An application approach of LET- and charge-weighted quality factors to space LET measurements

National Institutes for Quantum Science and Technology
(QST/NIRS)

Masayuki Naito, Satoshi Kodaira

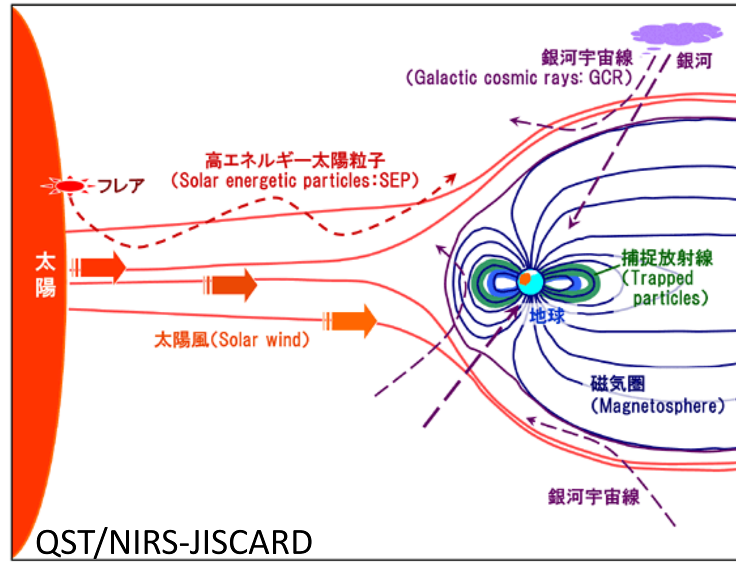
Outline

- Space radiation environment & quality factors
- Charge weighted quality factor, Q*
- Q* application to a space LET measurement
- Summary

Space radiation environment

The GCR dose levels in space are …

- ~200-300 mSv/yr on the ISS orbit
  (No atmosphere, Kodaira et al., RM 2013)
- ~600-700 mSv/yr in the deep space
  (No atmosphere & geomagnetic fields
  Zeitlin et al., Science 2013)

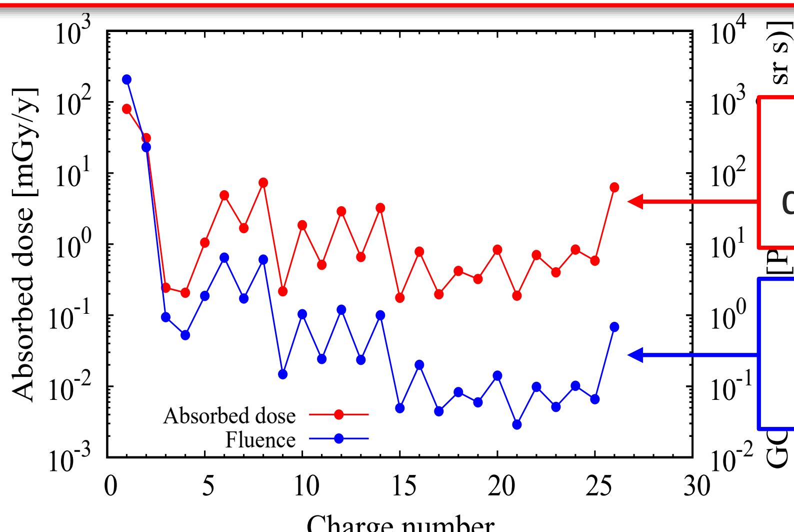


For long term space stays in future,

✓ **Dose assessment**

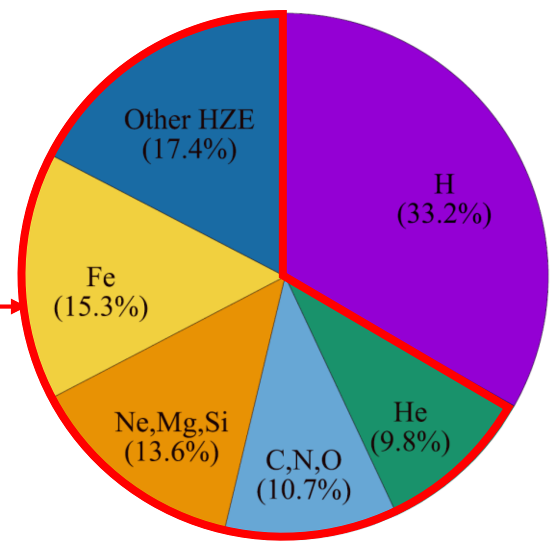
✓ Radiation shielding

are crucial from the aspect of radiation.



HZE contribution to dose equivalent: >60%

90% of fluence: H

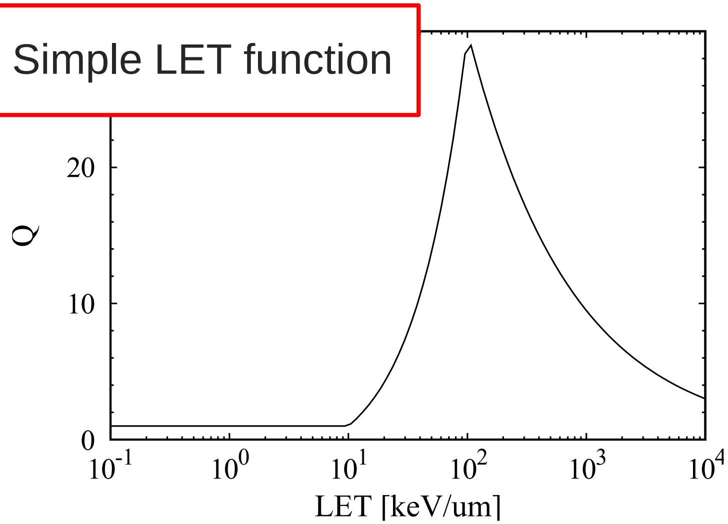


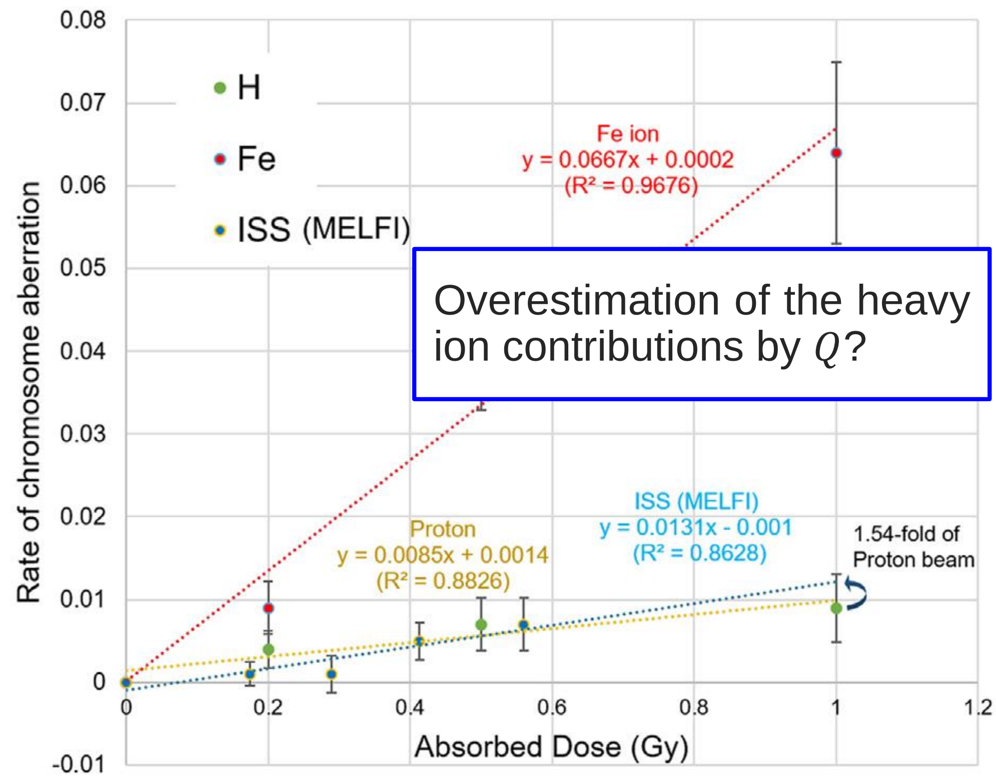
Dose equivalent contribution

The ICRP quality factor

Dose equivalent (H) has been derived from absorbed dose (D) and the ICRP quality factor (Q).

$$H = \Sigma\, D(LET) \cdot Q(LET)$$





Yoshida et at., Heliyon (2022)

Possible problems are…

- Some researches may imply overestimation of heavy ions
- No updates from 1990
- Ions with a specific LET and different charge have a common quality factor

The NASA quality factor

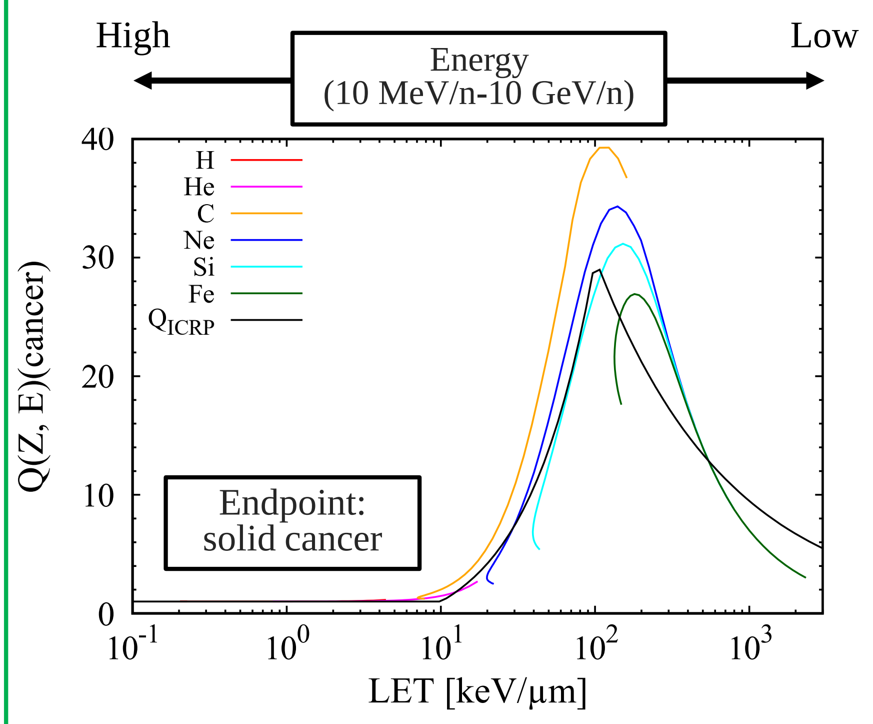
The NASA team has suggested a different quality factor (Q_{NASA}), based on the track structure model (Cucinotta et al., NASA/TP 2013, PLOS ONE 2015).

$$Q_{NASA}(Z,E) = \frac{6.24\sigma_0/\alpha_\gamma}{LET} P(Z,E) + 1 - P(Z,E) \qquad P(Z,E) = \left(1 - \exp\left(-\frac{Z^{*2}}{\kappa\beta^2}\right)\right)^m$$

Track core Track penumbra

✓ The charge and LET dependent. (Different values at a specific LET with different charge)

■ **Application to LET measurements** of the charged particles is not easy. Some space measurements obtain the LETs without discrimination of particle charges.



Motivation & approach

We suggest a new quality factor, Q*, which is applicable to LET spectra without fundamental changes in the measurement procedures.

$$H = \sum_{LET} D(LET) \cdot Q(LET)$$

$$D(LET) = \frac{k}{\rho} F(LET) \times LET$$

$$H = \sum_{LET} \sum_{Z} D(Z, LET) \cdot Q_{NASA}(Z, LET)$$

$$= \sum_{LET} D(LET) \sum_{Z} \frac{D(Z, LET)}{D(LET)} \cdot Q_{NASA}(Z, LET)$$

$$= \sum_{LET} D(LET) \sum_{Z} C(Z, LET) \cdot Q_{NASA}(Z, LET)$$

$$= \sum_{LET} D(LET) \cdot Q^{*}(LET)$$

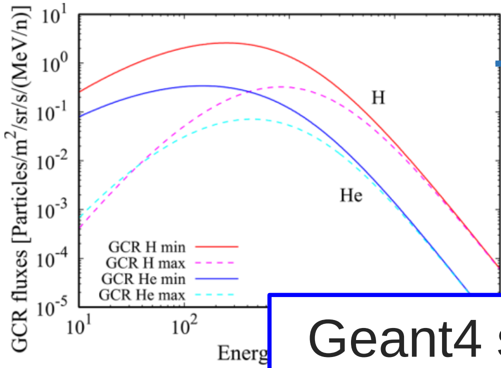
Charge contribution rates to absorbed dose at the specific LET:

$$C(Z, LET) = \frac{D(Z, LET)}{D(LET)}$$

$C(Z, LET)$ varies with the GCR solar modulation and surrounding shielding.

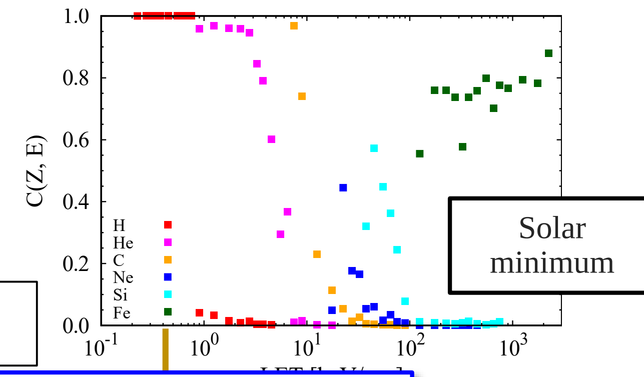
$C(Z, LET)$ values in typical environments were obtained through numerical calculation to identify its variation, determining plausible Q*.

Calculation flow



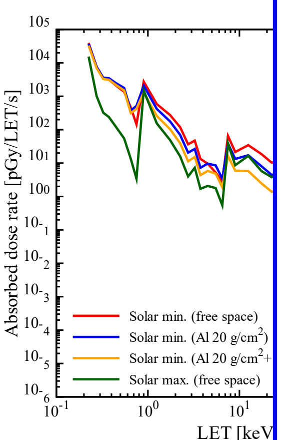
GCR spectra

Monte Carlo calculation

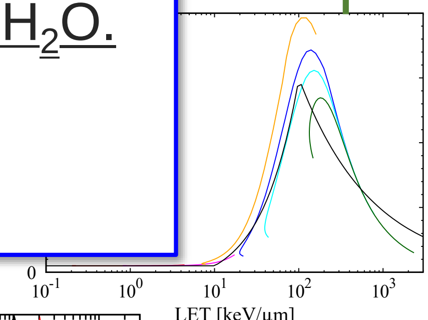


Geant4 simulation using the DLR GCR model with

- <u>Solar minimum at free space</u>
  Worst case
- <u>behind 20 g/cm² Al.</u>
  Assumption inside the uncrewed module
- <u>behind 20 g/cm² Al + 10 g/cm² H_2O.</u>
  Assumption inside the crewed module
- <u>Solar maximum at free space</u>
  Best case



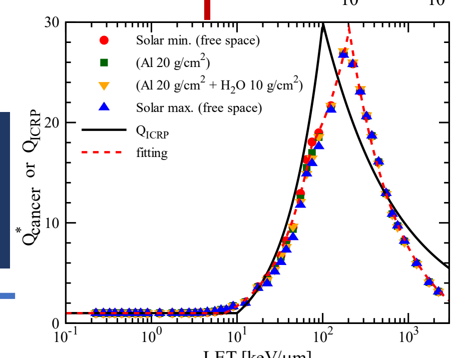
A(Z, LET)



LET integration

$$Q^*(LET) = \sum_Z Q(Z,E) \cdot C(Z,E)$$

Dose equivalent

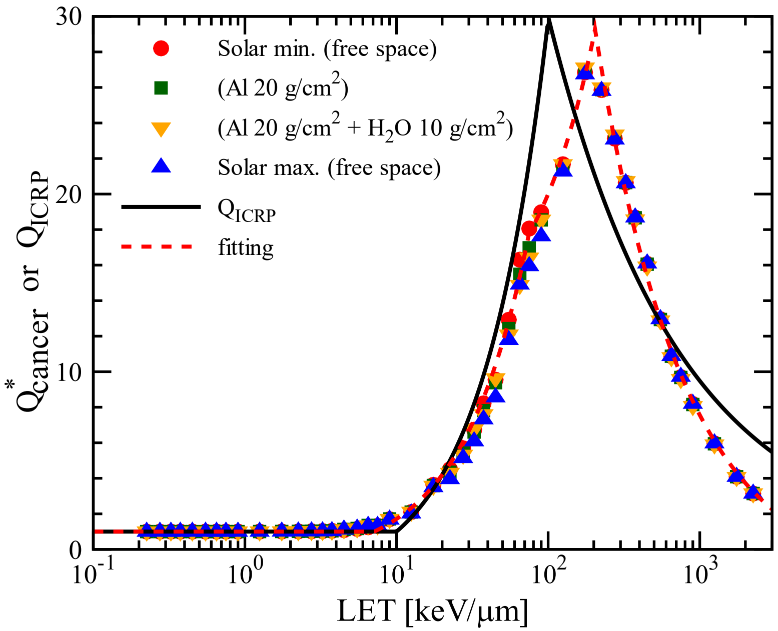


Q* comparison in different GCRs

QST

■ GCR spectra dependencies

- ✓ Q^*_{cancer} variations at specific LET; <10%
- ✓ Total dose equivalent variation; a few %
- ✓ Maximum at the solar minimum at free space
  ⇔ conservative dose assessment



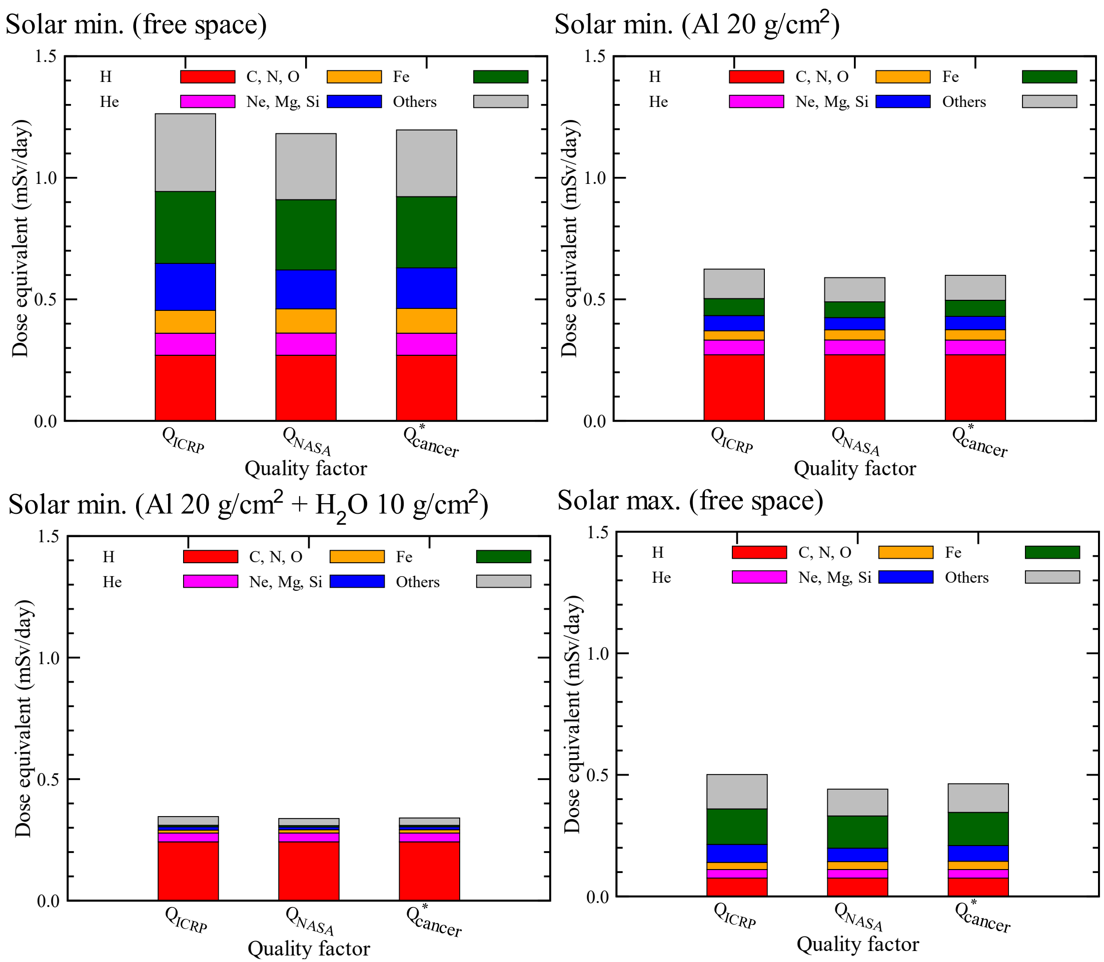
Comparison of the mean Q^*_{cancer} values applying different GCR energy spectra.

		The GCR energy spectra			
		Solar min. (free space)	Solar min. (20 g/cm² Al)	Solar min. (20 g/cm² Al + 10 g/cm² H_2O)	Solar max. (free space)
Q^*_{cancer}	Solar min. (free space)	2.66	1.64	1.17	3.12
	(20 g/cm² Al)	-----	1.63	----	-----
	(20 g/cm² Al + 10 g/cm² H_2O)	----	----	1.17	----
	Solar max. (free space)	-----	------	------	3.02

Quality factor comparison

- Q^*_{cancer} demonstrated the similar dose equivalents and charge contributions to Q_{NASA}.
  - ✓ **Successful conversion from the $Q_{NASA}(Z, LET)$ to the $Q^*(LET)$.**
- Heavy ion contributions in Q_{ICRP} were slightly higher than those in the Q_{NASA} and

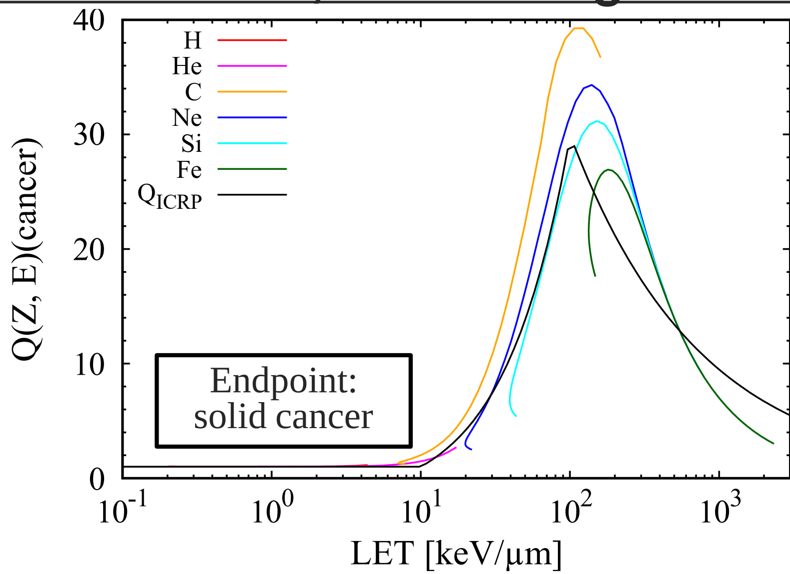
  Due to peak LET difference

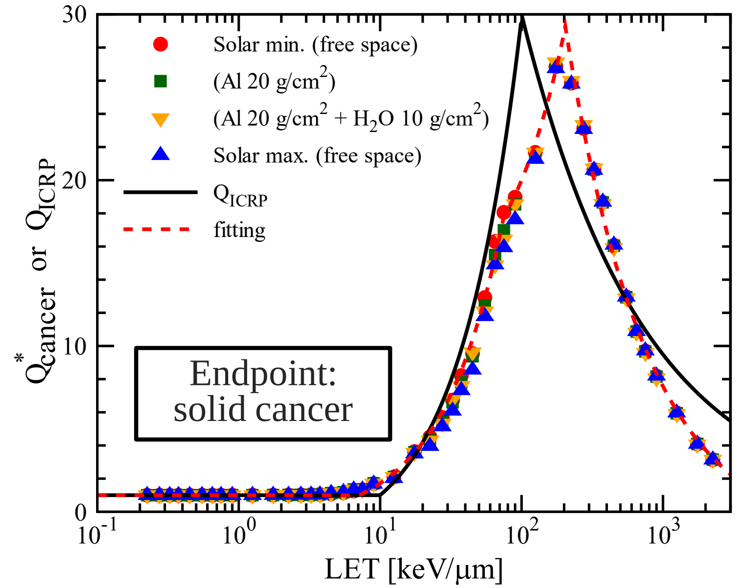


Charge contributions to the dose equivalents by the three quality factors, Q_{ICRP}, Q_{NASA}, and Q^*_{cancer}.

Q* advantages

✓ **Charge weighted quality factor, Q^*, is applicable to the space LET measurement, accounting the track structure model.**





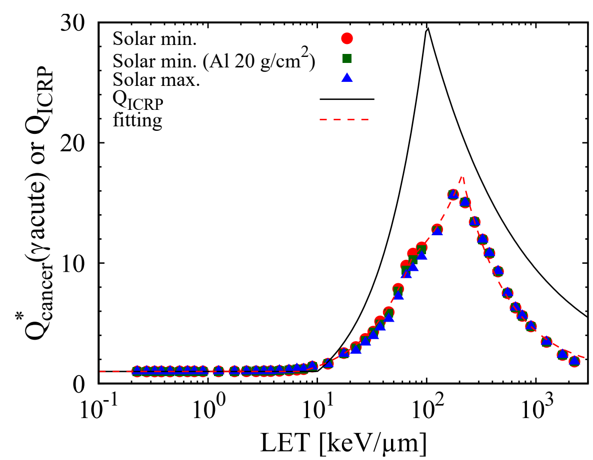
✓ **$C(Z, LET)$ is independent to the quality factor.**

The Q^* approach is also available for the other RBEs based on different models.

e.g.) $RBE_{\gamma acute}$ model

(Cucinotta, LSSR 2015, Edwards, JRP 1999)

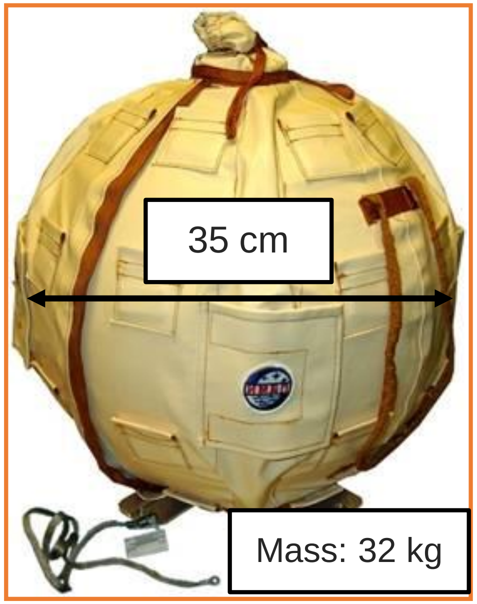
$$RBE_{\gamma acute} = DDREF \cdot \frac{6.24\sigma_0/\alpha_\gamma}{LET} P(Z,E) + 1 - P(Z,E)$$

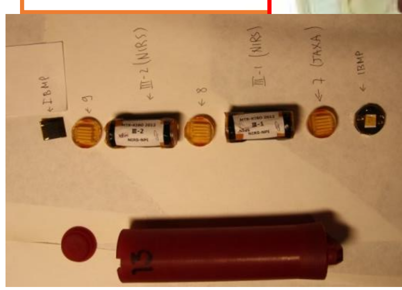


Q* application test to measurement

Q^*_{cancer} was tested by applying the MATROSHKA-R LET measurements.

MATROSHKA-R (MTR) experiment

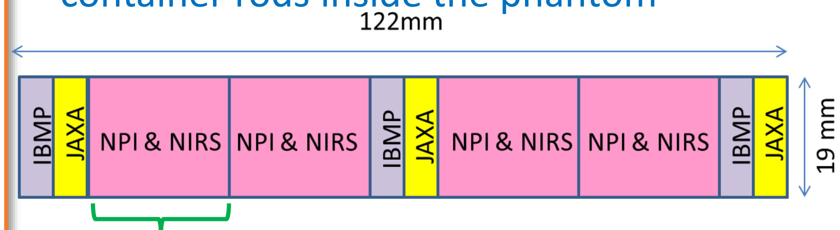


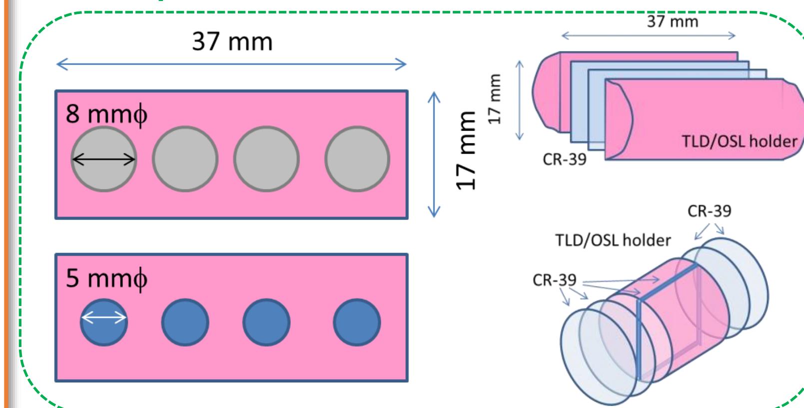


Dose distributions outside/inside a body phantom were measured in the ISS.

Containers

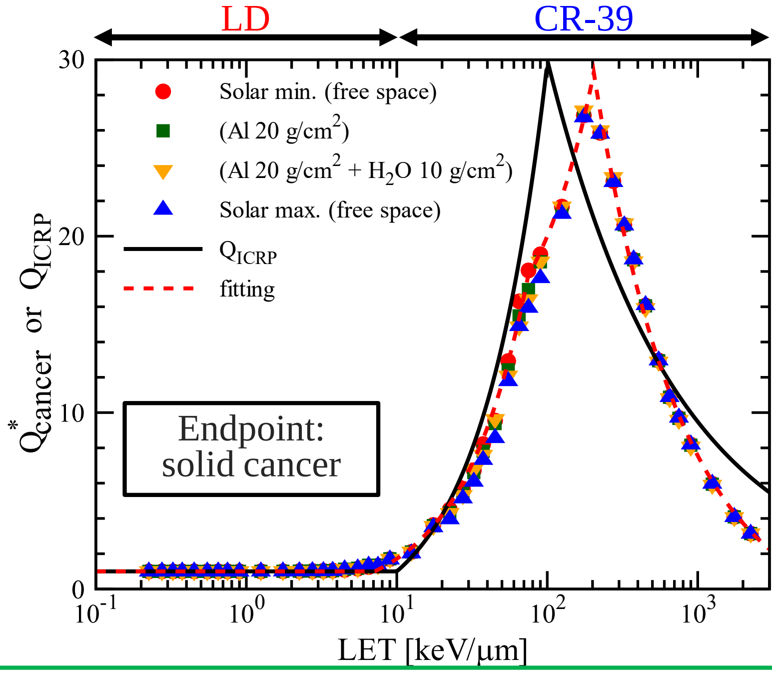
Totally 16 packages were installed in the 4 container rods inside the phantom





Kodaira et al., 40th COSPAR (2014)

Dose evaluation



Absorbed dose D:

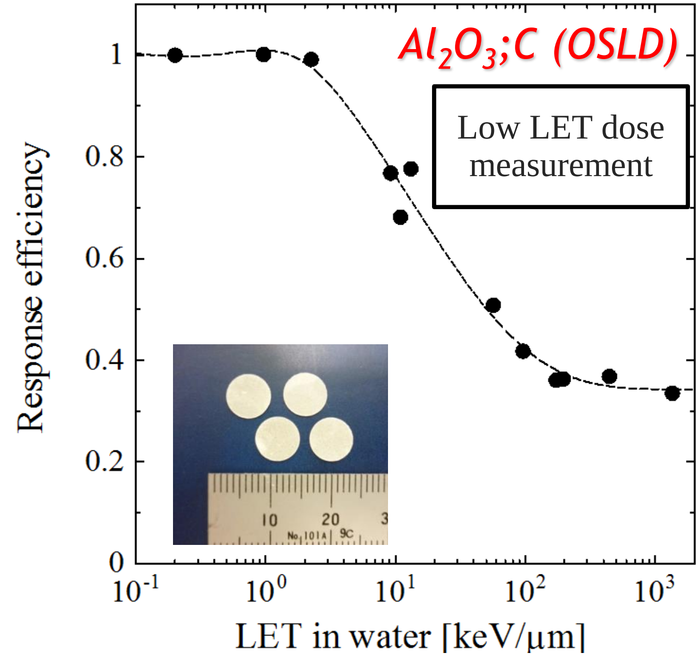
$$D = D_{\leq 10keV/\mu m} + D_{>10keV/\mu m}$$
$$= (D_{LD} - \kappa D_{CR-39}) + D_{CR-39}$$
$$= D_{LD} + (1 - \kappa) D_{CR-39}$$

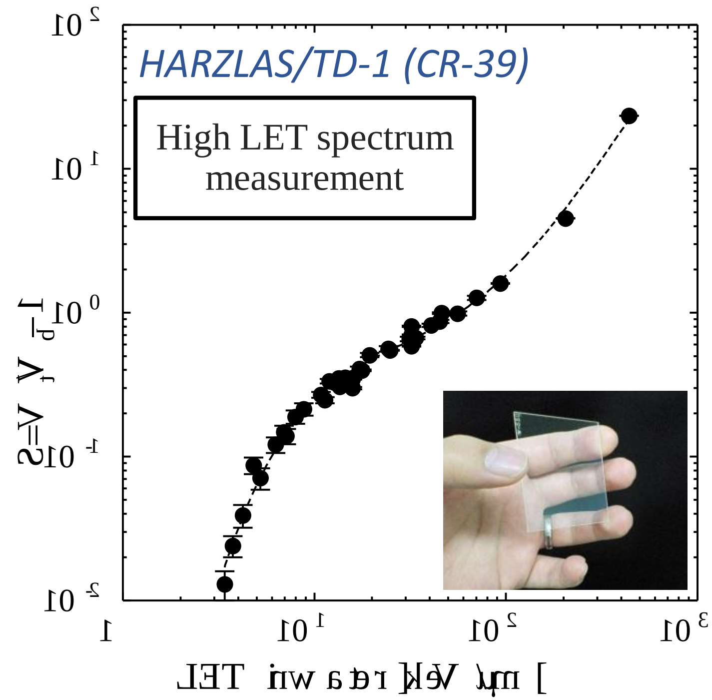
Dose equivalent H:

$$H = D_{\leq 10keV/\mu m} + H_{>10keV/\mu m}$$
$$= (D_{LD} - \kappa D_{CR-39}) + H_{CR-39}$$

κ: proportional constant

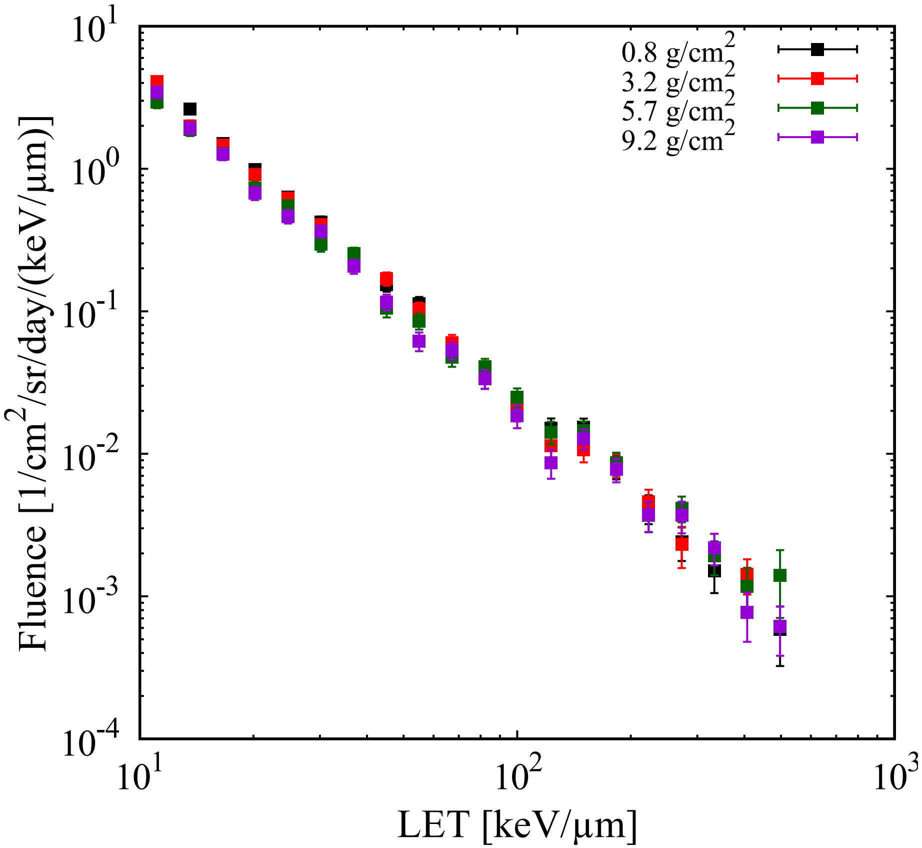
(Doke et al., RM 1995)

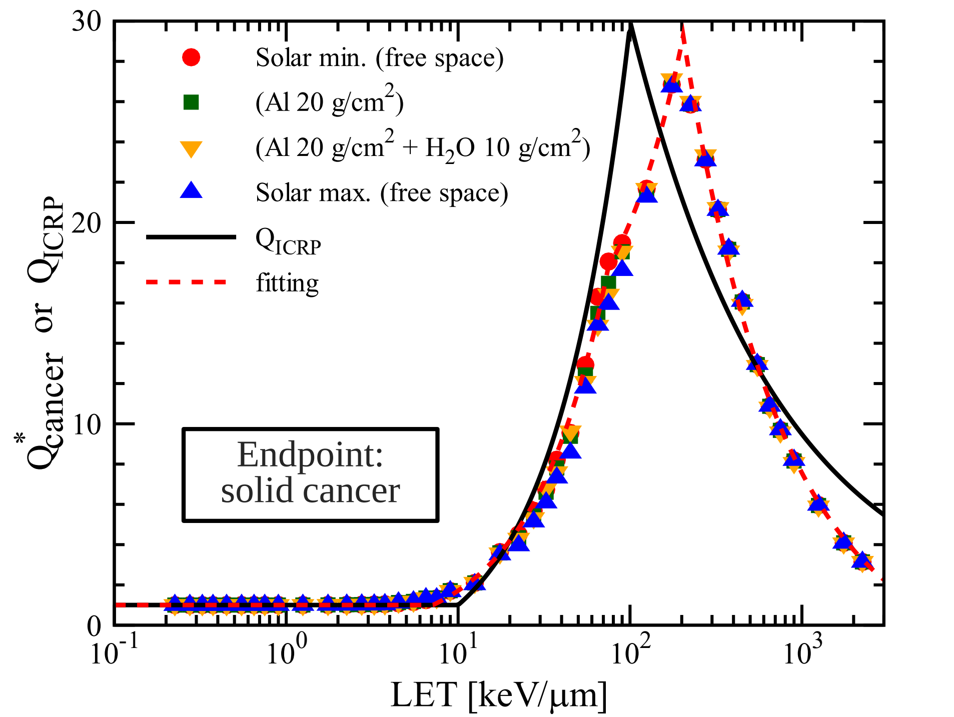




Kodaira et al., 40th COSPAR (2014)

Measured LET spectra



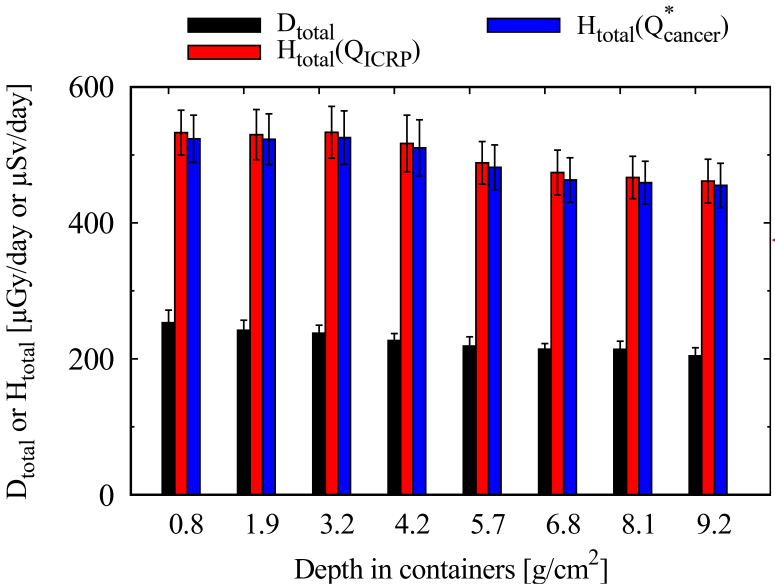


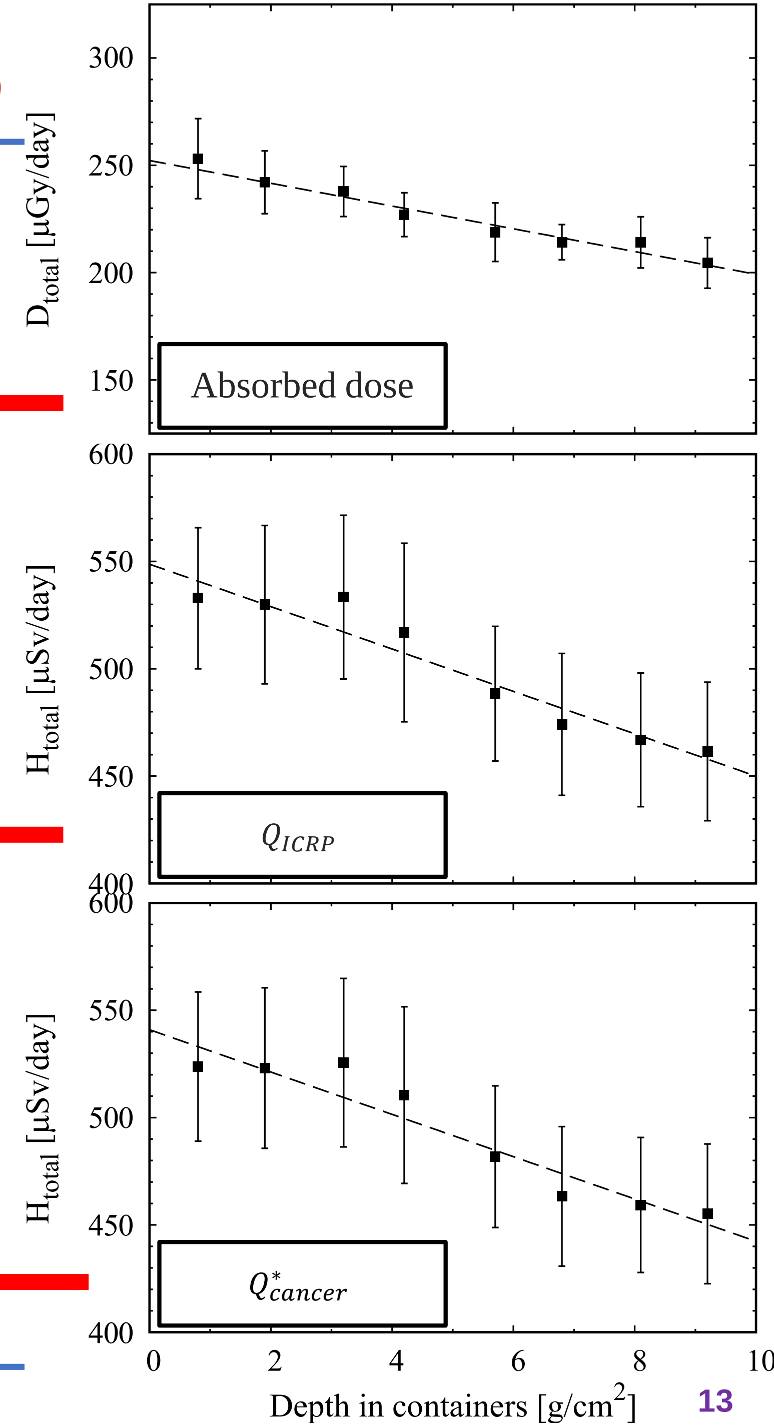
$$D(LET) = \frac{k}{\rho} F(LET) \times LET$$

$$H = \sum_{LET} D(LET) \times Q(LET)$$

Dose equivalents as a function of phantom depth were obtained by the Q_{ICRP} and Q^*_{cancer}.

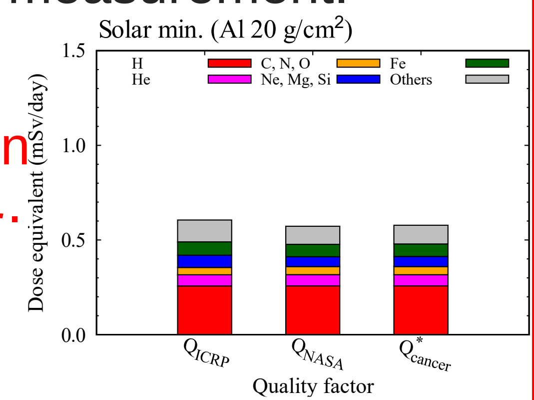
Dose depth dependence





The tendency in the calculation was also observed in the LET measurement.

✓ Plausible evaluation of Q_{NASA} by Q^{*}_{cancer}.

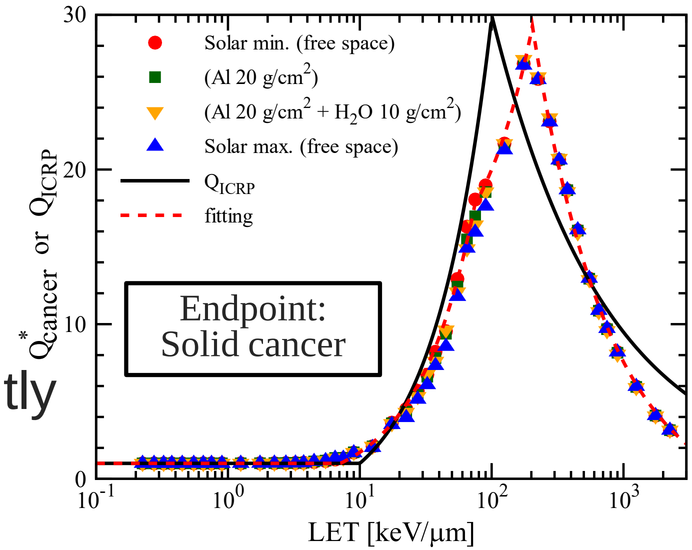


Summary

✓ Charge weighted quality factor, Q^*, was suggested to apply the charge and LET dependent quality factor (e.g., Q_{NASA}) to the space LET measurements.

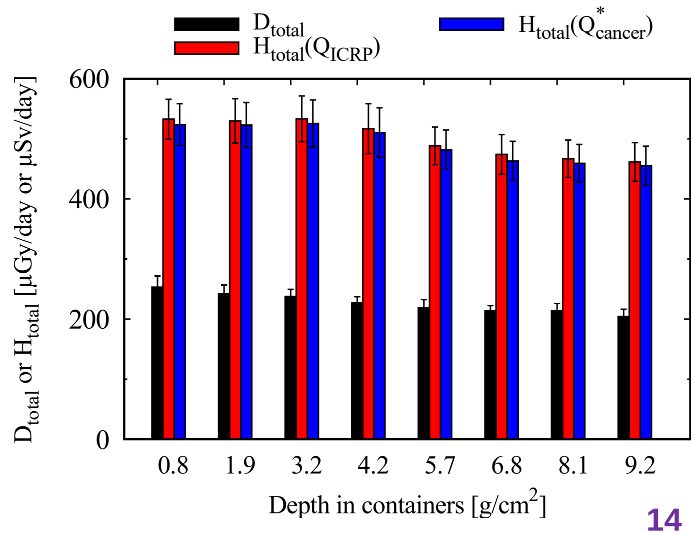
✓ Different GCR spectra provided insignificant variation (< a few %) in Q^*_{cancer}.

- The solar minimum GCR spectra achieved conservative dose assessment.



✓ Q^*_{cancer} derived from Q_{NASA} demonstrated slightly lower contribution of heavy ions than Q_{ICRP}.

- Consistent with some previous works.
  (e.g., Yoshida et al., Heliyon 2022,
  Naito & Kodaira, Scientific Rep. 2022)



Q^*_{cancer} is applicable for the space dose assessment by LET measurements, providing comparable results to Q_{NASA}, i.e., track structure model quality factor.

Danke schön, thank you!