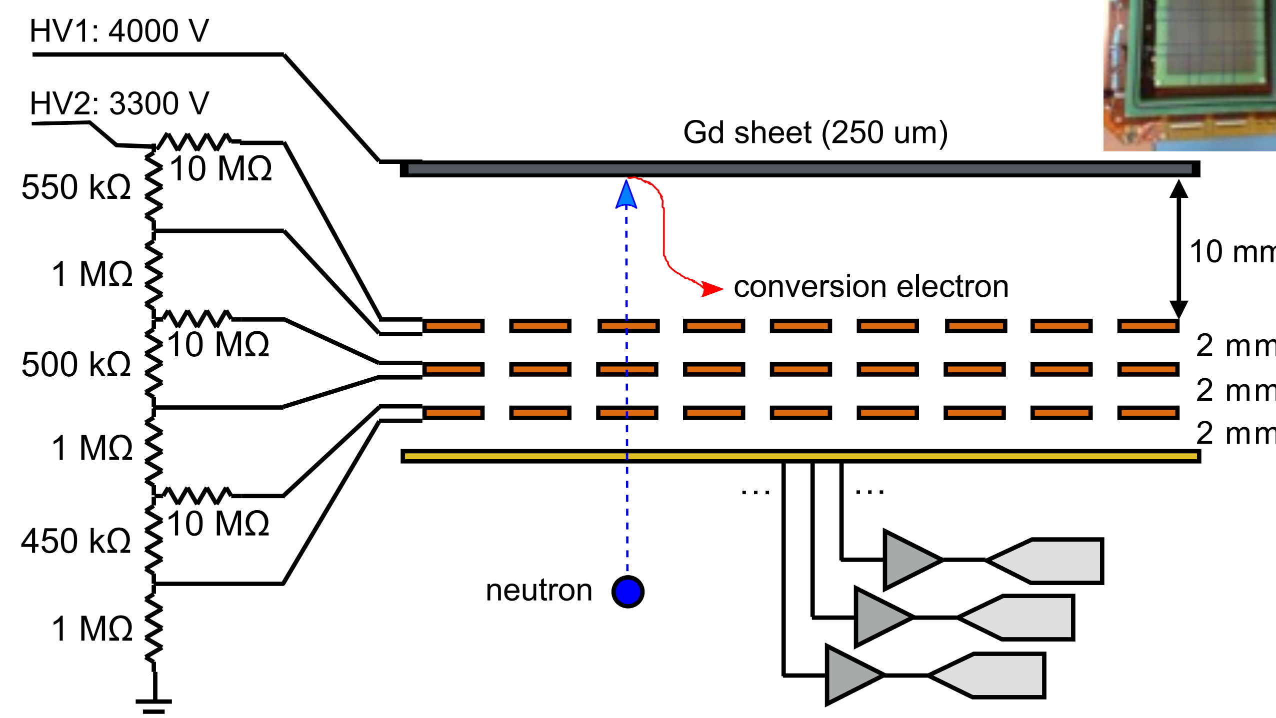
Generated using the Daresbury Laue Suite

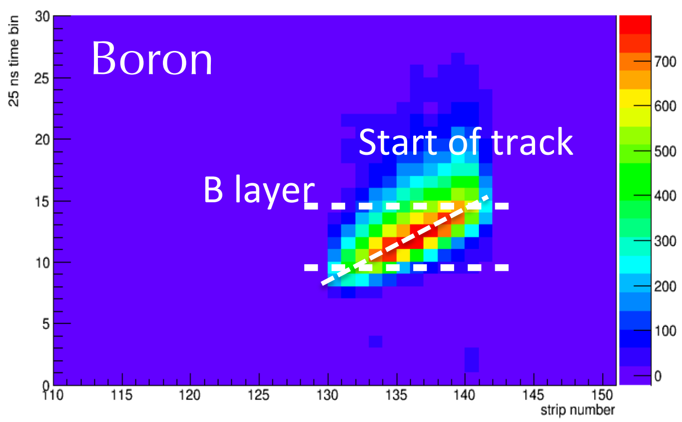
Campbell et al. J. Appl. Cryst. (1998). 31, 496-502
Artz et al. J. Appl. Cryst. (1999). 32, 554-562
Helliwell, J.R. et al. J. Appl. Cryst. (1989) 22, 483–497

Gd-GEM

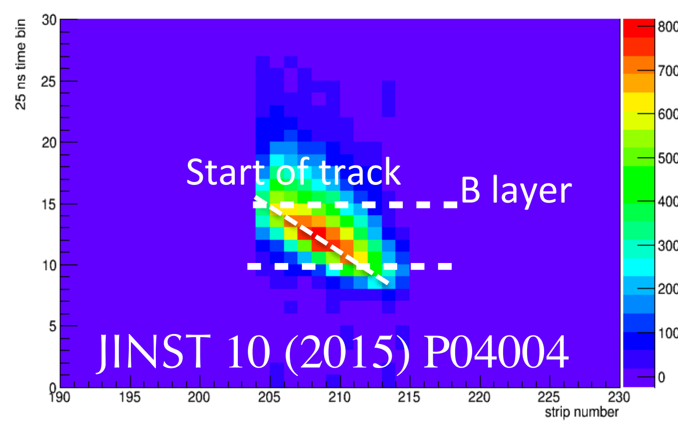


- NMX: <<1mm position resolution requirement, Time Resolved, ca. 1m^2 detector area
- Take Micro Time Projection Chamber concept from ATLAS experiment upgrade
- Resolution: use single layer Gd, look for electrons

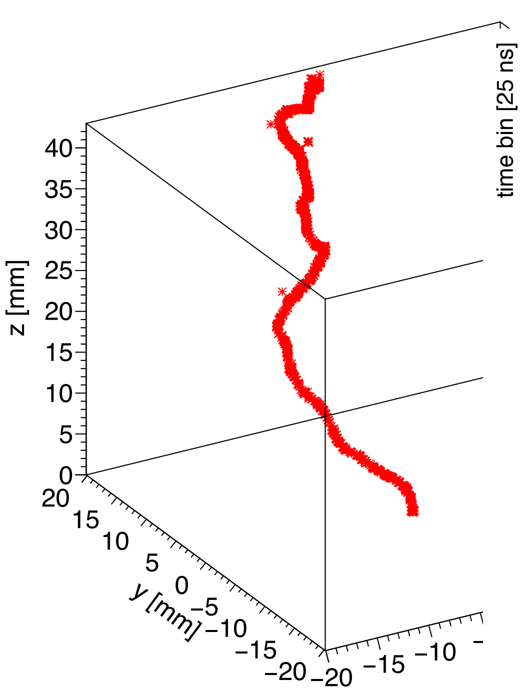


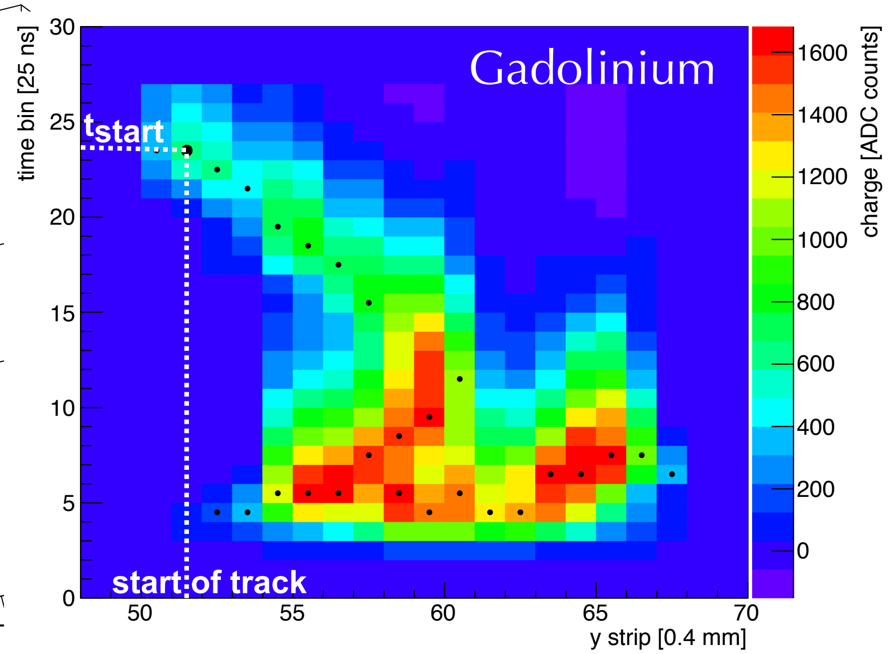


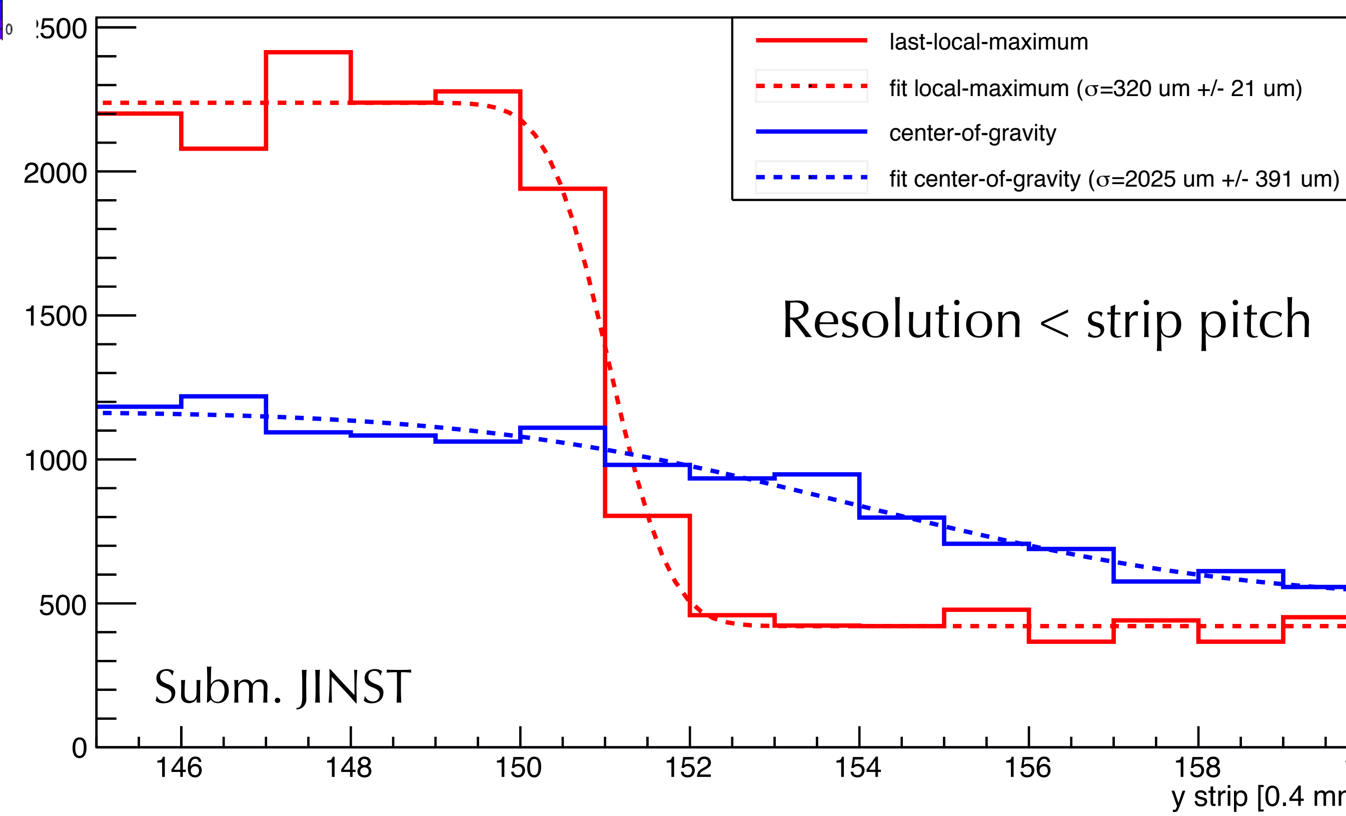
Track x



Track y







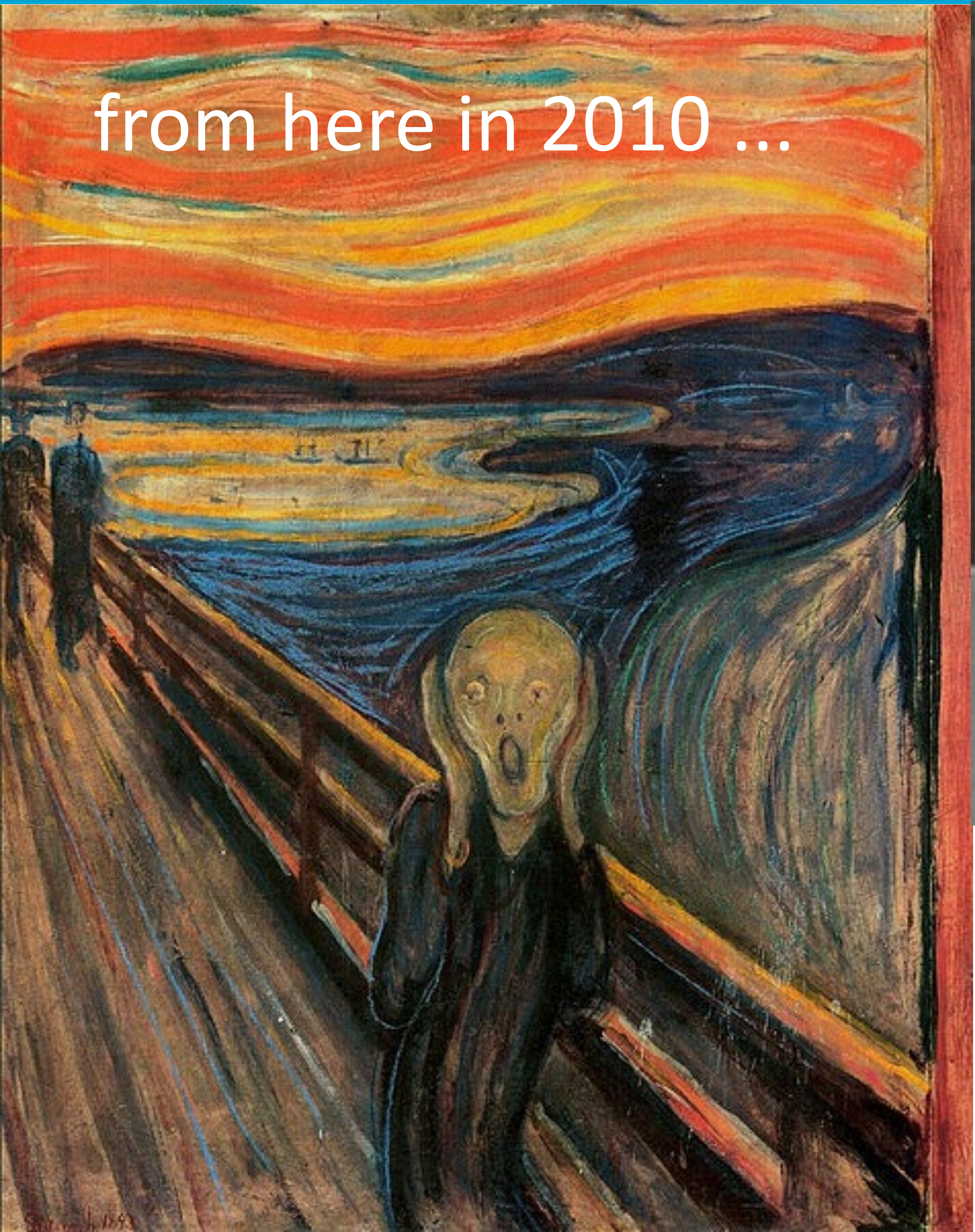
Summary

Collaborations for Construction Phase

Instrument construction started for first 3 instruments

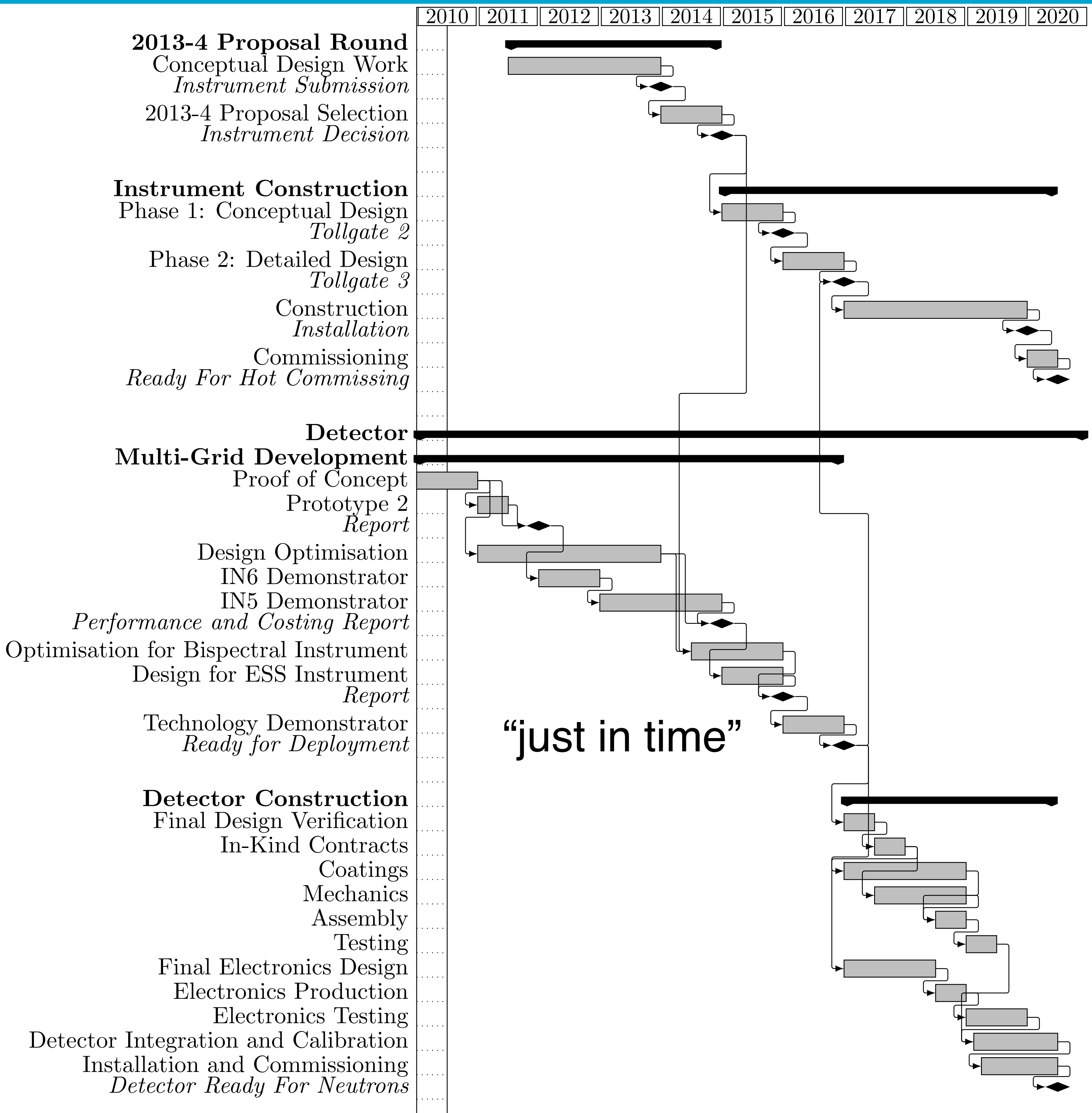
Challenge: select collaborative partners to build performant detectors

Mood Message for the R+D so far ...



- Development time is long: typically 10 years from conception to utilisation
- Solve challenges one at a time, and remain calm

Timeline for detectors



- Here is the timeline for a thermal chopper spectrometer with one concept for detector technology
- note: 10 years from concept to (potential) utilisation
- note: neither the proof of concept nor construction phases dominate the timeline, but rather the numerous prototyping and demonstration phases in between
- 2019 is tomorrow: it means that any detectors built for then are well progressed with developments now

Teamwork ...

Summary

- Huge progress from the community as a whole for solving the Helium-3 crisis
- Very significant challenges still ahead for detectors ...
- Instrument construction for ESS started ...
- Remember: typically 10 years concept to beamline
- We need to utilise the considerable expertise that exists across Europ
- Challenge is only achievable using in-kind
- Need to build up centres of excellence in Europe rather than a large numbers of all-rounders

- Used ESS as an example for how detector technologies are chosen

- Make sure that you define what you measure clearly and unambigiously
- Publish what you do: too many of the best results remain forgotten and are redone 3-10 years later