International Workshop on Muon Physics at the Intensity and Precision Frontiers (MIP2026)

Introduction of μSR detection techniques and recent progress

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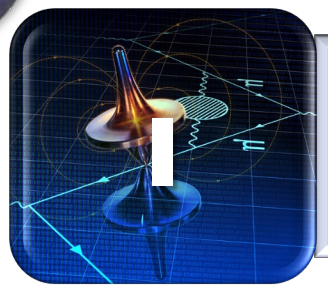
On behalf of all colleagues and collaborators from μSR instrumentation groups

Department of Modern Physics,

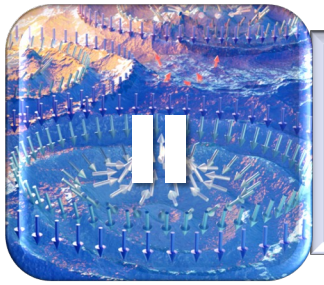
University of Science and Technology of China

2026/04/26, Huizhou

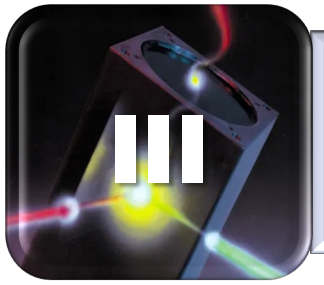
Content



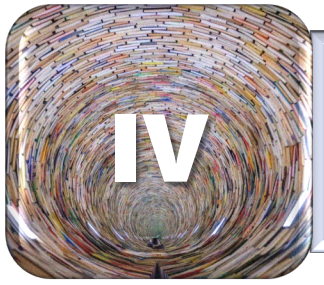
Properties, sources and applications



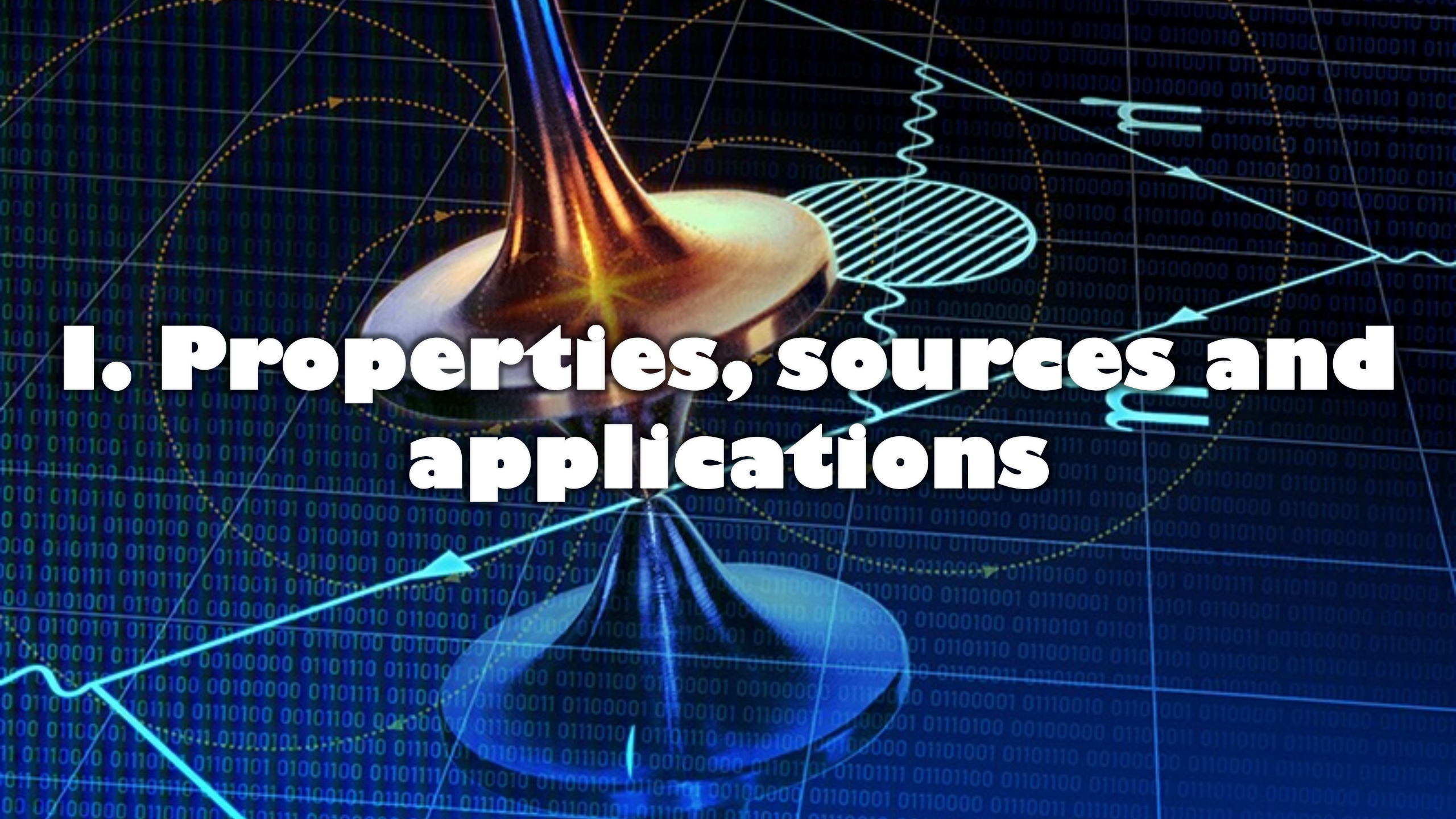
Introduction of μSR spectroscopy



Progress of spectrometer developments

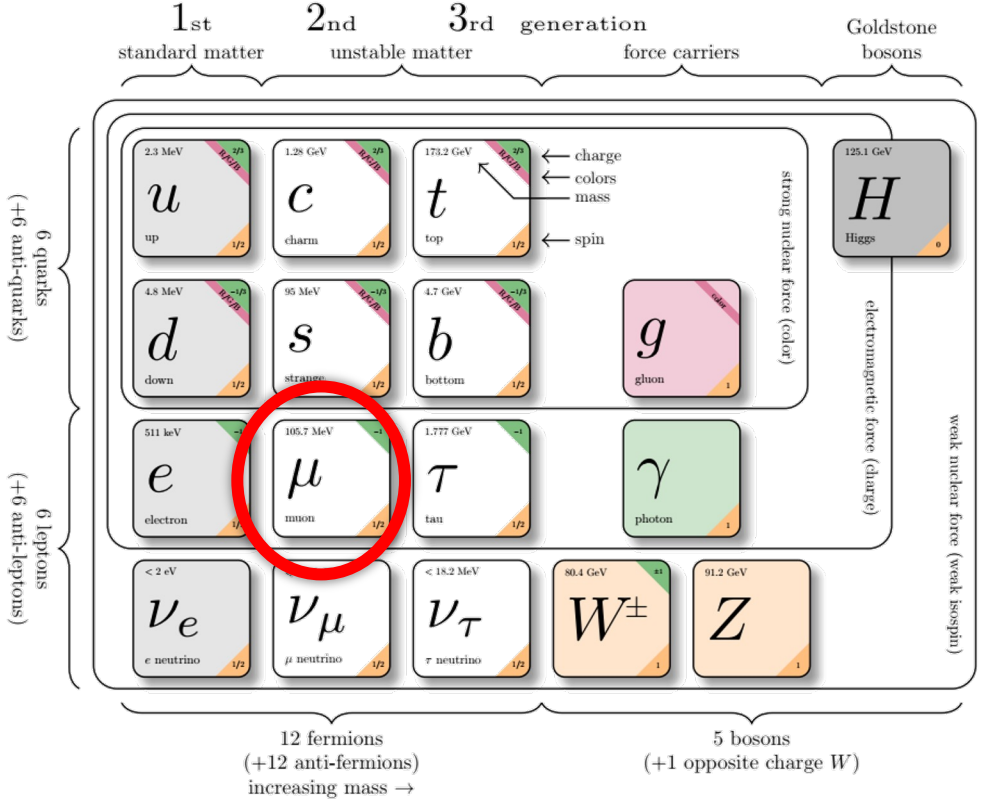


Summary and prospects

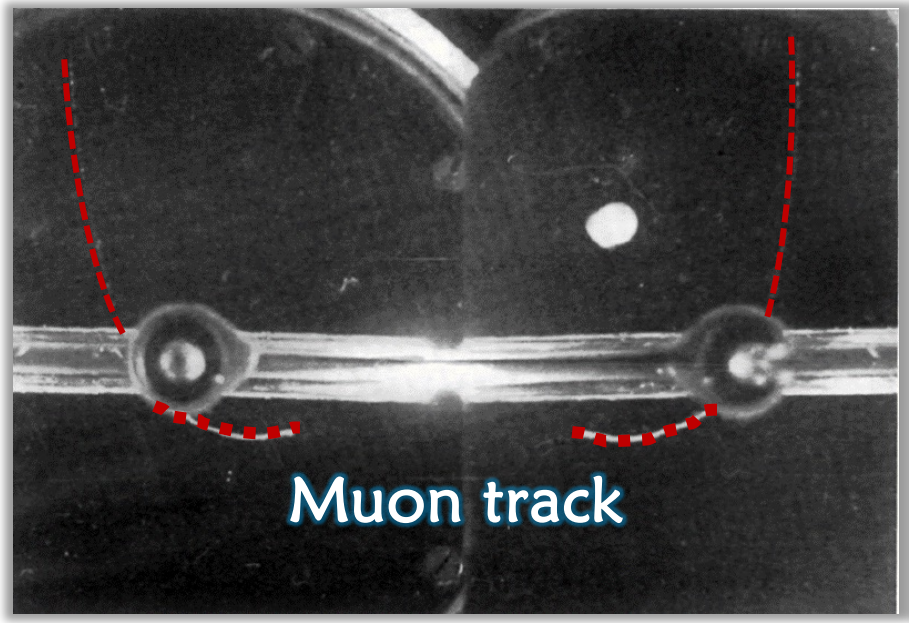


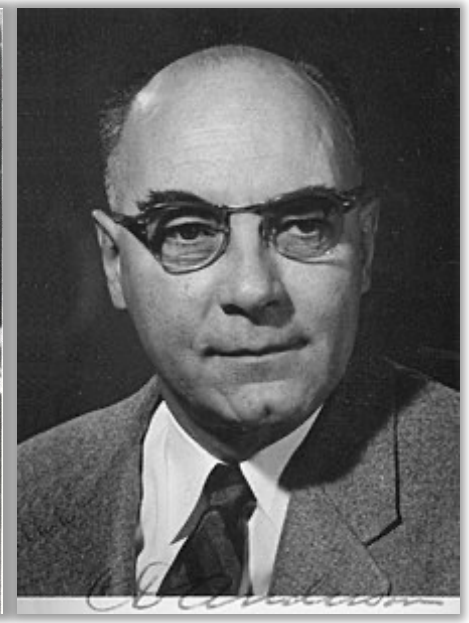
I. Properties, sources and applications

Basic properties



In 1936, Nobel Prize laureate C.D. Anderson discovered the first muon!

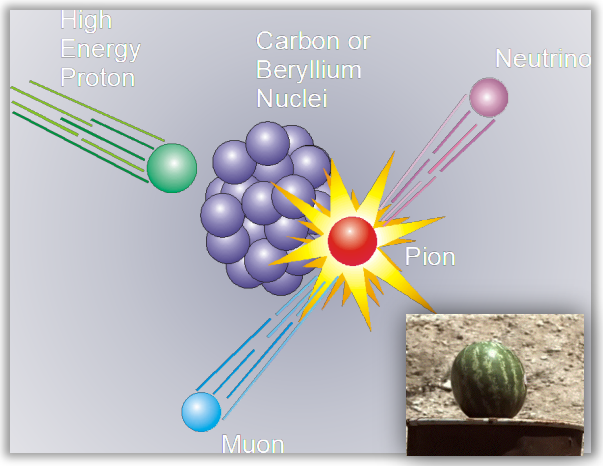




- Fundamental particle, $m_e < m_\mu < m_p$
- Unstable, average lifetime ~ 2.2 μs
- Spin ½, point-like, 100% polarized, a quantum magnetism probe

Main sources

Particle-Nucleus collision

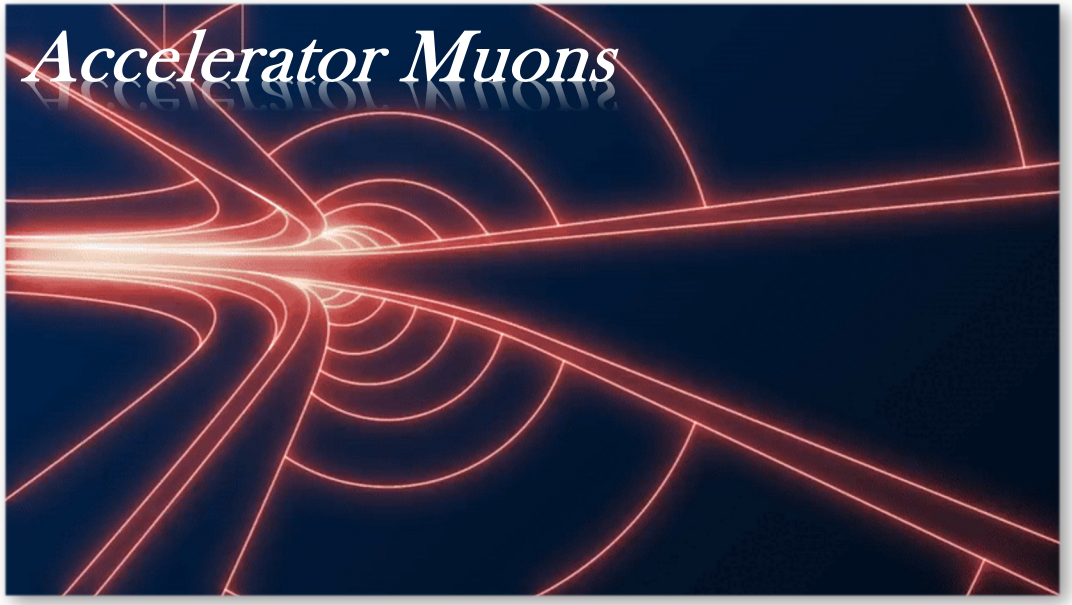


■ Proton-On-Target (POT)

$$p + p/n \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$

■ Electron-On-Target (EOT)

$$e^- + Z \rightarrow Z + \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$
$$\mu^+ + \mu^-$$



Accelerator muon facilities

Facility	Status	Location	Beam mode	Target mode	Energy	Application
TRIUMF	Operation	Canada	CW	POT	MeVs	FP, AS
FermiLab		US	Pulsed (12Hz)	POT	GeVs	FP
ISIS		UK	Pulsed (40 Hz)	POT	MeVs	AS
PSI		Switzerland	CW	POT	MeVs	FP, AS
CERN-SPS		Switzerland	Pulsed	POT	GeVs	FP
J-PARC		Japan	Pulsed (25 Hz)	POT	MeVs	FP, AS
RCNP		Japan	CW	POT	MeVs	FP, AS
CSNS	Construction	China	Pulsed (1 Hz)	POT	MeVs	FP, AS
RAON		South Korea	CW	POT	MeVs	AS
SNS	Consideration	US	Pulsed (50 kHz)	POT	MeVs	AS
JLab		US	CW	EOT	GeVs	FP
SHINE		China	Pulsed (50 kHz)	EOT	MeVs – GeVs	FP, AS
CiADS		China	CW	POT	MeVs	FP, AS
HIAF		China	Pulsed (3 Hz)	POT	GeVs	FP, AS

***CW**: Continuous Wave, **FP**: Fundamental physics, **AS**: Applied Sciences*

Muon projects in China

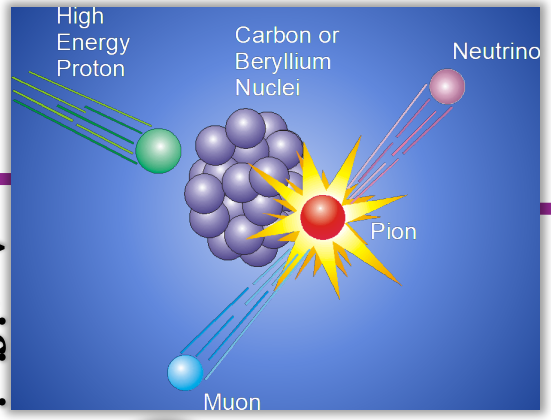
■ Indico links

- ✓ *CSNS-MELODY*
- ✓ *HIAF*
- ✓ *CiADS*
- ✓ *SHINE*

- *Details in Chen Wu/Liangwen Chen/Hanjie Cai/Jun Kai Ng's talks*

Research frontiers in muon sciences

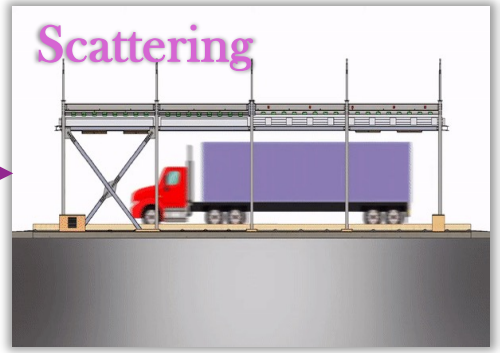
Muons: Bridging the Micro- and Macro-scopic Extremes of Universe!



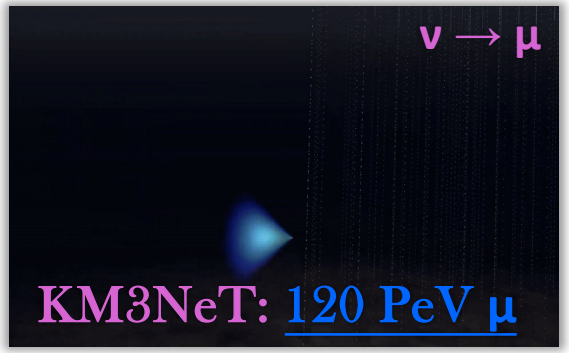
Artificial muons

Natural muons

Muography

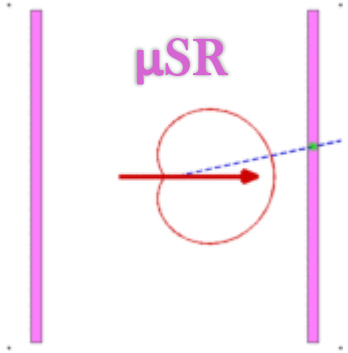


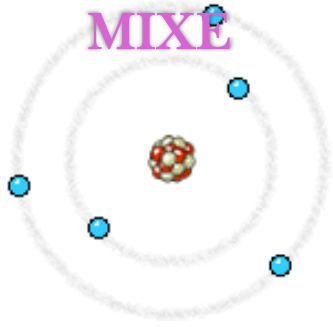
Cosmic messenger



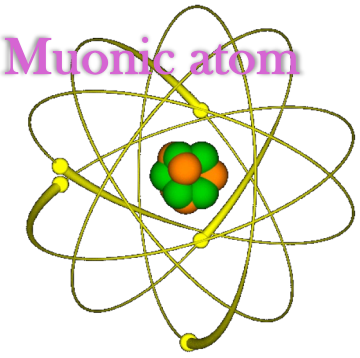
keV MeV GeV TeV

Material characterization



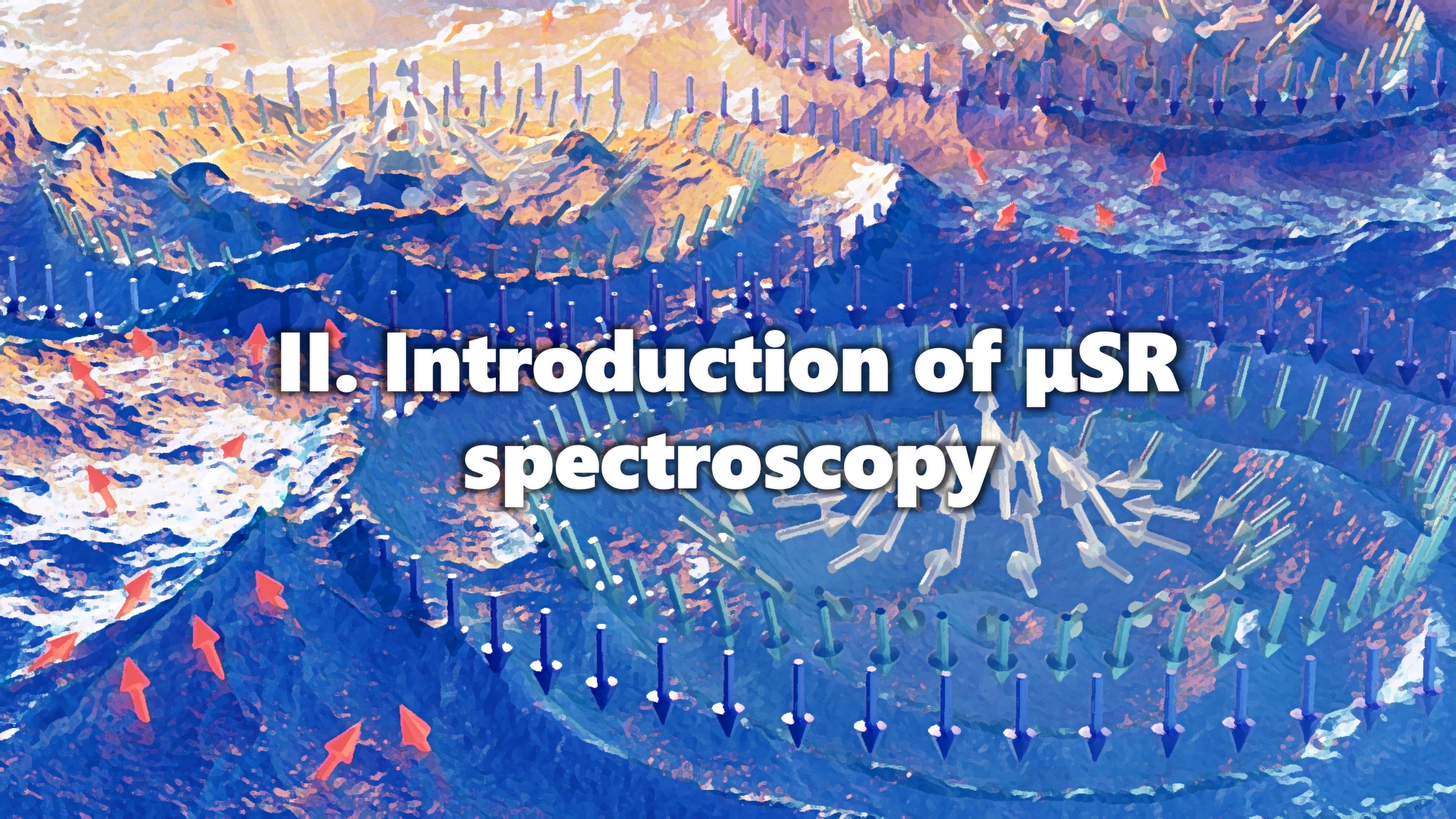


Precision measurement



Muon collider

** * * Applications not limited to this list!*

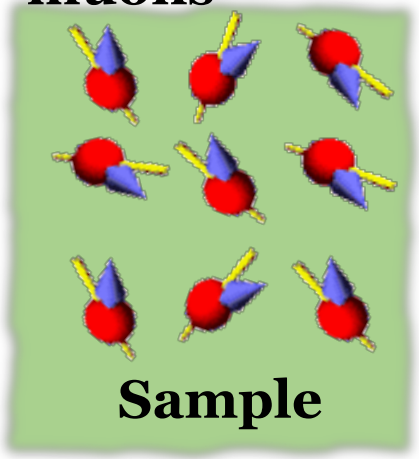


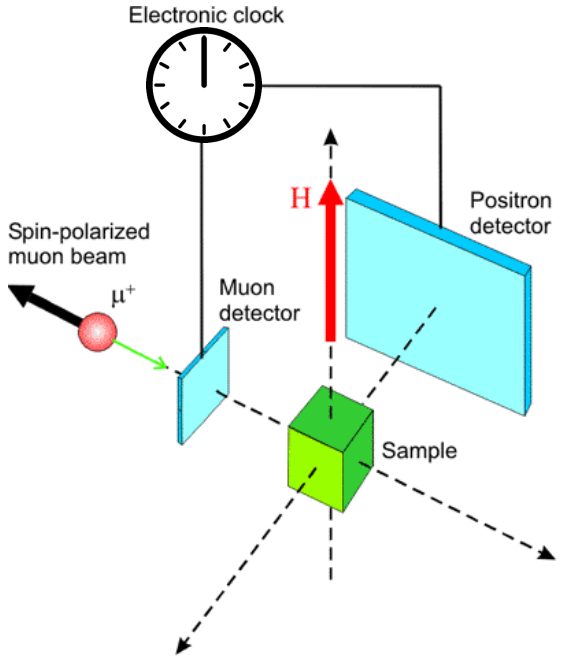
II. Introduction of μSR spectroscopy

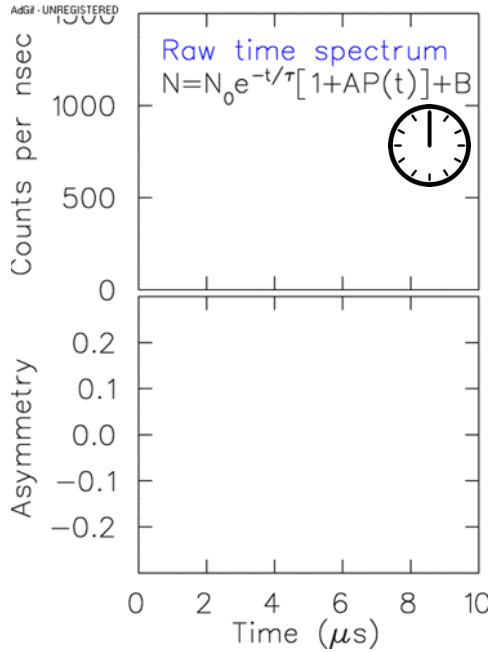
Principles

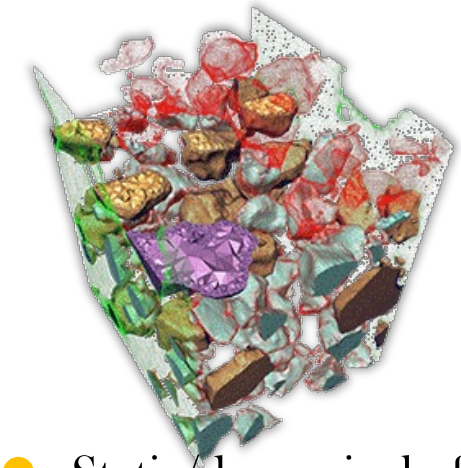
μSR: muon spin rotation/relaxation/resonance

Precession (spin interaction) → **Asymmetry** (positron detection) → **μSR spectra** (analysis) → **Material** (properties)









$$\frac{d\boldsymbol{S}_\mu(t)}{dt} = \gamma_\mu \boldsymbol{S}_\mu(t) \times \boldsymbol{B}_{\mathrm{loc}}(t)$$

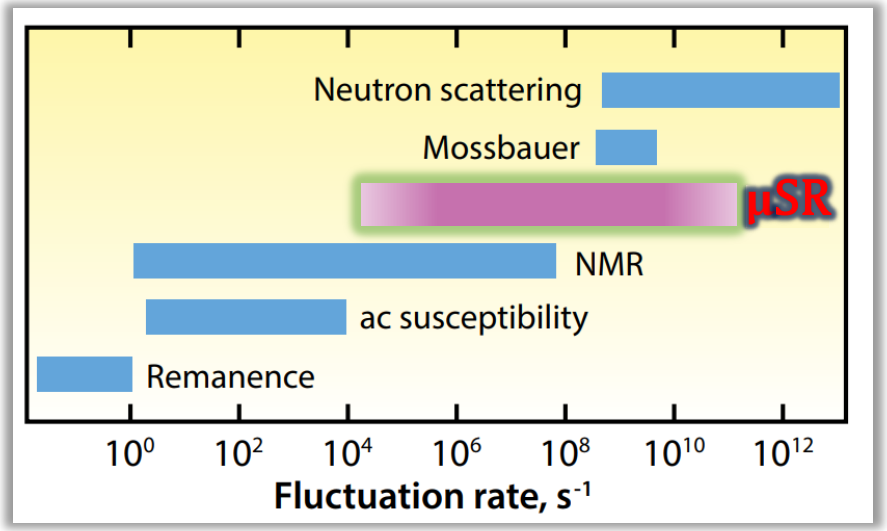
$$\mu^+ \rightarrow \boldsymbol{e}^+ + \nu_e + \bar{\nu}_\mu$$

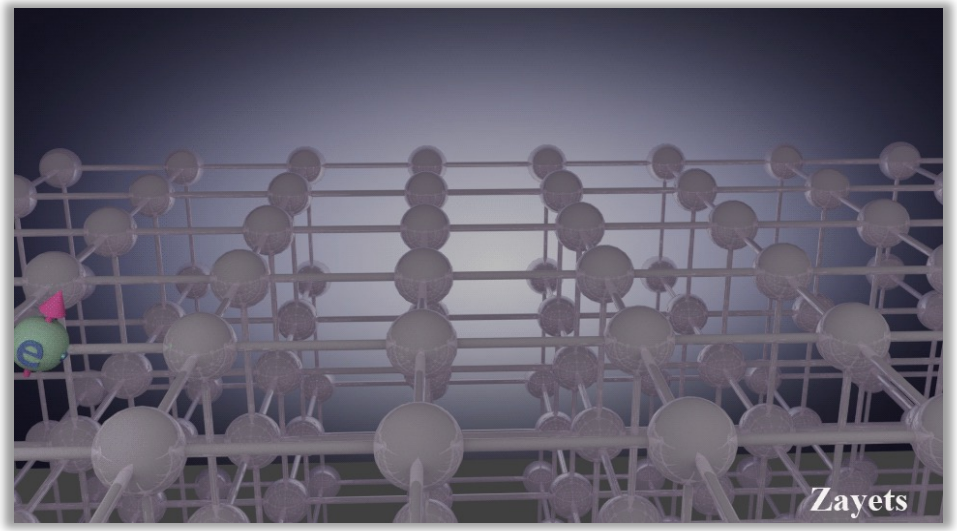
$$\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = A\boldsymbol{P}(t)$$

$$\boldsymbol{\omega} = \gamma_\mu \boldsymbol{B}_{\mathrm{loc}}$$

- Static/dynamical effect
- Magnetic fluctuation
- SC / magnetic phase
- Magnetic volume
- Charge diffusion
- Radicals
- …

Advantages





- **A local quantum magnetic probe** (no need to search reciprocal space)
- **Unique & wide time scale** (complementary to NMR/neutron scattering)
- **Very weak effects** (small moment magnetism ~ 10^{-3} μ_B/Atom)
- **Random & inhomogeneous magnetism** (e.g. spin glasses, quantum spin liquid)
- **Short range order** (where neutron scattering is not sensitive)
- **Full polarization in zero field** (independent of temperature, unique measurements without disturbance of the system)
- **Single particle detection** (with extremely high sensitivity)
- **No sample restrictions** (in choice of materials to be studied)

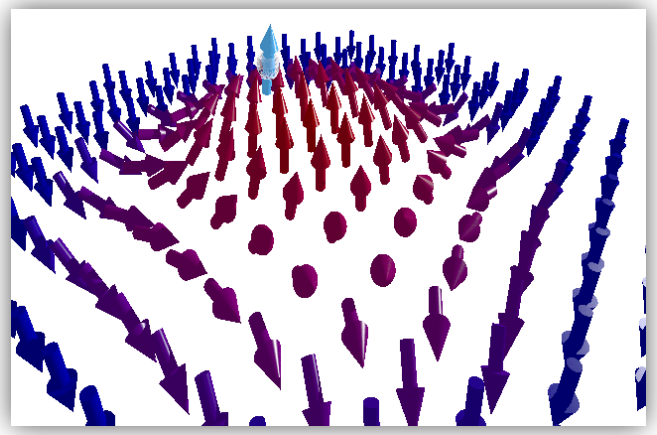
Applications

• Passive probe

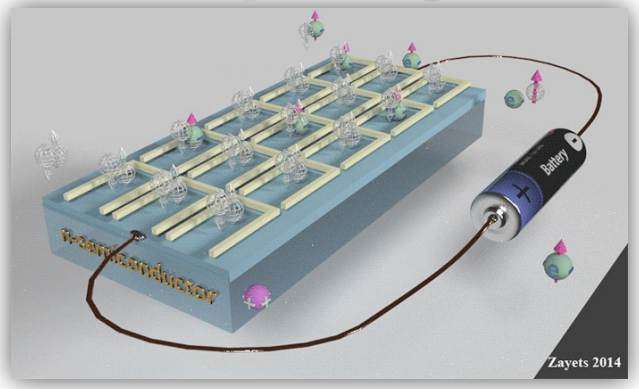
(heavy lepton)

Superconductor

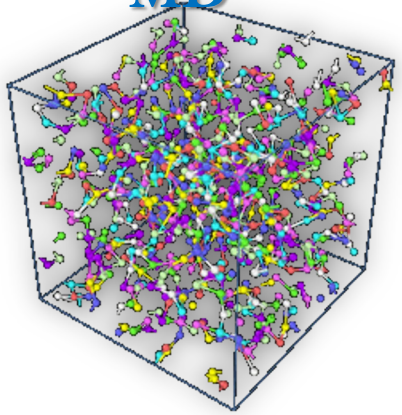
Magnetism



Charge transport



MD

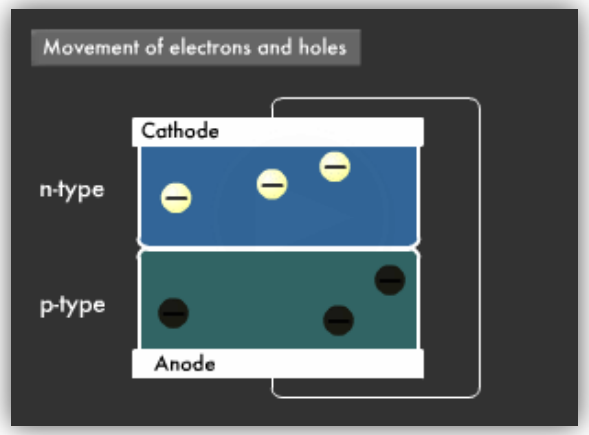


Nat. Rev. Meth. Prime. : Muon Spin Spectroscopy

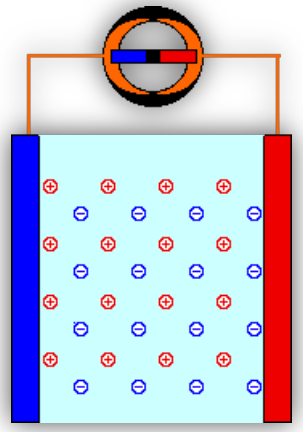
• Active probe

(light proton)

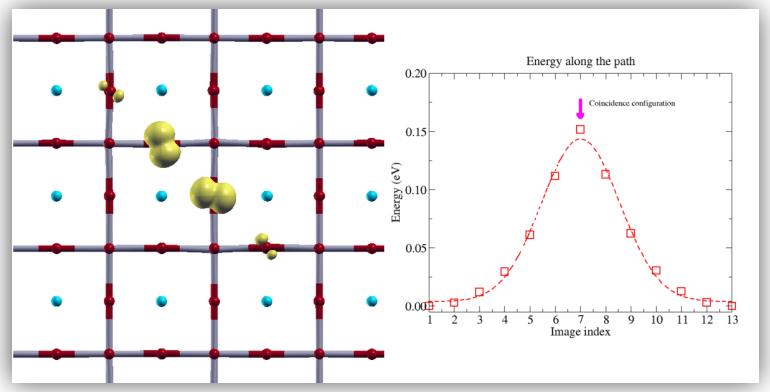
Semiconductor



Ionic conductor



Polaron motion

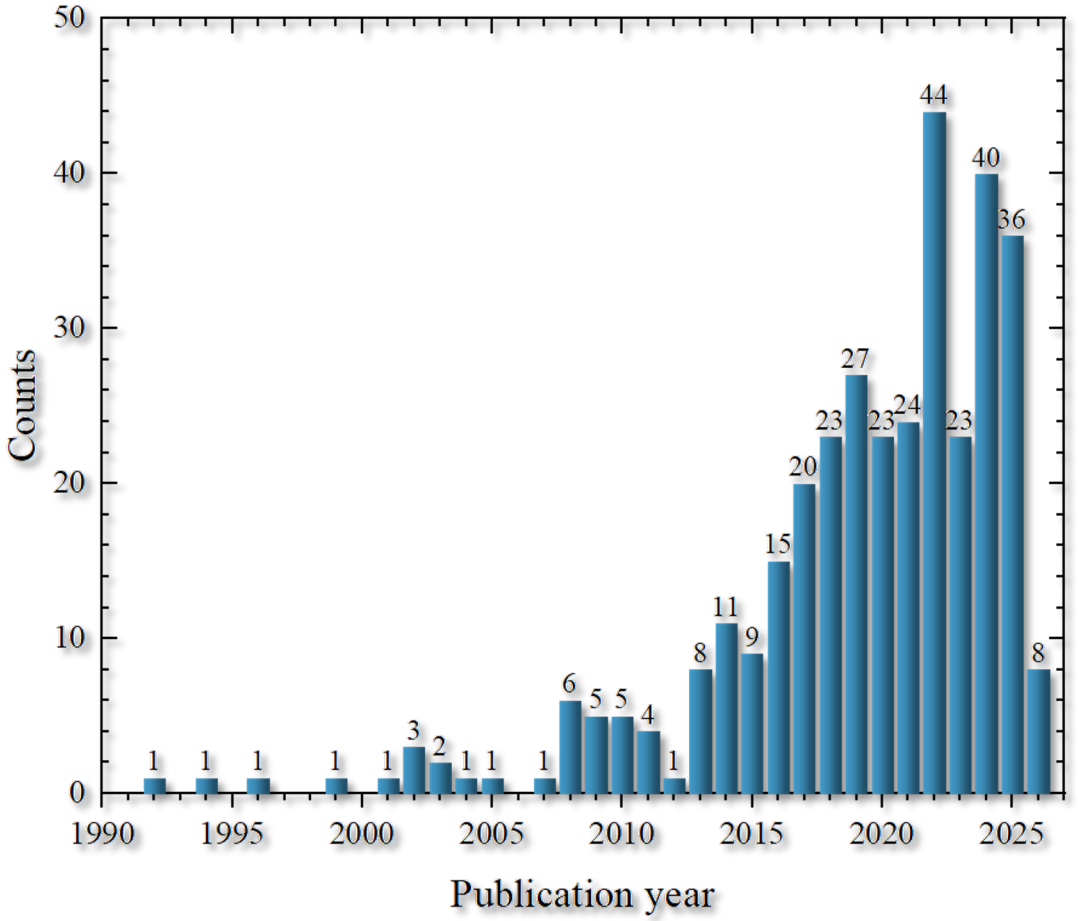


Courtesy Dr. Adrian Hiller @ ISIS Muons

...

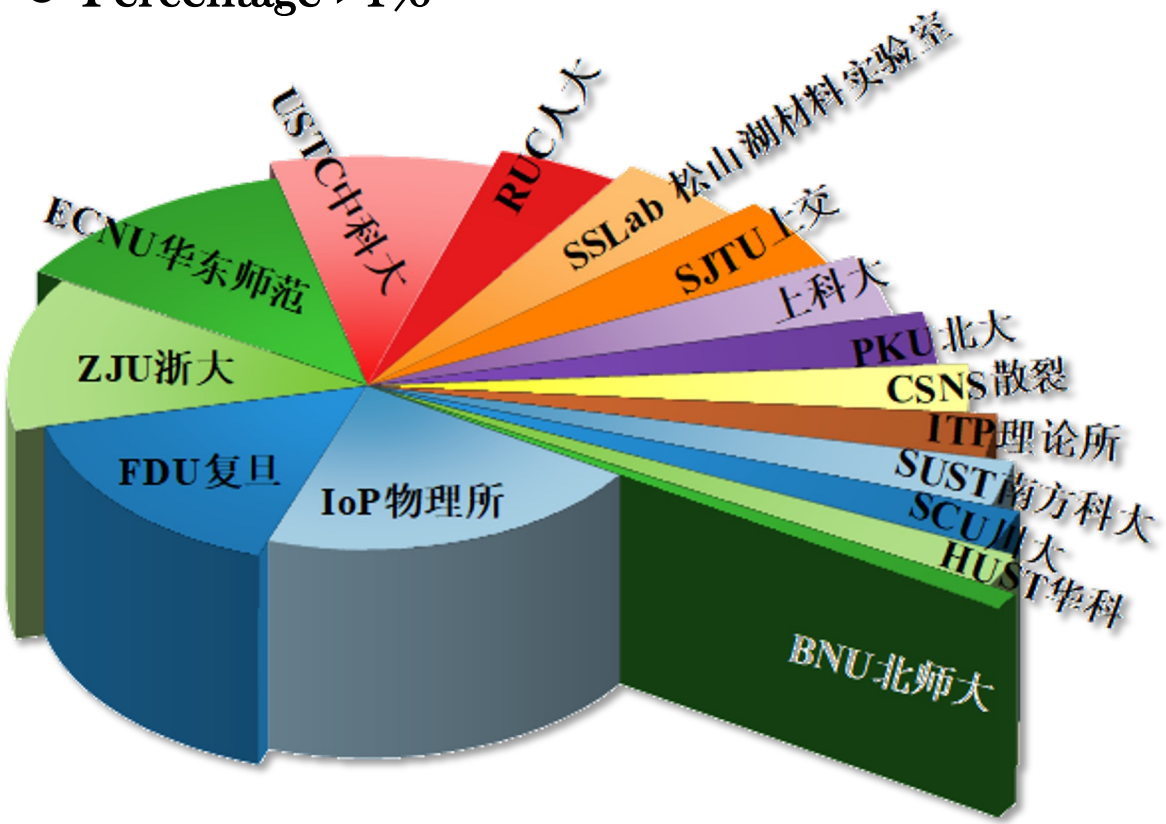
Statistics of Chinese users

~ 345 papers



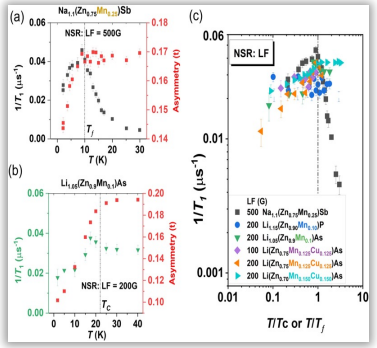
> 50 affiliations

- Percentage >1%



Web of Science analysis (muon spin spectroscopy / muon spin relaxation / muon spin rotation) 2026/4

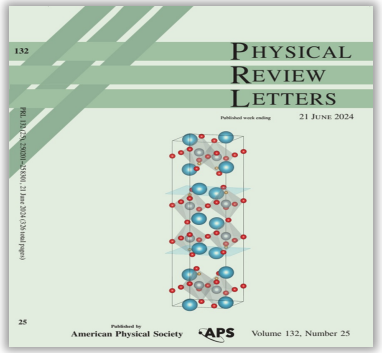
Chinese highlights in various fields



Dr. Guoqiang Zhao(赵国强) @ KITS

Editor's suggestion

- *Spin-charge interplay in the diluted magnetic semiconductor Na(Zn, Mn)Sb studied by multiprobe measurements and simulations,* **Physical Review B** *112, 075104 (2025)*
- ***Diluted magnetic semiconductors***

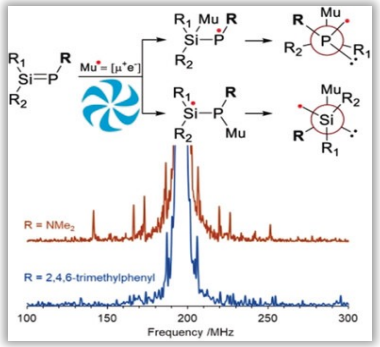


Prof. Lei Shu(殳蕾) @ FDU

Editor's suggestion and cover

- *Evidence of Spin Density Waves in $La_3Ni_2O_{7-\delta}$,* **Physical Review Letters** *132, 256503 (2024)*
- ***Ni-based superconductors***

PRL 2024 COLLECTION



Prof. Yuanjing Cai(蔡元婧) @ BUCT

- *Free Radical Chemistry of Phosphasilenes,* **Angewandte International Edition Chemie** *59, 16007 (2020)*
- ***Free radicals***

Continuous VS Pulsed

Continuous

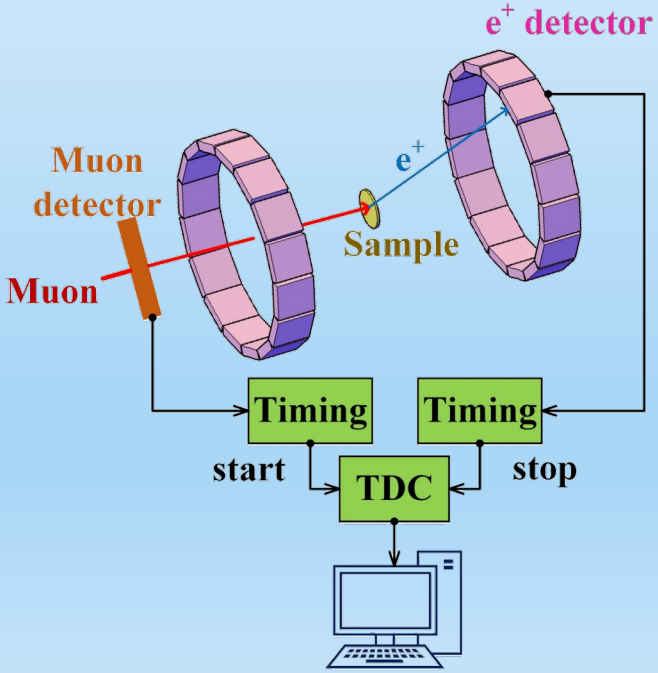
◆One μ^+ & one e^+

✓ High time resolution O(0.1 ns)

✓ Sensitive to fast relaxing signals

× Coincidence background

✓ 0 – 10 μs or shorter



Pulsed

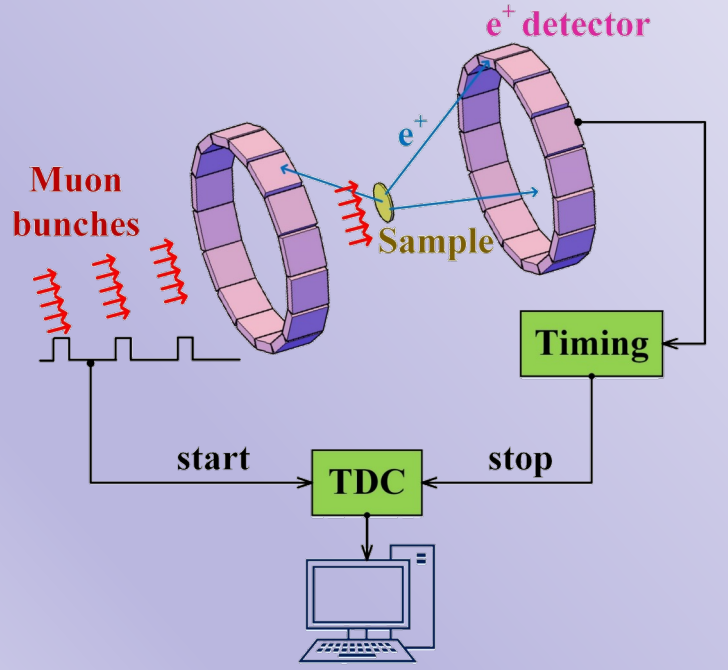
● One μ^+ bunch & multi e^+

× Low time resolution O(100 ns)

✓ Sensitive to slow relaxing signals

✓ No coincidence background

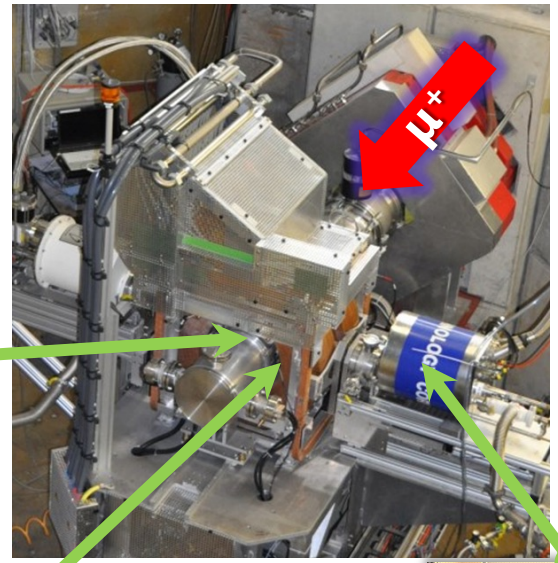
✓ 0 – 32 μs or longer

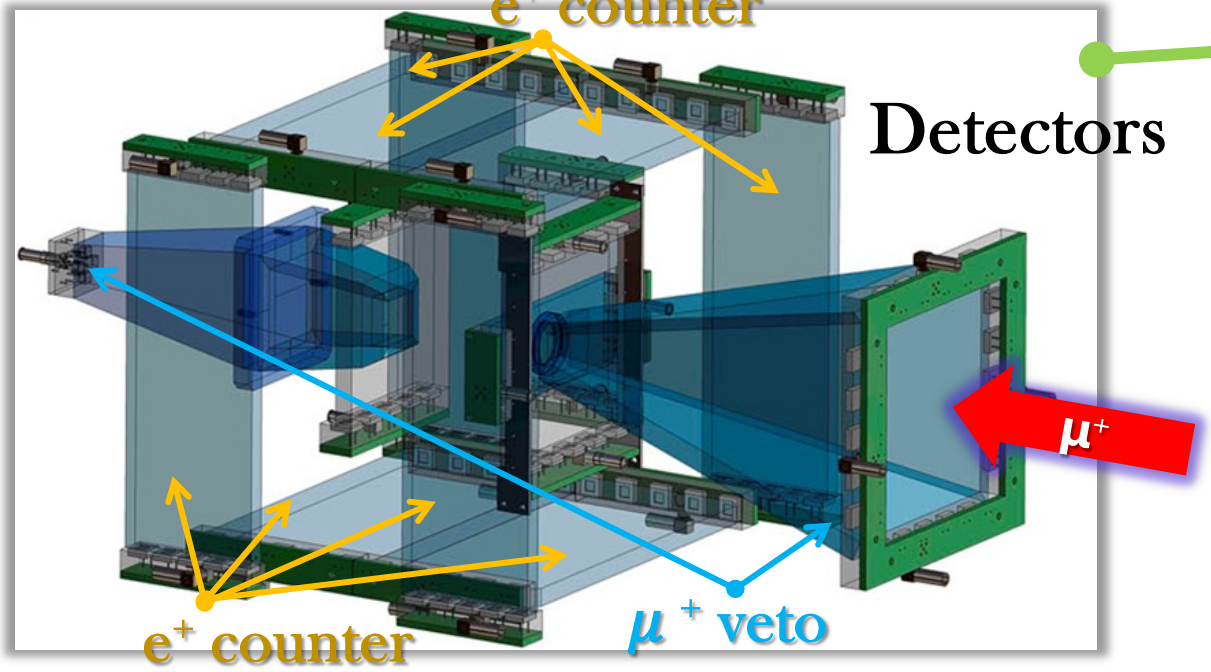


Spectrometer composition (continuous)

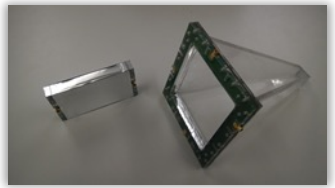
- Small volume, large solid angle, a few channels
- Three types of detectors (veto, μ^+ / e^+ counters)
- High time resolution is required

GPS @ PSI





Detectors



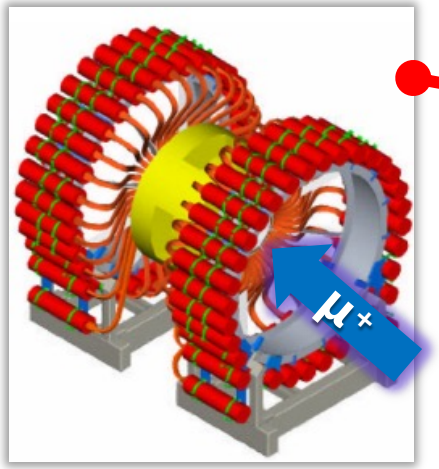
Magnets

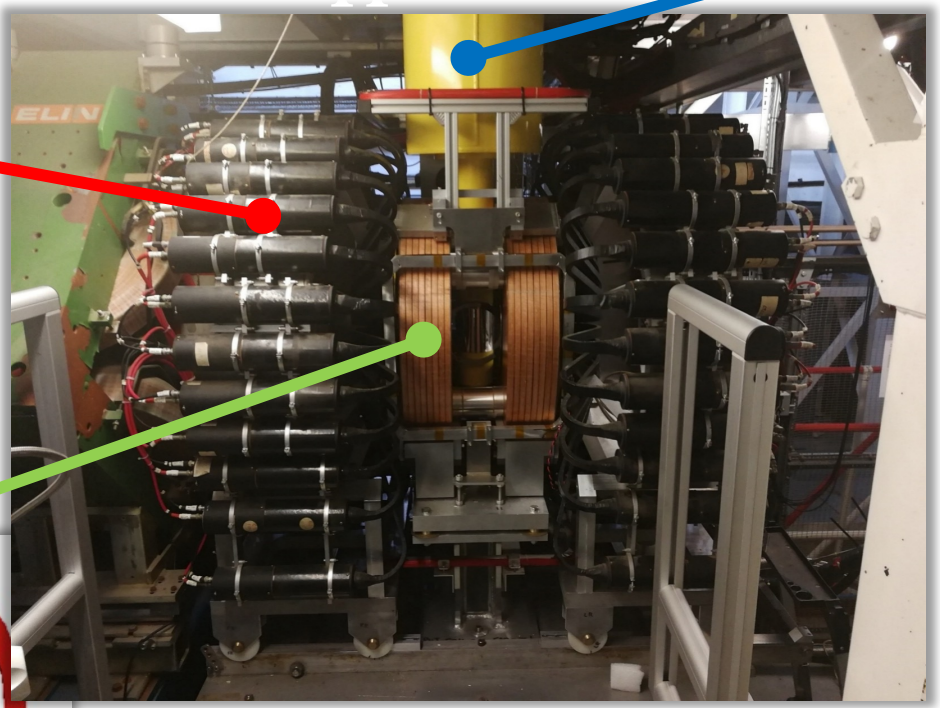
Sample environment

Spectrometer composition (pulsed)

- Large volume, limited solid angle, high granularity
- Only e^+ counters
- High counting rate is required

Detector

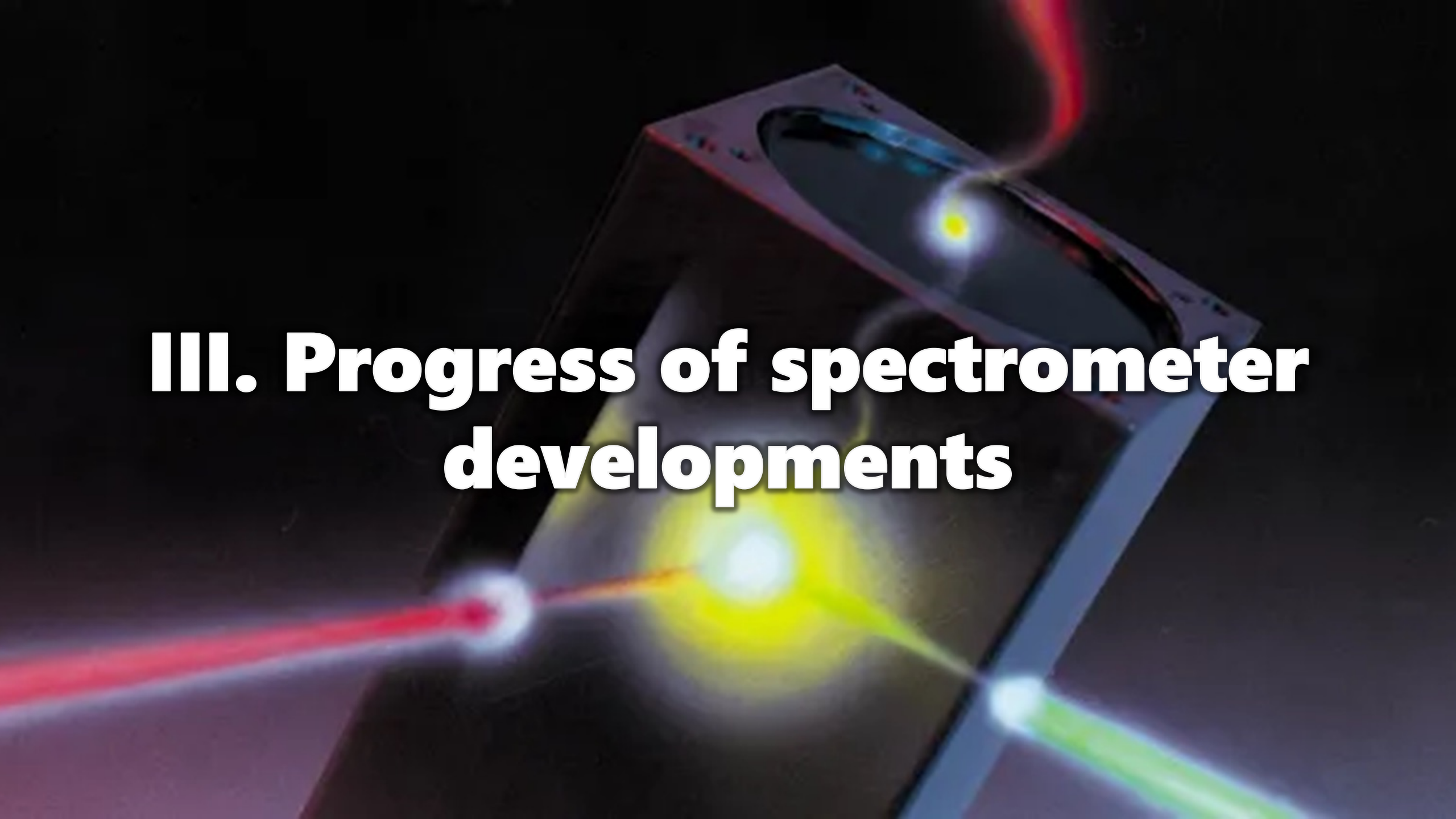




MuSR @ ISIS

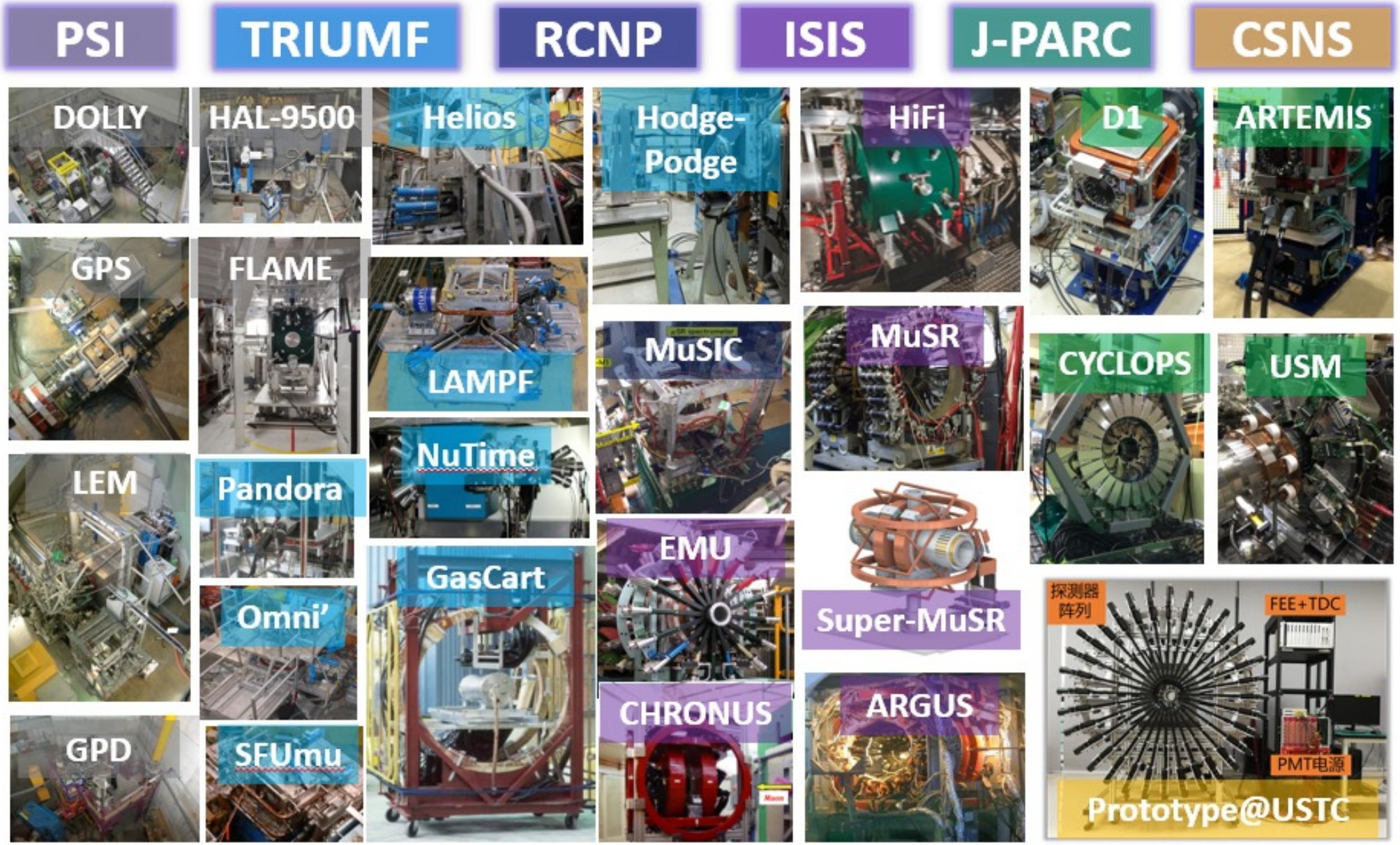
Sample environment

Magnets



III. Progress of spectrometer developments

Global μSR spectrometers



Global μSR spectrometers

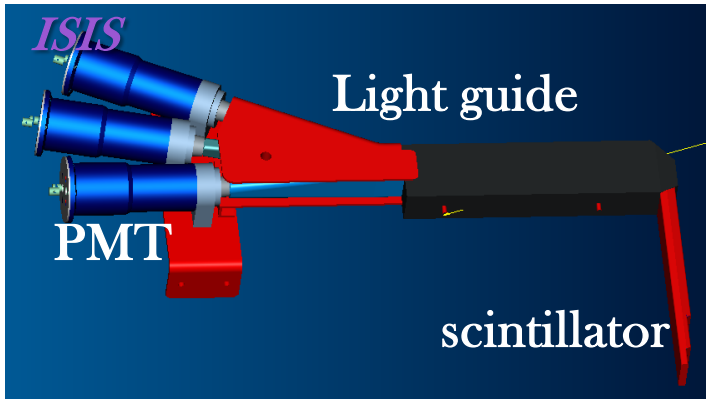
Spectrometers in operation

Facility	Mode	Spectrometer	Sensor	Counts
PSI	CW	DOLLY→VMS, GPS, GPD, HAL-9500, LEM, FLAME	SiPM	6
TRIUMF	CW	Helios, DR, NuTime, Omni Prime, LAMPF, SFUmu, Hodge-Podge, Gas Cart	PMT	8
MuSIC	CW	Reused from KEK	PMT	1
ISIS	Pulsed	MuSR→SuperMuSR, EMU, HiFi, ARGUS, CHRONUS	PMT/SiPM	5
J-PARC	Pulsed	D1, ARTEMIS, USM, CYCLOPS	SiPM	4
In total:				**24**

PMT: Photomultiplier tube
SiPM: Silicon Photomultiplier

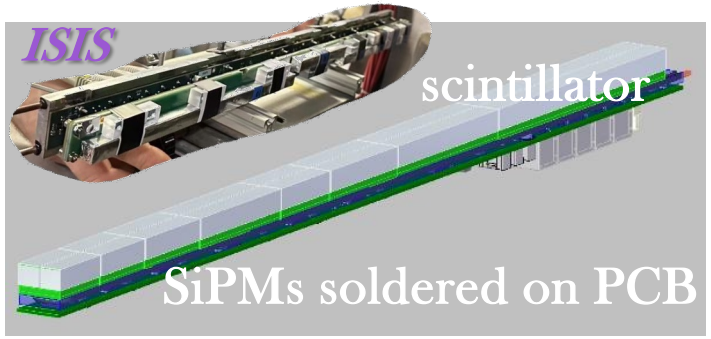
Detection technology developments

1st Gen
- PMT / Counting



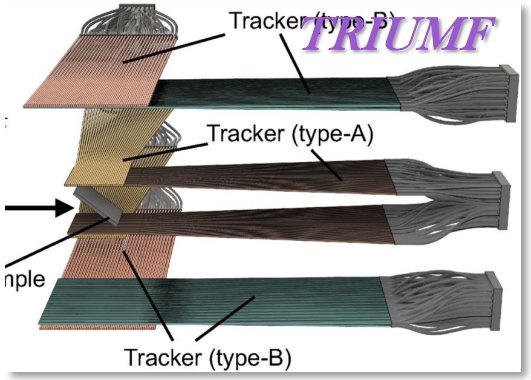
- PMTs sensitive to field
- Scintillator + light guide / fiber
- Large detector size
- Limited detector granularity O(100)
- Limited time resolution O(1ns)
- Bulk information

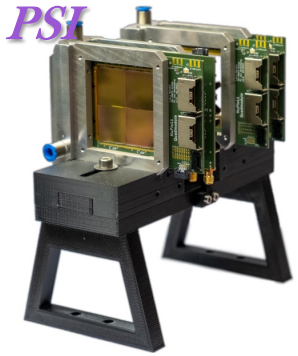
2nd Gen
- SiPM / Counting



- SiPMs insensitive to field
- Scintillator with/without fiber
- Compact size
- Large detector granularity O(1000)
- Better time resolution (0.1 ns)
- Bulk information

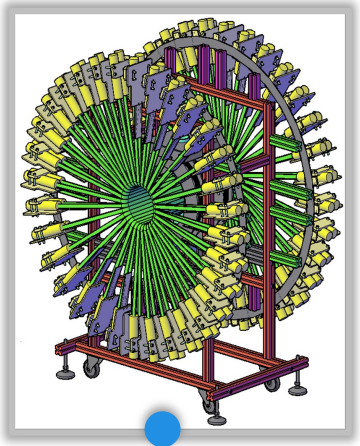
3rd Gen
- Pixel / Tracking

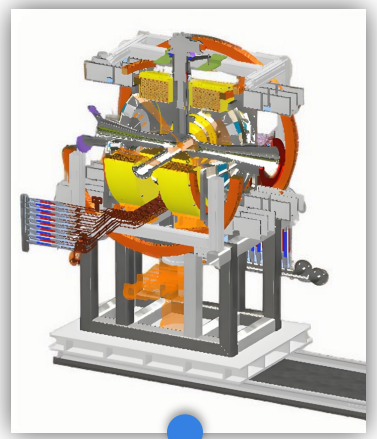


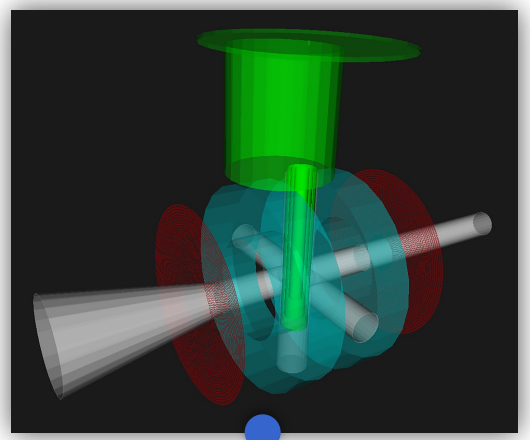


- Under development
- Pixelated detectors (fiber array / Silicon)
- Large detector granularity O(10000)
- Time resolution to be improved
- μ / e tracks and decay vertices
- 2D distribution of internal field?

Progress in MELDOY-CSNS







- *Details in MeichanFeng's talk*

1st Gen (2015 - 2021)

Demonstrator
128 channels

2nd Gen (2024 - 2029)

CSNS II
3024 channels

3rd Gen

New technology
LGAD

Contributors for MELODY μSR terminal

USTC: 潘子文、杨天艺、袁琦、李雪健、梁昊、叶邦角（科大负责人）；董靖宇、倪晓杰、邓凡水等多人已毕业

CSNS: 李强、李样、韦隽昊、宁常军、冯美婵、黎晃、顾旻昊、于永积、程辉、胡海韬、鲍煜(MELODY负责人)等

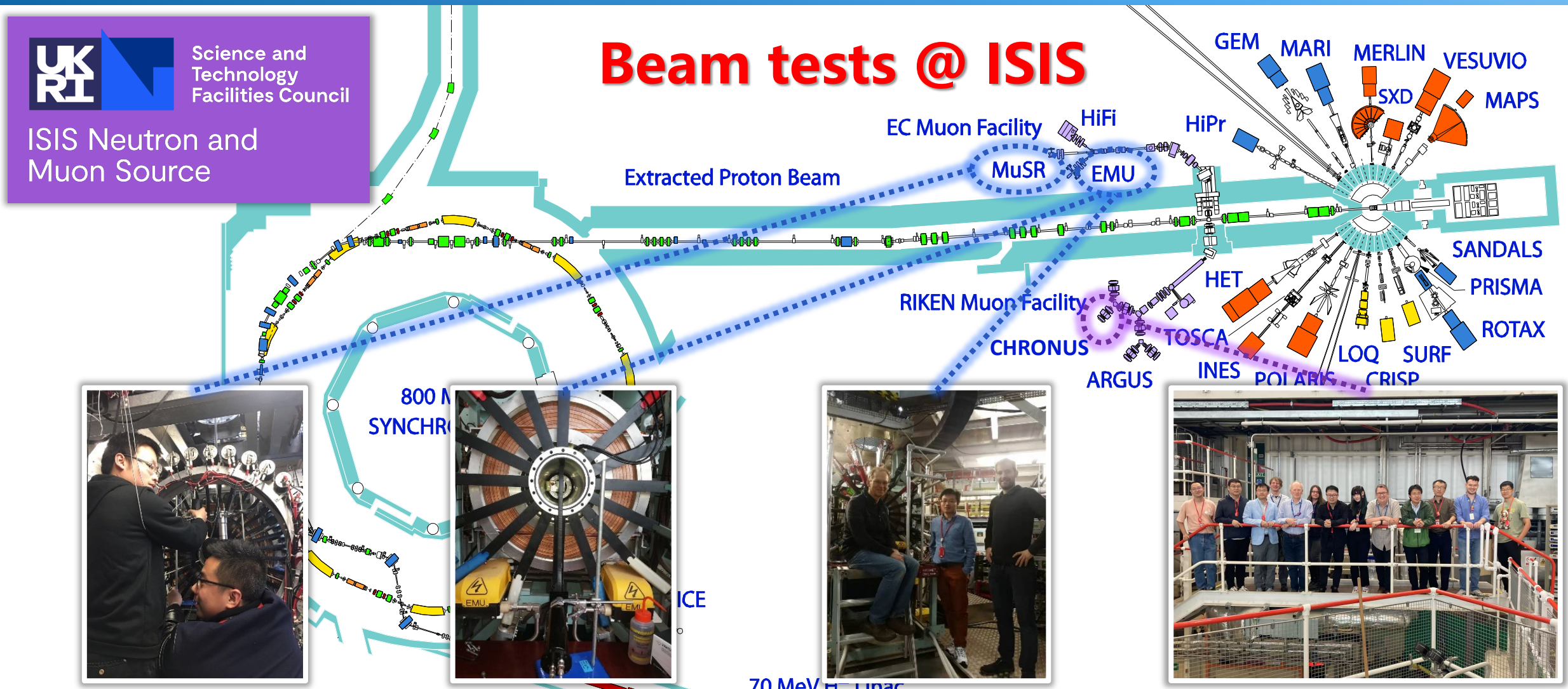
UCAS: 赵国强（数据采集与分析）

Progress in MELDOY-CSNS

Science and Technology Facilities Council

ISIS Neutron and Muon Source

Beam tests @ ISIS

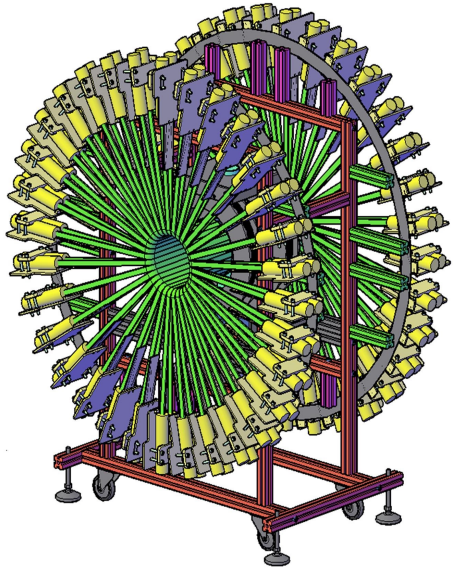


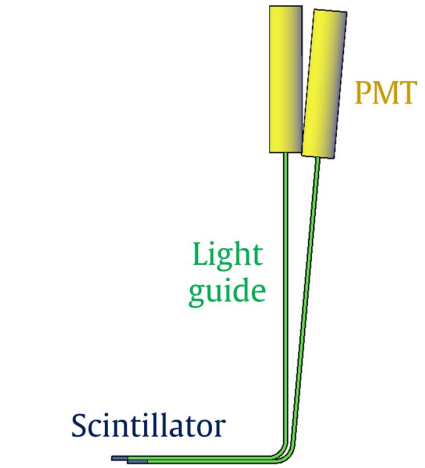
1-Gen detector 2018/03/14	1-Gen detector 2018/09/25	1-Gen detector 2019/11/13	2-Gen detector 2024/07/13

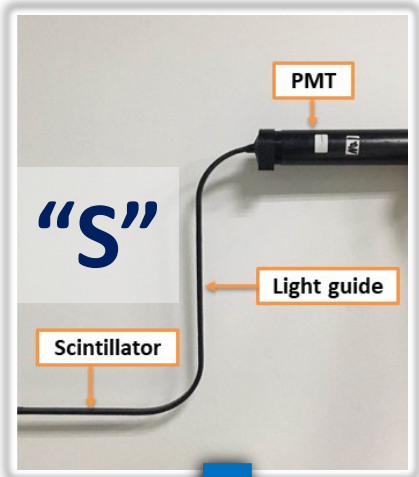
Progress in MELDOY-CSNS

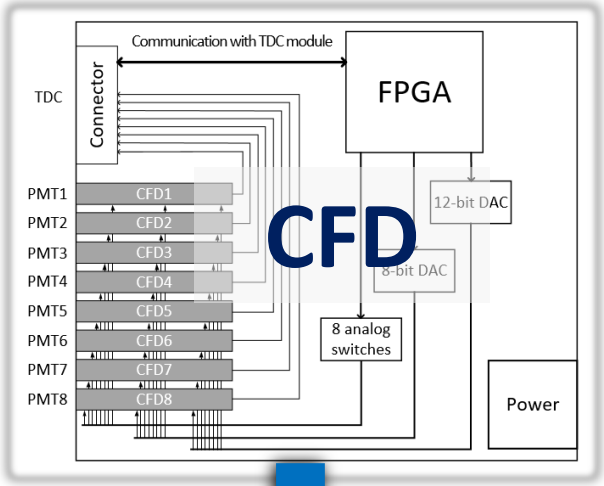
1st Gen spectrometer

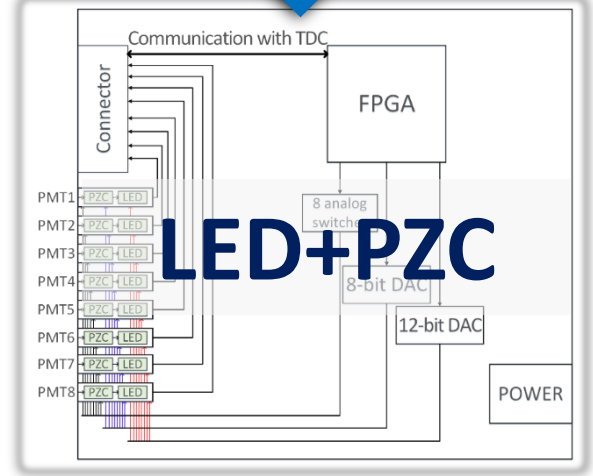
- *Lead by Prof. JingYu Tang and Prof. Bangjiao Ye*

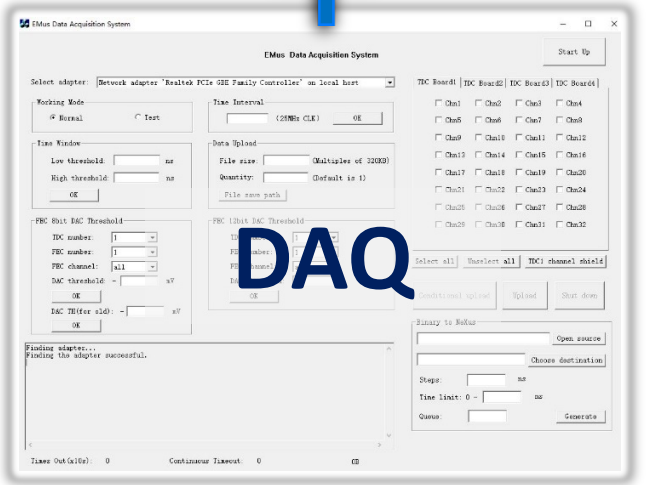












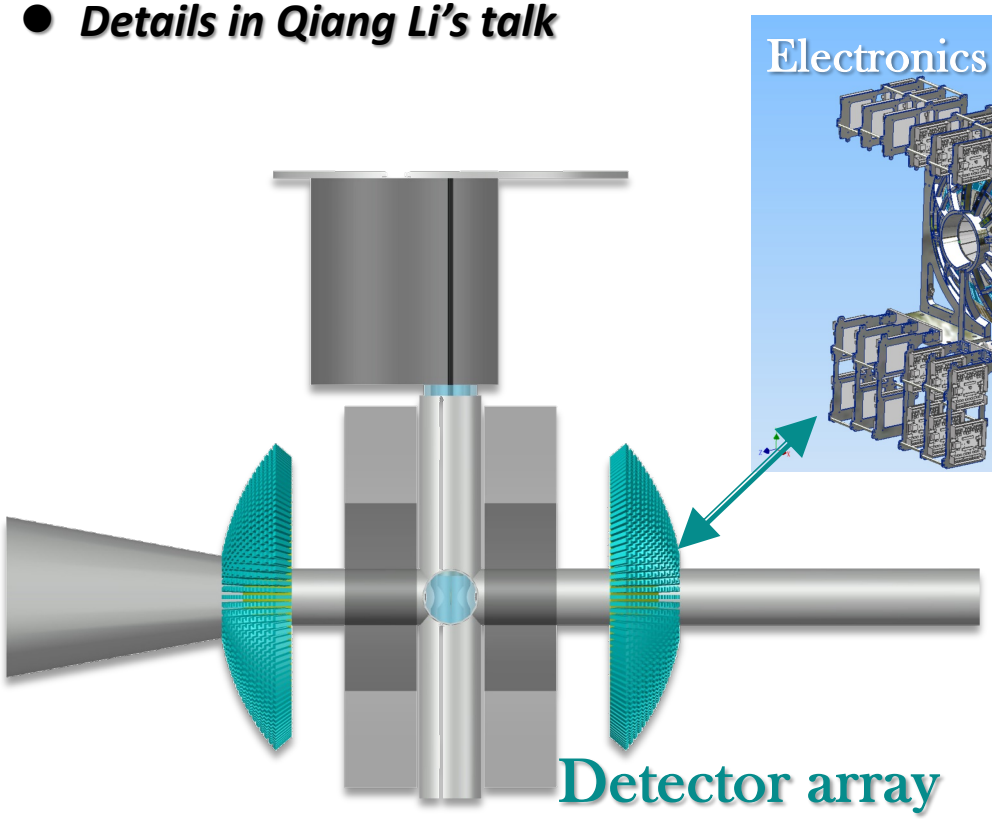
FEE: Front-End Electronics, LED: Leading-edge discrimination, PZC: Pole-Zero Cancellation

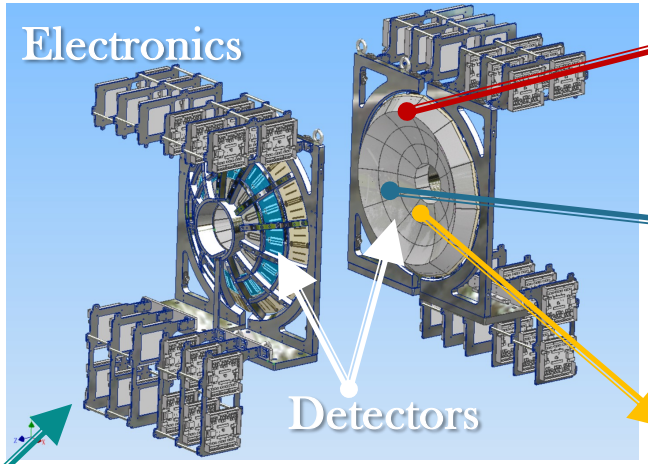
[Z. Pan, et. al., IEEE TNS 2021]

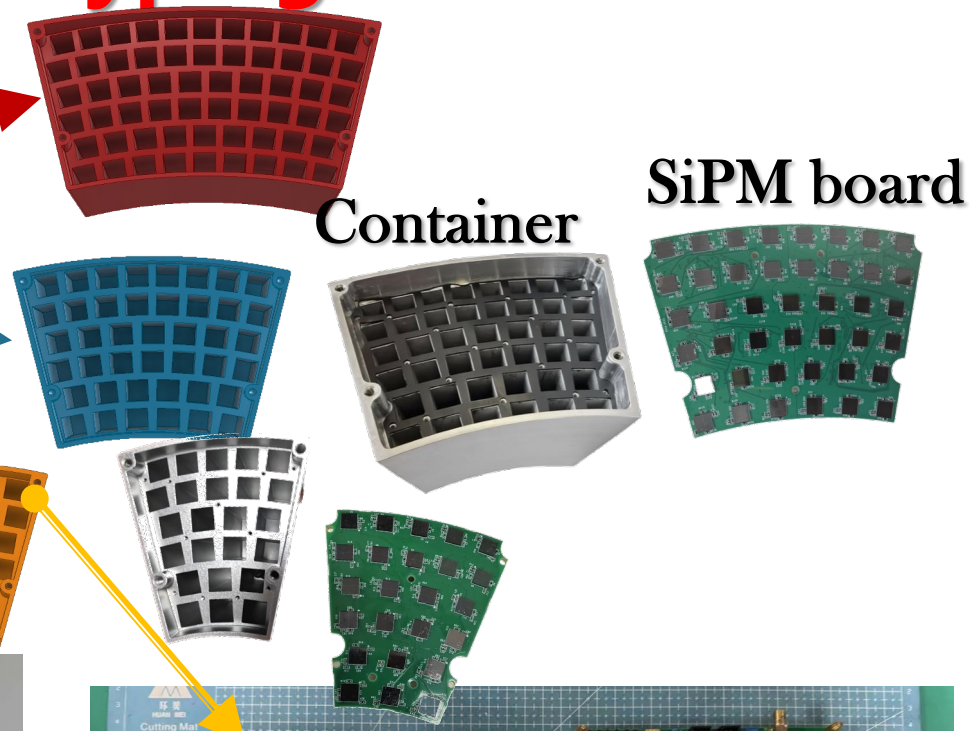
Progress in MELDOY-CSNS

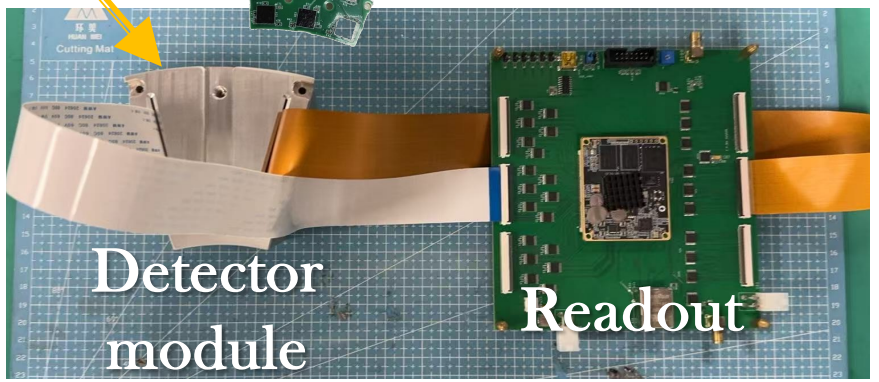
2nd Gen detector prototyping

- *Details in Qiang Li's talk*









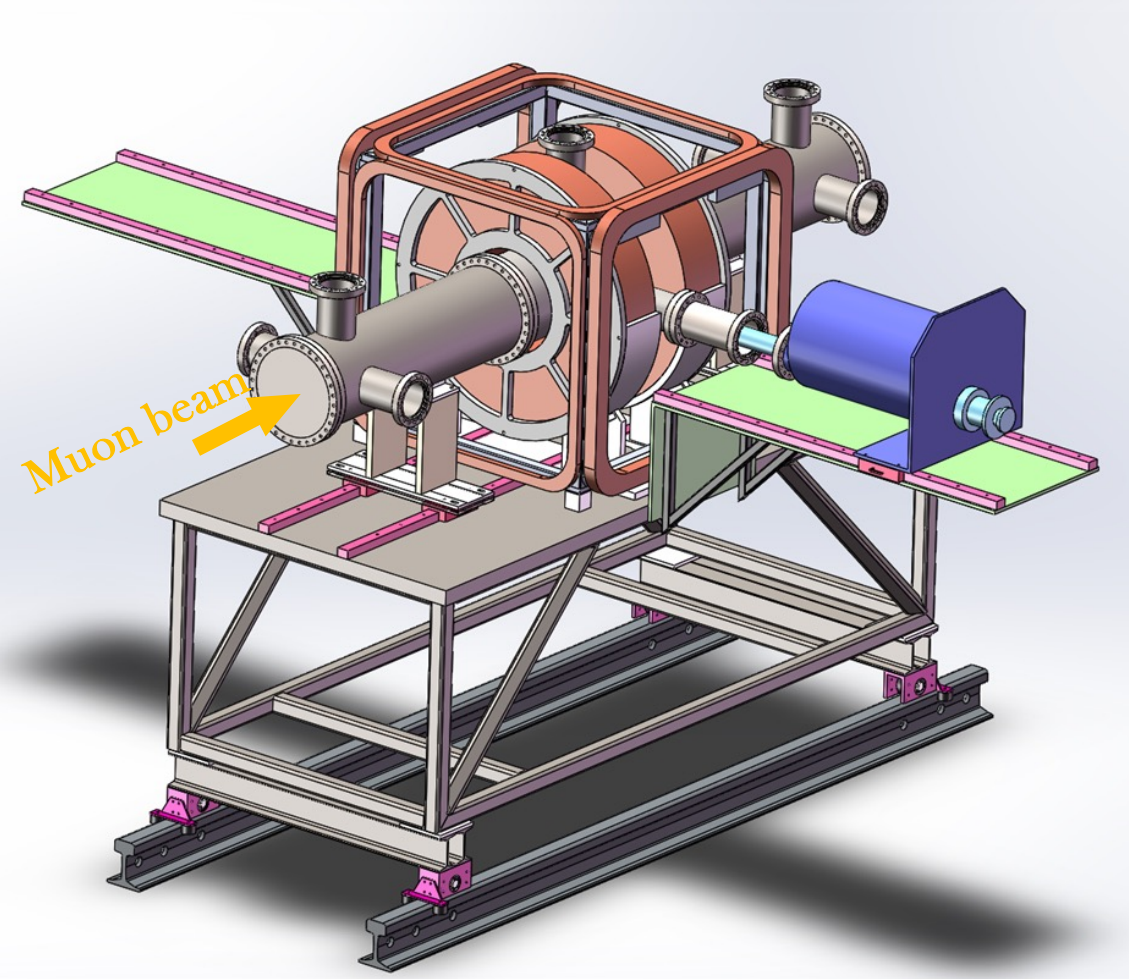
μSR2020 proceeding (2023)

μSR2025 proceeding (In production)

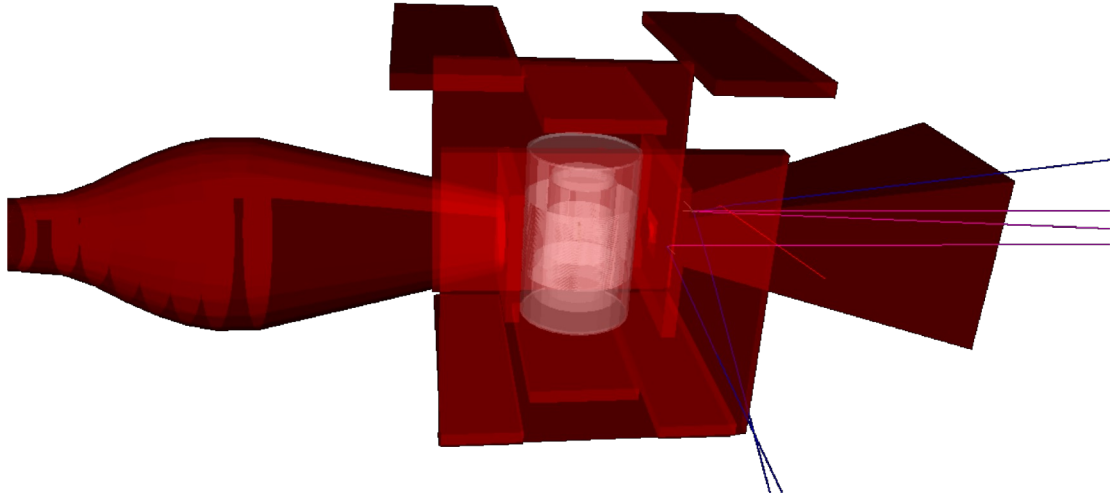
NIMA 1082 (2026) 170918

Progress in MuST-CiADS

- The spectrometer is under design!
- Details will be given in Dr. Rong Wang's talk.



Simulation model (refer to GPS@PSI)



- ✓ **Overall performance**: a general-purpose μSR with DR sample environment, high transverse field (~0.4) and high time resolution of detector (~300 ps)
- ✓ **Muon beam**: physics design just started, aims at small beam spot (<10 mm) and large angle spin rotation
- ✓ **Detector design**: some very preliminary results not finalized
- ✓ **Magnetic field**: a conceptual design almost done (0.55 T with high power supply)
- ✓ **Sample environment**: CCR (2K-300K) + He-4 flow (2K-300K) + DR (20mK-40K)
- ✓ **Mechanic design**: a preliminary design, a lot of refinements need to be done

IV. Summary and prospects

Summary

Muon sources

- **Cosmic-ray muon:** accessible to any beings
- **Accelerator muons:**
  - In operation: TRIUMF, PSI, MuSIC-RCNP, ISIS, J-PARC (mainly for applied sciences)
  - FermiLab, CERN (only for particle physics)
  - Under construction: MELODY-CSNS, RAON
  - In plans: SHINE, CiADS/HIAF@IMP, SEEMS@SNS

μSR detector technology

1st Gen	2nd Gen	3rd Gen
PMT / Counting	SiPM / Counting	Pixel / Imaging

Developments in China

- A pulsed μSR spectrometer is under construction at MELODY-CSNS
- A CW μSR spectrometer is under design at MuST-CiADS

Prospects: a tabletop muon source

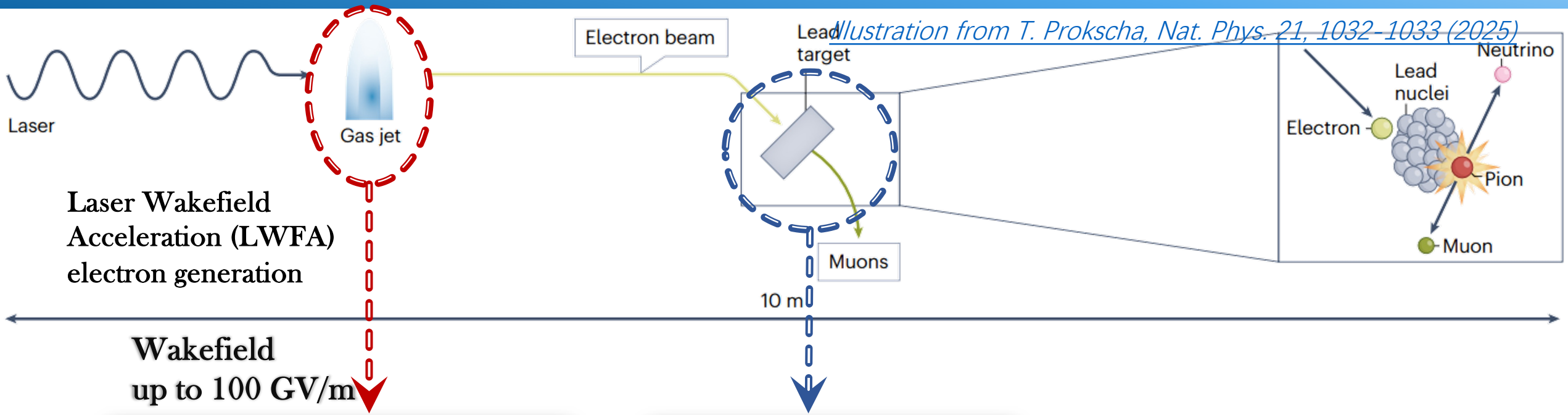
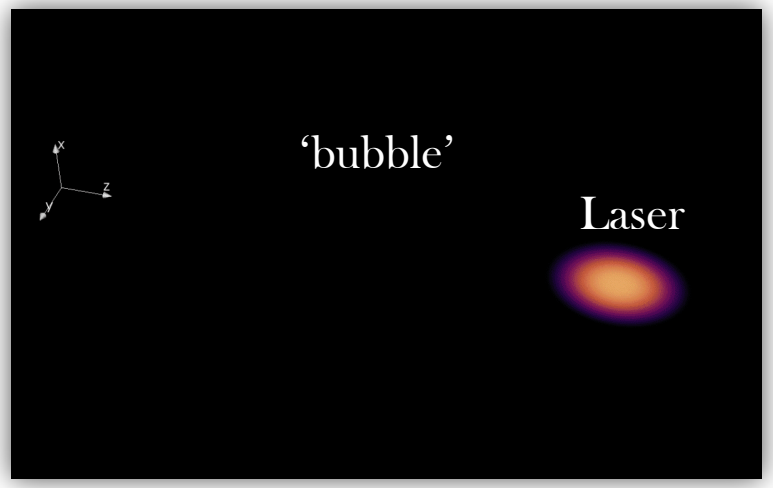
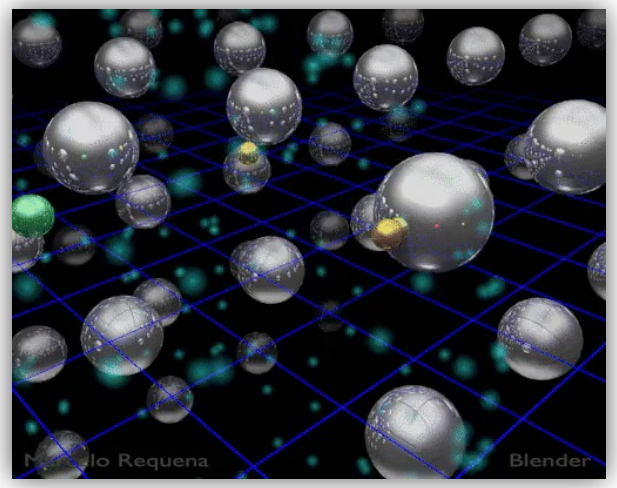


Illustration from T. Prokscha, Nat. Phys. 21, 1032-1033 (2025)

Laser Wakefield Acceleration (LWFA) electron generation

Wakefield up to 100 GV/m





$$e^- + Z \rightarrow Z + \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$
$$\mu^+ + \mu^-$$

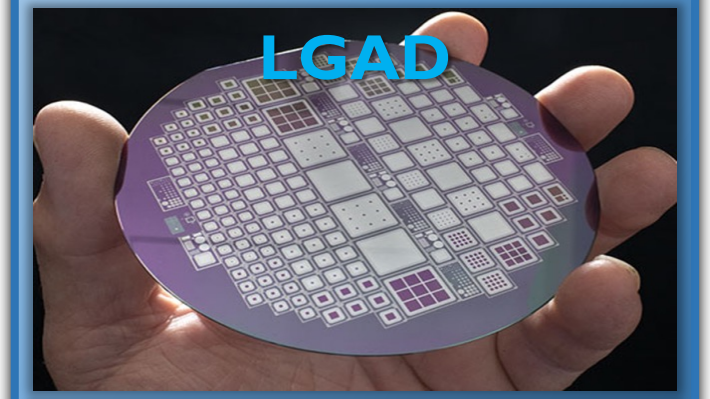
GeV e^- beams generated in cm scale!

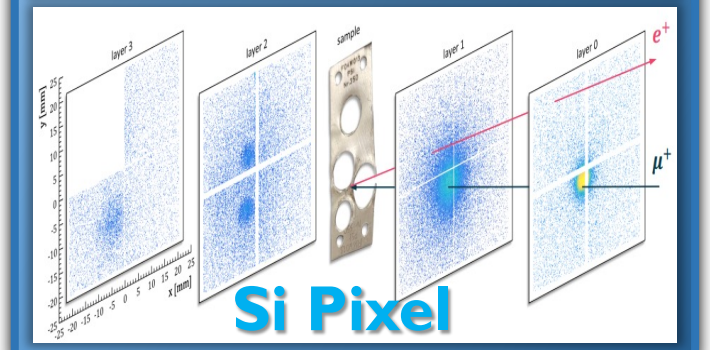
F. Zhang et al., Nat. Phys. 21, 1050-1056 (2025)

Prospects: spectrometer

Detector

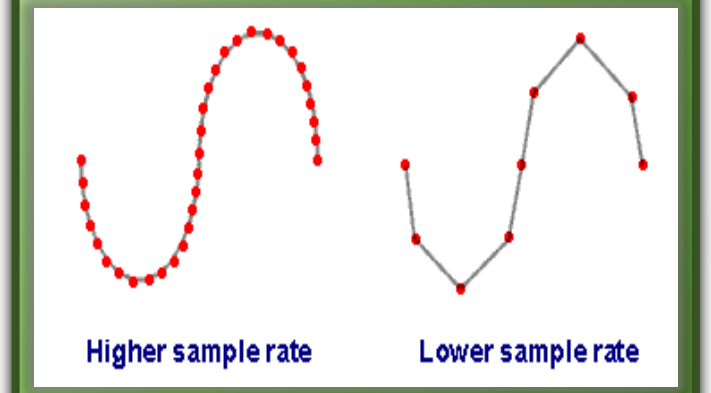
- ✓ High granularity
- ✓ μ^+ / e^+ tracking

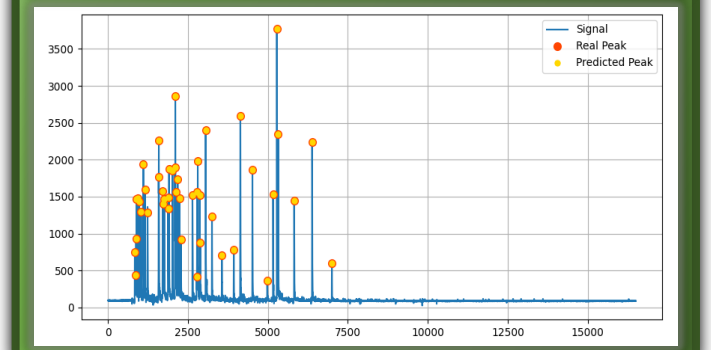




Electronics

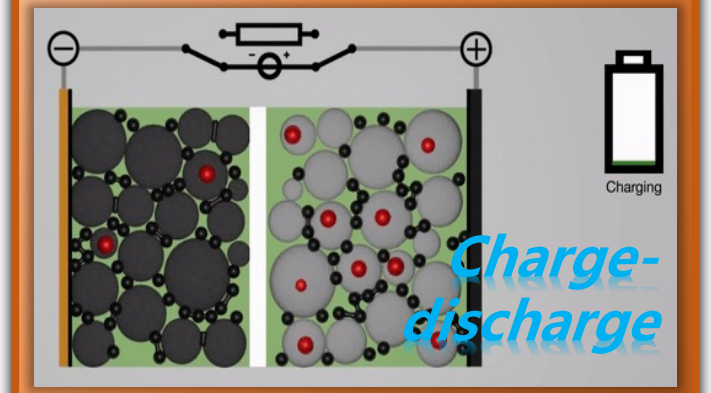
- ✓ Digitization
- ✓ Waveform fitting

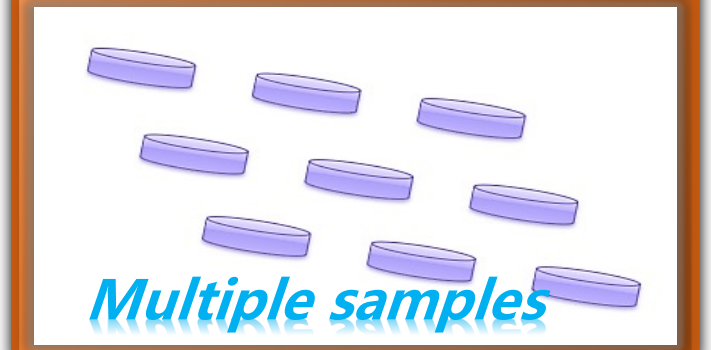




Measures

- ✓ In-situ/Operando
- ✓ Multi-samples





Thanks for your attention!

- *感谢μSR、MIXE、缪子成像等领域所有老师、同事及合作者对本人工作的支持！*
- *感谢国自然基金委、自然资源部、广东省粤惠联合基金、小米公益基金会对各项研究工作的经费支持！*