Human health risks from radiation

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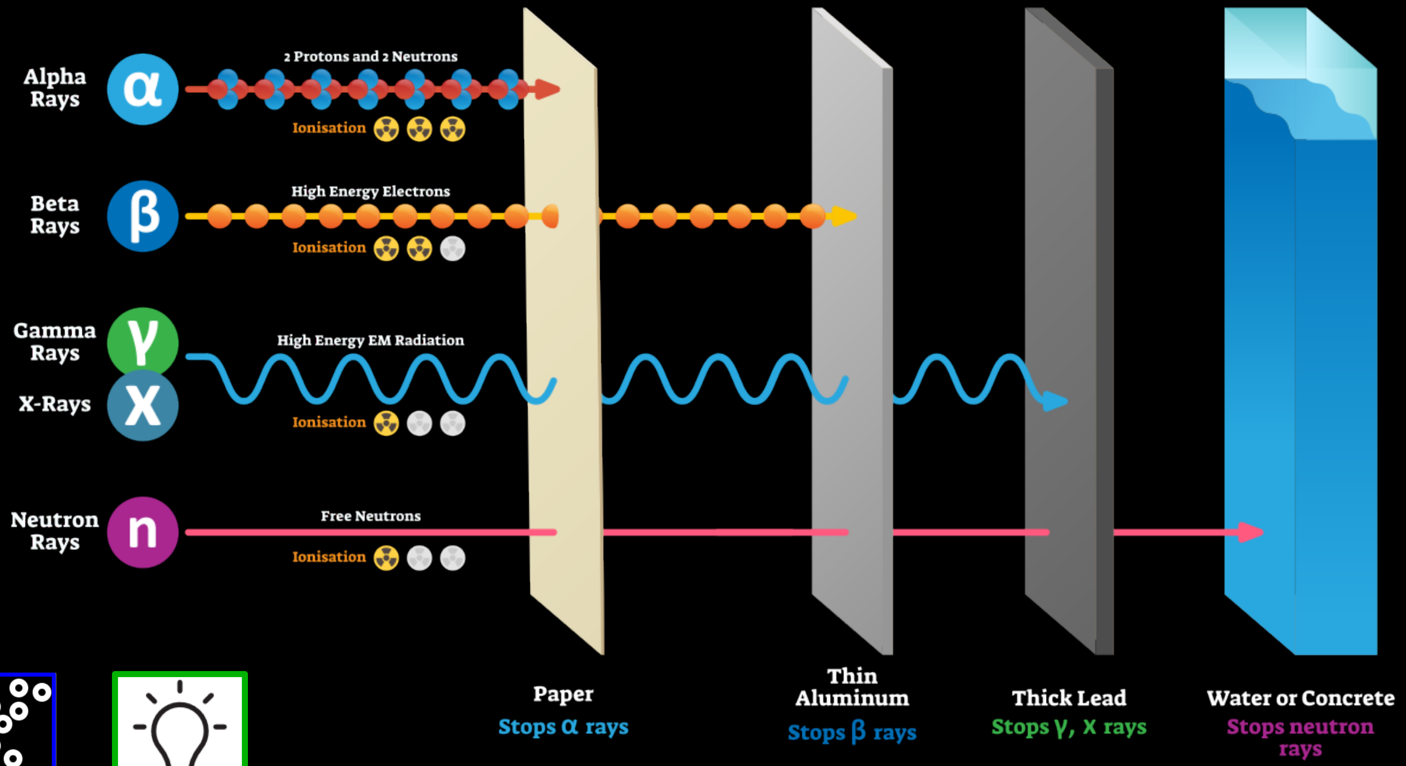
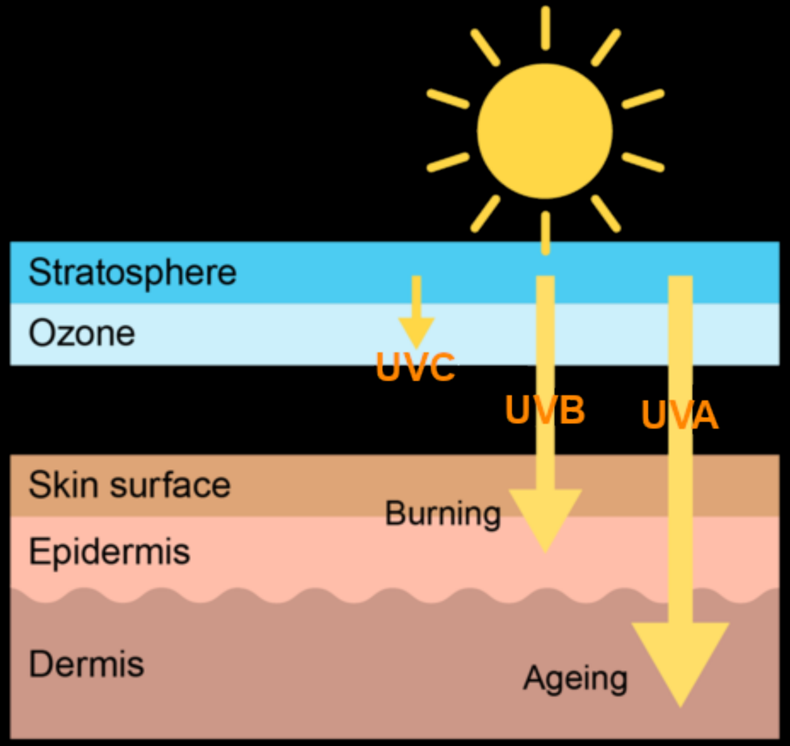
What is radiation?

Transfer of energy to materials: objects, human body, etc



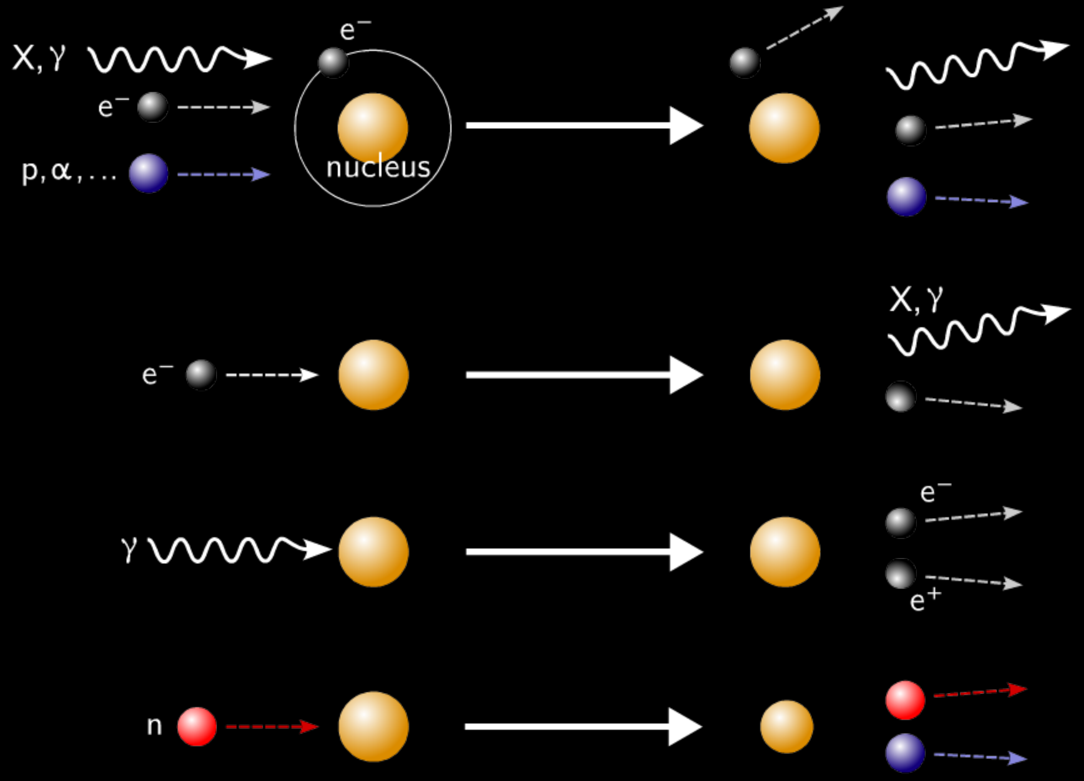
Adapted from American Nuclear Society

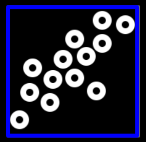


Adapted from Cancer Research UK

How does radiation affect materials?

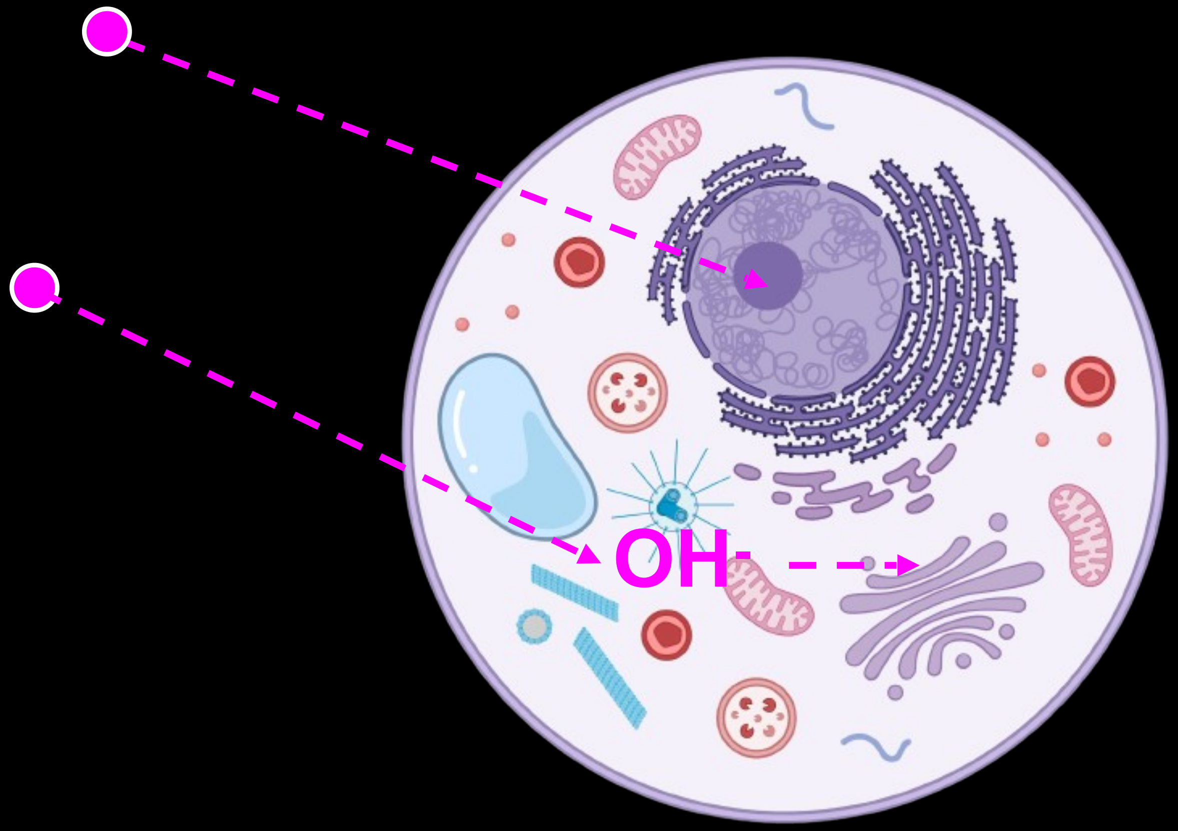
Mostly by ionizing the traversed matter: electrons are stripped out of atoms

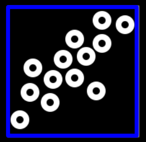




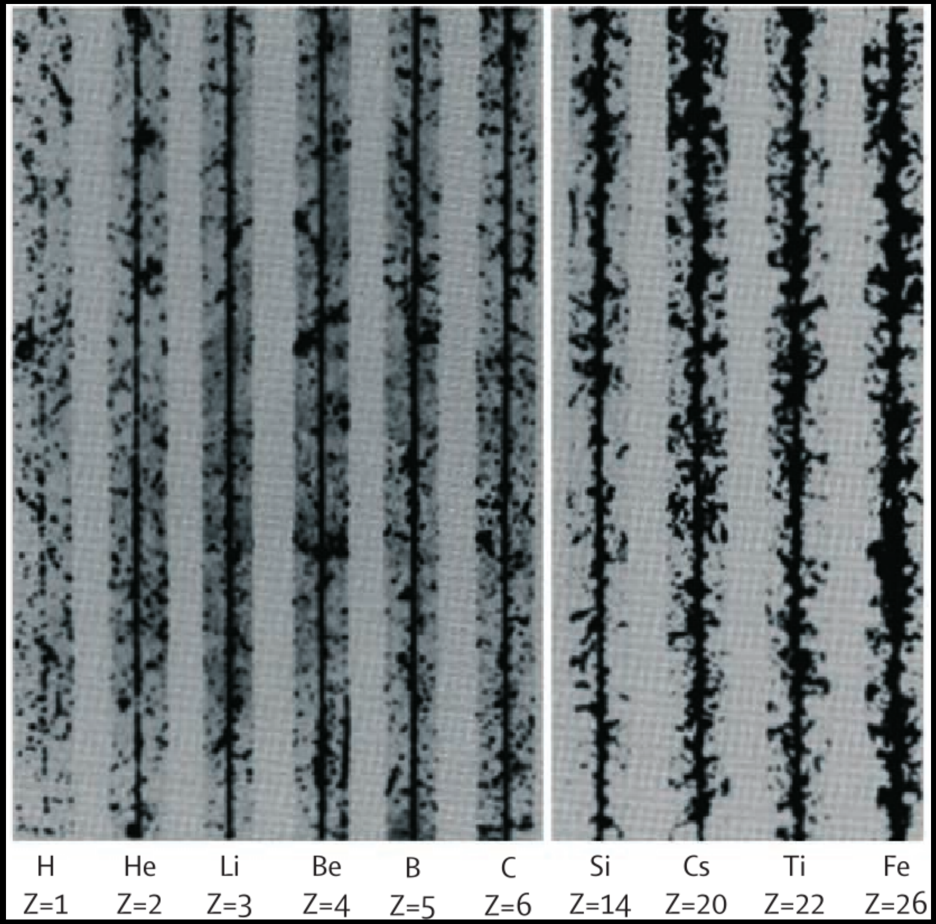
What is radiation biological impact?

- Direct impact: radiation or ejected electrons interact directly with DNA
- Indirect impact: radiation ionizes intra-cellular medium and produces free radicals (OH^-) which damage DNA and other cellular components





Quantifying radiation effects: LET

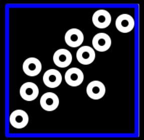


Adapted from Cucinotta & Durante (2006), DOI:10.1016/S1470-2045(06)70695-7

Linear Energy Transfer (LET): energy deposited per unit track length (keV/µm)

Low LET: X-rays, γ-rays, electrons
Sparse ionization ⇒ Simple and isolated DNA damages

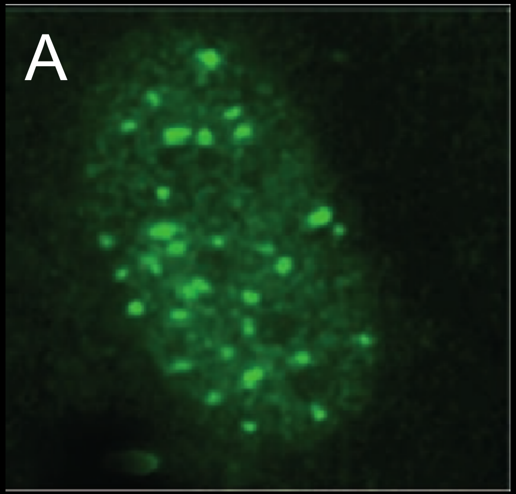
High LET: protons, α-particles, ions
Dense ionization ⇒ Complex and concentrated DNA damages



Quiz: Which radiation damaged which cell?

Every green dot corresponds to a broken DNA molecule in a human cell, which is proportional to the ionization density

1) Which cell has been exposed to ions and which one to γ-rays?
2) Which damage is most harmful for humans?



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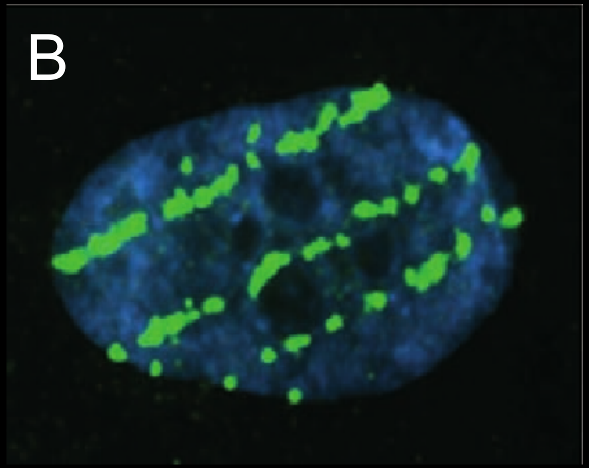

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Quiz: Which radiation damaged which cell?

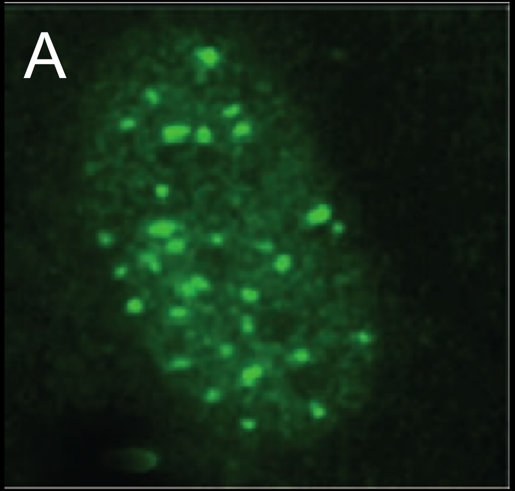
1) Which cell has been exposed to ions and which one to γ-rays?

A: sparse ionization ⇒ low LET ⇒ γ-rays

B: dense ionization ⇒ high LET ⇒ ions

2) Which damage is most harmful for humans?

Ions: high LET ⇒ complex and concentrated DNA damage



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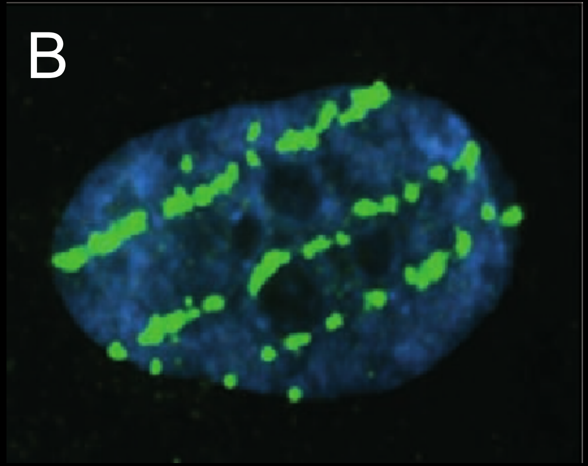

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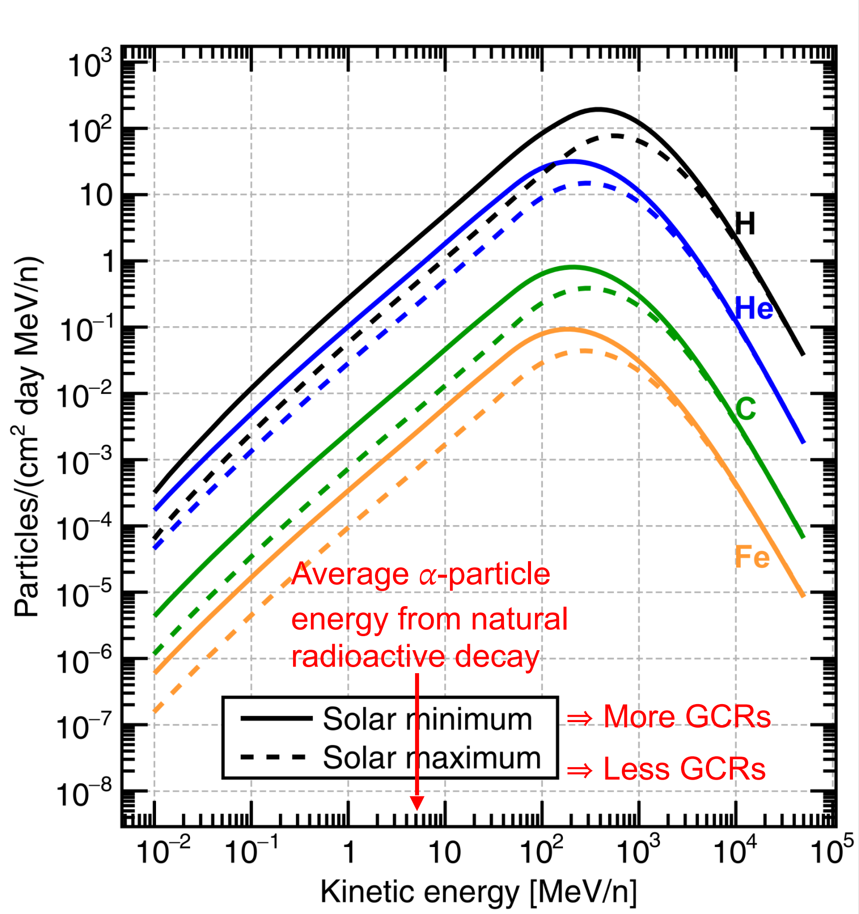
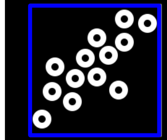
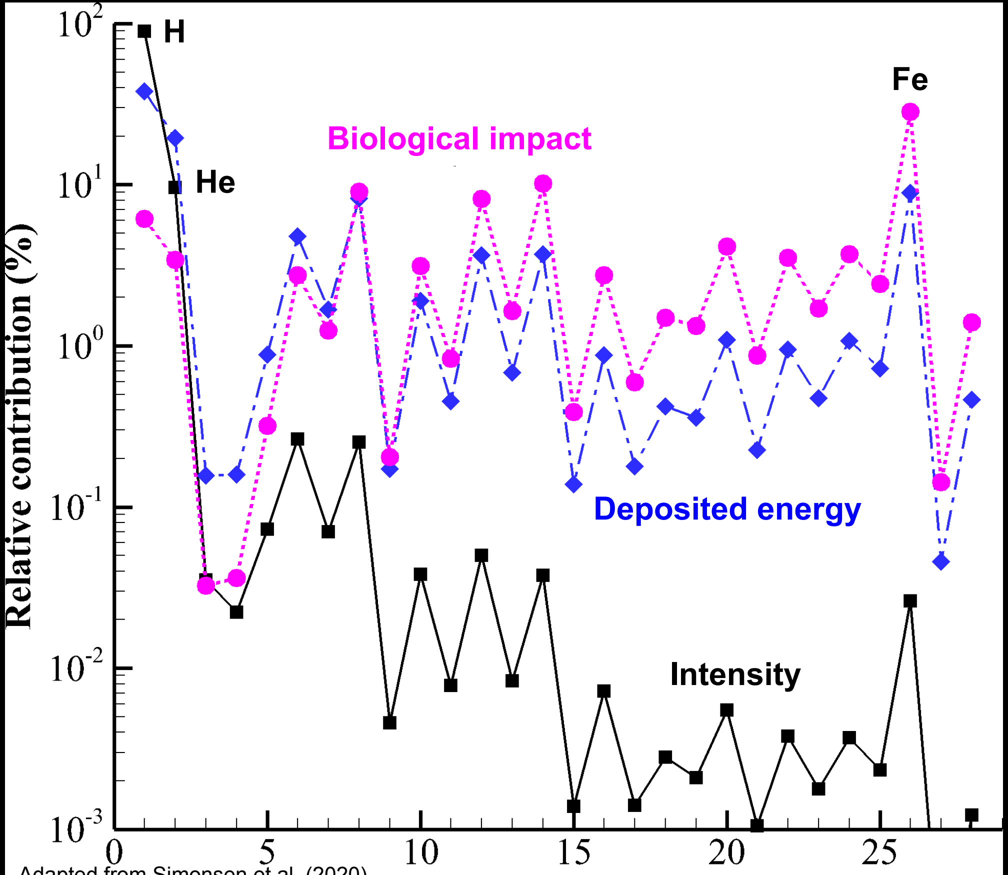
Radiation in space: Galactic Cosmic Rays

GCRs: ions accelerated in our galaxy, spanning wide range of energies



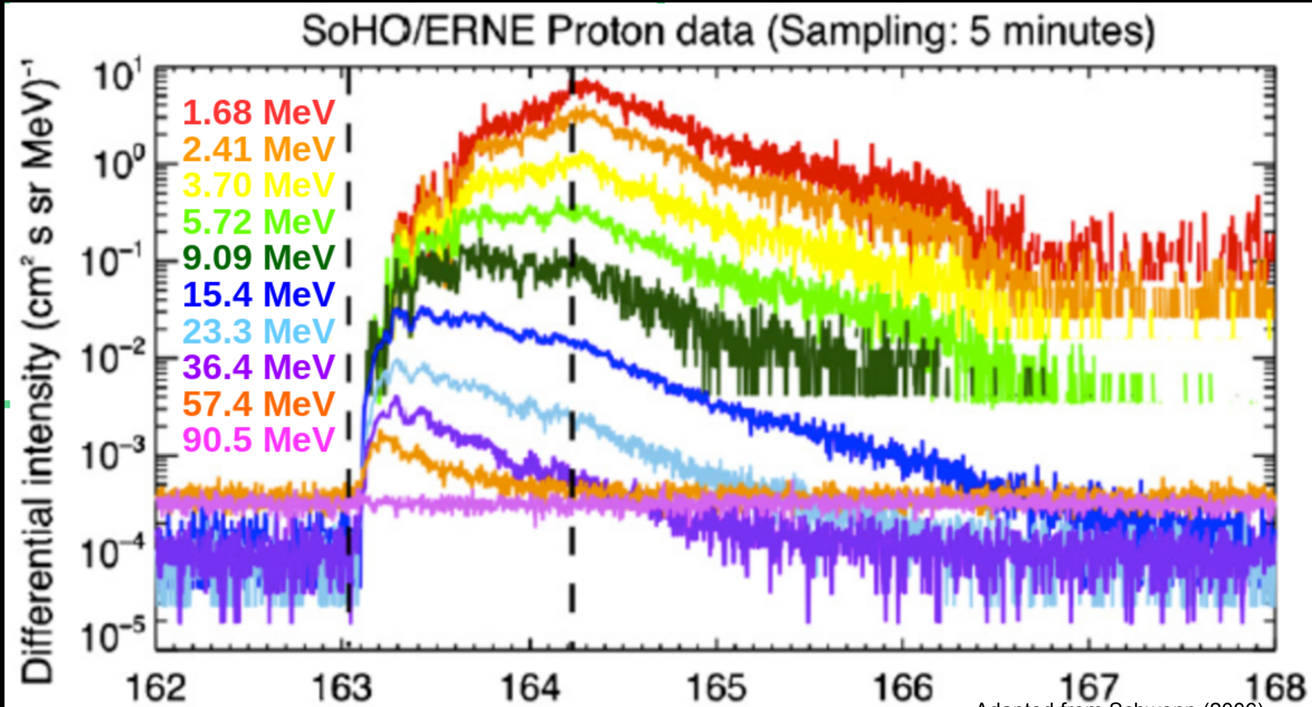




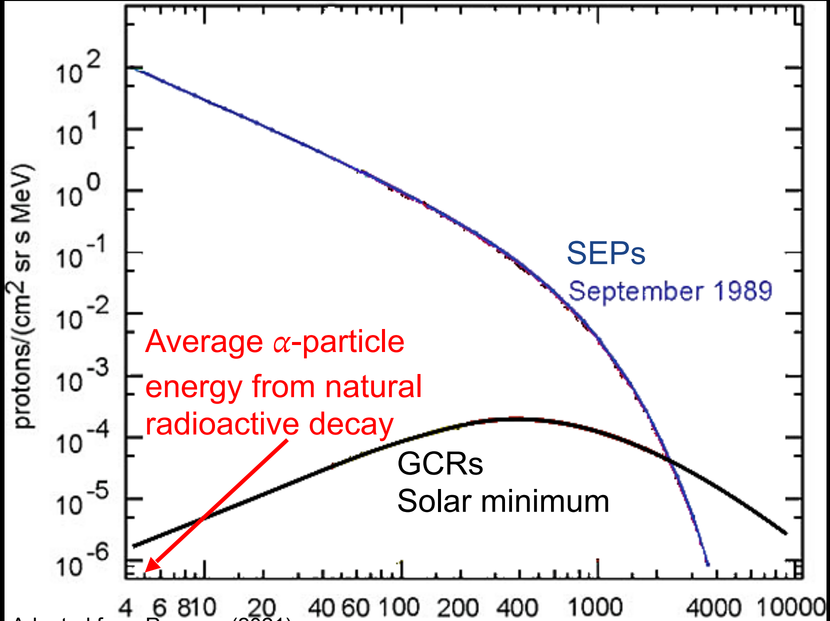
Adapted from Simonsen et al. (2020), DOI: 10.1371/journal.pbio.3000669

Radiation in space: Solar Energetic Particles

SEPs: ions accelerated in Sun’s eruptions (more likely during solar maximum), with lower energies than GCRs, but much higher intensities.
Can last from hours to days



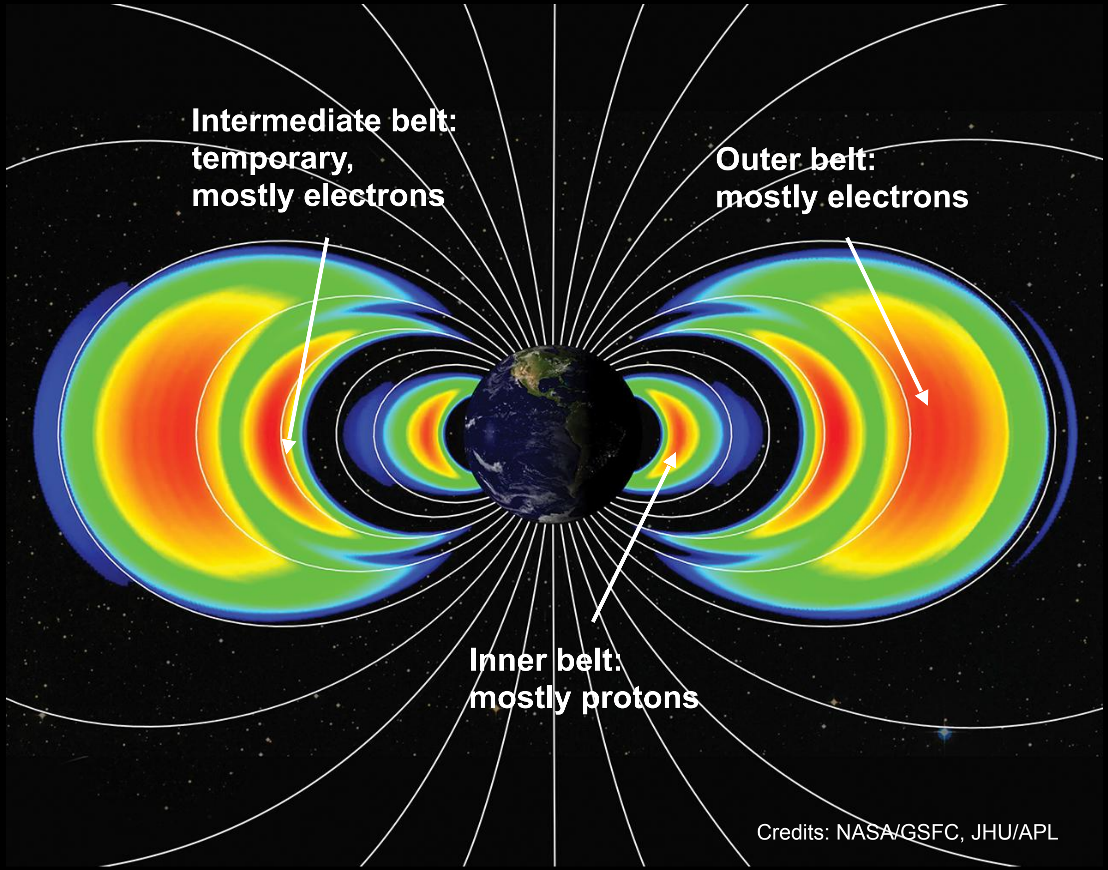
Adapted from Schwenn (2006),
DOI: 10.1007/s41116-021-00030-3

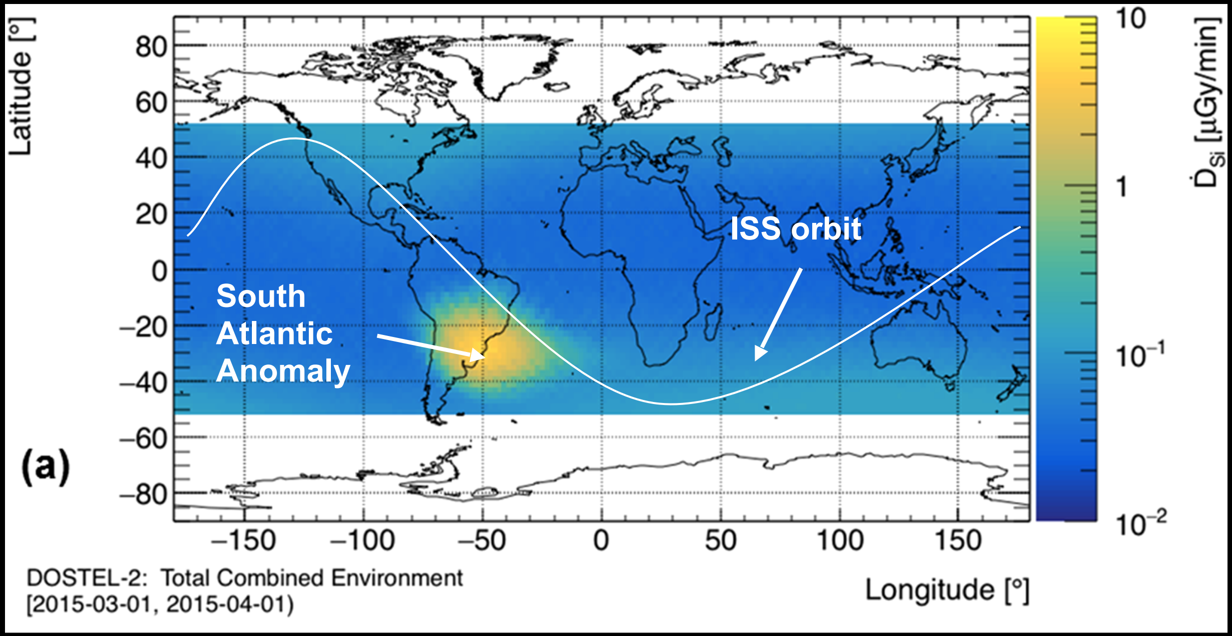


Adapted from Reames (2021),
DOI: 10.1007/978-3-030-66402-2

Radiation in space: Van Allen belts

Protons (up to GeV) and electrons (300 keV – 10 MeV) trapped in Earth's magnetic field.
However, Earth's magnetic field deflects low-energy SEPs and GCRs

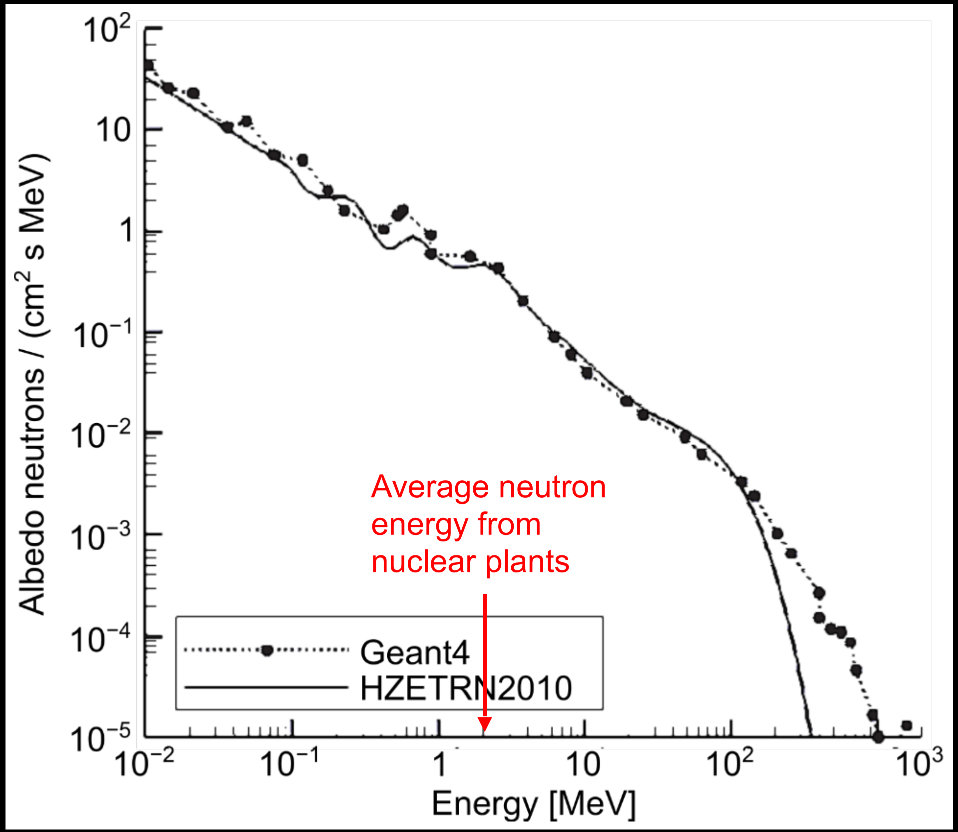


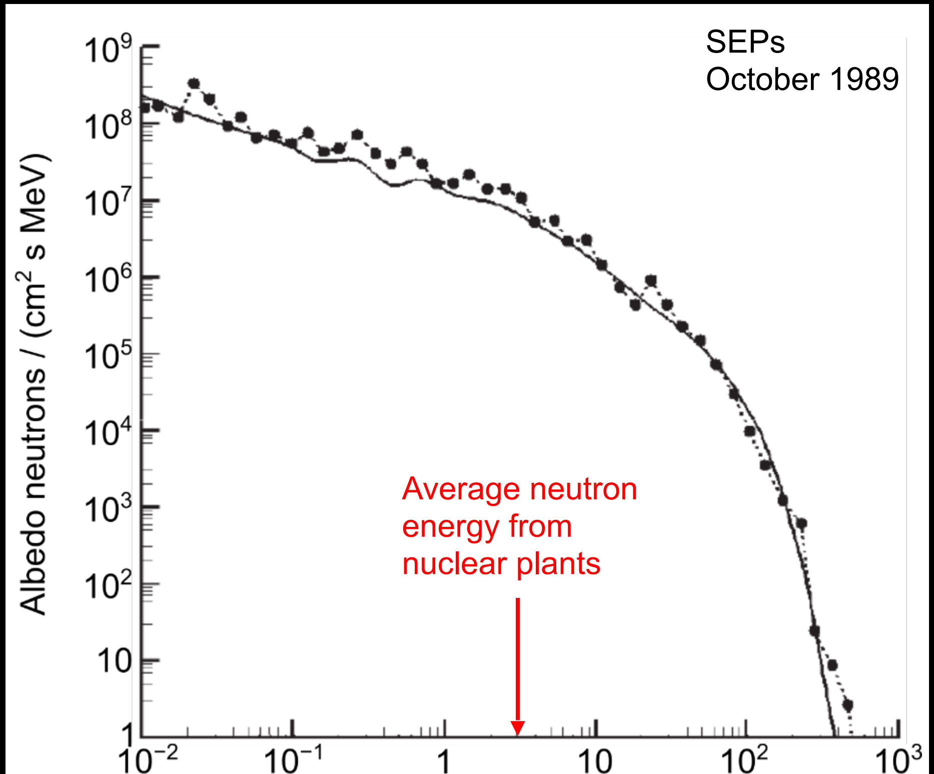


Adapted from Berger et al. (2020),
DOI:10.1051/swsc/2020028

Radiation in space: Moon surface

GCRs and SEPs impinging on the lunar surface eject large amounts of neutrons from the surface with higher energies than what we see on Earth





Adapted from Slaba et al. (2011), DOI:10.1667/RR2616.1

Quantifying radiation effects: particle spectrum

Effects of space radiation depend on:

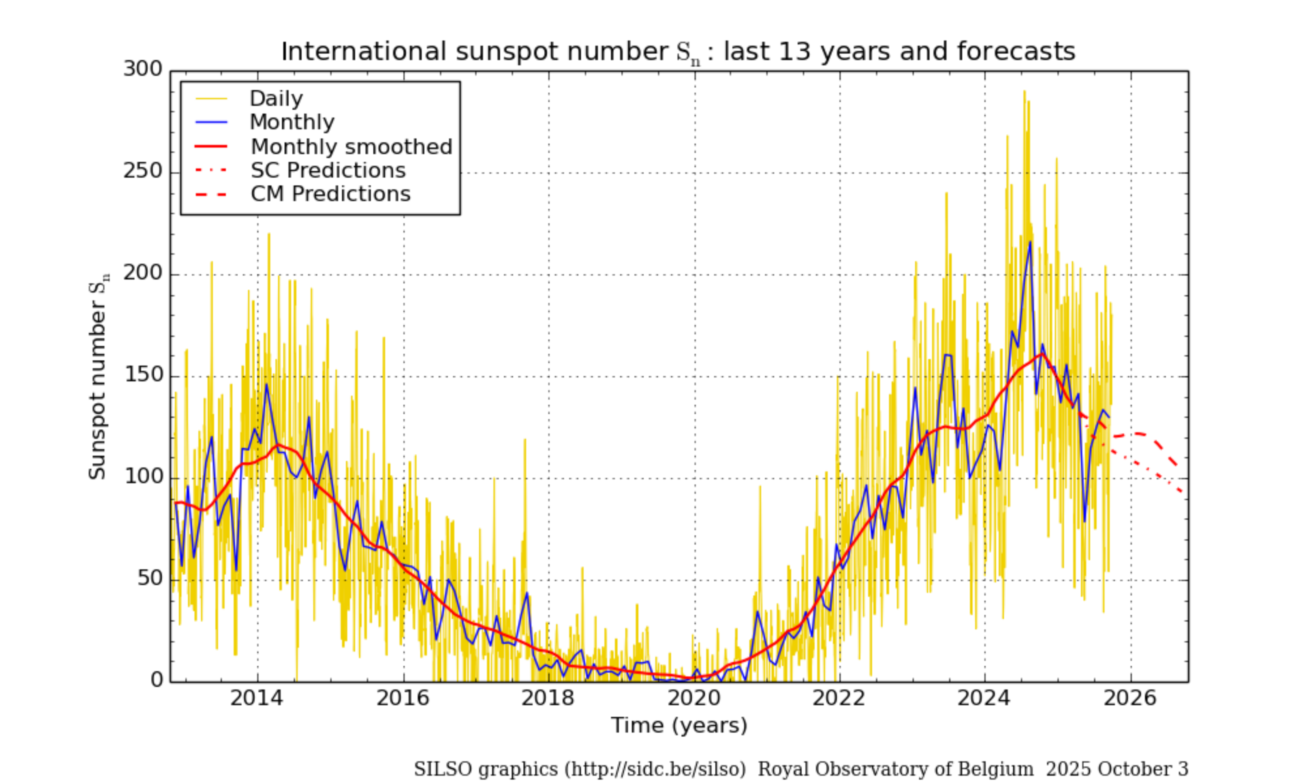
- particle type (electrons, nuclei with different charge number)
- particle energy (how fast particles move)
- particle intensity (how many particles per unit area and time)

Particle spectrum (intensity vs energy) is a key factor in understanding space radiation effects:

- Soft spectrum: fast decrease of intensity with increasing energy
  ⇒ less particles at high energy
- Hard spectrum: slow decrease of intensity with increasing energy
  ⇒ more particles at high energy

Quiz: When to travel in space?

What is the best period in the solar cycle to launch a deep-space mission?
Hint: which exposure is better to minimize, GCRs or SEPs?



Quiz: When to travel in space?

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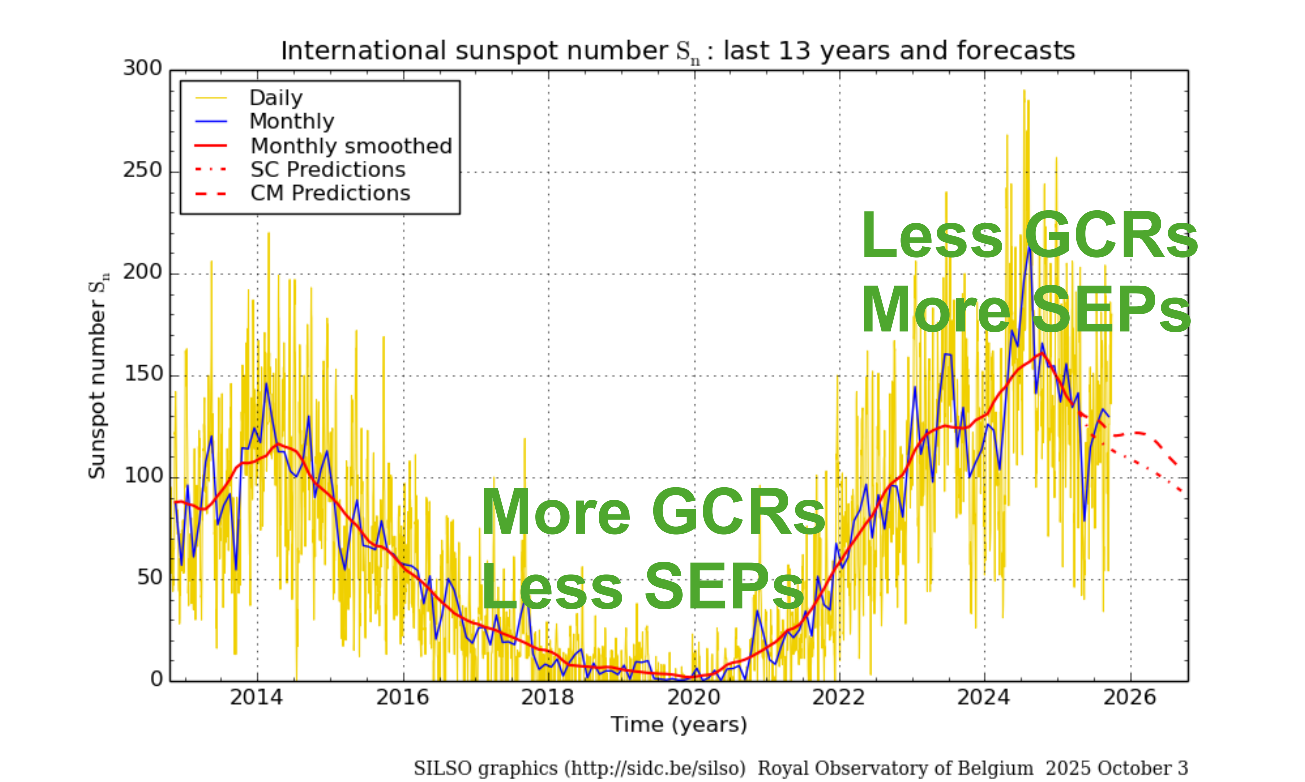
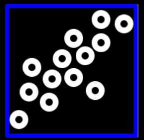


GCRs:
hard spectrum, low intensity

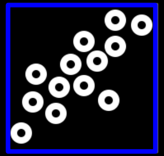
SEPs:
soft spectrum, high intensity

At what point less particles with high energy have the same biological impact of more particles with low energy?

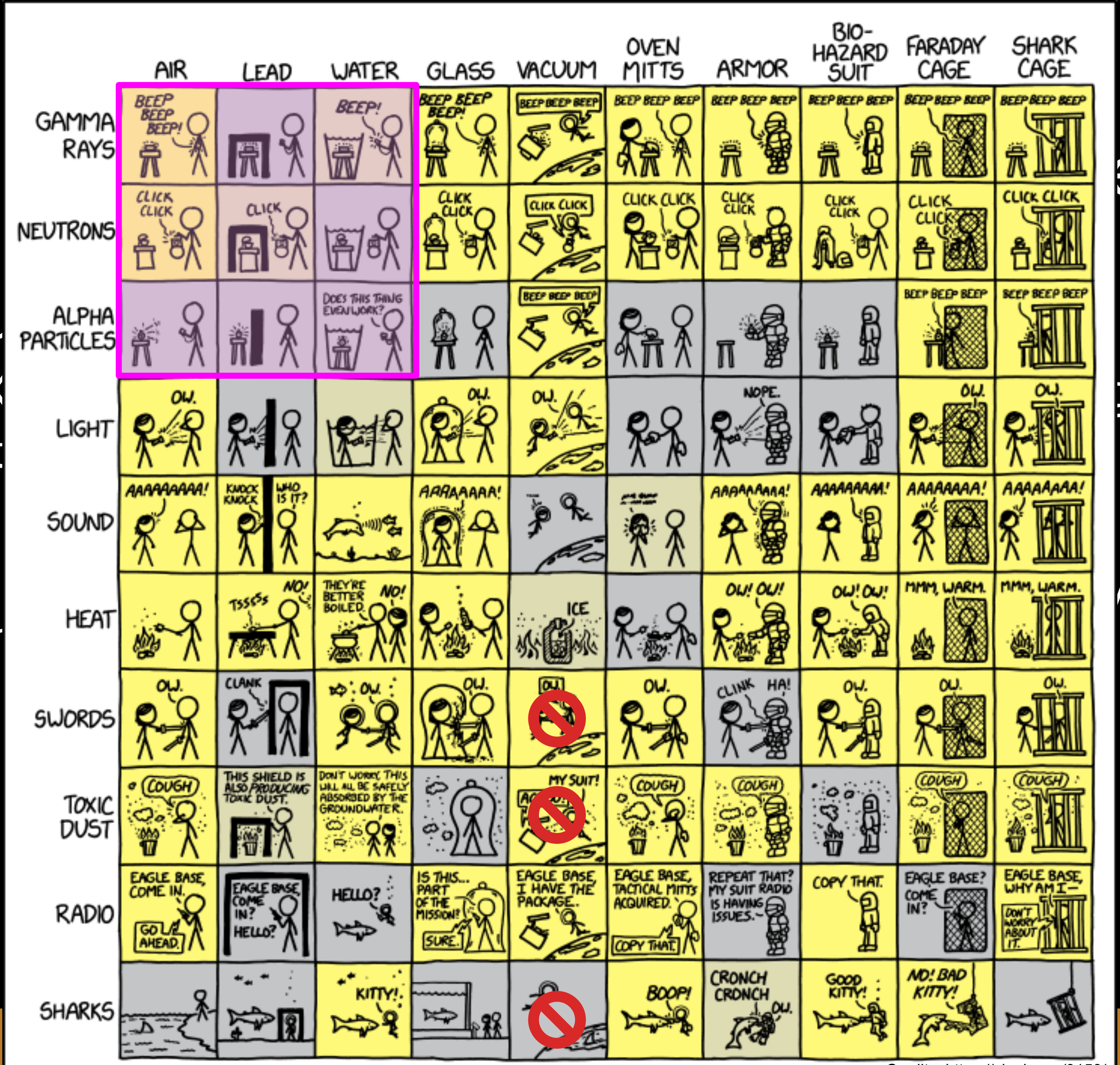


We cannot answer without the concepts of shielding and dose e?

- Solar U
- Solar X ... gh, very low intensit



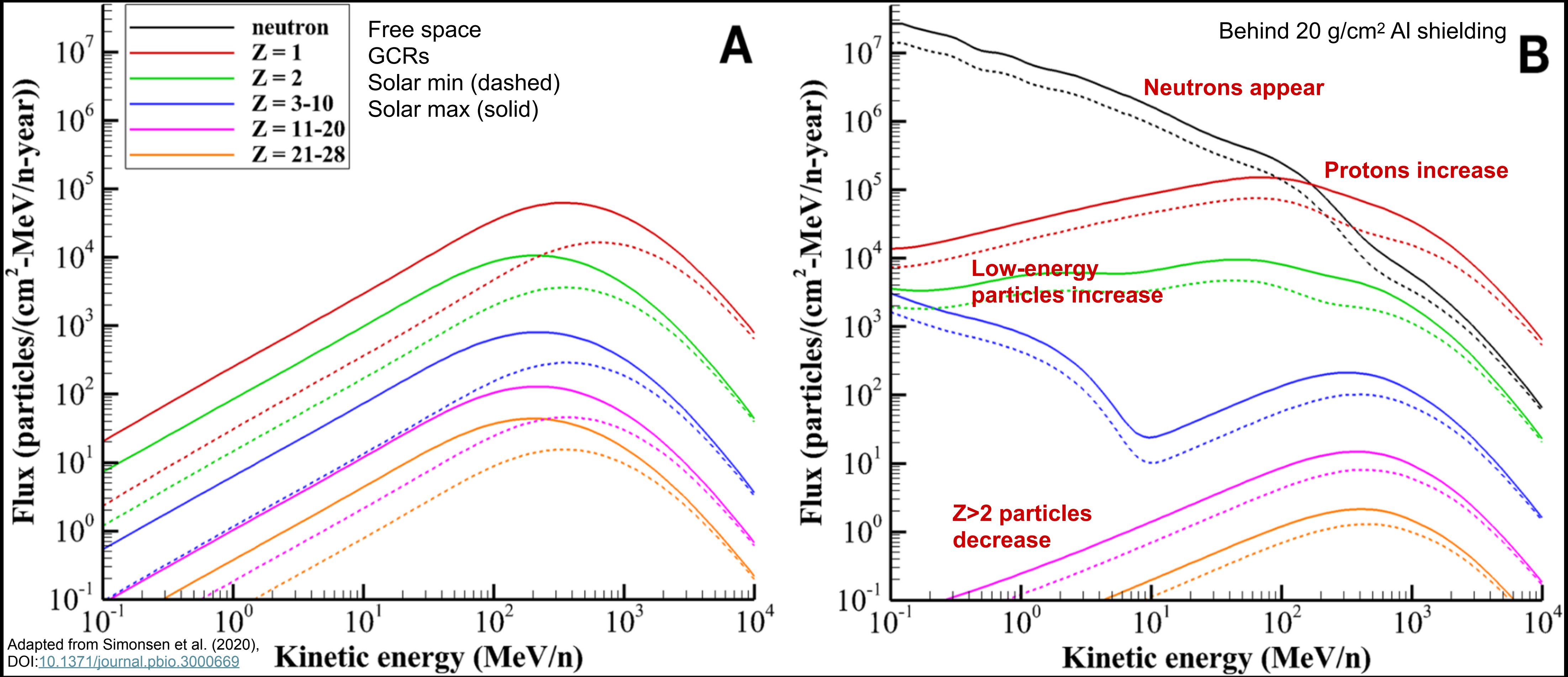
- SEPs (
- GCRs, ... attenuated. More th



Credits: https://xkcd.com/3158/

Radiation shielding: what effects?

Shielding reduces overall energy and charge number of radiation



Adapted from Simonsen et al. (2020), DOI:10.1371/journal.pbio.3000669

Radiation shielding: which materials?

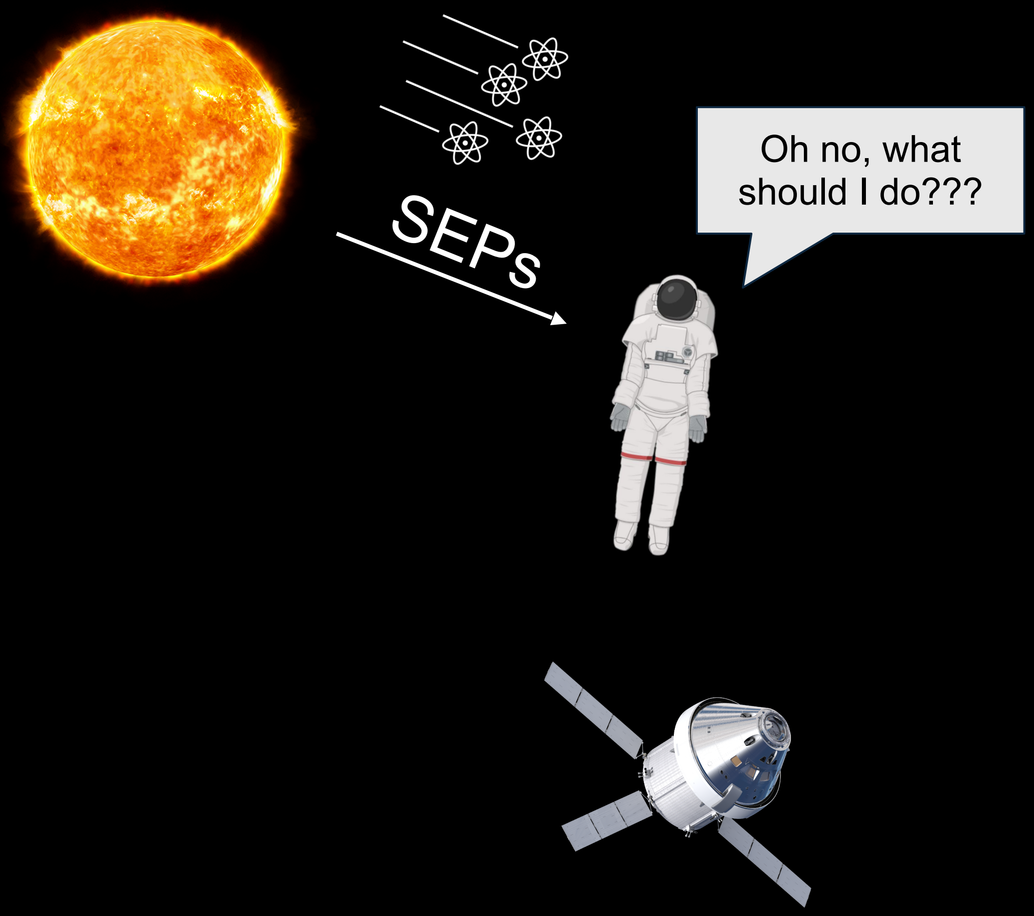
Reference material is Aluminum (Z = 26): low weight, very good mechanical and thermal properties

Low charge-number (Z < 8) materials lead to less nuclei fragmentation and are more effective at slowing down protons and neutrons, but have worse mechanical properties

Liquid hydrogen (Z = 1) minimize nuclei fragmentation and maximize proton and neutron attenuation, but it's highly flammable and can explode when mixed with air

Polyethylene (C_2H_4) can reduce dose from secondary neutrons with respect to Aluminum: reduction factor depends on free space radiation spectrum and shielding thickness

Quiz: What should the astronaut do?



Select the best answer:

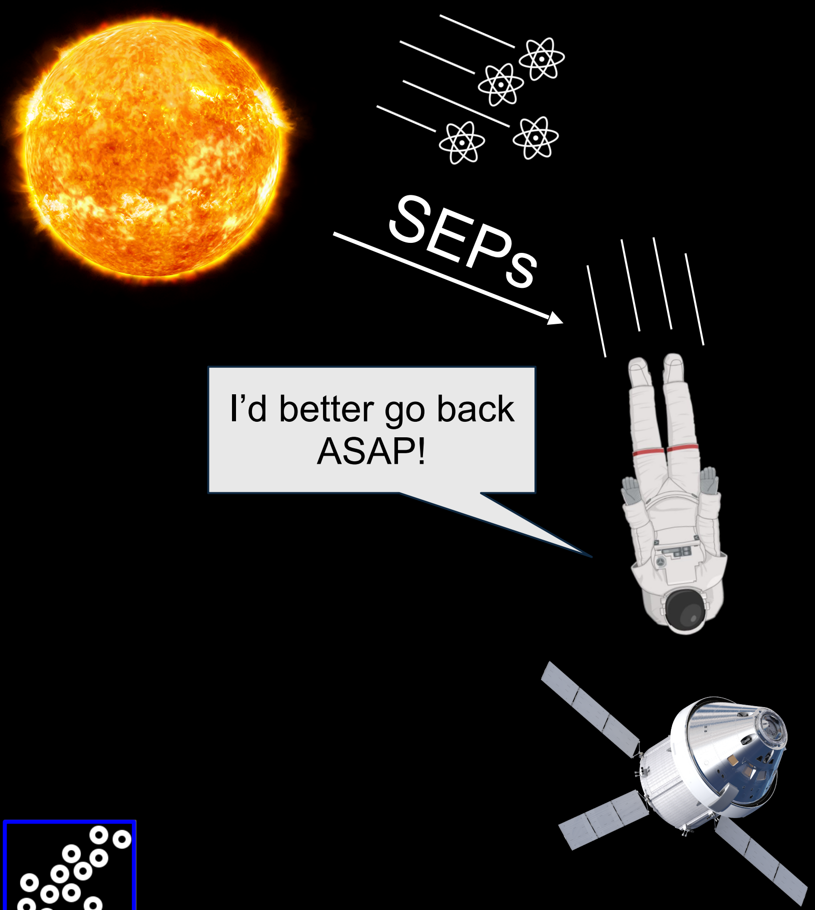
A) Keep floating outside the spacecraft

B) Go back to the spacecraft

C) Go back to the spacecraft and cover with an Aluminum blanket

D) Go back to the spacecraft and cover with a plastic blanket (hint: plastic materials are rich in Carbon)

Quiz: What should the astronaut do?



A) Keep floating outside the spacecraft
Bad: spacesuit shielding is too thin to stop SEPs

B) Go back to the spacecraft
Better! Spacecraft stop most of SEPs; only high energy SEPs (low intensity) can penetrate

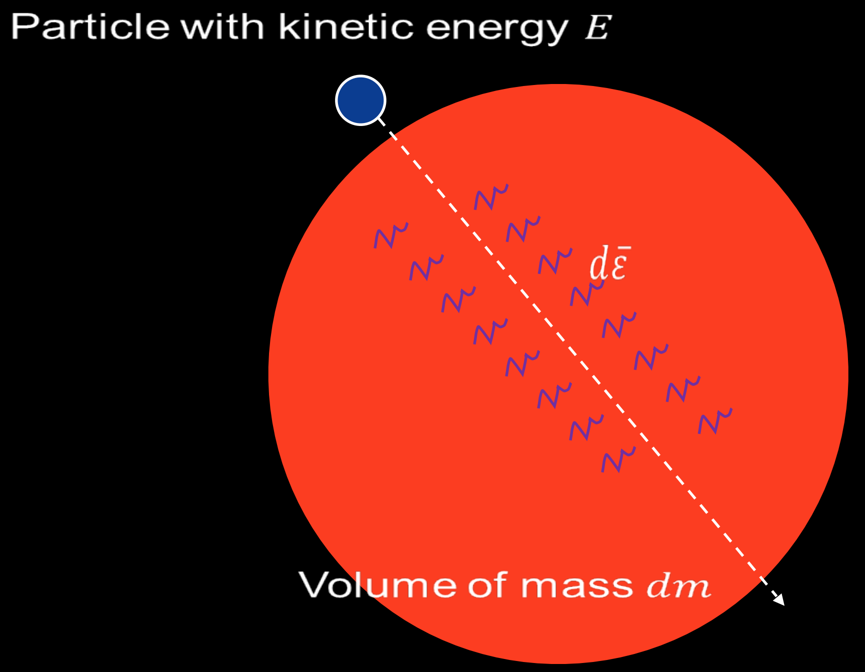
C) Go back to the spacecraft and cover with an Aluminum blanket
Even better! Aluminum will provide additional shielding against high energy SEPs

D) Go back to the spacecraft and cover with a plastic blanket
Best! Plastic shields more than Aluminum

Caveat: actual procedures depend on real-time conditions and operational requirements

Quantifying radiation: absorbed dose

Absorbed dose: mean energy ($d\bar{\varepsilon}$) deposited in matter per unit mass (dm)
Units: 1 Gy (Gray) = 1 J/kg
Symbol: *D*



- Mass-normalized energy deposition
- Not sufficient for evaluating biological impact
- Density dependent
- Material dependent
    - In general, *D* in silicon ≠ *D* in human tissue for identical exposures: D_{Water}/D_{Si} = 1.2 – 1.4

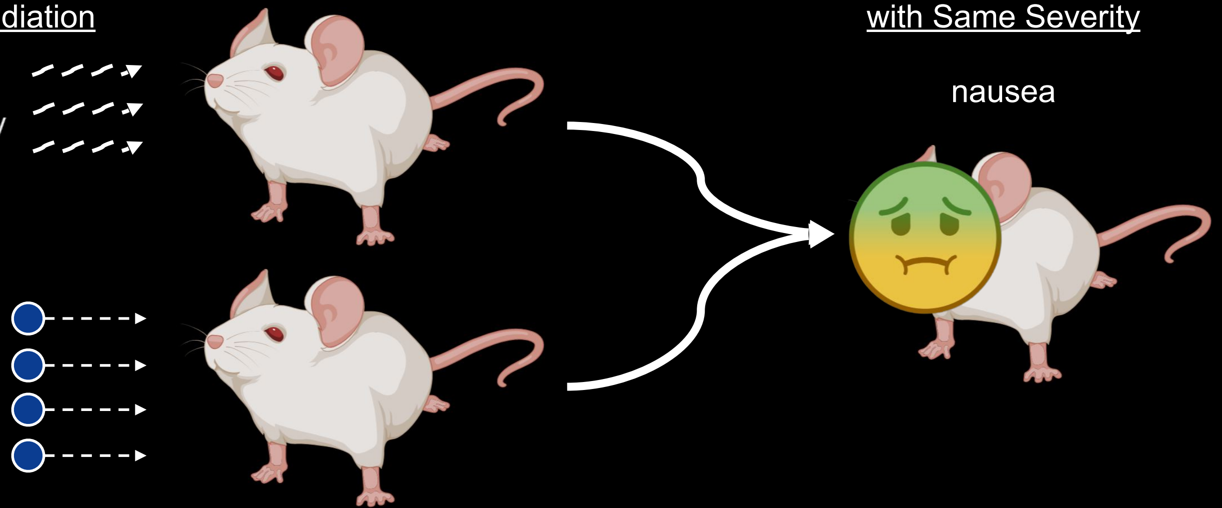
Quantifying radiation effects: RBE-weighted dose

Dose weighted by Relative Biological Effectiveness: normalize *D* from different radiation types for the same biological effect (endpoint)

Units: Gy-eq (Gray equivalent)
Symbol: *D* (= *RBE* × *D*)

$$RBE = \frac{D \text{ from reference radiation for given endpoint}}{D \text{ from radiation of interest for given endpoint}}$$

Incident Radiation	Biological Endpoint with Same Severity	Resulting RBE	Resulting RBE-Weighted Dose
1 MeV γ-rays, $D_{reference} = 1$ Gy	nausea		Reference exposure; (1 Gy = 1 Gy-eq)
0.75 MeV protons, $D_{interest} = 0.5$ Gy		$RBE = \frac{1 \text{ Gy}}{0.5 \text{ Gy}} = 2$	$RBE \times D = 1$ Gy-eq



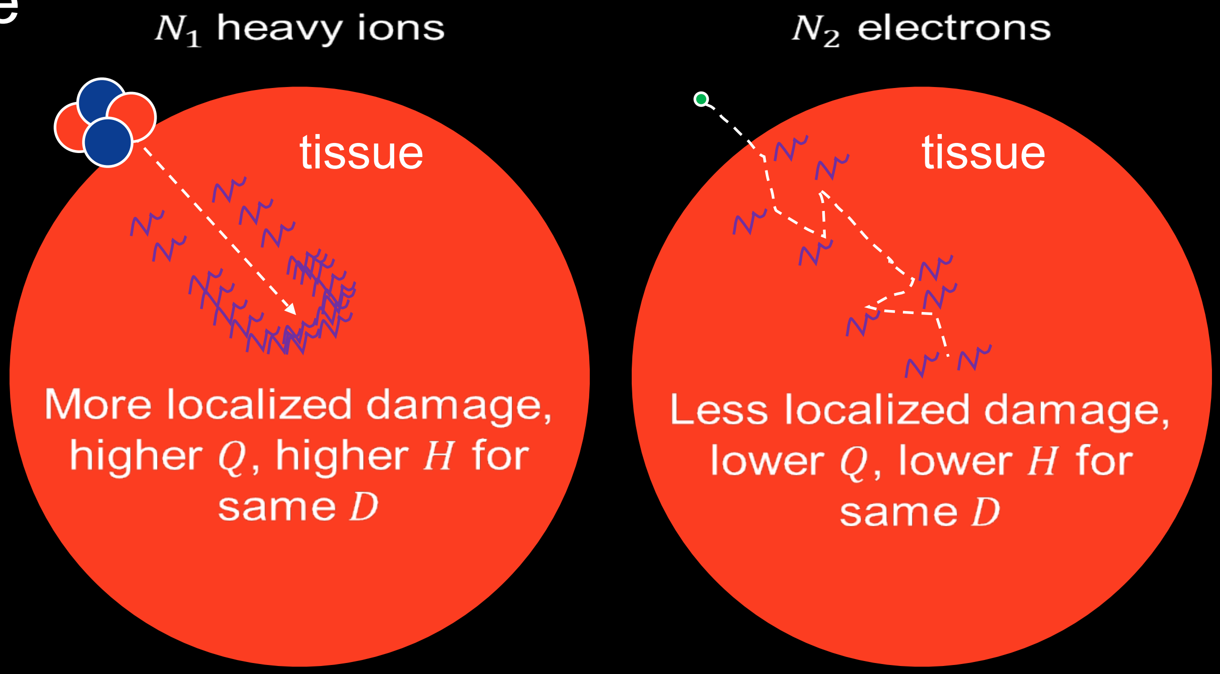
Useful for establishing *non-cancer dose limit recommendations*

Quantifying radiation effects: dose equivalent

Dose equivalent: absorbed dose scaled by radiation type, related to increased probability of cancer incidence

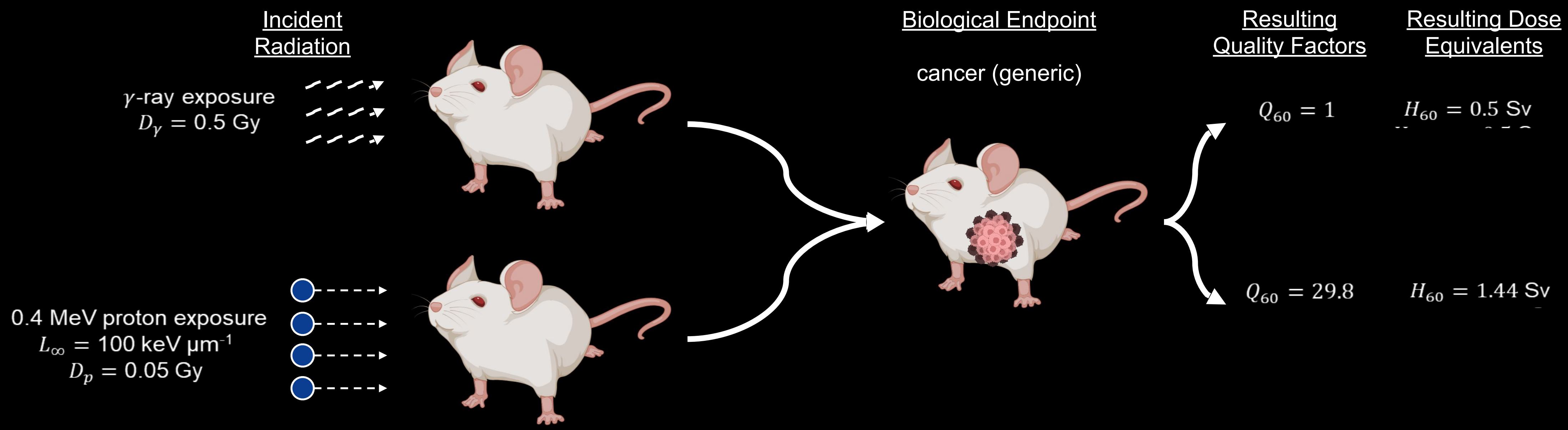
Units: Sv (Sievert)
Symbol: $H = Q \times D$

- Q = quality factor, derived from RBE for cancer endpoint
- Can depend on particle type, kinetic energy, LET



Slide credit: SRAG

Quantifying radiation effects: dose equivalent



Smaller absorbed dose ≠ smaller dose equivalent!

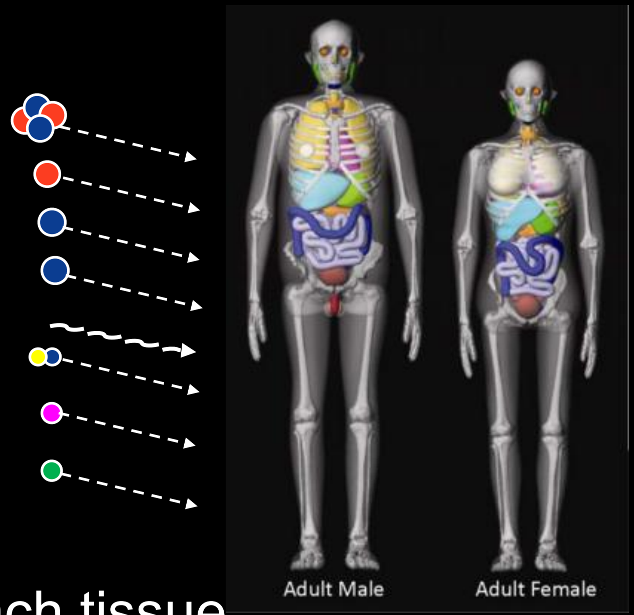
Quantifying radiation effects: effective dose

Effective dose: whole-body averaged dose equivalent, accounting for different tissue radiosensitivity

Units: Sv (Sievert)
Symbol: $\varepsilon = \sum_T w_T H_T$

w_T = tissue weighting factor

$w_{lung} > w_{liver}$



Need to know equivalent dose separately for each tissue

Useful for establishing *cancer-related dose limit recommendations*

Quantifying radiation effects: standards

- ICRP 60
  - *Q* depends only on LET
  - w_T are the same for males and females (except for sex-specific organs)
- NASA
  - *Q* depends on particle type, kinetic energy, and LET and are different for solid cancer vs leukemia (tissues vs blood)
  - w_T depends on sex and are different for non-smokers vs general population and for GCR vs non-GCR exposure

Same exposure can result in different dose equivalent and effective dose when using different standards

Quiz: From measurements to health effects

In the table below, the concepts, quantities, and units rows are all mixed up. Please, match the **concept**, **quantity**, and **units**, then sort them in the order needed to derive health effects for a specific radiation field.

Concept	Quantity	Units
Biological impact on specific tissue	Spectrum	Gy-eq
Particles	RBE, RBE-weighted dose	Sv
Whole-body cancer risk	Dose equivalent	particles/(area time energy)
Dose measurement	Effective dose	Sv
Lab experiment for biological endpoint	Absorbed dose	Gy

Quiz answers: From measurements to health effects

Concept	Quantity	Units
Particles	Spectrum	particles/(area time energy)
Dose measurement	Absorbed dose	Gy
Lab experiment for biological endpoint	RBE, RBE-weighted dose	Gy-eq
Biological impact on specific tissue	Dose equivalent	Sv
Whole-body cancer risk	Effective dose	Sv

What are radiation health effects?

Deterministic Effects

- Severity increases with dose
- Threshold dose required to observe effect
- E.g, **tissue reactions**
  - Acute radiation syndrome
  - Skin erythema
- Associated with absorbed dose or RBE-weighted dose
  - Gy or Gy-eq

Stochastic Effects

- Probability increases with dose
  - Severity does *not*
- No dose threshold
- E.g., **cancer**
- Associated with organ dose equivalent or effective dose
  - Sv

Slide credit: SRAG

Radiation vs alcohol

Deterministic Effects

high dose rate

acute exposure

binge drink ? nausea, alcohol poisoning

Stochastic Effects

low dose rate

chronic exposure

drink once-a-day ? long-term effects

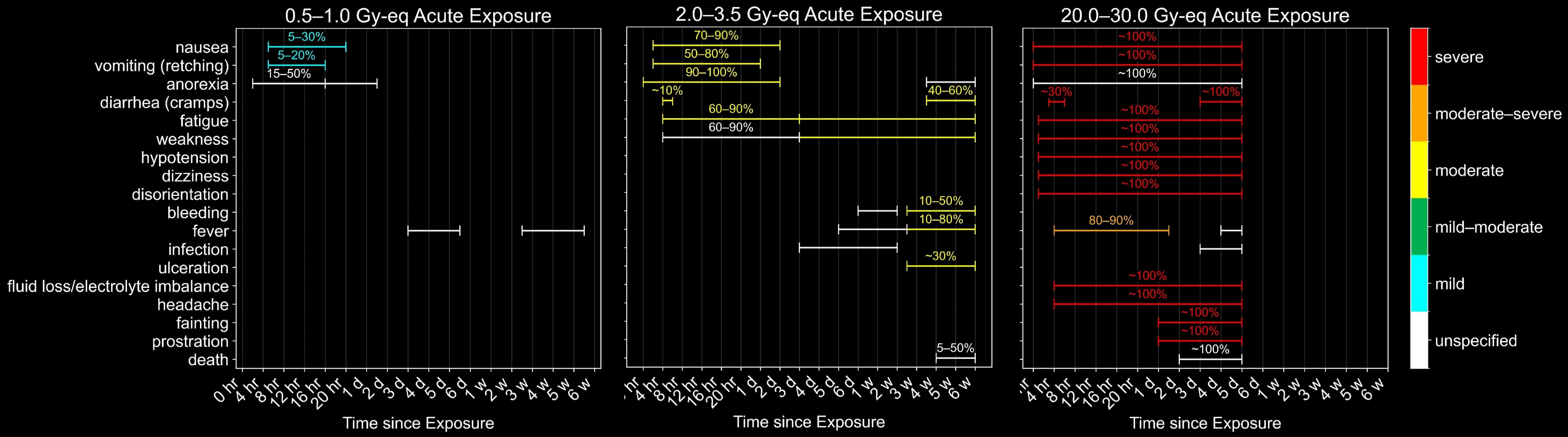
Neither option is healthy! High dose rate consequences are just more *obvious*

Acute radiation exposure: symptoms

- Symptoms
- Probability of symptoms
- Severity of symptoms

depend on

- Total dose
- Dose rate



Stochastic radiation exposure

Location, location, location!

Location	Dose equivalent
Flight (LA – NY round trip)	0.04 mSv
Single X-ray scan	0.1 – 3 mSv (depends on organ)
Average US natural background	3.1 mSv/year
Commercial airline flight crew	2 – 4 mSv/year
Typical ISS mission (~6 months)	100 – 150 mSv
~3-year Mars mission	~1 Sv (no SEPs, varies with solar cycle and mission design)

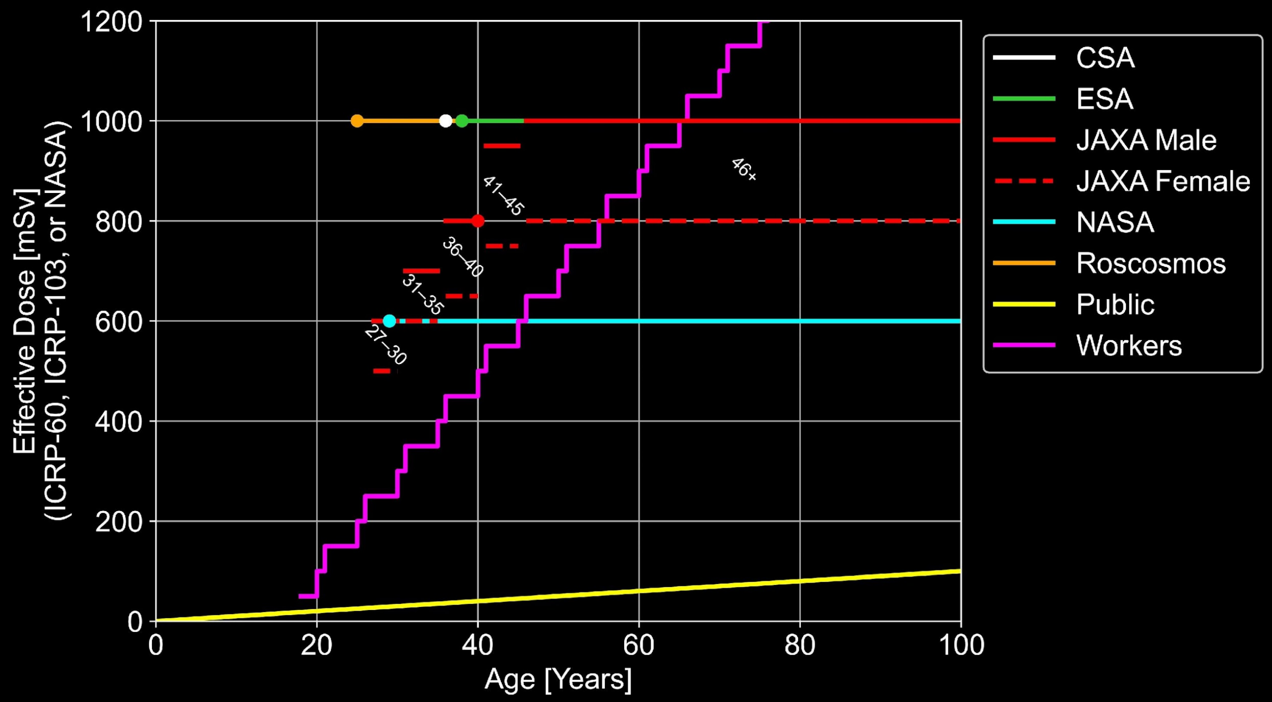
Source: DOE

1 Sv is roughly equivalent to a 5% increased excess risk of cancer mortality (ICRP)

Radiation exposure recommended limits

- Cancer-related career dose limits
- Each agency uses a different standard: dose limits are not directly comparable, but endpoint (increased excess risk) is similar for all agencies

- Organ-specific non-cancer NASA dose limits
- Cover both acute radiation symptoms and long-term functional degradation



Organ	30-Day Limit	1-Year Limit	Career
Lens of eye	1000 mGy-Eq	2000 mGy-Eq	4000 mGy-Eq
Skin	1500 mGy-Eq	3000 mGy-Eq	6000 mGy-Eq
Blood-Forming Organs (BFO)	**250 mGy-Eq**	500 mGy-Eq	N/A
Circulatory system	250 mGy-Eq	500 mGy-Eq	1000 mGy-Eq
Central nervous system	500 mGy	1000 mGy	1500 mGy
Central nervous system ($Z \geq 10$)	N/A	100 mGy	250 mGy

NASA JSC Space Radiation Analysis Group

Strategies for human radiation health protection:

Model mission doses and health risks that inform vehicle and shelter design

Develop flight rules and shelter procedure

Develop and deploy radiation dosimeters to monitor the environment

Space weather monitoring and forecasting technologies:
ISEP collaboration between SRAG, CCMC, and M2M SWAO

Slide credit: SRAG

Minimizing radiation exposure

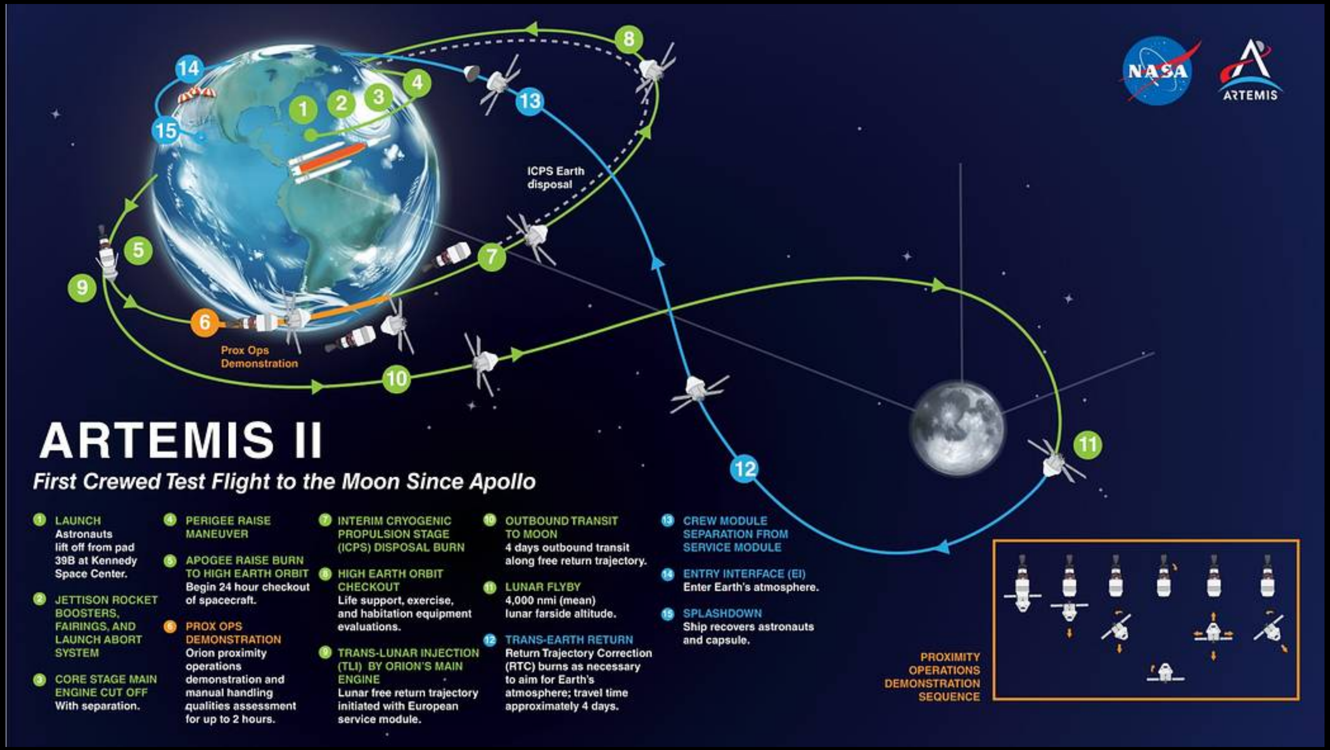
- As Low As Reasonably Achievable (ALARA)
  - Minimize radiation exposure within mission specifications and within reason
- SEP data and forecasts are used to determine conditions for ISS:
  - All-Clear: Nominal conditions and no ESPE is forecasted
  - Watch: Nominal conditions and ESPE is forecasted
  - Warning: Enhanced radiation environment but no ESPE observed, SPE/ ESPE may be forecasted
  - Contingency: ESPE observed, action may be taken to minimize exposure
- SEP forecasts should address three questions:
  - Will there be a SEP event?
  - How big will it be?
  - How long it will last?

Solar Proton Event (SPE)
>10 MeV integral proton flux exceeds 10 pfu
Energetic Solar Proton Event (ESPE)
>100 MeV integral proton flux exceeds 1 pfu

Artemis II mission trajectory

- Crewed lunar flyby
- 10-day mission
- Launch: February 2026

- <u>Radiation specific details:</u>
  - Astronauts will exit the protection of the Earth's magnetosphere for several days
  - There will be three Van Allen Belt transits

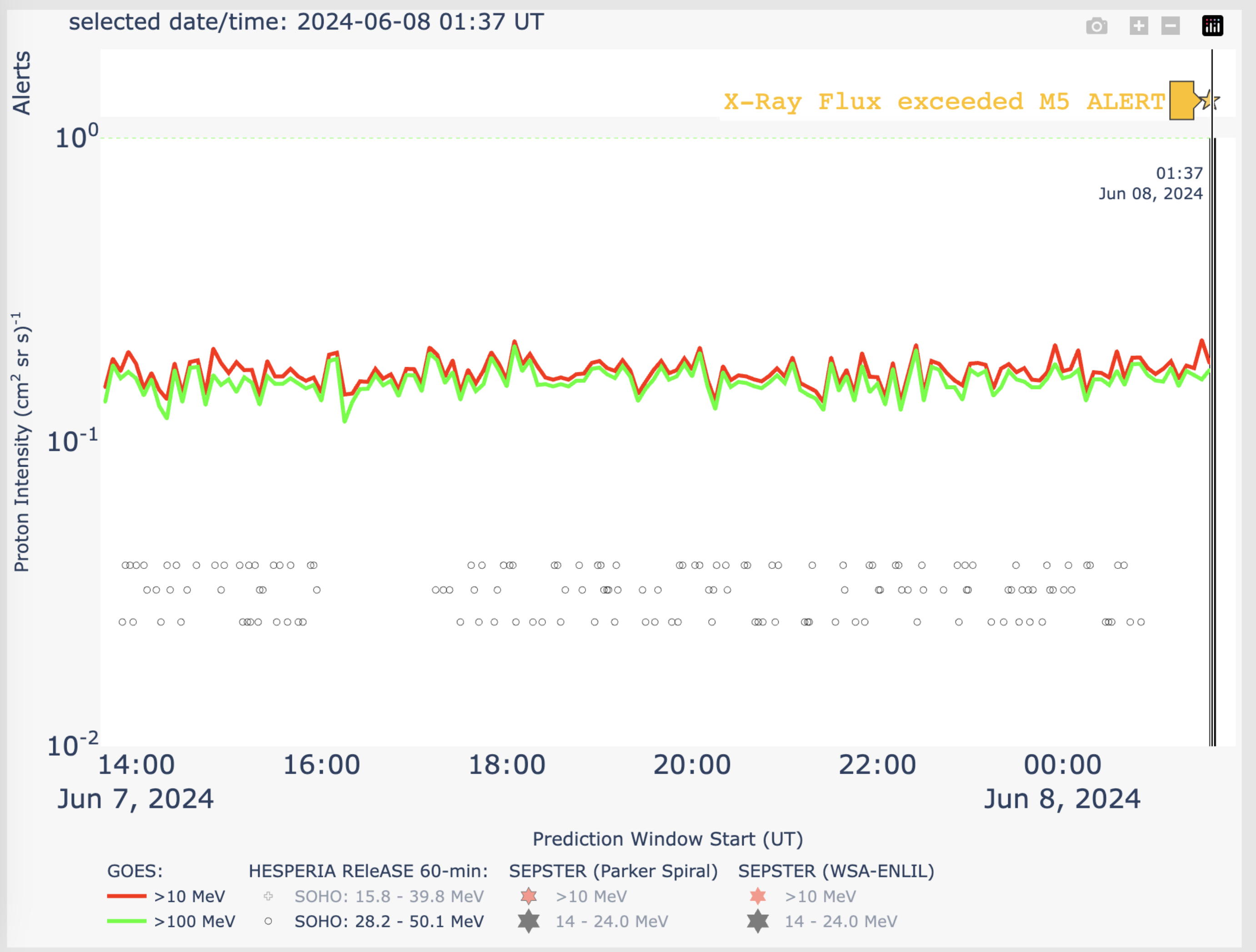


Draft Artemis II Radiation Mitigation

- Measured highest dose rate >50 µGy/min ⇒ establish shelter configuration
  - Dosimeters failure ⇒ shelter at GOES >100 MeV >50 pfu
- Measured highest dose rate <20 µGy/min ⇒ terminate shelter configuration
  - Dosimeters failure ⇒ terminate shelter at GOES >100 MeV <20 pfu
- Avoid low shielded areas
- Shelter: stowage reconfiguration

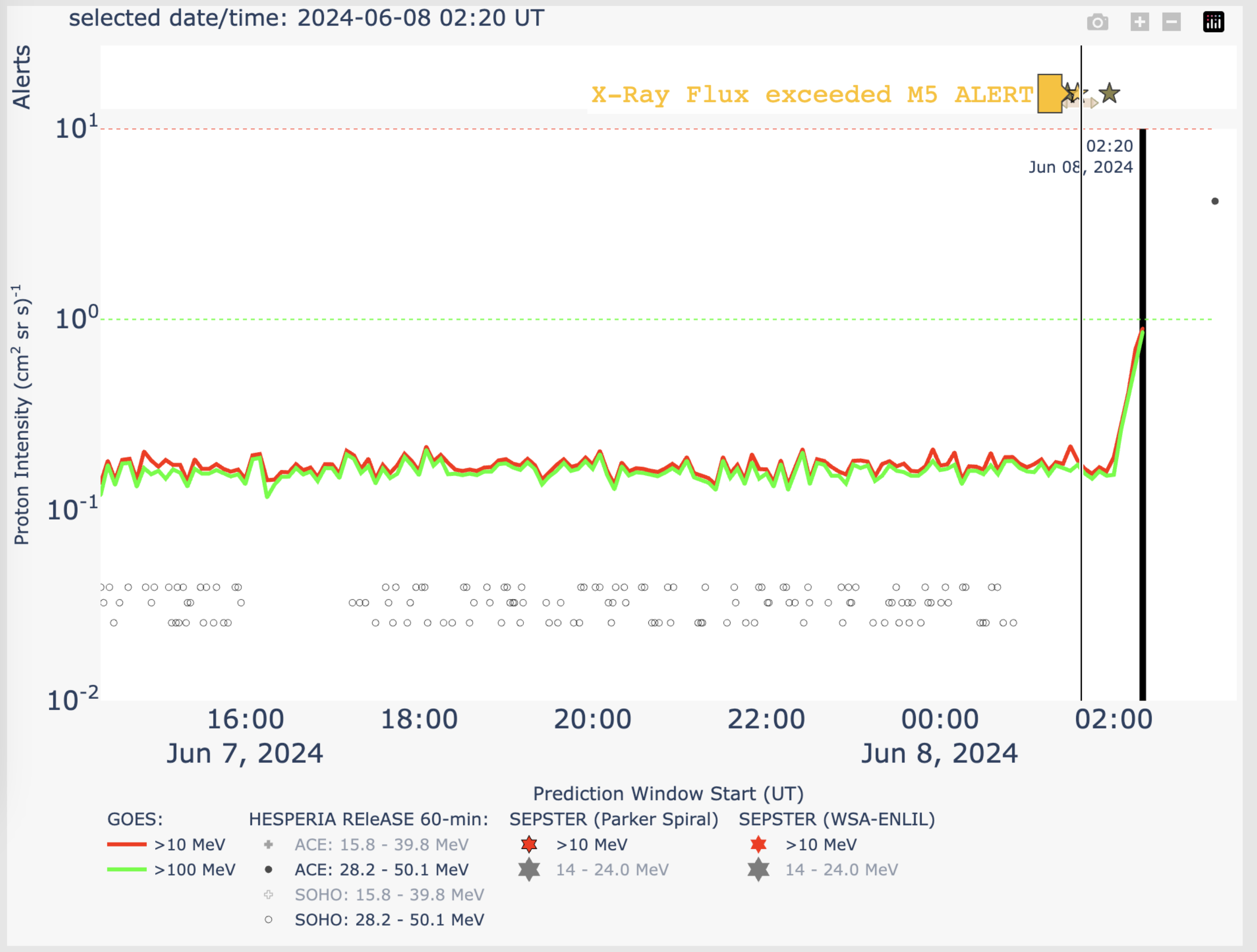
SEP event time evolution and time scales

- Solar flare: 01:37 UT



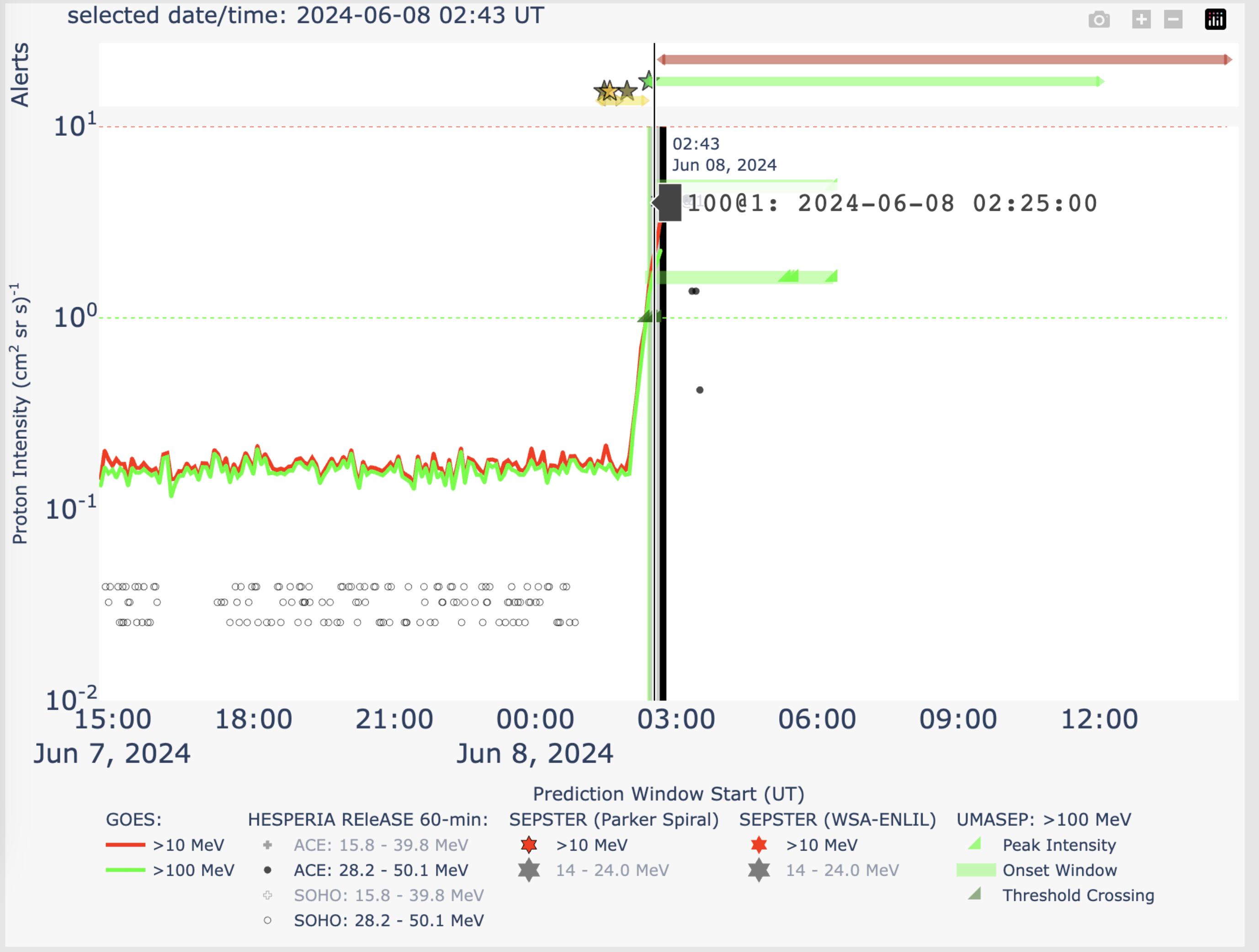
SEP event time evolution and time scales

- Solar flare: 01:37 UT
- Particle increase: 02:00 UT
  Flare + 23 min



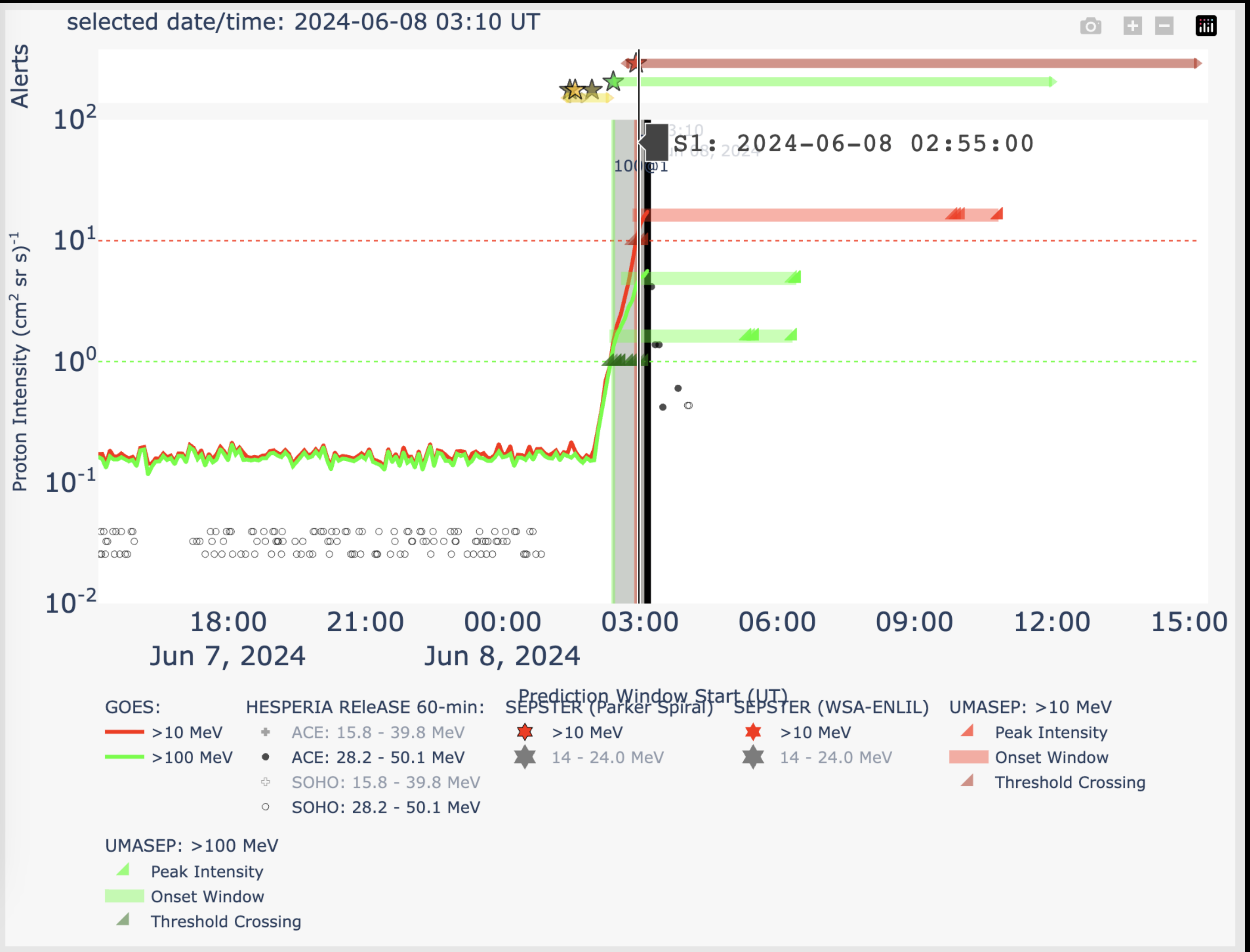
SEP event time evolution and time scales

- Solar flare: 01:37 UT
- Particle increase: 02:00 UT
  Flare + 23 min
- >100 MeV, >1 pfu: 02:25 UT
  Flare + 48 min



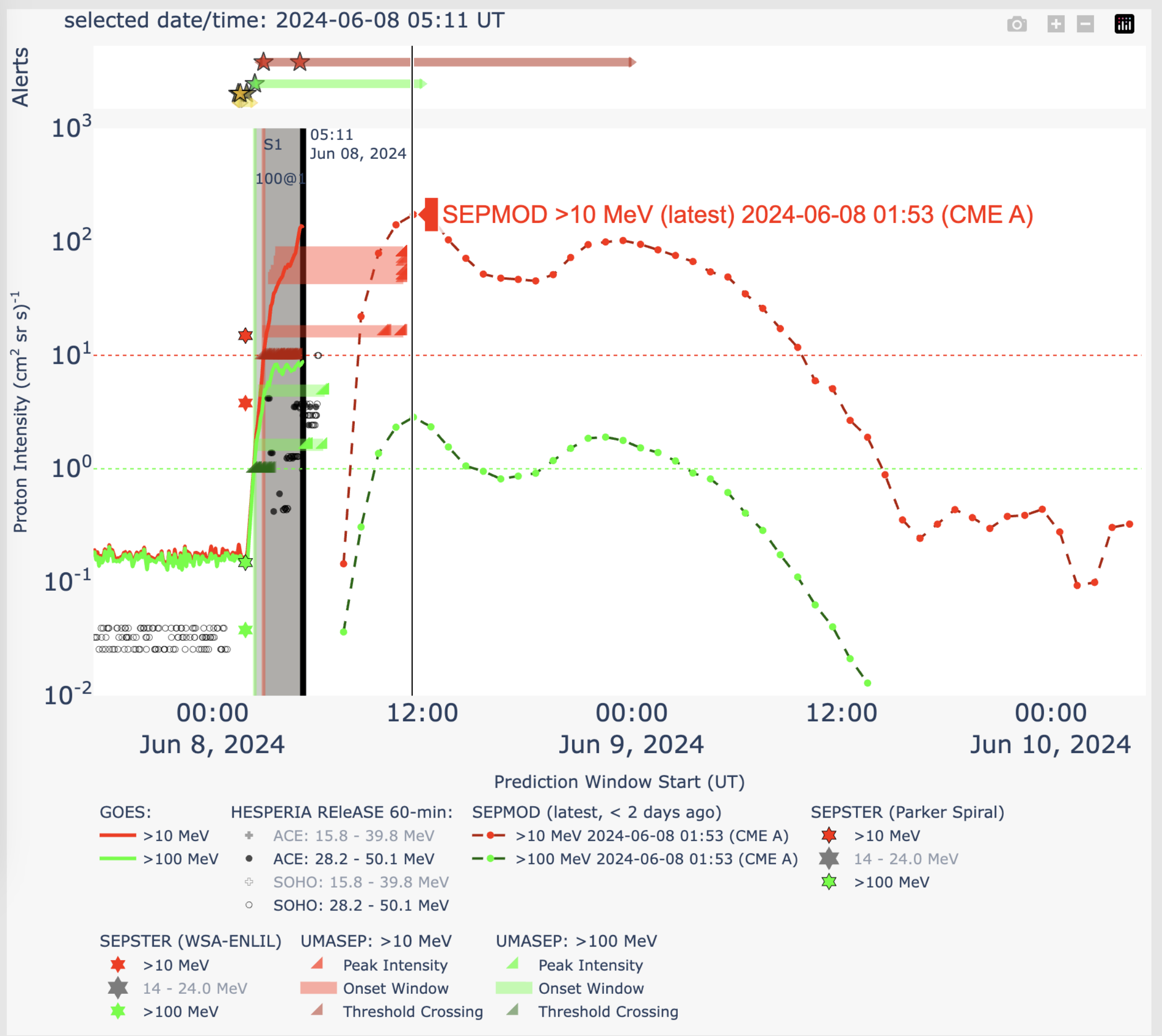
SEP event time evolution and time scales

- Solar flare: 01:37 UT
- Particle increase: 02:00 UT
  Flare + 23 min
- >100 MeV, >1 pfu: 02:25 UT
  Flare + 48 min
- >10 MeV, >10 pfu: 02:55 UT
  Flare + 1 hour 18 min



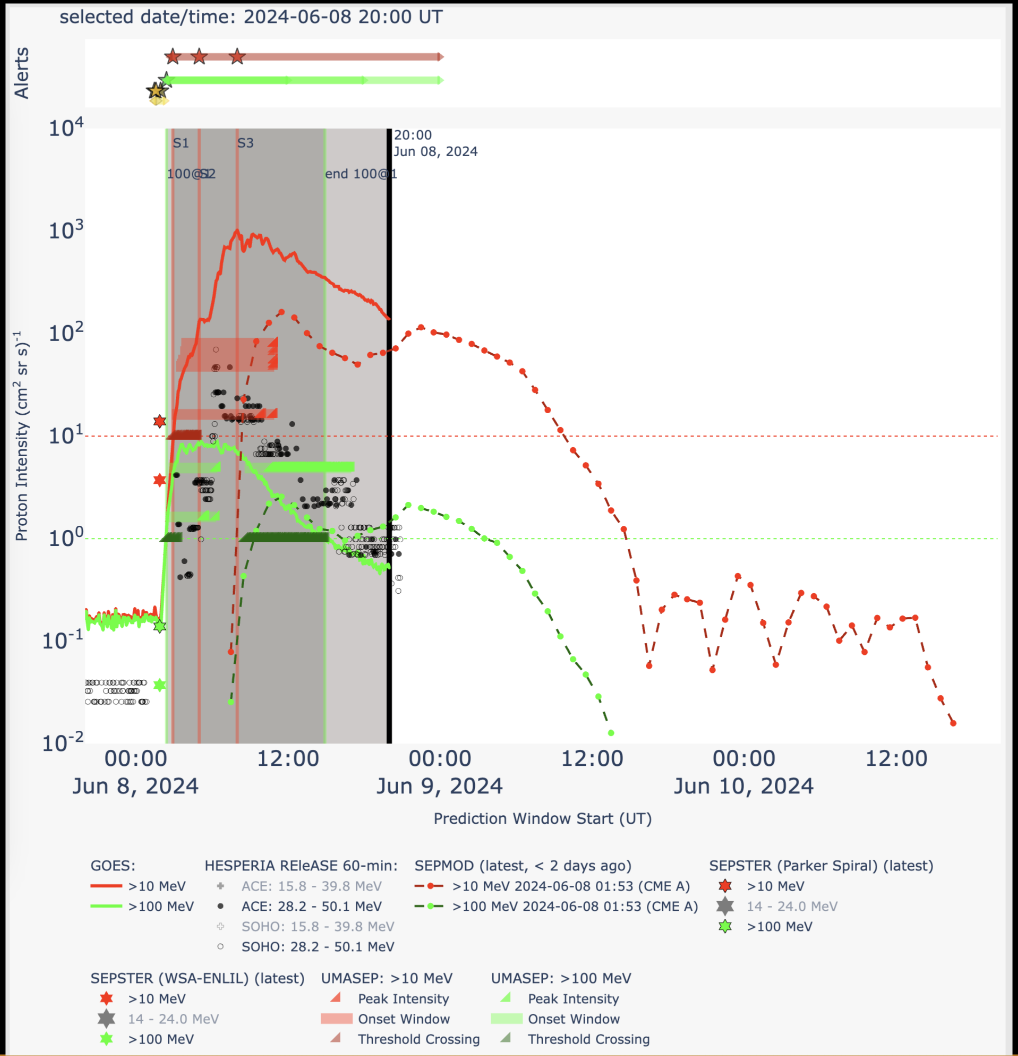
SEP event time evolution and time scales

- Solar flare: 01:37 UT
- Particle increase: 02:00 UT
  Flare + 23 min
- >100 MeV, >1 pfu: 02:25 UT
  Flare + 48 min
- >10 MeV, >10 pfu: 02:55 UT
  Flare + 1 hour 18 min
- SEPMOD: 05:11 UT
  Flare + 3 hours 34 min



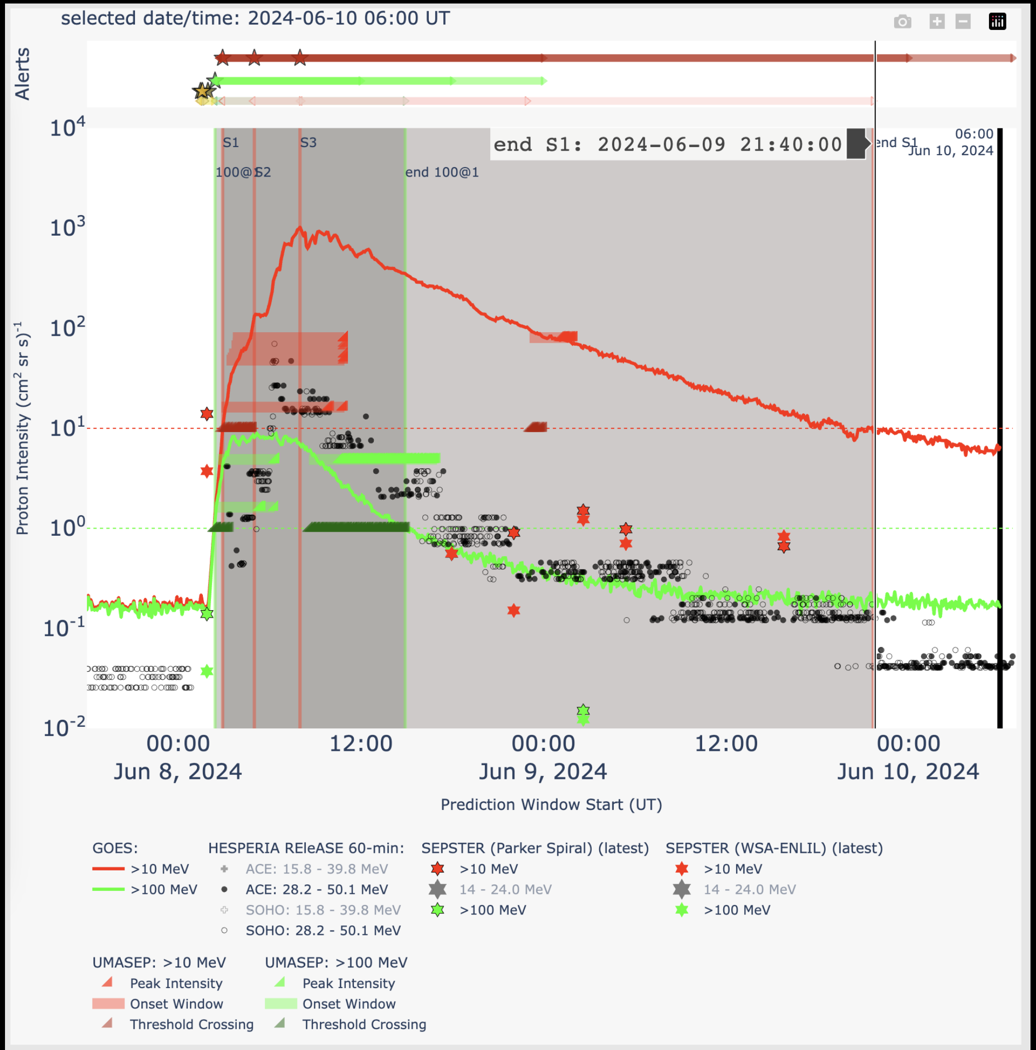
SEP event time evolution and time scales

- Solar flare: 01:37 UT
- Particle increase: 02:00 UT
  Flare + 23 min
- >100 MeV, >1 pfu: 02:25 UT
  Flare + 48 min
- >10 MeV, >10 pfu: 02:55 UT
  Flare + 1 hour 18 min
- SEPMOD: 05:11 UT
  Flare + 3 hours 34 min
- >100 MeV, <1 pfu: 14:55 UT
  Flare + 13 hours 18 min



SEP event time evolution and time scales

- Solar flare: 01:37 UT
- Particle increase: 02:00 UT
  Flare + 23 min
- >100 MeV, >1 pfu: 02:25 UT
  Flare + 48 min
- >10 MeV, >10 pfu: 02:55 UT
  Flare + 1 hour 18 min
- SEPMOD: 05:11 UT
  Flare + 3 hours 34 min
- >100 MeV, <1 pfu: 14:55 UT
  Flare + 13 hours 18 min
- >10 MeV, <10 pfu: 21:40 UT (next day)
  Flare + 1 day 20 hours 3 min



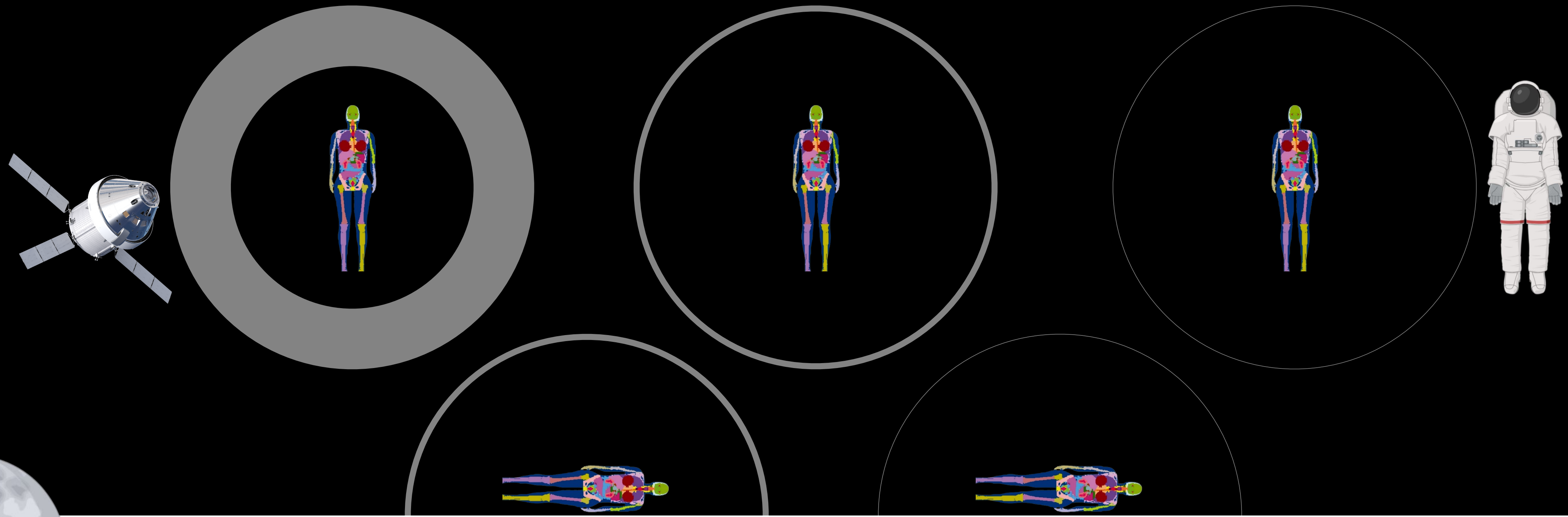
Example events and risk assessment

Shielding scenarios

30 g/cm^2
Thick (Transit vehicle)

3 g/cm^2
Thin (Lunar lander)

0.3 g/cm^2
Very thin (Spacesuit)



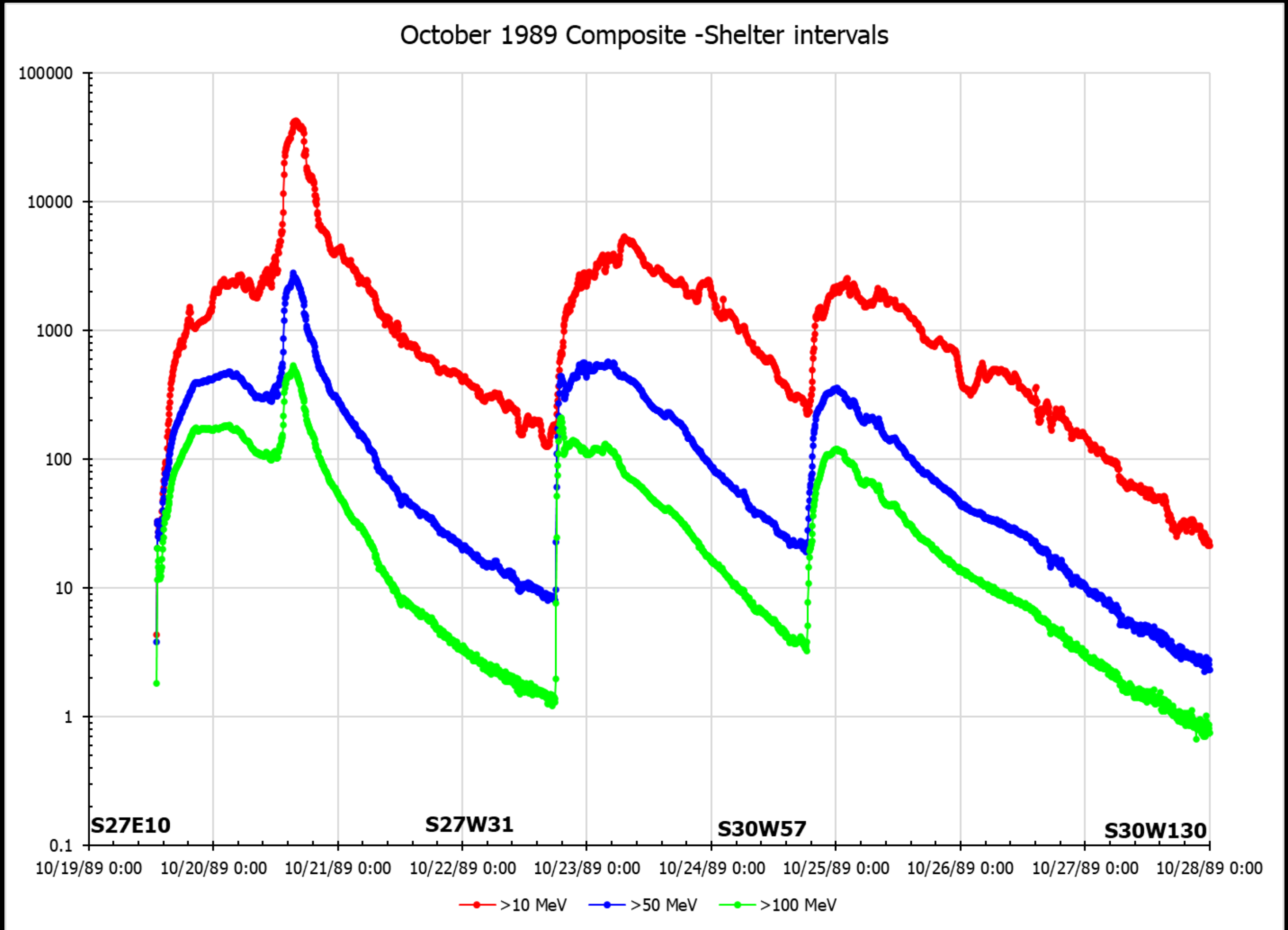
Lunar surface: 2π shielding
Moon blocks all radiation from below

SRAG reference event October 1989

The October 1989 composite events are used as SRAG's design basis event profile

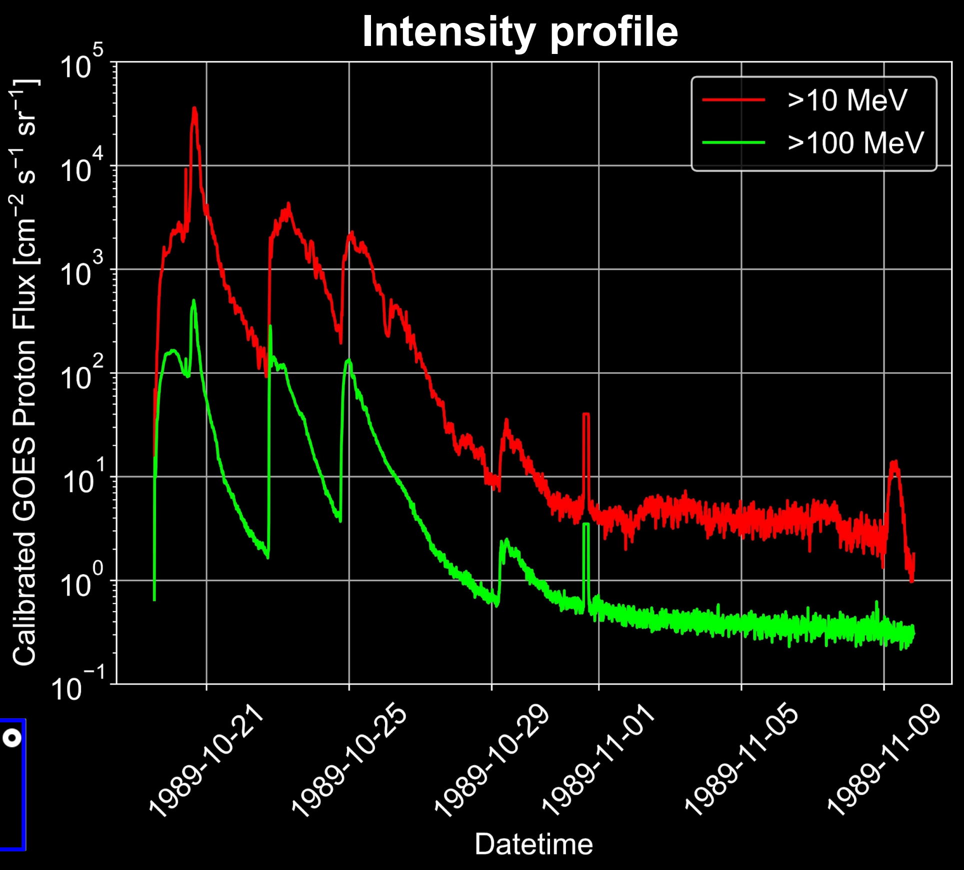
Largest in 40 years

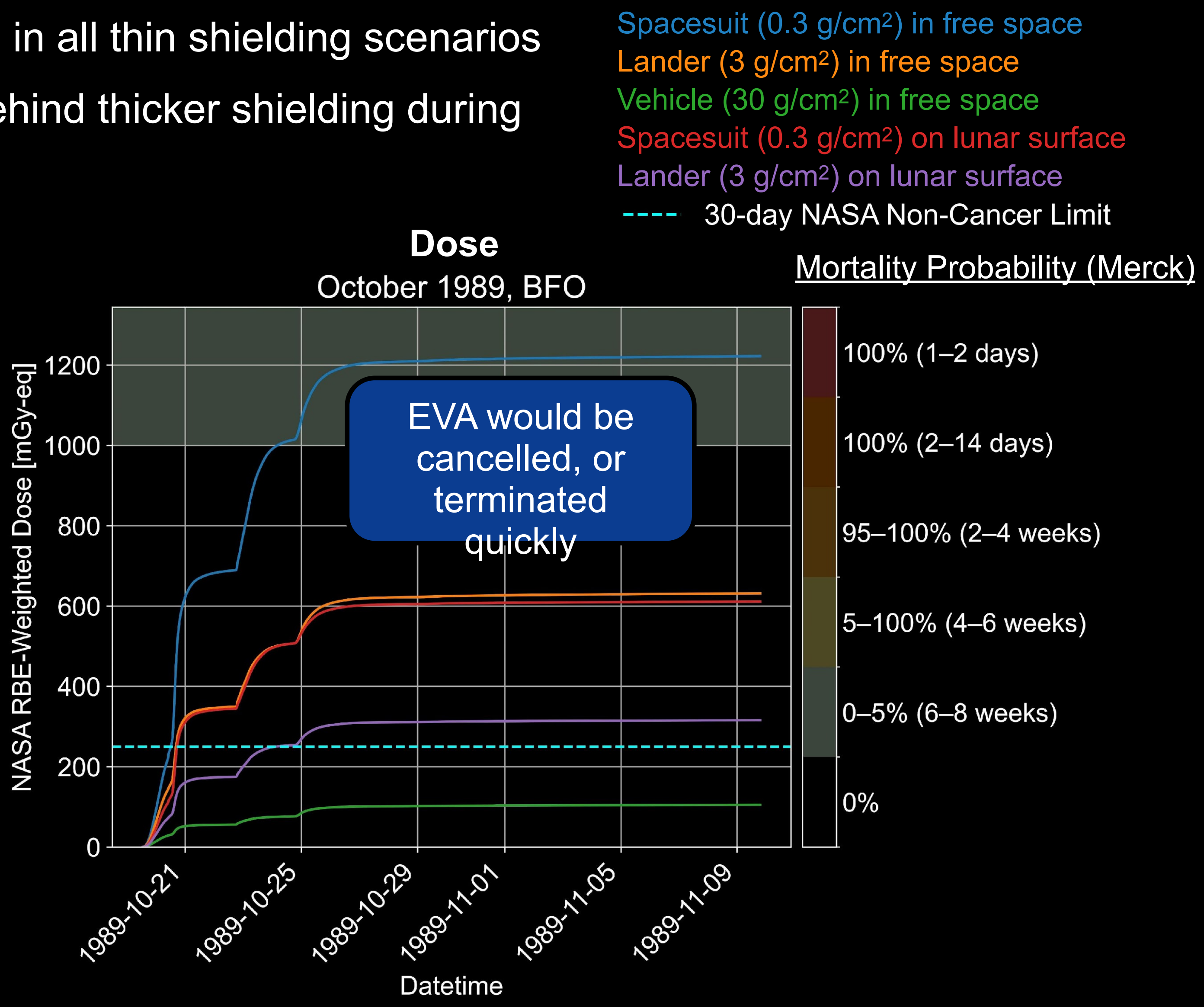
Well characterized by measurements



SRAG reference event October 1989

- 30-day NASA non-cancer limits exceeded in all thin shielding scenarios
- Operationally, astronauts would shelter behind thicker shielding during highest flux periods





Slide credit: SRAG

SRAG reference event October 1989
Acute radiation symptoms

- Use BFO as surrogate for whole-body RBE-weighted dose
- **CAVEAT: symptoms assume exposure occurs all at once and crew takes no protective action during event**

Free Space, Suit

Total dose: 1.2 Gy-eq

Severity: Mild–Moderate

Possible Symptoms:
Nausea
Vomiting
Anorexia
Fatigue
Weakness
Bleeding
Fever
Infection

Mortality: 0–5%

Free Space, Lander

Total dose: 630 mGy-eq

Severity: Mild

Possible Symptoms:
Nausea
Vomiting
Anorexia
Fever

Mortality: 0%

Free Space, Vehicle

Total dose: 100 mGy-eq

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Lunar Surface, Suit

Total dose: 600 mGy-eq

Severity: Mild

Possible Symptoms:
Nausea
Vomiting
Anorexia
Fever

Mortality: 0%

Lunar Surface, Lander

Total dose: 300 mGy-eq

Severity: None

Possible Symptoms:
No effect

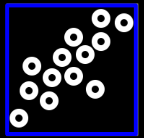
Mortality: 0%

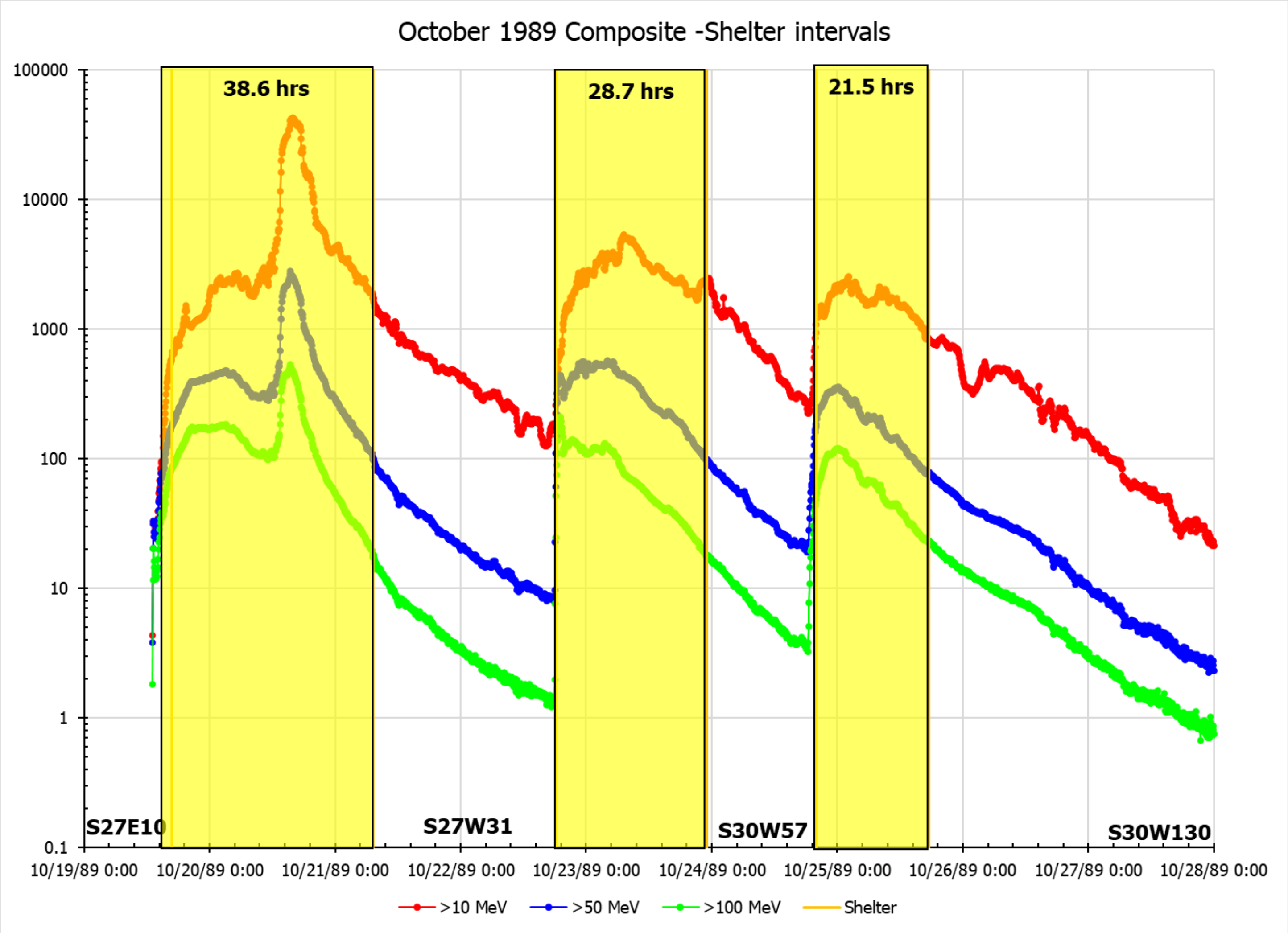
SRAG reference event October 1989

Periods during which Orion crew would shelter if October 1989 were to occur during Artemis II

Event duration: 8.5 days

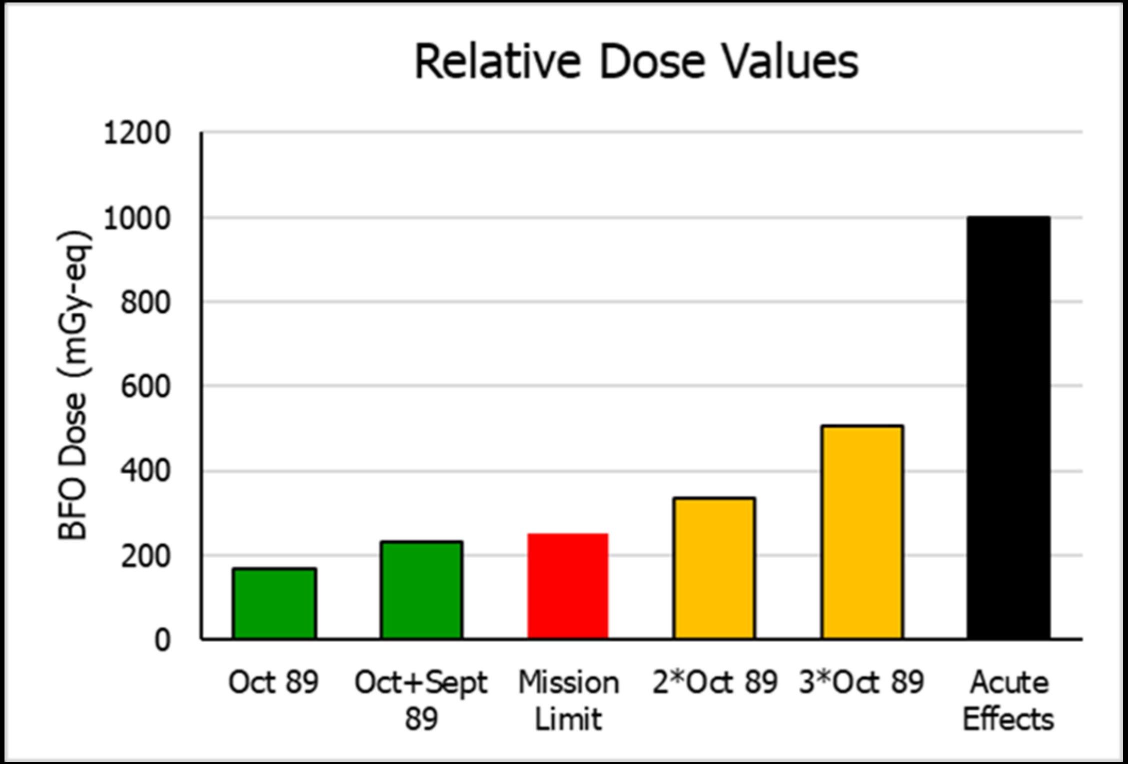
Shelter duration:
89 hours (3.7 days)





SRAG reference event October 1989
What are the risks?

- It would take about 6x the Oct 1989 event to get to an exposure with acute effects
- Typical events: Slight increase in lifetime cancer risk and no observable acute effects
- Extreme events: Significant increase in lifetime cancer risk and low probability risk of moderate effects behind thin shields (EVA)
- Operational procedures (shelter) can mitigate these risks
- EVAs last a maximum of 8 hours, due to oxygen constraints and would be terminated in progress (or cancelled entirely) if dose rate thresholds are exceeded
- Lethal exposures are *extremely* unlikely, even behind thin shields (3 g/cm^2)



Slide credit: SRAG

Quiz: radiation protection & space exploration

The sentences below have multiple options in the brackets: please, choose the best answer to complete each sentence.

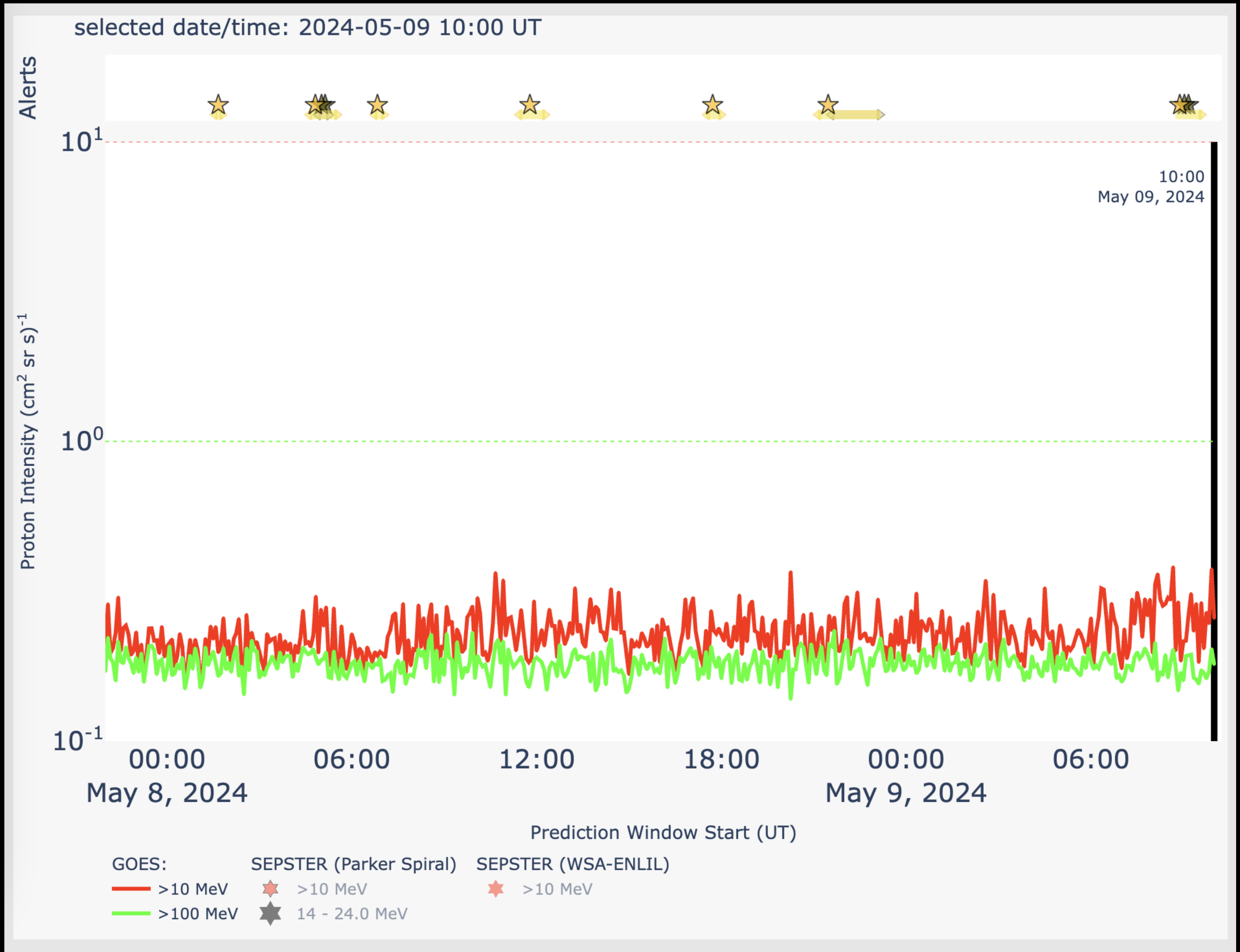
- Space radiation environment is [mild/extreme] compared to terrestrial radiation
- Radiation monitoring, operations, shielding analysis, risk assessment, space weather analysis: [all/some] are necessary to ensure crew health and safety and maintain exposures ALARA
- SEP events inducing mild health symptoms [can/cannot] disrupt operations
- GCR exposure [can/can not] lead to acute radiation symptoms
- SEP events [or/and] GCR exposures contribute to excess cancer risk

Quiz: radiation protection & space exploration

- Space radiation environment is <u>extreme</u> compared to terrestrial radiation
- Radiation monitoring, operations, shielding analysis, risk assessment, space weather analysis: <u>all</u> are necessary to ensure crew health and safety and maintain exposures ALARA
- SEP events inducing mild health symptoms <u>can</u> disrupt operations
  Seemingly mild health impacts can result in undesirable consequences, e.g., astronaut vomits in a spacesuit leading to earlier termination of EVA
  ⇒ Need to understand interactions between operations and health impacts
- GCR exposure <u>can not</u> lead to acute radiation symptoms
- SEP events <u>and</u> GCR exposures contribute to excess cancer risk

Group exercise 1 – May 2024 event

May 2024: Part A



Current time: 2024-05-09T10:00Z

Questions:

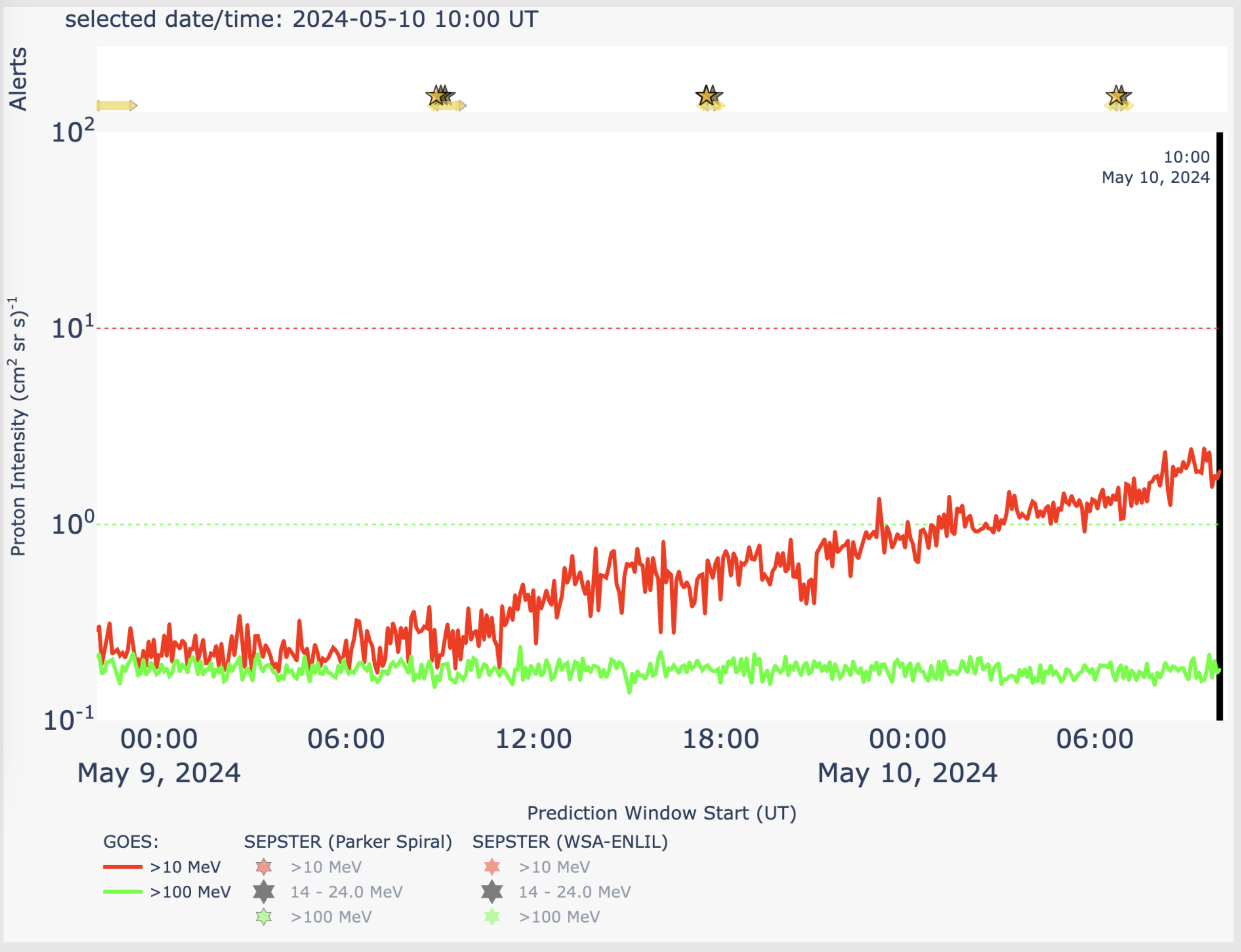
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part B



Current time: 2024-05-10T10:00Z

Questions:

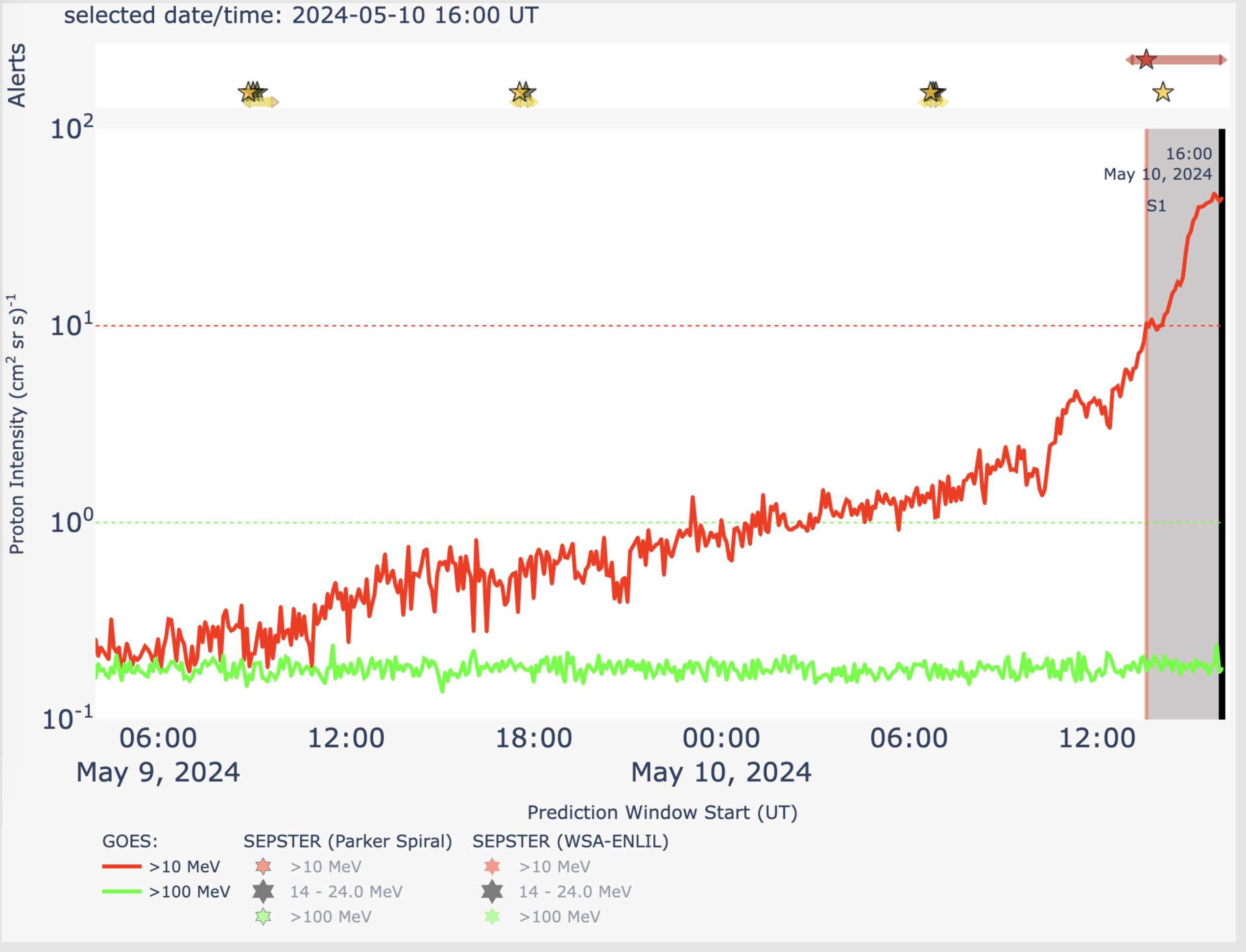
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part C



Current time: 2024-05-10T16:00Z

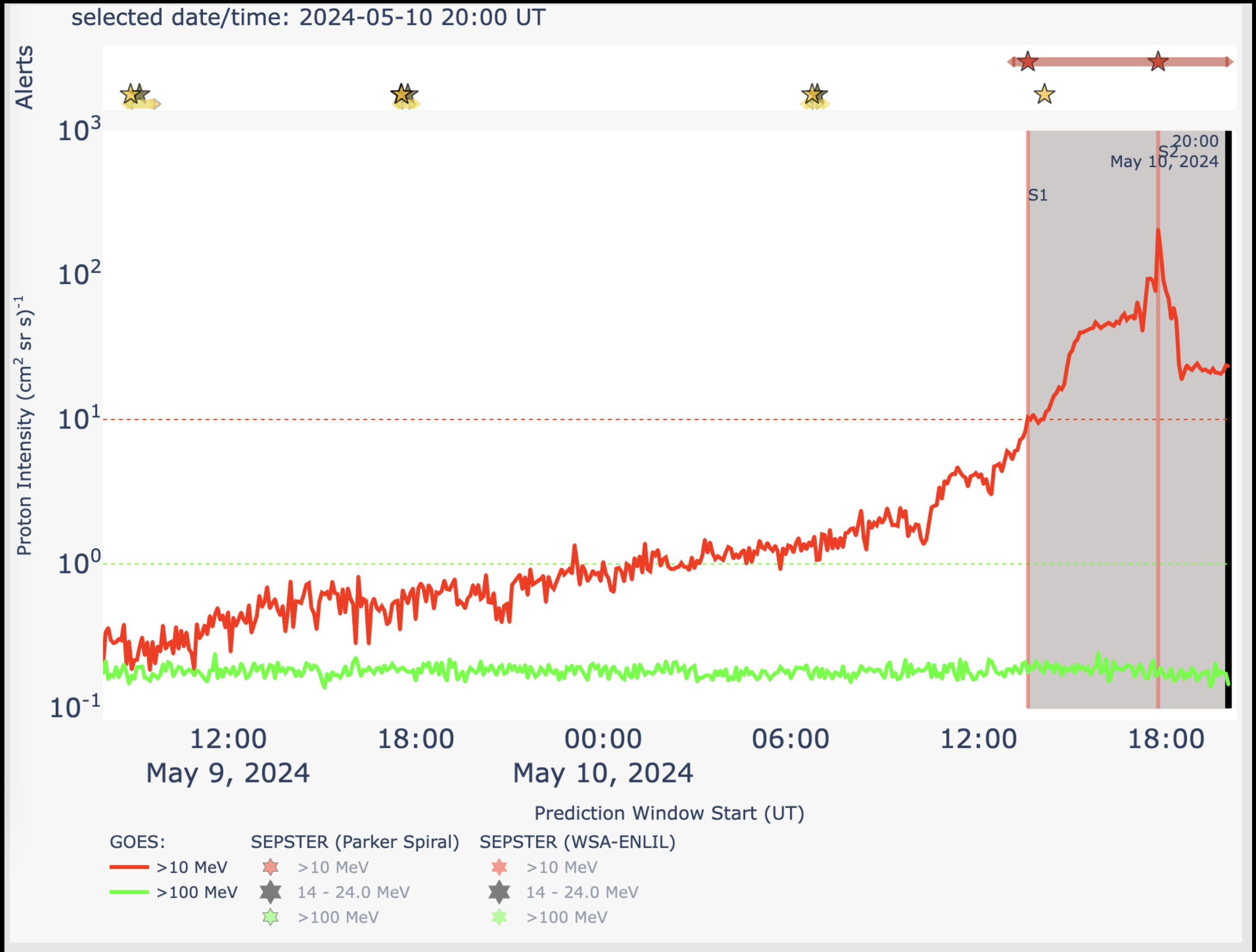
Questions:

1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]
- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part D



Current time: 2024-05-10T20:00Z

Questions:

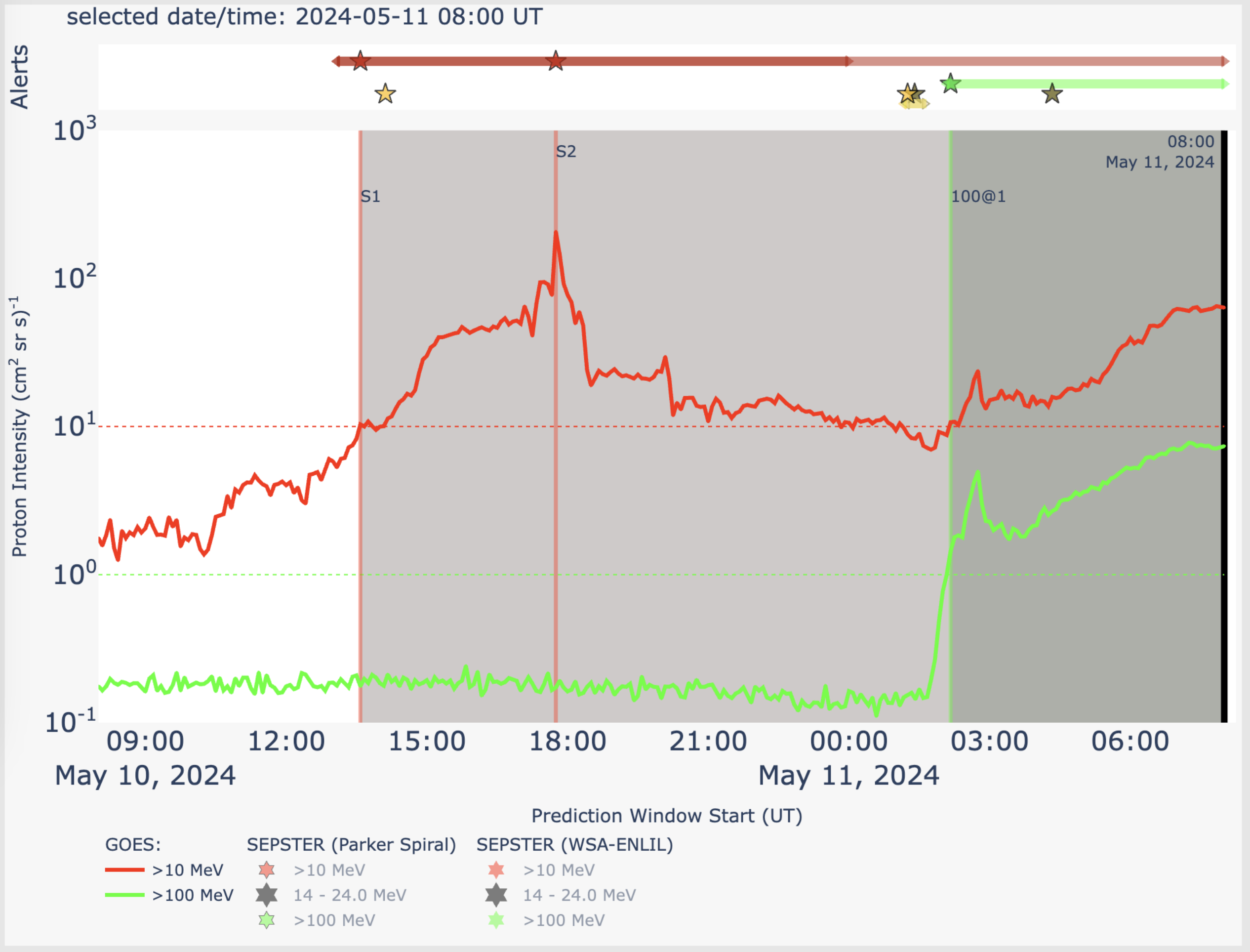
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part E



Current time: 2024-05-11T08:00Z

Questions:

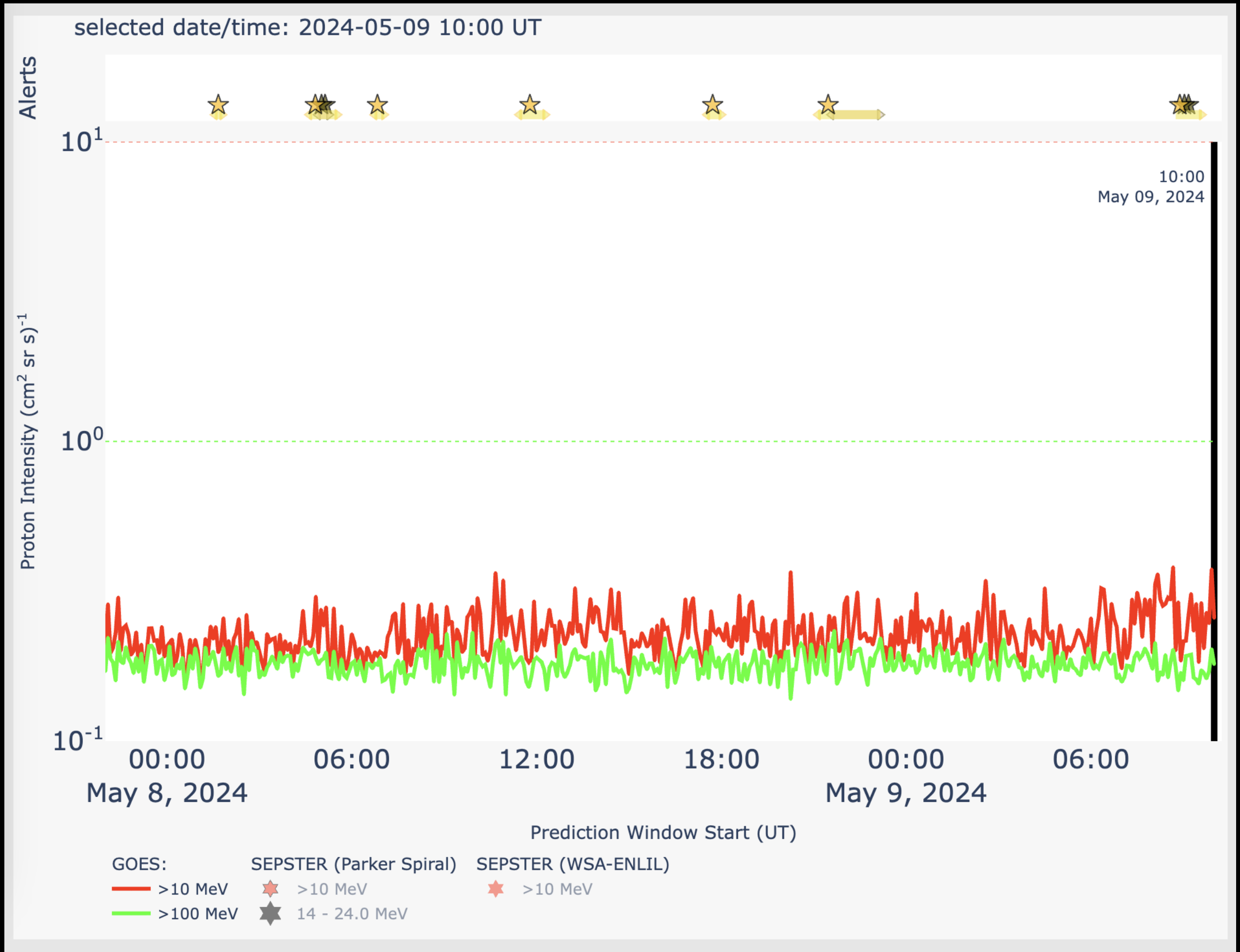
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part A answers



Current time: 2024-05-09T10:00Z

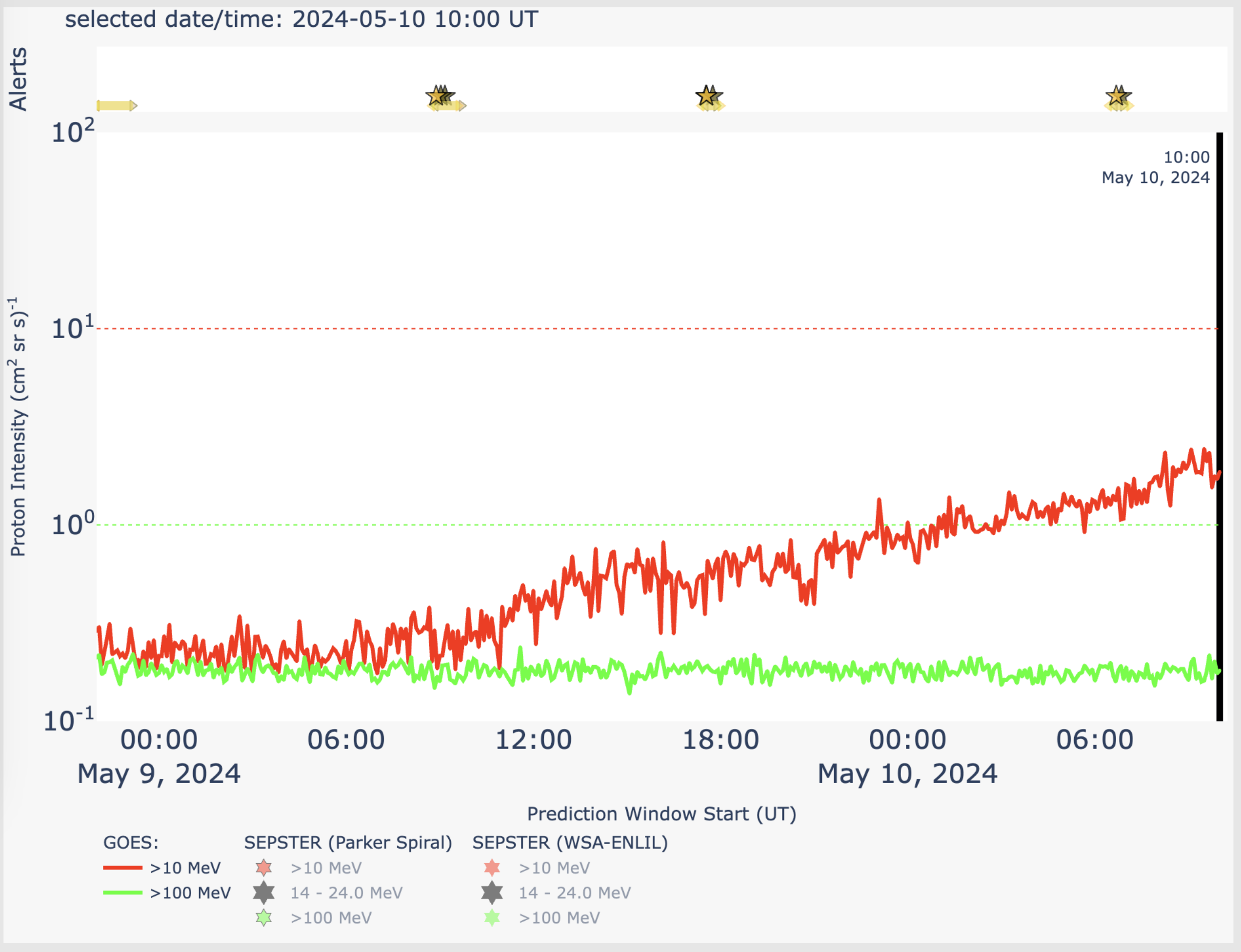
Questions:

1) Are conditions nominal (at background levels) or elevated? Nominal

2) Have any thresholds been exceeded?
- GOES >10 MeV >10pfu No
- GOES >100 MeV >1 pfu No
- GOES >100 MeV >50 pfu No

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? No

May 2024: Part B answers



Current time: 2024-05-10T10:00Z

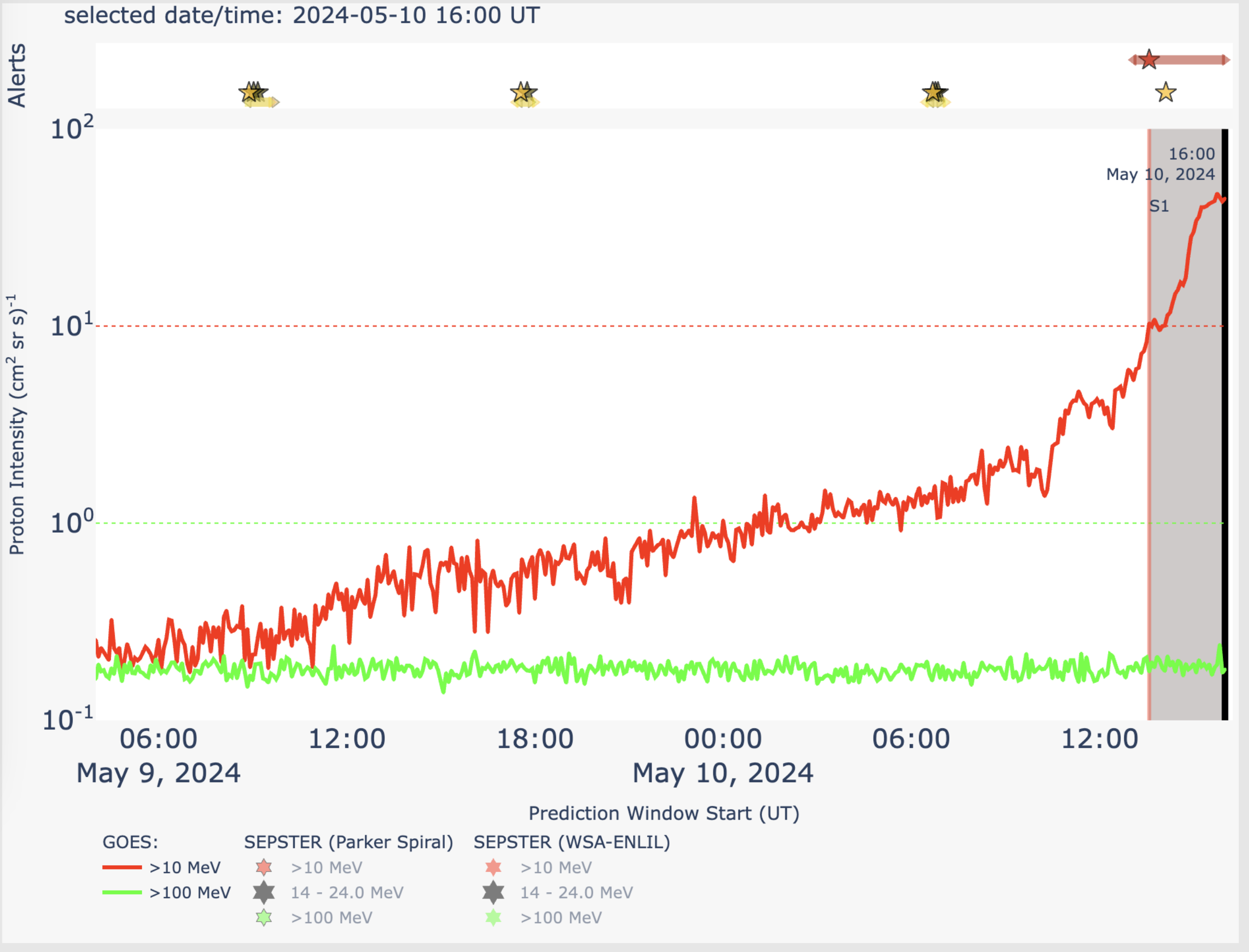
Questions:

1) Are conditions nominal (at background levels) or elevated? Elevated

2) Have any thresholds been exceeded?
- GOES >10 MeV >10pfu No
- GOES >100 MeV >1 pfu No
- GOES >100 MeV >50 pfu No

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? No

May 2024: Part C answers



Current time: 2024-05-10T16:00Z

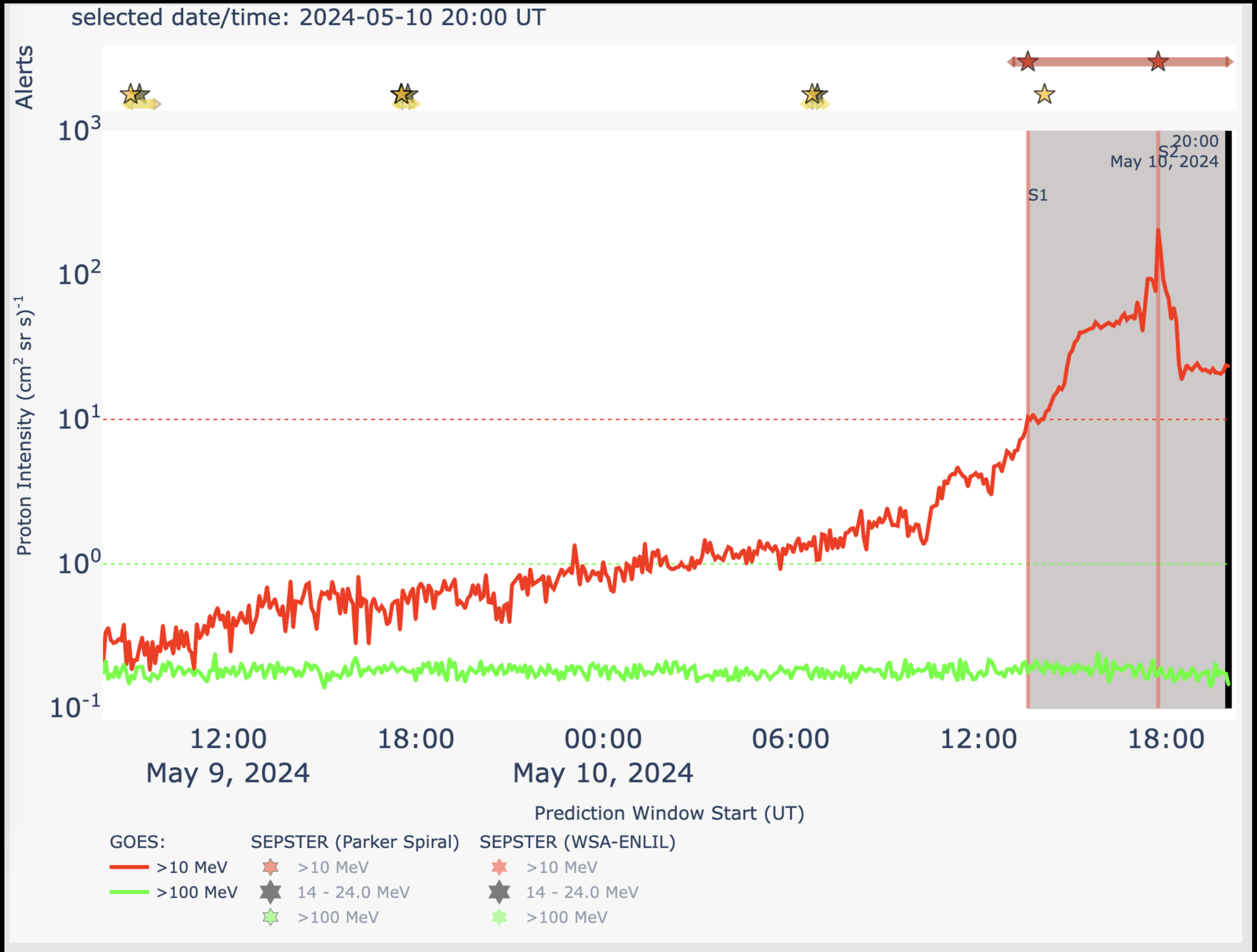
Questions:

1) Are conditions nominal (at background levels) or elevated? Elevated

2) Have any thresholds been exceeded?
- GOES >10 MeV >10pfu Yes
- GOES >100 MeV >1 pfu No
- GOES >100 MeV >50 pfu No

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? No

May 2024: Part D answers



Current time: 2024-05-10T20:00Z

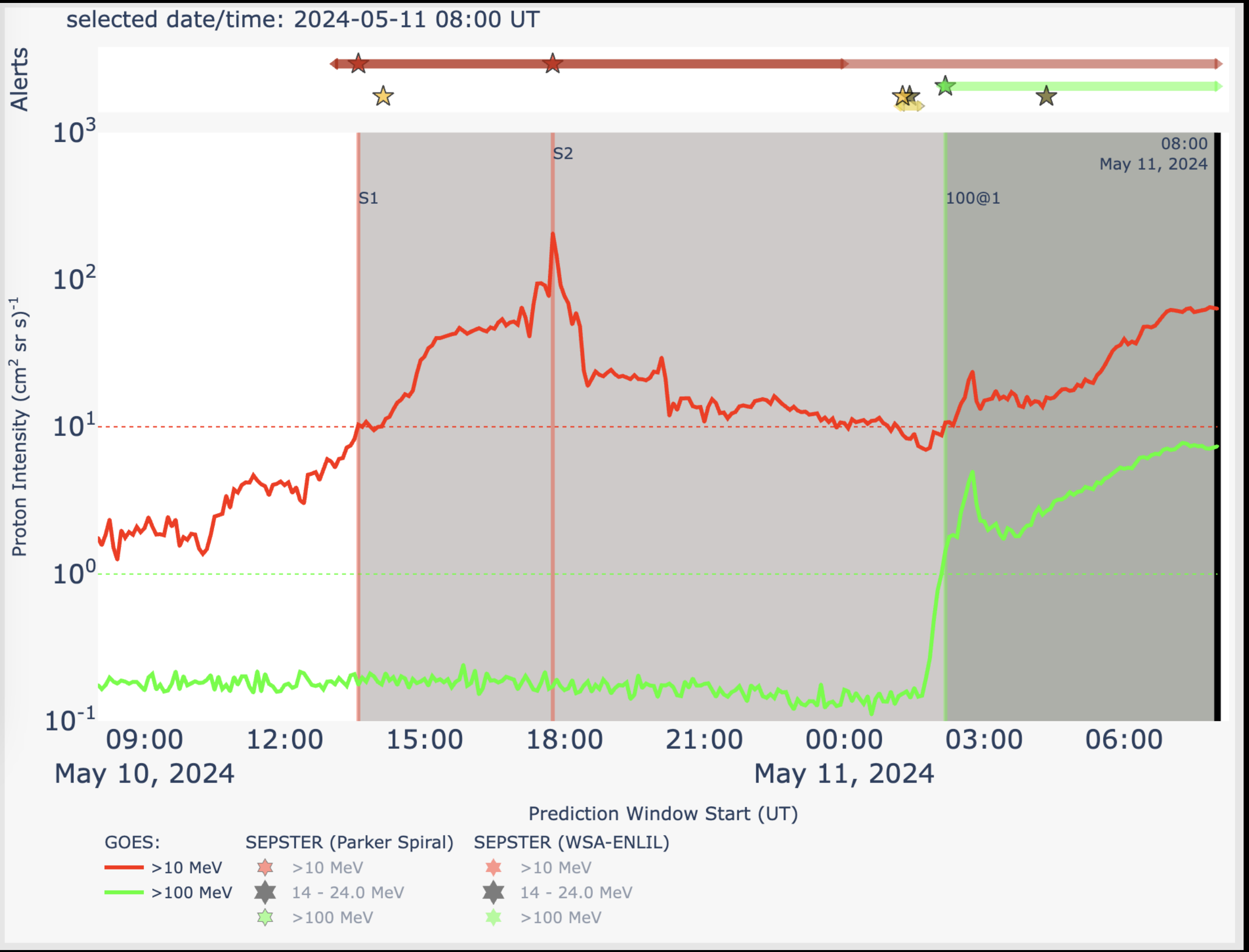
Questions:

1) Are conditions nominal (at background levels) or elevated? Elevated

2) Have any thresholds been exceeded?
- GOES >10 MeV >10pfu Yes
- GOES >100 MeV >1 pfu No
- GOES >100 MeV >50 pfu No

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? No

May 2024: Part E answers



Current time: 2024-05-11T08:00Z

Questions:

1) Are conditions nominal (at background levels) or elevated? Elevated

2) Have any thresholds been exceeded?
- GOES >10 MeV >10pfu Yes
- GOES >100 MeV >1 pfu Yes
- GOES >100 MeV >50 pfu No

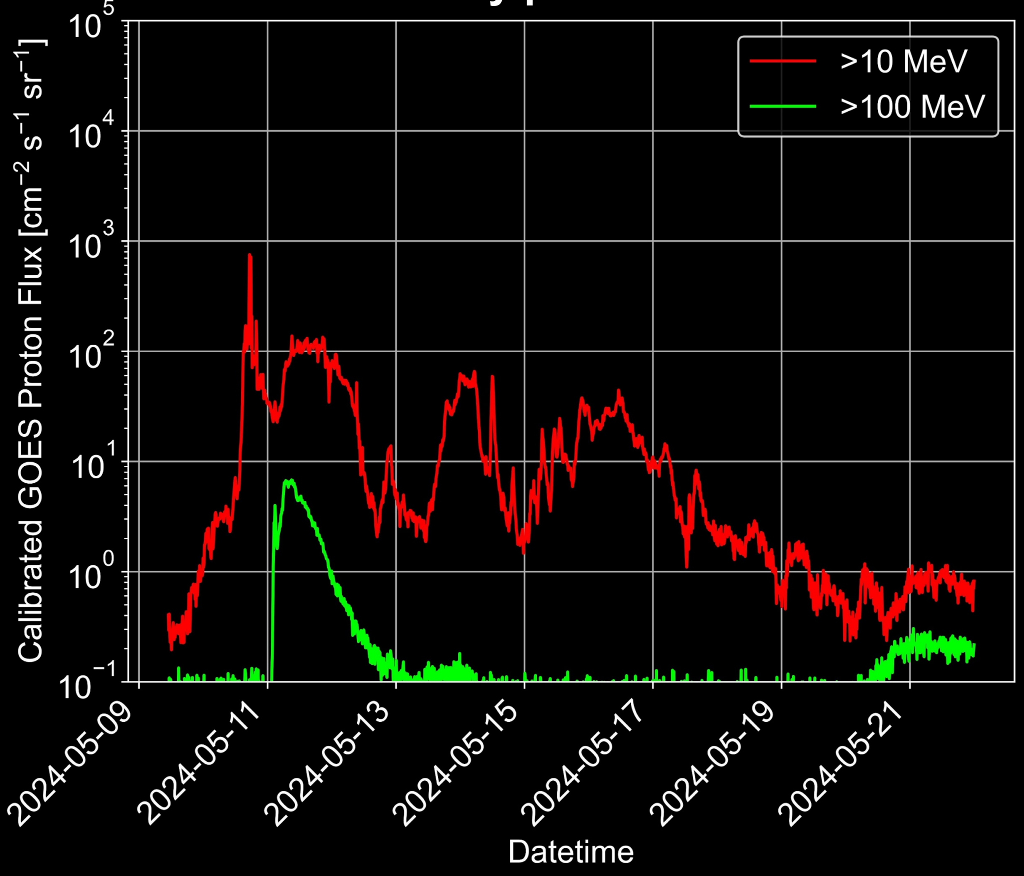
3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? No

May 2024: Part F

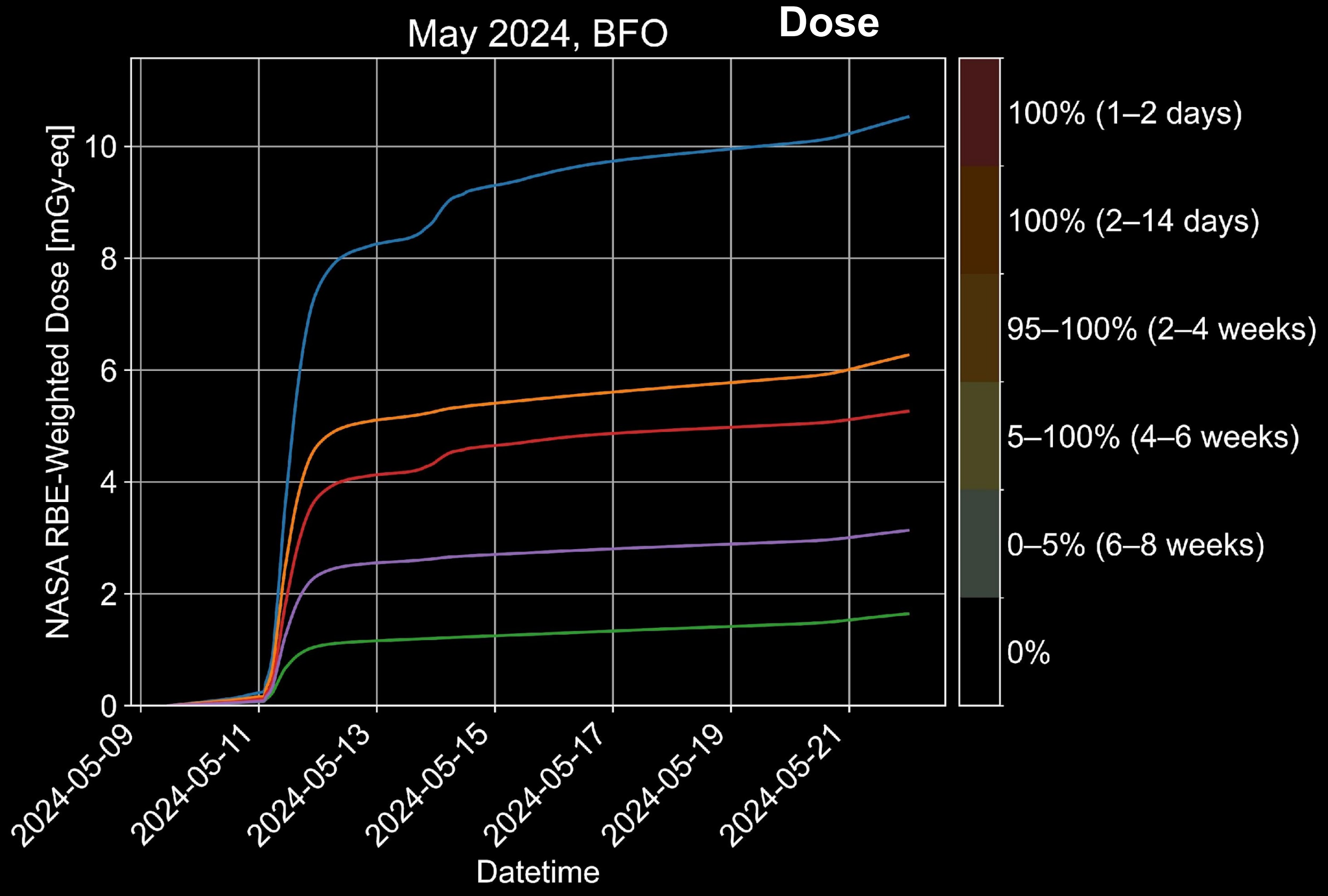
Questions:
1) Using the Dose plot, what is the mortality probability for this event, for each shielding scenario?
2) For the least shielded case (spacesuit in free space) what is the approximate dose? At this dose, will there be acute radiation effects (see slide 30 for symptoms)?

Spacesuit (0.3 g/cm²) in free space
Lander (3 g/cm²) in free space
Vehicle (30 g/cm²) in free space
Spacesuit (0.3 g/cm²) on lunar surface
Lander (3 g/cm²) on lunar surface

Intensity profile



Dose



Slide credit: SRAG

May 2024: Part F answers

- Use BFO as surrogate for whole-body RBE-weighted dose
- **<u>CAVEAT</u>: symptoms assume exposure occurs all at once and crew takes no protective action during event**

<u>Free Space, Suit</u>

<u>Total dose</u>: 11 mGy-eq

<u>Severity:</u> None

<u>Possible Symptoms:</u>
No effect

Mortality: 0%

<u>Free Space, Lander</u>

<u>Total dose</u>: 6 mGy-eq

<u>Severity:</u> None

<u>Possible Symptoms:</u>
No effect

Mortality: 0%

<u>Free Space, Vehicle</u>

<u>Total dose</u>: 5 mGy-eq

<u>Severity:</u> None

<u>Possible Symptoms:</u>
No effect

Mortality: 0%

<u>Lunar Surface, Suit</u>

<u>Total dose</u>: 3 mGy-eq

<u>Severity:</u> None

<u>Possible Symptoms:</u>
No effect

Mortality: 0%

<u>Lunar Surface, Lander</u>

<u>Total dose</u>: 2 mGy-eq

<u>Severity:</u> None

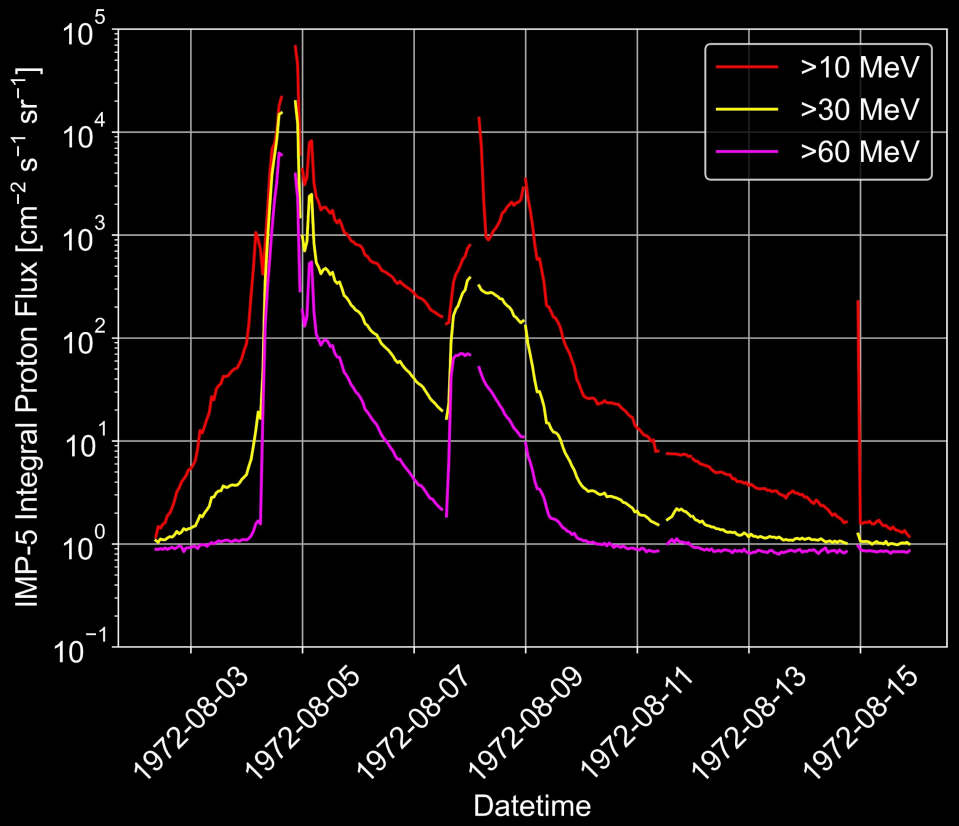
<u>Possible Symptoms:</u>
No effect

Mortality: 0%

Slide credit: SRAG

Group exercise 2 – August 1972 event

This event occurred between the Apollo-16 and Apollo-17 missions
Common wisdom claims it would have killed astronauts: is that true?



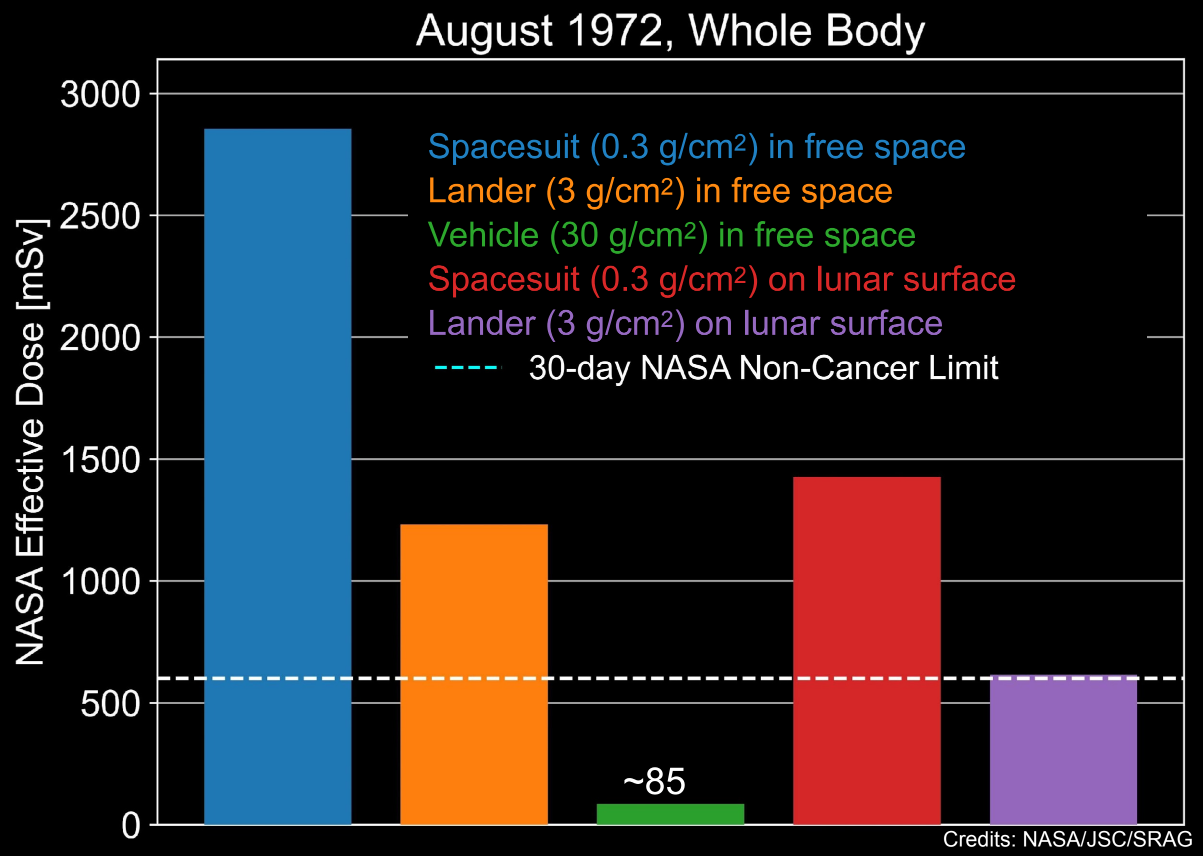
Dose rate profile unavailable

In the absence of reliable high energy proton data, King (1972) differential fluence spectrum used (no time resolution)

King, Solar proton fluences for 1977–1983 space missions. (1974). *J. Spacecraft*, *11(6)*

August 1972: Part A

Question: Which shielding scenarios lead to an exceedance of the career dose limit?

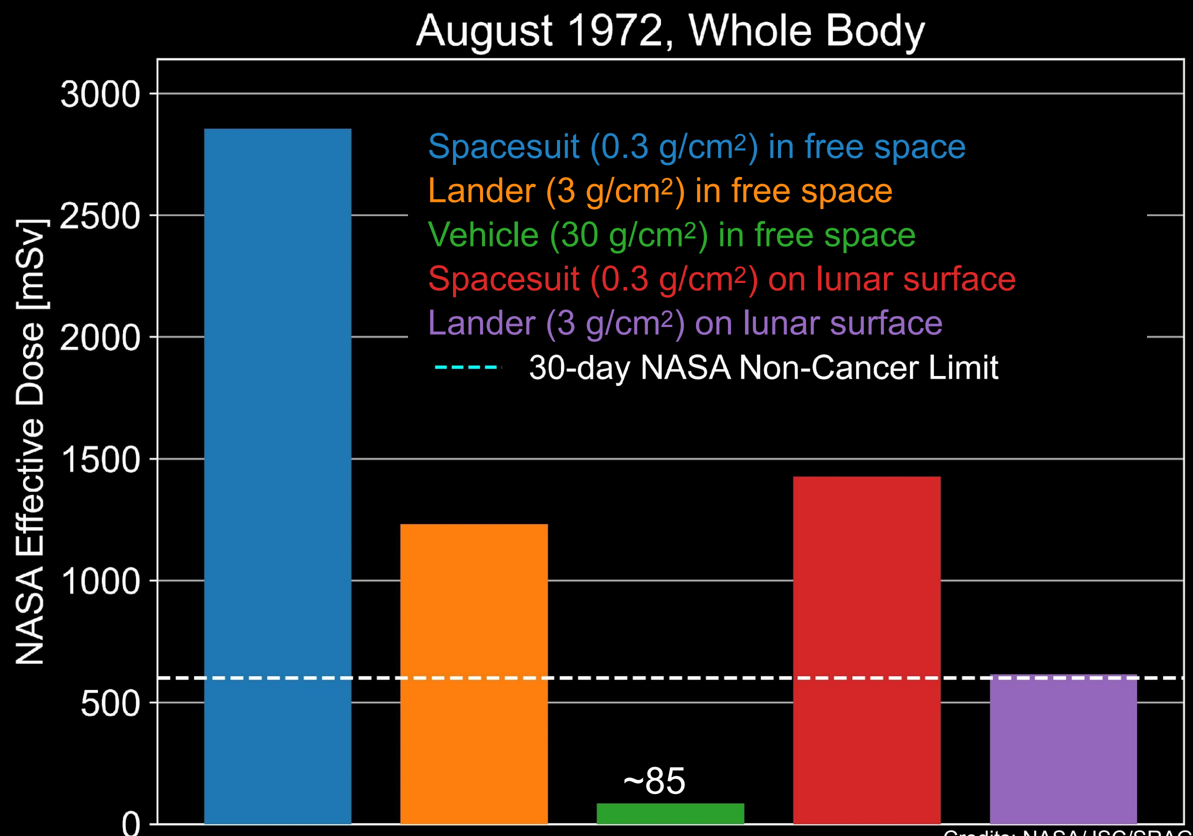


Caveat: Assumes extended exposure period with non-realistic conditions (12-day EVA)

August 1972: Part A answers

Question: Which shielding scenarios lead to an exceedance of the career dose limit?

Answer: Career dose limit exceeded in all scenarios, except in vehicle (thick shielding)



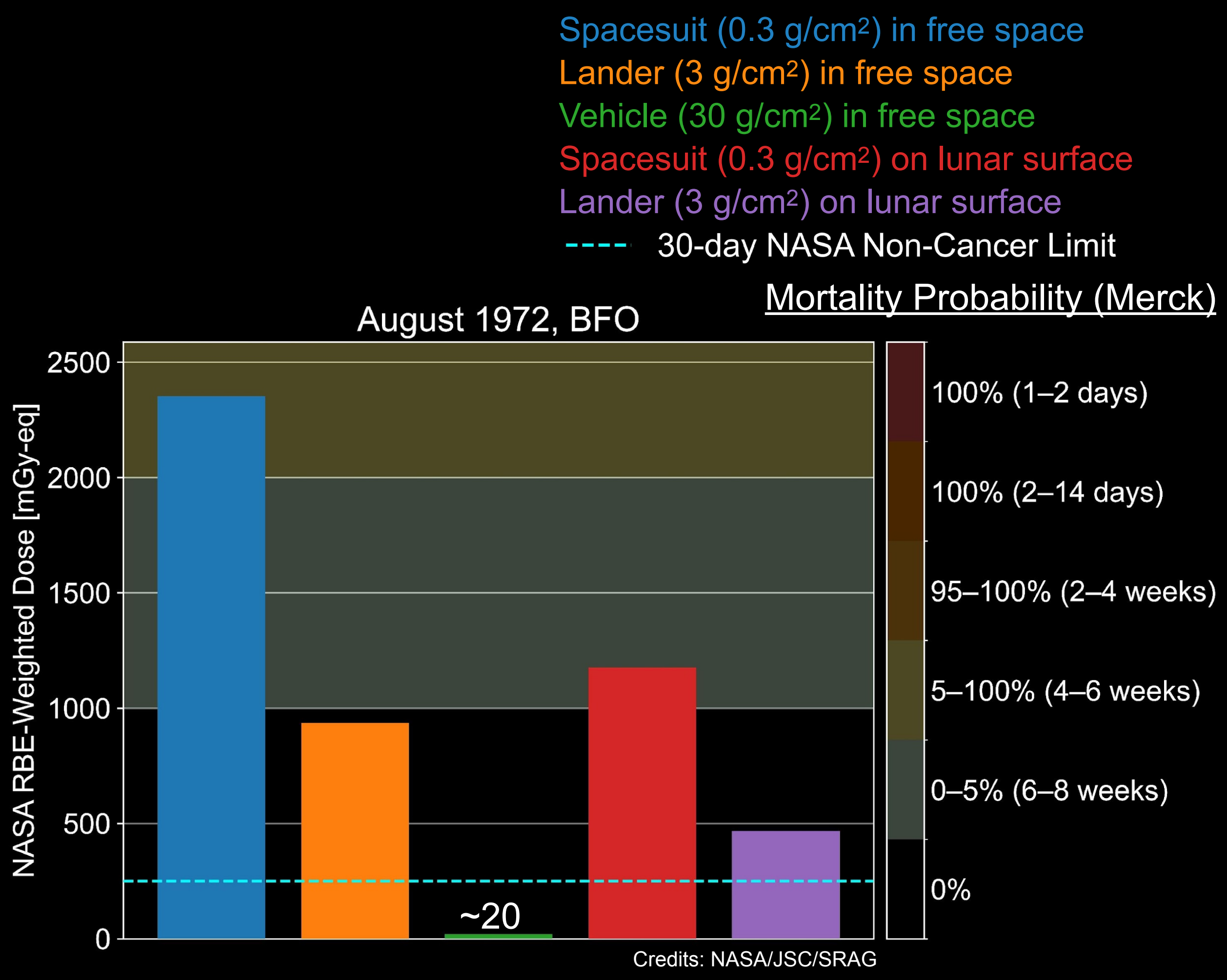
Credits: NASA/JSC/SRAG

Caveat: Assumes extended exposure period with non-realistic conditions (12-day EVA)

August 1972: Part B

Question 1: Which shielding scenarios lead to an exceedance of the 30-day NASA non-cancer dose limit?

Question 2: What is the mortality probability in each shielding scenario?



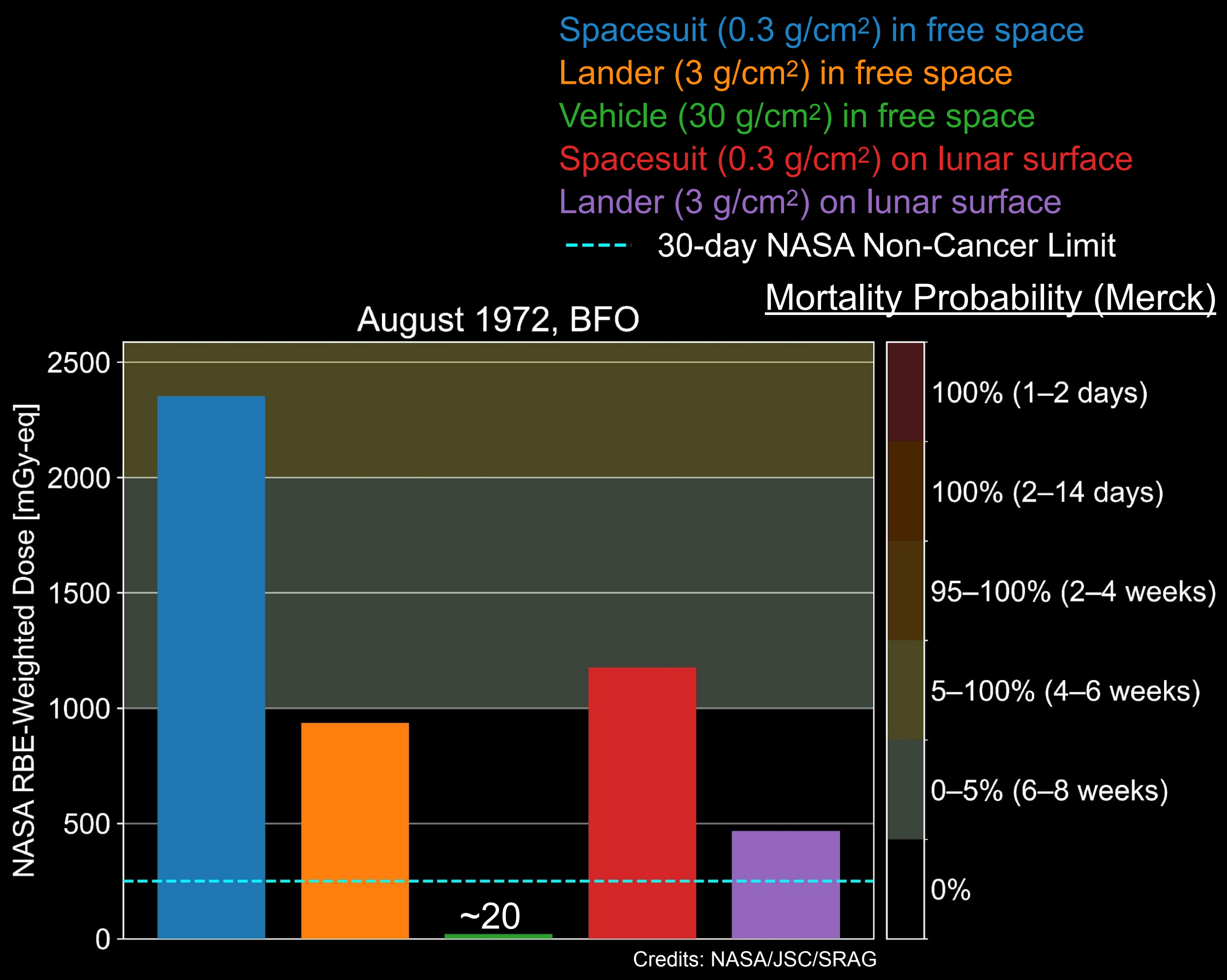
Caveat: Assumes extended exposure period with non-realistic conditions (12-day EVA)

August 1972: Part B answers

Question 1: Which shielding scenarios lead to an exceedance of the 30-day NASA non-cancer dose limit?
Answer: 30-day NASA non-cancer limits exceeded in all scenarios, except in vehicle (thick shielding)

Question 2: What is the mortality probability in each shielding scenario?
See next slide

Caveat: Assumes extended exposure period with non-realistic conditions (12-day EVA)



August 1972: Part B answers

- Use BFO as surrogate for whole-body RBE-weighted dose
- **CAVEAT: symptoms assume exposure occurs all at once and crew takes no protective action during event**
- Moderate severity health effects in suit-only shield cases

Free Space, Suit

Total dose: 2.3 Gy-eq

Severity: Moderate

Possible Symptoms:
Nausea
Vomiting
Anorexia
Diarrhea
Fatigue
Weakness
Bleeding
Fever
Ulceration

Mortality: 5–50%
(closer to 5% than 50%)

Free Space, Lander

Total dose: 940 mGy-eq

Severity: Mild

Possible Symptoms:
Nausea
Vomiting
Anorexia
Fever

Mortality: 0%

Free Space, Vehicle

Total dose: 20 mGy-eq

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Lunar Surface, Suit

Total dose: 1.2 Gy-eq

Severity: Mild–Moderate

Possible Symptoms:
Nausea
Vomiting
Anorexia
Fatigue
Weakness
Bleeding
Fever
Infection

Mortality: 0–5%

Lunar Surface, Lander

Total dose: 480 mGy-eq

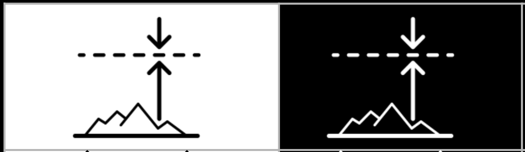
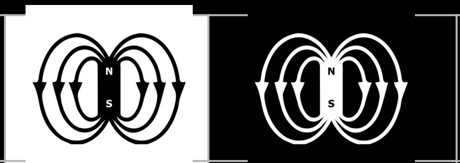
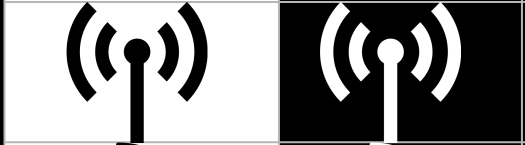
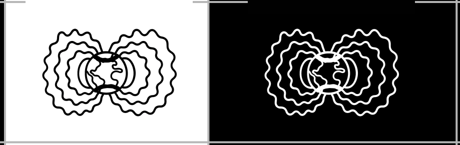
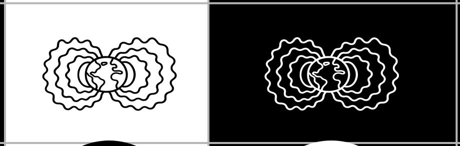
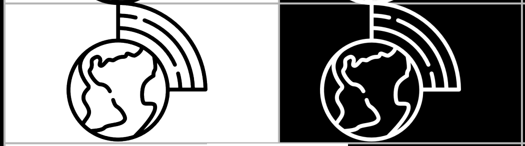
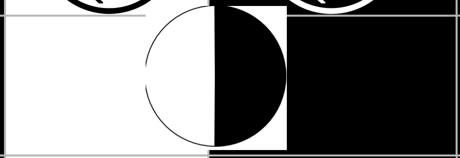
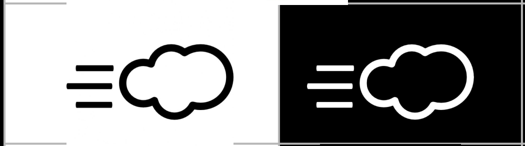
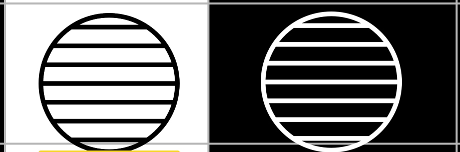
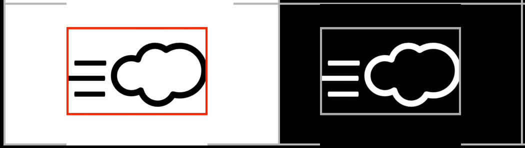
Severity: None

Possible Symptoms:
No effect

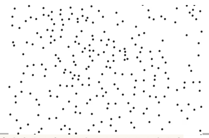
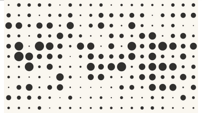
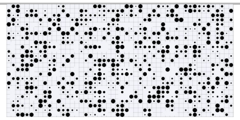
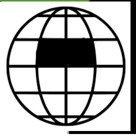
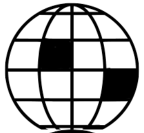
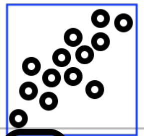
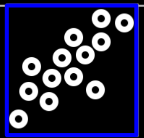
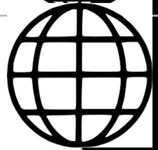
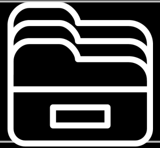
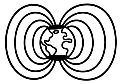
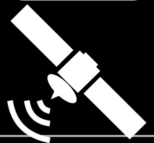
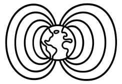
Mortality: 0%

Backup slides

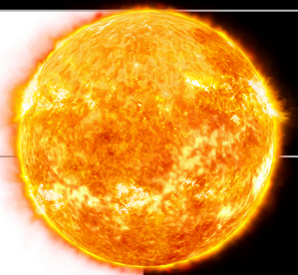
Icons

	Altitude		dipole
	Antenna		disturbed magnetic field auroral oval
	atmosphere polar cap		disturbed magnetosphere
	atmosphere		earth continents
	blue earth		Earth day/night
	cloud with wind no frame		earth latitude
	cloud with wind		EGSOL

Icons

		electrons scintillation			planet
		electrons scintillation			IO
		electrons scintillation			scintillation
		EM radiation			velekken copy
		energetic particles			earth
		folder archive icon			magnetosphere polar caps
		FP Satellite Icon			magnetosphere

Icons

		mass			sun!
		plane			
		polar caps			transmit time
		position earth			fast particles 2
		radiation			
		satellite			
		scale			

Quiz: From measurements to health effects

In the table below, the concepts, quantities, and units rows are all mixed up. Please, match the **concept**, **quantity**, and **units**, then sort them in the order needed to derive health effects for a specific radiation field.

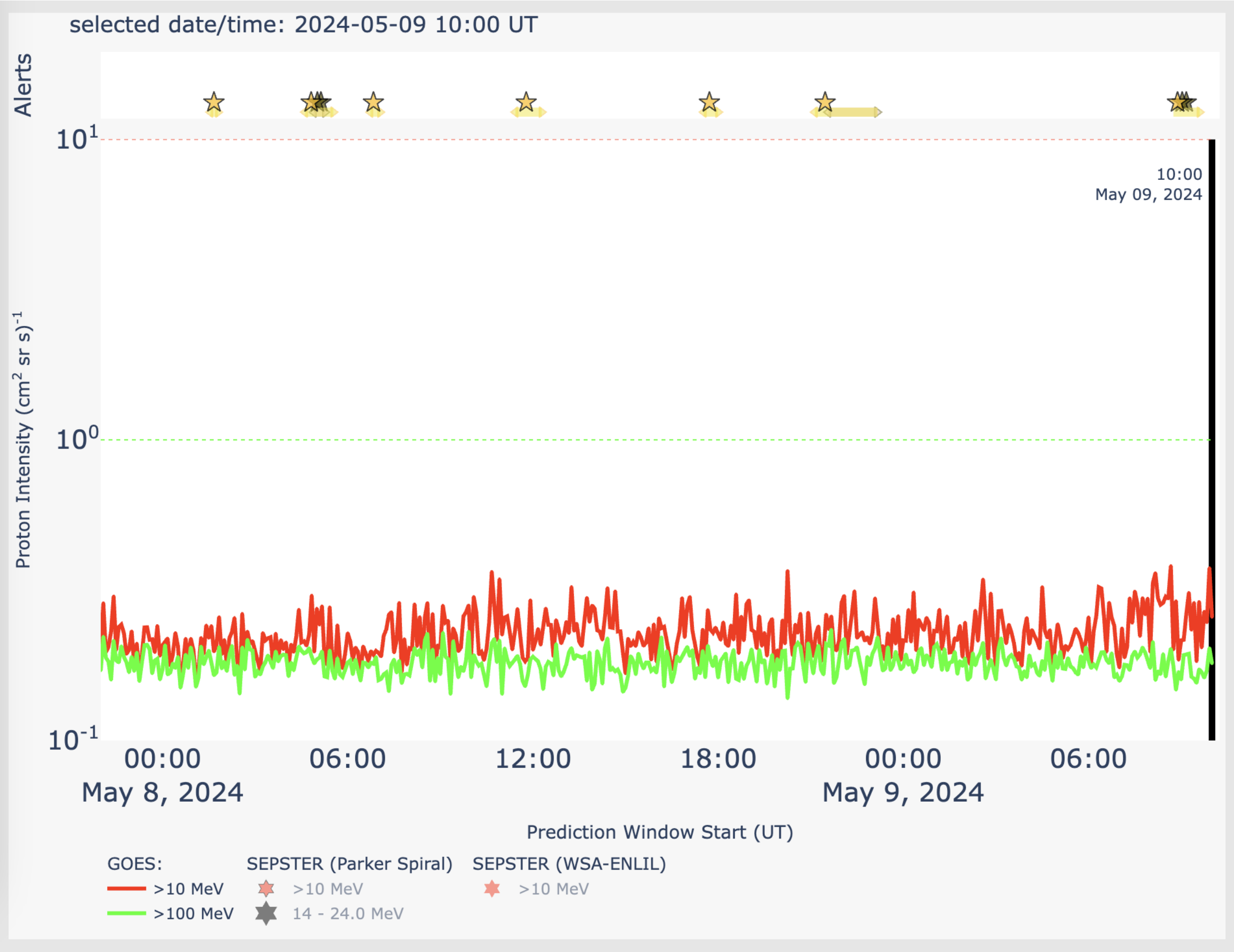
Concept	Quantity	Units
Biological impact on specific tissue	Spectrum	Gy-eq
Particles	RBE, RBE-weighted dose	Sv
Whole-body cancer risk	Dose equivalent	particles/(area time energy)
Dose measurement	Effective dose	Sv
Lab experiment for biological endpoint	Absorbed dose	Gy

Quiz: radiation protection & space exploration

The sentences below have multiple options in the brackets: please, choose the best answer to complete each sentence.

- Space radiation environment is [mild/extreme] compared to terrestrial radiation
- Radiation monitoring, operations, shielding analysis, risk assessment, space weather analysis: [all/some] are necessary to ensure crew health and safety and maintain exposures ALARA
- SEP events inducing mild health symptoms [can/cannot] disrupt operations
- GCR exposure [can/can not] lead to acute radiation symptoms
- SEP events [or/and] GCR exposures contribute to excess cancer risk

May 2024: Part A



Current time: 2024-05-09T10:00Z

Questions:

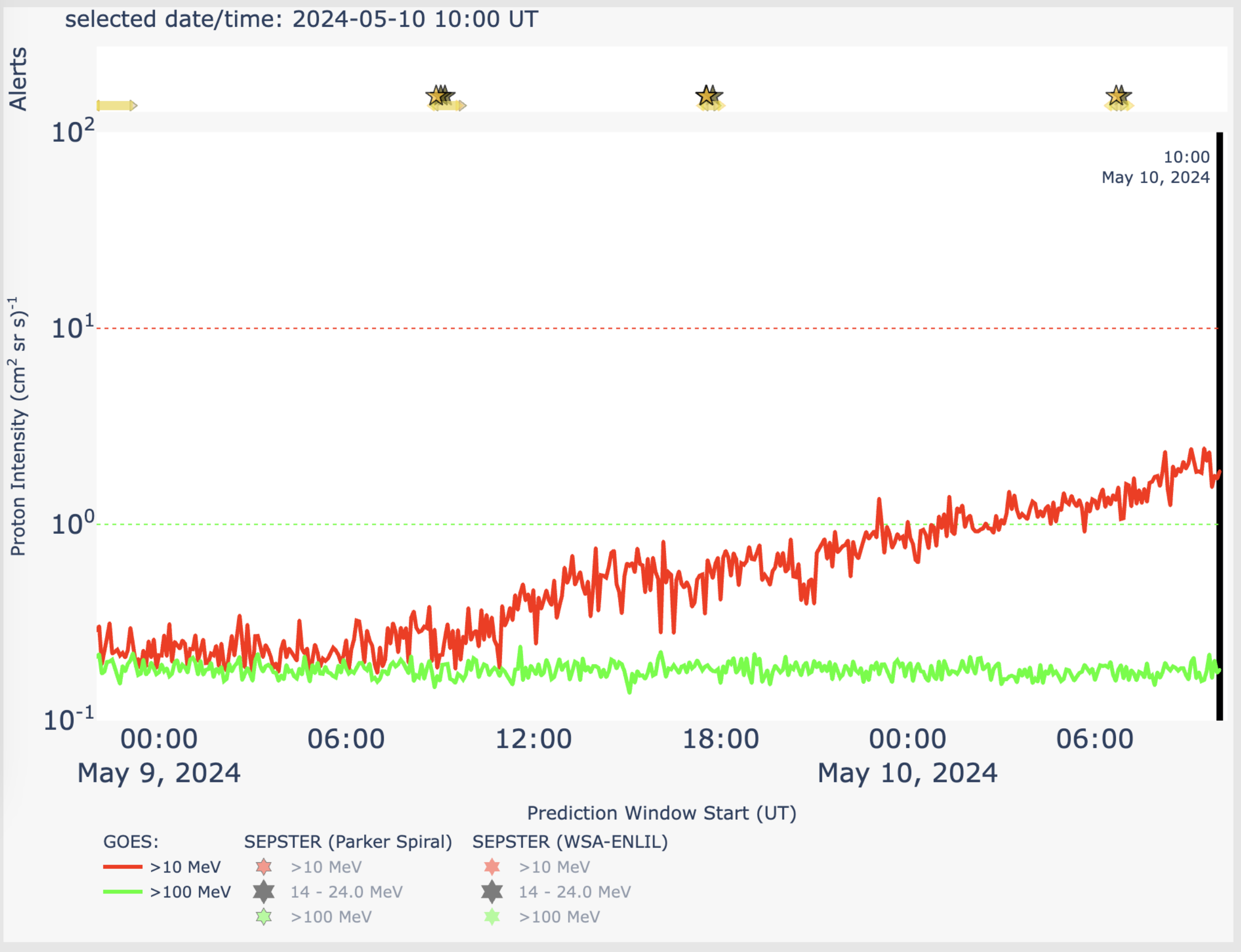
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part B



Current time: 2024-05-10T10:00Z

Questions:

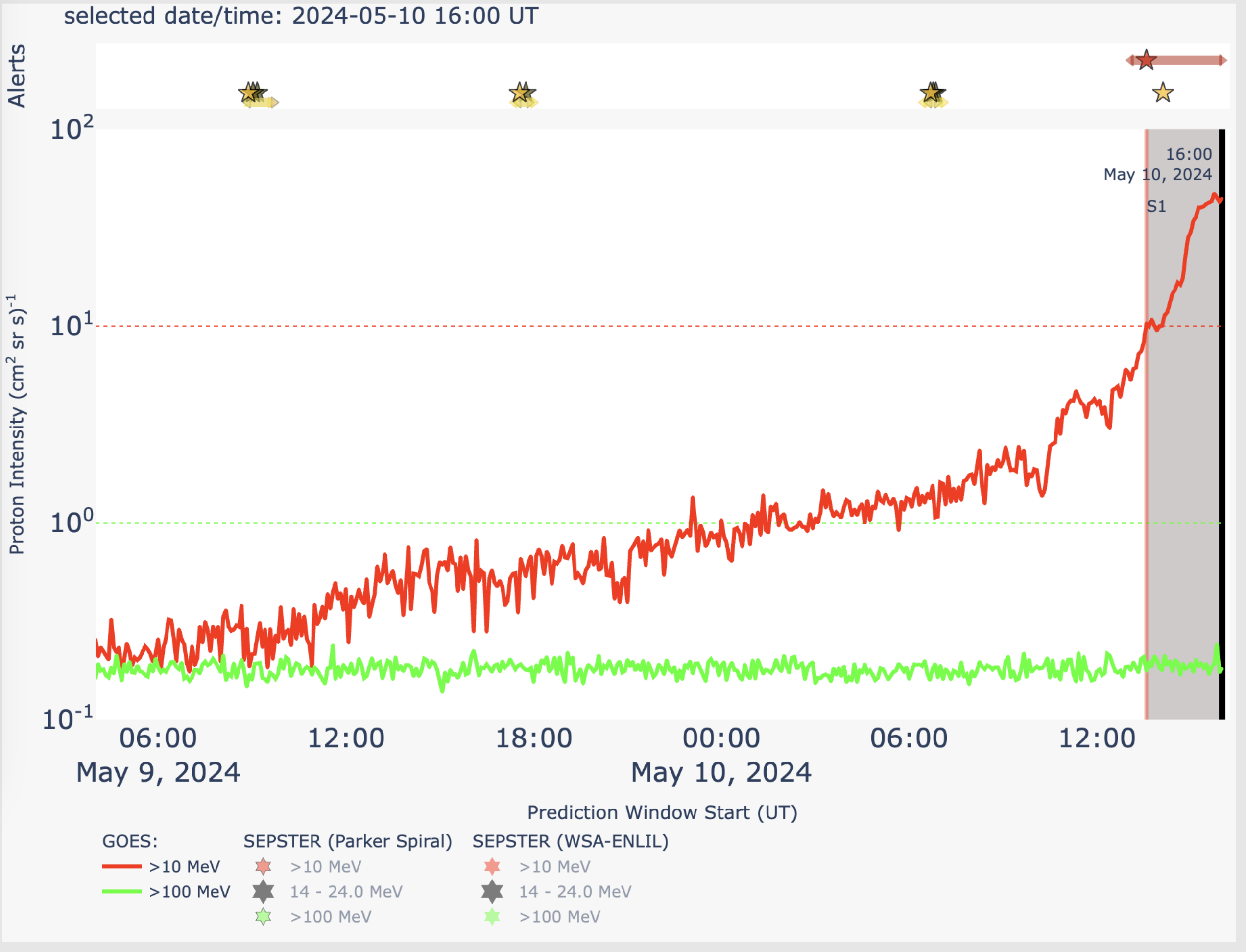
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part C



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Questions:

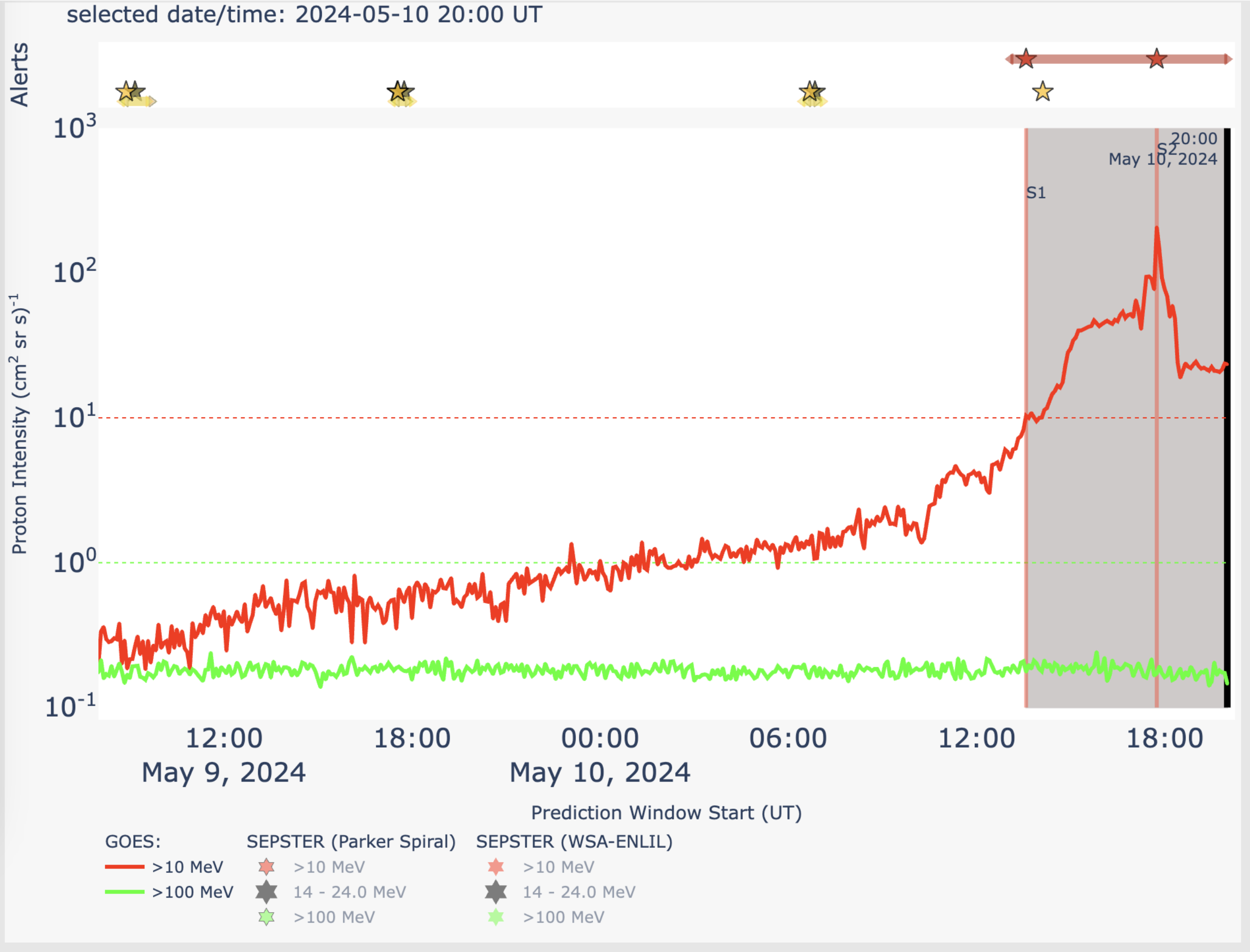
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part D



Current time: 2024-05-10T20:00Z

Questions:

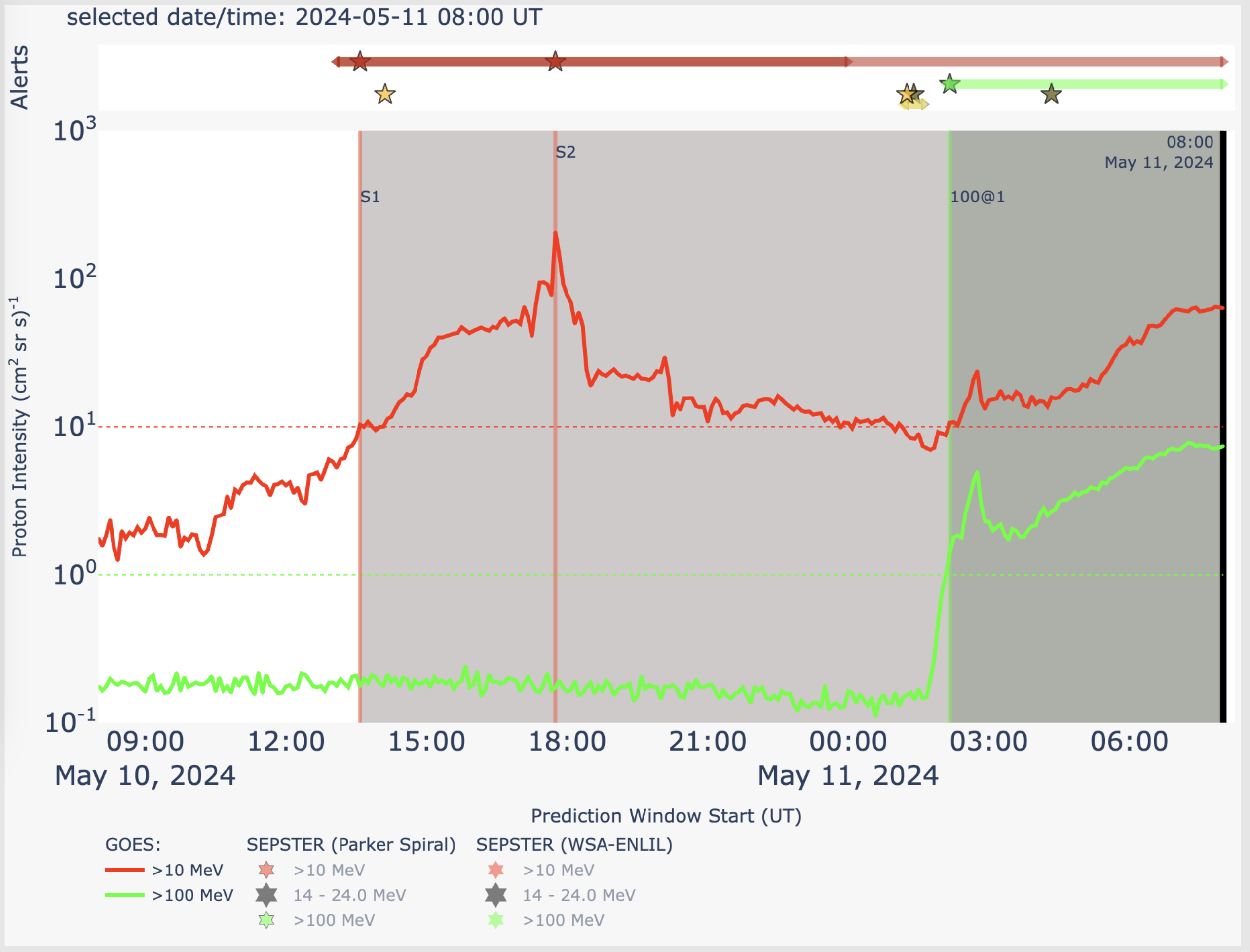
1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

May 2024: Part E



Current time: 2024-05-11T08:00Z

Questions:

1) Are conditions nominal (at background levels) or elevated? [Nominal/Elevated]

2) Have any thresholds been exceeded? [Yes/No for each]

- GOES >10 MeV >10pfu (EVA Contingency)
- GOES >100 MeV >1 pfu (ISS/Artemis Contingency)
- GOES >100 MeV >50 pfu (Artemis Shelter: assume no working dosimeters)

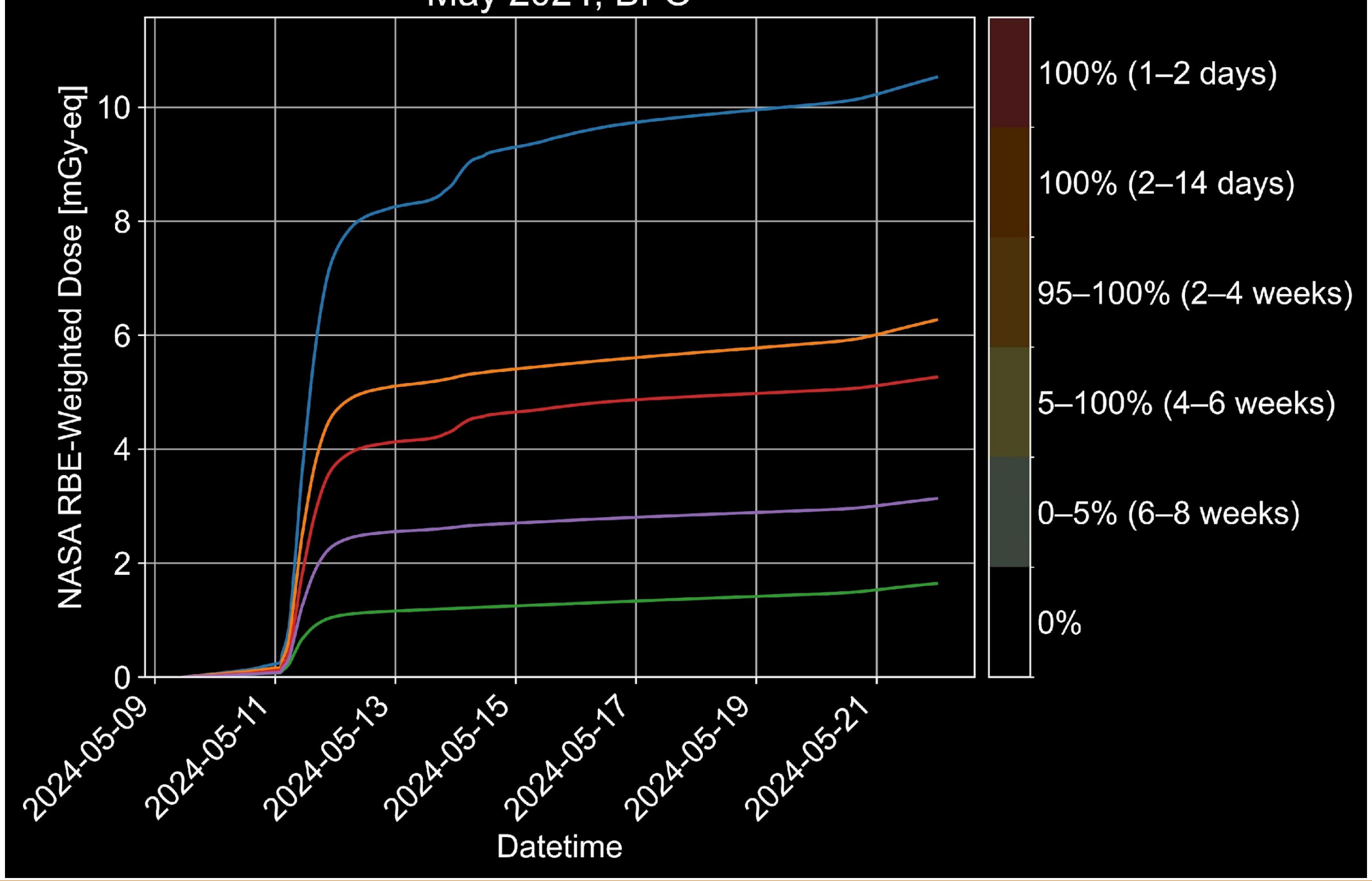
3) Based on the current SEP intensity value, do you think any action would be taken to minimize radiation exposure? [Yes/No]

Questions:
1) Using the Dose plot, what is the mortality probability for this event, for each shielding scenario?
2) For the least shielded case (spacesuit in free space) what is the approximate dose? At this dose, will there be acute radiation effects (see slide 30 for symptoms)?

Spacesuit (0.3 g/cm²) in free space
Lander (3 g/cm²) in free space
Vehicle (30 g/cm²) in free space
Spacesuit (0.3 g/cm²) on lunar surface
Lander (3 g/cm²) on lunar surface

Intensity profile

Dose



Slide credit: SRAG

Acute radiation exposure: symptoms

- Symptoms
- Probability of symptoms
- Severity of symptoms

depend on

- Total dose
- Dose rate