# μSR Methods

## *Basic Physics and Techniques*

("Sufficiently Advanced Technology")

by

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UBC Physics & Astronomy

TRIUMF

# Tentative Outline

- *Basic Principles*
- *Accelerators*
- *Muon Beams*
- *μSR Spectrometers*
- *Techniques:* ZF-, LF- *&* TF-*μSR*; FT-*μSR*, *μ*ALCR, RF-*μSR*
- *"Themes" in μSR*
- *Typical Applications*

# Basic Principles

## . . . a brief introduction to

# Pion Decay: $\pi^+ \rightarrow \mu^+ + \nu_\mu$

A pion **stops** in the "skin" of the primary production target.
It has zero linear momentum and zero angular momentum.

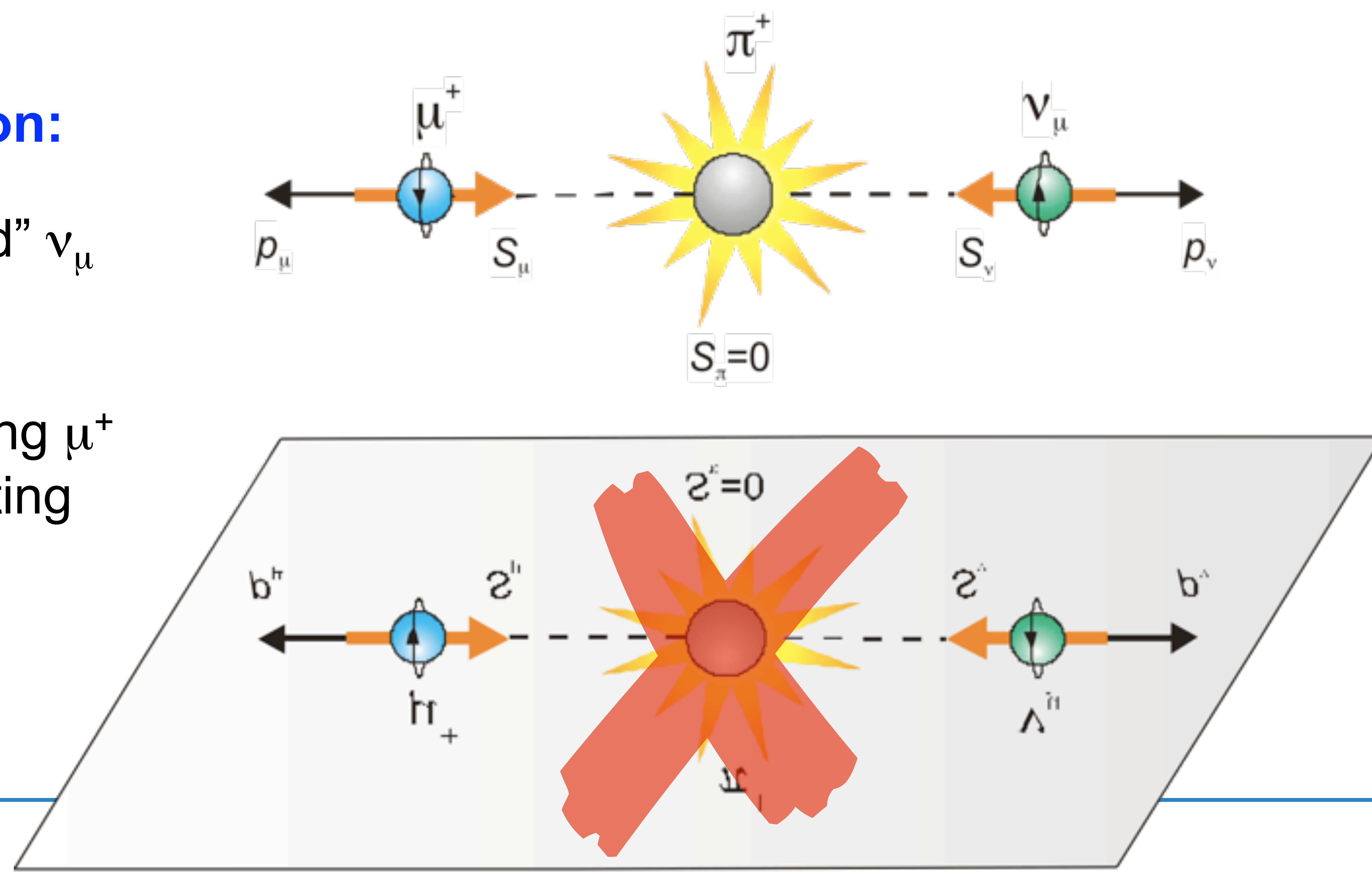
**Conservation of Linear Momentum:** The $\mu^+$ is emitted with momentum equal and opposite to that of the $\nu_\mu$.

**Conservation of Angular Momentum:** $\mu^+$ & $\nu_\mu$ have equal & opposite spin.

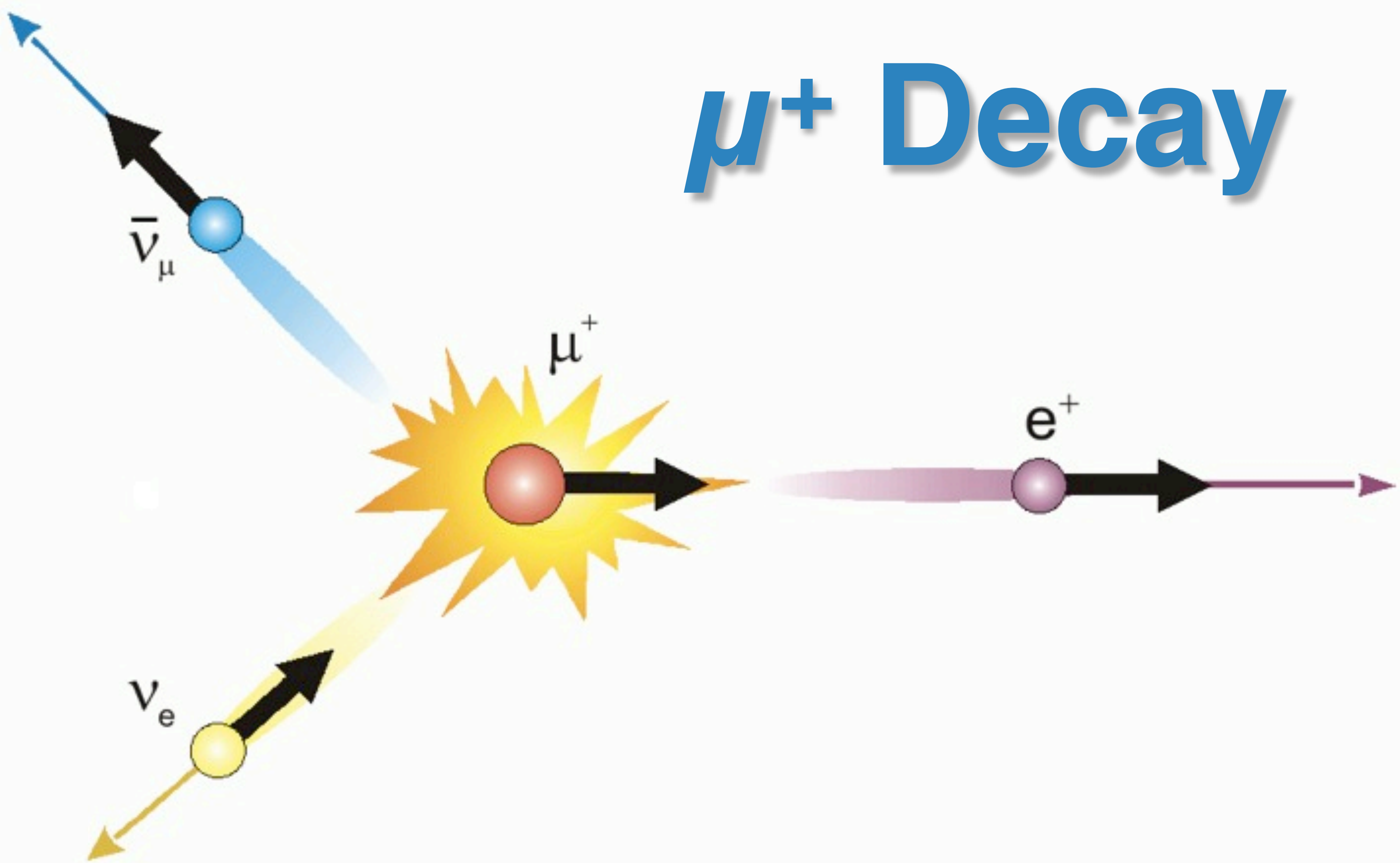
**Weak Interaction:**

Only "left-handed" $\nu_\mu$ are created.

Thus the emerging $\mu^+$ has its spin pointing antiparallel to its momentum direction.



# $\mu^+$ Decay

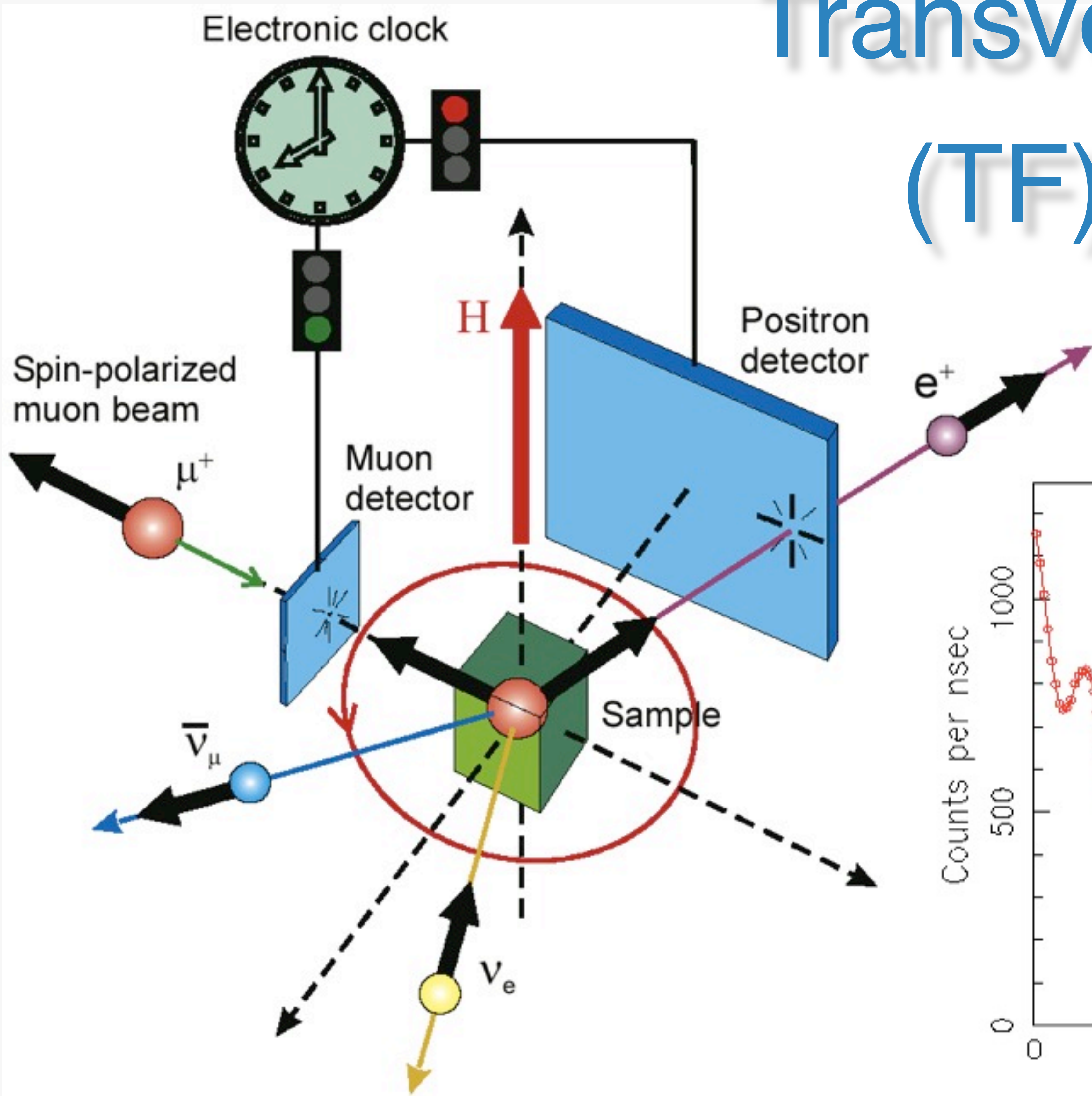


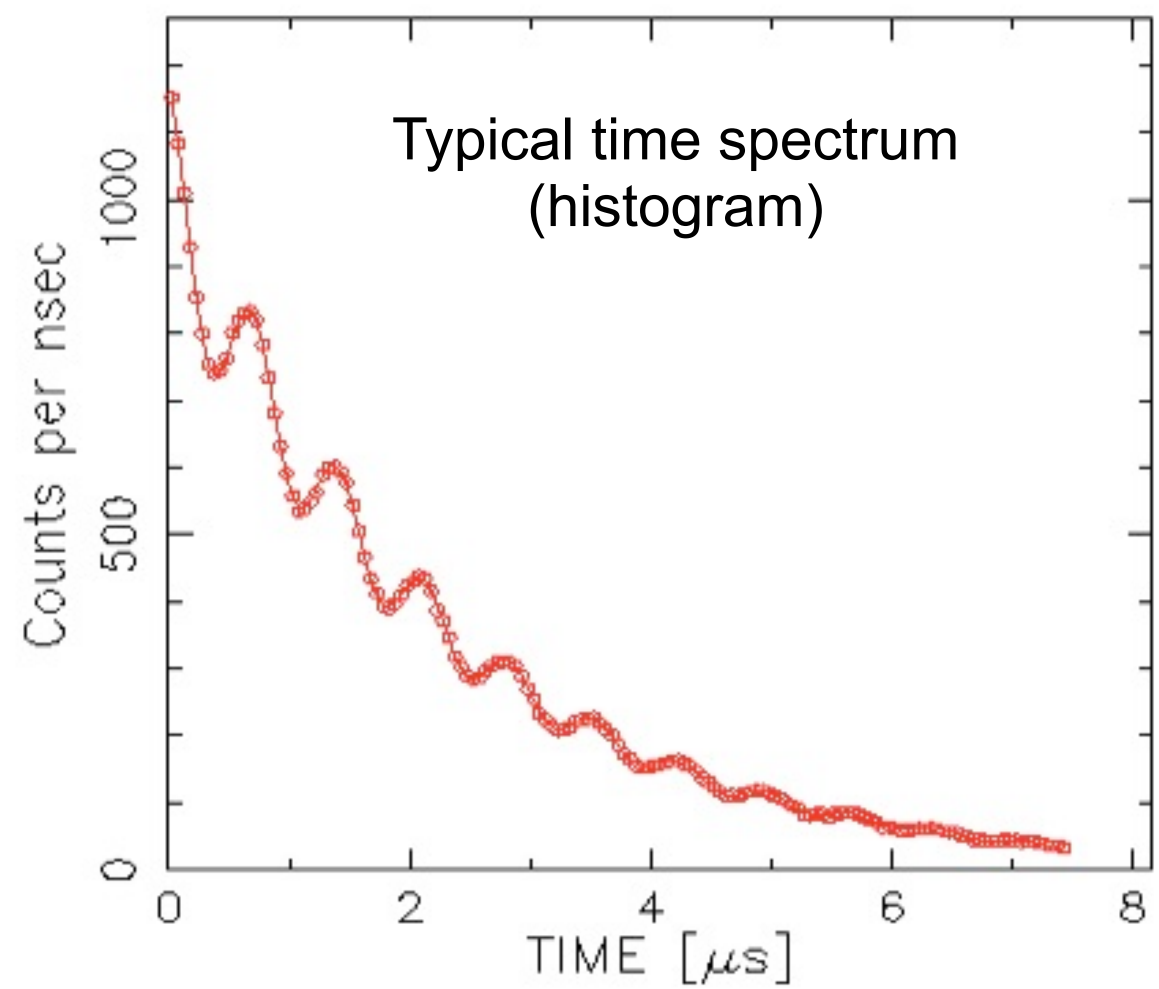

Neutrinos have *negative helicity*, antineutrinos positive.

An ultrarelativistic positron behaves like an antineutrino.

Thus the positron <u>tends</u> to be emitted along the $\mu^+$ spin when $\nu_e$ and $\bar{\nu}_\mu$ go off together (highest energy $e^+$).

# Transverse Field (TF)-$\mu^{+}$SR



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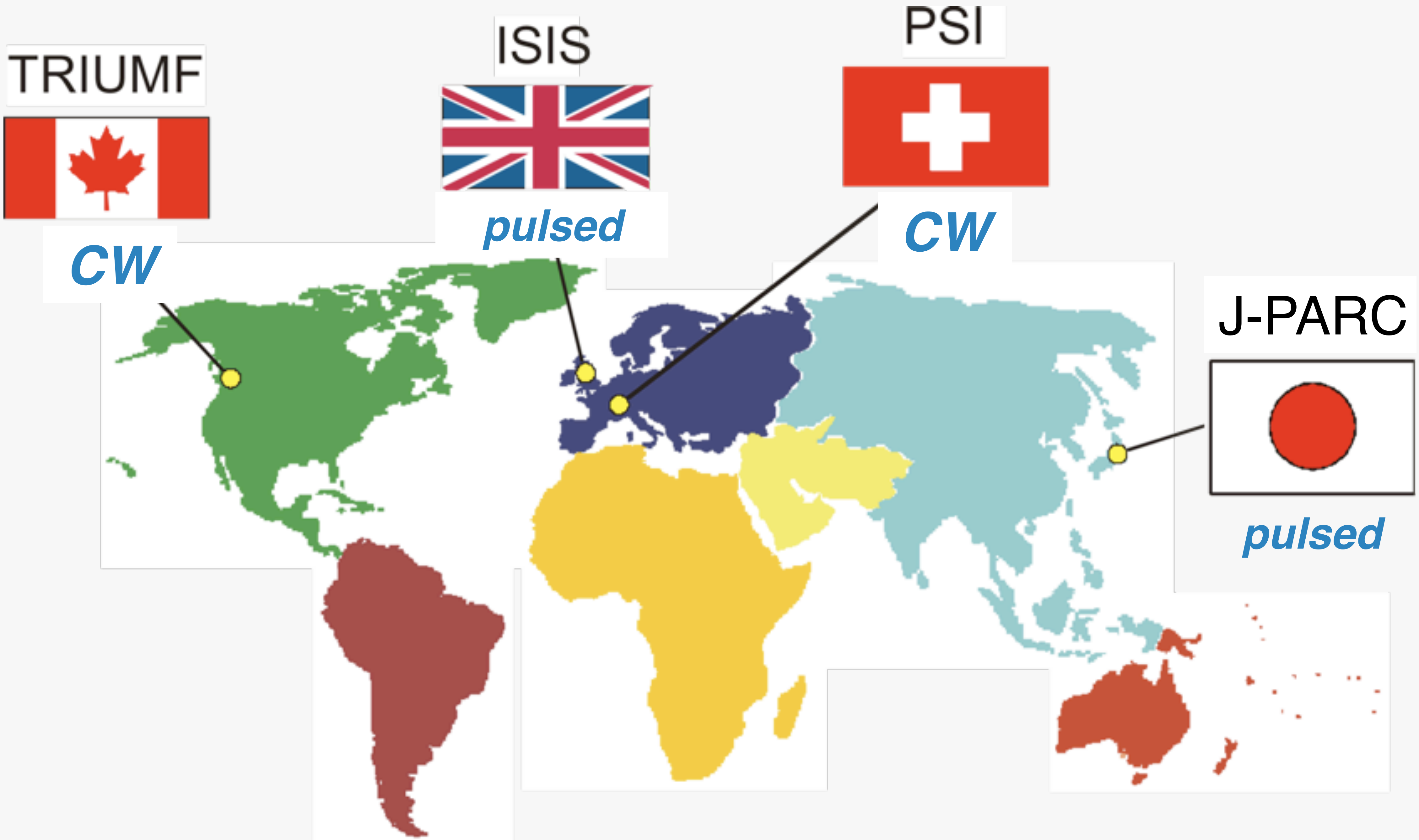
...but...

# First you need an ACCELERATOR!

# CW & Pulsed μSR facilities



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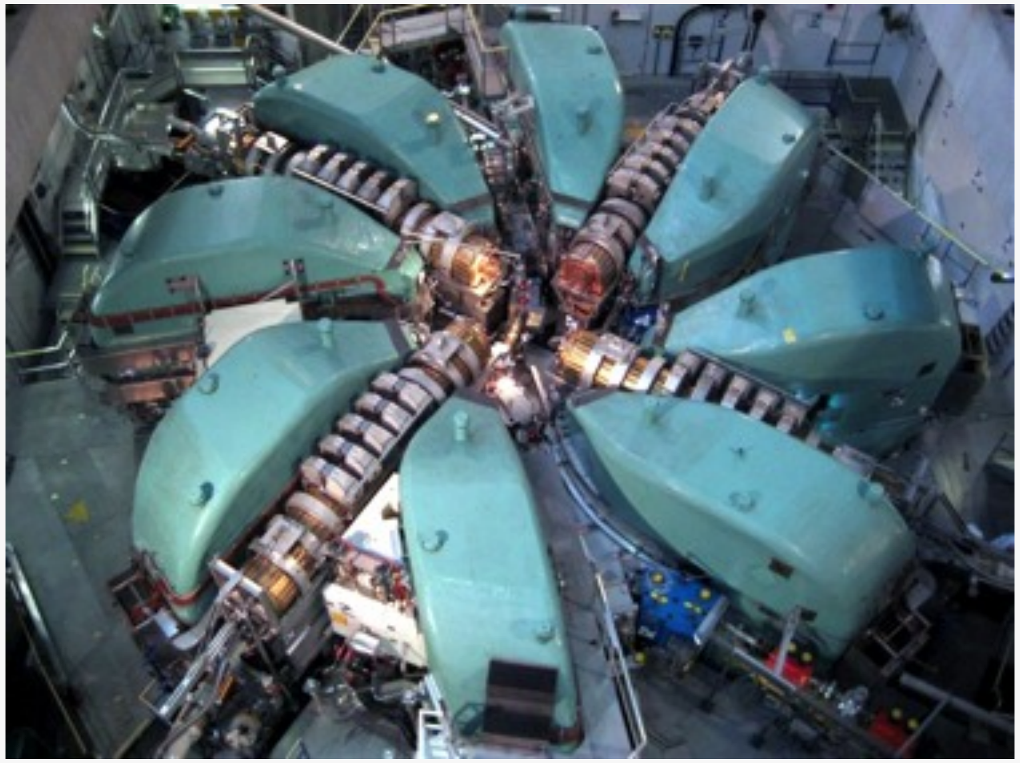
## 1972

## ISIS site plan

## PSI Ring Cyclotron

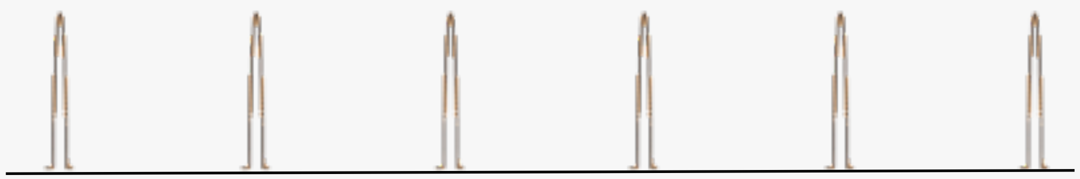


## J-PARC synchrotron

# Proton Beam Time Structure

## TRIUMF

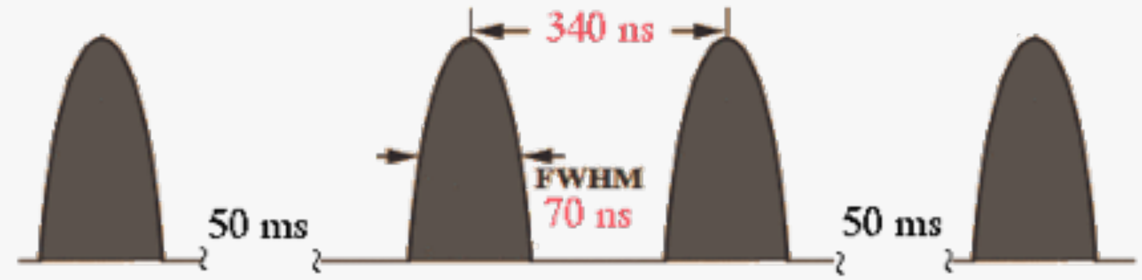
3 ns wide pulse of **480-500 MeV** protons *every 43 ns*.



Average current **100-150 μA**.

## ISIS

Two *70 ns* pulses of **800 MeV** protons 340 ns apart delivered *every 50 ms*.




Average current 200(?) μA.

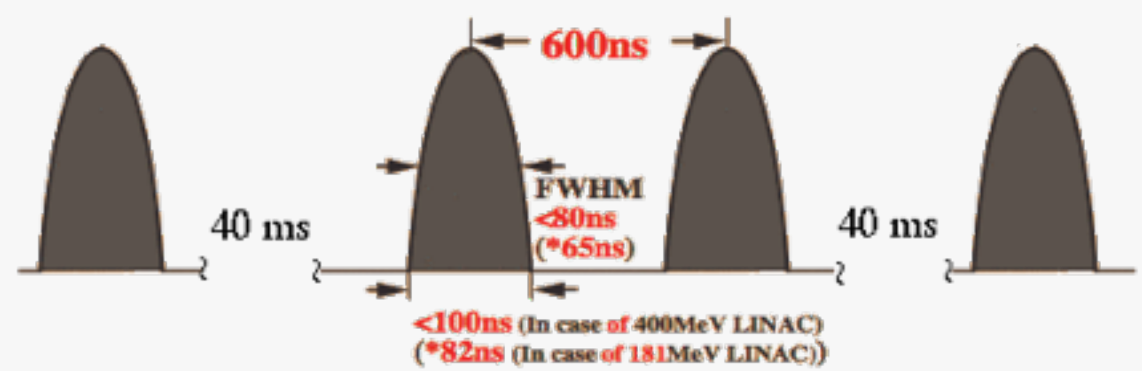
## PSI

1-2(?) ns wide pulse of **590 MeV** protons *every 20 ns*.

Average current up to **2.2 mA**.

## J-PARC

Two *70 ns wide* pulses of **3 GeV** protons 600 ns apart delivered *every 40 ms* (with gaps to fill 50 GeV ring).

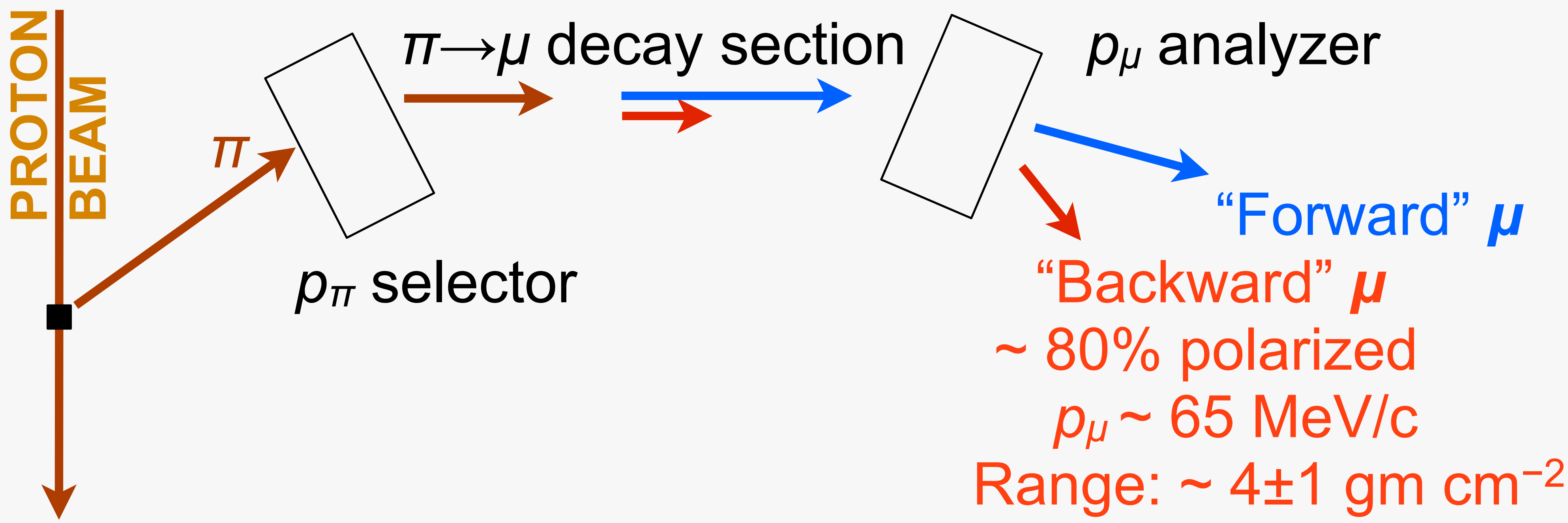



Average current **333 μA**.

# …then you need some polarized MUONS!

# Forward & Backward Decay Muons

## DECAY MUON CHANNEL ($\mu^+$ or $\mu^-$)



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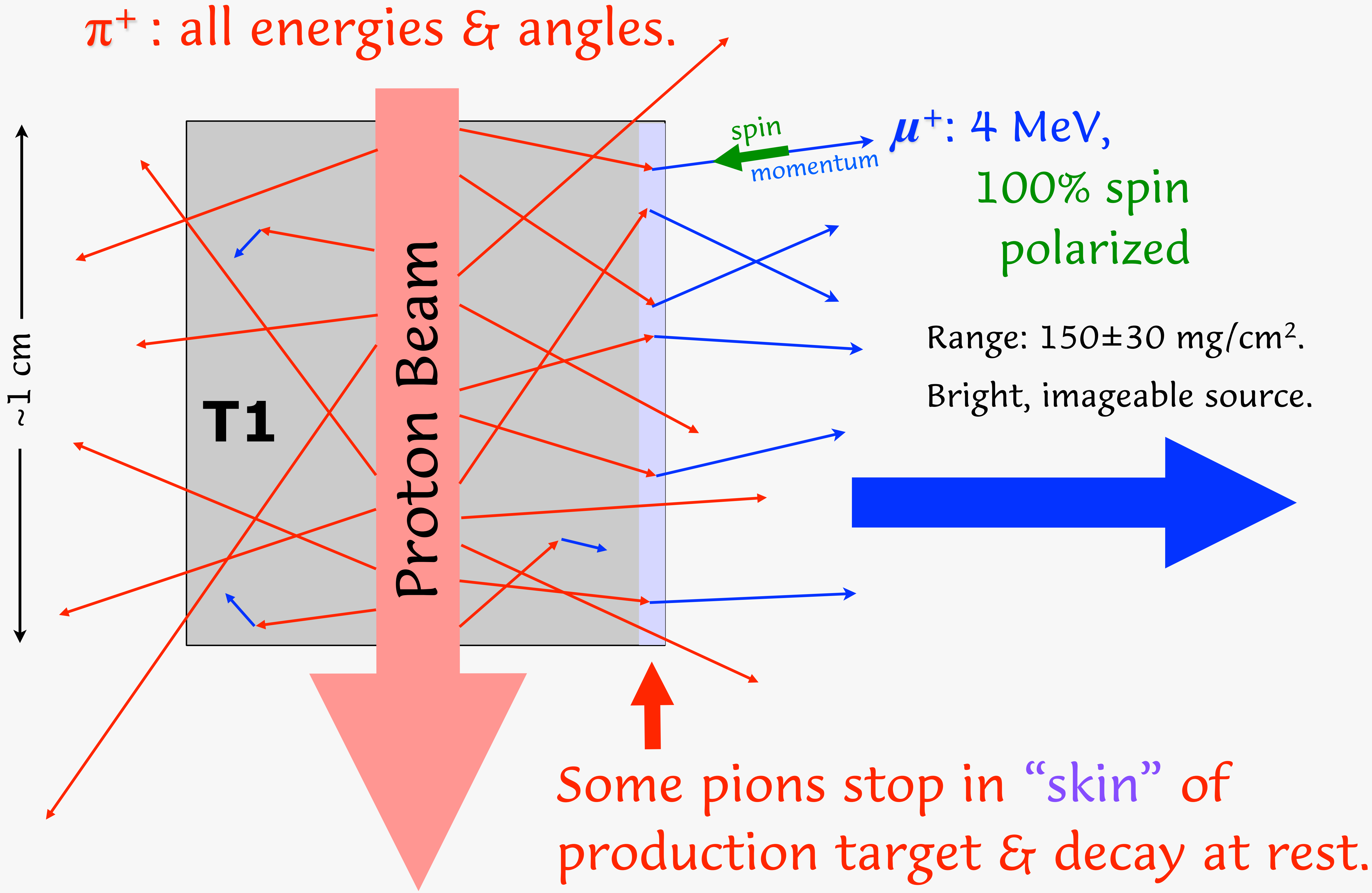
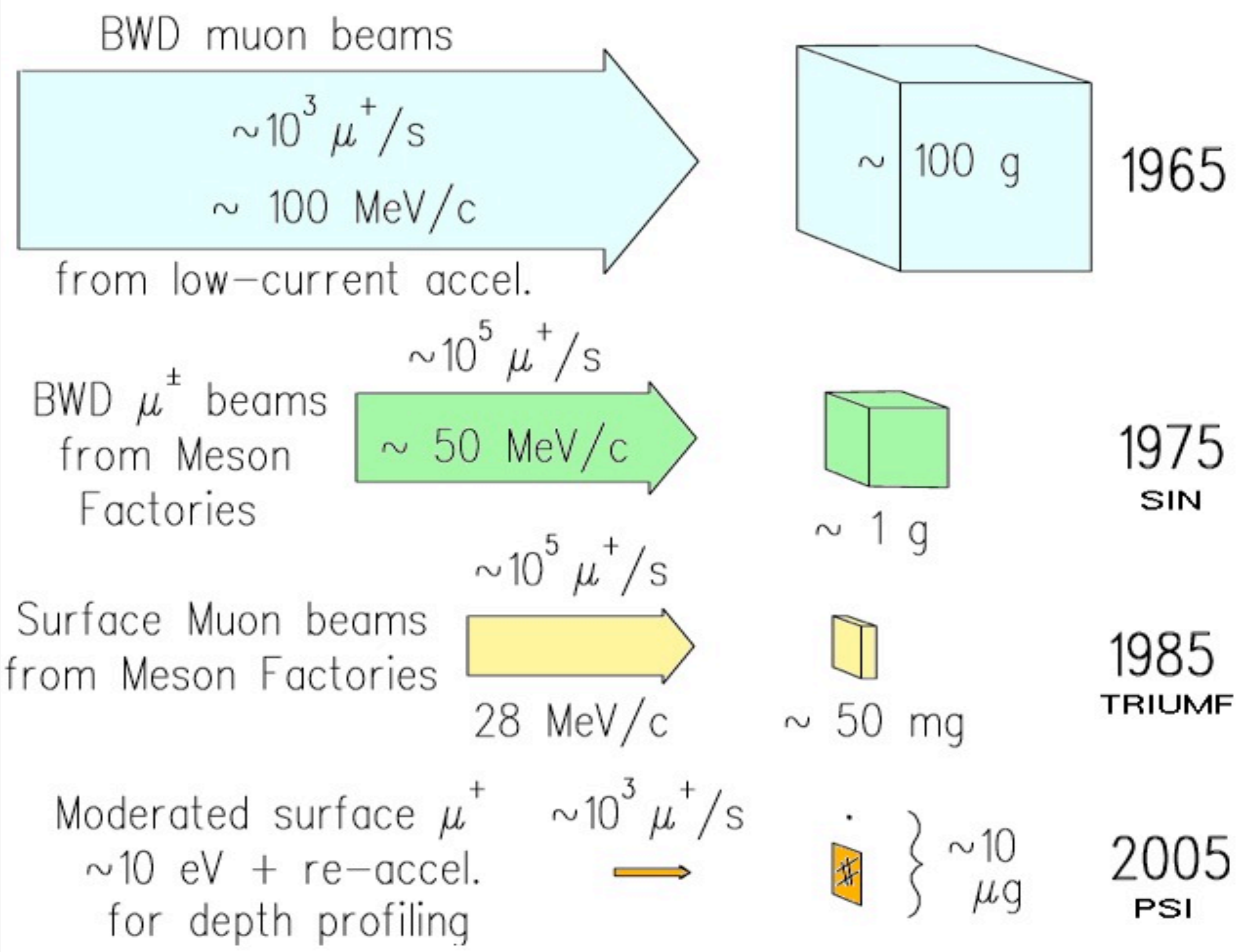
# Surface Muons



# $\mu^+$ Stopping Luminosity



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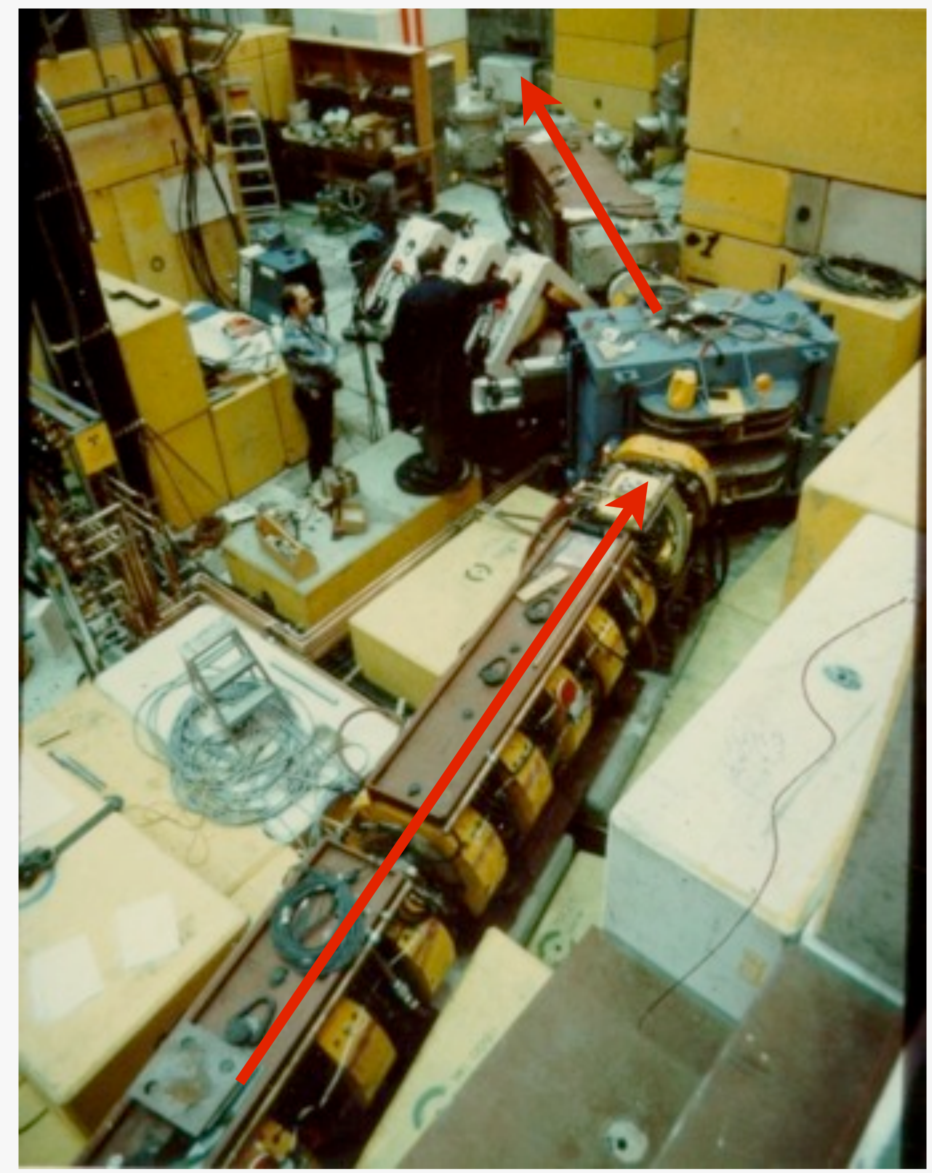
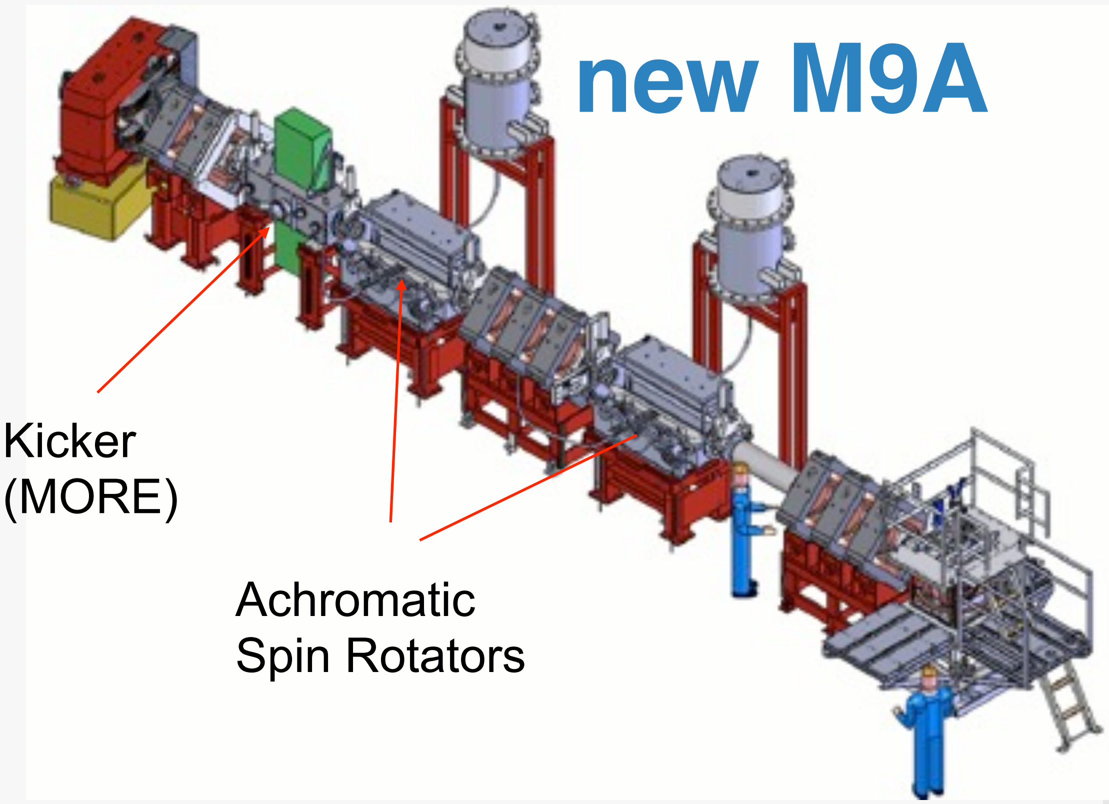
# ghosts of TRIUMF past

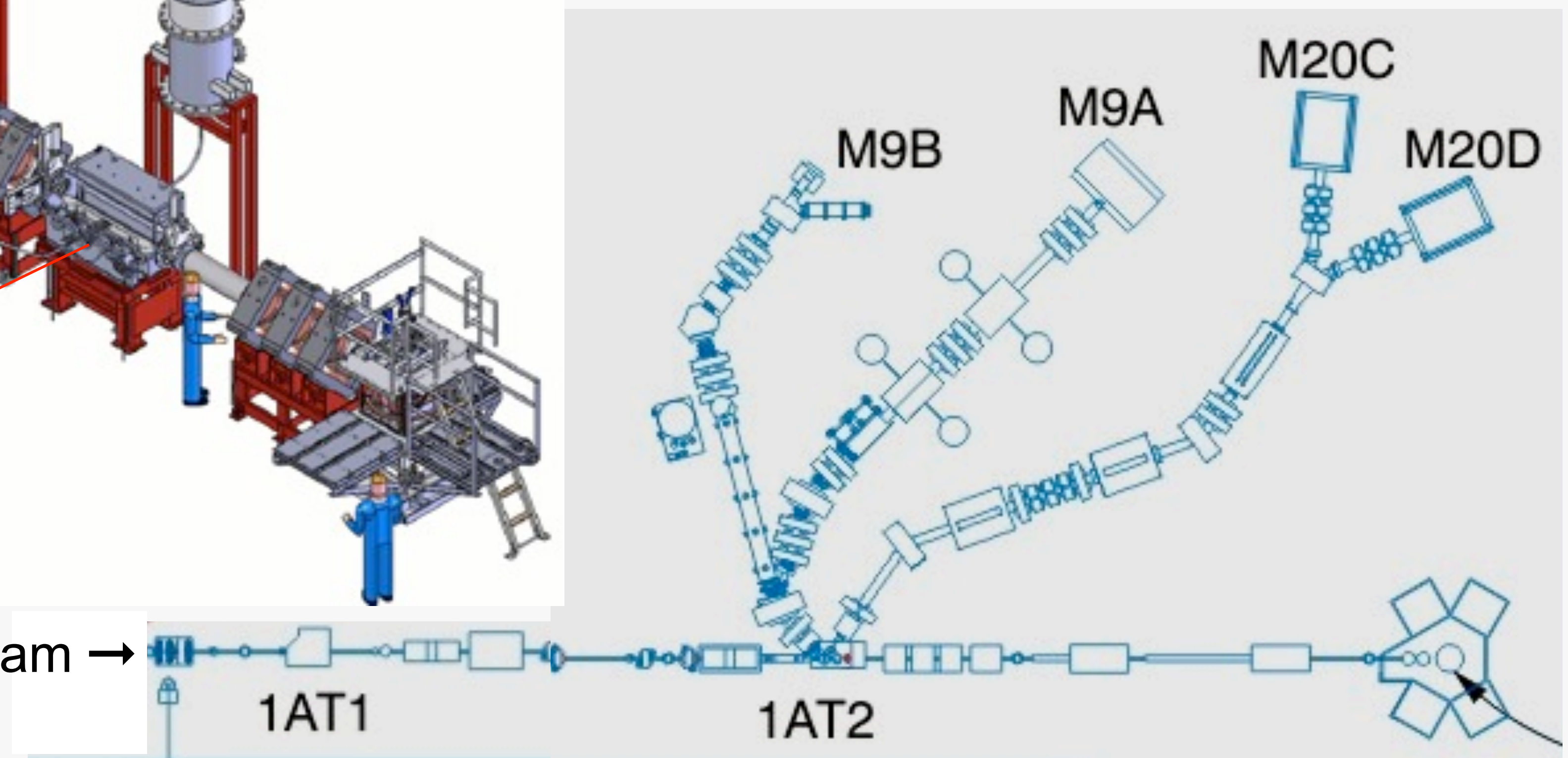
M9B

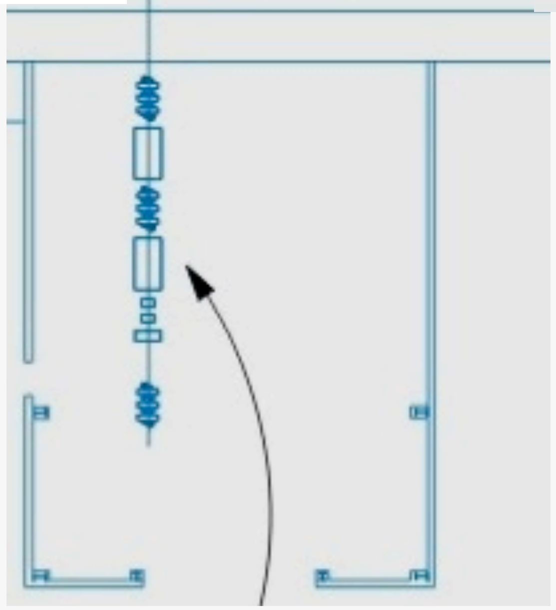
old M20

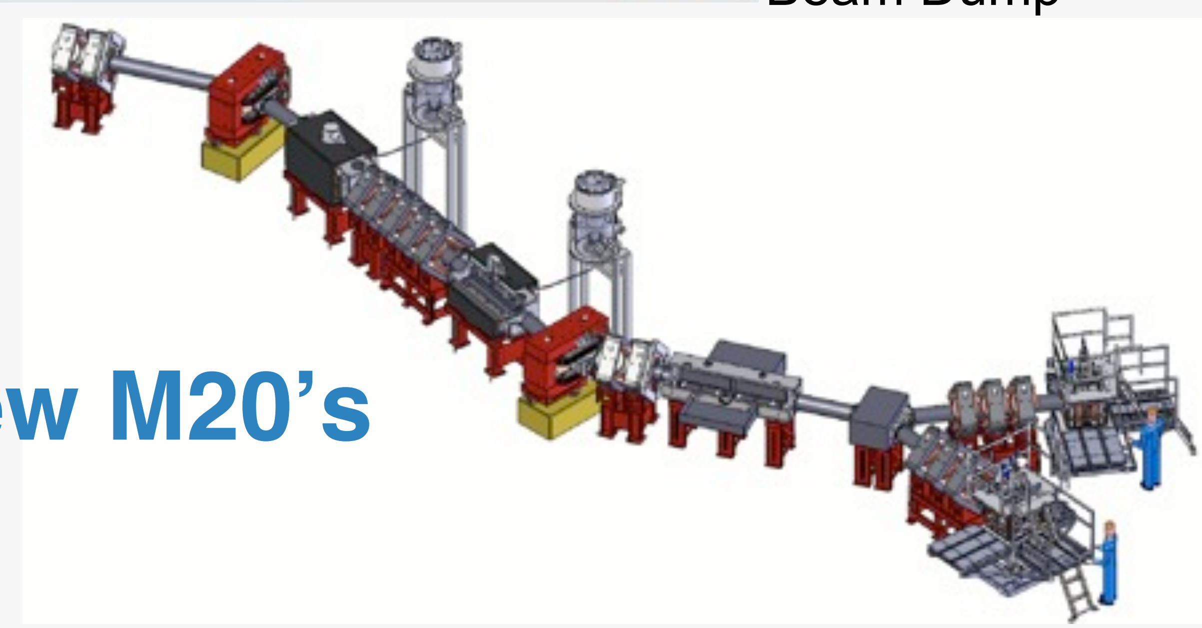


# TRIUMF real soon now



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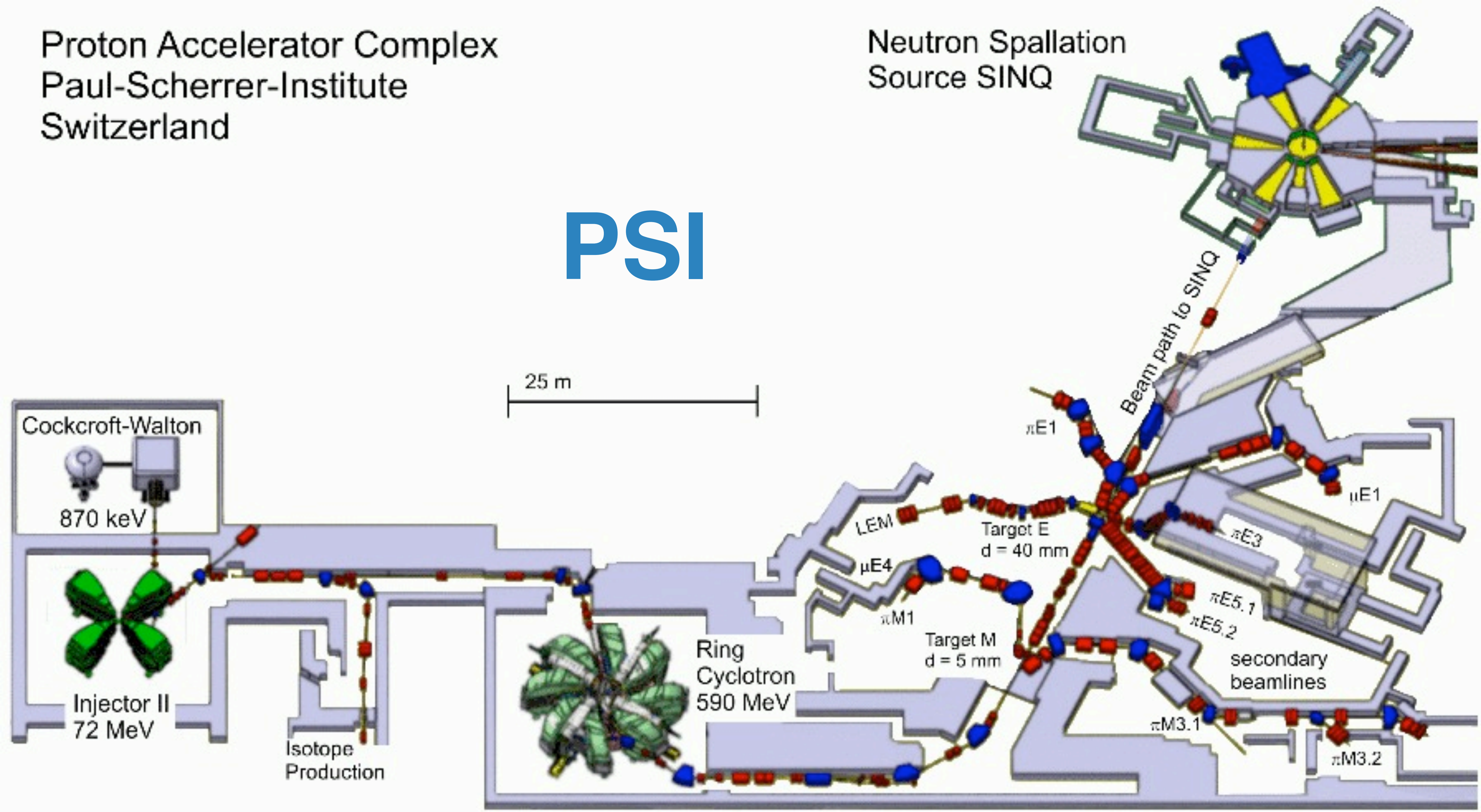
# PSI



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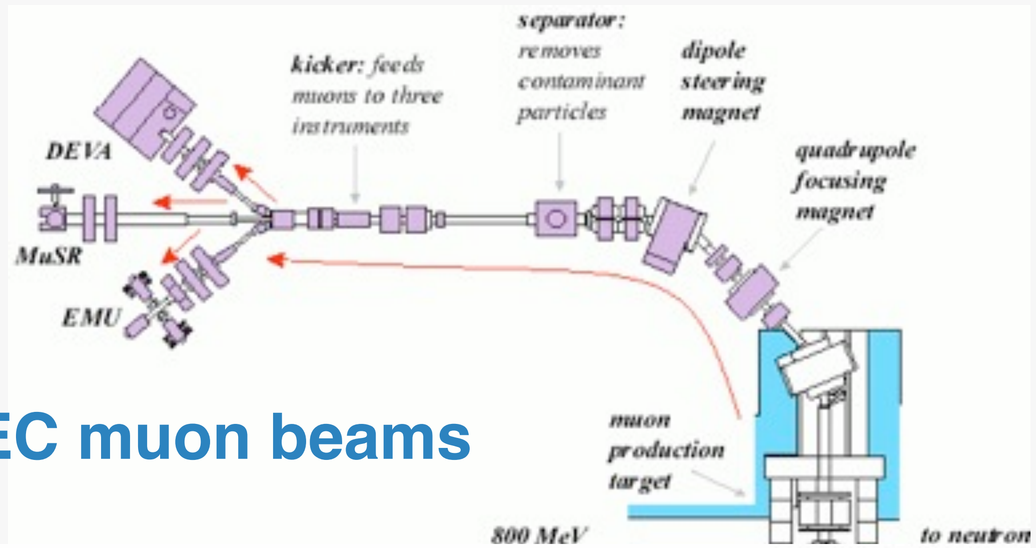
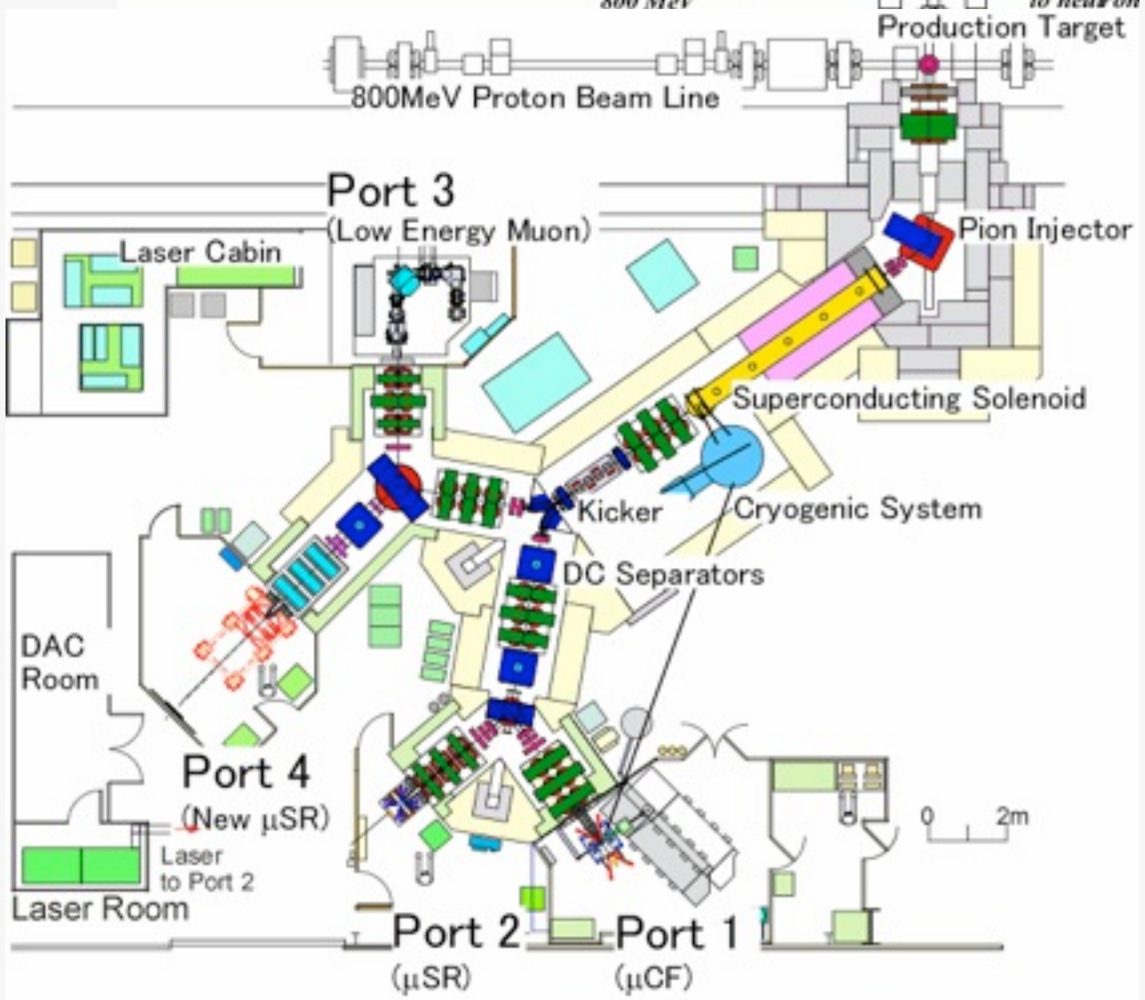
# ISIS

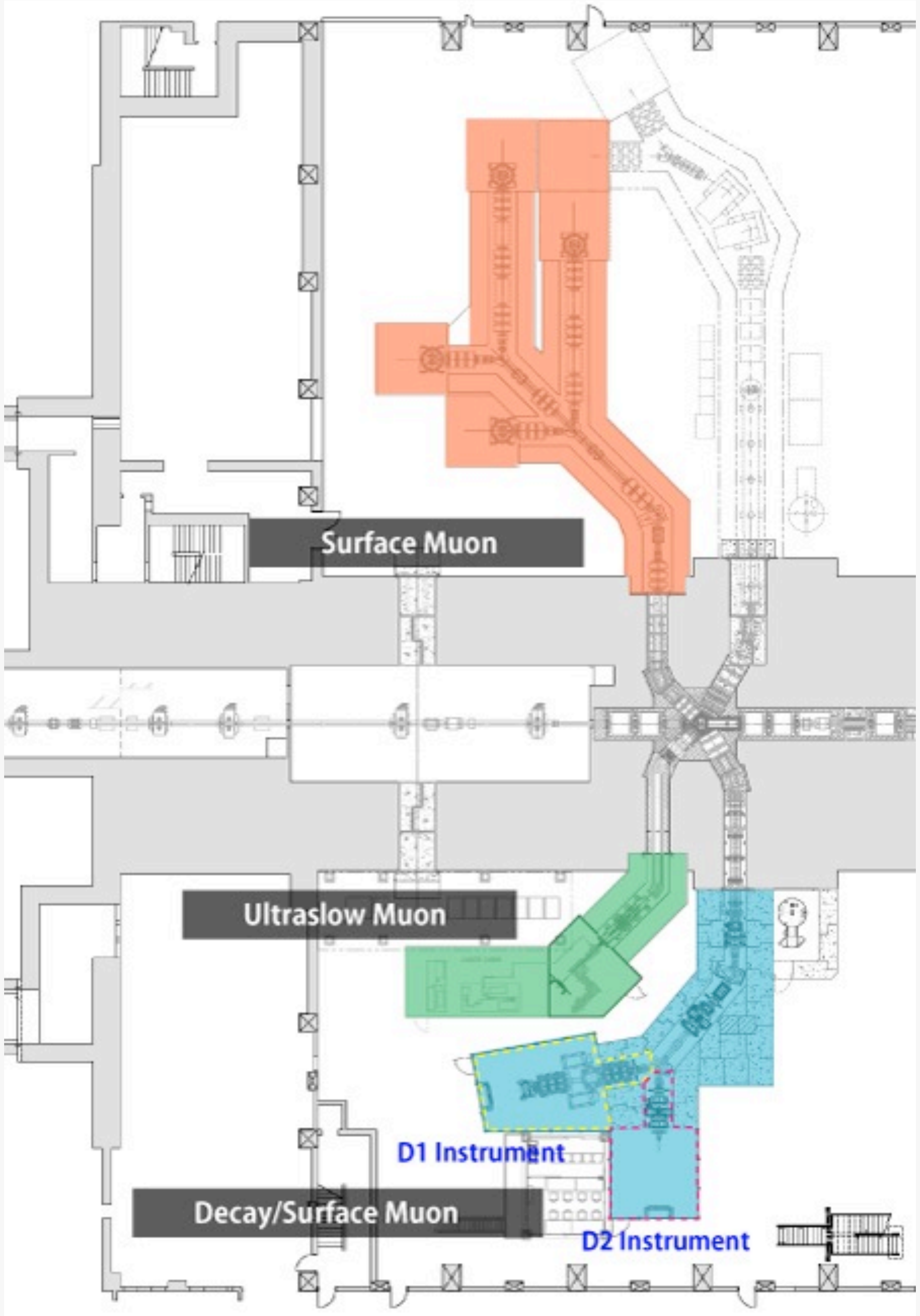



EC muon beams




RIKEN-RAL muon facility

# J-PARC MuSE



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# Performance of Muon Beams for μSR

### *REQUIREMENTS:*

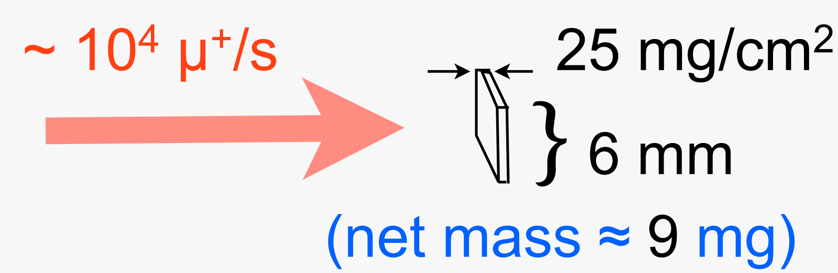
- HIGH POLARIZATION
- HIGH FLUX (>2x$10^4$ $s^{-1}$ on target)
- SMALL SPOT SIZE (< 1 $cm^2$)
- SHORT STOPPING RANGE
  ⇒ low momentum
- LOW CONTAMINATION of *π*, *e* etc.

### *HISTORY of IMPROVEMENTS:*

| | | |
|---|---|---|
| Before Meson Factories: | ***Q*** ~ $10^2$ | (1970) |
| Decay channels at Meson Factories: | ***Q*** ~ $10^5$ | (1975) |
| Surface $\mu^+$ beams at Meson Factories: | ***Q*** ~ $10^6$ | (1980) |
| “3rd generation” surface muon beams: | ***Q*** ~ $10^7$ | (1990) |

∴ ***“QUALITY FACTOR”***

$$Q = \frac{(\text{POLARIZATION})^2 \times \text{FLUX}}{(1 + \text{CONTAM.}) \times \text{RANGE} \times (\text{SPOT SIZE})}$$

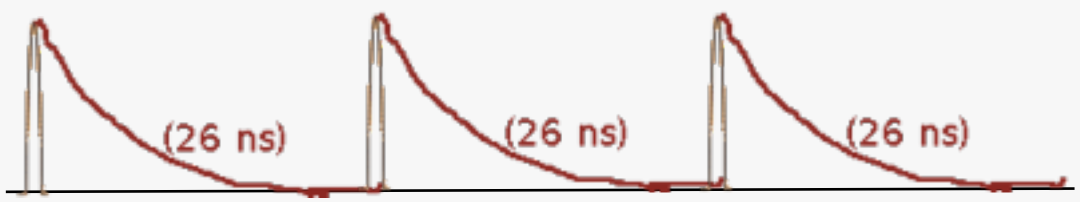



**L**ow **E**nergy (moderated) **M**uons at PSI: ***Q*** ~ $10^9$ (2005)

# Muon Beam Time Structure

## TRIUMF

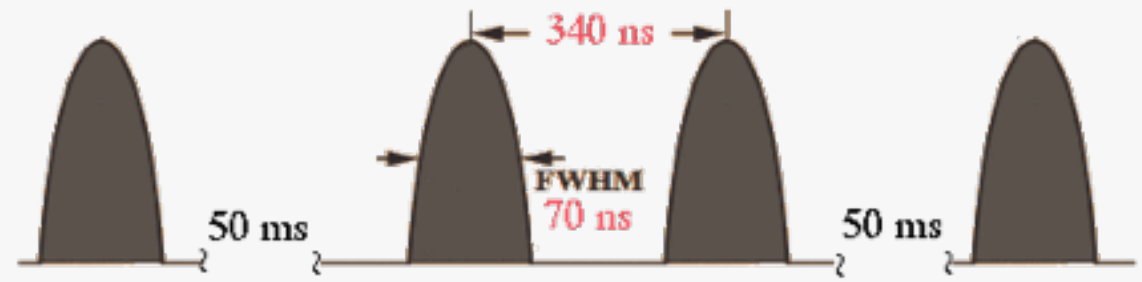
26 ns wide pulse of **28-90 MeV/c** muons *every 43 ns*.




Average rates ~ **$10^6$ $\mu^+$/s**.

## ISIS

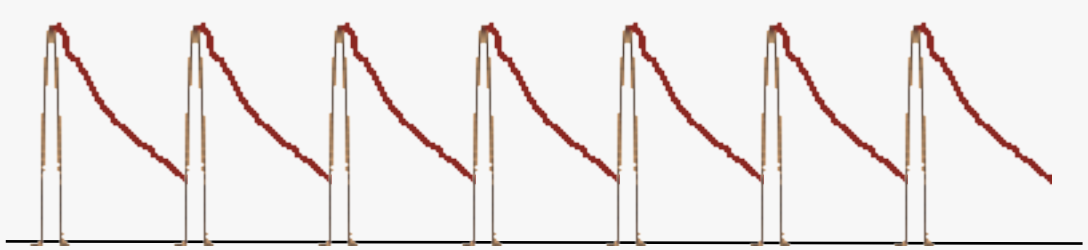
Two *70 ns* pulses of **800 MeV** protons 340 ns apart delivered *every 50 ms*.




Average rates up to **$10^7$** (?) **$\mu^+$/s**.

## PSI

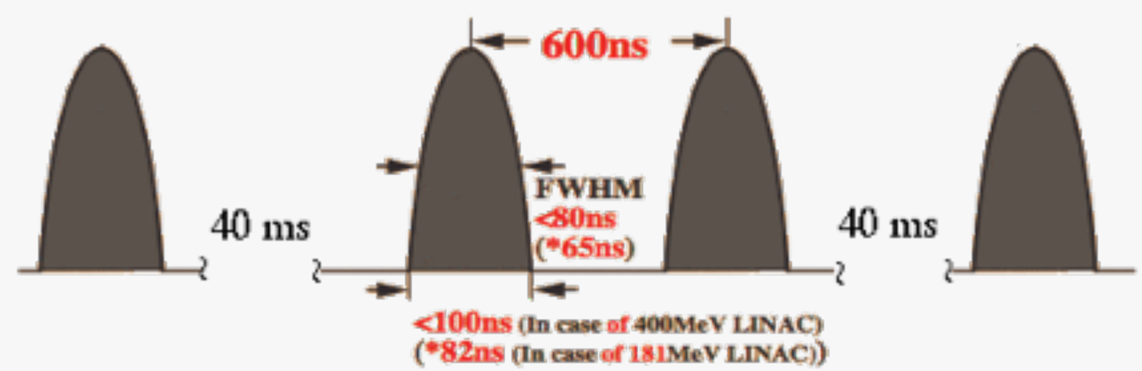
26 ns wide pulse of **0-100 MeV/c** muons *every 20 ns*.



Average rates up to **$10^8$ $\mu^+$/s**.

## J-PARC

Two *70 ns wide* pulses of **3 GeV** protons 600 ns apart delivered *every 40 ms* (with gaps to fill 50 GeV ring).




Average rates up to **$10^8$** (?) **$\mu^+$/s**.

TRIUMF

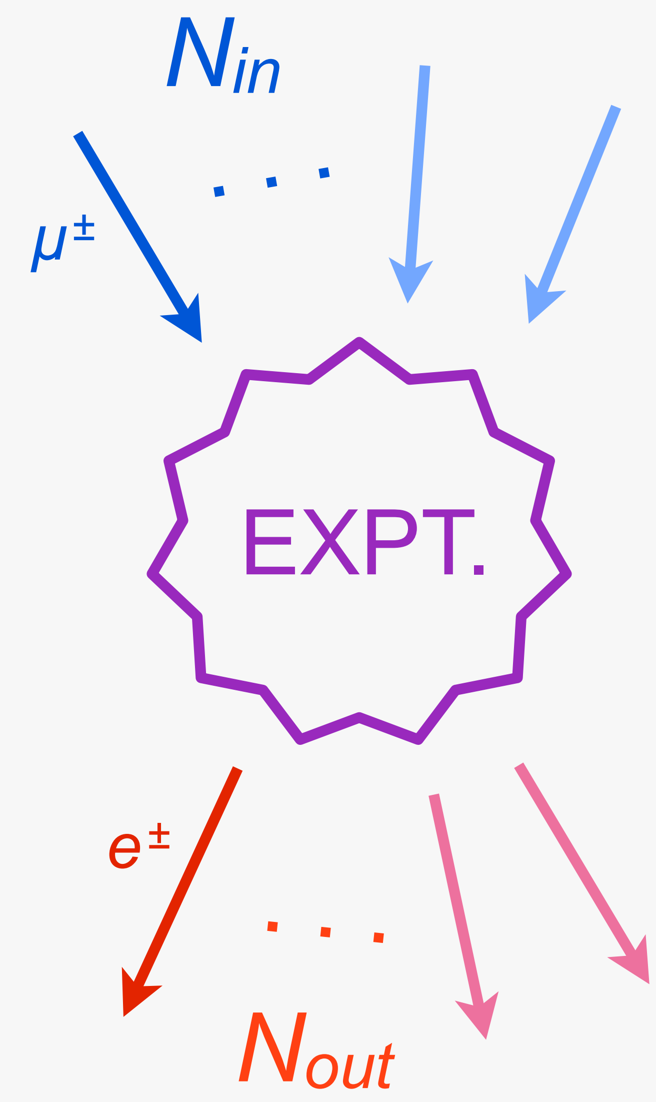
# Pulsed vs. CW muons

"Advantage factor" for Pulsed over CW muon beams:

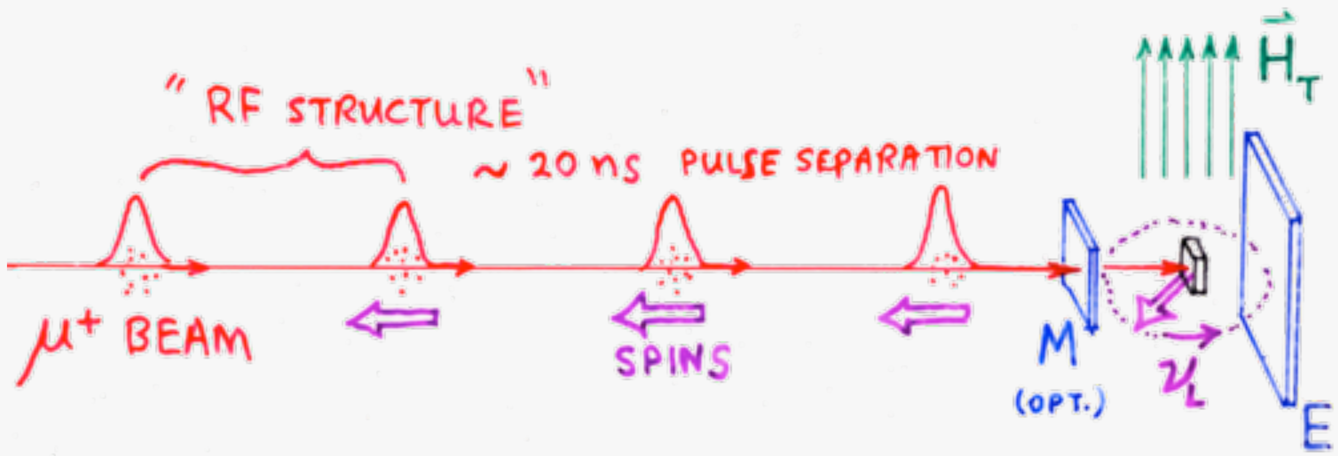
$$A_P = \log(N_{in} / N_{out})$$

where $N_{in}$ is the number of *synchronized* "*inputs*" (*e.g.* the $\mu^{\pm}$, RF, lasers, . . . )

and $N_{out}$ is the number of *correlated* "*outputs*" (*e.g.* decay $e^{\pm}$, $n$, $\gamma$, fission fragments, recoils, . . . )



# Strobo-μSR



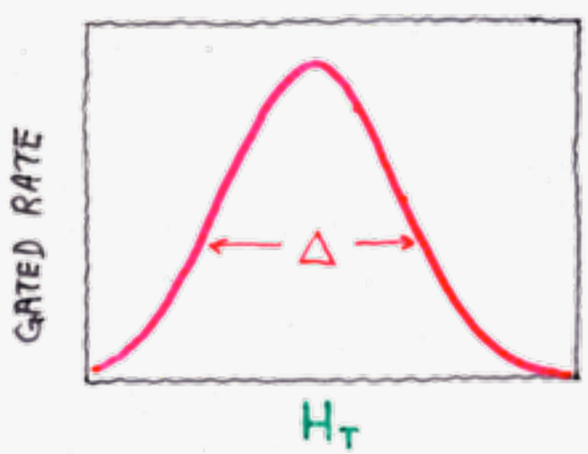

WHEN $1/\nu_L$ (PRECESSION PERIOD) IS

$1/n$ × INTERVAL BETWEEN MUON PULSES,

↑integer (~1 or 2)

ALL MUONS ARRIVE "IN PHASE" AND GATED COUNT RATE [AT APPROPRIATE TIME RELATIVE TO PULSE ARRIVAL] IS MAXIMIZED.

$$2\pi \nu_L = \gamma_\mu H_T$$

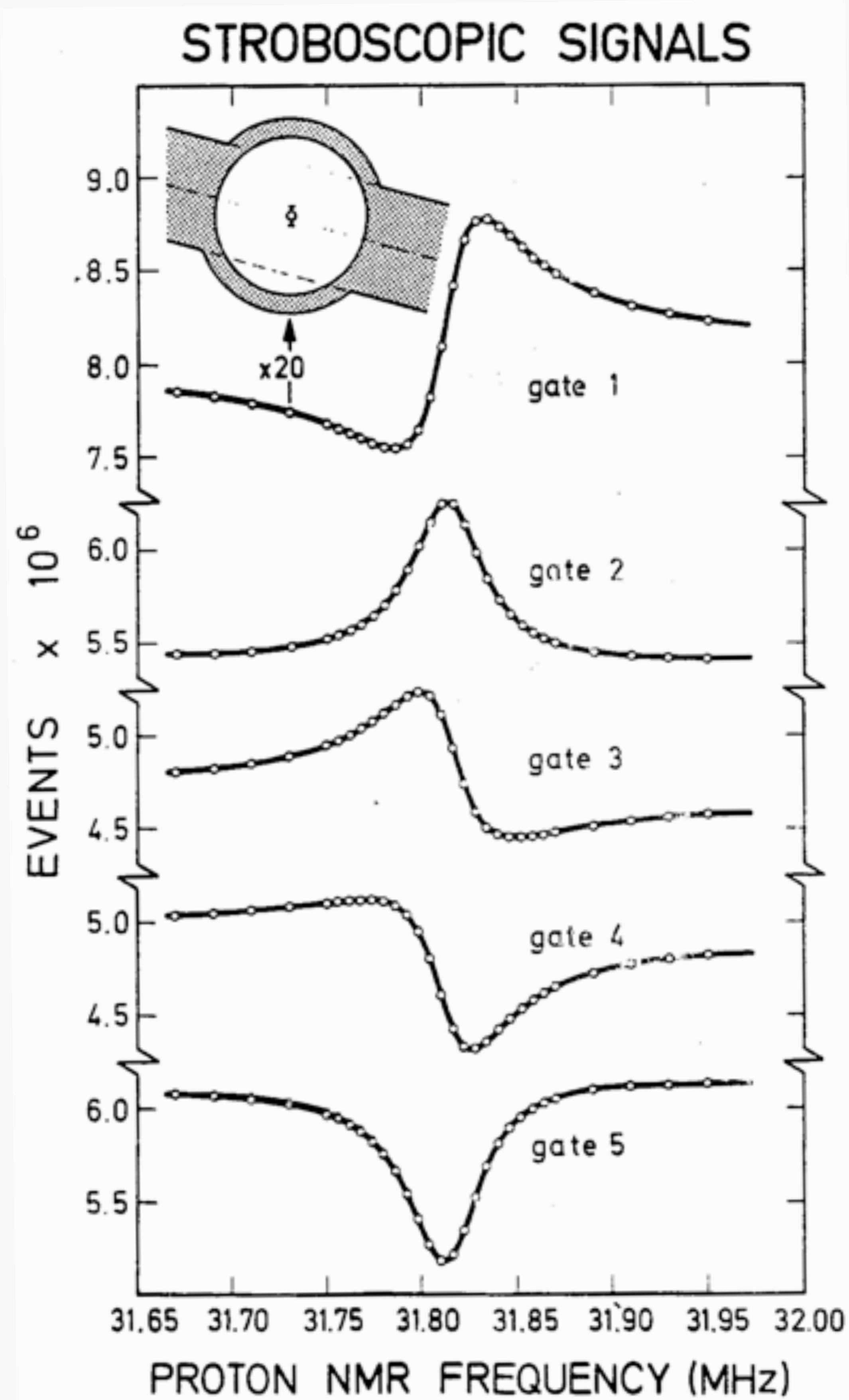



- NO RATE LIMIT! (MANY MUONS IN TARGET)

Gives KNIGHT SHIFTS to ~1 ppm

- PROBLEM: INTRINSIC WIDTH

$$\Delta = \frac{1}{\tau_\mu} = 0.454\ \mu s^{-1}$$



# *…then you need a μSR Spectrometer!*


OXFORD
GPS
LTF

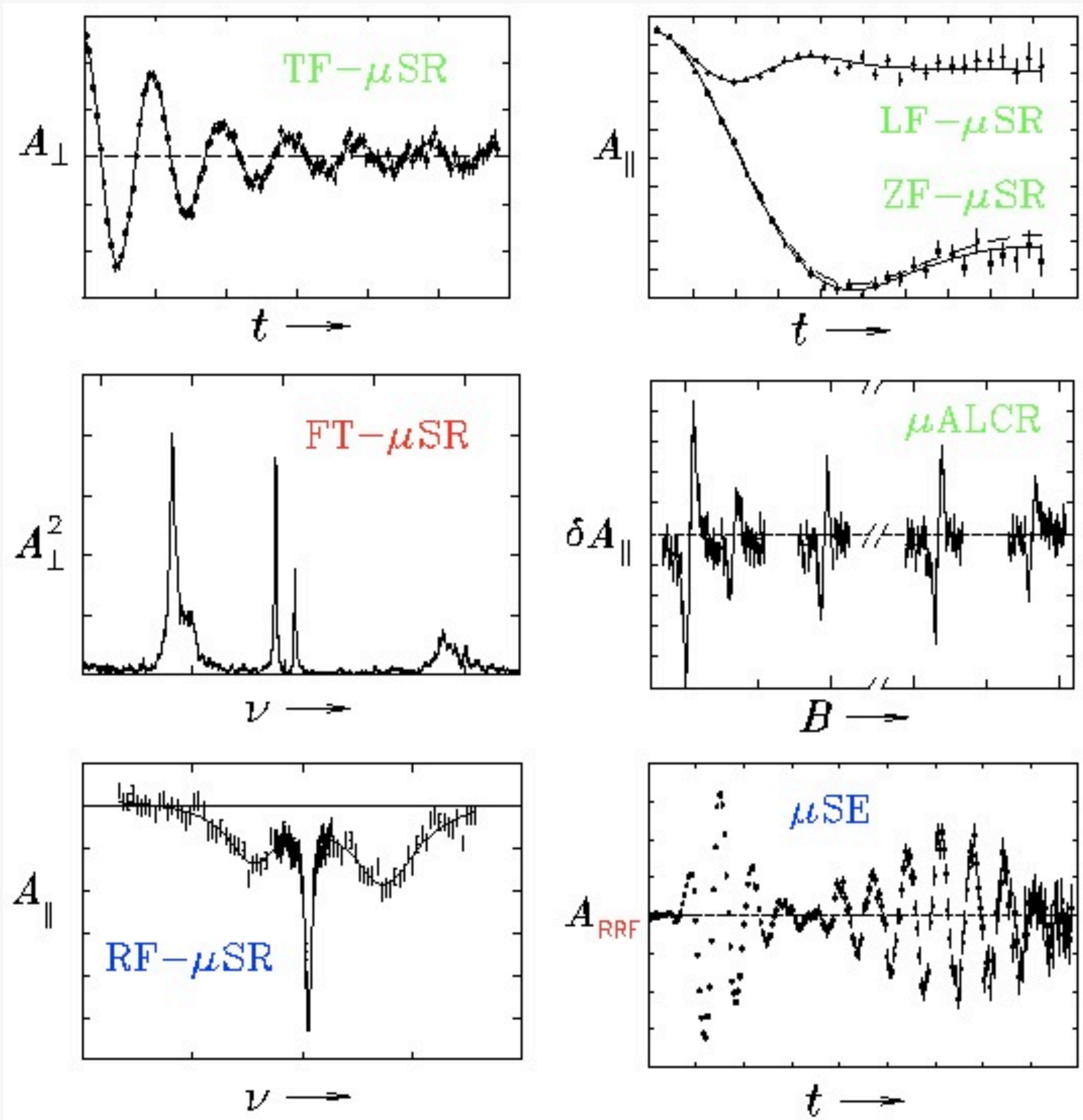
*...then you need some μSR Techniques!*

# Brewer's List of μSR Acronyms

Transverse Field

Longitudinal Field

Zero Field




Fourier Transform μSR

Avoided Level Crossing Resonance

Muon Spin Resonance

Muon Spin Echo

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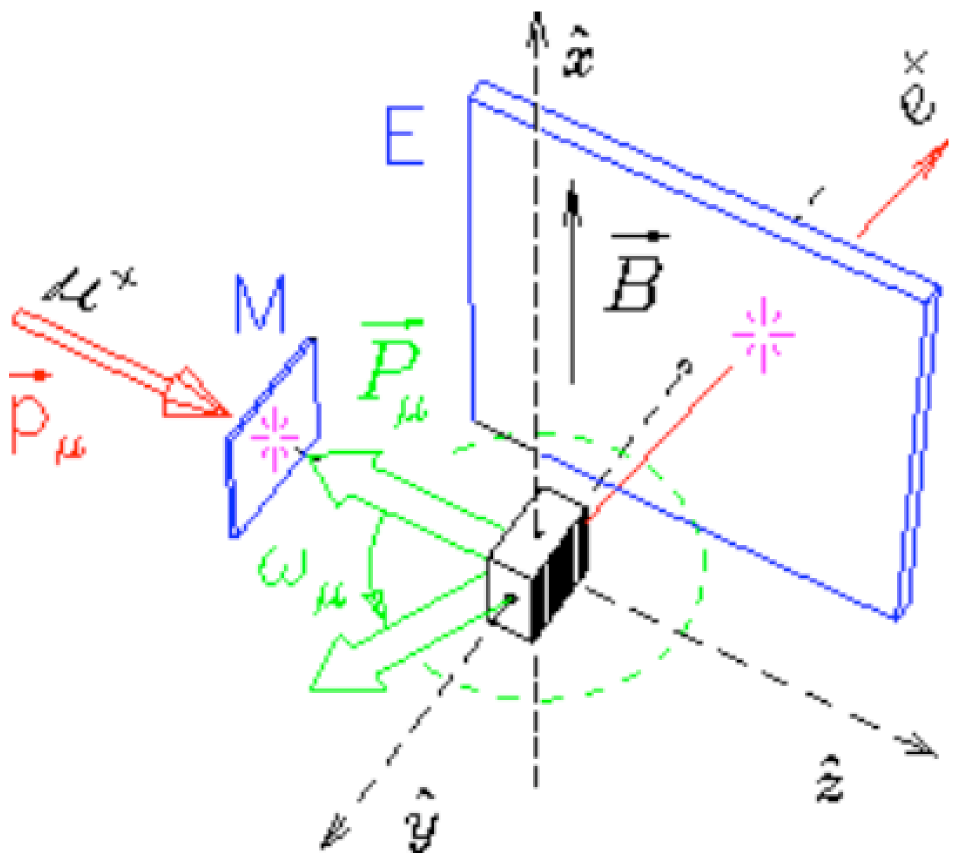
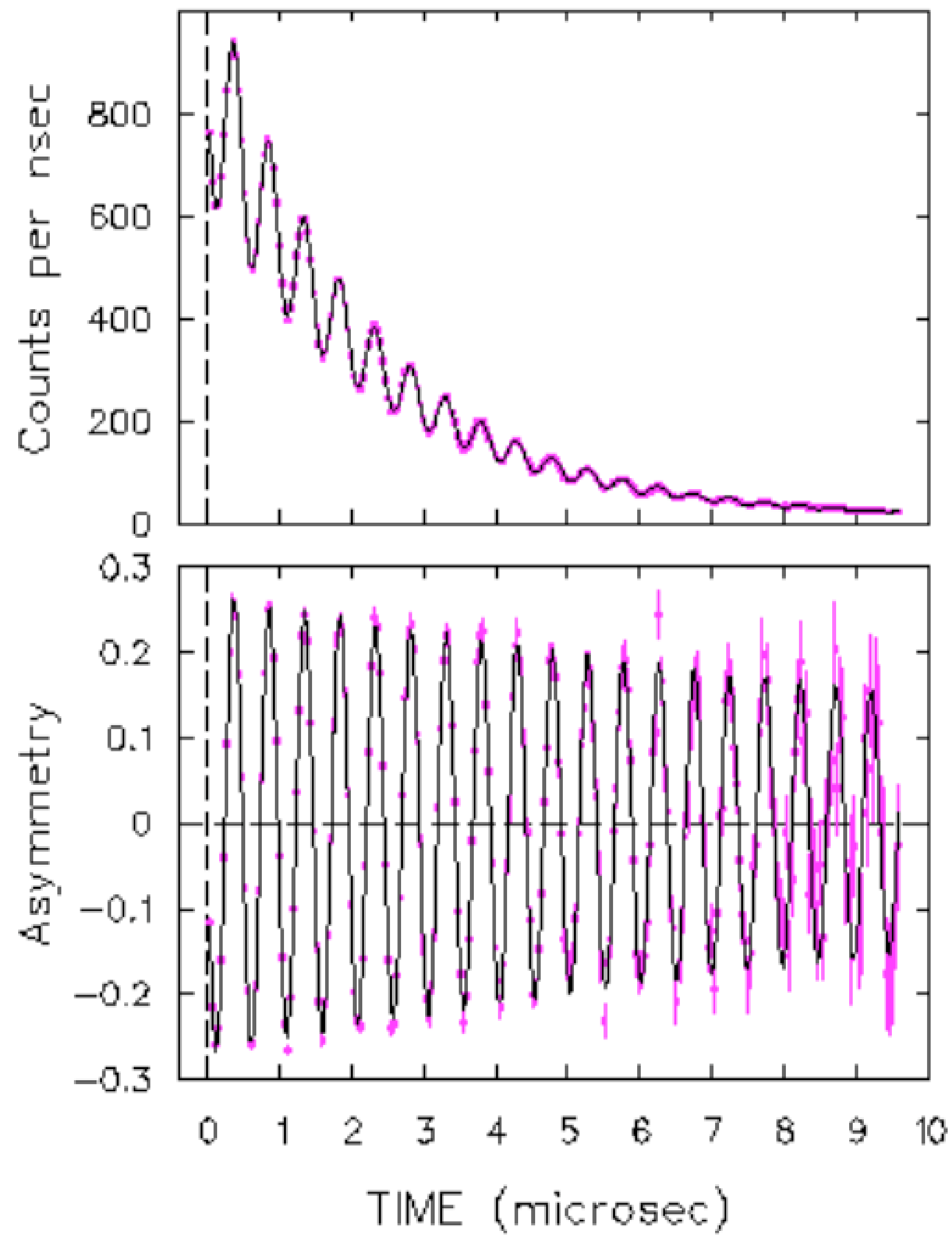
# wTF-μ⁺SR:

$$N(t) = N_0 \left\{ B + e^{-t/\tau_\mu} \left[ 1 + A_0 G_{xx}(t) \cos(\omega_\mu t + \phi) \right] \right\}$$




$$A(t) = [N(t) - N_0 B]\, e^{+t/\tau_\mu} - 1$$
$$= A_0 G_{xx}(t) \cos(\omega_\mu t + \phi)$$



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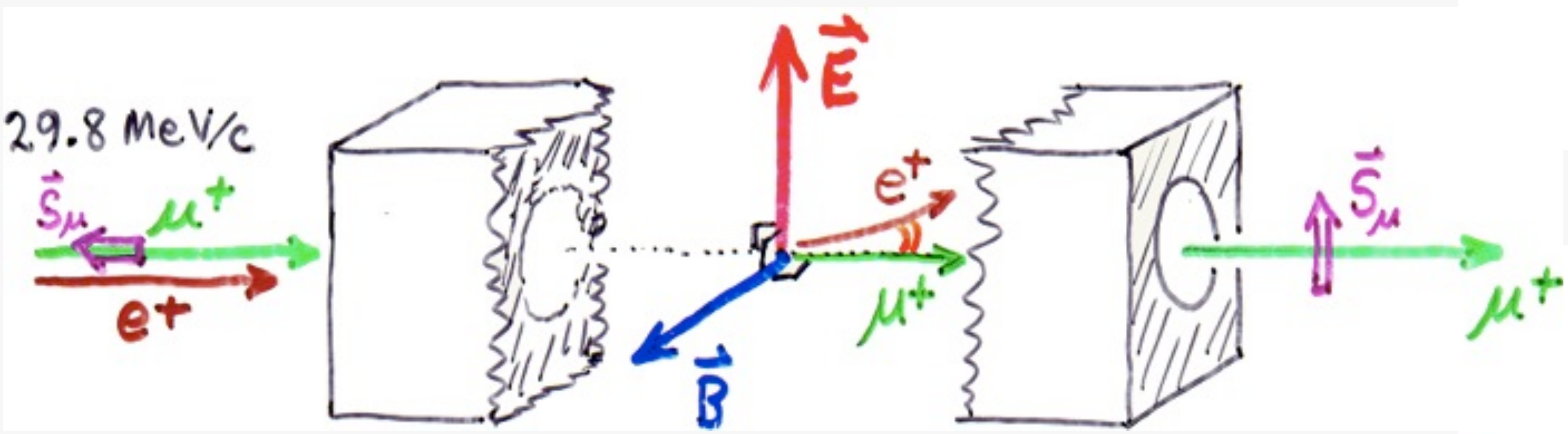
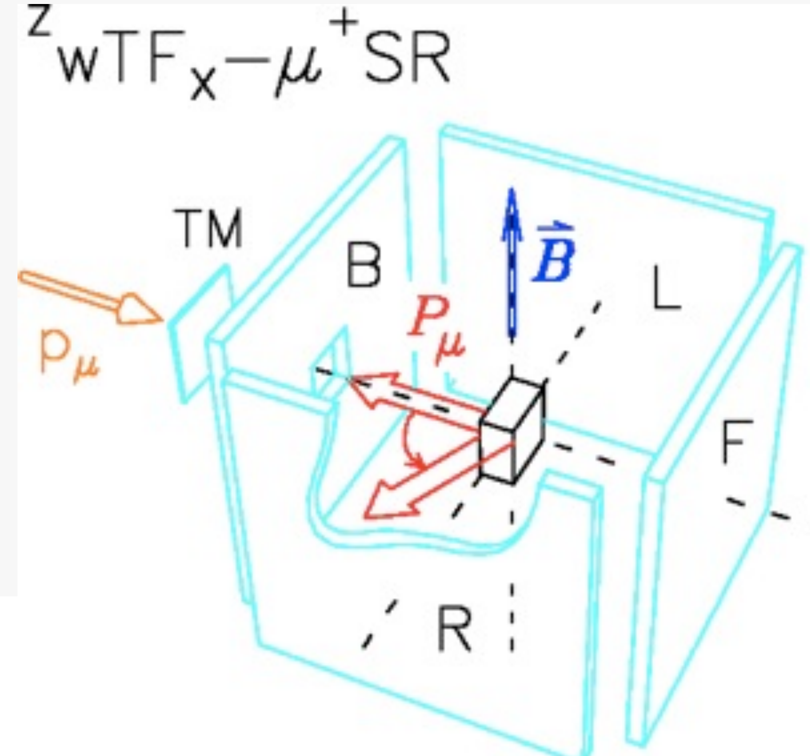
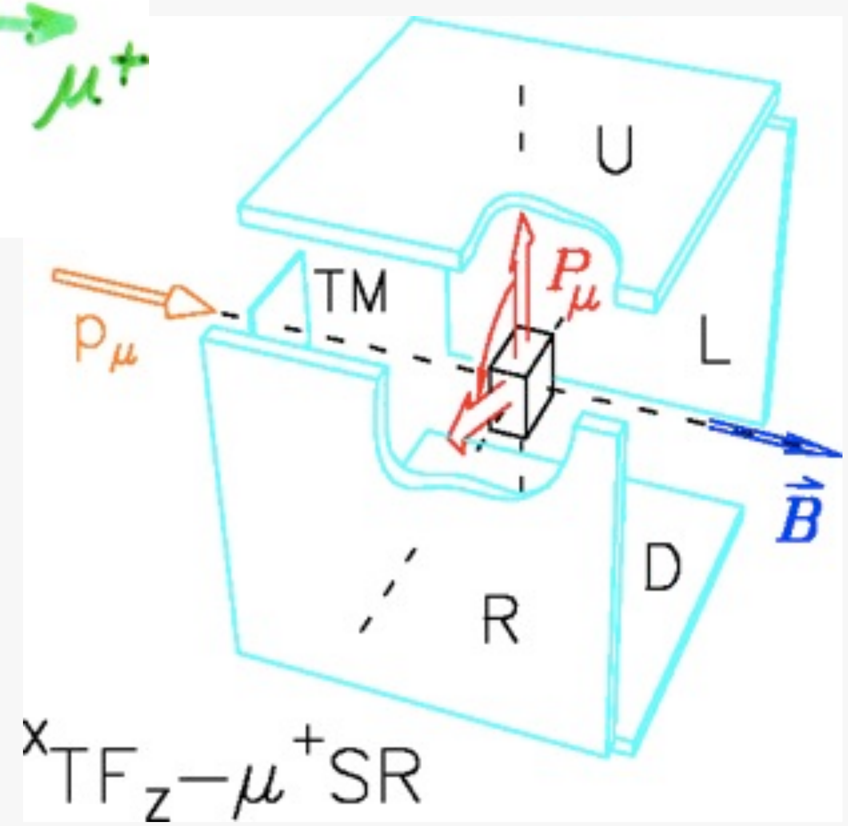
# $E \times B$ velocity selector

("DC Separator" or Wien filter) for **surface muons**:




- Removes beam positrons
- Allows TF-$\mu^+$SR in high field (otherwise ***B*** deflects beam)



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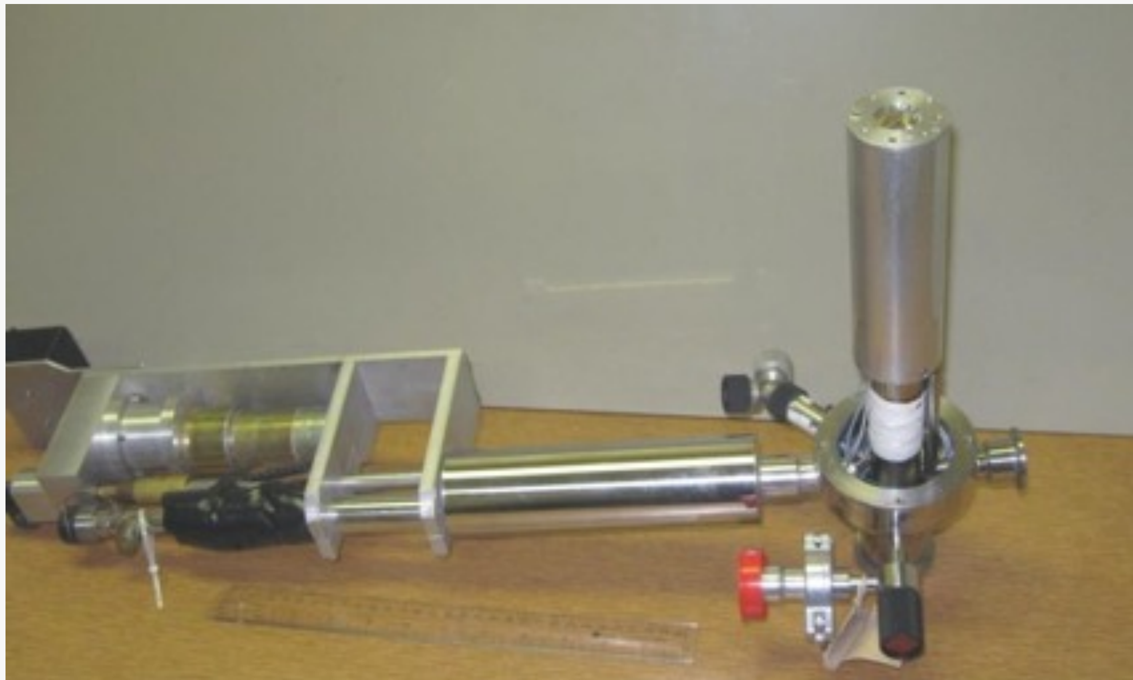
# High Field μSR

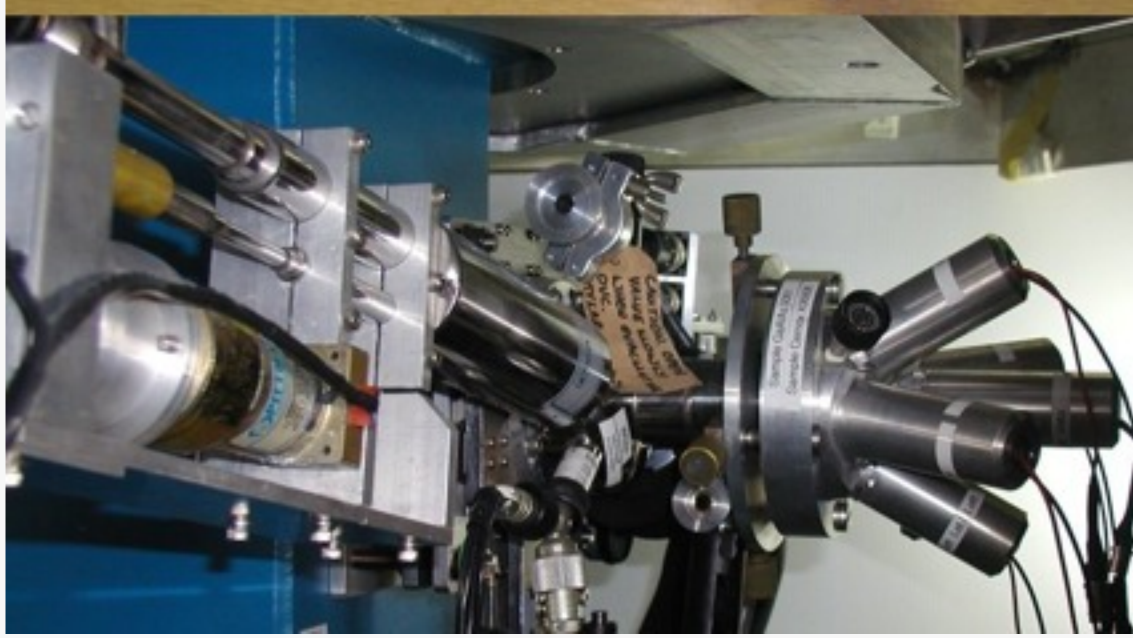
**TRIUMF**: Fields of up to 8 T are now available, requiring a "business end" of the spectrometer only 3 cm in diameter (so that 30-50 MeV decay positron orbits don't "curl up" and miss the detectors) and a time resolution of ~150 ps. Muonium precession frequencies of over 2 GHz have been studied.

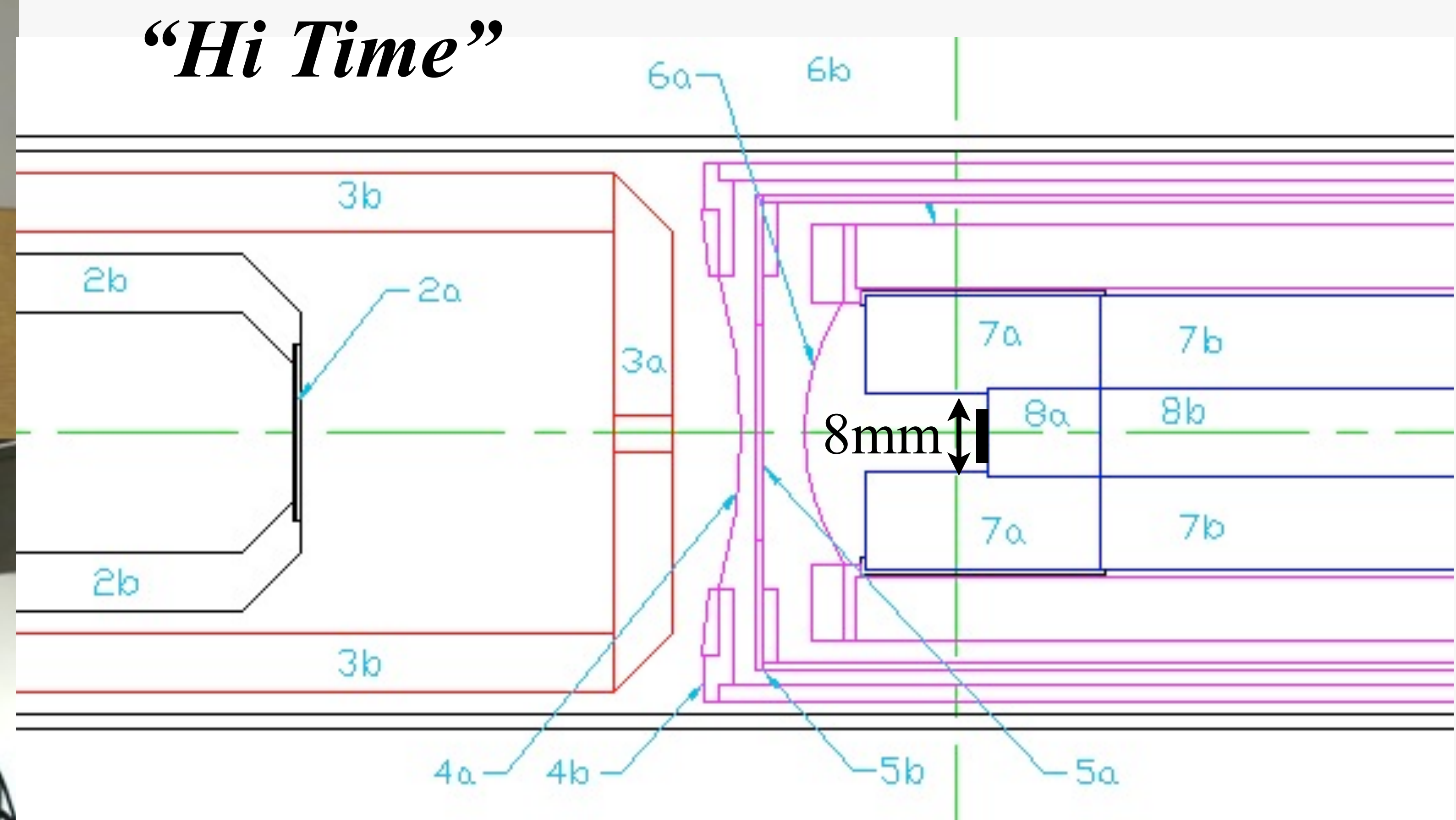
**PSI**: 9.5 T spectrometer commissioned in 2011.

**ISIS**: 5 T spectrometer (LF only).

# High Field ⇒ Miniaturization







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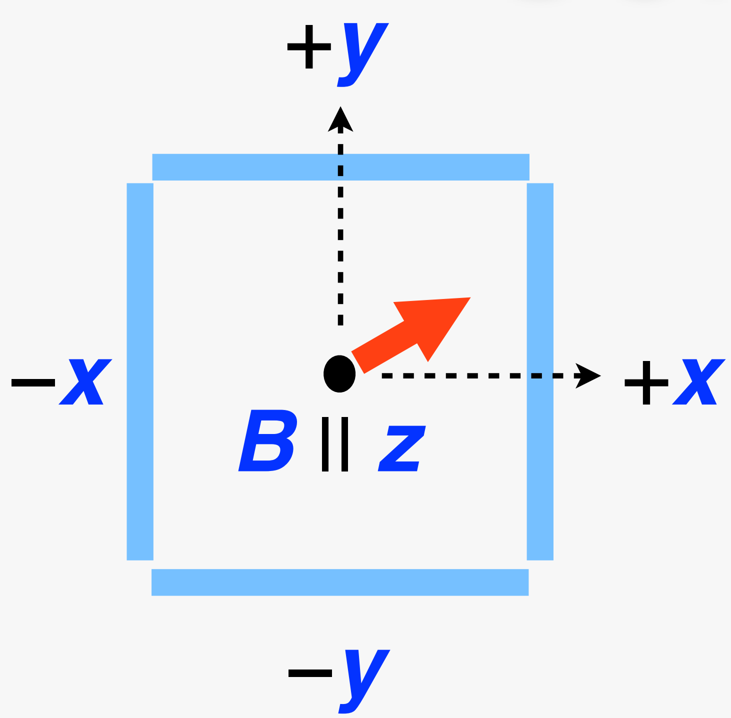
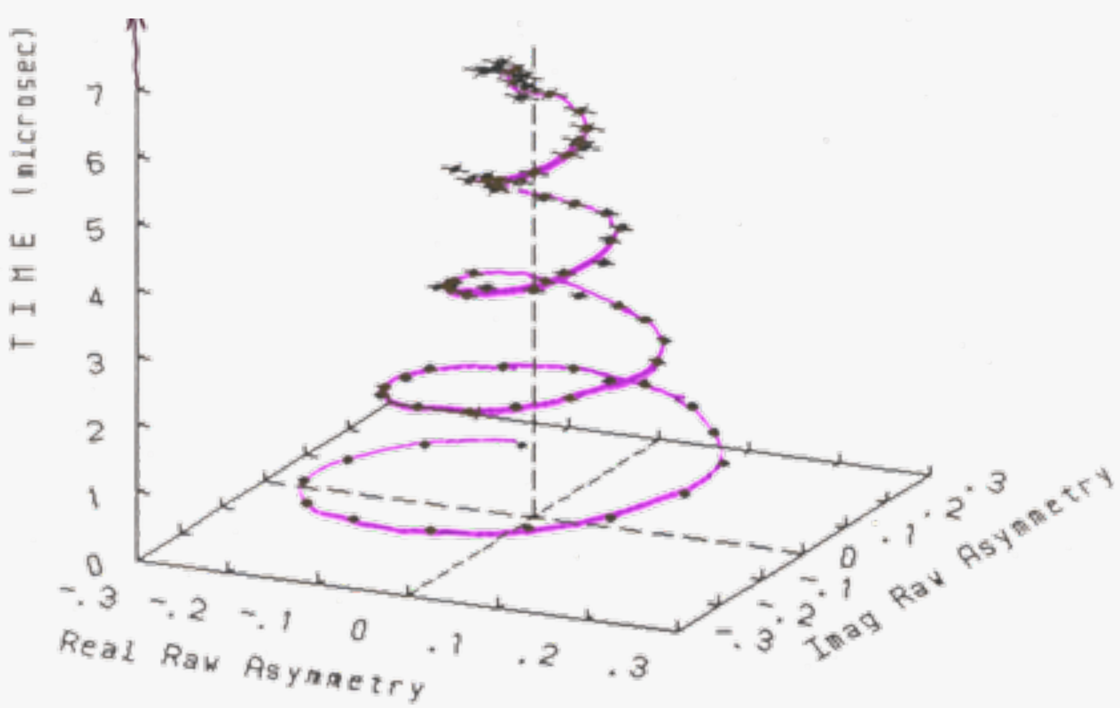
# Complex TF Asymmetry




$\mathcal{R}e\,\mathcal{A}(t) = A_x(t) = \left[A_x^+(t) - A_x^-(t)\right]/2$

$\mathcal{I}m\,\mathcal{A}(t) = A_y(t) = \left[A_y^+(t) - A_y^-(t)\right]/2$

$$\mathcal{A}(t) = A_x(t) + i\,A_y(t)$$

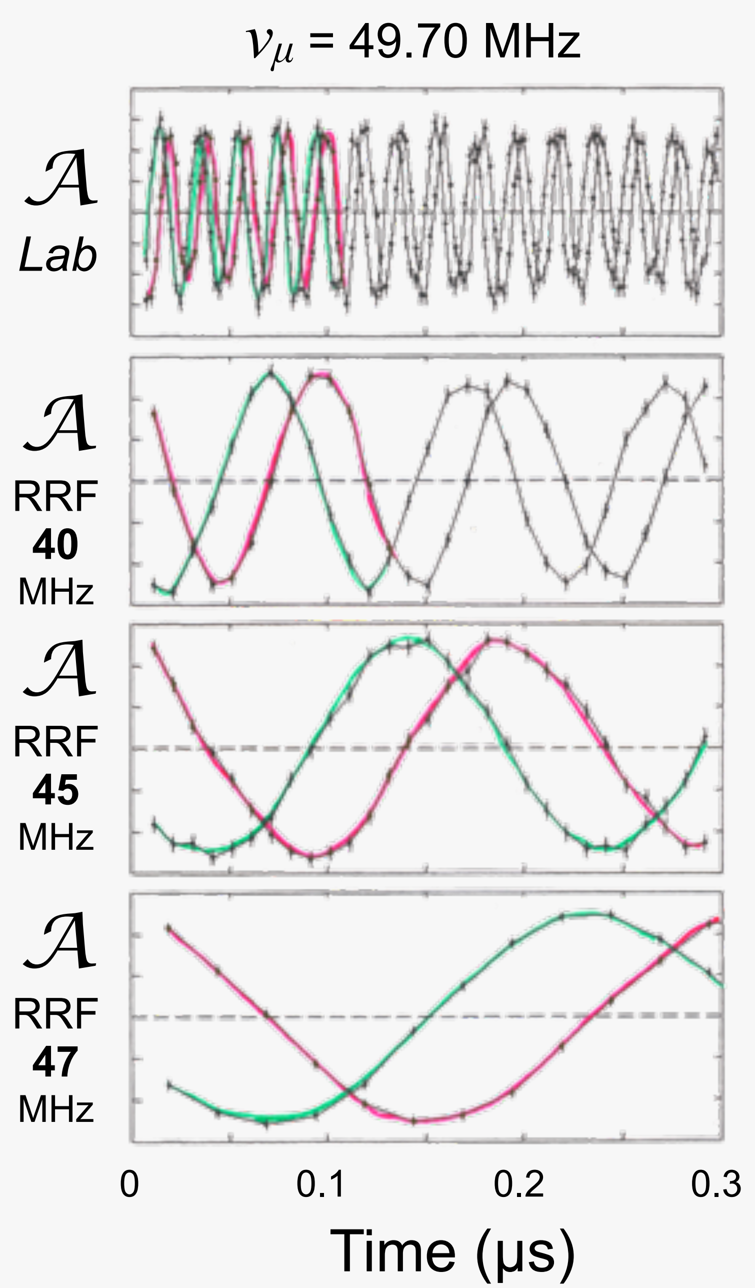



For High Transverse Field (HTF), transform into the Rotating Reference Frame (RRF):

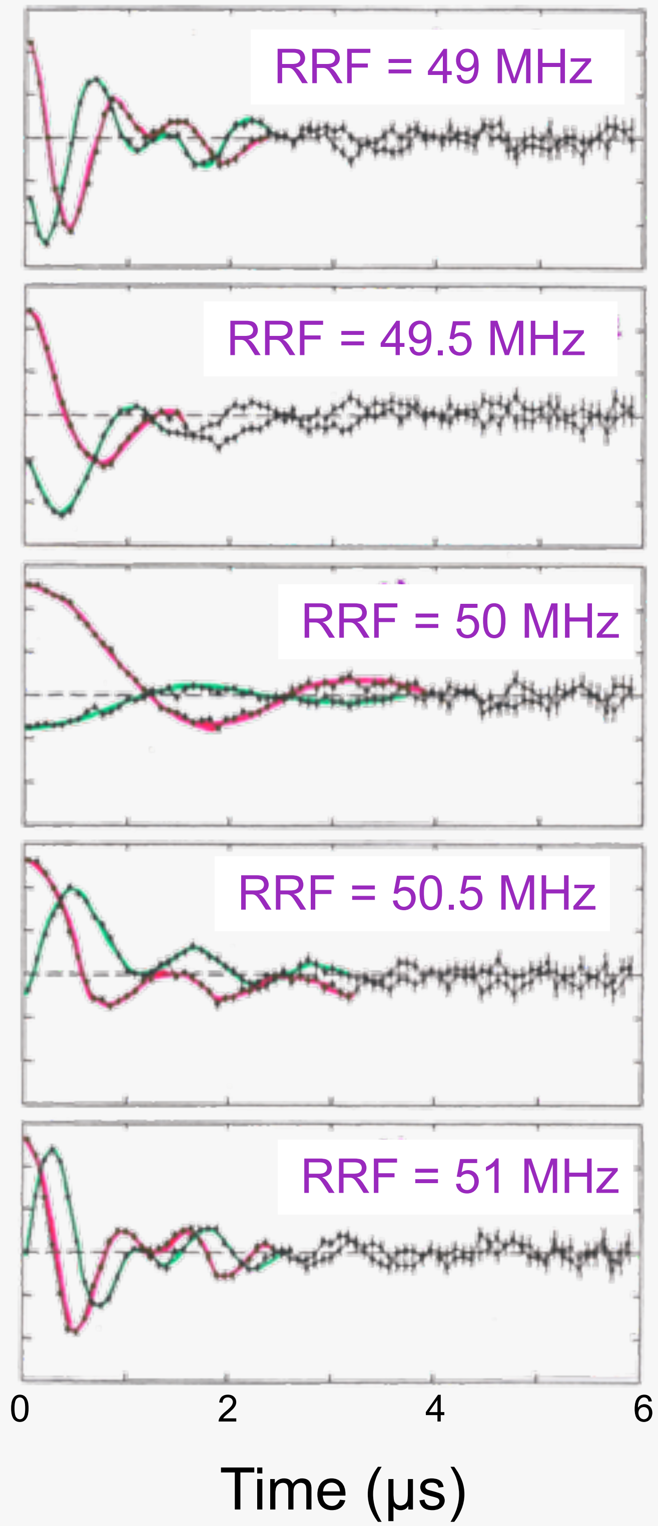
$$\mathcal{A}_{\rm LAB}(t) = A_x(t) + iA_y(t)$$

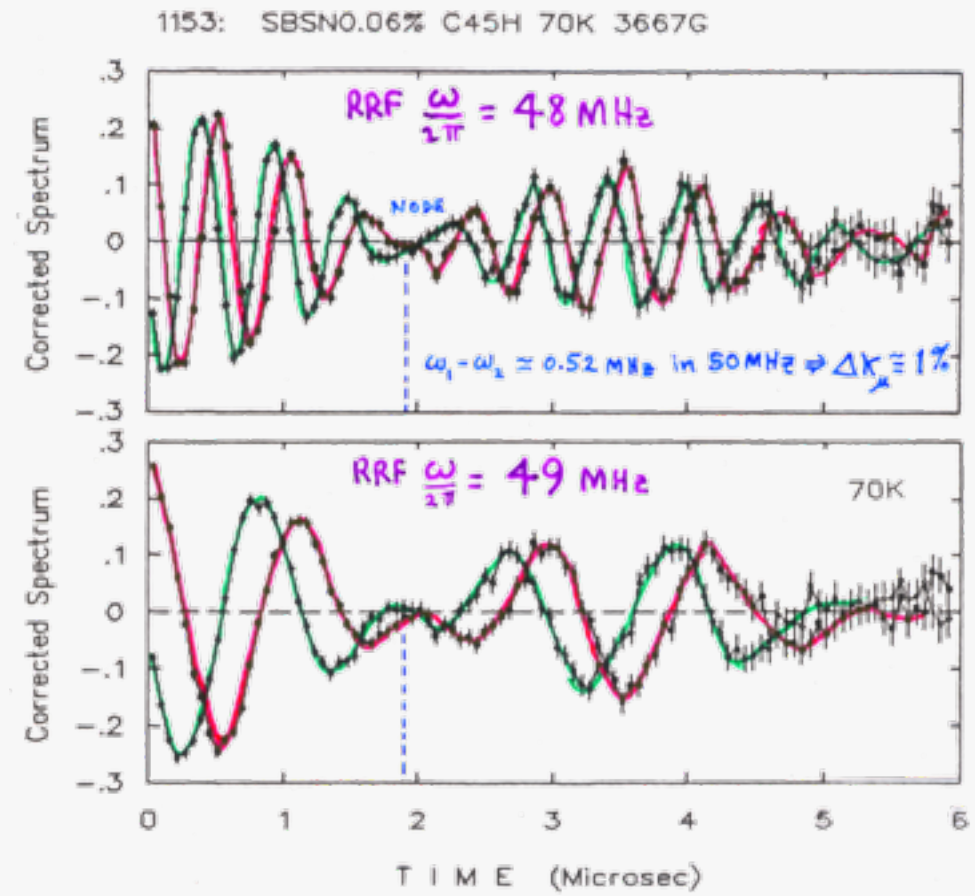
$$\mathcal{A}_{\rm RRF}(\Omega, t) = e^{-i\Omega t}\,\mathcal{A}_{\rm LAB}(t)$$

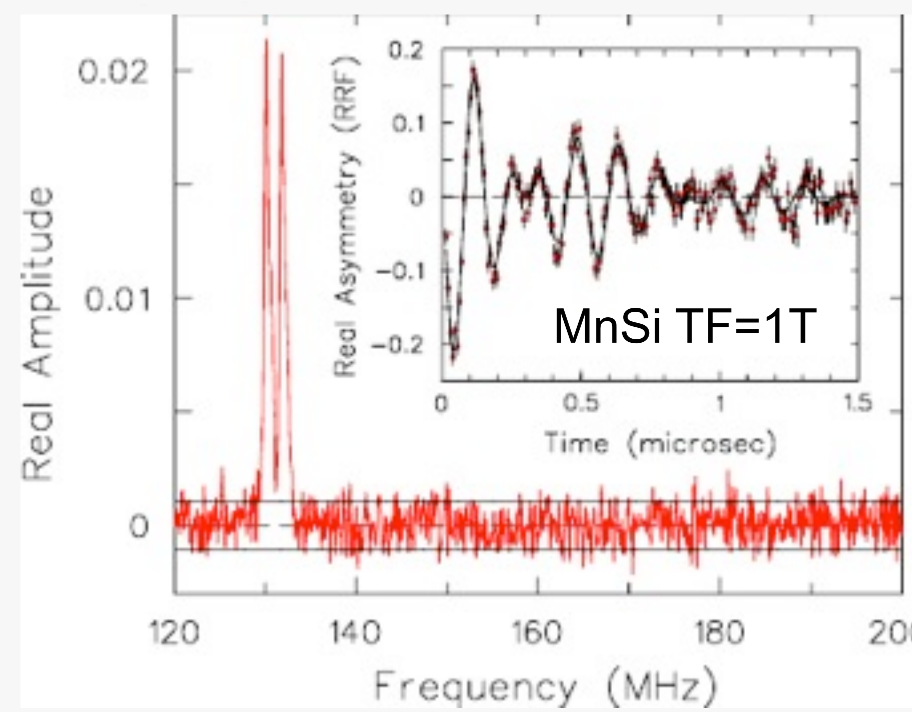
# Rotating Reference Frame



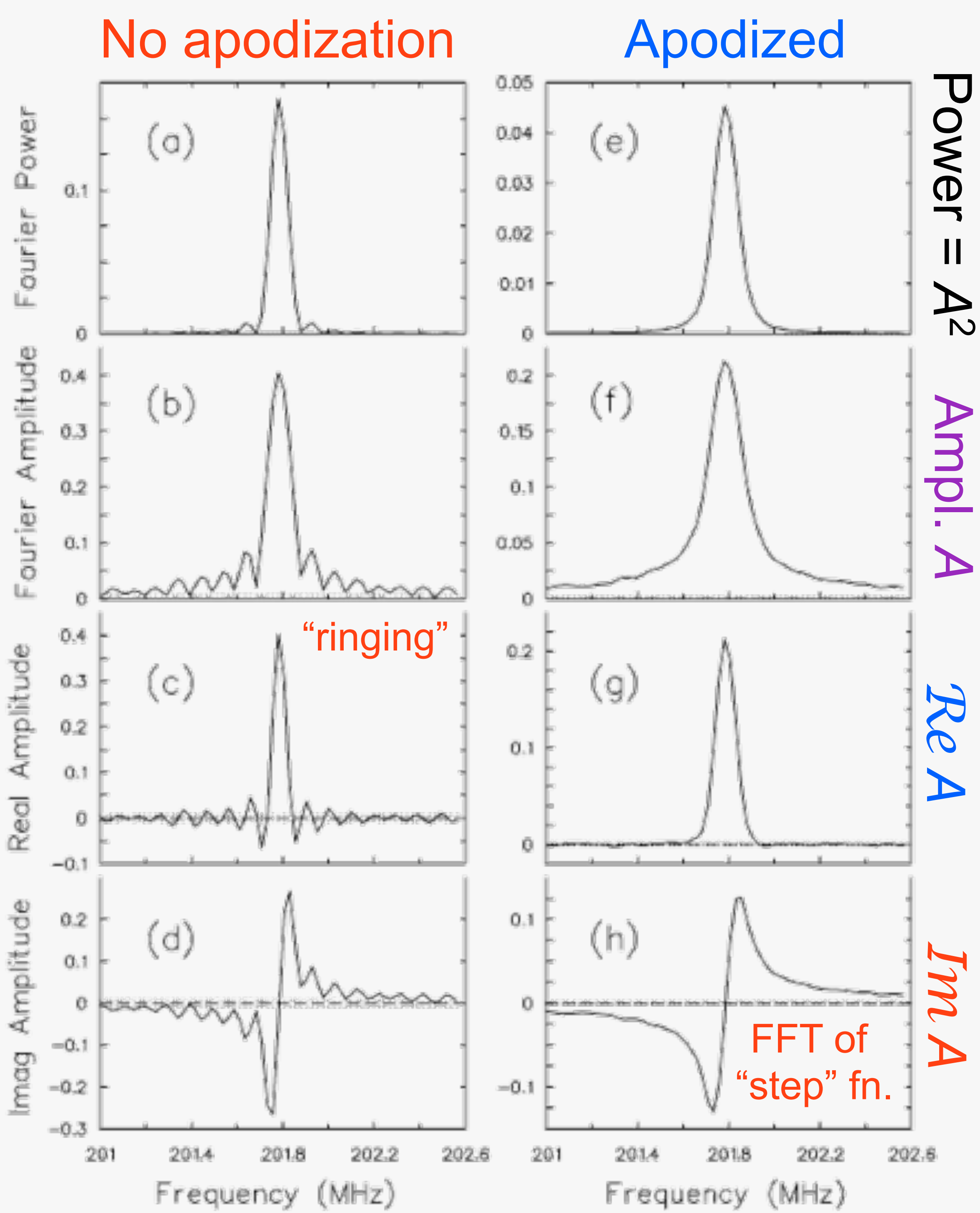

Slower oscillations ⇒ wider bins, less “noise”

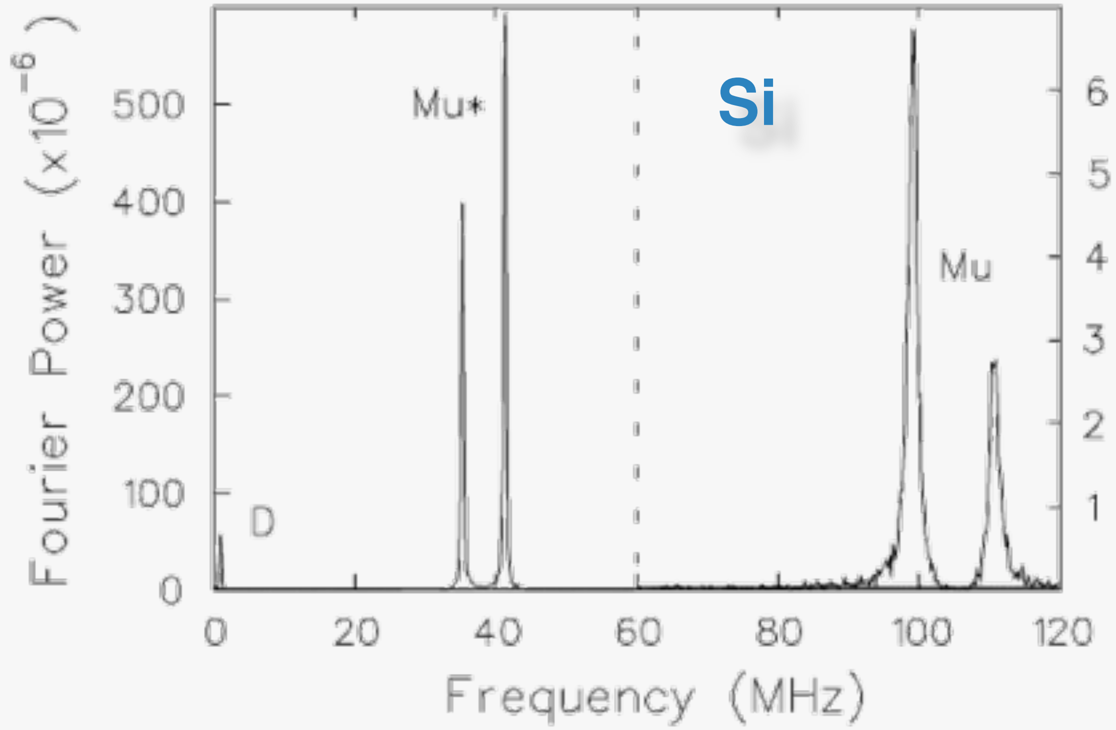


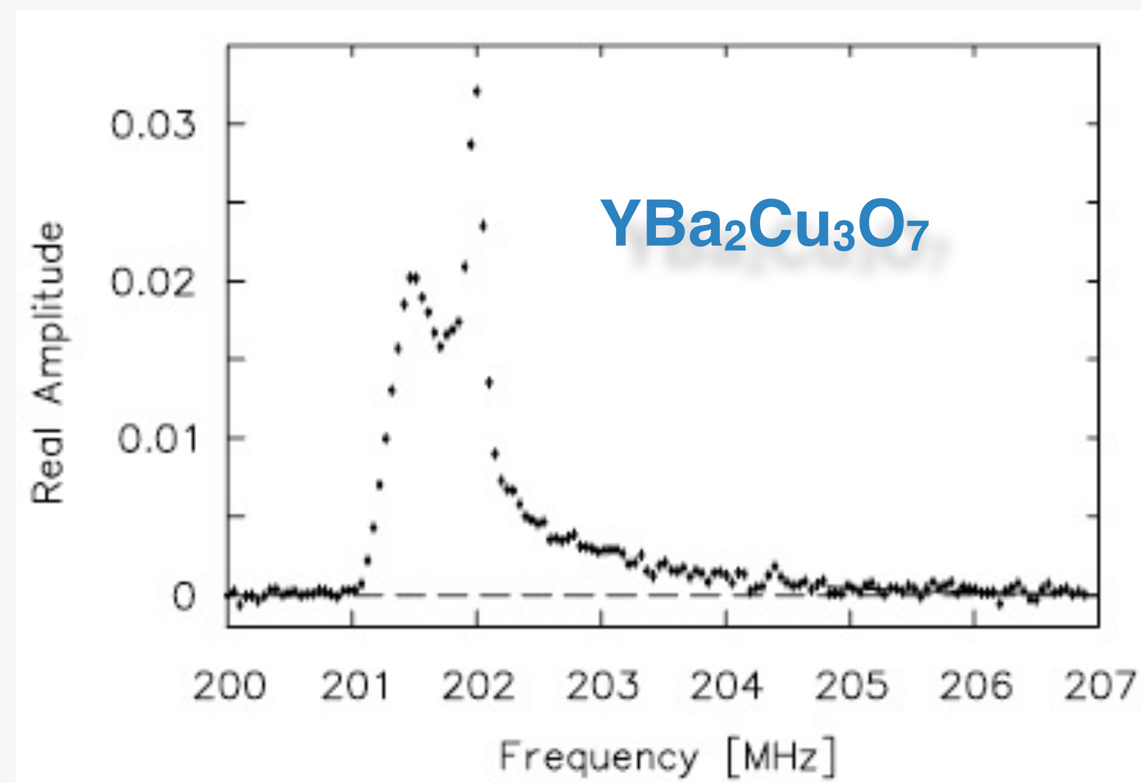



# Fourier Transforms

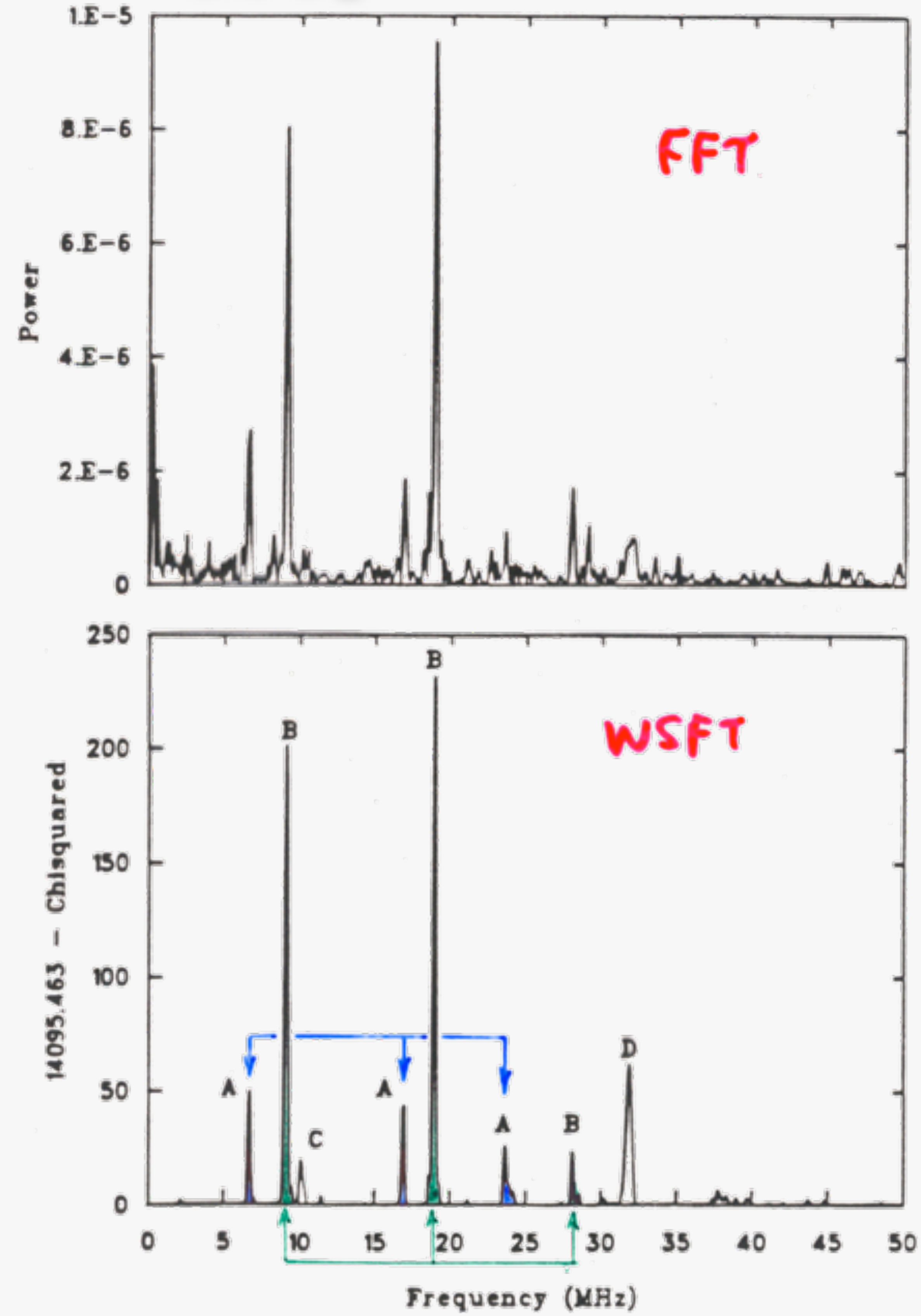


# World's Slowest Fourier Transform

$GeO_2$ D.P. Spencer, 1978



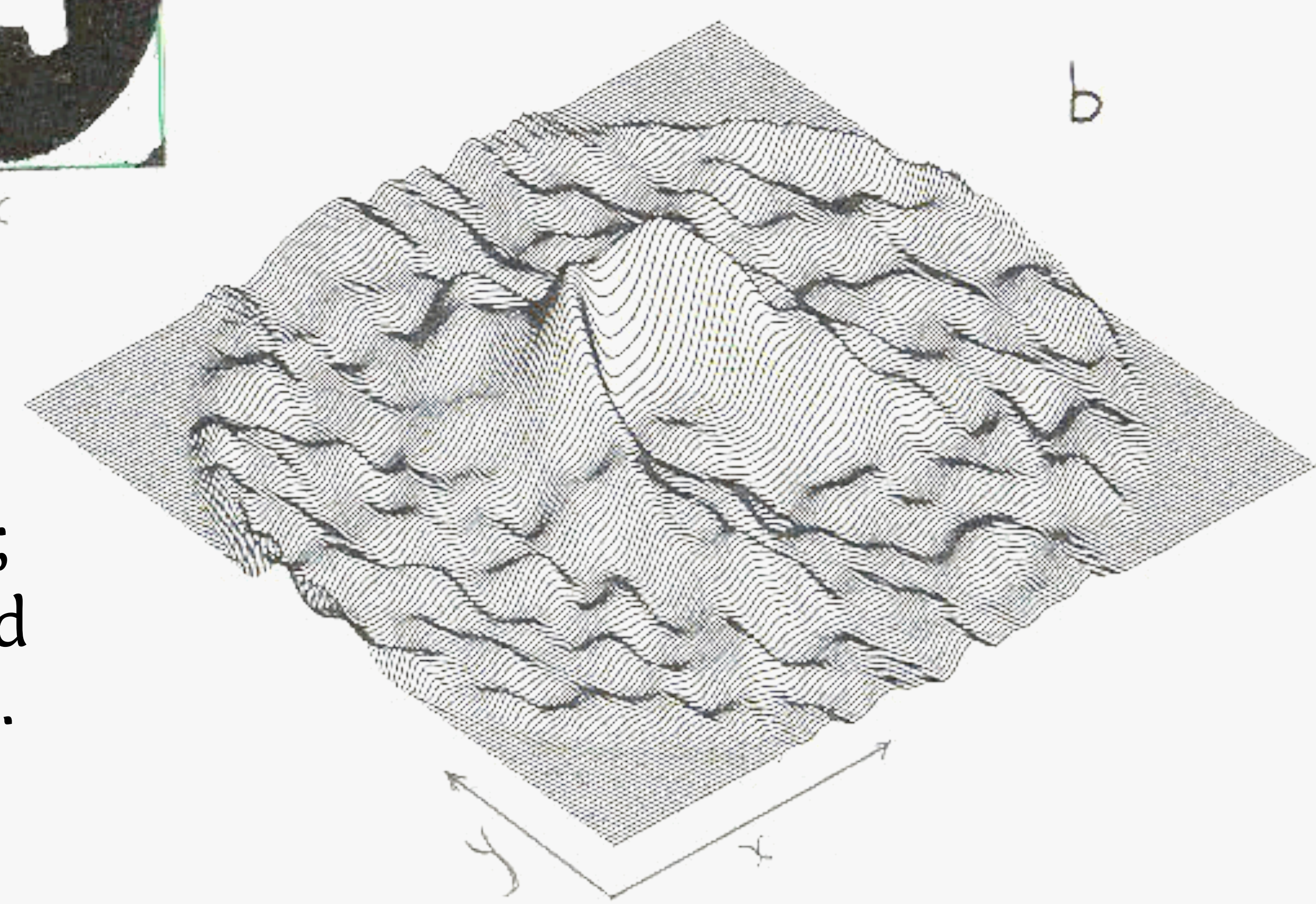

Instead of Fourier power, plot decrease in $\chi^2$ as a function of one fitted frequency.

Rarely used.

# Muon Spin Imaging

Crude silver cutout of a “**μ**” placed on a depolarizing background.


Proposed by Noam Kaplan and tested at TRIUMF but never developed further.




Magnetic field gradients applied in various directions; Fourier transforms combined to produce image of the “**μ**”.

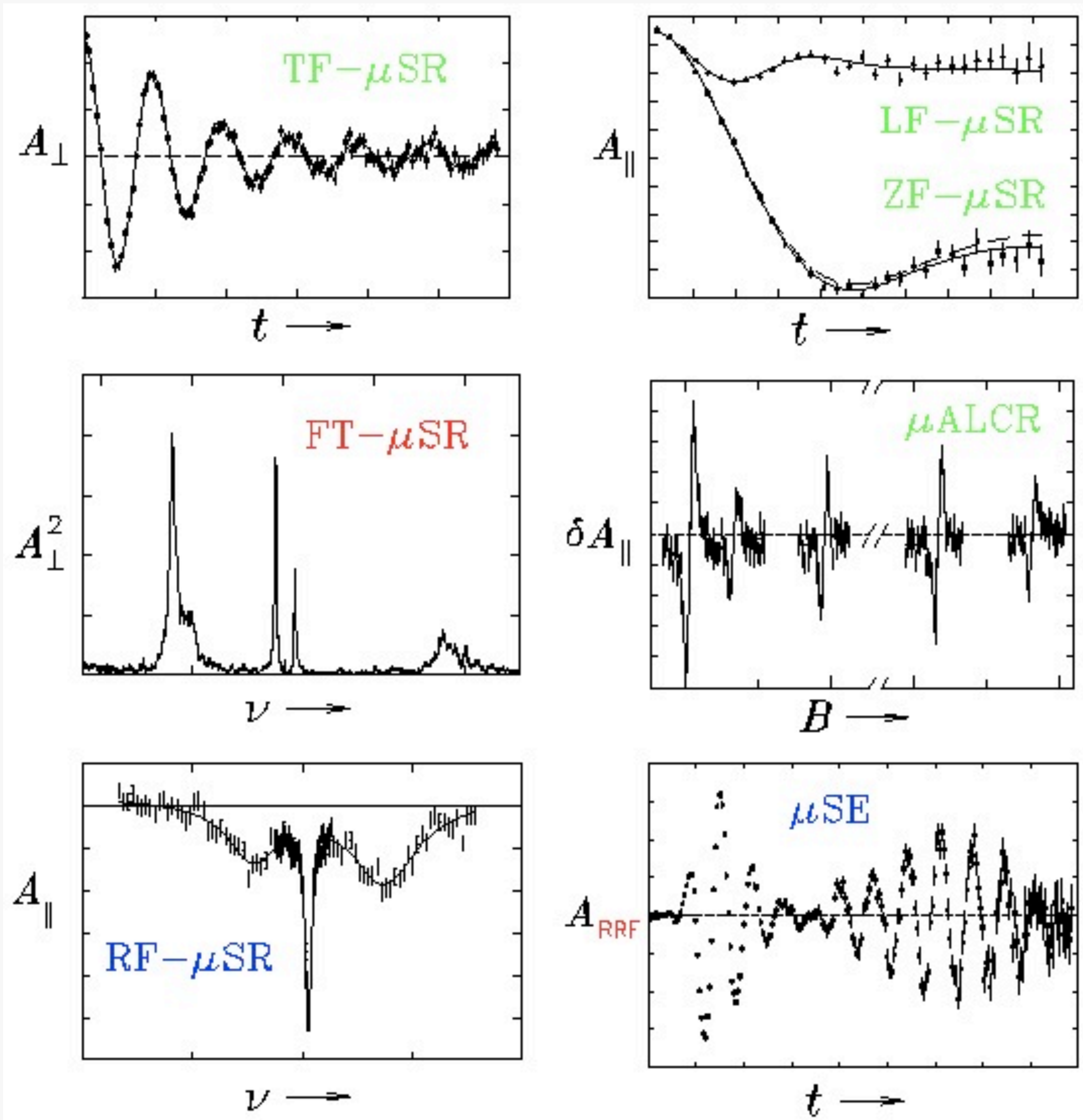
(Well, sort of....)

# Brewer's List of μSR Acronyms

Transverse Field

Fourier Transform μSR

Muon Spin Resonance




Longitudinal Field

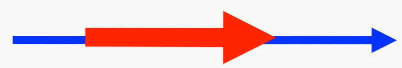
Zero Field

Avoided Level Crossing Resonance

Muon Spin Echo

# Motion of Muon Spins in Static Local Fields

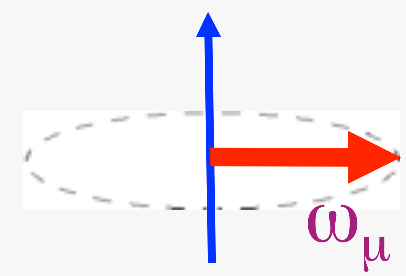

$S_\mu$ = Expectation value of a muon's spin direction

*(a)* All muons "see" same field $\boldsymbol{B}$:  for $\boldsymbol{B} \parallel S_\mu$ nothing happens.

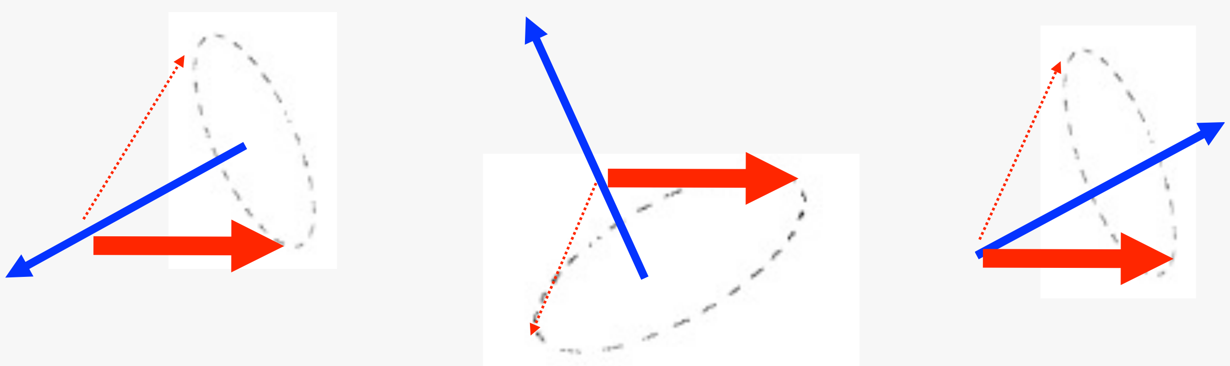
$\omega_\mu = 2\pi\, \gamma_\mu\, |\boldsymbol{B}|$

$\gamma_\mu = 135.5$ MHz/T

for $\boldsymbol{B} \perp S_\mu$ Larmor precession:

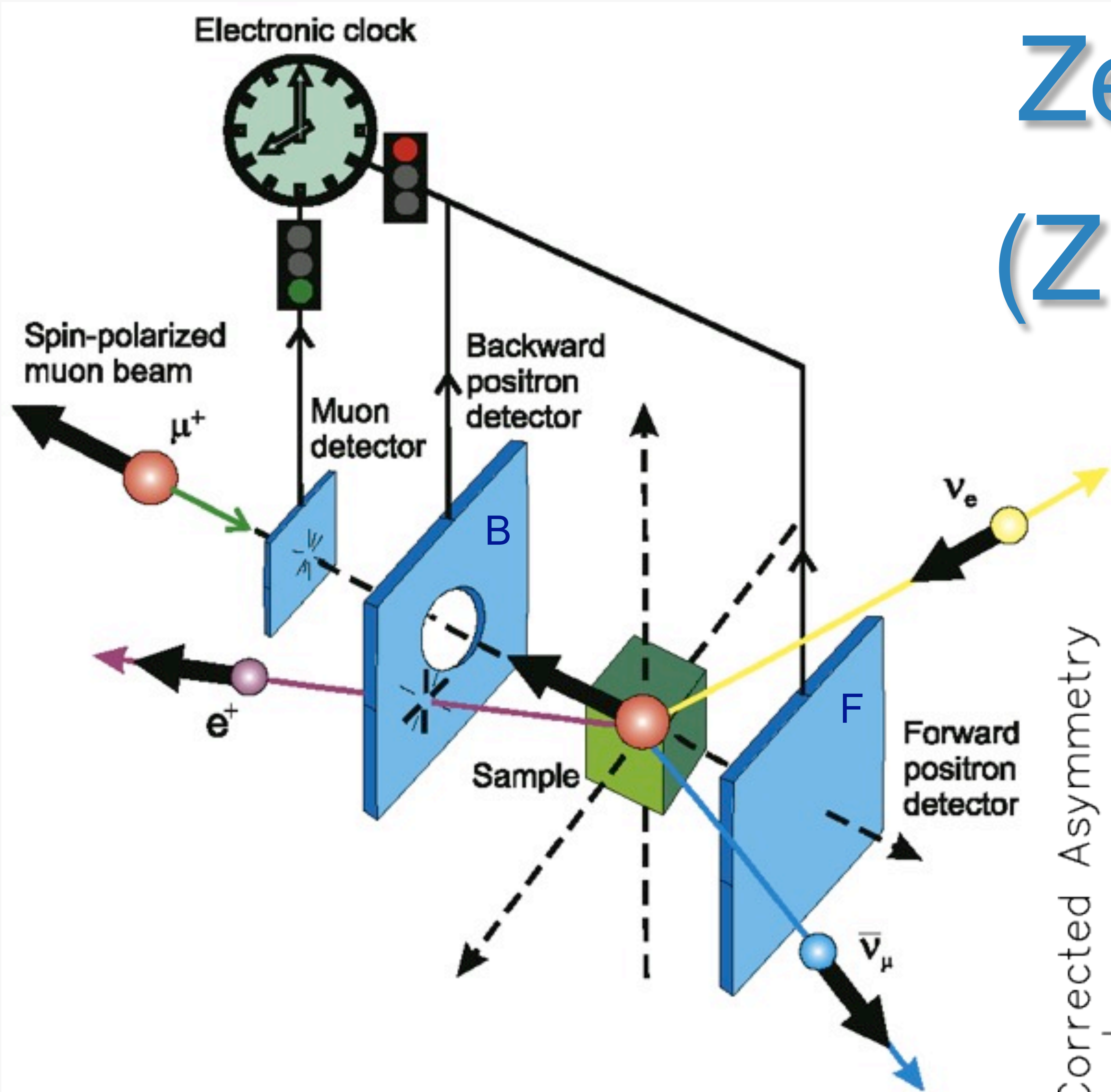



*(b)* All muons "see" same $|\boldsymbol{B}|$ but **random direction** :



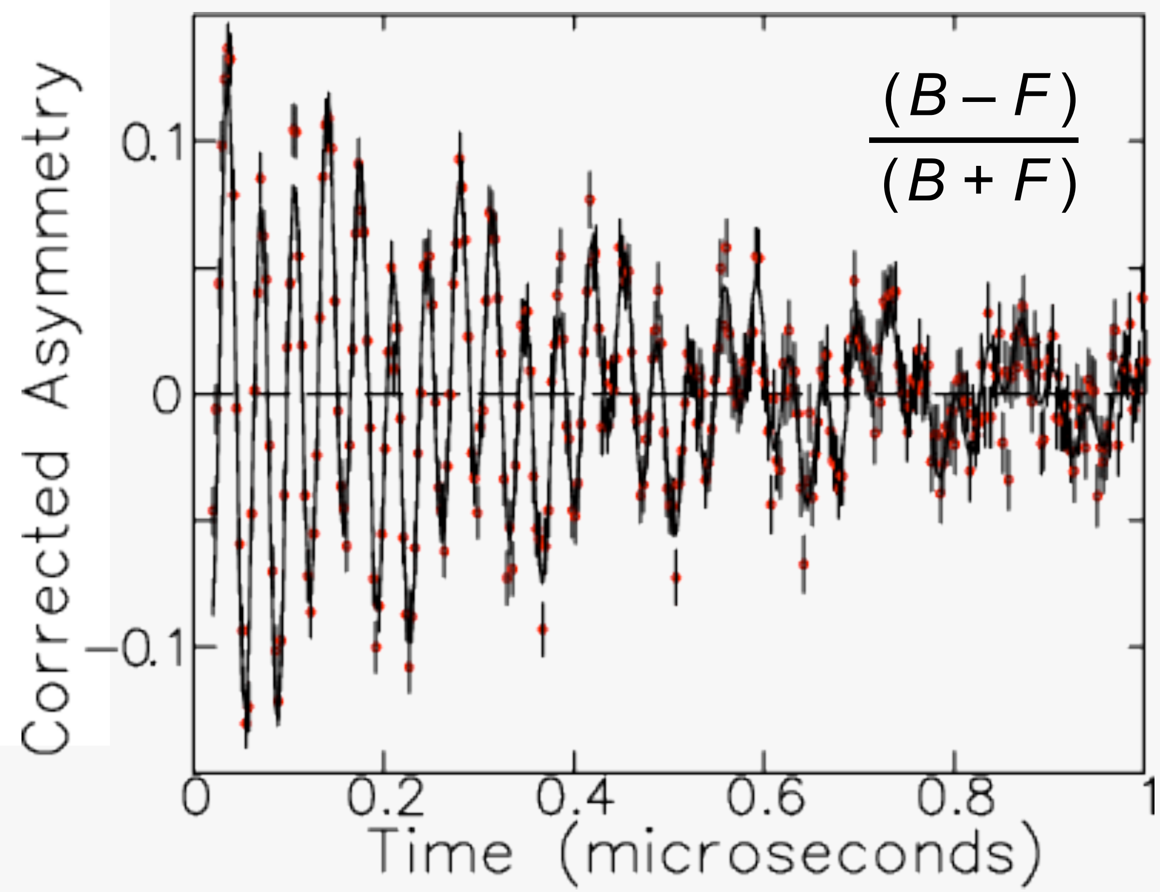
2/3 of $S_\mu$ **precesses** at $\omega_\mu$

1/3 of $S_\mu$ **stays constant**




# Zero Field (ZF)-$\mu^+$SR

Typical asymmetry spectrum



# Motion of Muon Spins in Static Local Fields

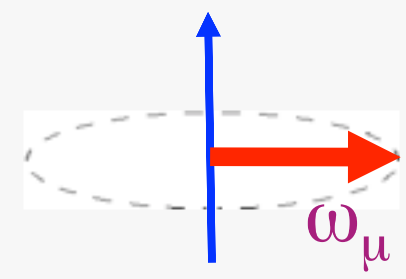
$\mathbf{S}_\mu$ = Expectation value of a muon's spin direction

*(a)* All muons "see" same field $\mathbf{B}$: for $\mathbf{B} \parallel \mathbf{S}_\mu$ nothing happens.

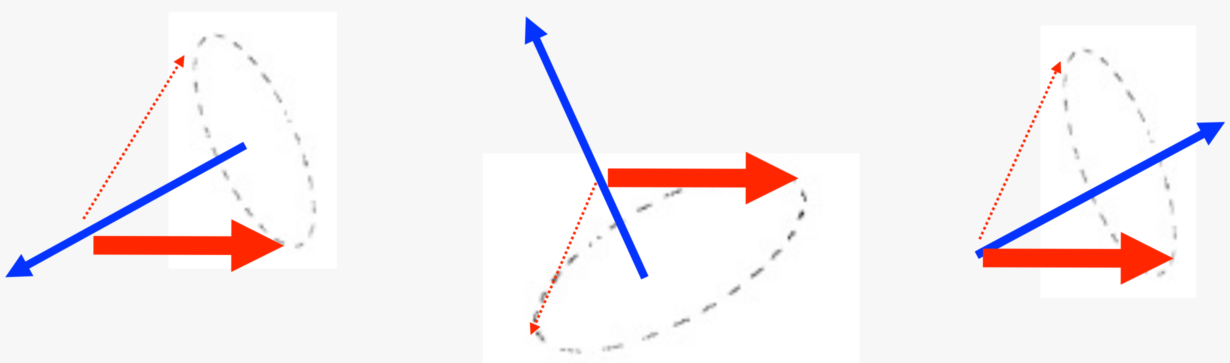
$\omega_\mu = 2\pi\,\gamma_\mu\,|\mathbf{B}|$

$\gamma_\mu = 135.5$ MHz/T

for $\mathbf{B} \perp \mathbf{S}_\mu$ Larmor precession:




*(b)* All muons "see" same $|\mathbf{B}|$ but **random direction**:



2/3 of $\mathbf{S}_\mu$ **precesses** at $\omega_\mu$

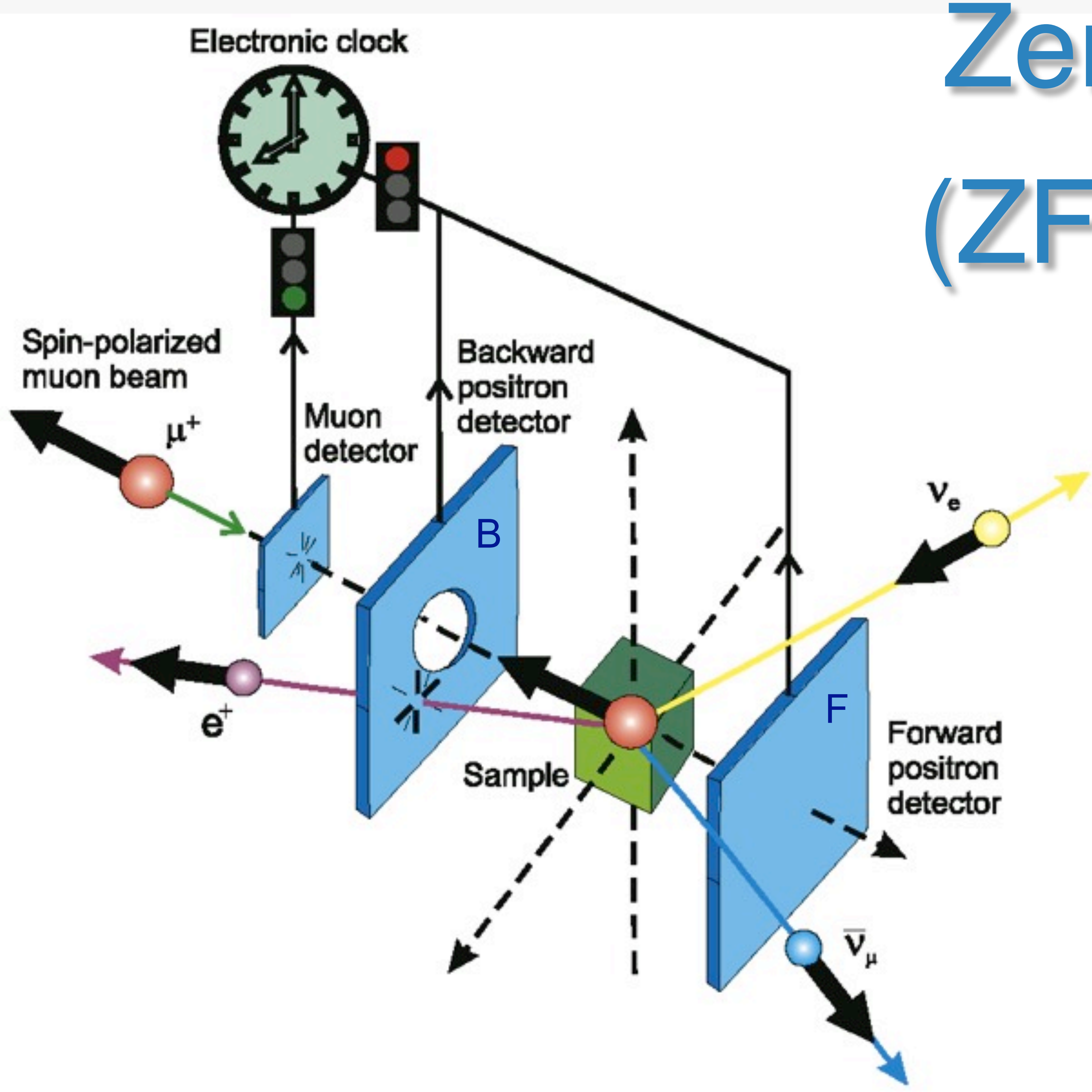
1/3 of $\mathbf{S}_\mu$ **stays constant**

*(c)* Local field $\mathbf{B}$ **random** in **both** magnitude **and** direction:

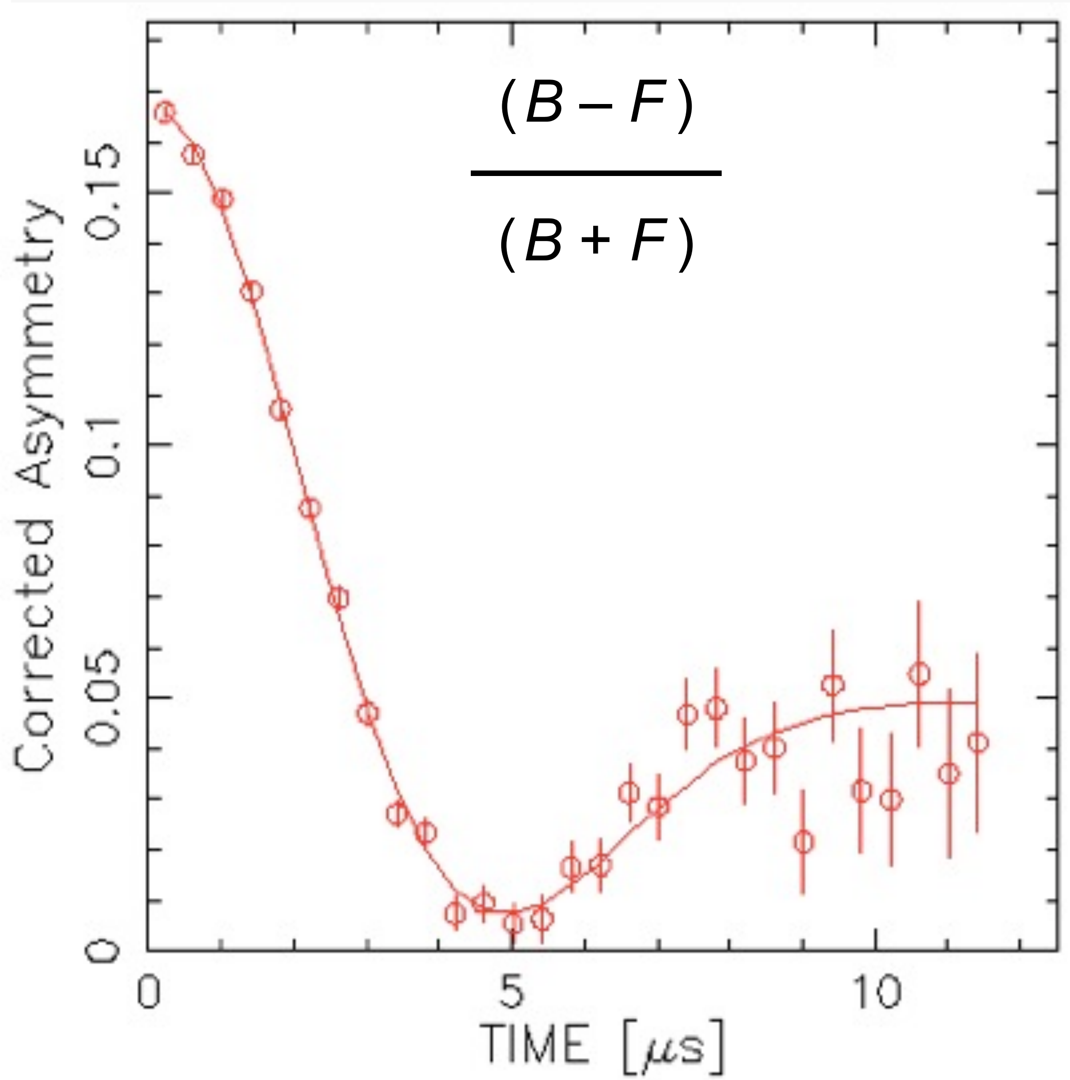
All ↗ do not return to the same orientation at the same time

(dephasing) $\Rightarrow$ $\mathbf{S}_\mu$ "**relaxes**" as $G_{zz}(t)$ [Kubo & Toyabe, 1960's]

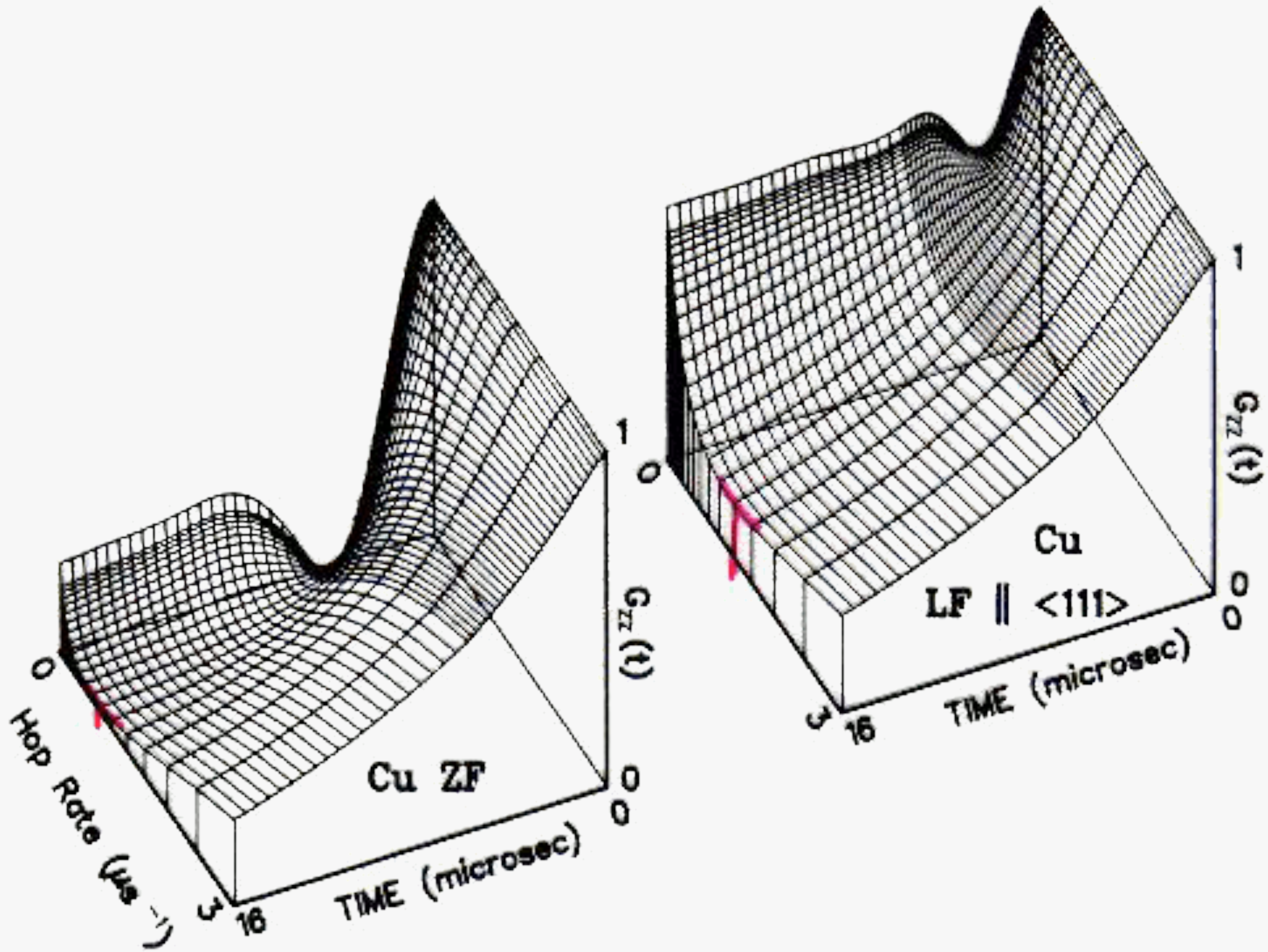
# Zero Field (ZF)-$\mu^+$SR




Typical asymmetry spectrum

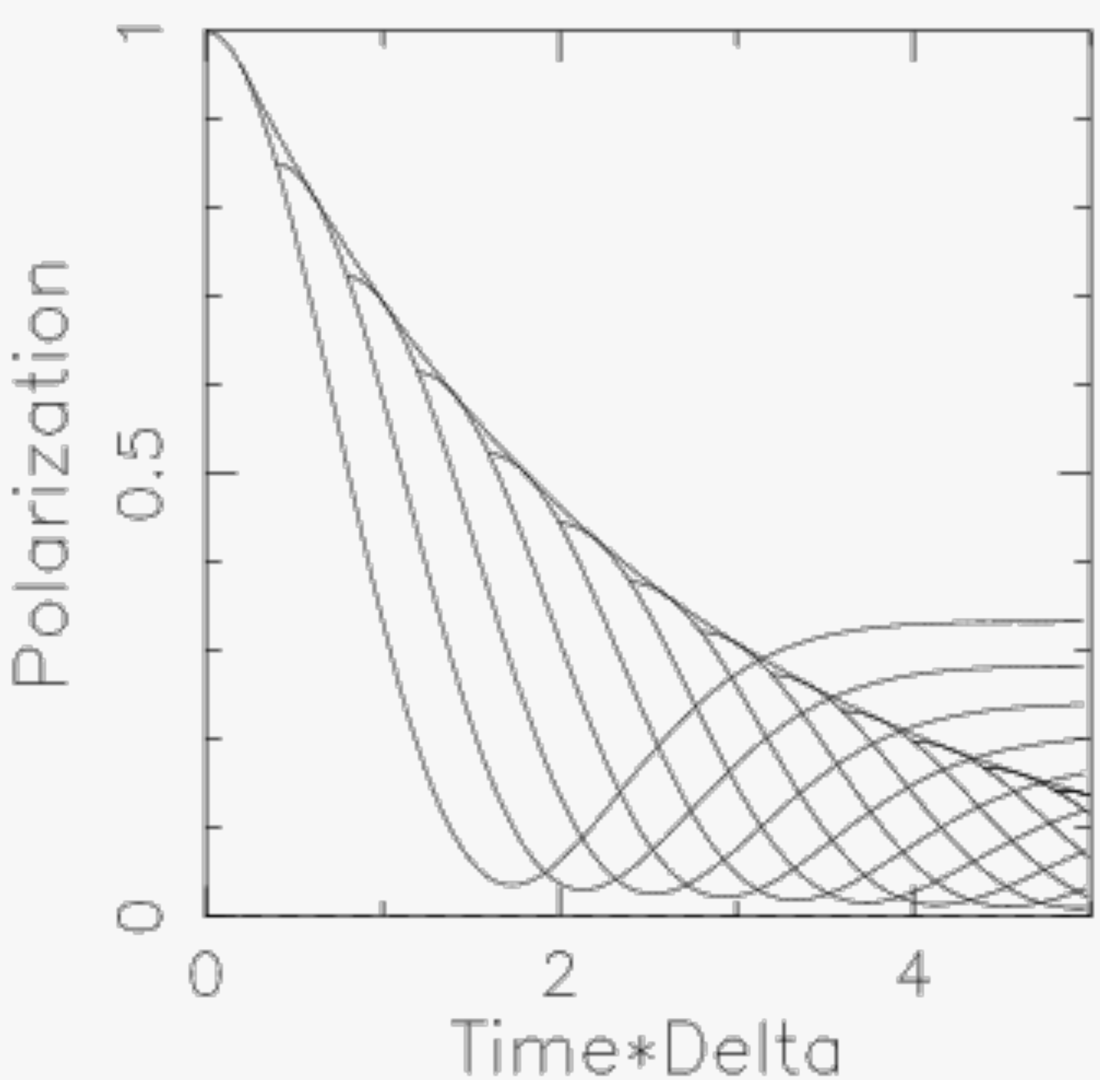


# Dynamic Gaussian Kubo-Toyabe $G_{zz}(t)$ in Cu: ZF *vs.* LF



# Motion of $\mu^+$ Spins in Fluctuating Local Fields

"Strong Collision" model: local field is reselected at random from the same distribution each time a fluctuation takes place, either from muon hopping (plausible) or from reorientation of nearby moments (unlikely to change so completely).




Kehr's recursion relation:

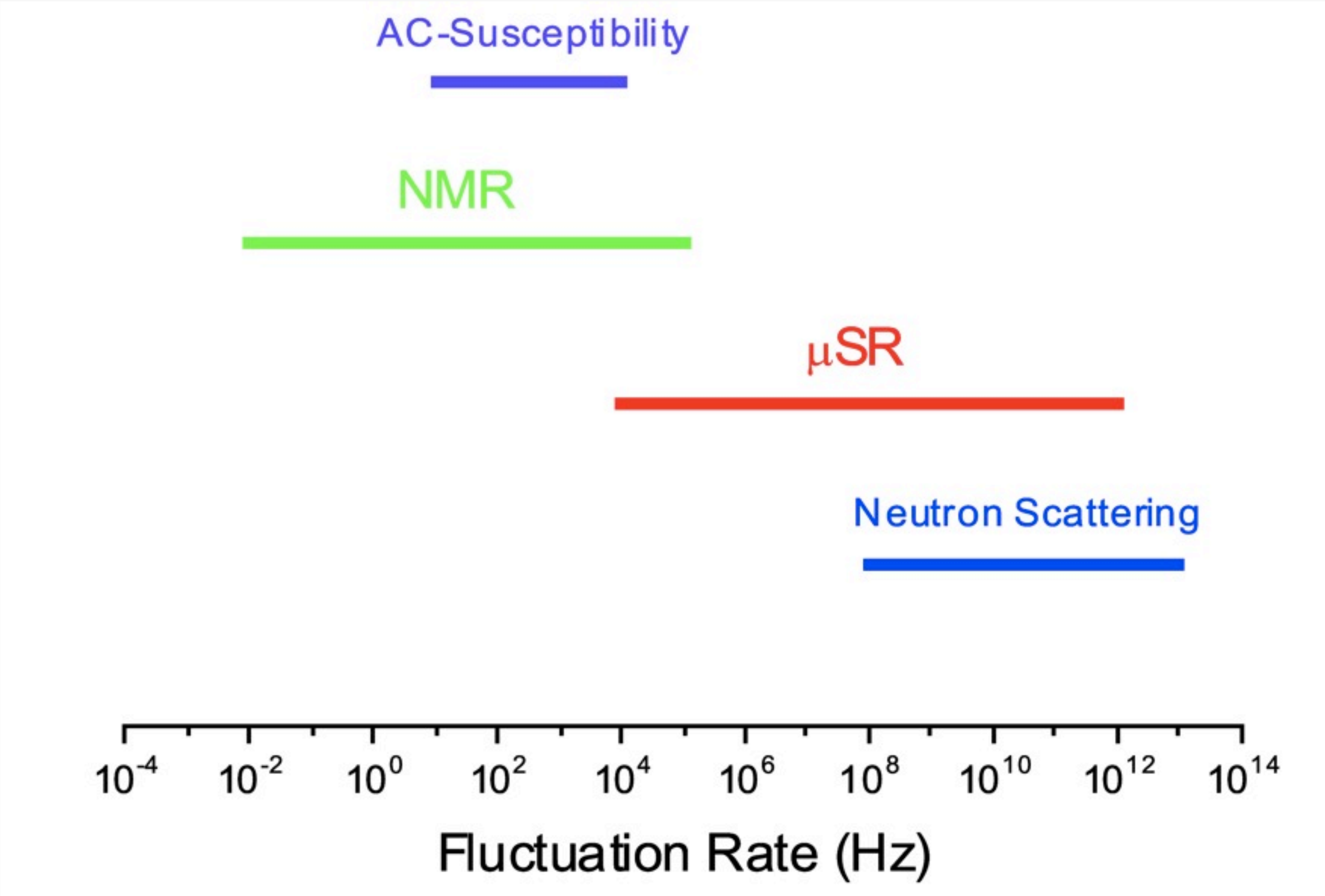
$$G(\Delta, t, \nu) = g(\Delta, t)e^{-\nu t} + \nu \int_0^t G(\Delta, t-\tau)g(\Delta, \tau)\, e^{-\nu\tau}\, d\tau$$

Sometimes solvable using Laplace transforms; numerical methods usually work too.

Used to extract "hop" or fluctuation rate $\nu$.

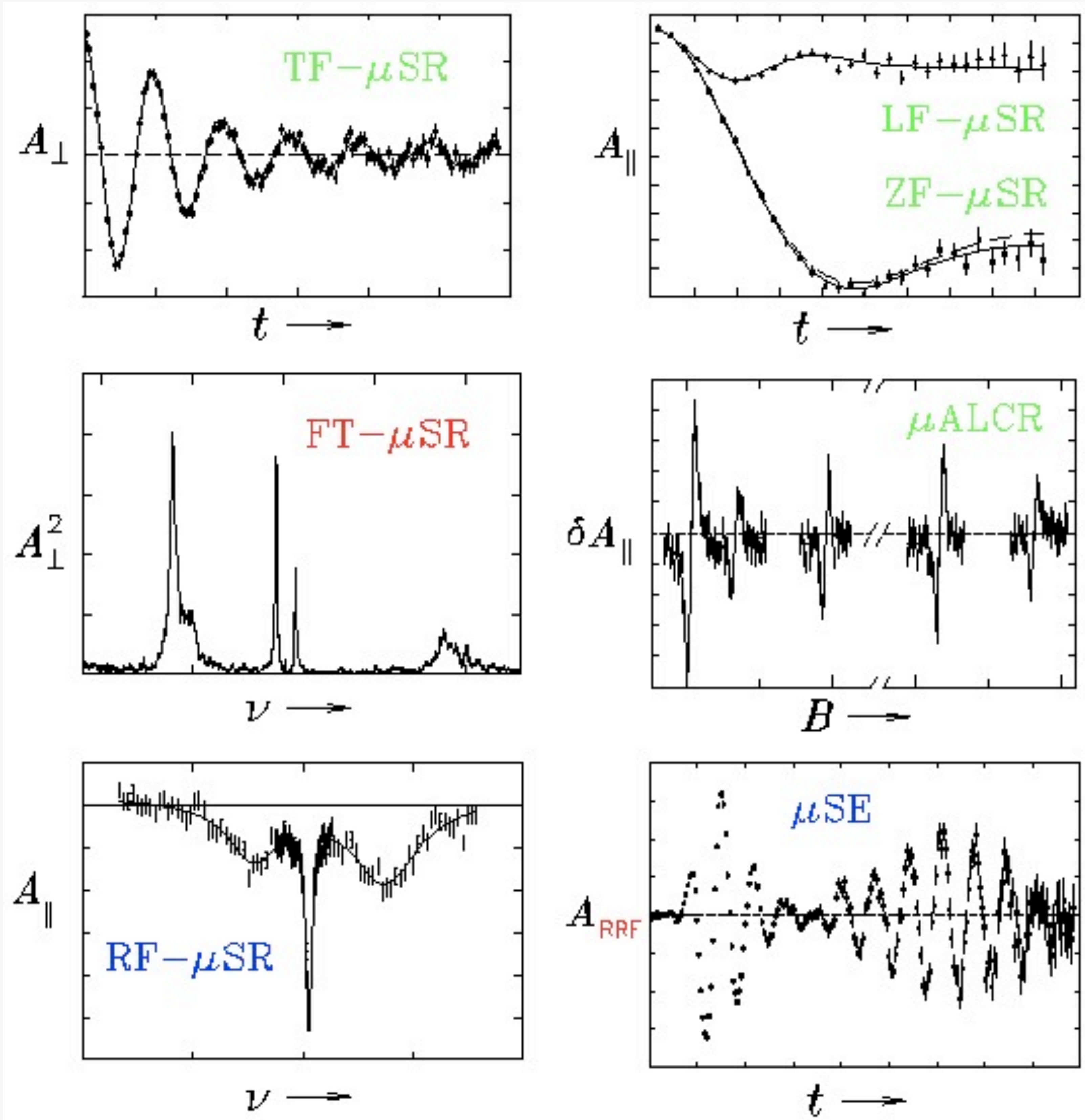
TRIUMF

# Time Scales



# Brewer's List of μSR Acronyms

Transverse Field




Longitudinal Field

Zero Field

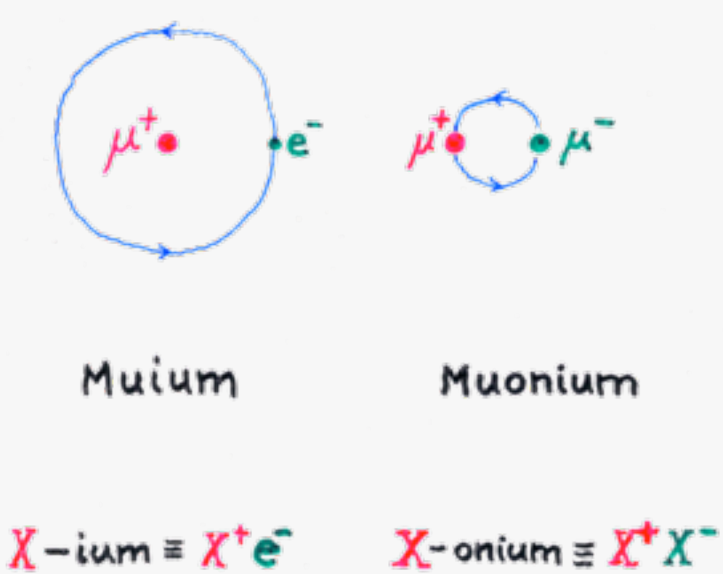
Fourier Transform μSR

Avoided Level Crossing Resonance

Muon Spin Resonance

Muon Spin Echo

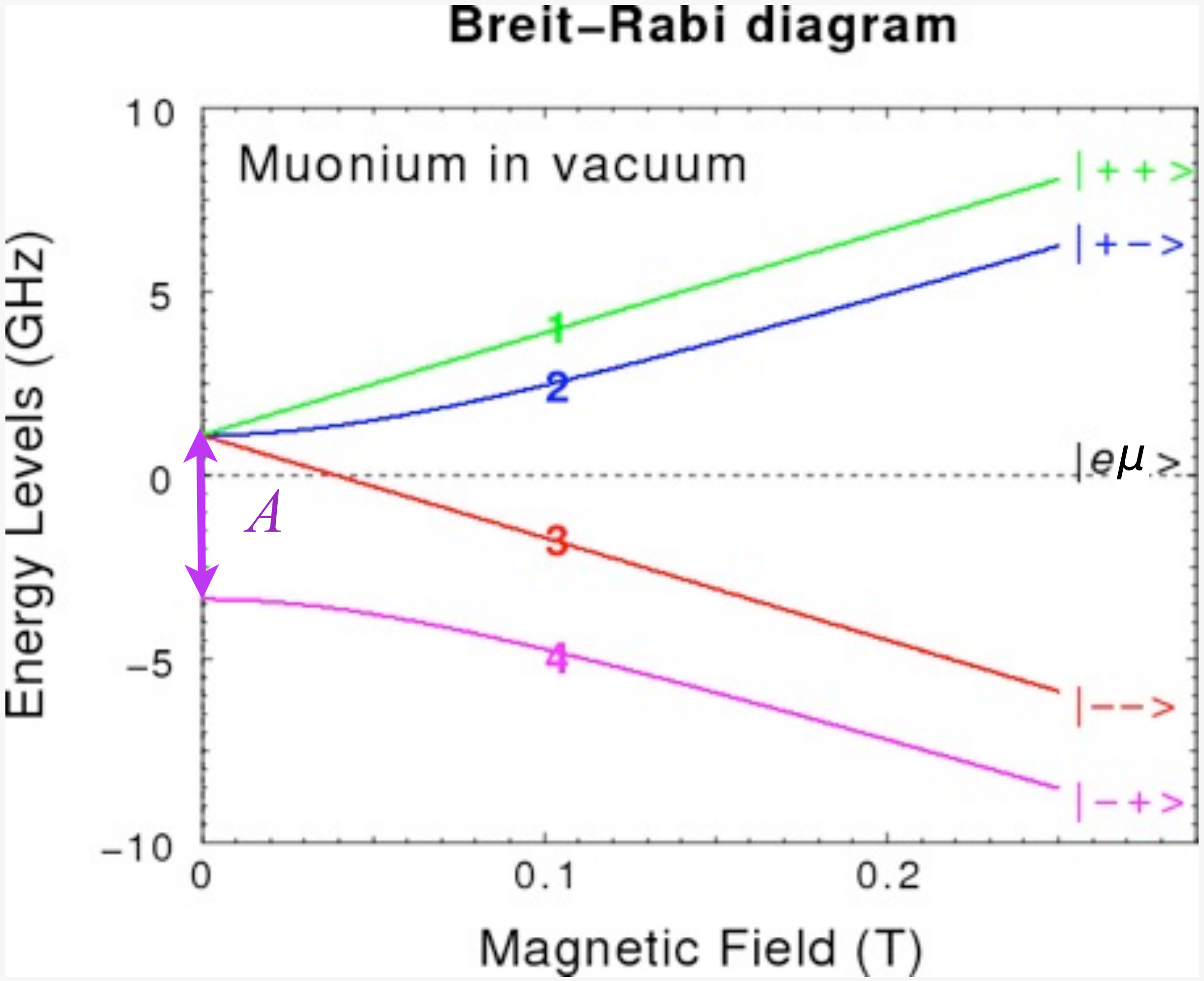
# Muonium States in Semiconductors

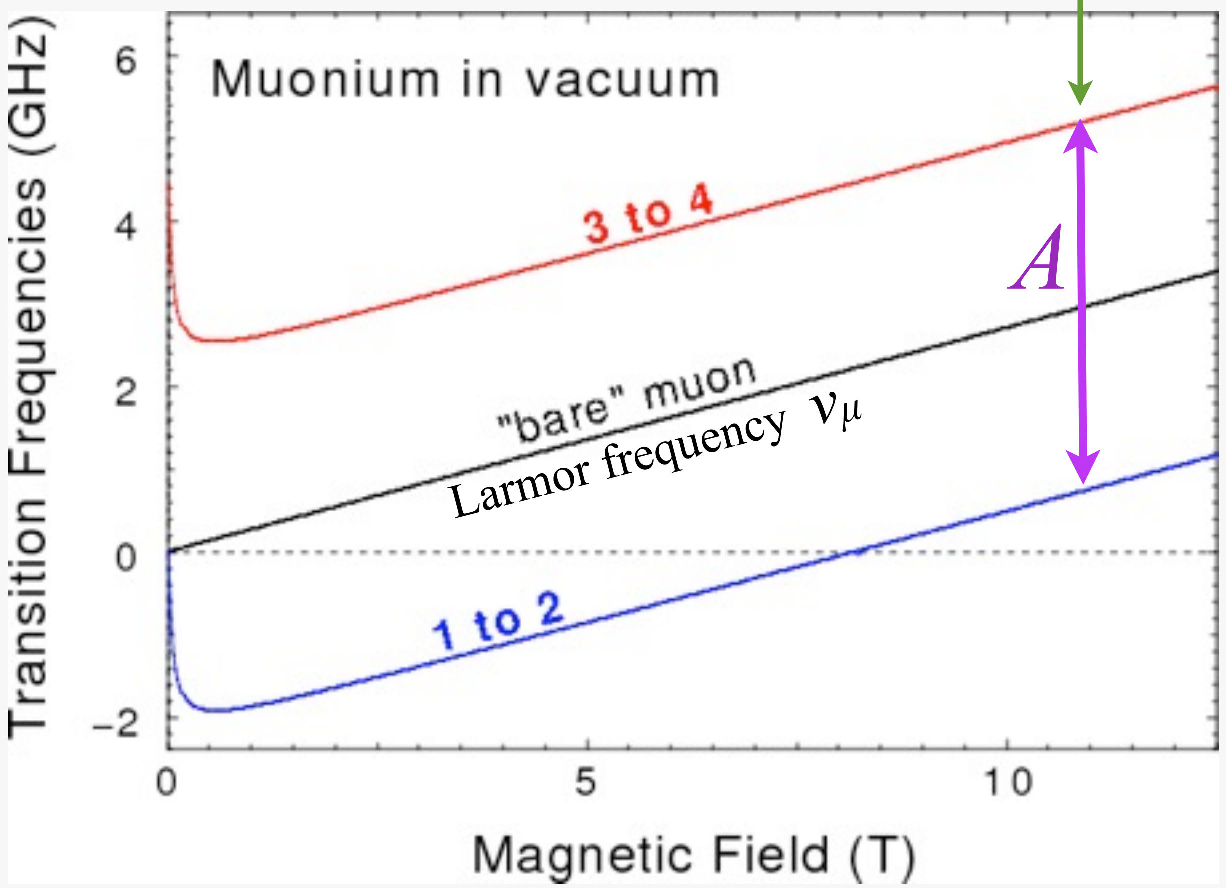




Two spins coupled by HF contact interaction evolve less simply with time.

# *Muonium* (Mu≡$\mu^+e^-$) *Spectroscopy*

In a *μSR* experiment one measures a time spectrum at a given field and extracts **all** frequencies *via* FFT.




"**Signature**" of **Mu** (or other hyperfine-coupled $\mu^+e^-$ spin states) in **high transverse field**: ***two frequencies*** *centred on* $\nu_\mu$ *and separated by the* ***hyperfine splitting A***$\propto r^{-3}$.



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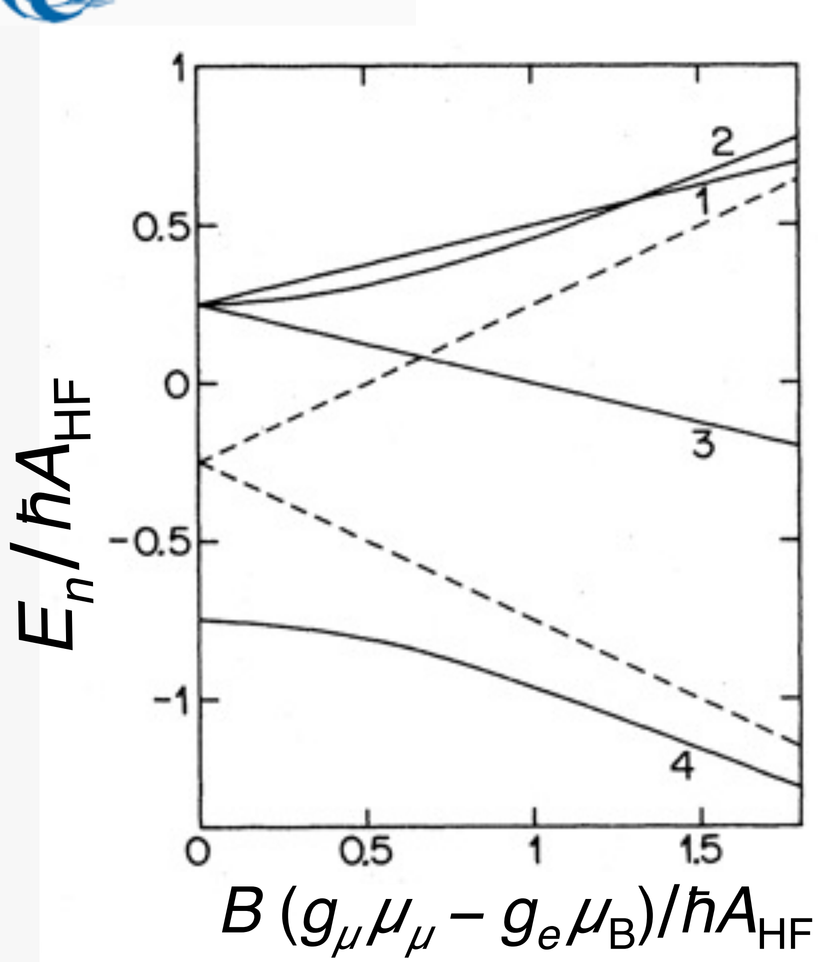
# Deep vs. "Shallow" Mu centers




← Breit-Rabi diagram

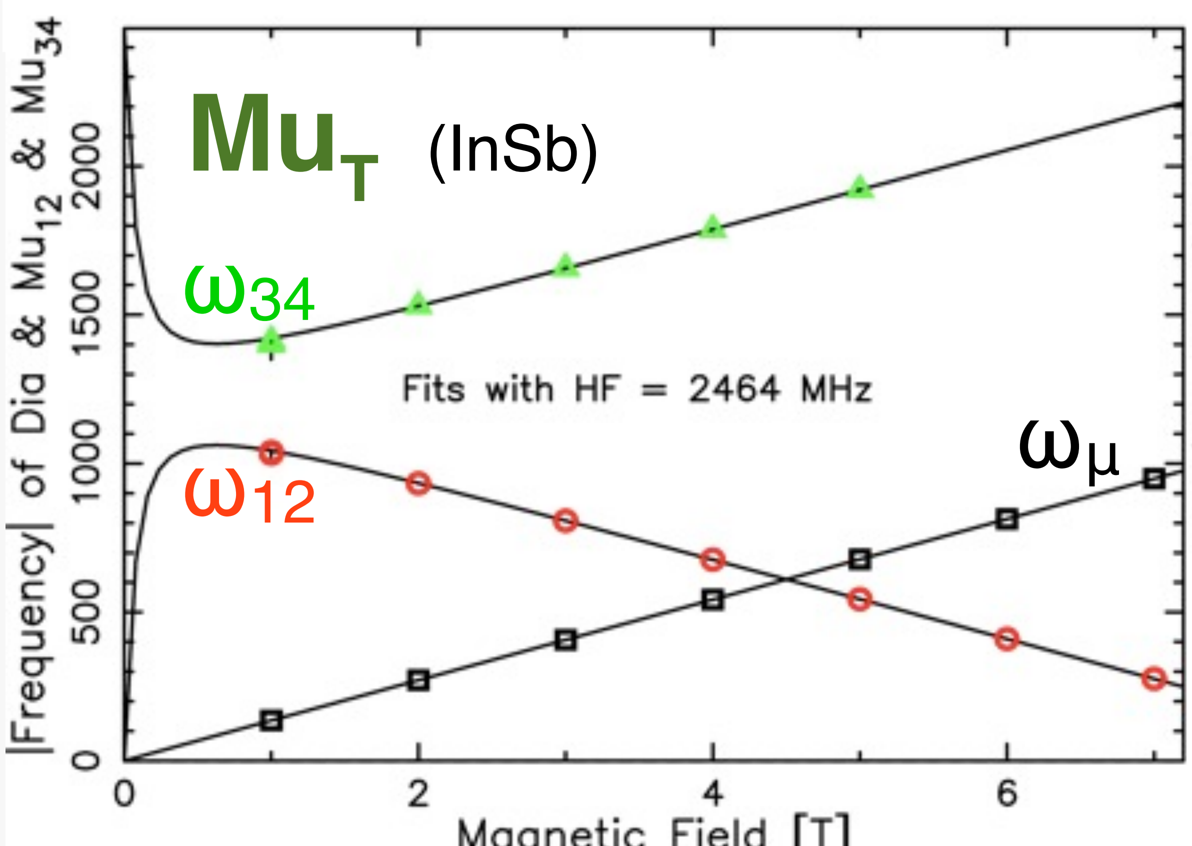
Mu atom in vacuum: $A_{HF}$ = 4463 MHz

Wide-gap insulators: ~ same $A_{HF}$ as in vacuum

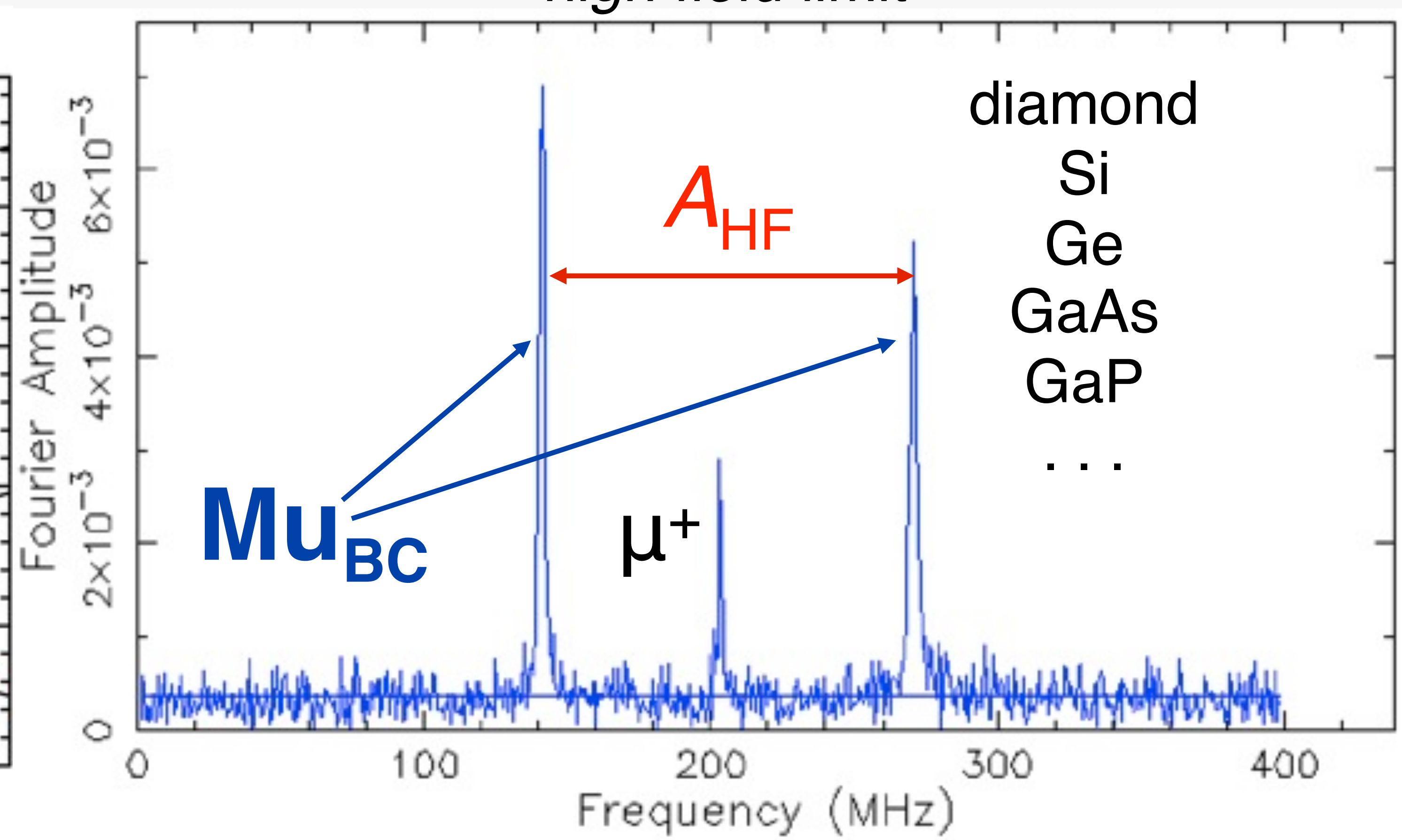
Semiconductors ($Mu_T$): $A_{HF}$ ~ 2000 MHz

Semiconductors ($Mu_{BC}$): $A_{HF}$ ~ 100 MHz

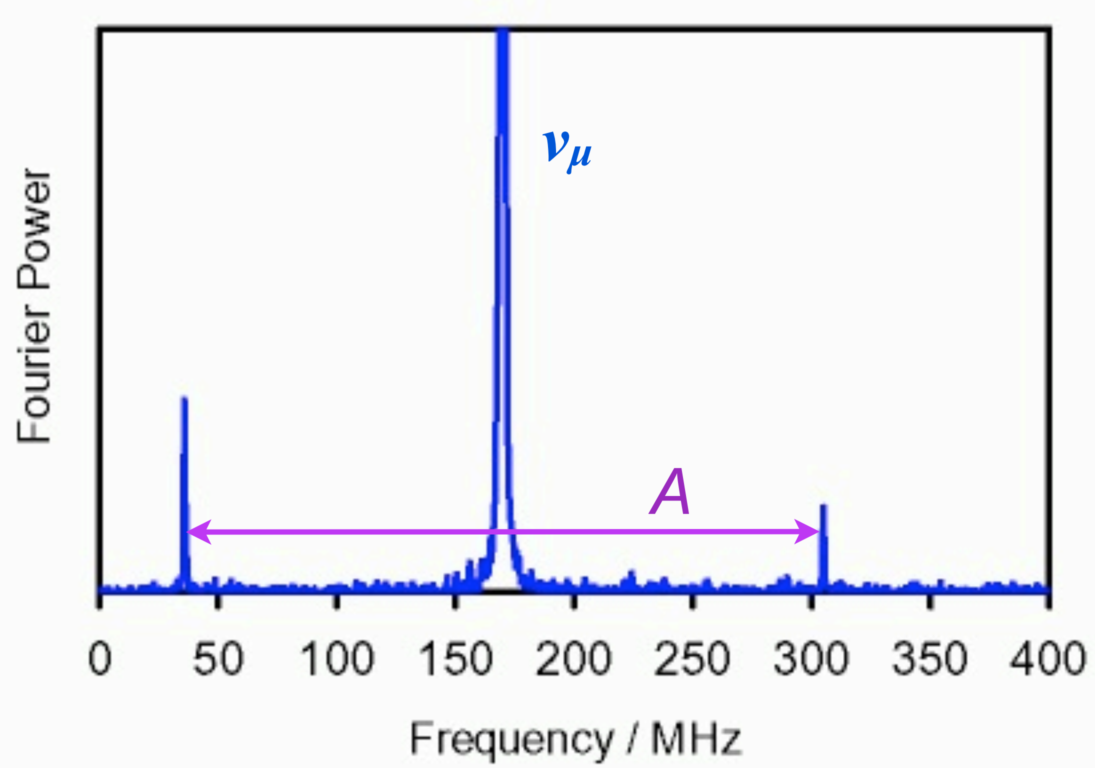
Semiconductors ($Mu_{WB}$): $A_{HF}$ ~ 0.2 MHz

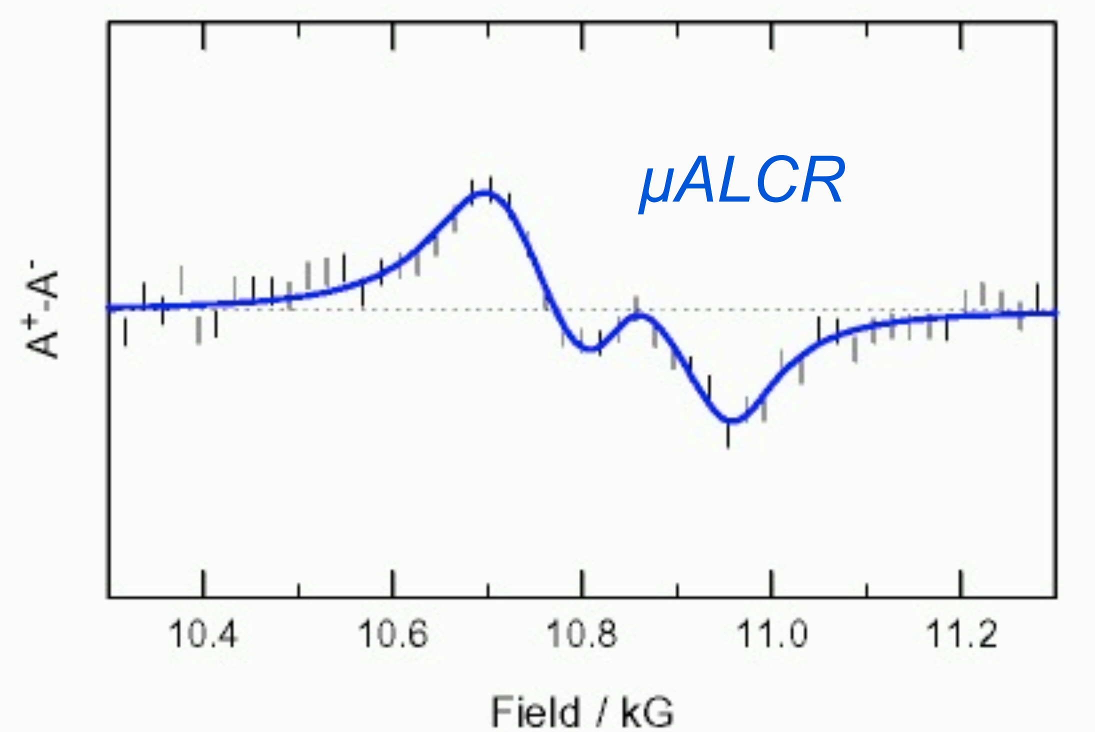



*high field limit*



# Muonated Radicals



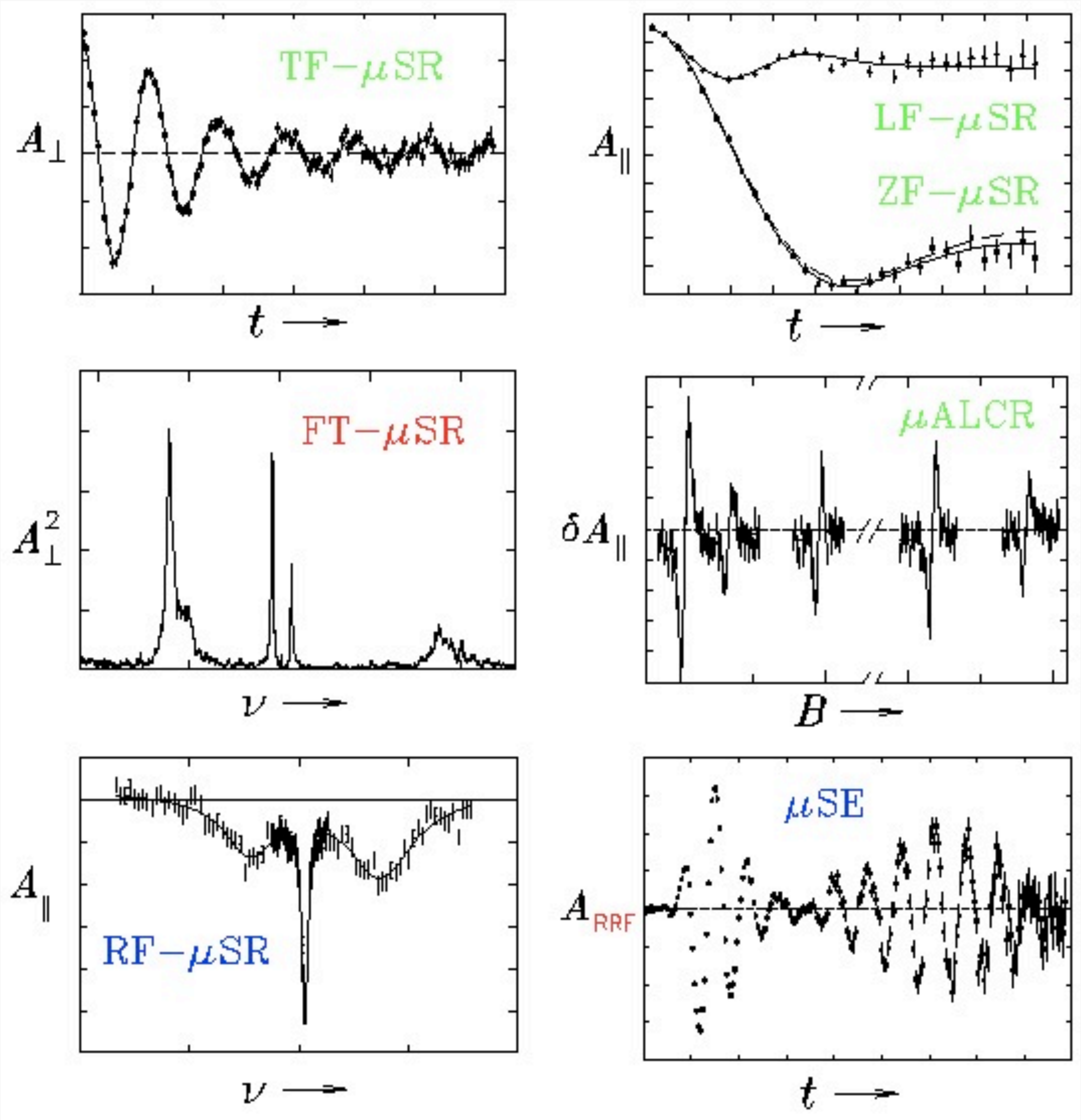




## Organic Free Radicals in Superheated Water

*Paul W. Percival, Jean-Claude Brodovitch, Khashayar Ghandi, Brett M. McCollum, and Iain McKenzie*

Apparatus has been developed to permit muon avoided level-crossing spectroscopy ($\mu$LCR) of organic free radicals in water at high temperatures and pressures. The combination of $\mu$LCR with transverse-field muon spin rotation (TF-$\mu$SR) provides the means to identify and characterize free radicals via their nuclear hyperfine constants. Muon spin spectroscopy is currently the only technique capable of studying transient free radicals under hydrothermal conditions in an unambiguous manner, free from interference from other reaction intermediates. We have utilized the technique to investigate hydrothermnal chemistry in two areas: dehydration of alcohols, and the enolization of acetone. Spectra have been recorded and hyperfine constants determined for the following free radicals in superheated water (typically 350°C at 250 bar): 2-propyl, 2-methyl-2-propyl (tert-butyl), and 2-hydroxy-2-propyl. The latter radical is the product of muonium addition to the enol form of acetone and is the subject of an earlier Research Highlight.   The figure shows spectra for the **2-propyl** radical detected in an aqueous solution of 2-propanol at 350°C and 250 bar.

# Brewer's List of μSR Acronyms




Transverse Field

Longitudinal Field

Zero Field

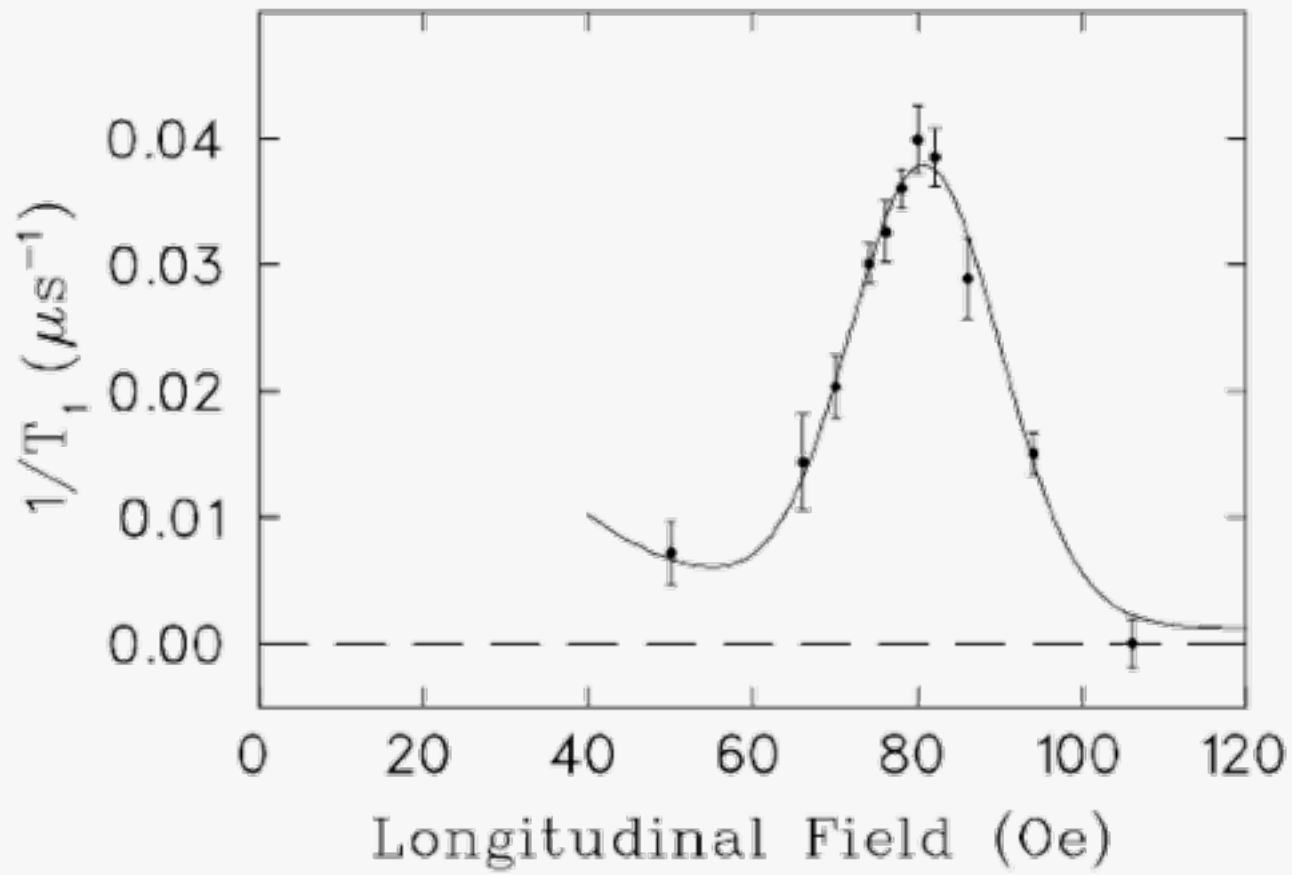
Fourier Transform μSR

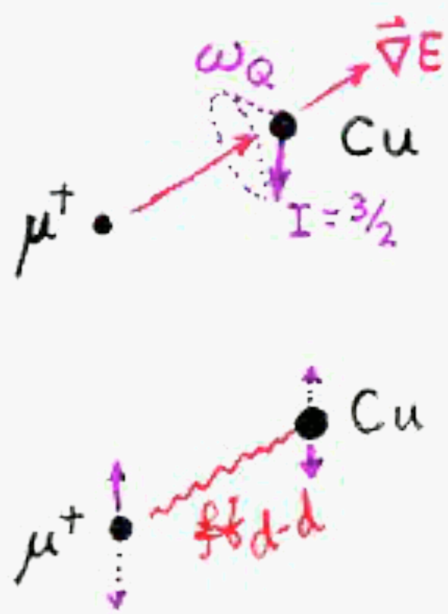
Avoided Level Crossing Resonance

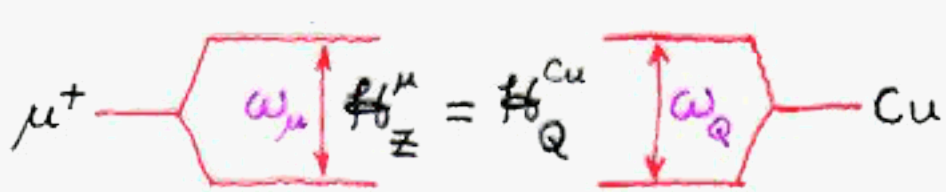
Muon Spin Resonance

Muon Spin Echo

# Quadrupolar μALCR




First observation of μALCR (1986): Matching muon Zeeman splitting with the electric quadrupole splitting of Cu nuclei due to the muon's electric field gradient.

Normally, longitudinal field (LF) *decouples* $\mu^+$ spin from Cu nuclear dipolar fields (~ 4 Oe) and so *quenches* $\mu^+$ spin relaxation.

But when $\omega_\mu = \gamma_\mu B$ matches $\omega_Q^{Cu}$, energy can be transferred between the $\mu^+$ and Cu (*via* the dipole-dipole interaction) with no net change in angular momentum ("Flip-Flop" transitions).

Speculated at the time: there should be many other types of μALCR . . .



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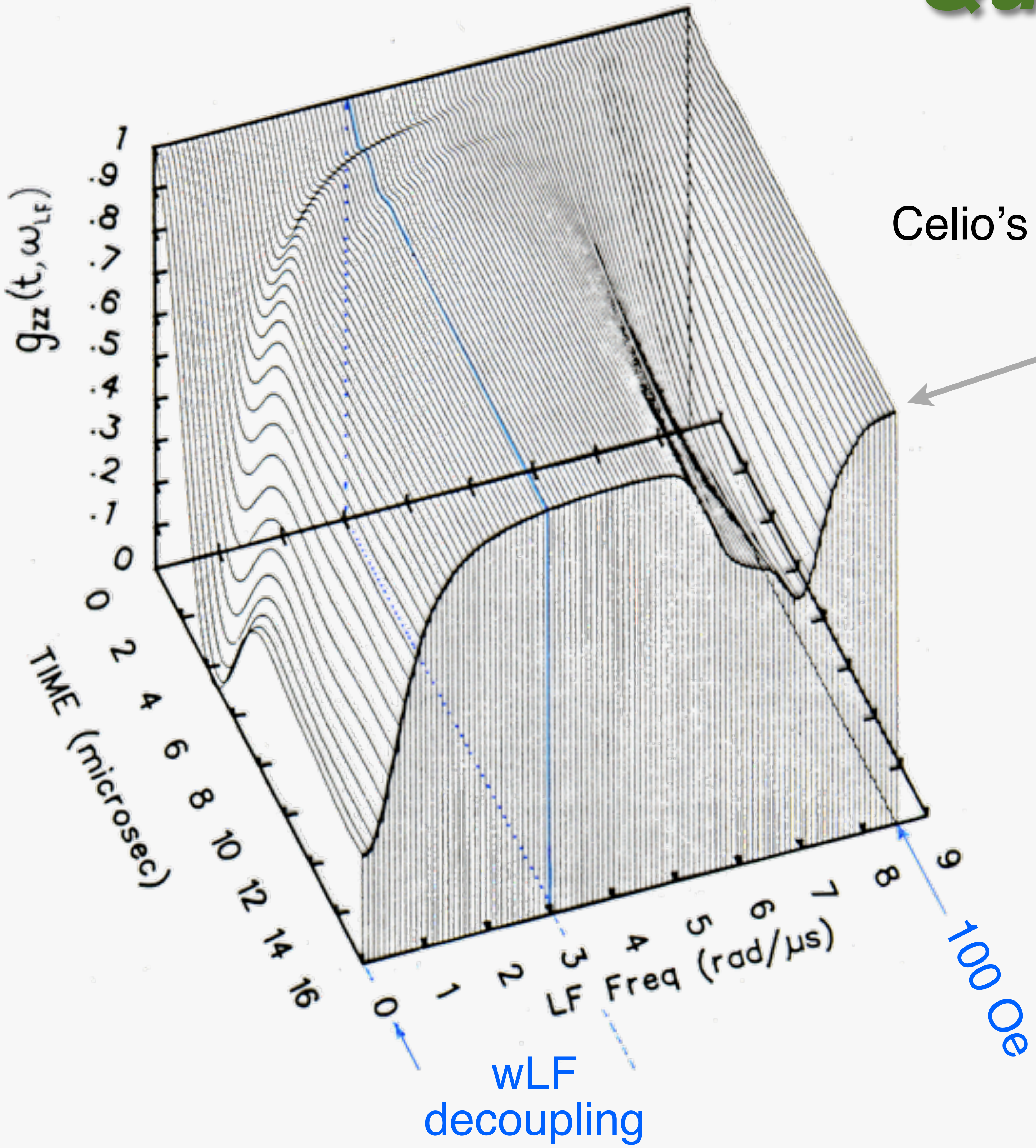
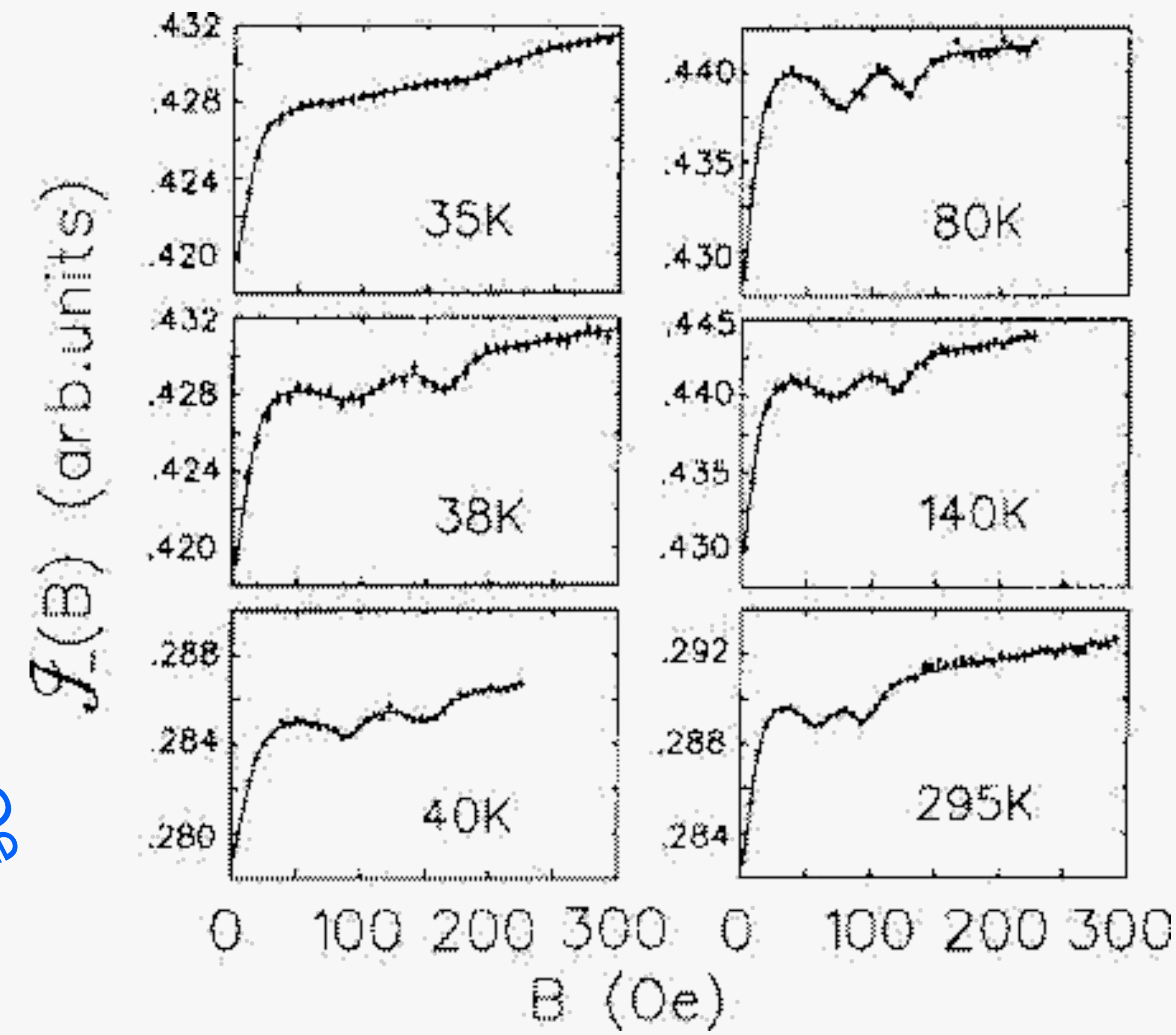
# Quadrupolar μALCR

## *in* Cu <100> || *B* :

Celio's calculation of static "relaxation" function




## . . . *and in* MnSi :



# Time-Integral $\mu^+$SR


Simply **SCALE** decay $e^+$ counts in "+" and "–"

$R$ = rate of arrival of muons

$\epsilon_\pm$ = efficiency of $e$ detector along(+) or opposite(−) $\mu$ polarization

$B_\pm$ = backgound rate in said $e$ detector

$A_\pm$ = intrinsic asymmetry of $e$ detector [Count rate $\sim (1 \pm A_\pm)$ for muons fully polarized along (opposite) detector axis of symmetry.]

$G_{zz}(t)$ = longitudinal relaxation function

The number of counts in time $T \gg \tau_\mu$ is

$$N_\pm = B_\pm T + RT\epsilon_\pm \pm RT\epsilon_\pm A_\pm \mathcal{L}(G_{zz}),$$

where $\mathcal{L}(G_{zz}) \equiv \int_0^\infty e^{(-t/\tau_\mu)} G_{zz}(t) \frac{dt}{\tau_\mu}$

is the *Laplace Transform* of $G_{zz}(t)$.

Experimental Asymmetry:

$$\mathcal{A} \equiv \frac{N_+ - N_-}{N_+ + N_-} \qquad \text{or}$$

$$\mathcal{A} = \frac{b_- + (1-\alpha) + (1+\alpha\beta)A_+\mathcal{L}(G_{zz})}{b_+ + (1+\alpha) + (1-\alpha\beta)A_+\mathcal{L}(G_{zz})}$$

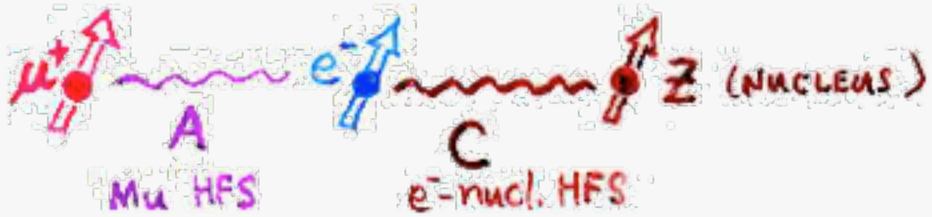
where $b_\pm \equiv \frac{B_+ \pm B_-}{R\epsilon_+}$, $\alpha \equiv \frac{\epsilon_-}{\epsilon_+}$, $\beta \equiv \frac{A_-}{A_+}$.

Approximations: $B_\pm \approx 0$, $A_\pm \approx A$ and $\epsilon_+ \approx \epsilon_-$,

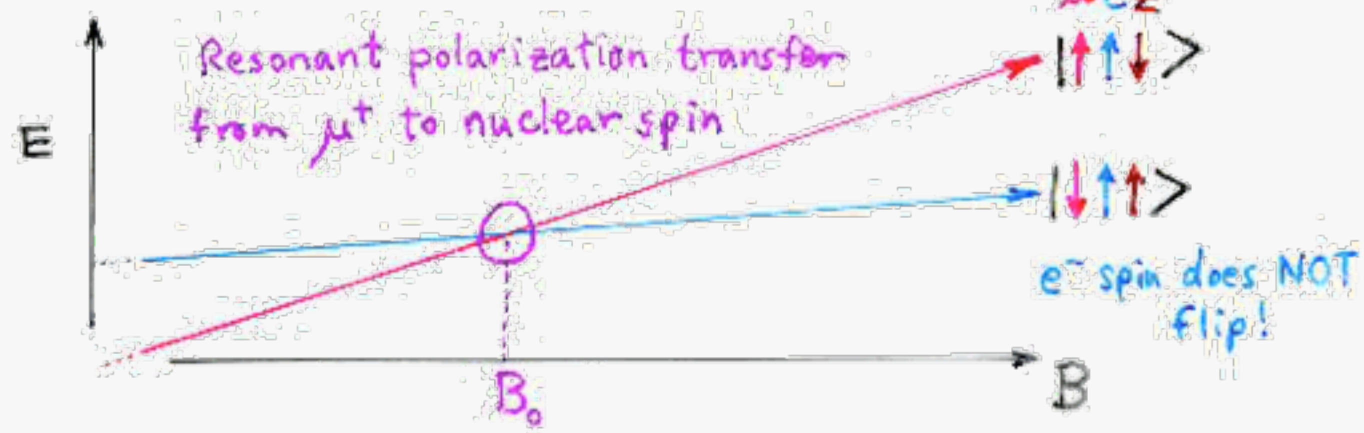
giving $\alpha \approx \beta \approx 1$, $b_\pm \approx 0$ and

$$\mathcal{A} \approx \frac{(1-\alpha)}{(1+\alpha)} + \frac{2}{(1+\alpha)} A_+ \mathcal{L}(G_{zz})$$

# Paramagnetic μALCR




HIGH LF: "ACCIDENTAL DEGENERACY" muon-nucleus FLIP-FLOP




SCANNING for RESONANCES: For SPEED, use "Time Integral μSR"

$$a \equiv \frac{B-F}{B+F}$$ where B & F = TOTAL COUNT RATES in Bwd & Fwd e⁺ detectors.

To beat systematic fluctuations, use "Field-Differential" Time-Integral μSR:

At each $B_0$, measure

$a_\pm \equiv a(B_0 \pm B_1)$ then look at $\Delta a \equiv a_- - a_+$ vs $B_0$

↳ "TOGGLE FIELD" (and hope $B_1 \gtrsim$ line width)

"Muonated" FREE RADICALS:

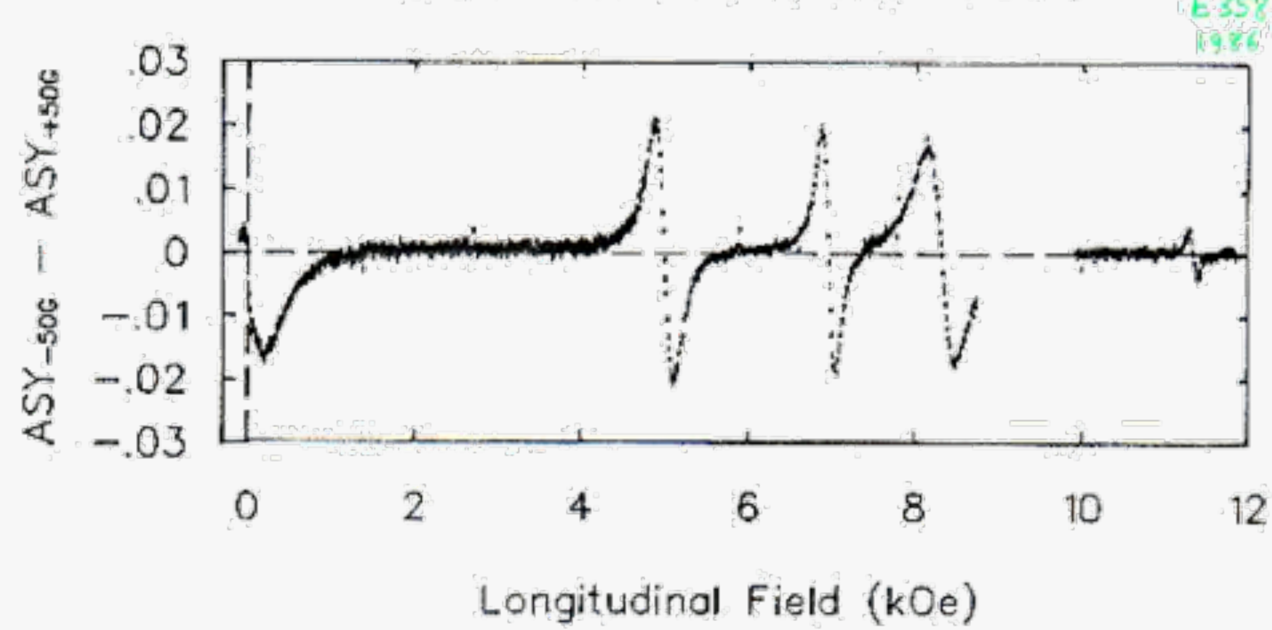

ALMOST IDENTICAL to "Hydrogenated" version!

• Unpaired electron has HYPERFINE (SPIN-SPIN) INTERACTIONS with $\mu^+$ spin and with $^{19}$F spins.

At "LEVEL-CROSSING RESONANCE" values of applied magnetic field, ⇐ ENERGY LEVELS of spin states (↑↑↓) and (↓↑↑) are EQUAL (μ e F)

⇒ Transitions take place freely and MUON GETS DEPOLARIZED!

$C_6F_6$ Muonic Radical LCR @ 50°C




⇒ MEASUREMENT of (e−F) INTERACTIONS -- nearly identical to those of "Hydrogenated" version.

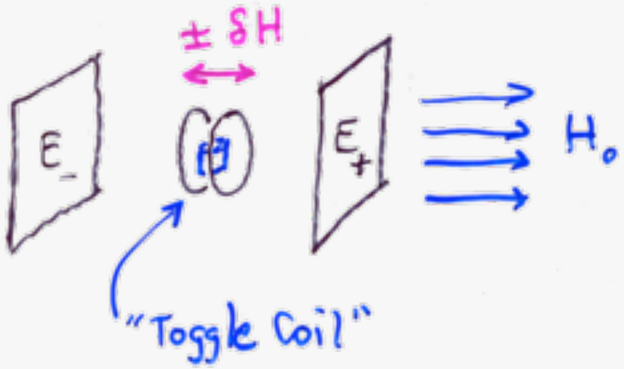
→ Learn REACTION RATES of TRANSIENT RADICALS (important in biochemistry, polymer synthesis, ...)

→ From TEMP.-DEPENDENCE, learn DYNAMICS of MOLEC. STRUCT.

# Paramagnetic μALCR

## Field-Differential I-μSR:

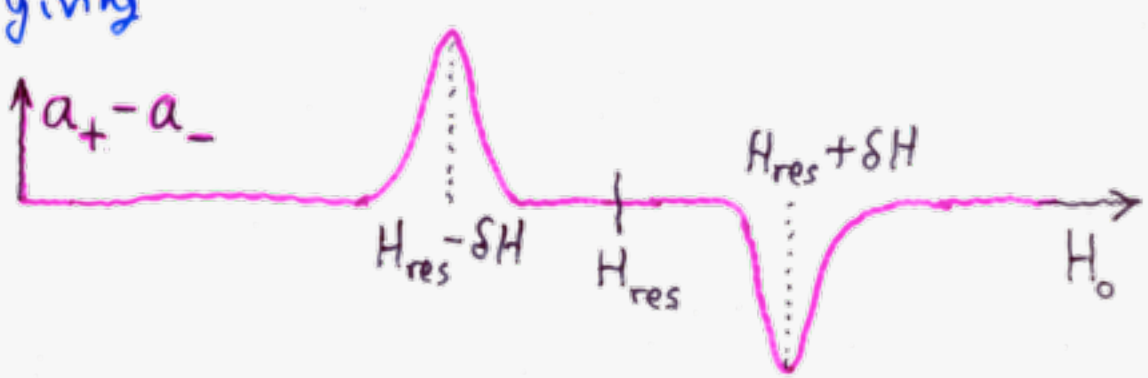
If "SYTEMATICS" cause $a \equiv \frac{N_+ - N_-}{N_+ + N_-}$ to FLUCTUATE while all indep. var. are held constant, try this:



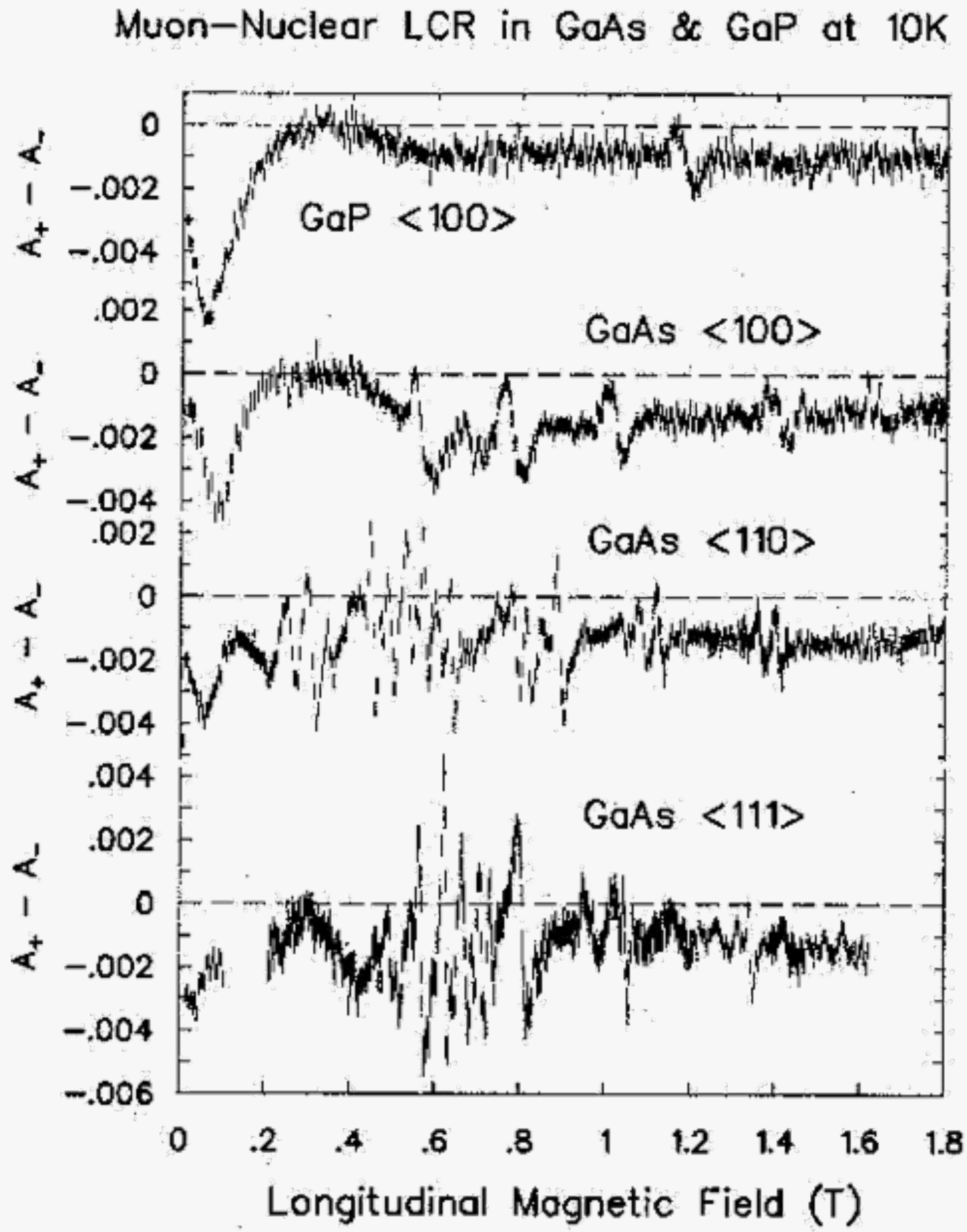

$a_\pm \equiv a$ with $H = H_o \pm \delta H$

(alternate ± rapidly wrt. systematic fluct.)

giving

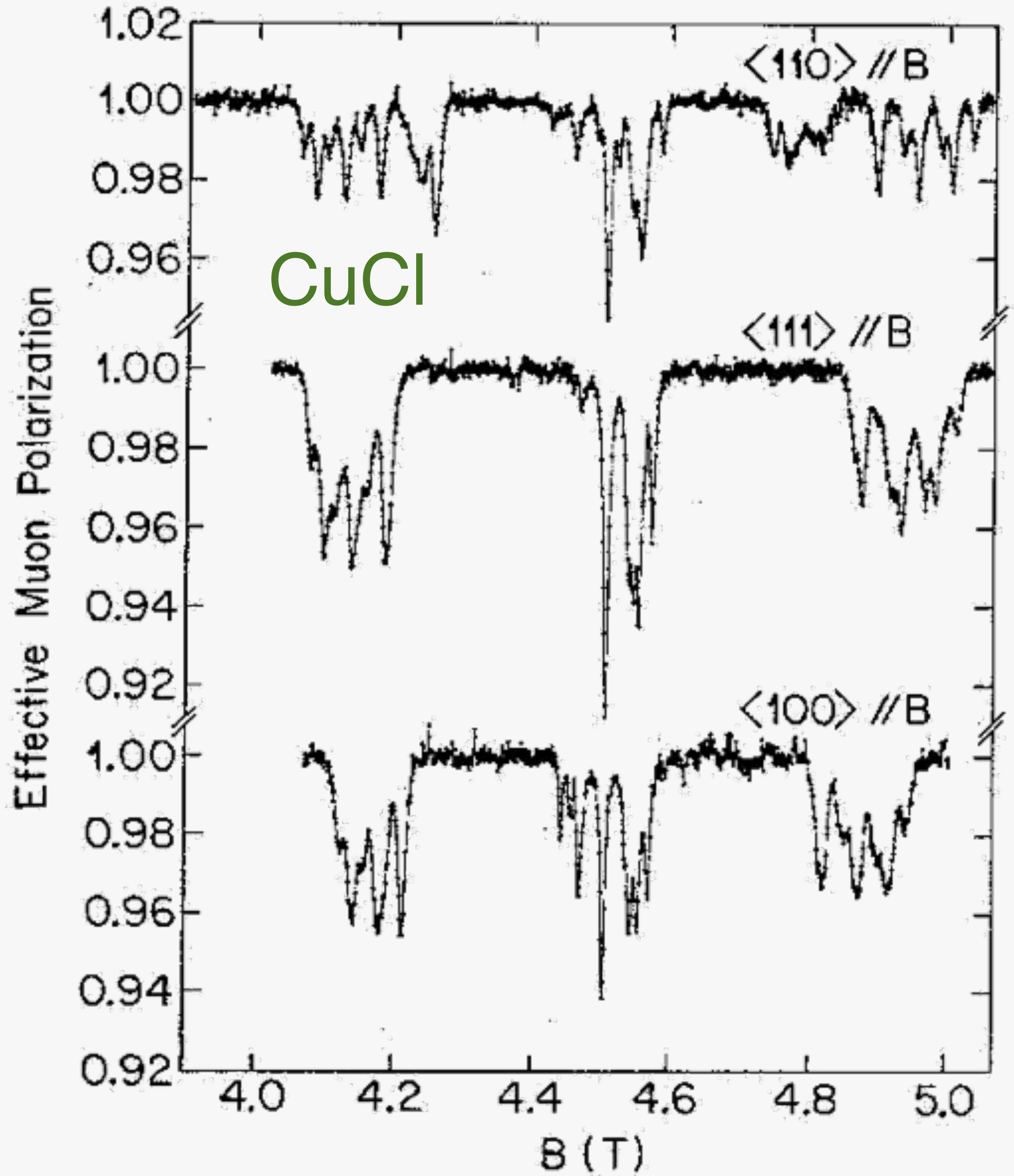



NOTE: NOT a true DERIVATIVE $\frac{da}{dH}$ !



# Paramagnetic μALCR

If the beam is very stable and there are no “gremlins” in the counters or fast electronics, it is possible to skip the “field-differential” method and look at the resonances directly.

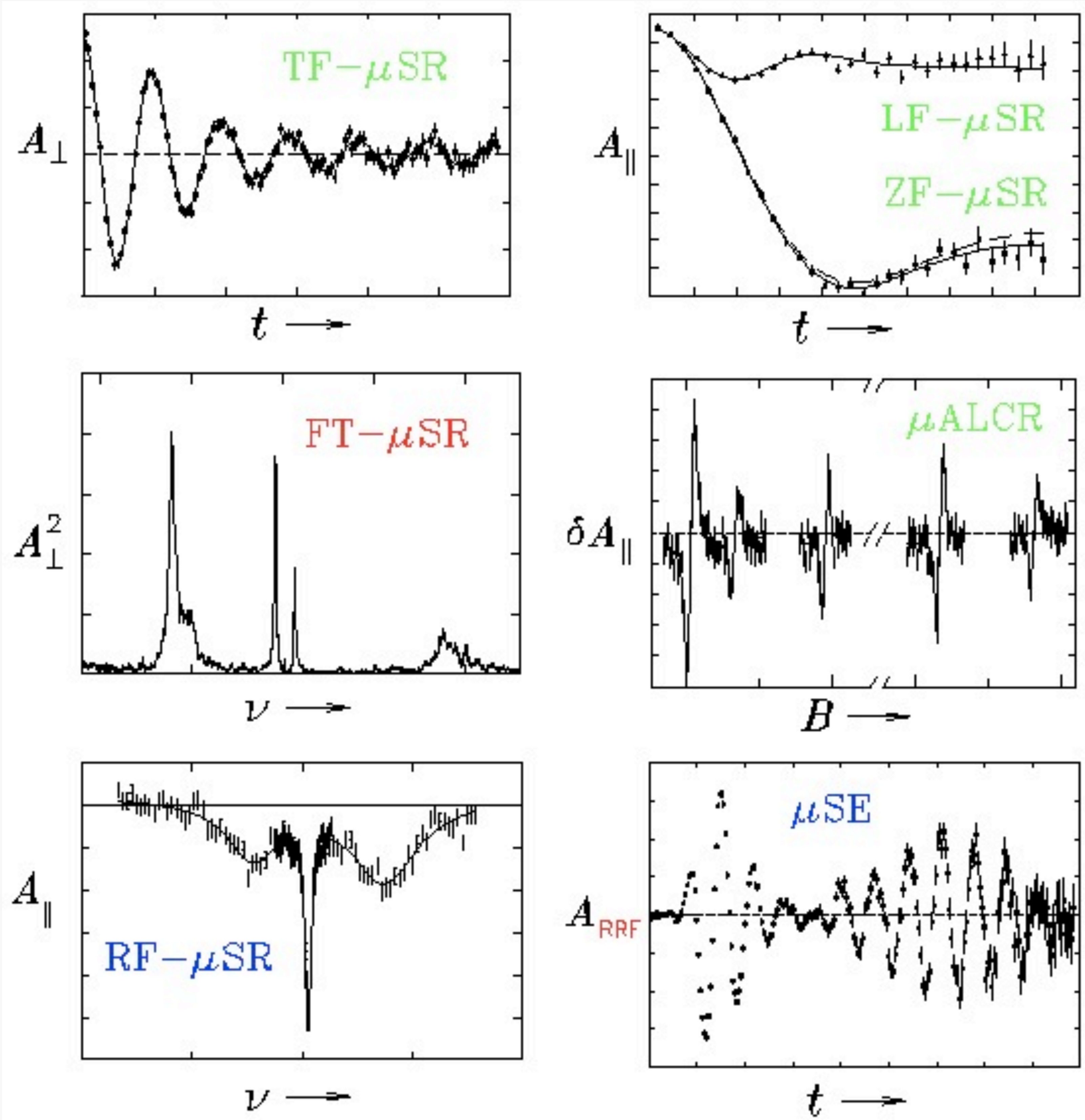


# Brewer's List of μSR Acronyms

Transverse Field

Fourier Transform μSR

Muon Spin Resonance




Longitudinal Field

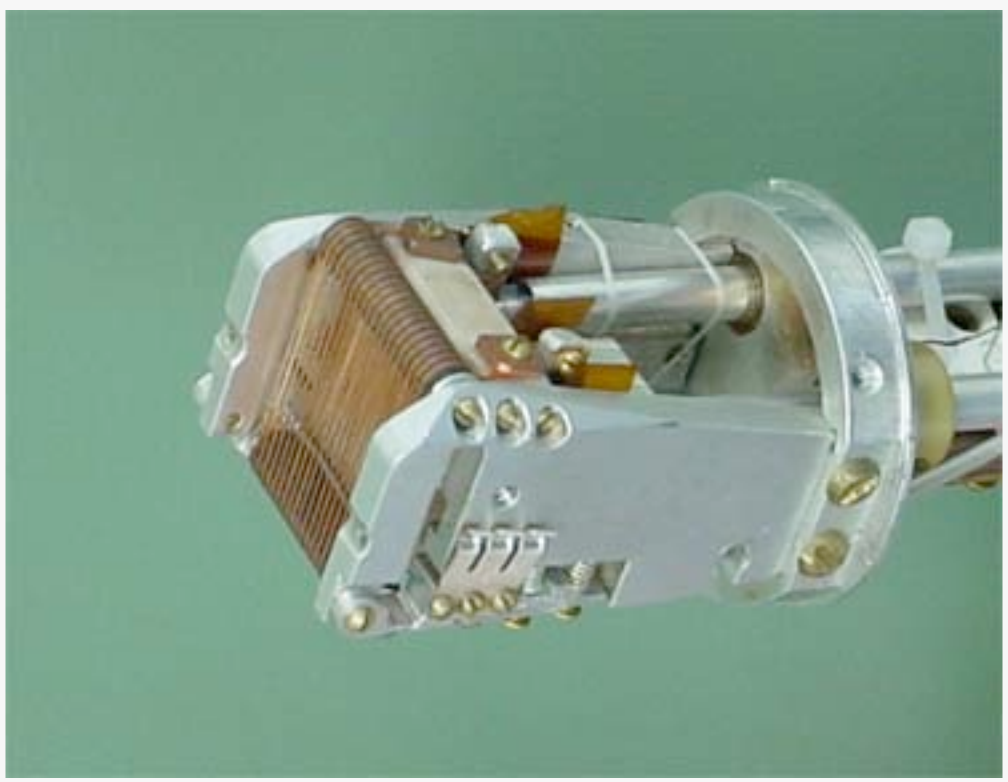
Zero Field

Avoided Level Crossing Resonance

Muon Spin Echo

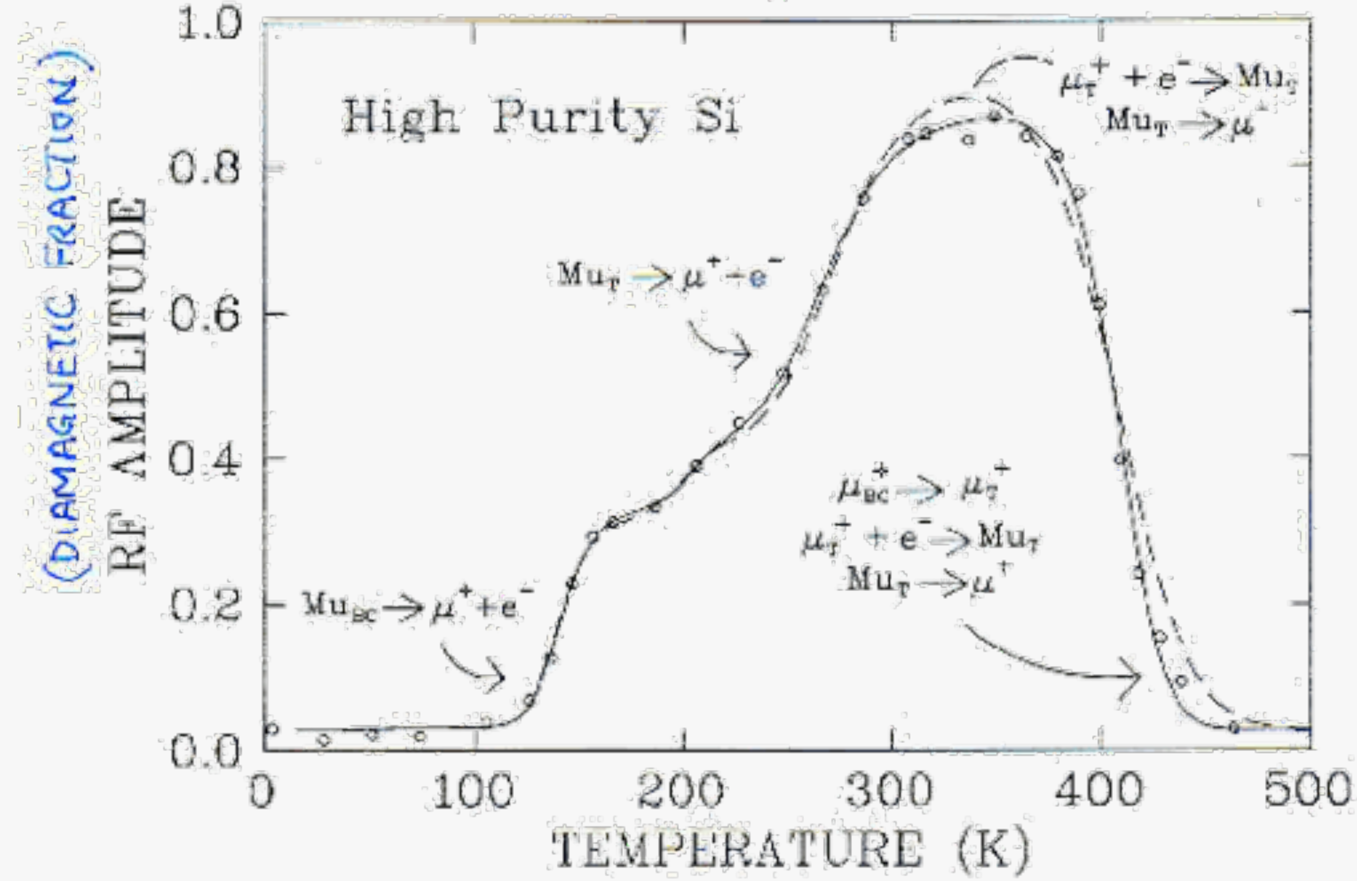
TRIUMF

# RF Resonance



## RF RESONANCE of $\mu^+$ in SILICON:

METASTABILITY



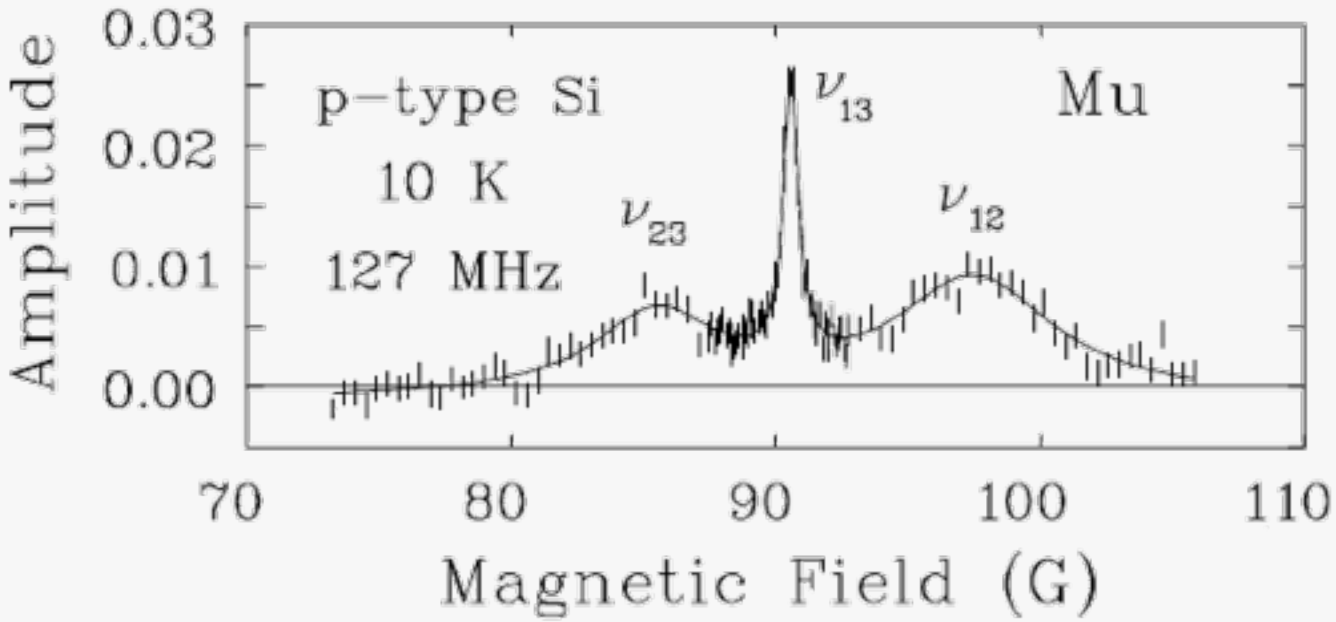

$Mu_T$ = neutral muonium atom @ tetrahedral interstitial site: vacuum-like state, rapidly diffusing (delocalized). METASTABLE.

$Mu_{BC}$ = Mu atom @ Si—•—Si bond centre interstitial site: axisymm. state, localized.

$\mu^+$ = generic non-paramagnetic state

Note: H PASSIVATES MANY IMPORTANT DEFECTS & IMPURITIES!

# *RF Resonance* on *Muonium*

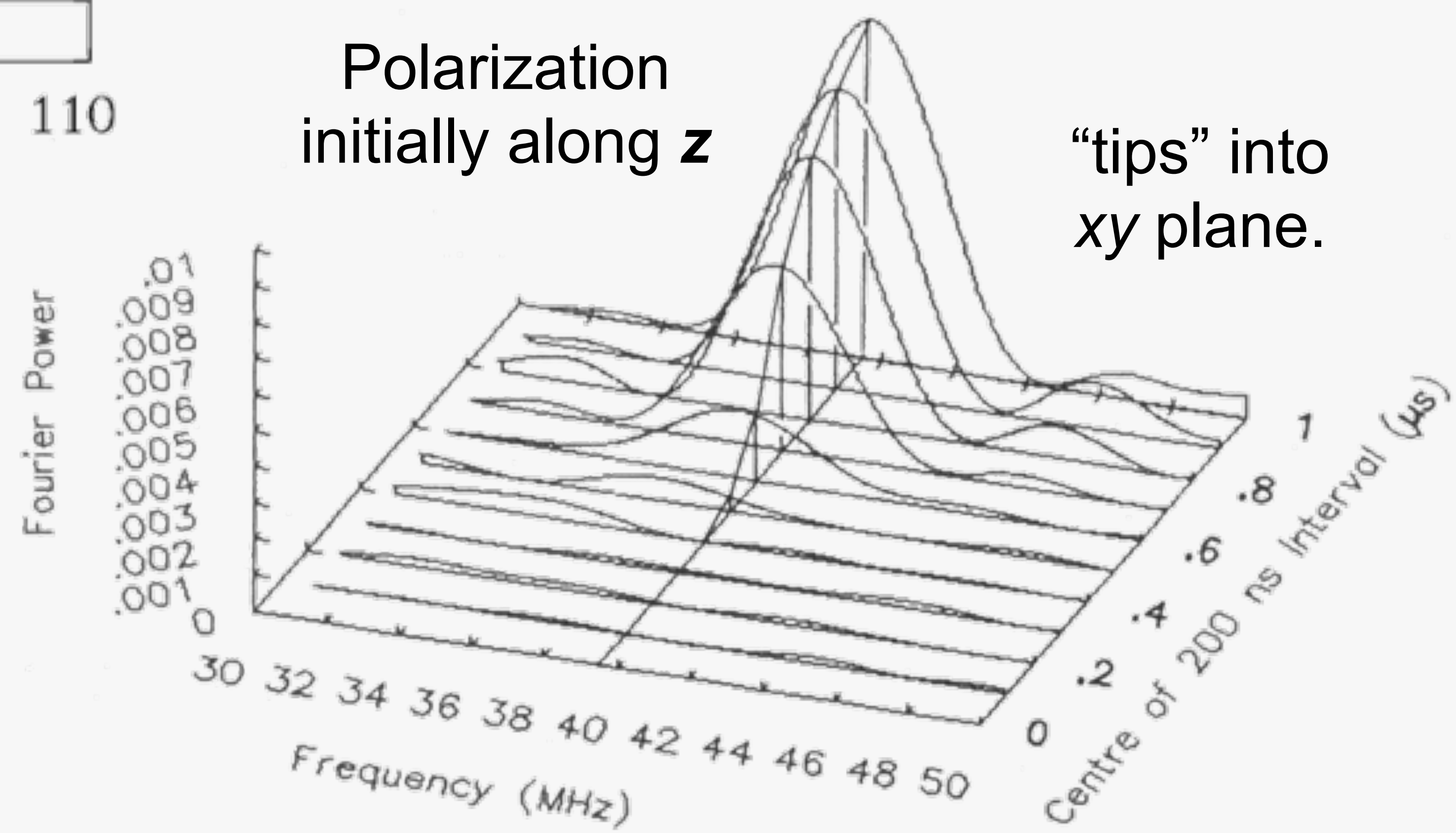



Done at TRIUMF,
*one muon at a time*
(inefficient!)

# "$\pi/2$" *RF pulse* in *amorphous MnSi*

Polarization initially along ***z***

"tips" into *xy* plane.




Amorphous MnSi 300K RF 90° pulse on LF = 2.92 kOe

# "Themes" in μSR

## Muonium as light Hydrogen

(Mu = $\mu^+e^-$) (H = $p^+e^-$)

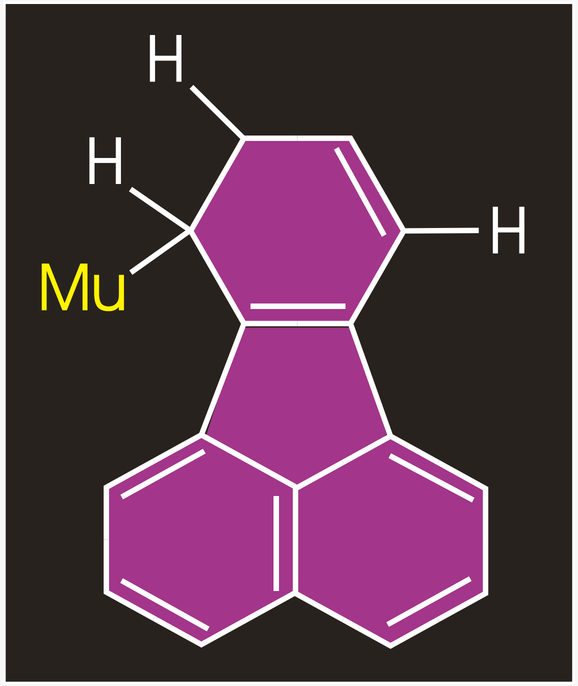
- **Mu vs. H atom Chemistry:**
  - gases, liquids & solids
  - Best test of reaction rate theories.
  - Study "unobservable" H atom rxns.
  - Discover new radical species.
- **Mu vs. H in Semiconductors:**
  - Until recently, $\mu^+$SR → **only** data on metastable H states in semiconductors!

## The Muon as a Probe

- **Probing Magnetism:** unequalled sensitivity
  - Local fields: electronic structure; ordering
  - Dynamics: electronic, nuclear spins
- **Probing Superconductivity:** (esp. $HT_cSC$)
  - Coexistence of SC & Magnetism
  - Magnetic Penetration Depth $\lambda$
  - Coherence Length $\xi$

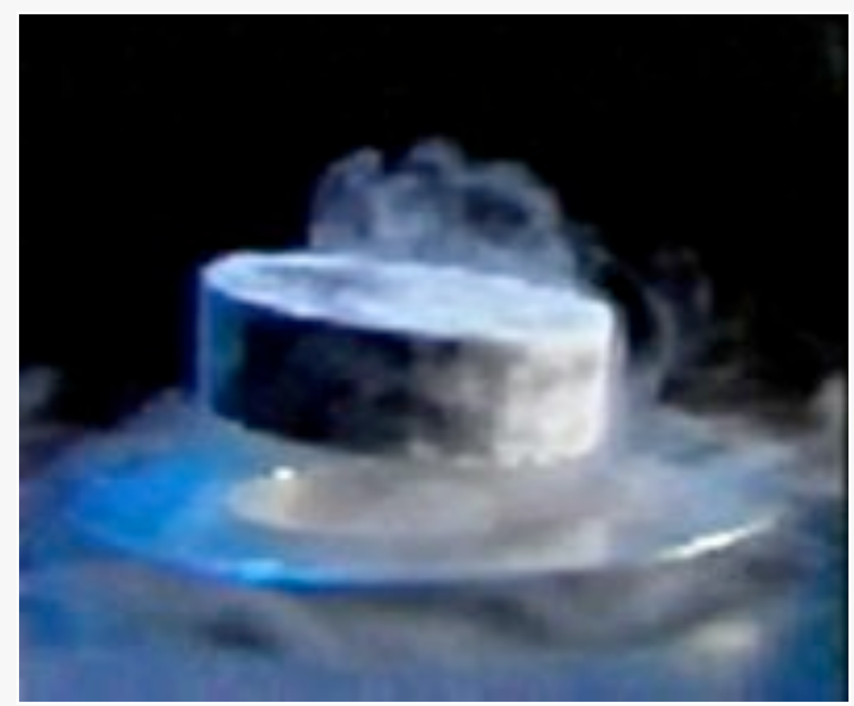
- **Quantum Diffusion:** $\mu^+$ in metals (compare $H^+$); Mu in nonmetals (compare H).

# Recent Applications of μSR




- > Molecular Structure & Conformational Motion of Organic Free Radicals
- > Hydrogen Atom Kinetics
- > "Green Chemistry" in Supercritical $CO_2$
- > Catalysis
- > Mass Effects in Chemical Processes
- > Ionic Processes at Interfaces
- > **Reactions in Supercritical Water**
- > Radiation Chemistry & Track Effects in Condensed Media
- > Reaction Studies of Importance to Atmospheric Chemistry
- > Reaction Kinetics as Probes of Potential Energy Surfaces
- > Electron Spin Exchange Phenomena in Gases & Condensed Media.

- > Molecular Magnets & Clusters
- > Hydrogen in Semiconductors
- > **Magnetic Polarons**
- > Charged Particle Transport
- > Quantum Impurities
- > Metal-Insulator Transitions
- > Colossal Magnetoresistance
- > Spin Ice Systems
- > Thermoelectric Oxides
- > Photo-Induced Magnetism
- > Magnetic Vortices
- > Heavy Fermions
- > Frustrated Magnetic Systems
- > Quantum Diffusion
- > **Exotic Superconductors**



# C'est fini!