FERMILAB-SLIDES-24-0016-SQMS

Liberty Lykia Hotel, Ölüdeniz - Fethiye, Muğla, Türkiye | 27th April - 4th May, 2024

Magnetic fluctuations as a potential source of losses in superconducting quantum devices

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

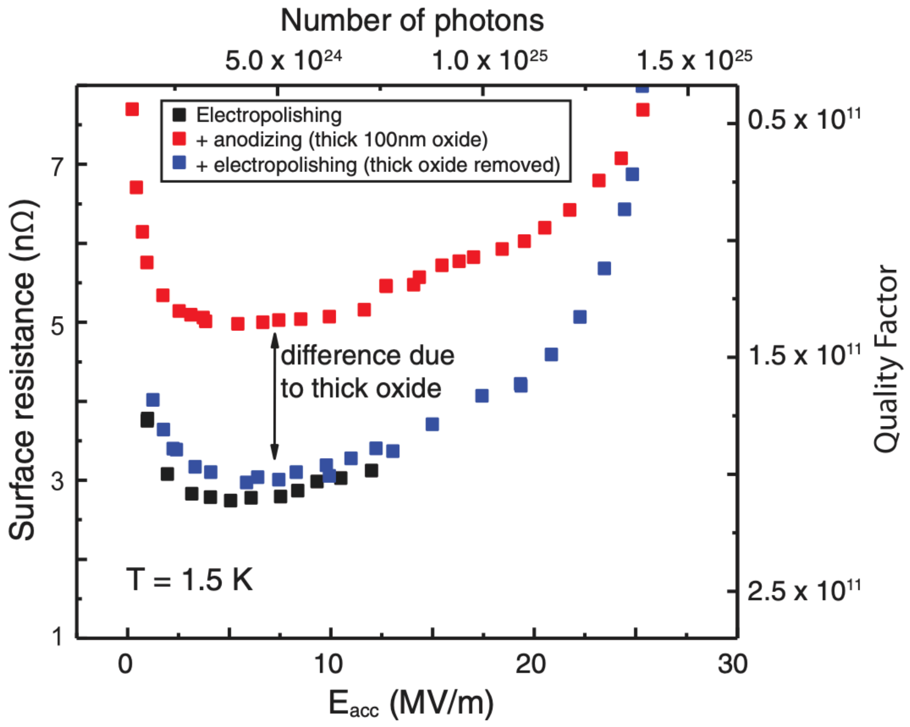
Yulia Krasnikova, Akshay Murthy, Mustafa Bal, Franceso Crisa, Jae-Yel Lee, Arely Cano, David van Zanten, Anna Grassellino, Alex Romanenko,

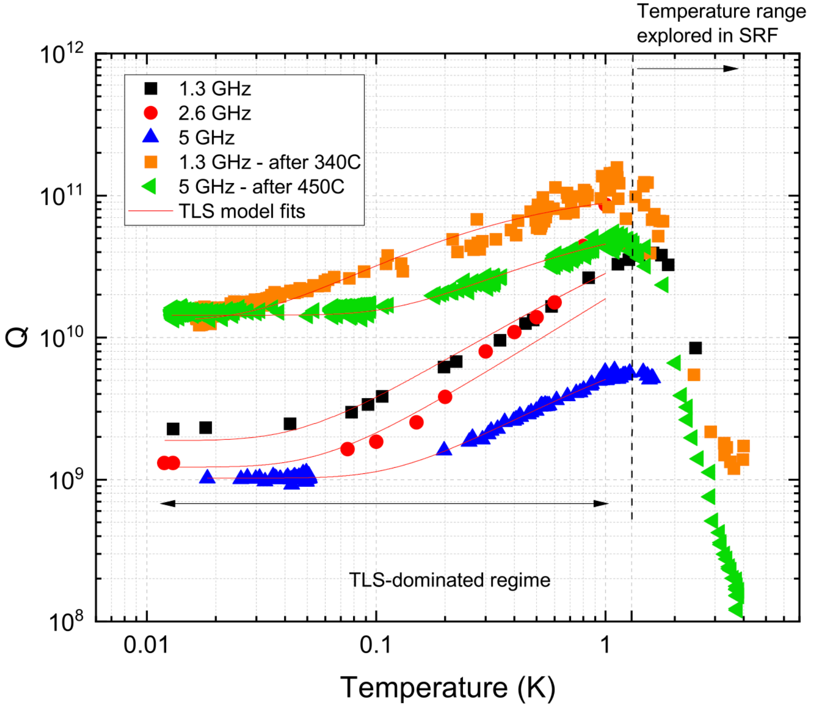
Andreas Suter, Thomas Prokscha, Zaher Salman

PAUL SCHERRER INSTITUT

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

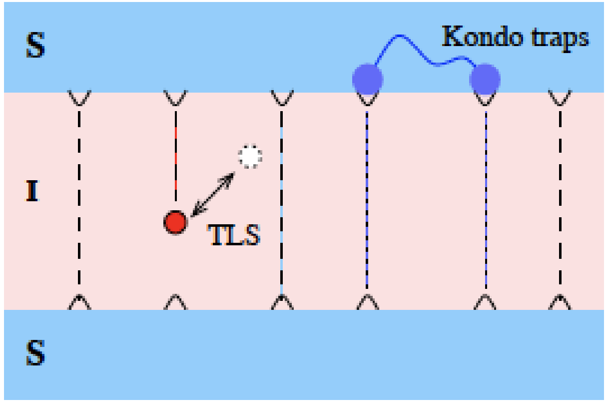
Motivation





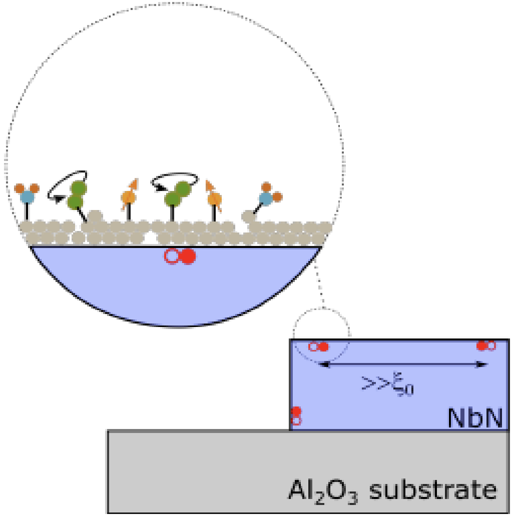
- Low field quality factor depends on oxide thickness
- Low temperature quality factor decreases with cooling below 1.3 K

[*Romanenko and Schuster* PRL **119** 26480 (2017), *Romanenko et al.* PRA **13** 034032 (2020)]



Microscopic mechanisms of decoherence

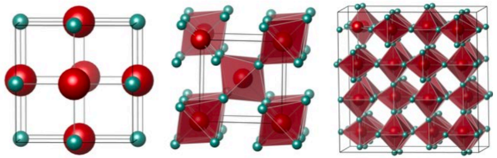
Faoro and Ioffe PRL **76**, 047001 (2006)



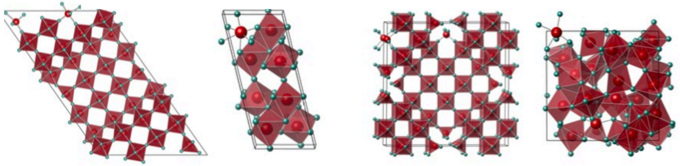
TLS due to trapped quasiparticles

de Graaf et al. Science Advances **6**, 5 (2020)

Motivation: recent DFT modeling of possible magnetism in NbOx



NbO Pm3m	NbO_2 Rutile, $P4_2/mnm$	NbO_2 $I4_1/a$
$4d^3$	$4d^1$	$4d^1$
Planar	Octahedral	Octahedral
Paramagnetic	Paramagnetic	Paramagnetic



$N\text{-}Nb_2O_5$ C2/m	$B\text{-}Nb_2O_5$ C2/c	$M\text{-}Nb_2O_5$ I4/mmm	Nb_2O_5 Amorphous
$4d^0$	$4d^0$	$4d^0$	$4d^0$
Octahedral+ Tetrahedral	Octahedral	Octahedral+ Tetrahedral	4-, 5- and 6- coordinated
Diamagnetic	Diamagnetic	Diamagnetic	Diamagnetic

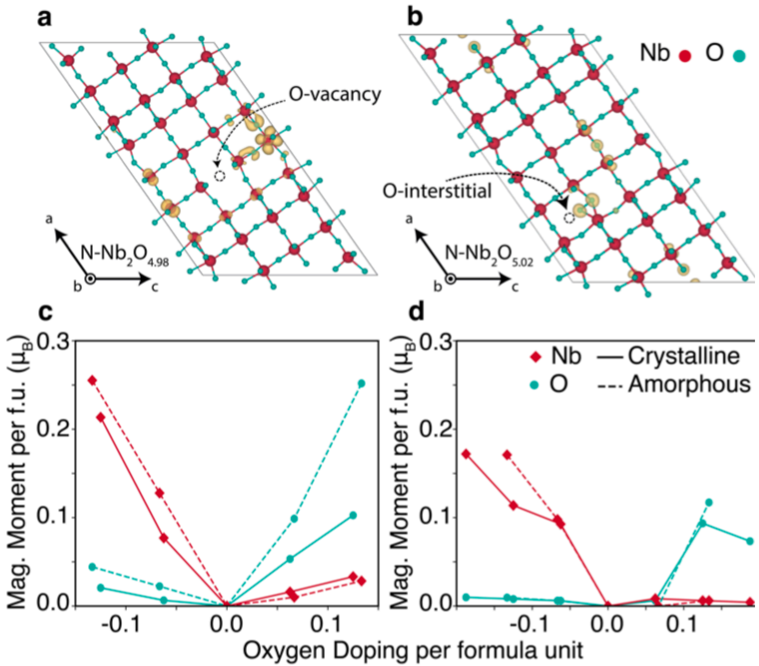
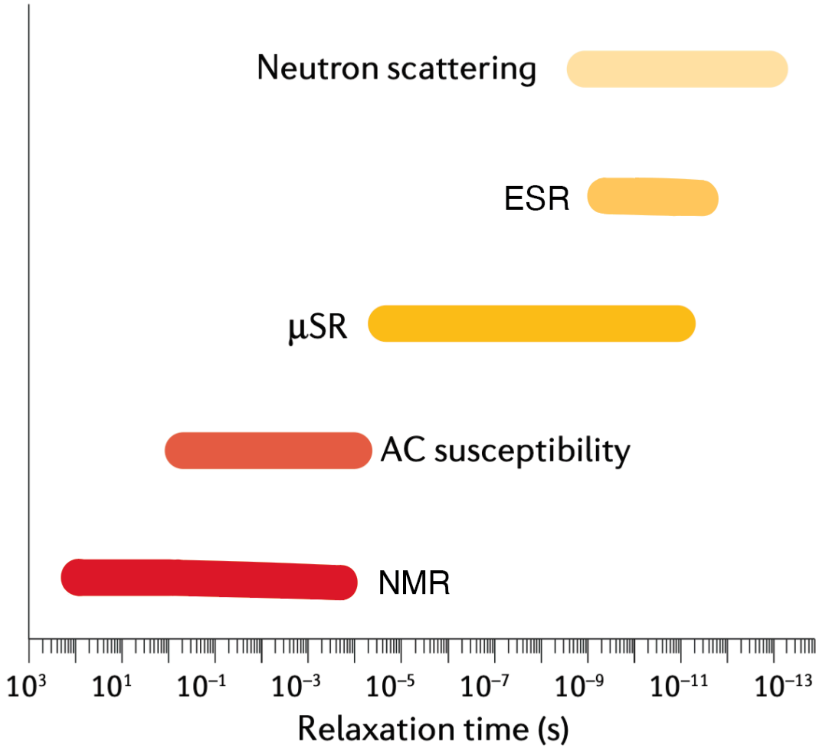


FIG. 2. (a) Real space charge density projection of mid-gap states for $N\text{-}Nb_2O_5$ in the case of (a) an O-vacancy and (b) an O-interstitial. The calculated magnetic moments per formula unit (per Nb_2O_5) are shown as a function of the change in O stoichiometry (defined as the value of x in Nb_2O_{5+x}) for the rigid band approximation (c) and explicit O doping (d) for the crystalline $N\text{-}Nb_2O_5$ and the amorphous Nb_2O_5 (configuration 5) structure.

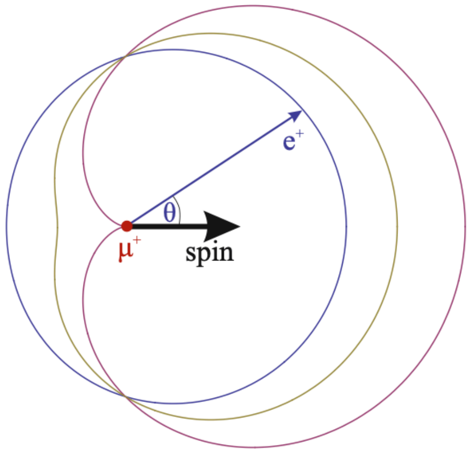
E. Sheridan et al. arXiv:2111.11684v1 (2021)

μSR – muon spin resonance/rotation/relaxation

Hillier, A.D., Blundell, S.J., McKenzie, I. *et al.* Muon spin spectroscopy. *Nat Rev Methods Primers* **2,** 4 (2022), PhD thesis T. Matthias, ETH Zurich (2015)



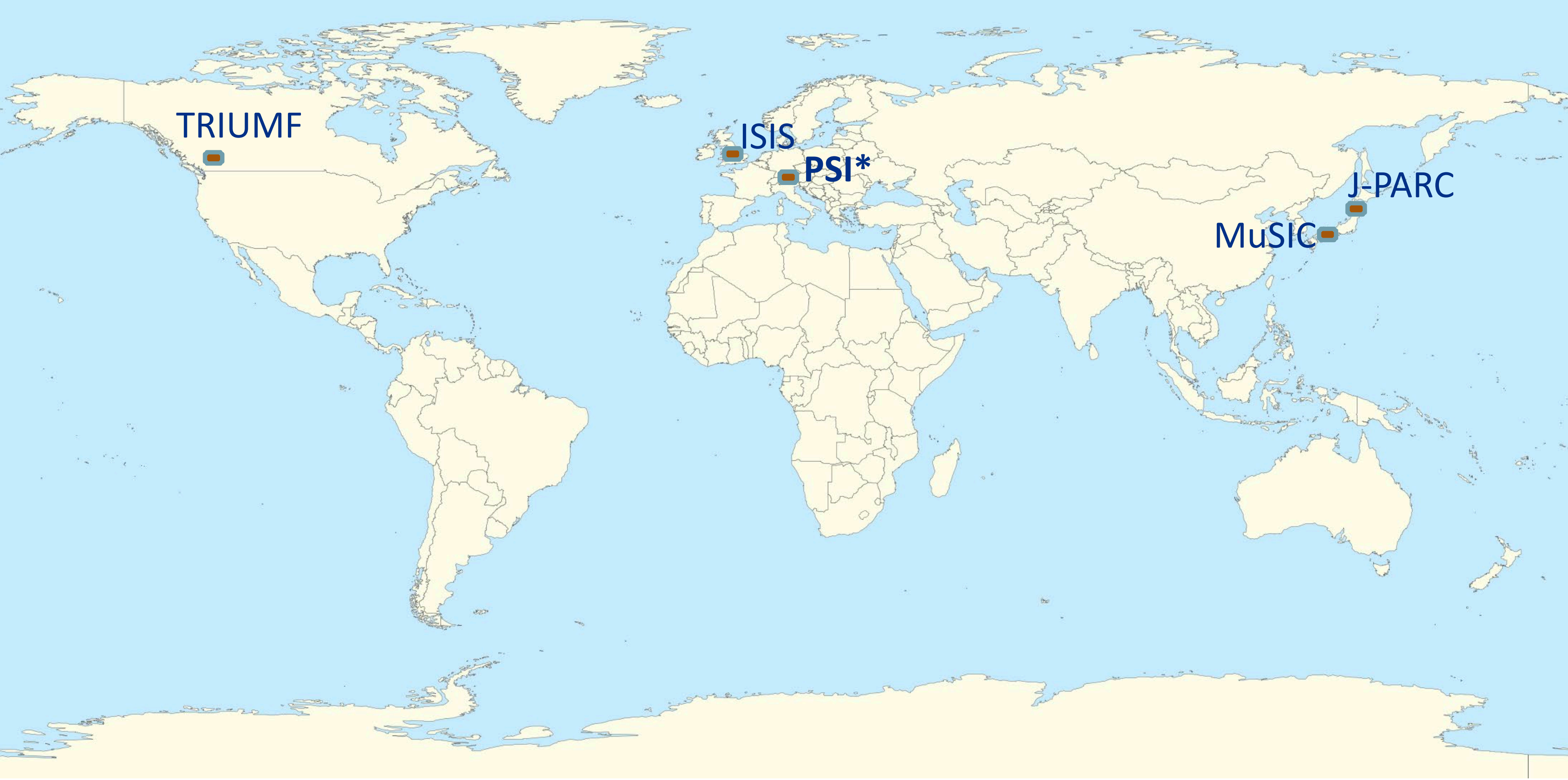
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$



- Polarized muons are working as probes of local magnetic field
- Polarization of muon defines muon's decay direction
- Positron counts give information about polarization behavior on time

$$P \propto \chi'' \propto \int_{-\infty}^{+\infty} dt \, \langle S_i(0) S_k(t) \rangle e^{-i\omega t}$$

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER



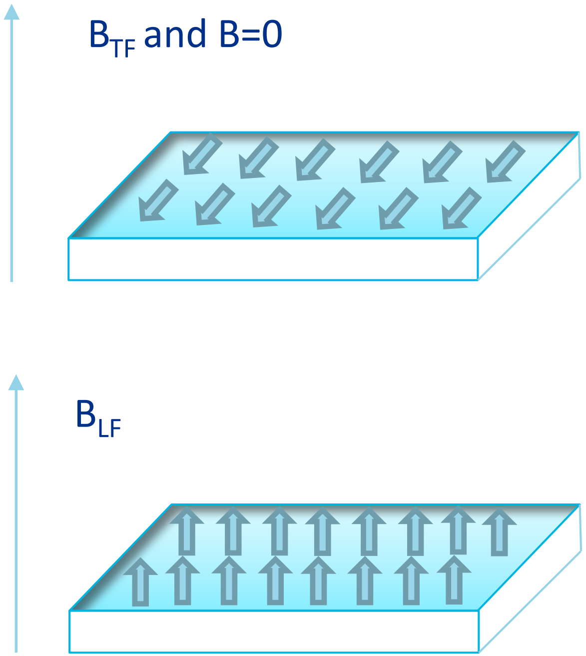
Map is based on wiki image

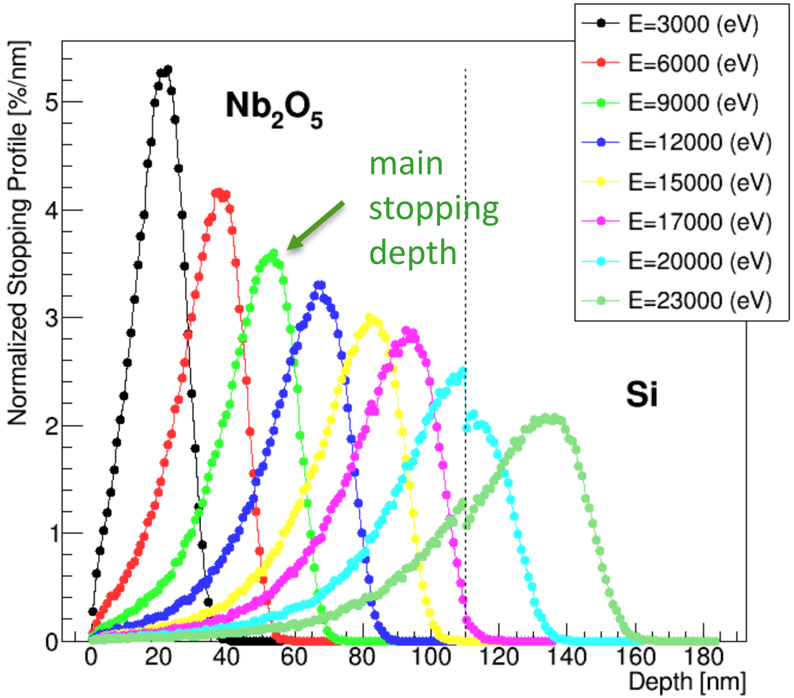
 μSR facilities

*Low-energy muons

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

μSR in thin films

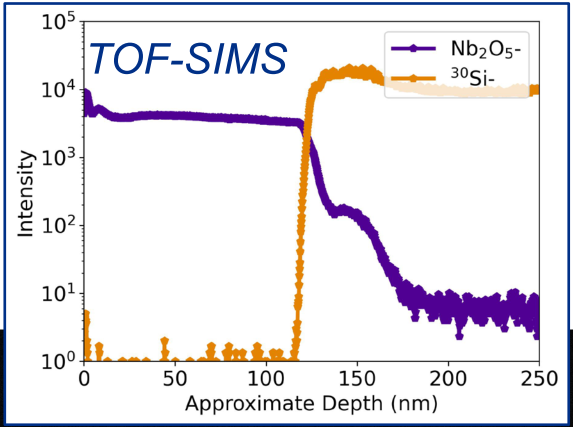


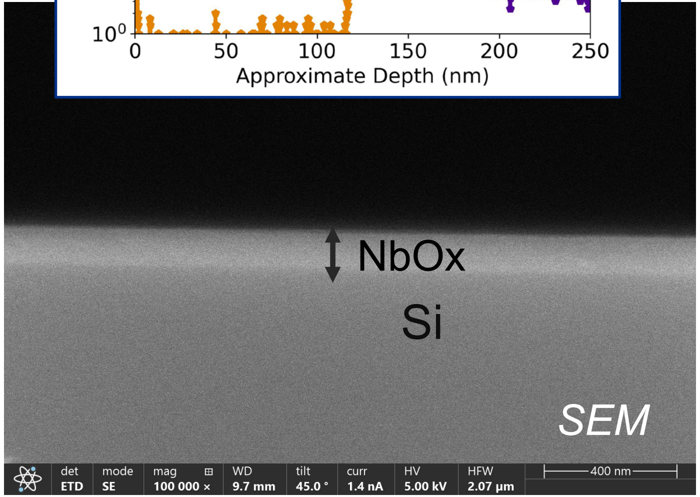


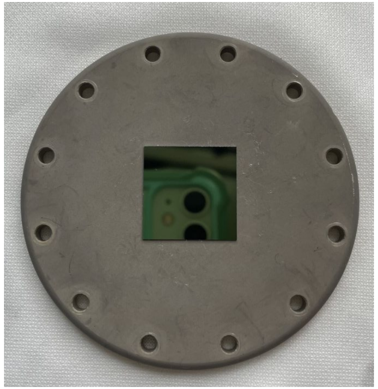
- Magnetic field* variation for LEM facility:
- ZF (zero field): muon spins are in plane of the sample
- TF (transverse field): transverse to the spins, muon spins are in plane of the sample
- LF (longitudinal field): field is orthogonal to the sample plane

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Sample and environment







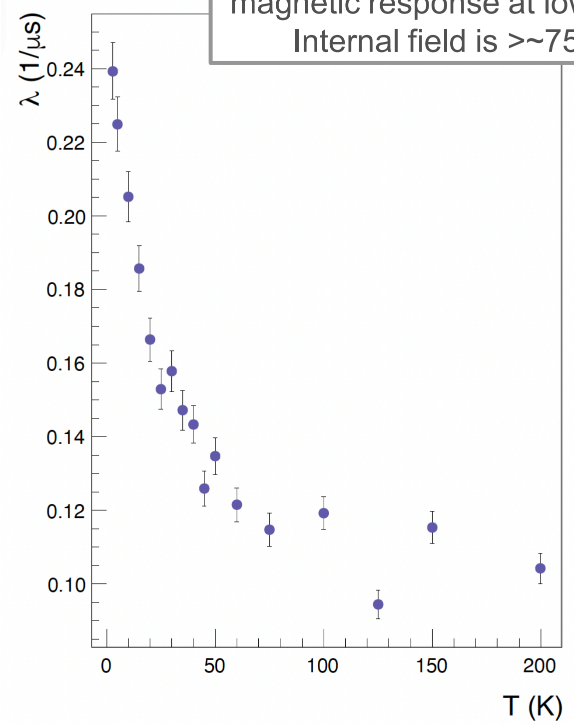
110 nm film Nb2O5/Si glued on sample holder

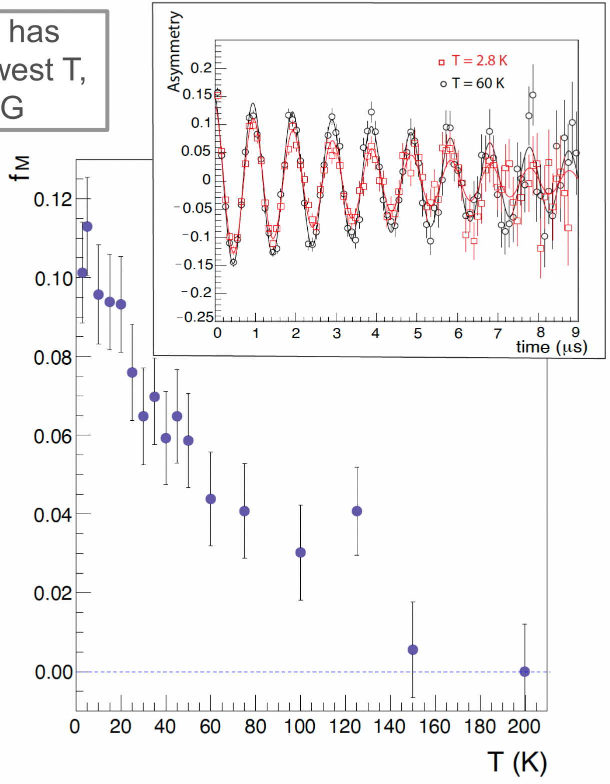
- Temperature down to 2.7 K (cold finger)
- Vacuum 10^{-9} mbar
- Magnetic field LF, TF or ZF up to 3400 G
- Beam energy 1-30 keV

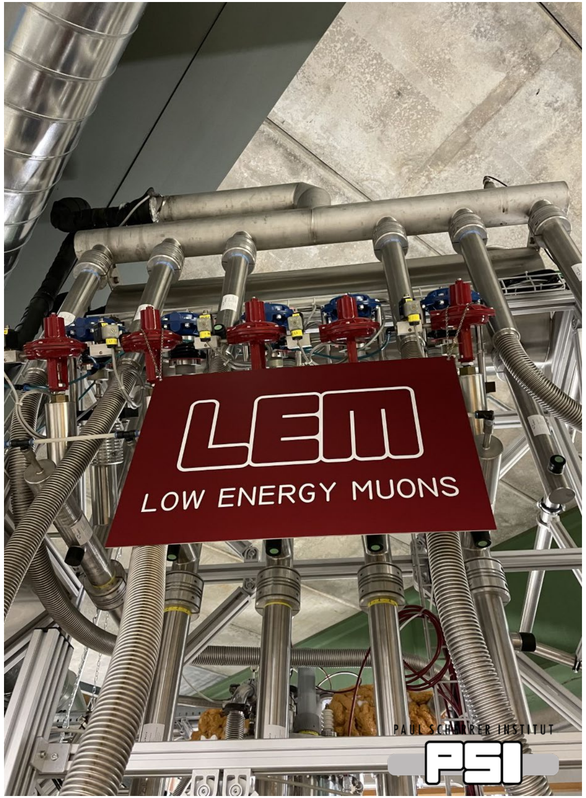
μSR in transverse field

$$P_x(t) = A(T)\exp(-\lambda t)\cos(\gamma_\mu B t + \phi)$$

10% of sample volume has magnetic response at lowest T, Internal field is >~75G



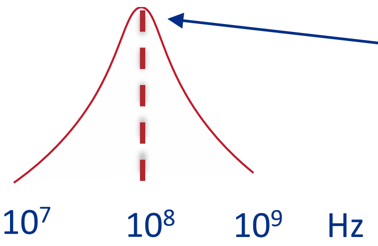


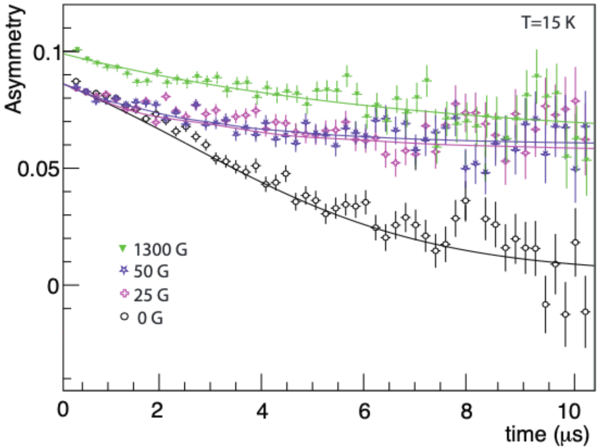


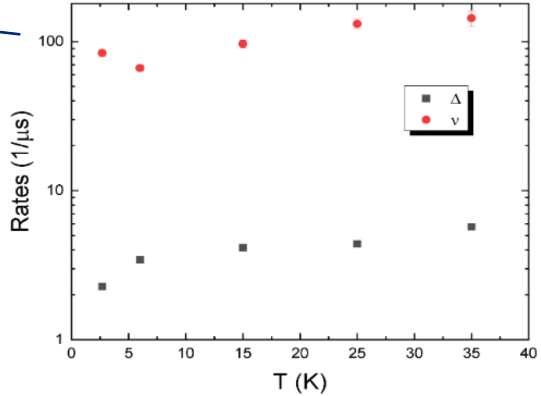
μSR in longitudinal field

Hopping rate=fluctuations rate of internal magnetic field

μSR sensitivity to local field fluctuations







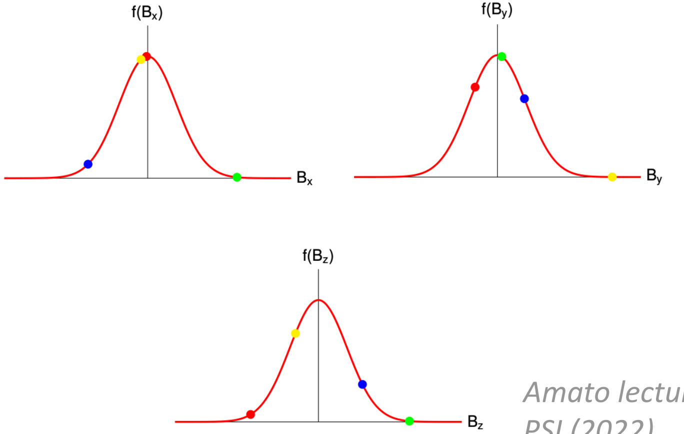
$\nu - hopping\ rate,$
$\Delta - static\ contribution$

$$\overline{B_{\rm loc}(t_0)B_{\rm loc}(t_0+t)} = \overline{(B_{\rm loc})^2}\exp\left(-\nu|t|\right),$$

$$P_z^{\rm stat}(t) = A\left(\frac{1}{3} + \frac{2}{3}\exp\left(-1/2\Delta^2t^2\right)(1-\Delta^2t^2)\right)$$

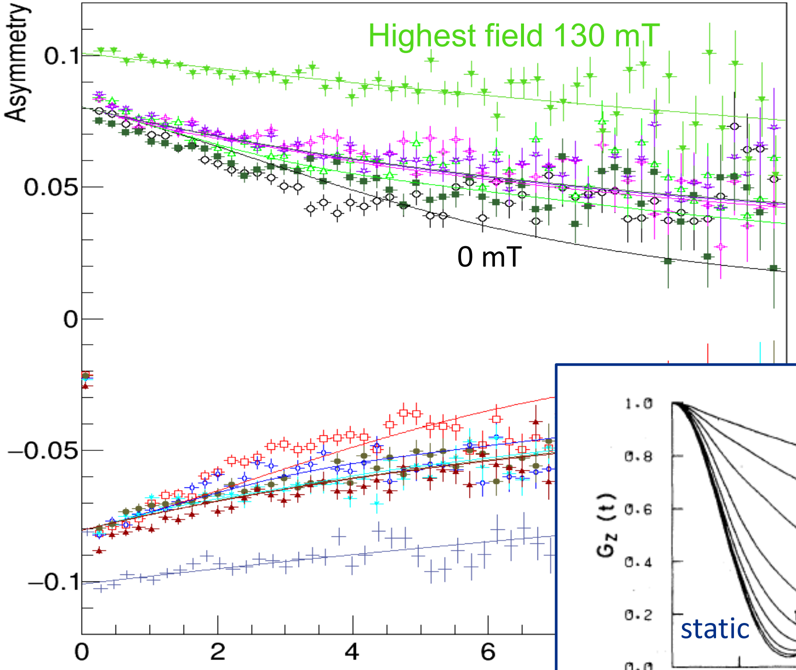
$$P_z(t) = P_z^{\rm stat}(t)\exp(-\nu t) +$$

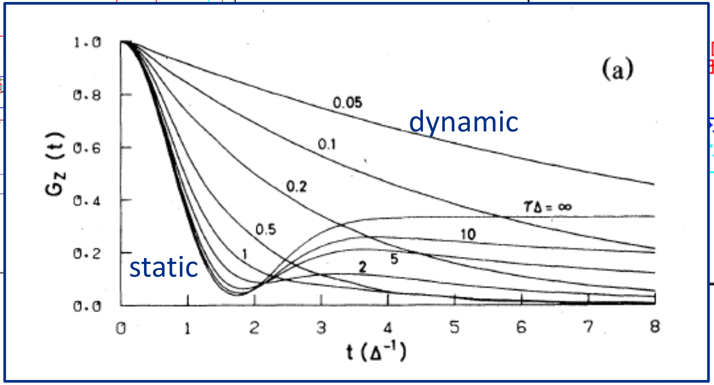
$$+\nu\int_0^t P_z(t-t')P_z^{\rm stat}(t')\exp(-\nu t')dt',$$

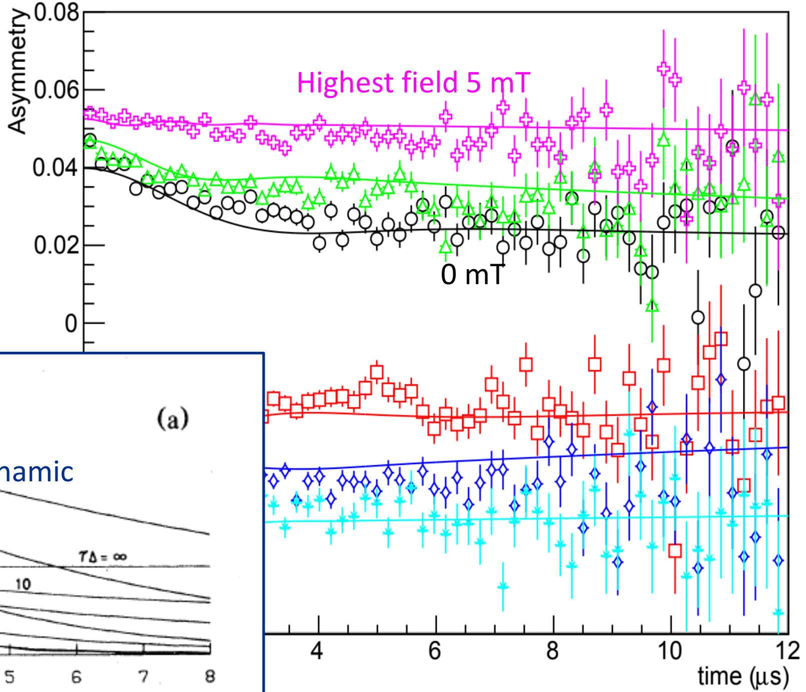


Amato lectures PSI (2022)

Nb_2O_5 vs Ta_2O_5







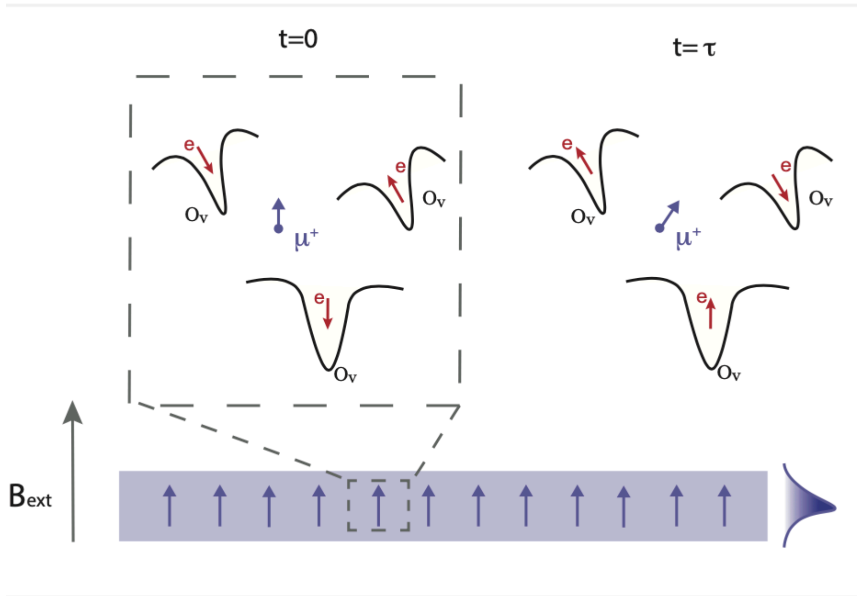
No fluctuations in Ta_2O_5

Hayano et al, PRB 20 (1979)

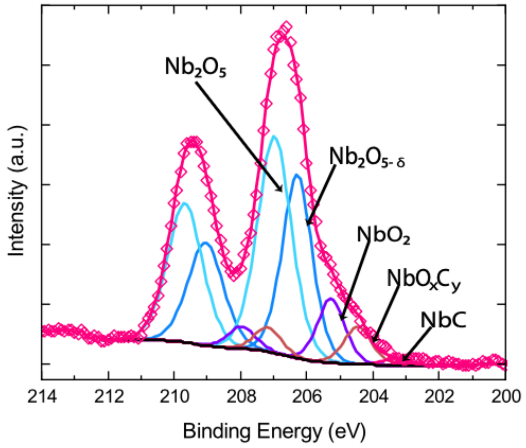
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

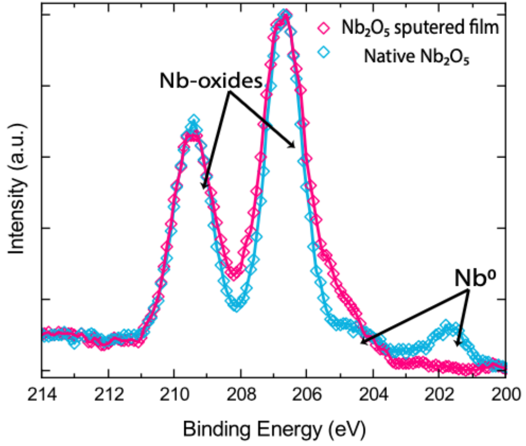
arXiv:2312.10697

Source of magnetic response for Nb_2O_{5-x}



Oxygen vacancies could explain magnetic response





SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

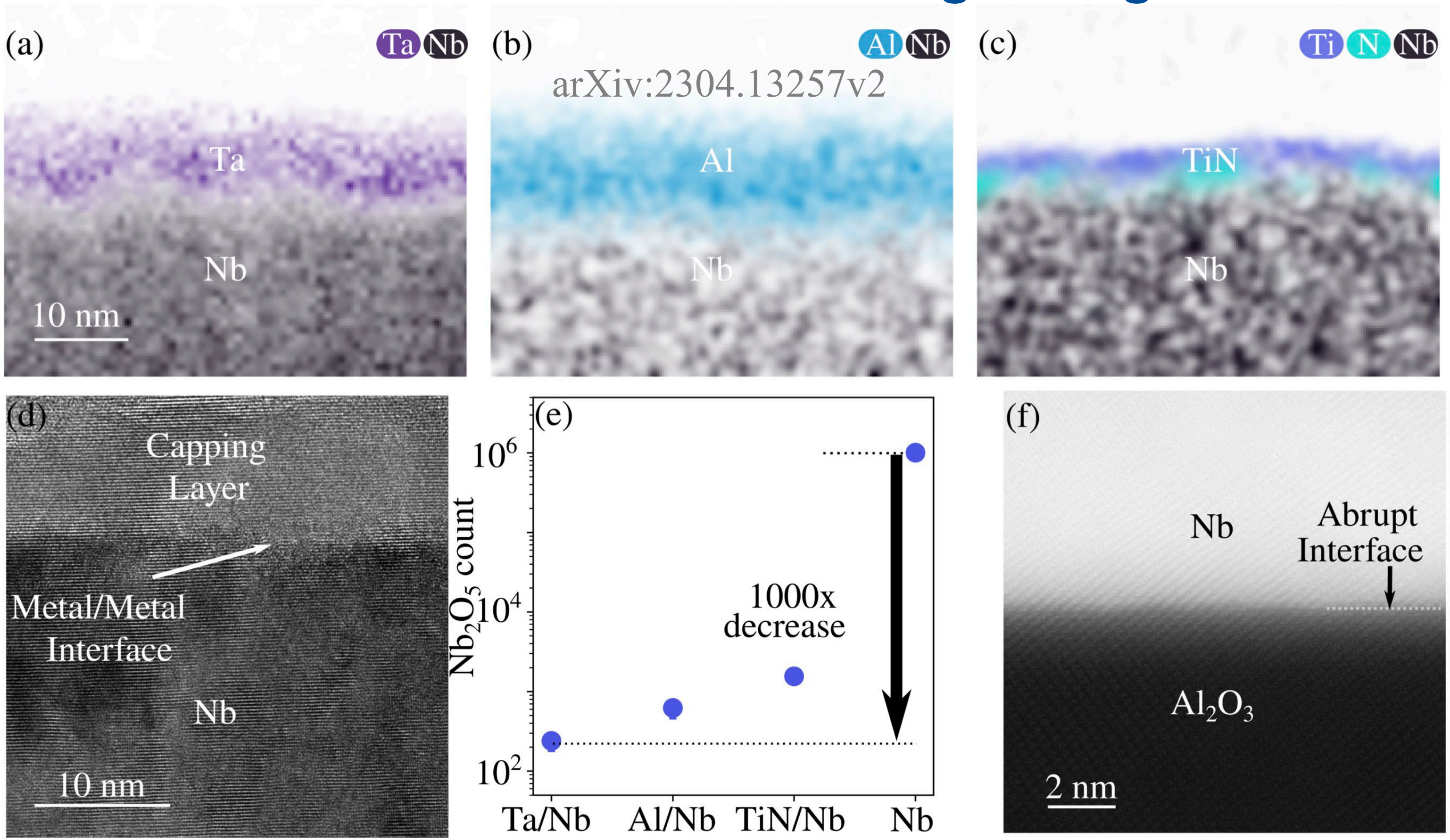
Why magnetic fluctuations are important for qubits and superconducting Nb-based devices?

- Source of microwave loss: Fluctuations = Dissipation
- Could lead to superconductivity suppression and depairing due to proximity effect
- Giving a clue about potential noise sources mechanisms and spurious modes:

easily overlaps with qubit frequency

- Not suppressed at low temperatures
- Might explain temperature-dependent changes of flux in flux-tunable devices
- Could explain why Nb-based devices have worse performance in comparison with Ta-based devices

Improvement of coherence with oxide mitigation growth strategy



*Follow us on social media **@sqmscenter***

Twitter / X

Instagram