Neutron and **X-ray Scattering** of **Quantum Materials**

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Spectroscopy of Quantum Materials
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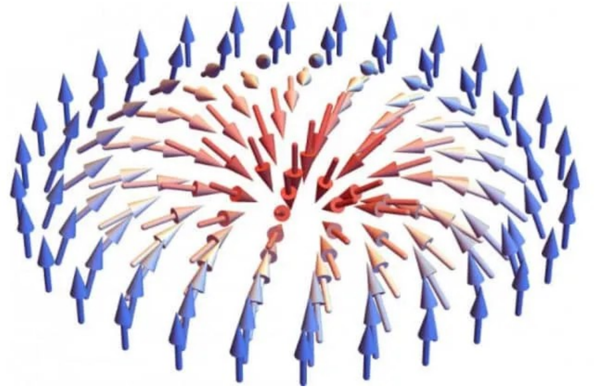
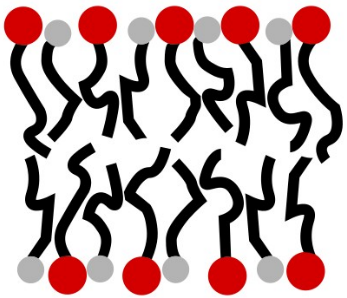
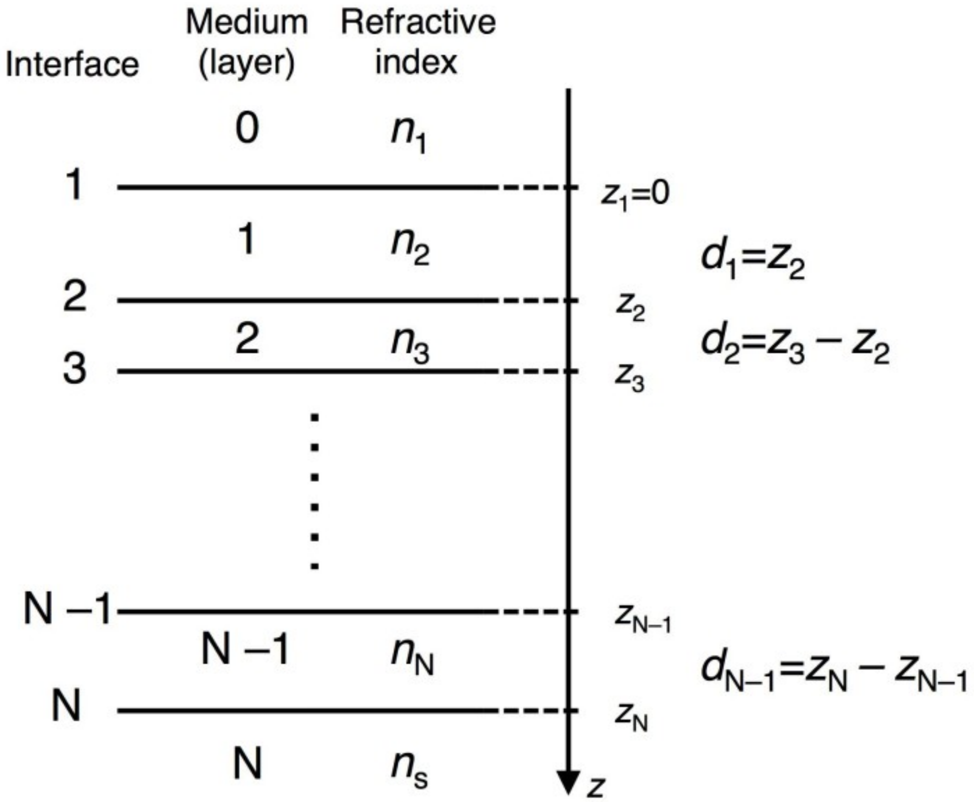
Outline for today

- Recap from two weeks ago (Chapters 7 and 8)
- Information about the exam
- Inelastic neutron scattering

From last week: SANS and reflectometry



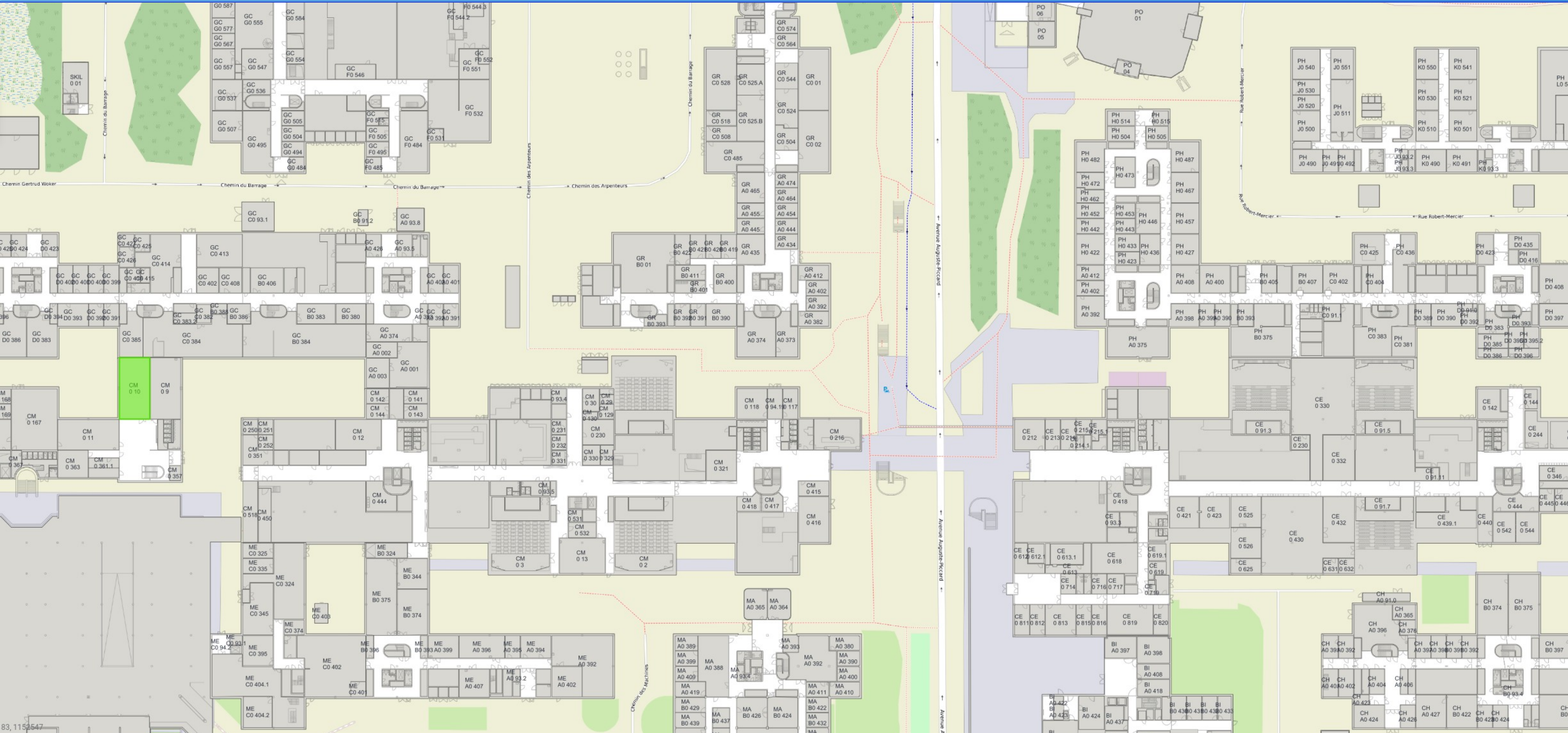




Information about the exam

- Date: 13th of January 2025
- Place: CM010
- Format:
  - Oral, 25 min (15 min presentation + 10 min questions / discussion)
  - Preparation, 25 min (books and notes allowed)
  - 8-10 topics, known in advance but picked at random at the exam
- Course evaluation takes place right after the exam

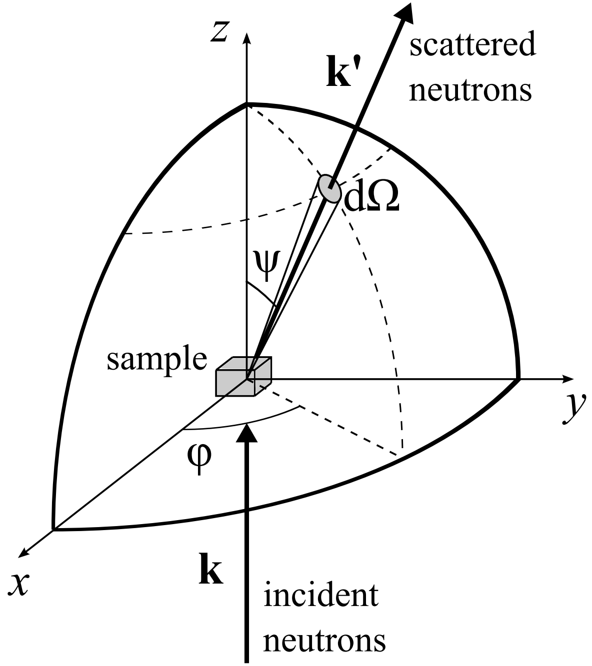
Information about the exam



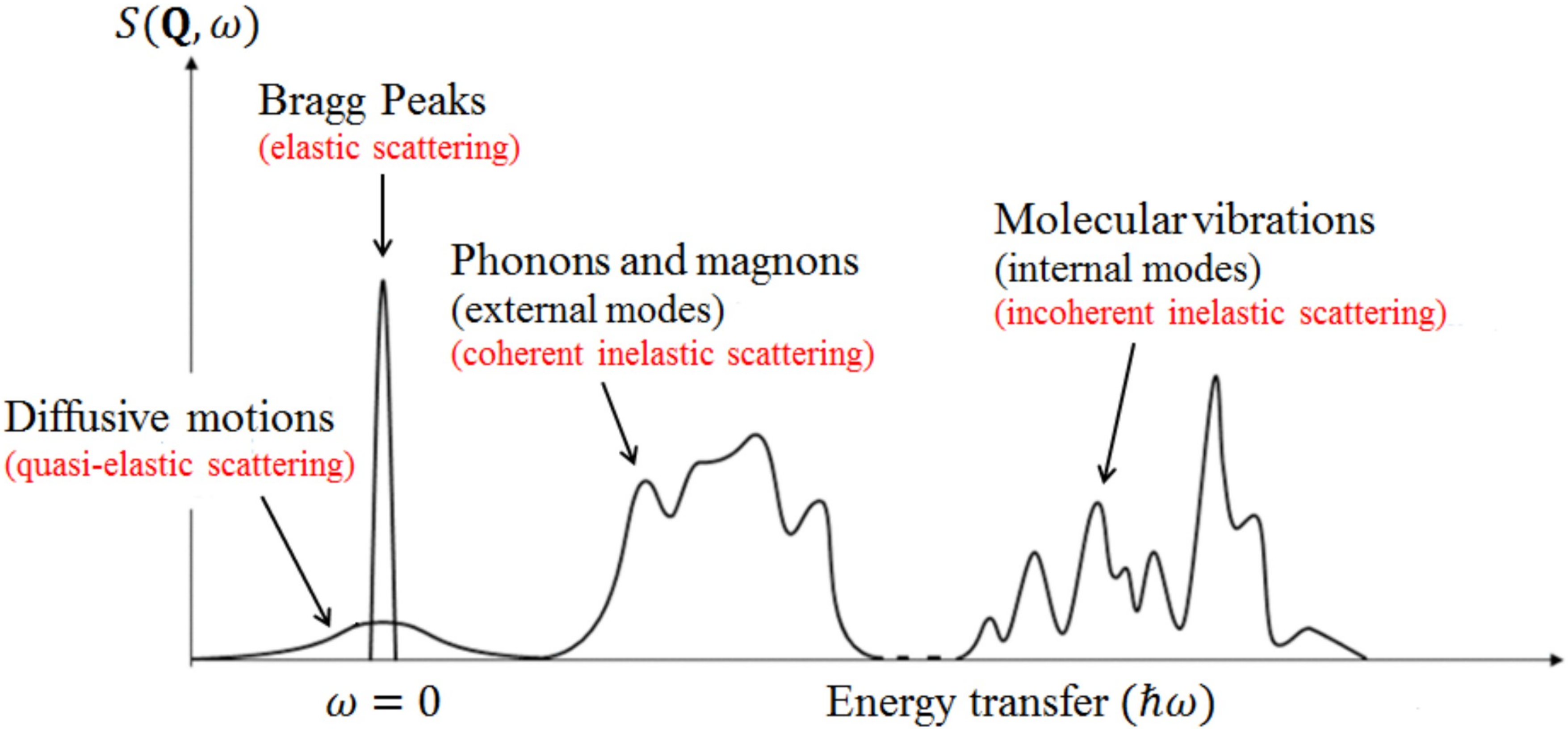
Inelastic neutron scattering

Partial differential scattering cross section

$$\frac{d^2\sigma}{d\Omega\, dE_f} = \frac{1}{\Psi}\frac{number\ of\ scattered\ neturons \in d\Omega \wedge with\ energies \in the\ interval\,[E_f, E_f + dE_f]\ per\ second}{d\Omega\, dE_f}$$



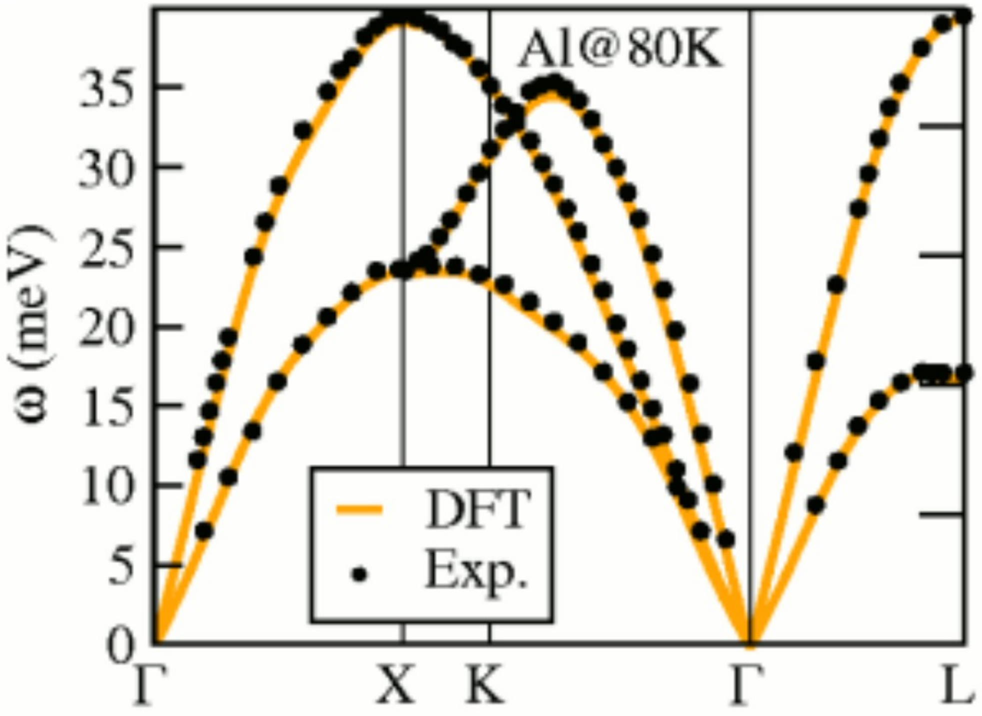
Inelastic processes accessible with neutrons



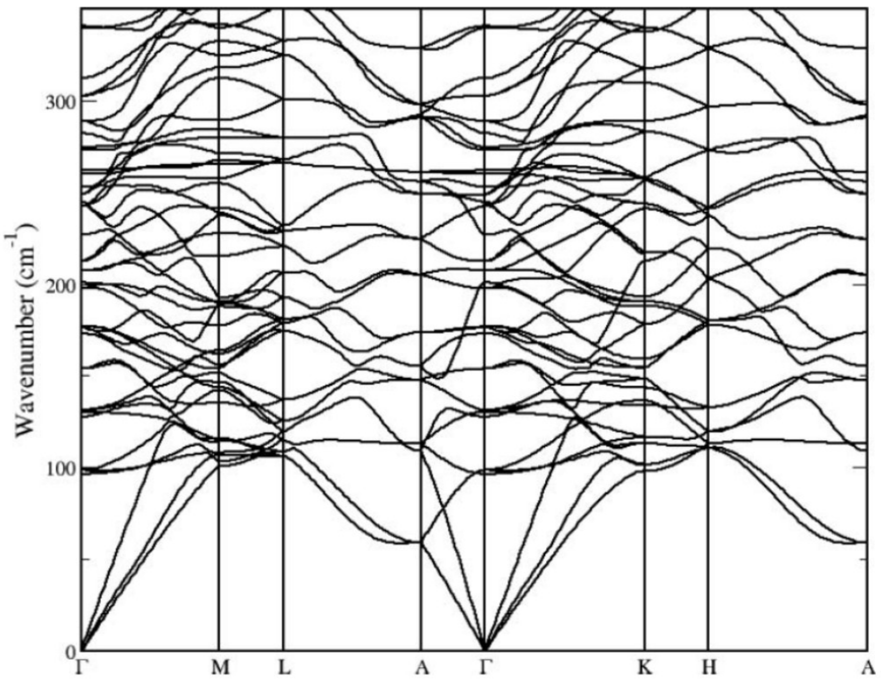
Backscattering
Spin echo

Triple-axis spectrometers
Time-of-flight spectrometers

Phonons



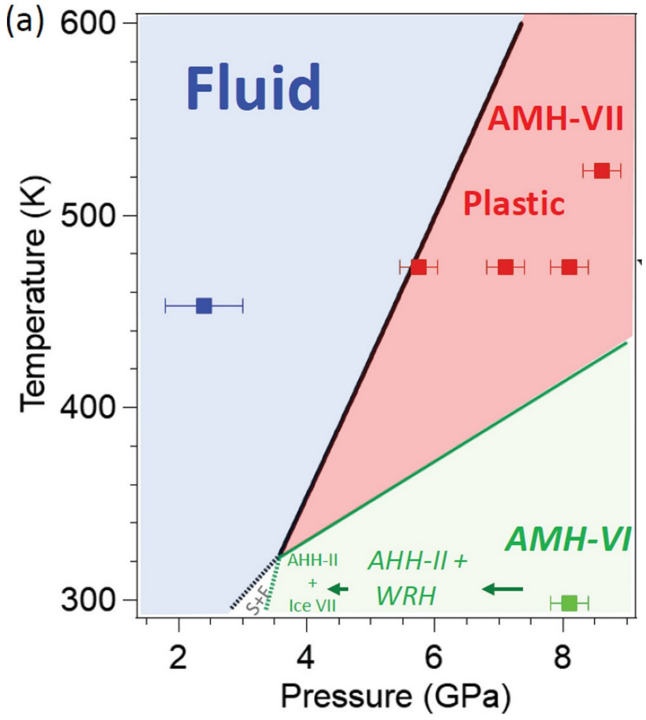
Aluminium

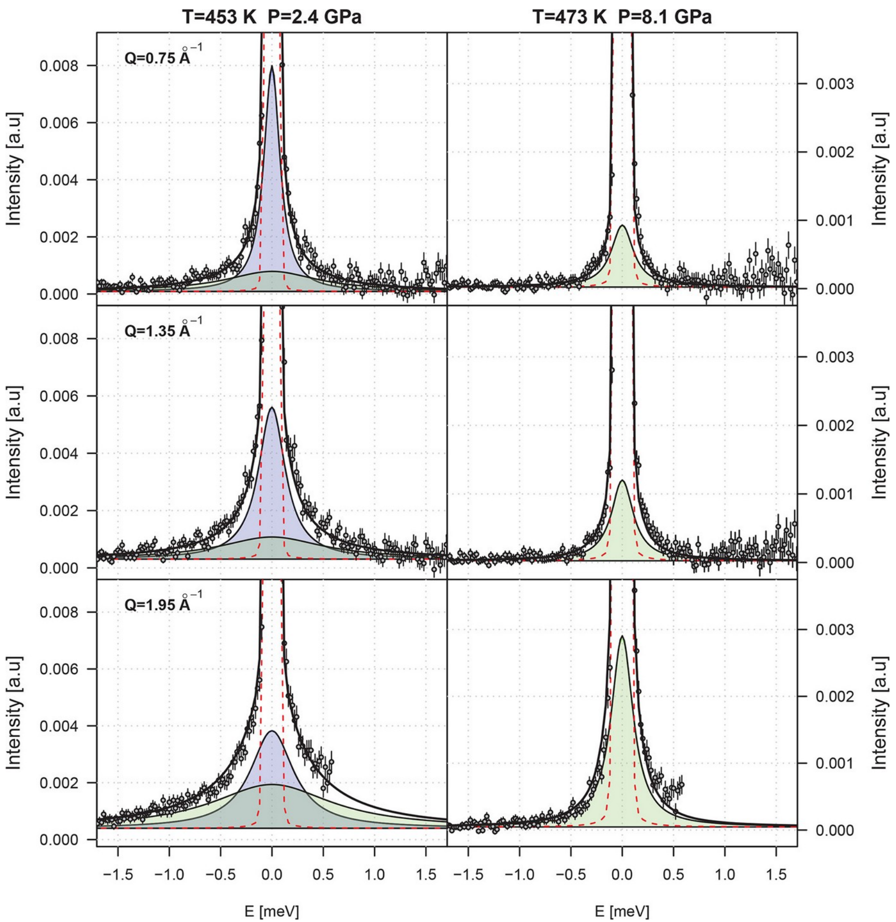


h-$YMnO_3$

Molecule motion

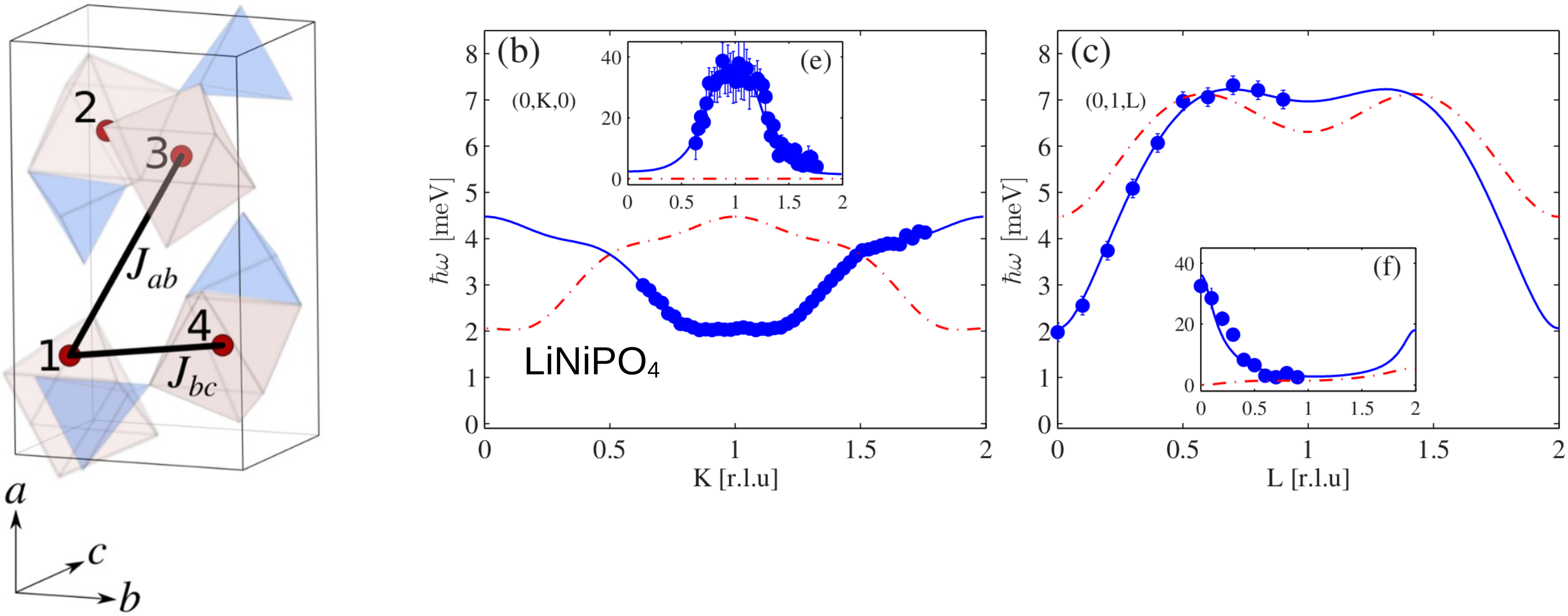
Water-ammonia mixture





H. Zhang *et al.*, J. *Phys. Chem. Lett.* **14**, 2301-2307 (2023)

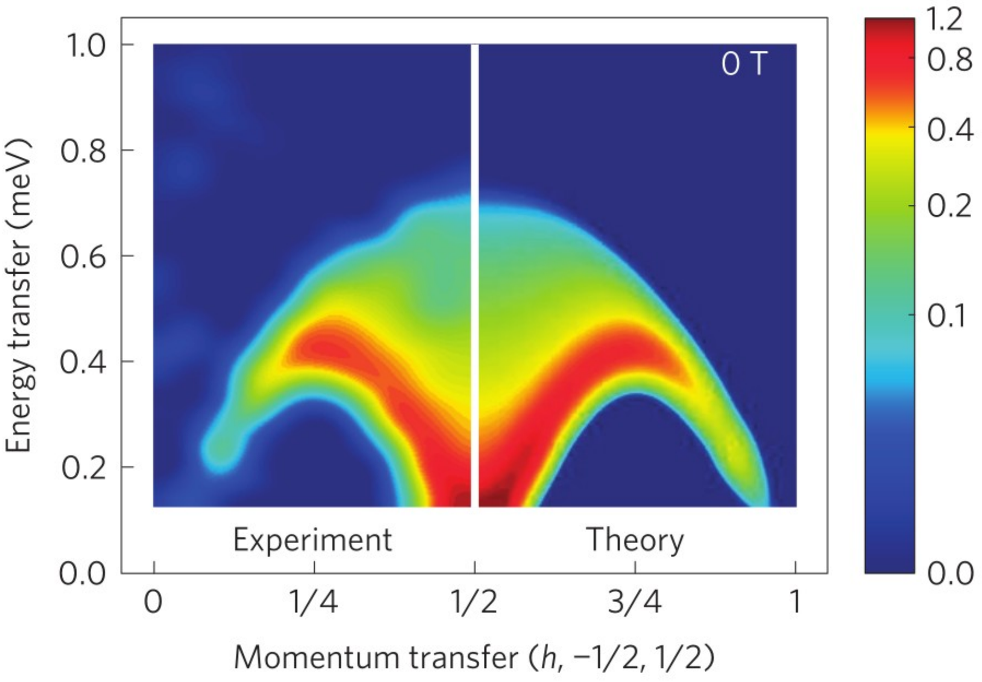
Magnetic excitations: “Classical” magnets



T. B. S. Jensen *et al.*, *Phys. Rev. B* **79**, 092413 (2009)

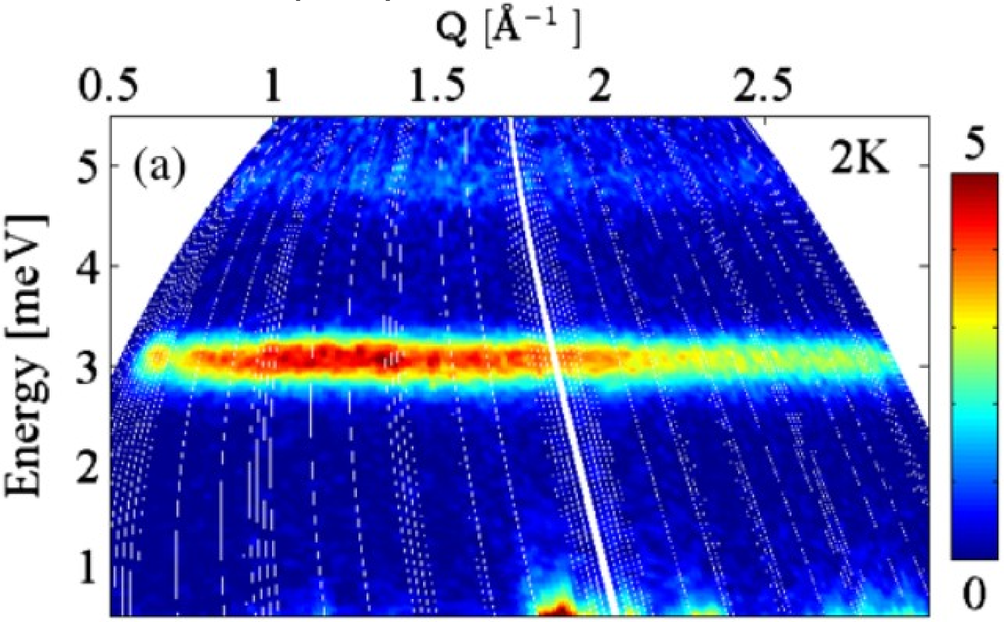
Magnetic excitations: Quantum magnets

$CuSO_4 \cdot 5D_2O$



M. Mourigal *et al.*, *Nature* **9**, 435-441 (2013)

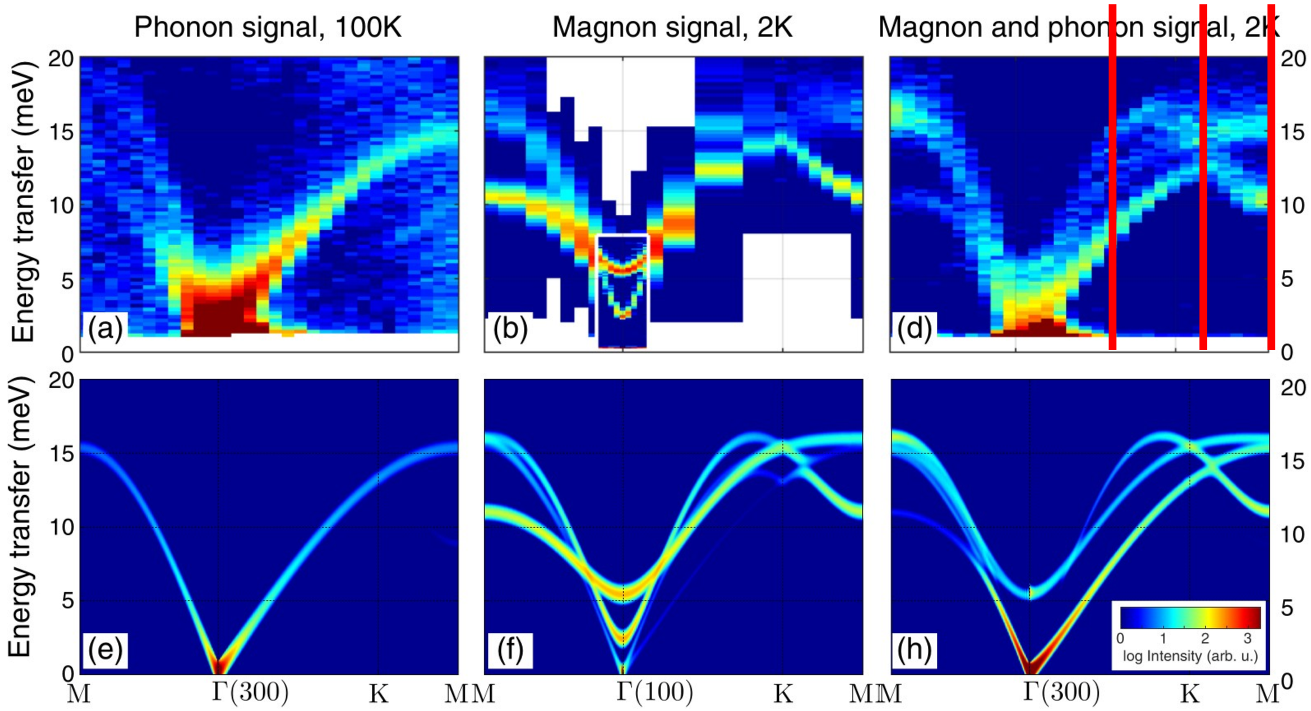
$SrCu_2(BO_3)_2$

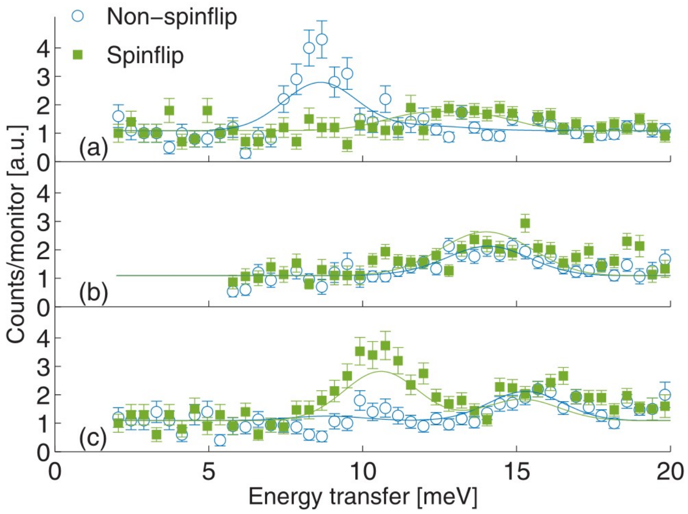


M. E. Zayed *et al.*, *Phys. Rev. Lett.* **113**, 067201 (2014)

When polarization analysis is handy

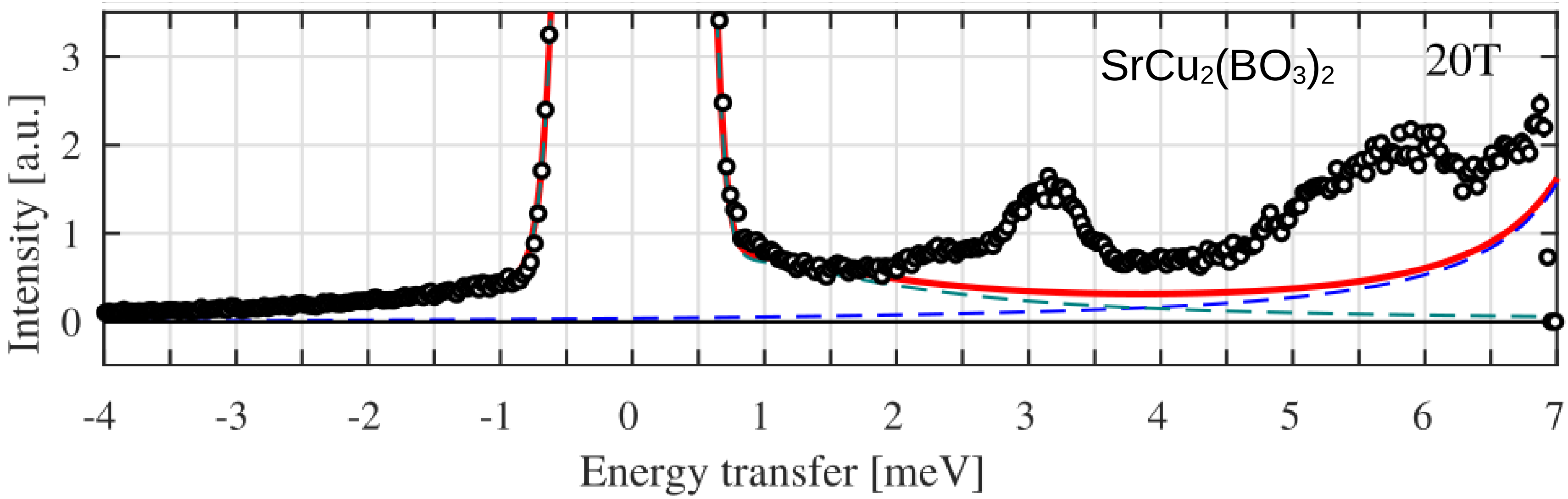
h-$YMnO_3$





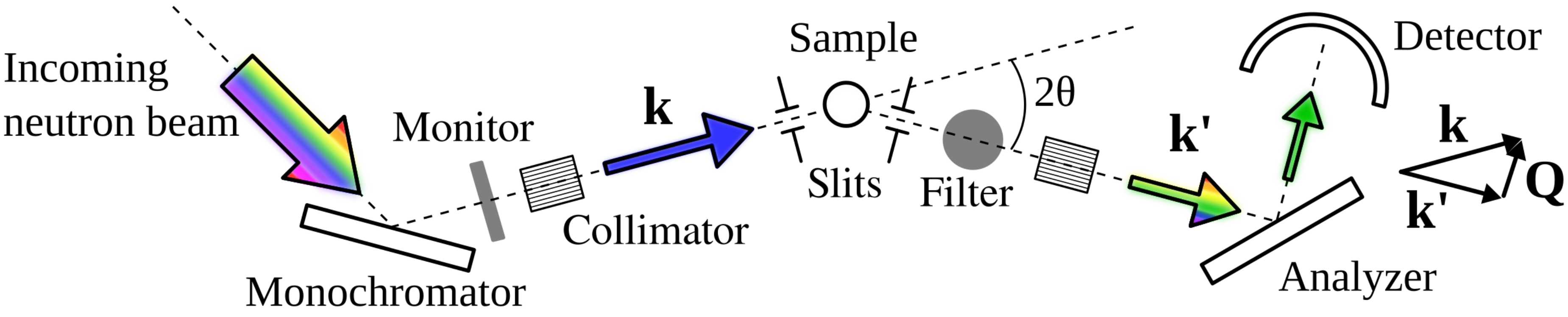
S. L. Holm *et al.*, *Phys. Rev. B* **97**, 134304 (2013)

Detailed balance



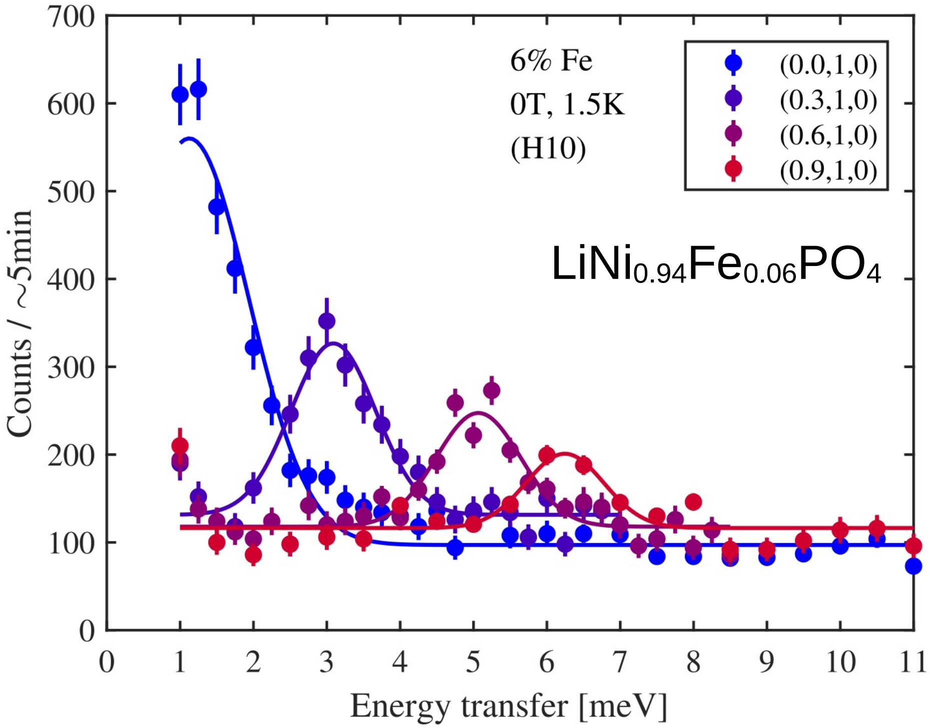
Neutron instruments for measuring excitations

Triple-axis spectrometer: Instrument layout

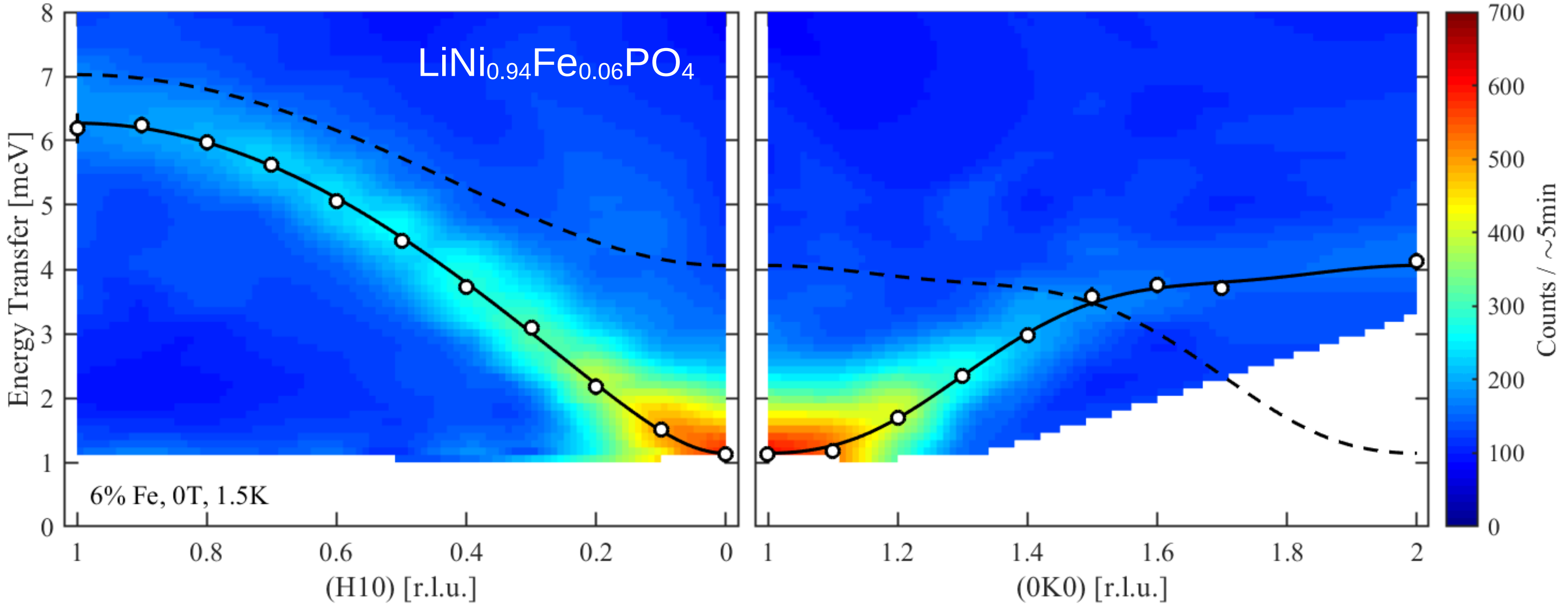


Triple-axis spectrometer: Data collection

- 1-dimensional data set
- Simple to visualize
- Data files are small
- Possible to focus on key points in E and **q**
- Flexible resolution function
- Ideal for parametric studies
- No overview

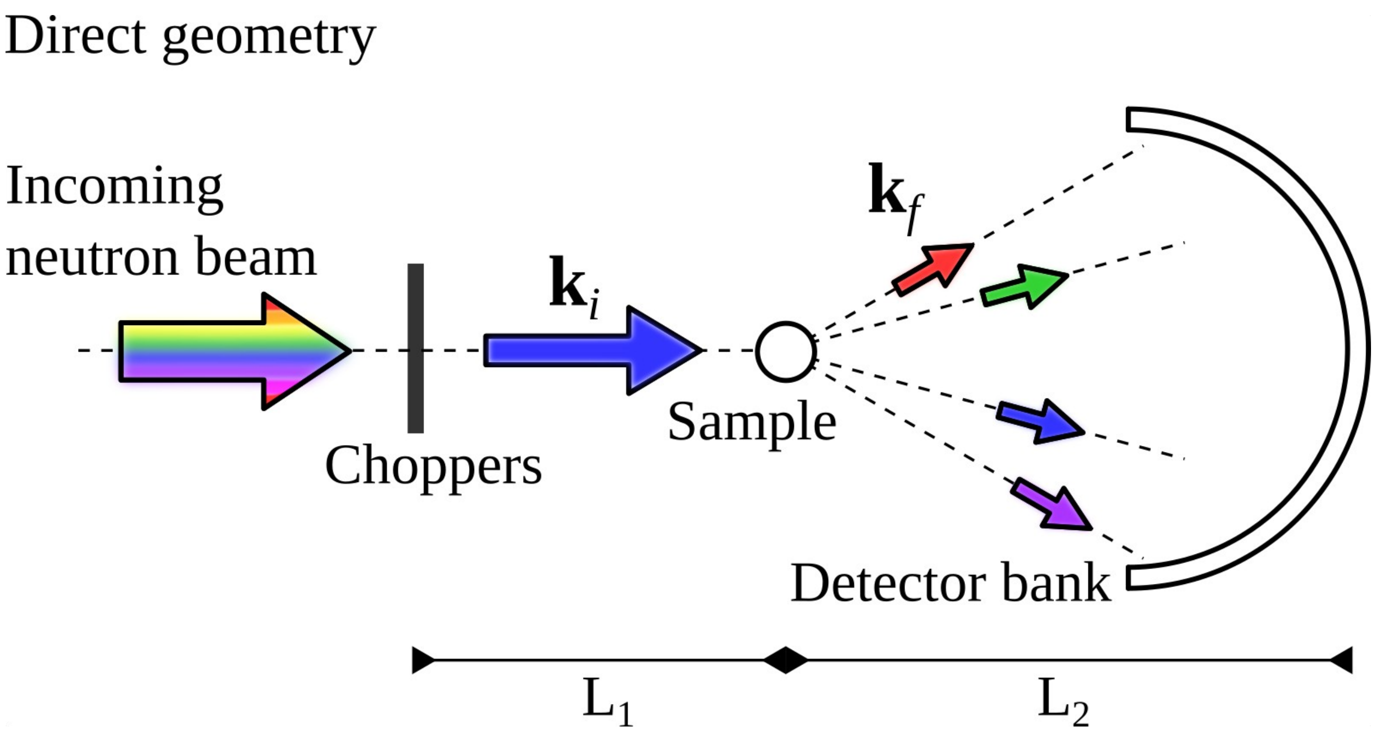


Triple-axis spectrometer: Data collection

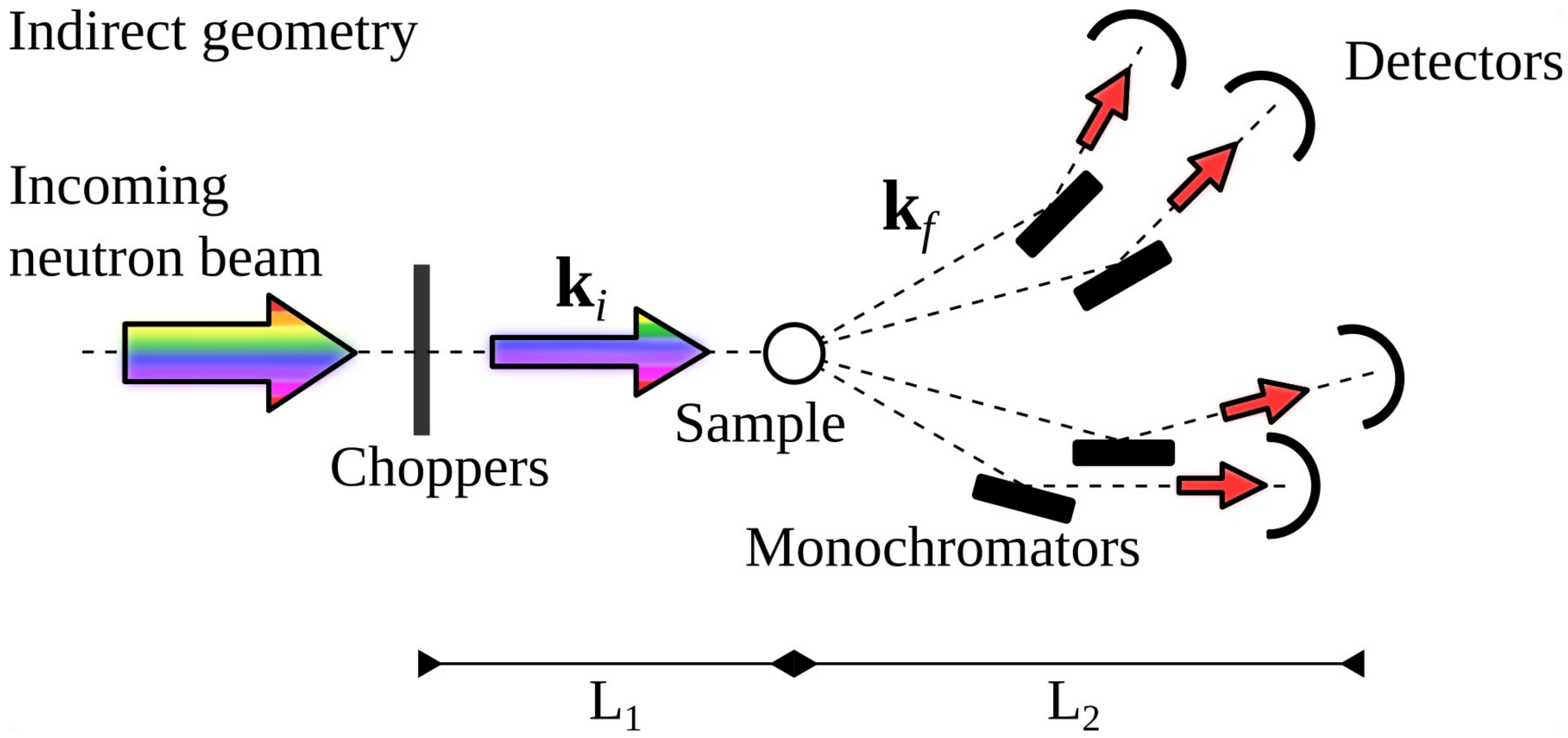


E. Fogh, PhD thesis, Technical University of Denmark (2019)

Time-of-flight spectrometer: Direct geometry

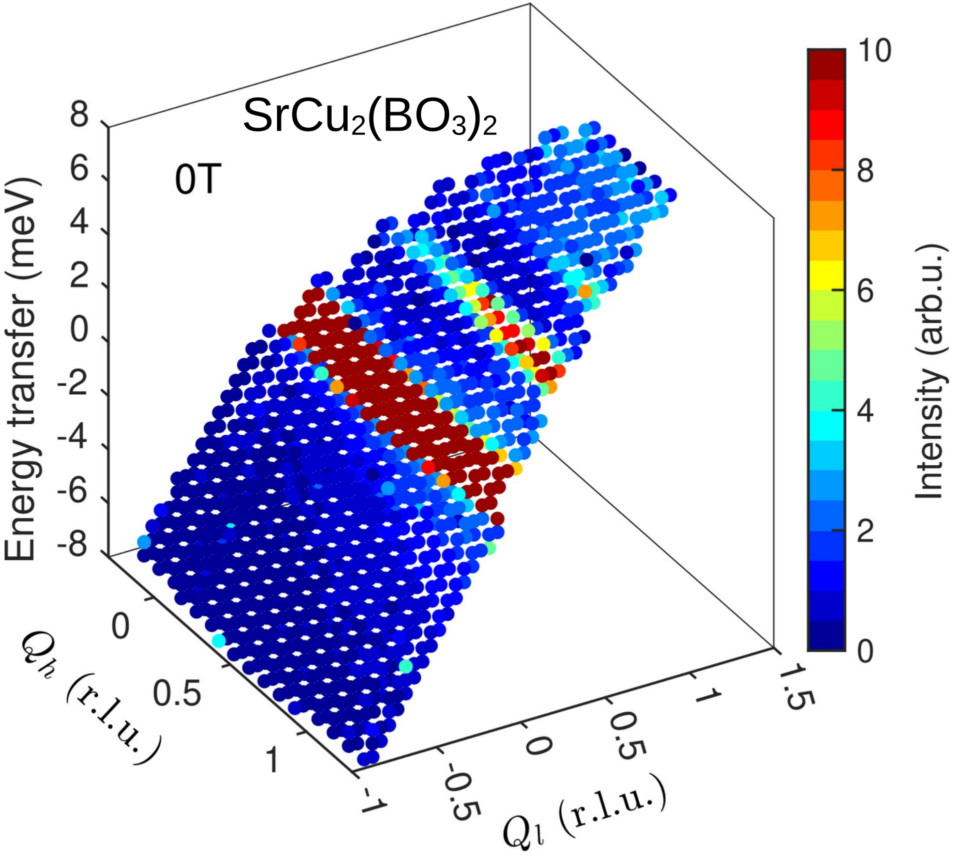


Time-of-flight spectrometer: Indirect geometry



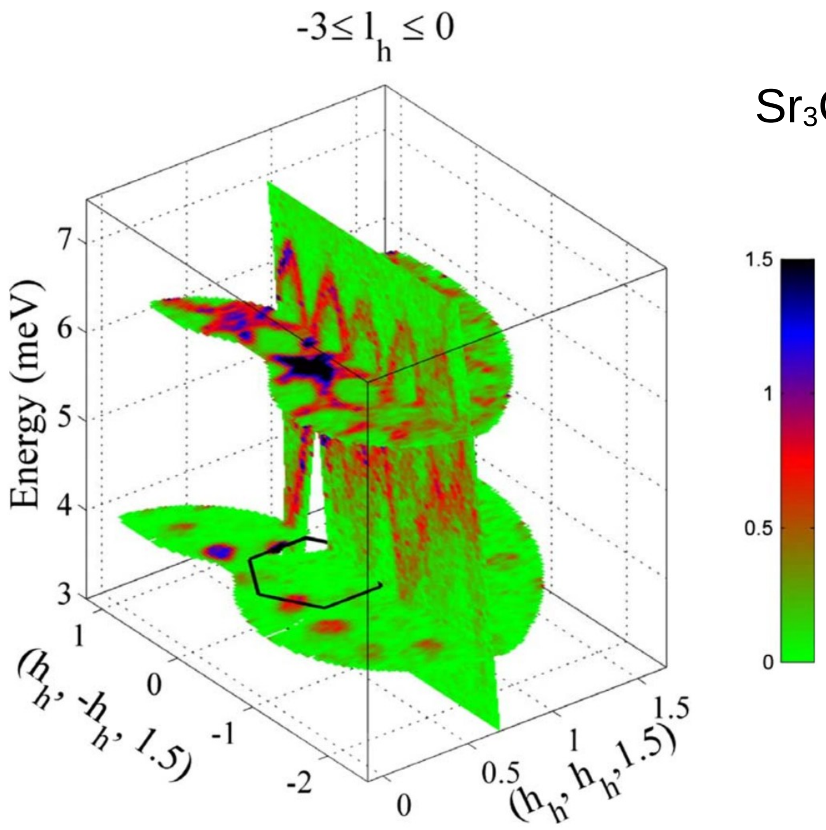
Time-of-flight spectrometer: Data collection

- 4-dimensional data set
- Need to slice and integrate
- Data files are rather large
- Need for specialized software
- Limited possibilities to adjust resolution
- You get everything in one go

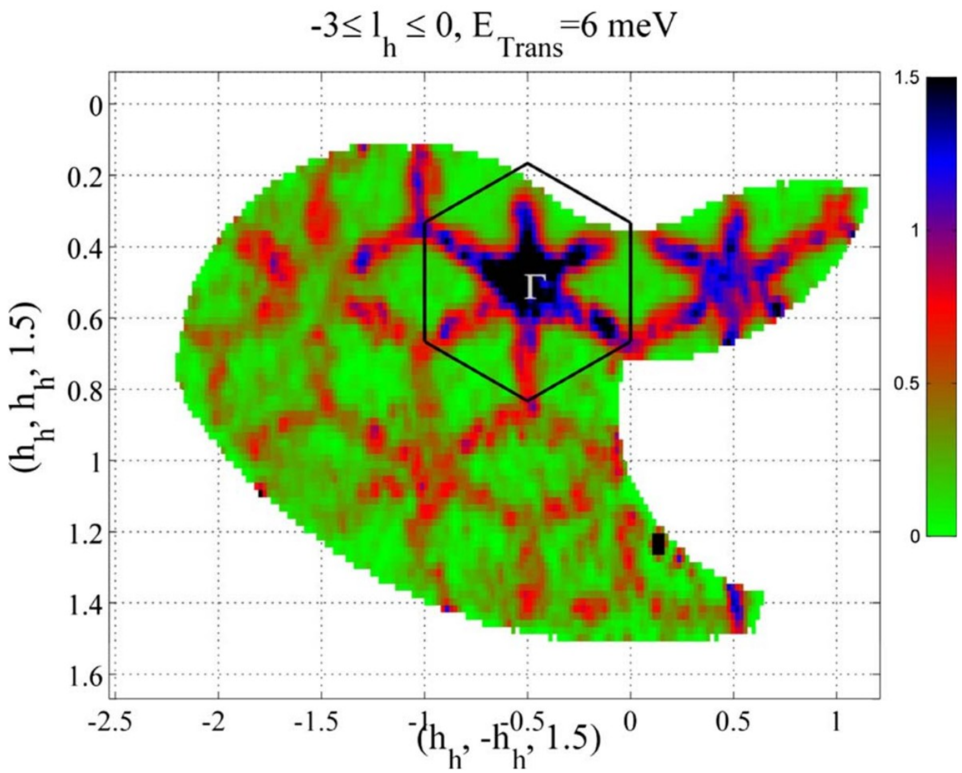


E. Fogh *et al.*, *Nat. Commun.* **15**, 442 (2024)

Time-of-flight spectrometer: Data collection

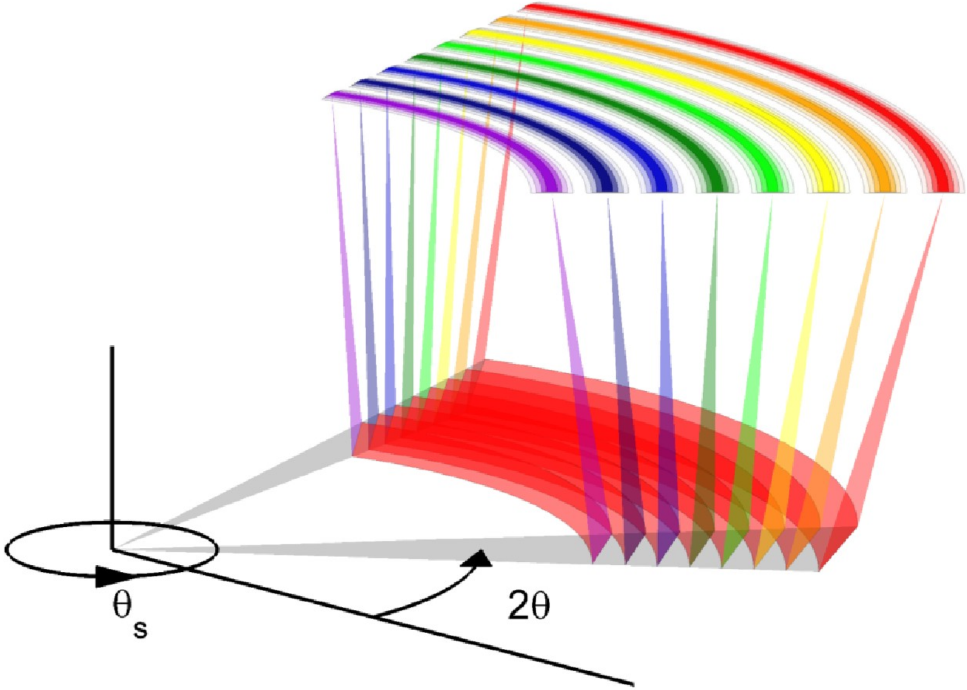


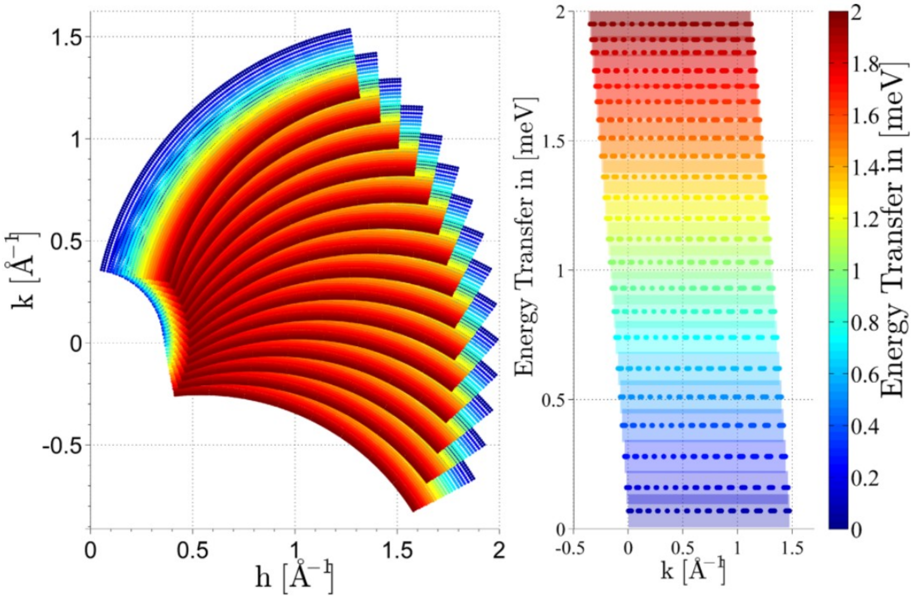
$Sr_3Cr_2O_8$



D. L. Quintero-Castro *et al.*, *Phys. Rev. B* **81**, 014415 (2010)

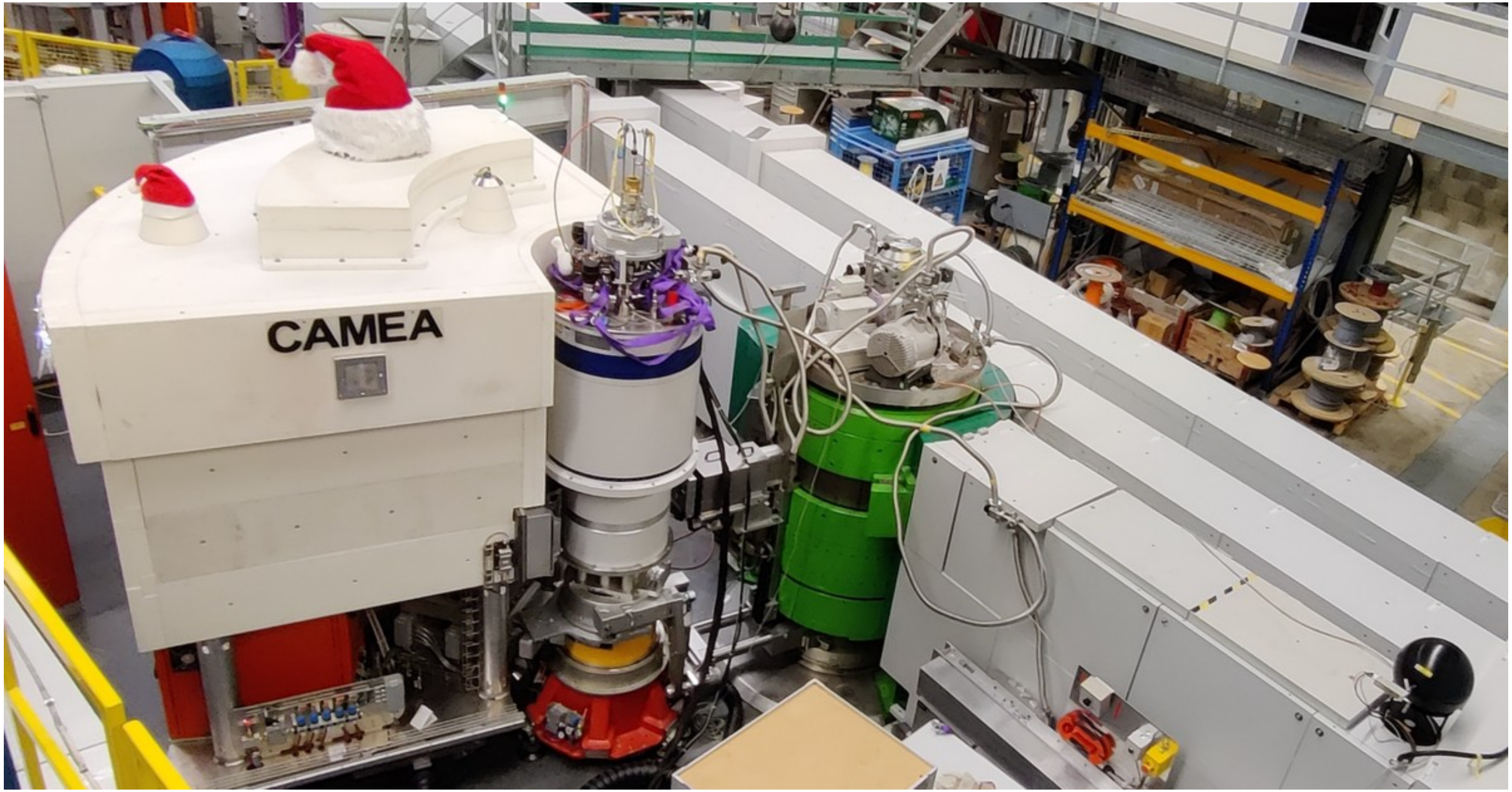
Multiplexing spectrometer: Instrument layout





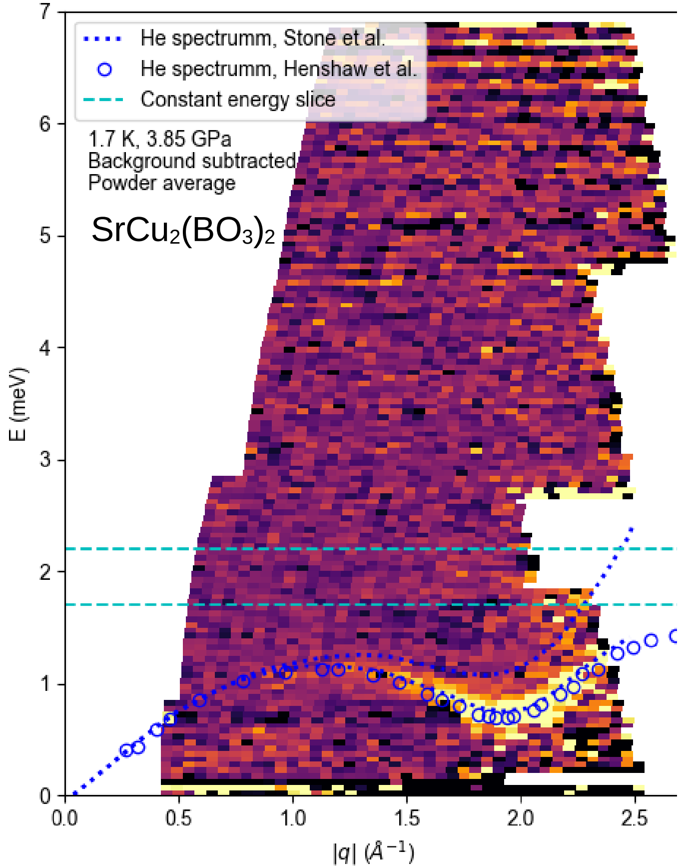
F. Groitl *et al.*, *Rev. Sci. Instrum.* **87**, 035109 (2016)

Multiplexing spectrometer: Instrument layout



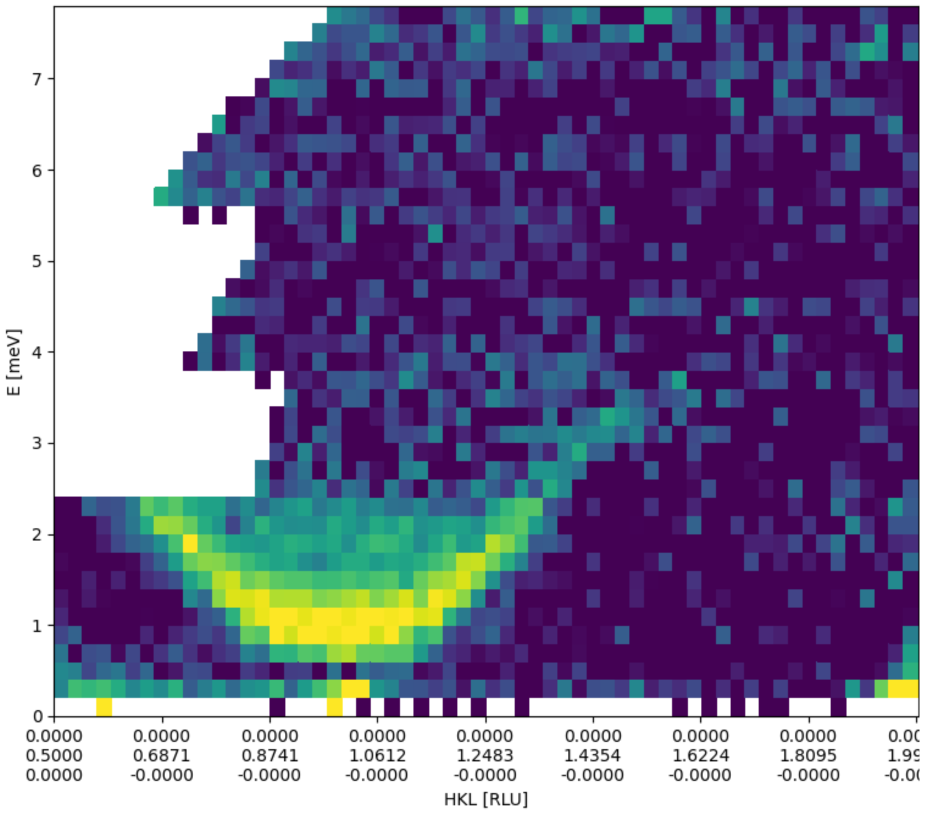
Multiplexing spectrometer: Data collection

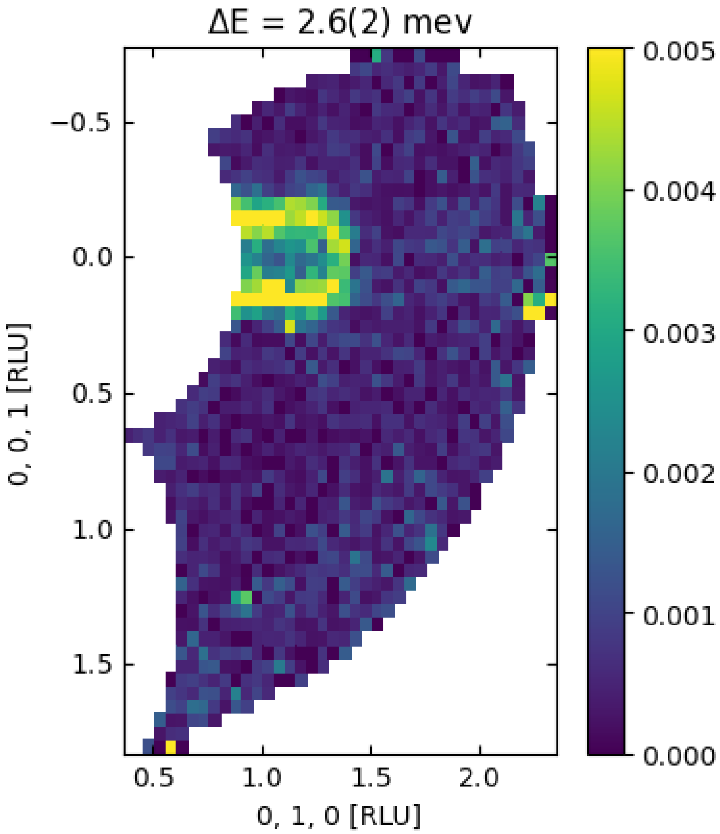
- Best of both worlds
- Need to slice and integrate
- Data files are rather large
- Need for specialized software
- More room to optimize resolution than TOF but not as much as TAS
- Better suited for parametric studies than TOF
- You can collect maps in (**q**,*E*) or focus on specific regions



Multiplexing spectrometer: Data collection

$LiNi_{0.8}Fe_{0.2}PO_4$ measured at CAMEA





Multiplexing spectrometer: Data collection