TRIUMF Summer Institute 2011

New Directions, Current Issues in μSR and βNMR

W.A. MacFarlane, UBC Chemistry

Plan

A. New Materials
B. New Technical Advances
C. New Independent Variables (not T,B)
D. New Syntheses

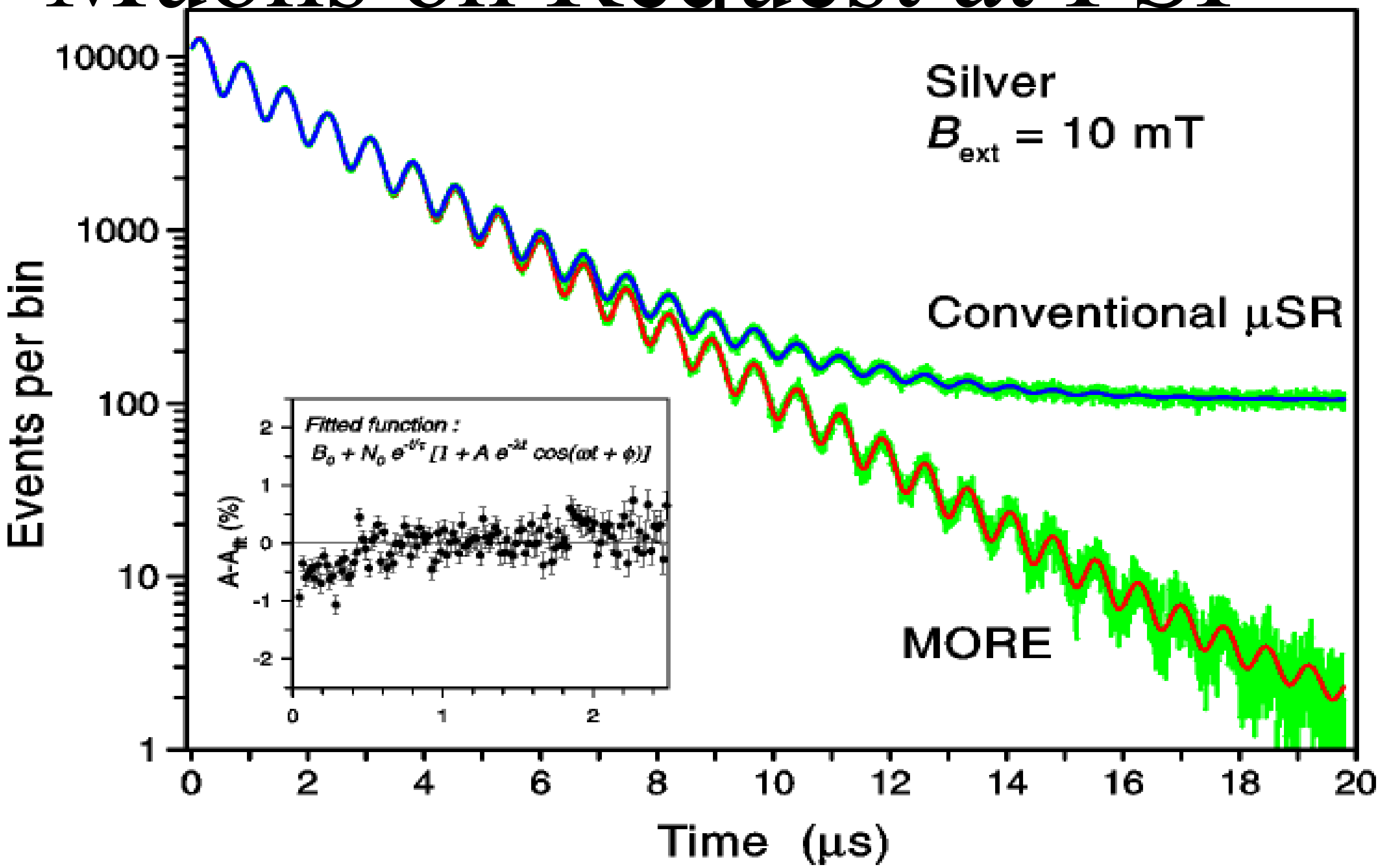
A. New Materials

New Superconductors, e.g. Fe-pnictides
New magnetic materials
Soft matter (see McKenzie, L19)
Less simple than single crystals: metamaterials, supramolecular materials, self assembled structures…

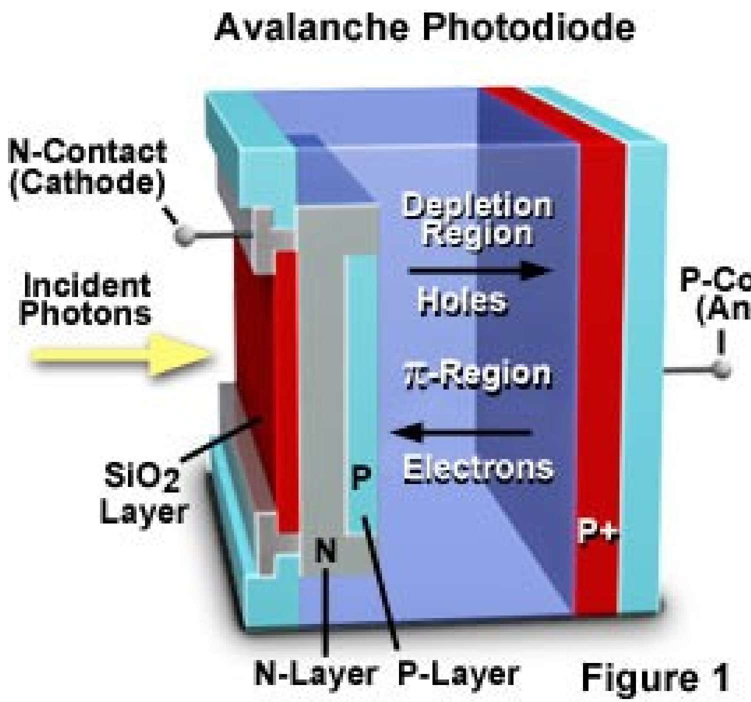
B. New Technical Advances

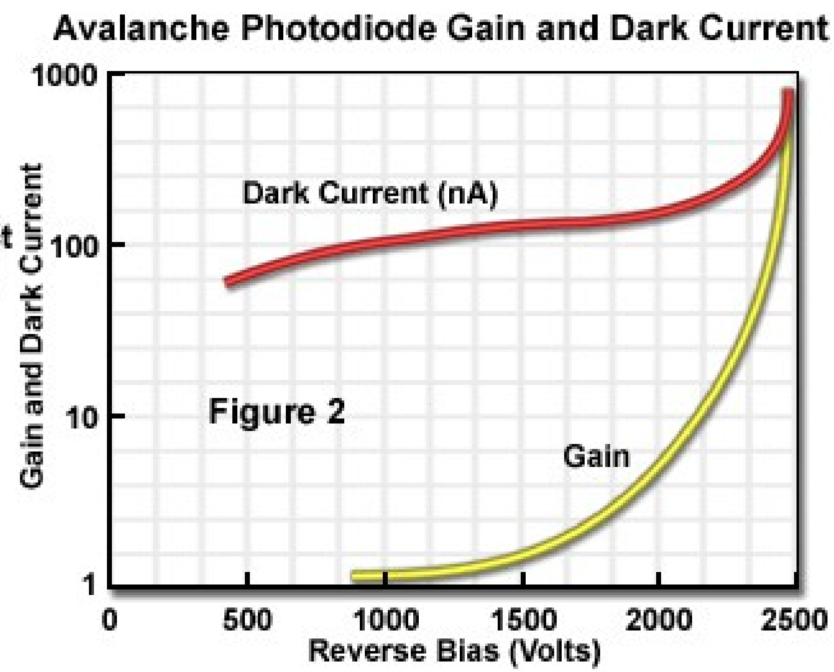
MORE (Muons On REquest) – for slower relaxations
MULTI – parallellism – many experiments at once with position-sensitive detectors
ssPMT – smaller, field independent detectors
High Magnetic Fields – high B phenomena, resolution of small relative shifts
Other βNMR probes – 11Be, 15O, …

Muons on Request at PSI



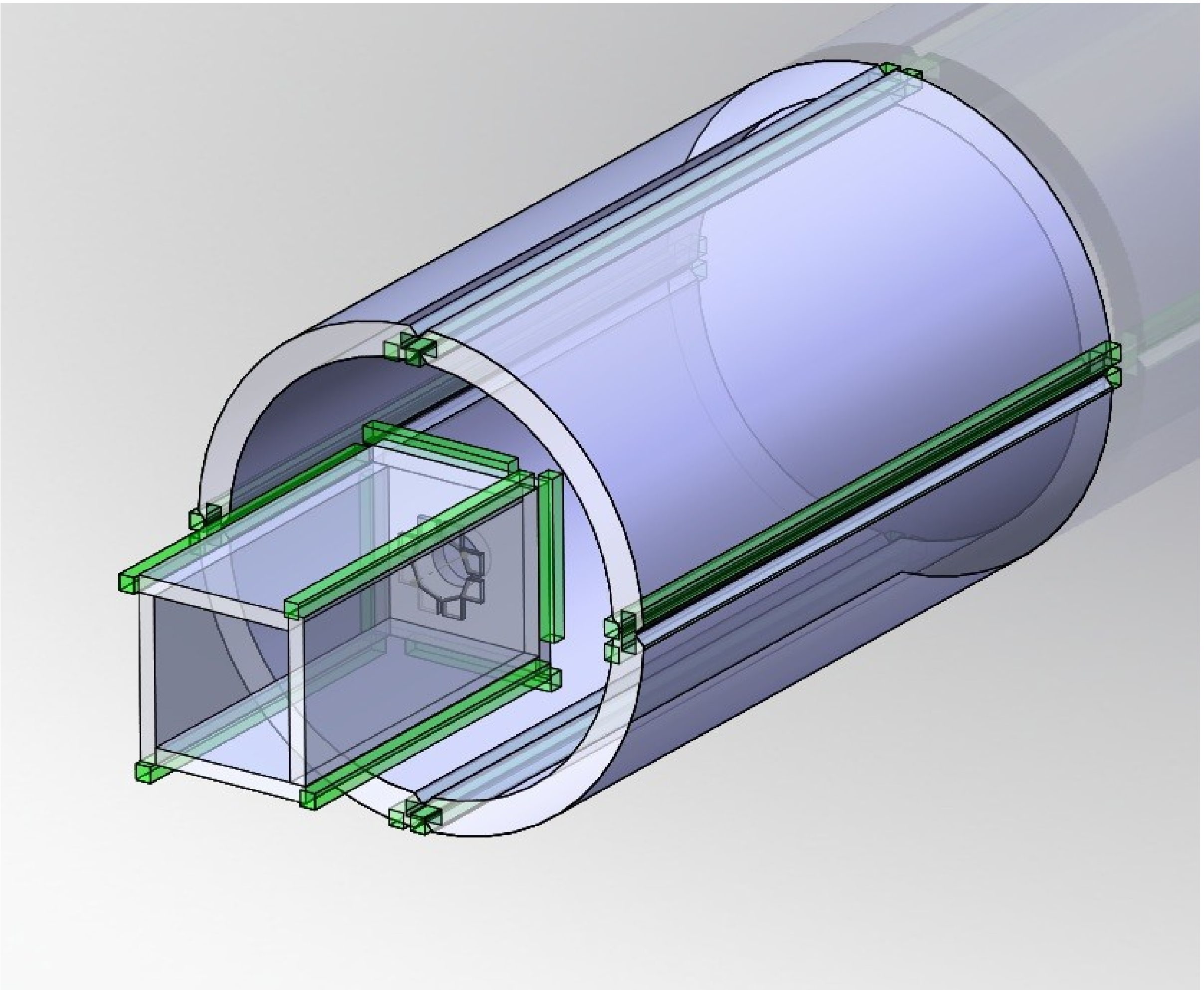
Avalanche Photodiodes (APD) solid-state "PMT"s





K. Boone, F. Retière

solid-state “PMT”s



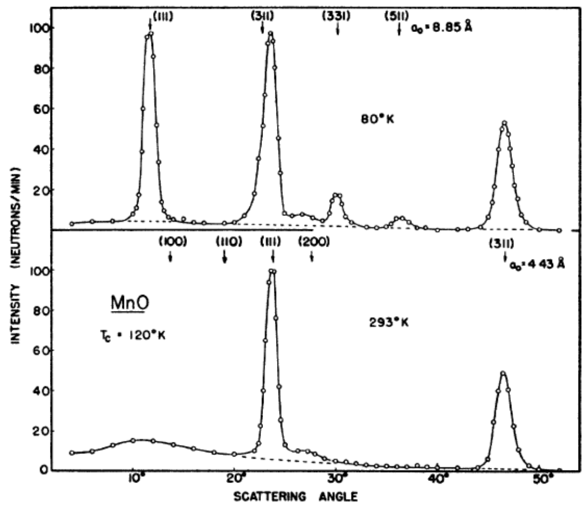
- Scintillator
- Wave shifting fibre
- APD

K. Boone, F. Retière

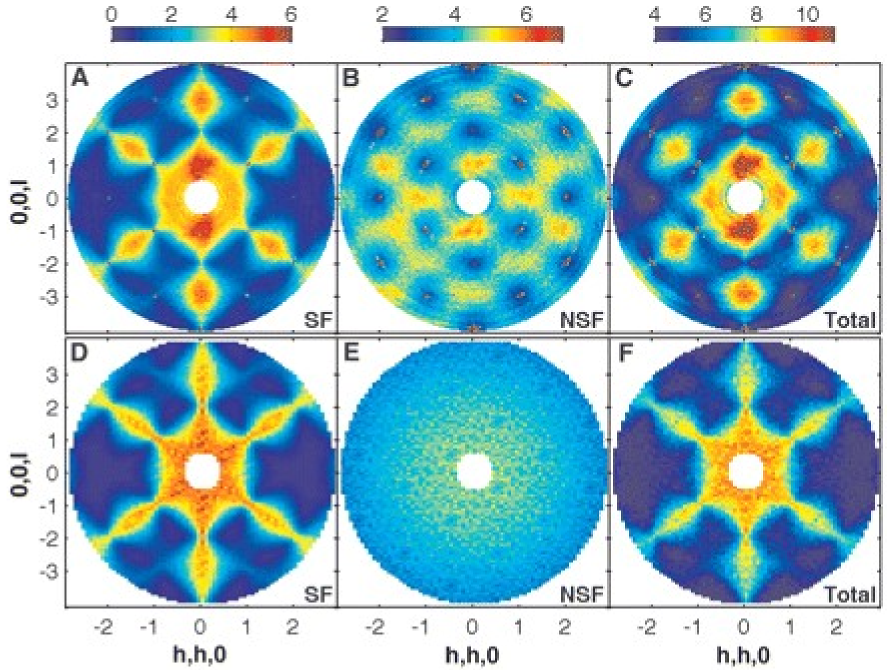
Data Analysis and Visualization

Data Analysis and Visualization

Elastic magnetic
neutron scattering
circa 1950

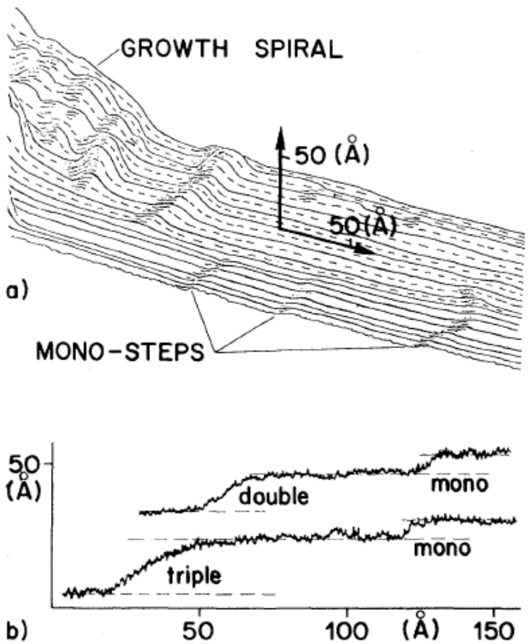


(Diffuse) Elastic magnetic
neutron scattering
circa 2009

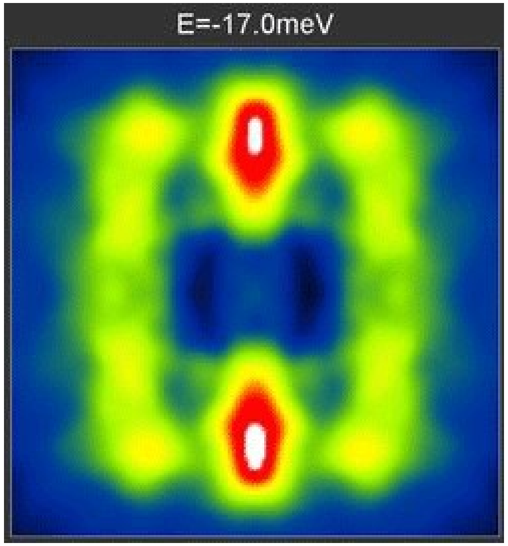


Data Analysis and Visualization

STM circa 1982



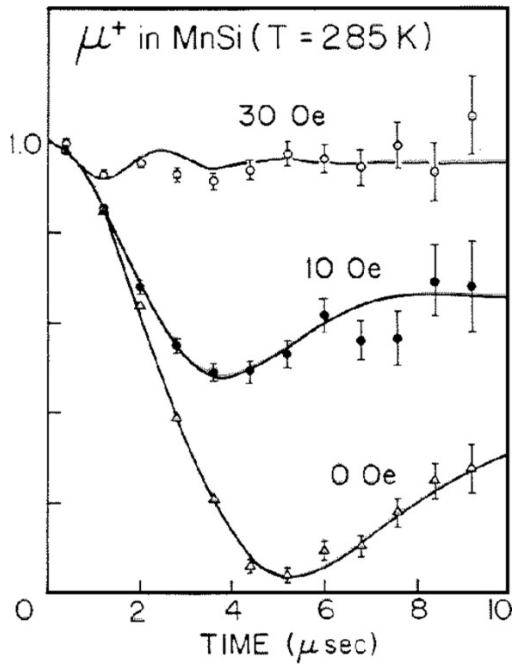
STM circa 2010



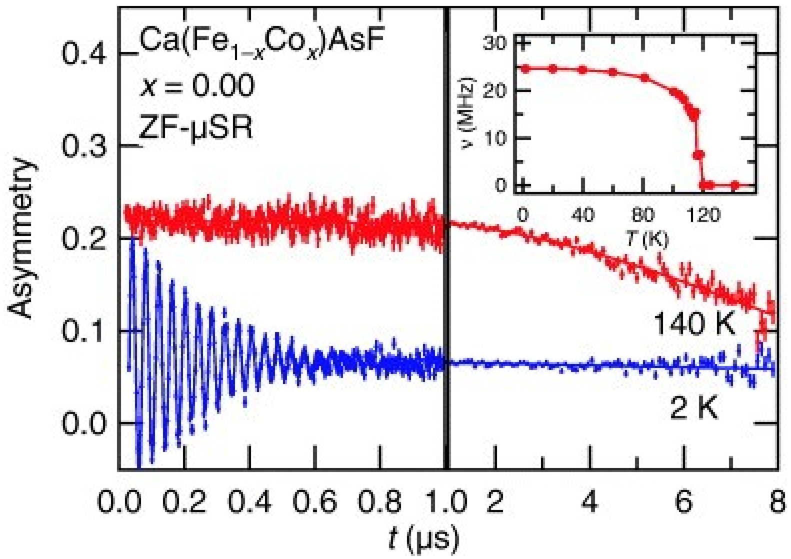
Fourier Transform of Conductance
- see Science 327, 181

Data Analysis and Visualization

μSR circa 1978



μSR circa 2009



Could use something …

http://www.gapminder.org/

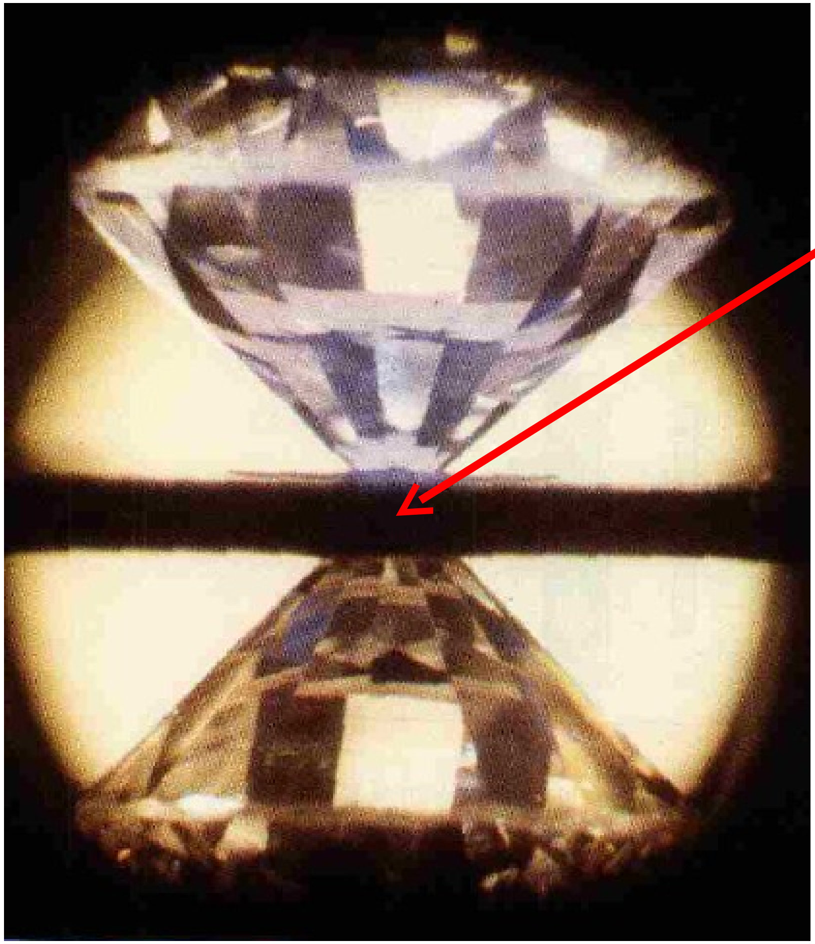
C. New Independent Variables

1. Pressure
2. Illumination
3. Electric Field
4. Electric Current
5. Probe Implantation Depth (LEμSR, βNMR)

1. Pressure

Why is pressure interesting?

A **diamond anvil cell** (up to 300 GPa)



A ring shaped metal gasket

The sample:

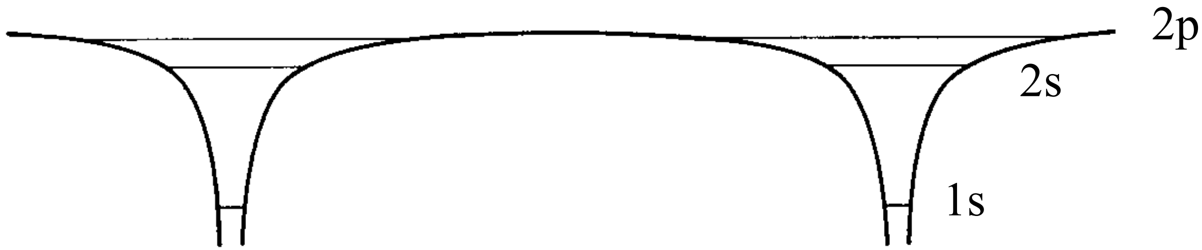
Density can be increased by more than 10× !

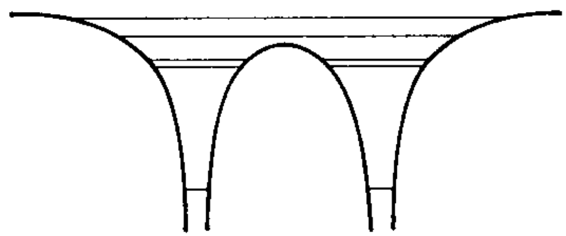
e.g. pressure can cause Insulator → Metal

see Hemley and Ashcroft, Physics Today, Aug. 1998

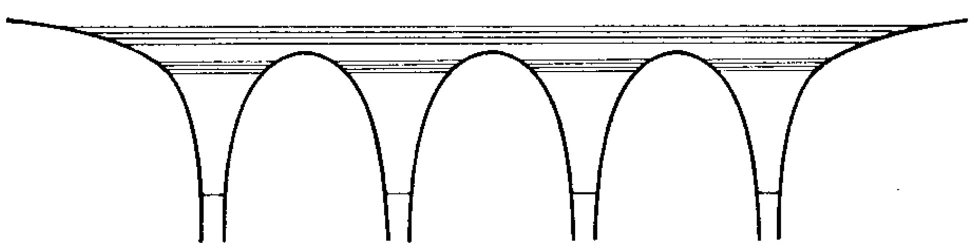
Formation of Energy Bands

Insulator



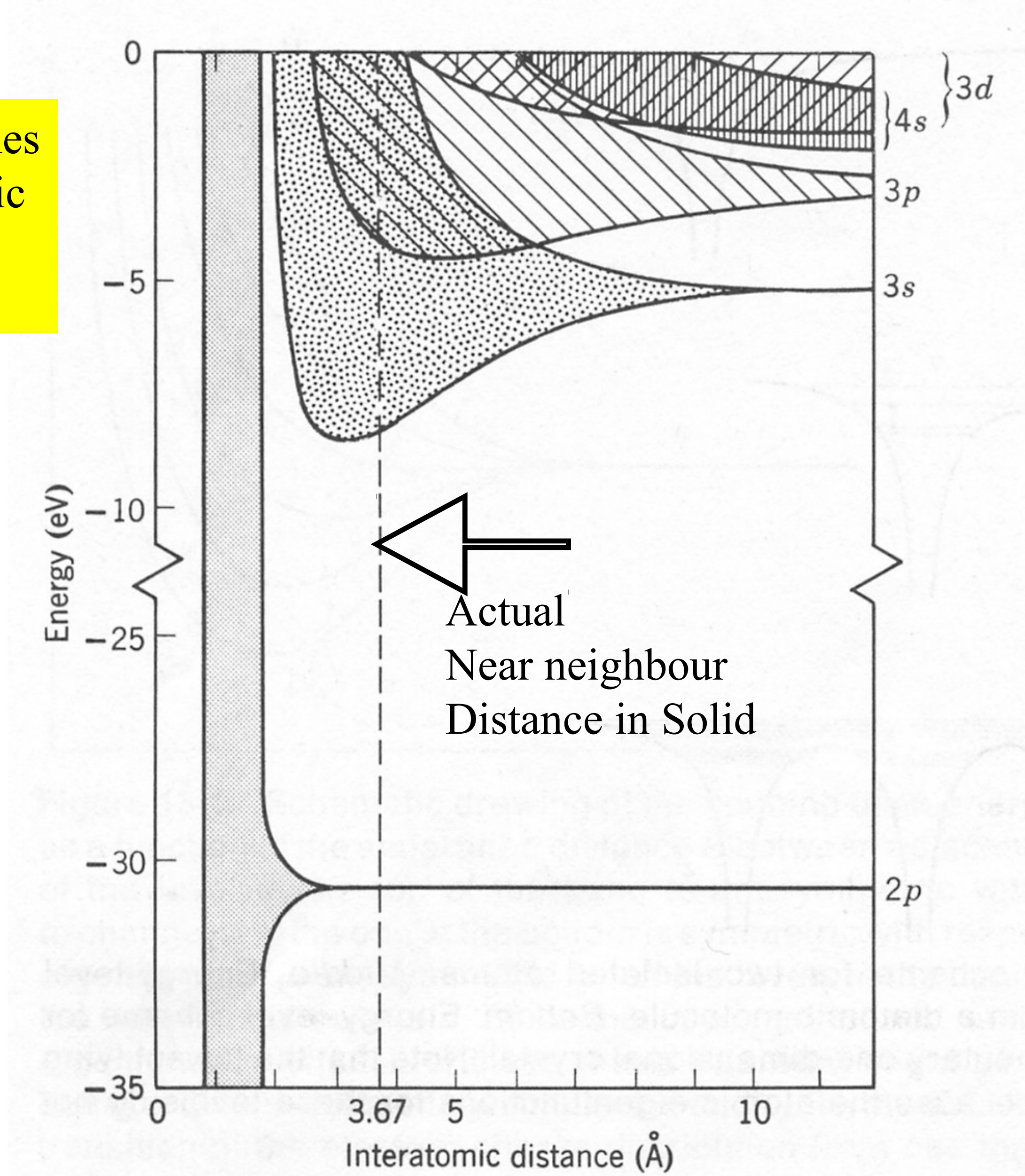


Possibly a metal



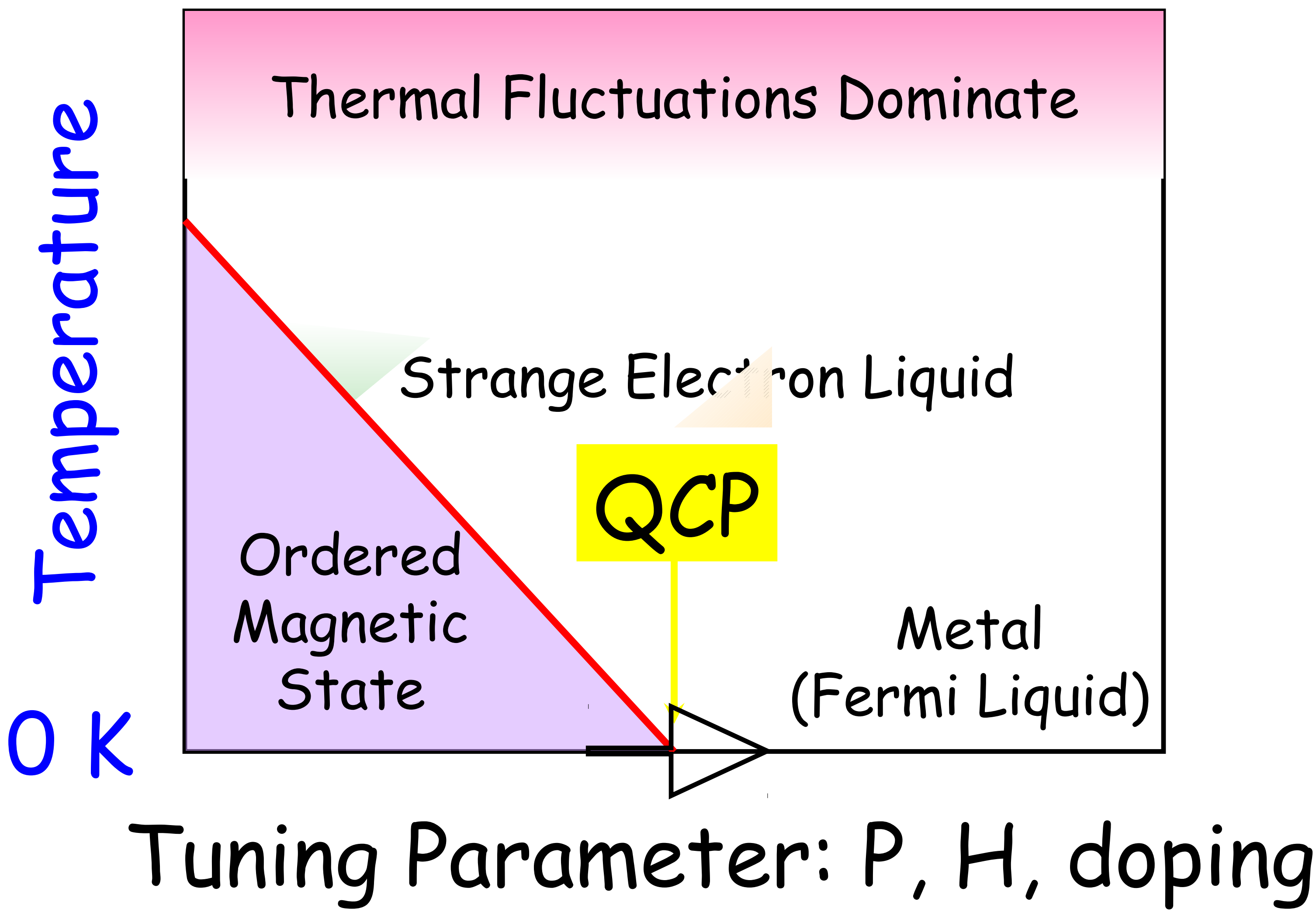
Bands in Na as *d* is varied

Pressure tunes the electronic structure of a solid!



At high enough pressure Na starts to behave as a transition metal

Quantum Criticality



An example

Manganese Silicide (MnSi)

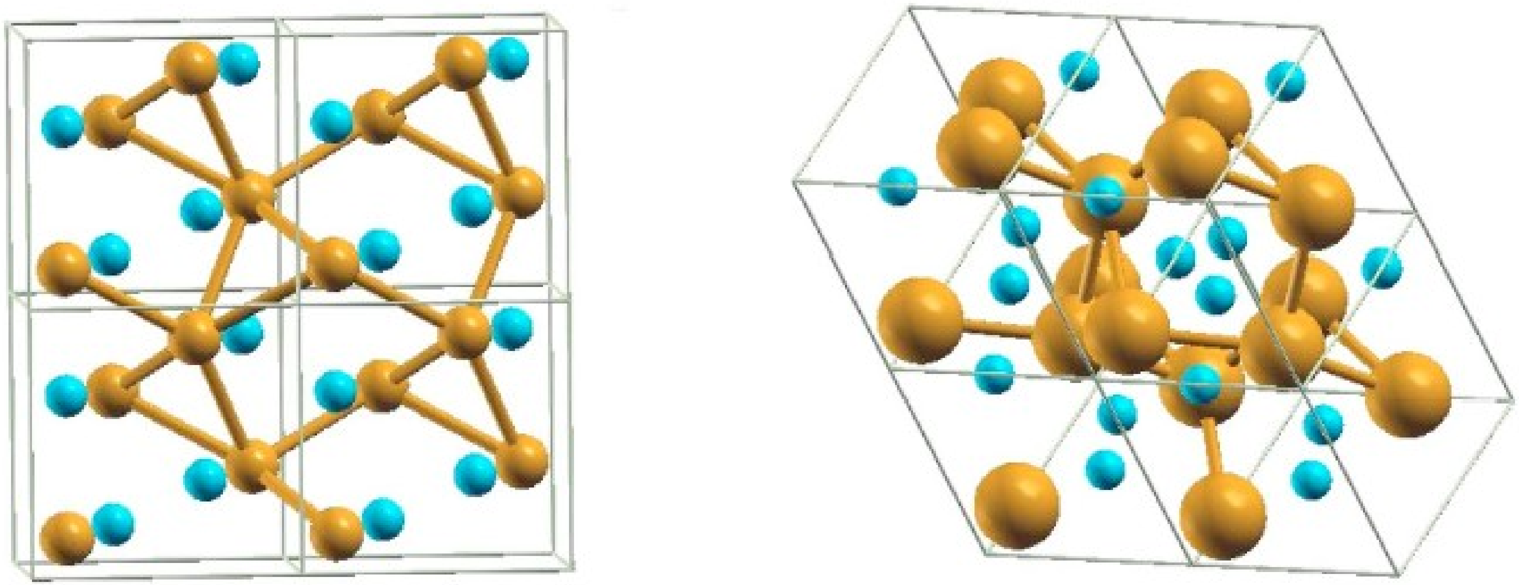
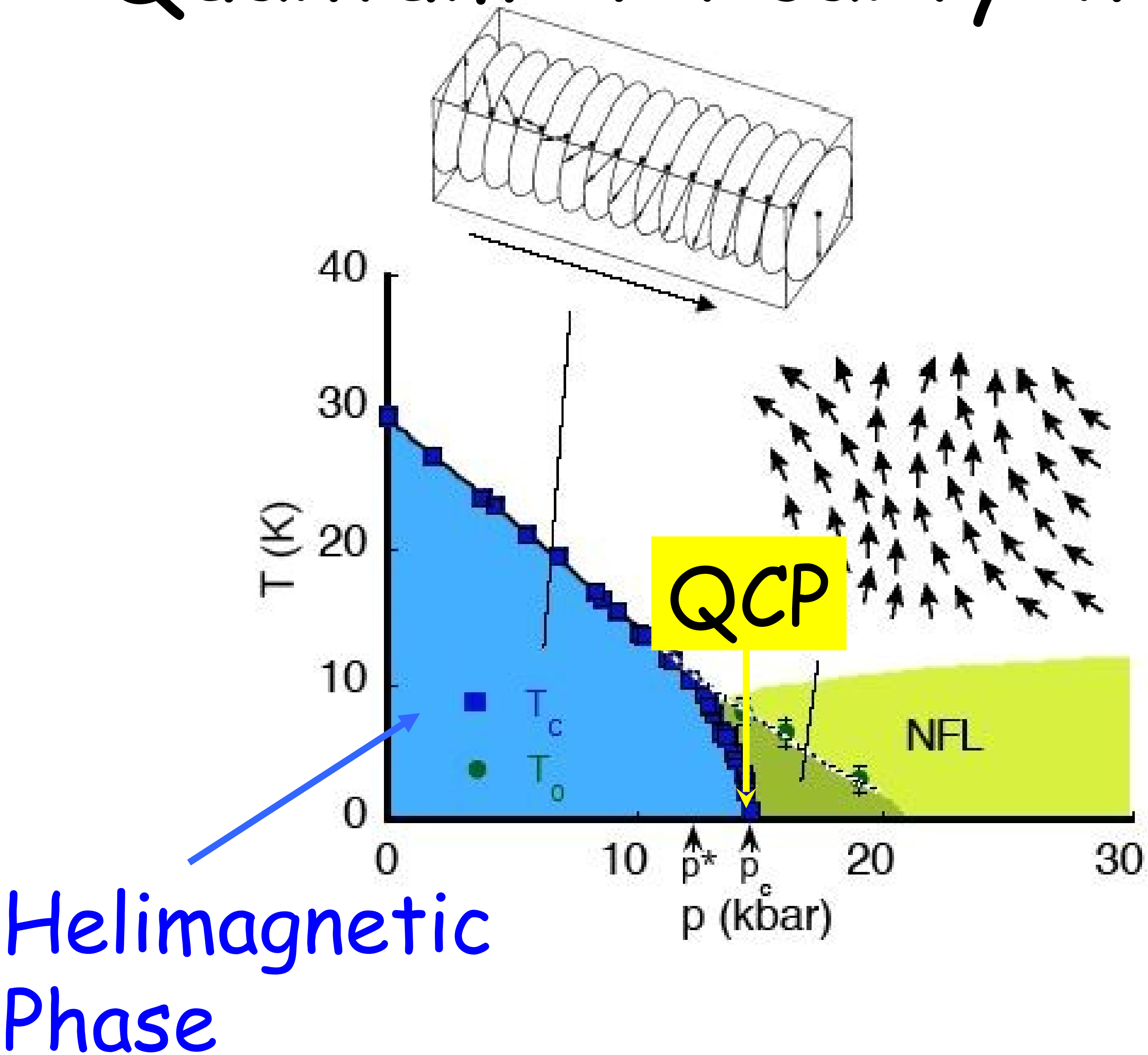


FIG. 1. (Color online) Two views of the B20 crystal structure of MnSi, showing four cubic cells. The larger atoms are Mn and are connected by sticks; the smaller spheres are Si atoms. Top: a view along the (111) direction. Bottom: view nearly along the (100) axis.

Jeong and Pickett PRB (04)

Quantum Criticality in MnSi



C. Pfleiderer

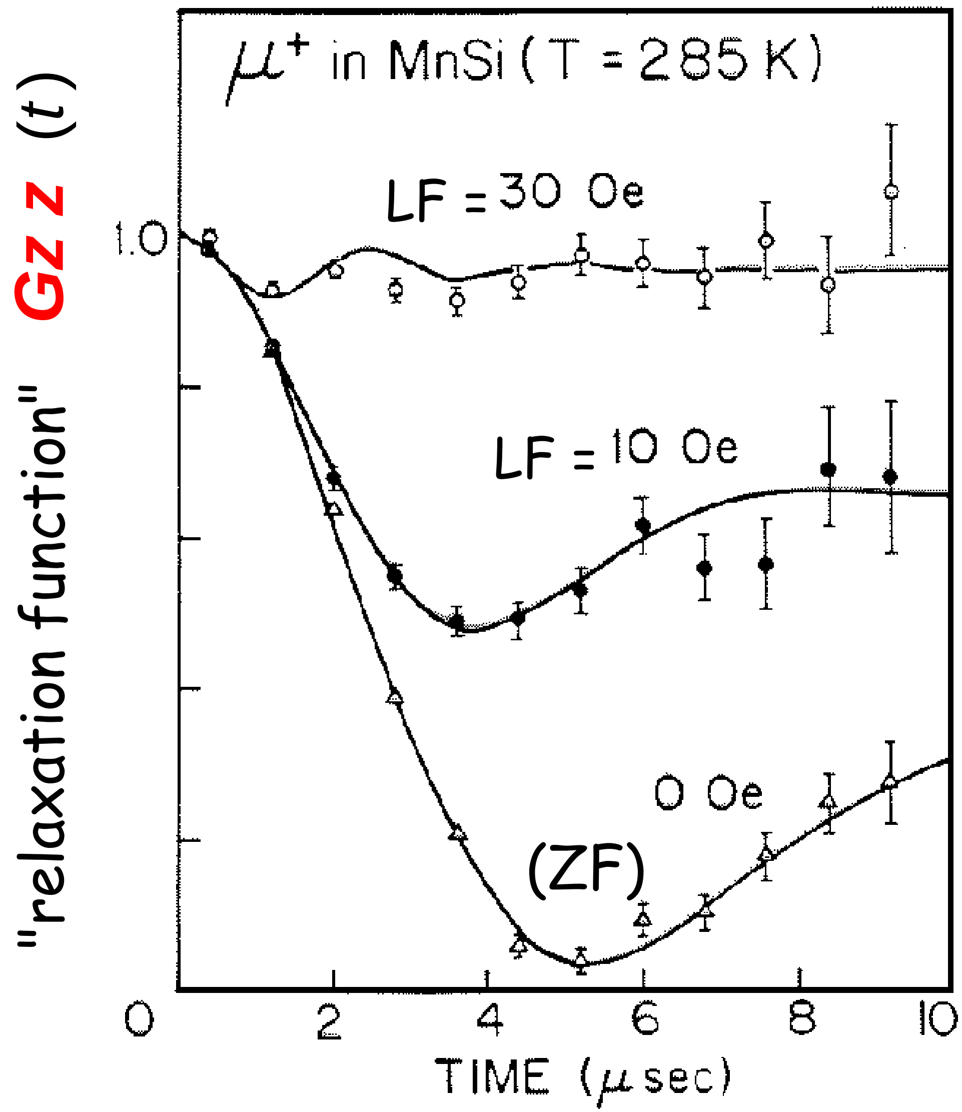
Non Fermi Liquid Resistivity

T3/2 above
critical
pressure
or TC

Pfleiderer, Julian, Lonzarich: PRB 1997

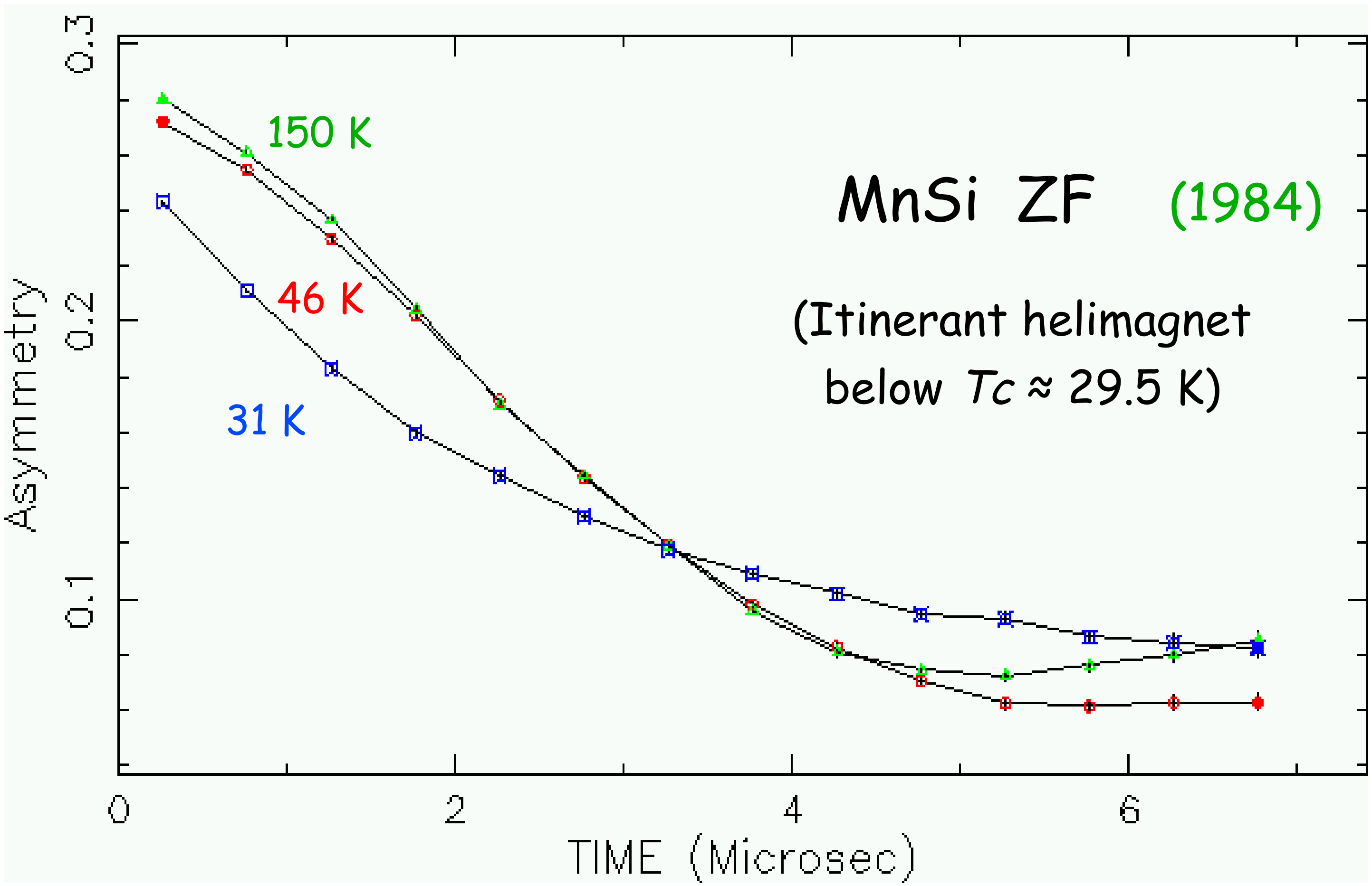
ZF-μ+SR:

Kubo-Toyabe Relaxation due to Nuclear Dipolar Fields



Hayano, Uemura *et al.*, 1978

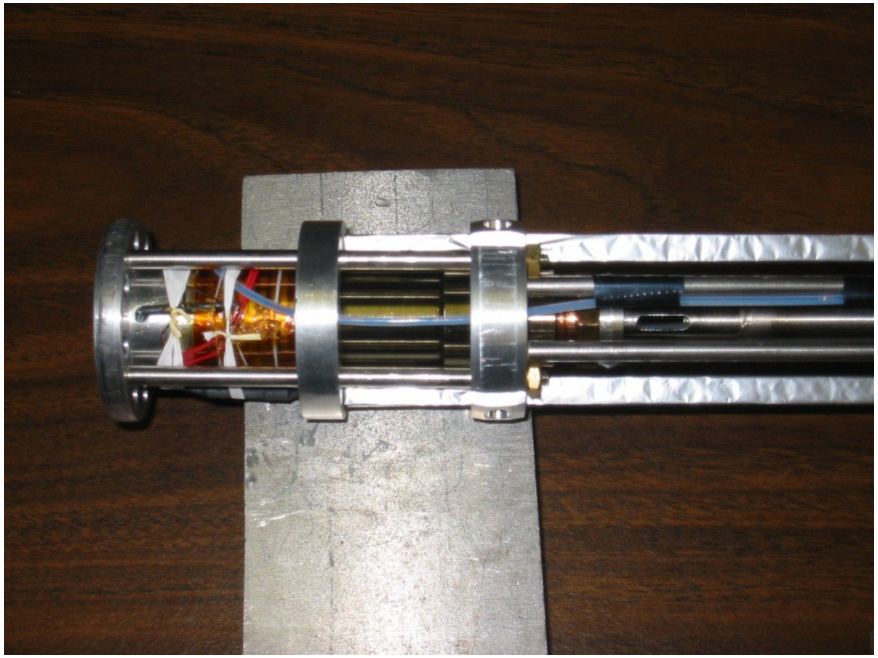
Combined Nuclear Dipolar and Paramagnetic Relaxation

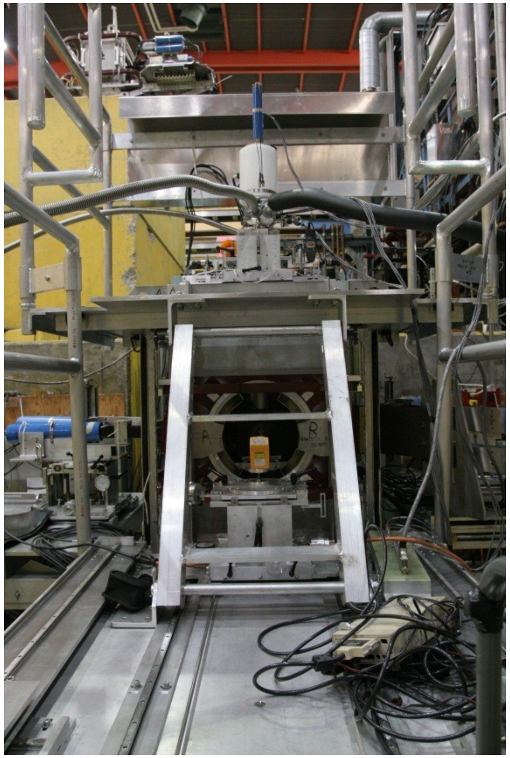


Brewer

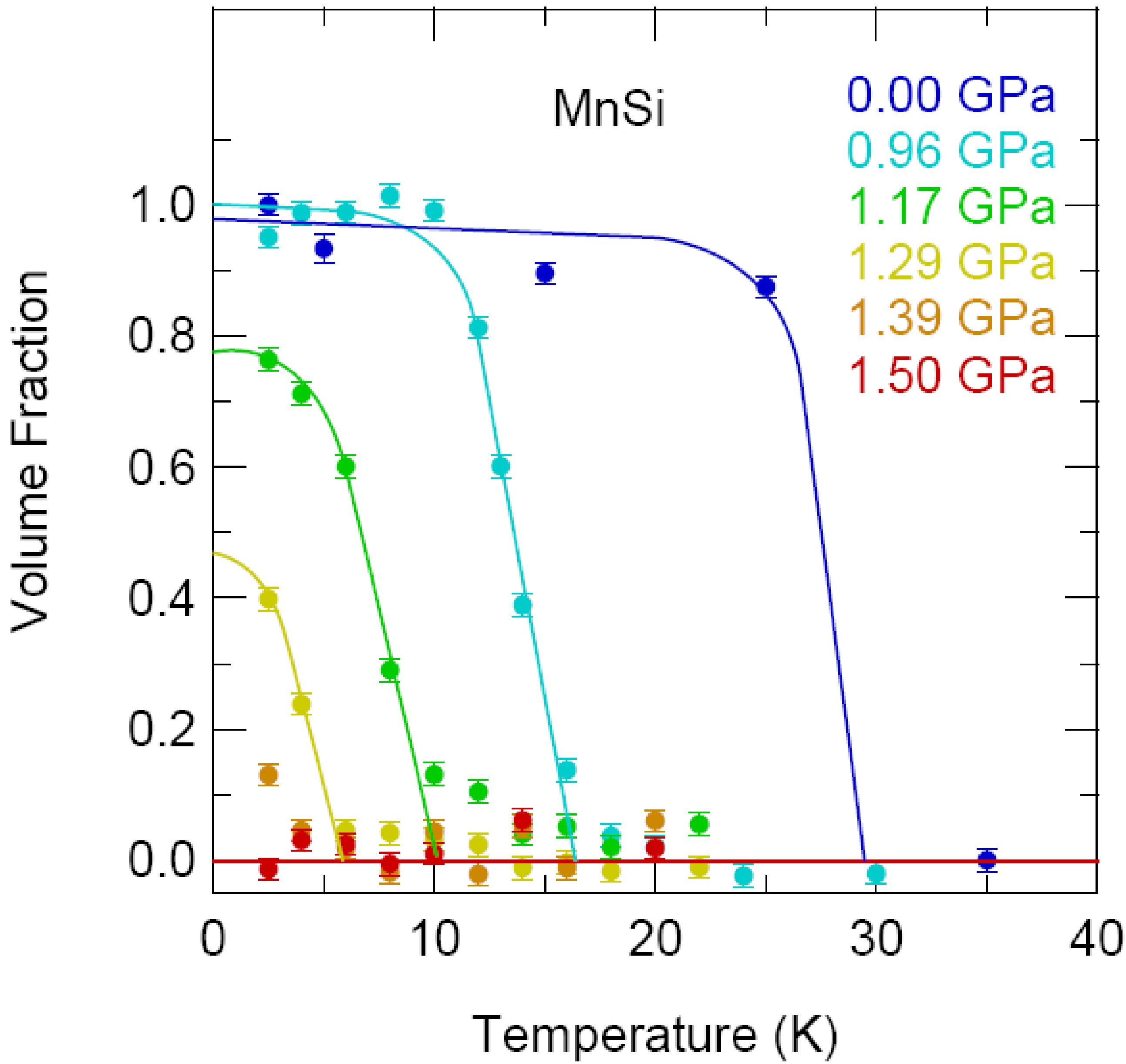
μSR Under Hydrostatic Pressure

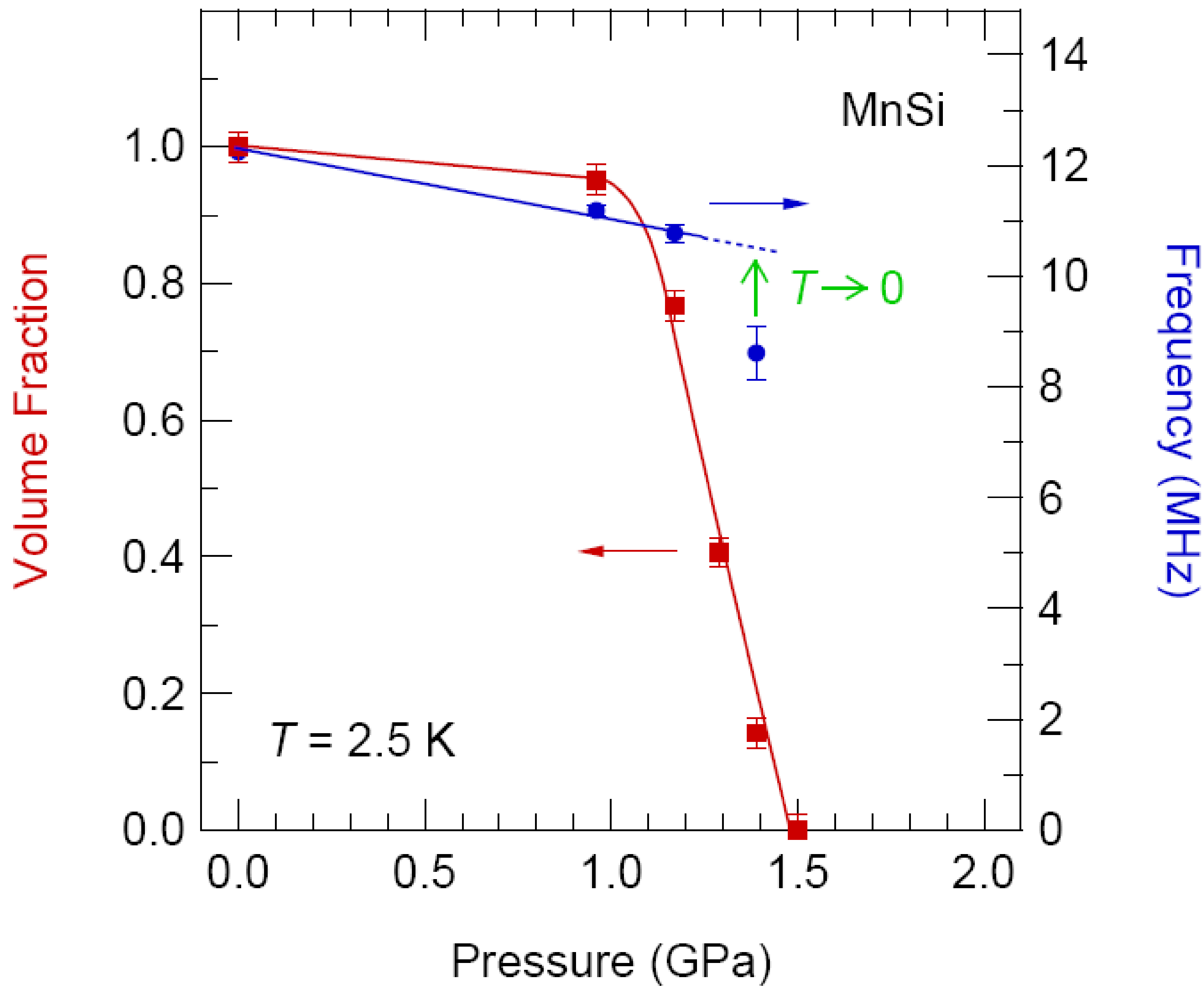
- Surface muons stop in about 0.1mm thickness, therefore can't get muons into pressure cell.
- Using higher energy muons from pions decaying in flight, can range muons into cell.

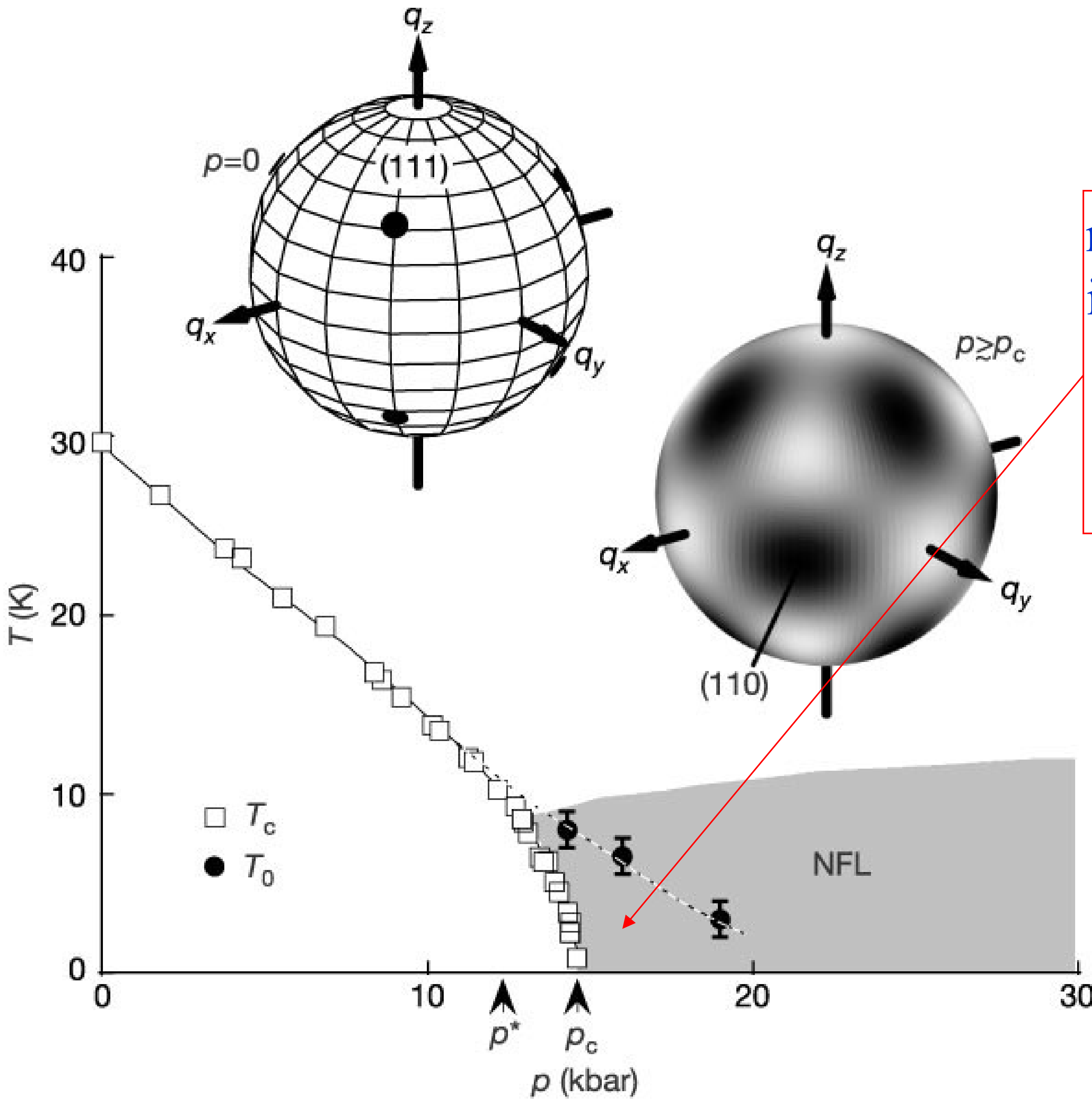




Uemura et al., Nature Physics **3**, 29 (2007).




MnSi
Volume Fraction
Frequency (MHz)
Pressure (GPa)
T → 0
T = 2.5 K
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.5
1.0
1.5
2.0
0
2
4
6
8
10
12
14

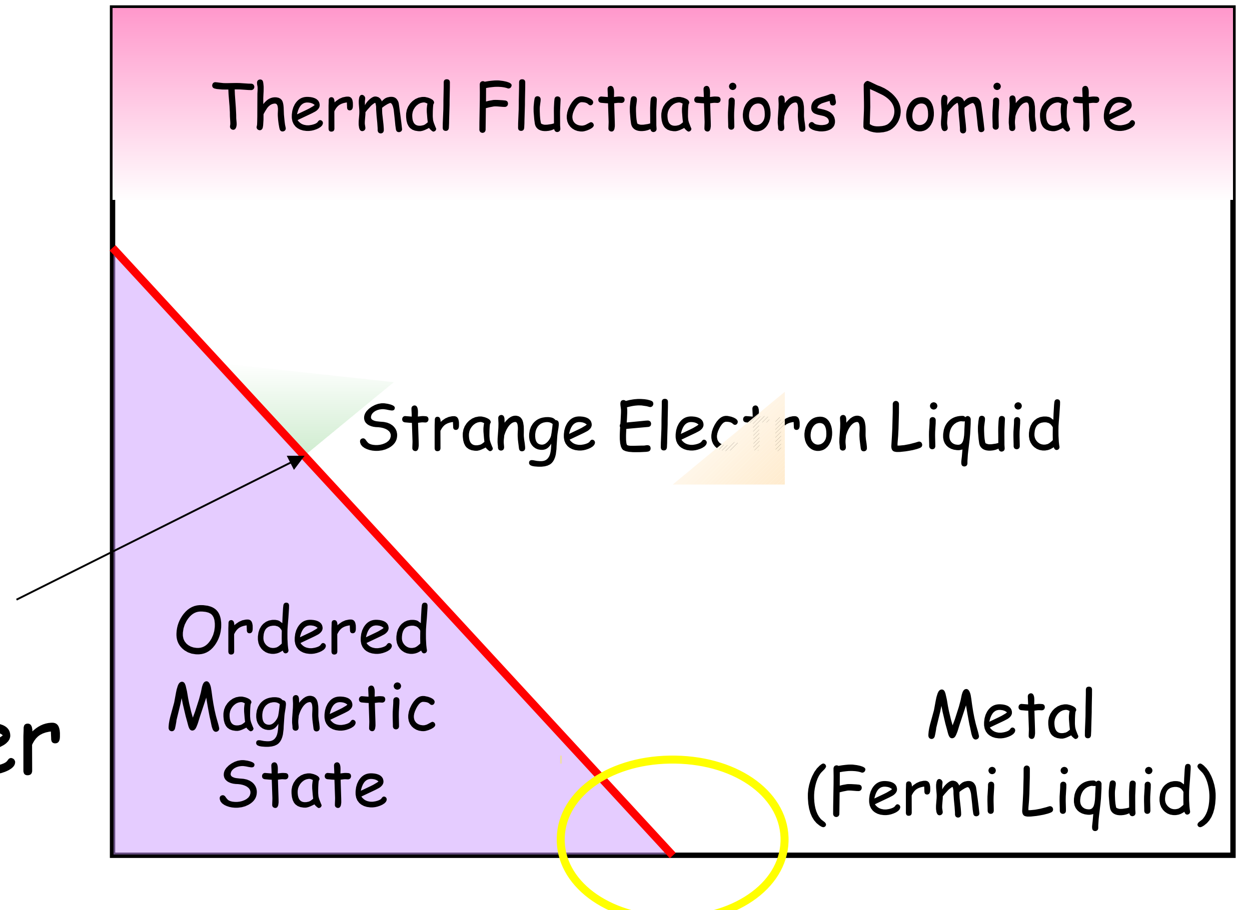


neutron quasielastic intensity

absence of muon relaxation

Pfleiderer et al., Nature 2004

Quantum Criticality



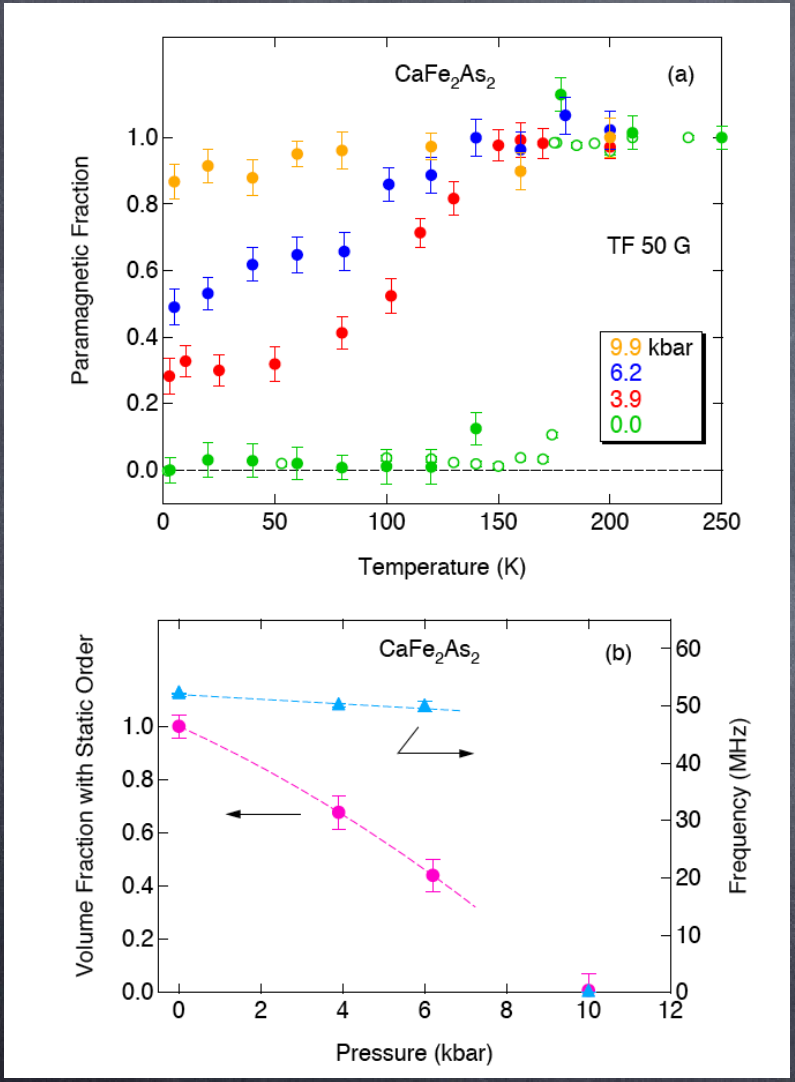
2nd order

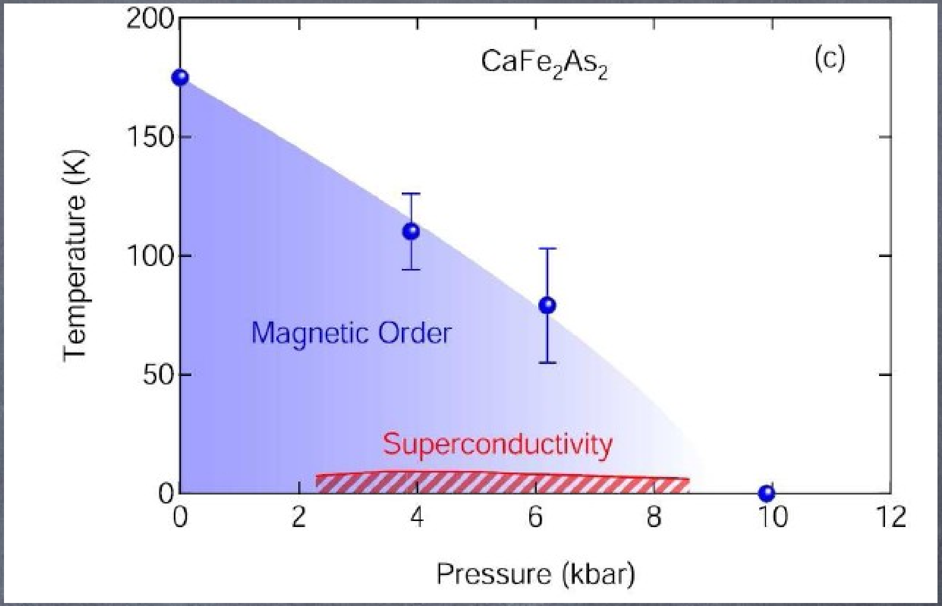
transition becomes 1st order (generic?)

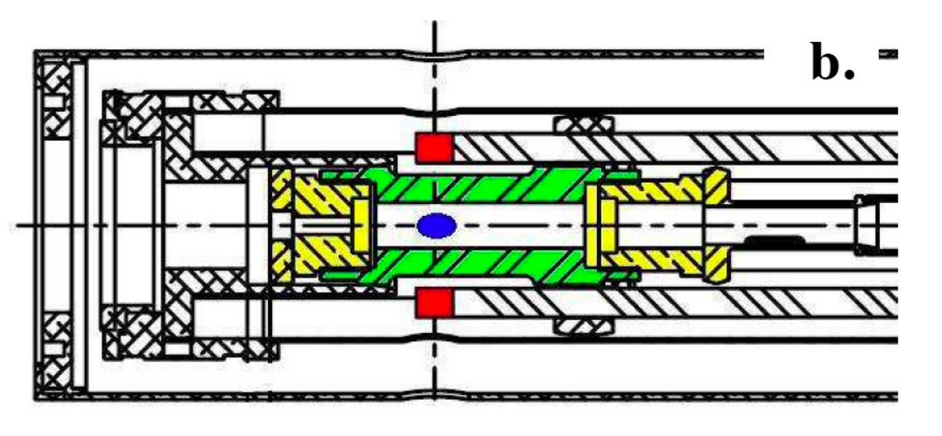
Another Example

G. M. Luke, L8

CaFe2As2 μSR in Hydrostatic Pressure





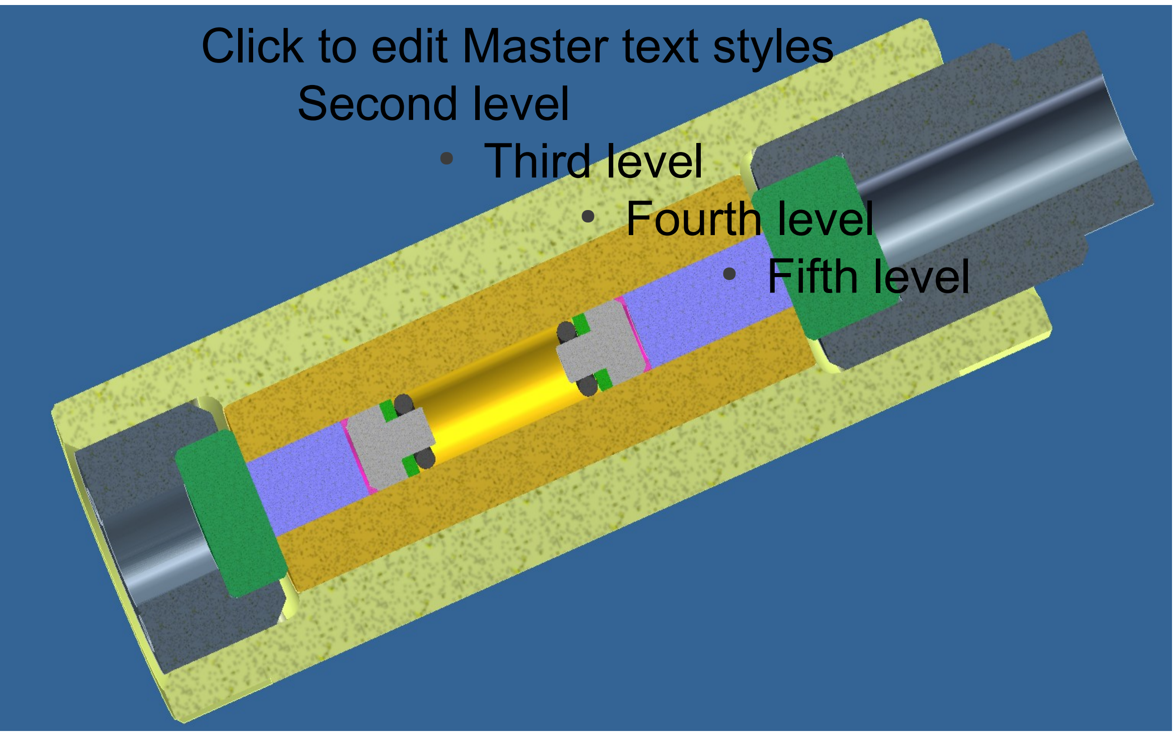


Goko et al., Phys. Rev. B 80, 024508 (2009)

Pushing the Pressure Limit

R. Khasanov

Double-wall pressure cell



Material: outer cylinder -- MP35N, inner cylinder – NiCrAl (Russian) alloy

Maximum pressure: ~2.8 GPa @ T~4K (~4GPa @ RT)

Pressure cell size: 26mm in diameter 72 mm height

Pressure media: Daphne oil 7373

Sample size: 6 mm in diameter 12mm height

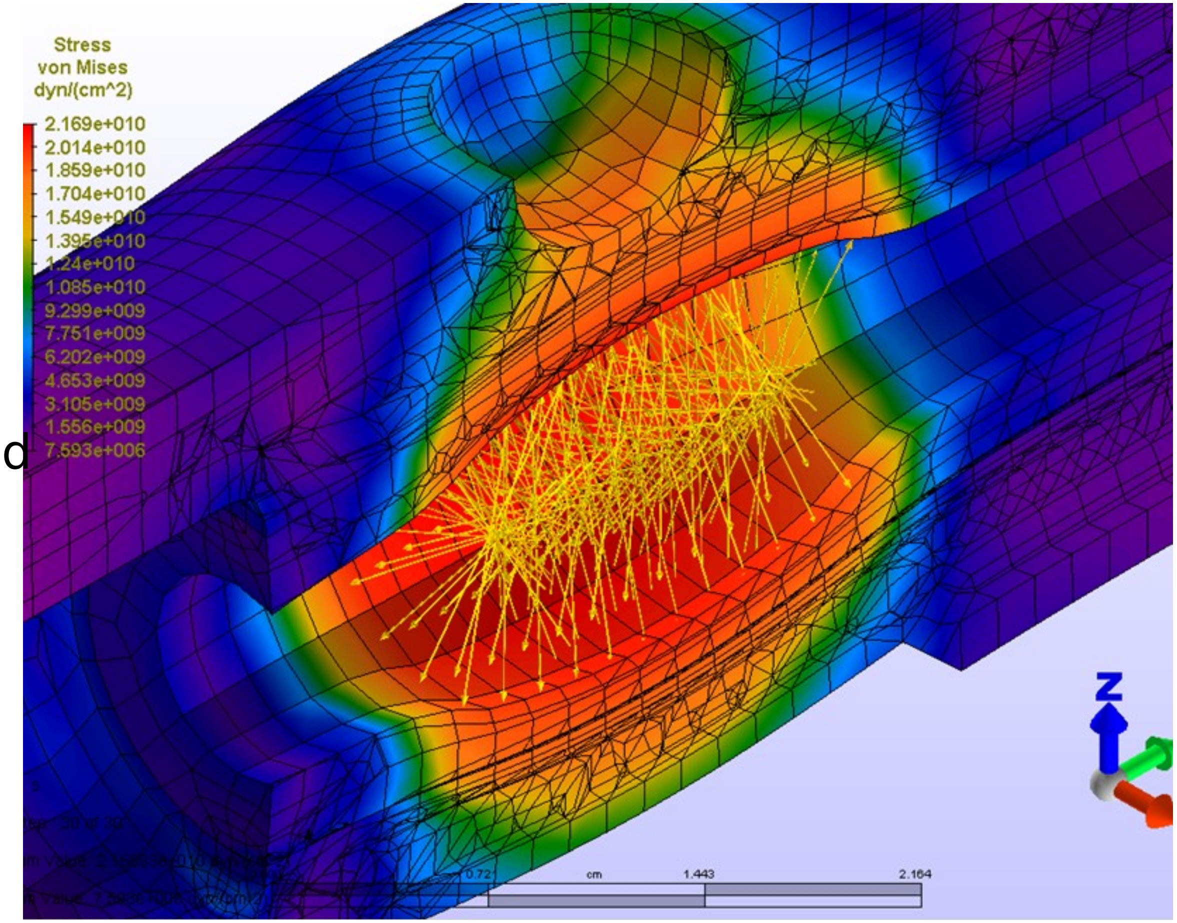
Muon stopping fraction:

TRIUMF Design P-Cell up to 2.5 GPa

Deformation magnified

Dimple: reduce background (muons in cell)

Double-walled cell

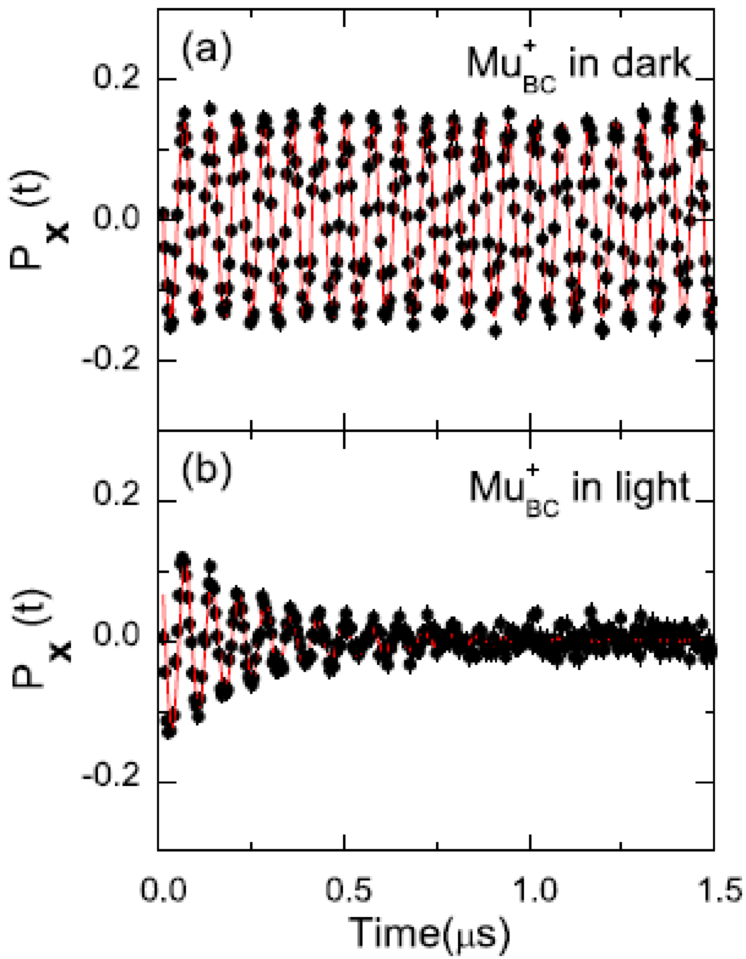


2. Illumination

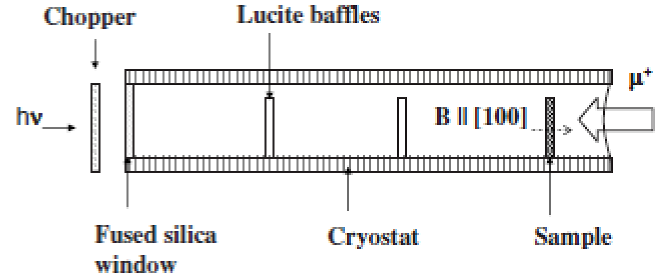
Optical Excitation

[*Si:* Fan et al., PRB **77,** 035203 (2008)]

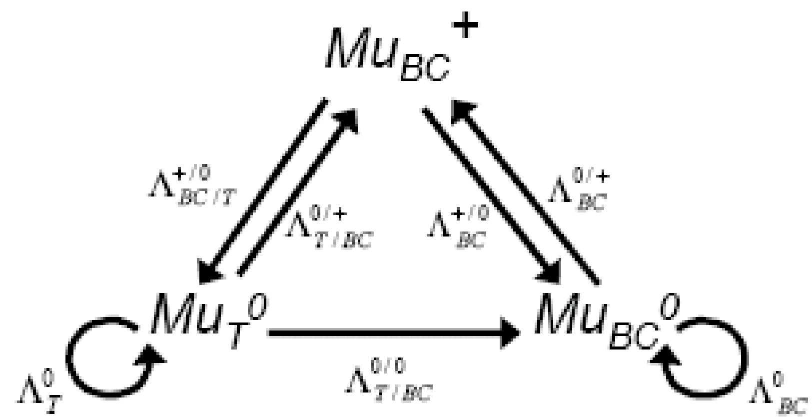
[*Ge:* Fan et al., PRB **78,** 153203 (2008)]



Backside illumination



Optically induced transitions:



Why to study photo-induced effects with muons?

- **Small changes of charge carrier concentration may induce dramatic changes of physical properties**; prominent examples are strongly correlated electron systems close to a metal-insulator transition (cuprates, manganites)
- **„Photo-doping“ allows to tune physical properties without introducing disorder due to chemical doping**
- **Interest in new functional devices** for optoelectronic and spintronic applications: photoswitches, photo-memories, phototransistors
- The **muon as a very sensitive local probe can provide complementary and potentially new information** to macroscopic techniques
- **Low-energy μSR with stopping depth < 200 nm ideally suited** due to overlap of muon stopping distribution and region of highest photon absorption close to the surface
- Many interesting systems consist of thin films of heterostructures with thickness < 100 nm
- Charge-carrier concentration can be varied by tuning light intensity and changing light energy
- Use Si and Ge as prototype systems where bulk μSR studies have been done

Example of photo-induced effects

FM order induced by photo-generated carriers in (In,Mn)As/GaSb

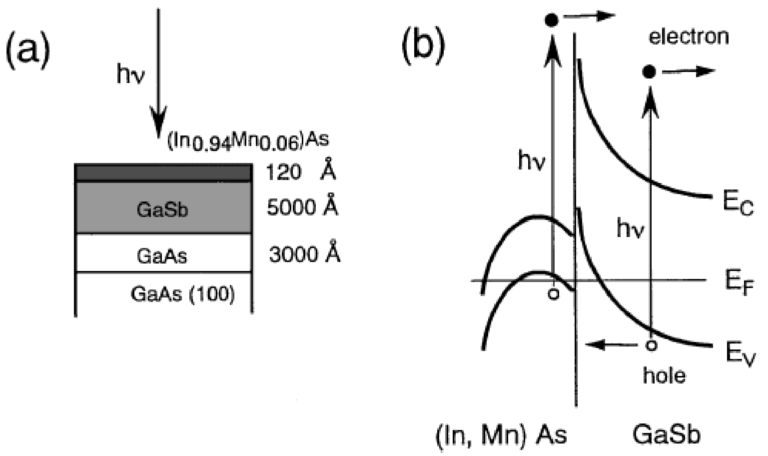


FIG. 1. (a) Structure of the sample. Direction of light irradiation is also shown by an arrow. (b) Band edge profile of (In,Mn)As/GaSb heterostructure. E_c, E_v, and E_F denote band edges of conduction band, valence band, and Fermi level, respectively.

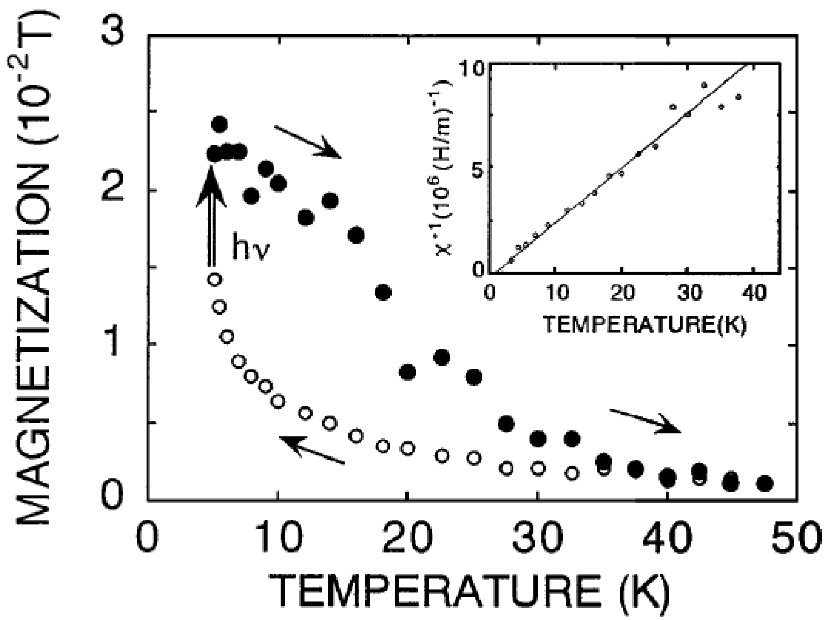
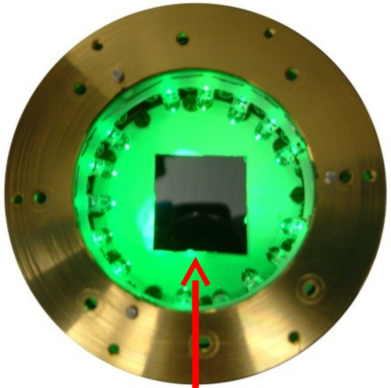


FIG. 2. Temperature dependence of magnetization observed during cooldown in the dark (open circles) and warmup (solid circles) under a fixed magnetic field of 0.02 T. Light irradiation at 5 K is also shown by an arrow. The Curie-Weiss plot for a sample in the dark is shown in the inset.

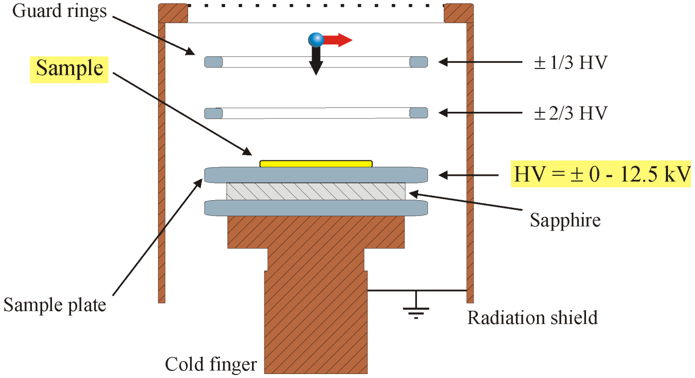
S. Koshihara et al, Phys. Rev. Lett. 78 (1997) 4617.

LE-μSR LED setup

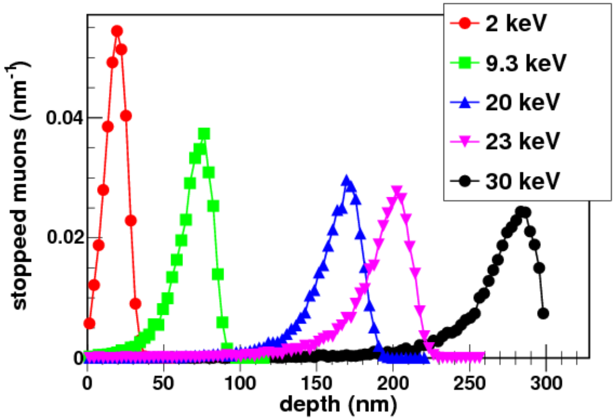
InGaN green, λ=525(39nm), 30mA/3.3V, 2Θ1/2= 20o,Kingbright L-7113VGC-Z
InGaN white λpeak=460,560 nm, 30mA/3.3V 2Θ1/2= 30o,Avago HLMP-CW36-UX00
GaN blue, λ=470(25) nm, 30mA/3.3V, 2Θ1/2= 16o,Kingbright L-7113QBC-D



Undoped Si (100), 3x3 cm2



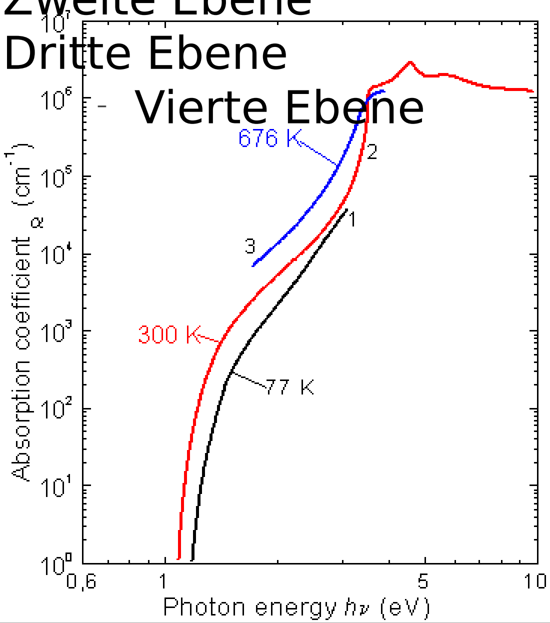
μ+ stop distribution in Si

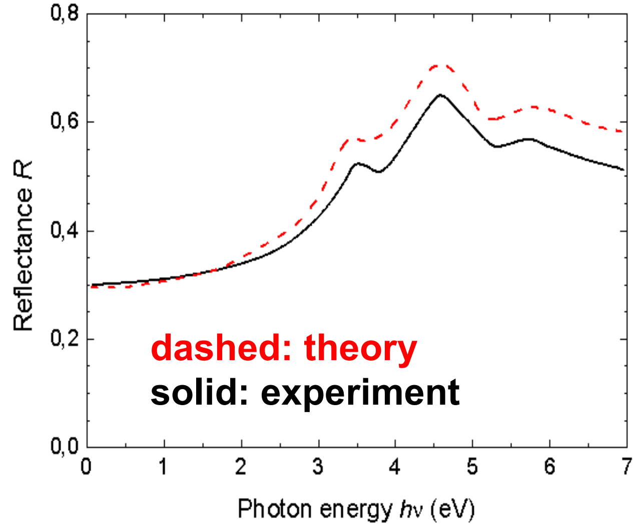


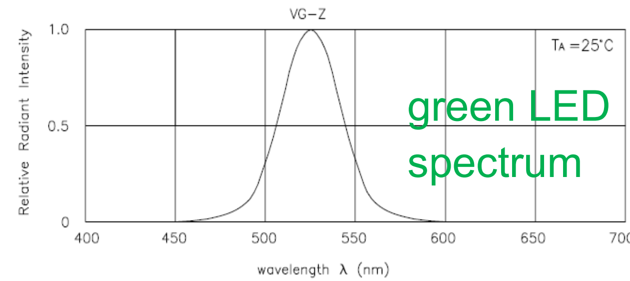
Absorption coefficent and Reflectance in Si

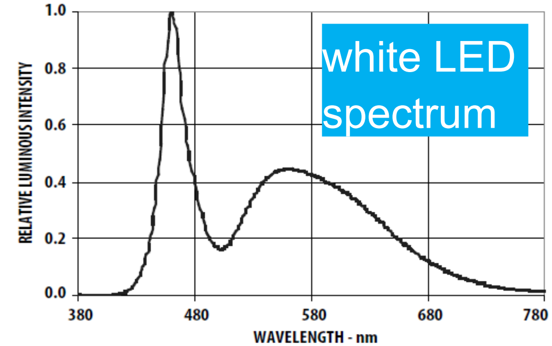
Mastertextformat bearbei...
Zweite Ebene
Dritte Ebene
Vierte Ebene

http://www.ioffe.ru/SVA/NSM/Semicond/Si/index.html:









Estimate of charge carrier density neh in Si at 30 mA LED current, 33 LEDs. Measured intensity I = 10 mW/cm2: nγ =2.6•1016γ/cm2s

neh ~ (1-R)•α•nγ•τ = 0.65•104/cm•2.6•1016γ/cm2s•2μs ≈ 3.5•1014/cm3

R: reflectivity of Si at 525 nm (2.36 eV, green LED)
α: absorption coefficient of Si at 2.36 eV
τ: charge carrier lifetime in Si including surface recombination [D. Klein et al., physica status solidi (b) 245 (2008) 1865.]

At present, steady state neh tunable in Si up to ≈ 1015/cm3

A Muonium Photochemistry Example

$Mu + H_2 \rightarrow MuH + H$

A simple fundamental gas phase chemical rxn

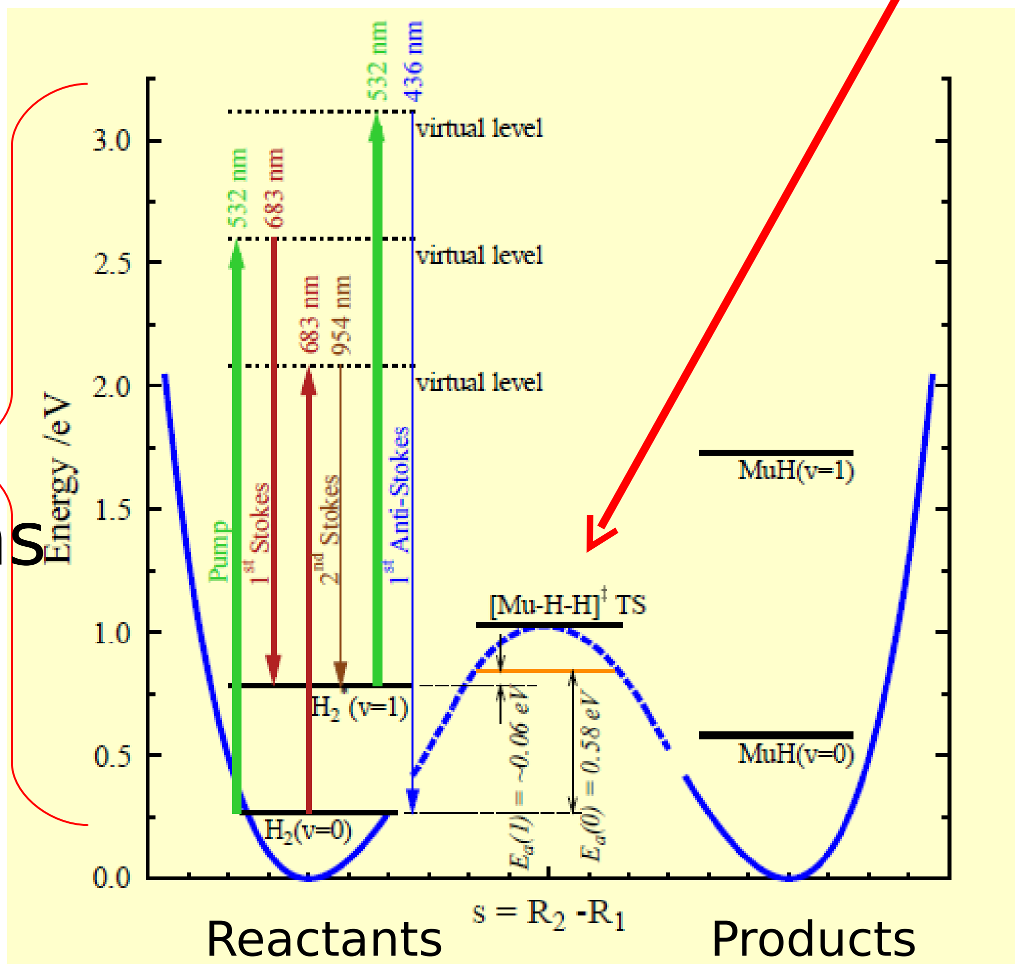
$Mu + H_2^* \rightarrow MuH + H$

How does optical excitation of the molecular vibrational level Of H2 affect the rxn rate?

Energetics

Transition State

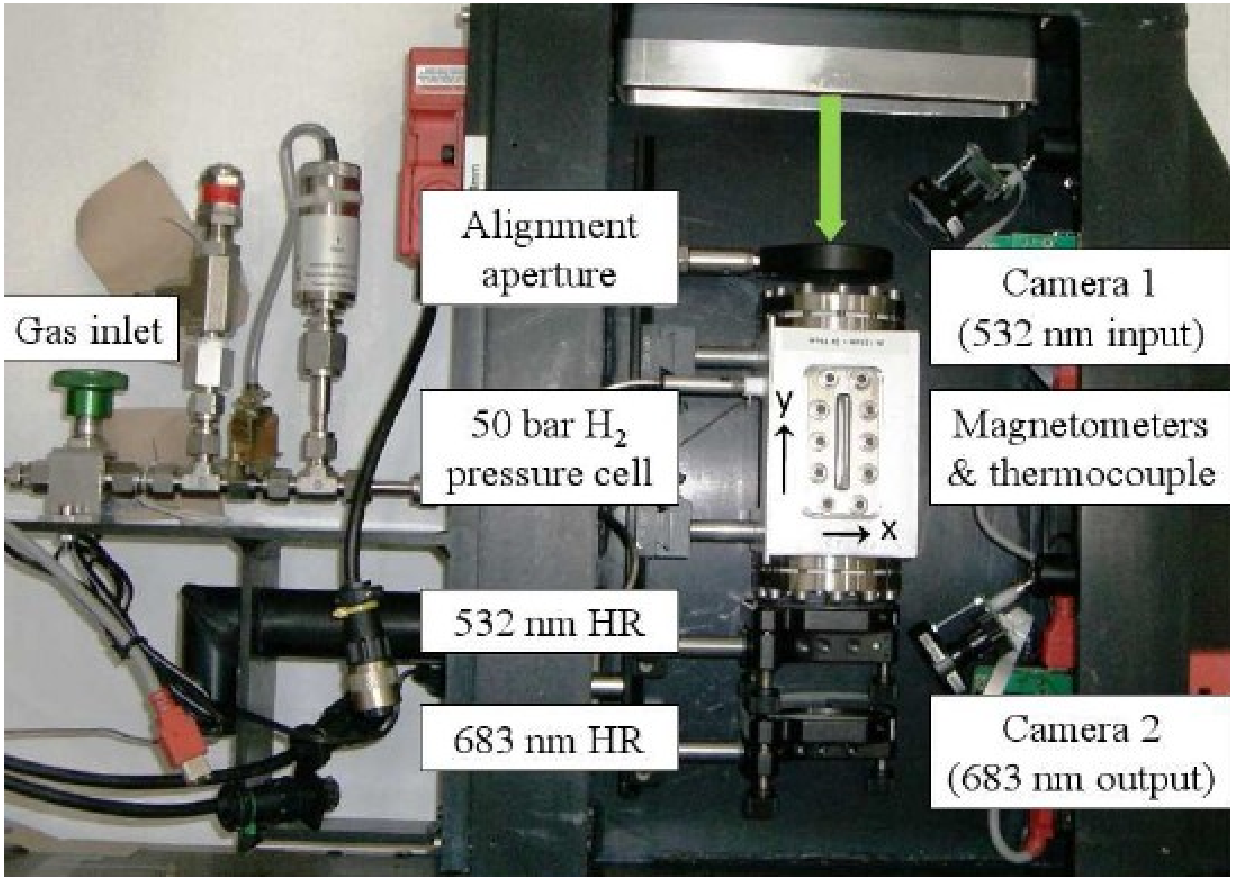
Optical Excitation of Vibrations of reactant H2



D.G. Fleming, UBC Chemist

The Experiment

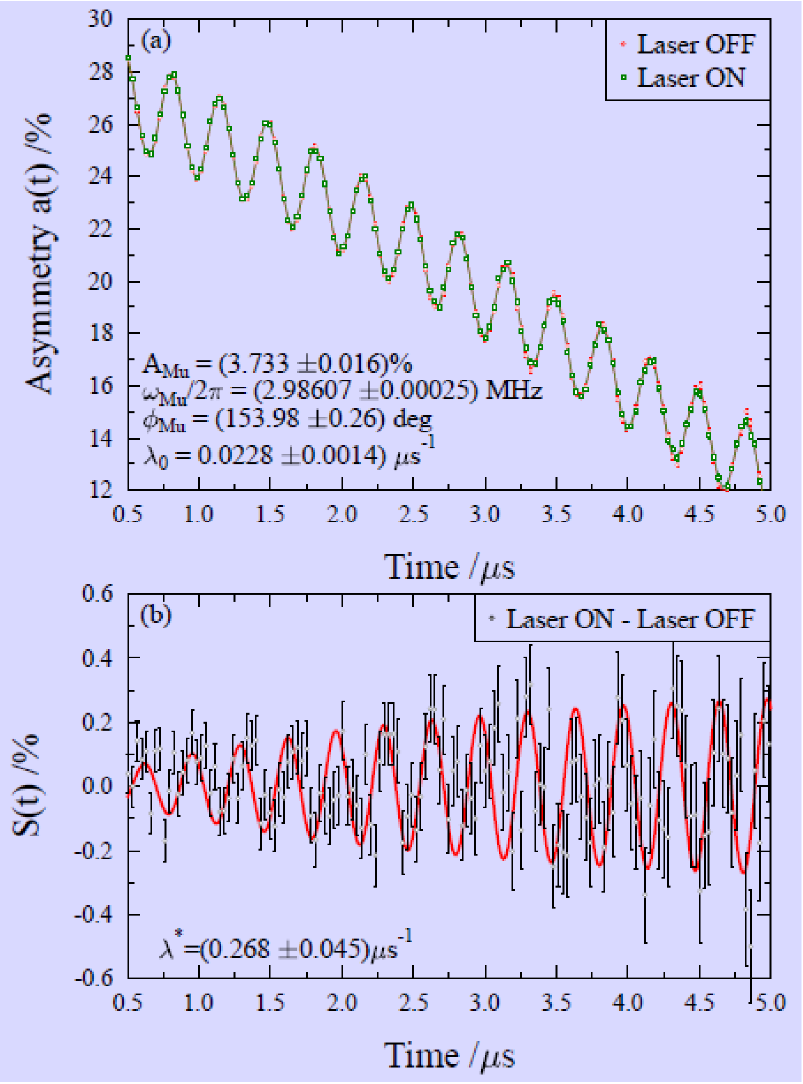
Pulsed Nd-YAG laser tuned to H2 levels



Pulsed muon beam at ISIS (UK)

D.G. Fleming, UBC Chemist

The Effect

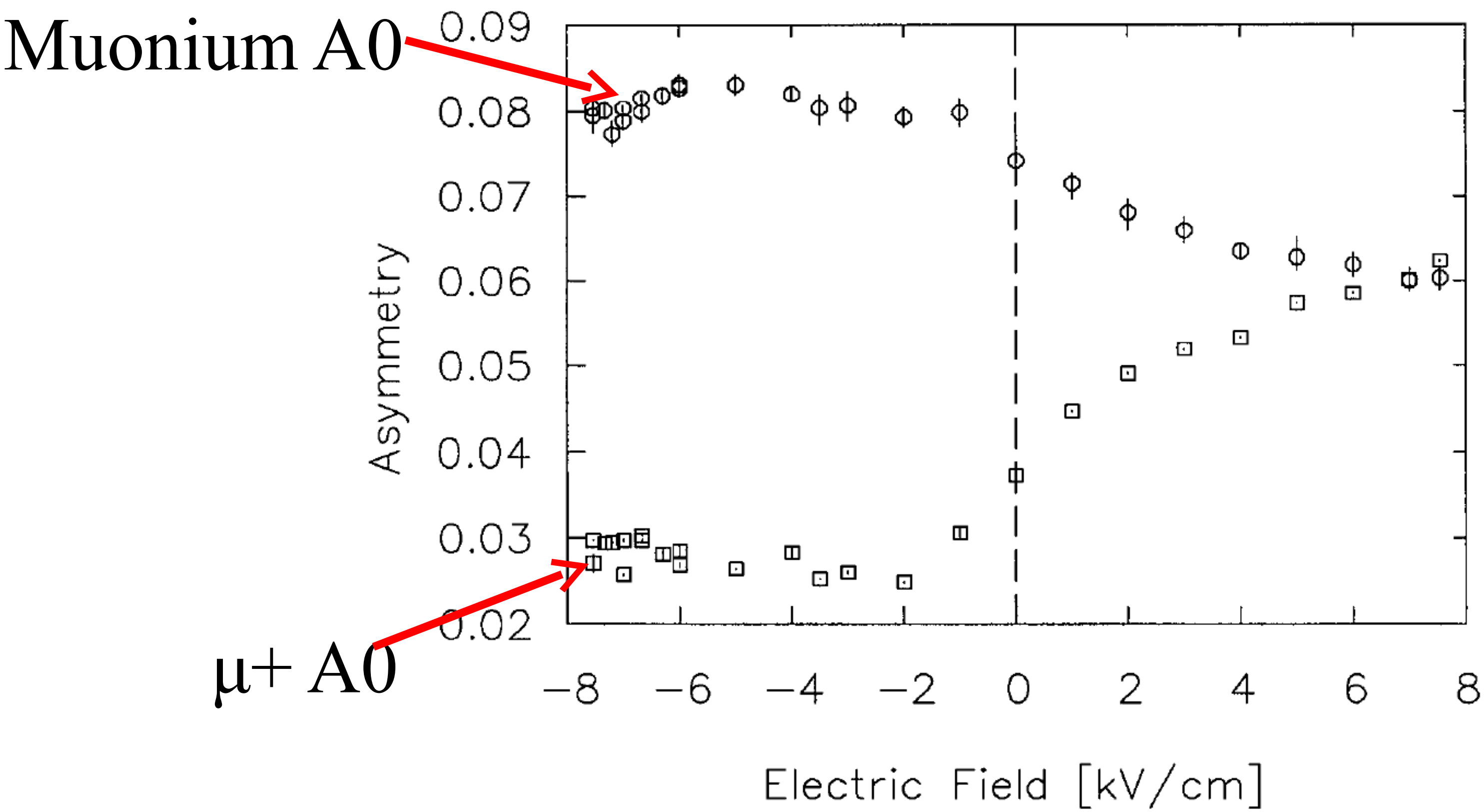


D.G. Fleming, UBC Chemist

3. Electric Field

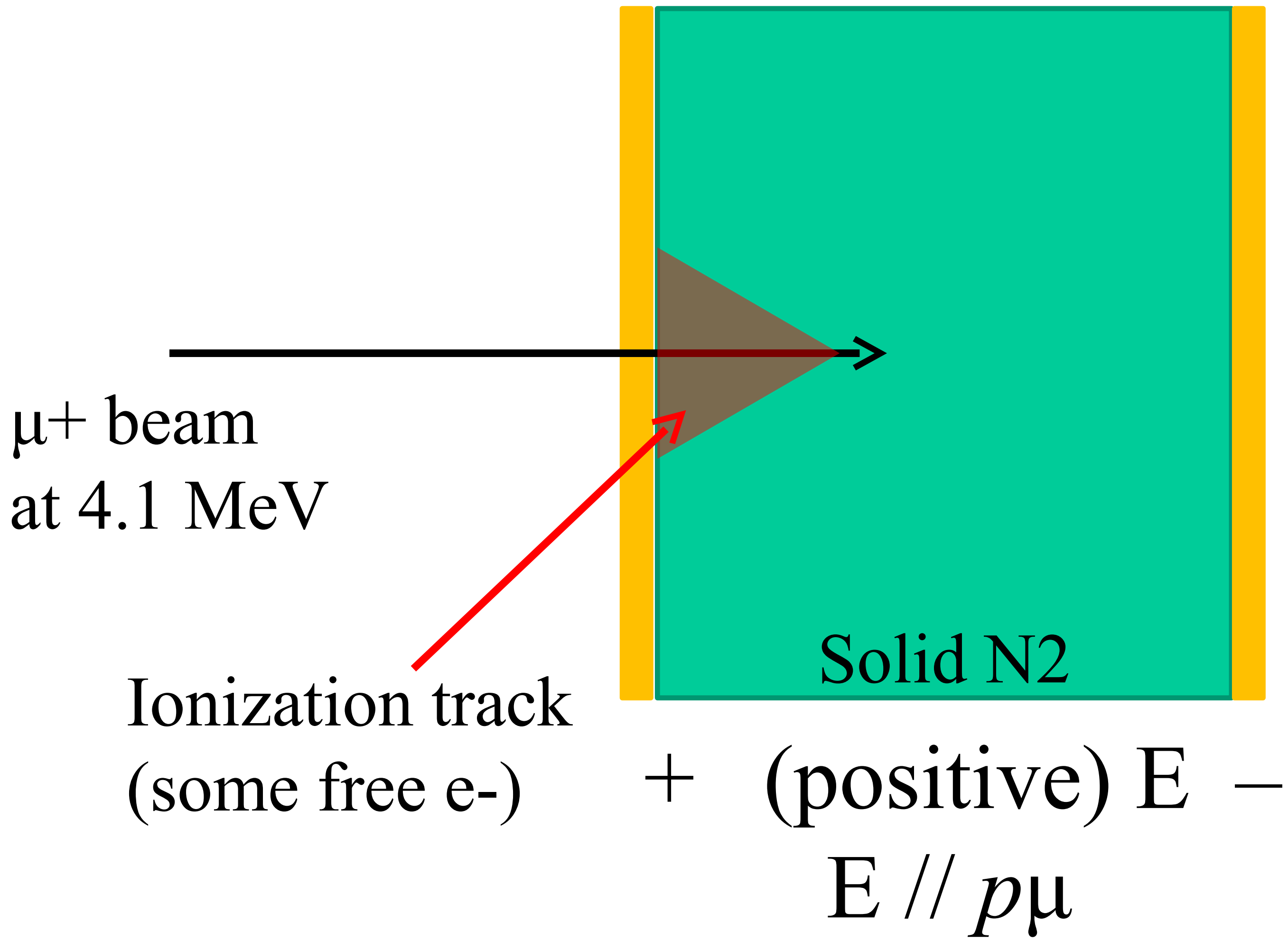
Muonium Formation depends on applied electric field in solid Nitrogen!

T = 20 K
B = 35 G



G.D. Morris, Ph.D. Thesis

Why Should E matter?



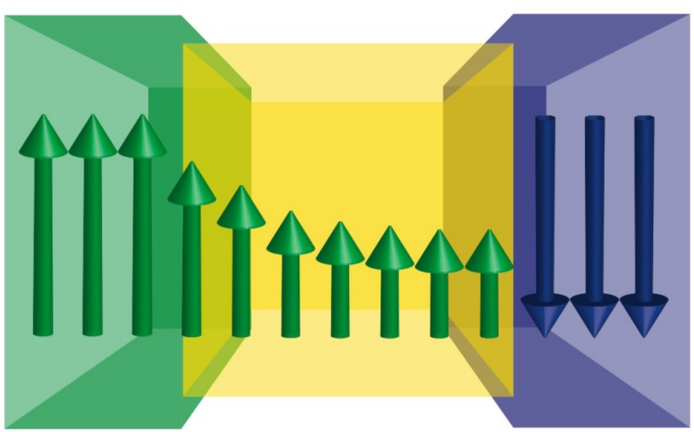
4. Electric Current

nature materials
ARTICLES
PUBLISHED ONLINE: XX MONTH XXXX | DOI: 10.1038/NMATXXXX

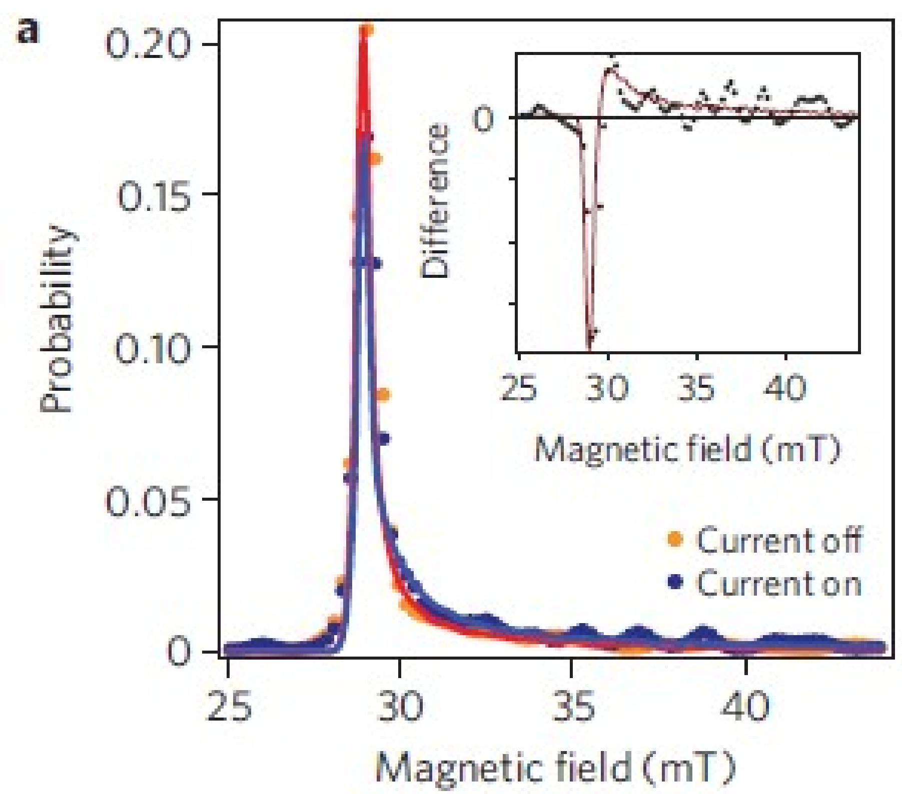
Jan. 2009

Direct measurement of the electronic spin diffusion length in a fully functional organic spin valve by low-energy muon spin rotation

A. J. Drew[1,2]*, J. Hoppler[1,3], L. Schulz[1], F. L. Pratt[4], P. Desai[2], P. Shakya[2], T. Kreouzis[2], W. P. Gillin[2], A. Suter[5], N. A. Morley[6], V. K. Malik[1], A. Dubroka[1], K. W. Kim[1], H. Bouyanfif[1], F. Bourqui[1], C. Bernhard[1], R. Scheuermann[5], G. J. Nieuwenhuys[5], T. Prokscha[5] and E. Morenzoni[5]



Nonmagnetic Organic Spacer



5. Probe Implantation Depth

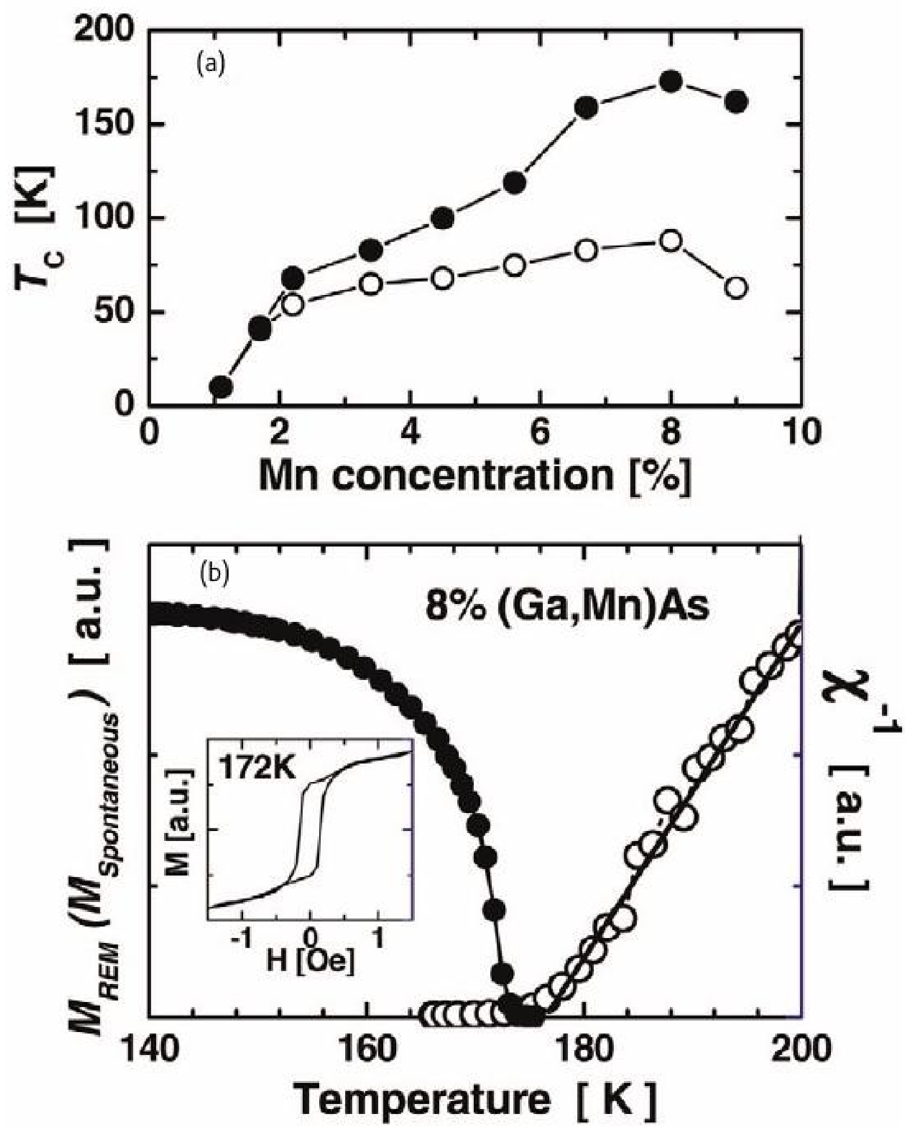
- Implantation Energy variable from e.g. 100 eV to 30 keV
- Study thin films, heterostructures, near surfaces
- Depth resolution

Why thin films?

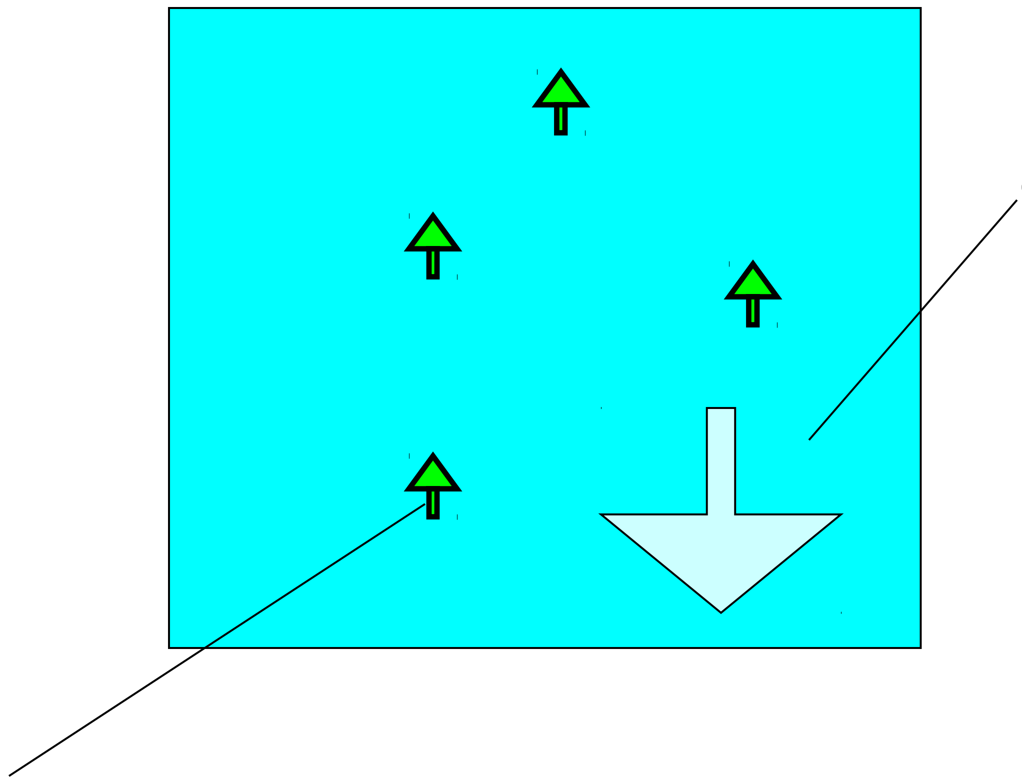
Technological importance
Some materials only exist as thin films
Vary material properties easily: strain, E, light, current injection
Interesting depth dependent, finite size, confinement effects (e.g. Meissner state)
Heterostructures differ from their bulk constituents
See Kiefl L17

An Example: Ga1-xMnxAs

Ga1-xMnxAs a dilute magnetic semiconductor



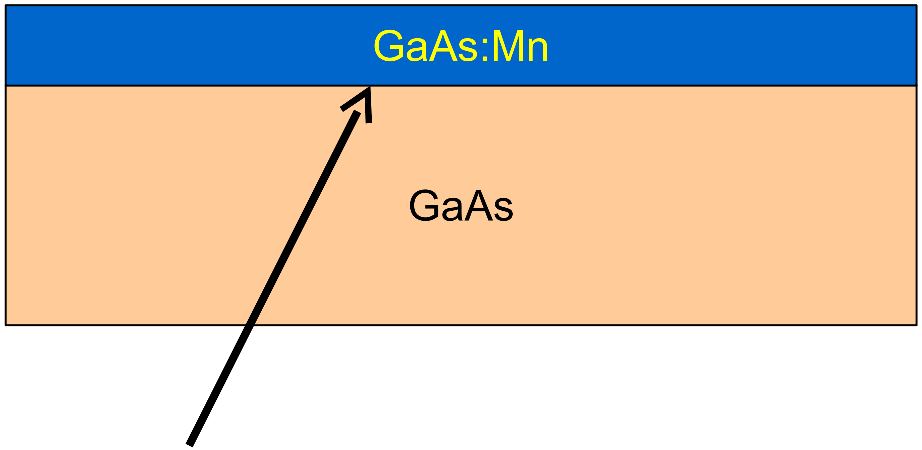
Dilute Magnetic Semiconductors



a background
of free carriers
(holes)

dilute local (atomic) magnetic moments
$Mn2+$ $S = 5/2$

Mn doped GaAs



180 nm thick
5.4% Mn, Tc ~ 72 K

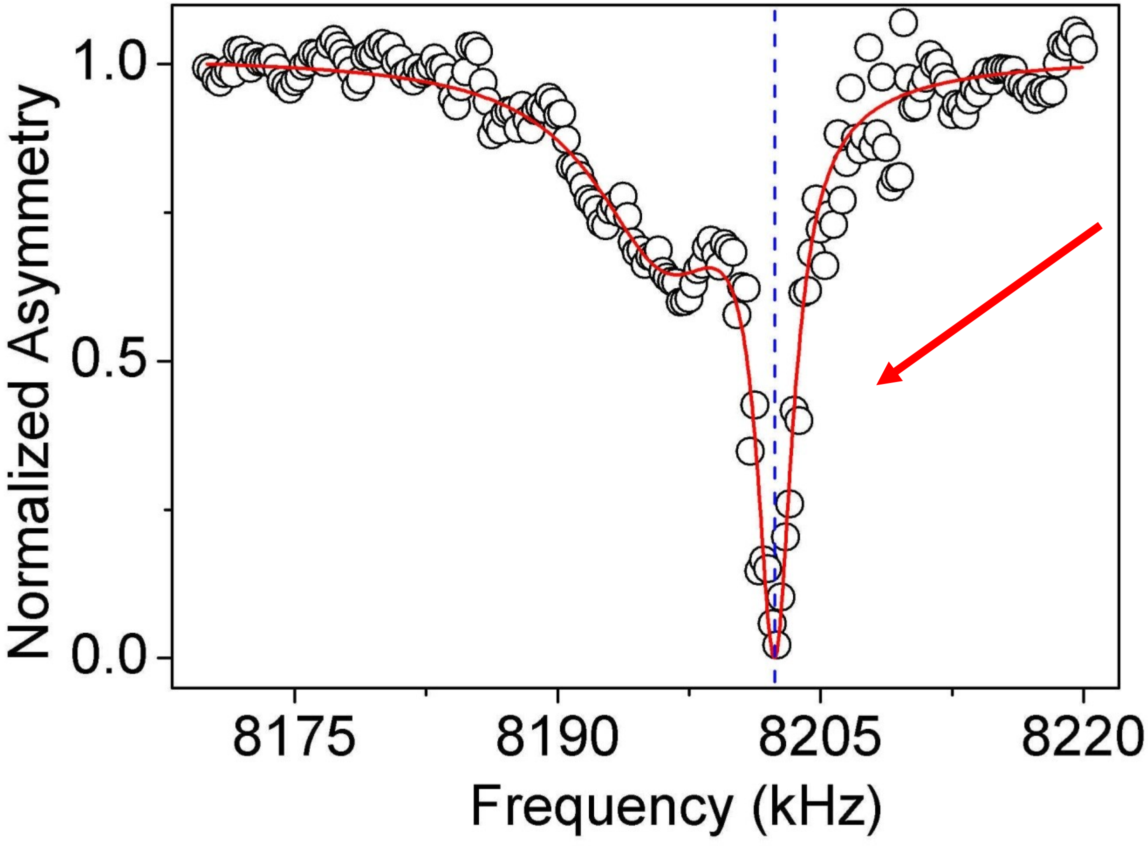
An alloy, metallic

less impedance mismatch
than with a metallic
ferromagnet like Fe

Far above the equilibrium solubility limit of Mn

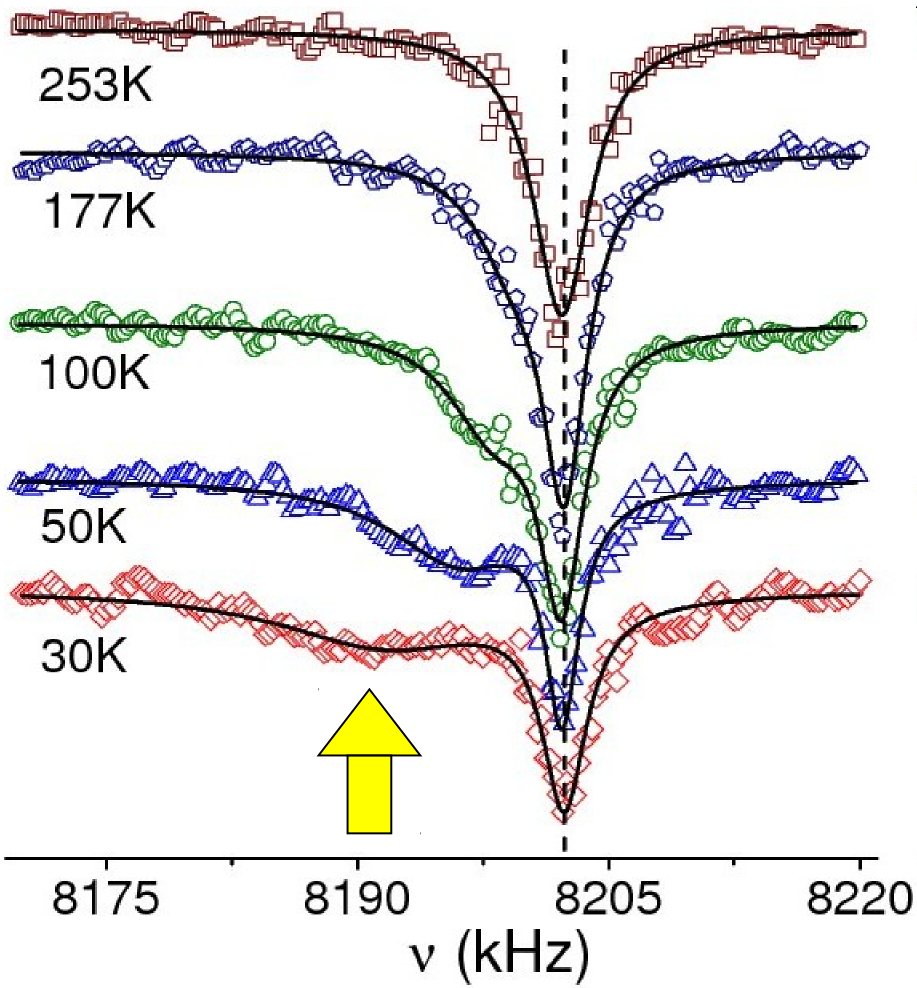
Sample: J.K. Furdyna, Notre Dame

8Li resonance in 180 nm Ga0.95Mn0.05As / GaAs



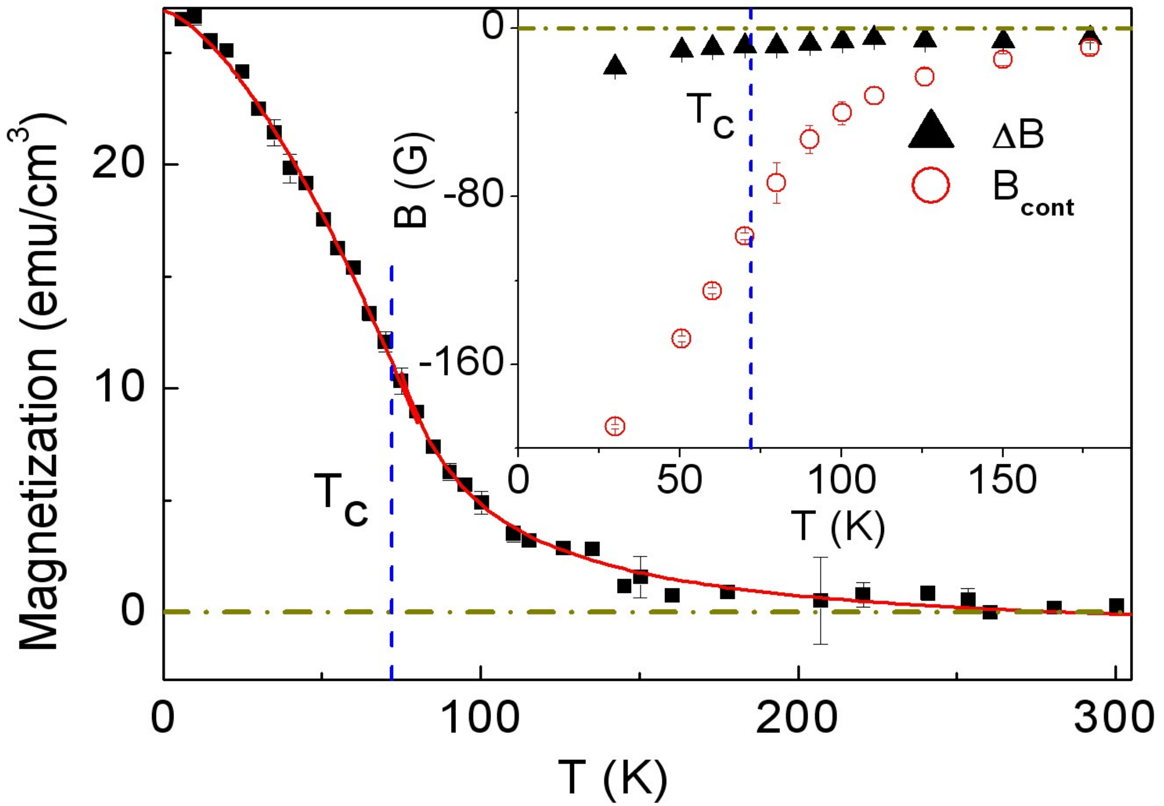
Sharp Substrate Line

Temperature Dependence



Q. Song et al., PRB 2011

SQUID Magnetization in 1.3 T

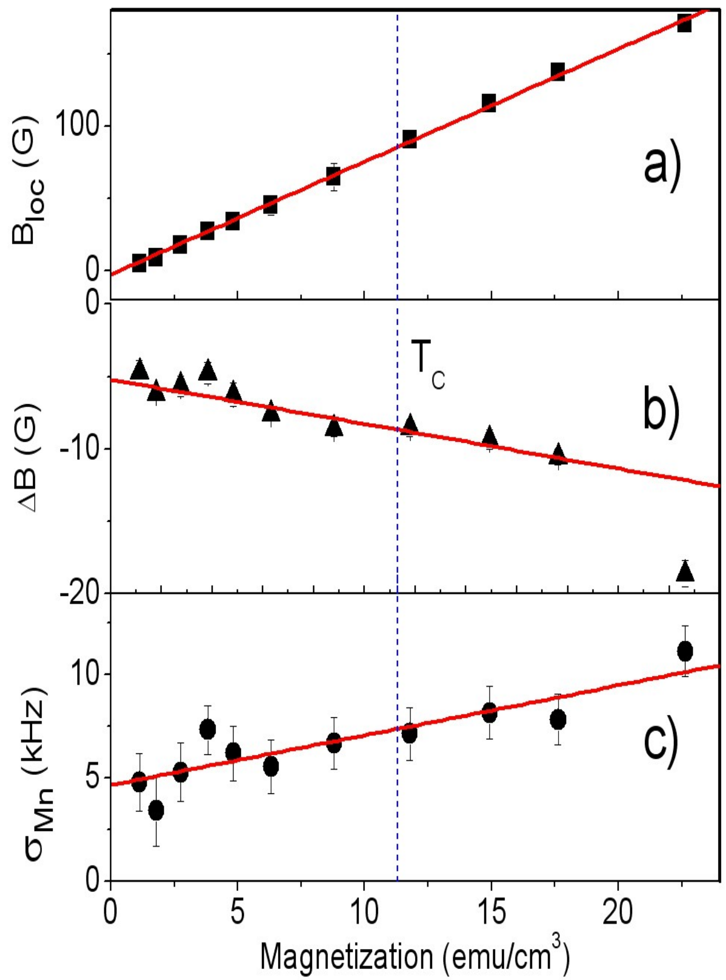


Clogston Jaccarino Analysis

The local field

raw resonance shift

linewidth



Q. Song et al., PRB 2011

D. New Syntheses (some examples)

βNMR and synchrotron Xray diffraction in $SrTiO_3$ Phys Rev B **83**, 224112 (2011)

μSR and neutron scattering: Magnetic excitations of $Fe_{1+y}Se_xTe_{1-x}$ in magnetic and superconductive phases, JPCM **22**, 142202 (2010)

LEμSR and ellipsometry: Dimensionality Control of Electronic Phase Transitions in Nickel-Oxide Superlattices, Science **332**, 940 (2011)

Spin dynamics and spin freezing behavior in the two-dimensional antiferromagnet $NiGa_2S_4$ Phys Rev B **77**, 054429 (2008)

Thanks (this talk)

Th. Prokscha, R. Khasanov, PSI
D.G. Fleming, G.D. Morris, G. M. Luke, S.R. Kreitzman, K.H. Chow, K. Boone
Q. Song

Thanks (TSI 2011)

Lecturers: J. Brewer, J. Sonier, G. Luke, R. Kiefl, K. Chow, T. Uemura, S. Kreitzman, P. Percival, I. McKenzie

Experiments: G. Morris, B. Hitti, D. Arseneau

Computing: H. Saadaoui, A. Warren, R. Parachoniak

Support: D. Giasson, M. Hapke

General Help: R. Abasalti, D. Vyas, K. Ghandi, J.-C. Brodovitch, D. Eldridge

Funding: TRIUMF and NSERC

And You!