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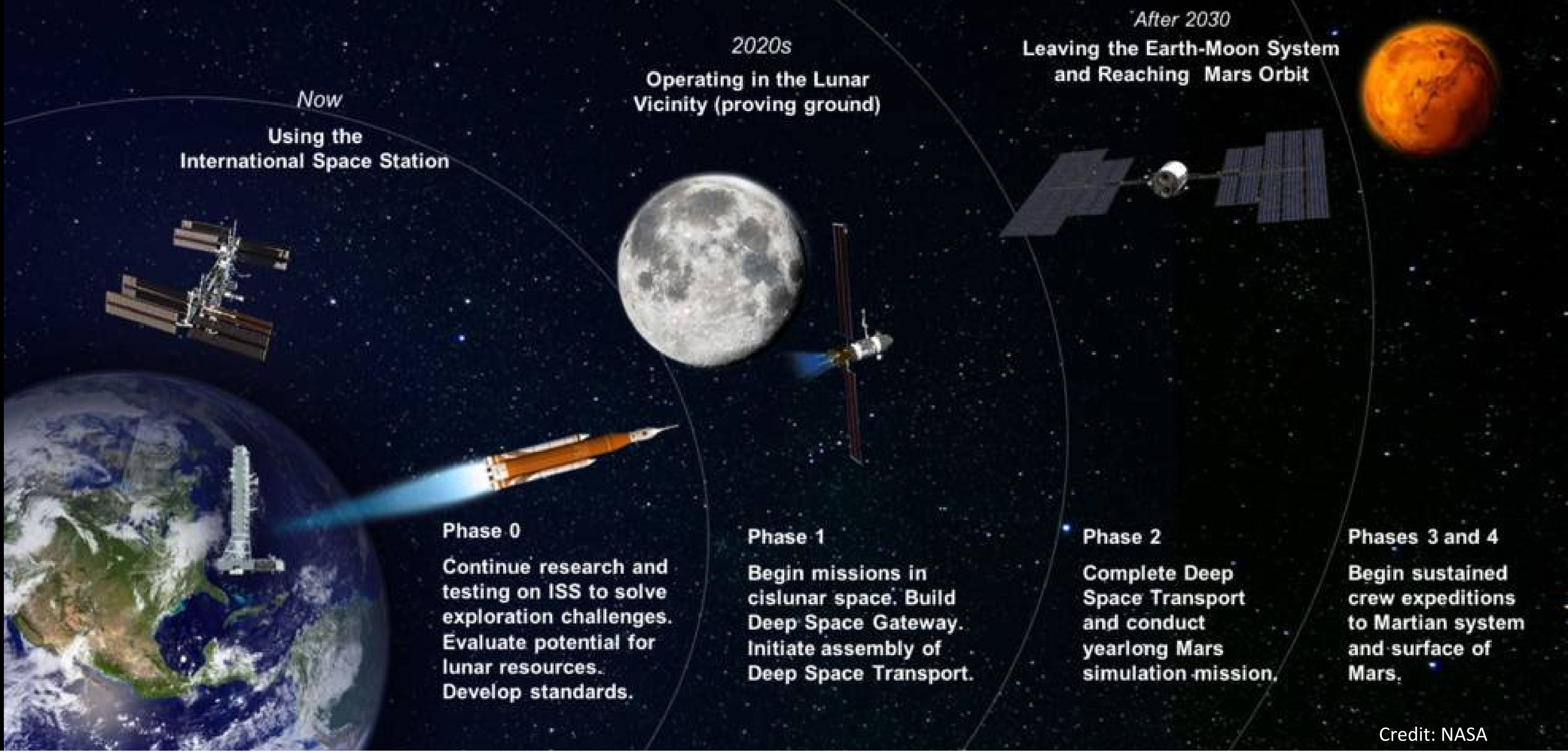
Development of on-site passive dosimetry for space applications

Satoshi Kodaira and Masayuki Naito

Institute for Radiological Science (NIRS)
National Institutes for Quantum Science and Technology (QST), Japan

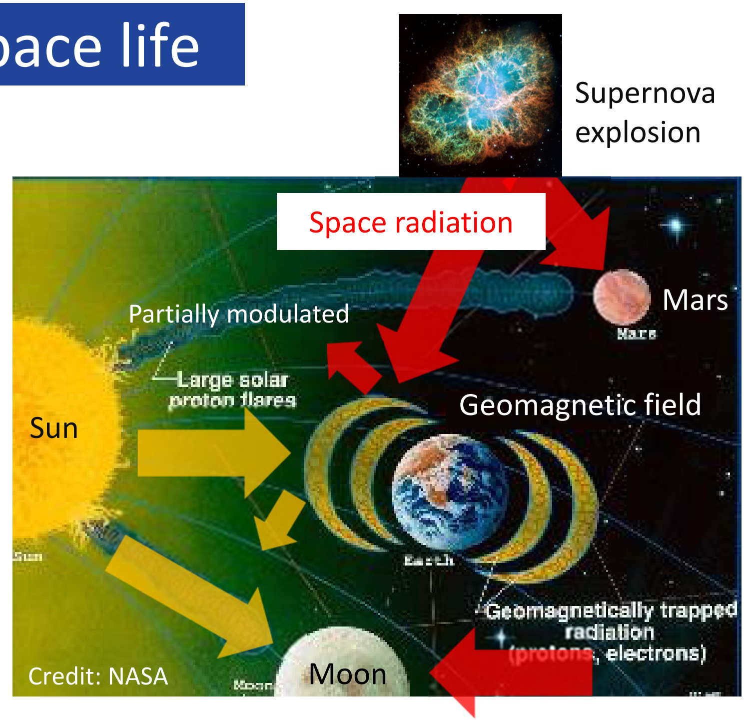
Toward Deep Space

Manned space explorations are currently being carried out in the ISS and will soon extend to the Moon and beyond



Issues to be addressed for space life

1) Restricted environmental condition
(Vacuum, Low temperature, Zero gravity)
2) Psychological effects in a confined space
3) Space radiation exposure

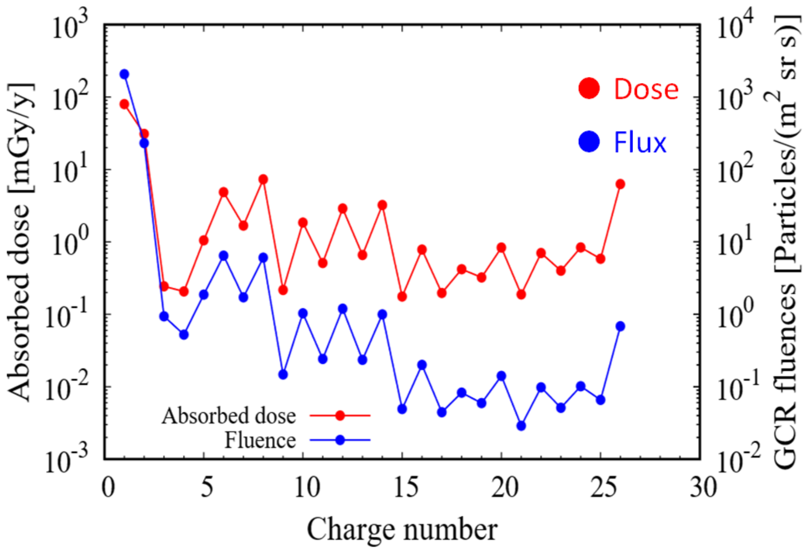


- **We are constantly exposed to space radiation in space**
  - Space radiation consists of high energy charged particles such as **H, He, C, Fe** generated by astronomical phenomena
- **Space radiation exposure**
  - Radiation dose increases in proportion to the duration of stay in space
  - Space radiation is modulated and shielded by the geomagnetic field and atmosphere on the Earth, while it reaches directly in free space or on the Lunar surface without magnetic filed and atmosphere
  - **Radiation dose in free space or on the Lunar surface will be much higher than that at LEO (Low Earth Orbit)**

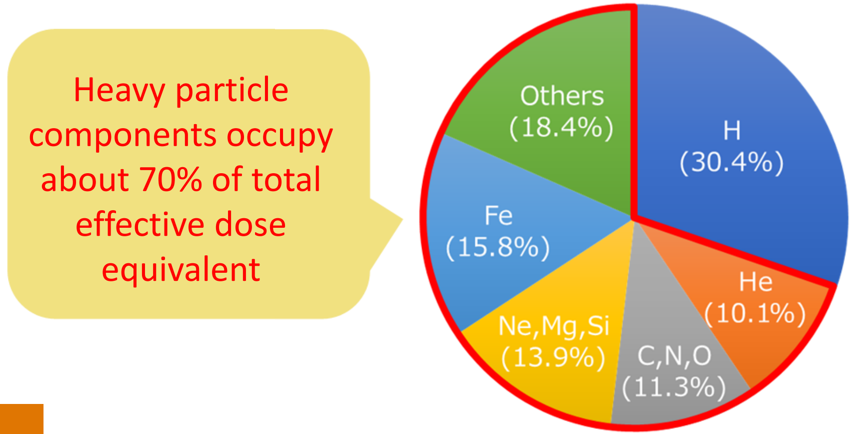
Strategic measures for appropriate dose assessment and shielding against space radiation are essential to enhance the safety of manned deep space missions

Space radiation dose and its protection in deep space

- **Typical radiation dose in the ISS at LEO**
  - Daily dose is 0.5-1mSv and then the total dose will reach 100 mSv by half year activity
- **Beyond the Earth:**
  - Annual dose on the Lunar surface will be ~400 mSv
  - Round trip journey to the Mars will be ~660 mSv *Zeitlin et al., Science (2013)*
  - Dose contribution of high LET (linear energy transfer) particles is much higher than at LEO, indicating the mean radiation quality factor increases in free space



- **What about the countermeasures?**
  - At the moment effective and strategic shielding is not applied yet
  - How to perform dosimetry in deep space should be investigated



Dose contribution of components in GCR

Naito, Kodaira et al., LSSR (2020)

On-site dosimetry based on the reliable, robust and sustainable system will be promising approach for future manned exploration

Current typical passive dosimetry

Luminescence dosimeters (TLD, OSLD, RPLD)

- ✓ Color centers are created in defects or ionic changes by trapping electrons or ions (holes) induced by ionization
- ✓ Measure the luminescence intensity emitted from color centers by optical or thermal stimulation, which is proportional to the dose

TLD (LiF:Mg,Ti, $CaSO_4$:Dy etc)

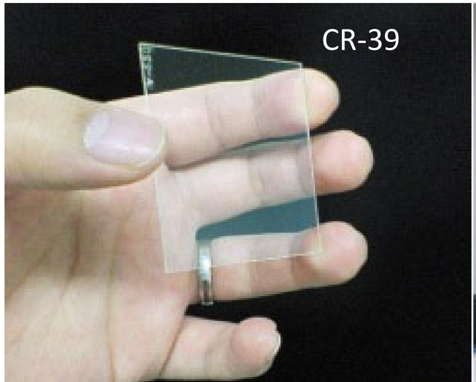
OSLD(Al_2O_3:C)

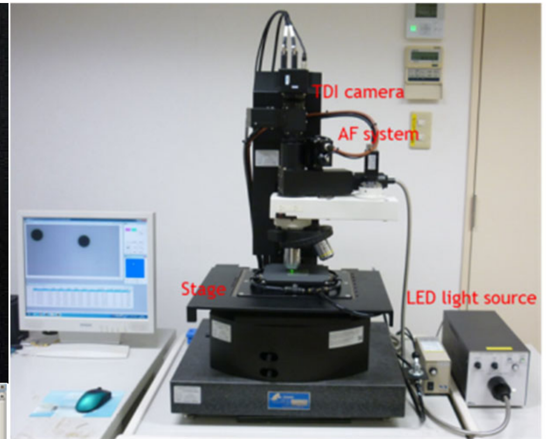
RPLD(Ag^+-activated phosphate glass)

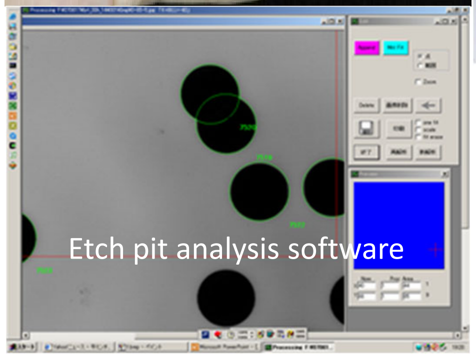
OSLD reader （microStar, LANDAUER)

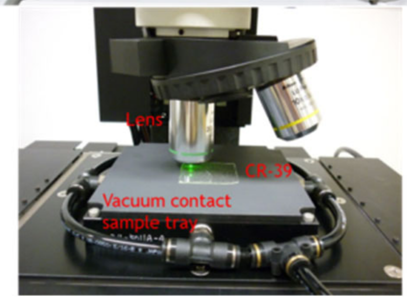
Solid state track detectors (CR-39 plastic)

- ✓ A radiation damage trail due to an ion passage is enlarged to be an etch pit by chemical etching, which is observed with an optical microscope
- ✓ A detector signal (etch pit size) depends on LET of the incident ion, which provides LET spectrum







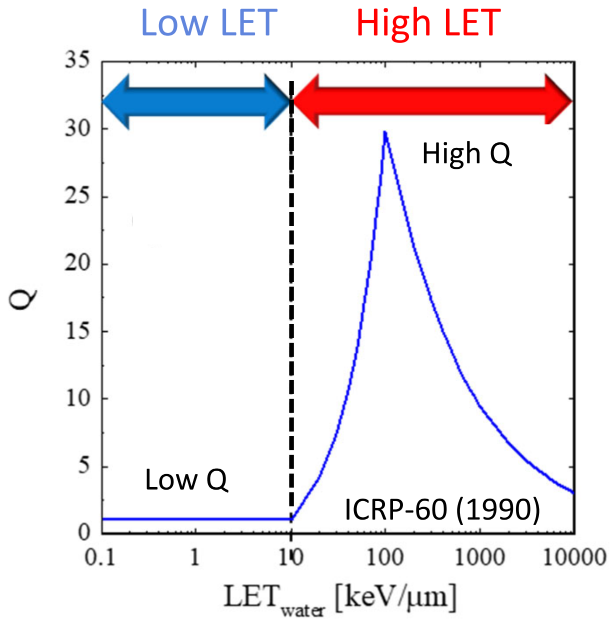


High speed imaging microscope (HSP-1000)
developed by SEIKO and NIRS/QST

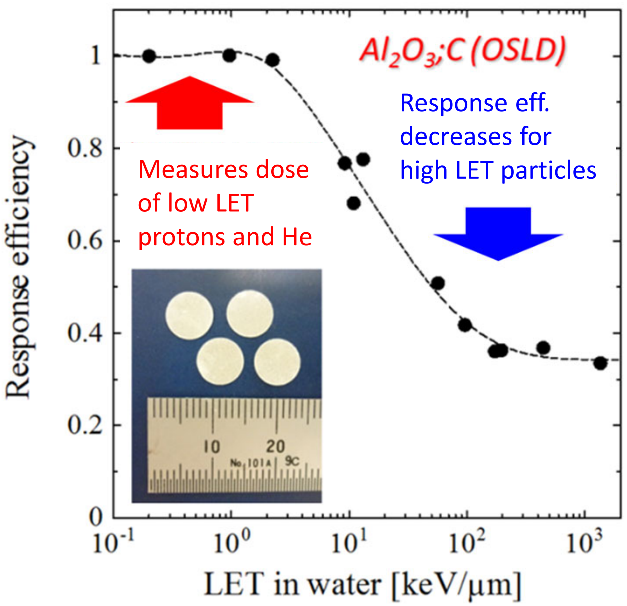
Current space radiation passive dosimetry

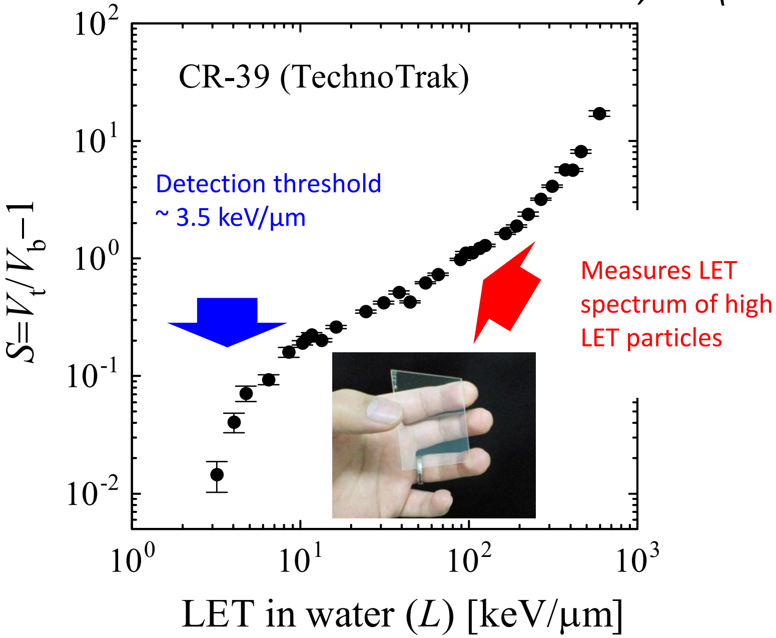
- Difficult to cover wide LET range of space radiation (10^{-1}~10^{3} keV/µm) with a single radiation detector

  → **Combine several detectors with different LET dynamic ranges**
- Current typical method is by a combination of <u>luminescent dosimeters (TLD /OSLD/RPLD) to cover low LET</u> range and <u>CR-39 detector to cover high LET</u> range
- Since the quality factor depends on LET (high LET range over 10 keV/µm), **<u>LET spectrum is measured using a CR-39 detector</u>**



Doke et al., RM (1995)
Benton et al., RM (2002)





Kodaira et al., NIM B (2016), Kodaira et al., RSI (2018)

<u>High LET dose from LET spectrum</u>

$$\begin{cases} D(LET) = \dfrac{1.602 \times 10^{-9}}{\rho} \sum_i F_i \cdot LET_i \\ H(LET) = \dfrac{1.602 \times 10^{-9}}{\rho} \sum_i Q_i \cdot F_i \cdot LET_i \end{cases}$$

<u>Total dose by LD+CR-39</u>

$$\begin{cases} D_{Total} = D_{\leq 10keV/\mu m} + D_{>10keV/\mu m} \\ \quad = (D_{LD} - \kappa D_{CR-39}) + D_{CR-39} \\ \quad = D_{LD} + (1-\kappa) D_{CR-39} \\ H_{Total} = D_{\leq 10keV/\mu m} + H_{>10keV/\mu m} \\ \quad = (D_{LD} - \kappa D_{CR-39}) + H_{CR-39} \end{cases}$$

Application of Fluorescent Nuclear Track Detectors (FNTDs) for space radiation dosimetry

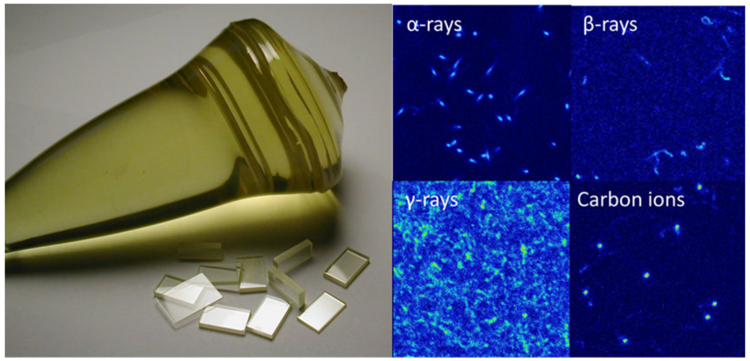
- CR-39 detector needs to be recovered on the ground due to the requirement for chemical etching
- Long-term exposure increases track overlap formed in CR-39 detector, which complicates the analysis

We are considering replacing CR-39 detector with FNTDs, which enables on-site dosimetry without the need for ground recovery

- ✓ LET spectrum can be measured similarly to CR-39, as the fluorescence intensity of the tracks correlates with LET
- ✓ Unlike CR-39, FNTD dose not require chemical etching, and its optical readout enables on-site dosimetry
- ✓ Track information can be erased through bleaching treatment, allowing for long-term operation

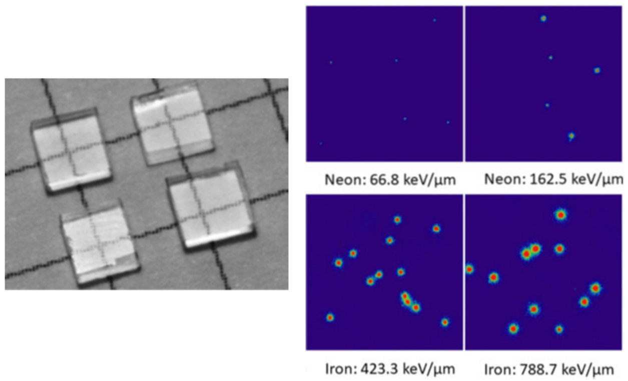
【Potential materials of FNTD】

Al_2O_3:C,Mg single crystal



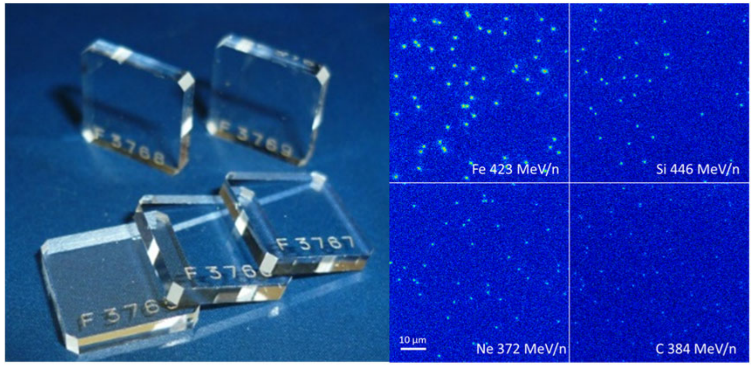
Akselrod & Kouwenberg, Radiat. Meas. (2018)

LiF single crystal



Bilski et al., J. Lumin. (2019)

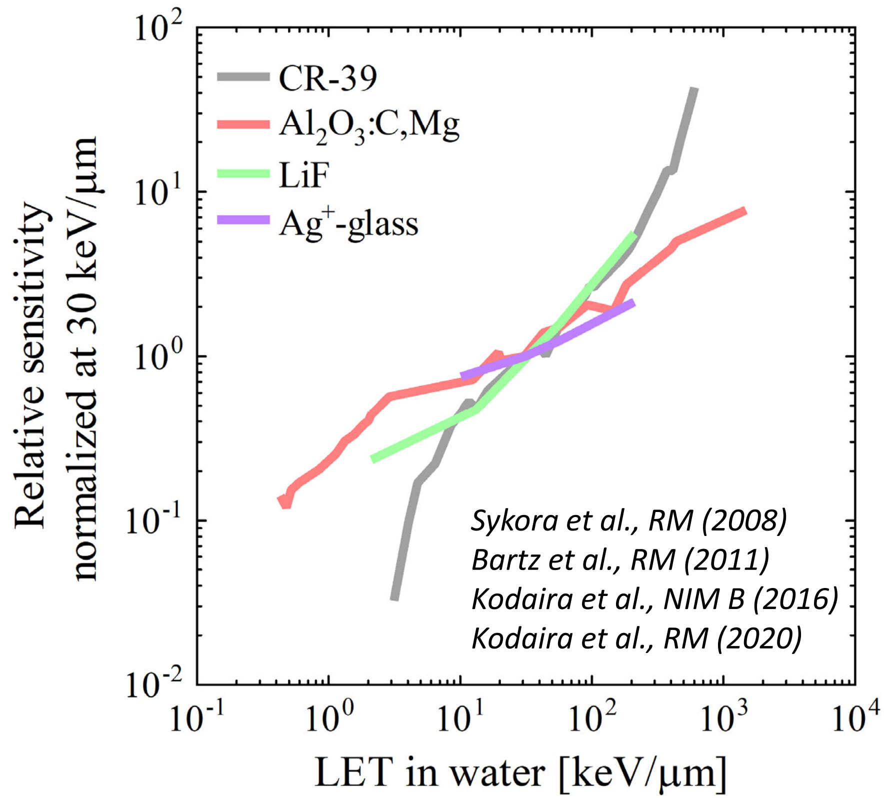
Ag^+-doped phosphate glass



Kodaira et al., Radiat. Meas. (2020)

Comparison of LET ranges in CR-39 and FNTDs

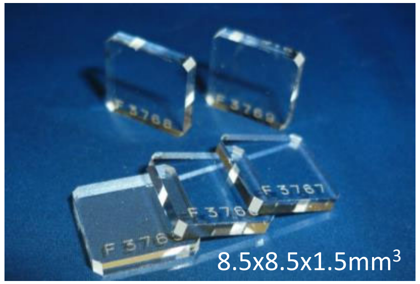
- Since **<u>Al_2O_3:C,Mg and LiF are highly sensitive to low LET particles</u>** such as protons and He, they have the potential to detect nearly all types of space radiations using a single detector
- Flux of protons is approximately three orders of magnitude higher than that of heavy ions, leading to overlapping tracks that complicate analysis
- **<u>Ag^+-glass has a high LET threshold comparable to CR-39</u>**, enabling selective detection of high LET particles
- Ag^+-glass functions as a conventional RPLD for low LET particles, making a combined RPLD (low LET) + FNTD (high LET) system feasible, which is similar to the current RPLD + CR-39 combination



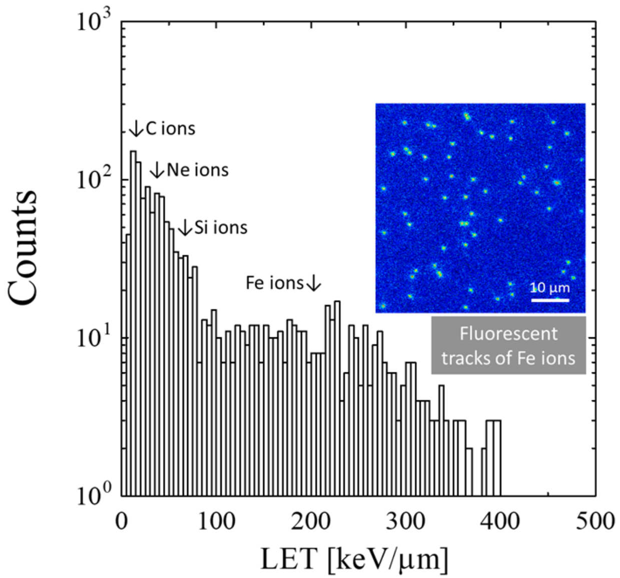
➡ Ag^+-doped phosphate glass is one of promising FNTD for space radiation dosimetry

	CR-39	Al_2O_3:C,Mg	LiF	Ag^+-glass
Excite / Emission [nm]	N/A	635 / 750	448 / 680	365 / 600
LET threshold [keV/μm-H_2O]	~5	~0.5	~2	~5

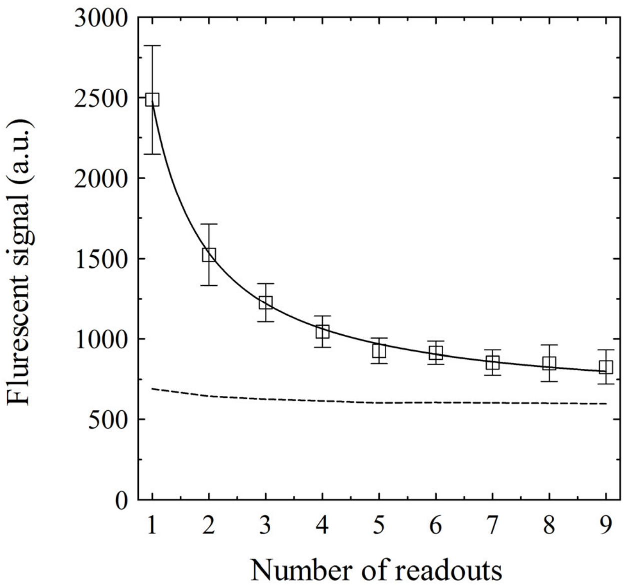
On-site personal dosimetry protocol in deep space



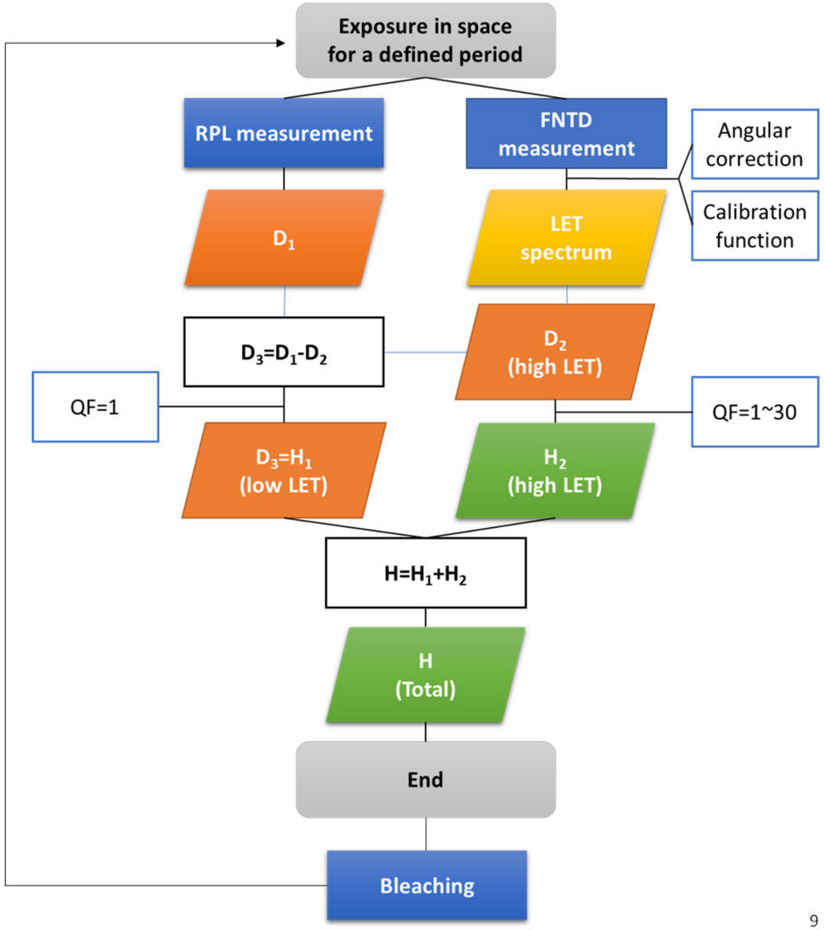
- We propose on-site personal dosimetry system with a small glass chip
- A glass chip will provide:
  1) Absorbed dose of low LET particles by RPL measurement (RPL mode)
  2) Absorbed dose and LET spectrum of high LET particles by Fluorescent track measurement (FNTD mode)
  3) Total dose by combining RPL + FNTD data, which is comparable to the current passive dosimetry



LET spectrum of high LET beams (Fe, Si, Ne and C) from HIMAC

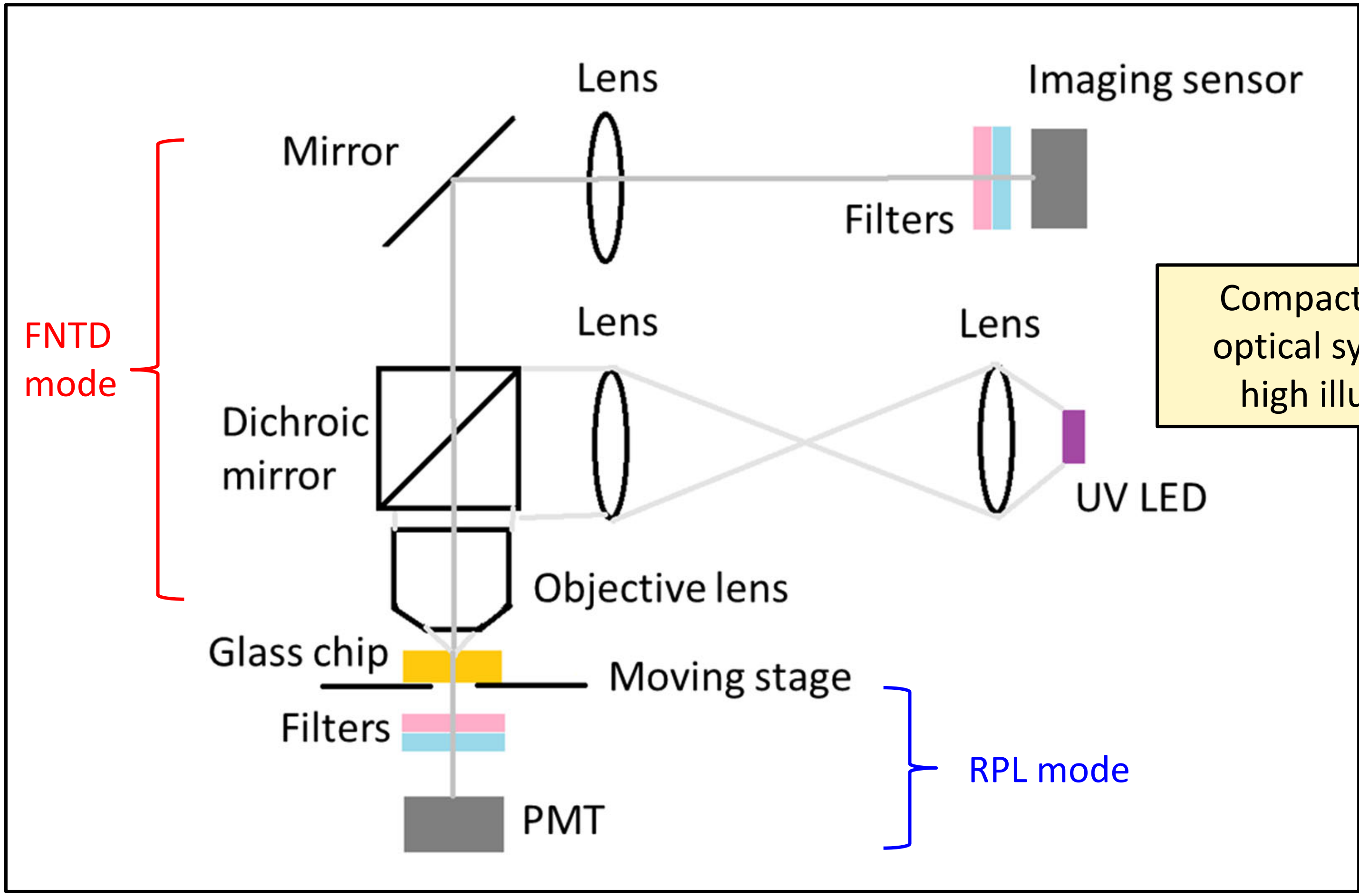


Erasing fluorescent tracks by repeating readout → Bleaching



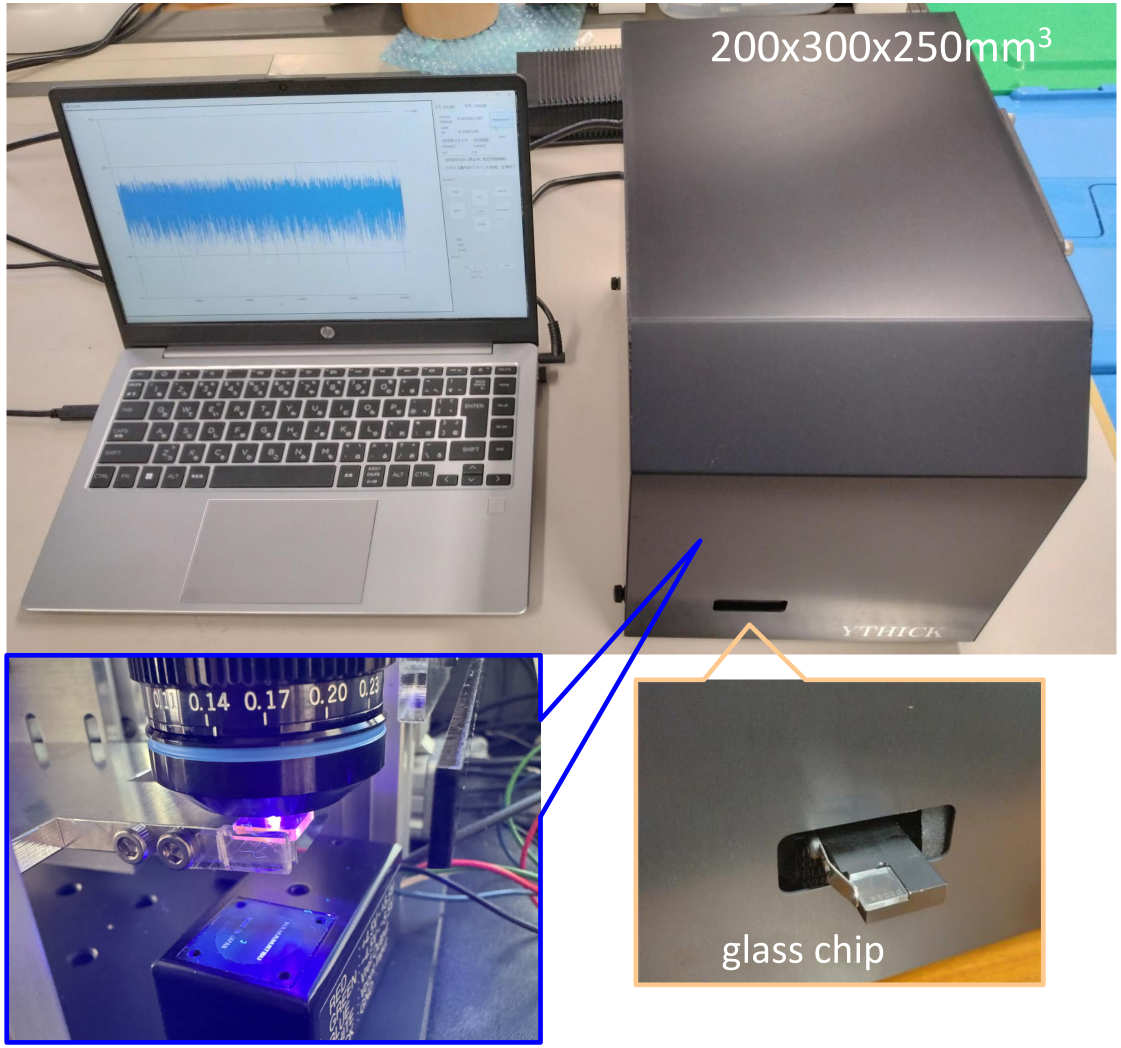
Design of readout system

Readout system consists of RPL detection system and fluorescent microscope

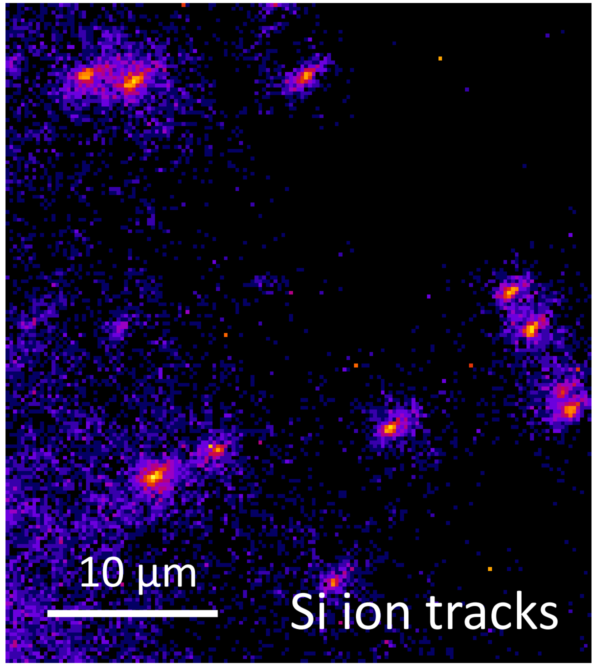


Compact model having two optical systems with a single high illumination UV-LED

Prototype of readout system



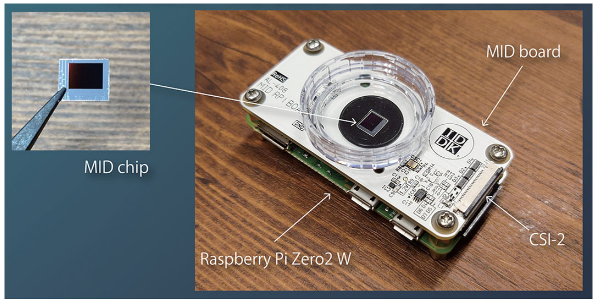
- Prototype of readout system consisting of two optical systems (RPL and FNTD models) has been produced
- Optimization of readout condition is currently investigated



Summary

- We propose on-site personal dosimetry system with Ag^{+}-doped phosphate glass chip
- Dosimetry system will provide absorbed dose and dose equivalent by considering LET spectrum, which will be comparable with current Luminescence + CR-39 combination
- Prototype of compact readout system consisting of two optical systems (RPL and FNTD models) was produced
- Further miniaturization will be investigated by replacing with MID (Micro Imaging Device) and light sheet LED, which may allow a *palm-size* without conventional optics and lens

Micro Imaging Device
(optics and lens free)



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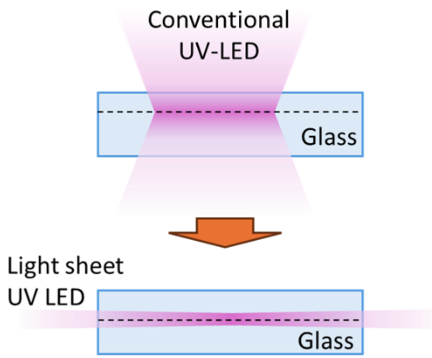

Light sheet LED
excitation

Acknowledgements

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Thank you for your kind attention