1ST SYMPOSIUM ON SHINE MUON SOURCE AND APPLICATIONS

Detector development for μSR spectroscopy and muonic X-ray analysis

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On behalf of all colleagues and collaborators from μSR and MIXE groups

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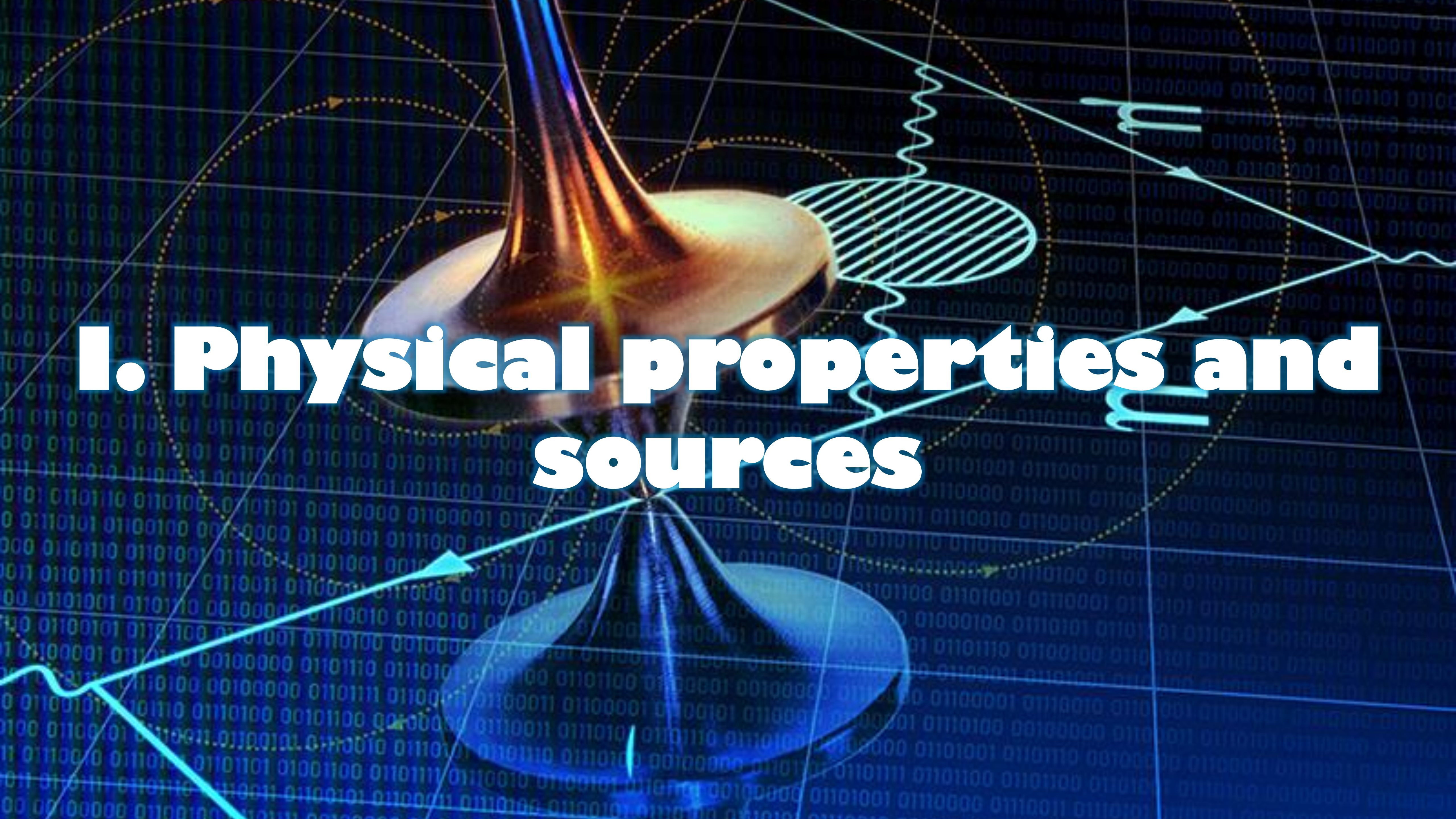
28th Nov. 2025, Shanghai

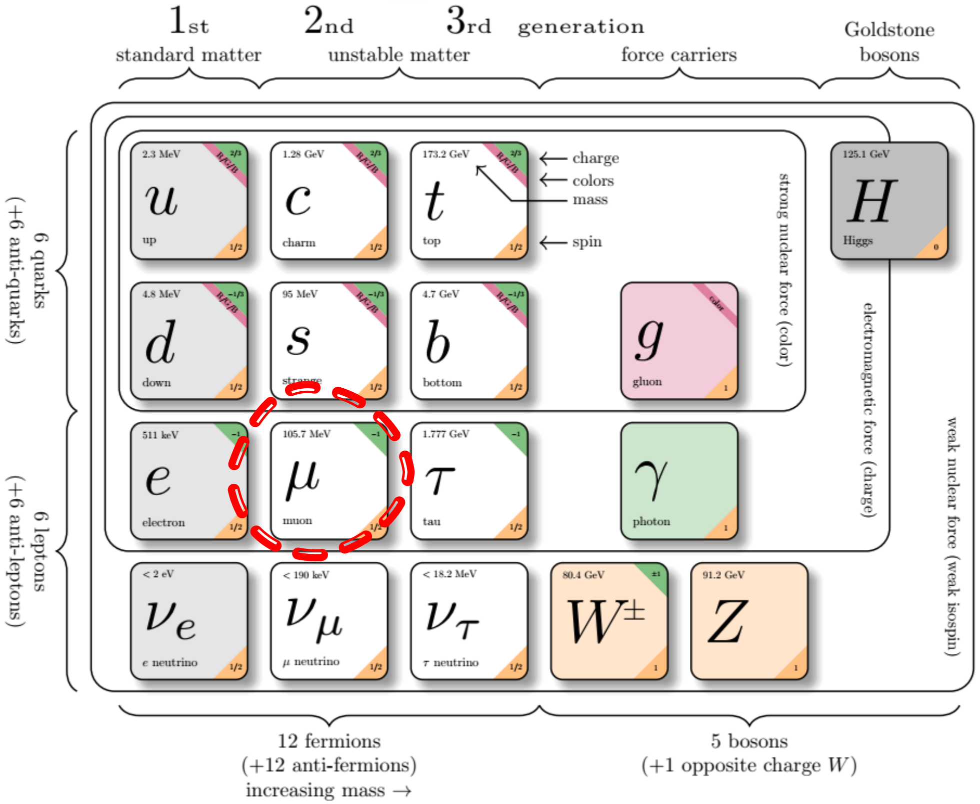
Content

- I Physical properties and sources
- II μSR spectrometer development
- III Muonic X-ray elemental imaging
- IV Summary and prospects

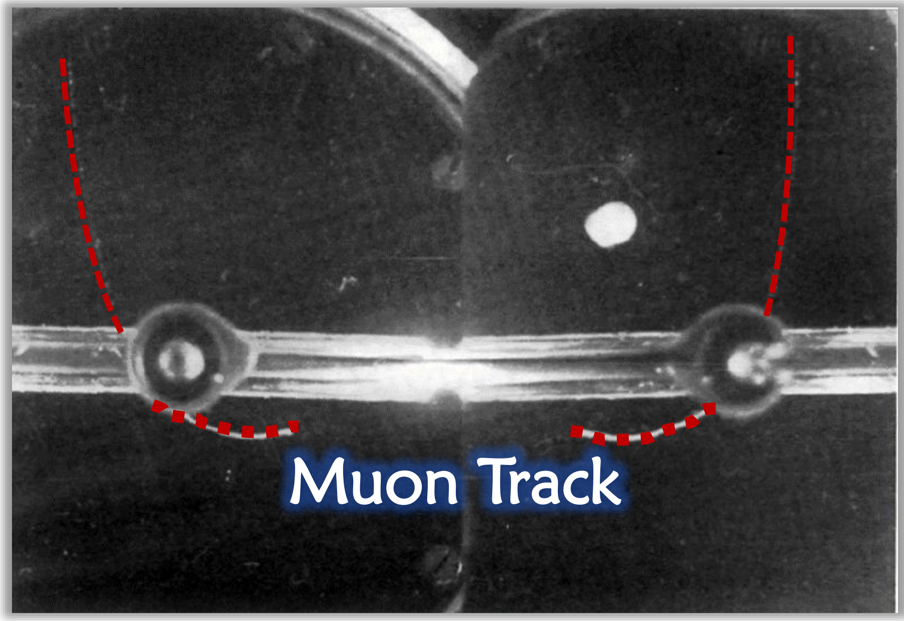
I. Physical properties and sources

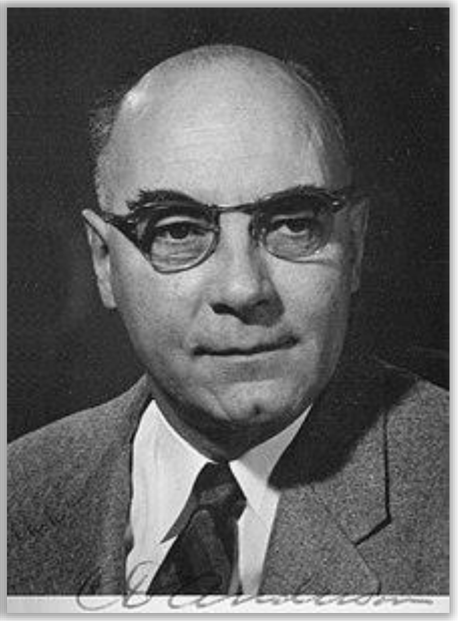


Physical nature of muons



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

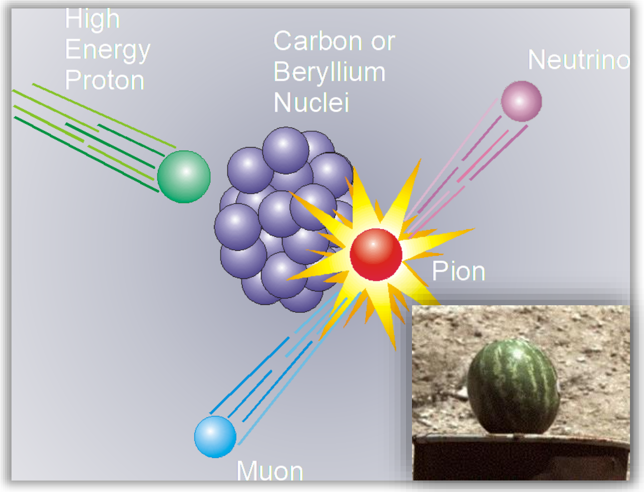




- Unstable, average lifetime ~ 2.2 μs
- Spin ½, point-like, born polarized, quantum magnetic probe
- Large mass, energetic X-ray emission, elemental probe
- Three originations: cosmic ray / accelerator / laser driven

Origin I: Cosmic-ray muons

High energy particle collisions

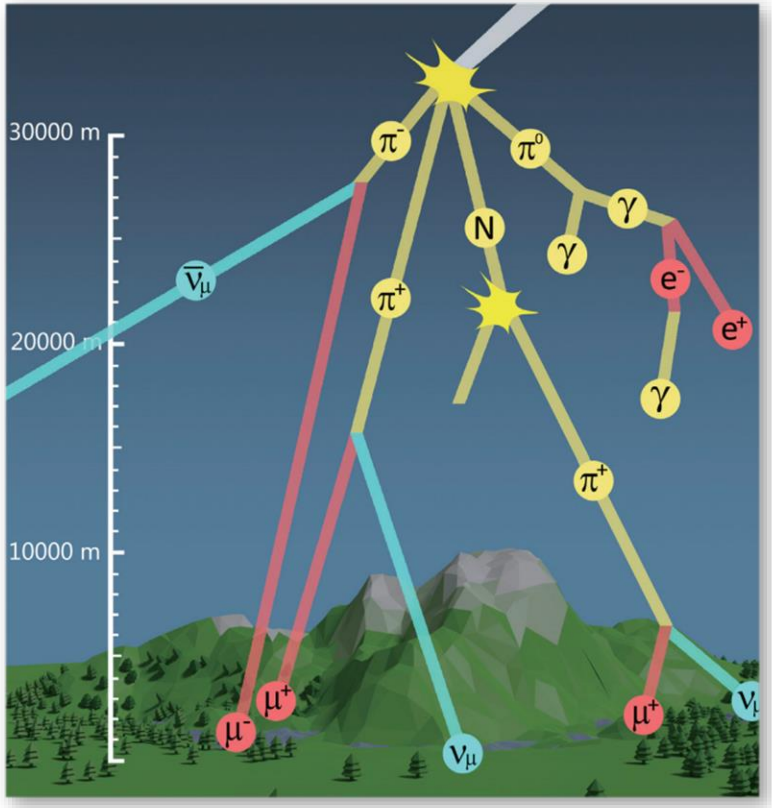


$$p + p/n \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$

- Proton-nucleus collision
- Electron-nucleus collision

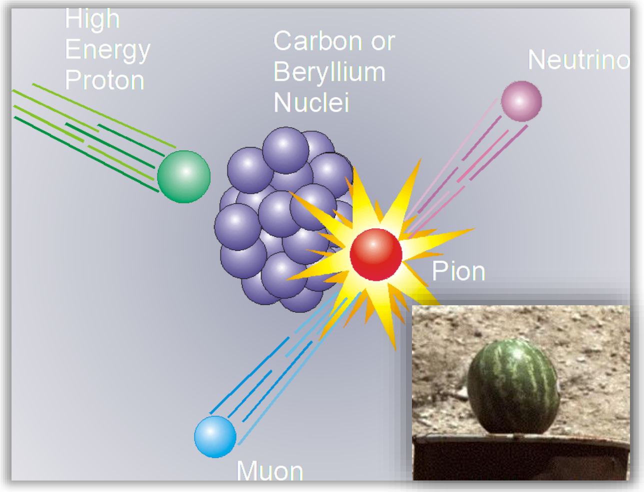
$$e^{-} + Z \rightarrow Z + \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$

$$\rightarrow \mu^{+} + \mu^{-}$$



Origin II: Accelerator muons

High energy particle collisions



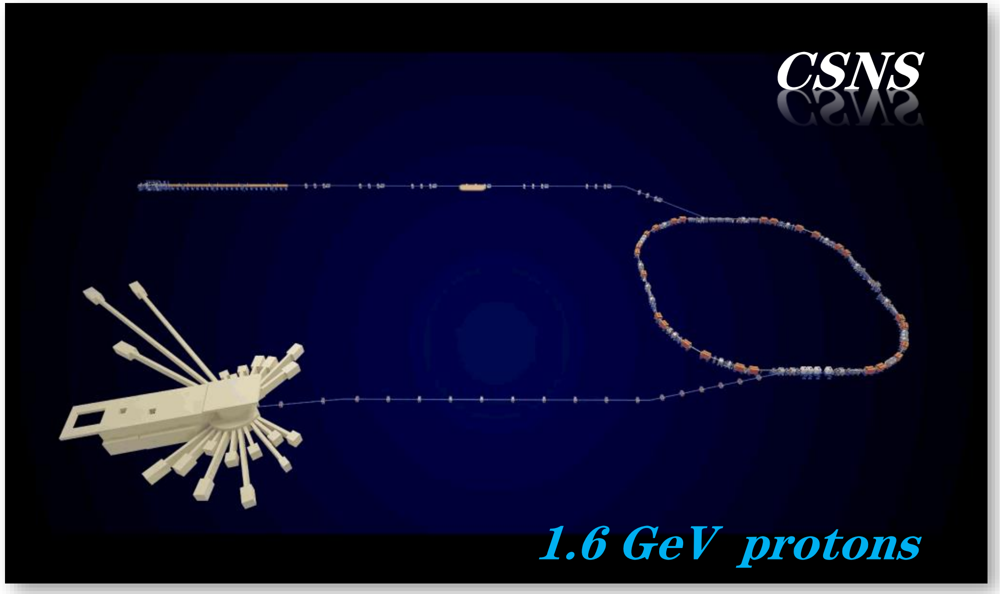
$$p + p/n \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}$$

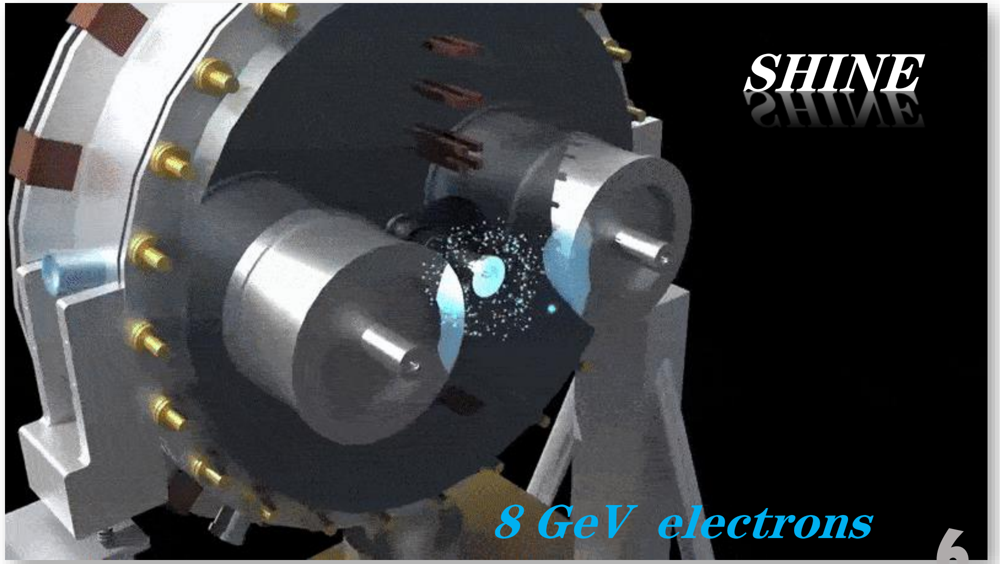
- Proton-target bombardment

- Electron-target bombardment

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

$$\rightarrow \mu^+ + \mu^-$$





Origin II: Accelerator muons

Origin II: Accelerator muons

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, **POT**: Proton on Target, **EOT**: Electron on Target, **FP**: Fundamental physics, **AS**: Applied Sciences*

Origin III: Laser driven muons

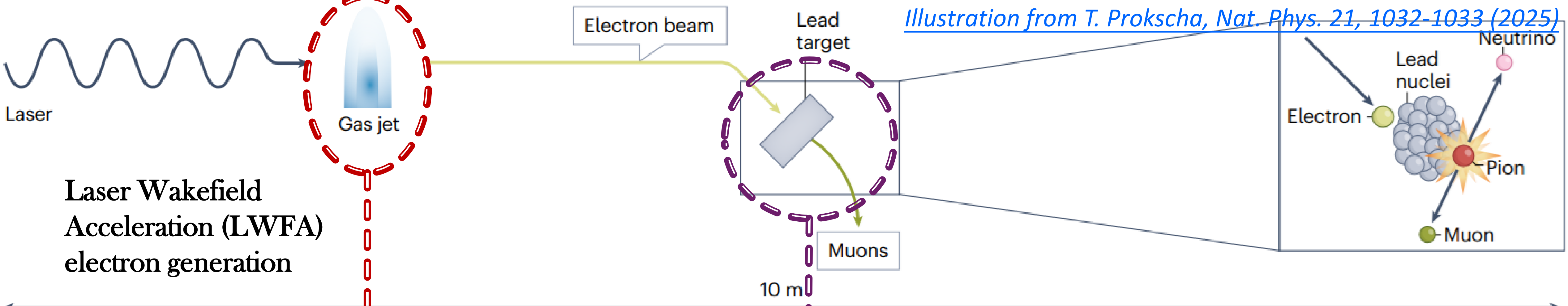
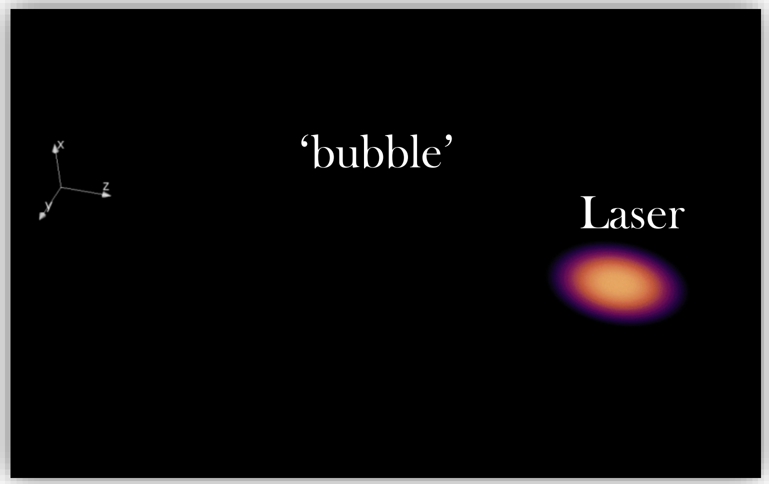
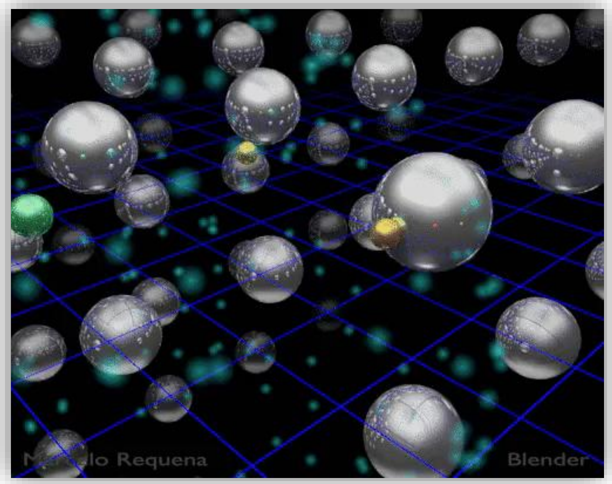


Illustration from T. Prokscha, Nat. Phys. 21, 1032-1033 (2025)

Laser Wakefield Acceleration (LWFA) electron generation

Wakefield up to 100 GV/m





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

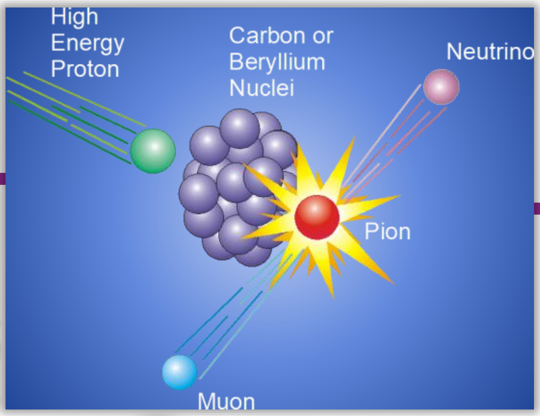
GeV e⁻ beams generated in cm scale!

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

Research frontiers in muon sciences

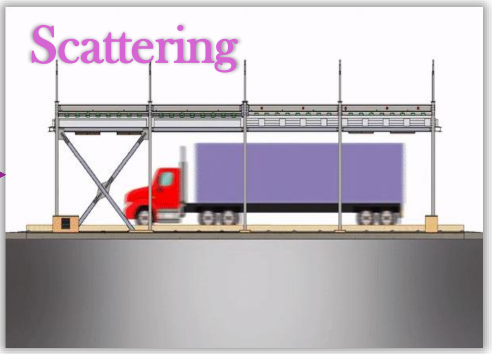
Muons: Bridging the Micro- and Macro-scopic Extremes of Universe!

Artificial muons

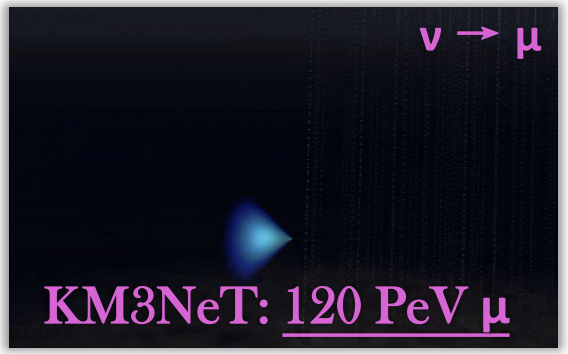


Natural muons

Muography

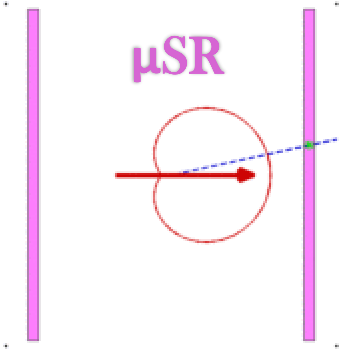


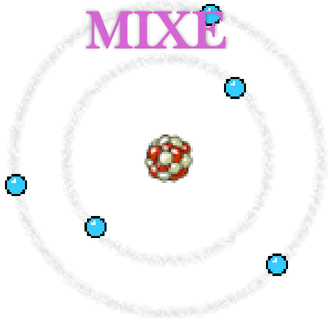
Cosmic messenger



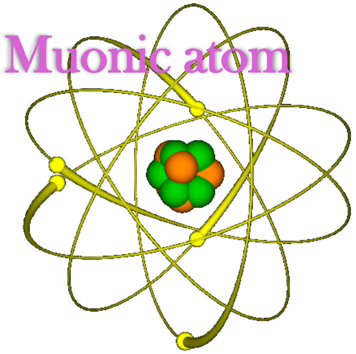
keV — MeV — GeV — TeV

Material characterization





Precision measurement



Muon collider

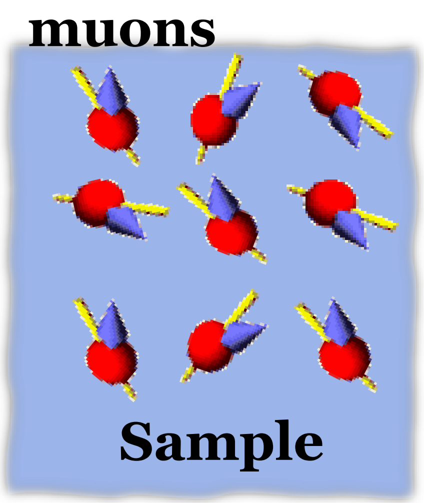
** * * Applications not limited to this list!*

II. μSR spectrometer development

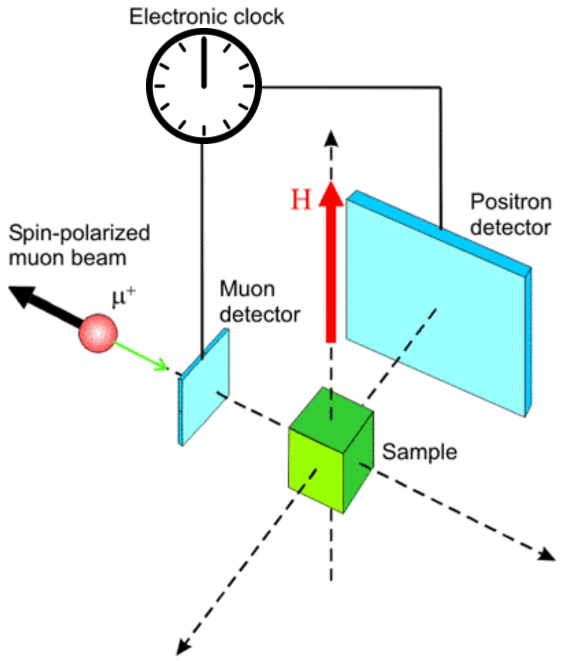
Principles

μSR: muon spin rotation/relaxation/resonance

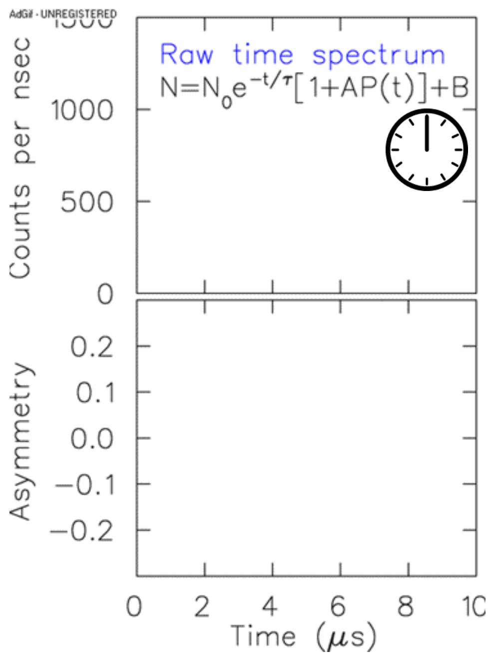
Precession (spin interaction) → **Asymmetry** (positron detection) → **μSR spectra** (analysis) → **Material** (properties)



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



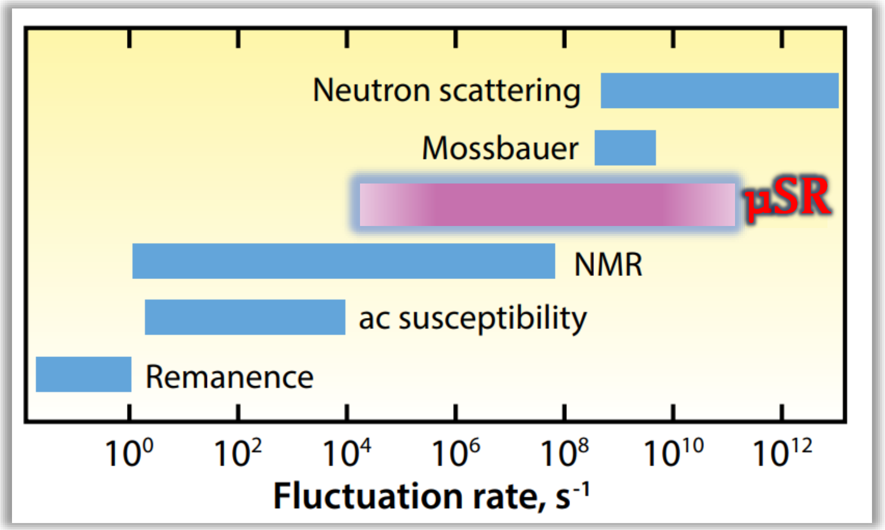
$$\mu^+ \to \boldsymbol{e}^+ + \nu_e + \bar{\nu}_\mu$$

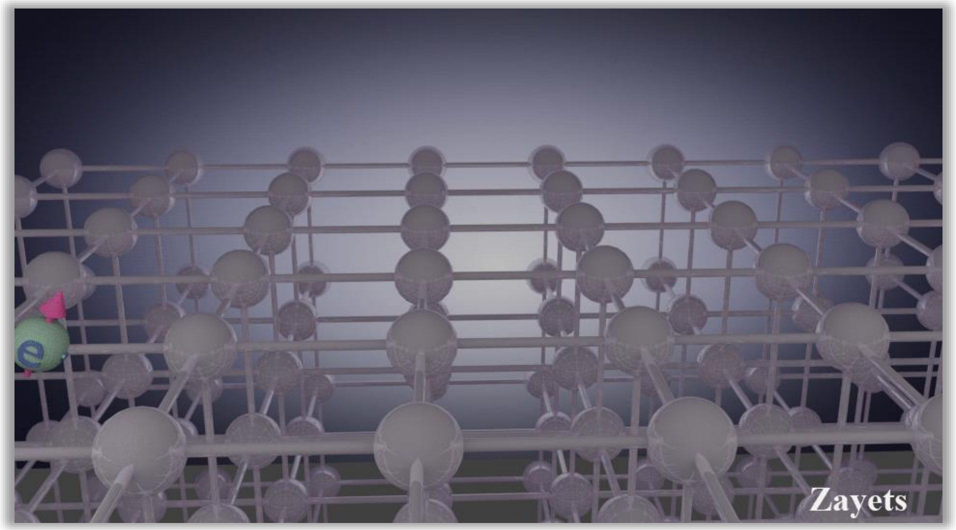


$$\frac{N_F(t) - N_B(t)}{N_F(t) + N_B(t)} = A\boldsymbol{P}(t)$$

- 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)

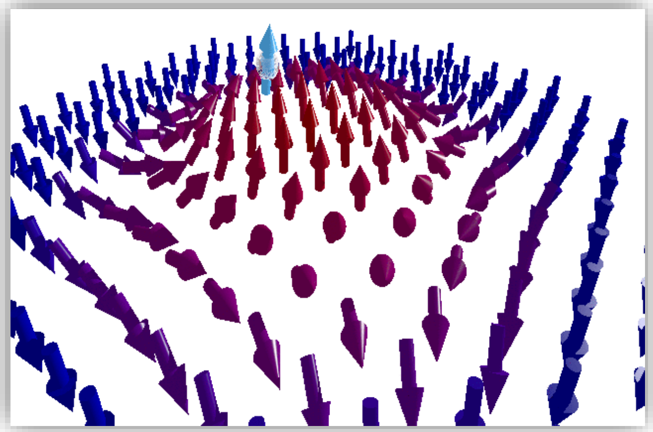
Applications

● Passive probe

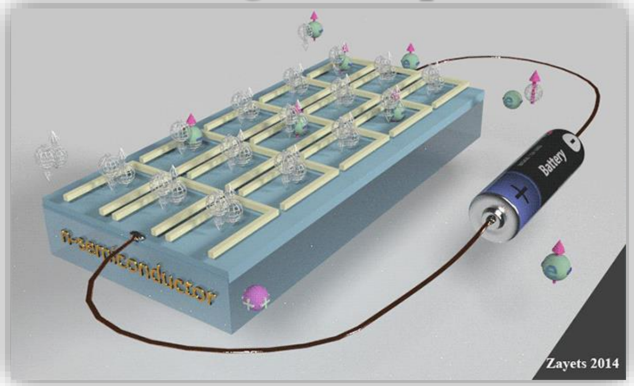
(heavy lepton)

Superconductor

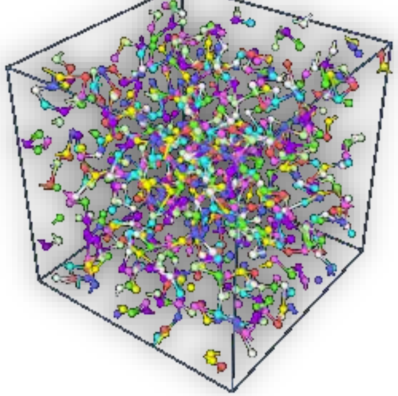
Magnetism



Charge transport



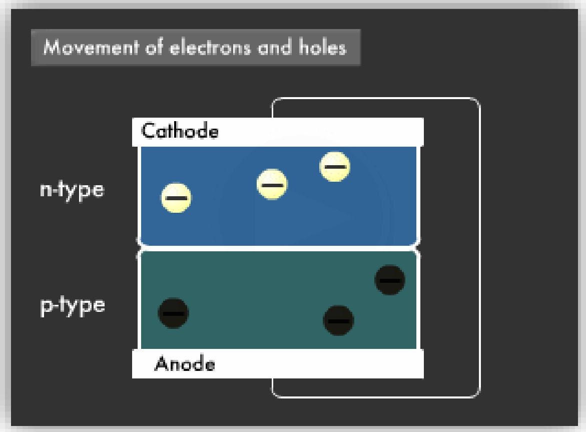
MD



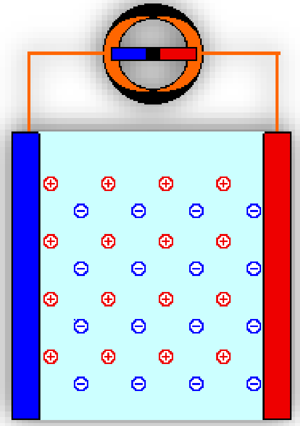
● Active probe

(light proton)

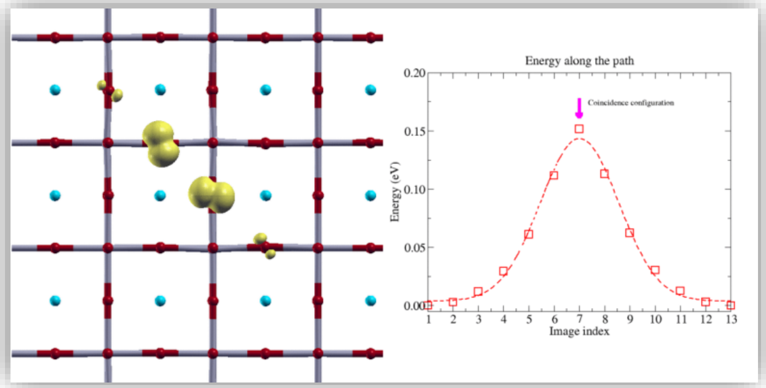
Semiconductor



Ionic conductor



Polaron motion



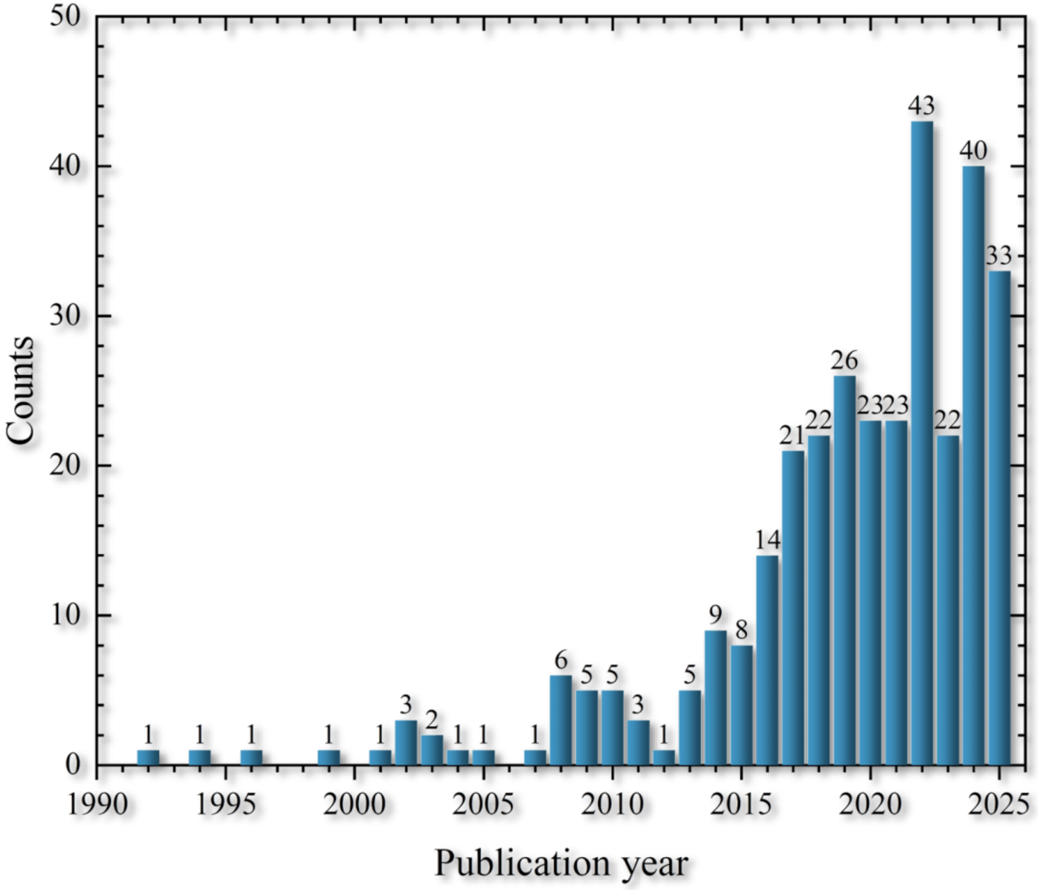
…

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

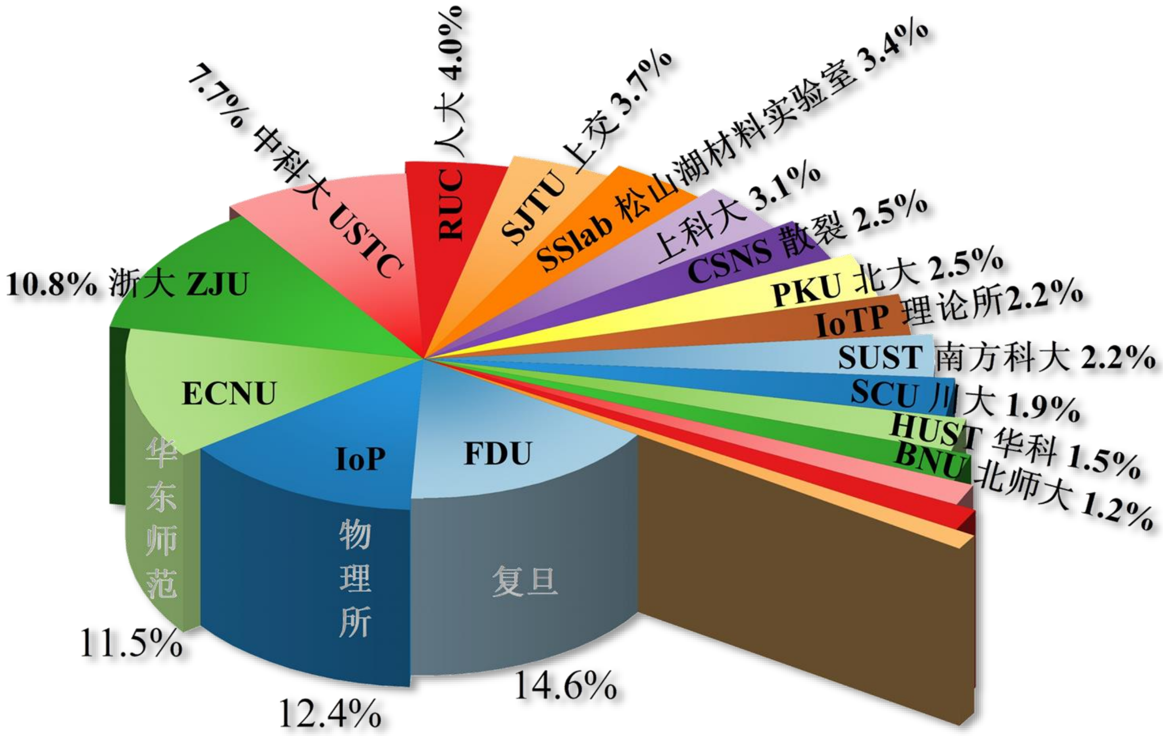
Courtesy Dr. Adrian Hiller @ ISIS Muons

Statistics of Chinese users

~ 320 papers



> 50 affiliations

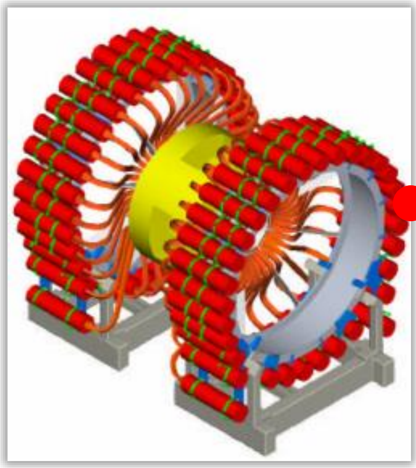


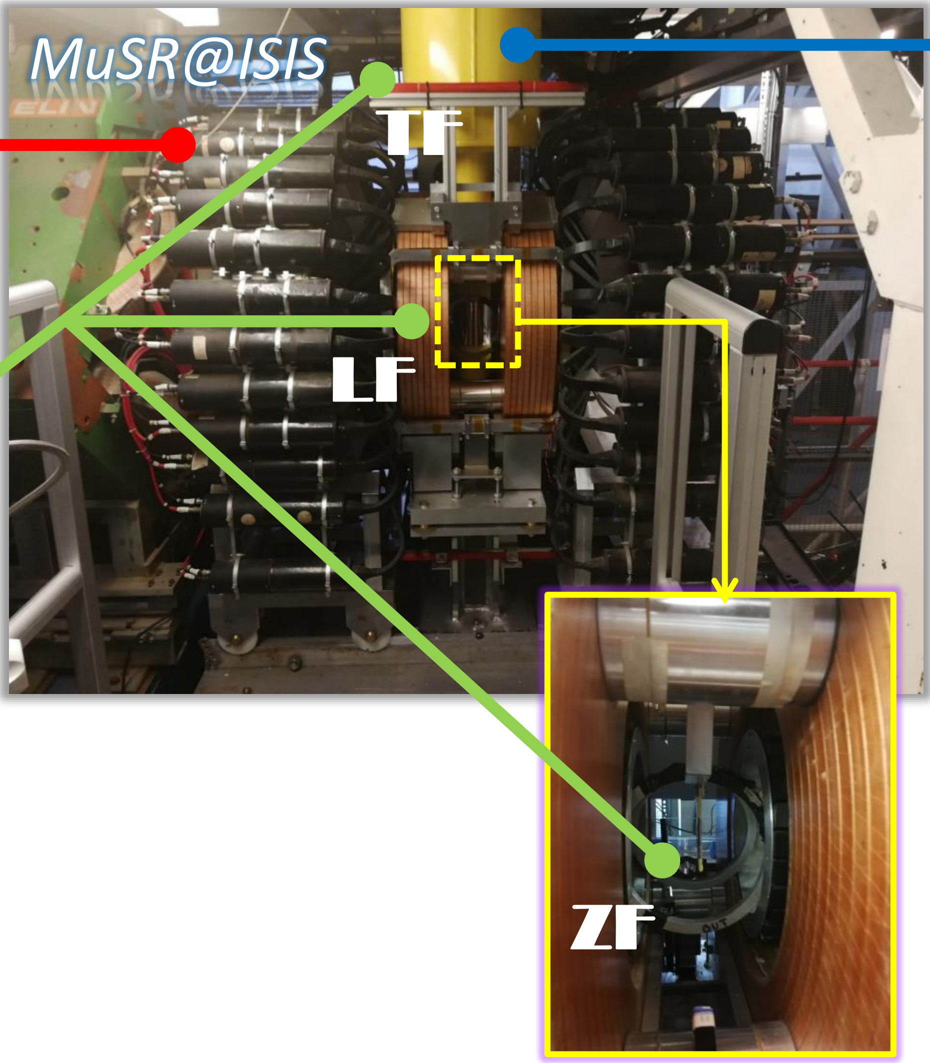
Web of Science analysis (muon spin spectroscopy / muon spin relaxation / muon spin rotation) 2025/11

目前国内研究者仅能申请国外缪子束流机时开展前沿研究工作！

Spectrometer composition

Detectors



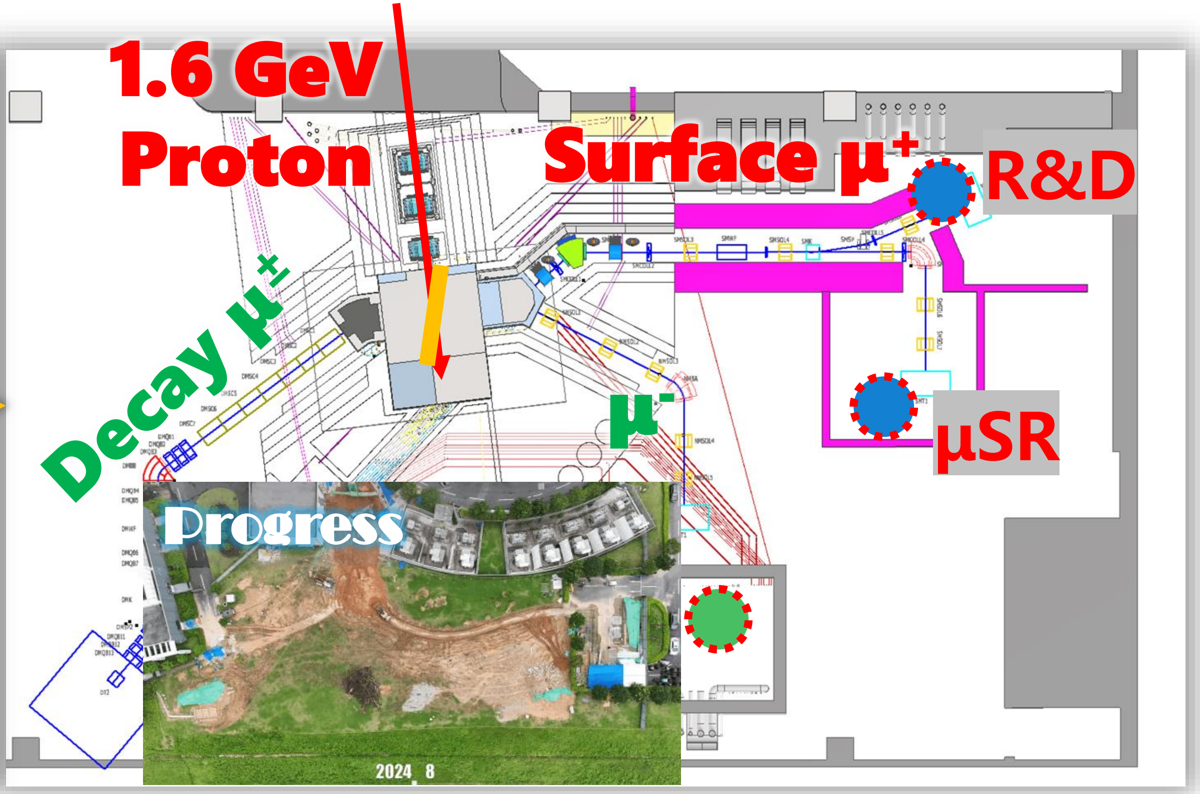


Refrigerator

Magnets

MELODY muon source @ CSNS II

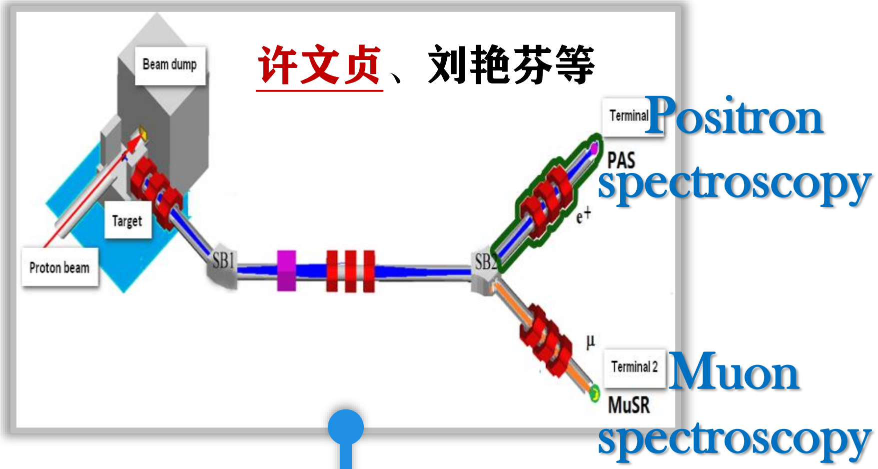
Muon station for sciEnce technoLOgy and inDustrY

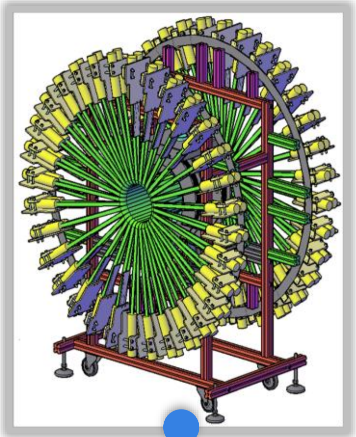


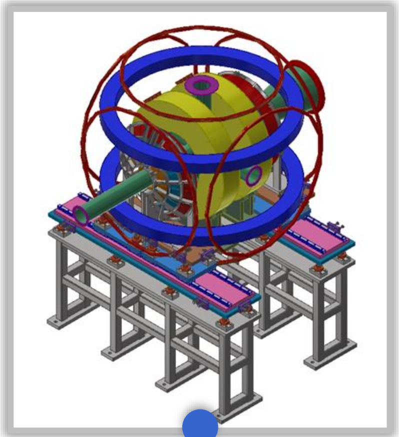
- CSNS II (2024 - 2029): target station, a surface muon beamline, a **μ**SR spectrometer
- 10^5 – 10^7 μ^+/s , > 95% polarization, pulse width 130 ns
- Surface **μ**: 28 MeV/c; Decay **μ**: up to 100 MeV/c

Dr. Yu Bao(鲍煜)'s talk

Instrumentation @ USTC/CSNS







Pre-study (2007 - 2014) → **Prototype R&D (2015 - 2020)** → **Construction (2024 - 2029)**

Beamline design

1st generation PMT-based detectors

2nd generation SiPM-based detectors

谱仪建设贡献者

USTC: 潘子文、杨天艺、袁琦、李雪健、梁昊、叶邦角；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

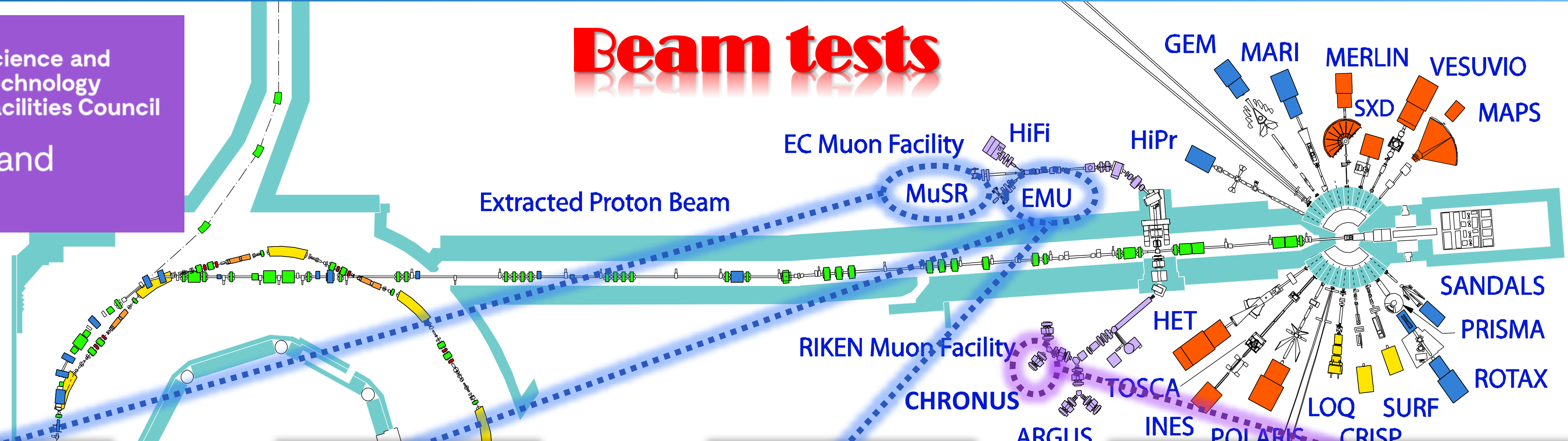
UCAS: 赵国强（数据采集与分析）

Instrumentation @ USTC/CSNS

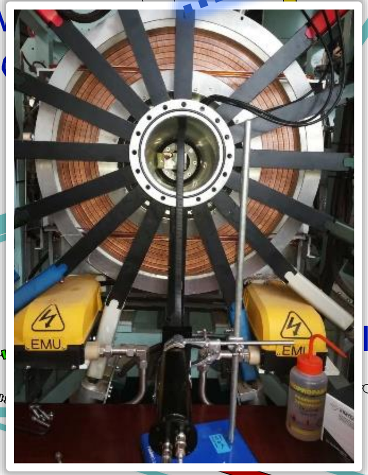
Science and Technology Facilities Council

ISIS Neutron and Muon Source

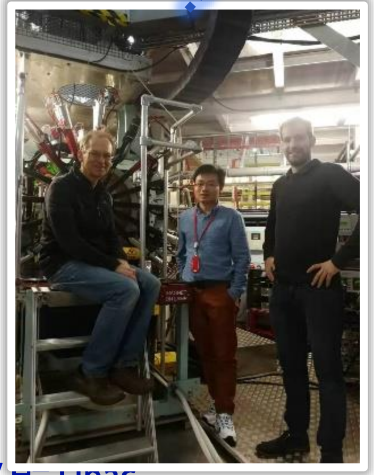
Beam tests



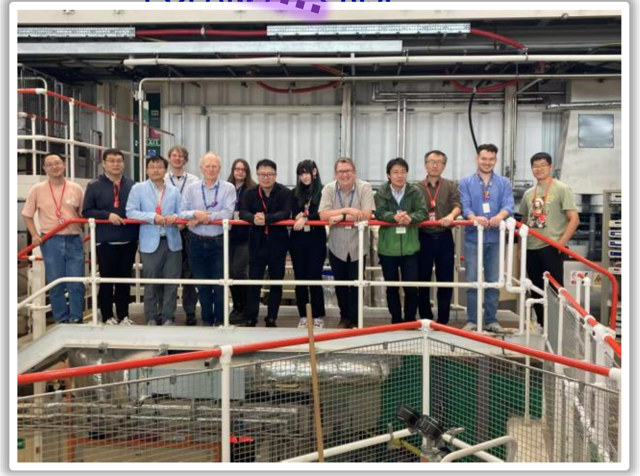
1-Gen detector 2018/03/14



1-Gen detector 2018/09/25



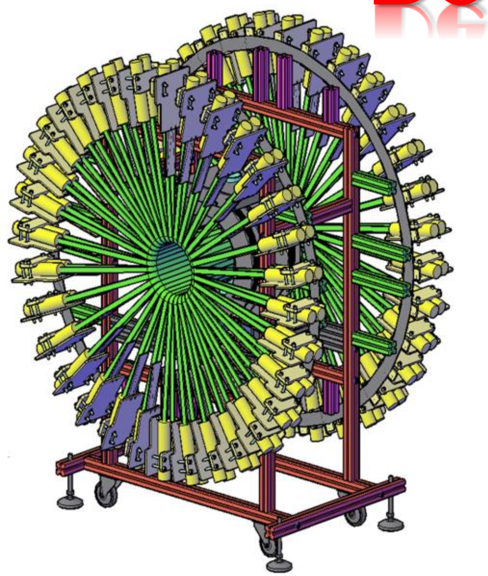
1-Gen detector 2019/11/13

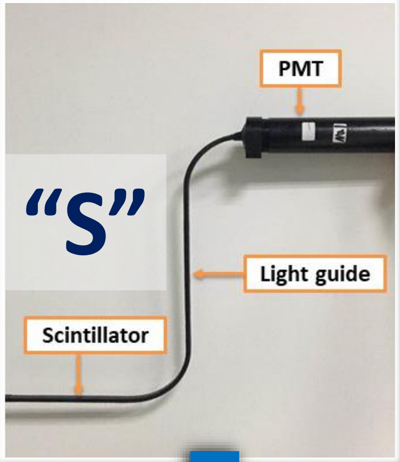


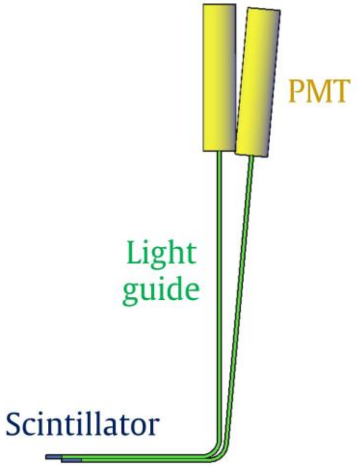
2-Gen detector 2024/07/13

1st-Gen PMT based spectrometer

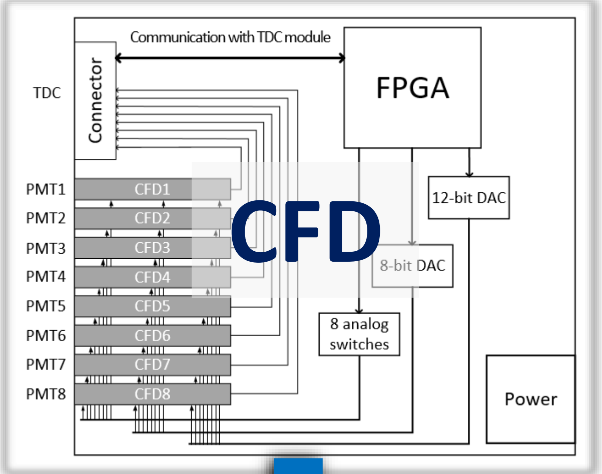
Detector

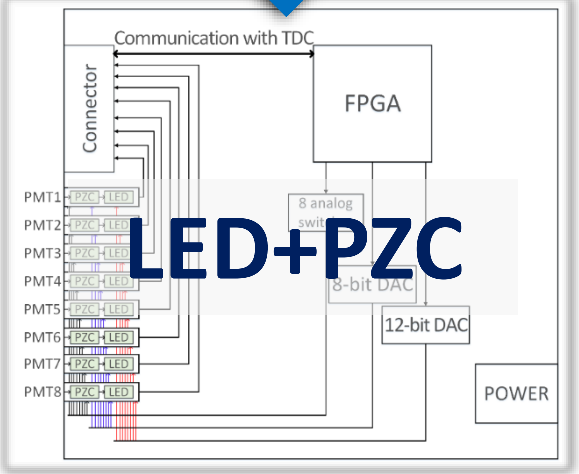






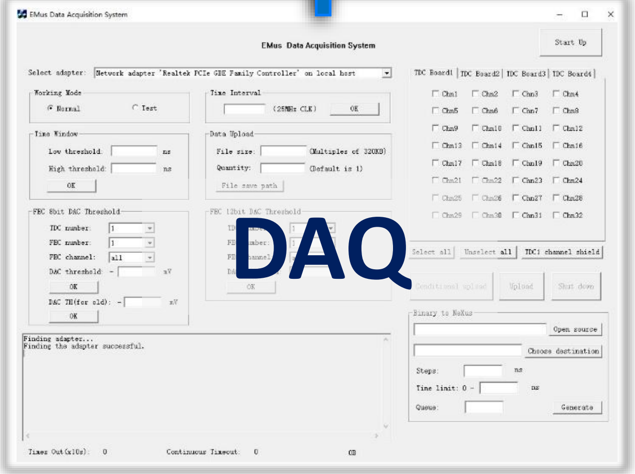
FEE





Readout

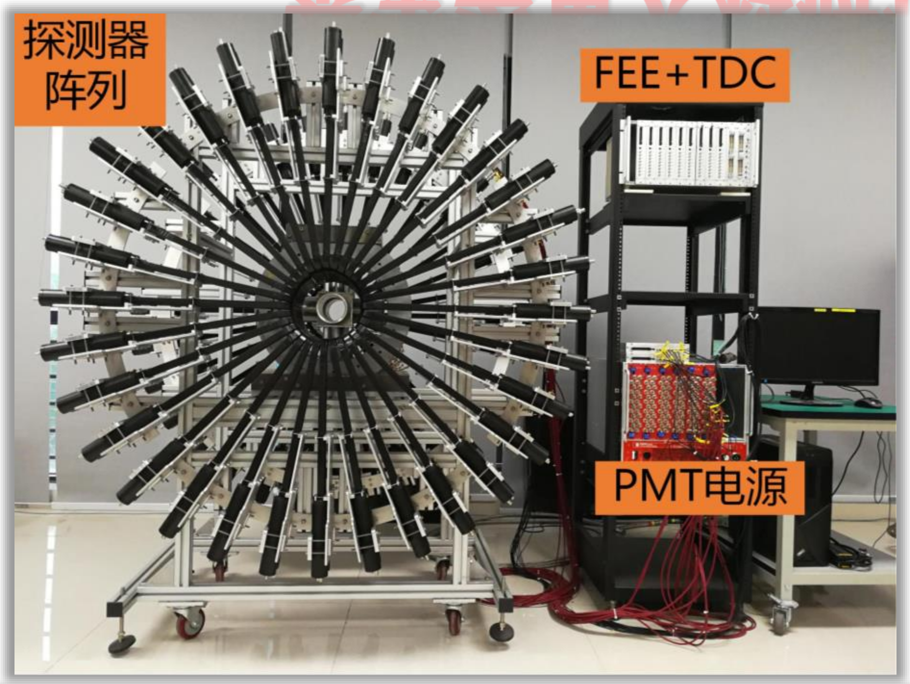
+

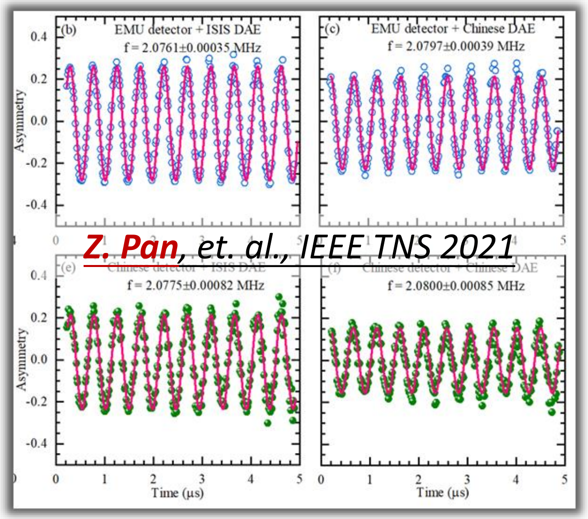


FEE: *Front-End Electronics,* ***LED:*** *Leading-edge discrimination*

1st-Gen PMT based spectrometer

基金委重大科研仪器项目专家组现场验收

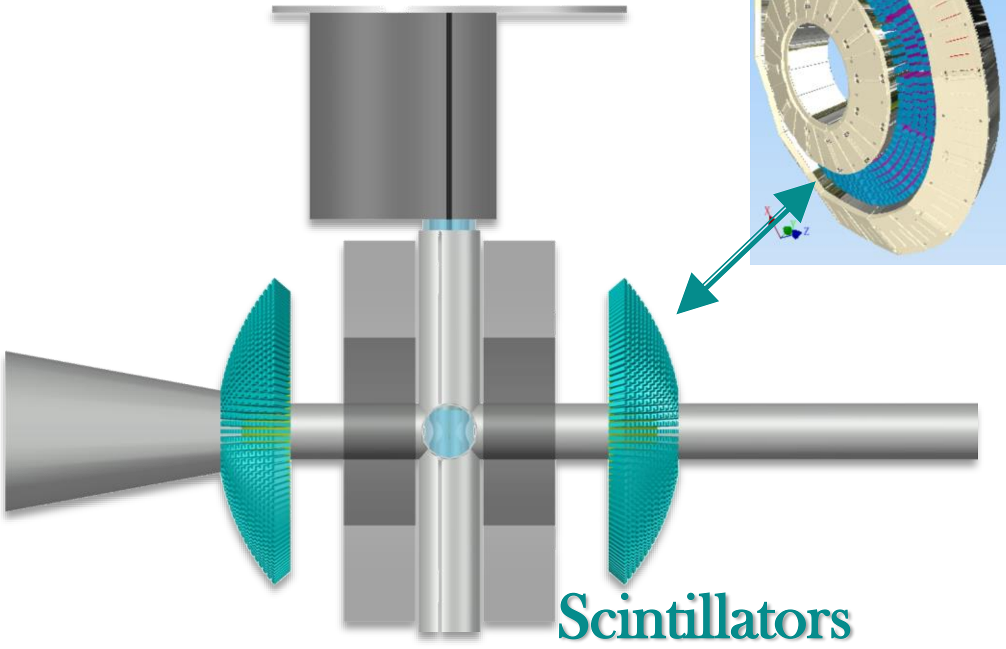


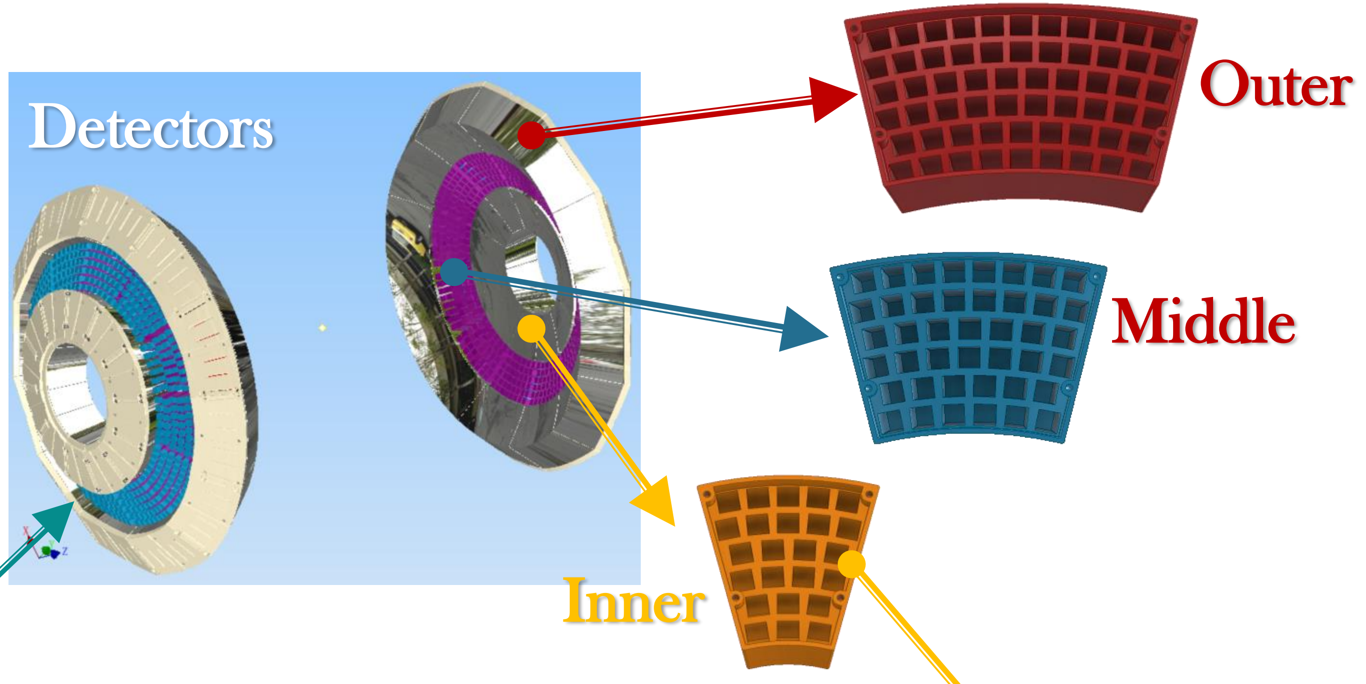


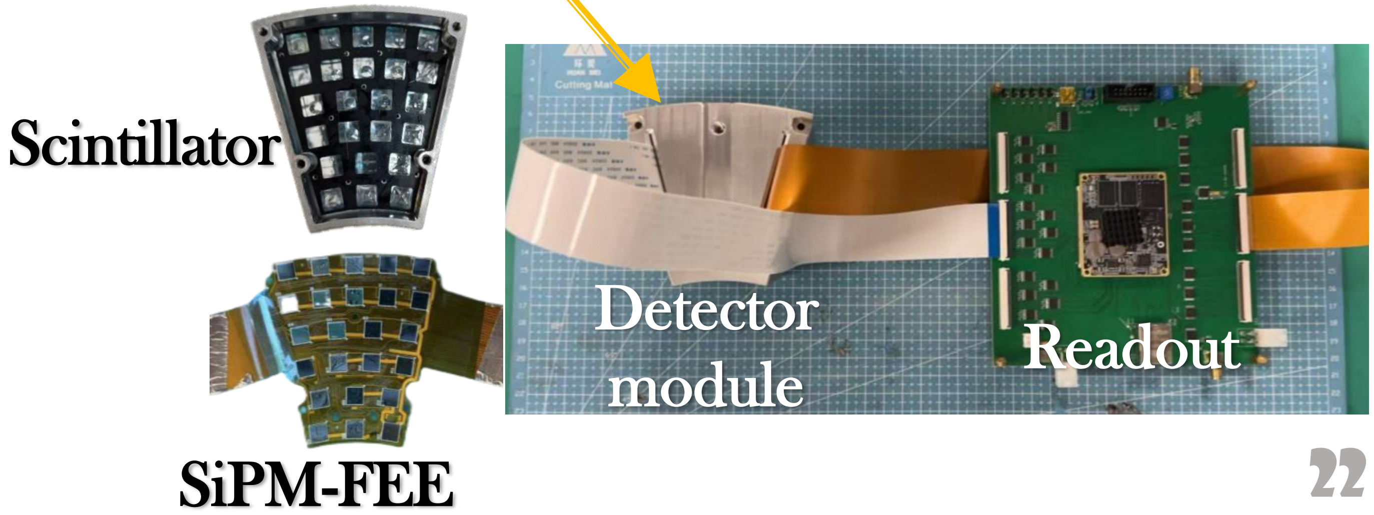
Z. Pan, et. al., IEEE TNS 2021

- ✓ 重大仪器研制项目《高流强缪子源关键技术研究》
- ✓ 总负责人：唐靖宇 ‖ 谱仪子课题：叶邦角
- ✓ 样机探测系统计数性能及非对称因子均国际领先
- ✓ 精确测量样品局域磁场，满足用户实验需求
- ✓ 重大仪器结题优秀，**谱仪为亮点工作**

2nd-Gen SiPM based spectrometer



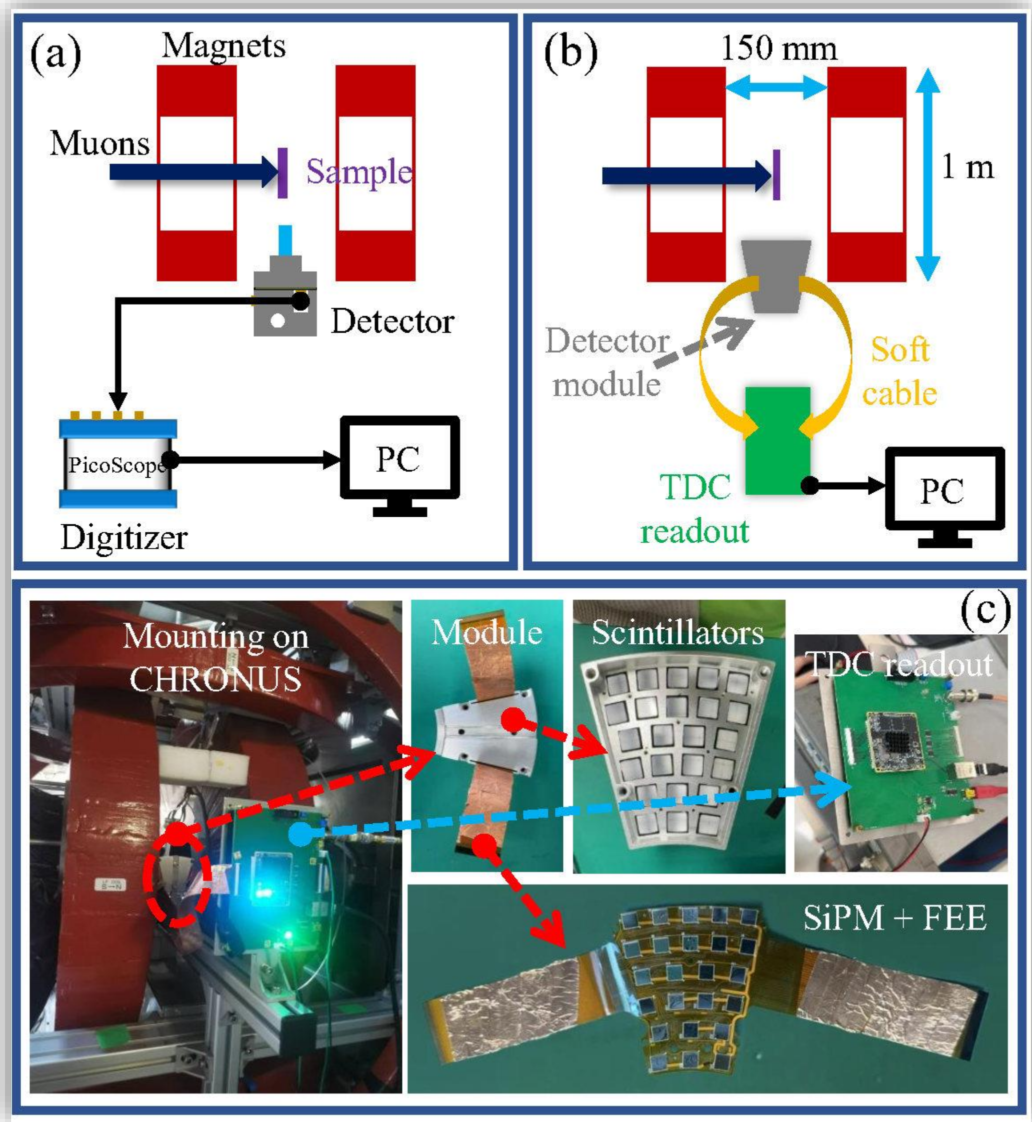


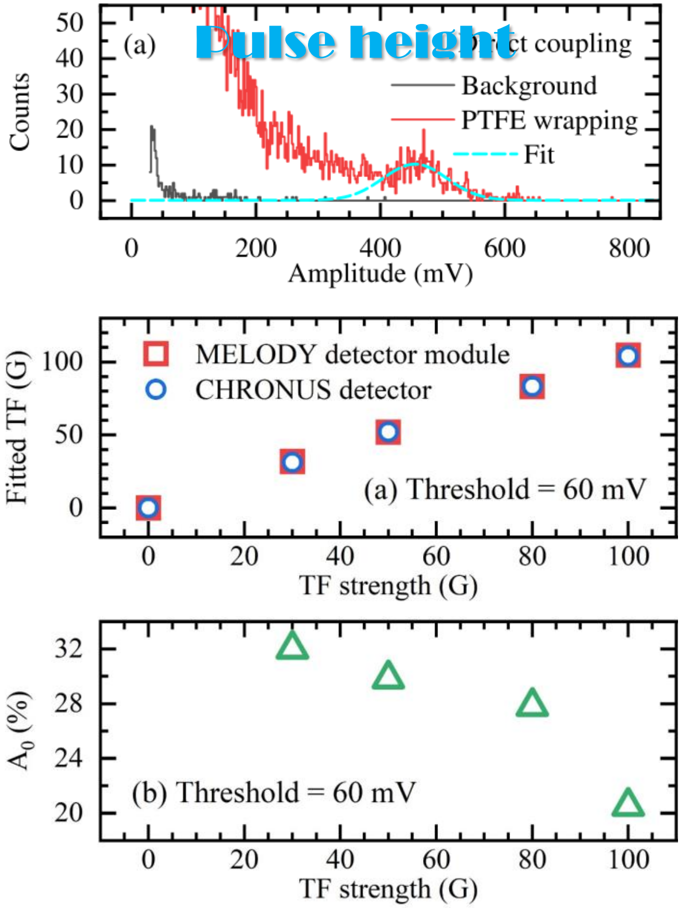


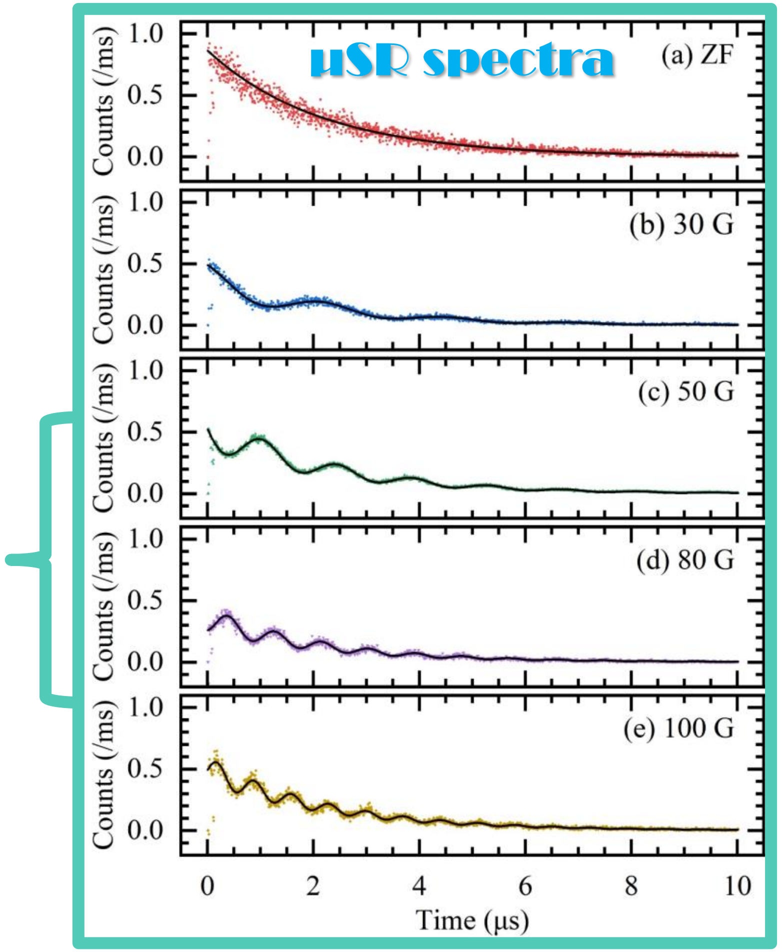
QL, ZWP, et al, μSR2020 proceeding (2023)

QL, ZWP, et al, μSR2025 proceeding (accepted)

2nd-Gen SiPM based spectrometer

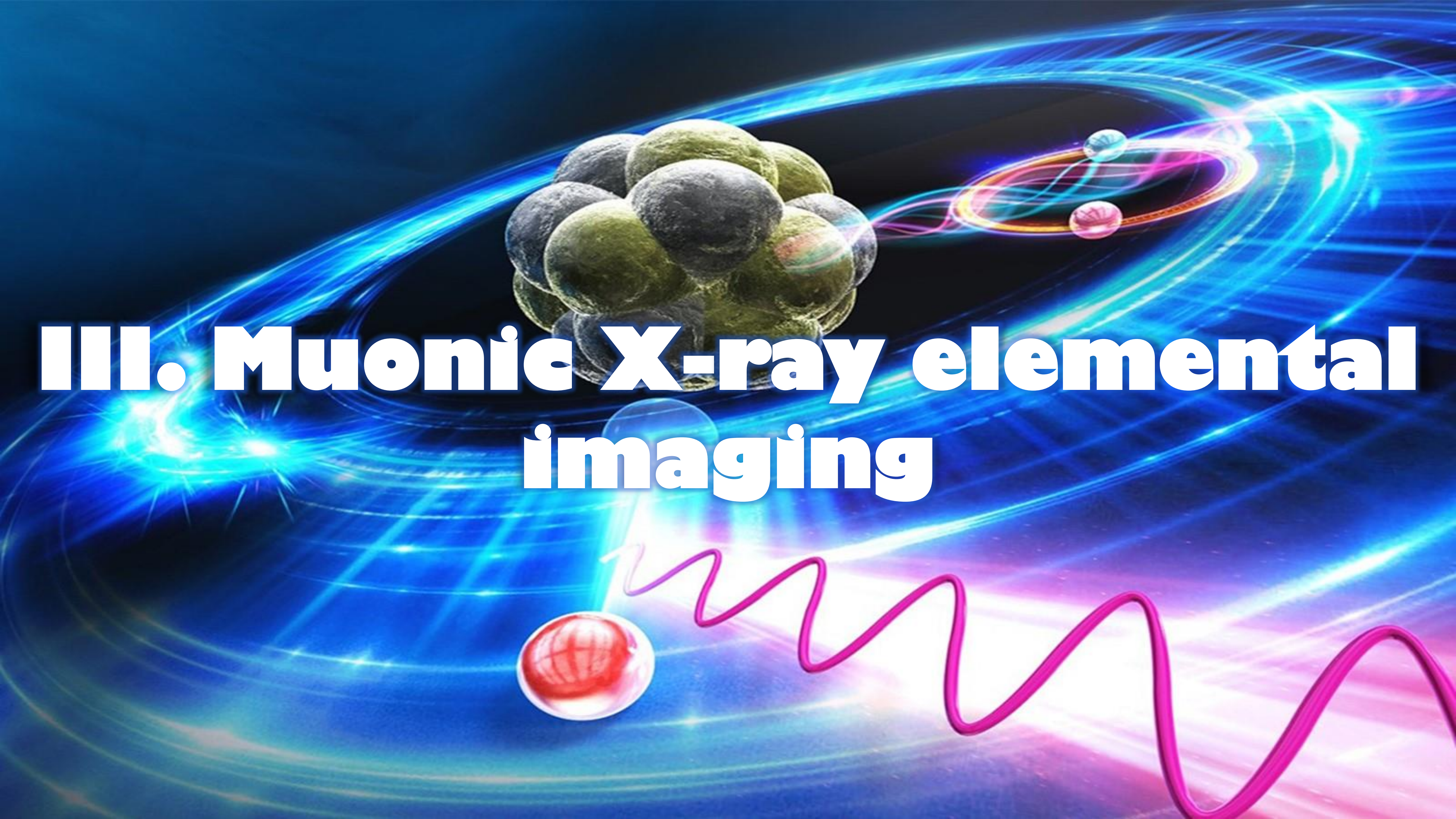






QL, ZWP*, et al., NIMA 1082 (2026) 170918*

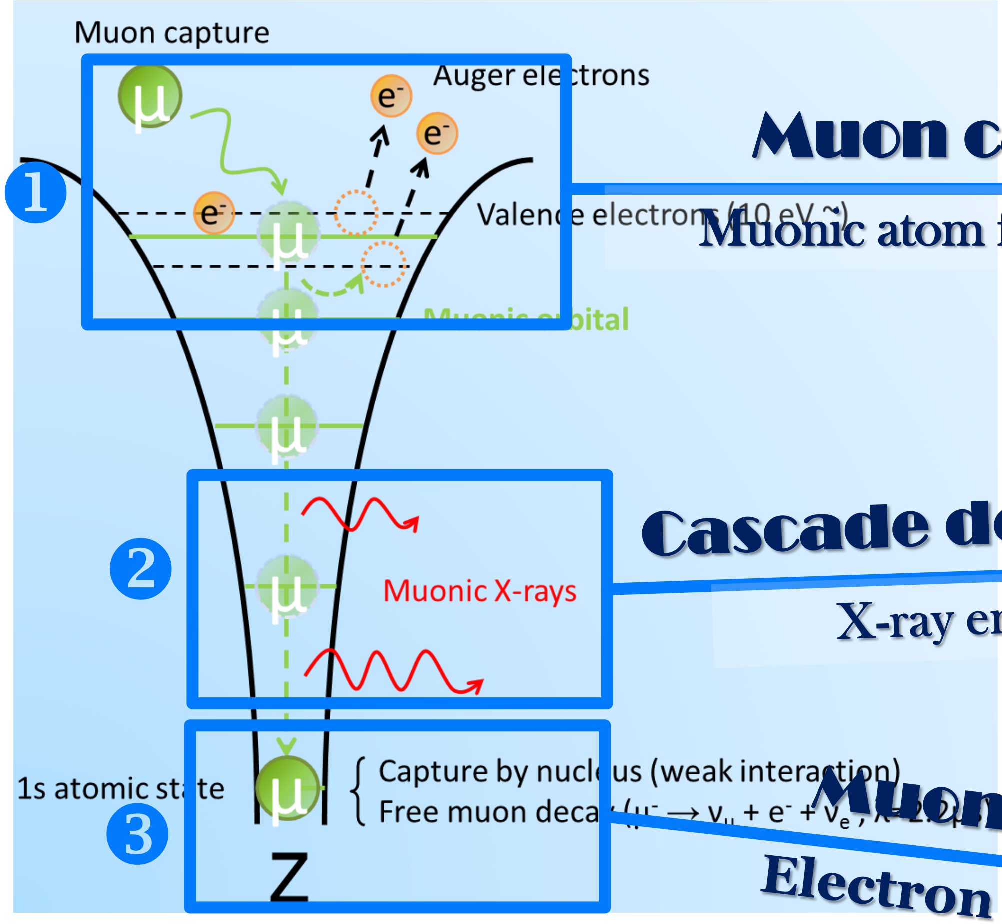
- The first version has been successfully demonstrated using ISIS muons
- The updated version is ready for muon beam test



III. Muonic X-ray elemental imaging

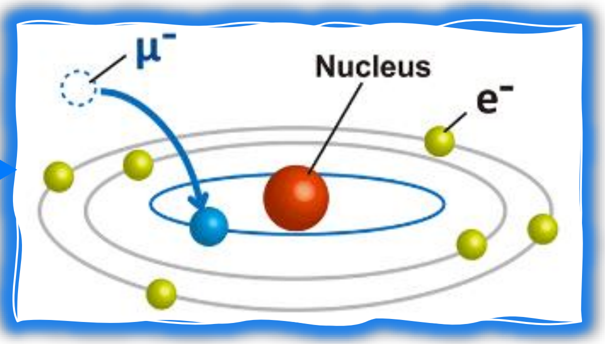
Physical processes

Muon Induced X-ray Emission (MIXE)



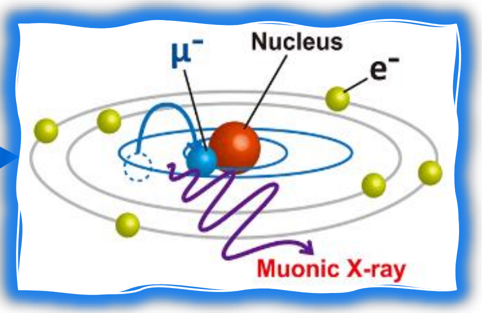
Muon capture

Muonic atom formation



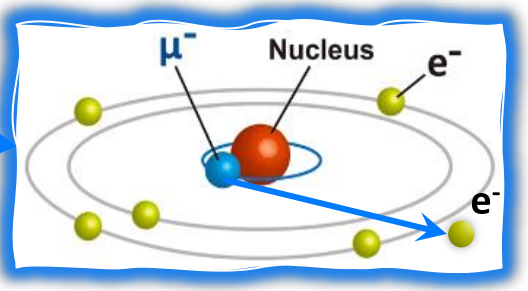
Cascade de-excitation

X-ray emission



Muon decay

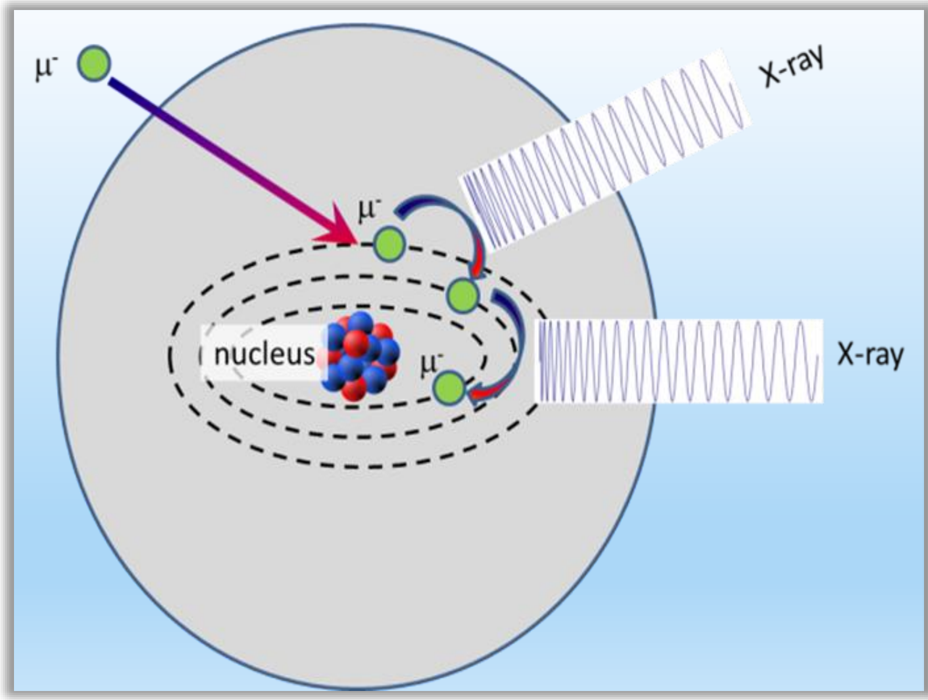
Electron emission

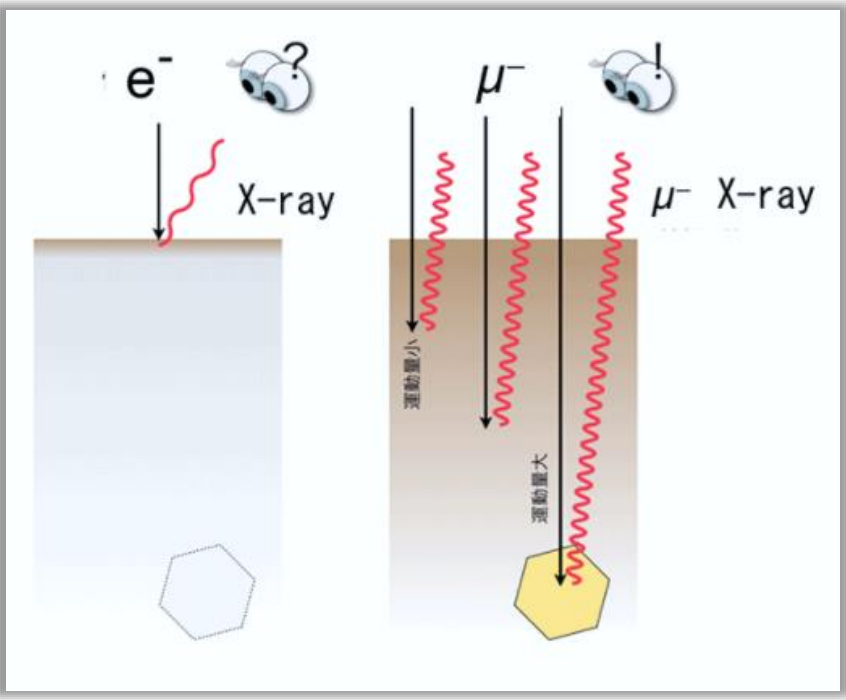


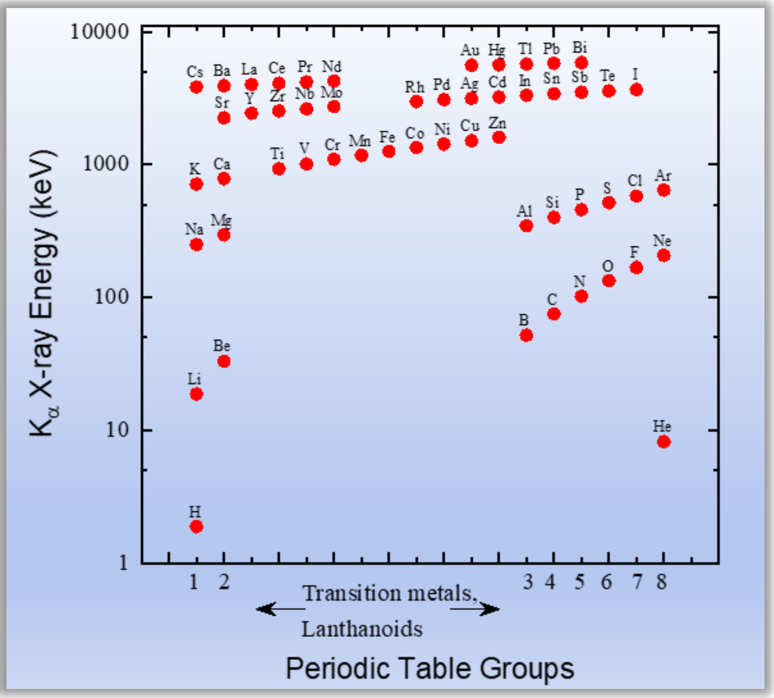
Muonic x-ray **Electronic x-ray**

$$E_{i\to f,\mu} = \frac{m_\mu}{m_e} R\left(\frac{1}{n_f^2} - \frac{1}{n_i^2}\right) \approx \frac{m_\mu}{m_e} E_{i\to f,e} \approx 207 \times E_{i\to f,e}$$

Advantages







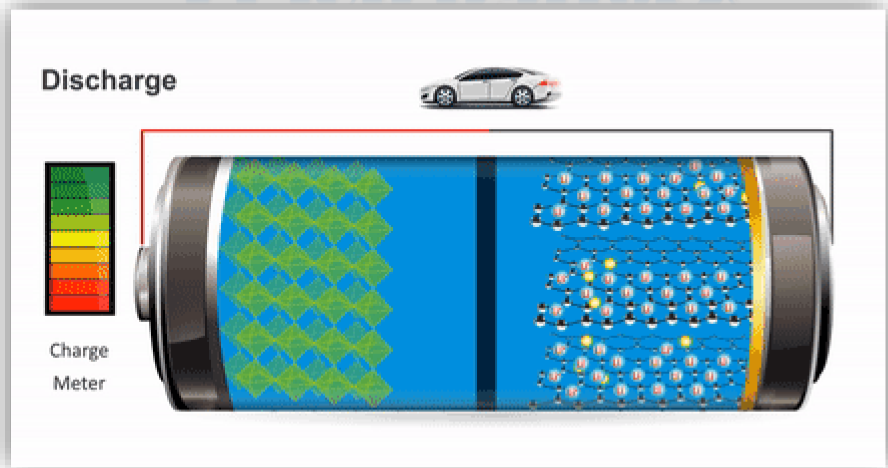
- **High energy, high penetrating capability** (~200 times of electrons, induced X-rays with an energy in 10s keV – 10MeV)
- **Energy dependency on atomic number** (multiple atoms/elements distinguishable at one time)
- **Better sensitivity to low-Z materials** (high X-ray energy that can be responded by detectors)
- **Adjustable muon beam momentum** (depth analysis of elemental distributions)
- **Non-destructive measurement** (no radiation risk to materials)

Multi-field applications

Meteorite

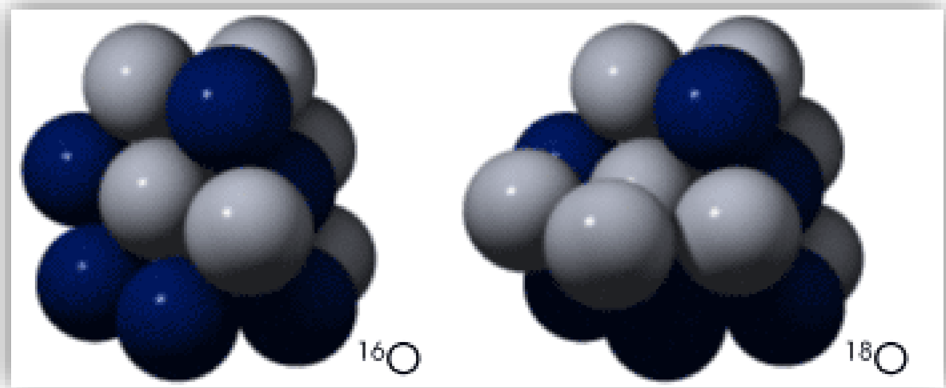
Cultural heritage

Li-ion battery



Biomaterials

Isotope analysis



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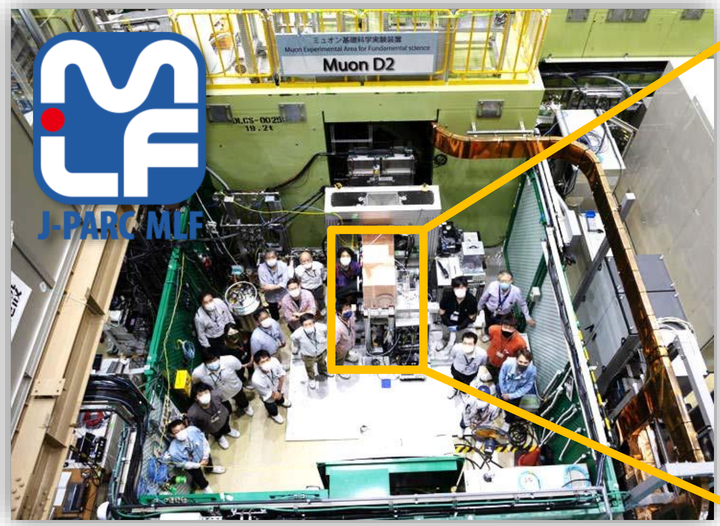
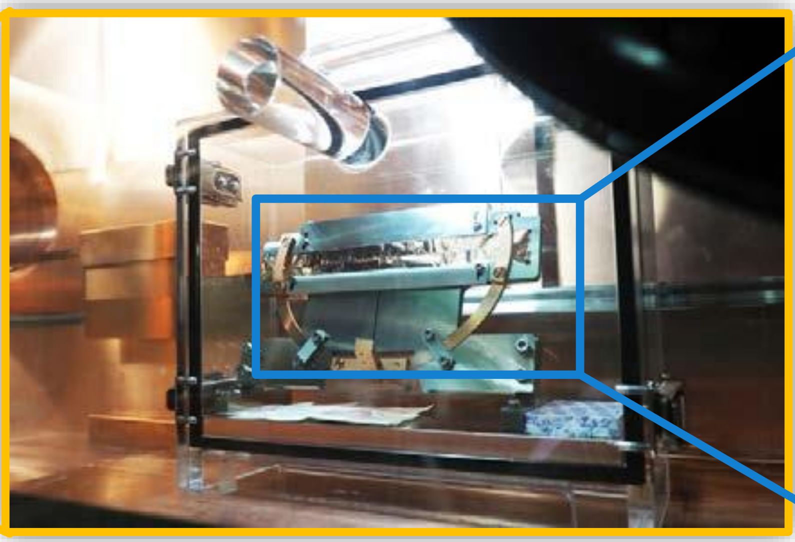
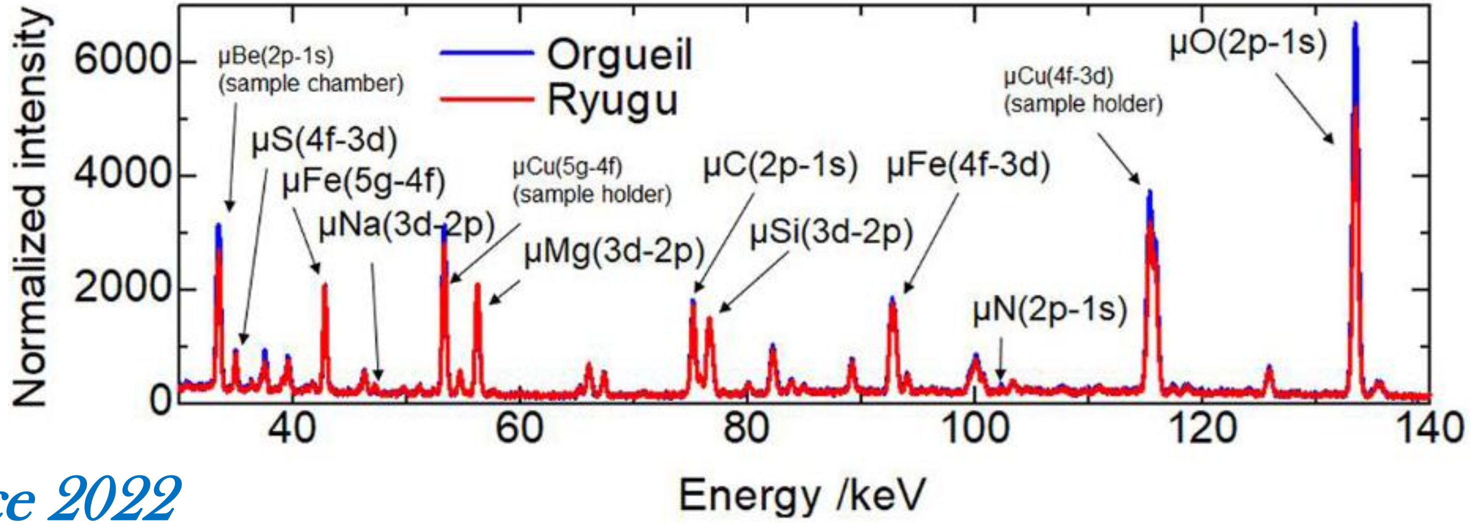
Adrian Hillier, et al., Handbook of Cultural Heritage Analysis, Chapter 3

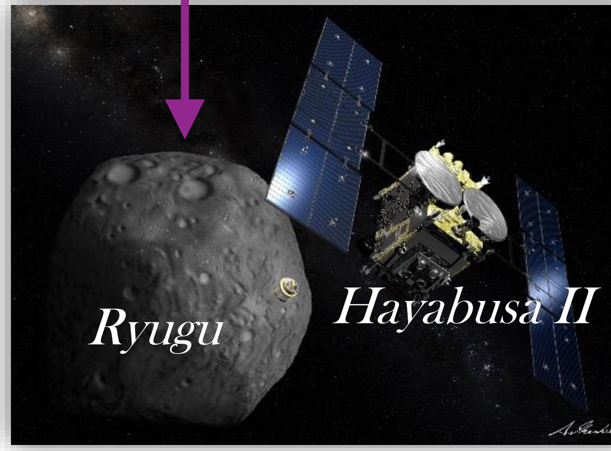
Status: elemental concentration analysis

Non-destructive Elemental Analysis of Asteroid 'Ryugu' Sample



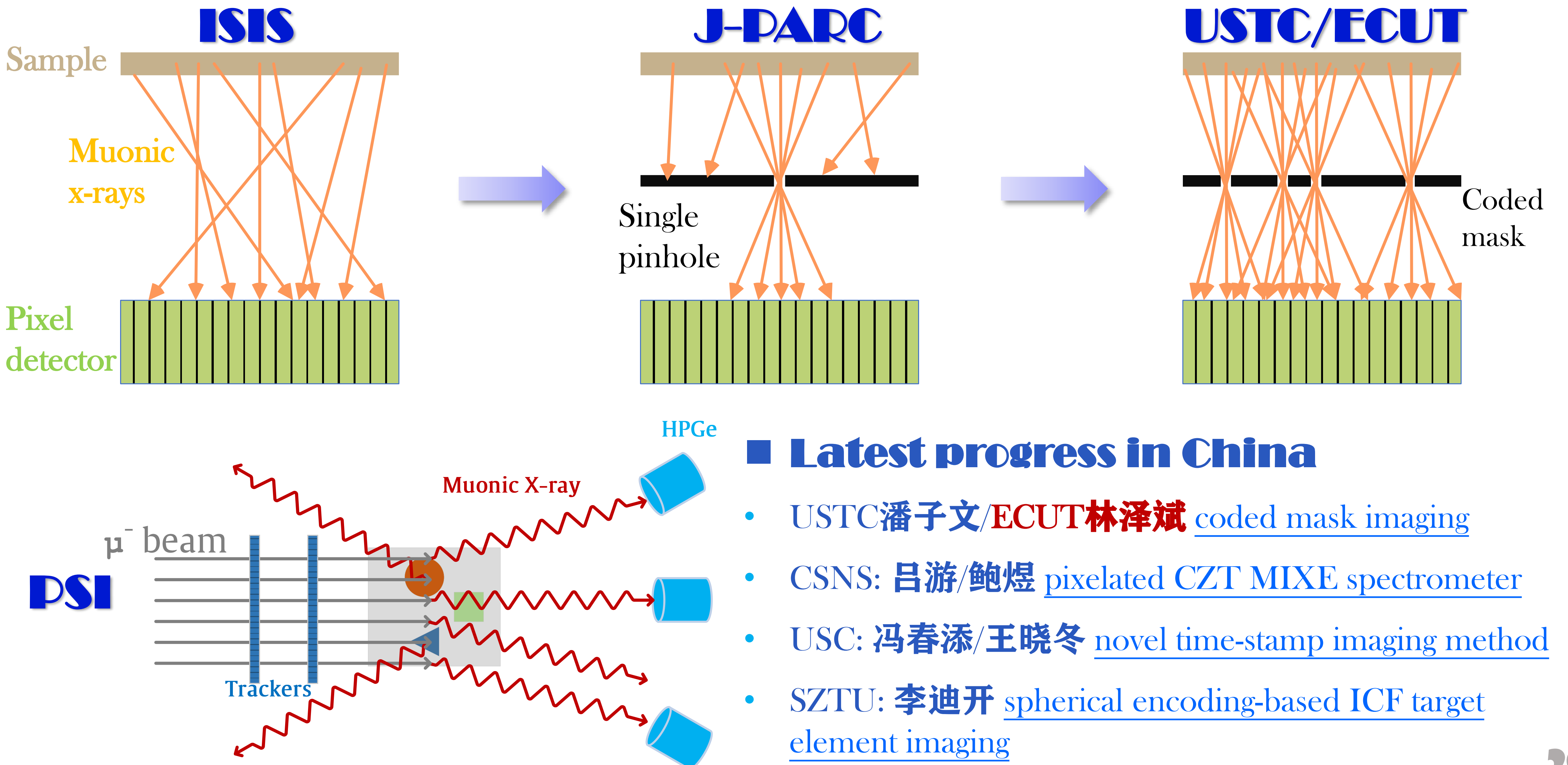






Science 2022

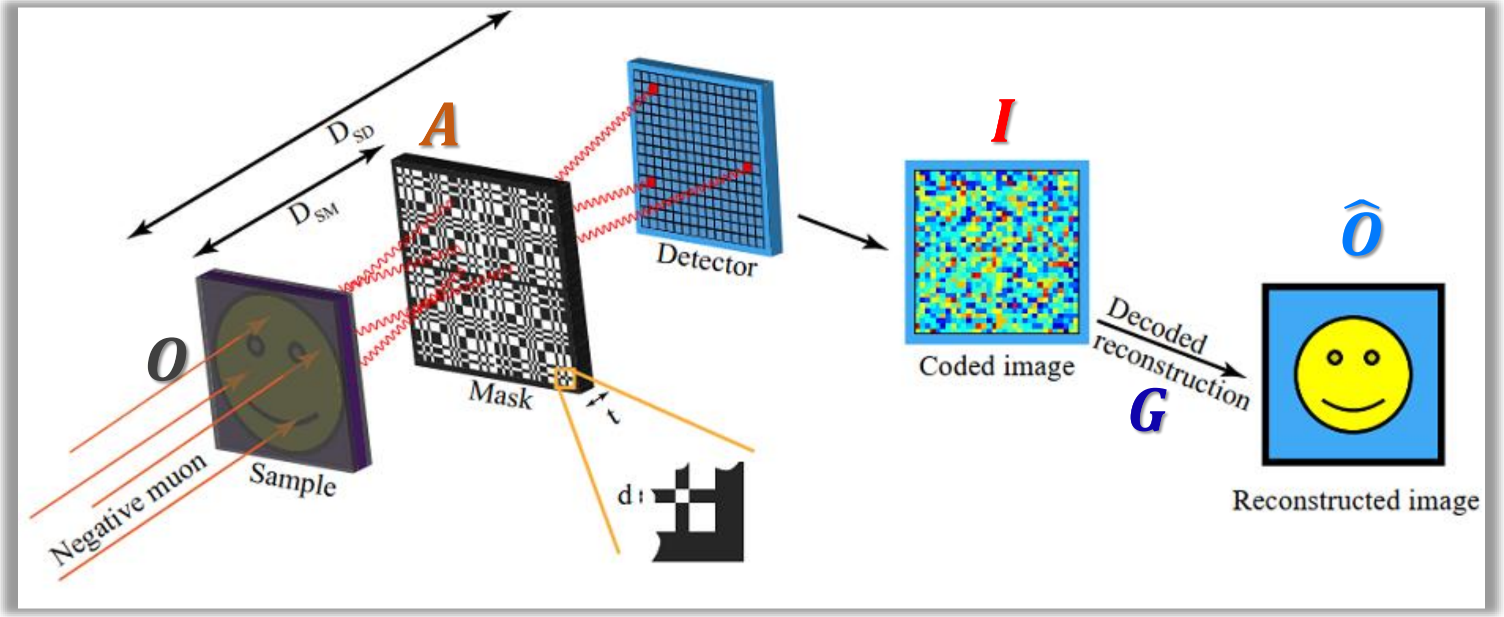
Progress: elemental imaging development



■ Latest progress in China

- USTC潘子文/ECUT林泽斌 coded mask imaging
- CSNS: 吕游/鲍煜 pixelated CZT MIXE spectrometer
- USC: 冯春添/王晓冬 novel time-stamp imaging method
- SZTU: 李迪开 spherical encoding-based ICF target element imaging

2D coded aperture imaging simulation



- **Muons**: 32.9 MeV/c @ 32×32 mm^2
- **Sample**: 31×31×2 mm^3
- **Mask**: MURA array 61×61 pixels
- **Detector**: CdTe detector
  32×32 mm^2 with 128 pixels
  cell size in 0.25×0.25 mm^2
  1.06% in energy resolution

$$\boldsymbol{I} = \boldsymbol{O} * \boldsymbol{A} + \boldsymbol{N}$$

$$\boldsymbol{A} \otimes \boldsymbol{G} = \boldsymbol{\delta}$$

$$\boldsymbol{A} = \begin{cases} \mathbf{1, hole} \\ \mathbf{0, wall} \end{cases} \qquad \boldsymbol{G} = \begin{cases} \mathbf{1, hole} \\ \mathbf{-1, wall} \end{cases}$$

$$\hat{\boldsymbol{O}} = \boldsymbol{I} \otimes \boldsymbol{G} = \boldsymbol{O} + \boldsymbol{N} \otimes \boldsymbol{G} \approx \boldsymbol{O}$$

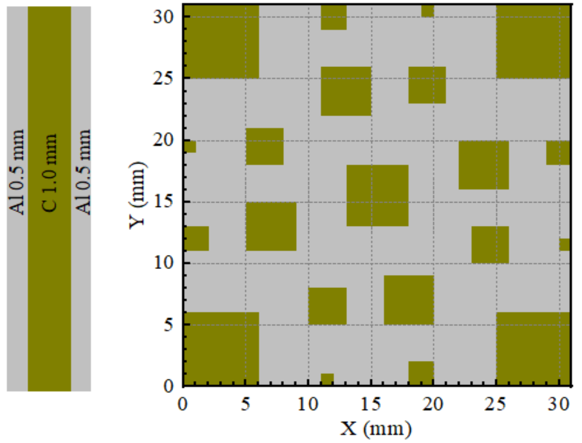
- ☐ **Image quality**: $Q = \dfrac{2\operatorname{cov}(O,\hat{O})}{\operatorname{var}(O) + \operatorname{var}(\hat{O})} \dfrac{2\bar{O}\cdot\bar{\hat{O}}}{\bar{O}^2 + \bar{\hat{O}}^2}$
- ☐ **Efficiency**: $\varepsilon = \dfrac{N_{D,X-ray}}{N_{Tot,muon}}$
- ☐ **Figure of merit**: $FoM = Q/|\ln(\varepsilon)|$

Z. Lin, Z. Pan et al., NIMA 1034 (2022) 166783*

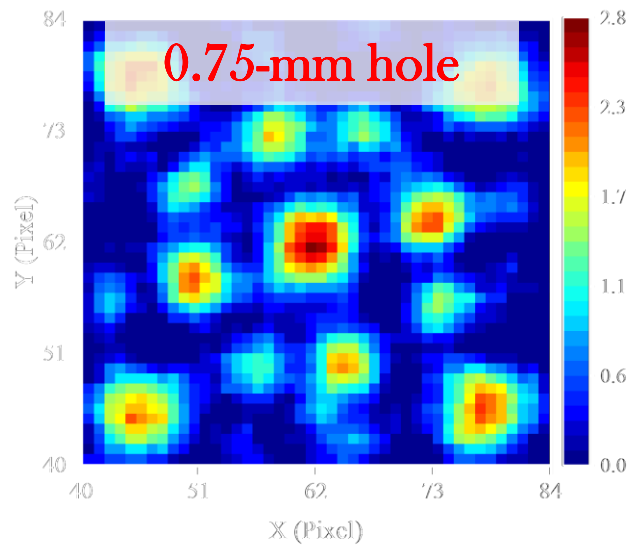
Coded mask imaging @ USTC / ECUT

2D coded mask imaging simulation

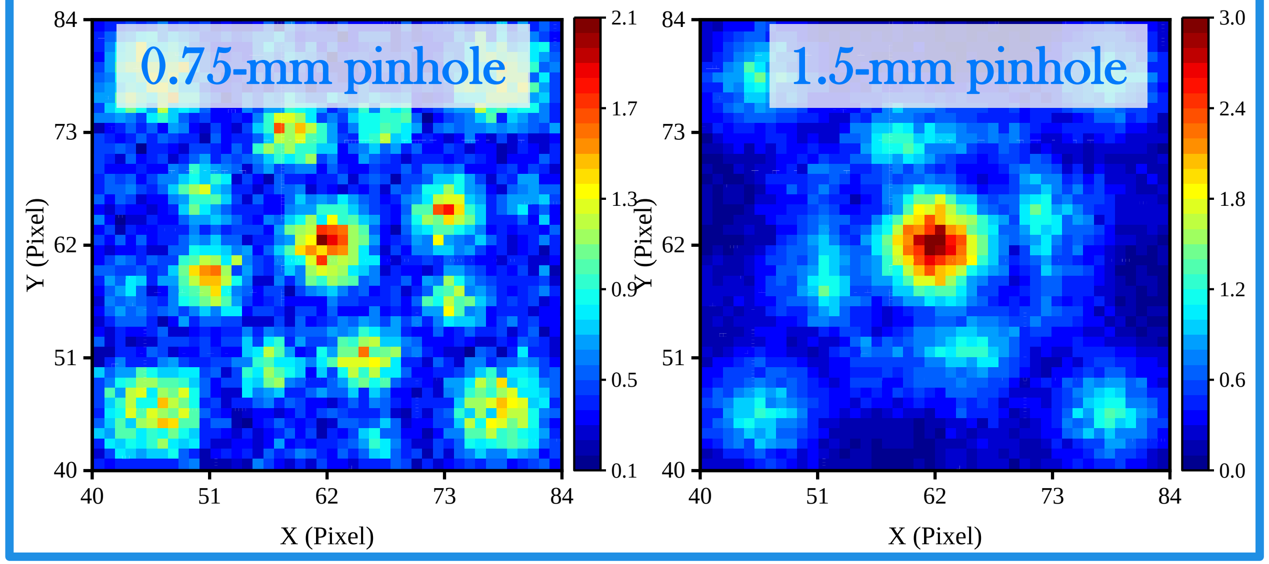
Sample



Coded aperture



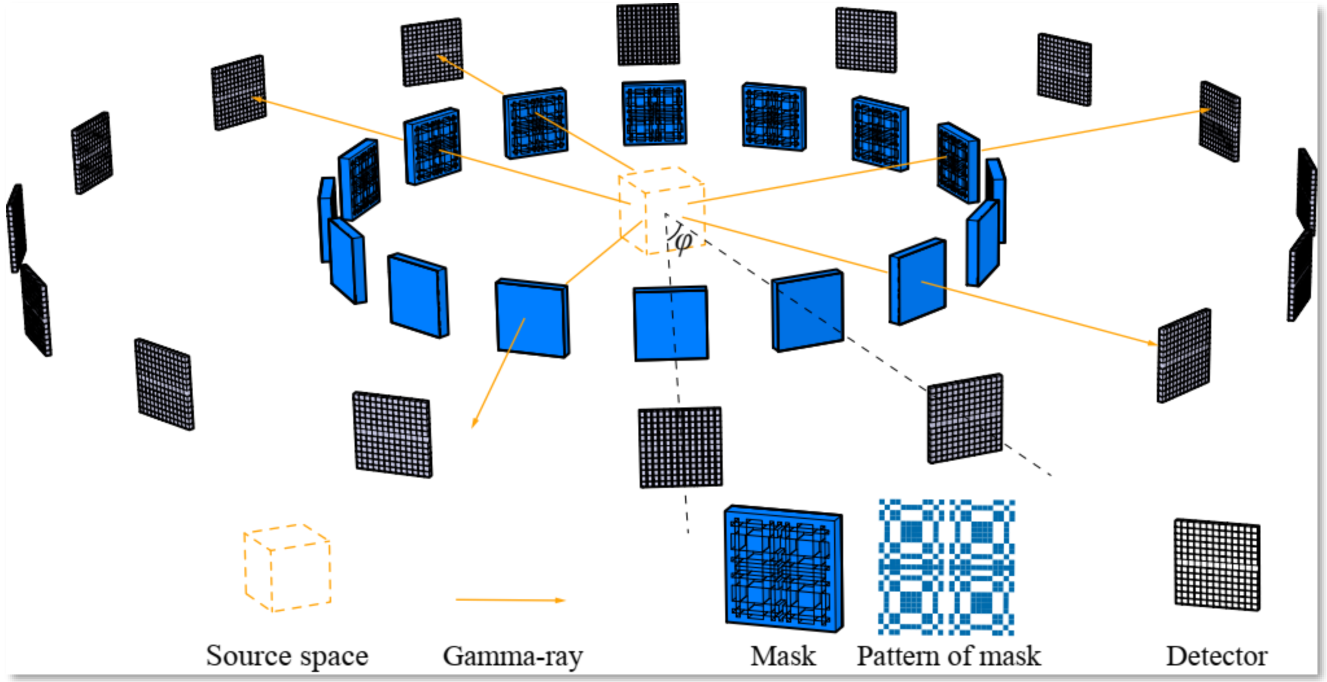
Single pinhole

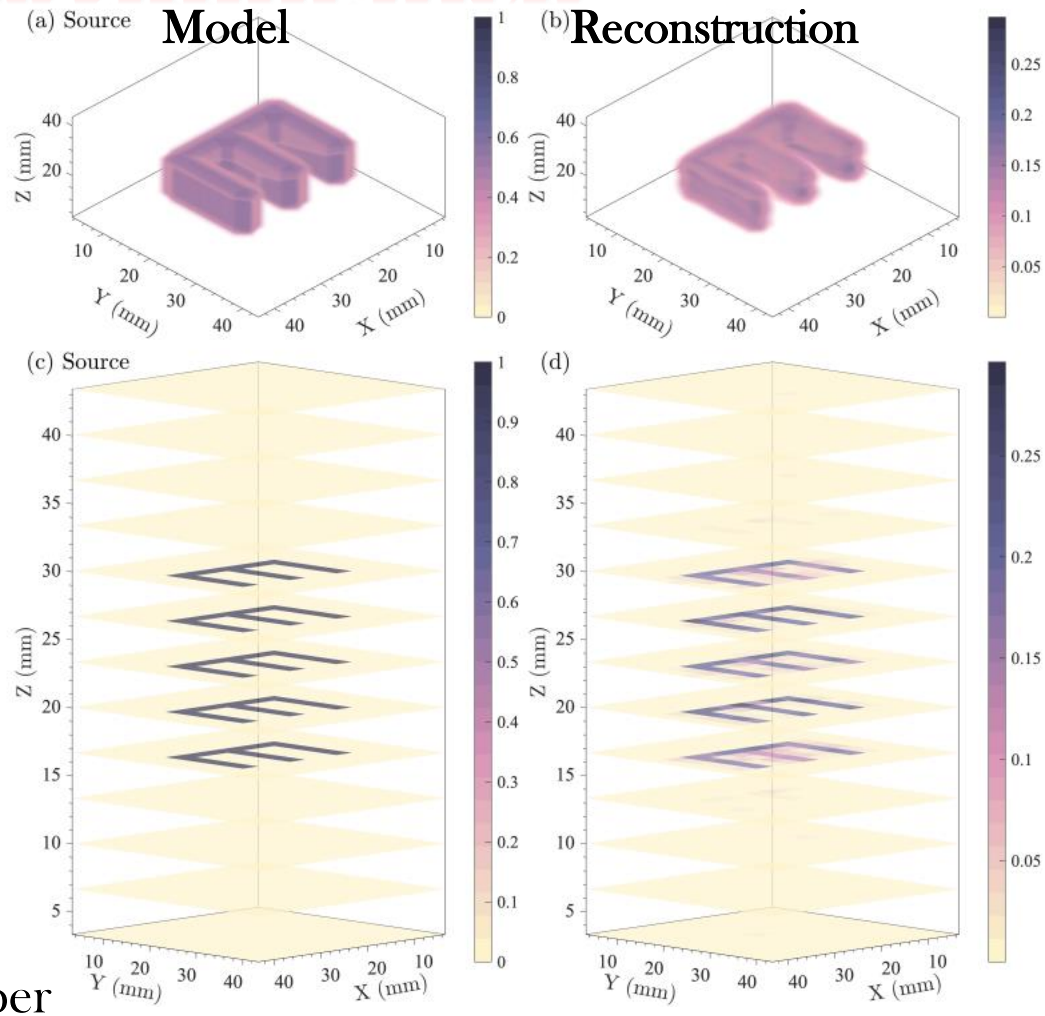


Imaging technique	Distance[Sample, Det]	Aperture size	Thickness	Q	ε	FoM
Coded aperture	80 mm	0.75 mm	1.0 mm	0.670	1.25×10^{-3}	0.100
Single pinhole	80 mm	0.75 mm	20.0 mm	0.649	2.06×10^{-5}	0.060
	80 mm	1.50 mm	20.0 mm	0.381	2.67×10^{-5}	0.036

*Z. Lin, Z. Pan * et al., NIMA 1034 (2022) 166783*

3D coded mask imaging simulation



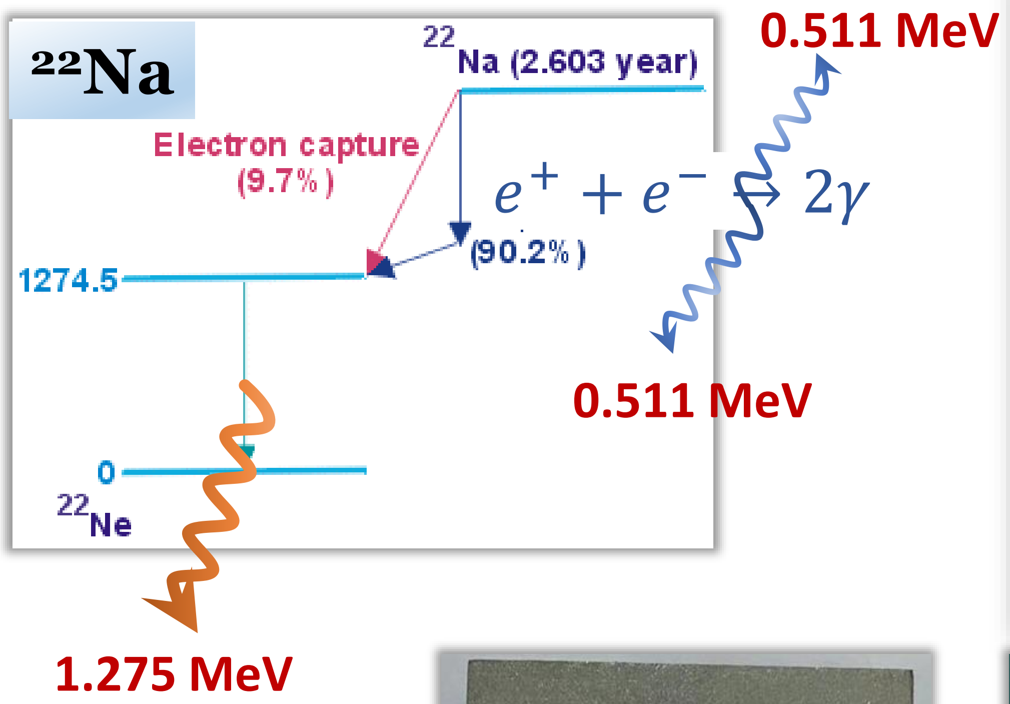


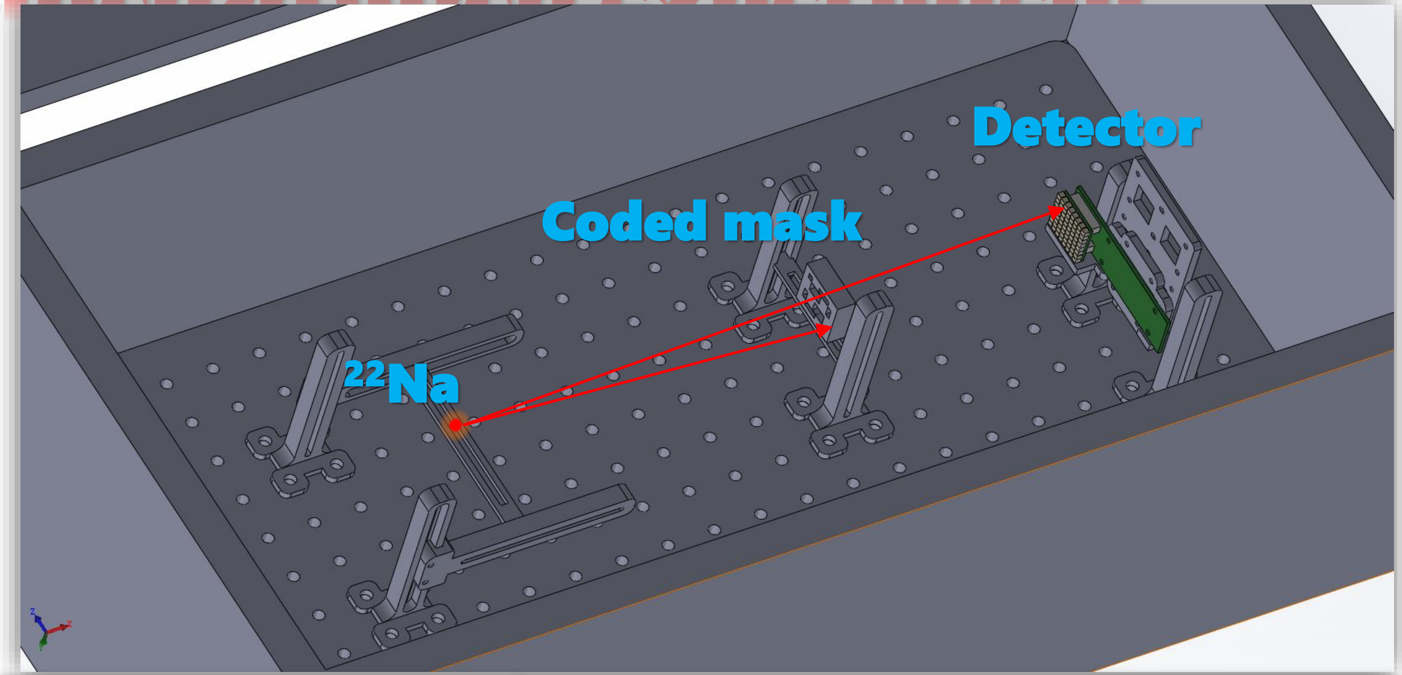
- **Developed** a 3D MLEM imaging method
- **Validated** the feasibility of this imaging method for complex source distribution through simulation
- **Proposed** a criterion to determine whether the count rate and number of iterations meet the optimization requirements for imaging quality

Z. Lin *, Z. Pan * et al., NET 58 (2026) 104012

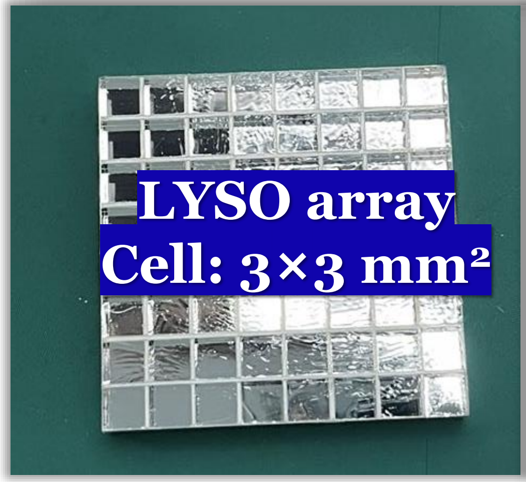
Coded mask imaging @ USTC / ECUT

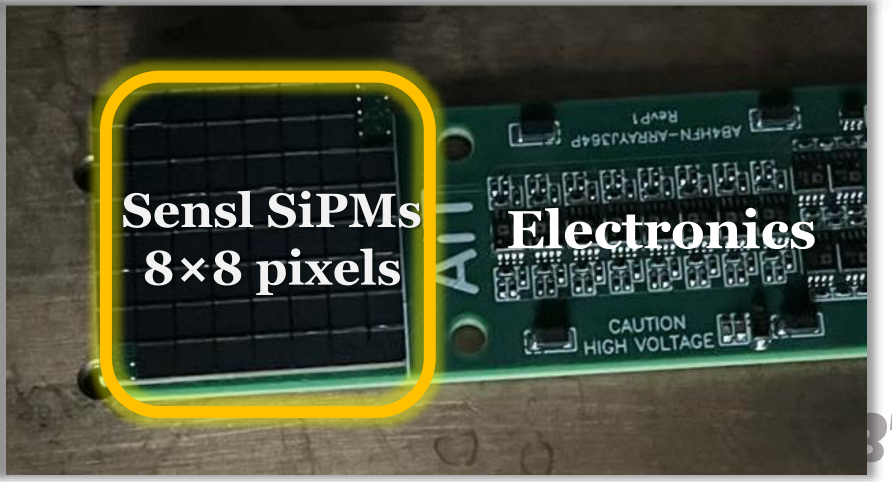
SiPM detector demonstration experiment



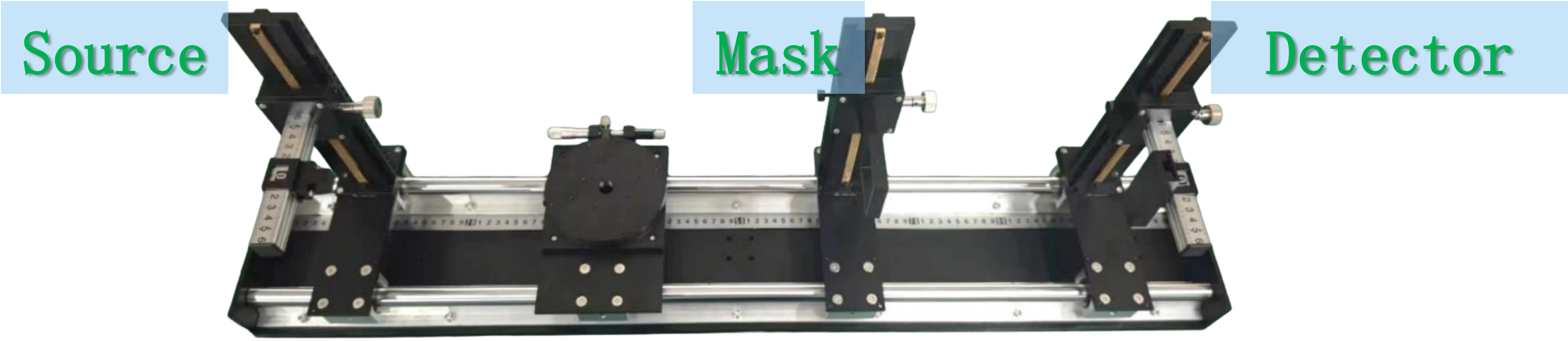


LYSO:
Cerium-doped
Lutetium
Yttrium
Orthosilicate

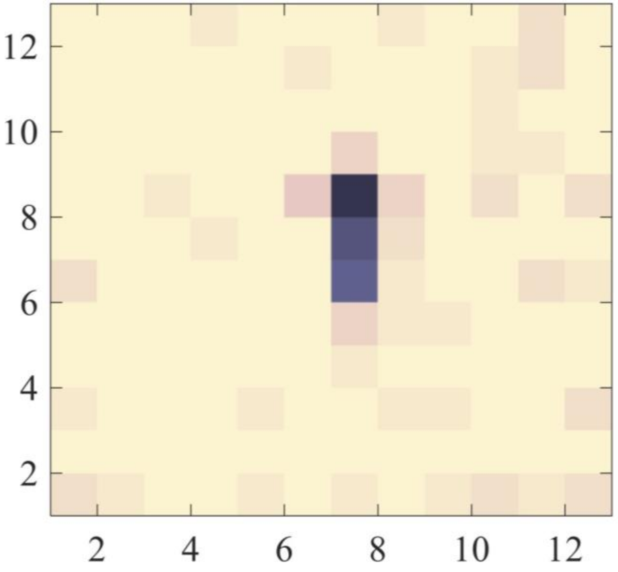




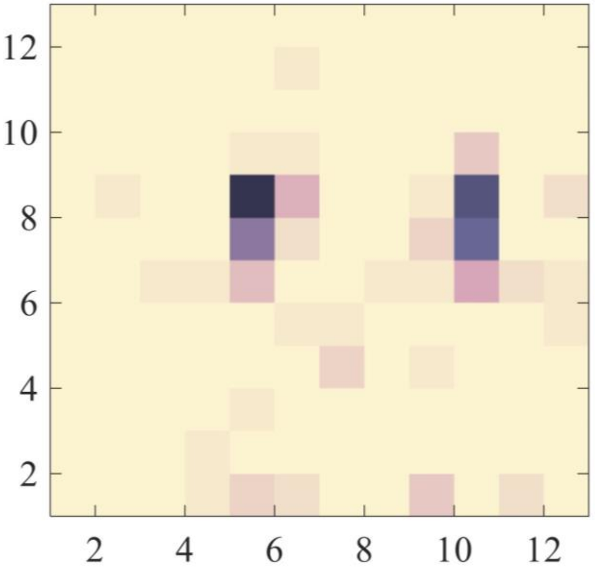
SiPM detector demonstration experiment



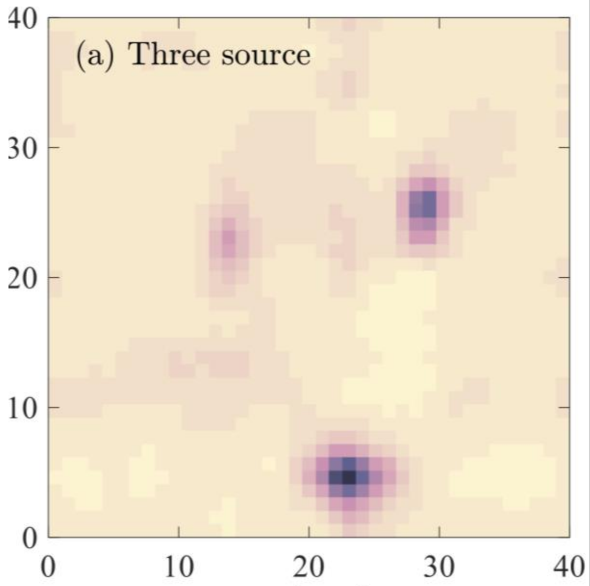
1 source



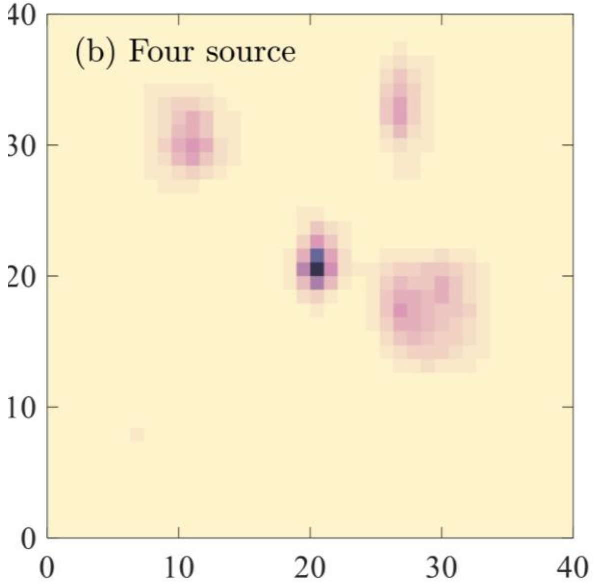
2 sources



3 sources



4 sources



Z. Lin, Z. Pan* et al., Radiation Measurements (Under review)*

IV. Summary and prospects

Overview

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, JLab
- **Laser driven muons** (Feng Zhang et al, Nature Physics 2025)

μSR spectrometer development

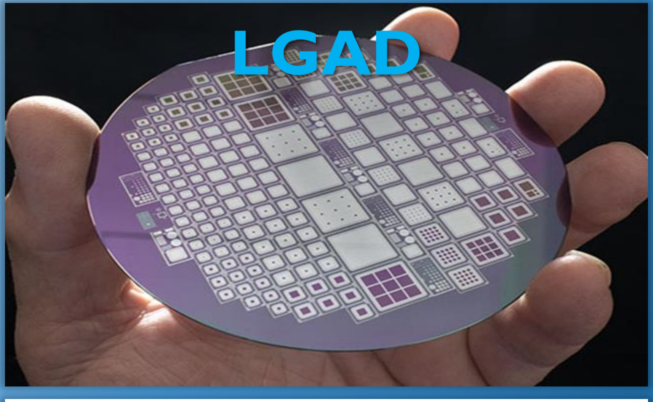
- MELODY is under construction in CSNS II (2024 - 2029)
- USTC group developed two generations of μSR spectrometers collaborated with CSNS group
- The SiPM spectrometer is about to be constructed

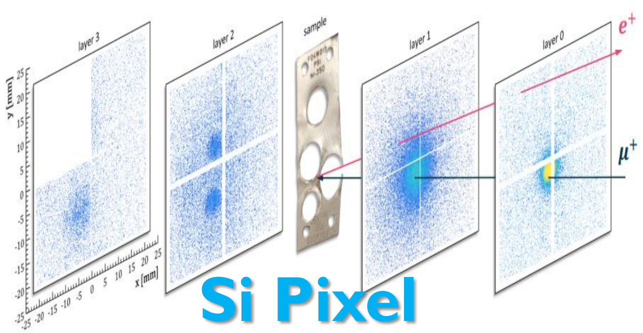
MIXE elemental imaging

- Four groups in China are working on methodology and instrument developments
- USTC/ECUT group proposed 2D/3D coded aperture muonic x-ray imaging methods, and demonstrated the 2D method in simulations and experiments

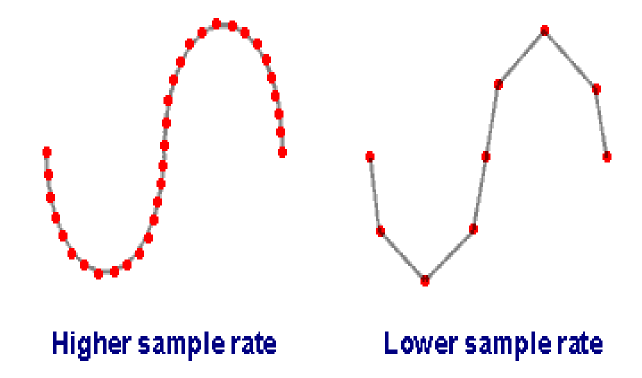
Prospects for μSR

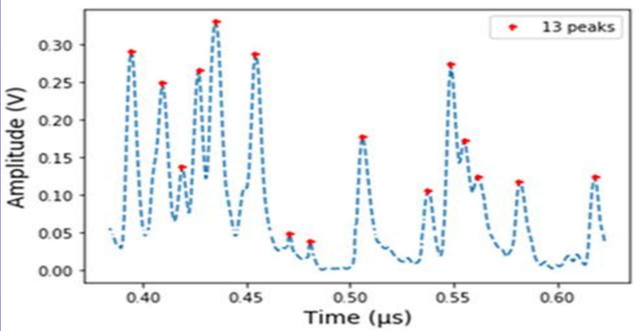
● Detector
- ✓ High granularity
- ✓ μ^+ / e^+ tracking



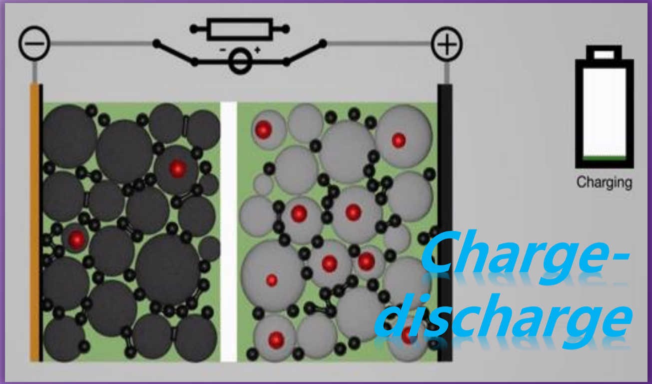


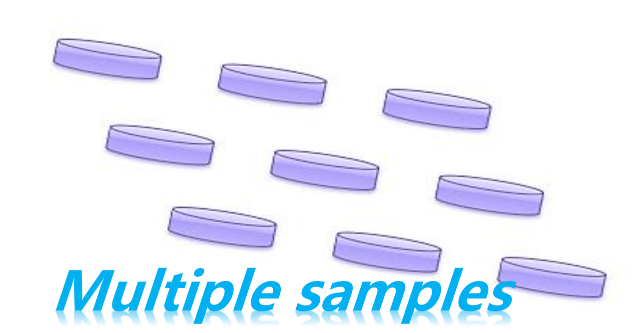
● Electronics
- ✓ Digitization
- ✓ Better resolution





● Measures
- ✓ In-situ
- ✓ Multi-samples

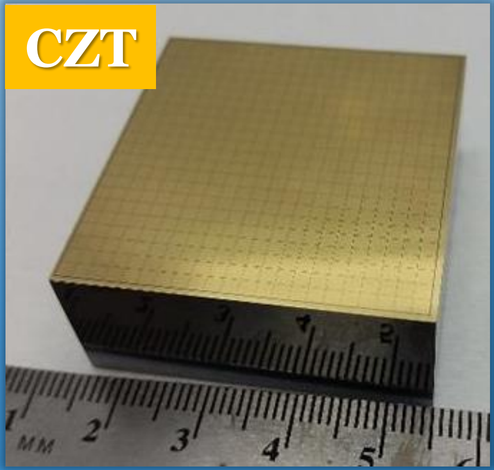


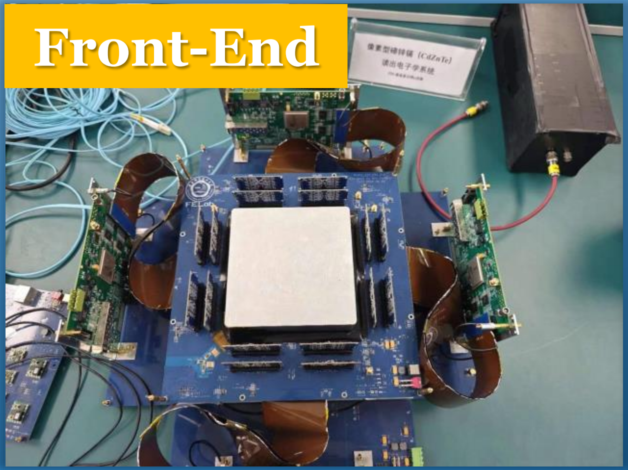


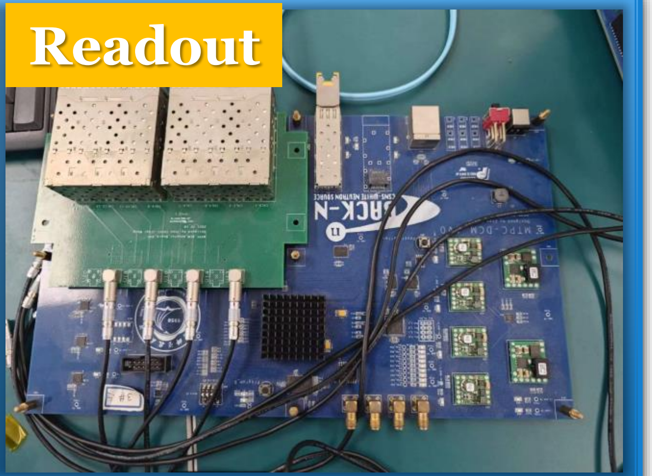
Prospects for MIXE imaging

•Detector

- ✓ CdZnTe: 16×16 cells
- ✓ ~ 1 mm^2 cell size
- ✓ Signal digitization

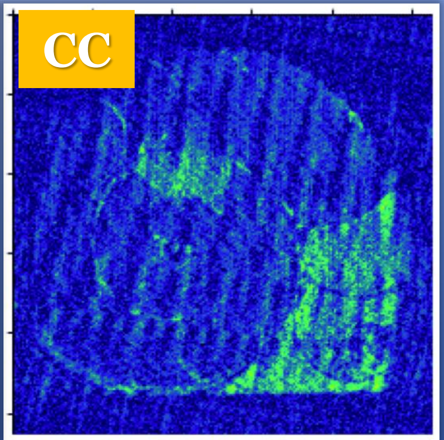


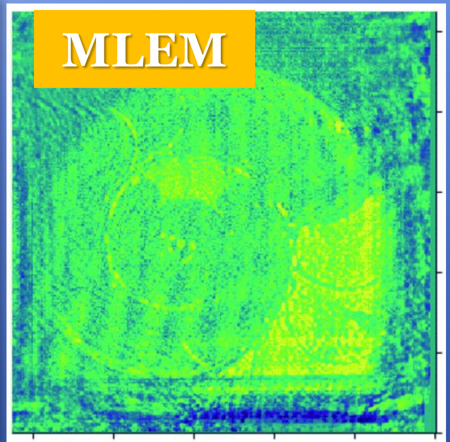


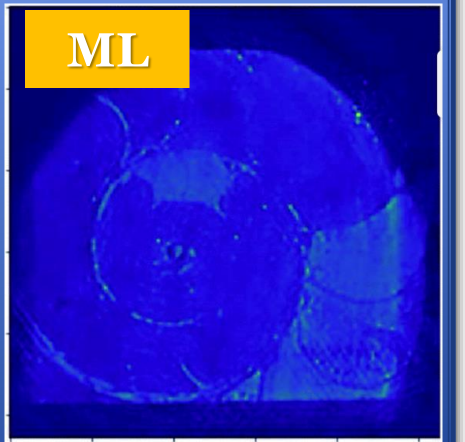


•Algorithm

- ✓ Cross-Correlation
- ✓ MLEM/FFT/T2S ...
- ✓ Machine learning







Thanks for your attention!

- *感谢加速器/宇宙线/激光缪子领域所有老师、同事及合作者对本人工作的支持与帮助！*
- *感谢国自然基金委、自然资源部、广东省粤惠联合基金、“小米青年学者”等多项基金对研究工作的经费支持！*