What are the human health risks of solar particle event radiation exposure, really?

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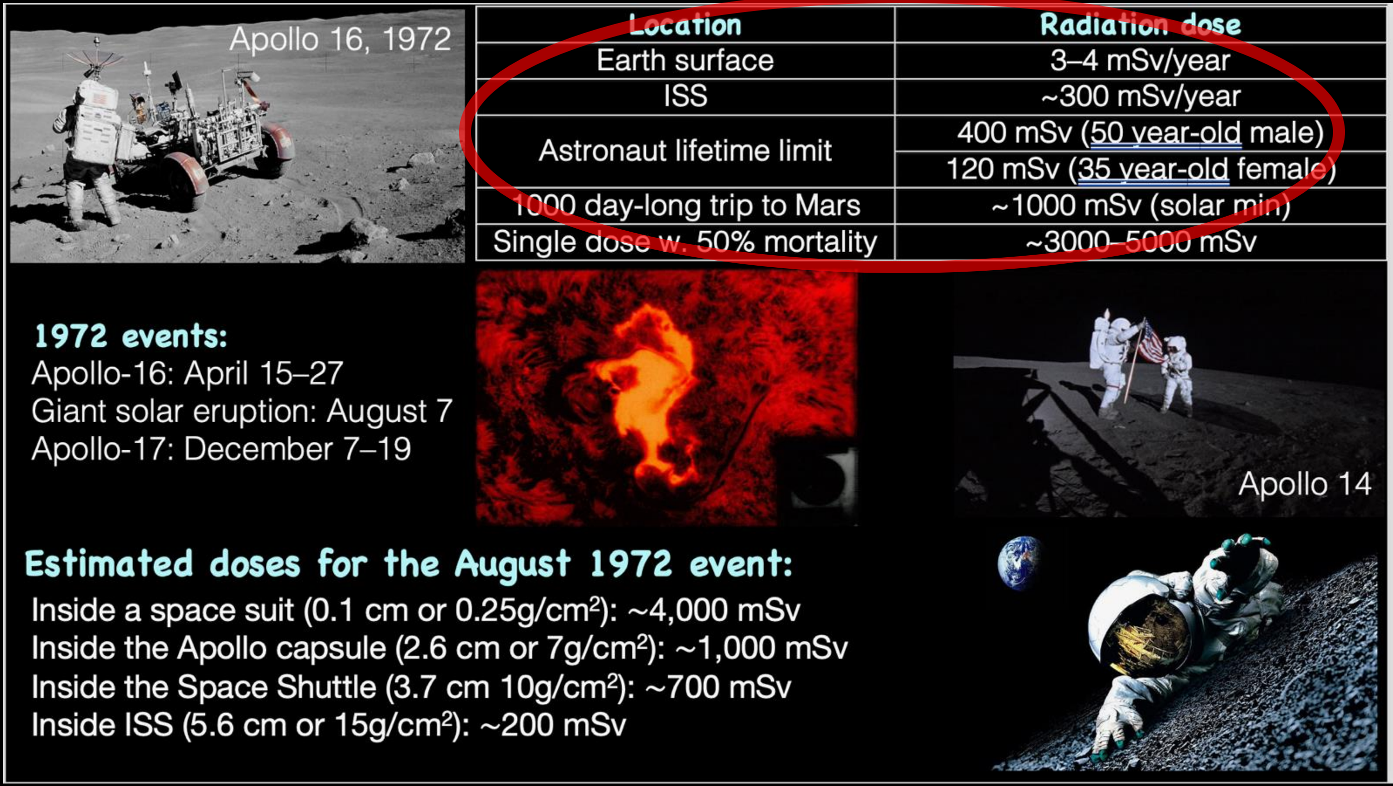
Motivation

- Appears to be some disconnect between
  - space weather experts
  - radiation protection experts
- Many claims of “lethality” in literature on SPEs
- Widespread misuse of radiation units and quantities

Example Slide

- Pros
  - Describes August 1972 event as a significant solar particle event (true!)
- Cons
  - Outdated information
  - Missing context
  - Lacks nuance



Example Slide

Location	Radiation dose
Earth surface	3–4 mSv/year
ISS	~300 mSv/year
Astronaut lifetime limit	400 mSv (50 year-old male)
	120 mSv (35 year-old female)
1000 day-long trip to Mars	~1000 mSv (solar min)
Single dose w. 50% mortality	~3000–5000 mSv

Location	Dose (note units)	Caveats
Earth's Surface	2.4 mSv/year (global average)	ICRP-103 Effective Dose
ISS	~150 mSv/year (solar max)	NASA Effective Dose
Astronaut Career Limit	600 mSv	NASA Effective Dose Sex-independent Equivalent to mean 3% REID for 35-year-old female astronaut
1000-day Mars Round Trip	800–1200 mSv	Estimates vary depending on length of surface stay, vehicle shielding profile (currently unknown), solar cycle
Lethal Dose	~3500 mGy-eq	Absorbed dose ≠ dose equivalent ≠ equivalent dose ≠ effective dose LD 50/30 – 50% of population dies within 30 days of receiving an acute exposure of this magnitude Large uncertainties

Overview

- Part I: Review of Radiation Protection Quantities
  - Quantities
  - Units
  - Hierarchy
- High Level Key Points
- Part II: Review of Radiobiological Effects
  - Stochastic Effects (cancer)
  - Deterministic Effects (tissue reactions)
- Part III: Estimation of Human Health Effects from Solar Particle Events
  - Typical Events
  - Extreme Events

Part I
Review of Radiation Protection Quantities

Dose Units

- Gy – how much radiation is absorbed in a material?
- Sv – how harmful is the radiation to human health?
  - Associated with the risk of cancer
- Gy-eq – how harmful is the radiation to human health?
  - Associated with the severity of a specific injury/ailment

Gray (Gy)
1 Gy = 100 rad = 1 J kg^{-1}

Energy Deposition per Unit Mass

Absorbed Dose

Sievert (Sv)
1 Sv = 100 rem =
1 J kg^{-1} $\times Q$ or w_R

Biological Damage
(long term effects)

Dose Equivalent
Equivalent Dose
Effective Dose

Gray-equivalent (Gy-eq)
1 Gy-eq = 1 J kg^{-1} $\times$ RBE

Biological Damage
(acute effects)

RBE-Weighted Dose

Radiation Protection Hierarchy

Physical Quantities
Things we can reliably measure

Radiometric Quantities
Describe the radiation field

Fluence: $\Phi = dN/dA$
Fluence rate (flux density): $\phi = d\Phi/dt$

Deterministic Dosimetric Quantities
Describe energy transfer to matter

Absorbed dose: $D = d\bar{\varepsilon}/dm$
Linear energy transfer: $L = dE/d\ell$

Bio-dosimetric Modifiers
Add context to assess biological impact

Relative biological effectiveness: RBE
Quality factor: Q
Radiation weighting factor: w_R
Tissue weighting factor: w_T

Biologically-Relevant Protection Quantities
Things we calculate to compare to dose limits and other standards

Dose equivalent: $H = QD$
Equivalent dose: $H = \sum_R w_R D_R$
Effective dose (ICRP): $\mathcal{E} = \sum_T w_T H_T$
Effective dose (NASA): $\mathcal{E}_{NASA} = \sum_T w_T \sum_{(Z,A)} \frac{1}{\rho_T} \int_0^\infty Q(Z,A,E) L(Z,A,E) \Phi_T(Z,A,E) dE$

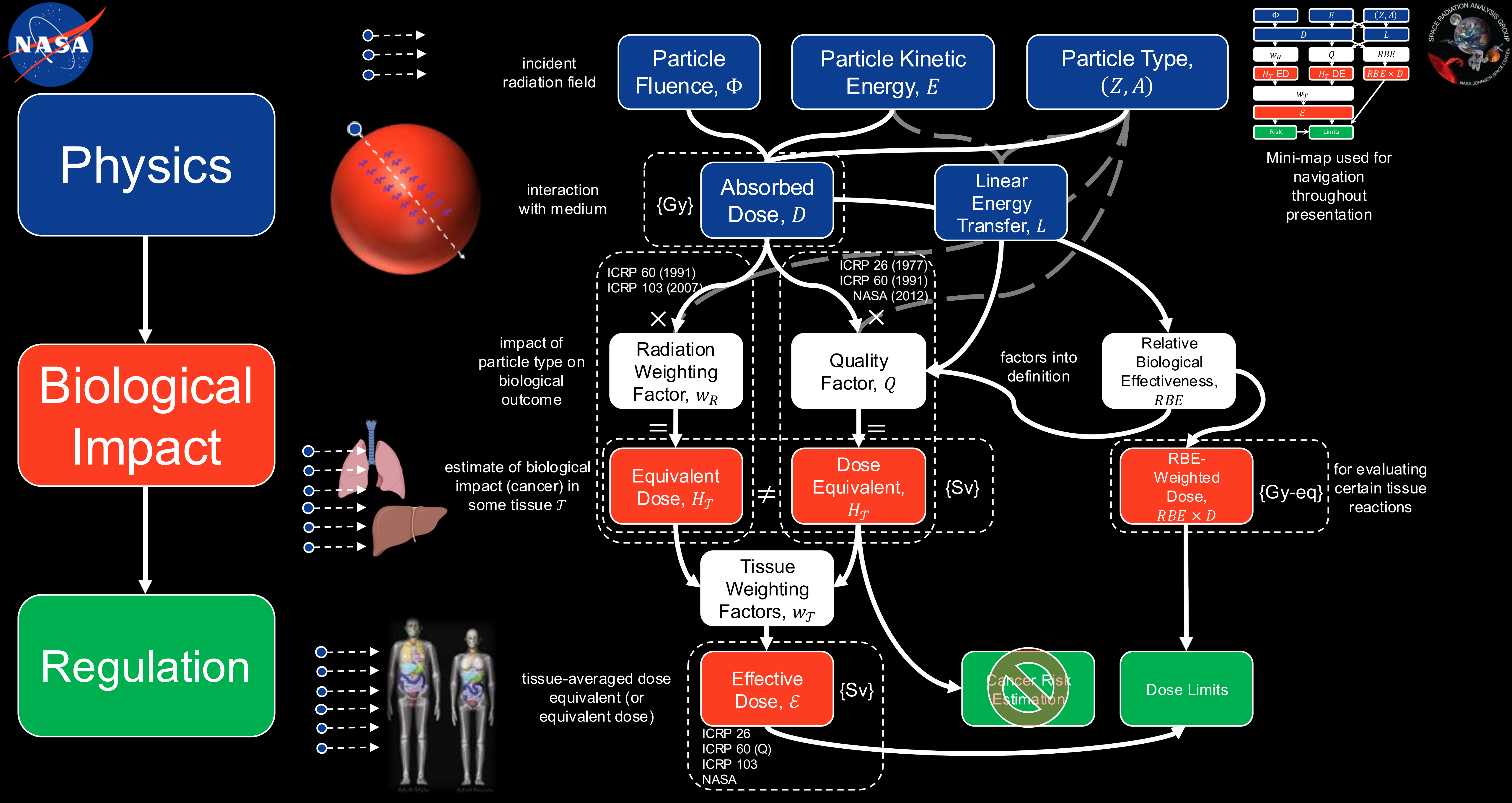
Epidemiological Modifiers
Add context to assess cancer incidence and mortality relative to a reference population

Survival functions: $S(a|e)$
Hazard functions: $\lambda(a,e,H)$

Cancer Risk Quantities
Things we calculate to evaluate radiogenic cancer incidence and mortality risk

Risk of exposure-induced cancer incidence: $REIC$
Risk of exposure-induced death: $REID$
Probability of causation: POC

Not addressed in this presentation
(could be another 100 slides)



Physics
Biological Impact
Regulation
incident radiation field
Particle Fluence, Φ
Particle Kinetic Energy, E
Particle Type, (Z, A)
interaction with medium
{Gy}
Absorbed Dose, D
Linear Energy Transfer, L
ICRP 60 (1991)
ICRP 103 (2007)
ICRP 26 (1977)
ICRP 60 (1991)
NASA (2012)
impact of particle type on biological outcome
Radiation Weighting Factor, w_R
Quality Factor, Q
factors into definition
Relative Biological Effectiveness, RBE
estimate of biological impact (cancer) in some tissue $\mathcal{T}$
Equivalent Dose, $H_\mathcal{T}$
Dose Equivalent, $H_\mathcal{T}$
{Sv}
RBE-Weighted Dose, RBE × D
{Gy-eq}
for evaluating certain tissue reactions
Tissue Weighting Factors, $w_\mathcal{T}$
tissue-averaged dose equivalent (or equivalent dose)
Effective Dose, $\mathcal{E}$
{Sv}
ICRP 26
ICRP 60 (Q)
ICRP 103
NASA
Cancer Risk Estimation
Dose Limits
Mini-map used for navigation throughout presentation
Φ
E
(Z, A)
D
L
w_R
Q
RBE
$H_\mathcal{T}$ ED
$H_\mathcal{T}$ DE
RBE × D
$w_\mathcal{T}$
$\mathcal{E}$
Risk
Limits
SPACE RADIATION ANALYSIS GROUP
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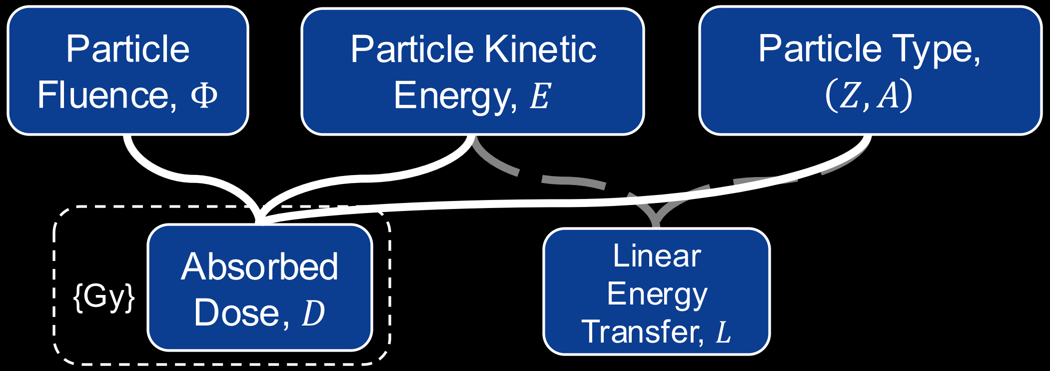
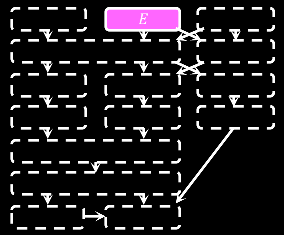
Radiation Protection Quantities Overview

- Absorbed Dose: energy deposited per unit mass
  - Measured by detectors
  - Simulated in materials via GEANT4, HZETRN, etc.
- Linear Energy Transfer (LET): energy lost by particle per unit path length
  - Measured by detectors with spatial resolution
  - Important to biological impact
- RBE-Weighted Dose: measure of near-term biological impact (radiation syndrome) due to absorbed dose from radiation field (e.g., protons) versus reference radiation field (e.g., photons)
  - Applies RBE of incident field to absorbed dose
  - Used by NASA to establish 30-day limits for
    - eye lens
    - blood-forming organs (primarily bone marrow, thymus, spleen, lymph nodes)
    - skin
    - cardiovascular disease
    - central nervous system effects
- Dose Equivalent: measure of long-term cancer incidence risk due to absorbed dose, considering the biologically damaging nature of each radiation type
  - Applies quality factors
  - Used by NASA as a steppingstone for cancer risk estimation
- Equivalent Dose: measure of long-term cancer incidence risk due to absorbed dose, considering the biologically damaging nature of each radiation type
  - Applies radiation weighting factors
  - Used by ICRP as a steppingstone for cancer risk estimation
- Effective Dose: dose equivalent or equivalent dose averaged over the whole body adjusted for sensitivity of different tissues to radiation
  - Applies tissue weighting factors
  - Used to define career dose limits
  - Several methodologies
    - ICRP 26, ICRP 60 (Q), ICRP 60, ICRP 103, NASA

Physics Quantities?





Particle Kinetic Energy

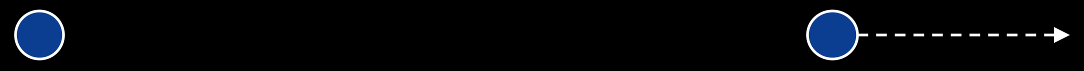
component of particle's total energy due to its motion

Quantity	Definition	SI Base Unit	Common Units
Particle Kinetic Energy	$E = (\gamma - 1)m_0c^2$	J	1 MeV = $10^6 q_e$ J

- m_0 – rest mass of particle
- c – speed of light
- $\gamma = \frac{1}{\sqrt{1-\left(\frac{v}{c}\right)^2}}$ – Lorentz factor, function of particle speed v

particle
rest mass energy m_0c^2

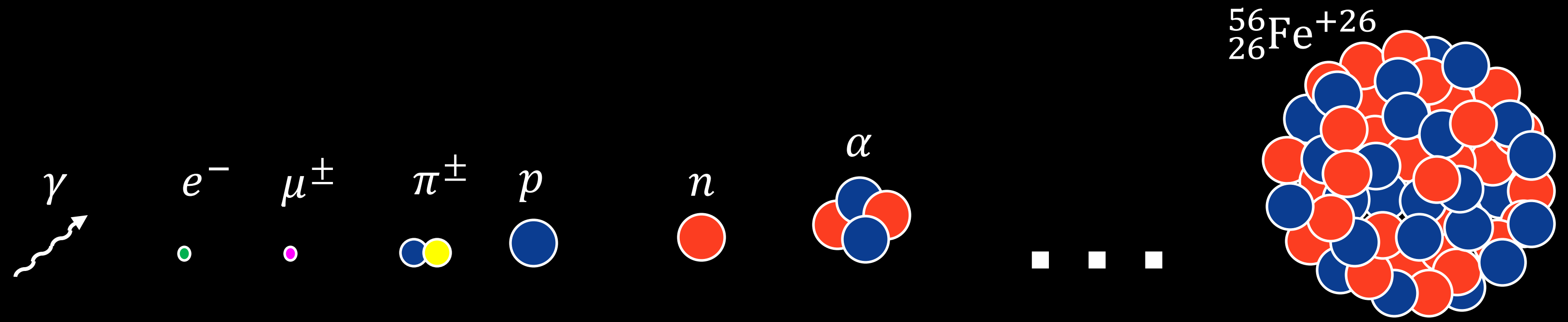
particle
rest mass energy m_0c^2
kinetic energy E



Particle Type

identifier of a fundamental or composite particle (e.g., electron, proton, pion, alpha)

- Often denoted with (Z, A, S) (atomic number, atomic mass, charge state)
  - ${}^{A}_{Z}X^{S}$
- Different particles interact with matter differently

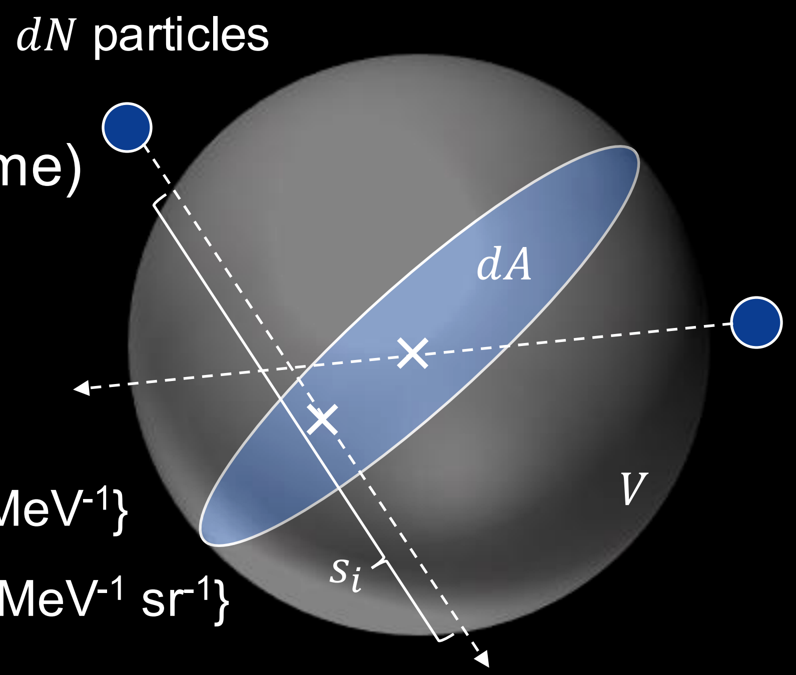


Particle Fluence

number of particles (dN) that penetrate a hypothetical sphere of cross section dA during a specified time interval

Quantity	Definition	SI Base Unit	Common Units
Particle Fluence	$\Phi \equiv \frac{dN}{dA}$	m^{-2}	$1\ cm^{-2} = 10^4\ m^{-2}$

- Radiometric quantity
- Equivalently, $\Phi \equiv \frac{\sum_i s_i}{V}$ (sum of path lengths per unit volume)
- Subcategories
  - Flux (density): $\phi = \frac{d\Phi}{dt}$ $\{cm^{-2}\ s^{-1}\} \Rightarrow \Phi = \int_0^t \phi dt$
  - Angular flux distribution: $\phi(;\vec{\Omega}) = \frac{\partial \phi}{\partial \Omega}$ $\{cm^{-2}\ s^{-1}\ sr^{-1}\}$
  - Differential flux distribution (in energy): $\phi(;E) = \frac{\partial \phi}{\partial E}$ $\{cm^{-2}\ s^{-1}\ MeV^{-1}\}$
  - Double-differential flux distribution: $\phi(;E,\vec{\Omega}) = \frac{\partial^2 \phi}{\partial E \partial \Omega}$ $\{cm^{-2}\ s^{-1}\ MeV^{-1}\ sr^{-1}\}$

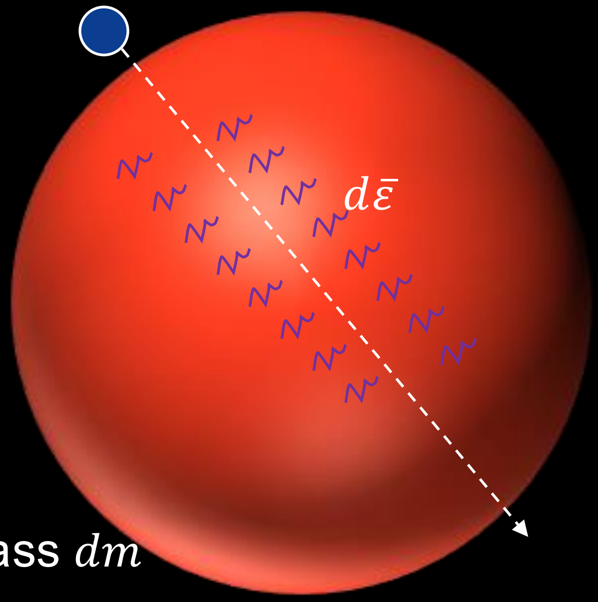


Absorbed Dose

(mean) energy deposited ($d\bar{\varepsilon}$) in matter by ionizing radiation per unit mass (dm)

Quantity	Definition	SI Base Unit	Common Units
Absorbed Dose	$D \equiv \frac{d\bar{\varepsilon}}{dm}$	J kg^{-1}	1 Gy = 100 rad = 1 J kg^{-1}

- 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

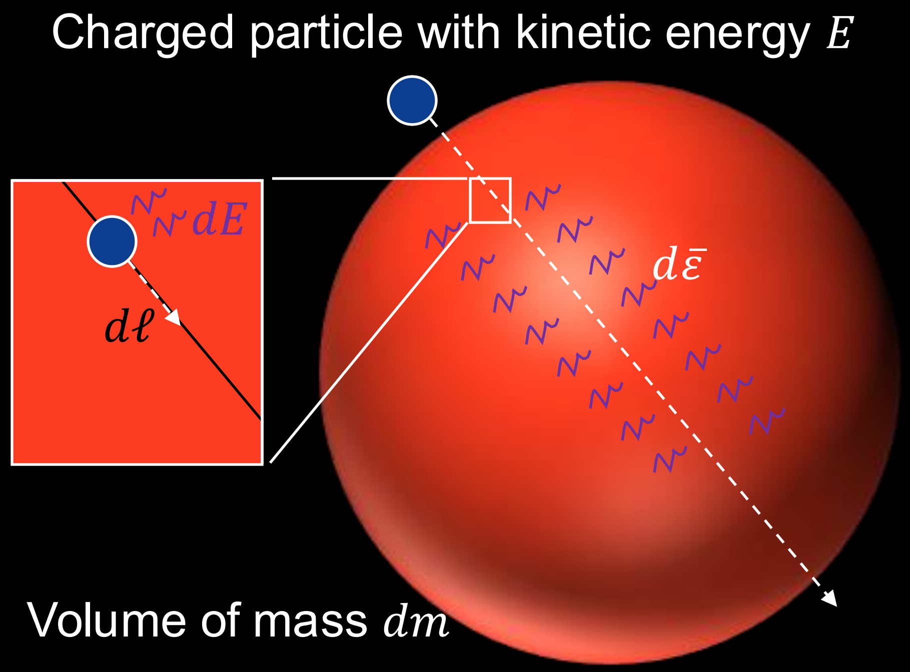


Linear Energy Transfer (LET)

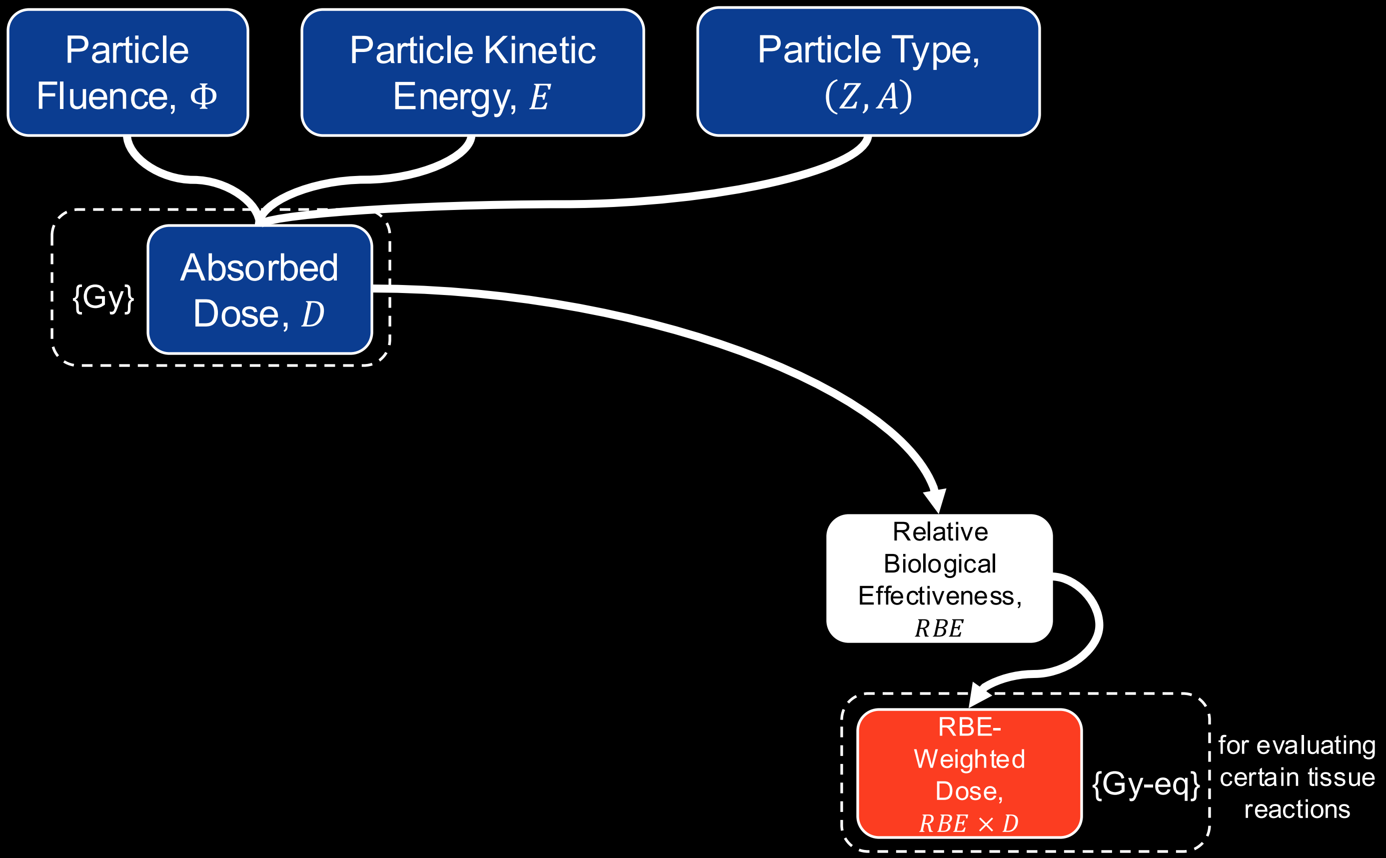
energy transferred by particle to medium (dE) per unit path length ($d\ell$)

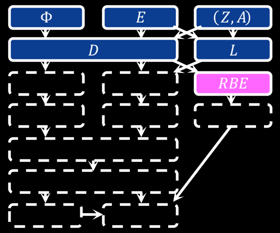
Quantity	Definition	SI Base Unit	Common Units
Linear Energy Transfer (LET)	$L_\infty \equiv \frac{dE}{d\ell}, L_\Delta \equiv \left(\frac{dE}{d\ell}\right)_\Delta$	J m^{-1}	1 keV µm^{-1} = $10^9 q_e$ J m^{-1}

- Describes energy density along ionization track
- Important to biological impact
  - High LET → dense ionization track
    - heavy ion energy deposition
  - Low LET → sparse ionization track
    - electron collisions
- L_Δ – restricted LET
  - "Local" energy transfer only
- L_∞ – unrestricted LET
  - Local and non-local energy transfers



How do we calculate RBE-Weighted Dose?





Relative Biological Effectiveness (RBE)

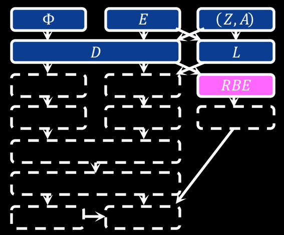
ratio of two absorbed doses from two different incident radiation fields required to reach the same biological endpoint

Quantity	Definition	SI Base Unit	Common Units
Relative Biological Effectiveness	$RBE = \frac{D_{reference}}{D_{interest}}$	None	None

- RBE is dependent on biological endpoint
  - Cancer
  - Tissue reaction (acute radiation syndrome, skin burn, etc.)
- $RBE = \frac{\text{absorbed dose from reference field resulting in defined endpoint}}{\text{absorbed dose from field of interest resulting in defined endpoint}}$
- Experimentally determined (rodent studies)
- $D_{reference}$ – typically 250 kVp X-rays or ^{60}Co γ-rays

Key Point: RBE

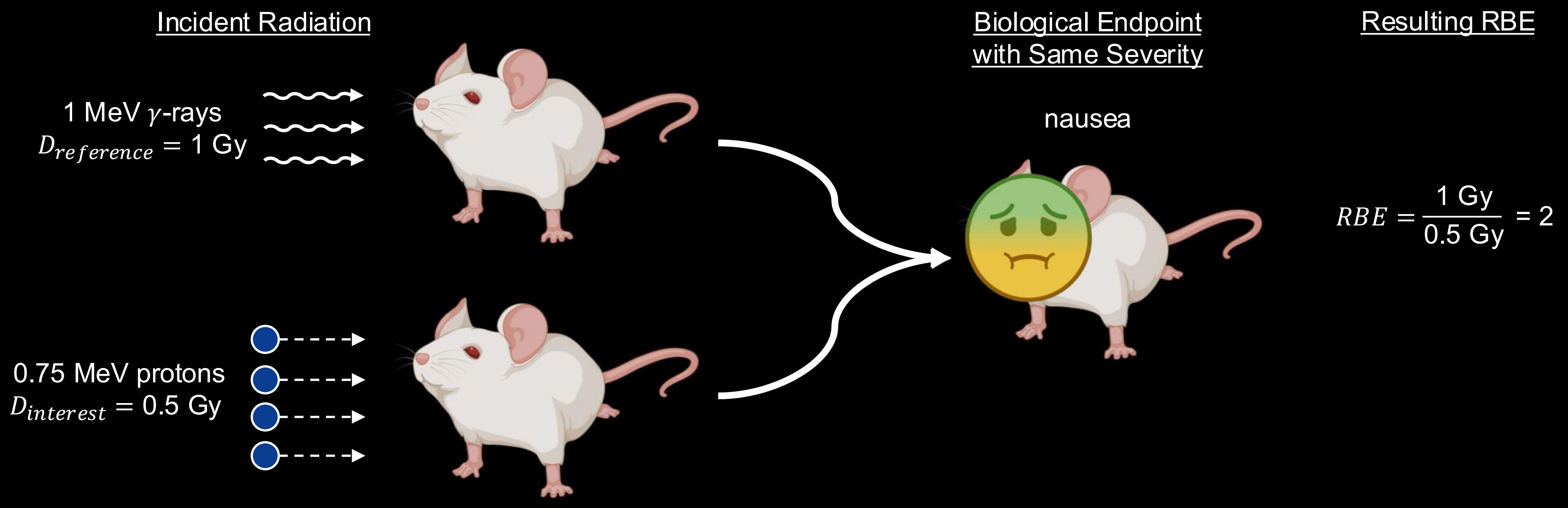
- RBE quantifies how biologically damaging a given type of radiation is compared to a standard (typically X-rays or γ-rays) for a specific biological effect.

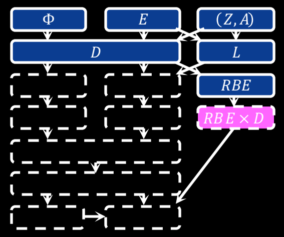


RBE Example

ratio of two absorbed doses from two different incident radiation fields required to reach the same biological endpoint

Quantity	Definition	SI Base Unit	Common Units
Relative Biological Effectiveness	$RBE = \frac{D_{reference}}{D_{interest}}$	None	None

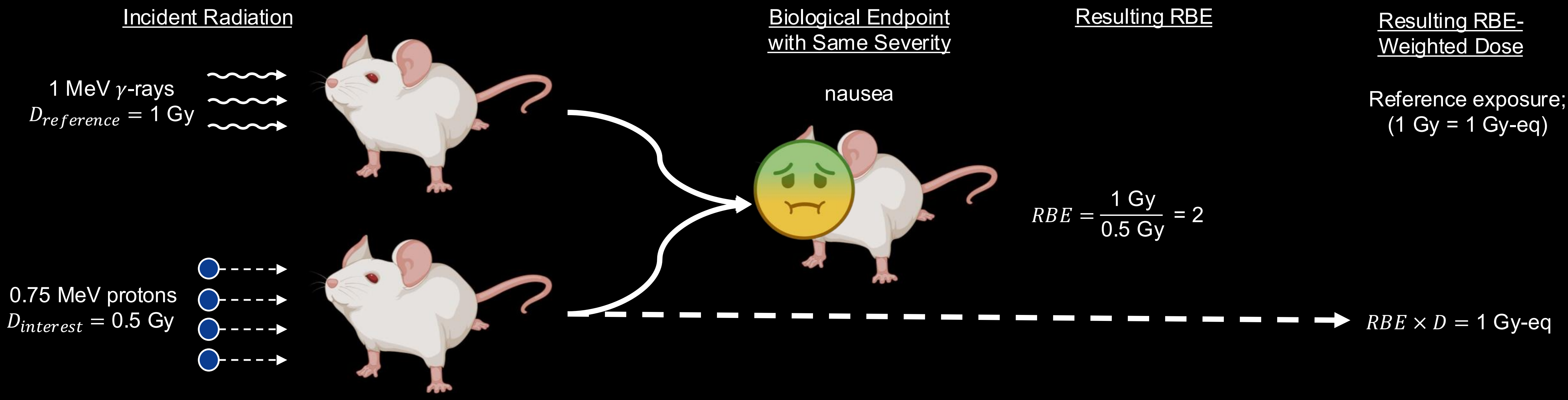




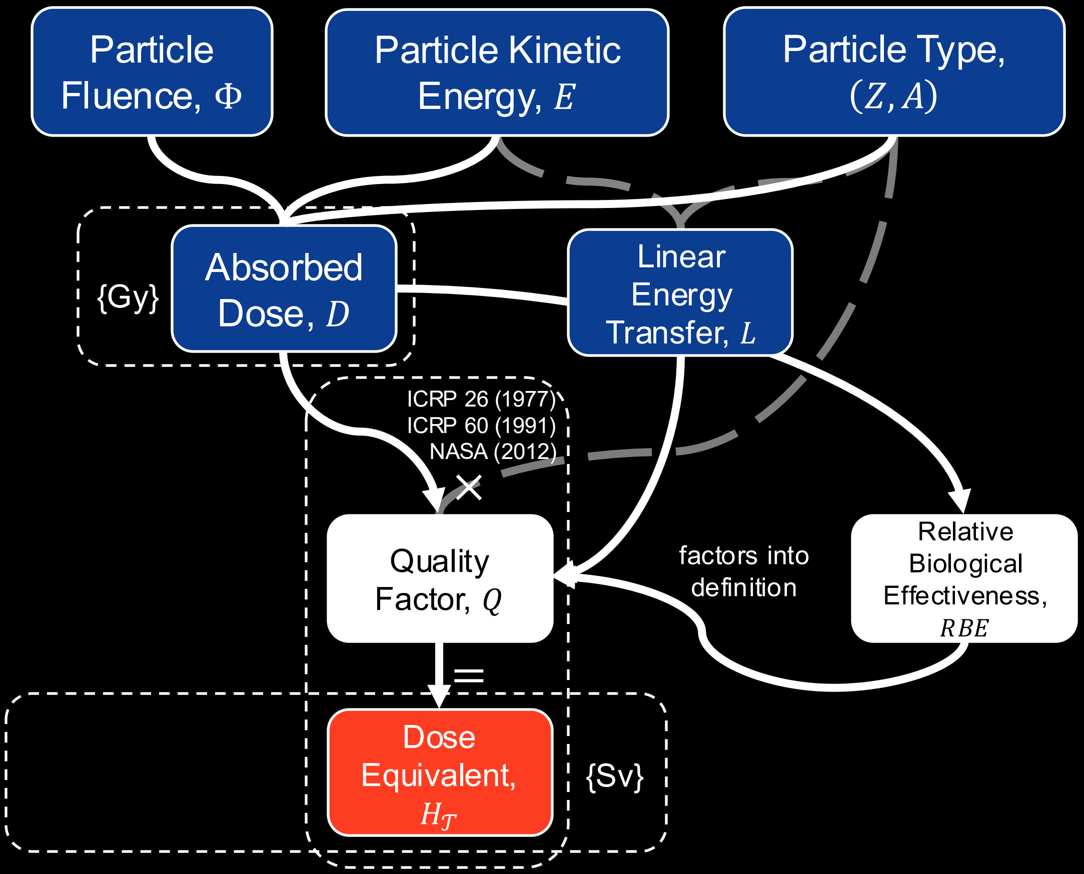
RBE-Weighted Absorbed Dose

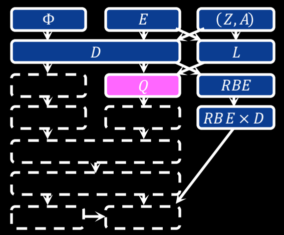
absorbed dose multiplied by RBE; compares impact of reference radiation field vs. radiation field of interest

Quantity	Definition	SI Base Unit	Common Units
RBE-Weighted Absorbed Dose	$RBE \times D$	J kg^{-1}	1 Gy-eq = 100 rad-eq = 1 J kg^{-1} × RBE



How do we calculate Dose Equivalent?





Quality Factor

dimensionless factor that converts absorbed dose to dose equivalent

Quantity	Definition	SI Base Unit	Common Units
Quality Factor	Various	None, $J\ kg^{-1}/(J\ kg^{-1})$	Officially dimensionless, may be interpreted as "$Sv\ Gy^{-1}$"

- Radiation quality differs between particle types (γ-rays, protons, heavy ions, etc.)
- Derived from RBE with <u>specific endpoint</u>: cancer incidence
- Multiple definitions
  - ICRP 26 (1977): $Q_{26}(L_\infty)$ – based on unrestricted LET in water, indirectly dependent on particle
  - ICRP 60 (1991): $Q_{60}(L_\infty)$ – refined version of $Q_{26}(L_\infty)$; reduced effectiveness $L_\infty > 100$ keV μm^{-1}
  - NASA: $Q_{NASA}(Z, A, E)$ – accounts for particle type (Z, A) and kinetic energy explicitly (E)

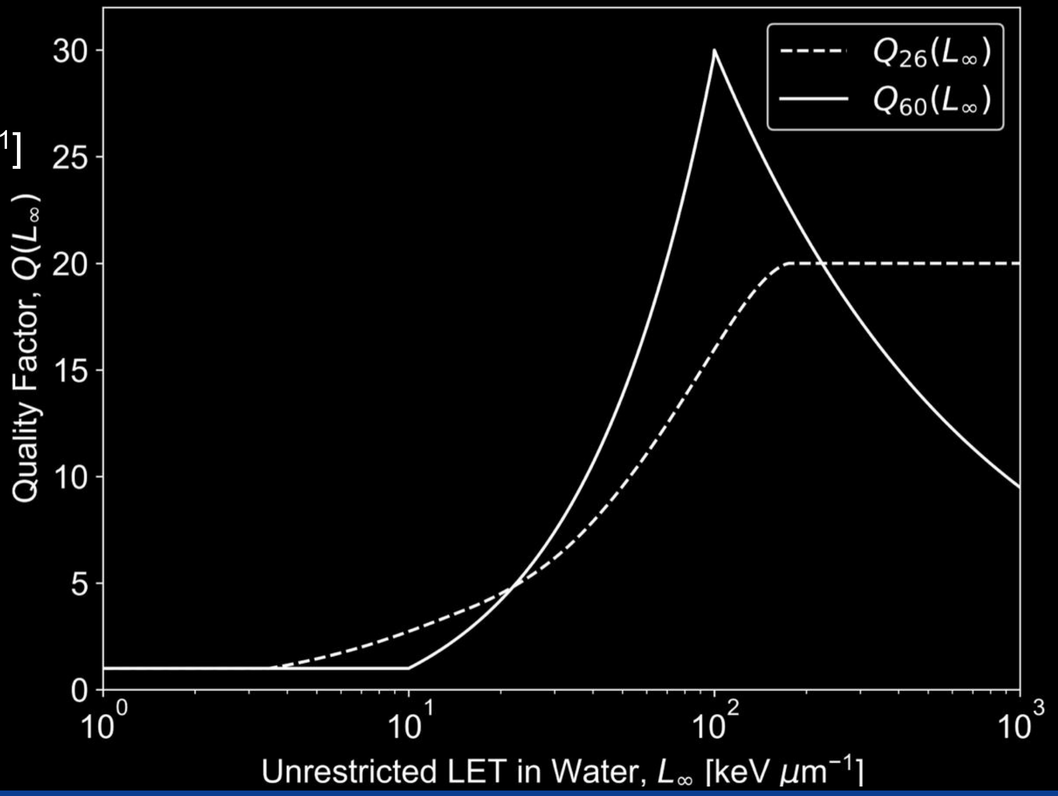
Key Point: Quality Factor

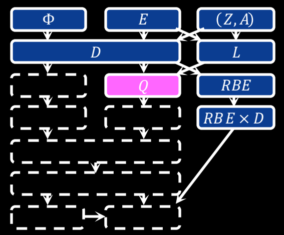
- Q_{NASA} is much more complicated than Q_{26} and Q_{60}
  - It is presumably more comprehensive as a result

- Q_{NASA} formulated to avoid excessive conservatism

ICRP 26 & ICRP 60 Quality Factors

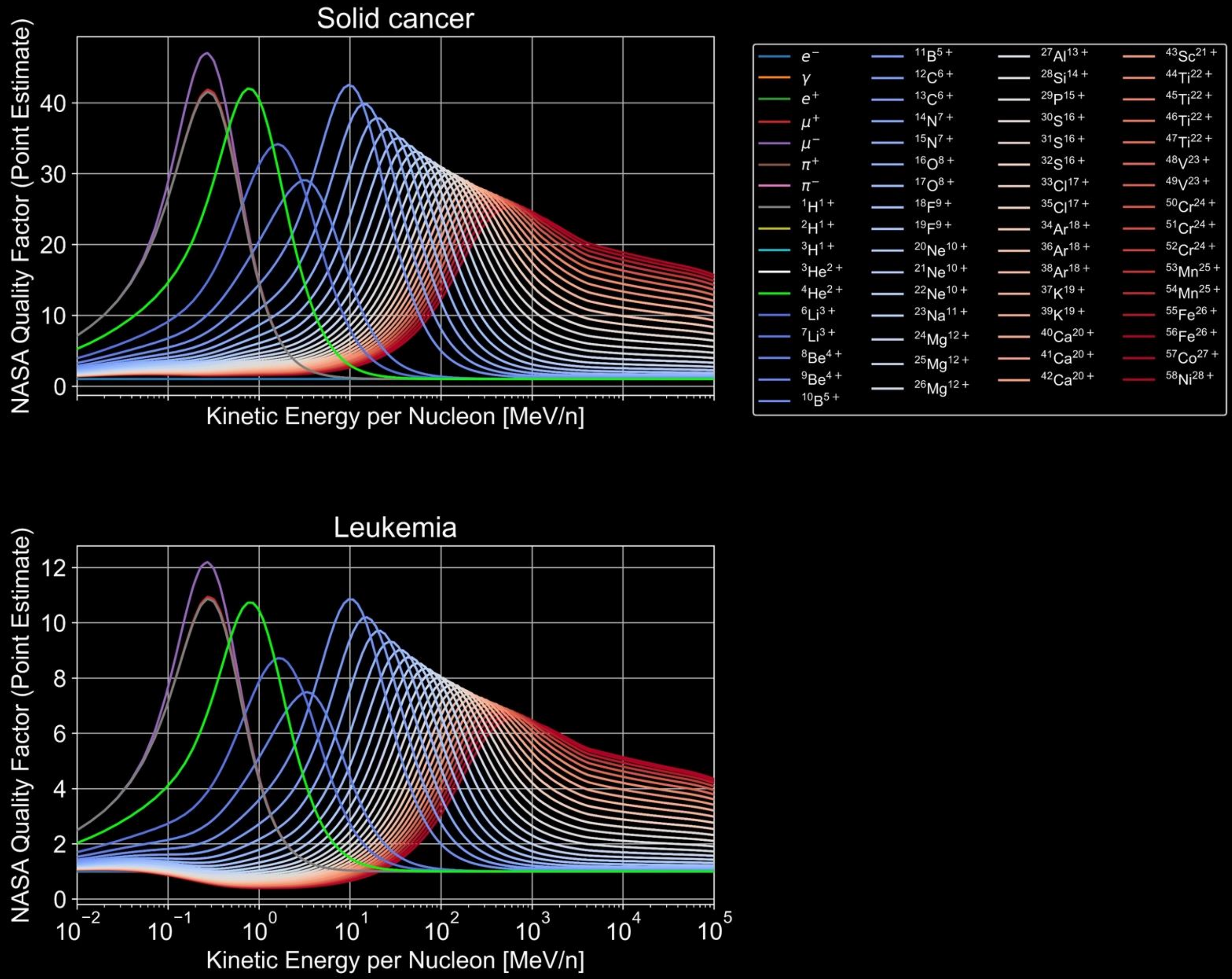
- $Q_{26}(L_\infty) = \begin{cases} 1, & L_\infty \leq 3.5 \\ 2, & L_\infty = 7 \\ 5, & L_\infty = 23 \\ 10, & L_\infty = 53 \\ 20, & L_\infty \geq 175 \end{cases}$ where L_∞ is in [keV μm^{-1}] (obsolete)
- $Q_{60}(L_\infty) = \begin{cases} 1, & L_\infty < 10 \\ 0.32L_\infty - 2.2, & L_\infty \in [10, 100] \\ 300L_\infty^{-1/2}, & L_\infty > 100 \end{cases}$ where L_∞ is in [keV μm^{-1}]
- Easy to apply
- Depends only on unrestricted LET in water
- *Know which quality factor to use or was used*

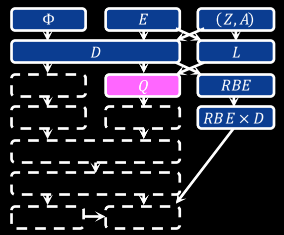




NASA Quality Factor

- $Q_{NASA}(Z,A,E) = 1 - P(Z,A,E) + \frac{\left(\frac{\Sigma_0}{\alpha_\gamma}\right)}{L(Z,A,E)} P(Z,A,E)$
  - $P(Z,A,E) = \left(1 - \exp\left(\frac{\left(\frac{Z^*}{\beta}\right)^2}{\kappa}\right)\right)^m \left(1 - \exp\left(-\frac{E}{E_{TD}}\right)\right)$
  - $\kappa,\ m,\ E_{TD},\ \Sigma_0,\ \alpha_\gamma$ – constants with uncertainty
  - $Z^* = Z\left(1 - \exp\left(-125\beta/Z^{2/3}\right)\right)$
  - $\beta = v/c$
- Specific to
  - Particle type (Z, A)
  - Cancer type (solid, leukemia)
  - Kinetic energy
- Larger uncertainties
- More difficult to apply
- *Know which quality factor to use or was used*





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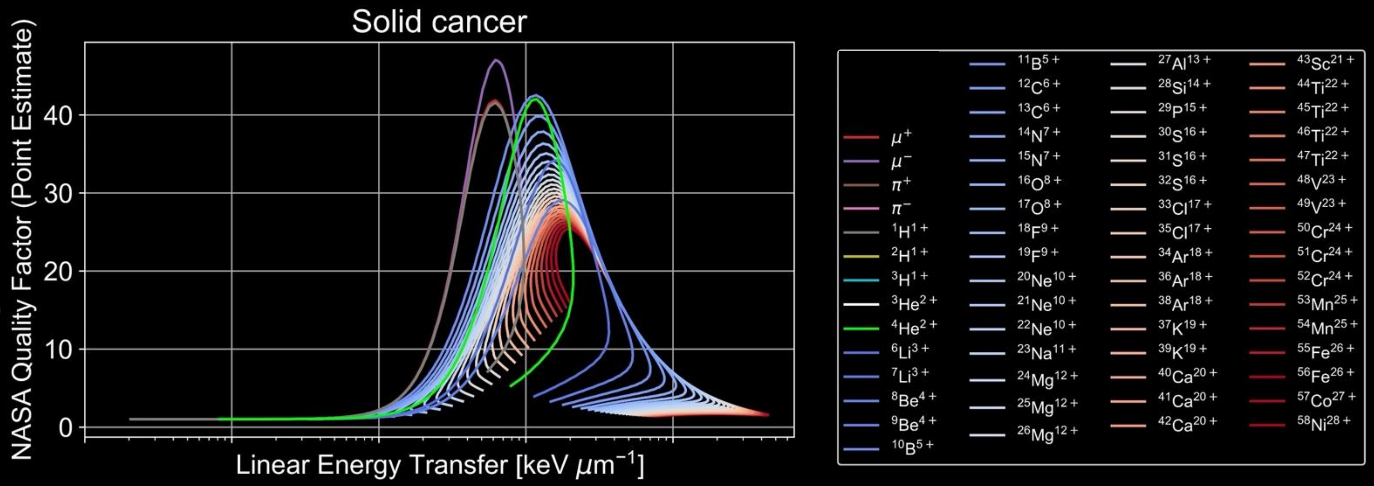

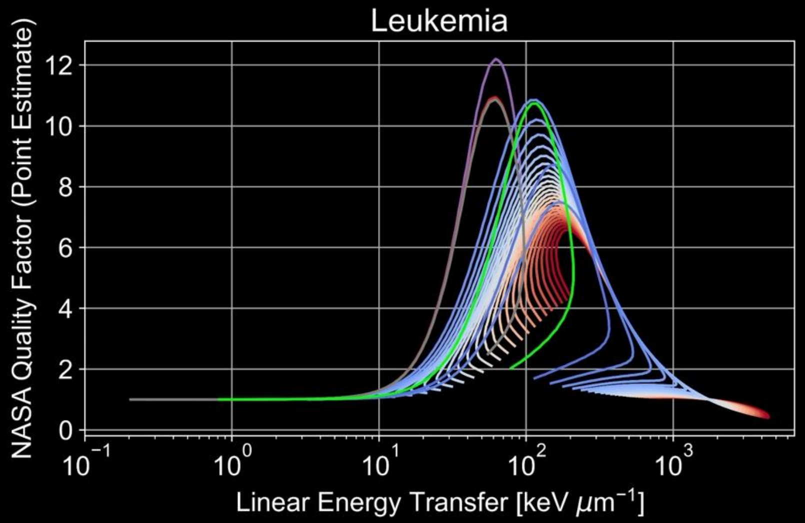

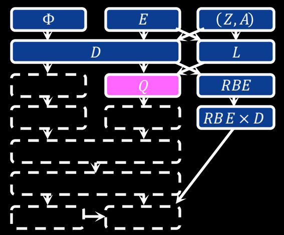

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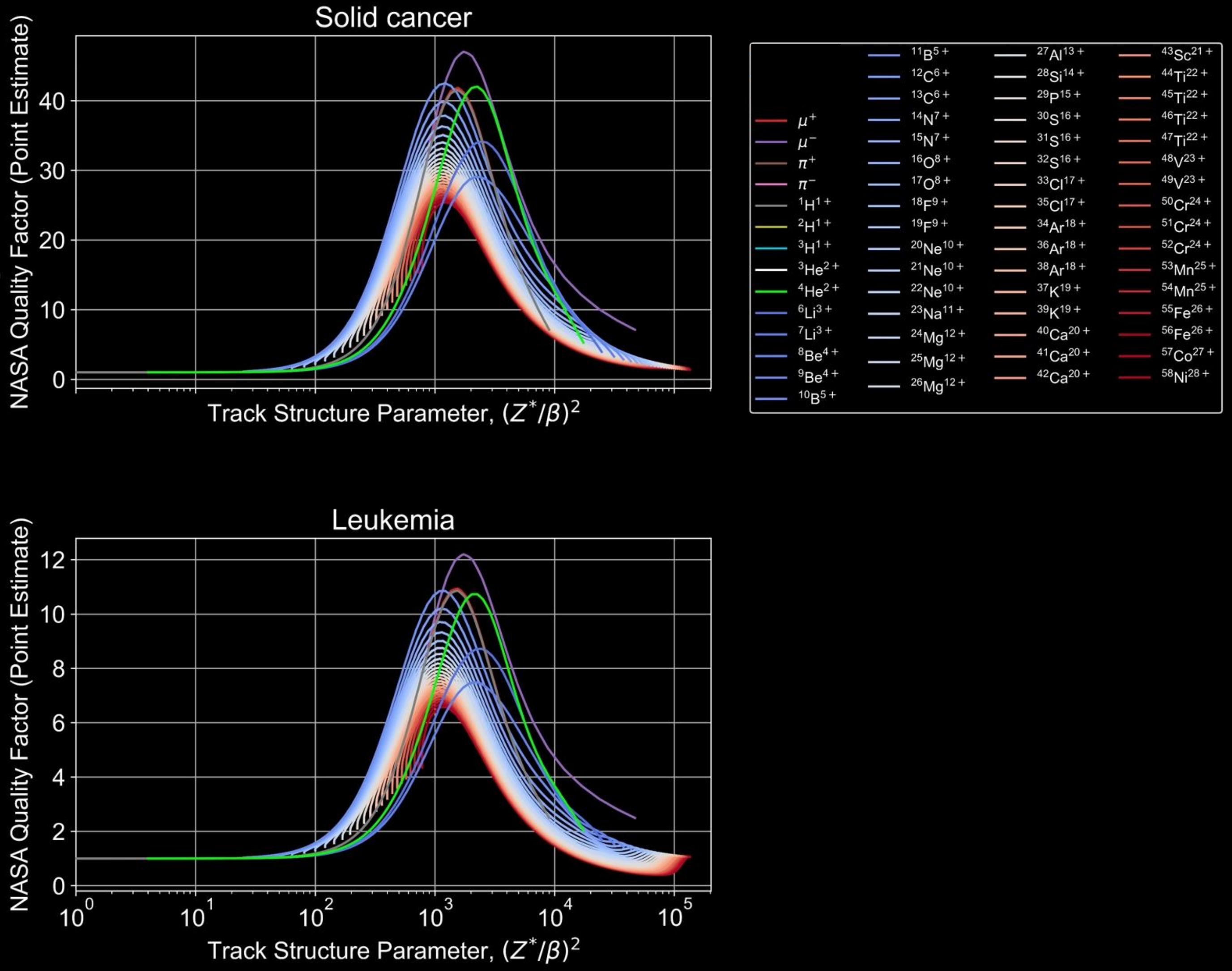
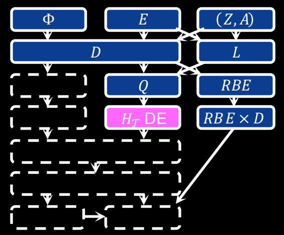


Dose Equivalent



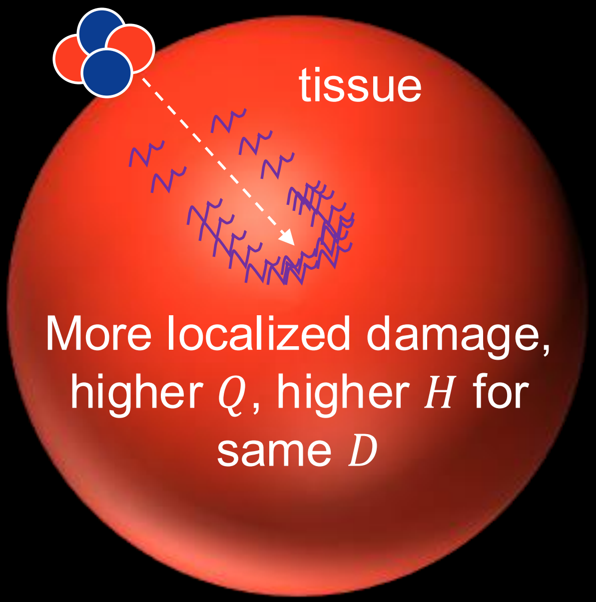
absorbed dose scaled by radiation type (using quality factors) that loosely relates to an increased probability of cancer incidence

Quantity	Definition	SI Base Unit	Common Units
Dose Equivalent	$H = QD$	J kg^{-1}	1 Sv = 100 rem = 1 J kg^{-1} × Q

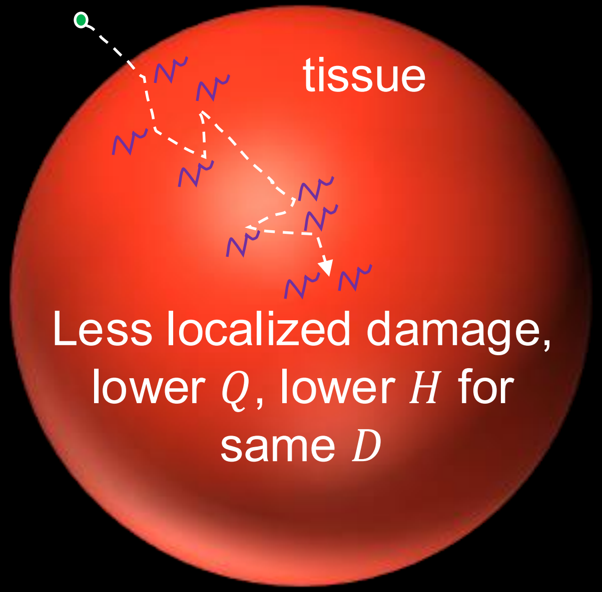
- Estimates biological damage from D

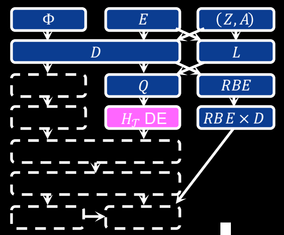
Assume each tissue sphere receives the same total absorbed dose D

N_1 heavy ions



N_2 electrons



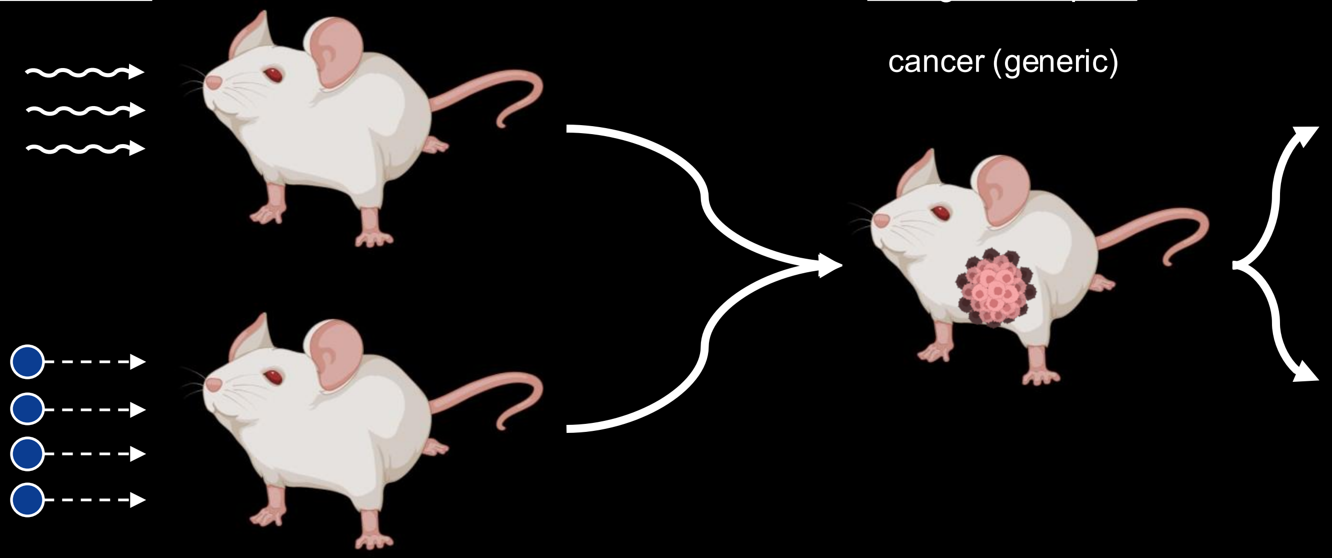


Quality Factor & Dose Equivalent Example

Incident Radiation

γ-ray exposure
$D_\gamma = 0.5$ Gy

0.4 MeV proton exposure
$L_\infty = 100$ keV μm^{-1}
$D_p = 0.05$ Gy



Biological Endpoint

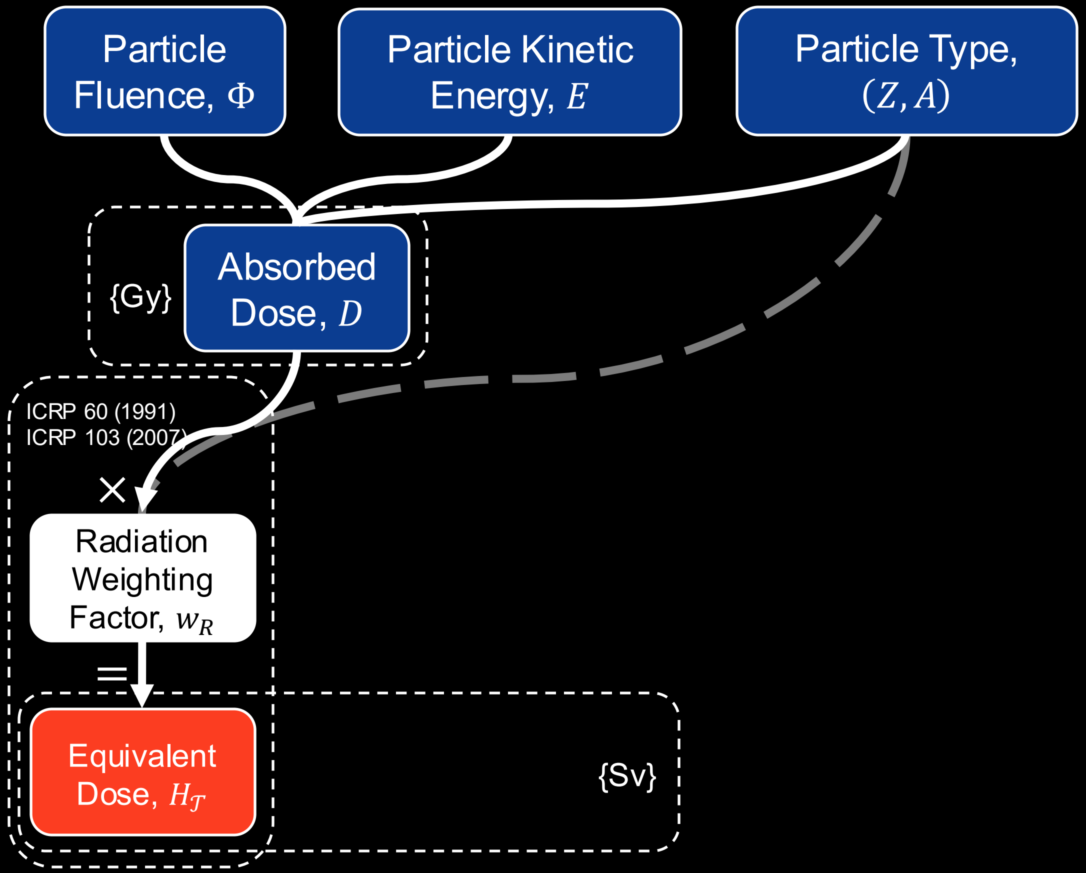
cancer (generic)

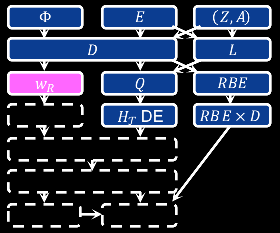
Resulting Quality Factors	Resulting Dose Equivalents
$Q_{60} = 1$ $Q_{NASA} = 1$	$H_{60} = 0.5$ Sv $H_{NASA} = 0.5$ Sv
$Q_{60} = 29.8$ $Q_{NASA} \approx 36$	$H_{60} = 1.44$ Sv $H_{NASA} \approx 1.8$ Sv

Key Point: Dose Equivalent

- Smaller absorbed dose ≠ smaller dose equivalent
- Different quality factors lead to different dose equivalent values
  - Leads to a different interpretation of the biological damage imparted by exposure
  - Leads to differences in calculated effective dose

How do we calculate Equivalent Dose?





Radiation Weighting Factor

dimensionless factors that convert absorbed dose to equivalent dose

Quantity	Definition	SI Base Unit	Common Units
Radiation Weighting Factor	Various	None, J kg^{-1}/(J kg^{-1})	Officially dimensionless, may be interpreted as "Sv Gy^{-1}"

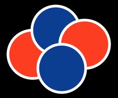
- Like quality factor; policy-driven instead of physics-driven, thus a bit simpler
- Characterizes effect particle type has on the potential of an absorbed dose to cause cancer
- Multiple definitions
  - ICRP 60 (1991): $w_{R,60}$
  - ICRP 103 (2007): $w_{R,103}$

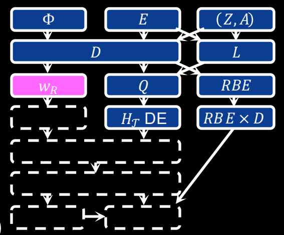
e^-

$w_R \sim 1$

α

$w_R \sim 20$

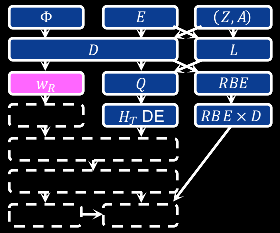




ICRP 60 Radiation Weighting Factors

Particle Type	$w_{R,60}$	Notes
photon, γ	1	
electron, e^-	1	excludes Auger electrons emitted from nuclei bound to DNA
muon, $\mu^\pm$	1	
proton, p	5	excludes $E \leq 2$ MeV and recoil protons
alpha, α	20	
fission fragment	20	
heavy ion	20	
neutron, n	$\begin{cases} 5, E < 0.01 \\ 10, E \in [0.01, 0.1] \\ 20, E \in (0.1, 2] \\ 10, E \in (2, 20] \\ 5, E > 20 \end{cases}$	E in [MeV], a smoothed fit was also recommended: $5 + 17\exp(-(\ln(2E))^2/6)$
all others	$\bar{Q}_{26}(10\text{ mm}) = \frac{1}{D}\int_0^\infty Q_{26}(L_\infty)D(L_\infty)dL_\infty$	Average ICRP-26 quality factor at 10 mm depth in ICRU sphere

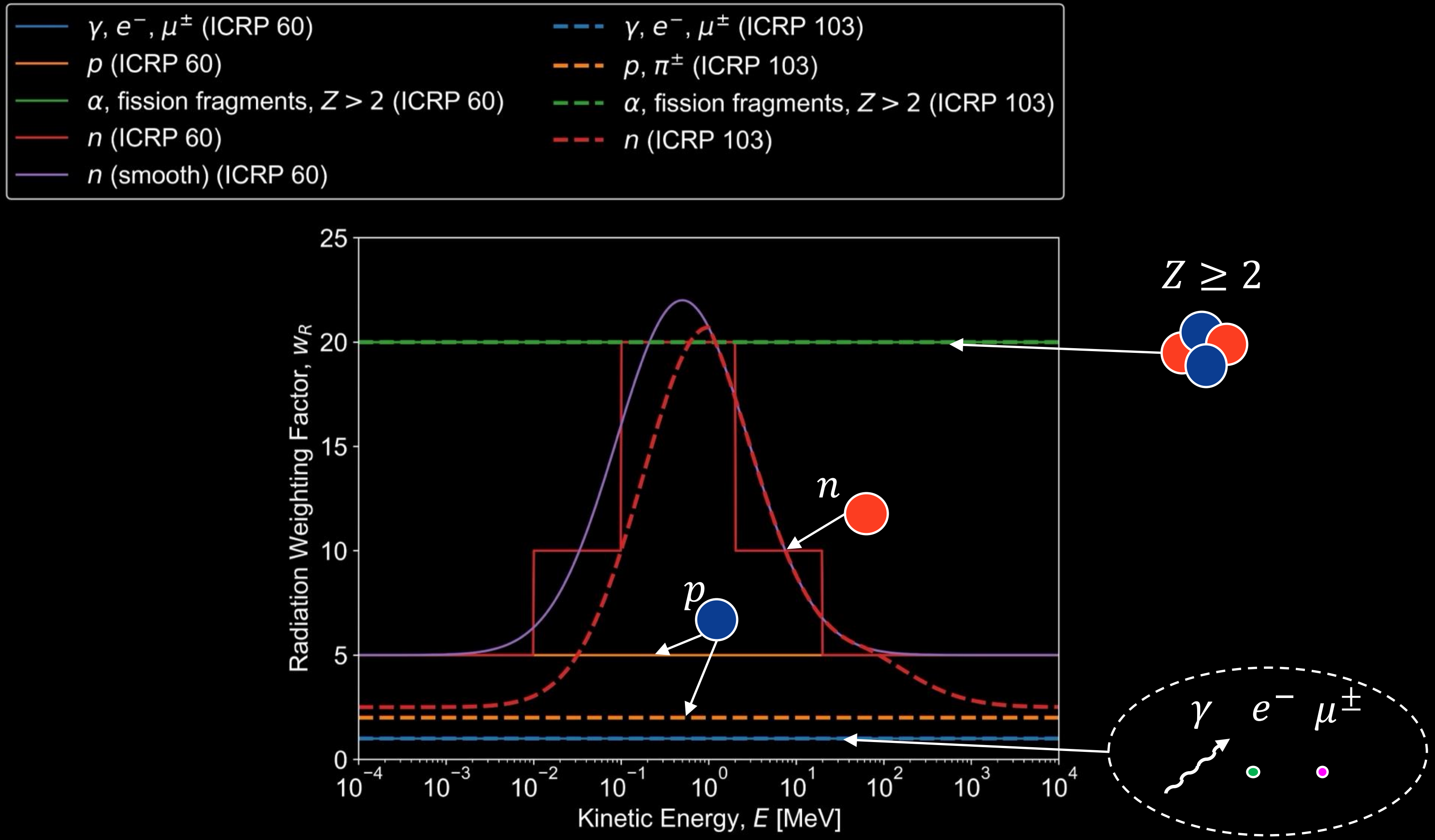
ICRP 103 Radiation Weighting Factors

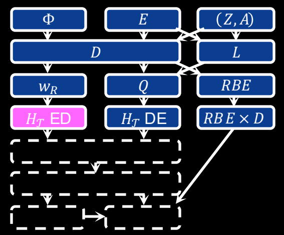


Particle Type	$w_{R,60}$	Notes
photon, γ	1	
electron, e^-	1	excludes Auger electrons emitted from nuclei bound to DNA
muon, $\mu^\pm$	1	
proton, p	2	
charged pions, $\pi^\pm$	2	
alpha, α	20	
fission fragment	20	
heavy ion	20	
neutron, n	$\begin{cases} 2.5 + 18.2\exp(-[\ln(E)]^2/6), E < 1 \\ 5.0 + 17.0\exp(-[\ln(2E)^2/6]), E \in [1,50] \\ 2.5 + 3.2\exp(-[\ln(0.04E)]^2/6), E > 50 \end{cases}$	E in [MeV]
all others	$\bar{Q}(10\text{ mm}) = \frac{1}{D}\int_0^\infty Q_{26}(L_\infty)D(L_\infty)dL_\infty$	Average ICRP-26 quality factor at 10 mm depth in ICRU sphere

Radiation Weighting Factors

ICRP 60 (1991) vs. ICRP 103 (2007)





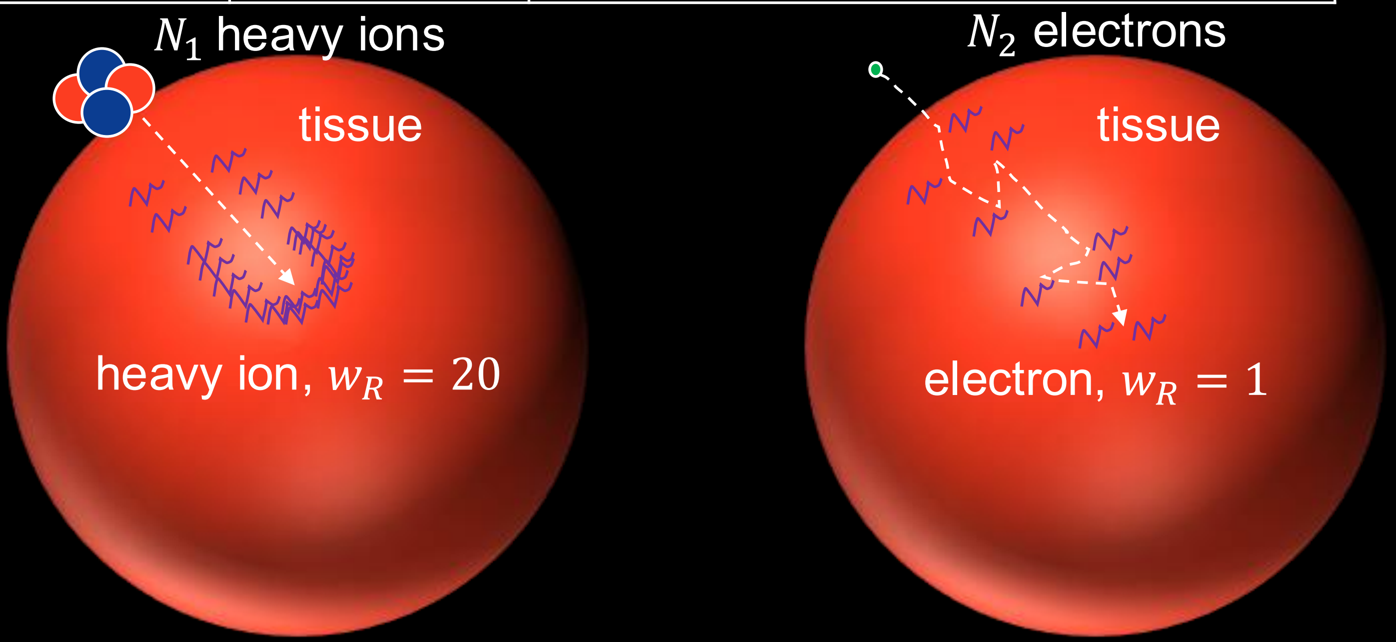
Equivalent Dose

absorbed dose scaled by radiation type (using radiation weighting factors) that loosely relates to an increased probability of cancer incidence

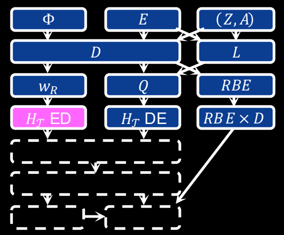
Quantity	Definition	SI Base Unit	Common Units
Equivalent Dose	$H = \sum_R w_R D_R$	J kg^{-1}	1 Sv = 100 rem = 1 J kg^{-1} × w_R

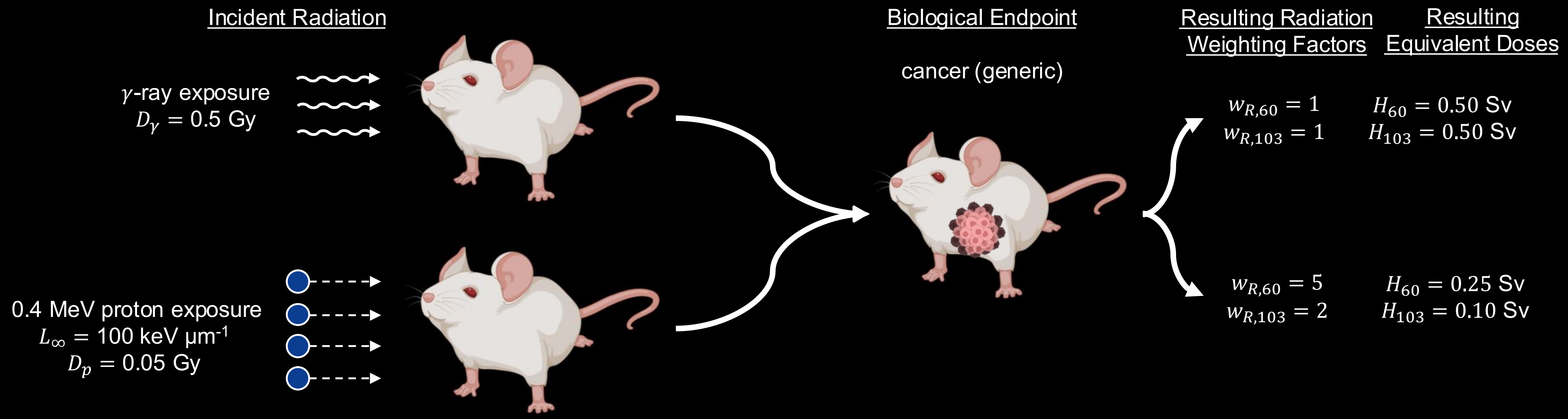
- Same concept as dose equivalent, evaluated differently
- equivalent dose ≠ dose equivalent

Assume each tissue sphere receives the same total absorbed dose D



Radiation Weighting Factor & Equivalent Dose Example

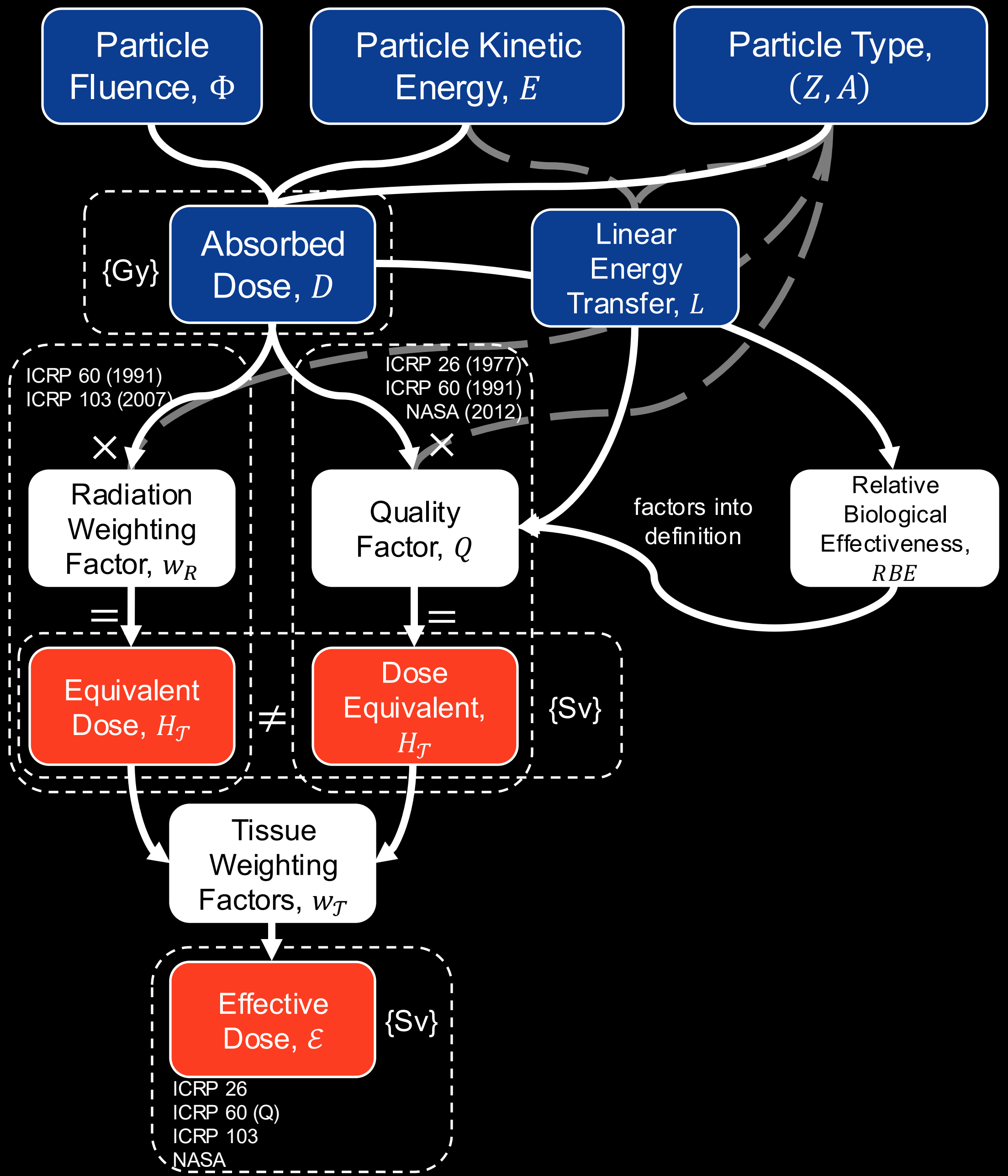


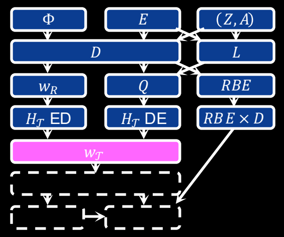


Key Point: Equivalent Dose

- Uses radiation weighting factors (not quality factors)
- Bad choice for space radiation protection
  - ICRP radiation weighting factors are constant for charged particles
  - ICRP 26, 60, and NASA quality factors depend (at least in part) on LET
    - Better reflect biological damage caused by high-LET charged particles
- Equivalent dose ≠ dose equivalent

How do we calculate Effective Dose?



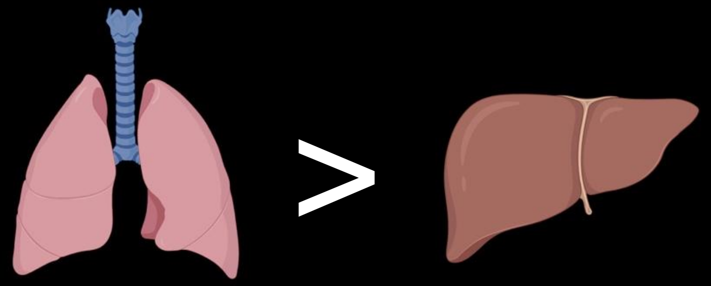


Tissue Weighting Factor

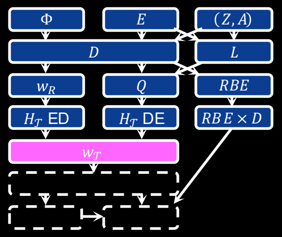
dimensionless factors that account for the radiosensitivity of different human tissues

Quantity	Definition	SI Base Unit	Common Units
Tissue Weighting Factor	Various	None	None

- Characterizes human tissue susceptibility to radiogenic cancer incidence
- $\sum_{\mathcal{T}} w_{\mathcal{T}} = 1$ (true weighting factors)
- Multiple definitions
  - ICRP 26: $w_{\mathcal{T},26}$
  - ICRP 60: $w_{\mathcal{T},60}$
  - ICRP 103: $w_{\mathcal{T},103}$
  - NSCR-2012: $w_{\mathcal{T},NASA}$ – depends on sex, smoking status, GCR vs. non-GCR exposure

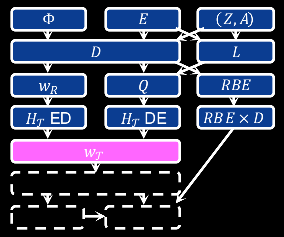


w_{lung} w_{liver}



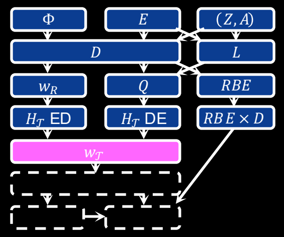
ICRP 26 Tissue Weighting Factor

Tissue	$w_{T,60}$	Notes
Gonads	0.25	gonads = { testes (male); ovaries (female)
Breast	0.15	
Bone marrow (red)	0.12	
Lung	0.12	
Thyroid	0.03	
Bone surface	0.03	
Remainder	0.30	



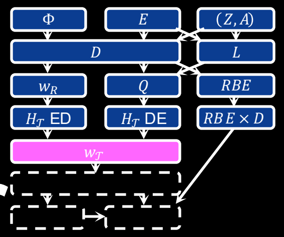
ICRP 60 Tissue Weighting Factor

Tissue	$w_{T,60}$	Notes
Gonads	0.20	gonads = { testes (male) / ovaries (female) }
Bone marrow (red)	0.12	
Colon	0.12	
Lung	0.12	
Stomach	0.12	
Bladder	0.05	
Breast	0.05	
Esophagus	0.05	
Liver	0.05	
Thyroid	0.05	
Bone surface	0.01	
Skin	0.01	
Remainder	0.05	*adrenals, brain, upper large intestine, small intestine, kidney, muscle, pancreas, spleen, thymus, uterus (female)* *If a single remainder tissue receives an equivalent dose greater than the highest equivalent dose any of the 12 non-remainder tissues, that remainder tissue is assigned a tissue weighting factor of 0.025 and the equivalent doses of the other remainder tissues are averaged and that average is associated with a tissue weighting factor of 0.025.*



ICRP 103 Tissue Weighting Factor

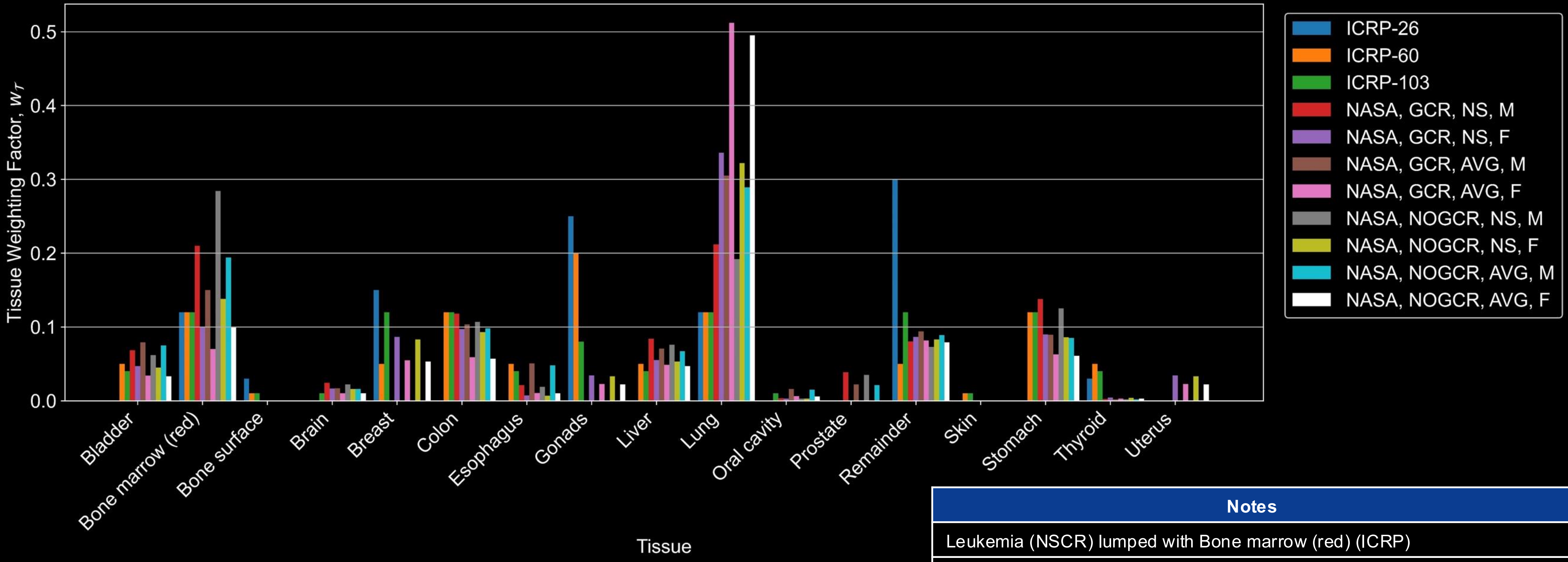
Tissue	$w_{T,103}$	Notes
Bone marrow (red)	0.12	
Breast	0.12	
Colon	0.12	
Lung	0.12	
Stomach	0.12	
Gonads	0.08	gonads = { testes (male); ovaries (female) }
Bladder	0.04	
Esophagus	0.04	
Liver	0.04	
Thyroid	0.04	
Bone surface	0.01	
Brain	0.01	
Salivary glands	0.01	
Skin	0.01	
Remainder	*0.12*	*adrenals, extrathoracic region, gallbladder, heart, kidneys, lymphatic nodes, muscle, oral mucosa, pancreas, prostate (male), small intestine, spleen, thymus, uterus/cervix (female)* *Individual remainder tissues are assigned a tissue weighting factor of* $\frac{0.12}{13}$ *(rendering the equivalent dose of the remainder tissues to be simply the arithmetic mean of remainder tissue equivalent doses). The large remainder dose rule from ICRP-60 no longer applies.*



NSCR-2012 Tissue Weighting Factor

Tissue	$w_{T,NASA}$							
	GCR Exposures				Non-GCR Exposures			
	Never Smokers		Average Population		Never Smokers		Average Population	
	male	female	male	female	male	female	male	female
Lung	0.212	0.336	0.305	0.512	0.192	0.322	0.289	0.495
Leukemia	0.21	0.1	0.15	0.07	0.284	0.138	0.194	0.100
Stomach	0.1379	0.0898	0.0896	0.0630	0.125	0.086	0.085	0.061
Colon	0.1181	0.0971	0.1033	0.0589	0.107	0.093	0.098	0.057
Liver	0.0839	0.0553	0.0707	0.0486	0.076	0.053	0.067	0.047
Other	0.0805	0.0867	0.0939	0.0816	0.073	0.083	0.089	0.079
Bladder	0.0684	0.0470	0.0791	0.0341	0.062	0.045	0.075	0.033
Prostate	0.0386		0.0221		0.035		0.021	
Brain	0.0243	0.0167	0.0169	0.0103	0.022	0.016	0.016	0.010
Esophagus	0.0210	0.00731	0.0506	0.01033	0.019	0.007	0.048	0.010
Oral cavity	0.00331	0.00313	0.01582	0.00620	0.003	0.003	0.015	0.006
Thyroid	0.00221	0.00418	0.00211	0.00310	0.002	0.004	0.002	0.003
Breast		0.0867		0.0548		0.083		0.053
Uterus		0.0345		0.0227		0.033		0.022
Ovary		0.0345		0.0227		0.033		0.022

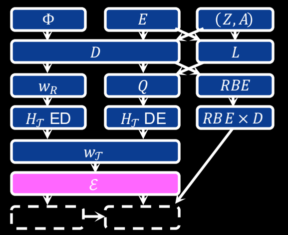
Tissue Weighting Factors



Notes
Leukemia (NSCR) lumped with Bone marrow (red) (ICRP)
Salivary glands (ICRP) lumped with Oral cavity (NSCR)
Ovary (NSCR) lumped with Gonads (ICRP)
Other (NSCR) lumped with Remainder (ICRP)

Key Point: Tissue Weighting Factors

- Different tissues are more radiosensitive than others
- Effective dose is heavily weighted toward radiosensitive tissues

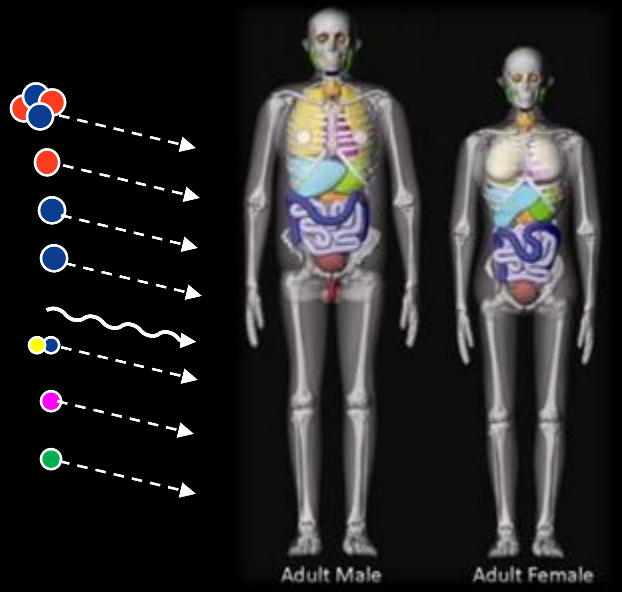


Effective Dose

Whole-body averaged dose equivalent (or equivalent dose), accounting for variable tissue radiosensitivity

Quantity	Definition	SI Base Unit	Common Units
Effective Dose	Various, $\mathcal{E} = \sum_\mathcal{T} w_\mathcal{T} H_\mathcal{T}$	J kg^{-1}	1 Sv = 100 rem = 1 J kg^{-1} $\times\, w_R$ (or Q) $\times\, w_\mathcal{T}$

- Widespread use as a protection quantity
  - Useful for establishing *dose limit recommendations*
- Multiple definitions:
  - in general: $\mathcal{E} = \sum_\mathcal{T} w_\mathcal{T} H_\mathcal{T} = \sum_\mathcal{T} w_\mathcal{T} \sum_R w_R D_{\mathcal{T},R}$



ICRP 60 & ICRP 103

$$\mathcal{E}_i = \sum_\mathcal{T} w_{\mathcal{T},i} \sum_R w_{R,i} D_{\mathcal{T},R}$$

for $i \in \{60, 103\}$

NASA

$$\mathcal{E}_{NASA} = \sum_\mathcal{T} w_{\mathcal{T},NASA} \sum_{(Z,A)} \frac{1}{\rho_\mathcal{T}} \int_0^\infty Q_{NASA}(Z,A,E) L(Z,A,E) \Phi_\mathcal{T}(Z,A;E) dE$$

NASA STD-3001 Radiation Limits

- As Low As Reasonably Achievable (ALARA)
  - Minimize radiation exposure within mission specifications and within reason

- Space Permissible Exposure Limit (SPEL)
  - Career effective dose from space radiation exposure <u>shall</u> be < 600 mSv
  - Calculated using NASA Space Cancer Risk model (NSCR-2012)
  - Purpose: reduce/prevent deleterious long-term stochastic effects (cancer)

NASA STD-3001 Radiation Limits

- Organ-Specific Limits
  - Covered by SPEL
  - Short- (non-cancer) and long-term limits

RBE = Relative Biological Effectiveness

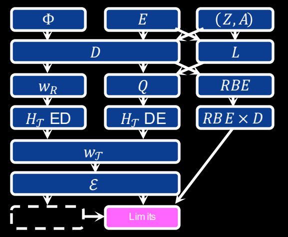
Suggested RBEs

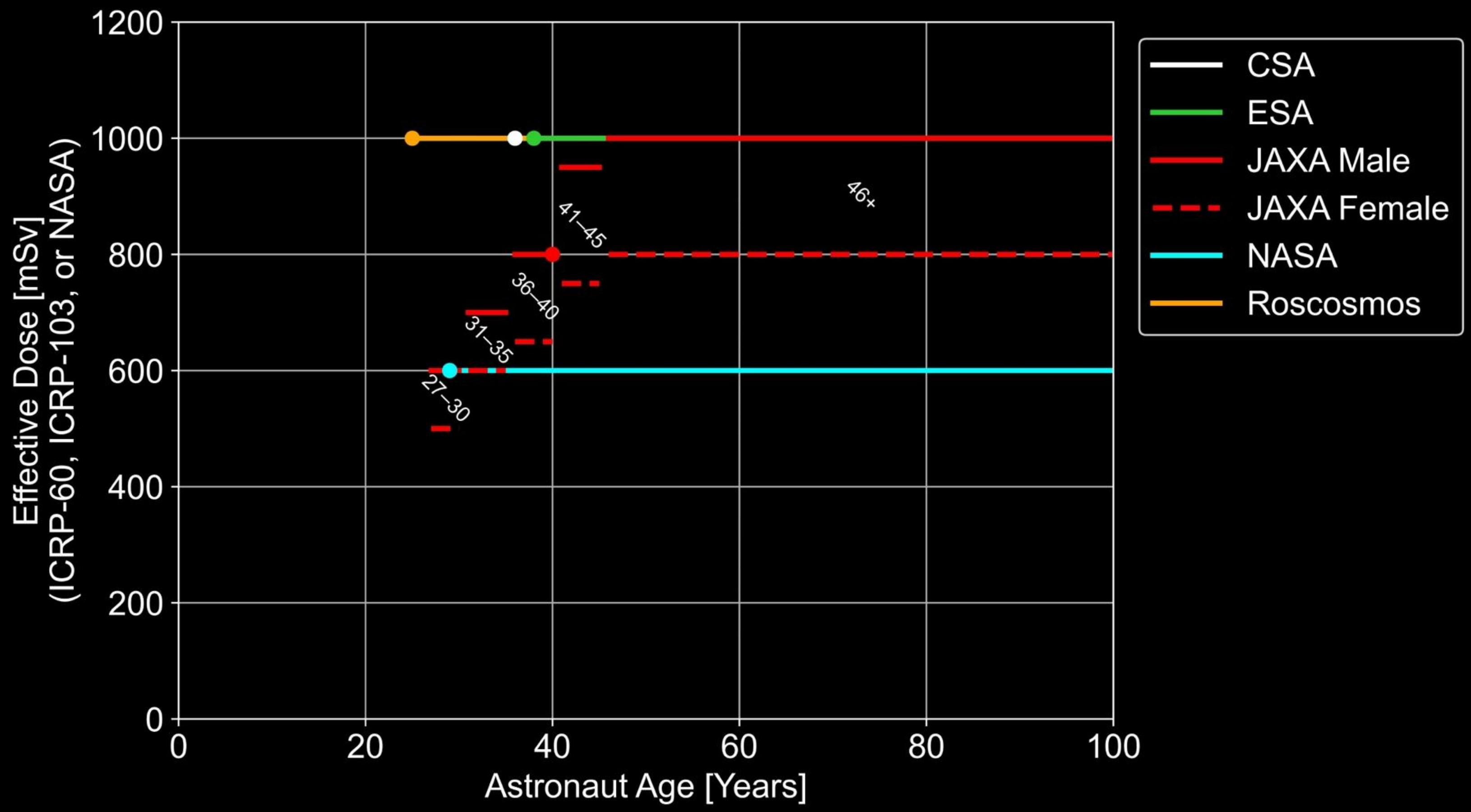
Radiation Type	Recommended RBE	Range
1 to 5 MeV neutrons	6.0	4 to 8
5 to 50 MeV neutrons	3.5	2 to 5
Heavy ions	2.5	1 to 4
> 2 MeV protons	1.5	N/A

Organ-Specific Non-Cancer Dose Limits

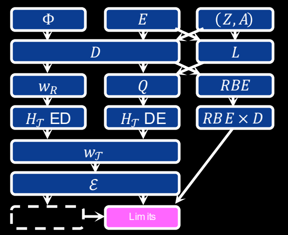
Organ	30-Day Limit	1-Year Limit	Career
Lens of Eye	1000 mGy-Eq	2000 mGy-Eq	4000 mGy-Eq
Skin	1500 mGy-Eq	3000 mGy-Eq	6000 mGy-Eq
Blood-Forming Organs (BFO)	250 mGy-Eq	500 mGy-Eq	N/A
Circulatory System	250 mGy-Eq	500 mGy-Eq	1000 mGy-Eq
Central Nervous System	500 mGy	1000 mGy	1500 mGy
Central Nervous System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

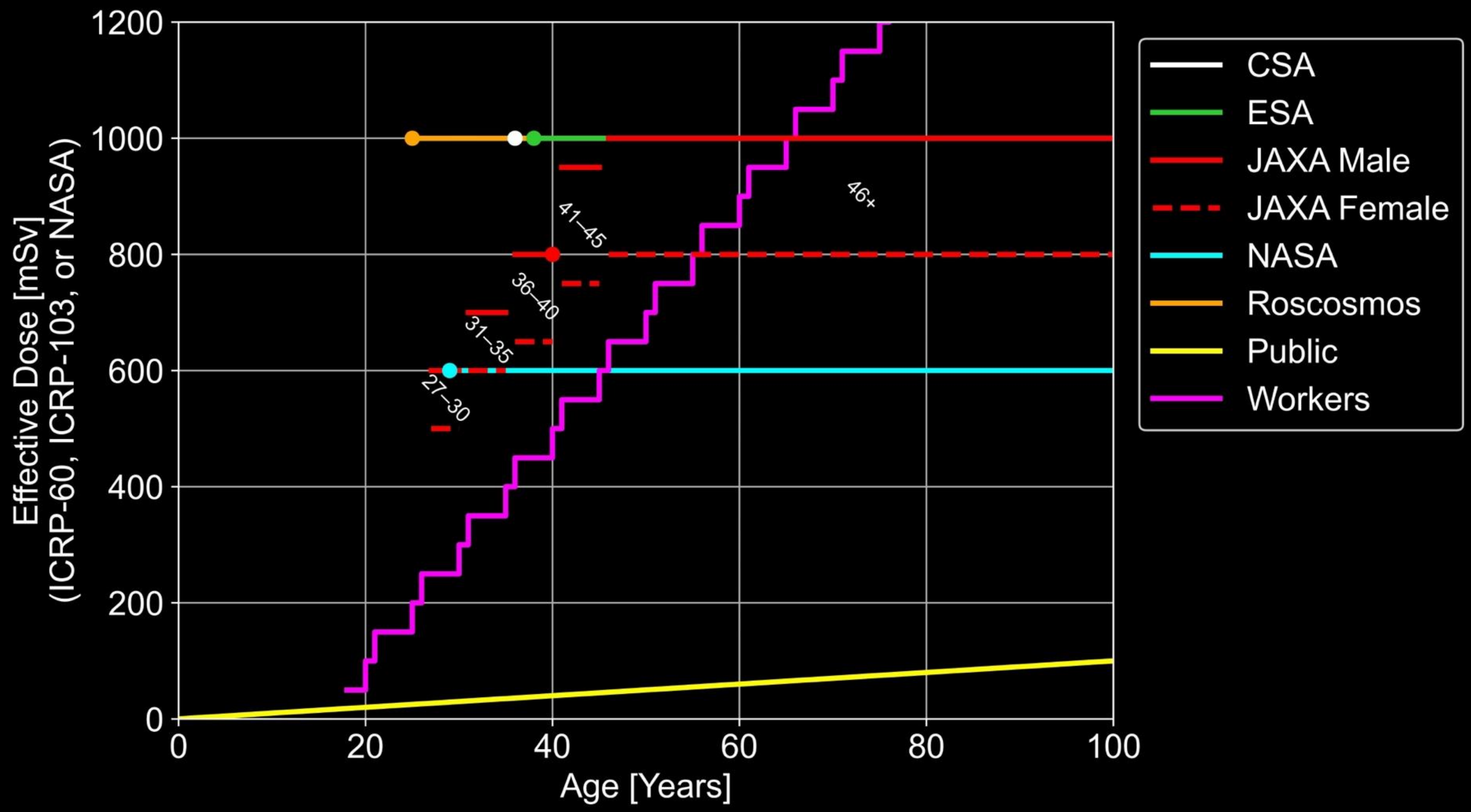
Career Dose Limits

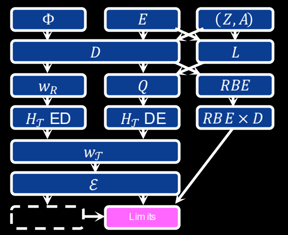




Career Dose Limits



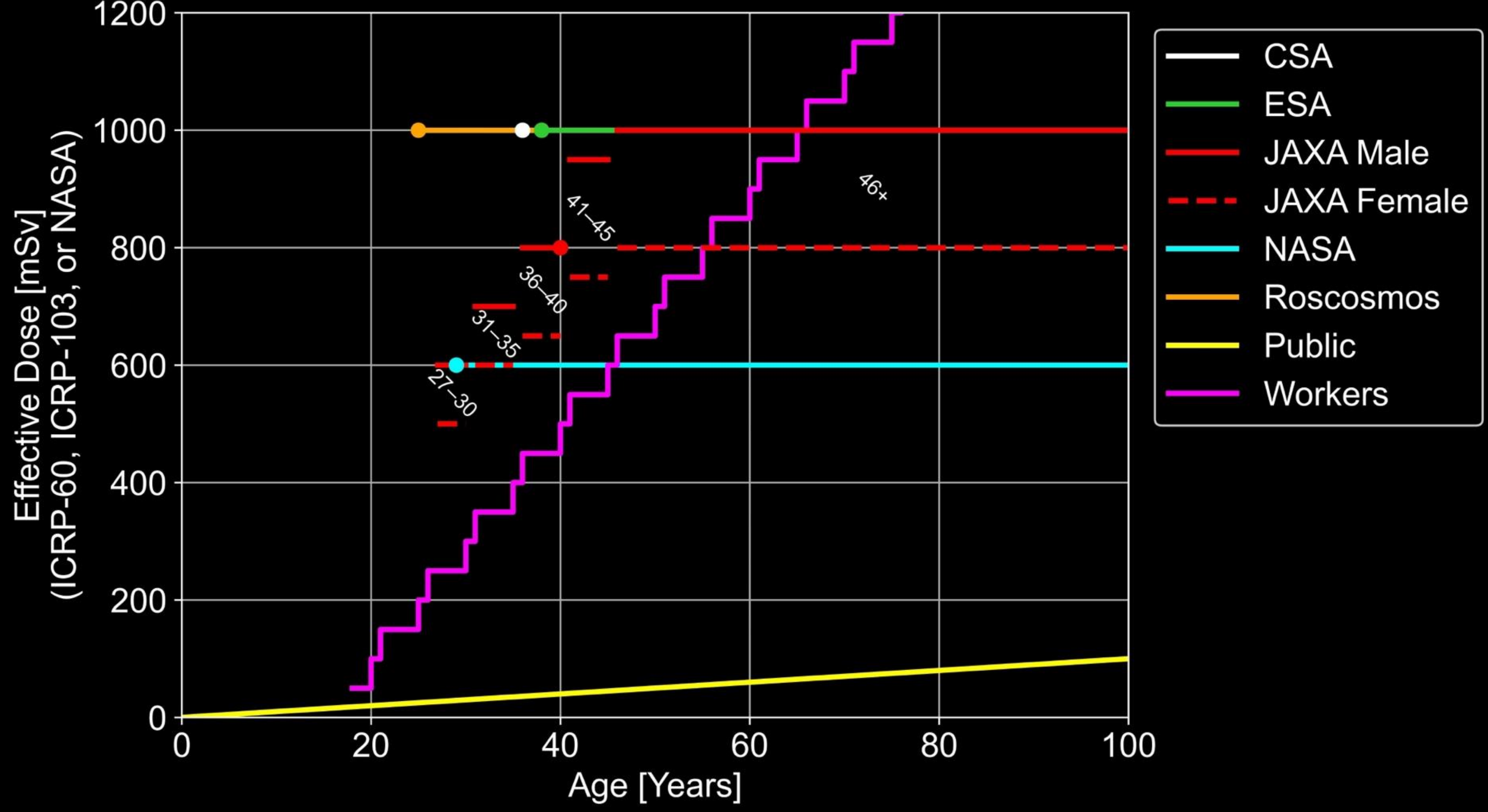




Career Dose Limits

- Different metrics!
- Not directly comparable – 1 Sv of ICRP 60 effective dose ≠ 1 Sv of NASA effective dose

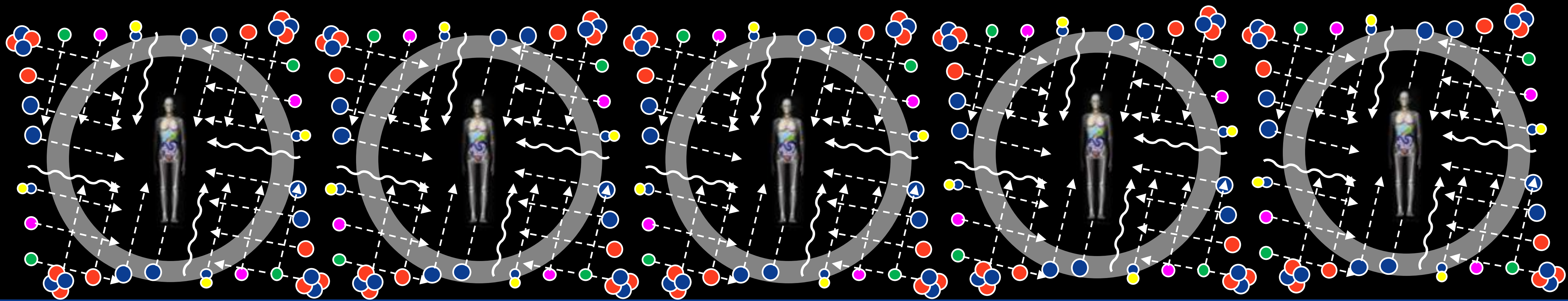
Cohort	Effective Dose Metric
CSA	ICRP 60
ESA	ICRP 60
JAXA	ICRP 103
NASA	NASA
Roscosmos	ICRP 60
Public	ICRP 103
Workers	ICRP 103



Comparison of Effective Dose Metrics

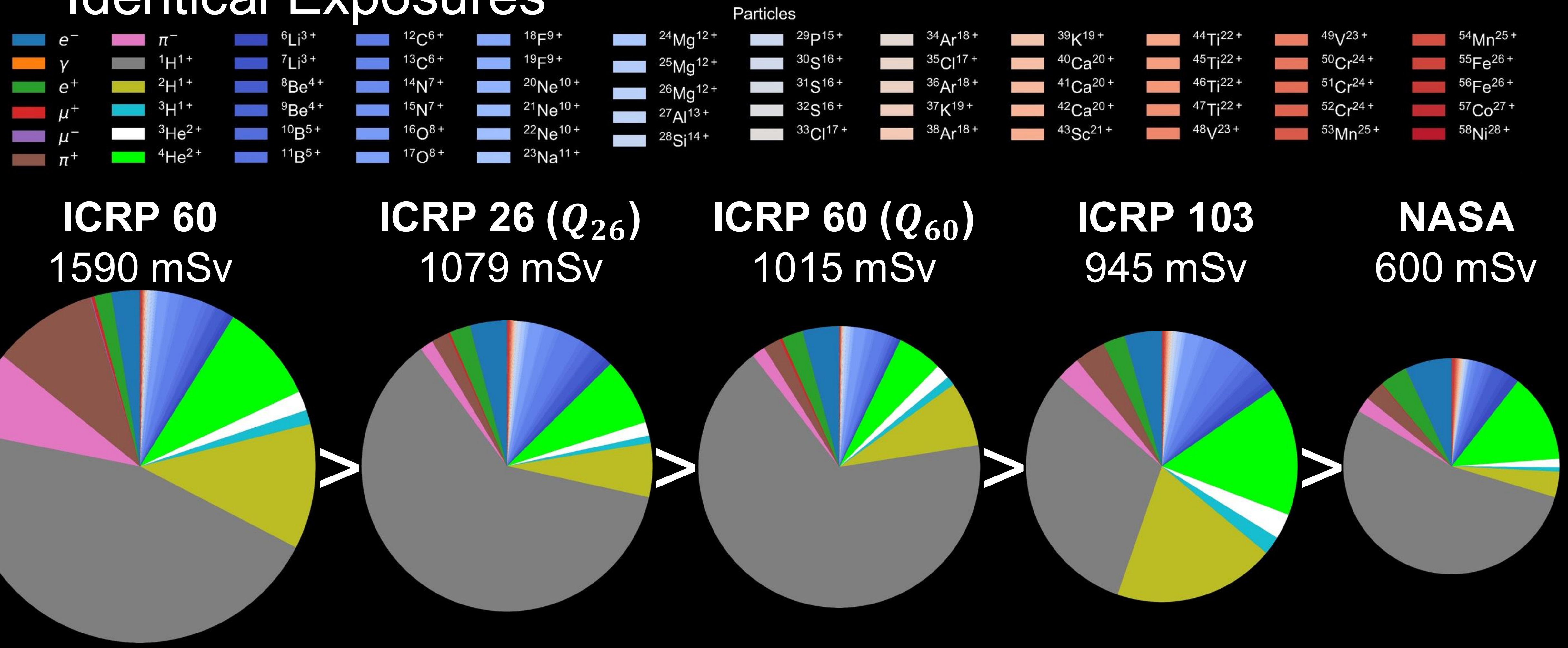
- How does effective dose vary with methodology?
  - Designed ISS mission duration resulting in 600 mSv NASA effective dose
    - Galactic cosmic ray and trapped proton environment exposure only
    - Female astronaut phantom (FAX)
  - To illustrate, let's calculate effective dose using 5 different methodologies assuming identical radiation fields

ICRP 60 | **ICRP 26 (Q_{26})** | **ICRP 60 (Q_{60})** | **ICRP 103** | **NASA**



Comparison of Effective Dose Metrics

Identical Exposures



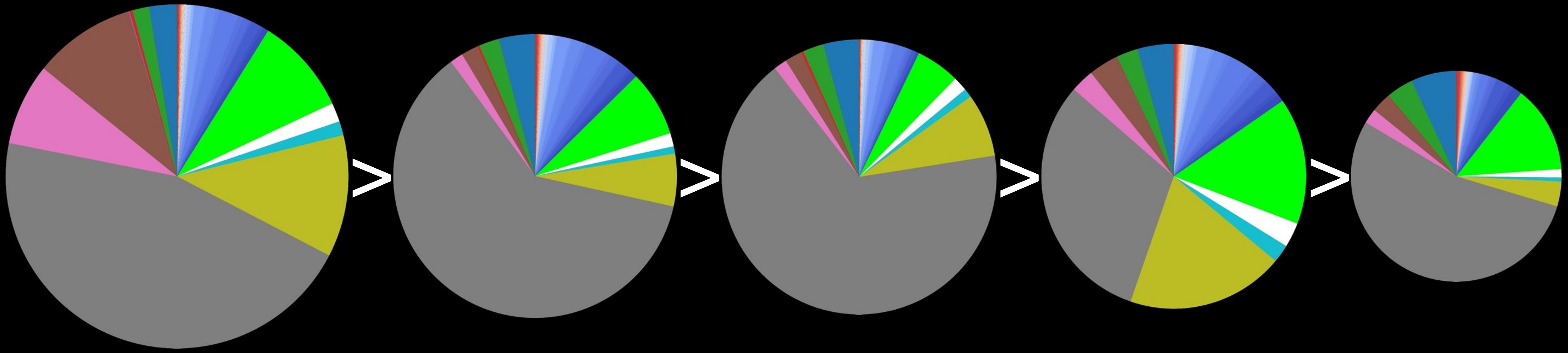
Relationships among method results (relative magnitudes, particle distributions) change depending on incident field

Comparison of Effective Dose Metrics

identical exposures → identical biological outcomes → different effective dose values!?

effective dose calculation methodology must be specified for results to be of any use

ICRP 60 1590 mSv > **ICRP 26 (Q_{26})** 1079 mSv > **ICRP 60 (Q_{60})** 1015 mSv > **ICRP 103** 945 mSv > **NASA** 600 mSv



Key Point: Effective Dose Methodologies

- Not all Sieverts are the same!
- Cite the methodology used when reporting effective dose

Summary of Radiation Protection Quantities

Quantity	Definition	SI Base Unit	Common Units
Particle Kinetic Energy	$E = (\gamma - 1)m_0c^2$	J	1 MeV = $10^6 q_e$ J
Particle Fluence	$\Phi \equiv \frac{dN}{dA} \equiv \frac{d(\sum_i s_i)}{dV}$	m^{-2}	1 cm^{-2} = 10^4 m^{-2}
Absorbed Dose	$D \equiv \frac{d\bar{\varepsilon}}{dm}$	J kg^{-1}	1 Gy = 100 rad = 1 J kg^{-1}
Linear Energy Transfer (LET)	$L_\infty \equiv \frac{dE}{d\ell}, L_\Delta \equiv \left(\frac{dE}{d\ell}\right)_\Delta$	J m^{-1}	1 keV µm^{-1} = $10^9 q_e$ J m^{-1}
Relative Biological Effectiveness	$RBE = \frac{D_{reference}}{D_{interest}}$	None	None
RBE-Weighted Absorbed Dose	$RBE \times D$	J kg^{-1}	1 Gy-eq = 100 rad-eq = 1 J kg^{-1} $\times RBE$
Quality Factor	Various	None, J kg^{-1}/(J kg^{-1})	Officially dimensionless, may be interpreted as “Sv Gy^{-1}”
Dose Equivalent	$H = QD$	J kg^{-1}	1 Sv = 100 rem = 1 J kg^{-1} $\times Q$
Radiation Weighting Factor	Various	None, J kg^{-1}/(J kg^{-1})	Officially dimensionless, may be interpreted as “Sv Gy^{-1}”
Equivalent Dose	$H = \sum_R w_R D_R$	J kg^{-1}	1 Sv = 100 rem = 1 J kg^{-1} $\times w_R$
Tissue Weighting Factor	Various	None	None
Effective Dose	Various, $\mathcal{E} = \sum_\mathcal{T} w_\mathcal{T} H_\mathcal{T}$	J kg^{-1}	1 Sv = 100 rem = 1 J kg^{-1} $\times w_R$ (or Q) $\times w_\mathcal{T}$

Key Points: Radiation Dose Measurements

- Dosimeters measure absorbed dose in Gy, typically in silicon or plastic. This value cannot be immediately translated to expected health impacts *without proper interpretation*.

- The appropriate way to predict health effects based on radiation exposure is to expose a computational phantom to the radiation field of choice, calculate a dose in each organ of interest, and then calibrate the computed dose to the measured dose via a normalization factor. In short, use physics to estimate the relative distribution of dose in the various tissues, then scale to "match" the measured dose.

- Dose values relevant to human health must incorporate factors that account for the relative damage output of different radiation types in tissue, and the sensitivity of different tissues (organs) to radiation. Not simple!

Key Points: Radiation Dose Limits for NASA

- The NASA career dose limit is 600 mSv of NASA effective dose, using NASA quality factor, and NASA tissue weighting factors.
  - The career dose limit is designed ensure that a 35-year old female astronaut not exceed an excess cancer risk of 3% (on the order the additional risk incurred by making unhealthy lifestyle choices, e.g., poor diet, sedentary behavior).
- Short-term 30-day limits are specified using RBE-weighted dose using NASA-defined RBEs for selected tissues, designed to avoid any noticeable health impacts by a large margin. Astronauts would experience noticeable health effects at much higher doses.
  - NASA 30-day Limit for Blood-Forming Organs: 250 mGy-eq
  - ~50% of exposed population would experience nausea: 1000 mGy-eq
- Space radiation operations uses the approach “As Low As Reasonably Achievable” (ALARA) with the aim to **reduce** astronaut dose while accomplishing mission goals.

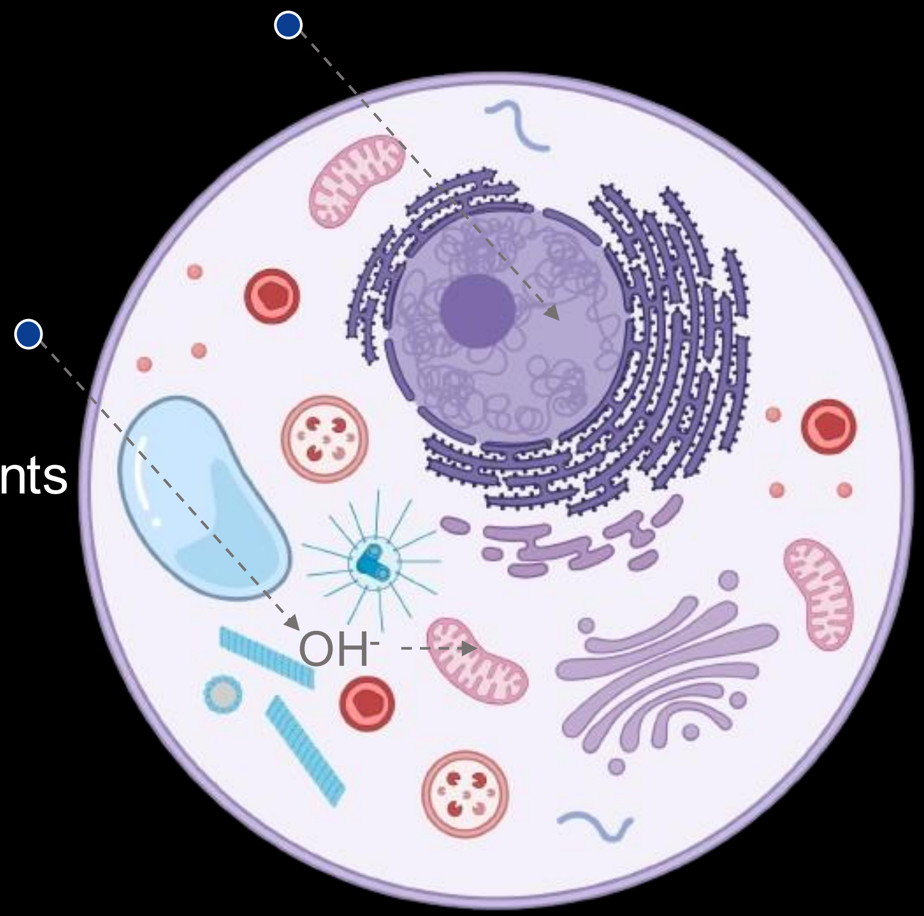
Part II

Review of Radiobiological Effects

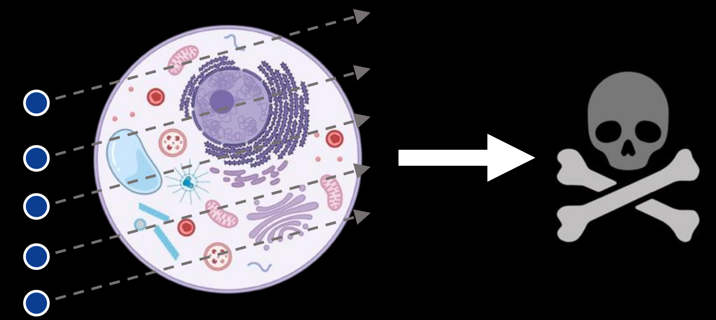
Deterministic Effects (Tissue Reactions) and Stochastic Effects

Radiation Interactions with Human Cells

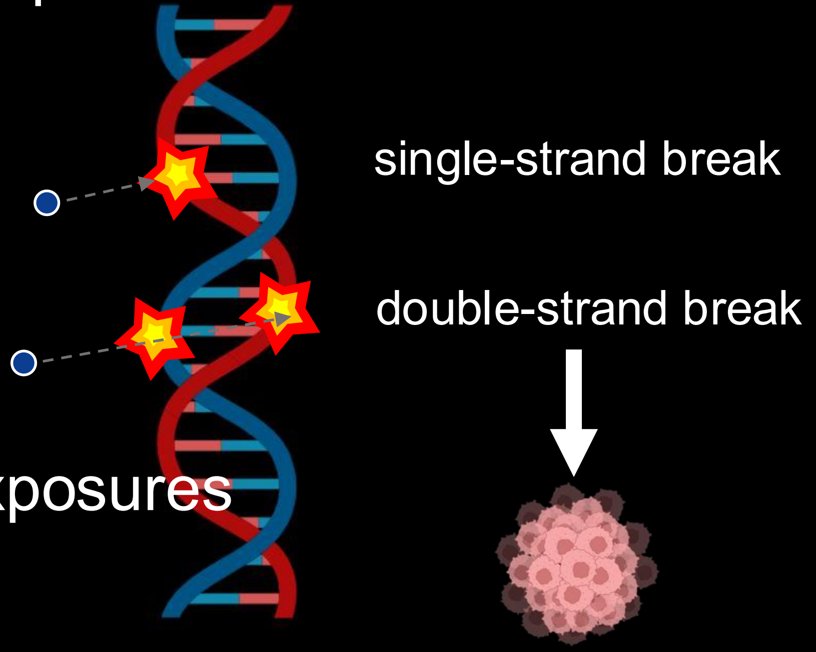
- Cellular level radiation interactions
  - Direct interaction:
    - radiation interacts with DNA directly
  - Indirect interaction:
    - radiation ionizes aqueous cytoplasm
    - produces free radicals (OH^-)
    - free radicals damage DNA and other cell components



Cell-Killing and DNA Damage



- Cell-killing
  - Cell dies → cell ceases to fulfill function
  - If many cells die in a concentrated area, tissue could cease to function
  - Associated with <u>deterministic effects</u>, acute exposures
- DNA damage
  - Single-strand breaks
    - Usually repaired
  - Double-strand breaks
    - More difficult to repair
    - Can lead to misrepair → mutation, cancer
  - Associated with <u>stochastic effects</u>, chronic exposures



Deterministic vs. Stochastic

Deterministic Effects

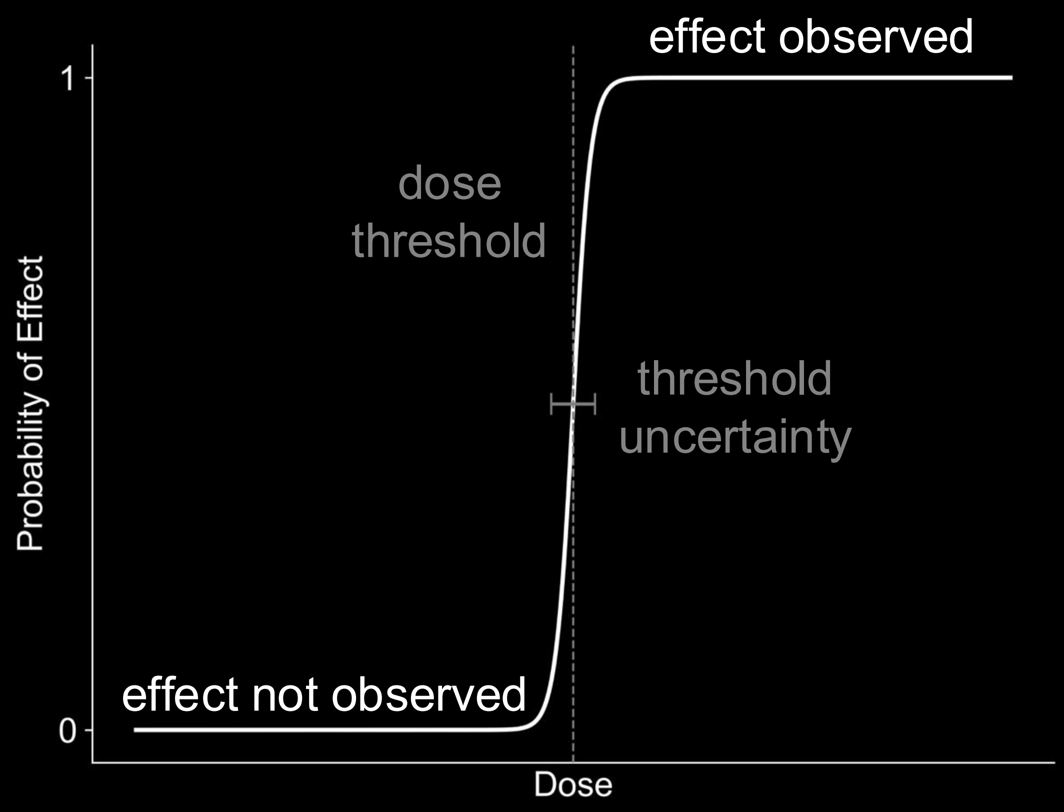
- Severity increases with dose
- Threshold dose required to observe effect
- E.g, **tissue reactions**
  - Acute radiation syndrome
  - Skin erythema
- Associated with absorbed dose or RBE-weighted dose
  - Gy or Gy-eq

Stochastic Effects

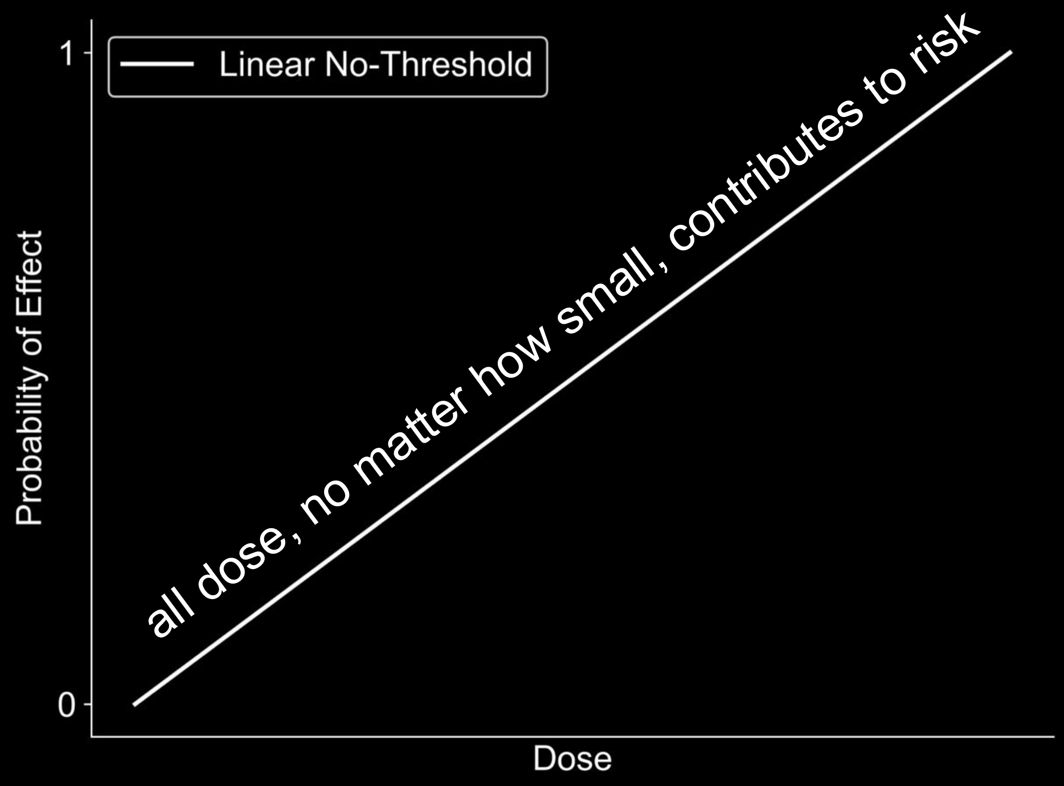
- Probability increases with dose
  - Severity does *not*
- No dose threshold
- E.g., **cancer**
- Associated with organ dose equivalent or effective dose
  - Sv

Deterministic vs. Stochastic

Deterministic Effects

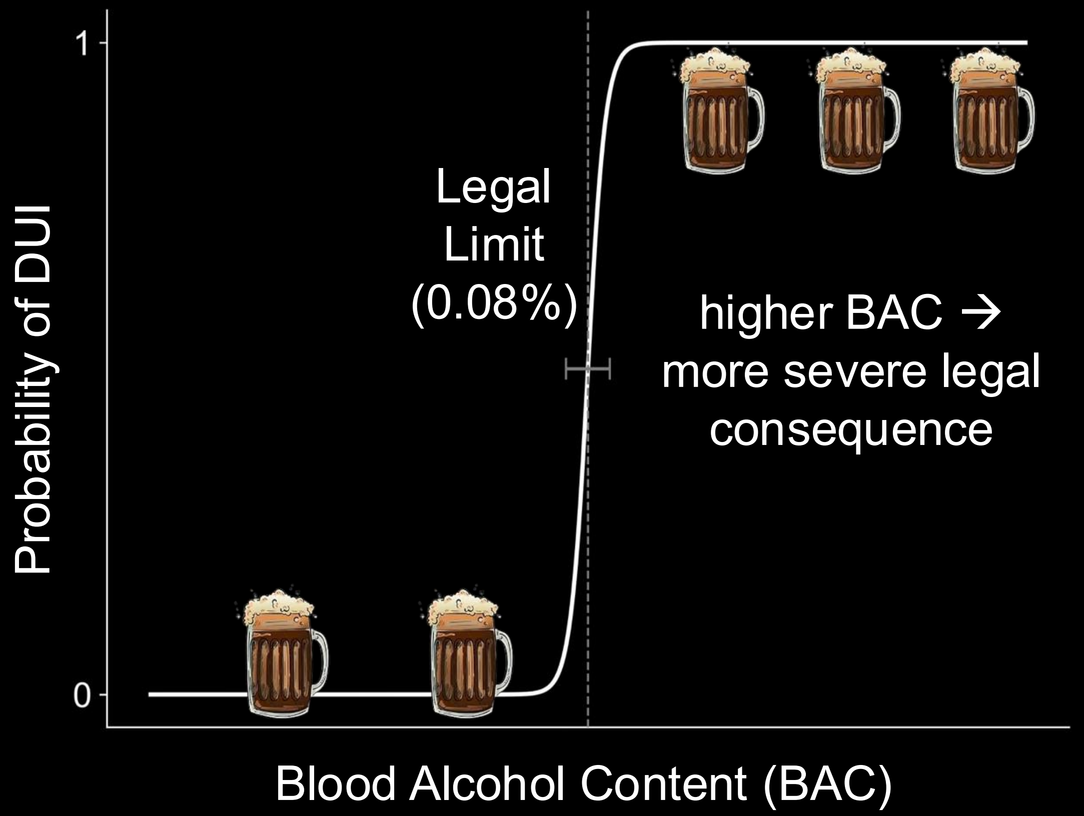


Stochastic Effects

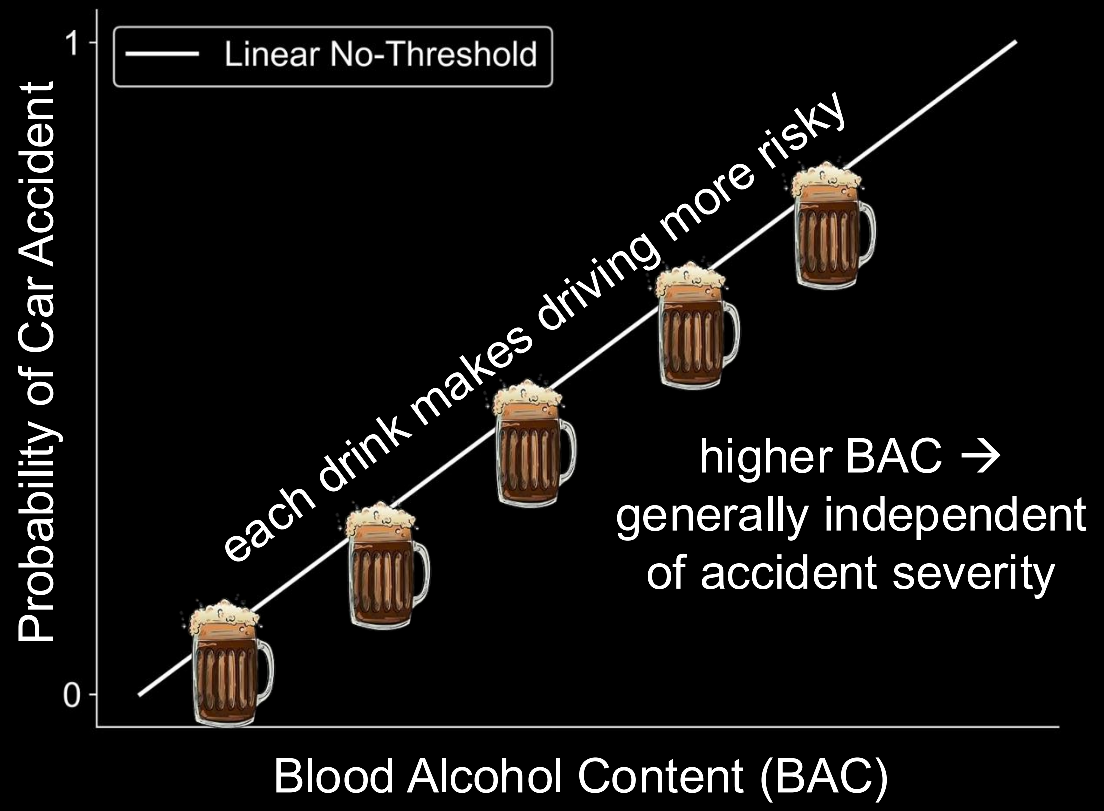


Deterministic vs. Stochastic
Alcohol Analogy

Deterministic Effects



Stochastic Effects

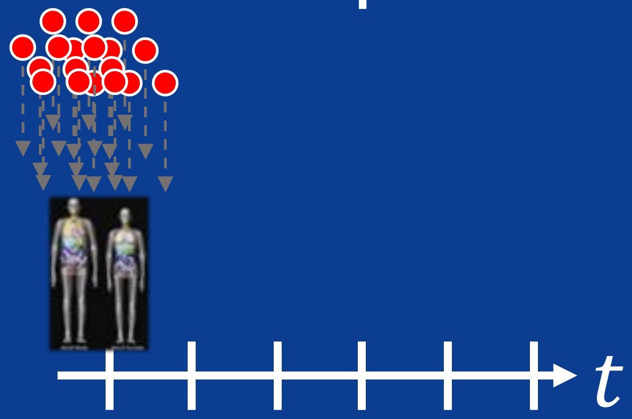


Dose Rate Effect

Deterministic Effects

high dose rate

acute exposure

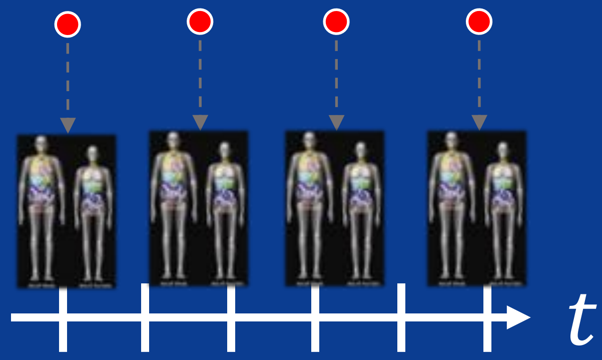


acute radiation syndrome

Stochastic Effects

low dose rate

chronic exposure



increased cancer risk

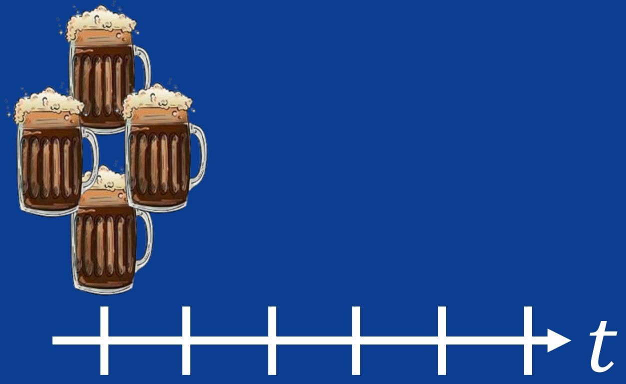
Dose Rate Effect

Alcohol Analogy

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

Dose Rate Effect

Deterministic Effects

high dose rate

acute exp

binge drink → nausea, alcohol poisoning

Stochastic Effects

low dose rate

ic exposure

t

drink once-a-day → long-term effects

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

Symptomology of Acute Exposures

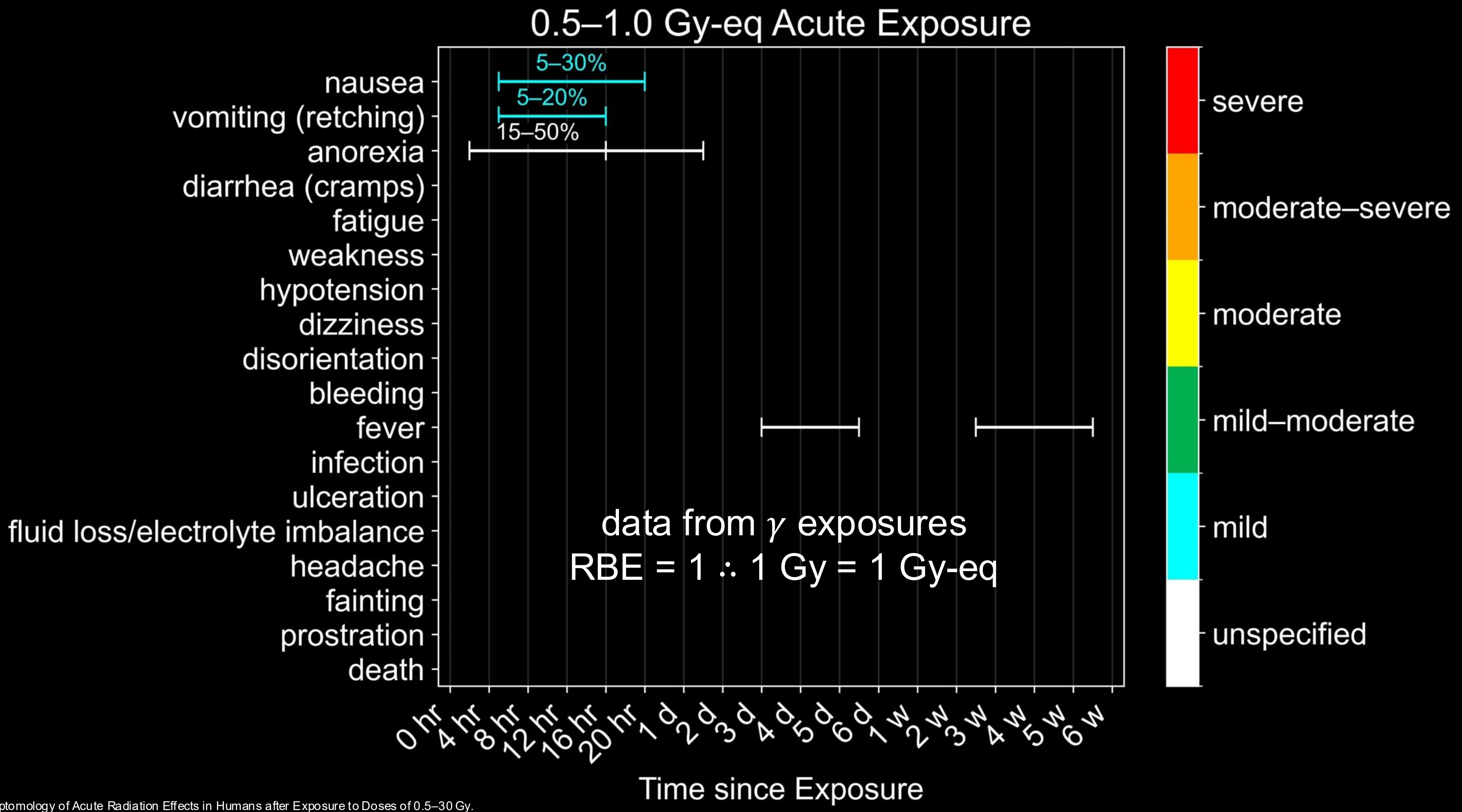
- Symptoms
- Probability of Symptoms
- Severity of Symptoms

depend on →

- Total Dose
- Dose Rate

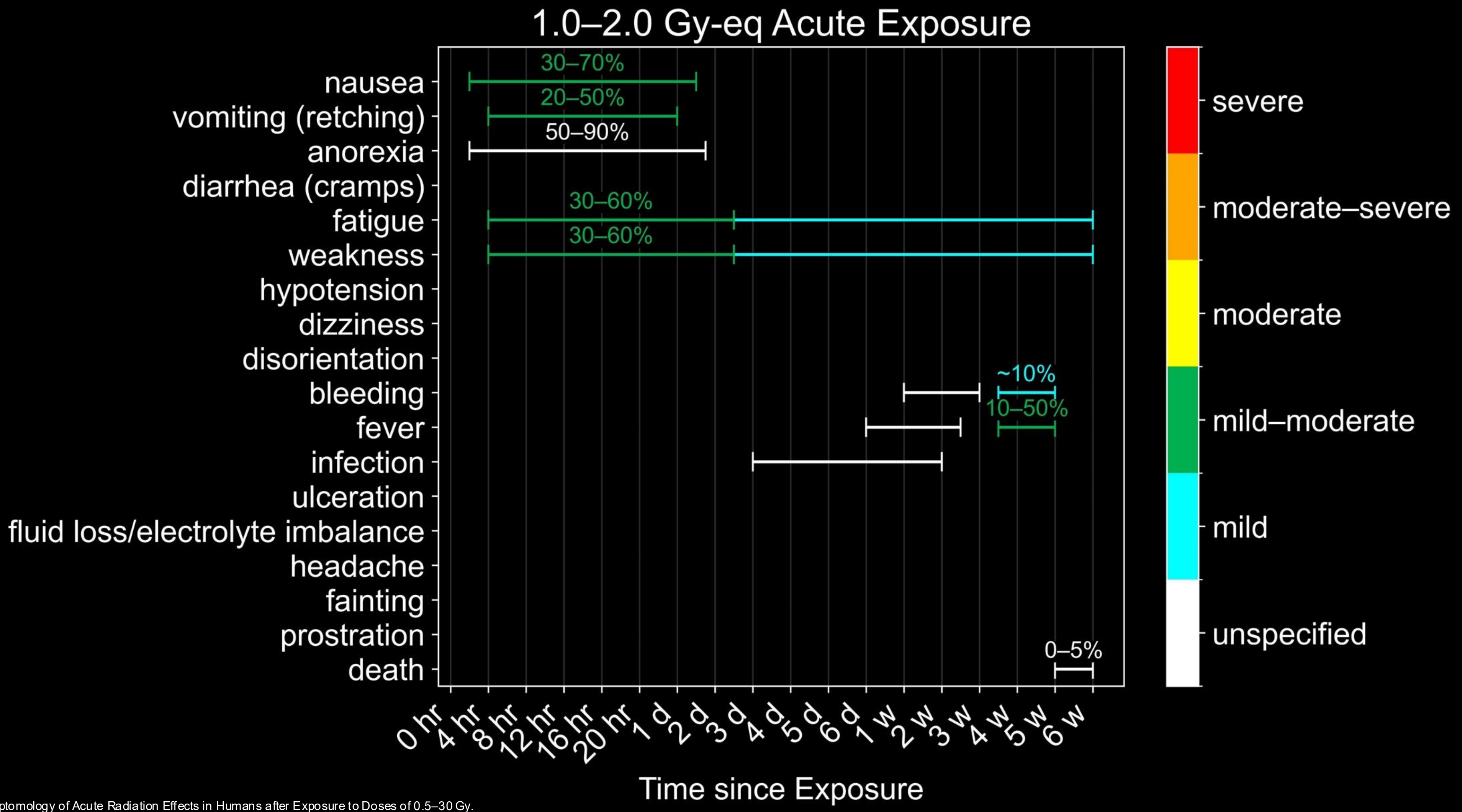
- Note that human data on deterministic effects associated with long-term exposures is scant
- “Acute” exposures typically refer to exposures that occur on the order of <u>seconds to minutes</u>

Symptomology of Acute Exposures



Anno *et al.*, 1988, Symptomology of Acute Radiation Effects in Humans after Exposure to Doses of 0.5–30 Gy.

Symptomology of Acute Exposures



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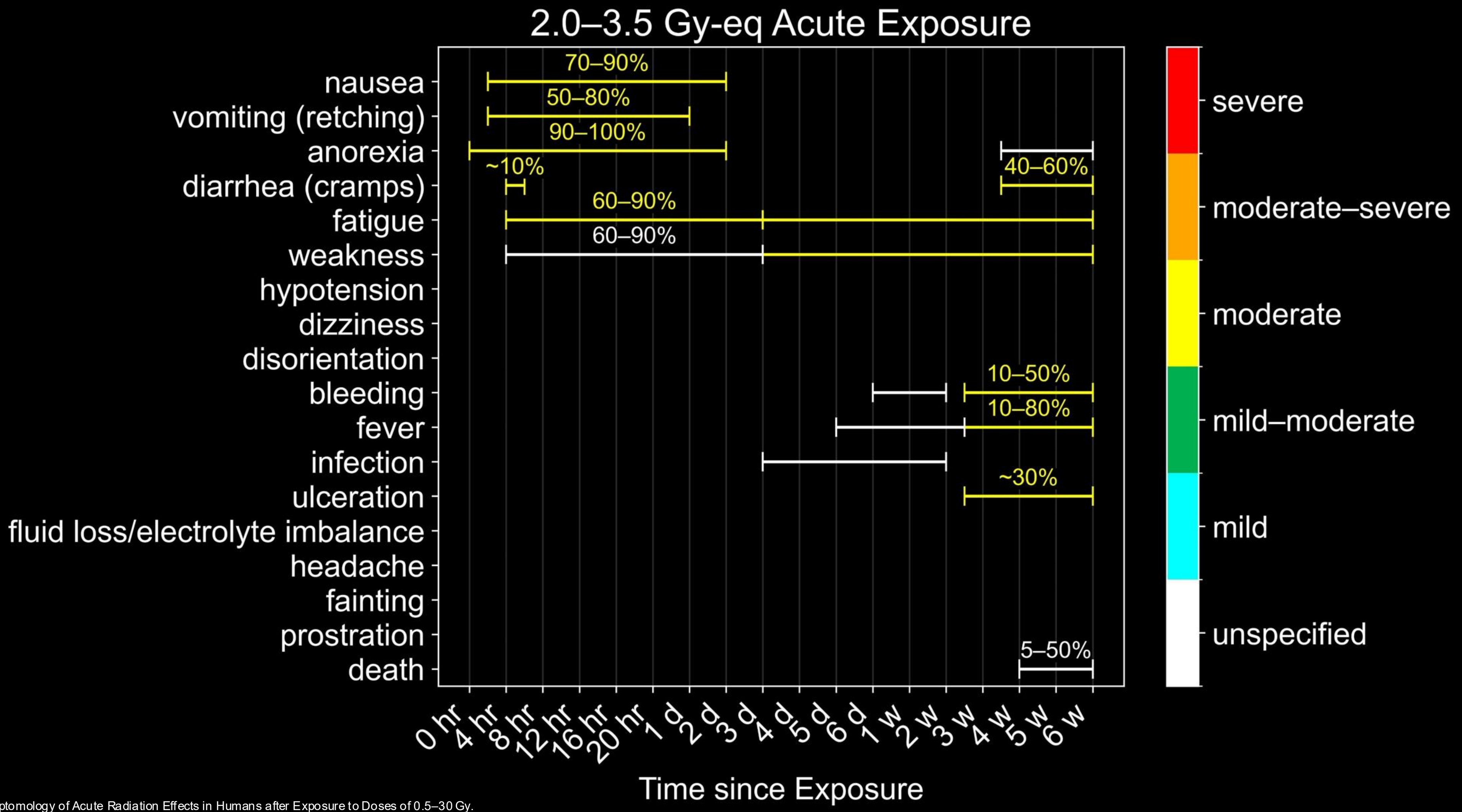
Symptomology of Acute Exposures



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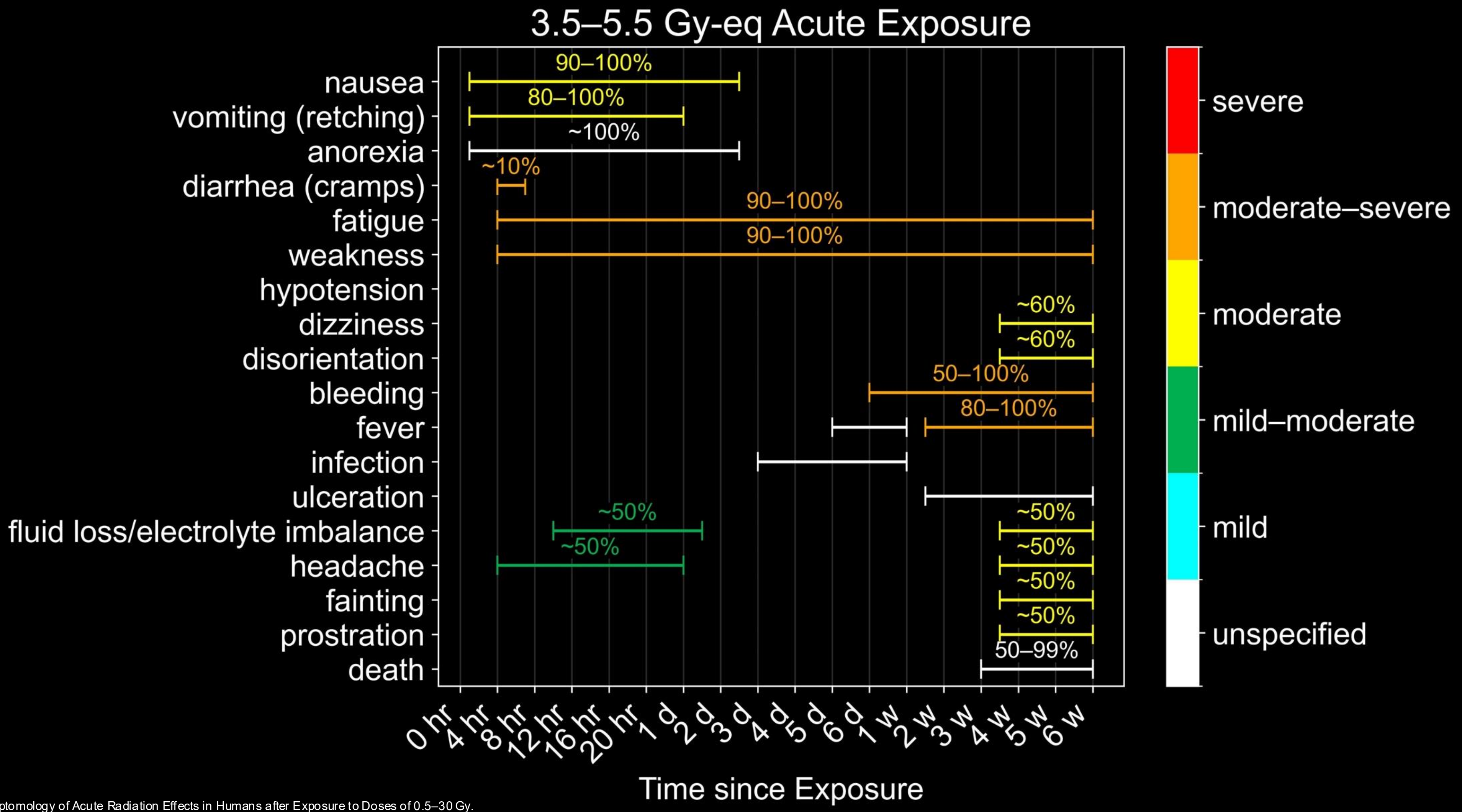
Symptomology of Acute Exposures



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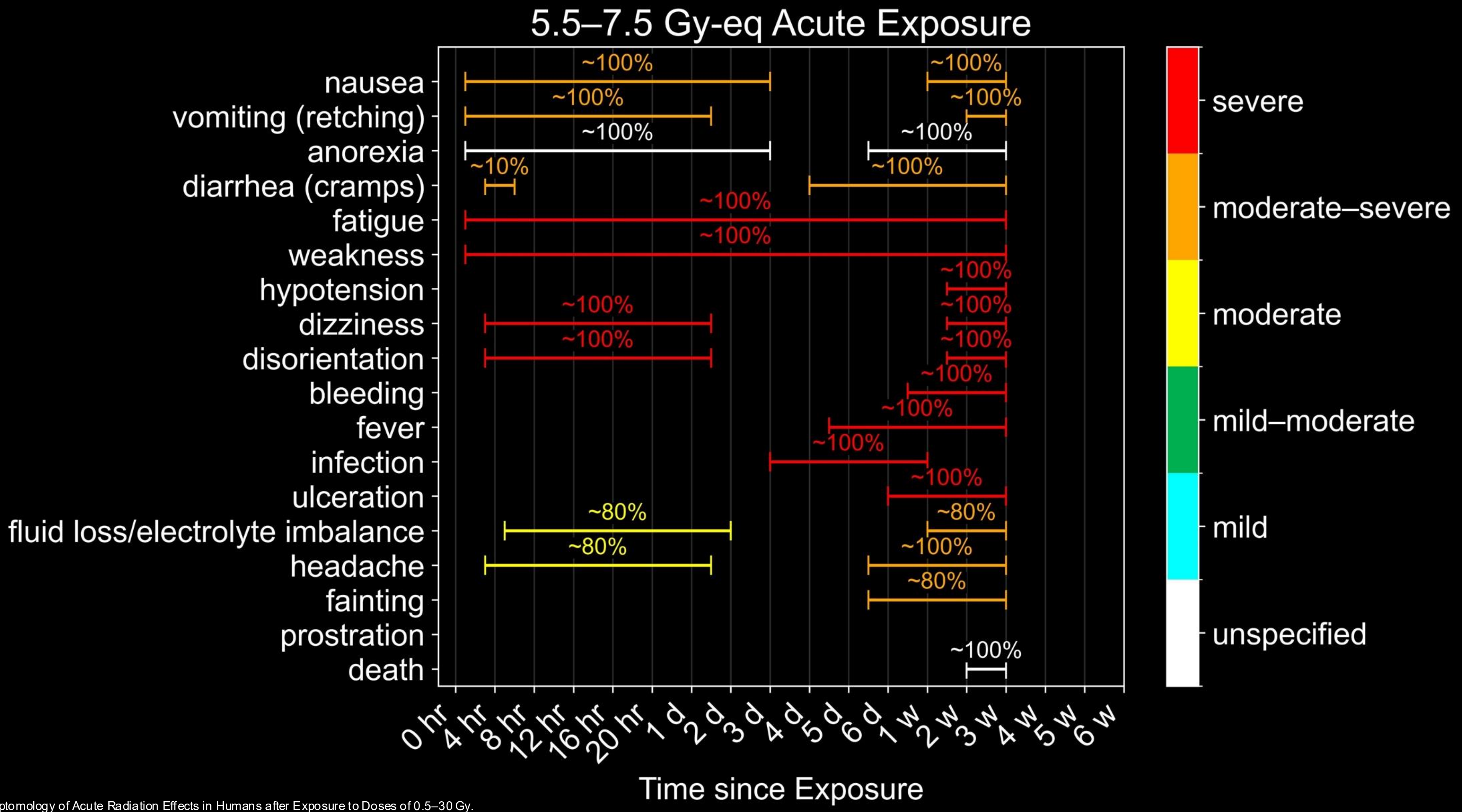
Symptomology of Acute Exposures



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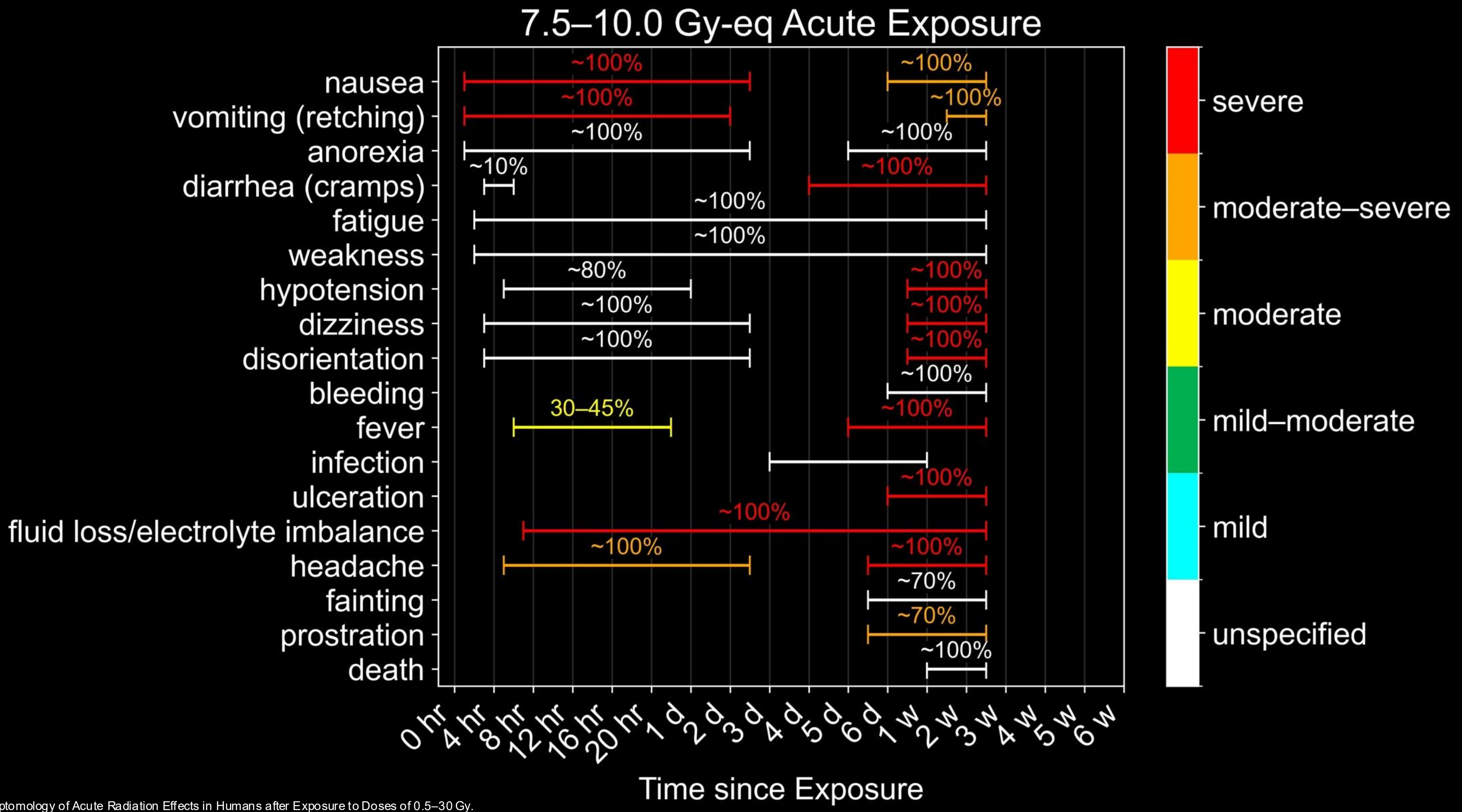

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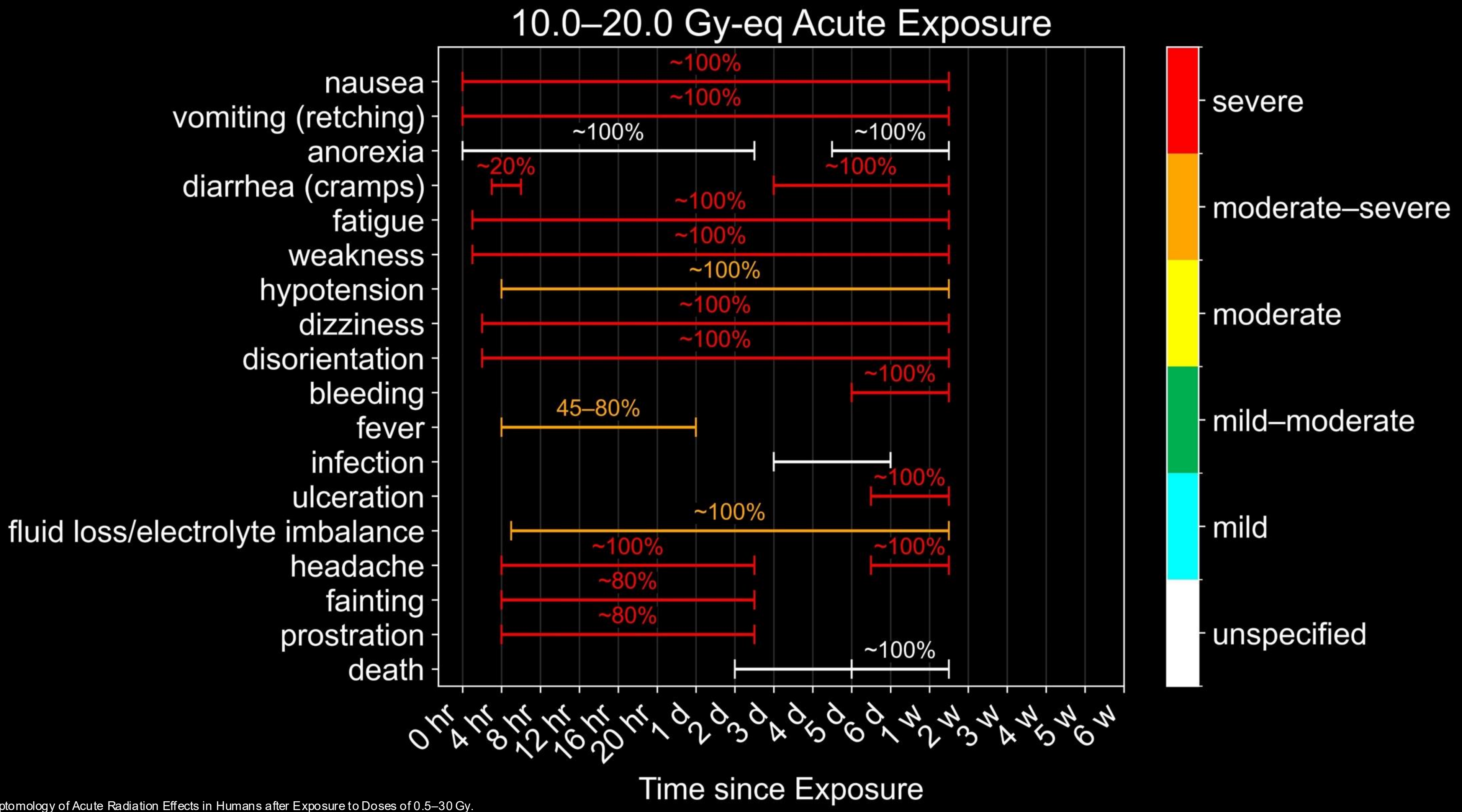
Symptomology of Acute Exposures



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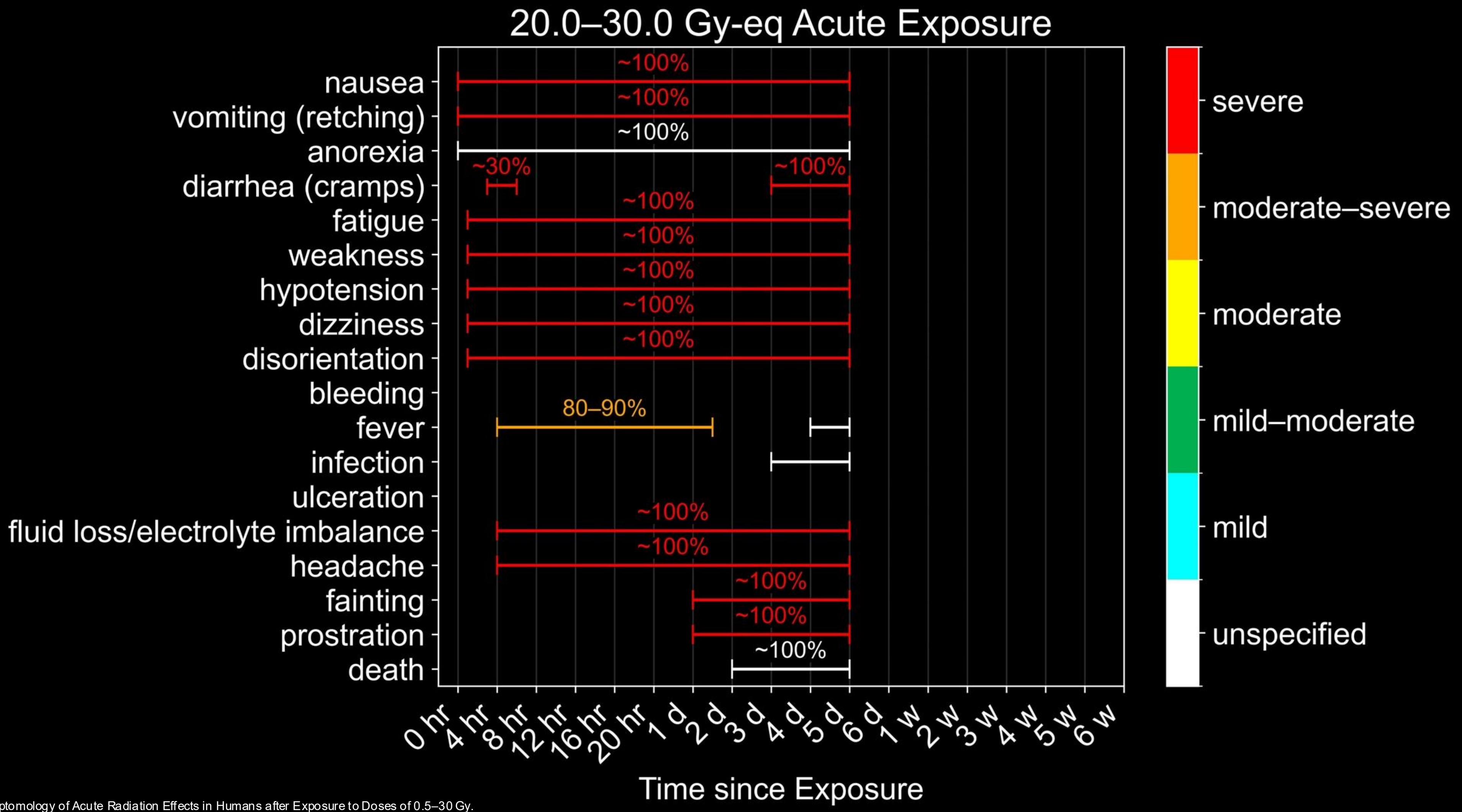
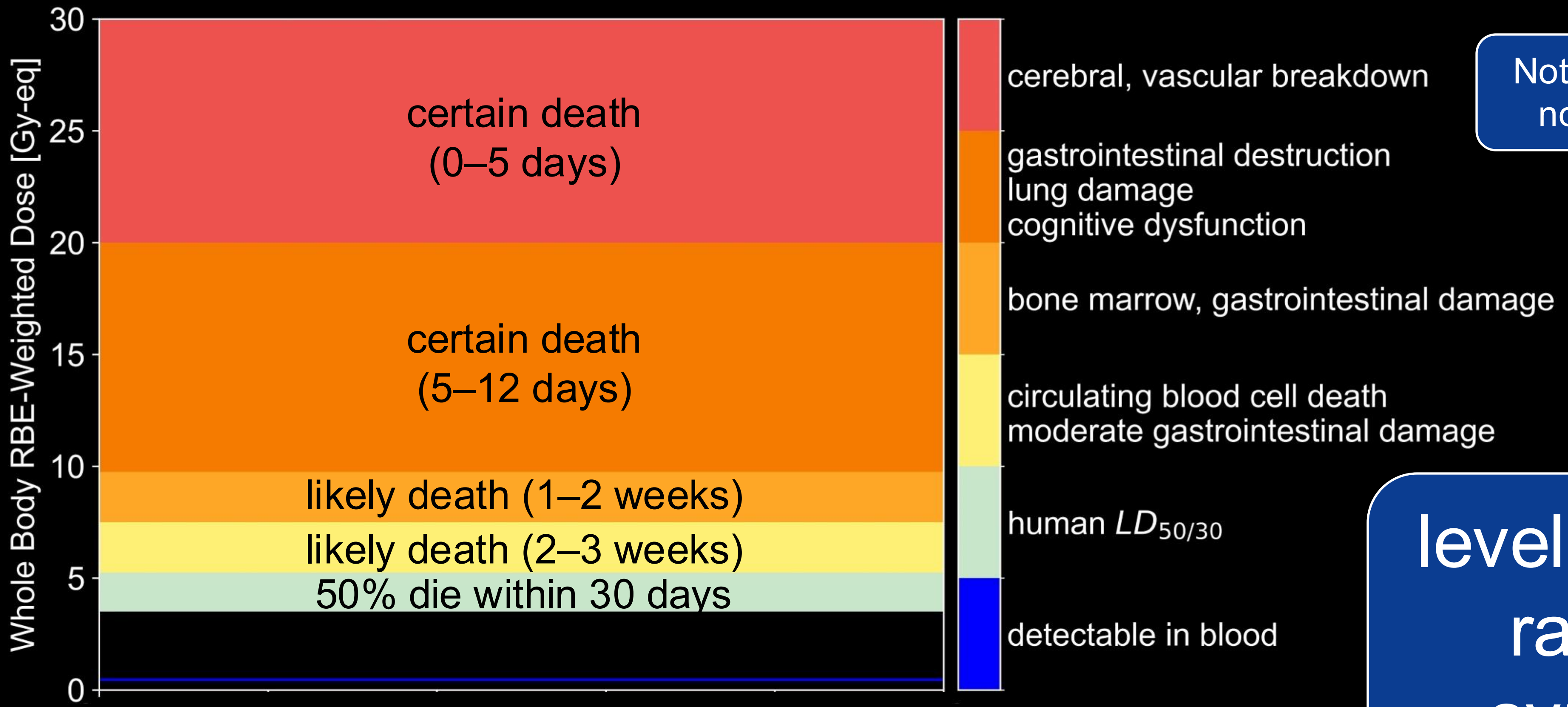
Symptomology of Acute Exposures



Anno *et al.*, 1988, Symptomology of Acute Radiation Effects in Humans after Exposure to Doses of 0.5–30 Gy.

Mortality Causes from Acute Exposures

According to the US Dept. of Energy



Note: this chart assumes no medical treatment!

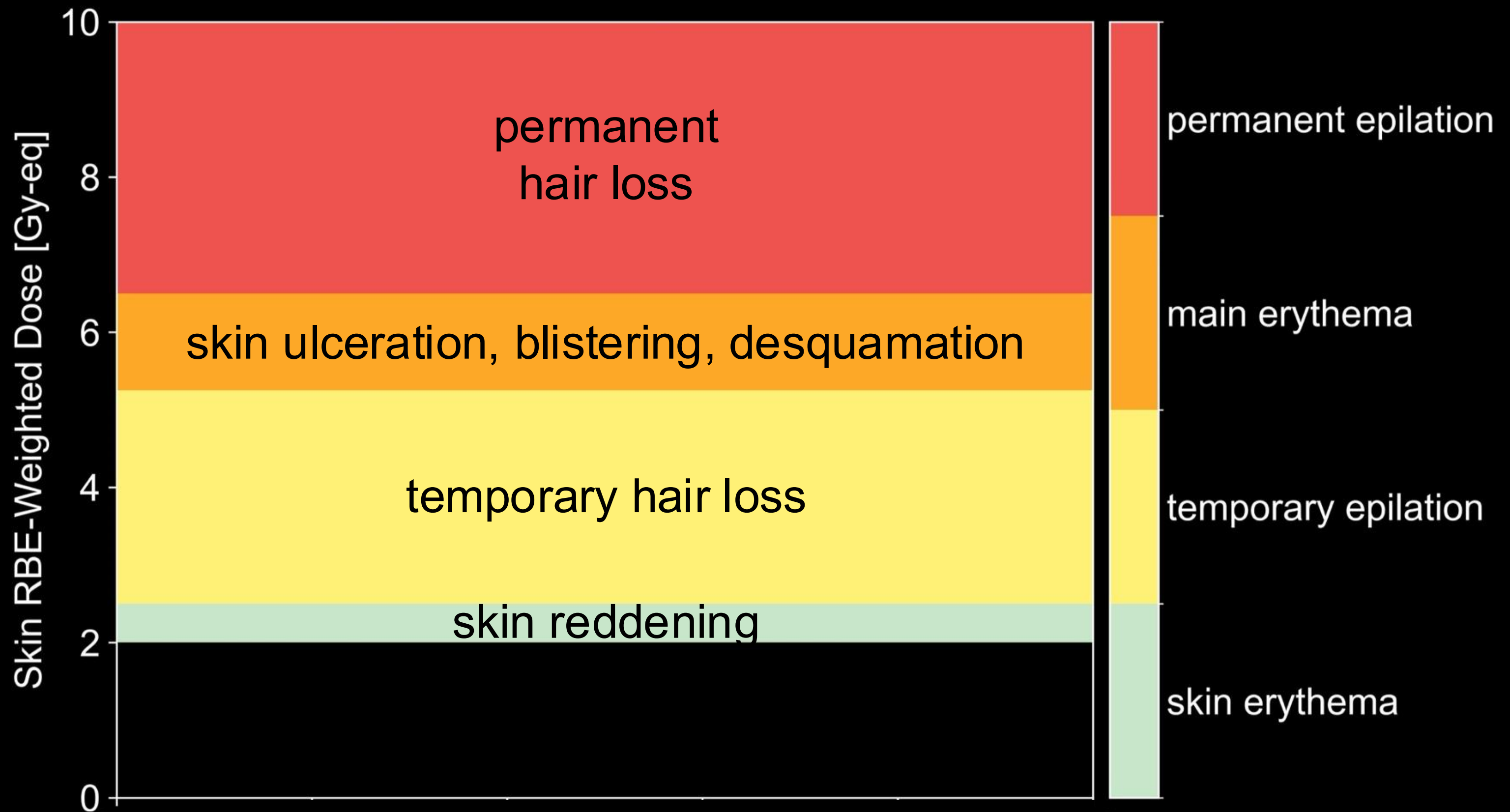
levels of acute radiation syndrome

These are rough guidelines!

*original source lists in Gy, but these are photon exposures, in which case 1 Gy = 1 Gy-eq

Skin Effects from Acute Exposures

According to the US Dept. of Energy



Note: this chart assumes no medical treatment!

epilation: hair loss
erythema: skin reddening
desquamation: skin shedding
dry (peels off like a sunburn)
wet (sloughs off, blisters)

These are rough guidelines!

acute skin exposure

*original source lists in Gy, but these are photon exposures, in which case 1 Gy = 1 Gy-eq

Mortality Probabilities for Acute Whole-Body Exposures

According to Merck

Probability of Death

(estimate of life remaining, assuming death occurs)

1 (1-2 days)

1 (2-14 days)

	with medical care
0.95-1 (2-4 weeks)	0.5-1 (2-4 weeks)
0.05-1 (4-6 weeks)	0.05-0.5 (4-6 weeks)

0-0.05 (6-8 weeks)

0

These are rough guidelines!

*original source lists in Gy, but these are photon exposures, in which case 1 Gy = 1 Gy-eq

Key Points: Health Effects

- Acute effects (e.g., nausea, skin erythema) are associated with RBE-weighted dose, measured in Gy-eq ("gray equivalent"), which relies on comparison with a reference radiation field. Each potential health effect has its own set of RBEs (relative biological effectiveness). Most RBEs are computed by comparing the radiation field of interest to a reference field of X-rays of a specific energy.

- Cancer risk is associated with the special unit Sv ("Sievert"). The relevant quantities in radiation-induced cancer risk estimation are the dose equivalent, equivalent dose, and effective dose. Dose equivalent and equivalent dose (two quantities that are nearly identical in meaning but calculated differently) scale the absorbed dose by a factor that accounts for how damaging the incident radiation particle type is (e.g., protons vs. photons). Effective dose is a weighted average of the dose equivalent (or equivalent dose) over a subset of tissues, where the tissues are weighted according to relative radiosensitivity. Dose equivalent, equivalent dose, and effective dose are computed via several methodologies (ICRP-26, ICRP-60 [Q], ICRP-103, NASA). *Different methodologies will yield different results, making intercomparison difficult without knowledge of the calculation method.*

- Career limits are typically defined in terms of effective dose (also in Sv).

Key Points: Deterministic vs. Stochastic Effects

- Acute health effects fall under the “deterministic” effect category. They are related to cell death. They show up after a threshold dose is exceeded (in a sufficiently short amount of time) and increase in severity as dose increases. SEP event exposure can be associated with short-term, high dose rate exposures (though, “high” is a relative term).

- Chronic health effects, like cancer, are stochastic in nature. Stochastic effects are related to DNA damage and increase in probability, but not necessarily in severity, as dose increases. Long-term GCR exposure is commonly associated with stochastic effects.

- Career dose limits are in place primarily to protect against excessive increases in cancer risk. Shorter term, non-cancer dose limits are in place to protect against acute effects, like acute radiation syndrome.

Part III
Estimation of Human Health Effects from SPEs

How would SEP events affect Astronauts?

SEP Events

- August 1972
  - Often cited as “lethal” to astronauts
- October 1989 Series
  - Highest total dose event, SRAG’s design reference
- March 7, 2012
  - Highest flux event of Solar Cycle 24
- May 2024 Gannon “Superstorm”
  - Most publicized event of Solar Cycle 25

Shielding Scenario

- Thin space suit (0.3 g cm^{-2}) in free space
- Thin vehicle (3 g cm^{-2}) in free space
  - Thin part of Gateway
- Thick vehicle (30 g cm^{-2}) in free space
  - Thicker than Orion
- Thin space suit (0.3 g cm^{-2}) on lunar surface
- Thin vehicle (3 g cm^{-2}) on lunar surface
  - Lunar lander, pressurized rover

SEP Events and Shielding Specifics

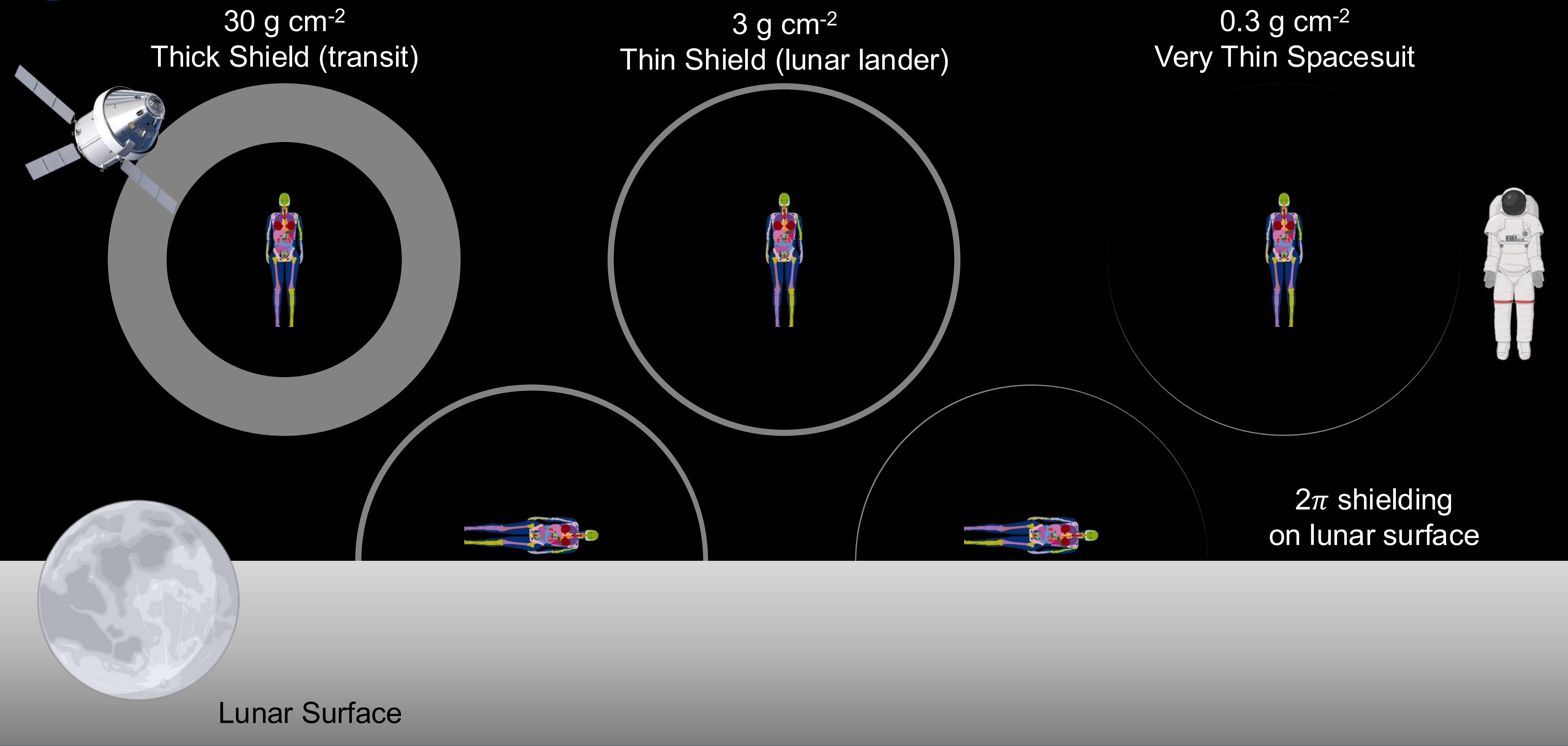
Event	Start Datetime (Analysis)	Stop Datetime (Analysis)
August 1972	1972-08-01 00:00:00	1972-08-16 00:00:00
October 1989	1989-10-19 00:00:00	1989-10-31 00:00:00
March 2012	2012-03-07 00:00:00	2012-03-16 00:00:00
May 2024	2024-05-10 00:00:00	2024-05-13 00:00:00

×

Shielding	Location	~Mass Thickness [g cm^{-2}]
Thin Spacesuit	Free Space	0.3
Thin Vehicle	Free Space	3
Thick Vehicle	Free Space	30
Thin Spacesuit	Lunar Surface	0.3
Thin Vehicle	Lunar Surface	3

Event	>10 MeV Onset	>100 MeV Onset	>10 MeV Start	>100 MeV Start	>10 MeV End	>100 MeV End	>10 MeV Return to Background	>100 MeV Return to Background
August 1972	1972-08-02 09:00:00		1972-08-03 04:00:00		1972-08-11 07:00:00		1972-08-15 21:00:00	
October 1989	1989-10-19 13:00:00	1989-10-19 13:00:00	1989-10-19 13:10:00	1989-10-19 13:05:00	1989-10-29 00:20:00	1989-10-27 23:25:00	1989-11-09 20:00:00	1989-11-02 12:00:00
March 2012	2012-03-07 03:15:00	2012-03-07 02:00:00	2012-03-07 05:10:00	2012-03-07 04:05:00	2012-03-12 20:50:00	2012-03-10 16:50:00	2012-03-13 17:30:00	2012-03-07 11:15:00
May 2024	2024-05-09 11:00:00	2024-05-11 01:45:00	2024-05-10 14:05:00	2024-05-11 02:10:00	2024-05-16 14:50:00	2024-05-12 00:30:00	2024-05-22 00:00:00	2024-05-13 08:00:00

Shields

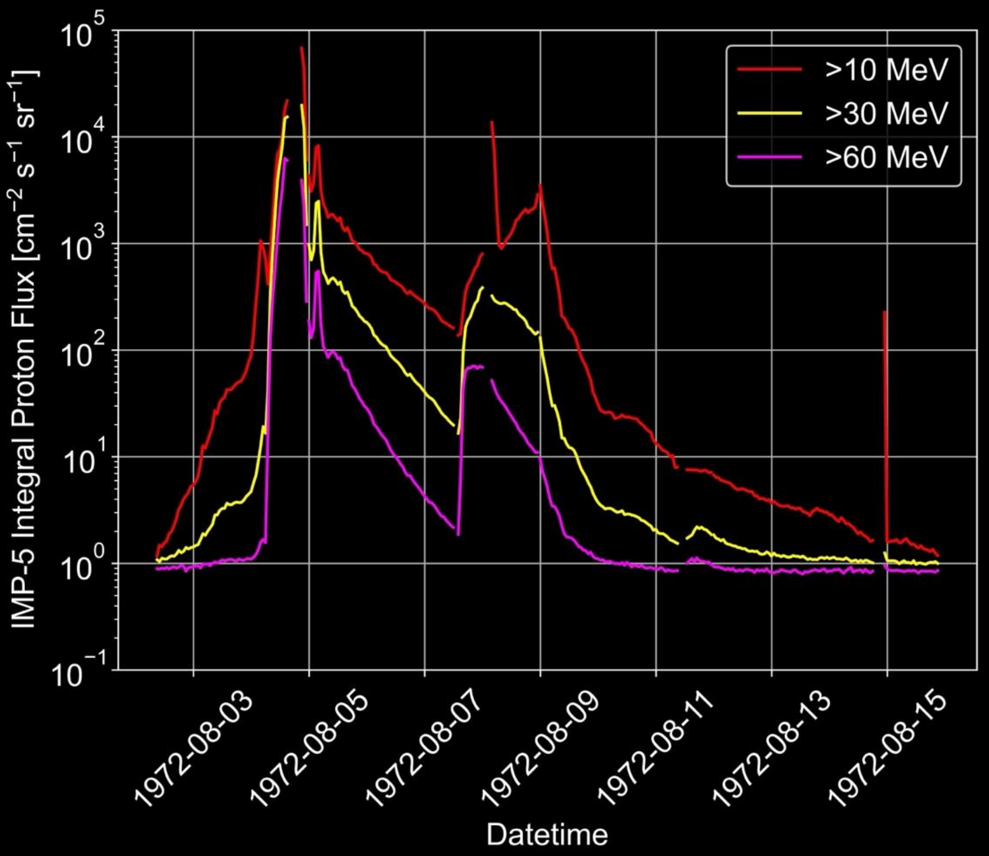


30 g cm-2
Thick Shield (transit)
3 g cm-2
Thin Shield (lunar lander)
0.3 g cm-2
Very Thin Spacesuit
2π shielding
on lunar surface
Lunar Surface

Assumptions

1) Astronaut remains behind the designated shielding for the entirety of each SEP event
   - Leads to silly scenario: EVAs lasting several days
   - Current maximum EVA time is 8 hours due to oxygen constraints
   - Operational constraints on how far crew is allowed to roam from vehicle
     - Maximum distance corresponding to <1 hour travel time
2) Female astronaut (FAX phantom)
   - Male phantom is larger, by default would incur lower dose
   - Males are, on average, less radiosensitive

Events
August 1972



Dose rate profile unavailable

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

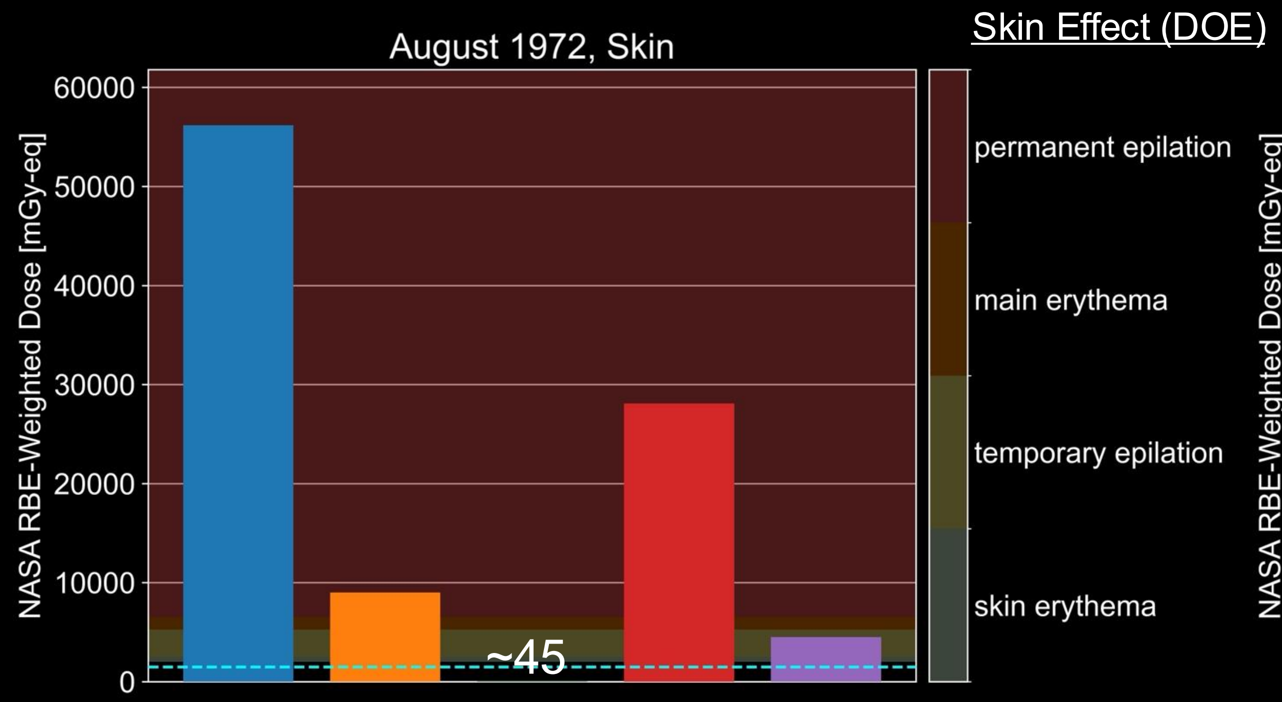
King, Solar Proton Fluences for 1977–1983 Space Missions. *J. Spacecraft.* Vol. 11, No. 6, June 1974.

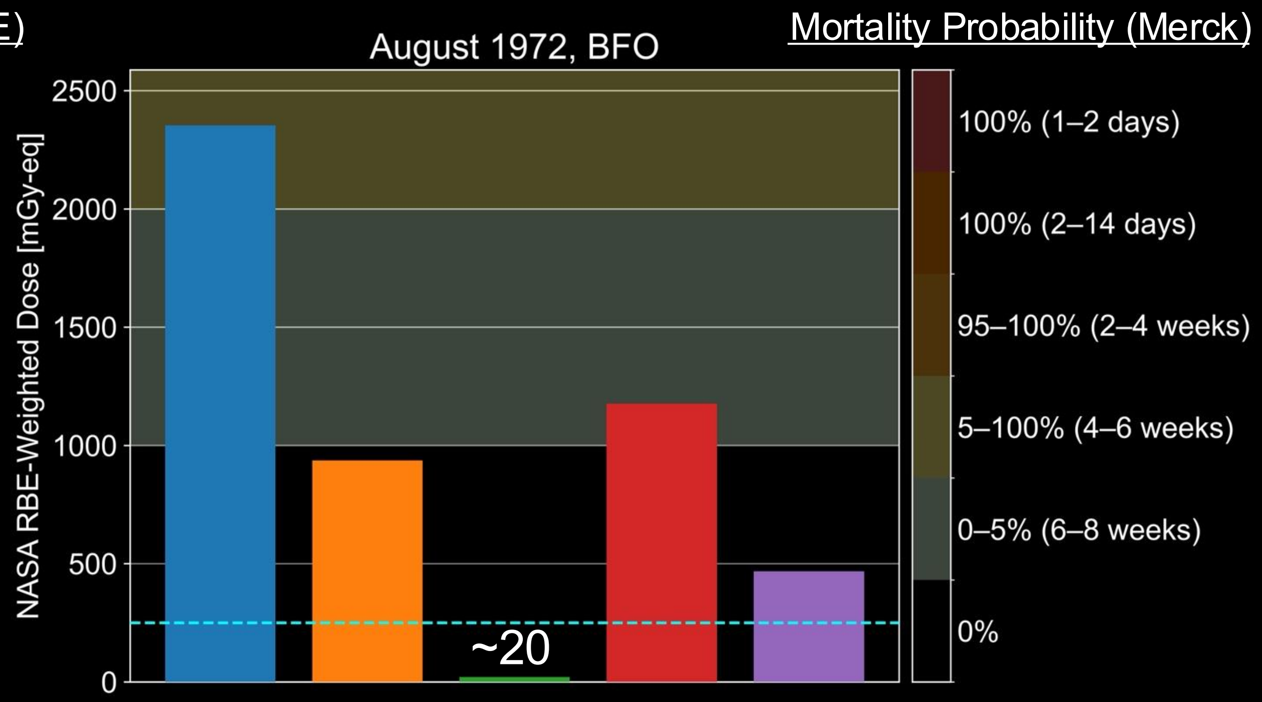
Events
August 1972

Free Space, 0.3 g cm^{-2}
Free Space, 3 g cm^{-2}
Free Space, 30 g cm^{-2}
Lunar Surface, 0.3 g cm^{-2}
Lunar Surface, 3 g cm^{-2}
30-day NASA Non-Cancer Limit
Career NASA Effective Dose Limit

- 30-day NASA non-cancer limits exceeded, except in thick shielding scenario
- Nonzero mortality probability in EVA scenarios (though, this would require ~12 day EVA)

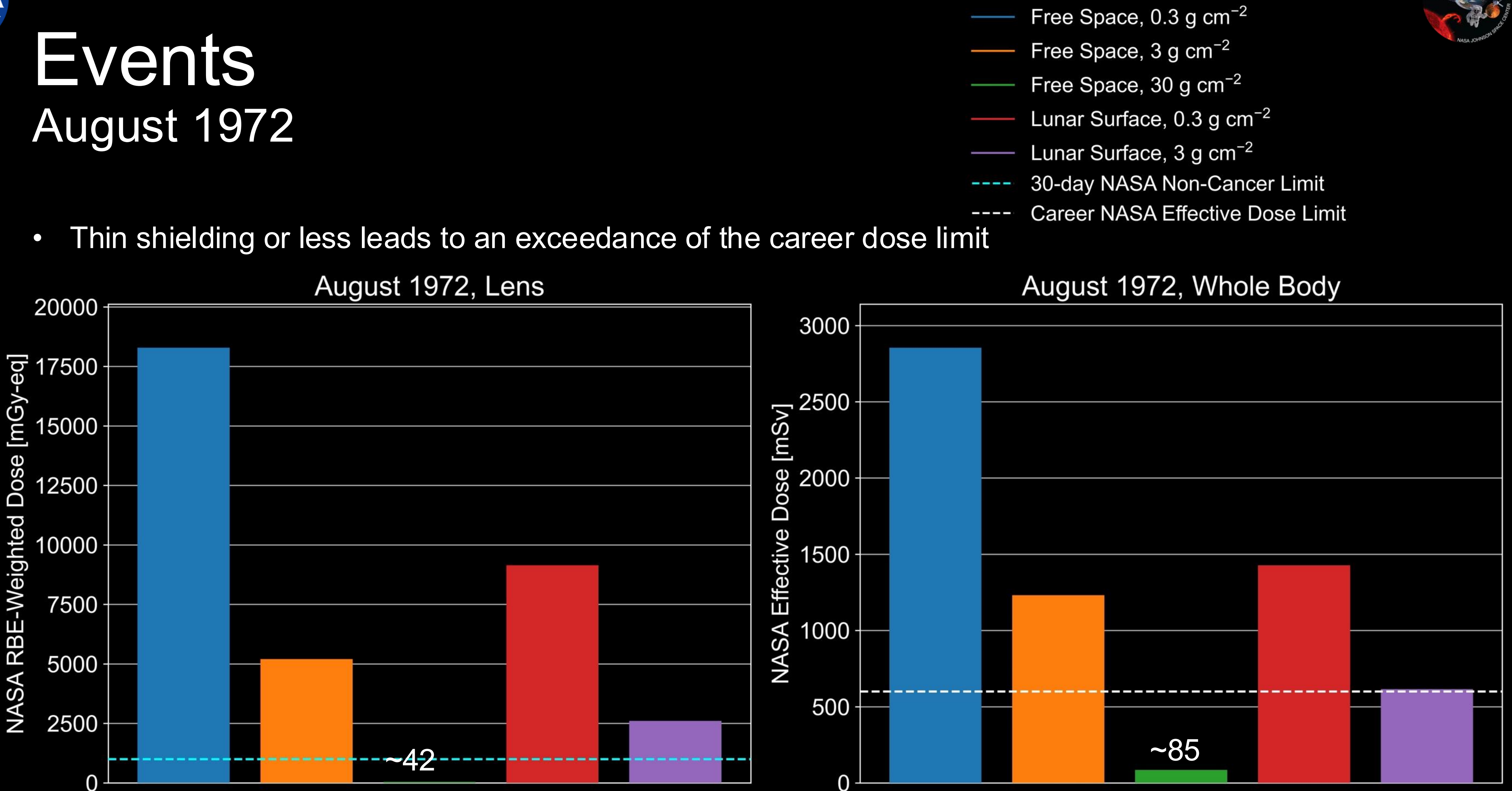
Assumes extended exposure period, and non-realistic conditions (12 day EVA)





Events
August 1972

- Thin shielding or less leads to an exceedance of the career dose limit



Events

August 1972 – Symptoms?

CAVEAT: symptoms assume exposure occurs all at once, and crew takes no protective action during event

Use BFO as surrogate for whole-body RBE-weighted dose

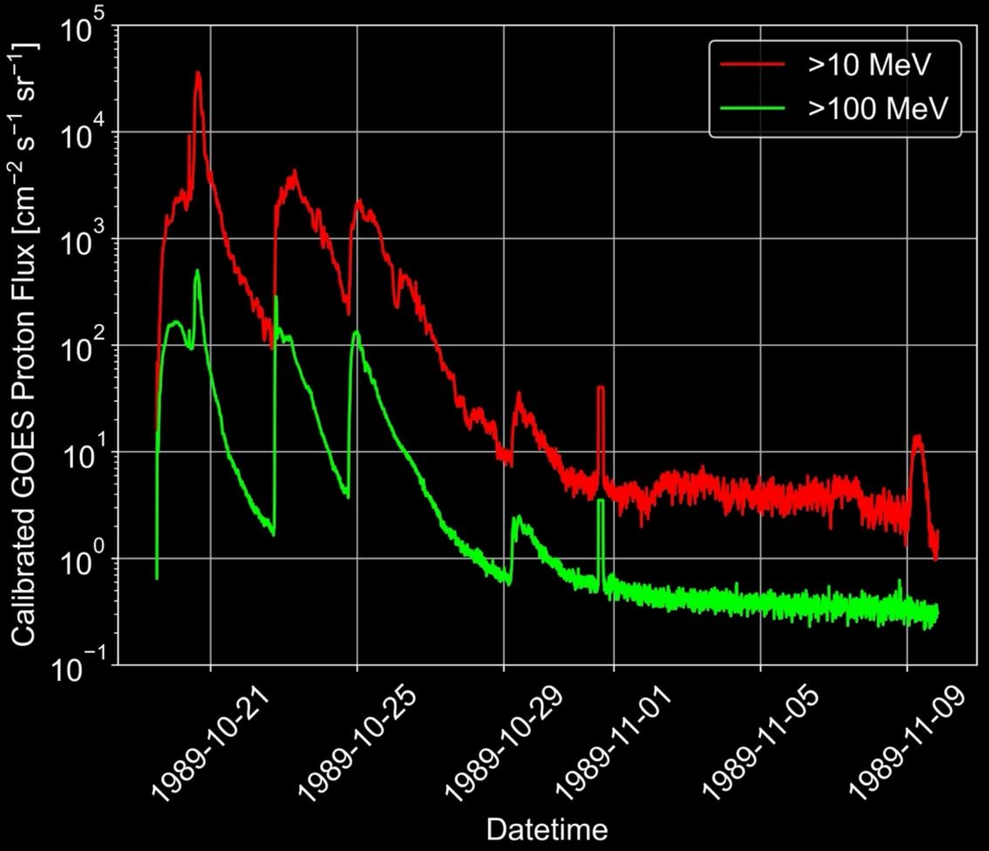
Moderate severity health effects in suit-only shield cases

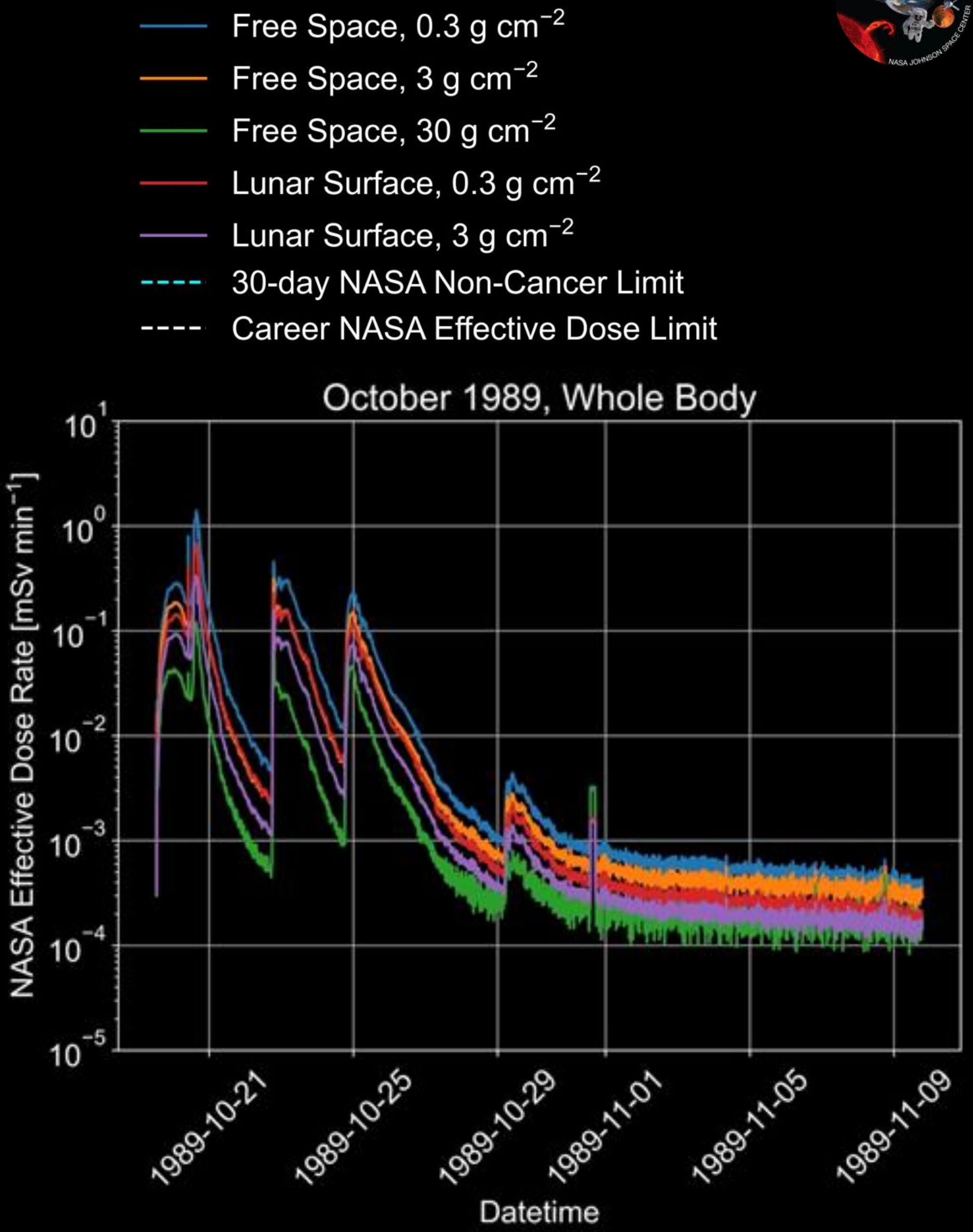
Free Space, Suit	Free Space, Thin	Free Space, Thick	Lunar Surface, Suit	Lunar Surface, Thin
Severity: Moderate	Severity: Mild	Severity: None	Severity: Mild–Moderate	Severity: None
Possible Symptoms: Nausea Vomiting Anorexia Diarrhea Fatigue Weakness Bleeding Fever Ulceration	Possible Symptoms: Nausea Vomiting Anorexia Fever	Possible Symptoms: No effect	Possible Symptoms: Nausea Vomiting Anorexia Fatigue Weakness Bleeding Fever Infection	Possible Symptoms: No effect
Mortality: 5–50% (closer to 5%)	Mortality: 0%	Mortality: 0%	Mortality: 0–5%	Mortality: 0%

Events

October 1989

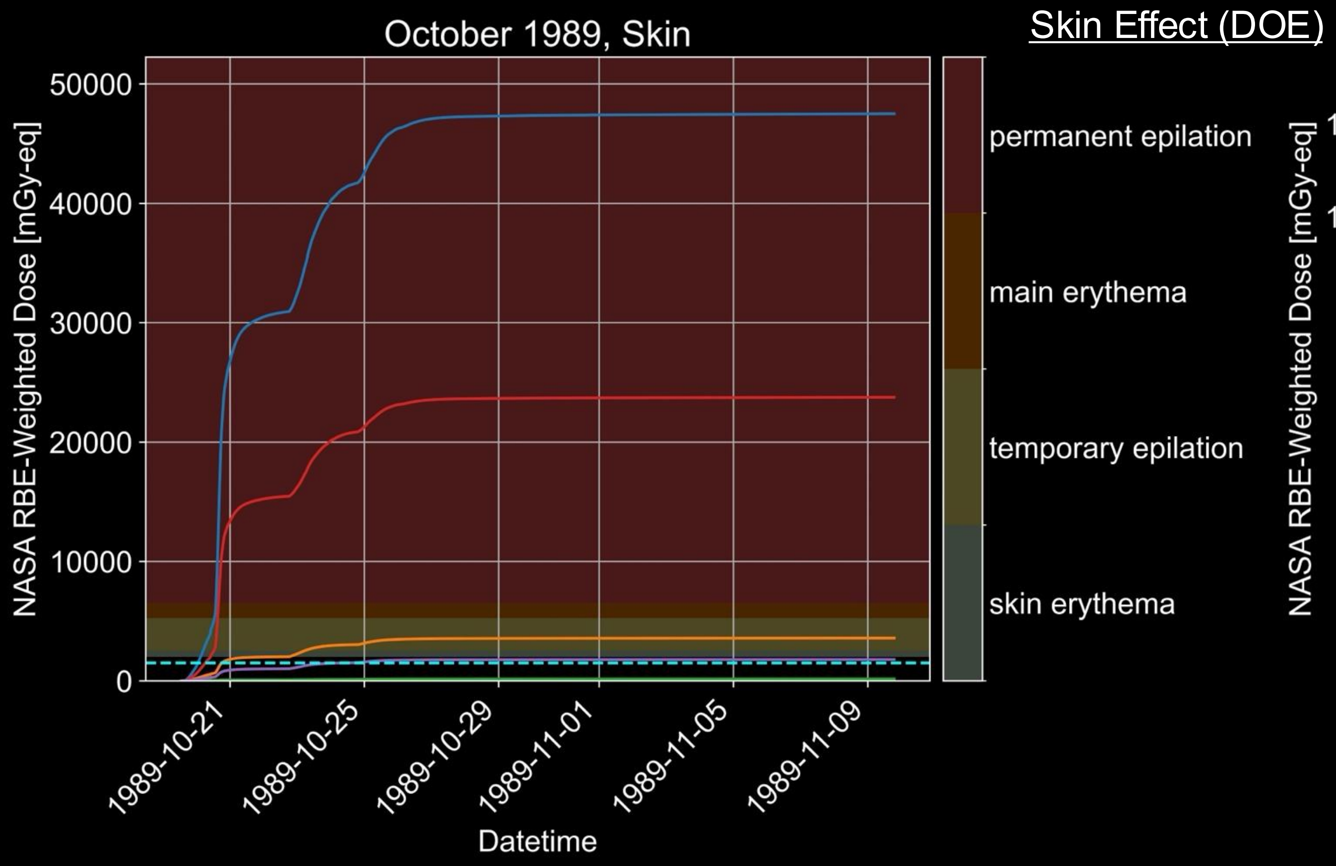
>10 MeV proton flux becomes less important as shield thickens

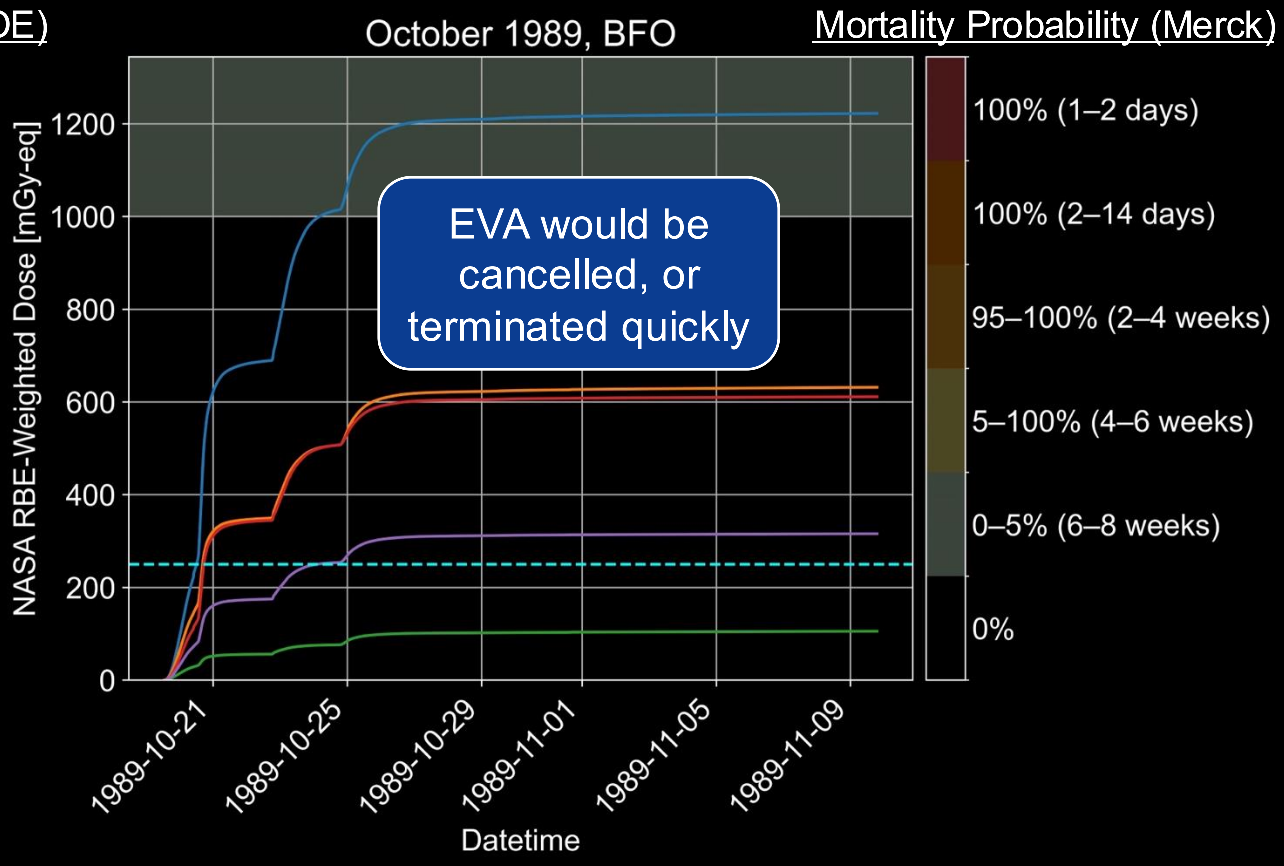




Events
October 1989

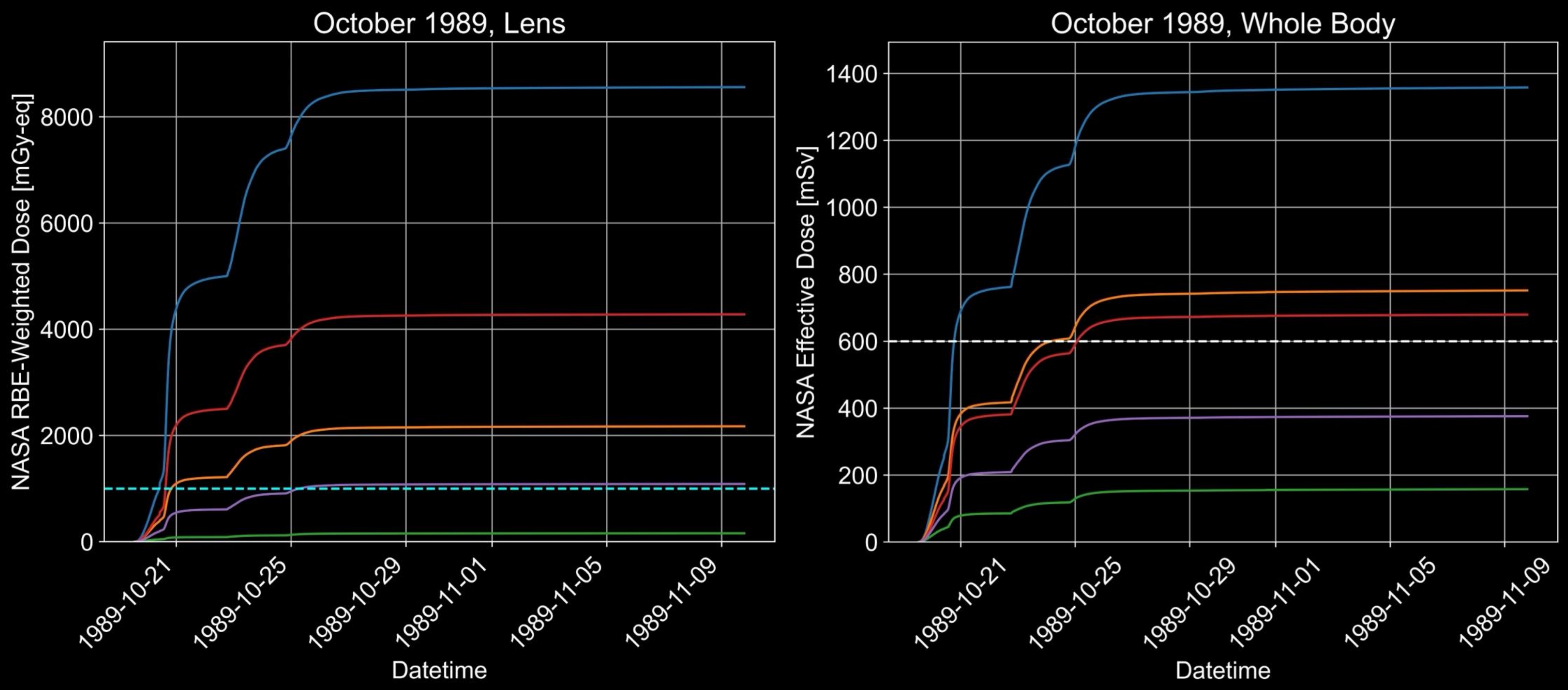
- 30-day NASA non-cancer limits exceeded in all thin shielding scenarios
- Operationally, astronauts would shelter behind thicker shielding during highest flux periods





Events
October 1989

- Career dose limit exceeded in thin shielding free space and lunar EVA cases



Events

October 1989 – Symptoms?

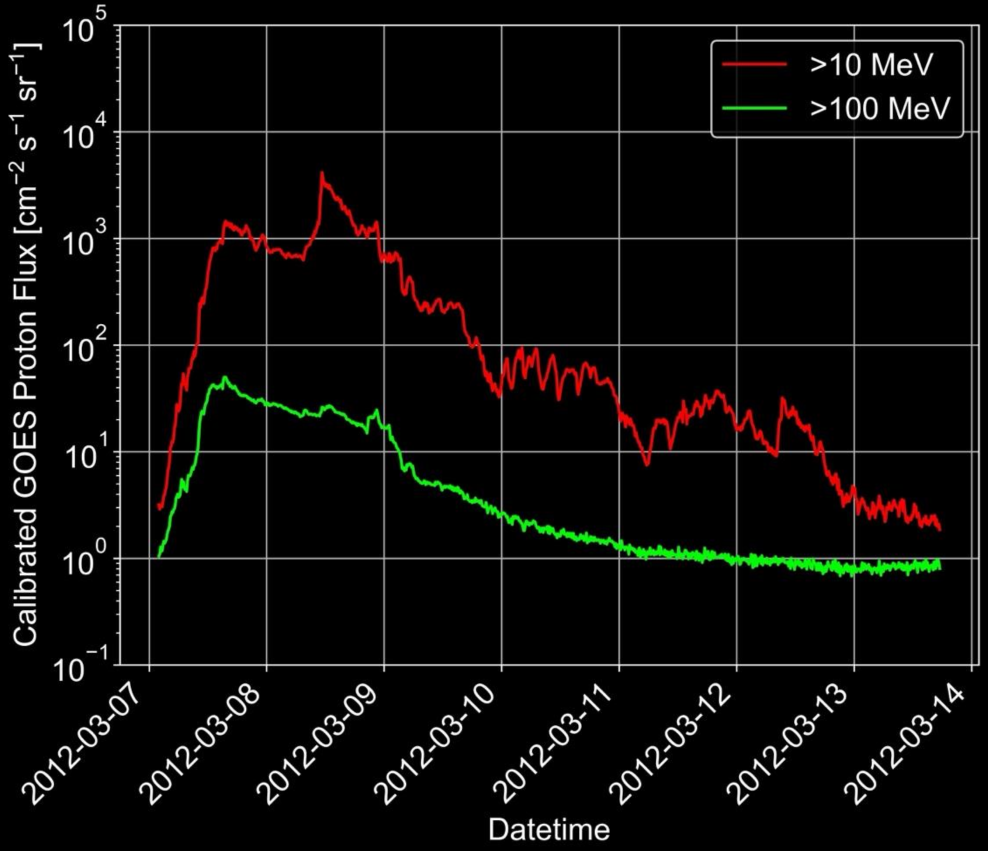
CAVEAT: symptoms assume exposure occurs all at once, and crew takes no protective action during event

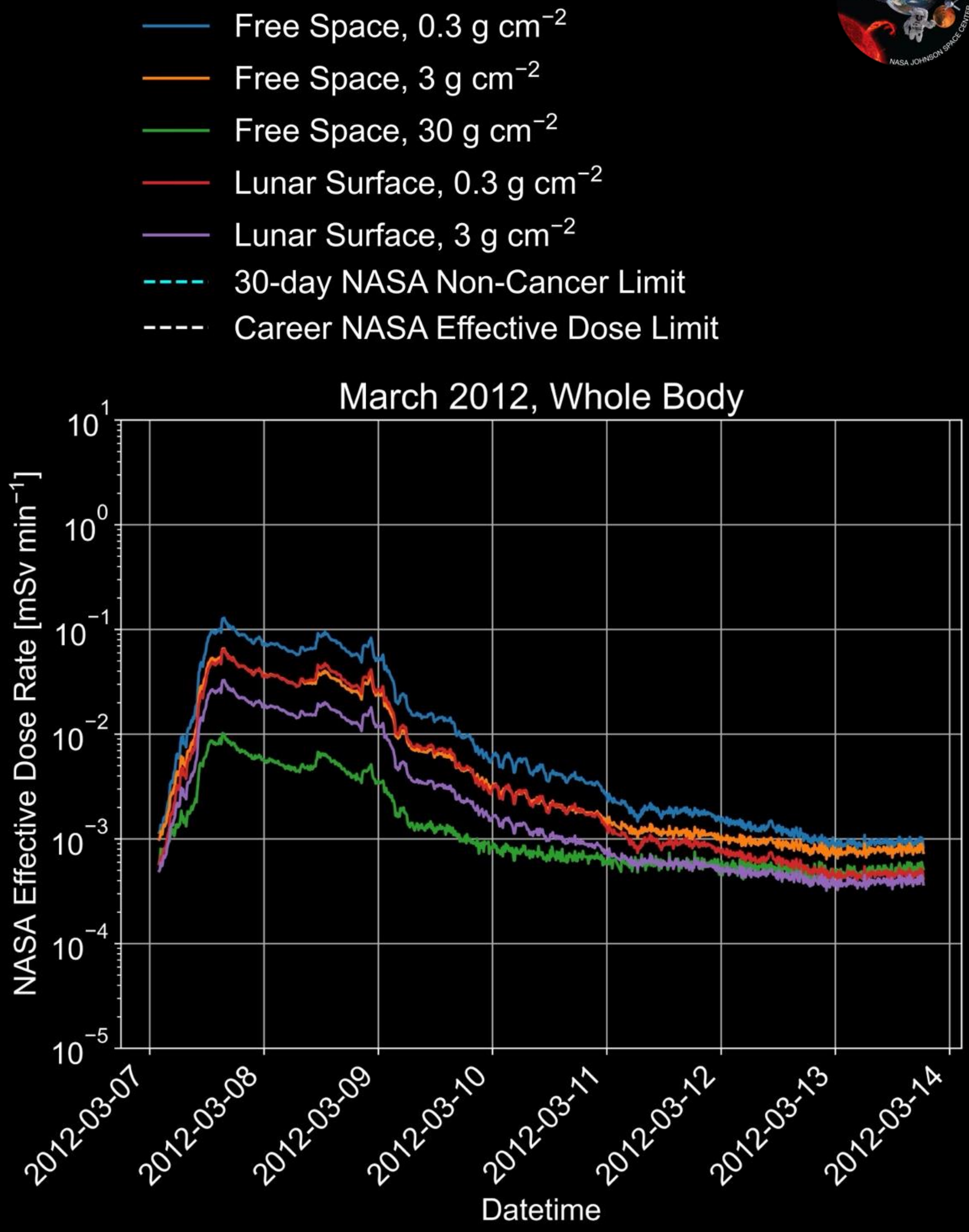
Use BFO as surrogate for whole-body RBE-weighted dose

Free Space, Suit	Free Space, Thin	Free Space, Thick	Lunar Surface, Suit	Lunar Surface, Thin
Severity: Mild–Moderate	Severity: Mild	Severity: None	Severity: Mild	Severity: None
Possible Symptoms: Nausea Vomiting Anorexia Fatigue Weakness Bleeding Fever Infection	Possible Symptoms: Nausea Vomiting Anorexia Fever	Possible Symptoms: No effect	Possible Symptoms: Nausea Vomiting Anorexia Fever	Possible Symptoms: No effect
Mortality: 0–5%	Mortality: 0%	Mortality: 0%	Mortality: 0%	Mortality: 0%

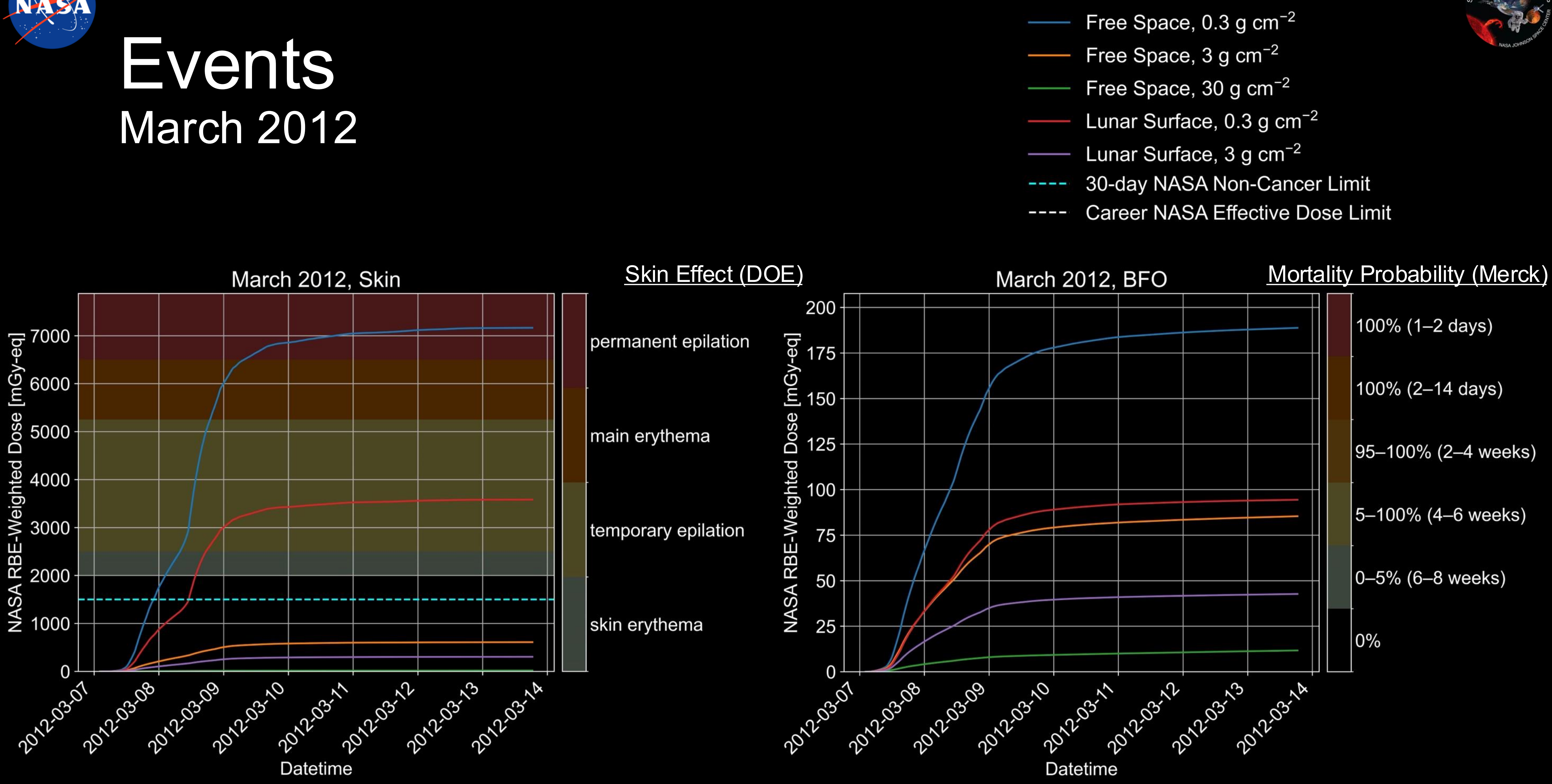
Events

March 2012



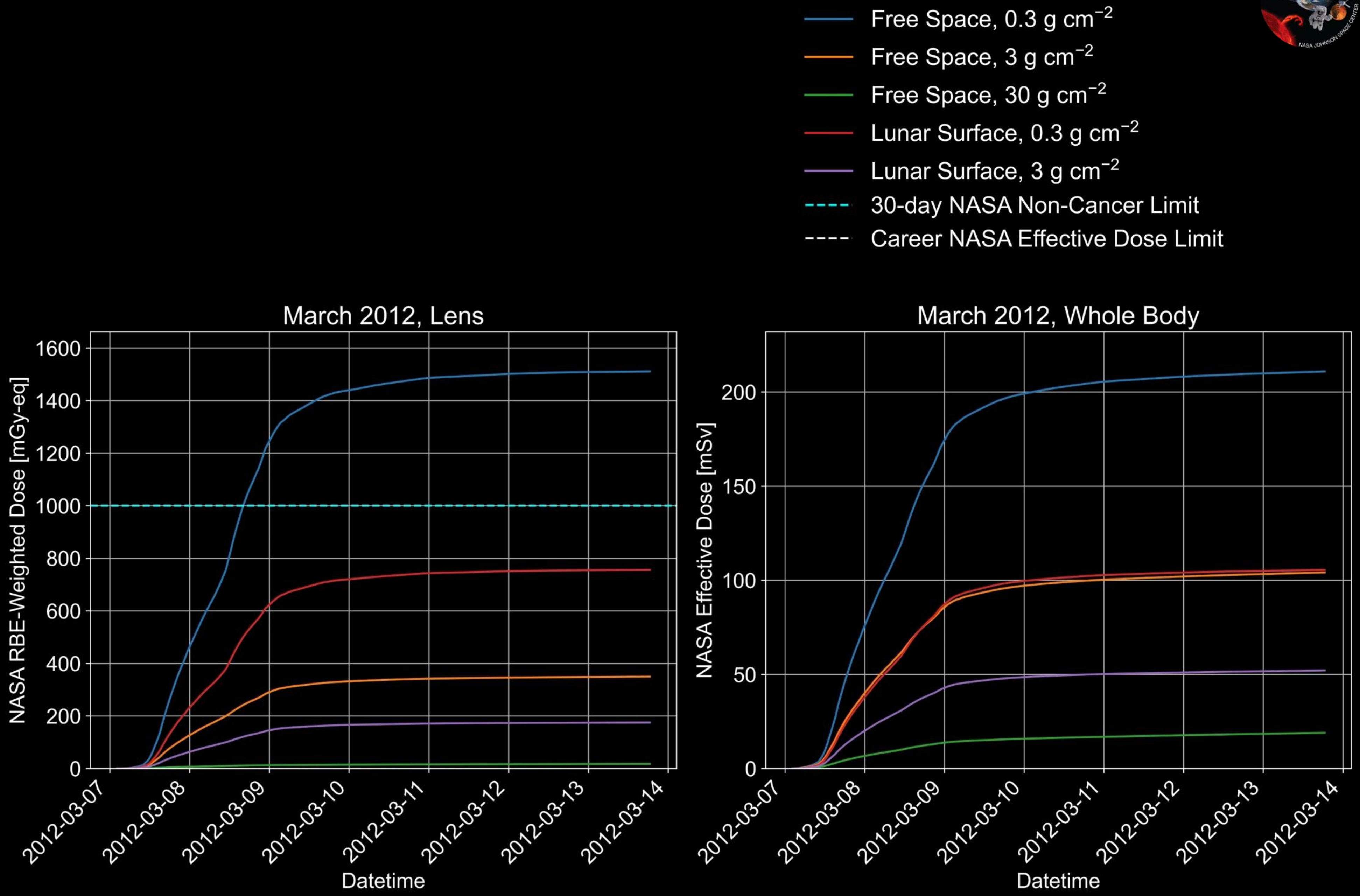


Events
March 2012



Events

March 2012



Events

March 2012 – Symptoms?

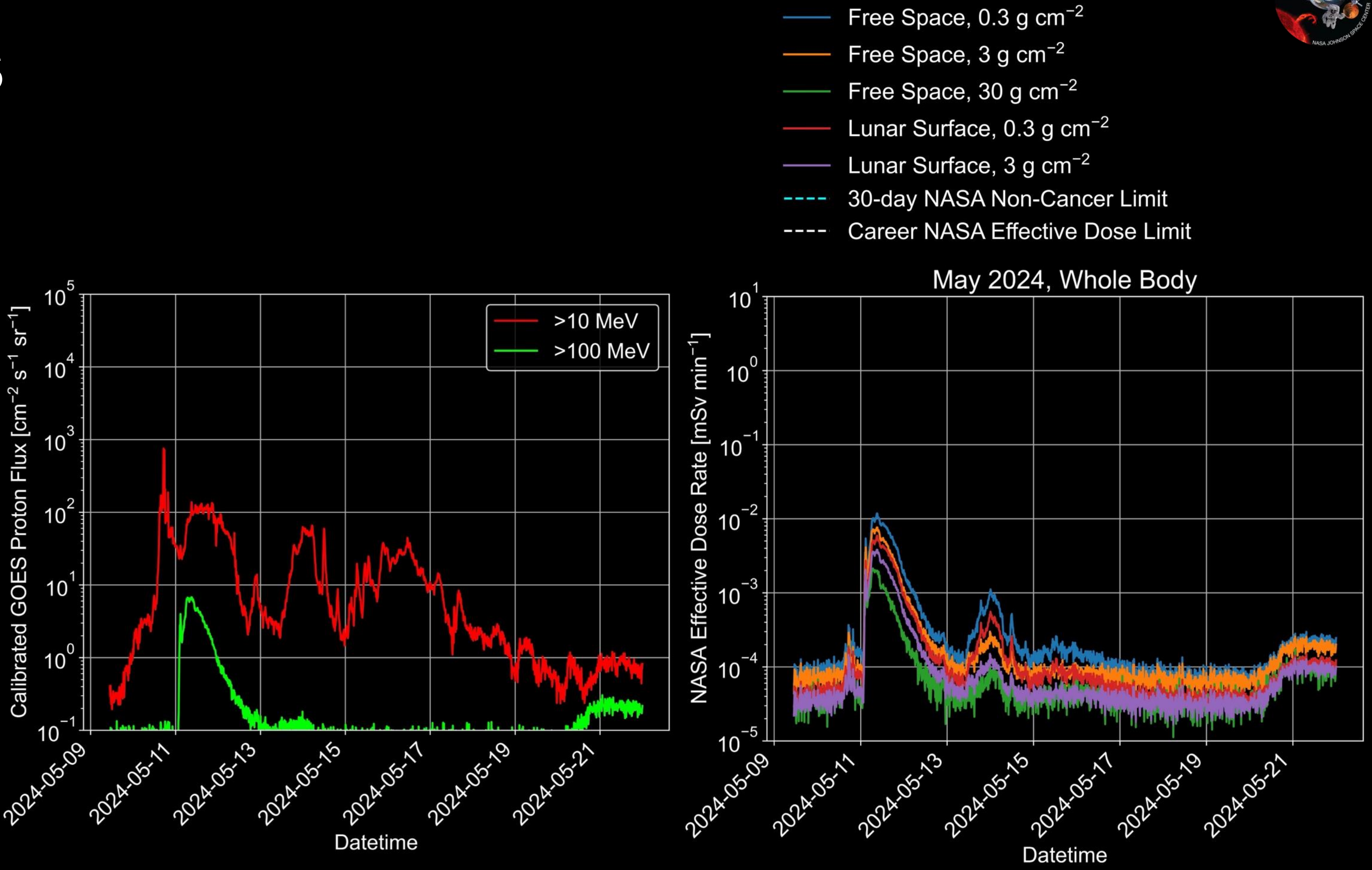
CAVEAT: symptoms assume exposure occurs all at once, and crew takes no protective action during event

Use BFO as surrogate for whole-body RBE-weighted dose

Free Space, Suit	Free Space, Thin	Free Space, Thick	Lunar Surface, Suit	Lunar Surface, Thin
Severity: None	Severity: None	Severity: None	Severity: None	Severity: None
Possible Symptoms: No effect	Possible Symptoms: No effect	Possible Symptoms: No effect	Possible Symptoms: No effect	Possible Symptoms: No effect
Mortality: 0%	Mortality: 0%	Mortality: 0%	Mortality: 0%	Mortality: 0%

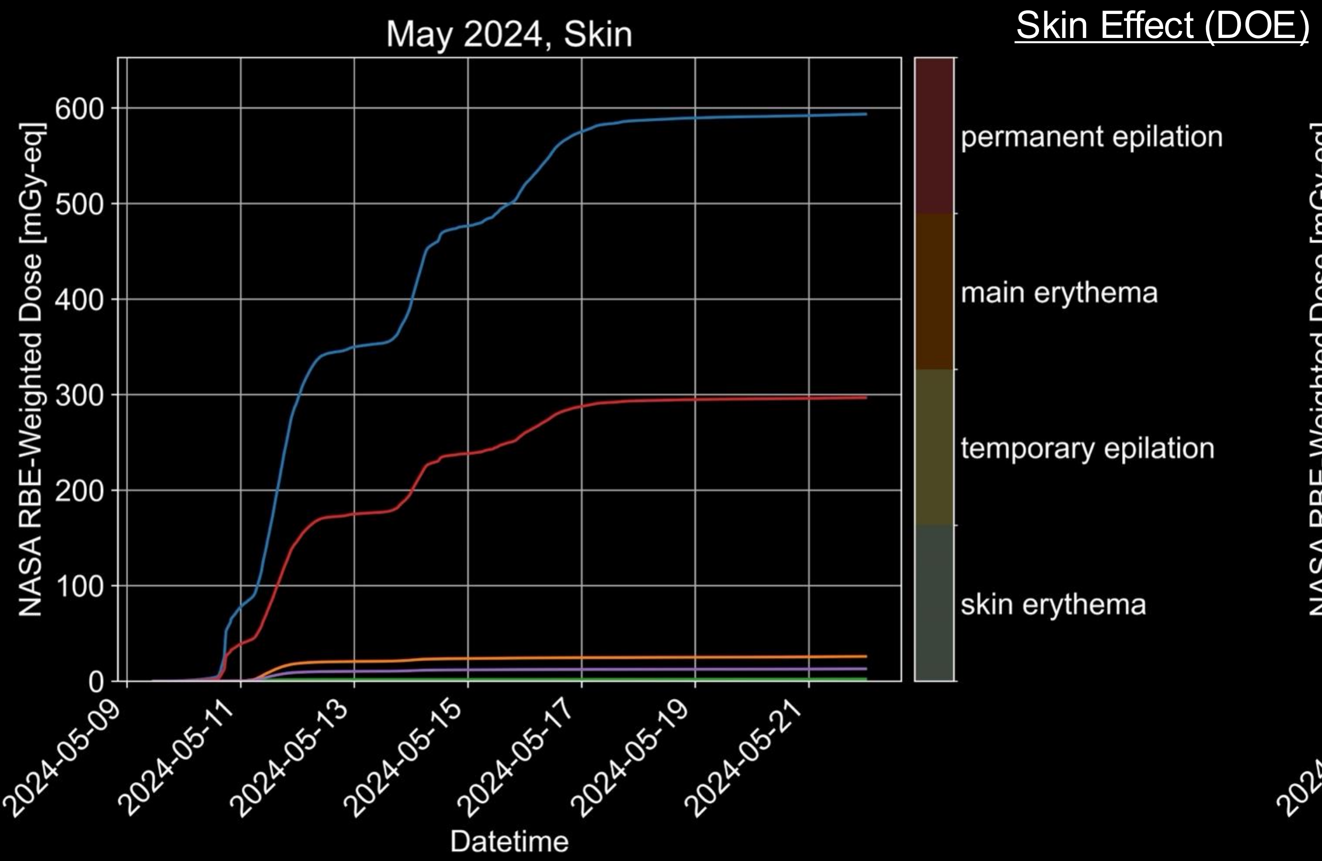
Events

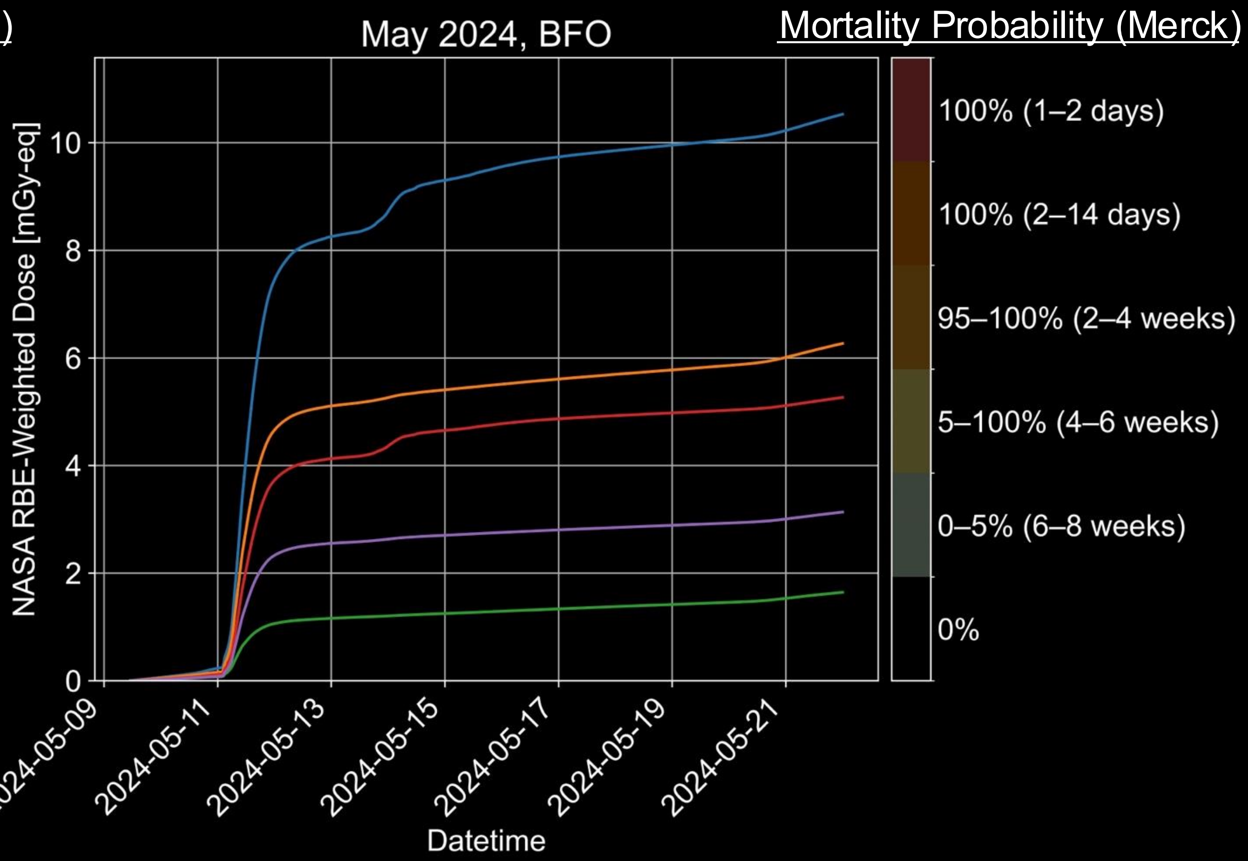
May 2024



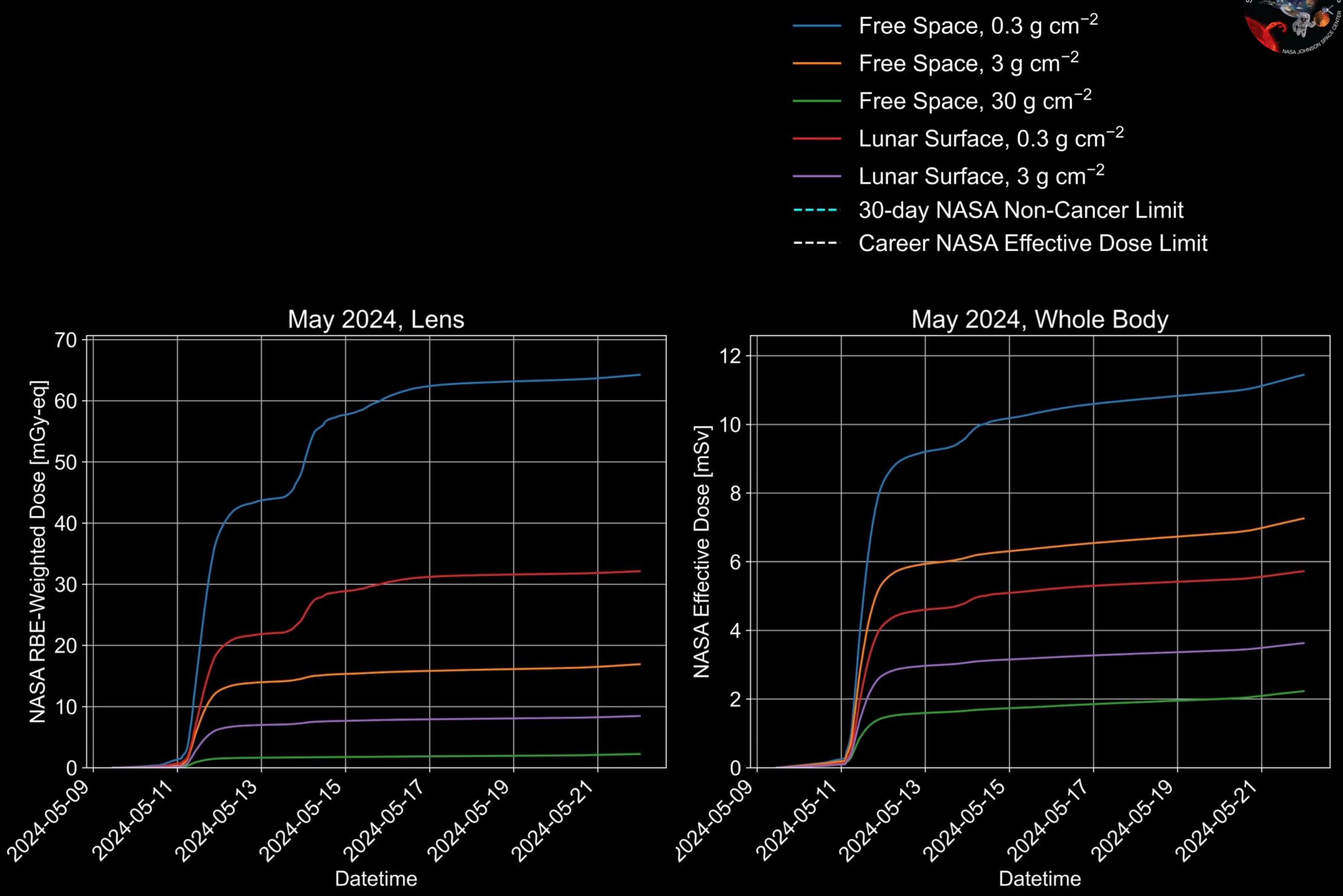
Events
May 2024

Free Space, 0.3 g cm^{-2}
Free Space, 3 g cm^{-2}
Free Space, 30 g cm^{-2}
Lunar Surface, 0.3 g cm^{-2}
Lunar Surface, 3 g cm^{-2}
30-day NASA Non-Cancer Limit
Career NASA Effective Dose Limit





Events
May 2024



Events

May 2024 – Symptoms?

CAVEAT: symptoms assume exposure occurs all at once, and crew takes no protective action during event

Use BFO as surrogate for whole-body RBE-weighted dose

Free Space, Suit

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Free Space, Thin

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Free Space, Thick

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Lunar Surface, Suit

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Lunar Surface, Thin

Severity: None

Possible Symptoms:
No effect

Mortality: 0%

Lethality?

- Seems unlikely that any astronaut would “die” from SEPs shown here
- What dose is required to cause death ~50% of the time?
    - ~3.5 Gy-eq
- ~100% of the time?
    - ~5.5 Gy-eq
- How many August 1972 events would it take to hit these thresholds?
- How many October 1989 series would it take to hit these thresholds?

Lethality?

August 1972

CAVEAT: symptoms assume exposure occurs all at once, and crew takes no protective action during event

- How many August 1972 events would be required to achieve…
  - 50% mortality rate? 100% mortality rate?

Free Space, Suit	Free Space, Thin	Free Space, Thick	Lunar Surface, Suit	Lunar Surface, Thin
50% Mortality: 1.5 × August 1972	50% Mortality: 3.7 × August 1972	50% Mortality: 170 × August 1972	50% Mortality: 3.0 × August 1972	50% Mortality: 7.5 × August 1972
~100% Mortality: 2.3 × August 1972	~100% Mortality: 5.9 × August 1972	~100% Mortality: 270 × August 1972	~100% Mortality: 4.7 × August 1972	~100% Mortality: 12 × August 1972

Lethality?

October 1989

CAVEAT: symptoms assume exposure occurs all at once, and crew takes no protective action during event

- How many October 1989 events would be required to achieve…
  - 50% mortality rate? 100% mortality rate?

Free Space, Suit	Free Space, Thin	Free Space, Thick	Lunar Surface, Suit	Lunar Surface, Thin
50% Mortality: 2.9 × October 1989	50% Mortality: 5.5 × October 1989	50% Mortality: 33 × October 1989	50% Mortality: 5.7 × October 1989	50% Mortality: 11 × October 1989
~100% Mortality: 4.5 × October 1989	~100% Mortality: 8.7 × October 1989	~100% Mortality: 52 × October 1989	~100% Mortality: 9.0 × October 1989	~100% Mortality: 17 × October 1989

So, what are the risks?

- Typical events
  - Slight increase in lifetime cancer risk
  - No observable acute effects
- Extreme events
  - Significant increase in lifetime cancer risk
  - Low probability risk of moderate prodromal effects behind thin shields (EVA)
    - Operational procedures (shelter) can mitigate these risks
    - EVAs last a maximum of 8 hours, due to oxygen constraints
    - EVAs 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})

Radiation Protection & Space Exploration

- Space radiation environment is extreme compared to terrestrial radiation
- Radiation monitoring, operations, shielding analysis, risk assessment, space weather analysis are all necessary to ensure crew health and safety and maintain exposures ALARA
  - **NASA SRAG** maintains expertise in all these areas
- Extreme SEP events pose multi-layered threats to astronauts
  - Need to understand risks when operations and radiation effects interact
  - Seemingly mild health impacts can result in undesirable consequences
  - E.g., astronaut vomits in a space suit
- SEP events and GCR exposures contribute to excess cancer risk

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    - Risk Analysis Environment (RAE)
- Tools
  - Quality images of mice, organs, Moon, eukaryotic cell created with Biorender.com

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