TRIUMF

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μSR

Keeping the Promise of Particle Physics

A science fiction adventure story

by

Jess H. Brewer

Department of Physics & Astronomy, University of British Columbia

UBC Physics & Astronomy → Physics Colloquium 24 April 2009 → University of Arkansas

Fantasy, Fiction, Physics

- **Fantasy**: violates "known laws of physics"
- **Science Fiction**: possible in principle, but impractical with existing technology. (**Clarke's Law**: *"Any sufficiently advanced technology is indistinguishable from magic."*)
- **Routine Physics**: "We can do that . . ."

Cast of Characters

in approximate order of appearance

Fantasy Era

Yukawa; Anderson; Rasetti

Science Fiction Era

Theory: Lee & Yang
Exp't: Wu; Friedman & Telegdi;
Garwin, *Lederman* & Weinrich

Frontier Era

USSR: Firsov; Nosov & Yakovleva
Ivanter & Smilga; *Gurevich*
QED: Hughes; Telegdi; *Crowe*
$\mu^+e^- \to \mu^-e^+$: Bowen & Pifer

Golden Era

SIN→PSI: *Schenck*, Kündig, *Patterson*,
Fischer, Kalvius, *Kiefl*
LAMPF: Hughes, *Heffner*, MacLaughlin
TRIUMF: Warren, *Fleming*, Brewer, *Crowe*,
Walker, Vogt, *Uemura*, Williams
KEK/BOOM: Kubo, *Yamazaki*, *Nagamine*
RAL/ISIS: Stoneham, *Cox*

Modern Era at TRIUMF

*Percival, Kreitzman, Kiefl, Luke, Sonier, MacFarlane, Uemura, Storchak, Sugiyama, hundreds of **Users**, dozens of **PDFs** and **Students**, **Visitors**, . . .*

Before 1956: *Fantasy*

- 1930s: **Mistaken Identity**

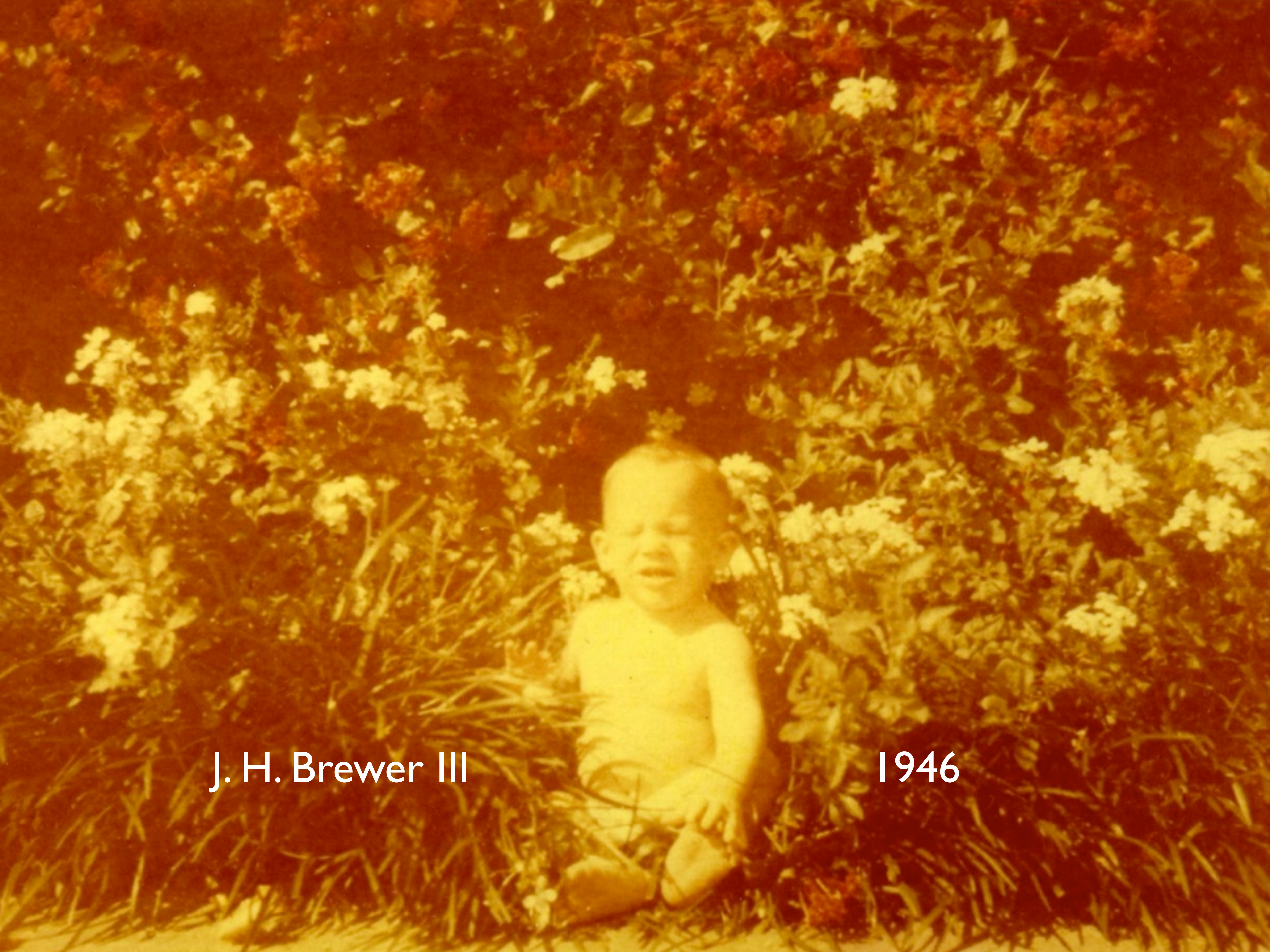
  Yukawa's "nuclear glue" mesons ≠ cosmic rays
  1937 Rabi: Nuclear Magnetic Resonance

- 1940s: "**Who Ordered That**?"

  1940 Phys. Rev. Analytical Subject Index: "mesotron"
  1944 Rasetti: 1st application of muons to condensed matter physics
  1946 Bloch: Nuclear Induction (modern NMR with FID *etc.*)
  1946 Various: "two-meson" π - μ hypothesis **_Brewer_: born**
  1947 Richardson: produced π & μ at Berkeley 184 in. Cyclotron
  1949 Kuhn: *"The Structure of Scientific Revolutions"*

- 1950s: "**Particle Paradise**"

  culminating in weird results with strange particles:
  1956 Cronin, Fitch, . . . : *"τ - θ puzzle"* (neutral kaons) → ***Revolution****!*


J. H. Brewer III
1946

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- 1956: Lee & Yang postulate
  ***P*-violation** in weak interactions
- 1957: Wu confirms *P*-violation in β decay;
  Friedman & Telegdi confirm *P*-violation in π-μ-*e* decay;
  so do Garwin, Lederman & Weinrich, using a prototype ***μSR*** technique.

PHYSICAL REVIEW VOLUME 104, NUMBER 1 OCTOBER 1, 1956

Question of Parity Conservation in Weak Interactions*

T. D. LEE, *Columbia University, New York, New York*

AND

C. N. YANG,† *Brookhaven National Laboratory, Upton, New York*

(Received June 22, 1956)

The question of parity conservation in β decays and in hyperon and meson decays is examined. Possible experiments are suggested which might test parity conservation in these interactions.

↓

Experimental Test of Parity Conservation in Beta Decay*

C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPES, AND R. P. HUDSON, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

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1957

Observations of the Failure of Conservation of Parity and Charge Conjugation in Meson Decays: the Magnetic Moment of the Free Muon*

RICHARD L. GARWIN,† LEON M. LEDERMAN, AND MARCEL WEINRICH

Physics Department, Nevis Cyclotron Laboratories, Columbia University, Irvington-on-Hudson, New York, New York

(Received January 15, 1957)

Nuclear Emulsion Evidence for Parity Nonconservation in the Decay Chain $\pi^+ - \mu^+ - e^+$*†

JEROME I. FRIEDMAN AND V. L. TELEGDI

Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

(Received January 17, 1957)

↓

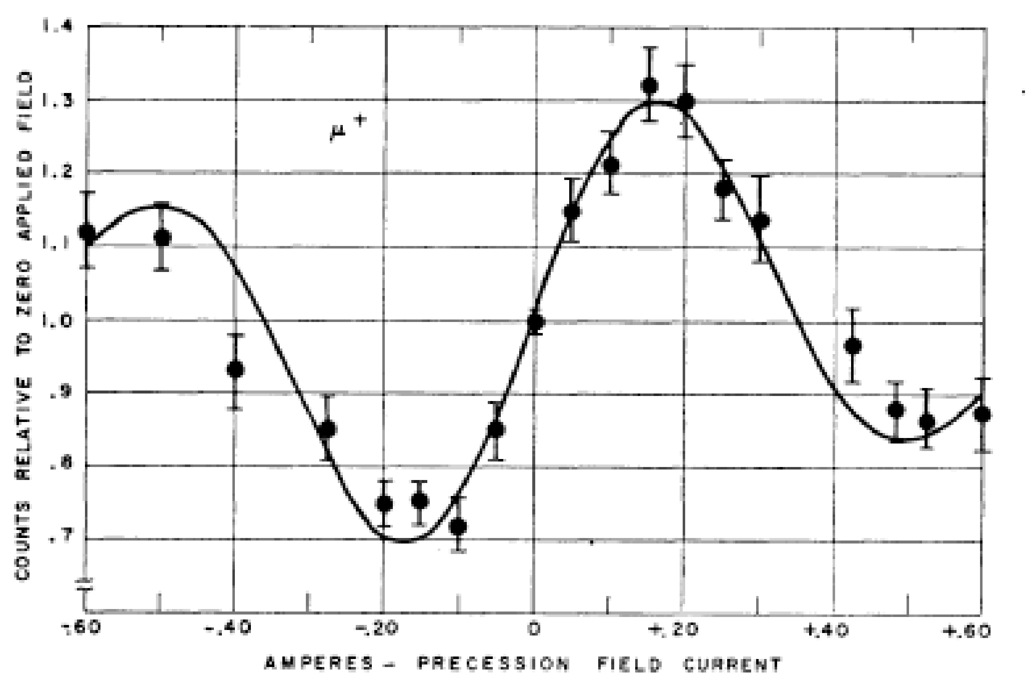


FIG. 2. Variation of gated 3–4 counting rate with magnetizing current. The solid curve is computed from an assumed electron angular distribution $1-\frac{1}{3}\cos\theta$, with counter and gate-width resolution folded in.

→

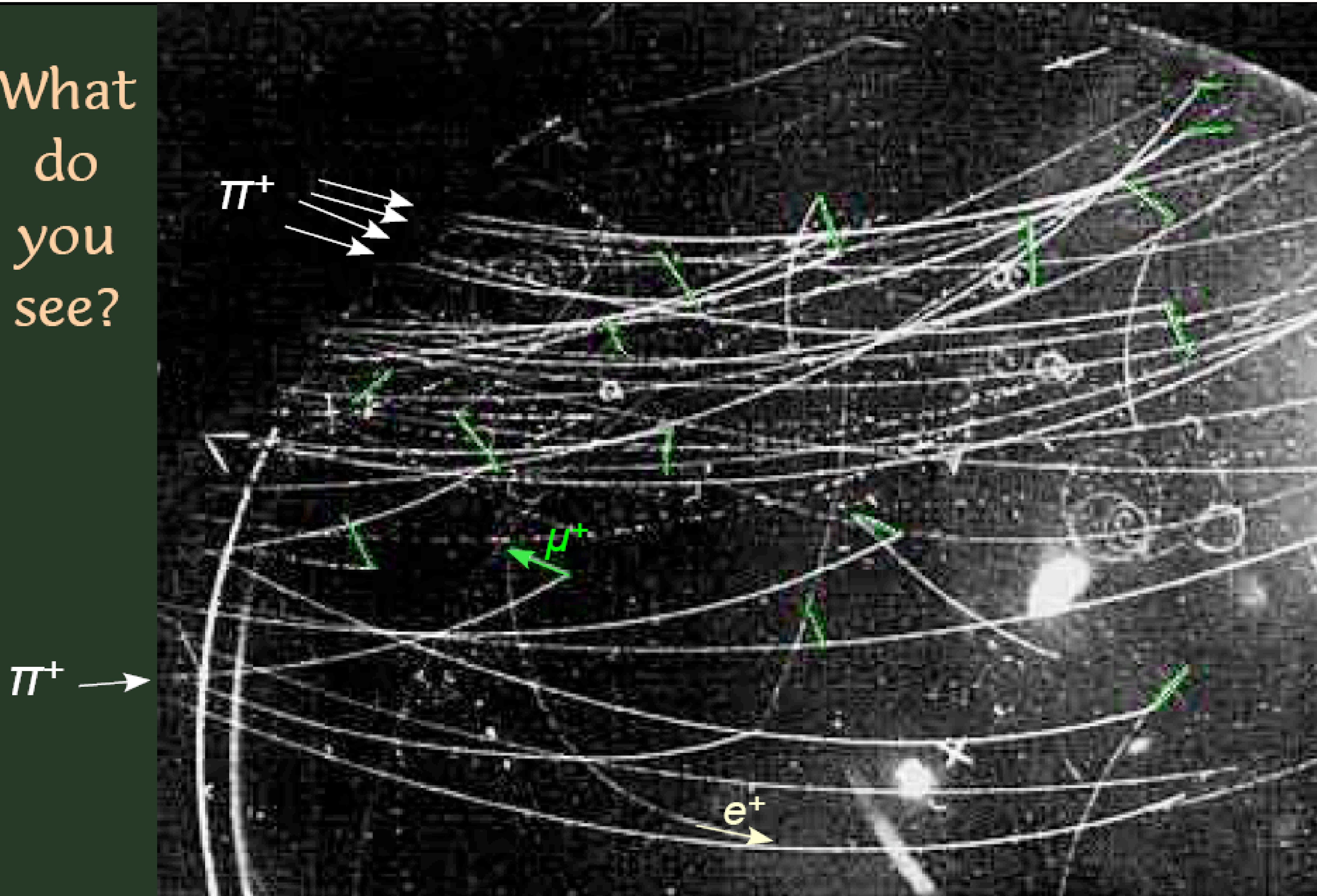
It seems possible that polarized positive and negative muons will become a powerful tool for exploring magnetic fields in nuclei (even in Pb, 2% of the μ^- decay into electrons[9]), atoms, and interatomic regions.

(The Promise)

So . . .

How does it work?

What do you see?



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.

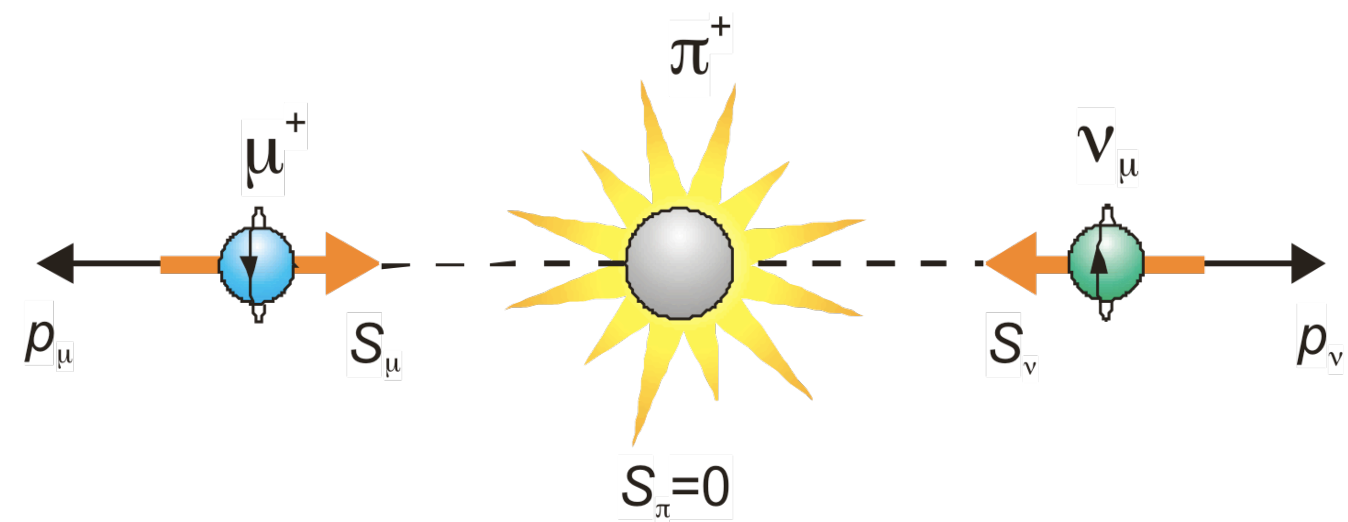
Conservation of Linear Momentum: The μ^+ is emitted with momentum equal and opposite to that of the ν_μ.

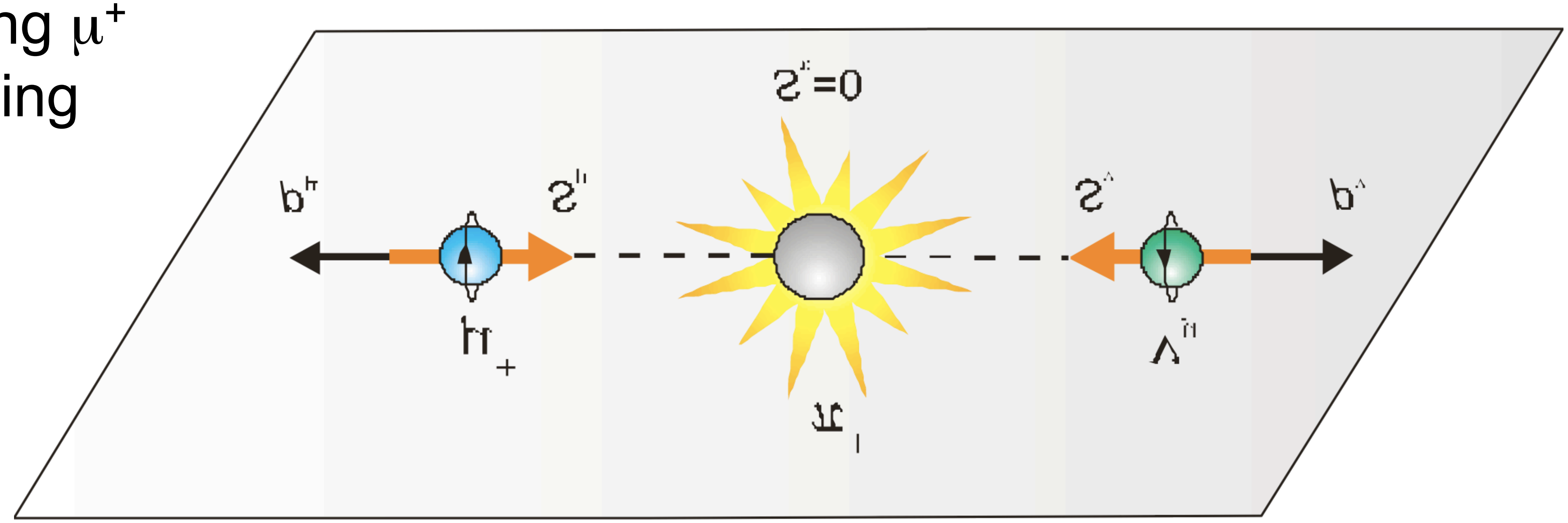
Conservation of Angular Momentum: μ^+ & ν_μ have equal & opposite spin.

Weak Interaction:

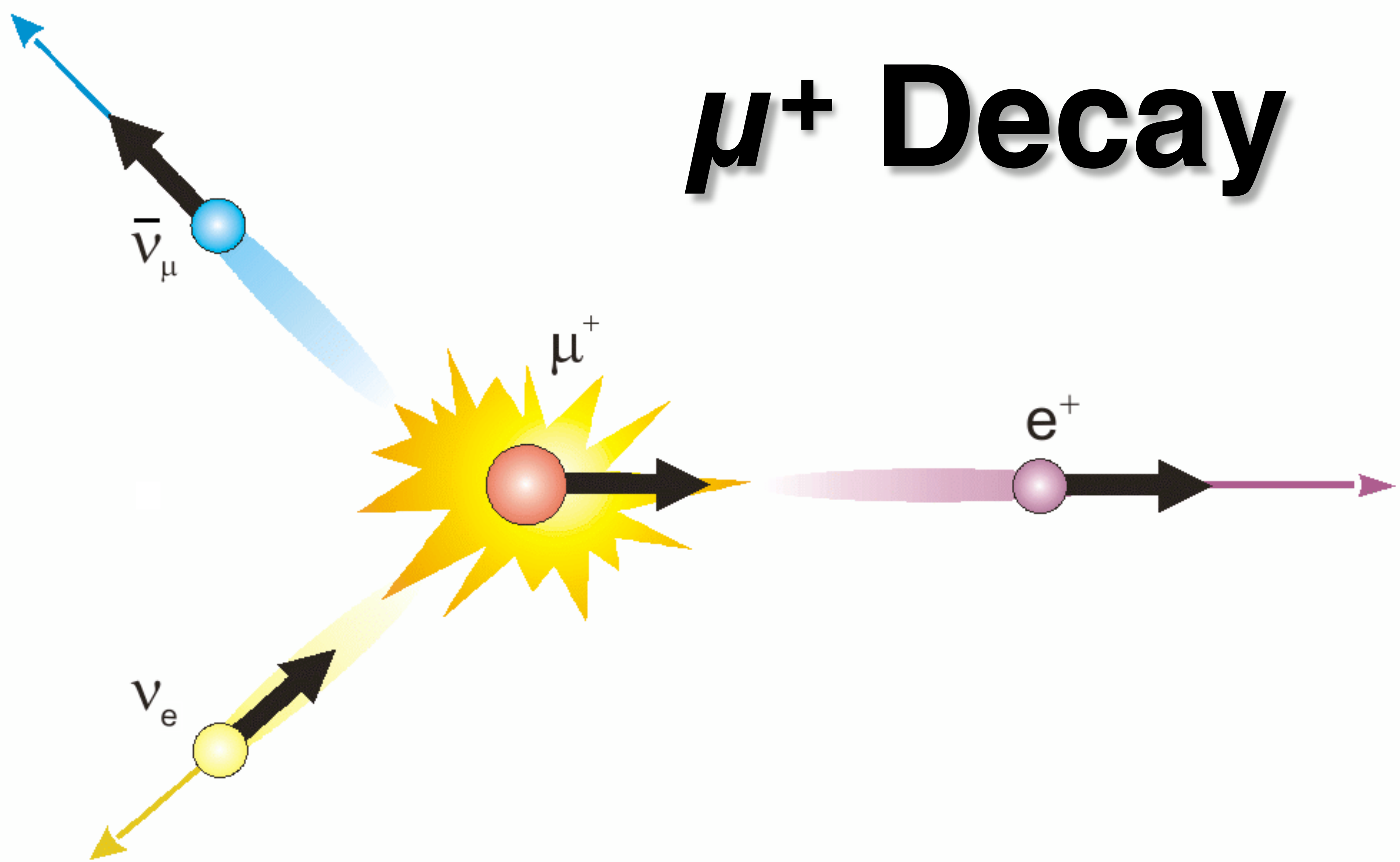
Only “left-handed” ν_μ are created.

Thus the emerging μ^+ has its spin pointing antiparallel to its momentum direction.





μ^+ Decay

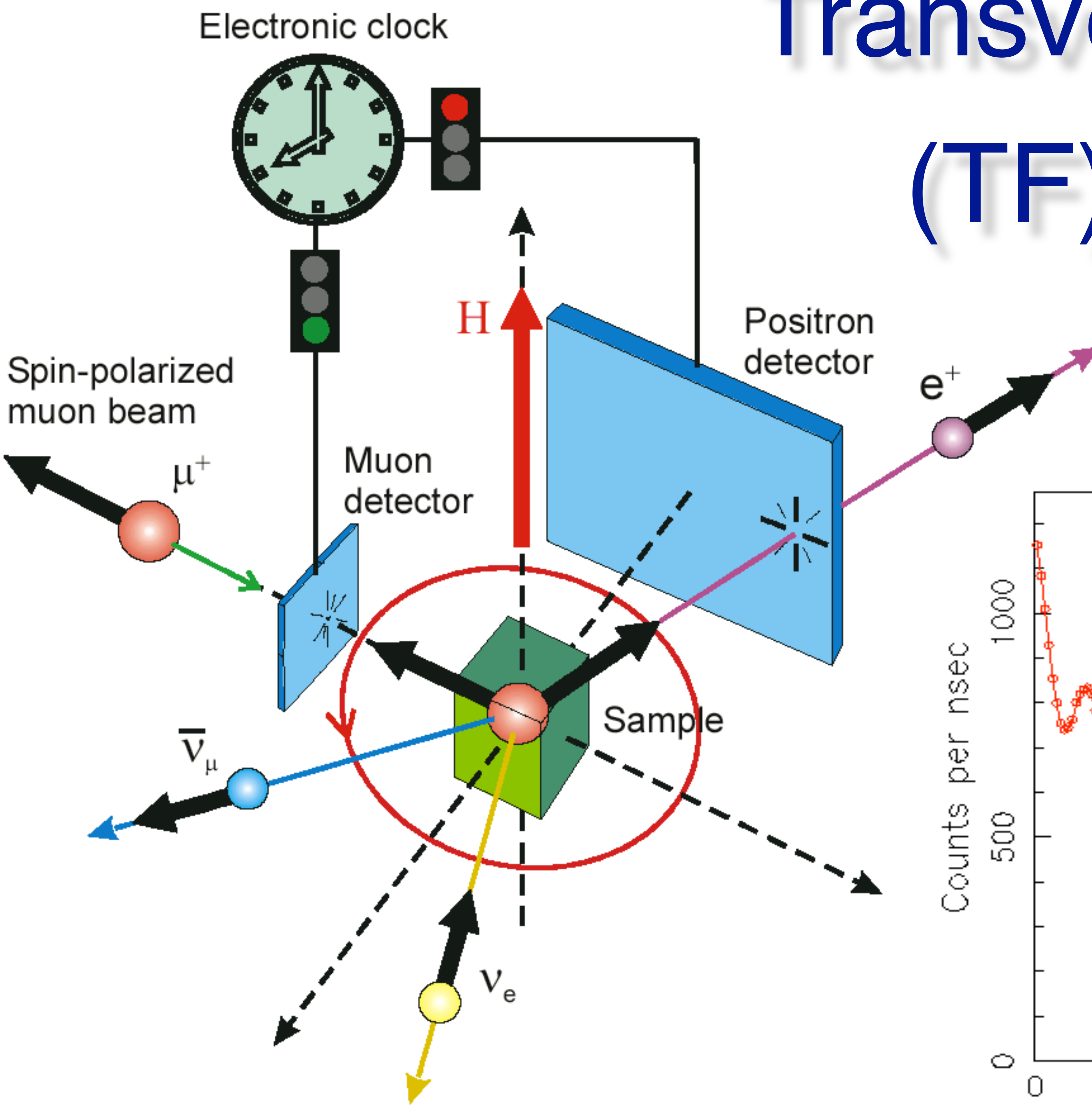


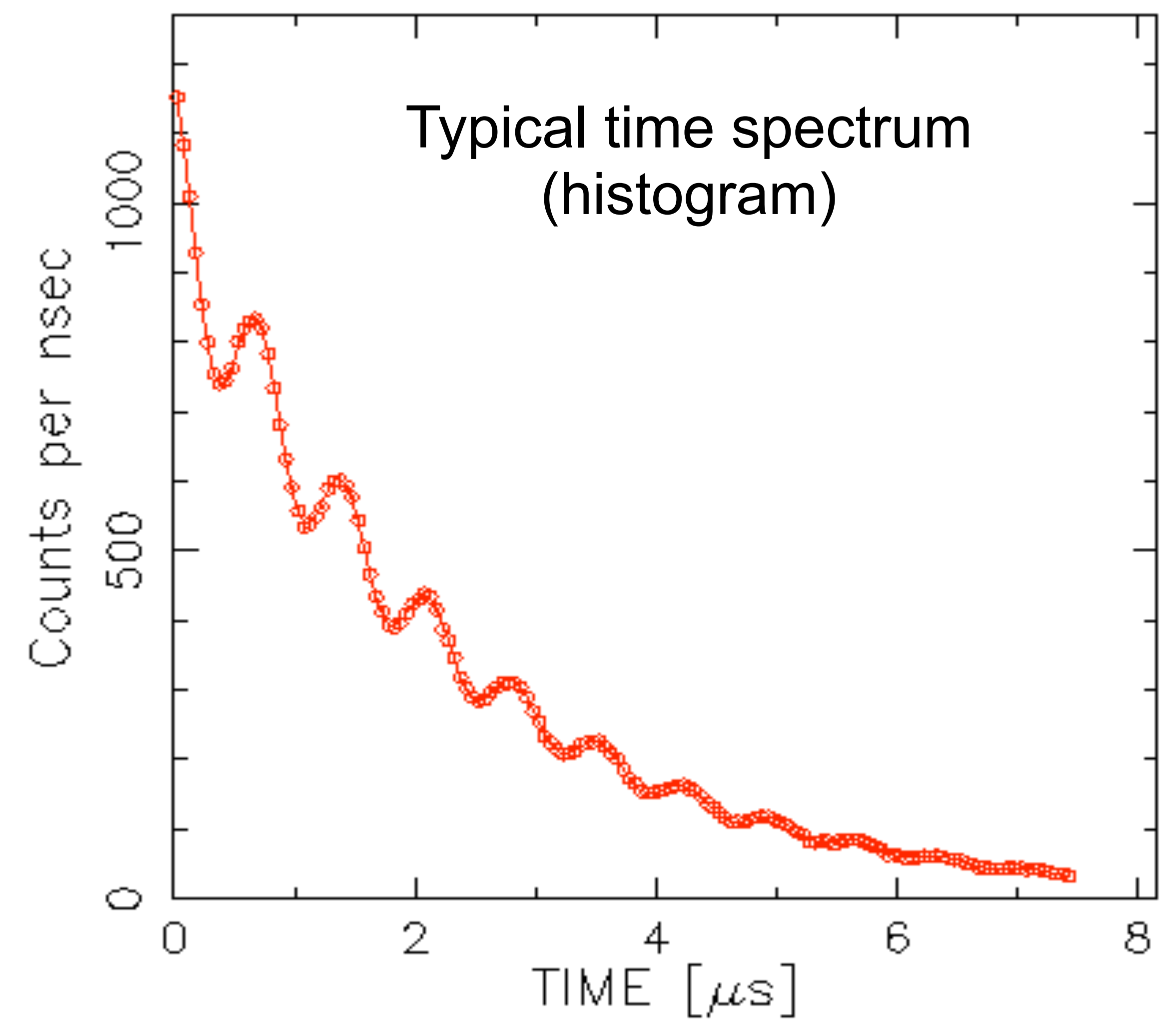
Neutrinos have negative helicity, antineutrinos positive.

An ultrarelativistic positron behaves like an antineutrino.

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

Transverse Field (TF)-μ^+SR





1958-1973: *Science Fiction*

- 1960s: **Fundamental Physics Fun!** — *Tours de Force*

  Michel Parameters = Weak Interaction Laboratory
  Heroic **QED** tests: A_{HF}(Mu), μ_μ, $g_\mu - 2$
  All lead to *refined μSR techniques*.
  Applications: Muonium Chemistry, Semiconductors, Magnetism

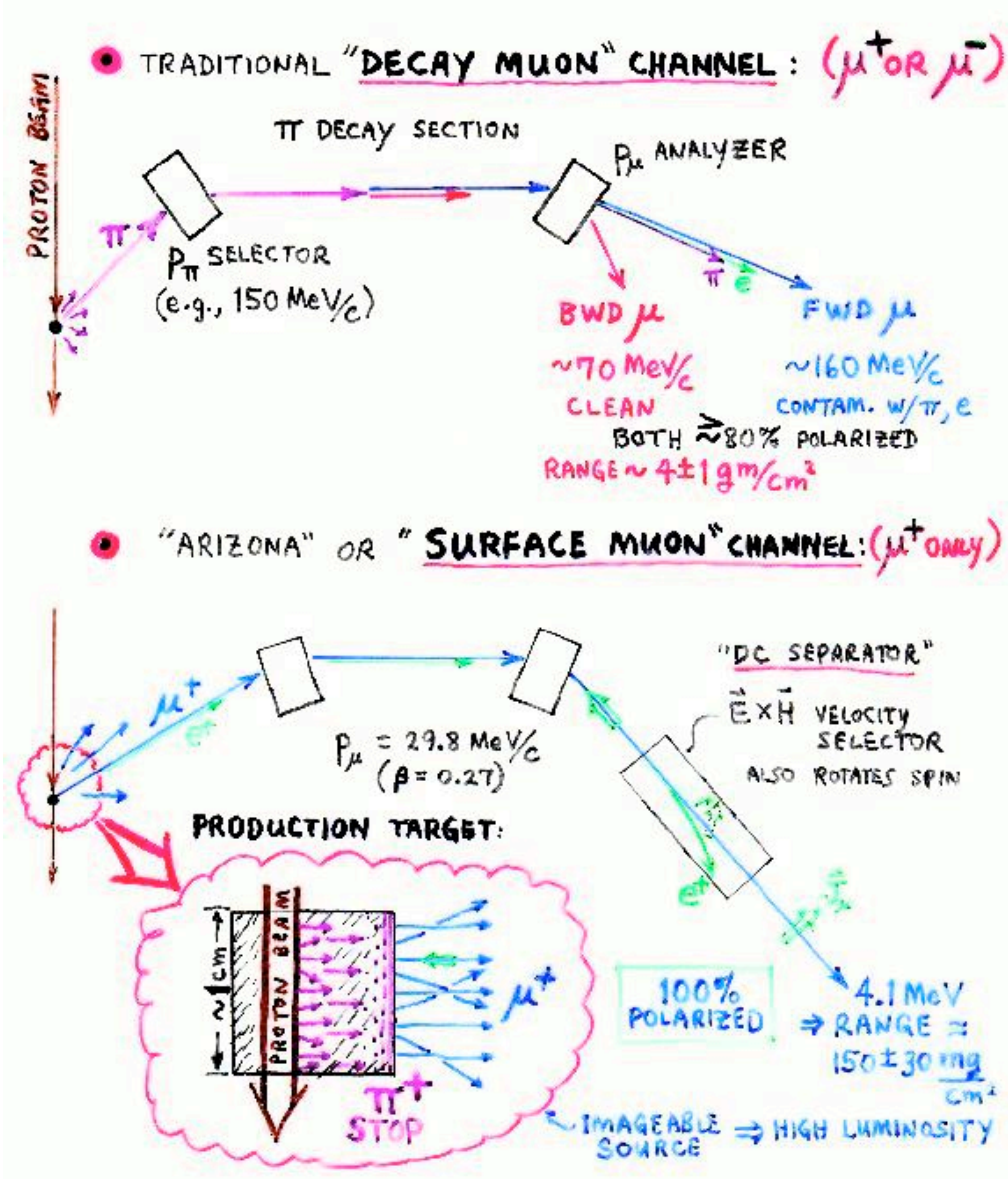
- 1967: **Brewer goes to Berkeley** — *to study Radicals*
  Rationale: a *science fiction author* needs credibility; what better credential than a Ph.D. in Physics? (But *μSR* was too much fun!)

- 1972: **Bowen & Pifer** build first Arizona/**surface muon beam** to search for for $\mu^+e^- \rightarrow \mu^-e^+$ conversion

- mid-1970s: **Meson Factories** — *Intensity Enables!*

  USA: **LAMPF** (now defunct)
  Canada: ***TRIUMF***
  Japan: **KEK/BOOM** (→ **J-PARC**)
  Switzerland: **SIN** (now **PSI**)
  UK: **RAL/ISIS**

Beamlines for Polarized Muons



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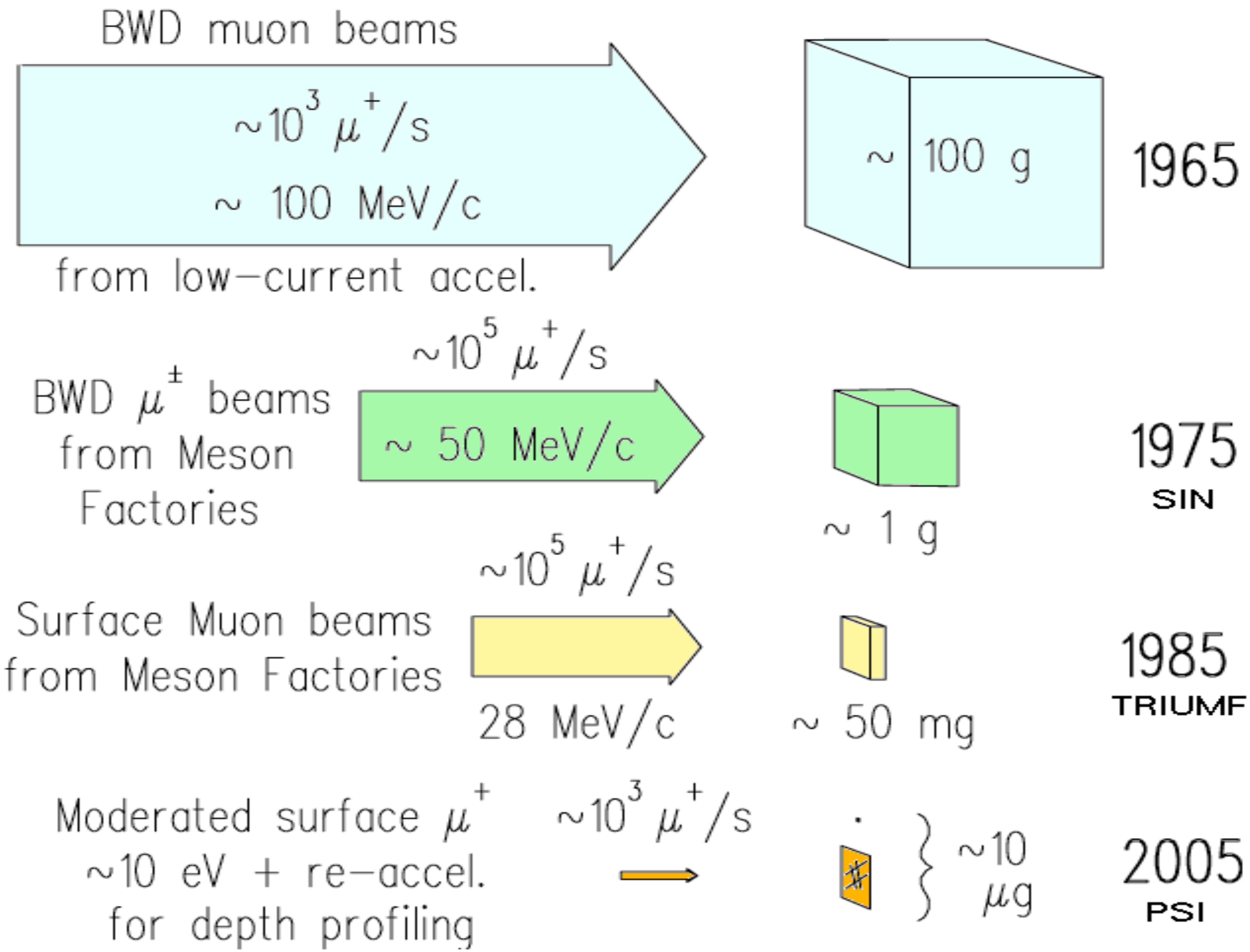
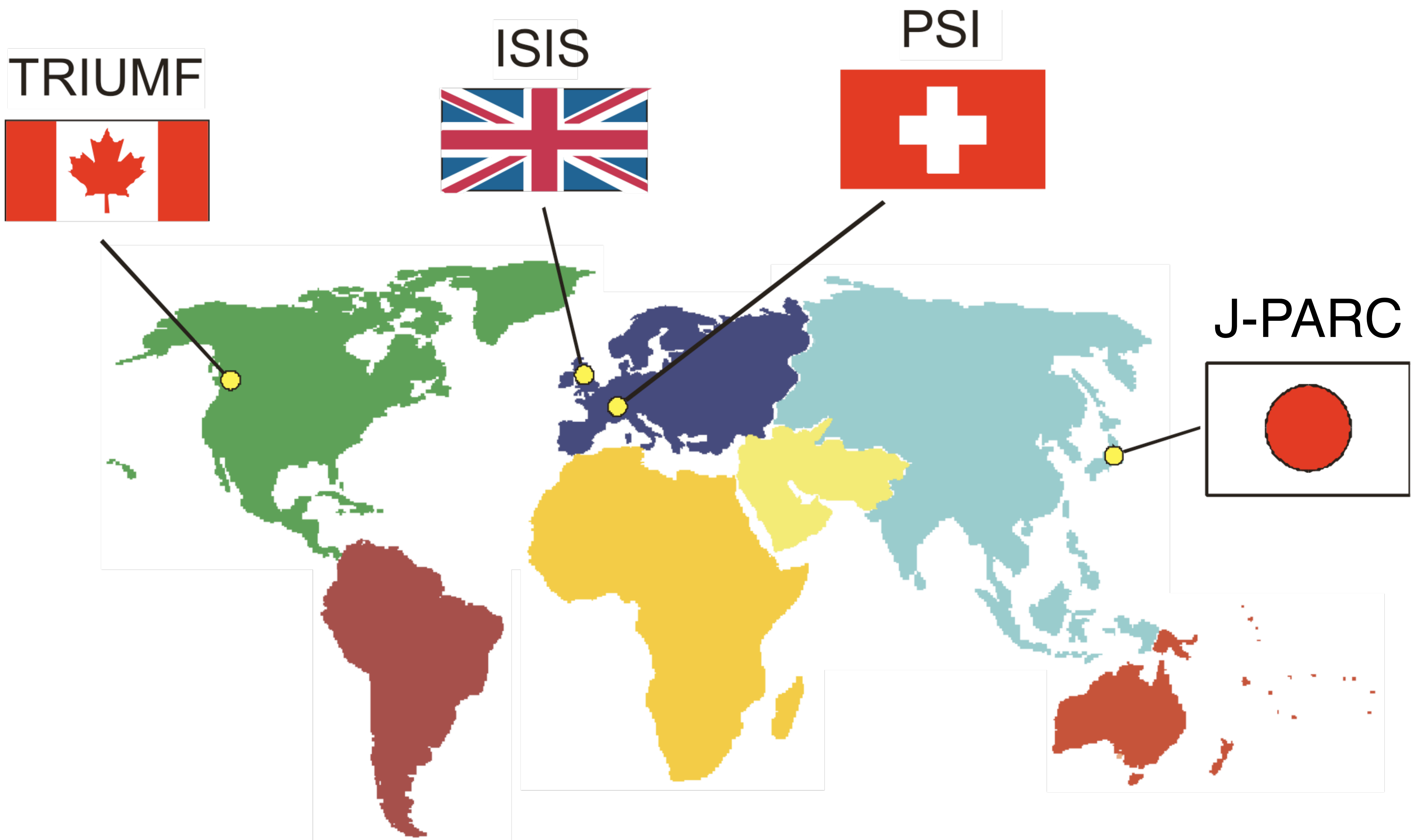
μ^+ Stopping Luminosity

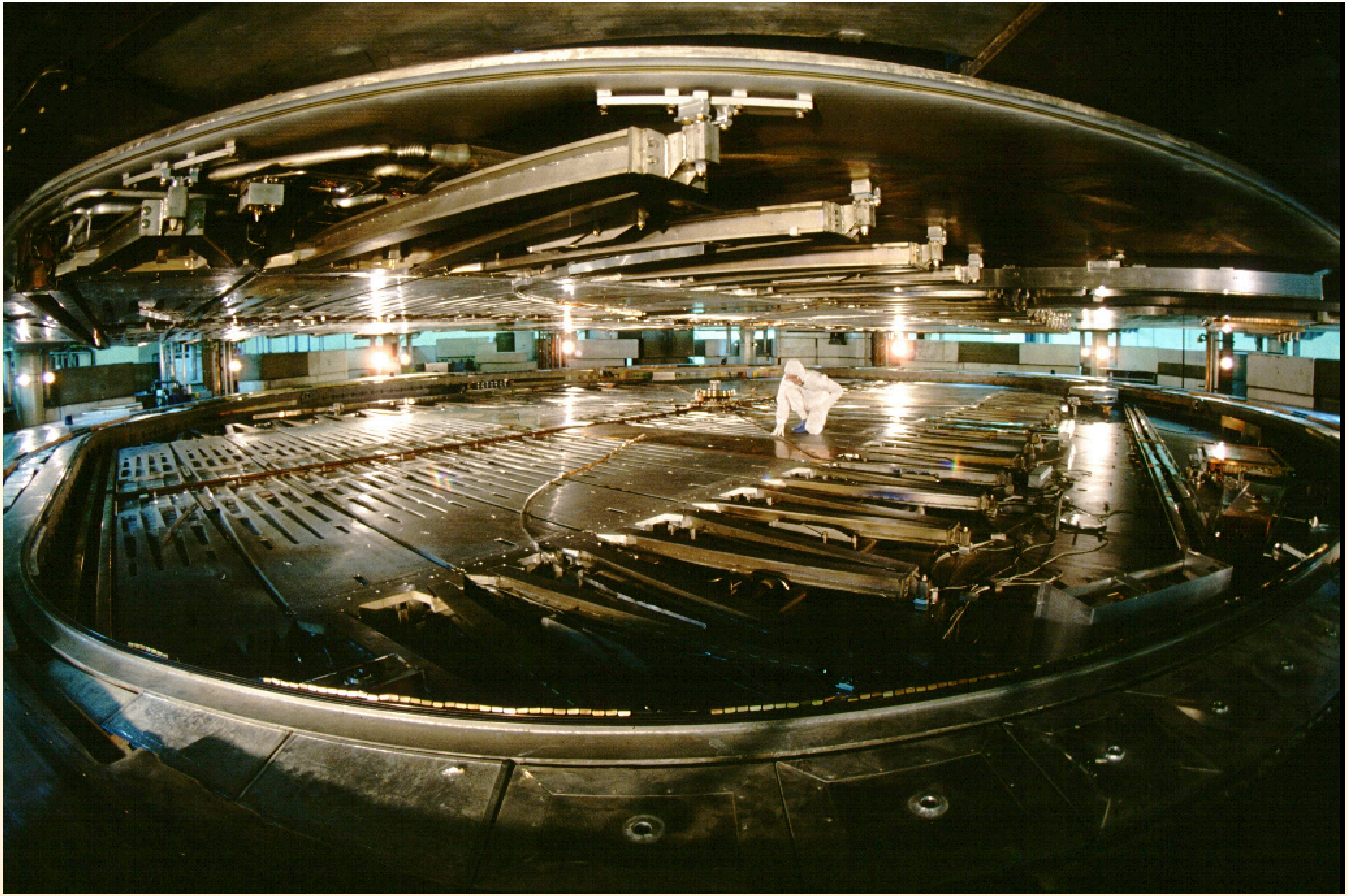


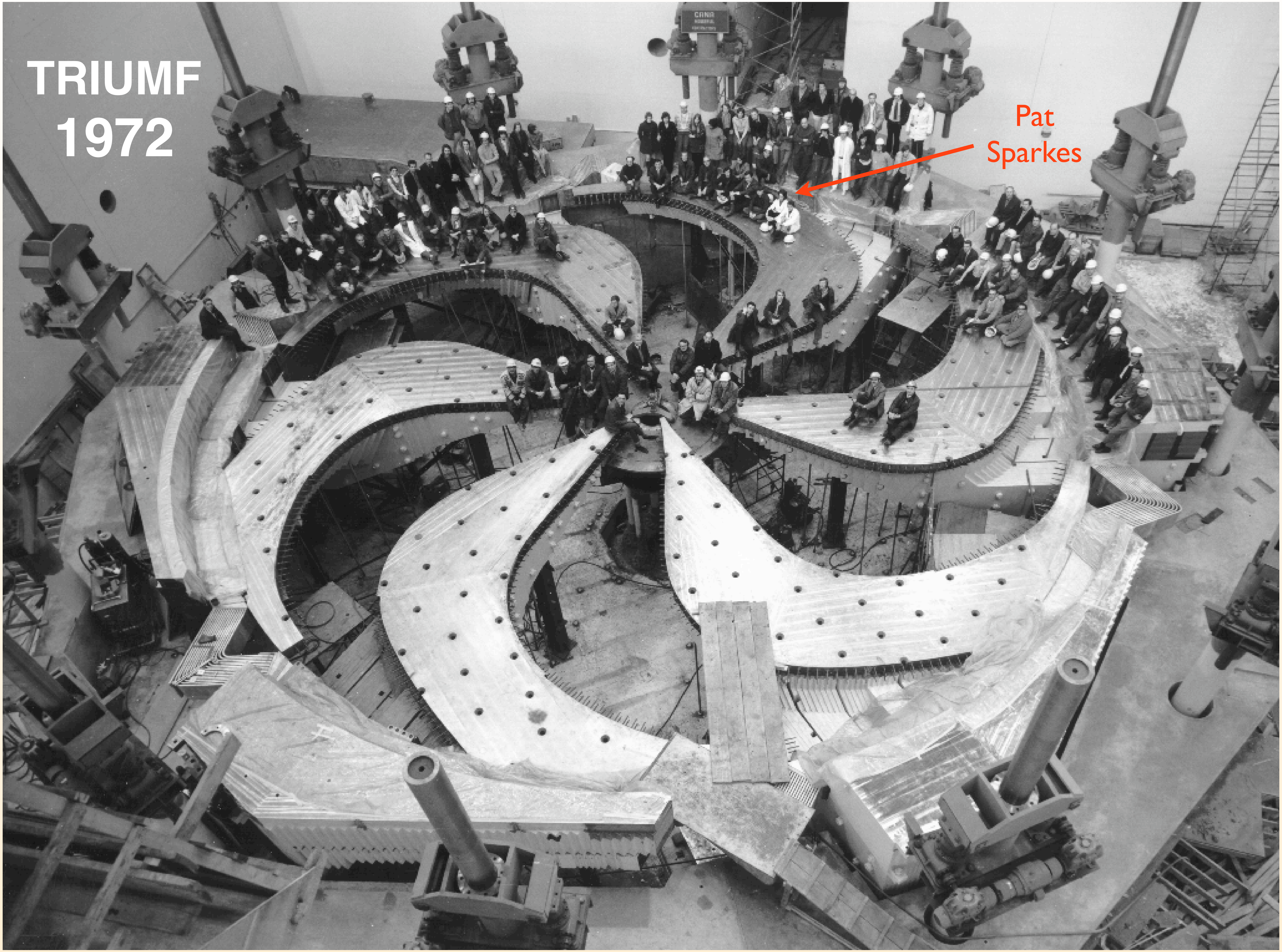
Where in the World is μSR?



TRIUMF

TRIUMF: World's Largest Cyclotron

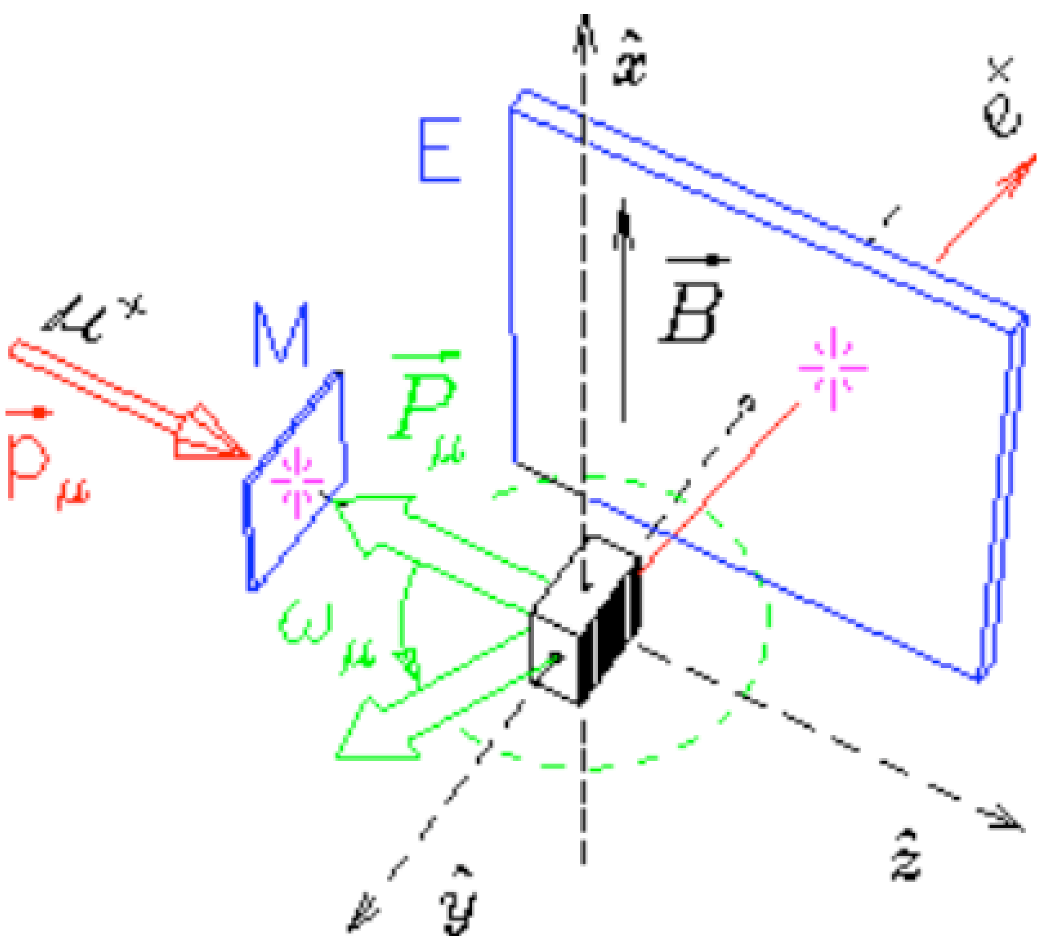


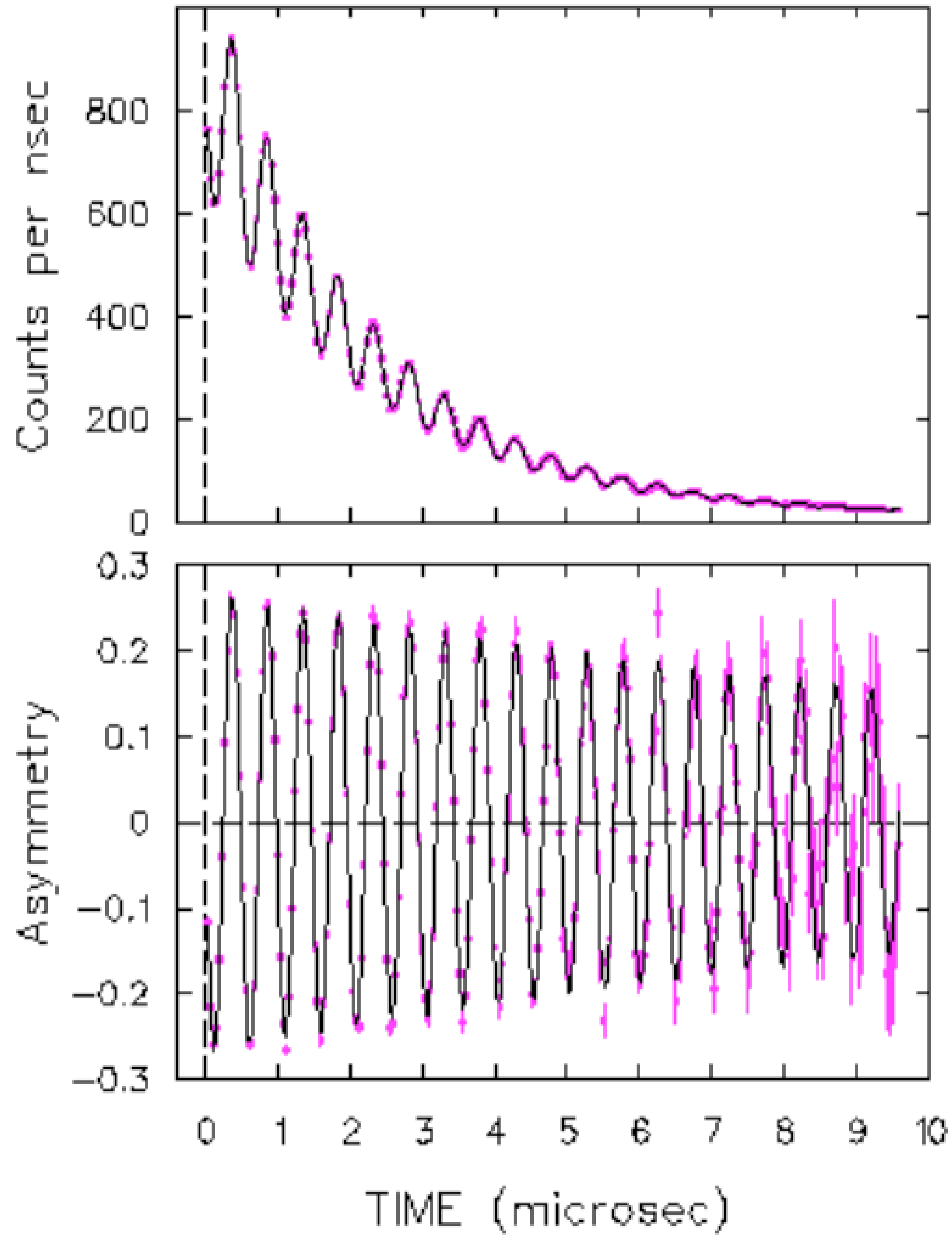

TRIUMF
1972
Pat
Sparkes

Back to **μSR** . . .

wTF-μ⁺SR:

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





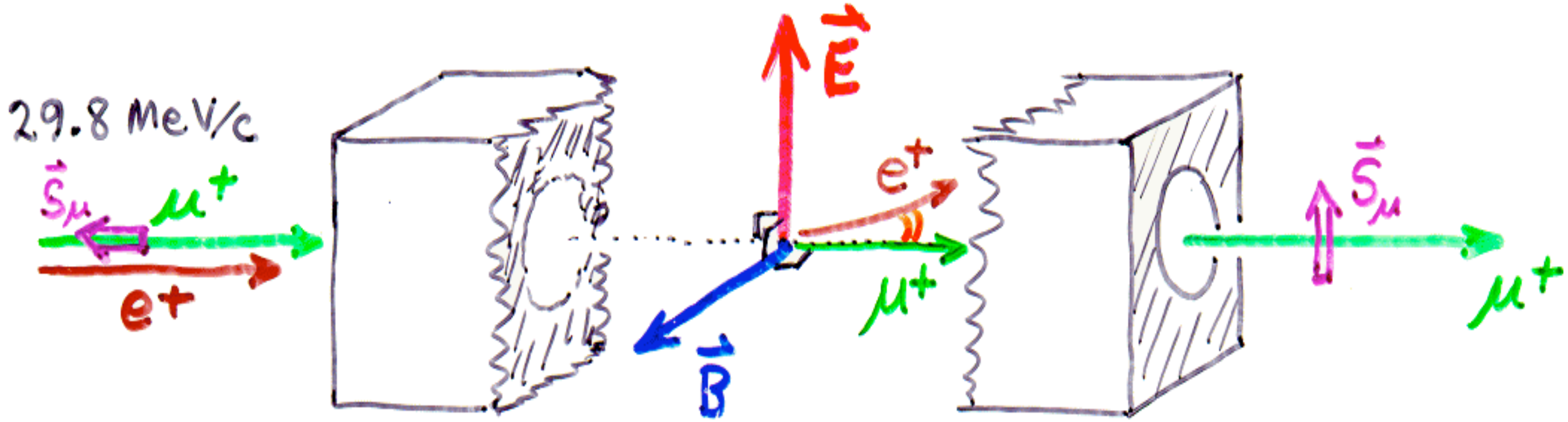
$$A(t) = [N(t) - N_0 B]\, e^{+t/\tau_\mu} - 1$$

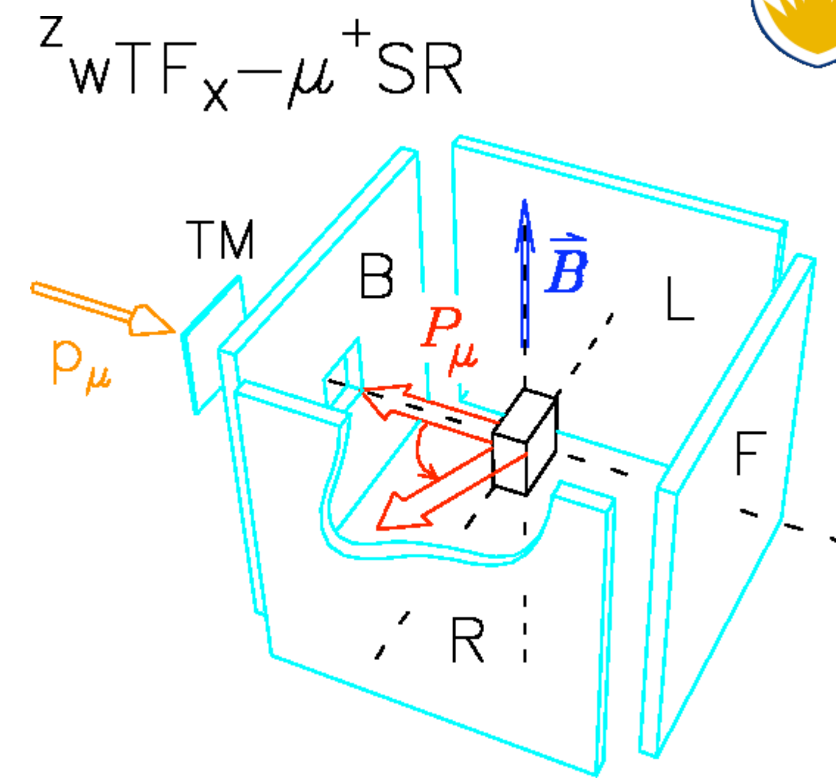
$$= A_0 G_{xx}(t) \cos(\omega_\mu t + \phi)$$

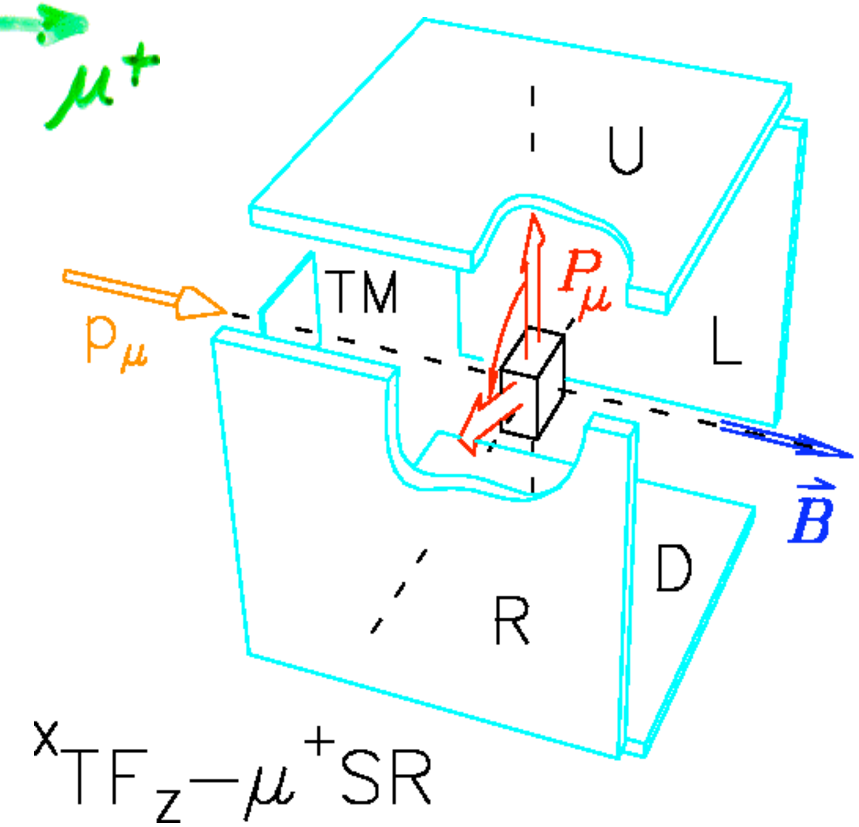
E×*B* velocity selector

("DC Separator" or Wien filter)

for **surface muons**:





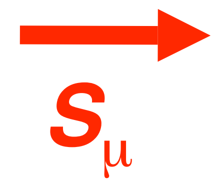


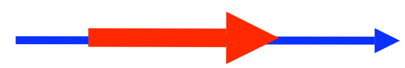
- Removes beam positrons
- Allows TF-μ^+SR in high field (otherwise ***B*** deflects beam)

High Field μSR

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.

Motion of Muon Spins in Static Local Fields

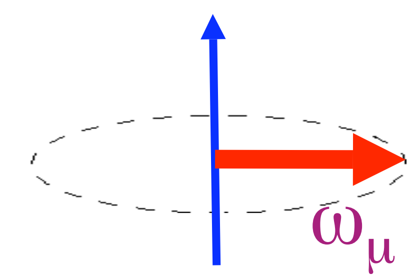

S_μ = Expectation value of a muon's spin direction

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

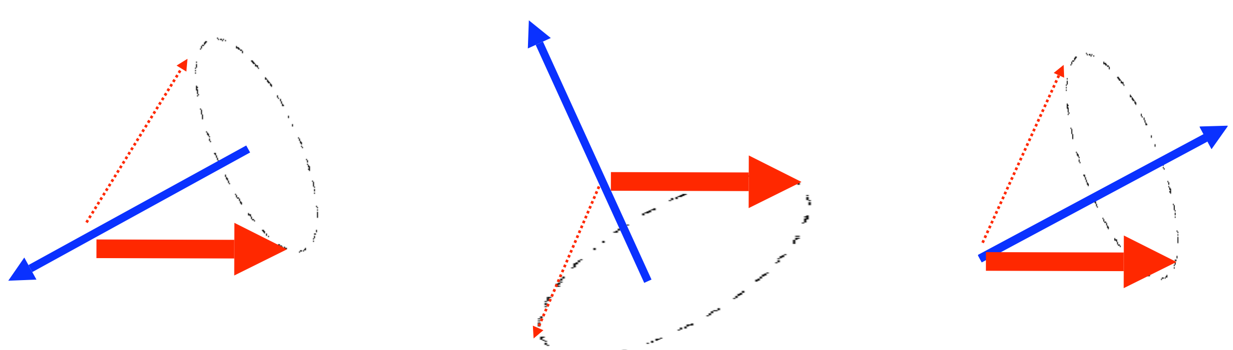
$\omega_\mu = 2\pi\, \gamma_\mu \, |\boldsymbol{B}|$

$\gamma_\mu = 135.5$ MHz/T

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



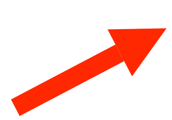
(b) All muons "see" same $|\boldsymbol{B}|$ but **random direction**:



2/3 of S_μ **precesses** at ω_μ

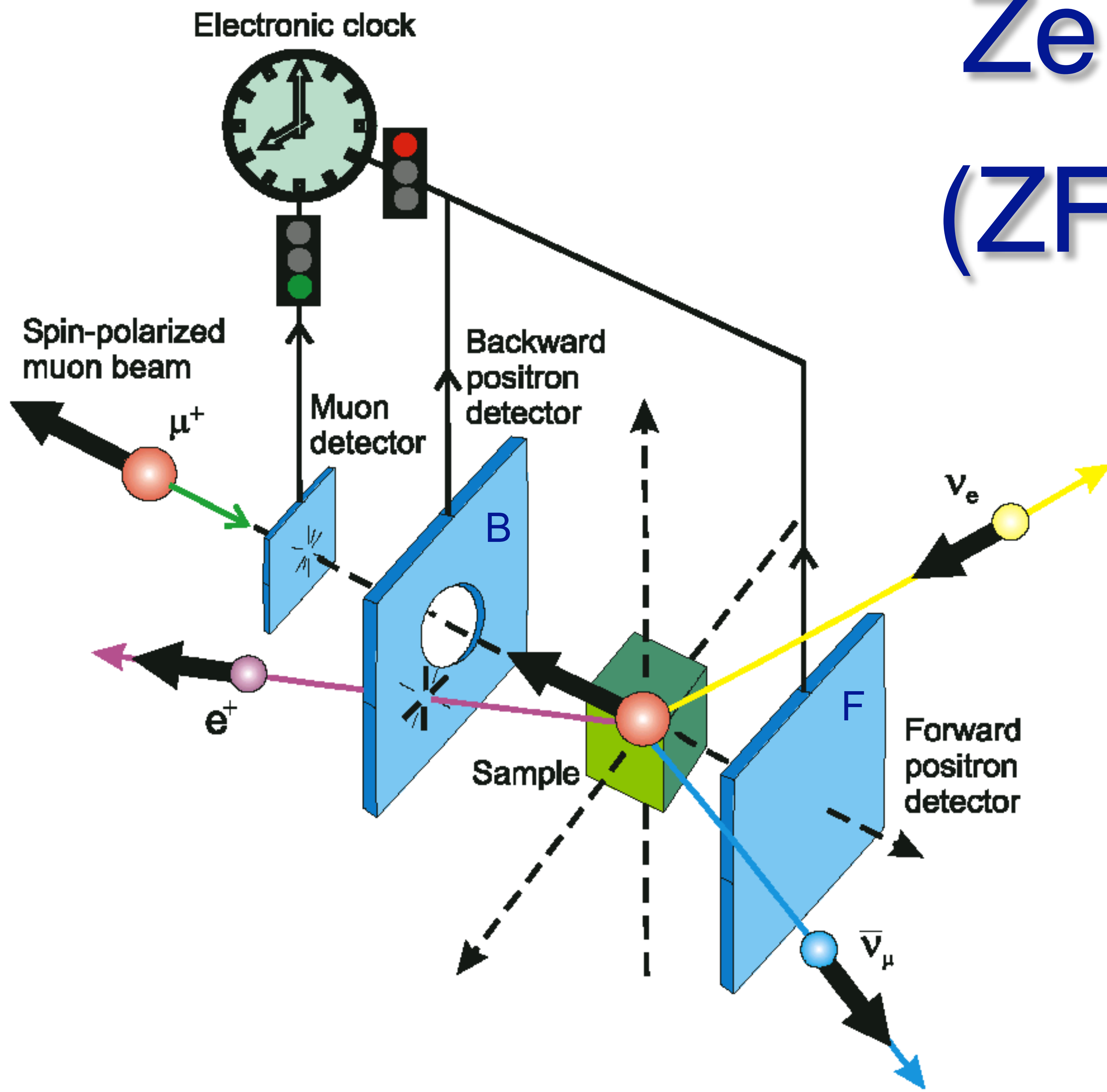
1/3 of S_μ **stays constant**

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

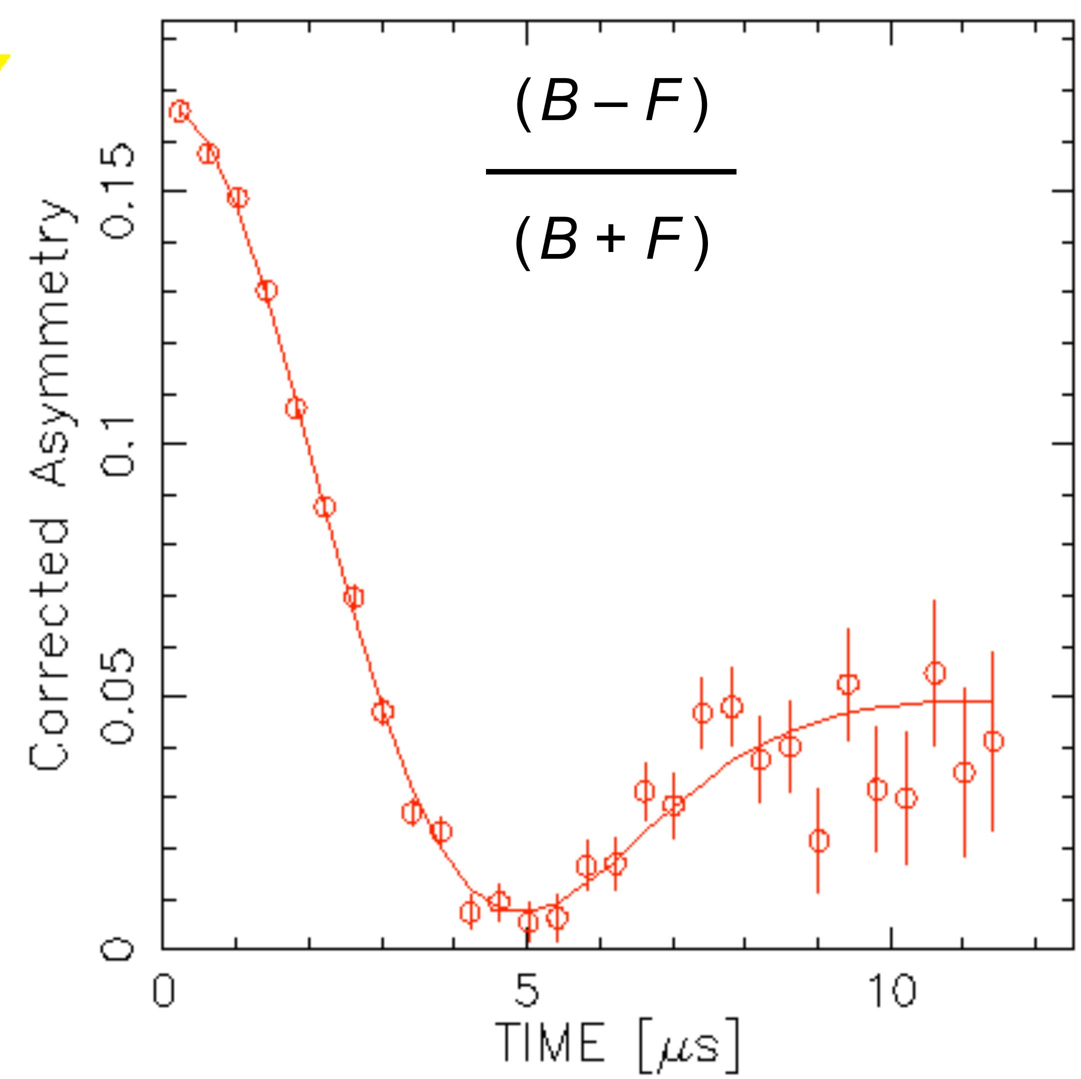
All  do not return to the same orientation at the same time

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

Zero Field (ZF)-μ^{+}SR

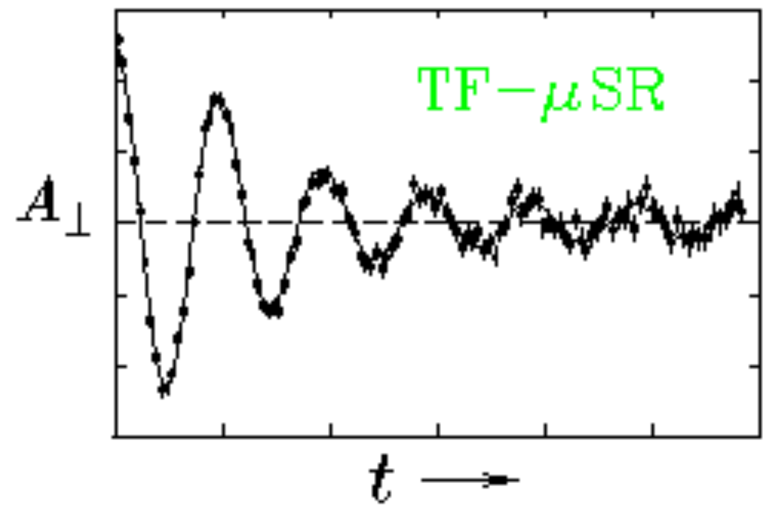


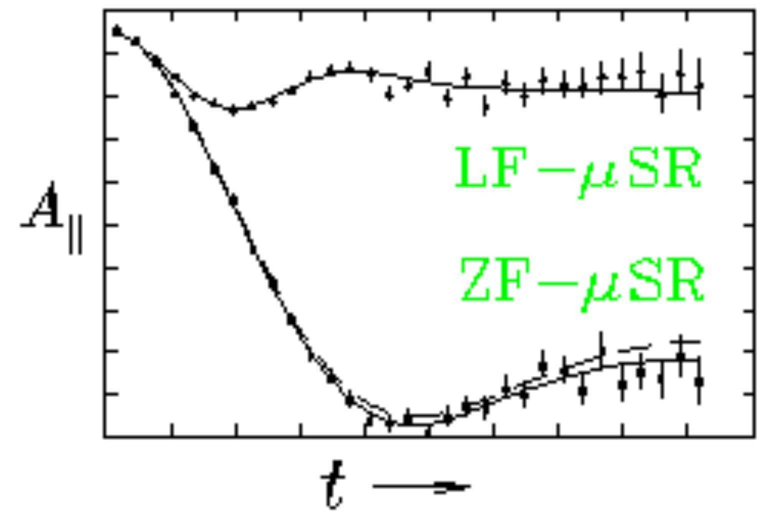
Typical asymmetry spectrum



Brewer's List of μSR Acronyms

Transverse Field

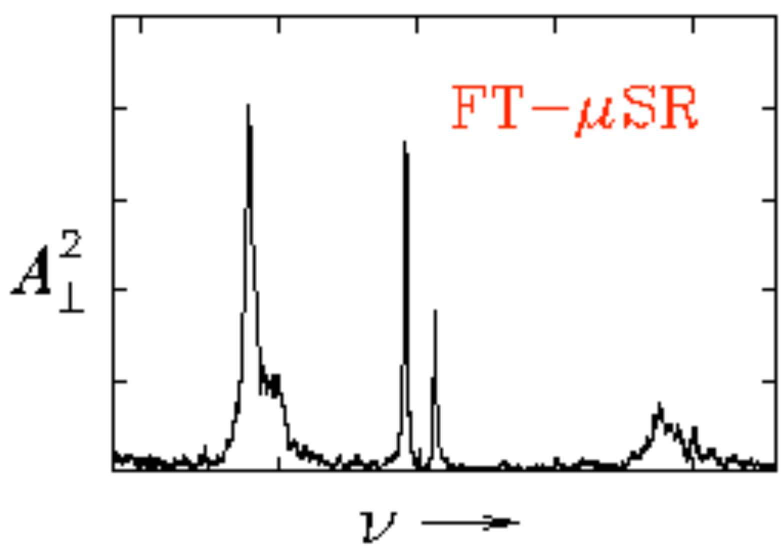


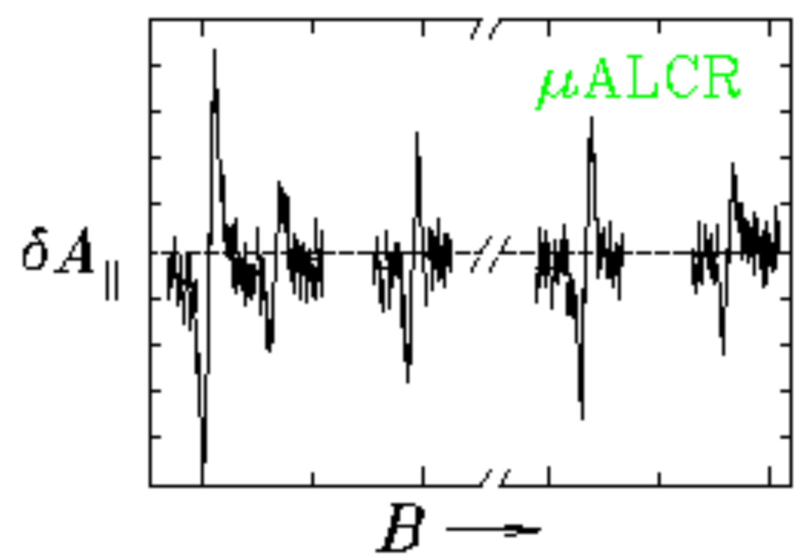


Longitudinal Field

Zero Field

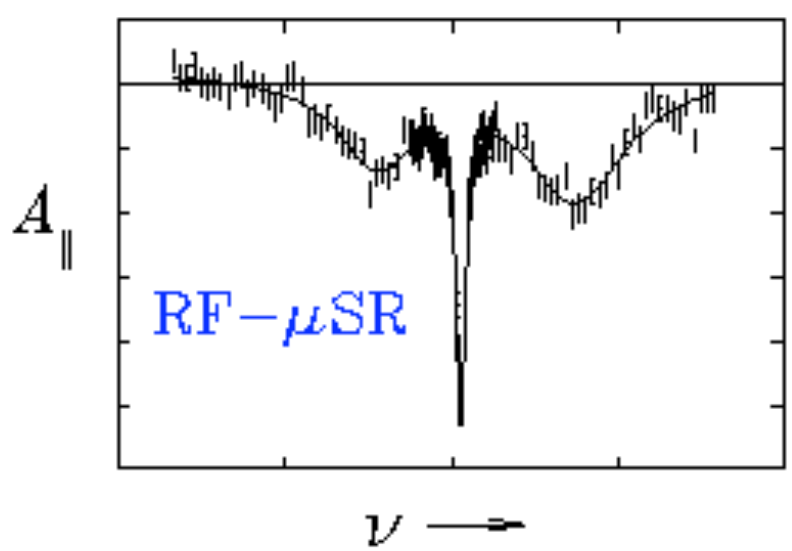
Fourier Transform μSR

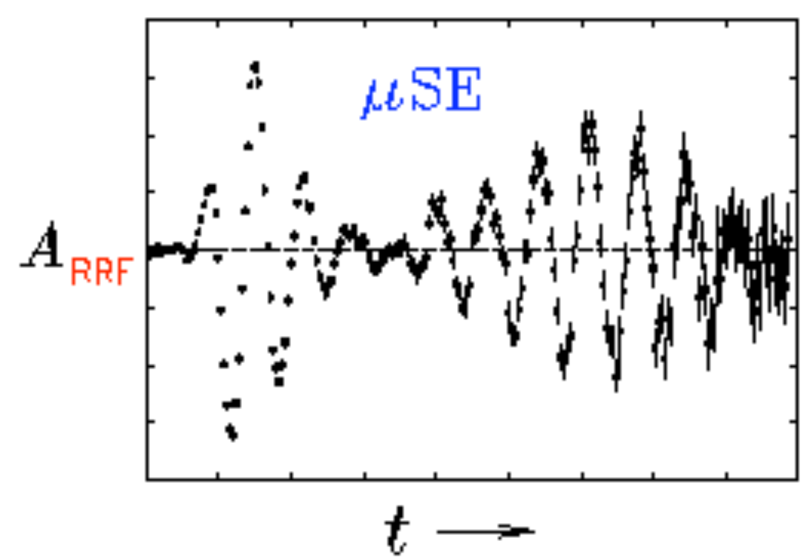




Avoided Level Crossing Resonance

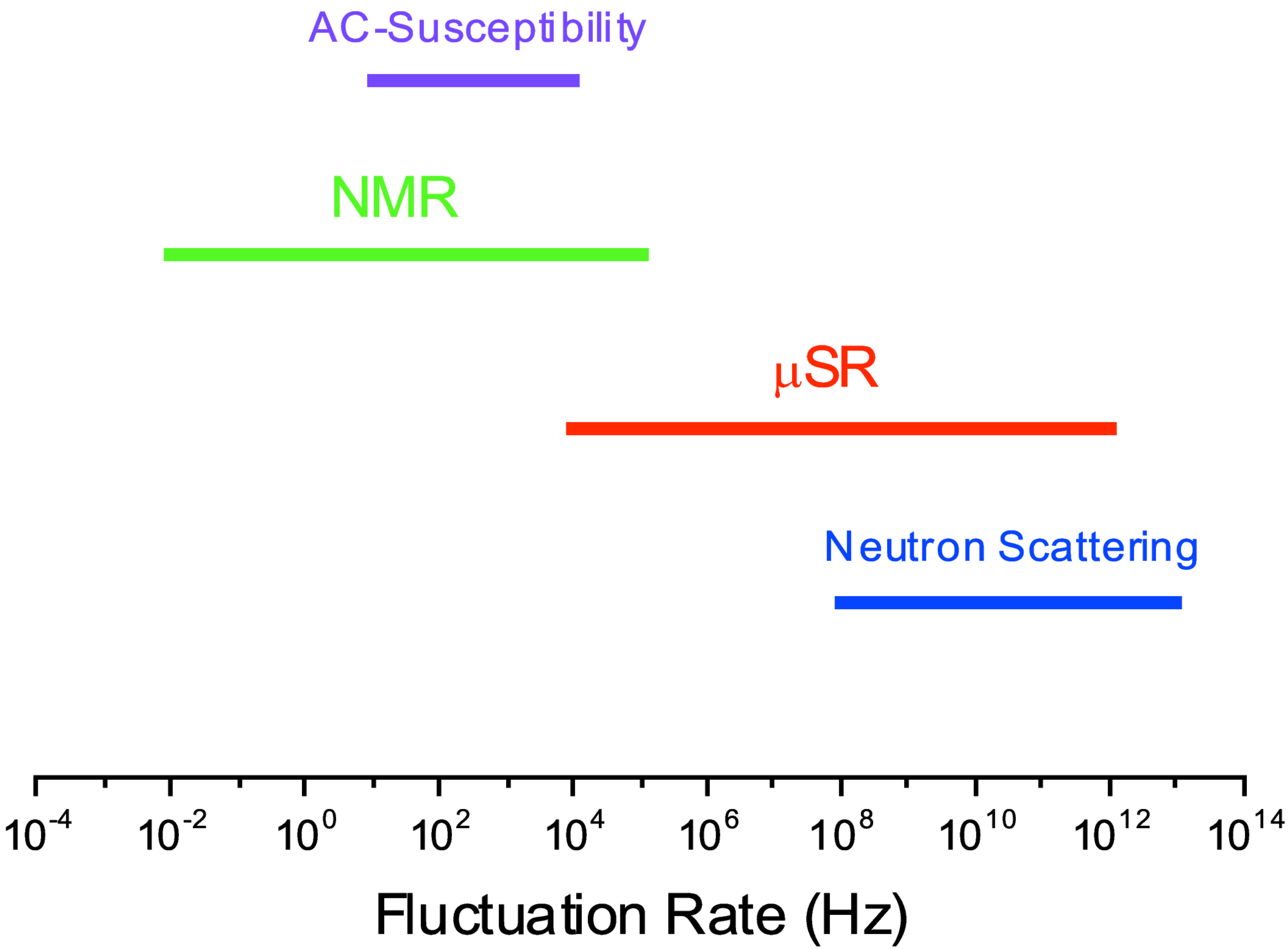
Muon Spin Resonance





Muon Spin Echo

Time Scales


AC-Susceptibility
NMR
μSR
Neutron Scattering
10^{-4} 10^{-2} 10^{0} 10^{2} 10^{4} 10^{6} 10^{8} 10^{10} 10^{12} 10^{14}
Fluctuation Rate (Hz)

"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, $\mu^+SR \rightarrow$ **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 λ
  - Coherence Length ξ

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

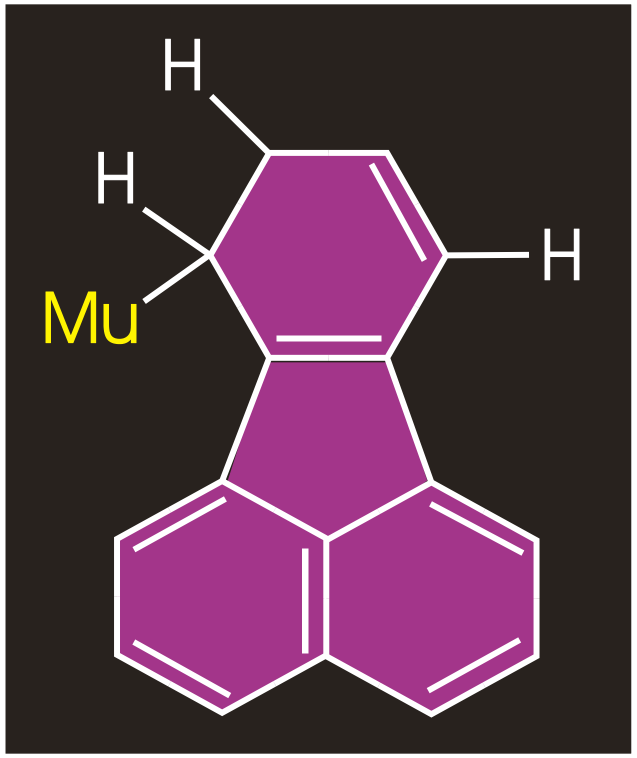
2000s: CMMS

The TRIUMF ***C***entre for ***M***olecular and ***M***aterials ***S***cience is an NSERC funded Facility at the TRIUMF National Laboratory, in Vancouver, Canada. It represents an expansion of the former TRIUMF *μSR* User Facility, with a mandate to facilitate research in chemistry and solid state physics using *μSR* and other accelerator-based techniques such as β-NMR.

Visit http://musr.ca for selected Research Highlights:

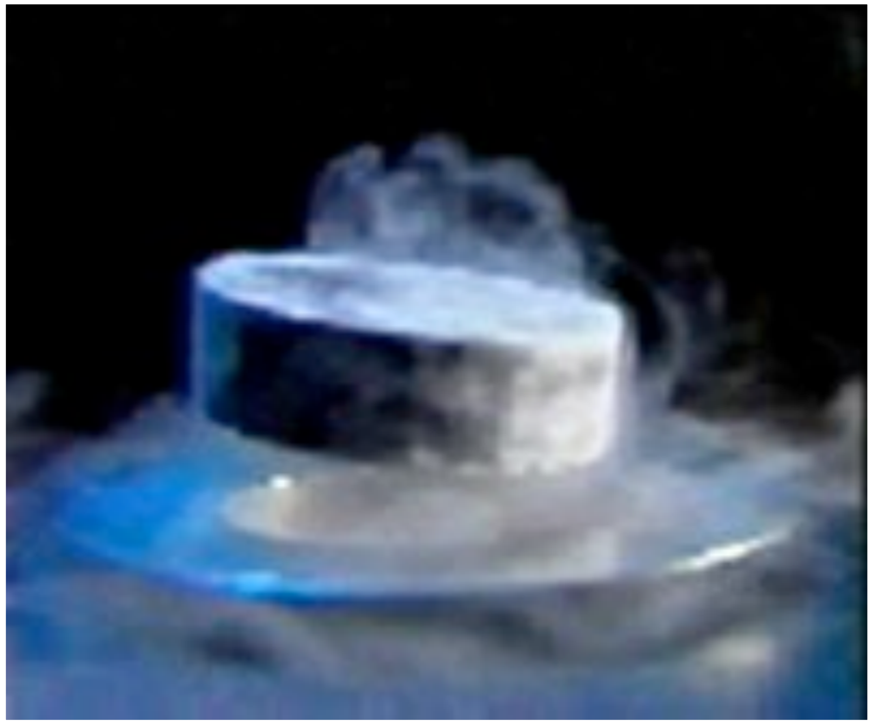
Chemistry Semiconductors Magnetism

Superconductors Fundamental Physics



Recent Applications of μSR

- > 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**



- > 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.

Magnetic Polarons

PHYSICAL REVIEW VOLUME 118, NUMBER 1 APRIL 1, 1960

Effects of Double Exchange in Magnetic Crystals*

P.-G. de Gennes†
Department of Physics, University of California, Berkeley, California

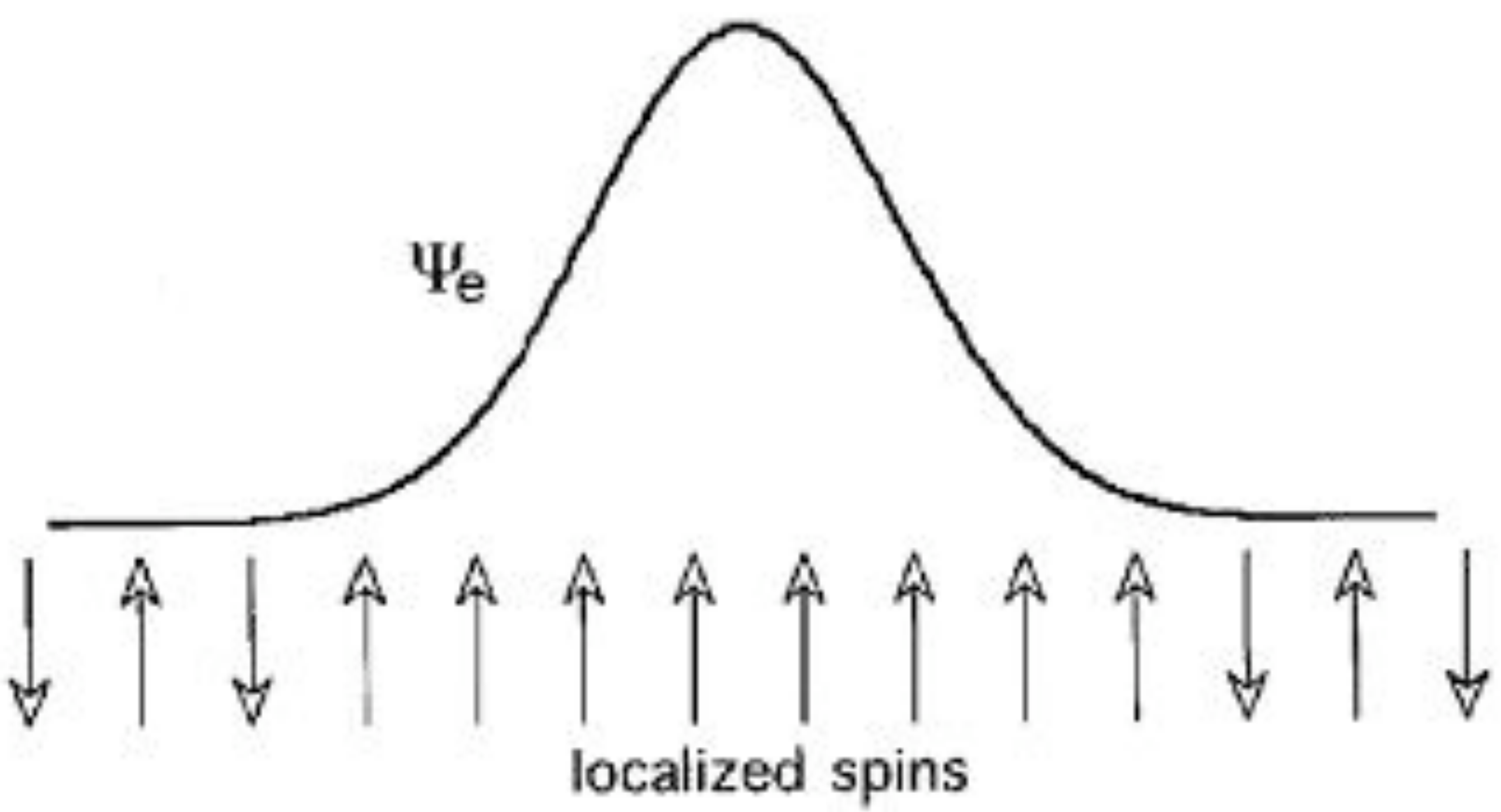
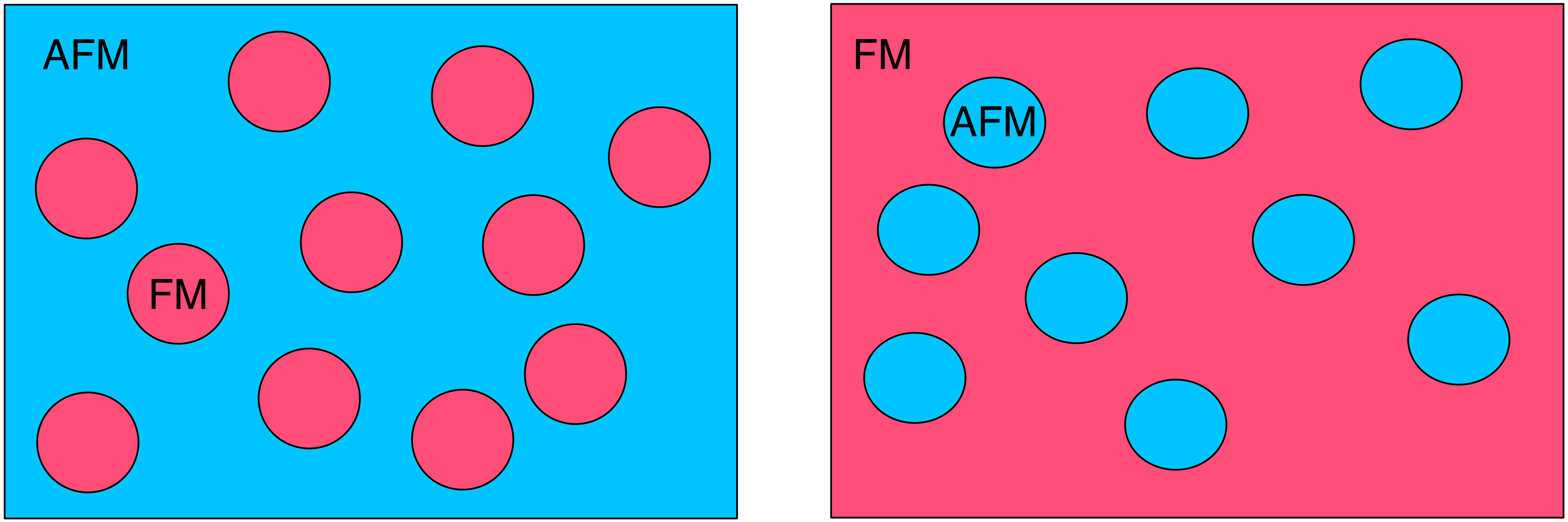


FIG. 1. Sketch of the Mott picture of the self-trapped magnetic polaron, indicating the disruption of the antiferromagnetic order and the creation of a ferromagnetic region, where the charge carrier becomes self-trapped. Arrows indicate the localized spins, while the line shows the wave function of the trapped electron.

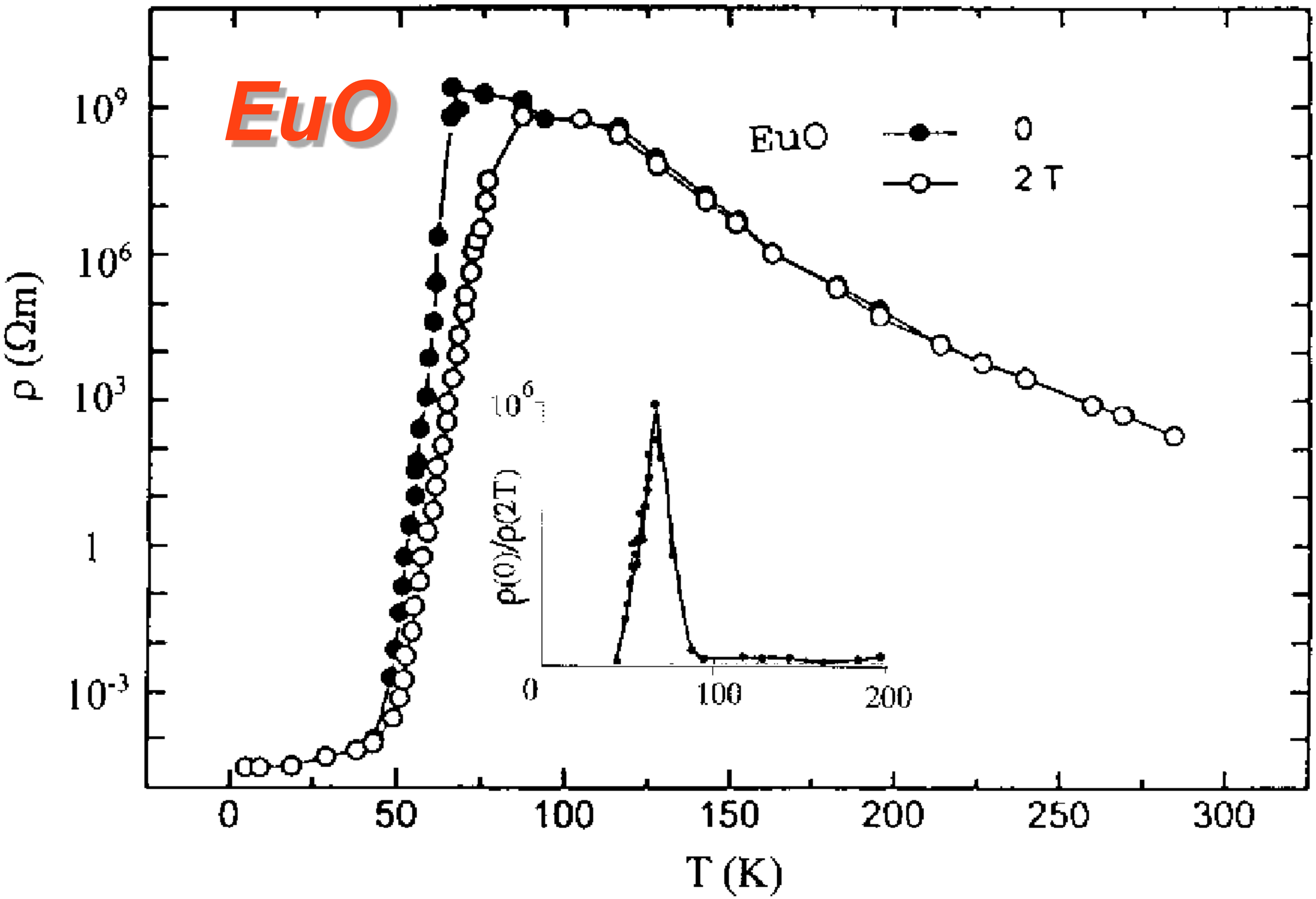
Phase Separation in
Degenerate Magnetic Semiconductors



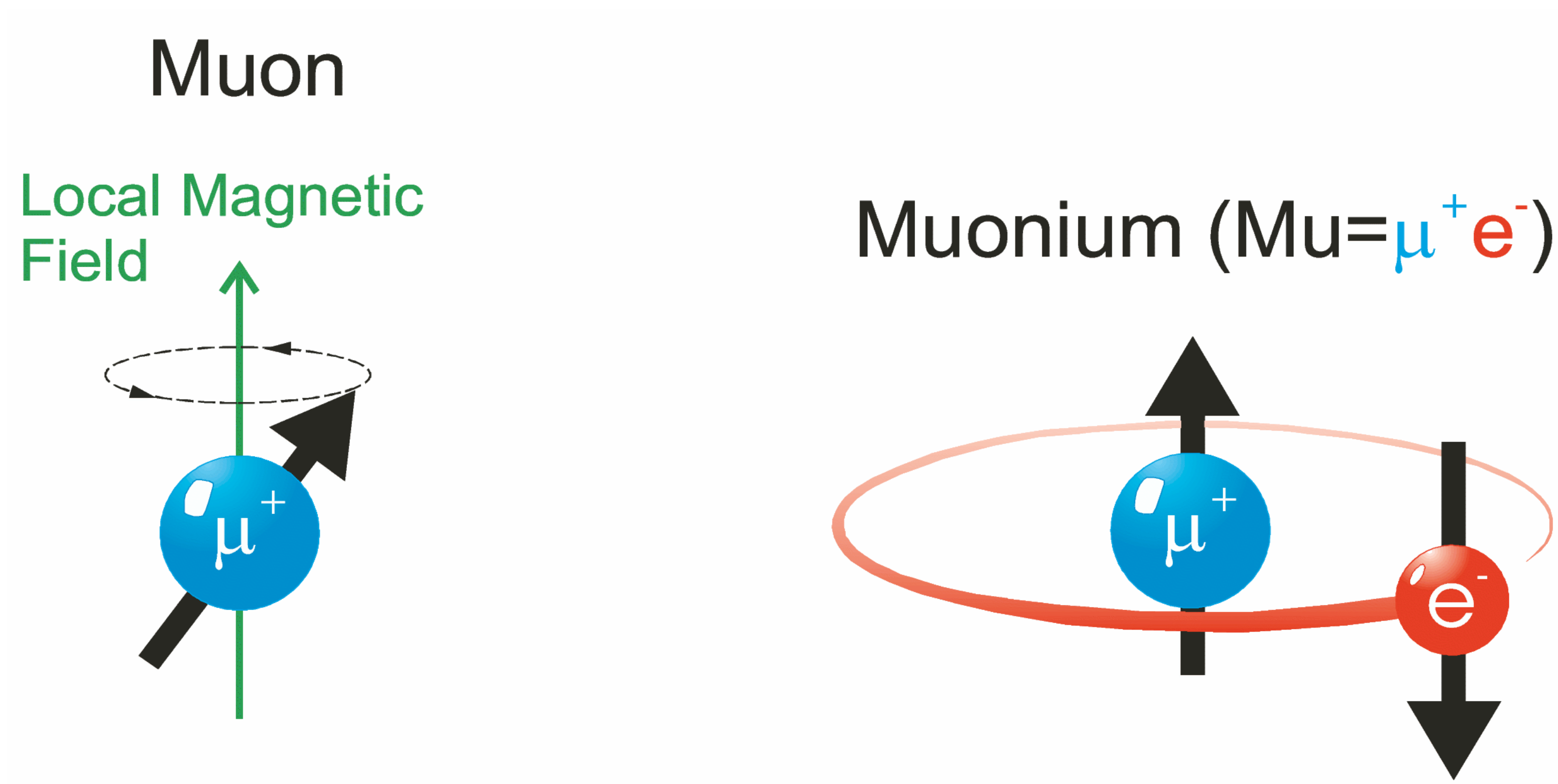
Phase-separated states of a degenerate semiconductor:
blue – *insulating* AFM; red – *conductive* FM

If an applied magnetic field can favor one phase over the other . . .

Metal-Insulator Transitions & CMR

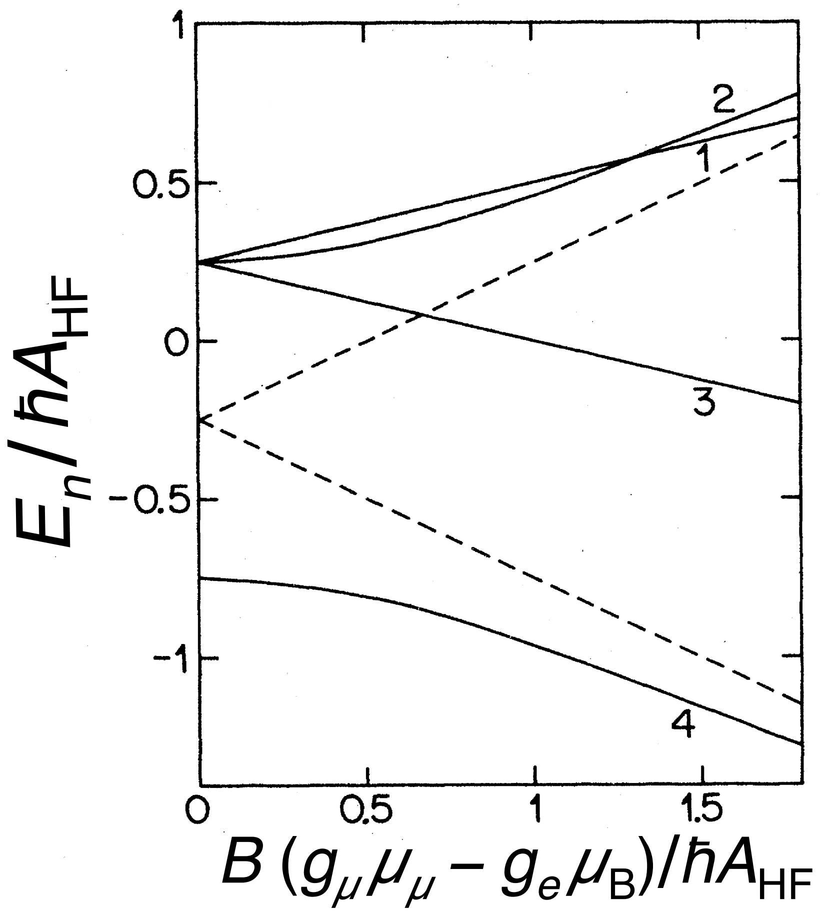


Muonium States in Semiconductors



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

Deep Mu centers *vs.* "Shallow" Mu centers



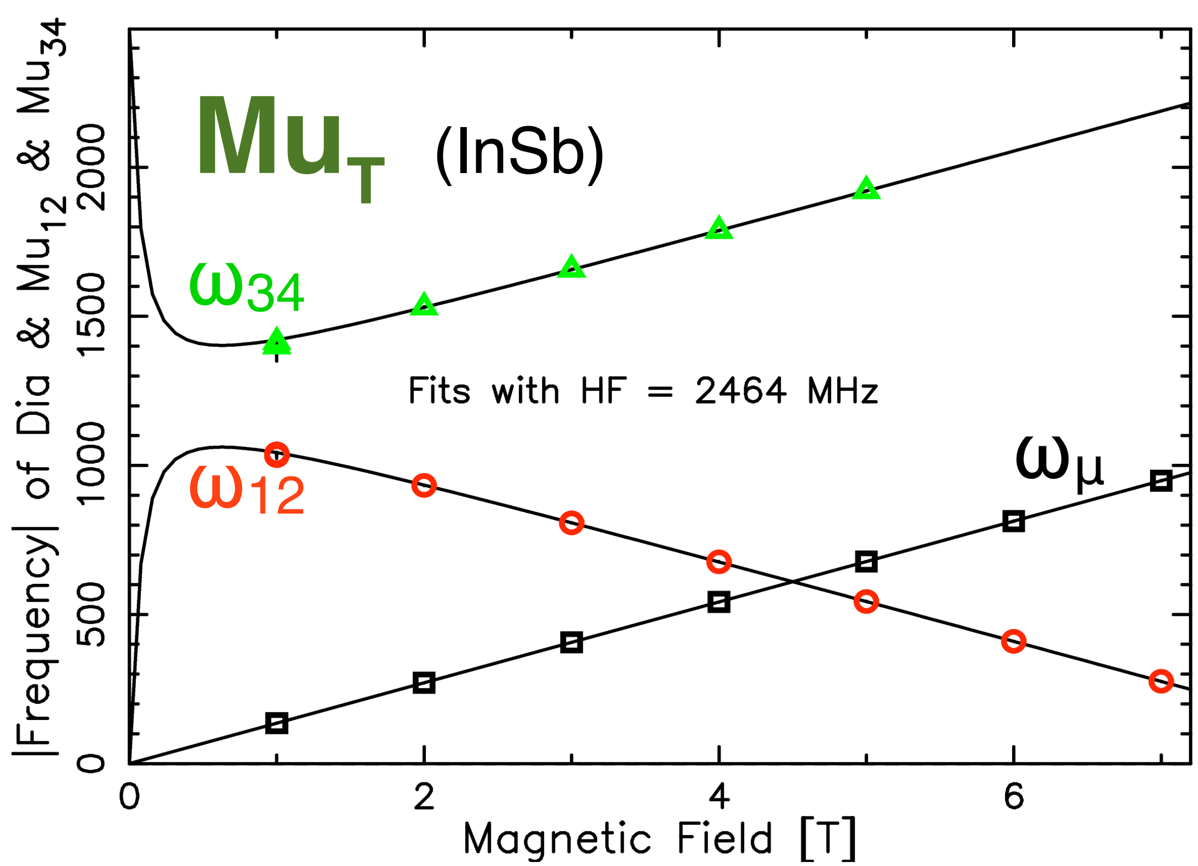
Breit–Rabi diagram

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

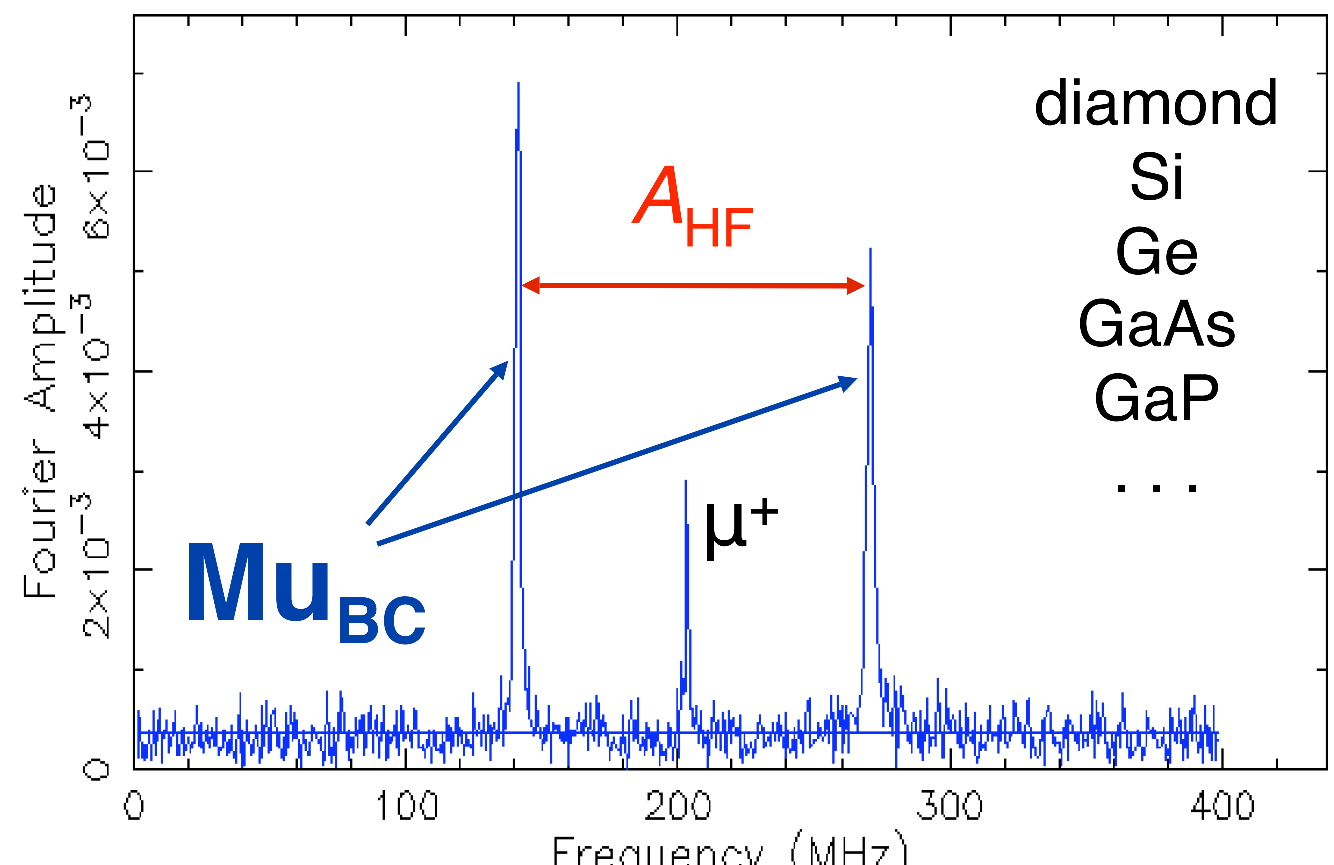
Wide-gap insulators: ~ same A_{HF} as in vacuum

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

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

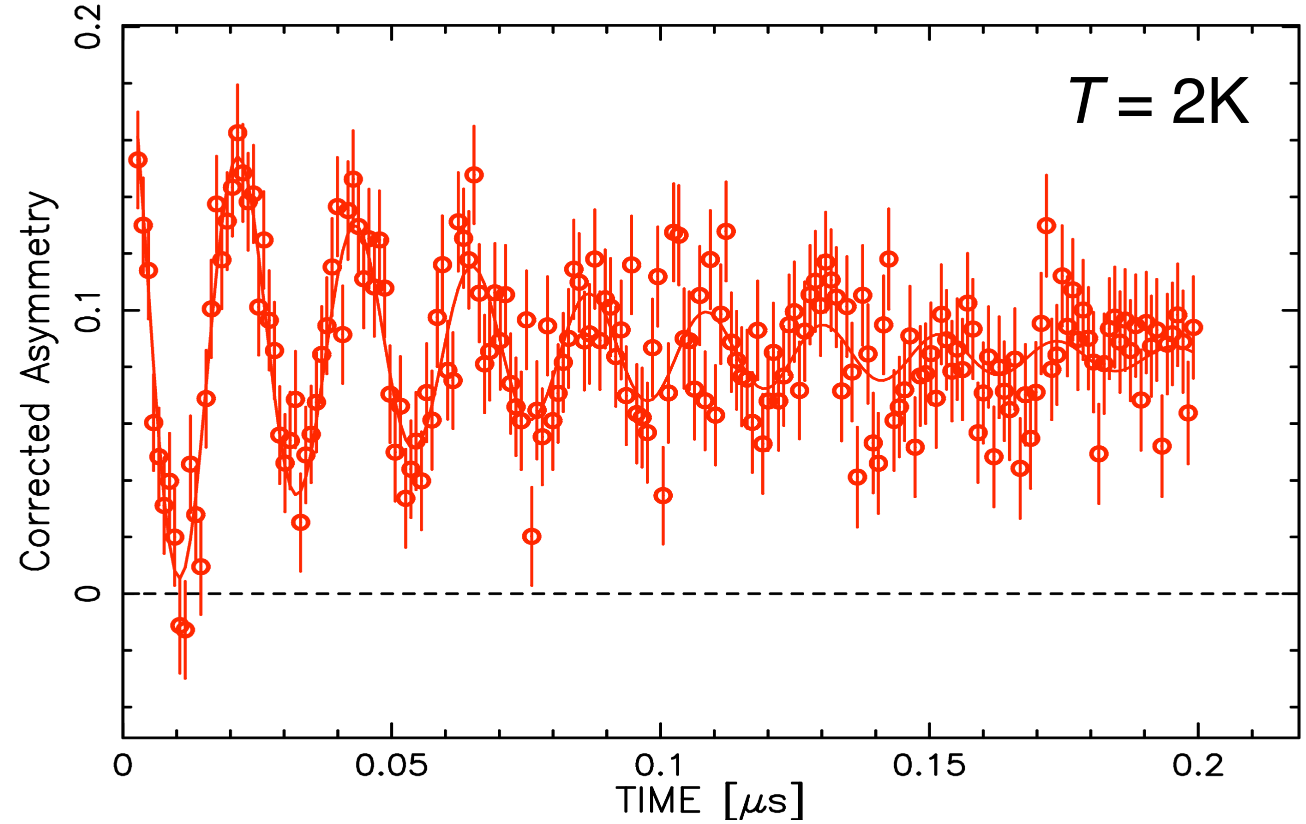


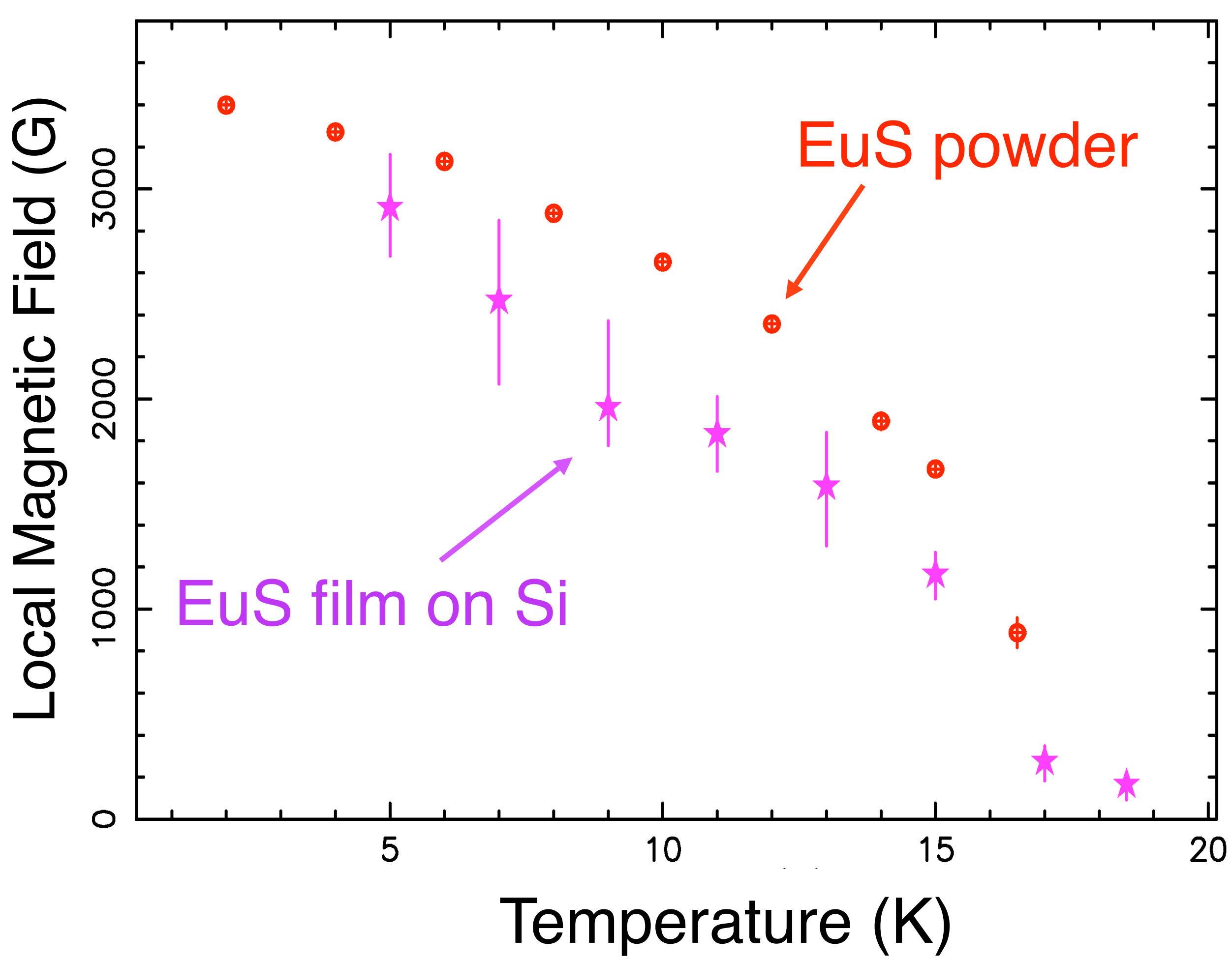
high field limit

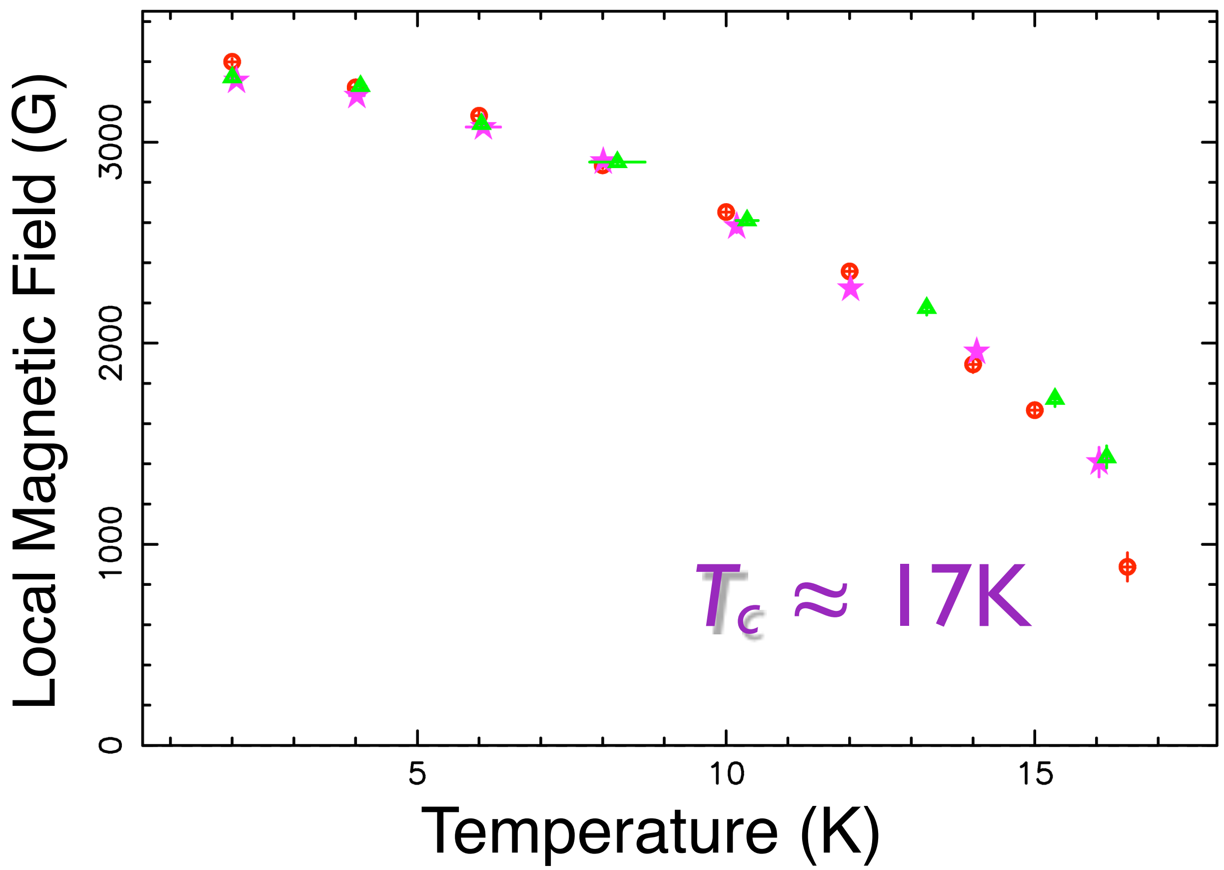


µSR in EuS

Zero applied magnetic field



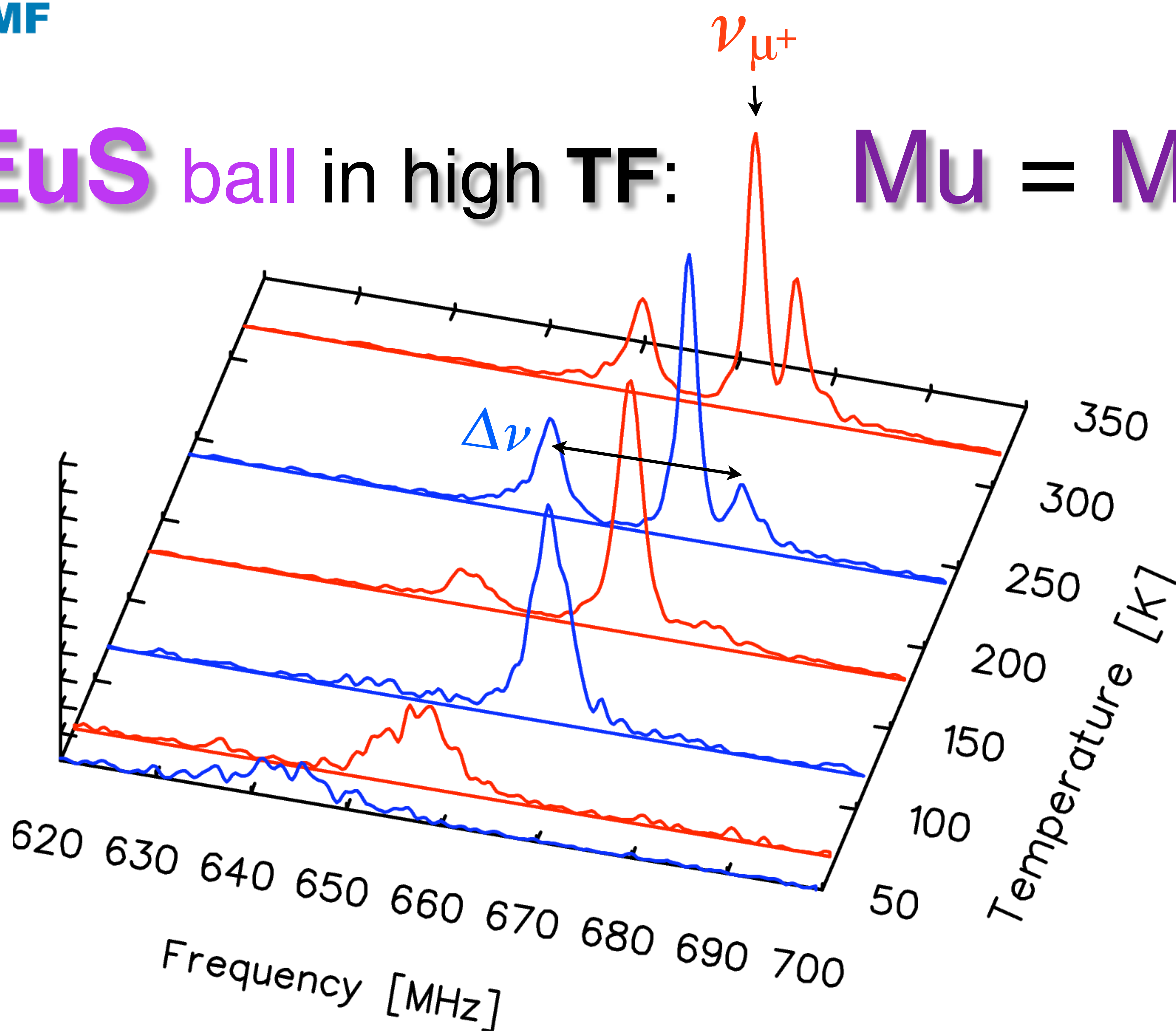




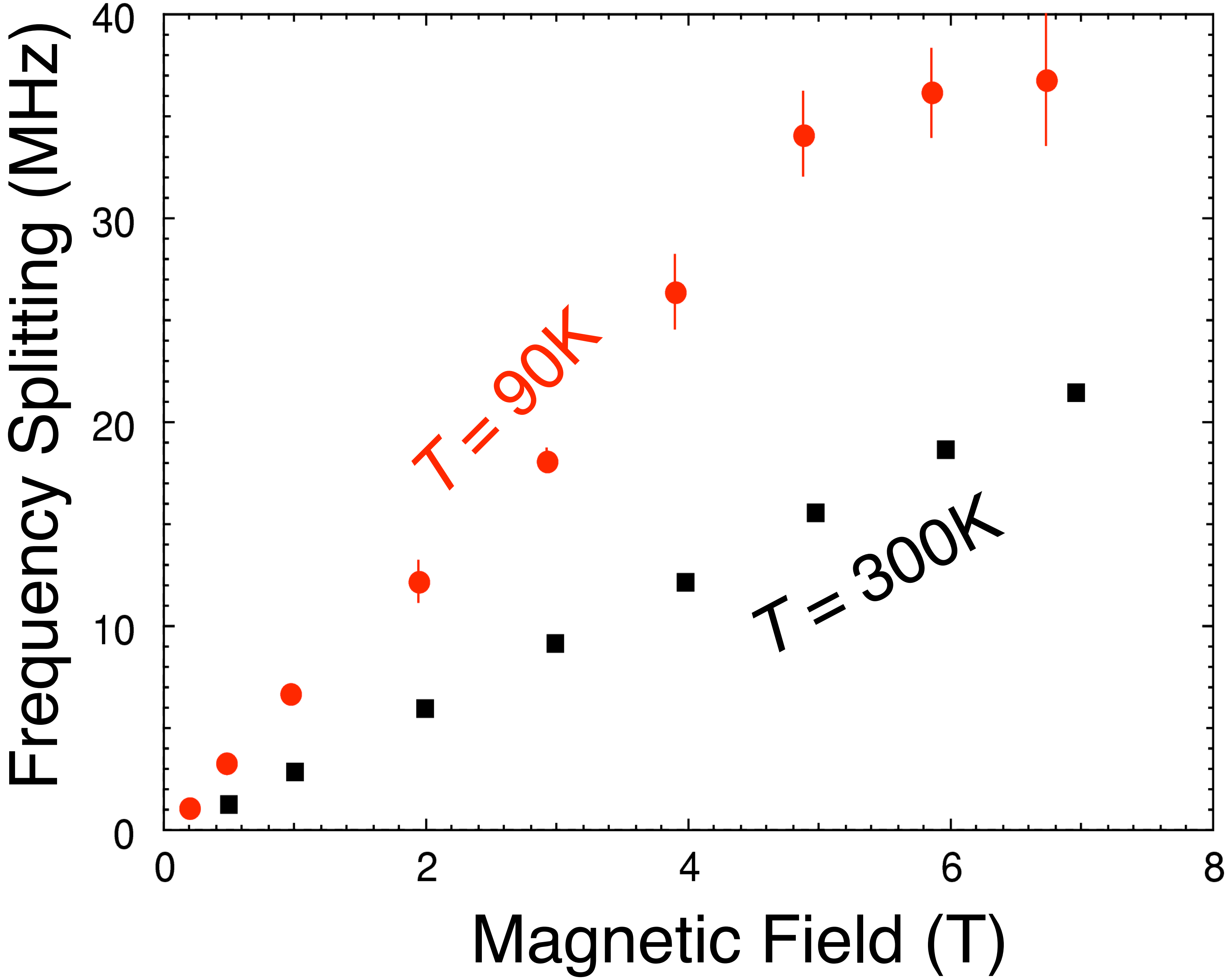
Single frequency (below T_c)

$\Rightarrow$ 1 site for bare μ^+

EuS ball in high TF: Mu = MP



EuS ball



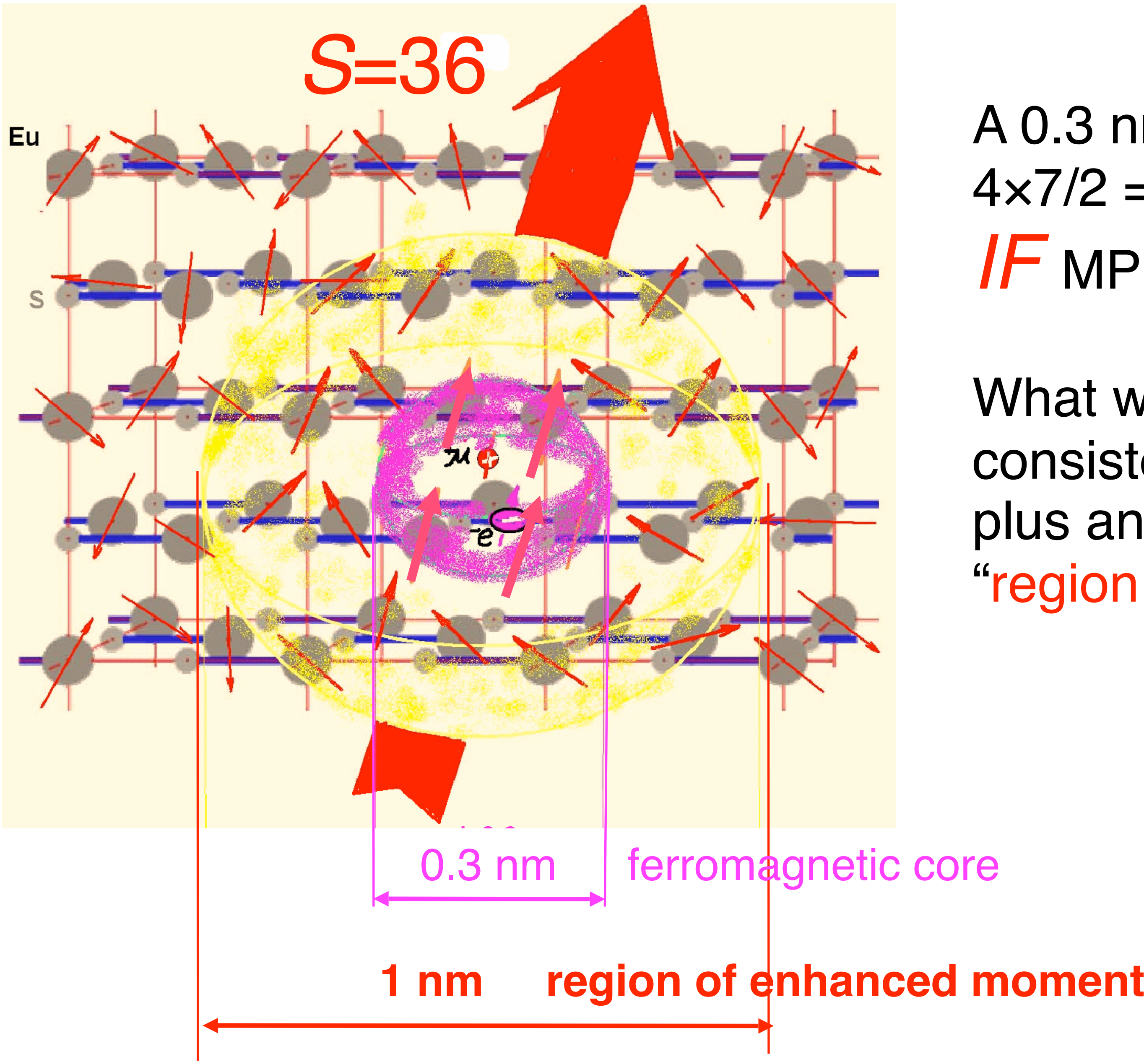
$A = (37 \pm 3)$ MHz

$R = 0.3$ nm

$S = 36 \pm 4$

$$\Delta\nu = A(g\mu_B B/3kT)(S+1)$$

The MP bound to the μ^+ in EuS:

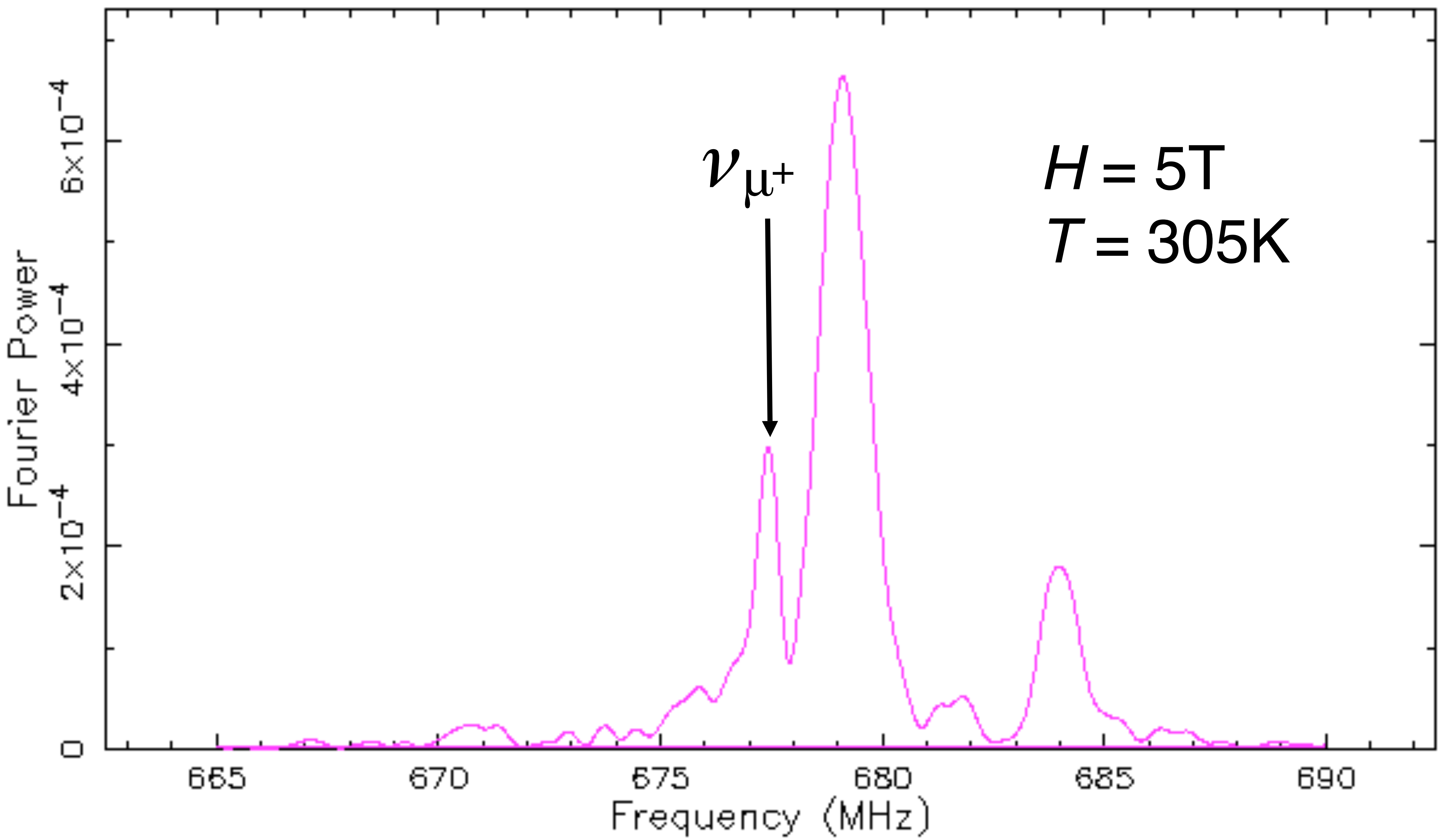


A 0.3 nm sphere contains 4 Eu atoms; 4×7/2 = 14, so total spin should be 14.5 *IF* MP is fully saturated.

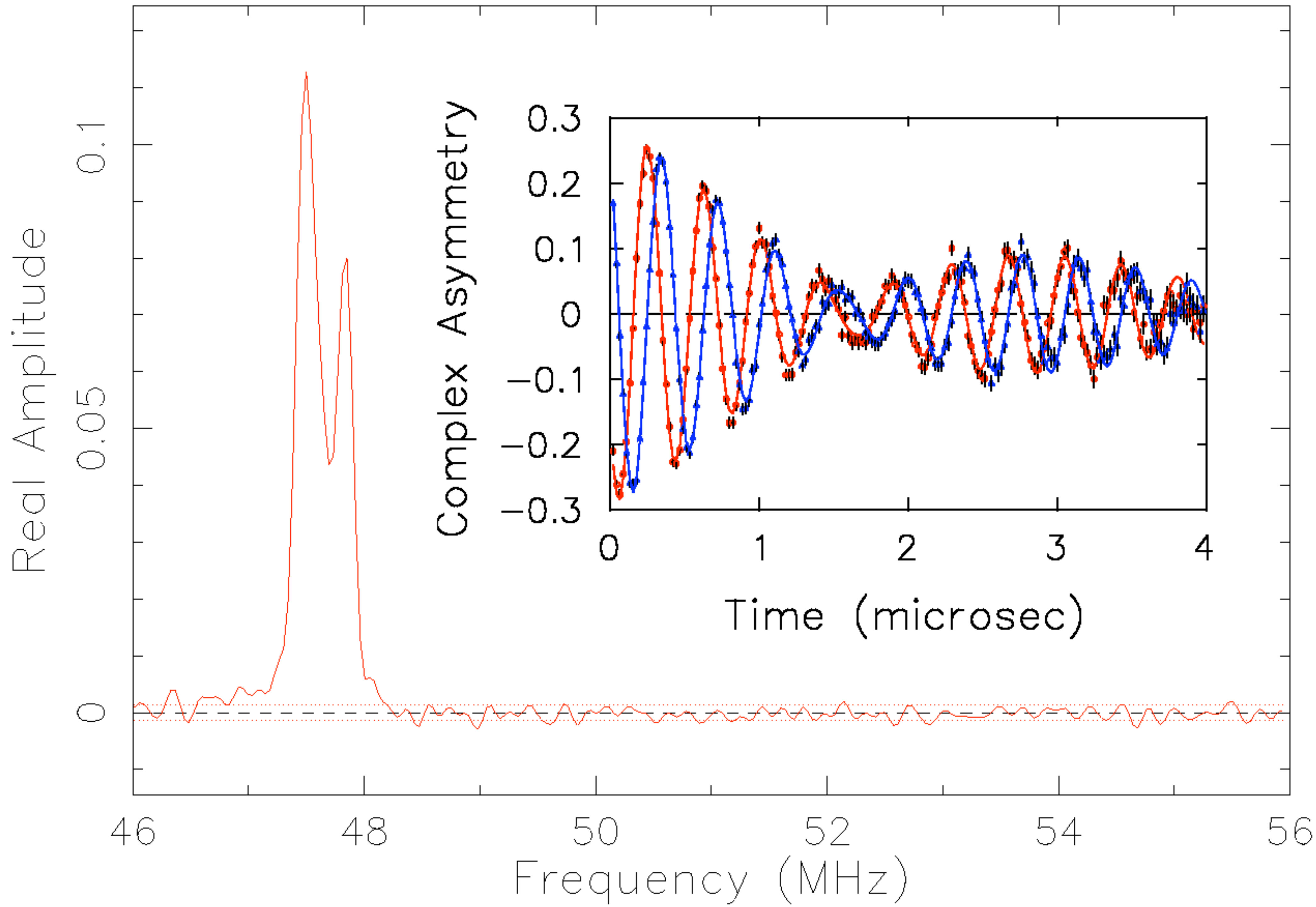
What we see is *S*=36,
consistent with a fully saturated core
plus an unsaturated
"region of enhanced magnetic moment"

Similar results in EuO, EuS, EuSe, EuTe.

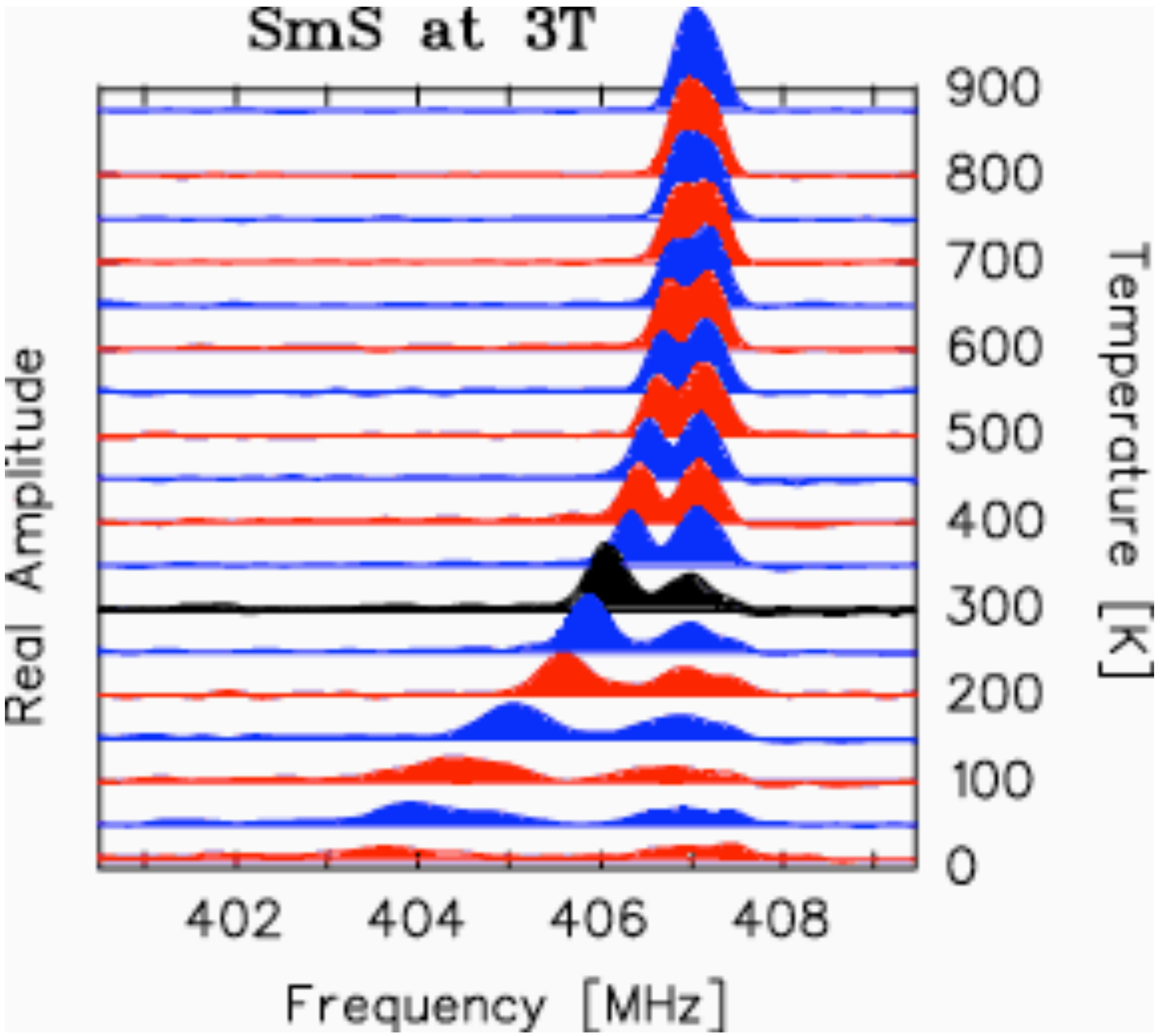
$CdCr_2Se_4$ single crystal

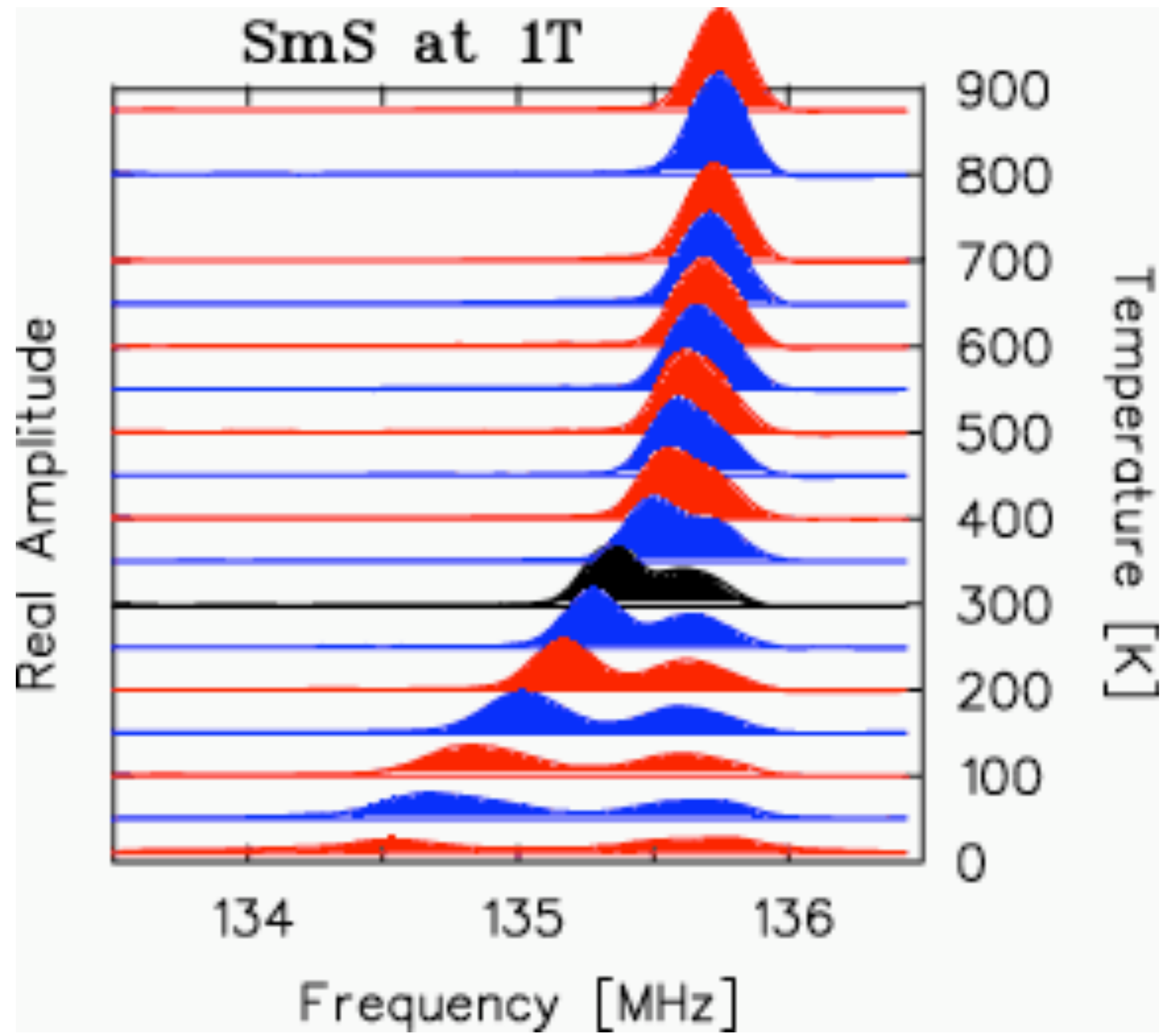


SmS $H = 0.35T$ $T = 40K$

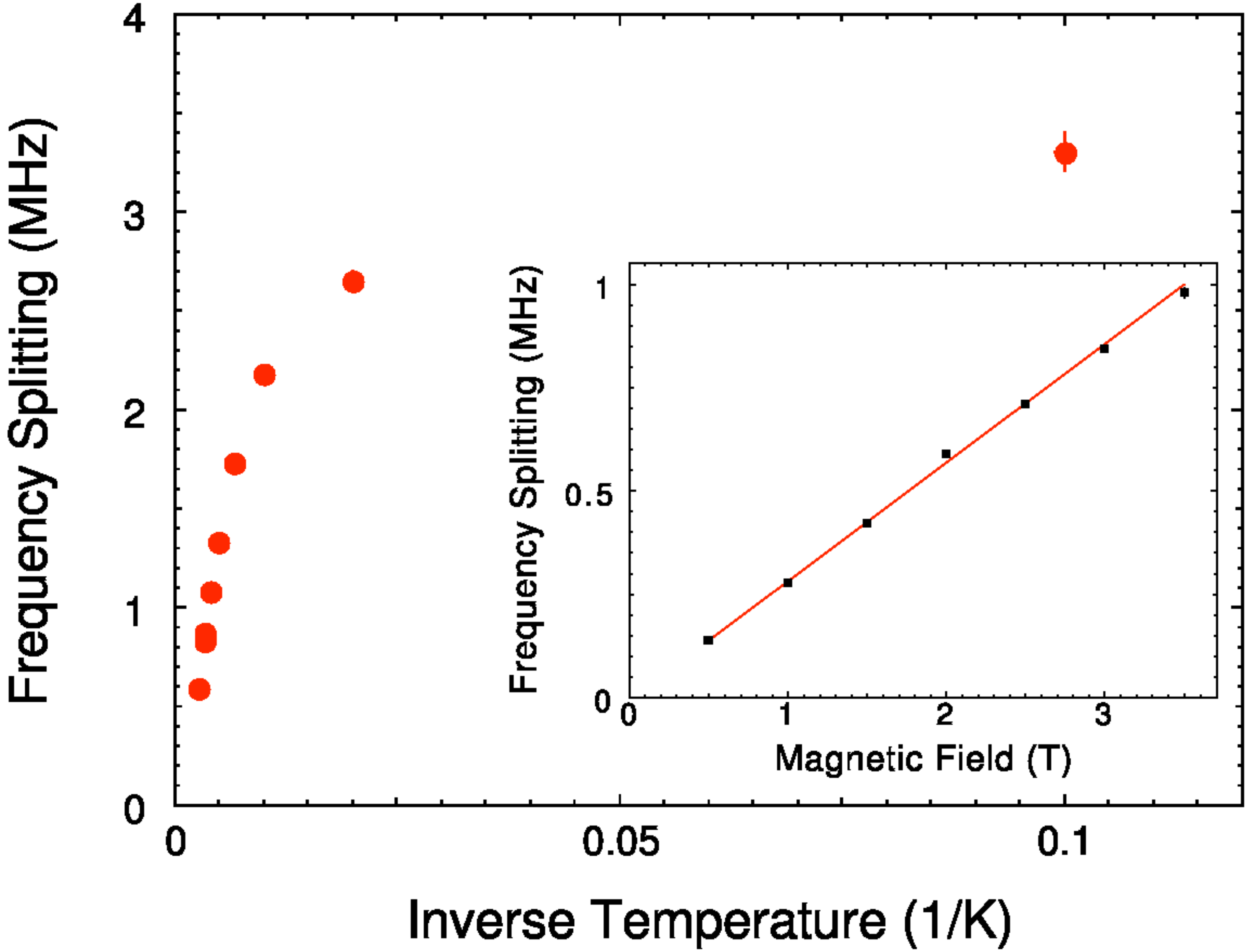


Magnetic Polaron in SmS





SmS



A = 3.5 MHz

R = 0.55nm

S = 30

$g\mu_B B/kT << 1 \quad \Rightarrow \quad \Delta\nu = A(g\mu_B B/3kT)(S+1)$

$g\mu_B B/kT >> 1 \quad \Rightarrow \quad \Delta\nu = A$

History of μSR

- pre-1956: Fantasy
- 1956-7: Revolution!
  π-μ-e decay and μSR
- 1958-73: Science Fiction
  Michel Parameters
  QED tests with Muonium
  "Problems" → Applications
- 1970s: Meson Factories
  SIN/PSI, LAMPF, TRIUMF,
  KEK/BOOM, RAL/ISIS
- '80s & '90s: Routine Science
  μSR Methods developed
  "Themes" in μSR
- 2000s: TRIUMF **CMMS**:
  Chemistry & Semiconductors
  Magnetism & Superconductors
  Fundamental Physics
- FUTURE: Applied Science
  (No more magic? Don't count on it!)

Finis