Toward next generation neutron detectors (for ESS and PIK)

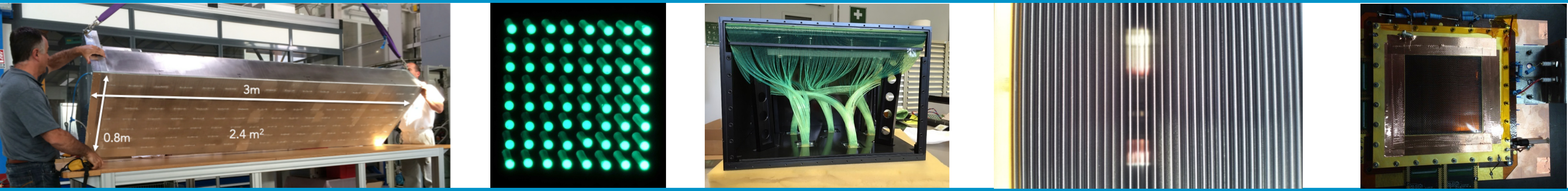
Richard Hall-Wilton

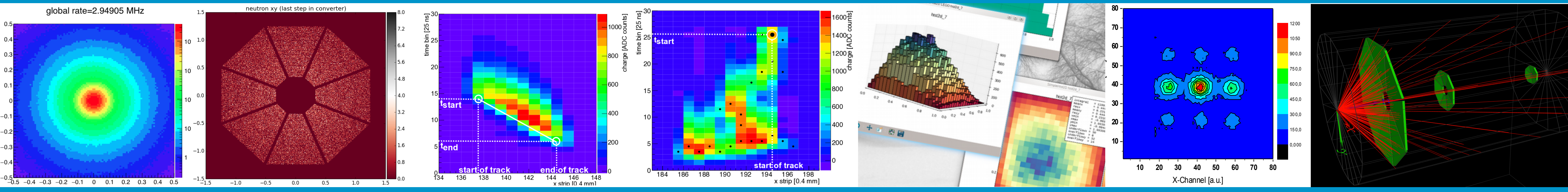
Detector Group Leader

On behalf of ESS Detector Group and Collaborators

www.europeanspallationsource.se

CREMLINPlus WP7 Meeting, 4 Sep 2020





Lighting

New materials

Solar energy

Food

Medicine

Tailor made materials

Pacemakers

Mobile phones

Cosmetics

Bio fuels

Implants

Transportation

Geo science

Neutron Science Pushes the Boundaries

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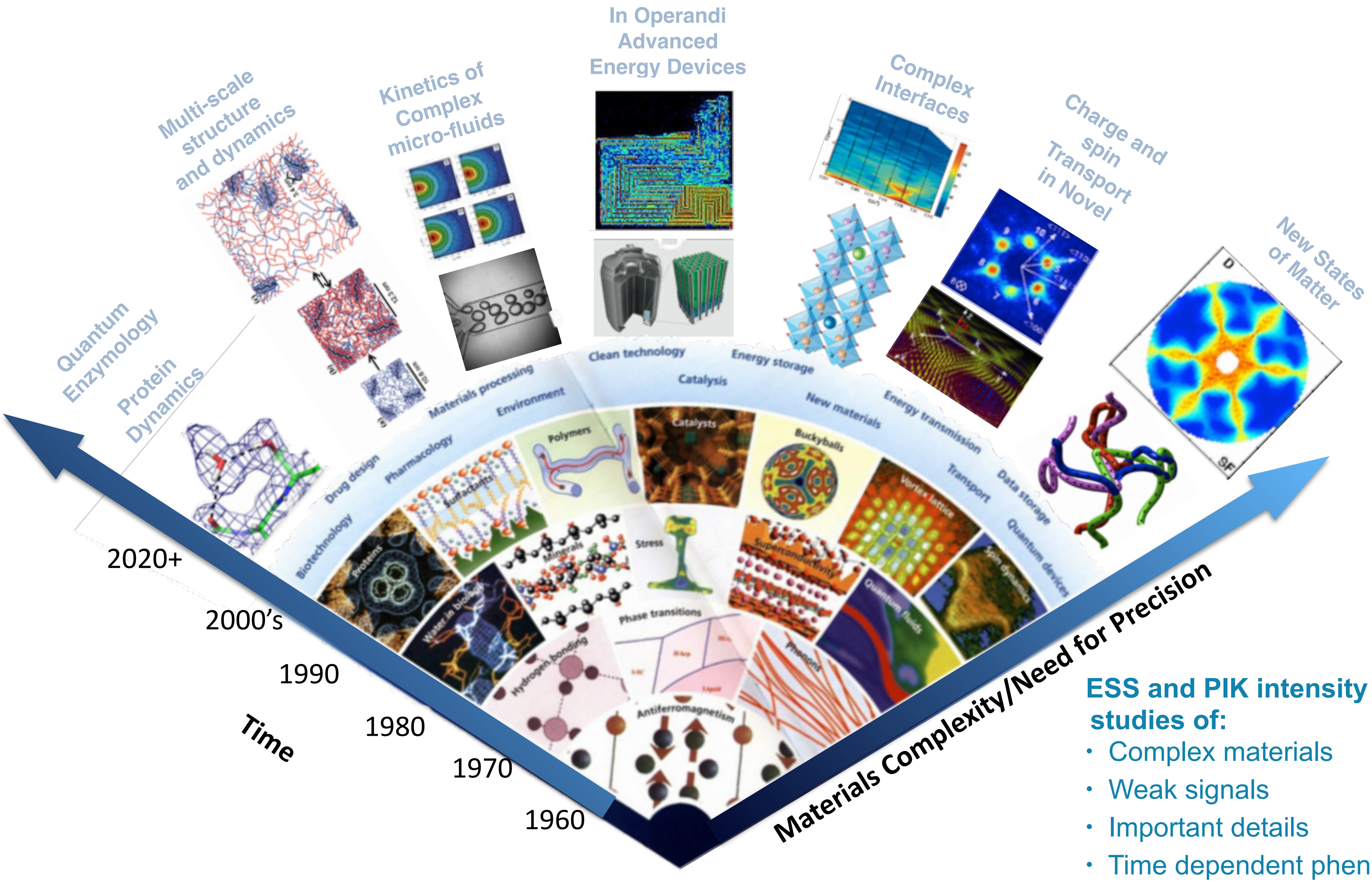
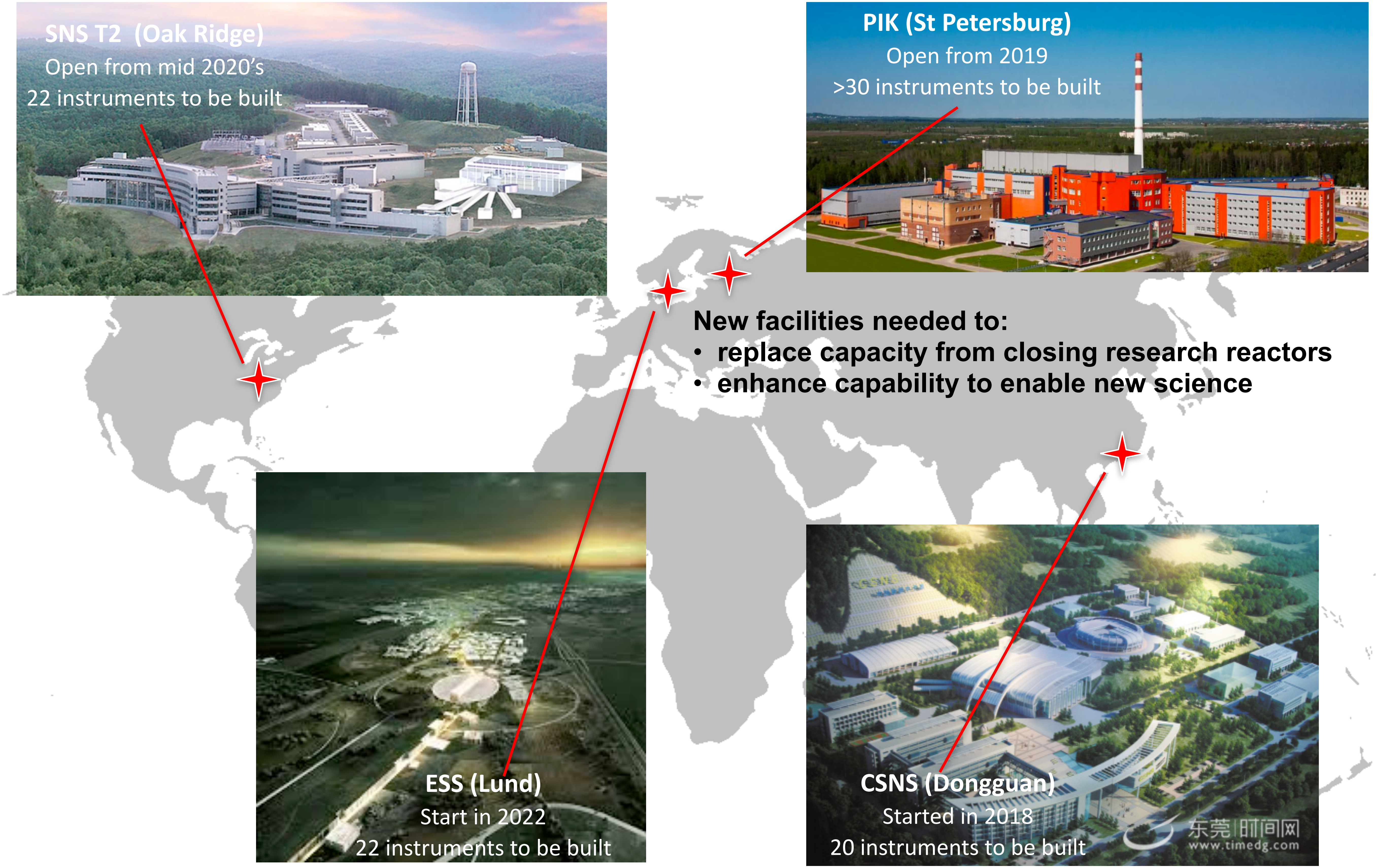


ESS and PIK intensity allows studies of:

- Complex materials
- Weak signals
- Important details
- Time dependent phenomena

Upcoming Research Facilities



SNS T2 (Oak Ridge)
Open from mid 2020's
22 instruments to be built

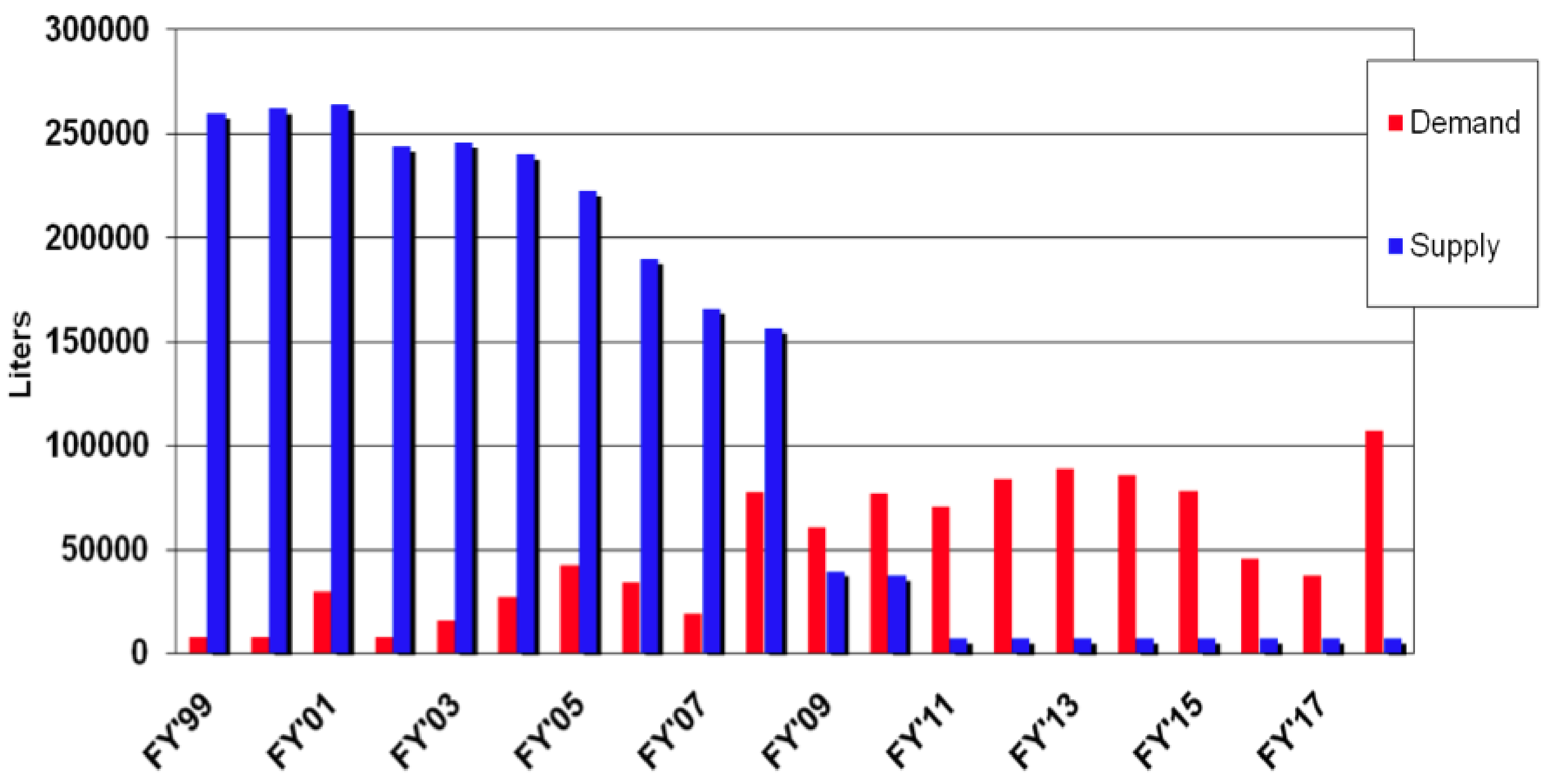
PIK (St Petersburg)
Open from 2019
>30 instruments to be built

New facilities needed to:
- **replace capacity from closing research reactors**
- **enhance capability to enable new science**

ESS (Lund)
Start in 2022
22 instruments to be built

CSNS (Dongguan)
Started in 2018
20 instruments to be built

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 … ?

….an appropriate initial reaction …

Since ca. 2009

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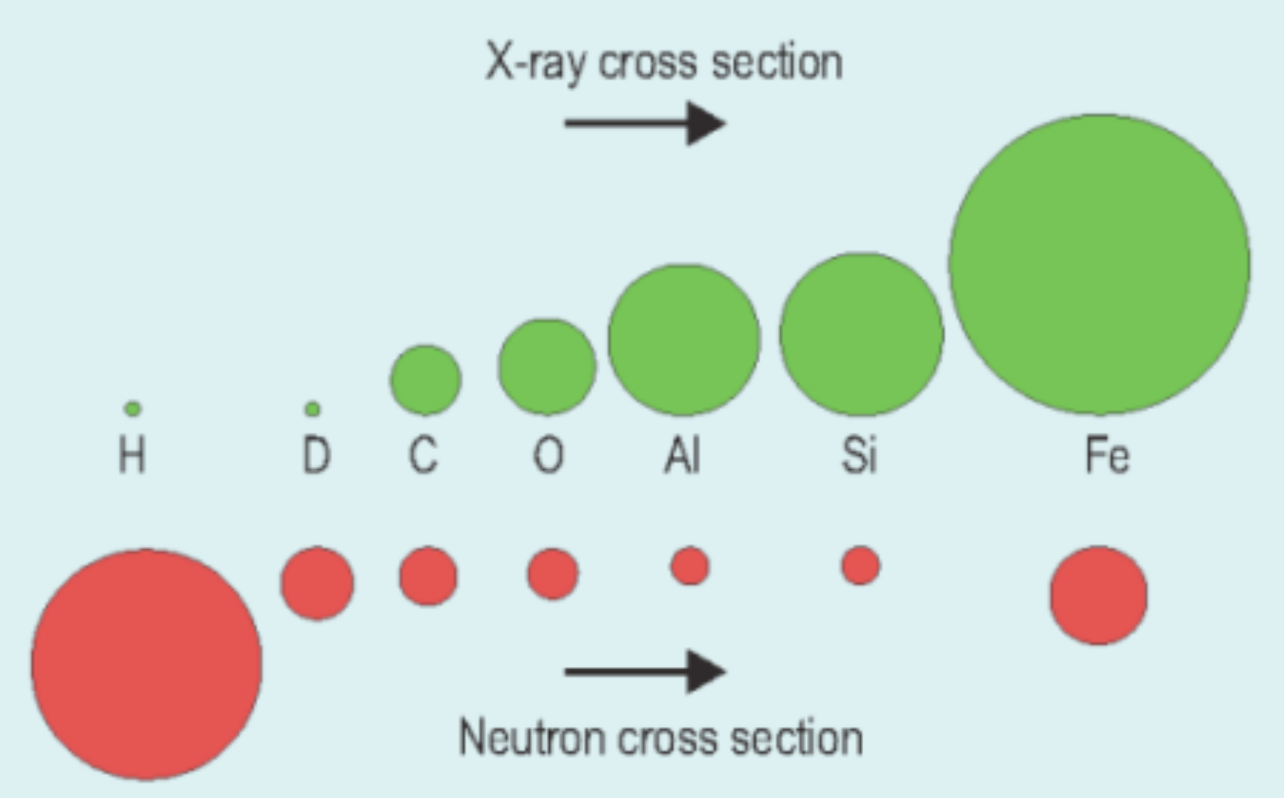
What is Neutron Scattering Science?

Why Neutrons?

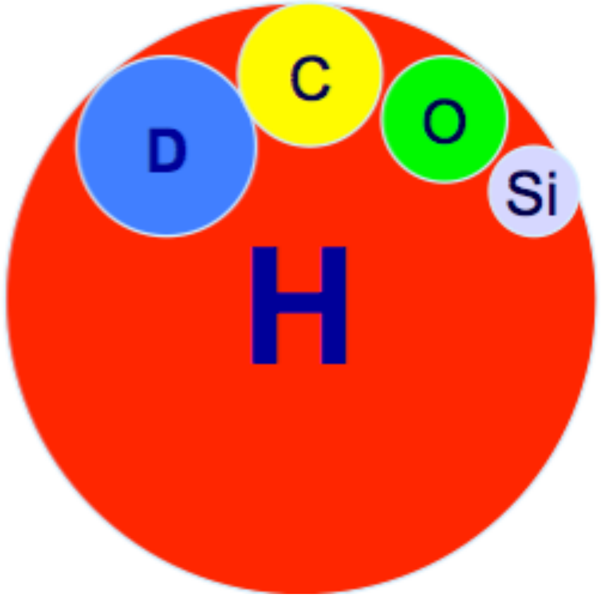
Neutrons are:

- **low energy**
- **non-damaging**
- **penetrating**
- **broad wavelength range**



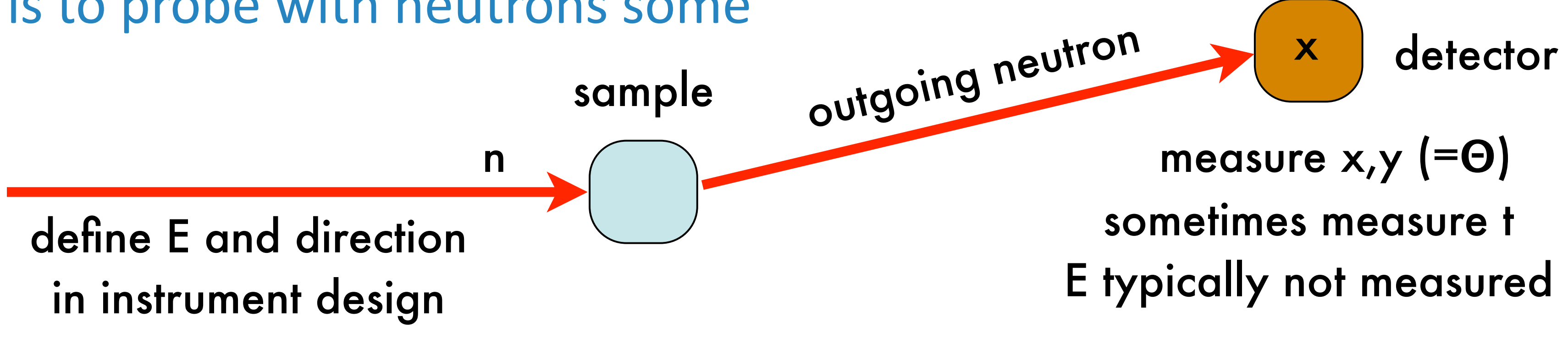
thermal and cold neutrons
meV
"with a small m"
wavelength ca. Å

1) Ability to measure both energy and momentum transfer
   Geometry of motion
2) Neutrons scatter by a nuclear interaction => different isotopes scatter differently
   H and D scatter very differently
3) Simplicity of the interaction allows easy interpretation of intensities
   Easy to compare with theory and models
4) Neutrons have a magnetic moment



Neutrons as a probe

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

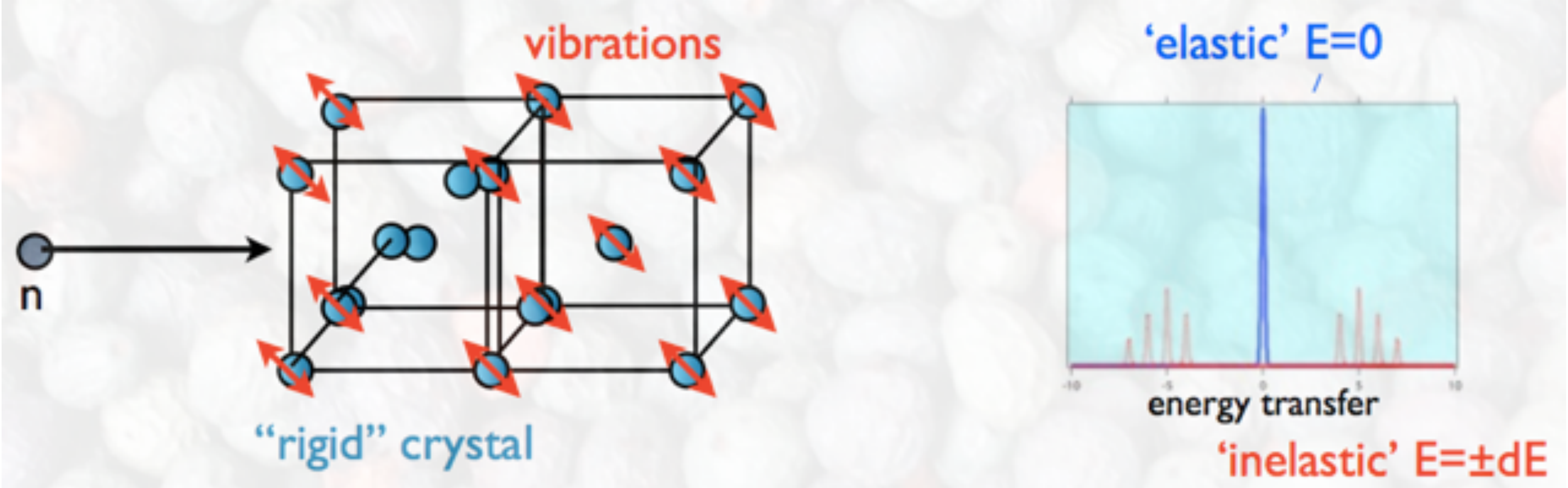


elastic $$\frac{d\sigma}{d\Omega}(\lambda, 2\theta, \psi)$$

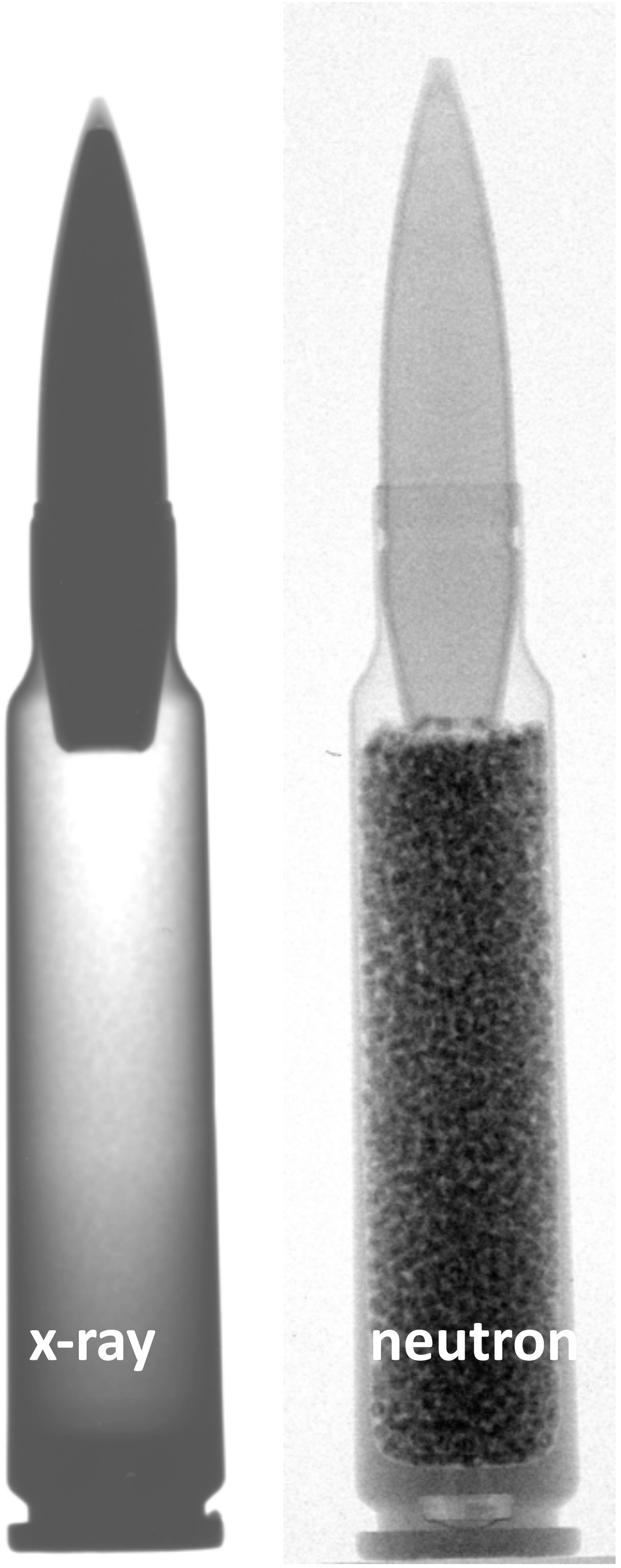
inelastic $$\frac{d^2\sigma}{d\Omega dE}(\lambda_{in}, \lambda_{sc}, 2\theta, \psi)$$

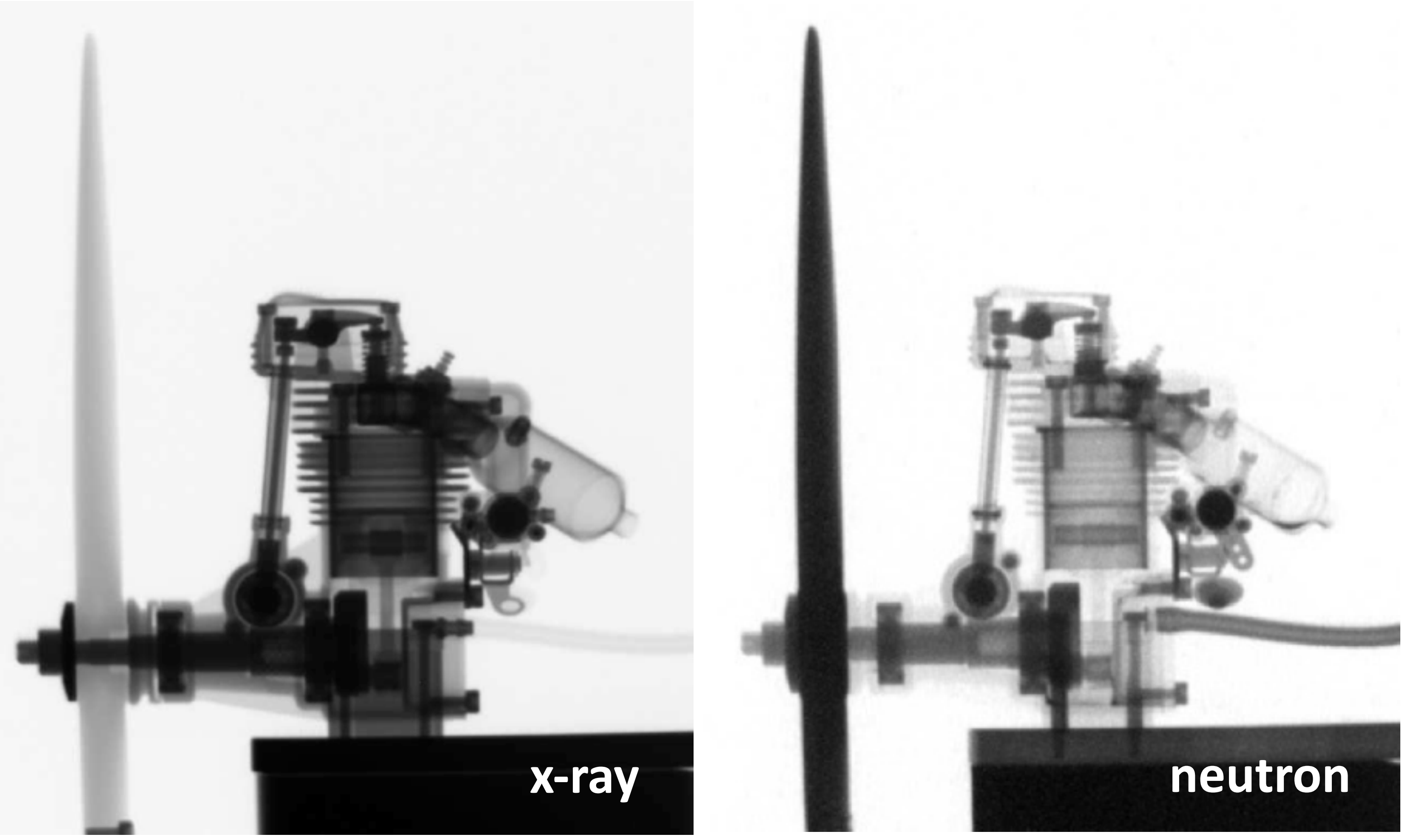
- Very generically, this can be divided into elastic and inelastic categories
  - elastic: gives information on where atoms are
  - inelastic: gives information on what atoms do (i.e., move)

Elastic vs Inelastic



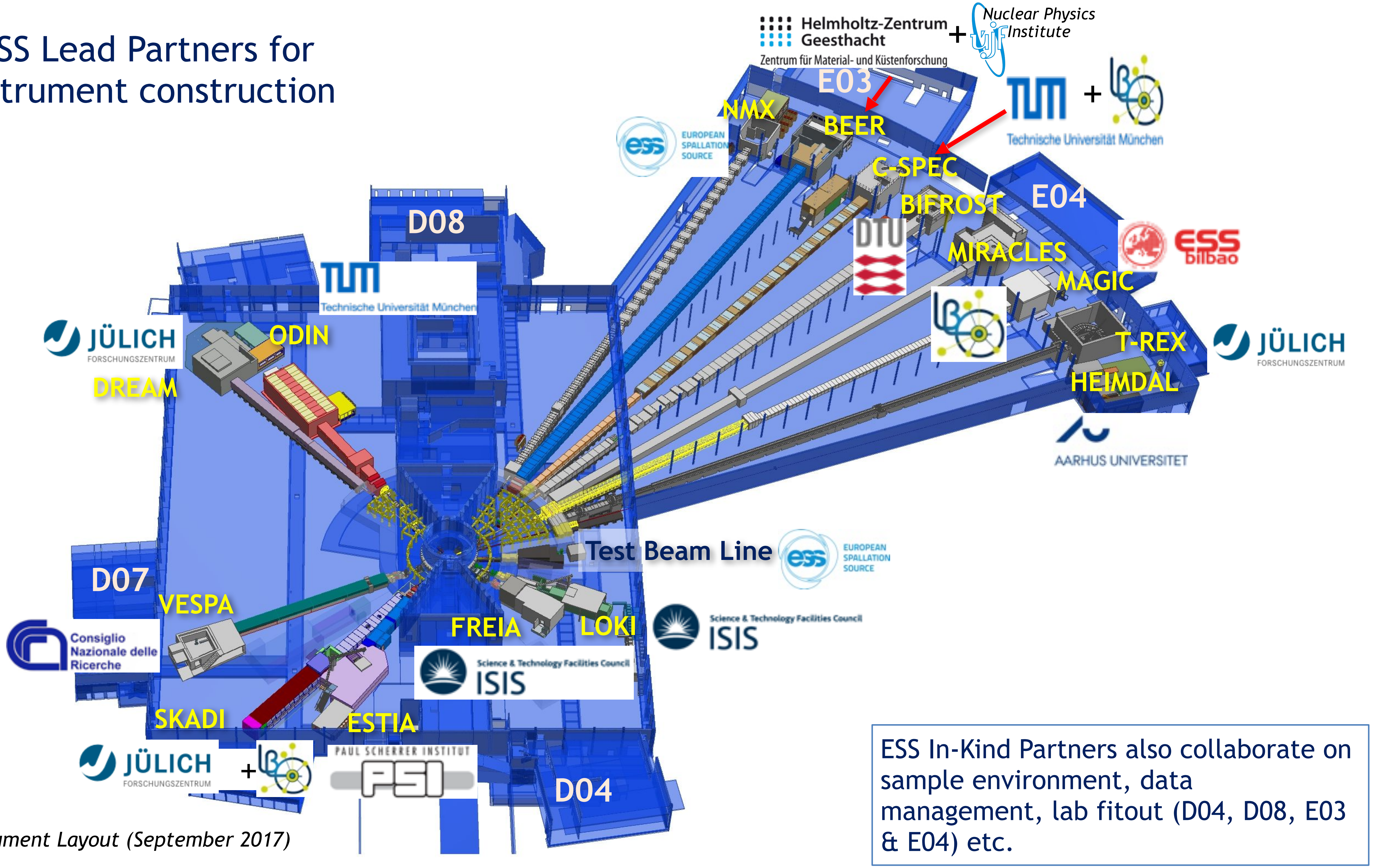
Neutrons see the Light Elements





NSS Project scope: *15 neutron instruments + test beamline + support labs*

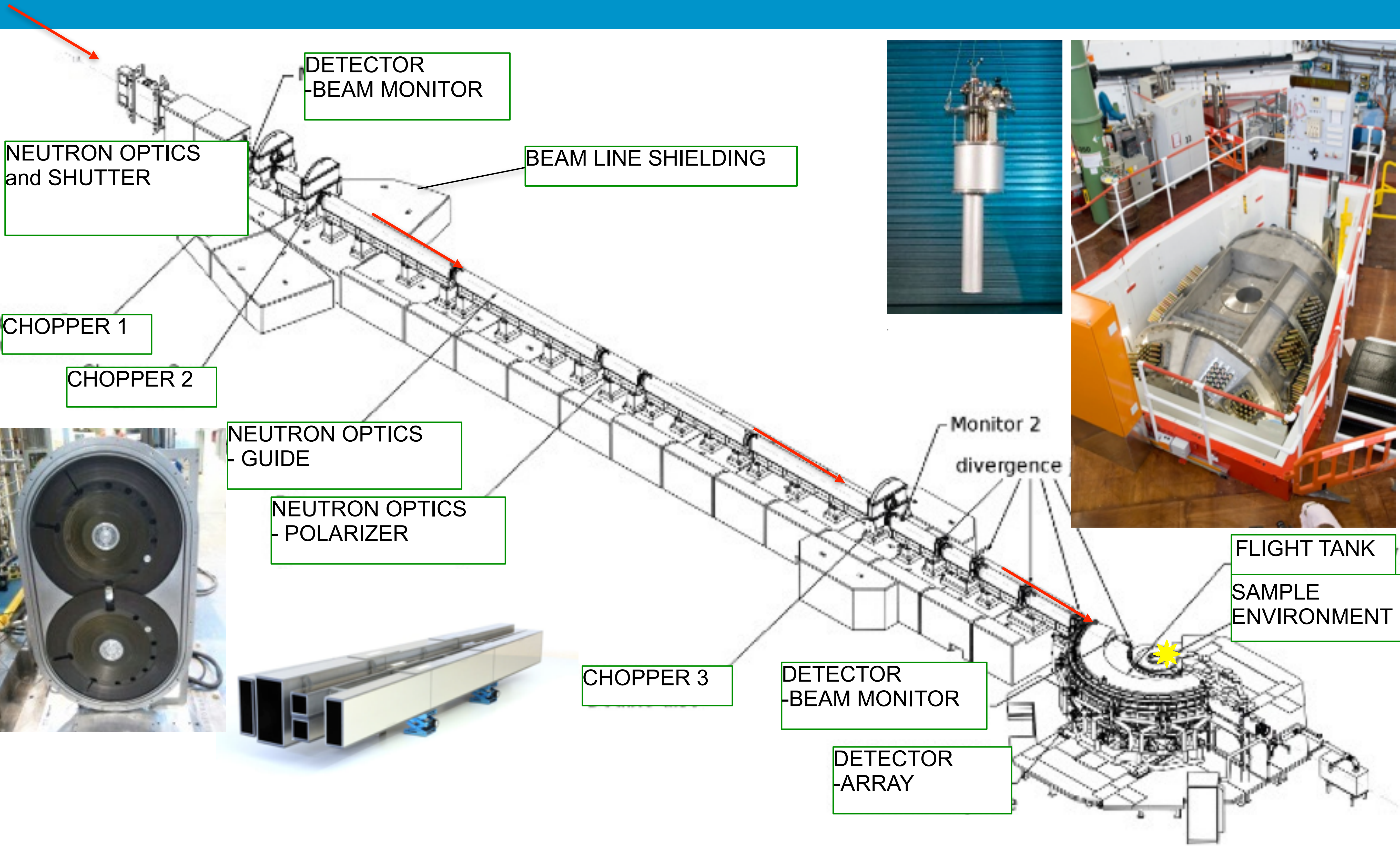
ESS Lead Partners for instrument construction



ESS Instrument Layout (September 2017)

ESS In-Kind Partners also collaborate on sample environment, data management, lab fitout (D04, D08, E03 & E04) etc.

Layout of a Neutron Instrument



DETECTOR
-BEAM MONITOR

NEUTRON OPTICS
and SHUTTER

BEAM LINE SHIELDING

CHOPPER 1

CHOPPER 2

NEUTRON OPTICS
- GUIDE

NEUTRON OPTICS
- POLARIZER

CHOPPER 3

DETECTOR
-BEAM MONITOR

DETECTOR
-ARRAY

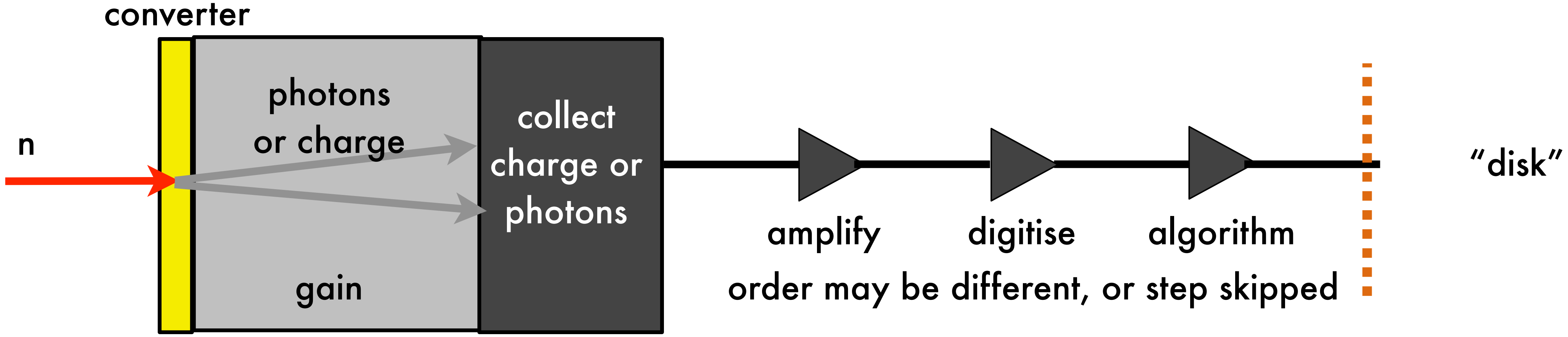
FLIGHT TANK

SAMPLE
ENVIRONMENT

Neutron Detectors

Neutron Detectors

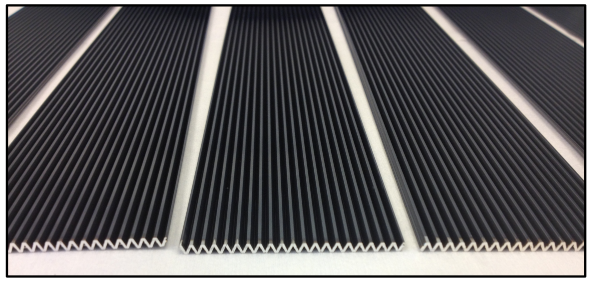
Efficient neutron converters a key component for neutron detectors



"Converter"

"Detector"

"Electronics"



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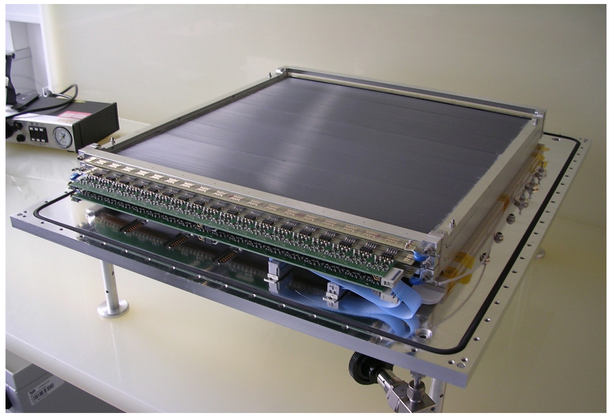

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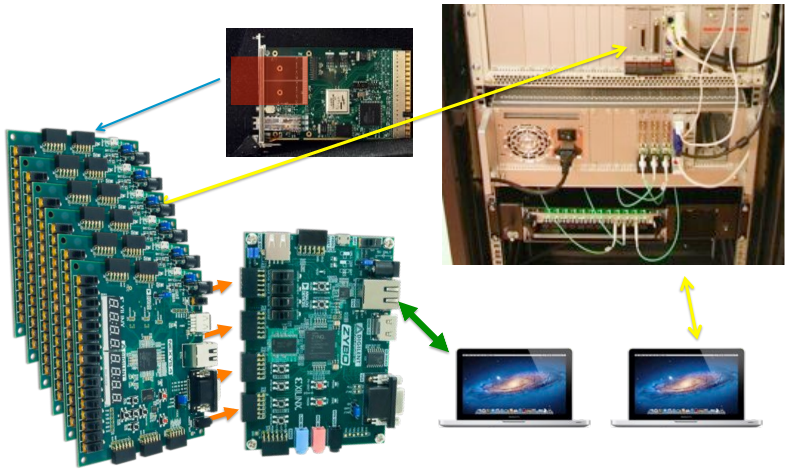
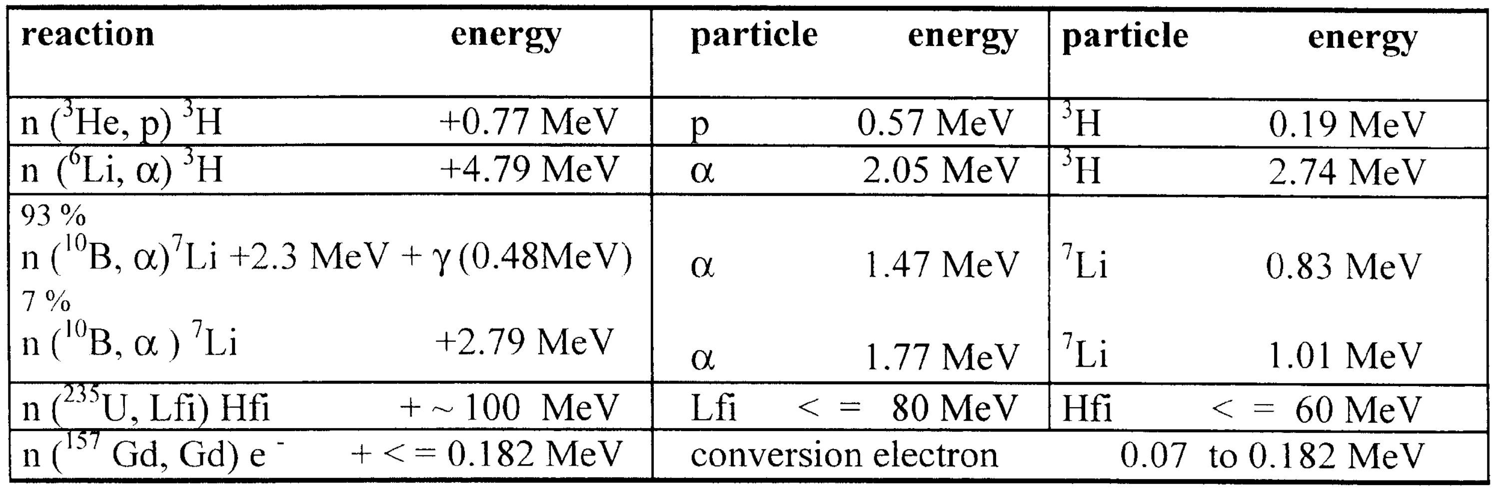


Isotopes Suitable as Cold and Thermal Neutron Convertors



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

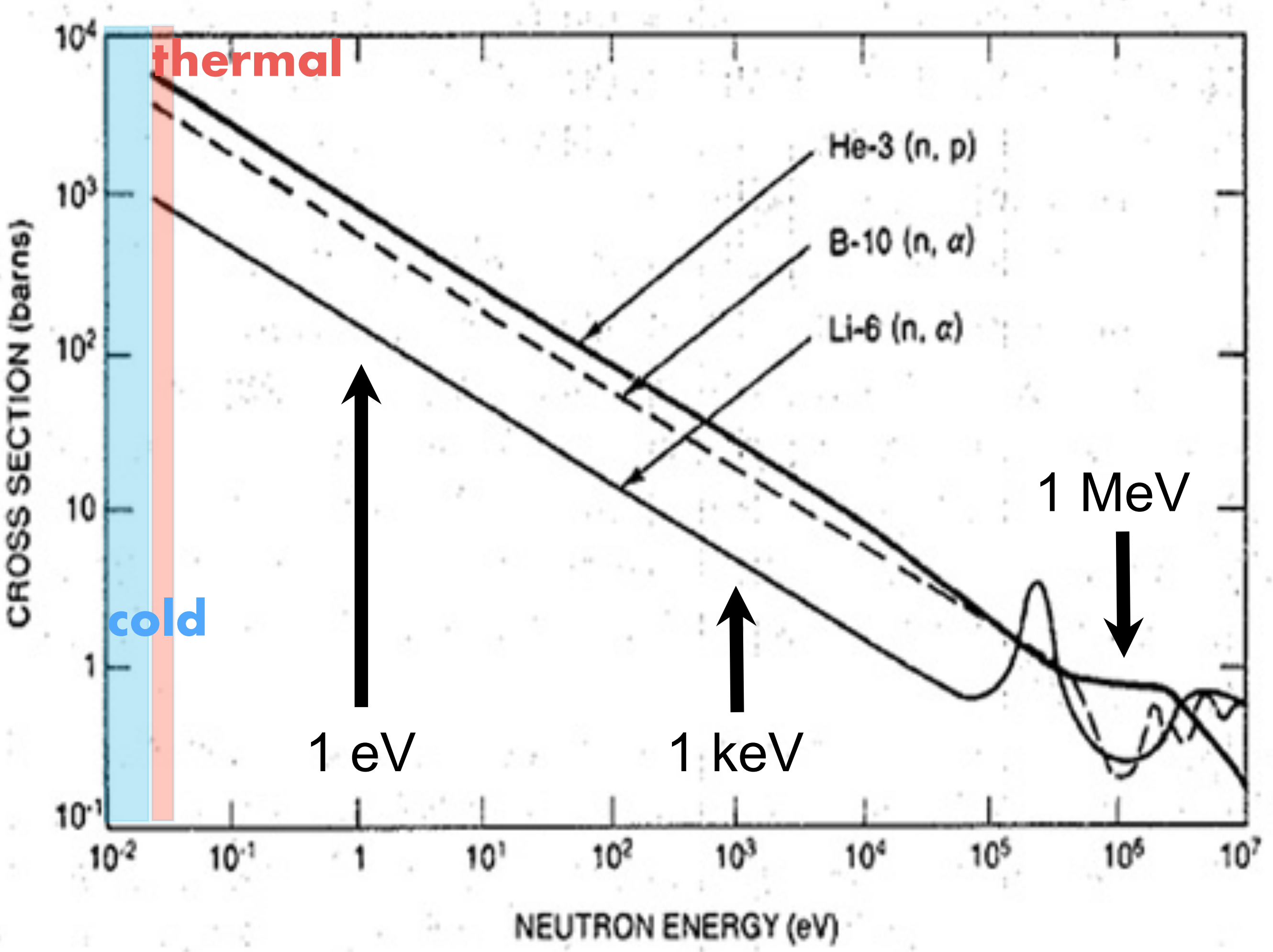
Table 1: Commonly used isotopes for thermal neutron detection, reaction products and their kinetic energies.

ILL Blue Book

- 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



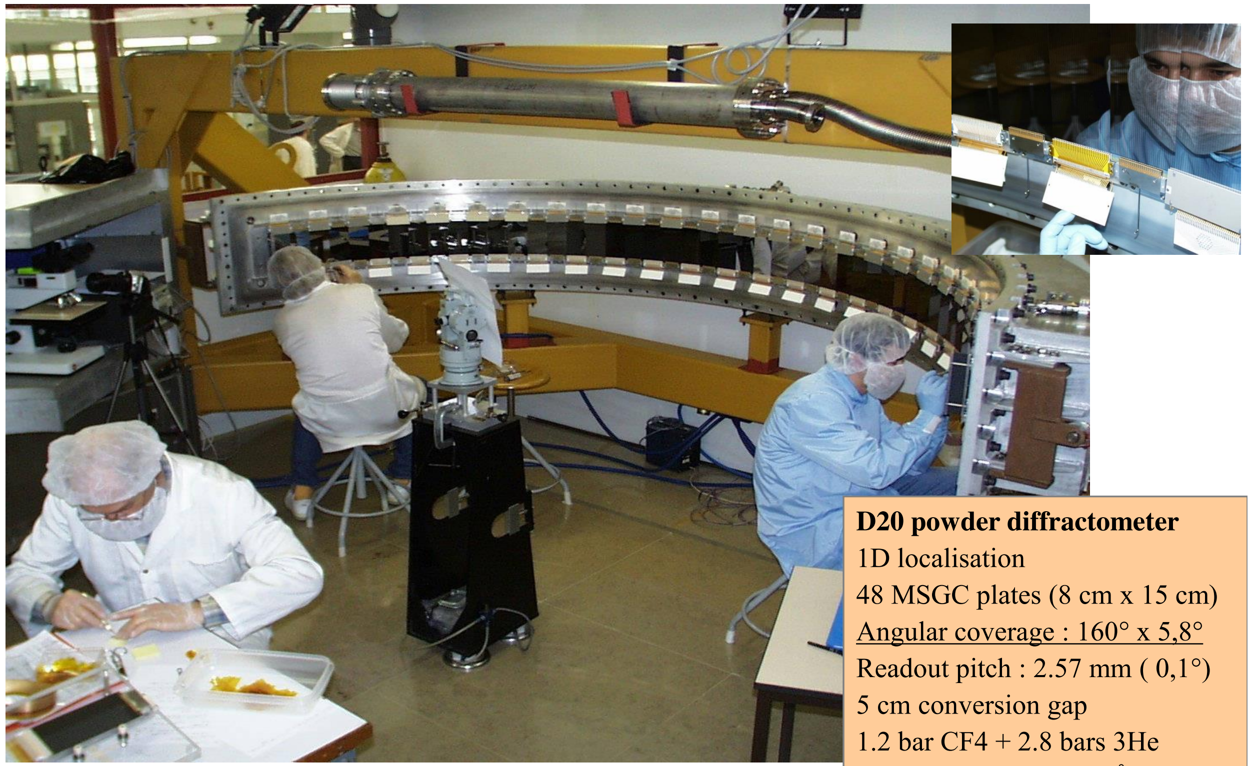
State of the Art of Neutron Detectors

- 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


can be large arrays of 10s of m^2

IN5@ILL

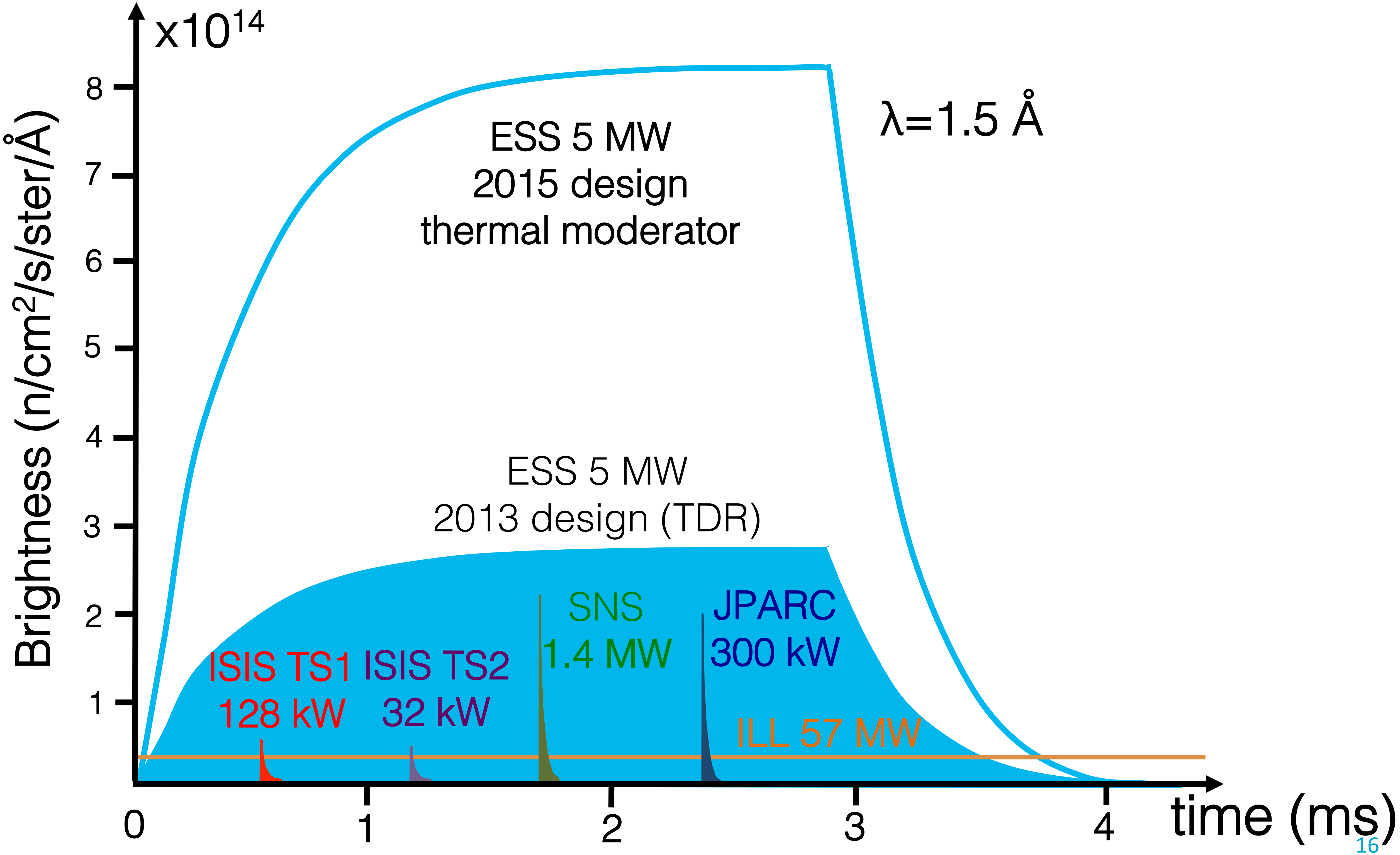
Curved 1D MSGC for the D20 Powder Diffractometer (2000)



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 CF4 + 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

Challenge for Rate



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

What can be done with this brightness?

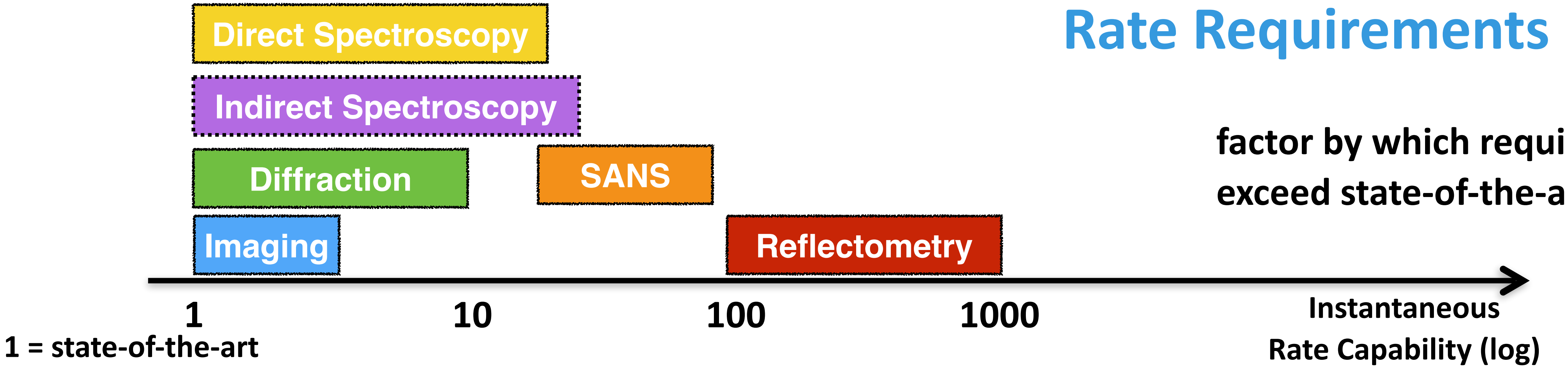
What does a factor 10 improvement imply for the detectors?

Implications for Detectors	Implications for Detectors
Better Resolution (position and time)	sqrt(10)
Channel count	pixelated: factor 10 x-y coincidence:sqrt(10)
Rate capability and data volume	factor 10
Lower background, lower S:B Larger dynamic range	Keep constant implies: factor 10 smaller B per neutron
Larger area coverage Lower cost of detectors	Factor of a few

Developments required for detectors for new Instruments

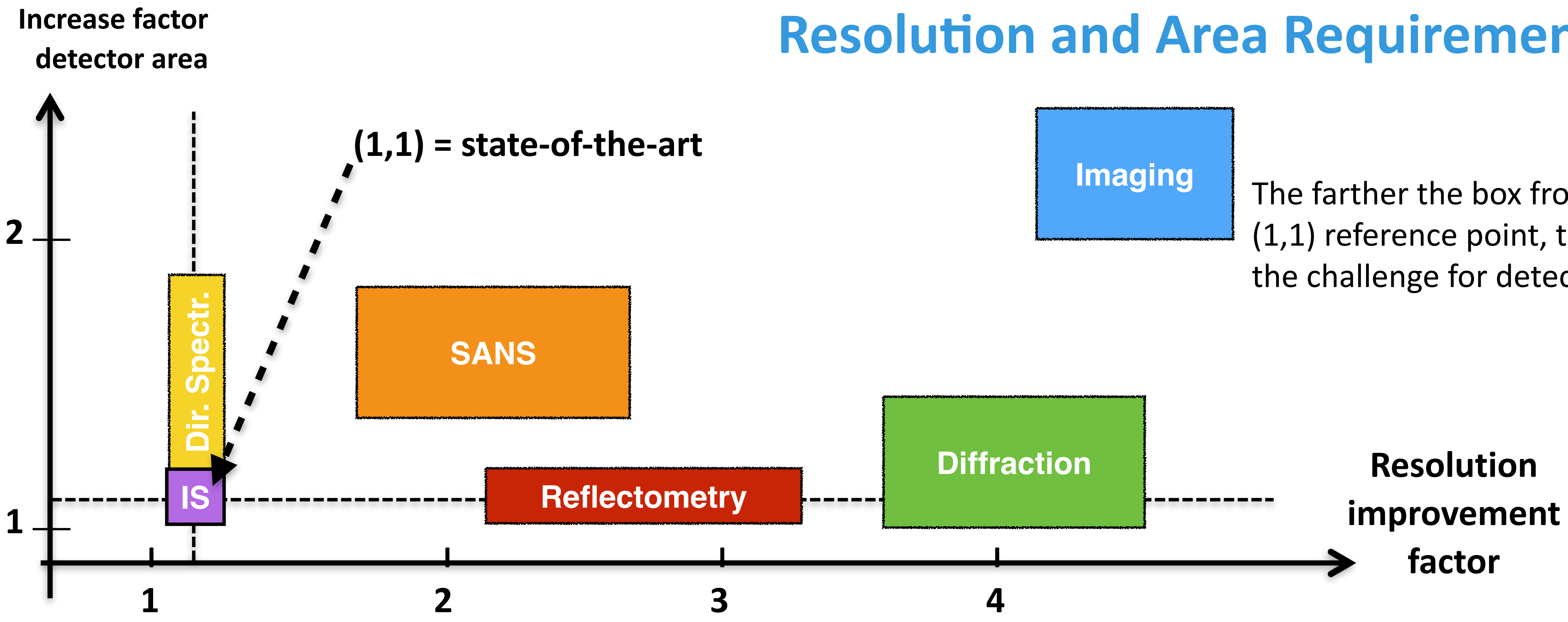
Requirements Challenge for Detectors for ESS: *beyond detector present state-of-the art*

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.

Baseline Detector Technologies for Initial Suite

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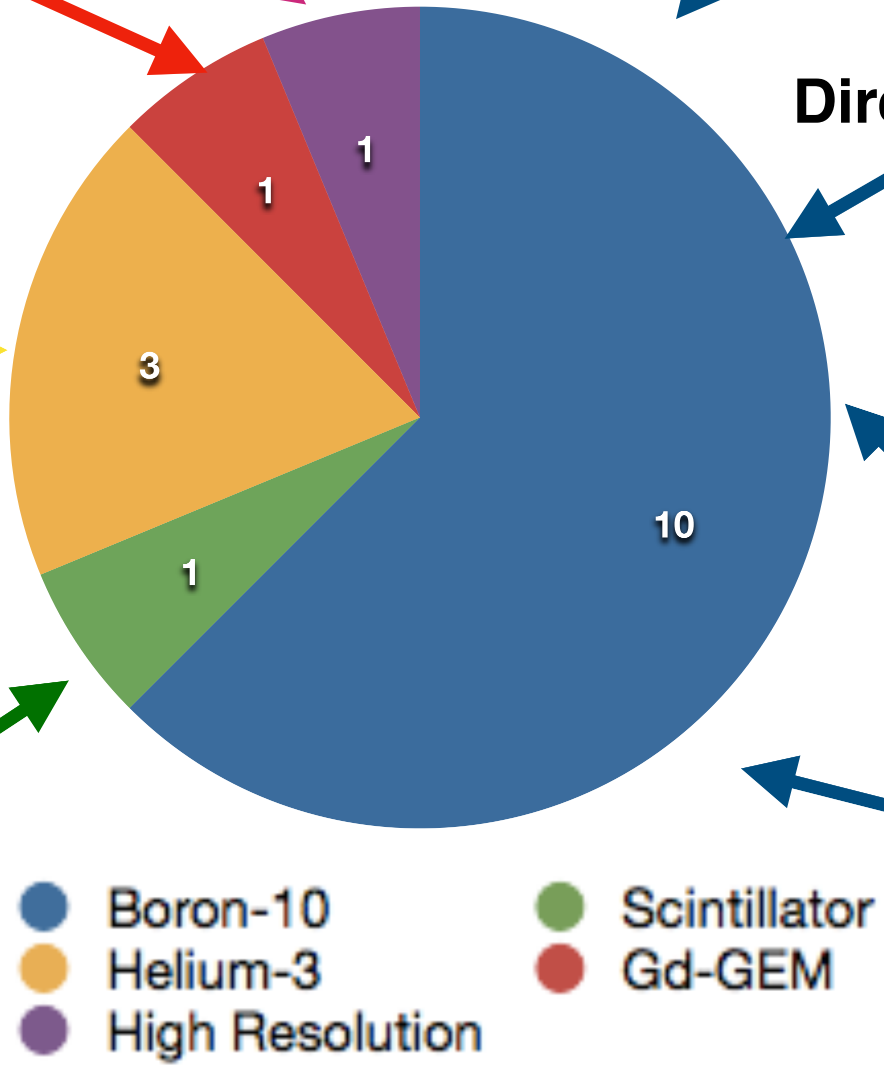
Detectors for ESS will comprise many different technologies

Imaging: 1 instrument
Various

NMX: 1 instrument
Gd-GEM

Indirect Spectroscopy: 3 instruments
He-3 PSD Tubes

SANS: 1 instruments
SoNDe



Diffraction: 4 instruments
Jalousie (3)
Am-CLD (1): B-10 MWPC

Direct Spectroscopy: 3 instruments
Multi-Grid

Reflectometry: 2 instruments
Multi-Blade

SANS: 1 instrument
Boron Coated Straws

Detectors for ESS: baseline for selected instruments

EUROPEAN SPALLATION SOURCE

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, area	Pixellated Scintillator	SonDe (EU SonDe)
		LOKI		10B-based	Boron Coated Straws
	Reflectometry	FREIA	Pixel size, count-rate	10B-based	MultiBlade (EU BrightnESS)
		ESTIA			
Diffraction	Powder diffraction	DREAM	Pixel size, count-rate	10B-based	Jalousie
		HEIMDAL		10B-based	Jalousie
	Single-crystal diffraction	MAGIC	Pixel size, count-rate	10B-based	Jalousie
		NMX	Pixel size, large area	Gd-based	GdGEMuTPC(EU)
Engineering	Strain scanning	BEER	Pixel size, count-rate	10B-based	AmCLD, A1CLD (HZG)
	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	He-3 PSD Tubes
		MIRACLES			He-3 PSD Tubes
		VESPA	Count-rate	3He-based	He-3 PSD Tubes
SPIN-ECHO	Spin-echo	tbd	tbd	3He-based/10B-based	

arXiv:1411.6194

Good dialogue and close collaboration needed for successful delivery and integration

Backgrounds

Background Observed in Detector = Background Flux at Detector X Sensitivity to Background

- Important in the design to reduce the background flux at the detector position
- (Don’t just design shielding for Radio Protection Concerns)
- Different Sensitivity to different background components
- Sensitivity is a function of Energy

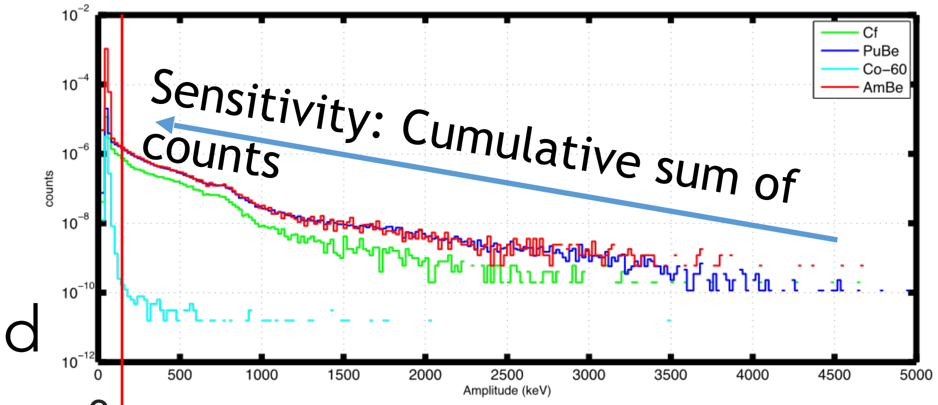
- There are many contributions to backgrounds:
- Non-Source Background:
  - Electronic noise: just needs to be eliminated
  - Cosmics, natural etc: shield locally and avoid local moderation
  - Alpha background from U and Th (esp. in Al): *A. Khaplanov et al., JINST 10 P10019 (2015) arXiv:1507.00607*

- Source-related background:
  - Gamma sensitivity: *A. Khaplanov et al., JINST 8, P10025 (2013) arXiv:1306.6247*
  - Fast Neutron sensitivity (Boron): *G. Mauri et al., JINST 13 P03004 (2018) arXiv:1712.05614*
  - Fast Neutron sensitivity (He3): *G. Mauri et al., subm. EPJ TI, arXiv:1902.09870*
  - Modelling local scattering: *E. Dian et al., NIM A 902 (2018) 173 arXiv:1801.05686*

E. Dian et al., "Suppression of intrinsic neutron background in the Multi-Grid detector", JINST 14 (2019) P01021, arXiv:1810.08706
G. Galgóczi et al., "Investigation of neutron scattering in the Multi-Blade detector with Geant4 simulations", JINST 13 (2018) P12031, arXiv: 1810.06241
M. Klausz et al., “Performance evaluation of the Boron Coated Straws detector with Geant4”, subm. NIM A, arXiv:1904.05082

Some Thoughts on Background

Fast neutron sensitivity



Sensitivity: Cumulative sum of counts

G. Mauri et al., Fast neutron sensitivity of neutron detectors based on boron-10 converter layers. [arXiv:1712.05614](https://arxiv.org/abs/1712.05614) JINST 13 P03004 (2018)

G. Mauri et al., Evidence of fast neutron sensitivity for 3He detectors and comparison with Boron-10 based neutron detectors, *subm. EPJ TI (2019), arXiv:1902.09870*

100 keV threshold

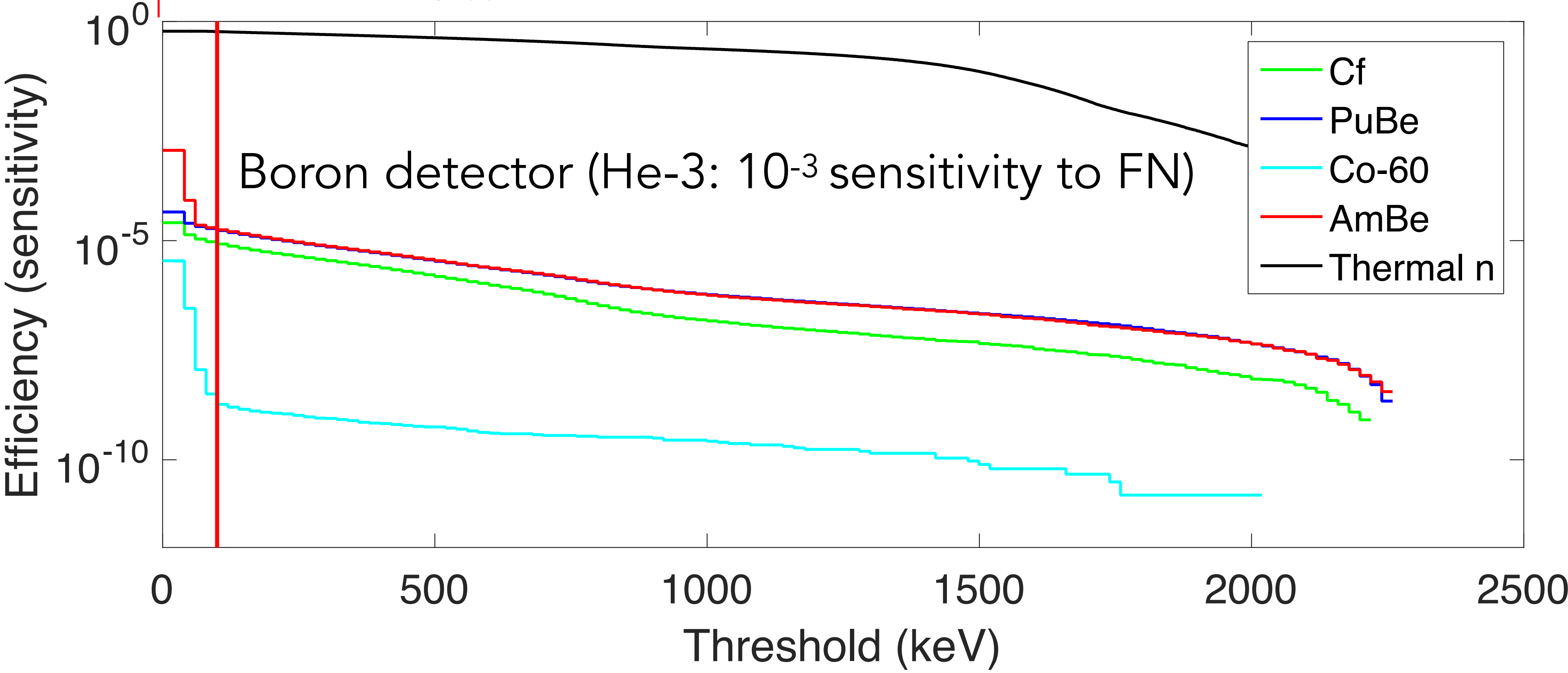
Thermal neutron ~0.6

Fast neutron ~ 10^{-5}

* first characterization for a thermal n detector

Gamma ~10^{-8}

✓ Agreement with previous work



Boron detector (He-3: 10^{-3} sensitivity to FN)

At the detector*, it is 100 times more important to remove *fast neutrons* than *gamma

At the detector*, it is 10000 times more important to prevent *scattering and local thermalisation* than remove *fast neutrons

Historically the emphasis has been opposite

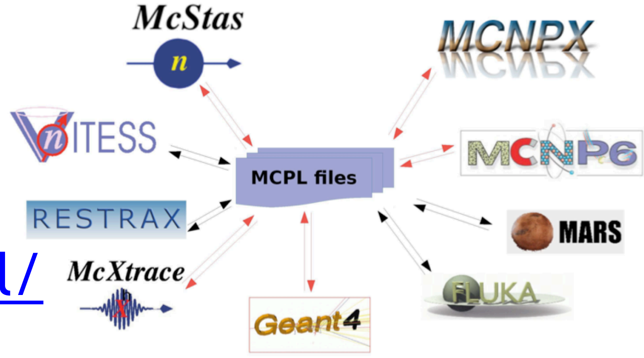
Simulation tools

- New tools & utilities are recently developed for neutron studies
  - Physics
    - Coherent scattering
    - Inelastic scattering
    - Single- and poly-crystals…
  - And more
    - Communication
    - Visualisation
    - Ready-to use…

NXSG4
doi:10.1016/j.cpc.2014.11.009
http://nxsg4.web.cern.ch/nxsg4/

NCrystal
https://github.com/mctools/ncrystal/wiki

MCPL -
Monte Carlo Particle List
https://mctools.github.io/mcpl/

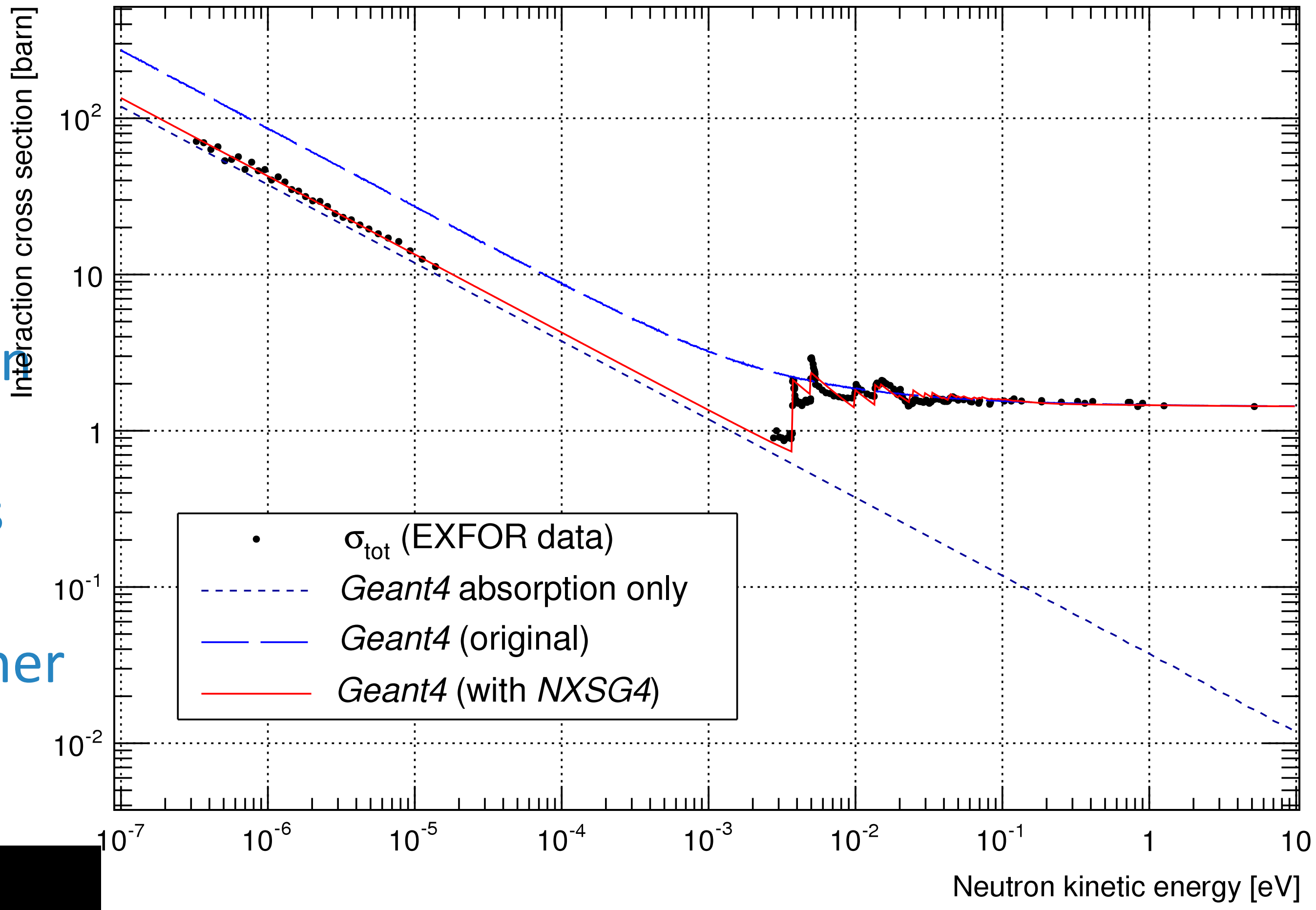


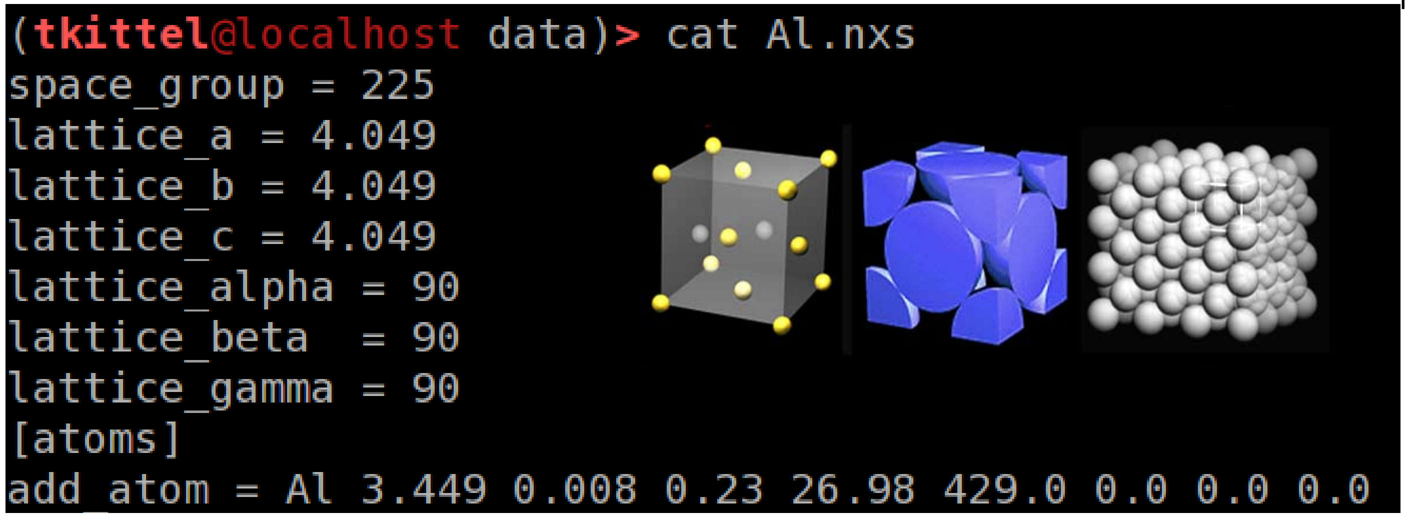
ESS Coding Framework -
Geant4 simulation framework Developed by ESS Detector Group
doi:10.1016/S0168-9002(03)01368-8
doi:10.1088/1742-6596/513/2/022017

K. Kanaki et al., "Simulation tools for detector and instrument design", Physica B https://doi.org/10.1016/j.physb.2018.03.025 arXiv.org:1708.02135

Neutron diffraction in polycrystalline materials: Add-on for GEANT4

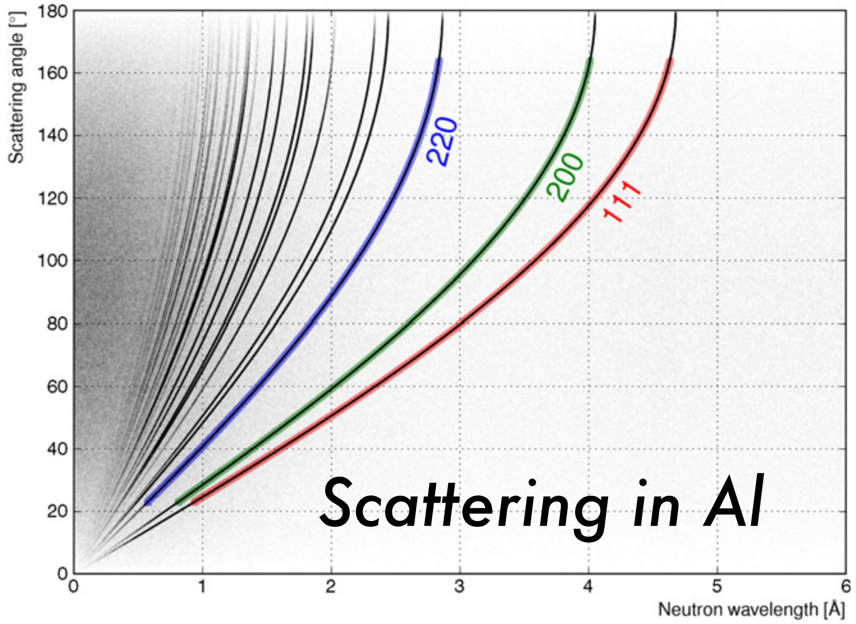
- GEANT4 is an invaluable simulation tool
- However, thermal/cold neutrons not well validated
- No support for crystal diffraction
- A new plugin NXSG4 allows neutron diffraction in polycrystalline materials
- Based upon nxs library, used in McStas, Vitess
- Using simple unit cell parameters, only low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



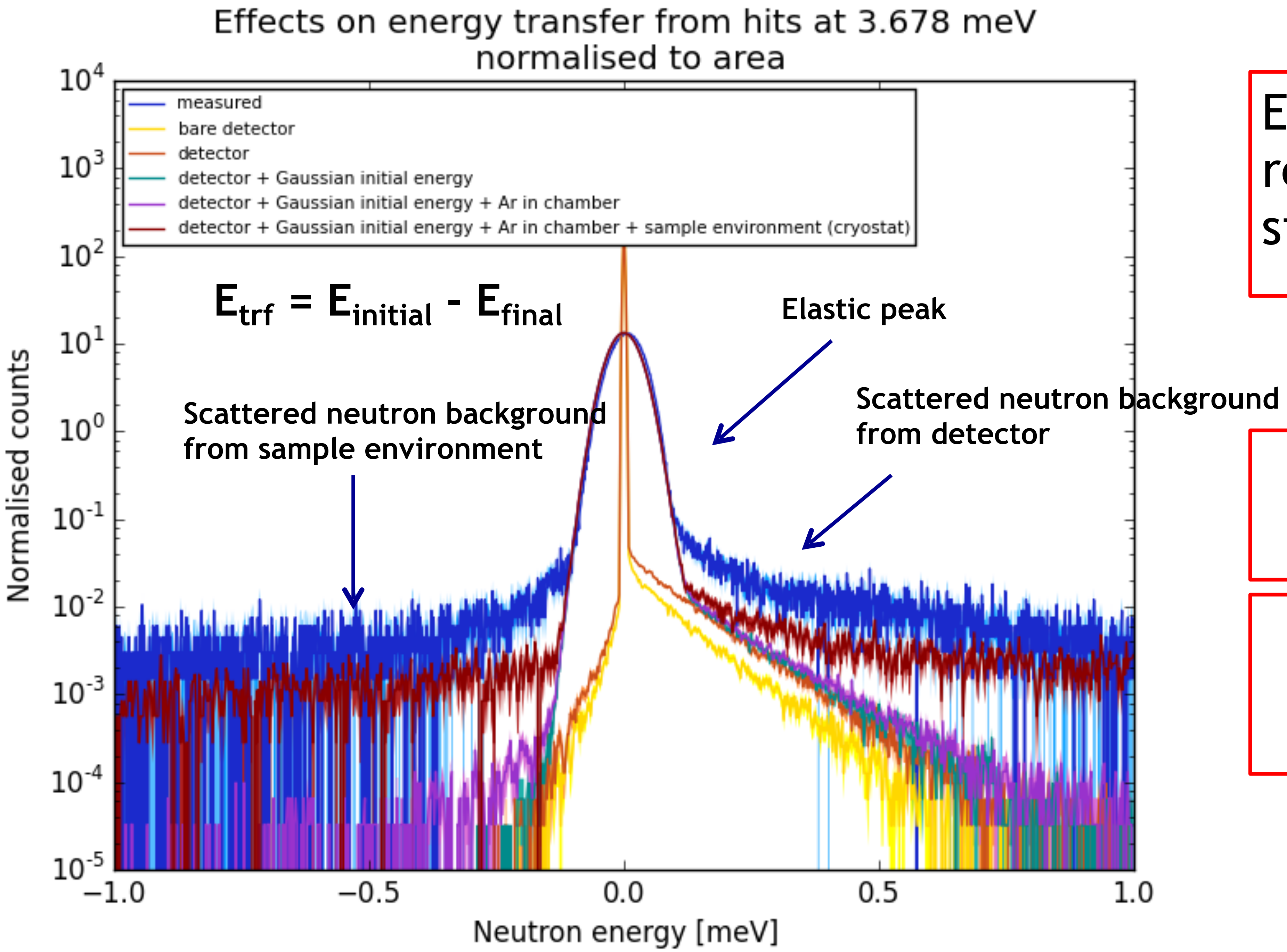


```
(tkittel@localhost data)> cat Al.nxs
space_group = 225
lattice_a = 4.049
lattice_b = 4.049
lattice_c = 4.049
lattice_alpha = 90
lattice_beta  = 90
lattice_gamma = 90
[atoms]
add_atom = Al 3.449 0.008 0.23 26.98 429.0 0.0 0.0 0.0
```

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



MultiGrid detector test at CNCS, SNS



Validation

Energy transfer reproduced with simulation at 3.678 meV ✓

Distinguish different sources of background

Detailed analysis and quantification of background effects

↓

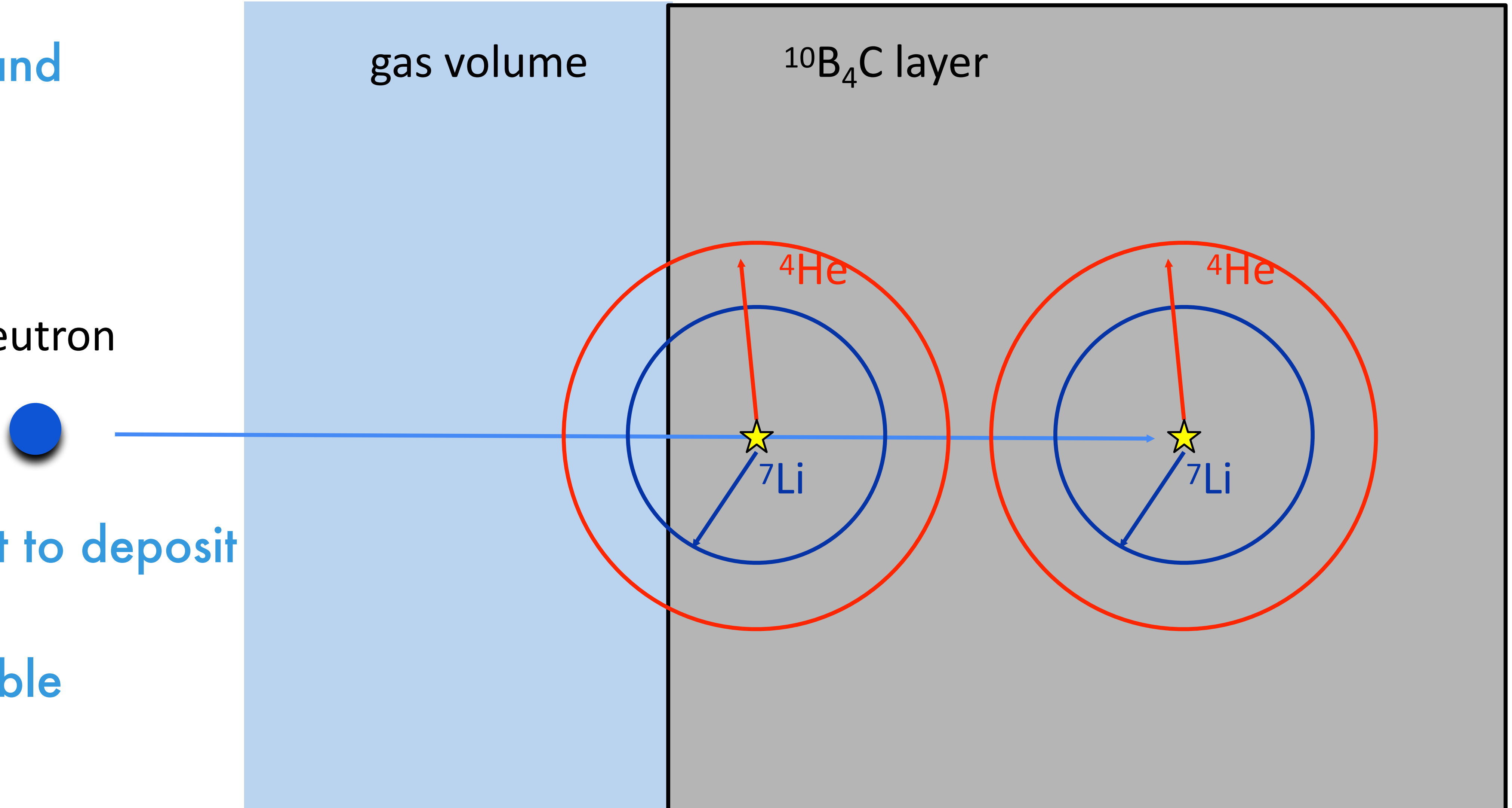
Optimization

^{10}Boron-based Thin Film Gaseous Detectors

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

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

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



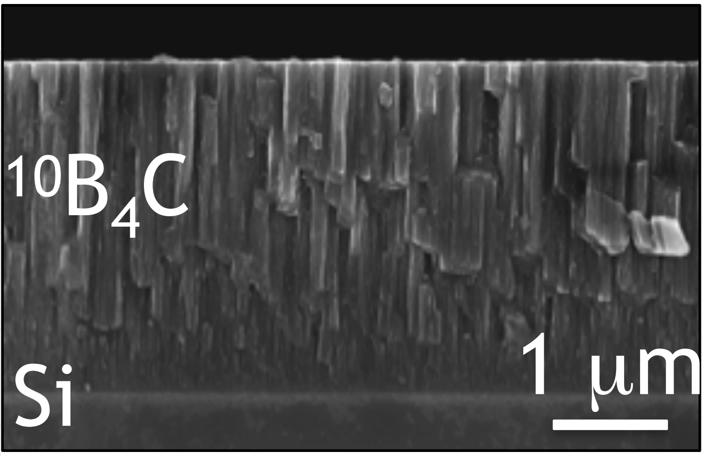
- Boron is difficult to deposit
- Use $^{10}B_4C$
- Conductive, stable

$^{10}B_4C$ Thin Film Coatings
ESS Thin Films Workshop

SOLVED

- Co-located w/ Linkoping University for synergies: expertise&facilities
- Industrial coatings machine and production line setup
- Capacity: several times ESS needs & cheap
- If interested in coatings: contact us

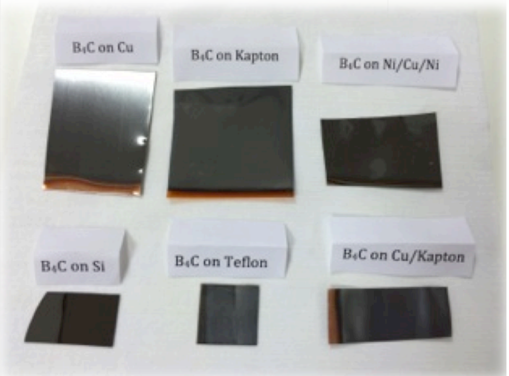
Required property	Result	OK?
Good adhesion	> 5 μm on Al, Si, Al_2O_3, etc	☺
Low residual stress	0.09 GPa at 1 μm $^{10}B_4C$	☺
Low impurities	H + N + O only ~1 at.%	☺
High ^{10}B content	79.3 at.% of ^{10}B	☺
n-radiation hard	Survive 10^{14} neutrons/cm^2	☺

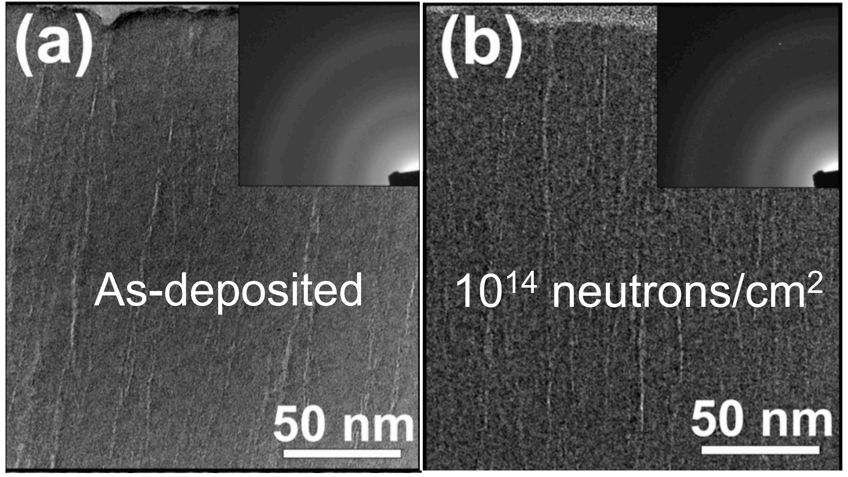


- PVD magnetron scattering
- Highly interdisciplinary effort

- Many substrates possible:

Solved	Ongoing
Al	Glass - ok solution
Al-foil	Ni and Ni-coated - ok solution
Stainless steel	Cu coat. Kapton
Al_2O_3	MgO
Si	
G10	
Ti	
Cu	
Teflon	
Kapton foil	
Kapton tape	

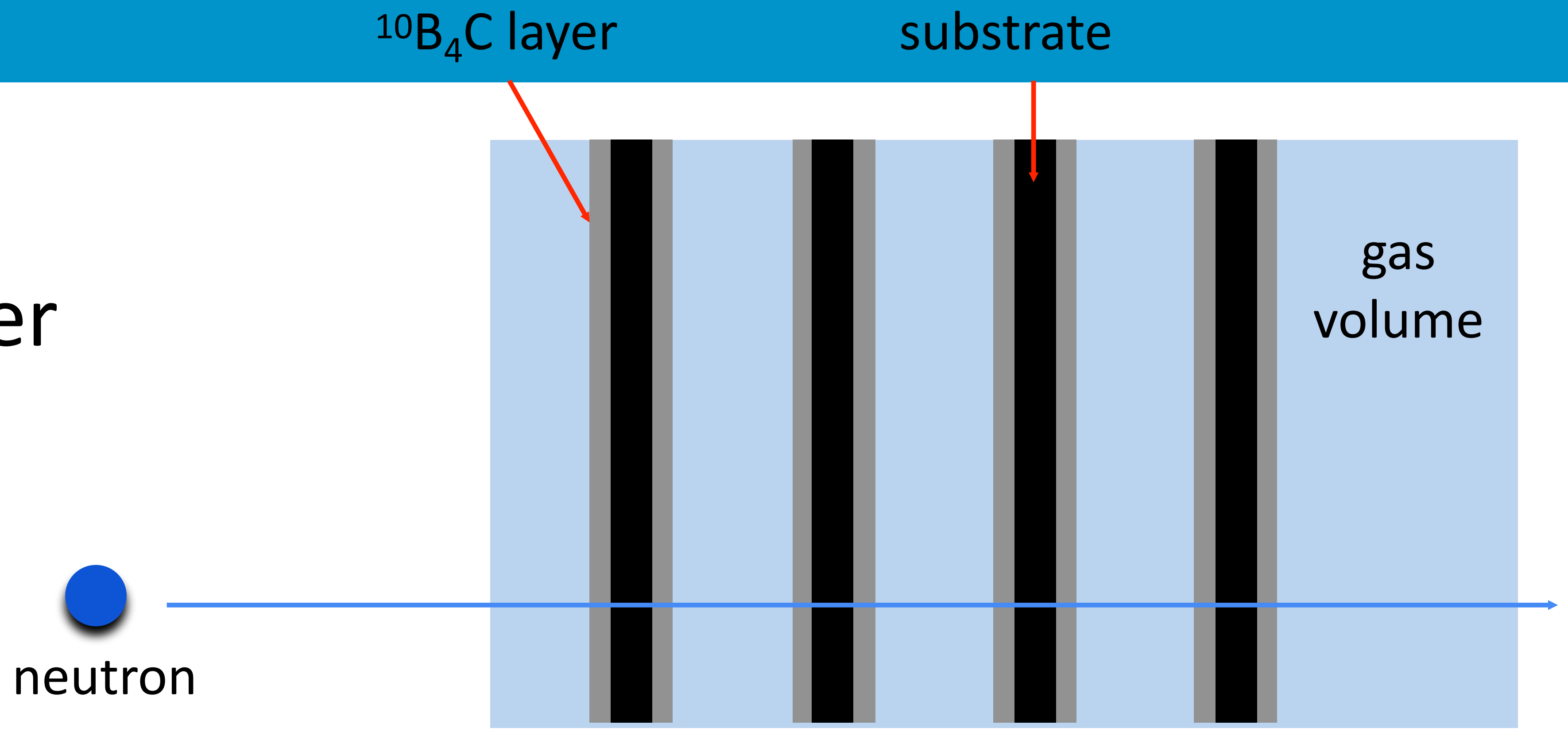




Publications:
*C. Höglund et al, J of Appl. Phys. 111, 104908 (2012)
*S. Schmidt et al, J. of Materials Science 51, Issue 23 (2016)
*C. Höglund, Rad. Phys. and Chem. 113 , 14-19 (2015);

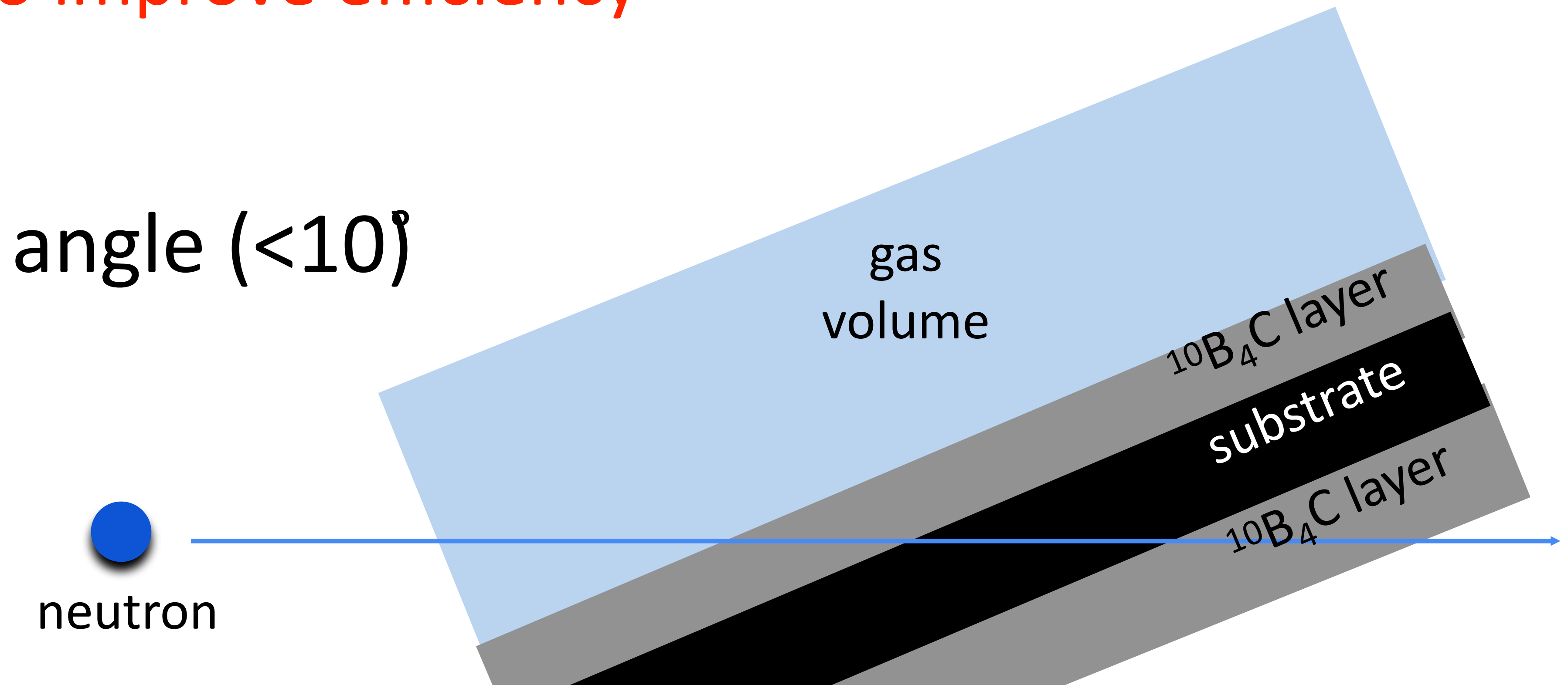
Enhancing the efficiency of ^{10}B-based Neutron Detectors

① Multi layer



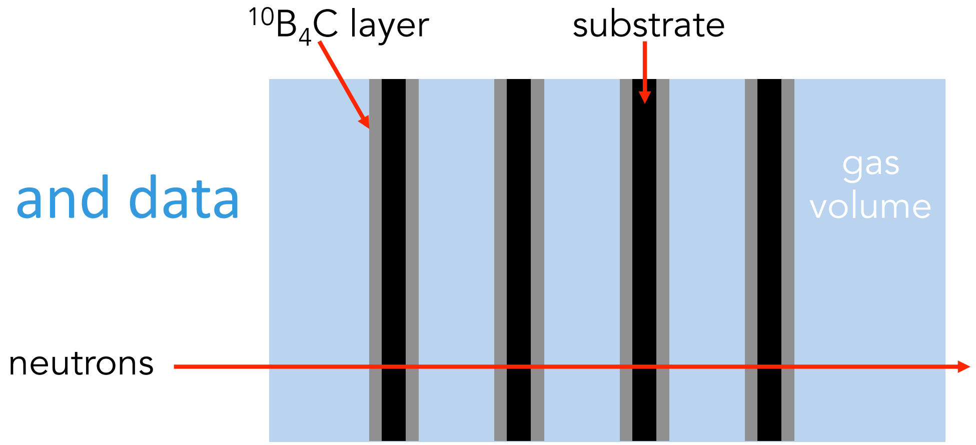
Generic approaches to improve efficiency

② Grazing angle (<10°)



Efficiency of ^{10}B Detectors: Perpendicular Geometry

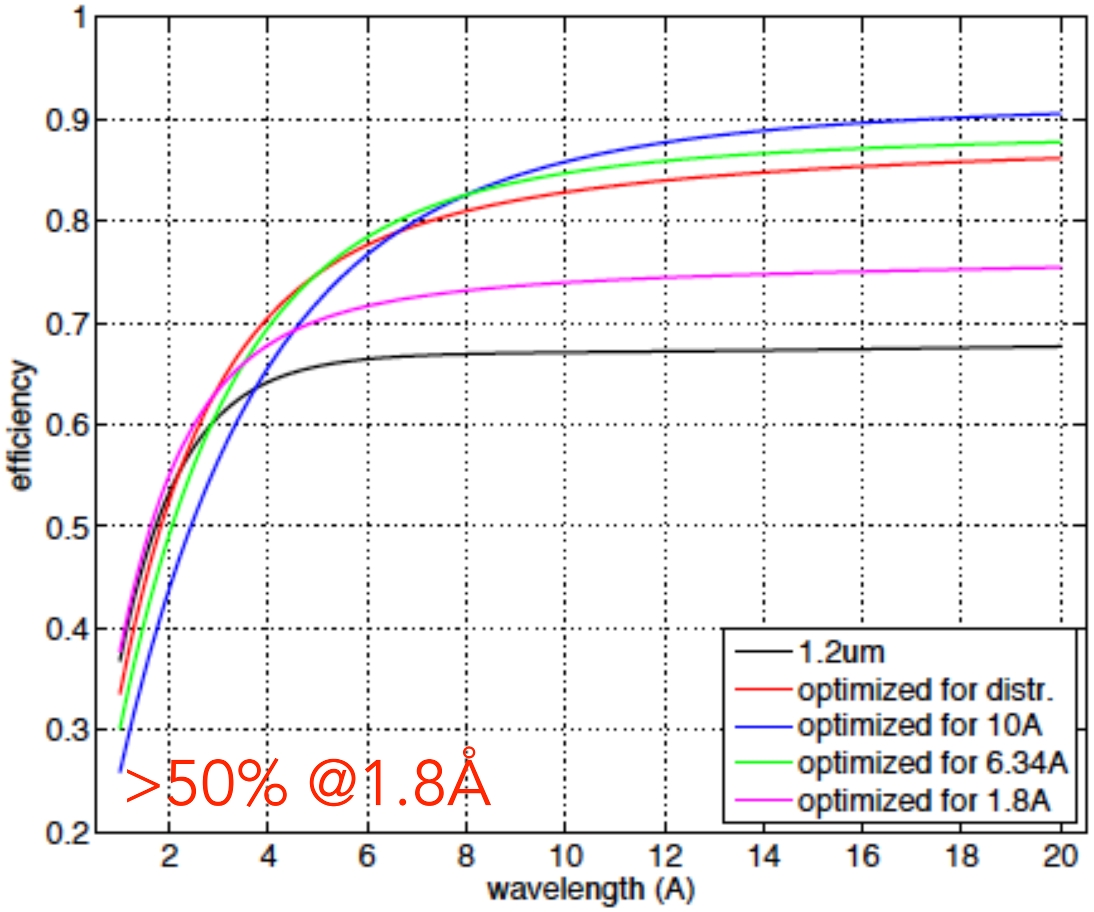
- Single layer is only ca.5%
- Calculations done by many groups
- Analytical calculations extensively verified with prototypes and data
- Details matter: just like for ^{3}He



- Multilayer configuration (example):

Multi-Grid

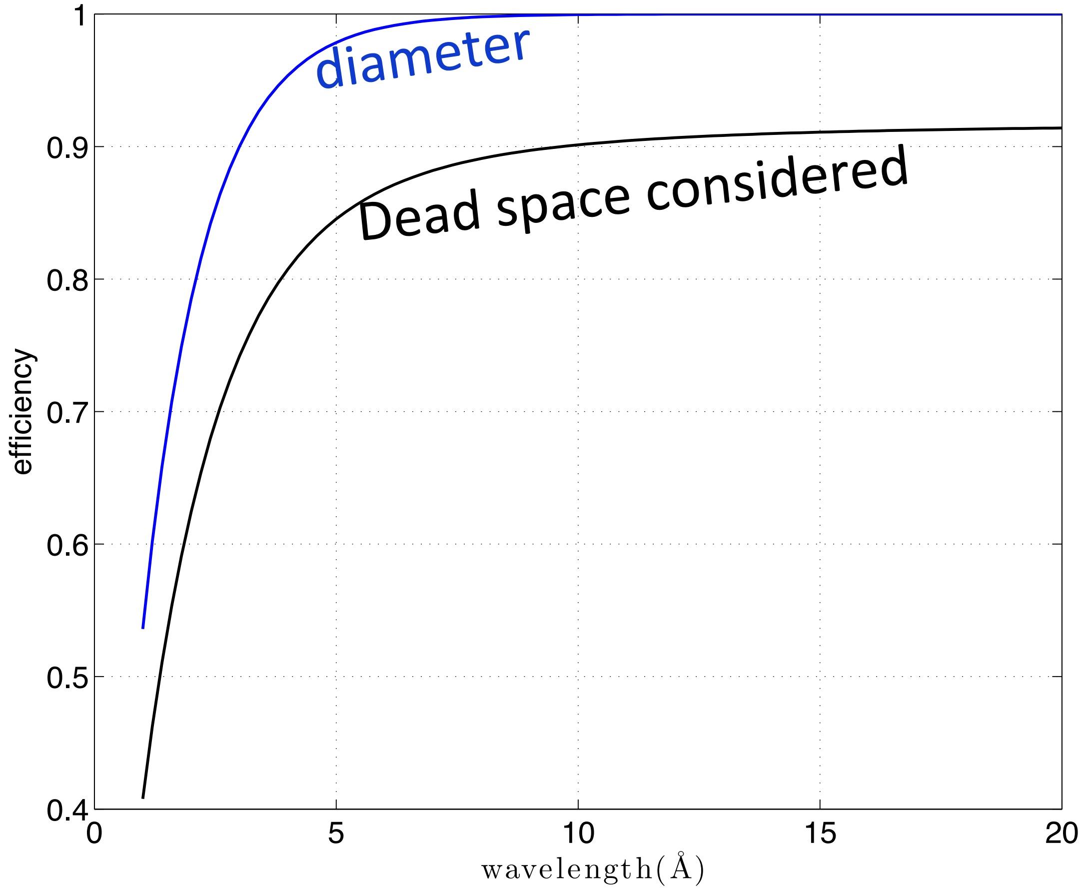
JINST 8 (2013) P04020



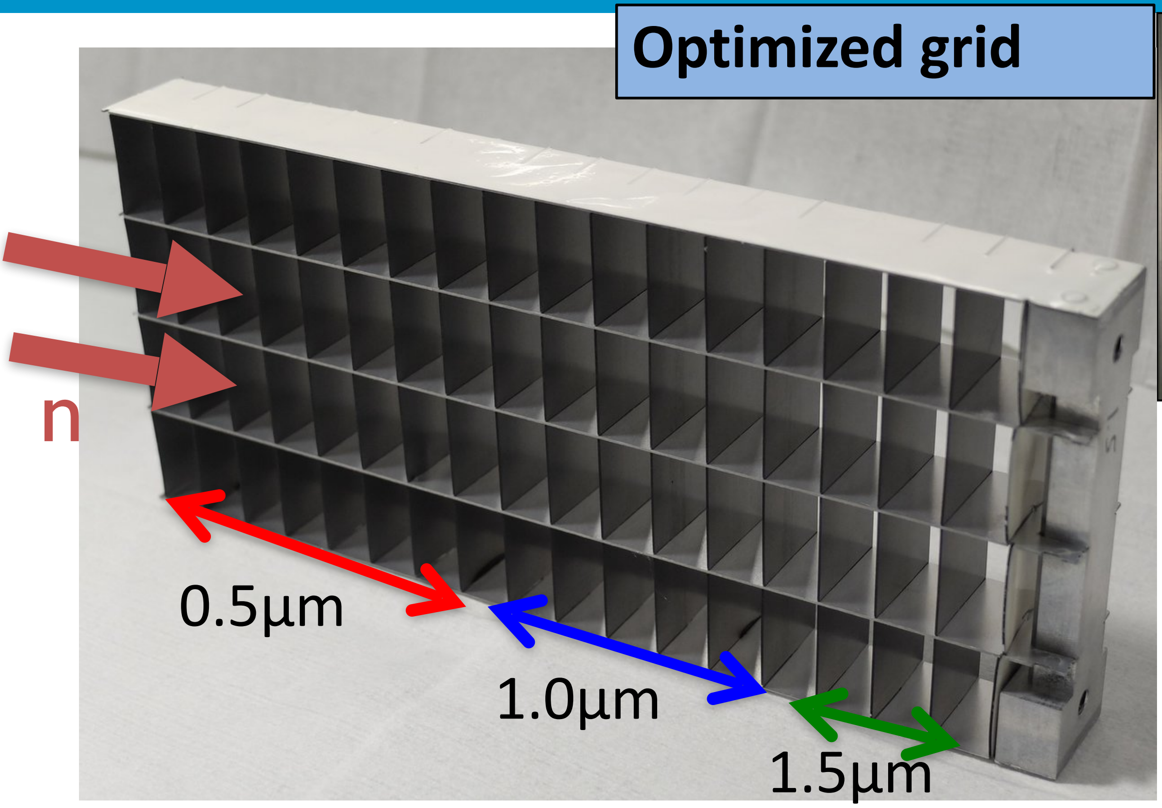
>50% @1.8Å

Calculator:
arXiv:1801.07124

^{3}He tubes – 1 inch – 4.75 bar



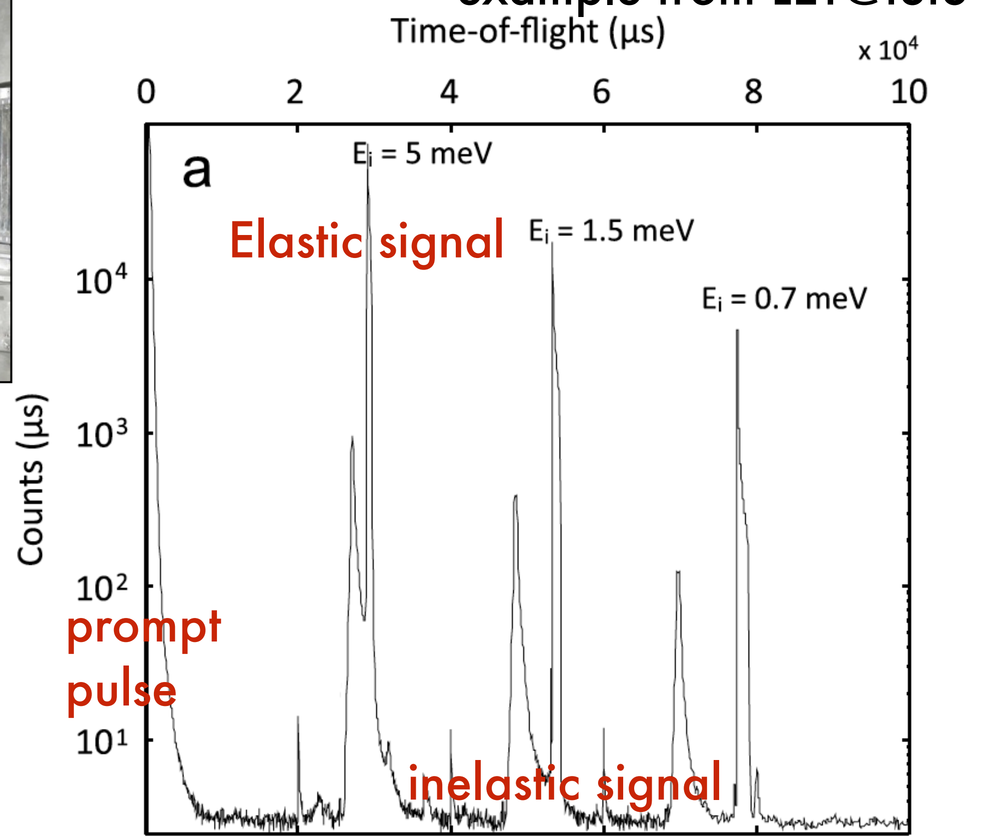
Multi-Grid Detector Design



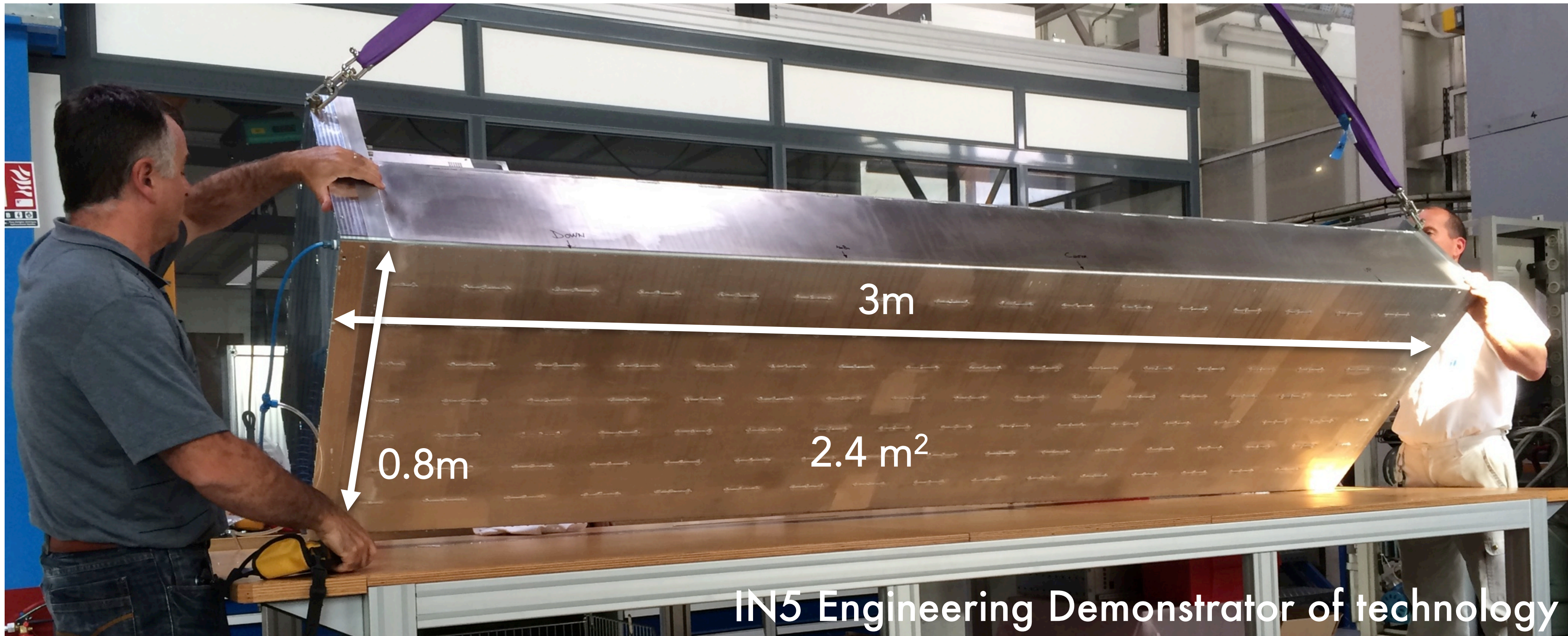

aim: replace He-3 for this

Very background sensitive technique

example from LET@ISIS

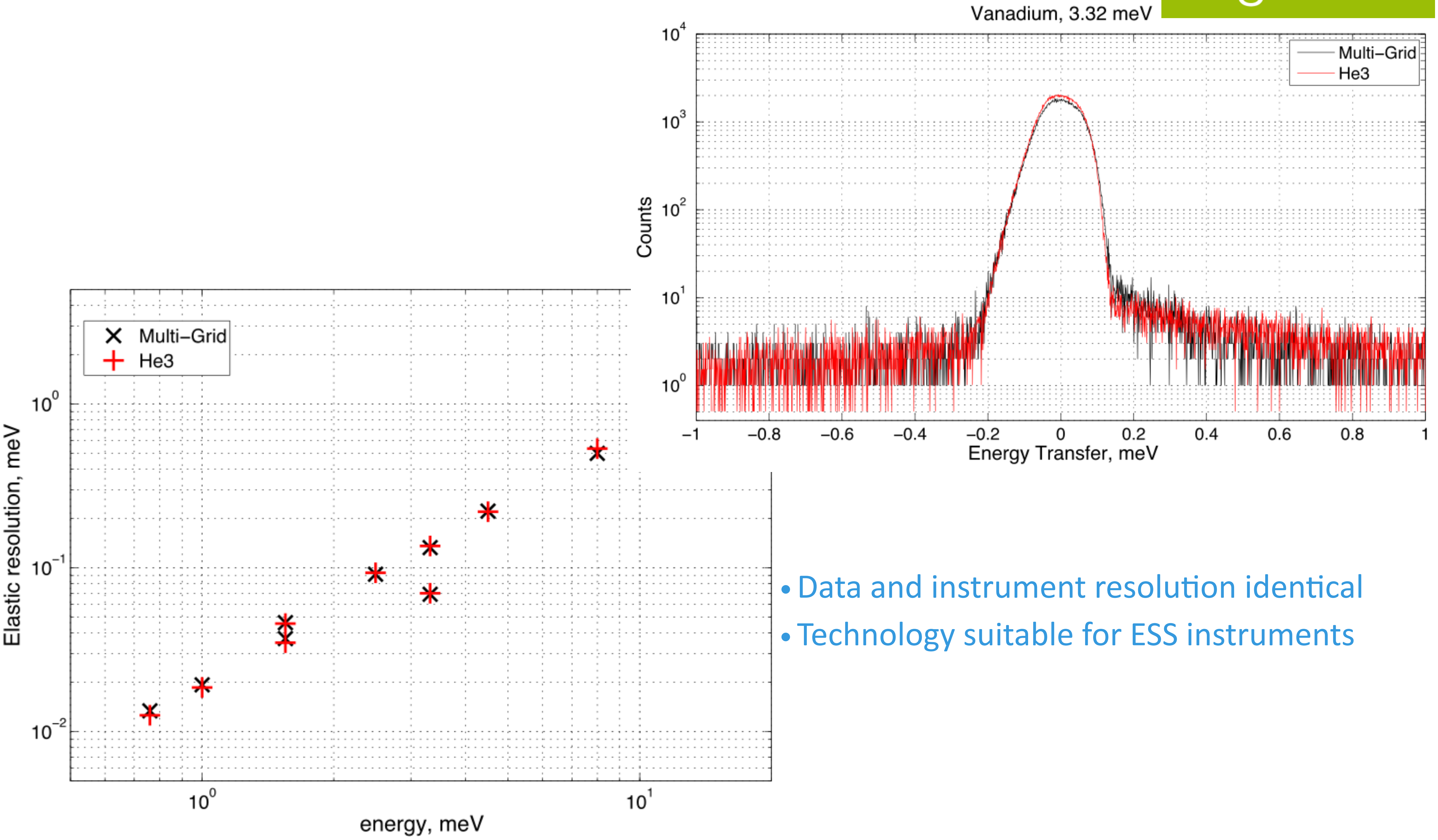


- Designed as replacement for He-3 tubes for largest area detectors
- Cheap and modular design
- Possible to build large area detectors again
- 20-50m² envisaged@ESS



IN5 Engineering Demonstrator of technology

Multi-Grid test at CNCS

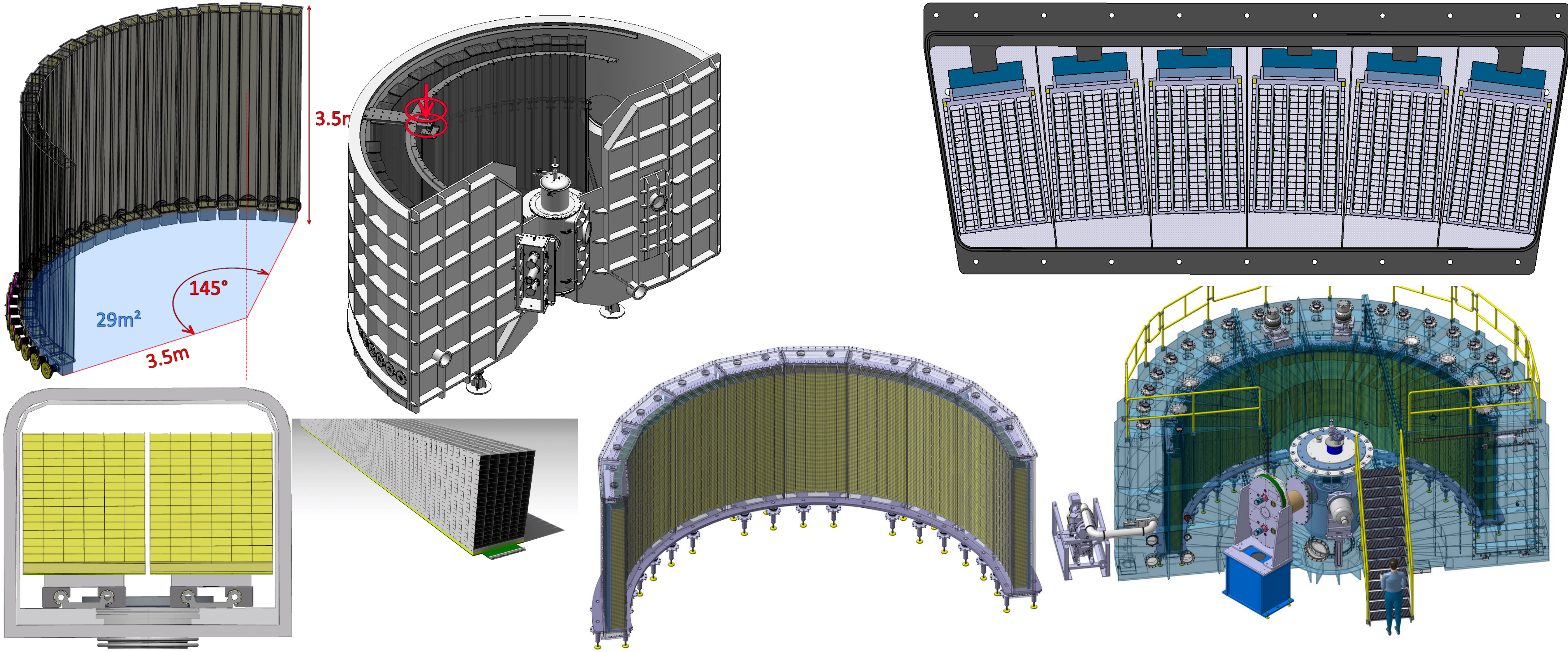


- Data and instrument resolution identical
- Technology suitable for ESS instruments

brightness

Realising Large Area Detectors

EUROPEAN SPALLATION SOURCE



CSPEC instrument

TREX instrument

Detailed Engineering Design, construction started

BrightnESS is funded by the European Union’s Horizon 2020 research and innovation programme under grant agreement No. 676548

The Intensity Frontier: The Multi-Blade Detector Design

The Multi-Blade project

High counting rate capability

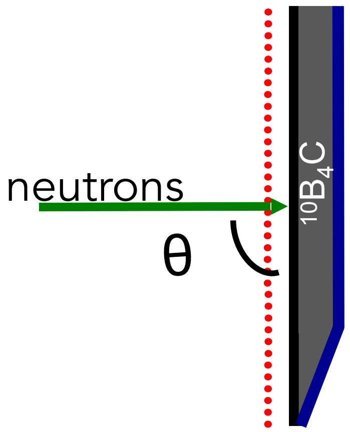
High spatial resolution

A single Boron layer inclined at 5 degrees

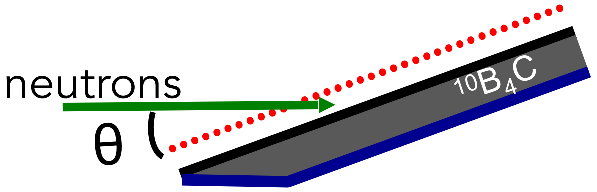
^{10}B-detector for reflectometers

Efficiency <5% at 2.5Å

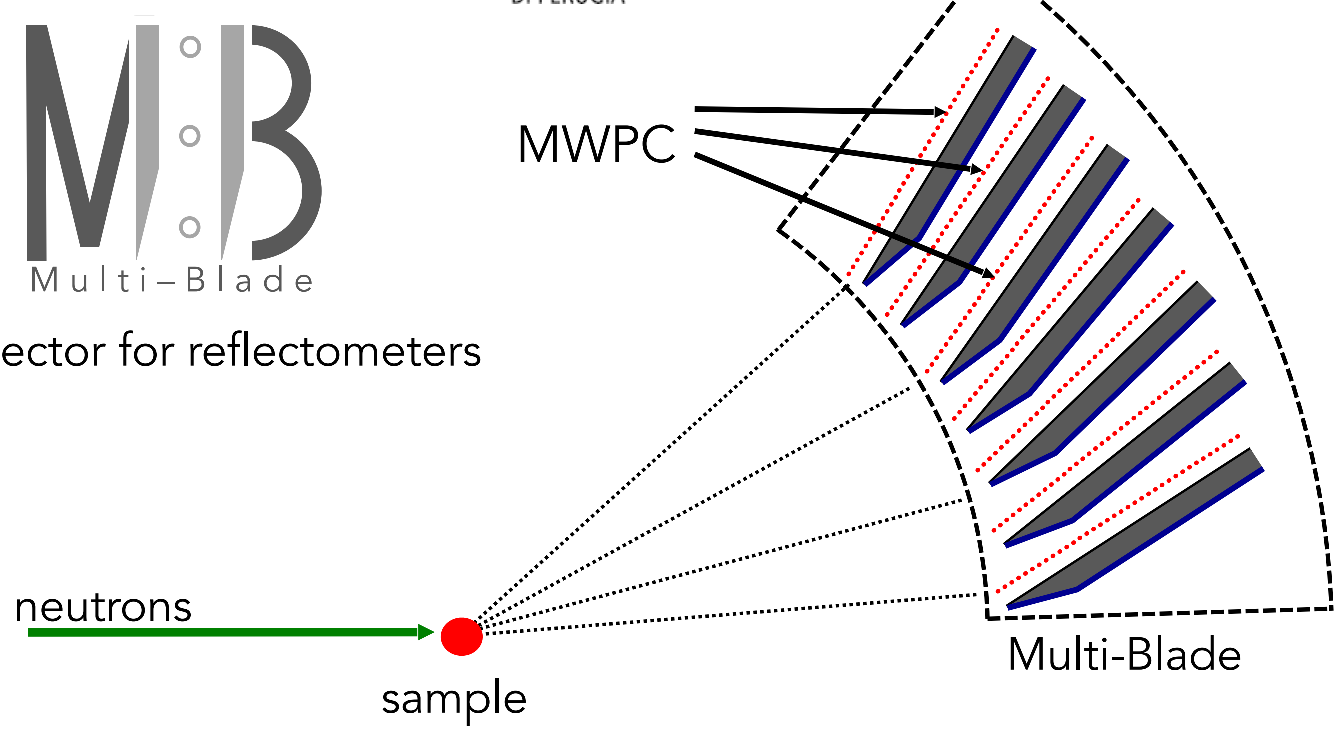
Efficiency 45% at 2.5Å

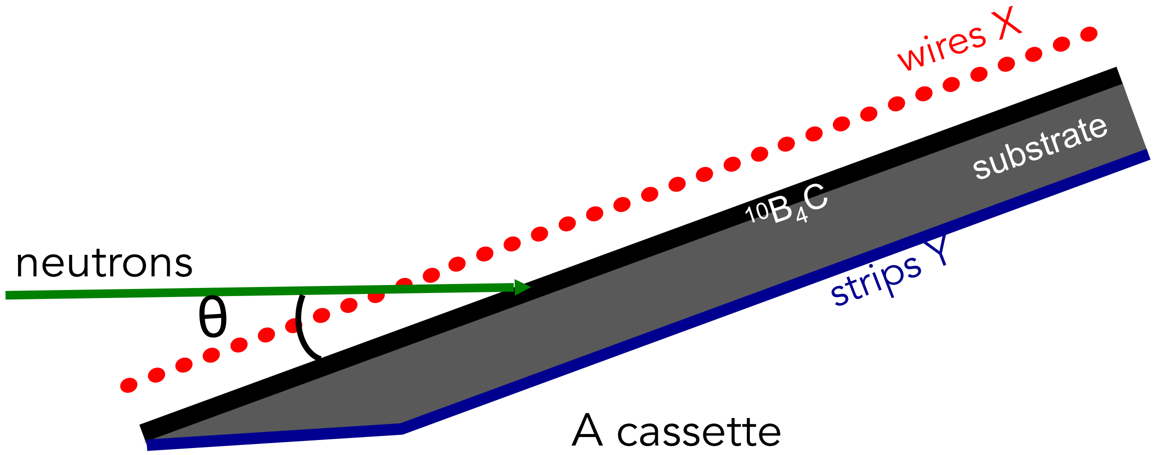


θ = 90 degrees



θ = 5 degrees





A cassette (unit)

θ = 5 degrees

F. Piscitelli et al, Journal of Instrumentation 12, P03013 (2017) - doi: 10.1088/1748-0221/12/03/P03013 , arXiv: 1701.07623

BrightnESS is funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No. 676548

Trend to follow in development within CREMLINPlus …?

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

Summary

- 4 major new neutron sources coming online in next decade

- Brightness and science goals mean that the requirements for detectors cannot be met with todays state-of-the-art detectors
- Helium-3 crisis means that the "gold standard" for neutron detection is no longer default option

- Helium-3 replacement technologies and the large amount of new instrumentation is driving the detector development.
- This is a very active topic

- Trend for better position resolution a good development path for CREMLINPlus ...