Мюонна спінова спектроскопія

Muon spin spectroscopy

μSR

Muon Spin Rotation/Relaxation

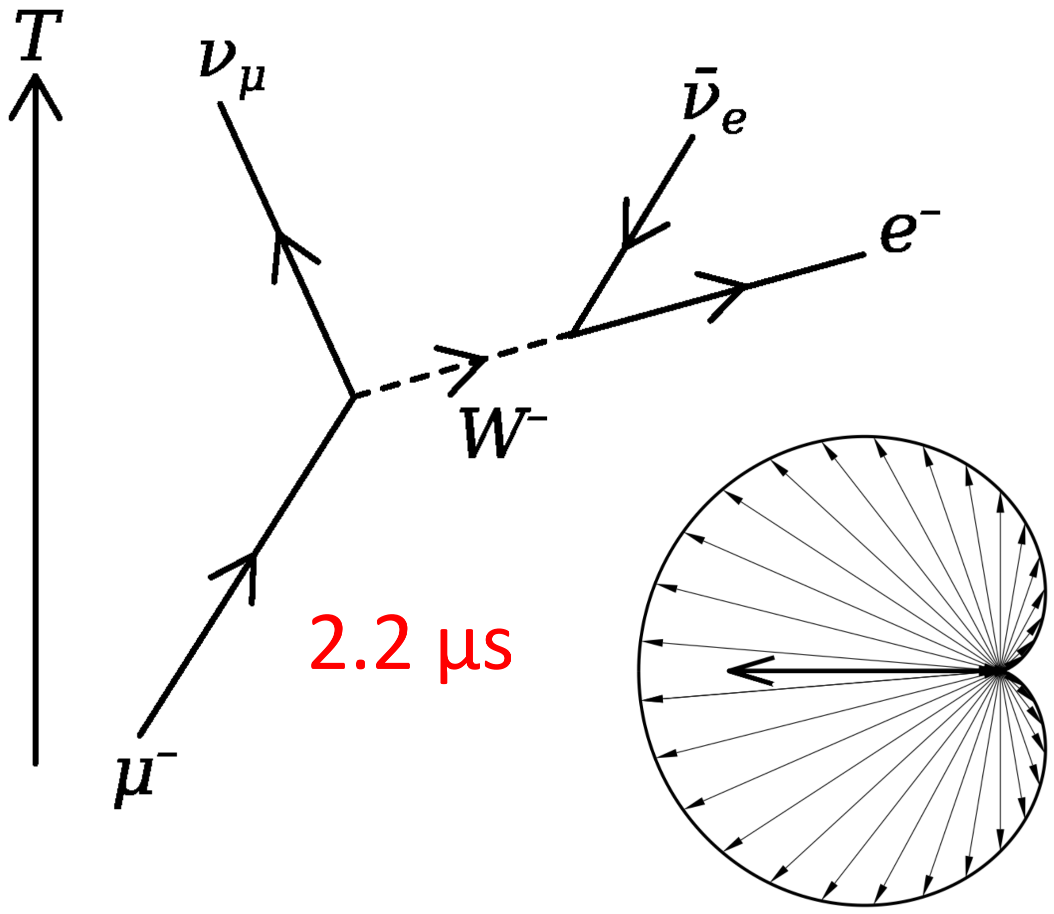
To read

1. S. J. Blundell (1999) Spin-polarized muons in condensed matter physics, *Contemporary Physics* **40**, 175-192 https://arxiv.org/abs/cond-mat/0207699v1
2. L. Nuccio *et al.* Muon spin spectroscopy: magnetism, soft matter and the bridge between the two. *J. Phys. D: Appl. Phys.* **47,** 473001 (2014) pdf
3. Белоусов Ю.М., Смилга В.П. Что такое мюонный метод исследования вещества. *Соросовский образовательный журнал* №1, с. 76-85 (1999) pdf
4. E. Morenzoni. Muon science with continuous beams at PSI (2014) https://www.isis.stfc.ac.uk/Pages/2014-morenzoni-psi.pdf
5. J. E. Sonier *et al.* mSR studies of the vortex state in type-II superconductors. *Reviews of Modern Physics* **72**, 769 (2000) pdf

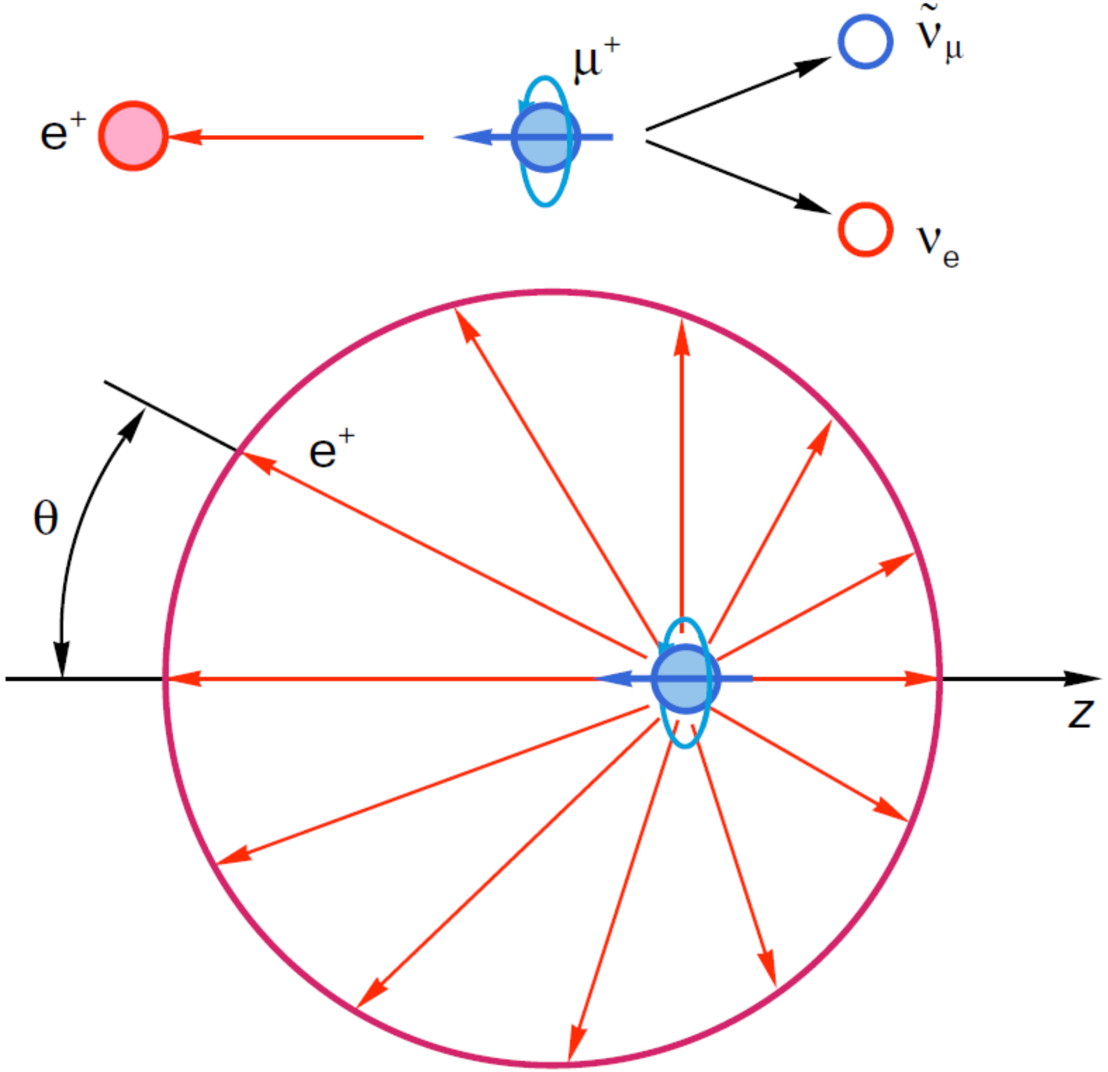
To watch

- Мюони – частинки, які підтверджують теорію відносності [MinutePhysics] https://youtu.be/nusyrYcoBjM
- Распад элементарных частиц — Дмитрий Казаков / ПостНаука https://youtu.be/YXBMSwqw6cA
- Analyzing μSR Spectra, Stephen Blundell (2018) https://youtu.be/T90ShkoyssQ
- Muon-spin rotation - Hugo Keller https://youtu.be/mwcSp2PEcOw

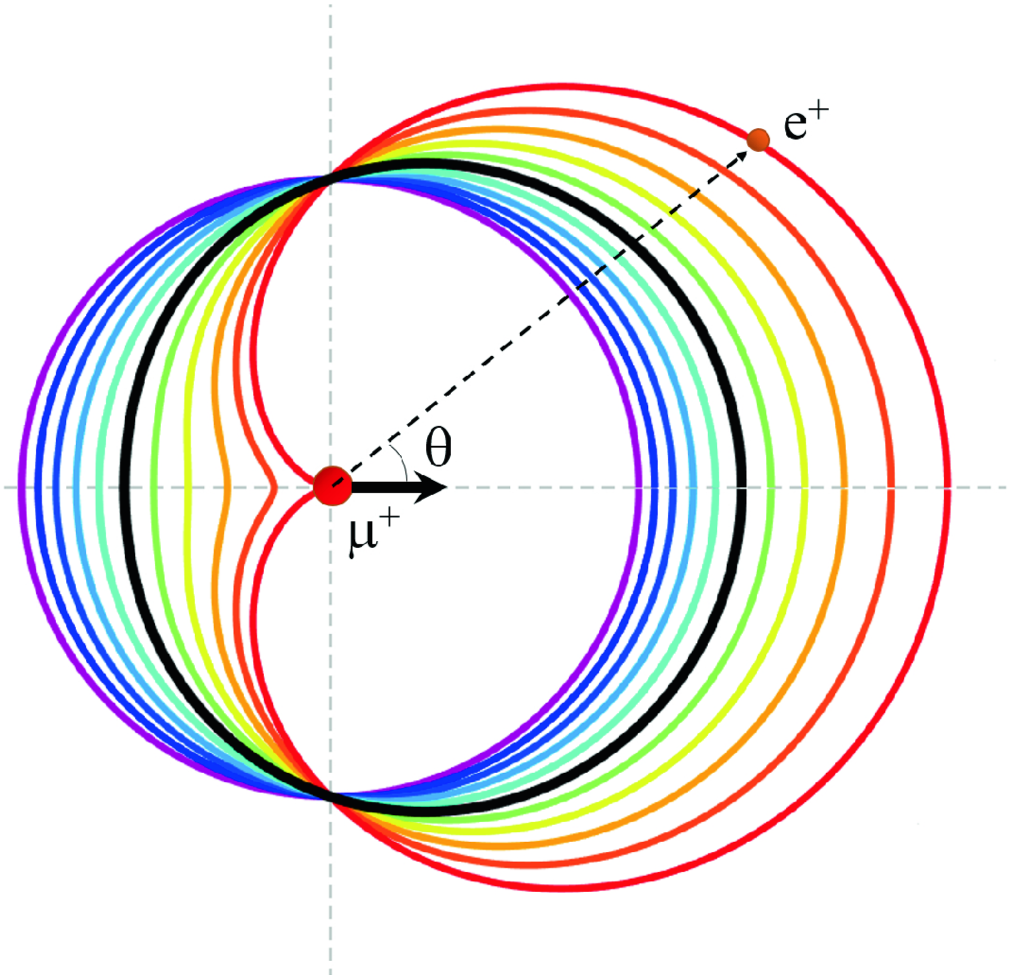
Muon decay

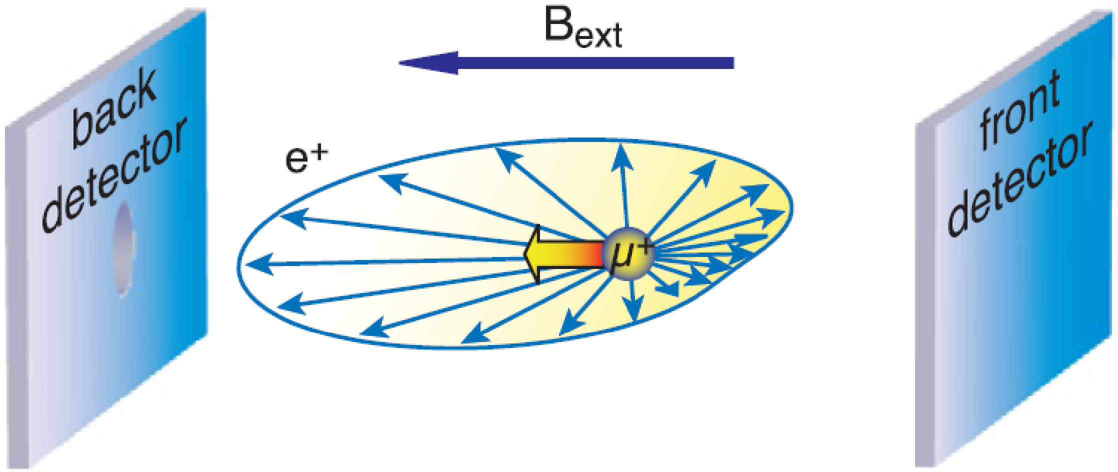


2.2 μs



Muon decay

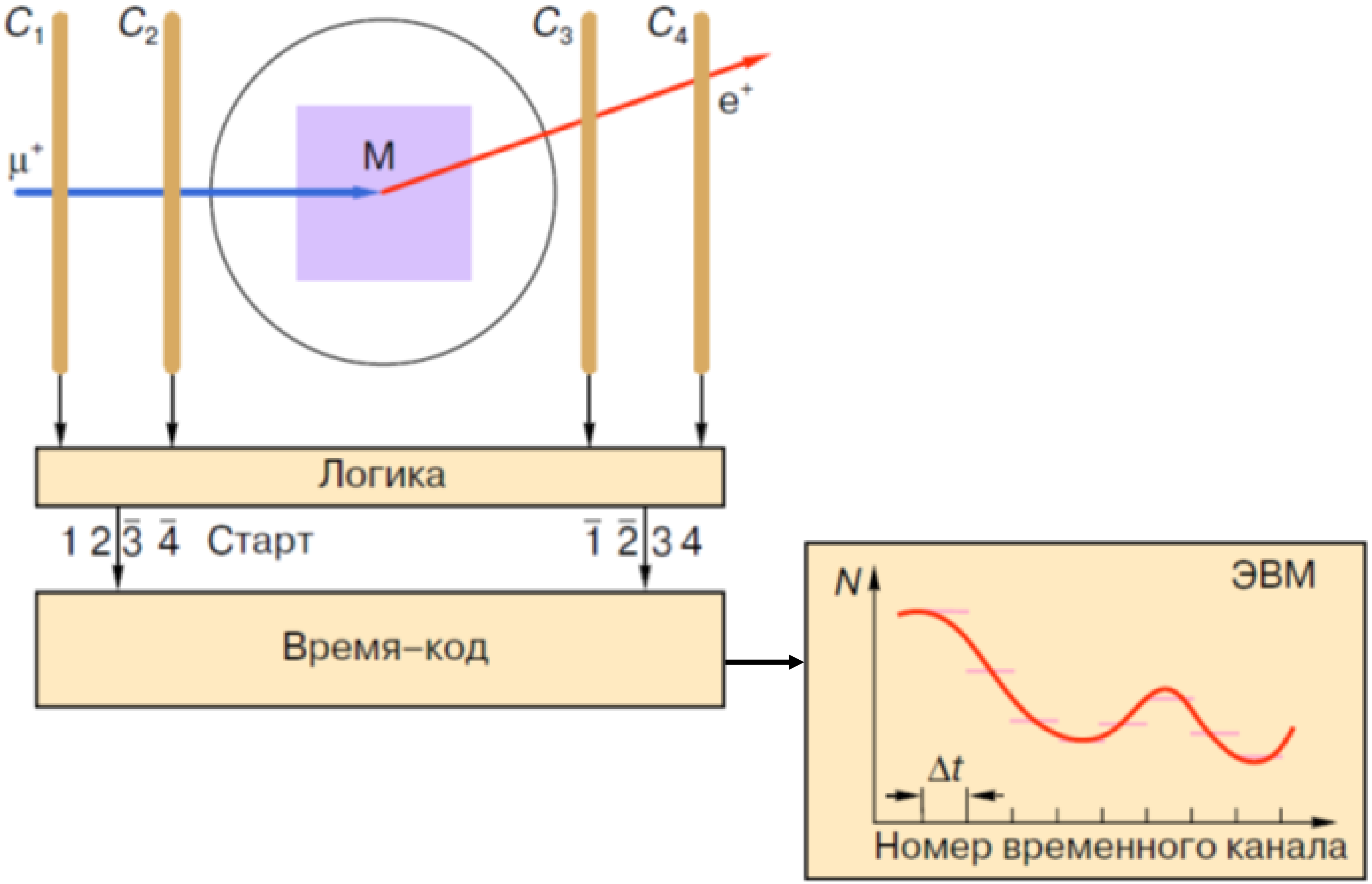




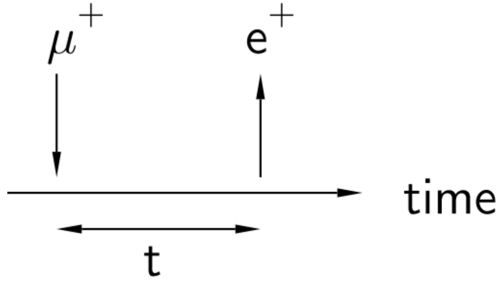
$$dW(\epsilon,\theta) = \frac{e^{t/\tau_\mu}}{\tau_\mu}[1 + a(\epsilon)\cos\theta]n(\epsilon)\,d\epsilon\,d\cos\theta\,dt,$$

where $a(\epsilon) = (2\epsilon - 1)/(3 - 2\epsilon)$, $n(\epsilon) = 2\epsilon^2(3 - 2\epsilon)$ and the reduced positron energy ϵ is defined as $\epsilon = E/E_{\max}$, where $E_{\max}$ is the maximum positron energy $E_{\max} = 52.83\,\mathrm{MeV}$.

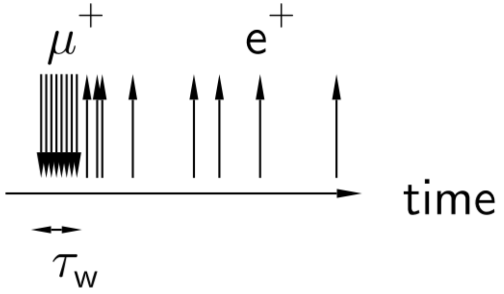
Nuccio 2014



continuous wave

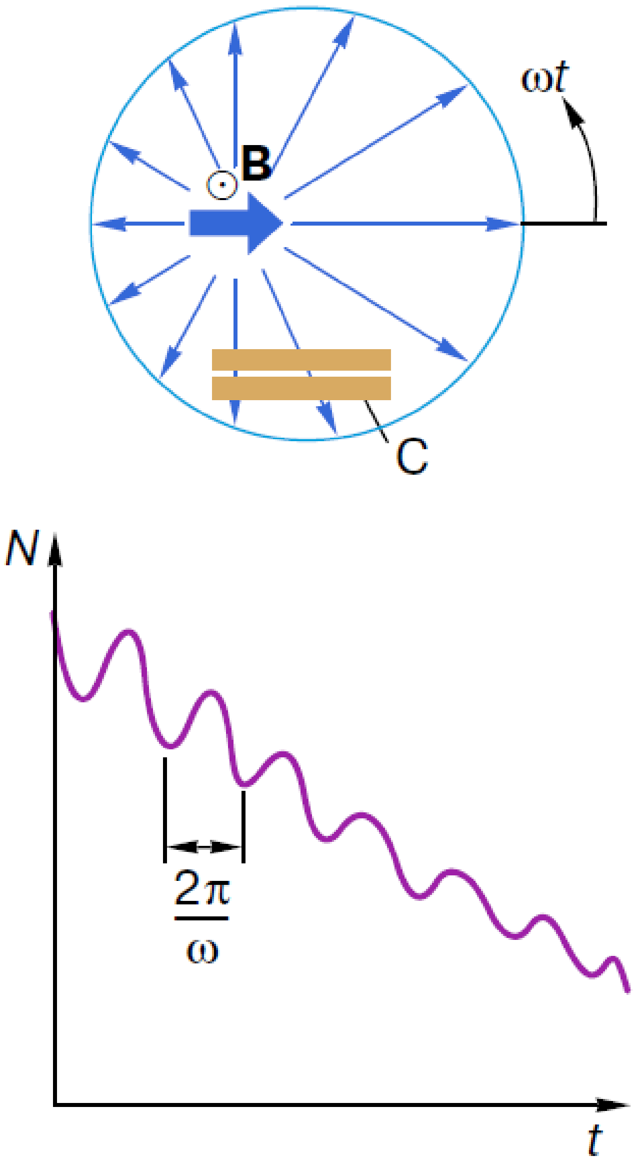


pulsed

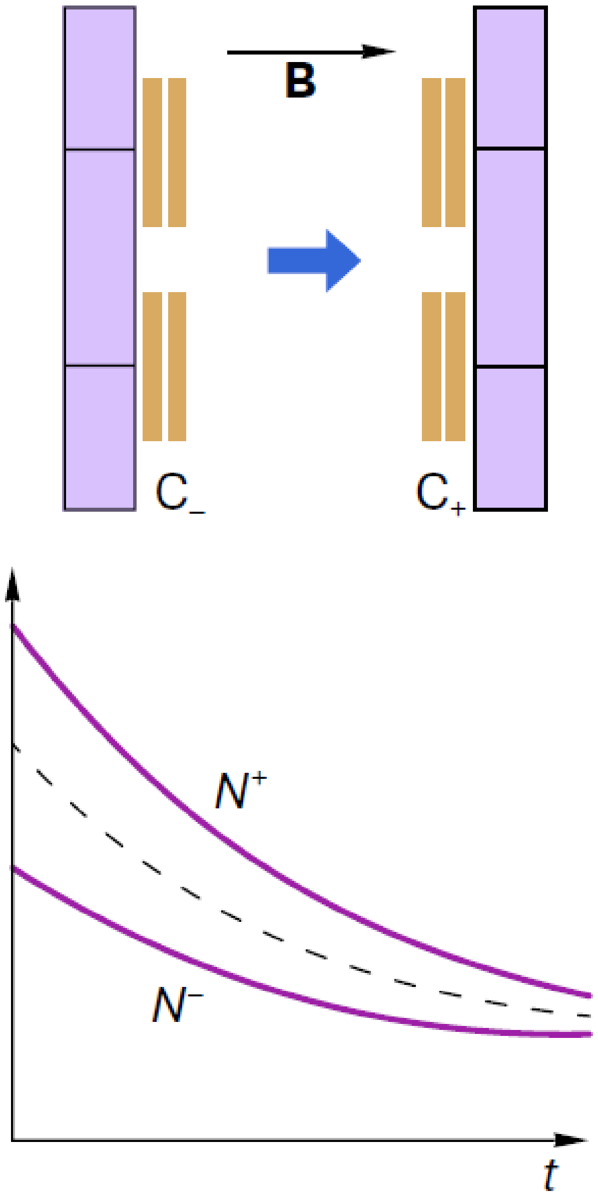


Белоусов, Смилга (1999)

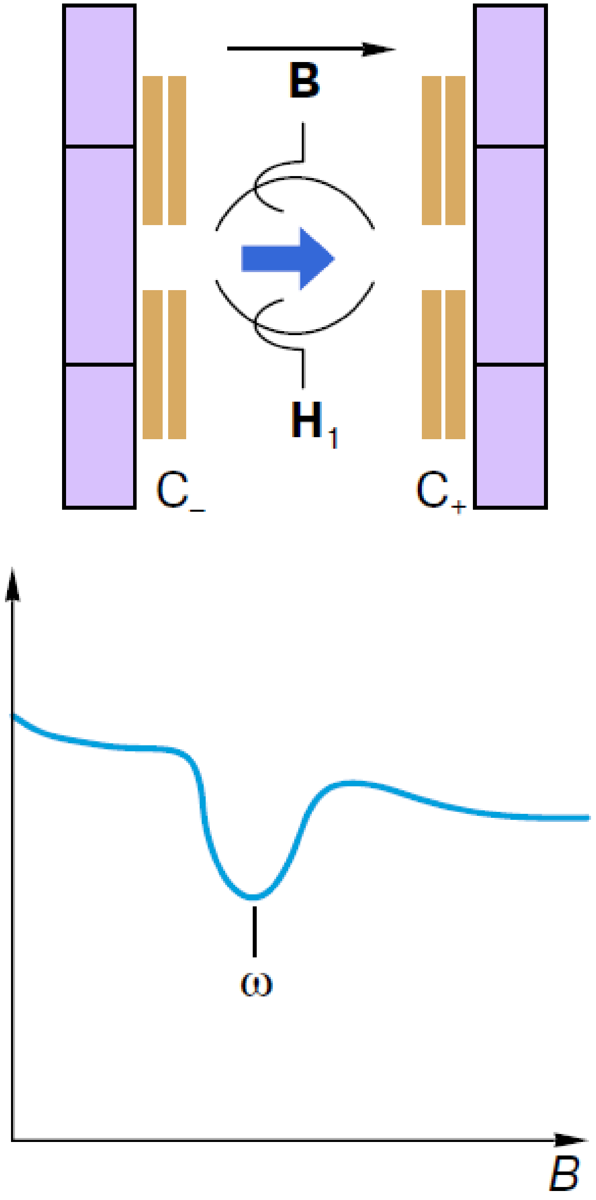
Вращение



Релаксация

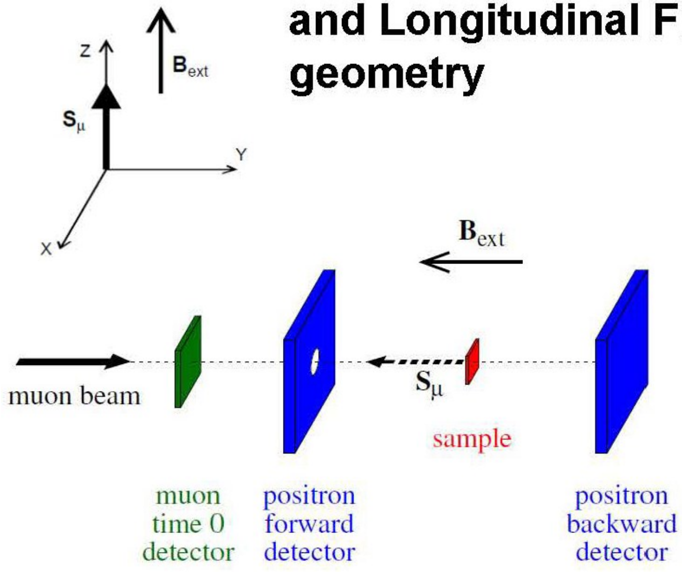


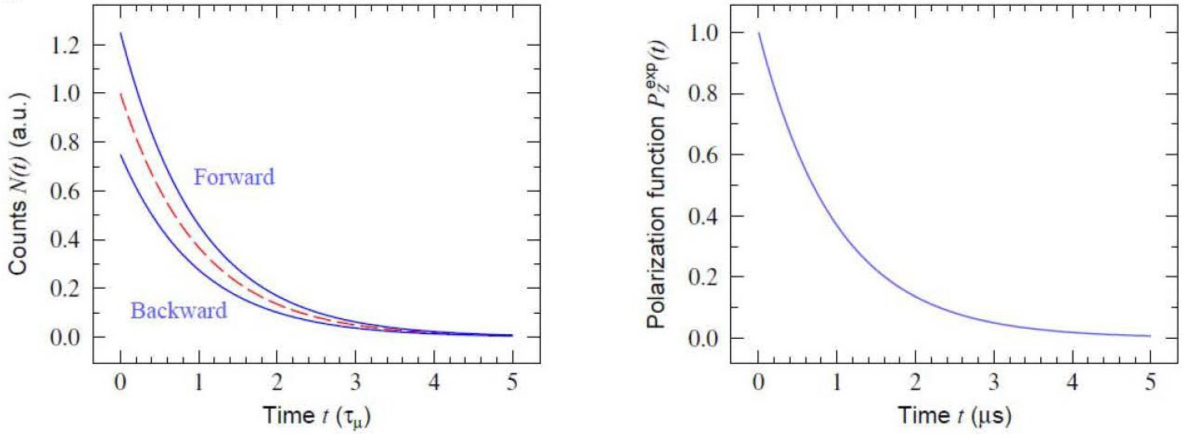
Резонанс



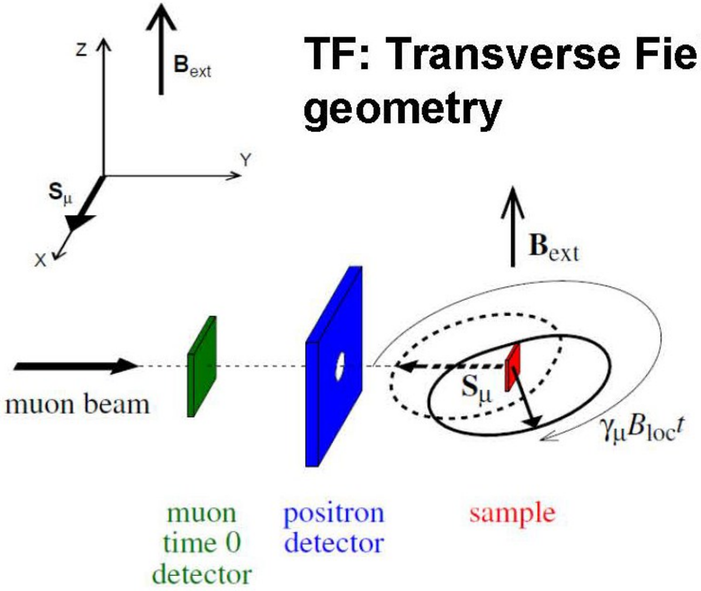
Белоусов, Смилга (1999)

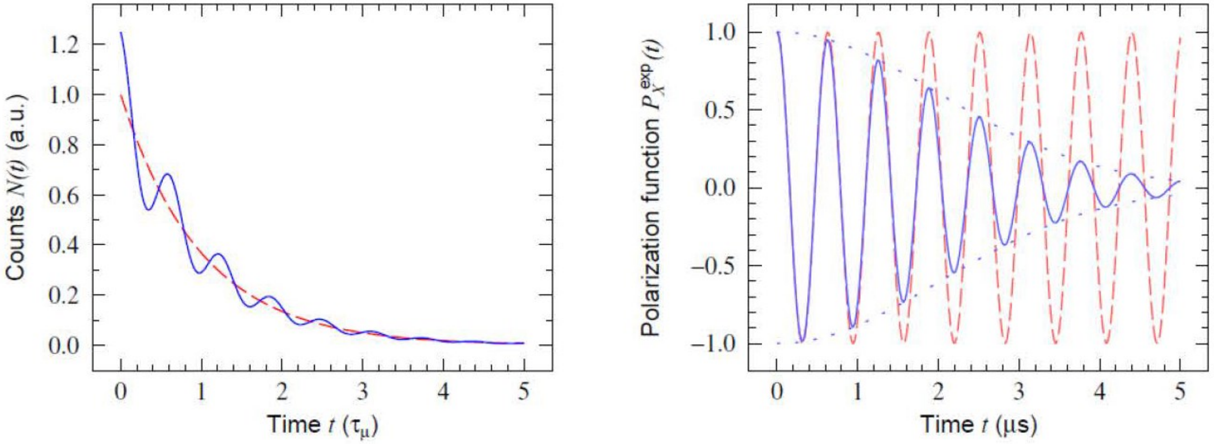
ZF and LF: Zero field and Longitudinal Field geometry





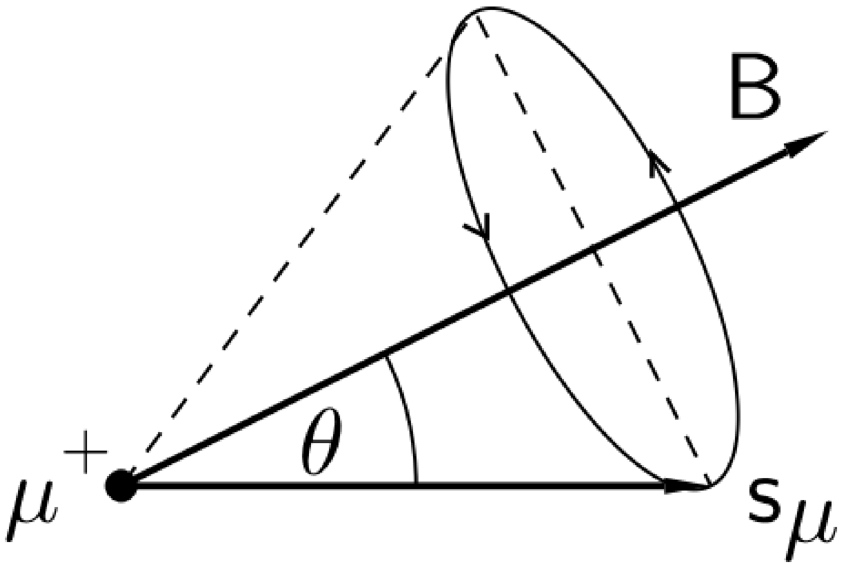
TF: Transverse Field geometry





Morenzoni 2012

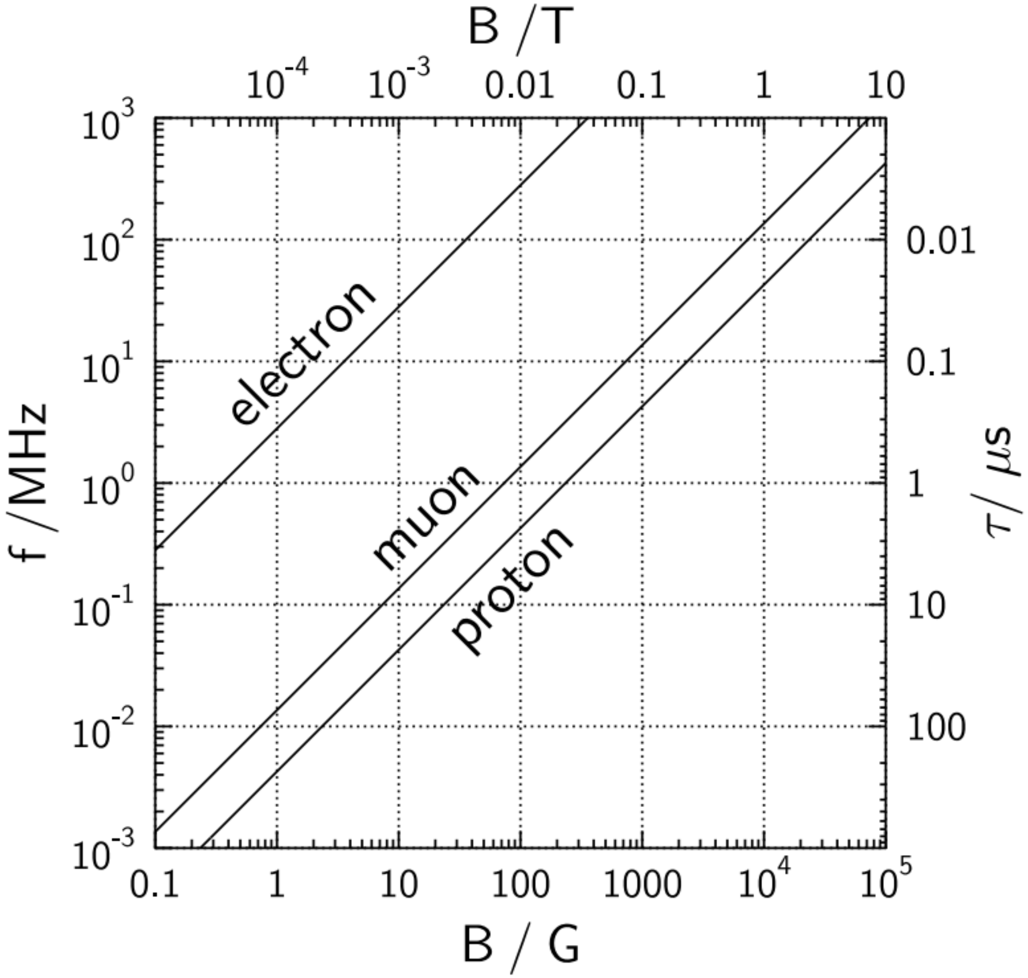
Muon-spin precession



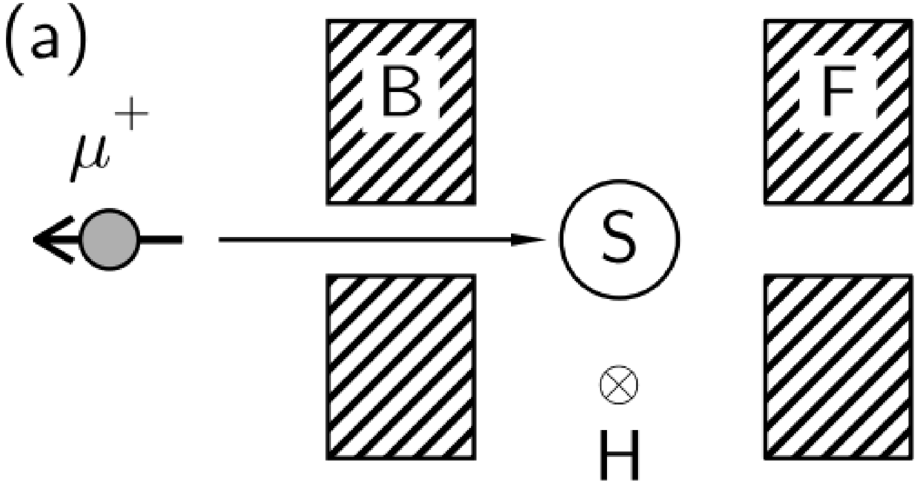
$$P_z(t) = \cos^2\theta + \sin^2\theta\cos(\gamma_\mu|B|t)$$

$|B|$ is the *modulus* of the local dipolar field

$$\gamma_\mu = ge/2m_\mu$$

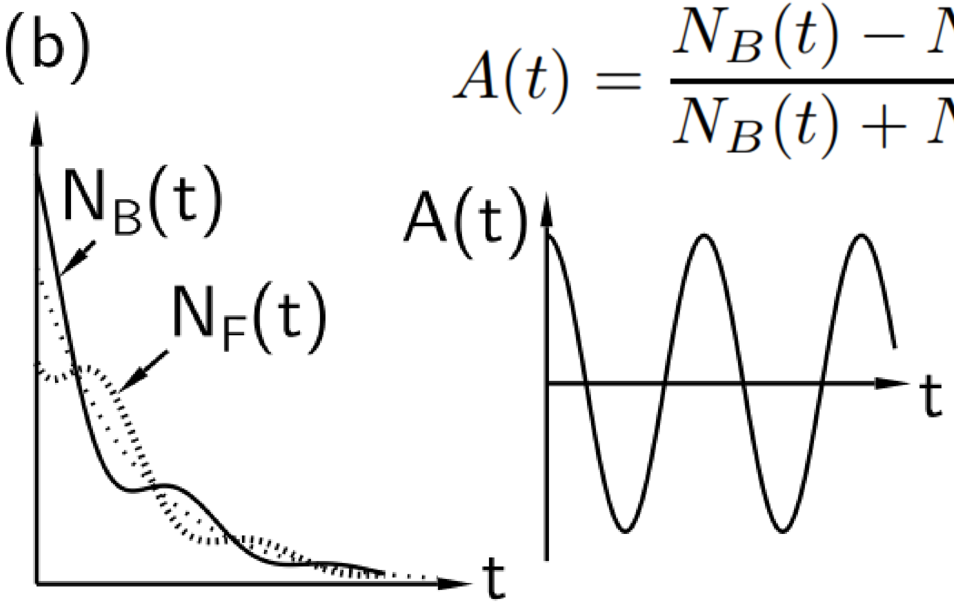


Blundell 1999



Schematic illustration of a μSR experiment. (a) A spin-polarized beam of muons is implanted in a sample S. Following decay, positrons are detected in either a forward detector F or a backward detector B. If a transverse magnetic field H is applied to the sample as shown then the muons will precess. (b) The number of positrons detected in the forward and backward detectors. *A*(*t*) - the asymmetry function.

$$A(t) = \frac{N_B(t) - N_F(t)}{N_B(t) + N_F(t)}$$



Blundell 1999

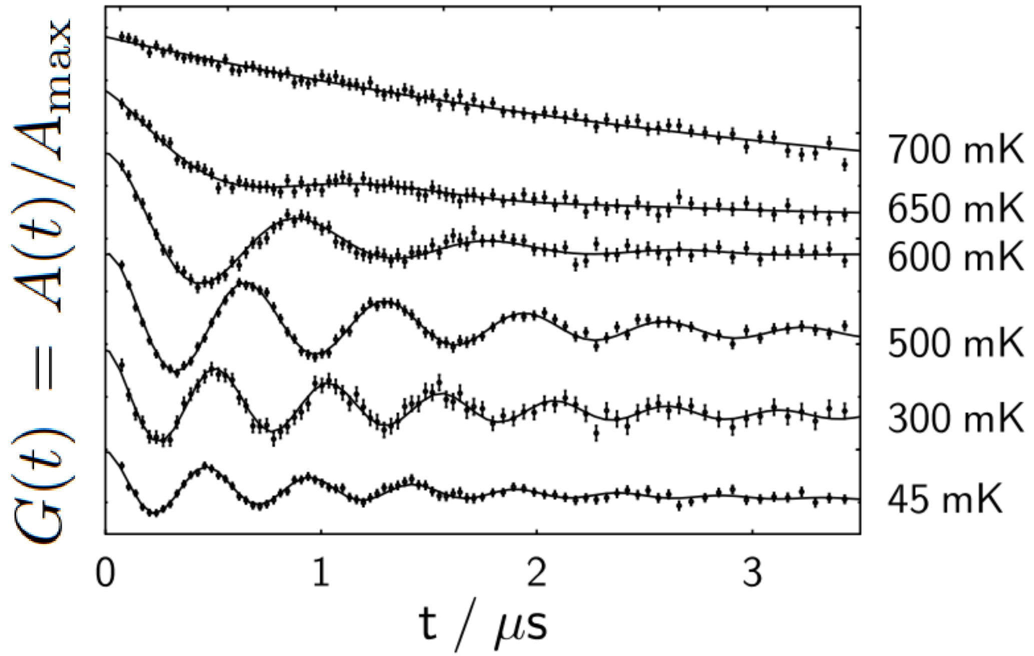


Figure 8: Zero-field muon spin rotation frequency in the organic ferromagnet *p*-NPNN (Blundell *et al.* 1995).

Kubo-Toyabe relaxation

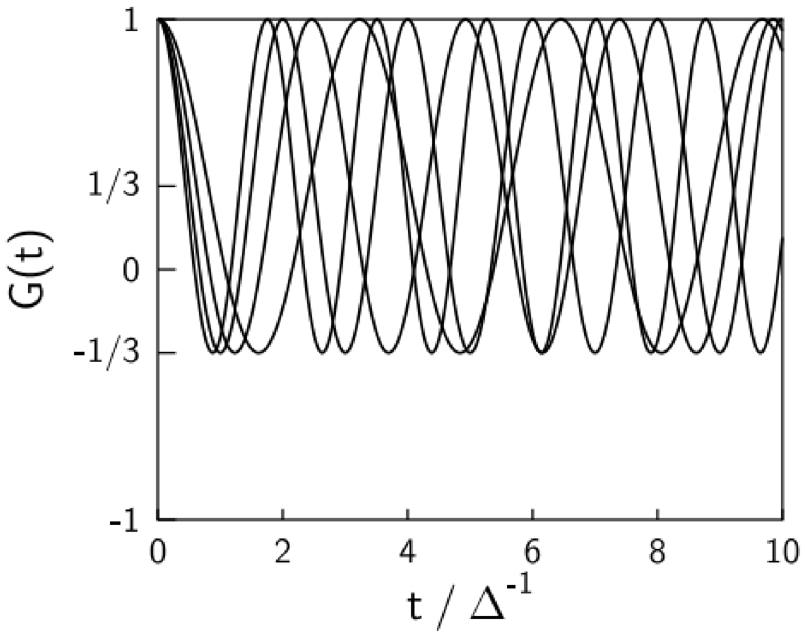
$$G(t) = \cos^2\theta + \sin^2\theta\cos(\gamma_\mu B t)$$

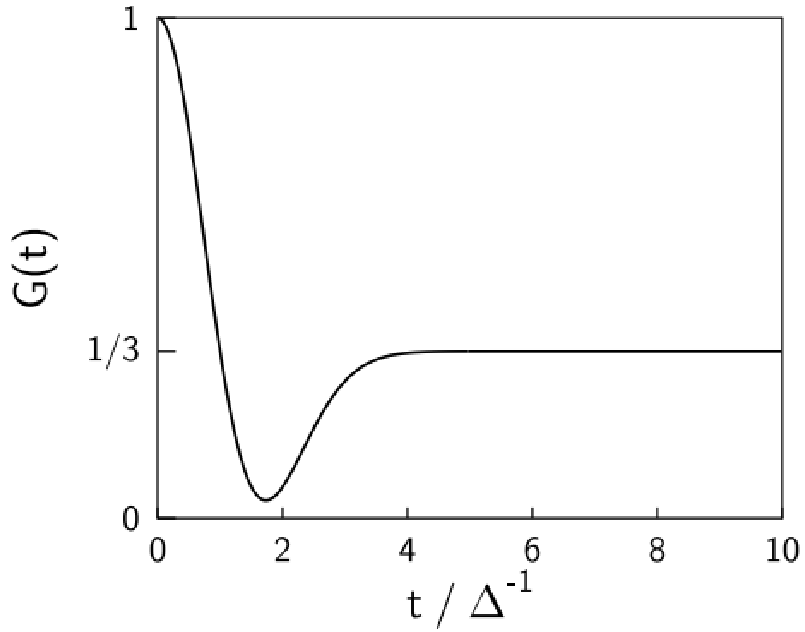
If the direction of the local magnetic field is entirely random then averaging over all directions would yield

$$G(t) = \frac{1}{3} + \frac{2}{3}\cos(\gamma_\mu B t)$$

If the strength of the local magnetic field is taken from a Gaussian distribution of width Δ/γ_μ centred around zero, then a straightforward averaging over this distribution gives

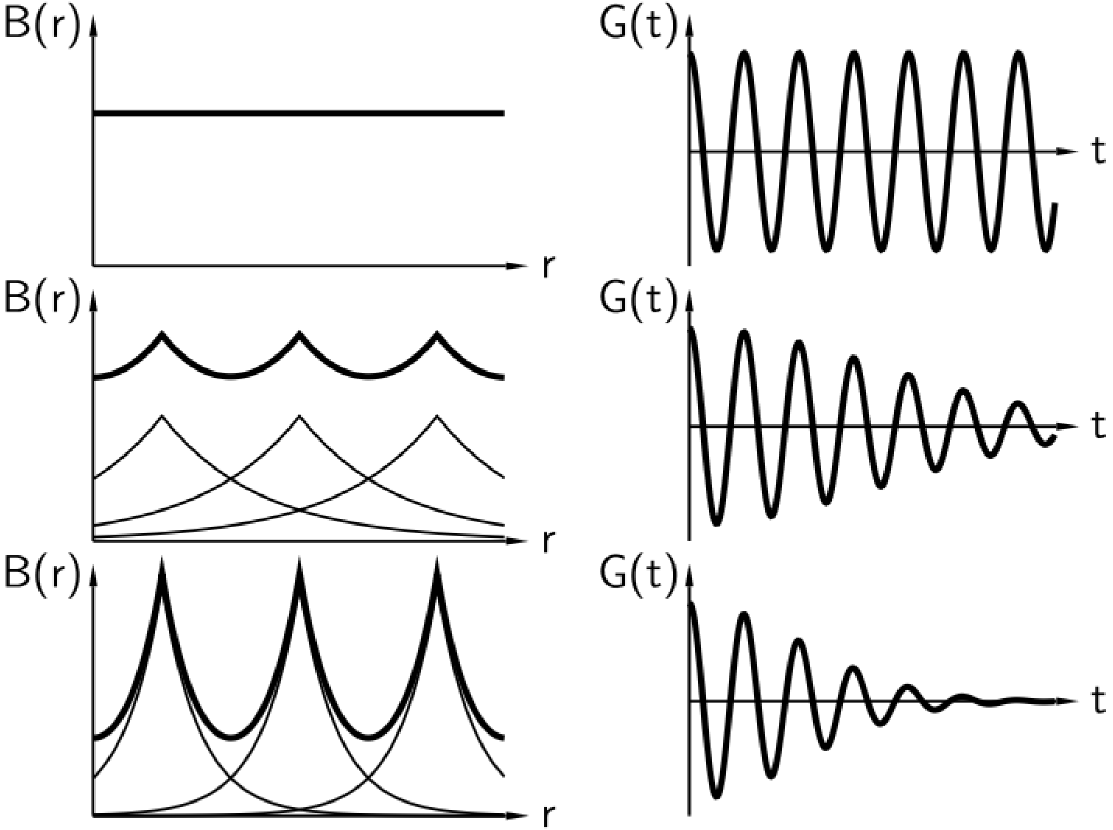
$$G(t) = \frac{1}{3} + \frac{2}{3}e^{-\Delta^2 t^2/2}(1 - \Delta^2 t^2)$$

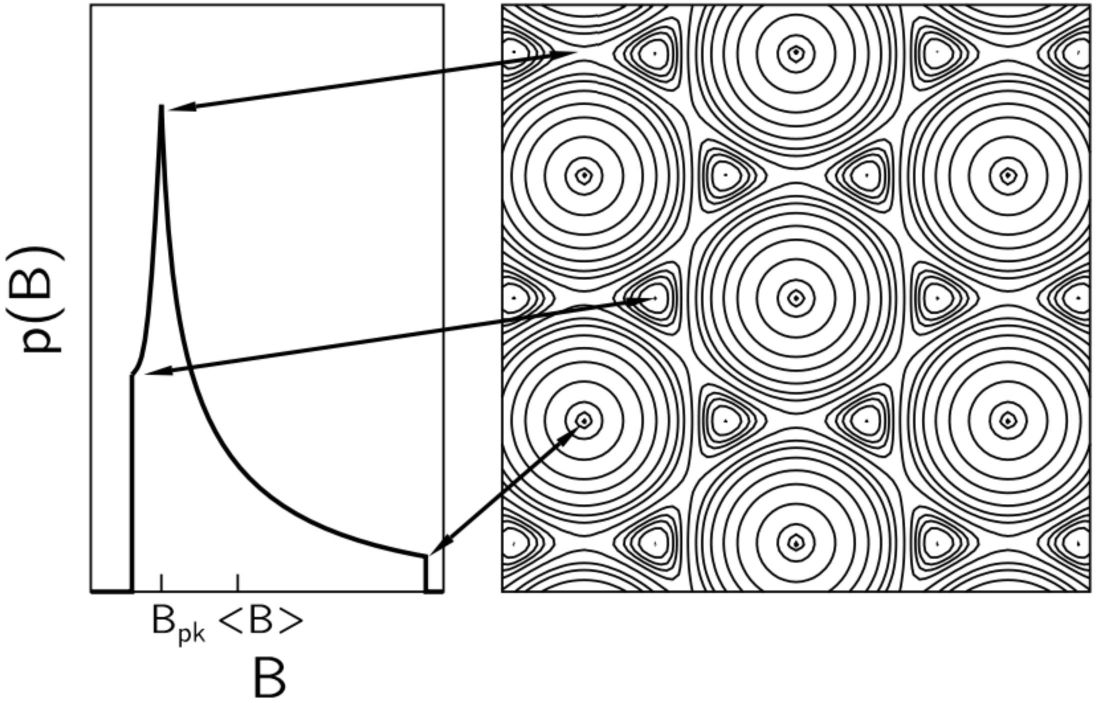




Blundell 1999

Abrikosov vortices

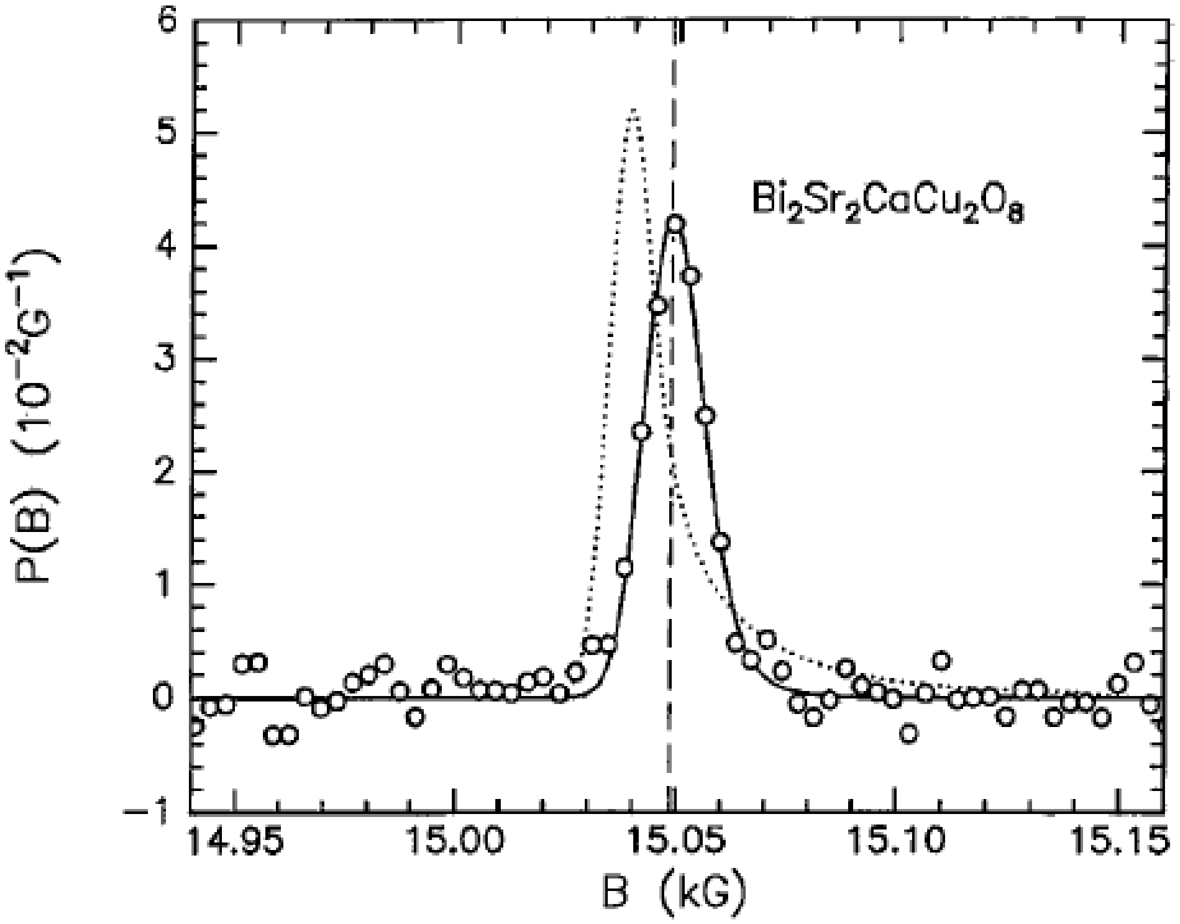


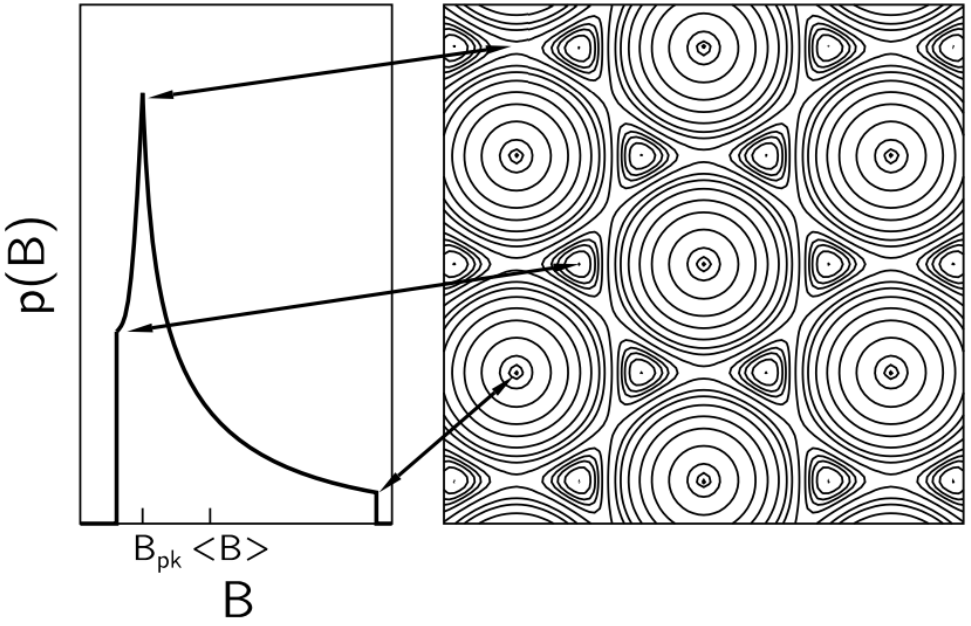


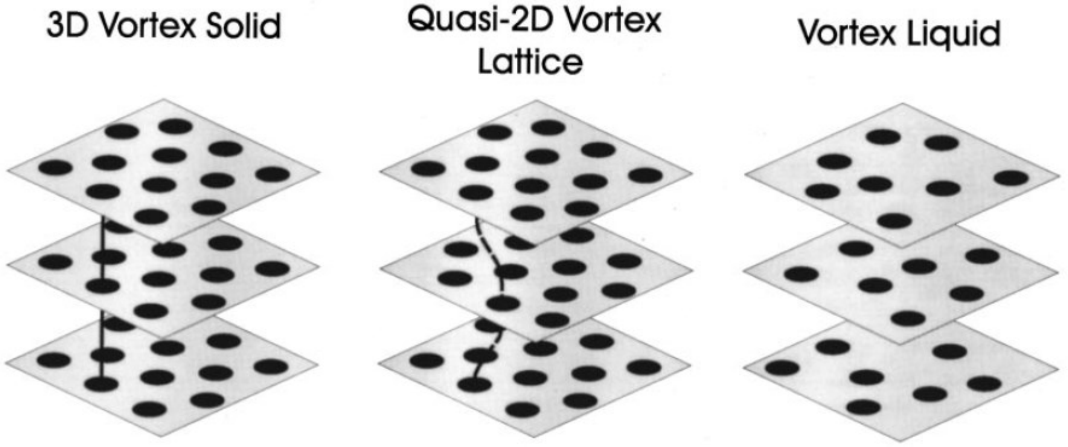
$$\sigma = \gamma_\mu \langle B(\mathbf{r}) - \langle B(\mathbf{r}) \rangle_{\mathbf{r}} \rangle_{\mathbf{r}}^{1/2} \approx 0.0609 \gamma_\mu \Phi_0 / \lambda^2$$

Blundell 1999

Abrikosov vortices

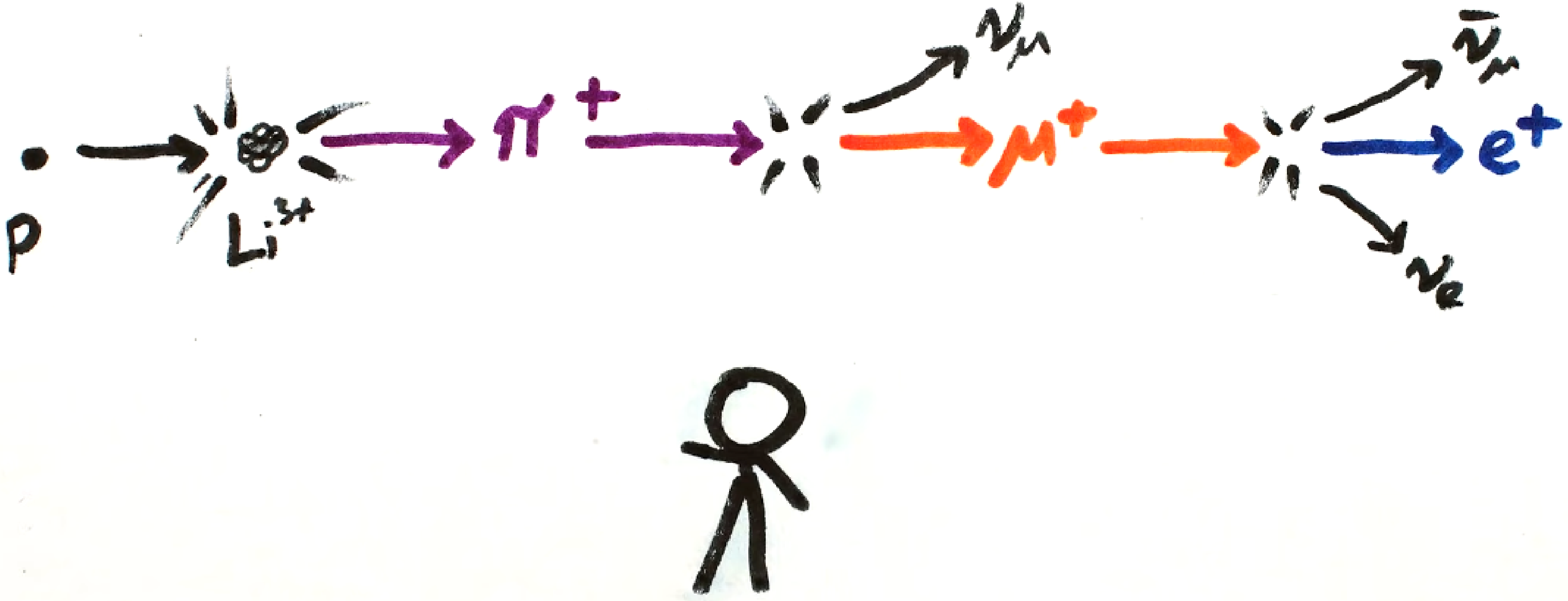






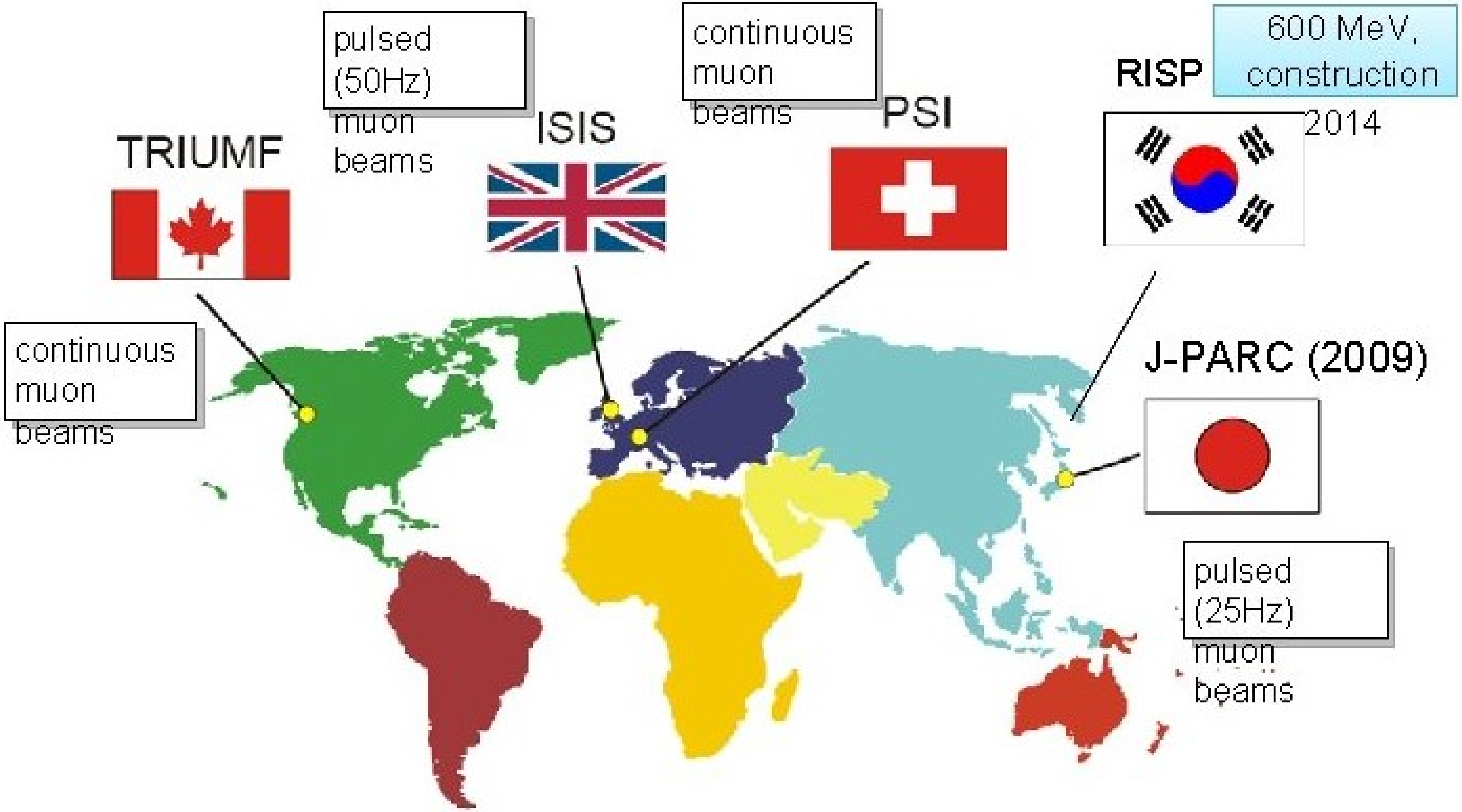
Sonier 2000

Muon decay



How To Make MUONS https://youtu.be/zBr9YiSwdzM

μSR Facilities around the World



TRIUMF

continuous muon beams

ISIS

pulsed (50Hz) muon beams

PSI

continuous muon beams

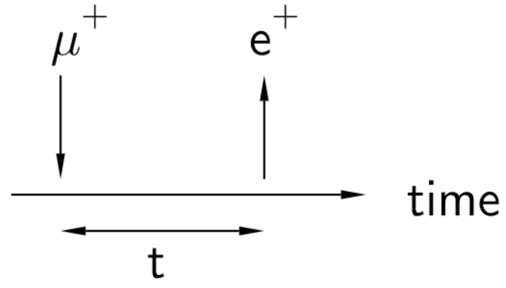
RISP

600 MeV, construction 2014

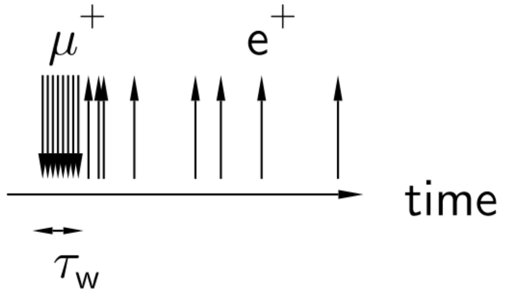
J-PARC (2009)

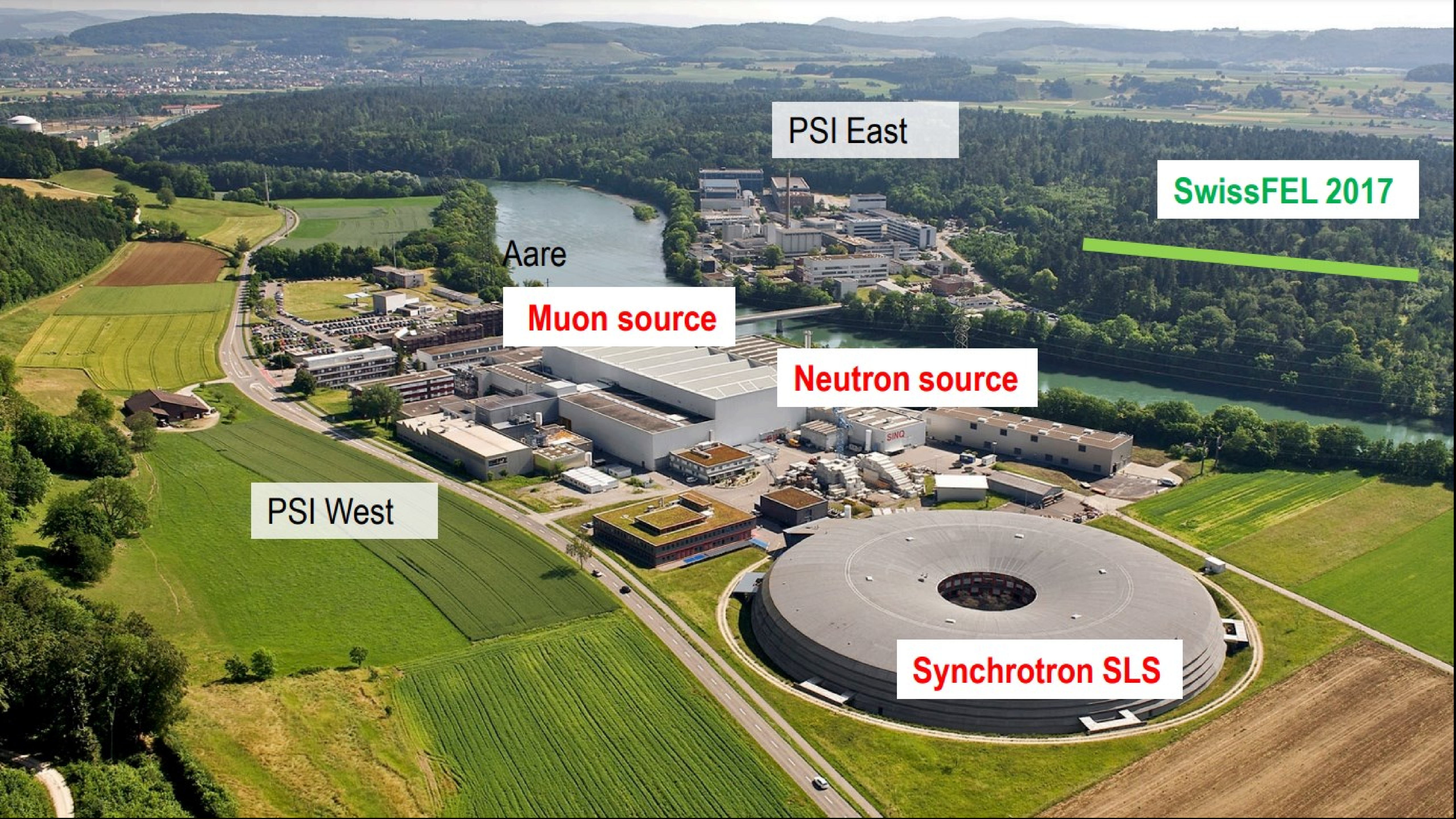
pulsed (25Hz) muon beams

continuous wave



pulsed




PSI East
SwissFEL 2017
Aare
Muon source
Neutron source
PSI West
Synchrotron SLS
SINQ

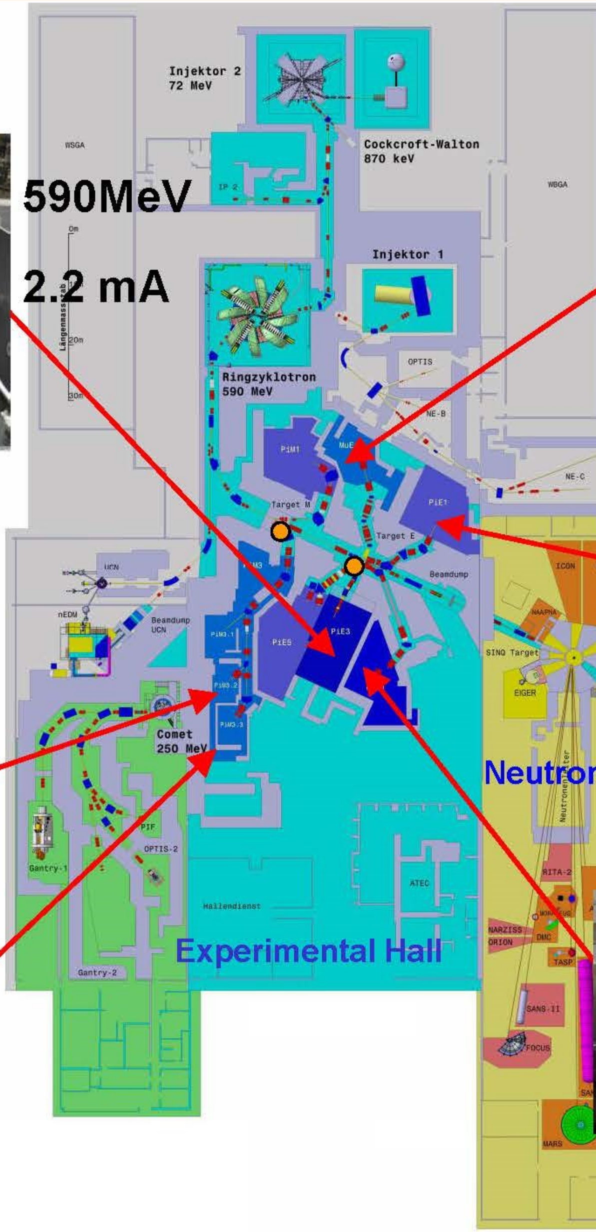
Muon Instruments at PSI : SμS (Swiss Muon Source)

HAL-9500

High Field and Low Temperature

9.5 T

< 20 mK



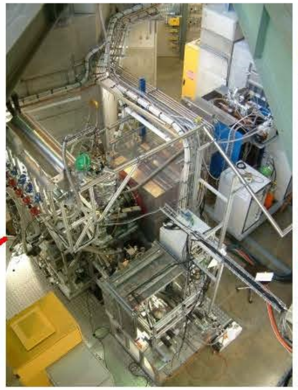
590MeV

2.2 mA

LEM

Low-energy muon beam and instrument , tunable energy (0.5-30 keV, μ⁺), *thin-film, near-surface and multi-layer studies*

(1-300 nm)



0.3 T

2.5 K

GPS

General Purpose Surface Muon Instrument

Muon energy: 4.2 MeV (μ⁺)

0.6 T, 1.6 K

DOLLY

General Purpose Surface Muon Instrument

μ⁺ energy: 4.2 MeV

0.5 T

250 mK

Shared Beam Surface Muon Facility (Muon On REquest)

LTF

Low Temperature Facility

Muon energy: 4.2 MeV (μ⁺)

3 T,

20 mK- 4 K

GPD

General Purpose Decay Channel Instrument Pressure studies

Muon energy: 5 - 60 MeV (μ⁺ or μ⁻)

0.5 T,

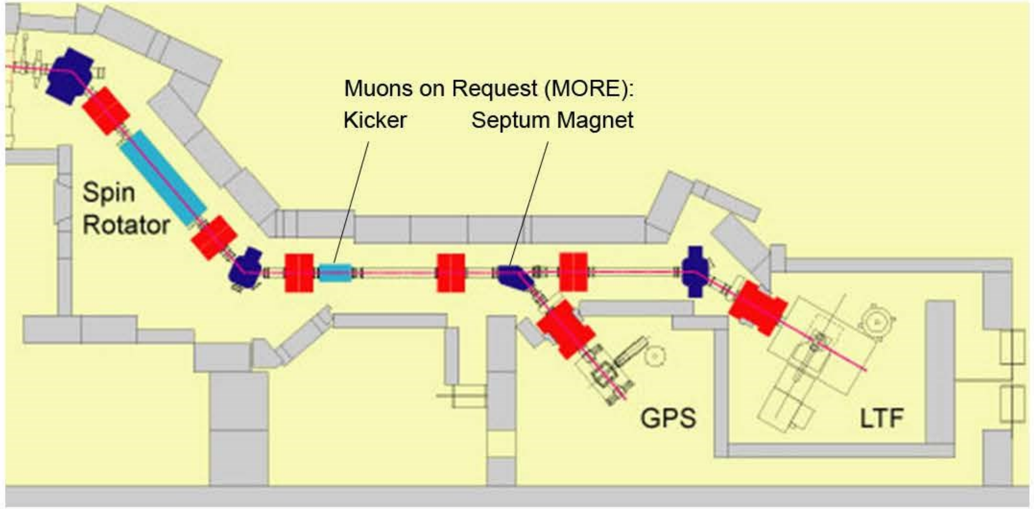
300 mK

2.8 GPa

Morenzoni 2014

Surface Muon Instruments – GPS/LTF/Dolly

πM3 beam line: shared by: General Purpose Spectrometer and Low Temperature Facility



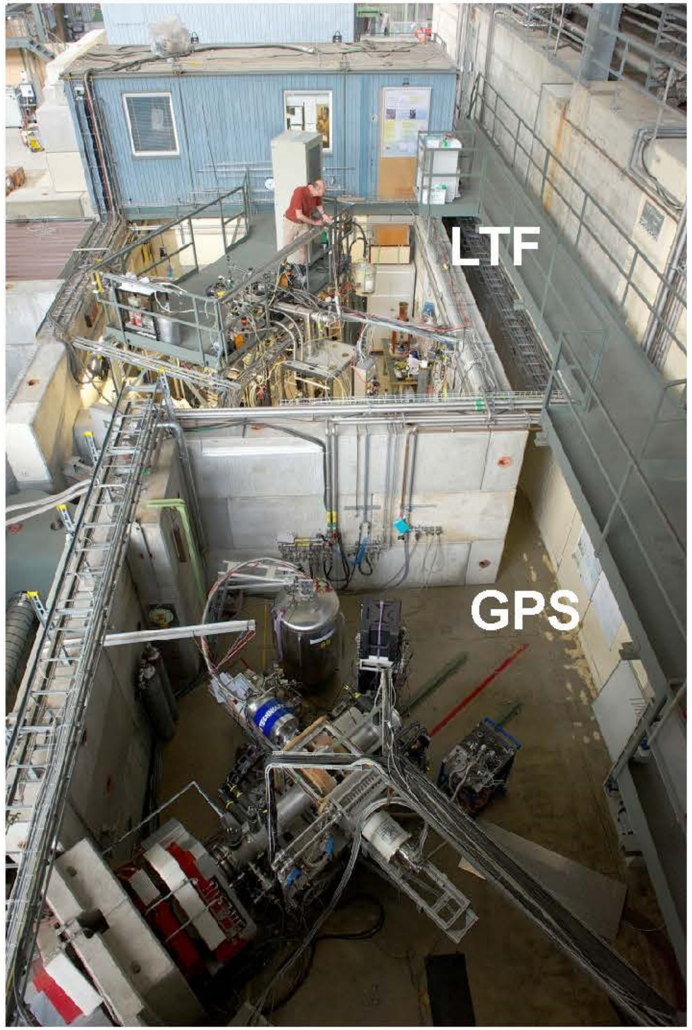
- 4 MeV μ^+, 100% polarized
- **B_{ext}** GPS: 0 - 0.6 T
  Dolly: 0 - 0.6 T
  LTF: 0 - 3 T
- **T** GPS: 1.8 - 1200 K
  Dolly: 0.3 – 300 K
  LTF(DR): 0.02 - 4.2 K

Veto system for low background and small samples:

Sample size:

~ 2 mm DIA

or ~ **30 mg**



Morenzoni 2014

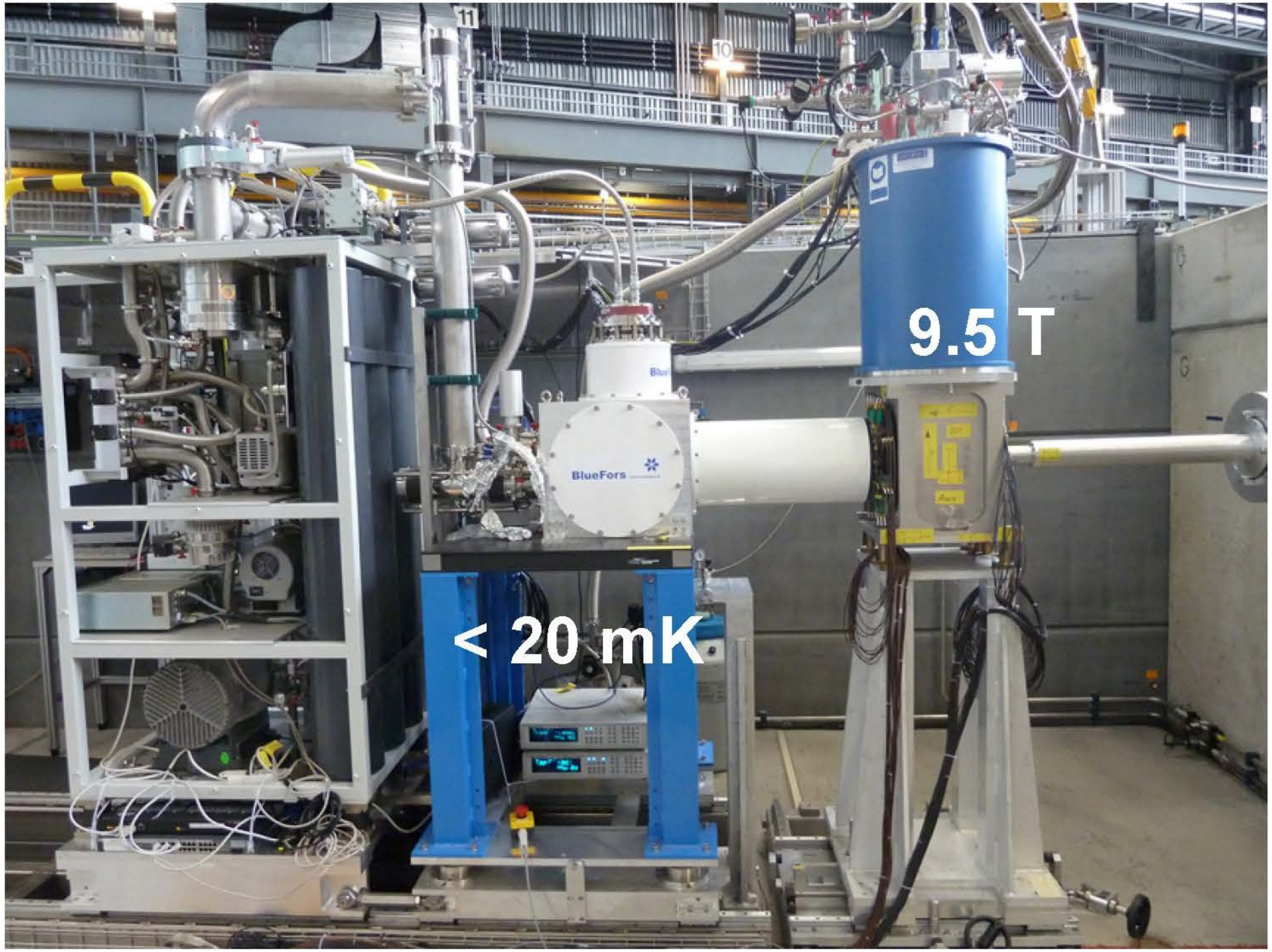
HAL-9500: High field And Low temperature μSR (9.5 T, < 20 mK)

Instrument

Beam line with 90° spin rotator

Morenzoni 2014

Horizontal dilution refrigerator, high field homogeneity (10^{-4} T)

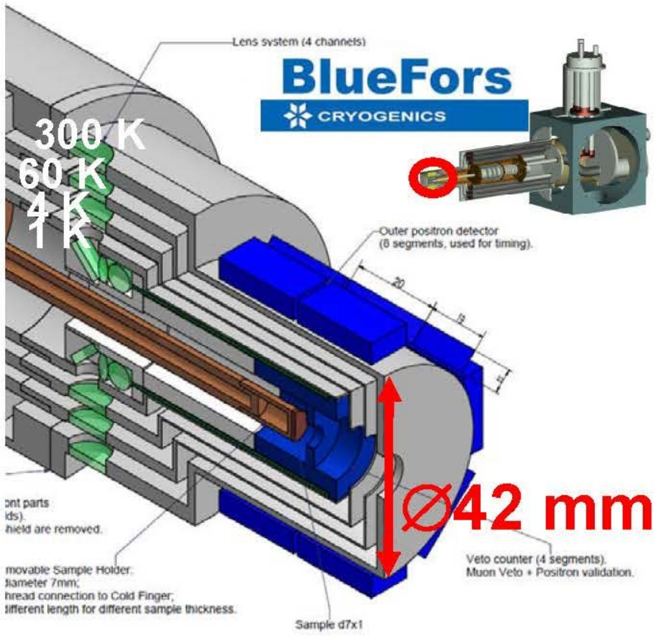


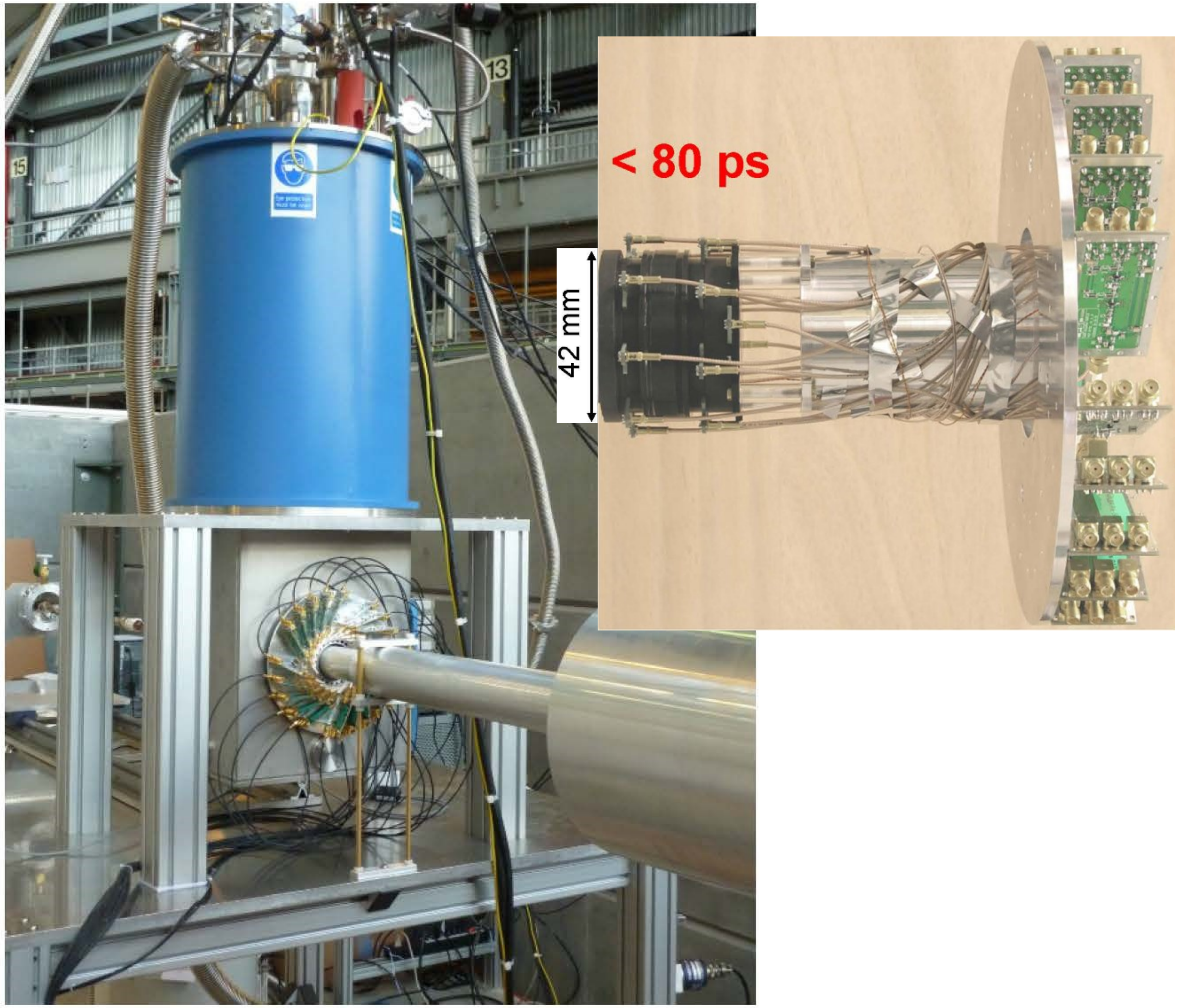
Option with He-Flow Cryostat 2K- 320 K

R. Scheuermann et al.

Morenzoni 2014

A compact and fast μSR spectrometer





Need spectrometer which is:

- **very compact** (spiraling radius of 30 MeV decay positron: 1 cm in 10 T)
- **very fast** Larmor precession frequency at 10 T ν_L ~1.35 GHz (remember $A(\nu_L)$)
- **field insensitive**

→Solid state detectors: Avalanche Photo Diodes (APDs)

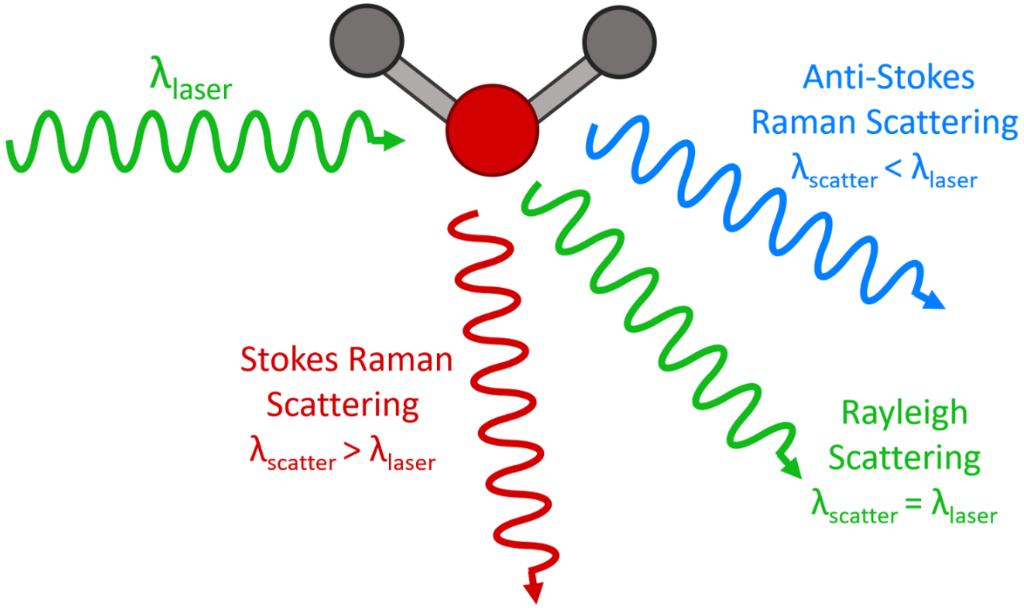
Morenzoni 2014

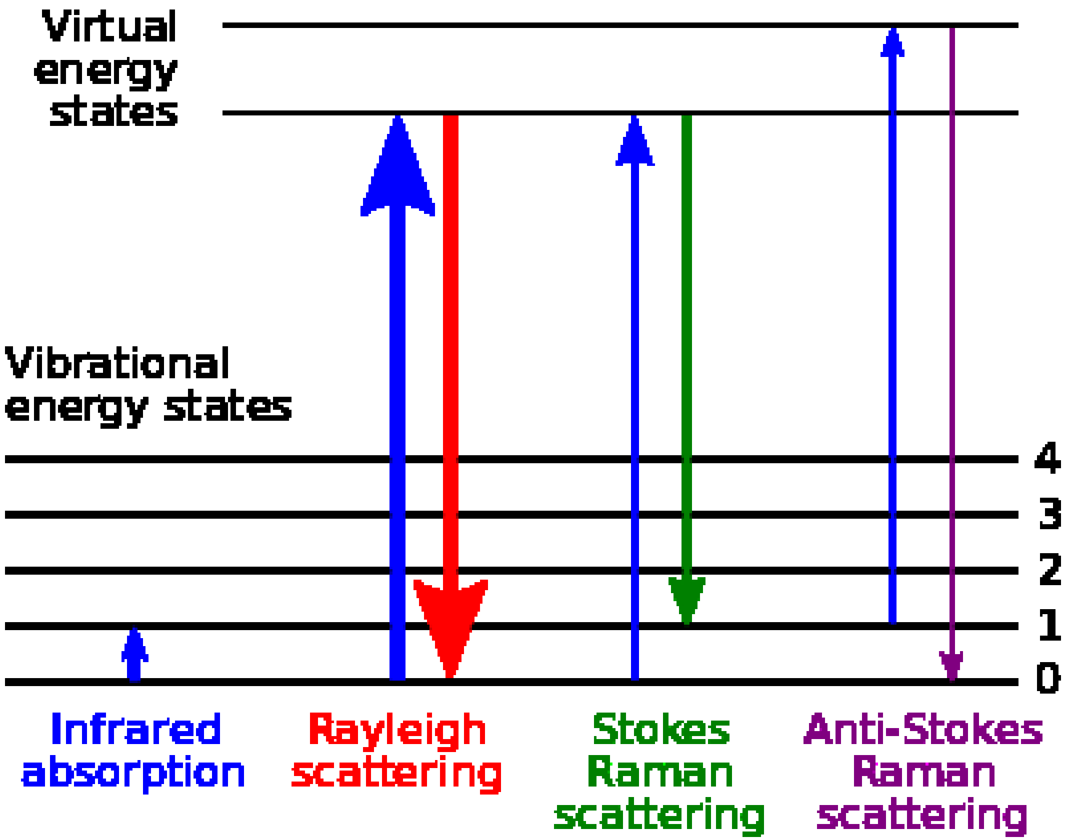
Raman spectroscopy

To read

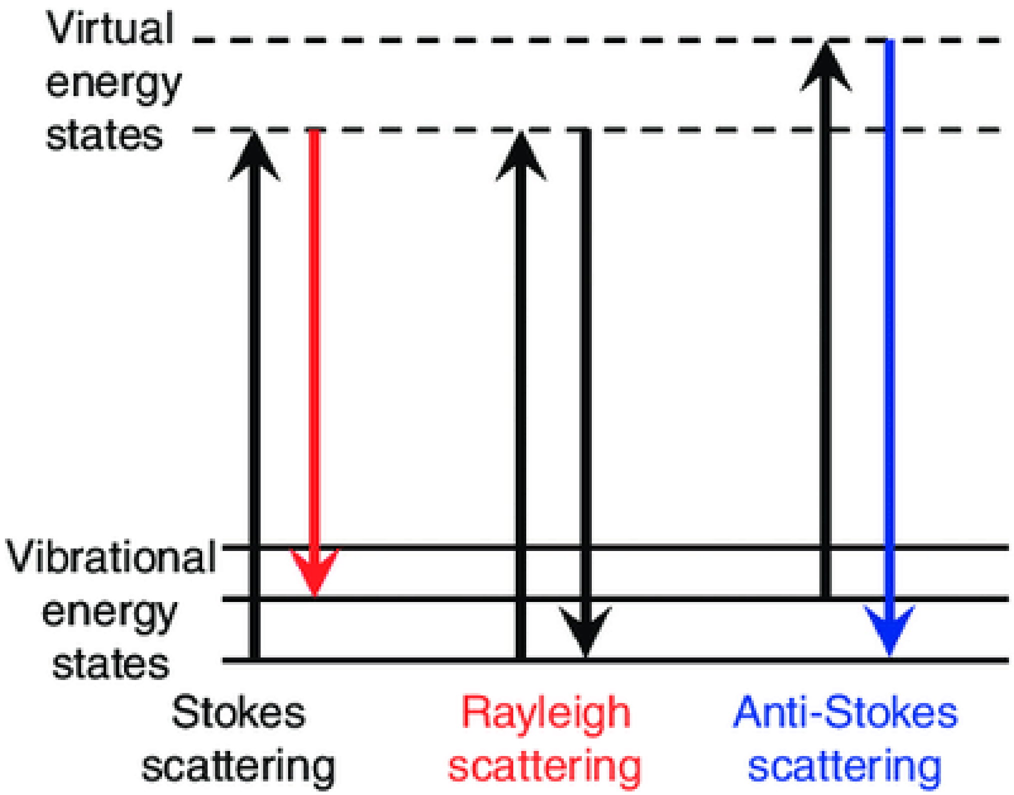
1. Modern Raman spectroscopy : a practical approach / Ewen Smith, Geoff Dent http://www.chemistry.uoc.gr/lapkin/Modern_Raman_Spectroscopy___A_Practical_Approach.pdf
2. M. Cardona. Raman scattering in high-Tc superconductors. *Physica C* **185-189**, 65 (1991) pdf
3. B. Moritz et al. An investigation of particle-hole asymmetry in the cuprates via electronic raman scattering. *Physical Review B* **84**, 235114 (2011) https://arxiv.org/pdf/1106.5798.pdf

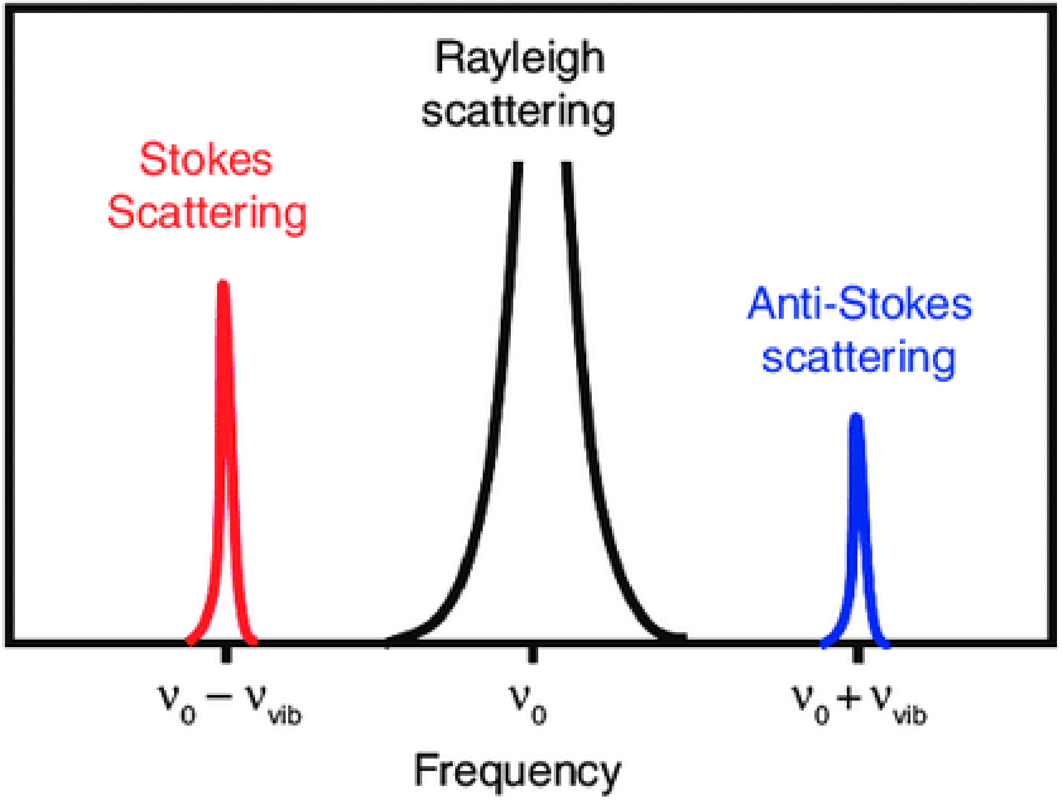
Raman spectroscopy



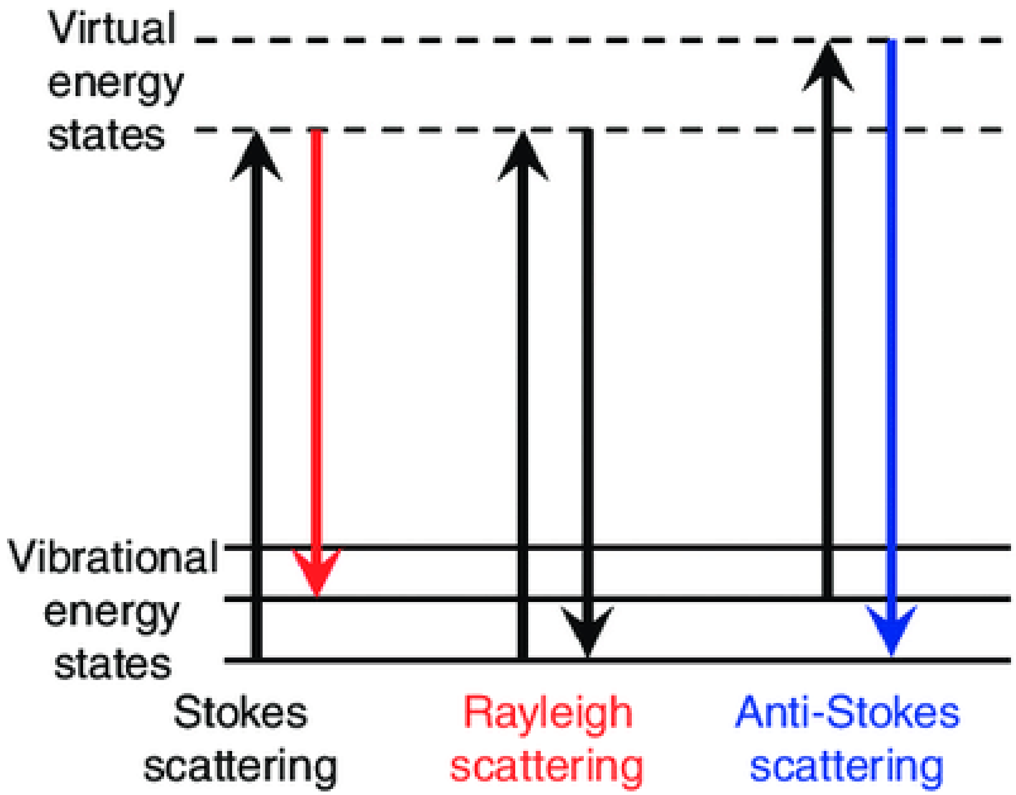


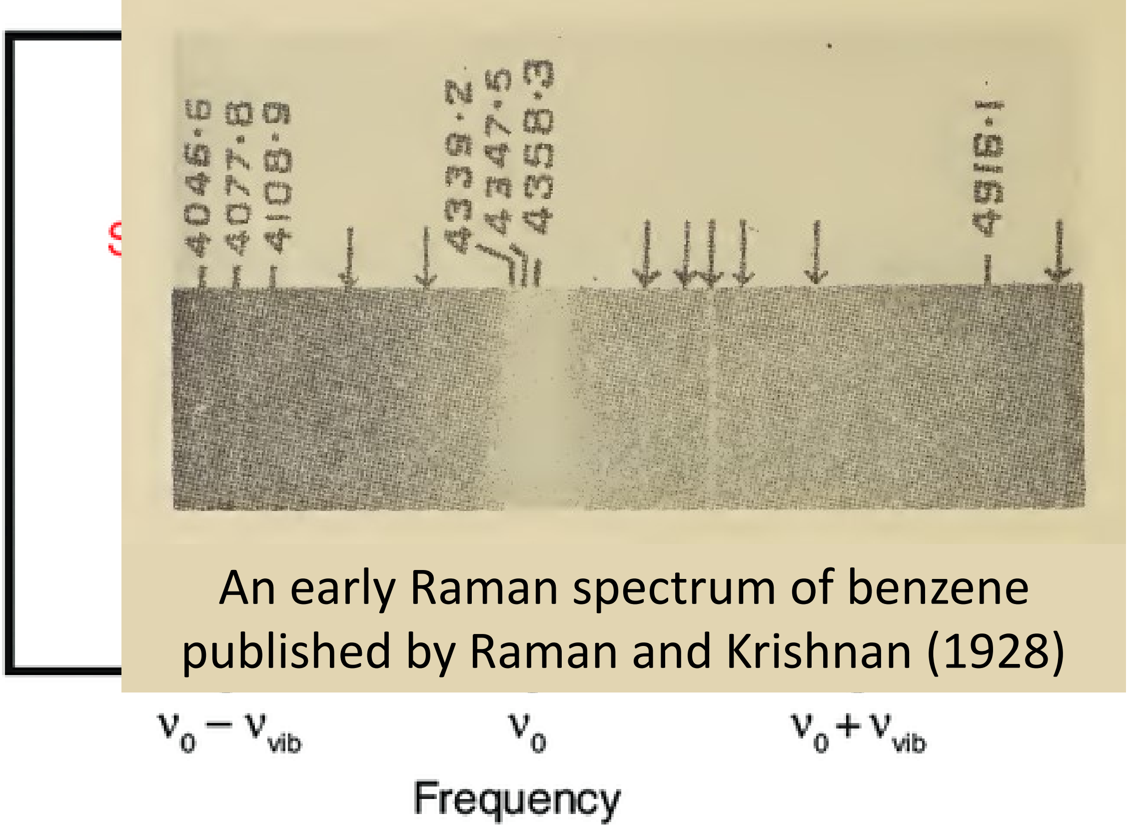
Raman spectroscopy



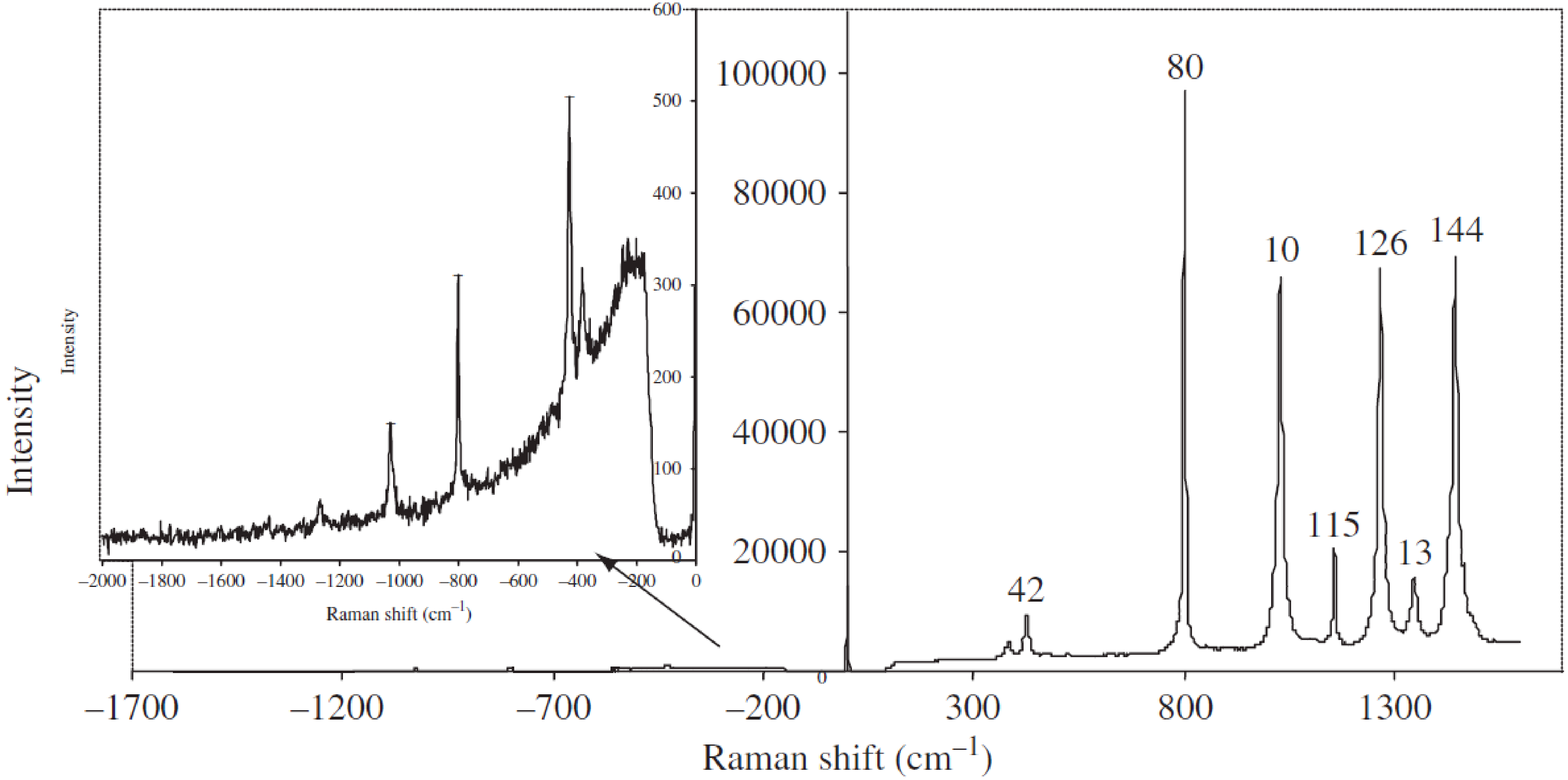


Raman spectroscopy



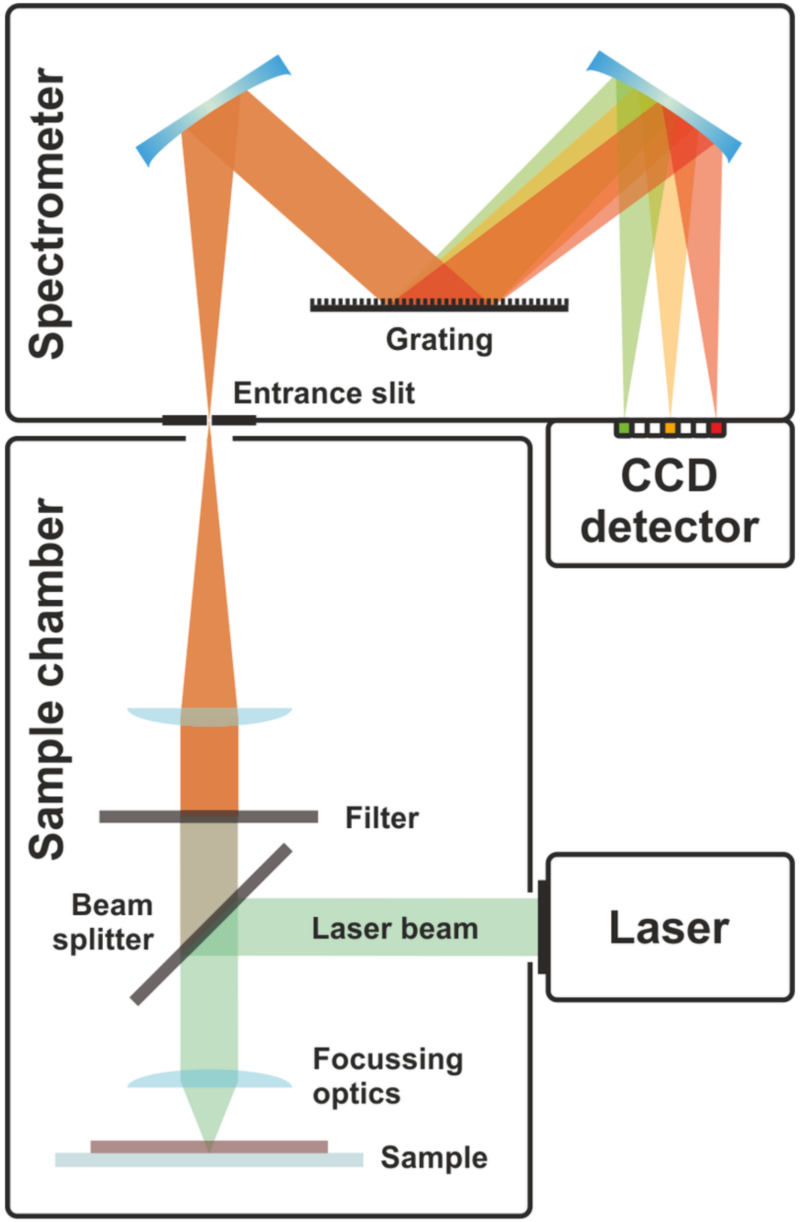


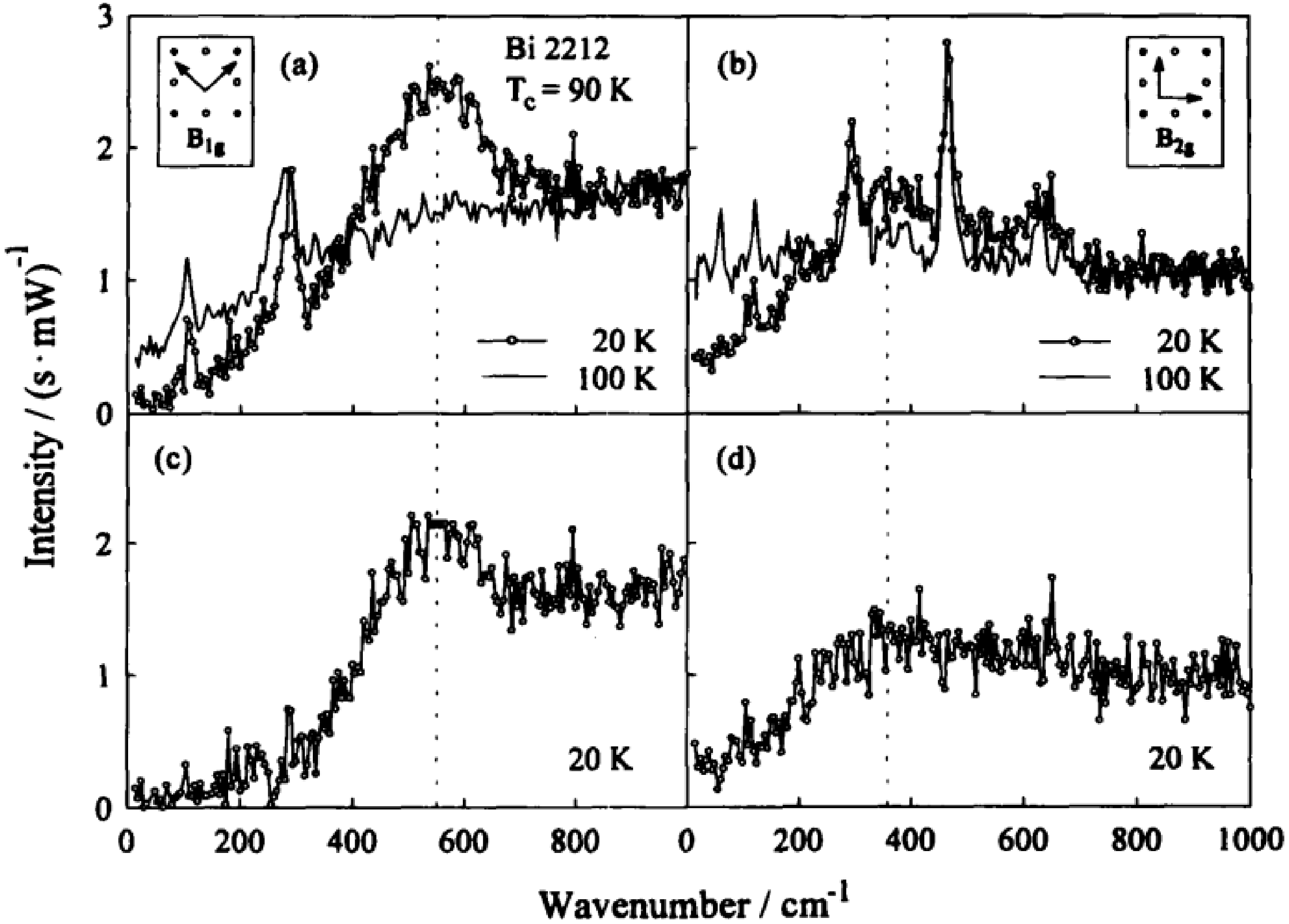
An early Raman spectrum of benzene published by Raman and Krishnan (1928)



Stokes and anti-Stokes scattering for cyclohexane. To show the weak anti-Stokes spectrum, the *y*-axis has been extended in the inset.

Raman spectrometer





(a, b) Normal and superconducting spectra (raw data) of Bi2212 for *B1g* and *B2g* symmetry. (c, d) Superconducting spectra after subtraction of the phonons.

D. Einzel and R. Hack (1996)

Resonant inelastic X-ray scattering

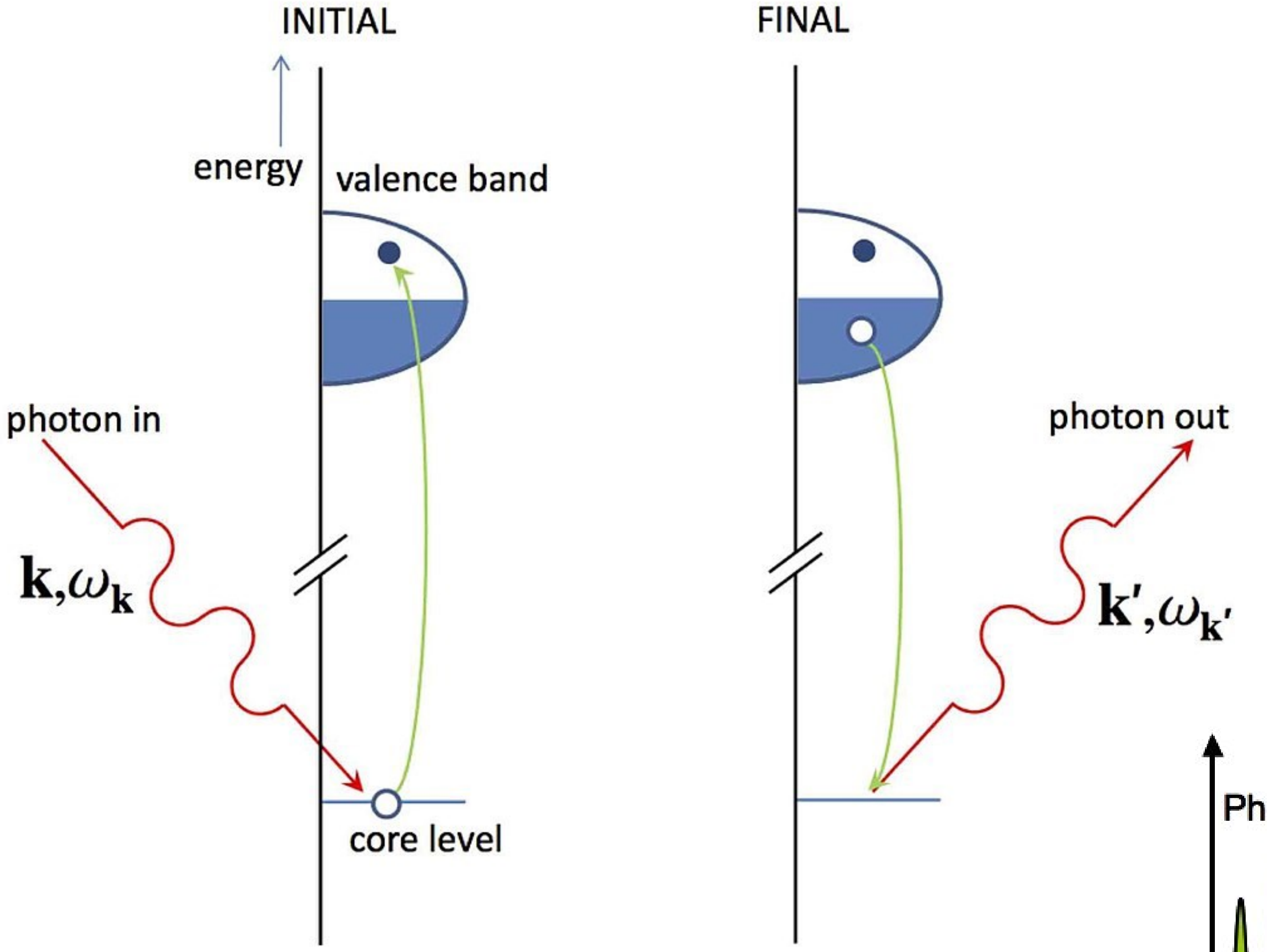
RIXS

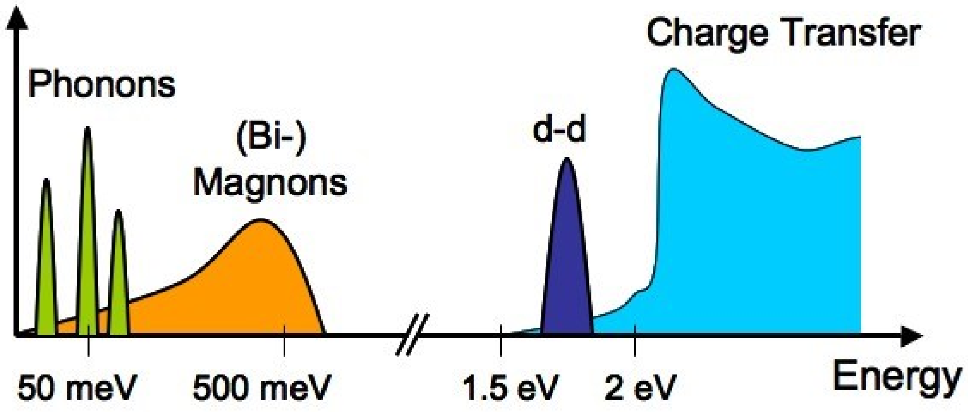
= Resonant X-ray Raman

To read

1. L. J. P. Ament et al. Resonant Inelastic X-ray Scattering Studies of Elementary Excitations. *Rev. Mod. Phys.* **83**, 705 (2011) https://arxiv.org/pdf/1009.3630.pdf

RIXS





https://arxiv.org/pdf/1009.3630.pdf

SRN

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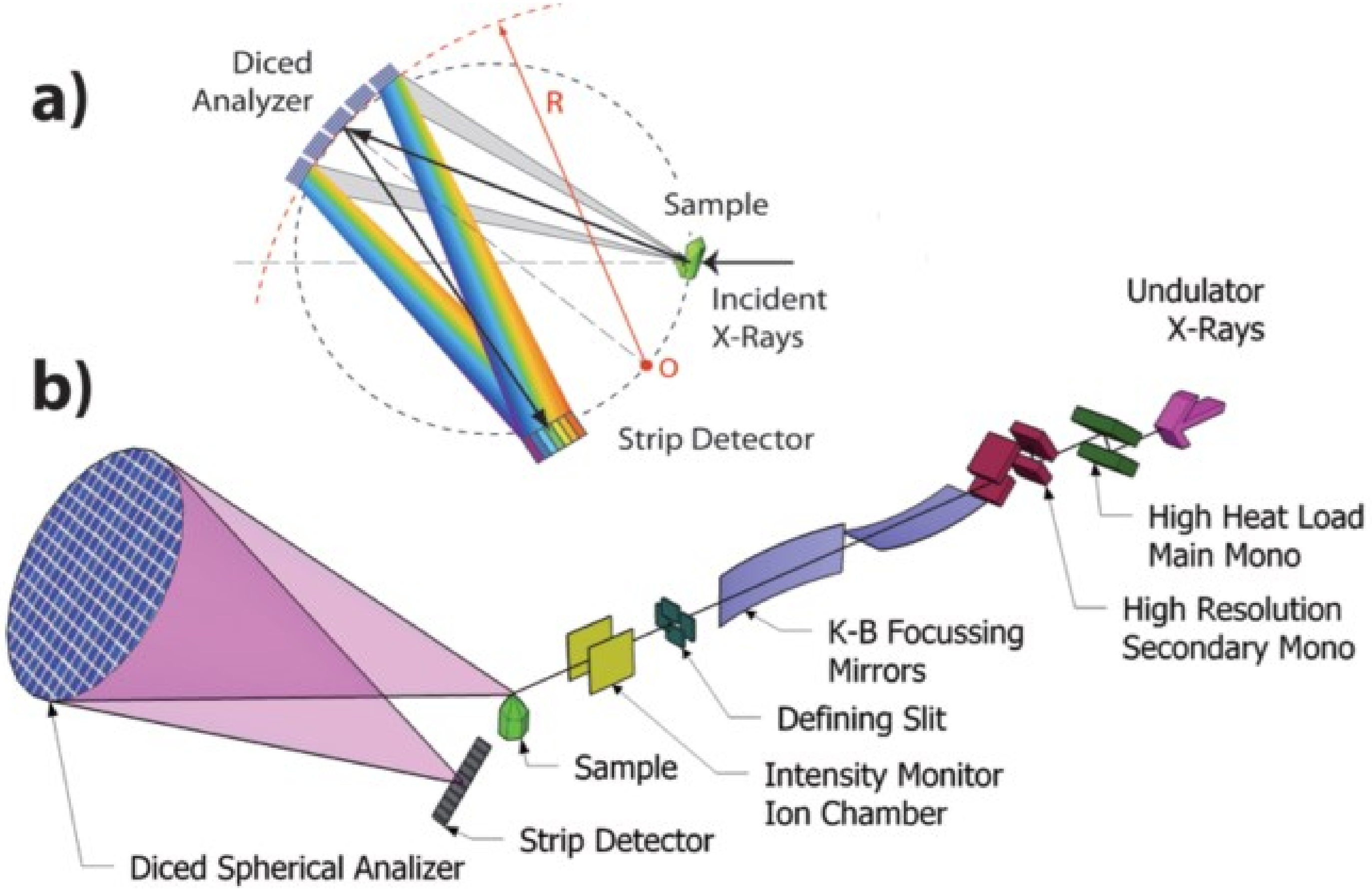
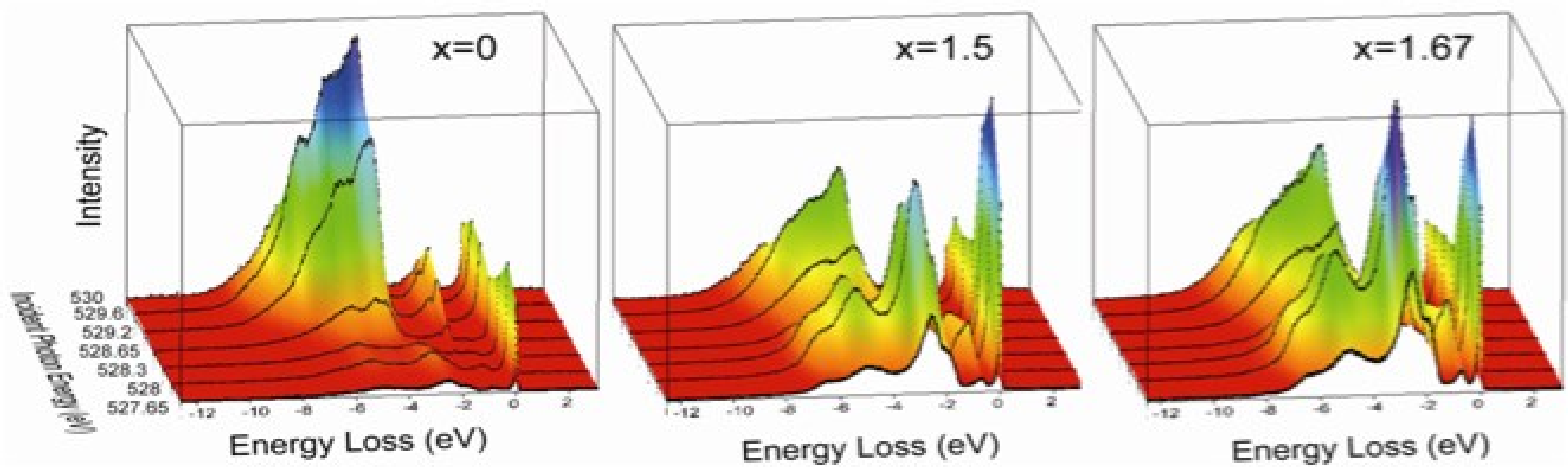
Synchrotron Radiation News
March/April 2018 • Vol. 31, No. 2

Resonant Inelastic
X-ray Scattering

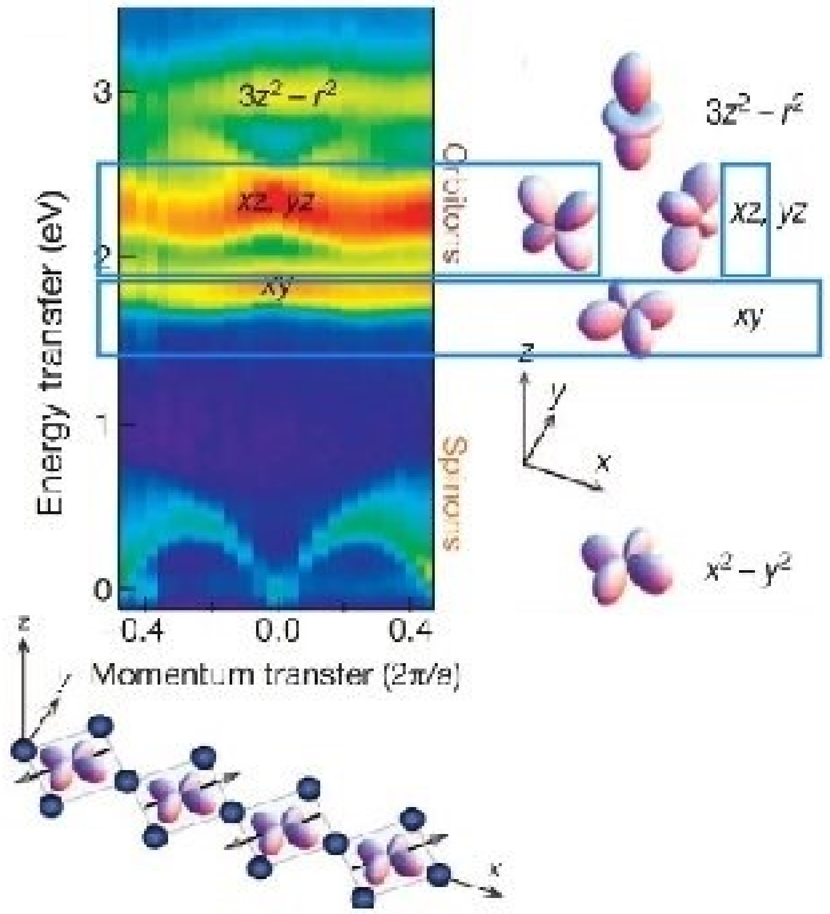




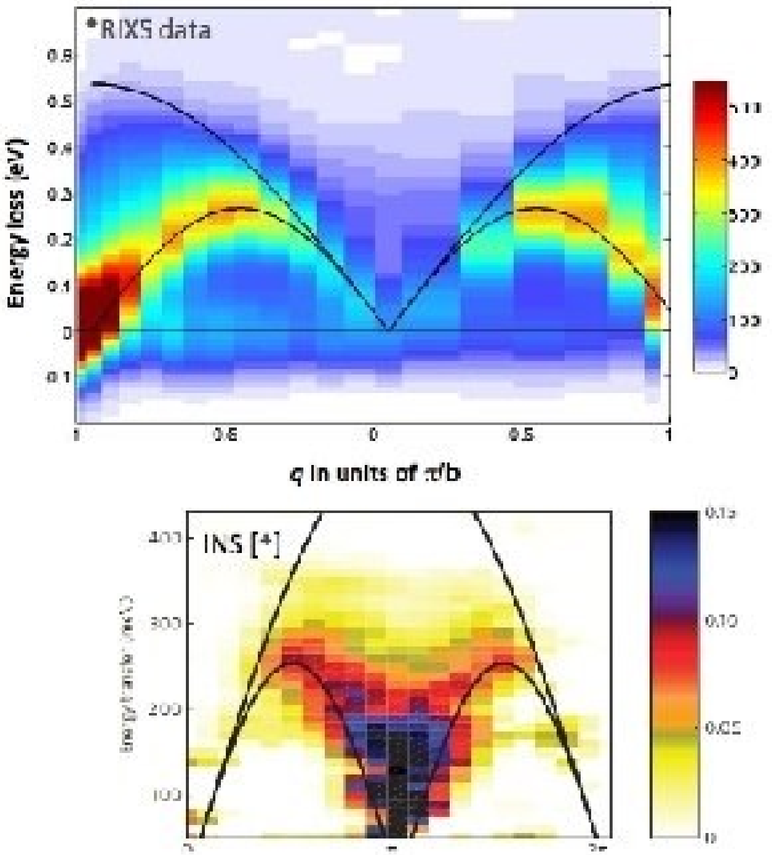
https://arpes.stanford.edu/research/tool-development/resonant-x-ray-scattering

2p3d RIXS in cuprates

Sr_2CuO_3



$CaCu_2O_3$



Schlappa et al., Nature (2012)

Bisogni et al., arXiv:1310.8346

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