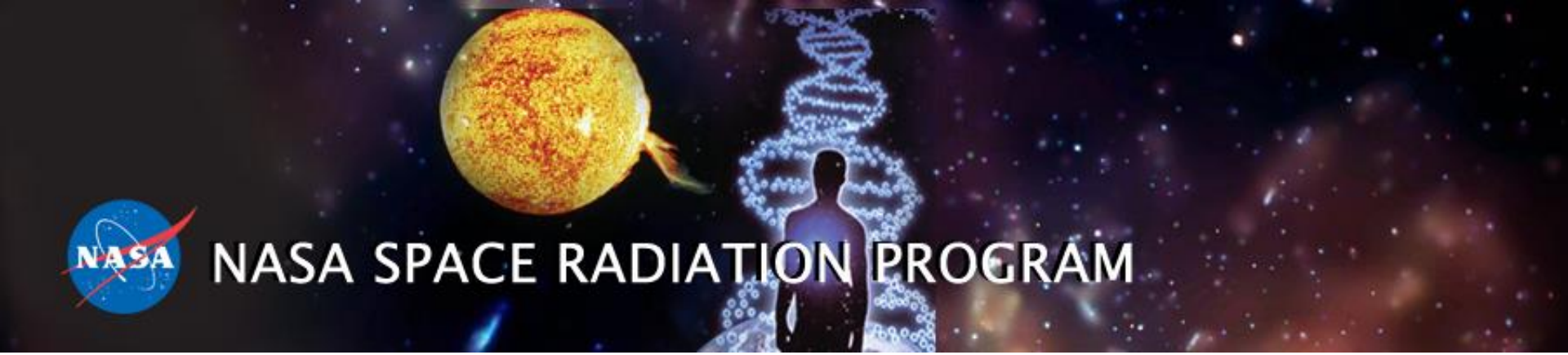

Exposure Risk Analysis for Human Exploration of Deep Space

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The 20th WRMISS, Sept. 8-10, 2015, Cologne, Germany

NSCR-2012 (NASA Space Cancer Risk-2012) Runner Up of 2013 NASA SOY Award

- Dr. Francis A. Cucinotta, NASA-SK

  Team Lead, Nuclear, transport, QF and cancer uncertainty models
- Dr. Myung-Hee Y. Kim, USRA

  Developer of SPE models and lead for Transport codes
- Ms. Lori J Chappell, USRA

  Statistician for Bayesian and cancer analysis
- Dr. Patrick O'Neill, NASA-EV

  Developer of BON Model. Expert on Electronics Damage
- Dr. Shaowen Hu, USRA

  WEB interface developer
- Dr. Ianik Plante, USRA

  Implement parallel processing approaches
- Dr. Hatem Nounu, USRA

  Documentation and V&V

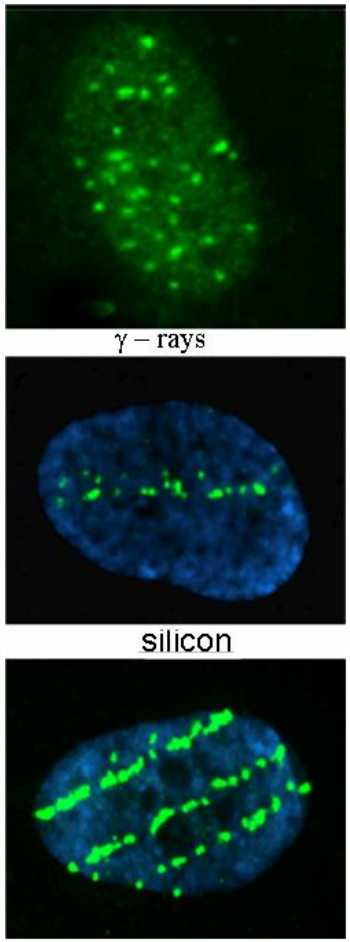
Background: The Space Radiation Problem

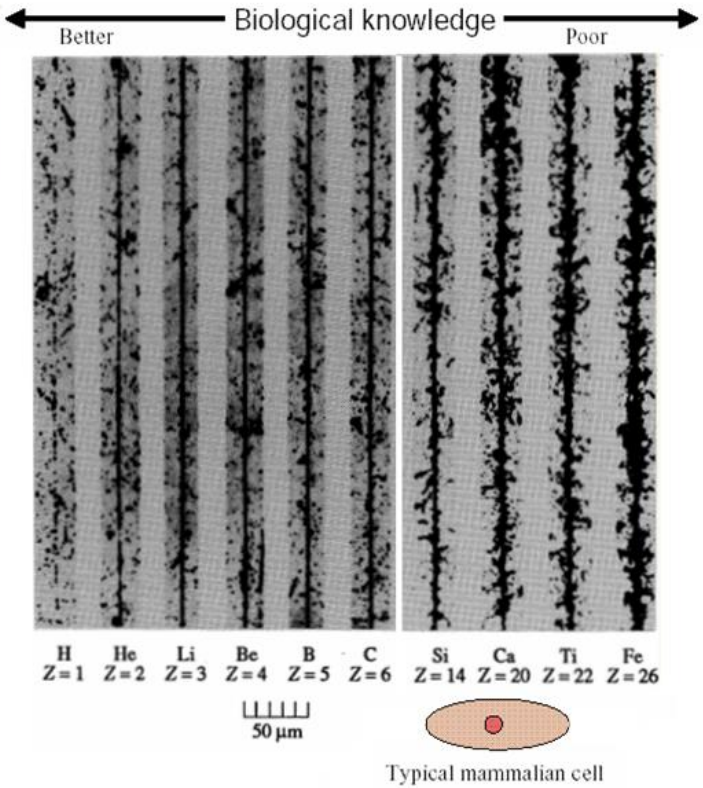
- Space radiation is comprised of high-energy protons and heavy ions (HZE's) and secondary radiation produced in shielding (neutrons, protons, heavy ions)
  - High Linear Energy Transfer (LET)
  - Shielding has excessive costs and will not eliminate GCR

- Unique damage occurred to biomolecules, cells, and tissues from HZE ions produces qualitatively distinct health risks from X-rays and gamma-rays on Earth

- No human data to estimate risk from HZE ions and the uncertainties in risk estimates
  - Radiation quality effects
  - Dose-rate effects
  - Human epidemiology data
  - Microgravity influence
  - Radiation environment
  - Transport models

⇒ NASA uses NASA Space Cancer Risk model (NSCR) for ISS medical operations and exploration studies.

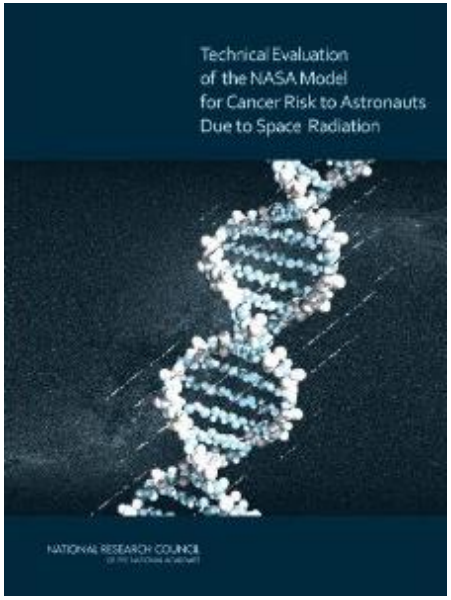




Cucinotta and Durante, Lancet Oncology (2006)

Overview of NSCR

- NASA approach to evaluate the cancer risk and the level of uncertainty that exists for each factor (total of over 50 parameters) in the model
  - 95% confidence intervals for risk limit of 3% risk of exposure induced death (REID)
  - Radiation quality as a probability distribution function (PDF) using track structure theory
  - Revised low LET risk coefficients, DDREF and uncertainty
  - Evaluation of uncertainties from all sources determines overall uncertainty
  - Never-smokers to represent healthy workers
- Reviewed by the National Research Council (NRC) in 2008 and 2012, and approved by NASA Chief Health and Medical Officer (CHMO) for NASA use in August 2012
  - Currently in use for ISS crew selection and exploration mission decisions
- Validated by over 500 research publications by comparing model to accelerator, flight, experimental radiobiology and human epidemiology data
- Applications include Medical Operations, Exploration Studies including shielding studies, and risks from medical diagnostics (X-rays and CT scans).



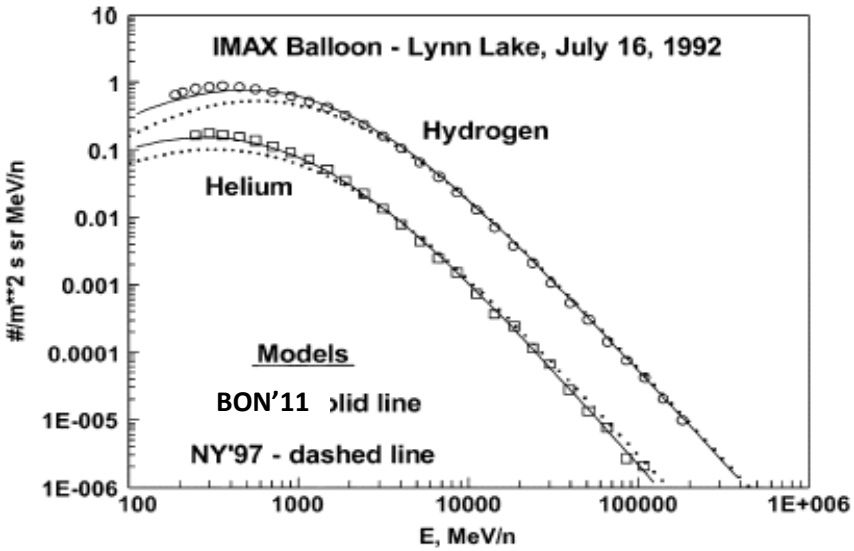
NRC, *Technical Evaluation of the NASA Model for Cancer Risk to Astronauts Due to Space Radiation.* National Academies Press (2012)

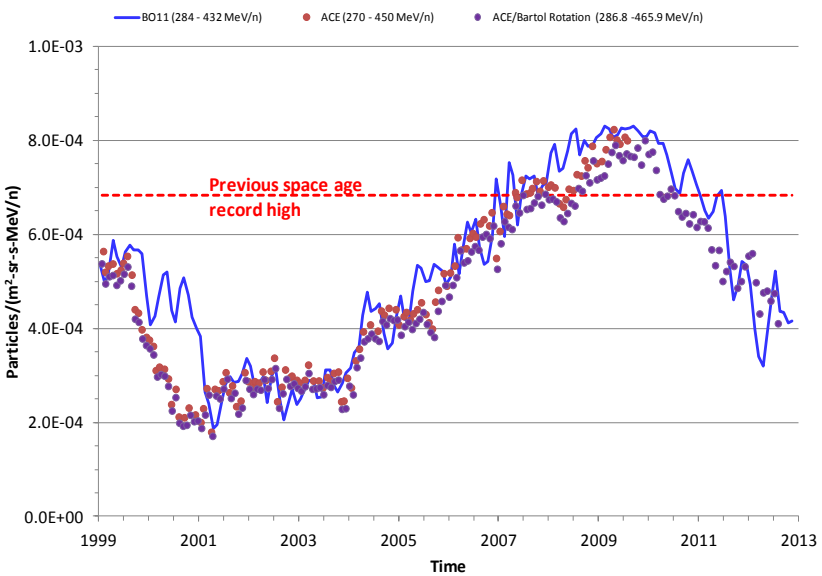
Development History

- Prior to 1999, NASA used NCRP Report No. 98, however with no data base of organ dose equivalents or cancer risk implemented by NASA.
- In 2000, the NCRP released Report No. 132 with new dose to risk conversion factors; updating NCRP-98 report (1989).
- In 1999-2002, NASA Space Radiation Program (Dr. Cucinotta and colleagues) developed a data base for Medical Operations of space organ dose equivalents and cancer risks for all crew members from all past space flights (Mercury to ISS).
  - First to implement NCRP132 methodology
- NCRP methods were not applicable to Exploration missions because of higher contributions from GCR heavy particles.
  - In 1996, the NRC estimated uncertainties in health risks estimates to be 5 to 10-fold for GCR
- In 2001-2005, NASA SRP (Dr. Cucinotta and colleagues) developed uncertainty assessment approach based on recommendations from NRC and NCRP reports.
  - Using improved methods for uncertainty analysis, GCR uncertainties reduced to about 4-fold

Badhwar-O'Neill (BON) GCR Model

- The BON model developed at JSC provides a self-consistent solution to Fokker-Plank equation for particle transport in the heliosphere.
  - Accounts for solar modulation of each element (Hydrogen to Nickel) at all energies
  - Propagates local interstellar spectrum (LIS) through heliosphere
  - Uses the smoothed mean sunspot number to determine the modulation potential
  - Model parameters derived from extensive satellite and balloon spectrometry data
- BON 2011 considers distinct modulation of protons and high charge (Z>1) elements.
- BON is an accurate GCR model in numerous comparisons:
  - BON11 root-mean-square errors <10% for all elements

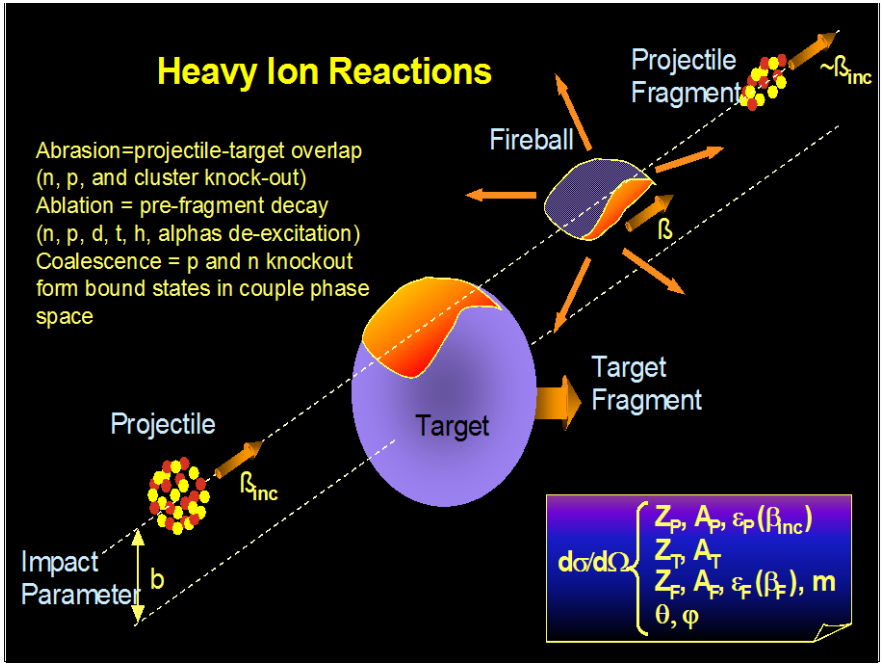




Solar Modulation of GCR Fe Nuclei

Transport Theory

- ❑ HZETRN uses solutions to Boltzmann equation to propagate BON GCR flux into atmosphere, shielding, and tissue
- ❑ Atomic and nuclear processes
- ❑ Physical perturbations for atomic, elastic, and nuclear interactions
- ❑ NASA's HZETRN/QMSFRG code has a very high degree of congruence
  - ❑ Ground-based studies with defined beams and material layouts
  - ❑ Inter-comparison of transport code results for matched boundary conditions
  - ❑ Comparisons to flight measurements
    - Dosimetry measurements within ±15% on ISS or in transit to Mars
- ❑ More importantly, transport calculations continue to be compared to spaceflight measurements to provide necessary "ground truth" data



Analysis of the RAD experiment on the Curiosity rover:

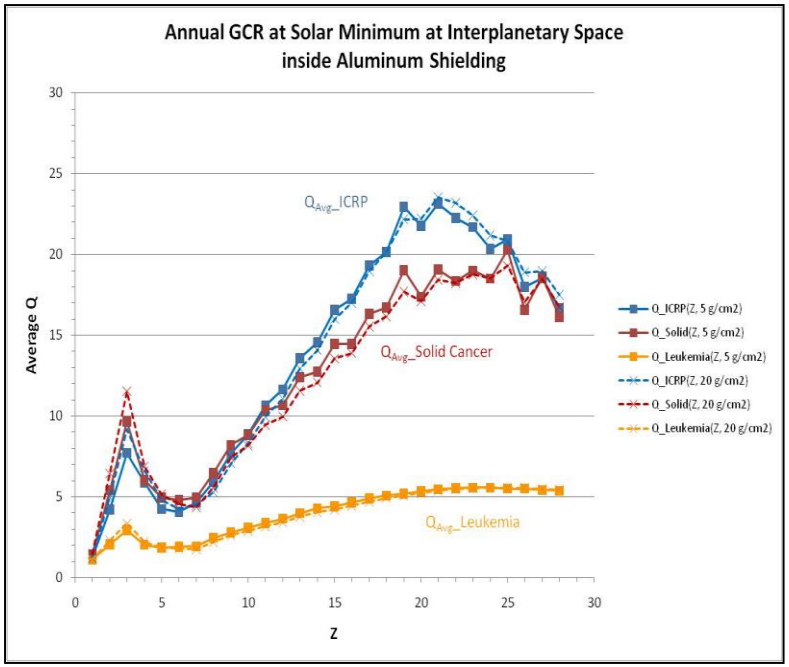
- ❑ Zeitlin, C. J., et al. (2013), *Science*, 340.

Analysis of the RAD experiment with attenuation of GCR and SPE by Martian atmosphere, soils, and the rover:

- ❑ Hassler, D. M., et al. (2014), *Science*, 343.
- ❑ Kim, M.-H. Y., et al. (2014), *JGR Planets*, 119, 1311-1321.

Radiation Quality Factors (QFs)

- New QFs based on microscopic energy deposition, and the most recent research results on particle cancer risks by NASA grants and others.
  - QF depends on particle charge and energy not LET alone as used by international committees
  - Distinct QF for solid cancer and leukemia
  - Approach to characterize uncertainties and perform new experiments to reduce them
- Supported by NRC and approved by NASA.
- Considered by ICRP for international use

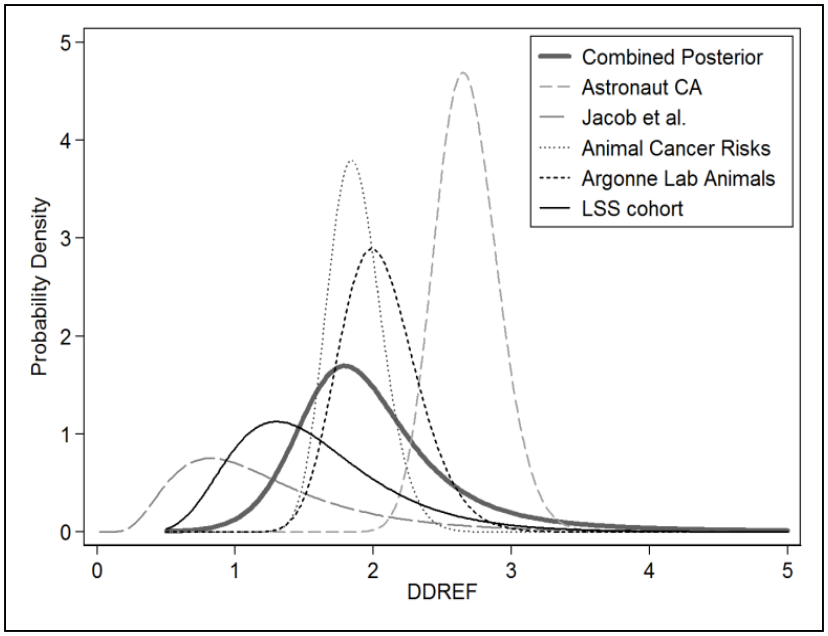


Comparison of Average QF behind shielding from Each GCR charge group

Dose-Rate Modifiers

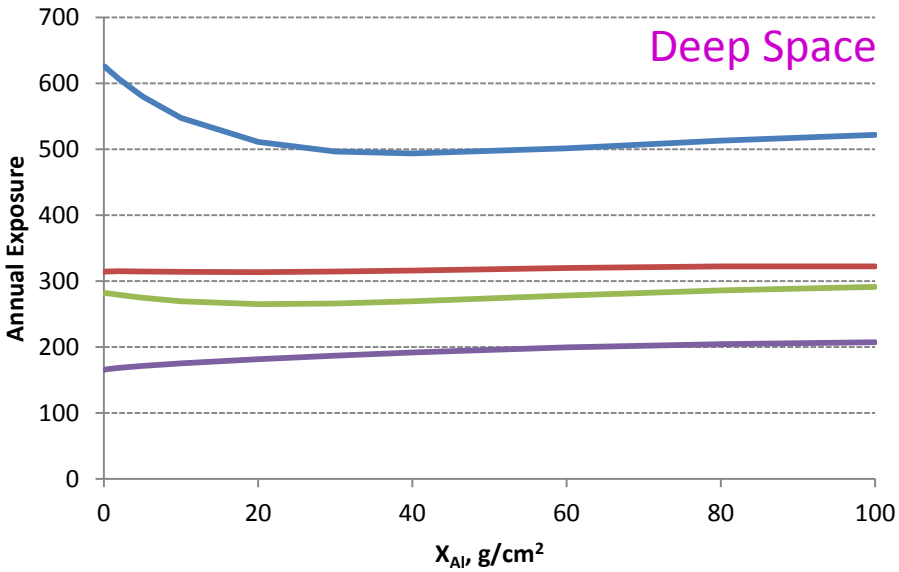
Basic Cancer Risk Estimates from Life-Span Study from Acute Exposure:

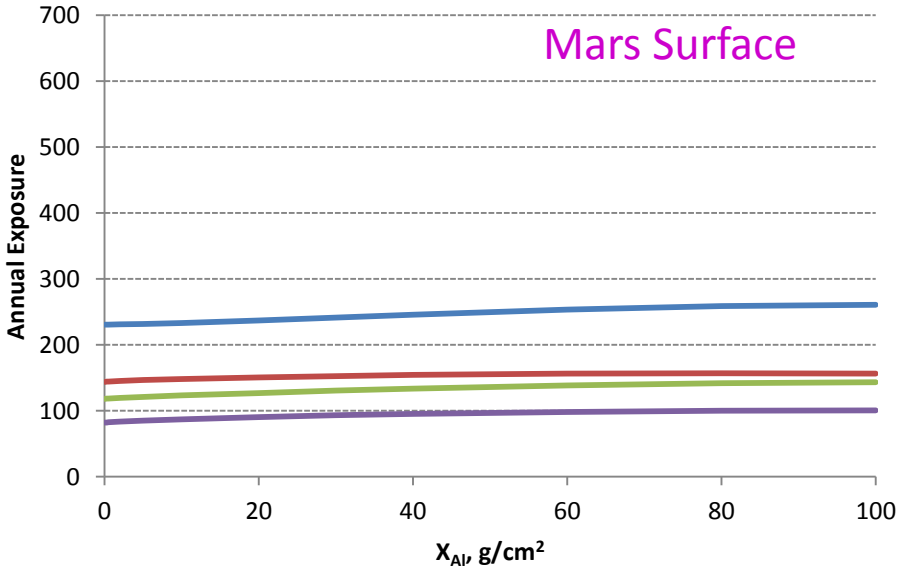
- The Dose and Dose-rate Reduction Effectiveness Factor (DDREF) is used to reduce risk estimates from acute exposure for chronic exposure risk estimates (GCR or SPE)
  - The value of the DDREF used by NASA has a larger impact for GCR risk estimates compared to shielding of more than 1 meter of polyethylene or water
- Extensive Bayesian analysis to formulate an uncertainty distribution from the DDREF to improve the accuracy of NASA risk estimates

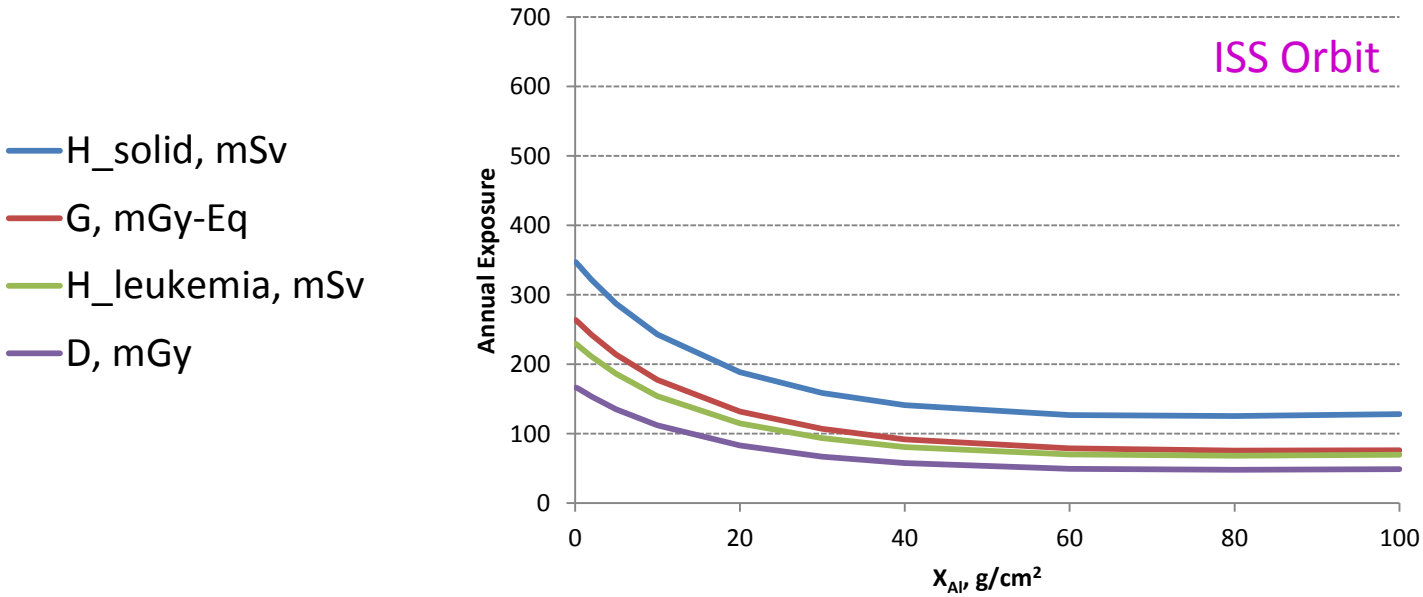


Bayesian Analysis of the DDREF PDF with Prior Distribution combining knowledge from Human studies, Mouse tumor studies and Astronaut Biomarker data for Chromosomal Aberrations (CA)

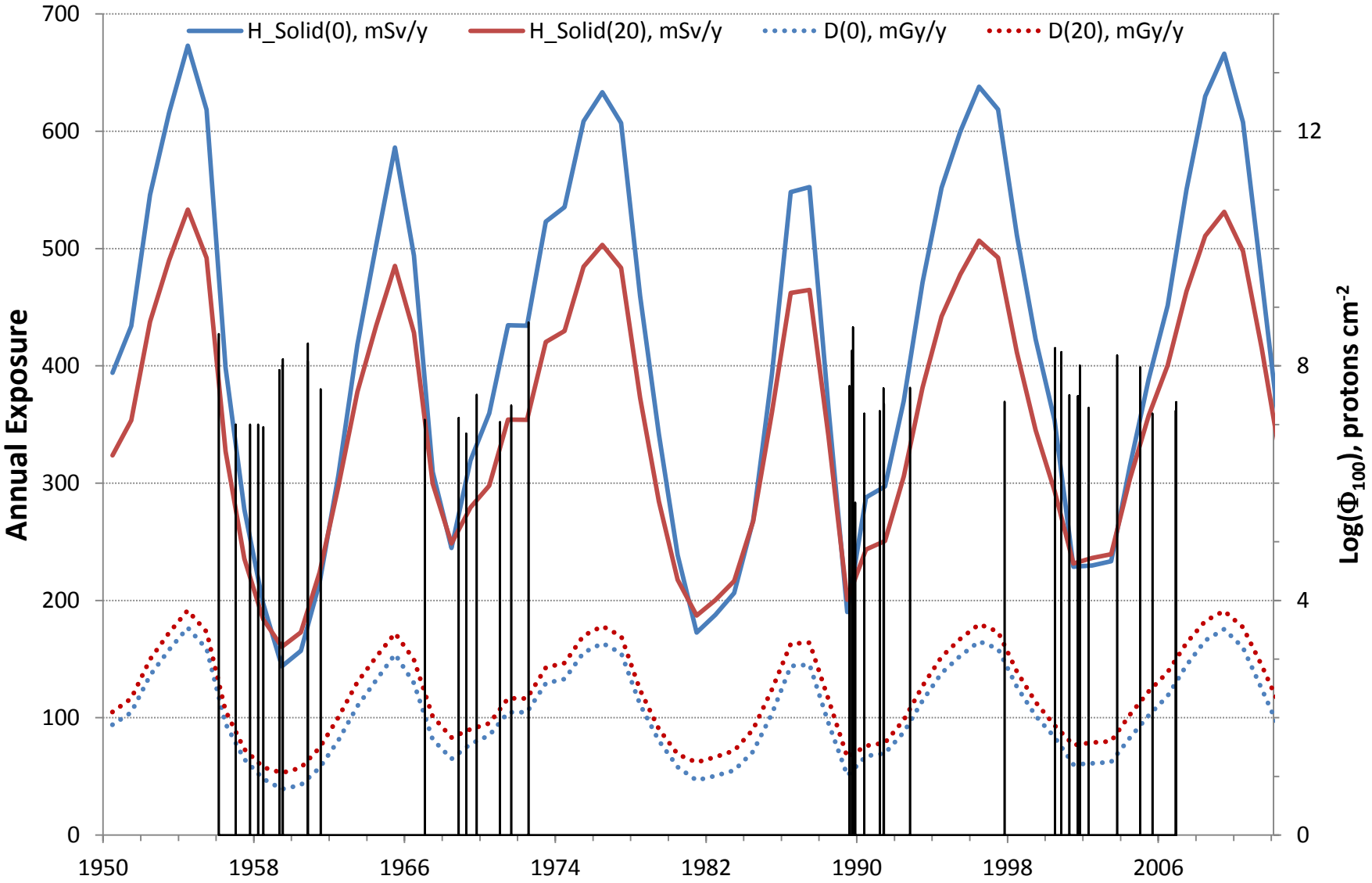
GCR Organ Dose Characterization at Average Solar Minimum





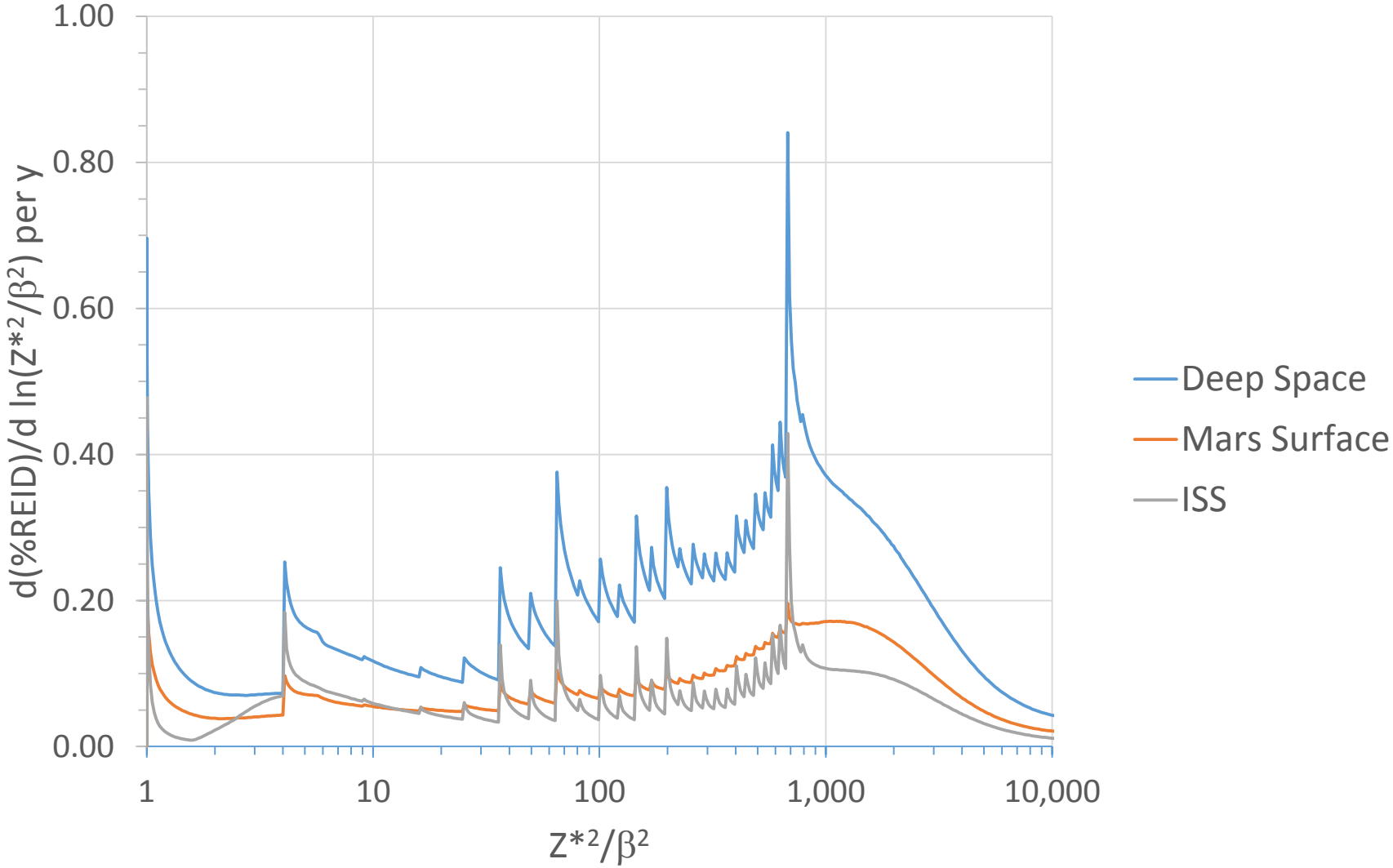


GCR Dose-Rates and SPE Occurrence



Distribution of %REID for Solid Cancer for GCR at Average Solar Minimum

-45-y Male inside 20 g/cm^2 Al-



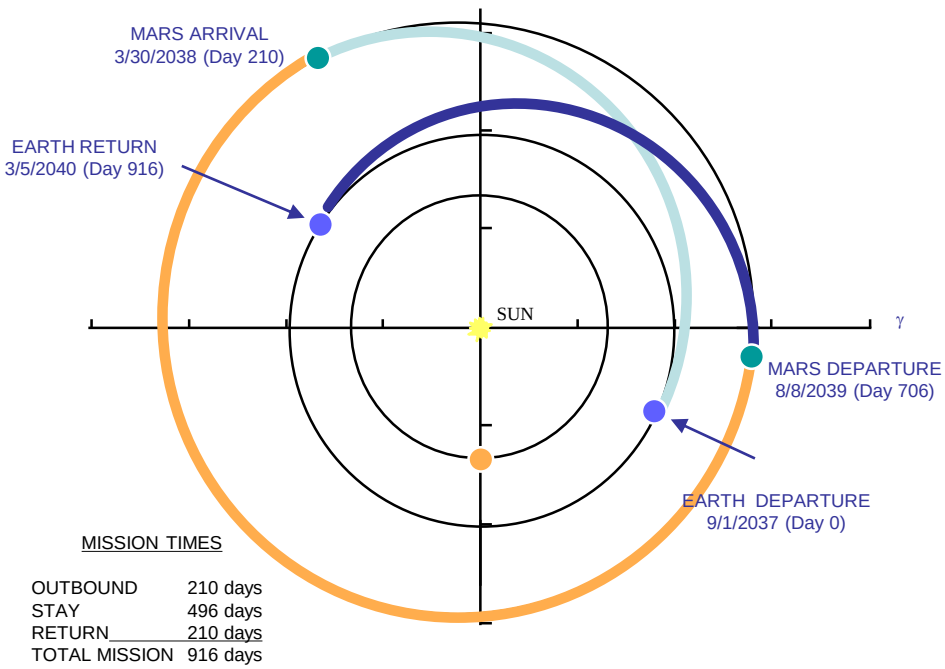
Design Reference Missions Categories

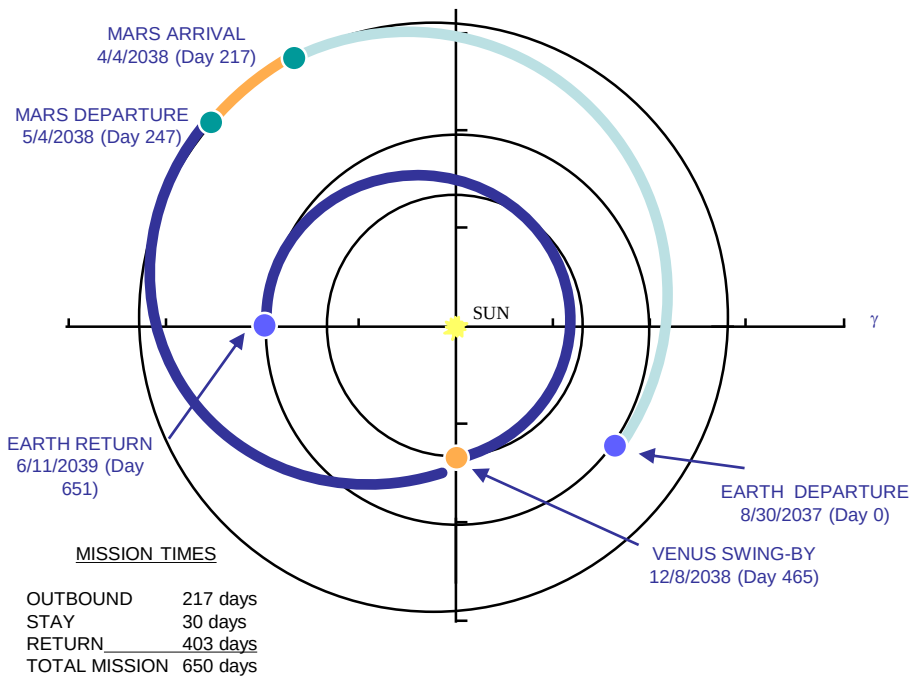
- 1-yr ISS Mission
- 1-yr Lunar Outpost
- 1-yr Asteroid Mission
- Mars Design Reference Architecture 5.0 Study
  - Conjunction class missions with long Mars surface stays
  - Opposition class missions with short Mars surface stays

Mars Design Reference Architecture 5.0 Study

Human Exploration of Mars Design Reference Architecture 5.0. NASA SP 2009-566, B. G. Drake, Ed., Washington DC.

Conjunction Class - Long Stay Mission					
Departure Date	Total Trip (days)	Outbound (days)	At Mars (days)	Inbound (days)	Min Perihelion Passage (AU)
7/24/2020	**940**	200	540	200	0.99
Opposition Class - Short Stay Missions					
Departure Date	Total Trip (days)	Outbound (days)	At Mars (days)	Inbound (days)	Min Perihelion Passage (AU)
2/28/2027	**840**	530	60	250	0.99
5/17/2033	**520**	150	60	310	0.62





Risk Assessment Parameters

- Heliospheric conditions
  - Average solar minimum
  - Deep solar minimum
- Crew transfer vehicle/ISS spacecraft
  - 20 g/cm^2 equivalent aluminum shielding
- Martian/Lunar surface habitat
  - 10 g/cm^2 equivalent aluminum shielding
- Martian atmosphere
  - 18 g/cm^2 vertical height of CO_2
- Demographic-specific analysis
  - Astronauts represented by never-smoker population (versus US average population)
- Combined REID: cancer and circulatory diseases for space missions
  - Fatal cancer risks using NSCR-2012
  - Results from a recent epidemiological analysis* of radiation risks for circulatory diseases from human exposure to low LET radiation

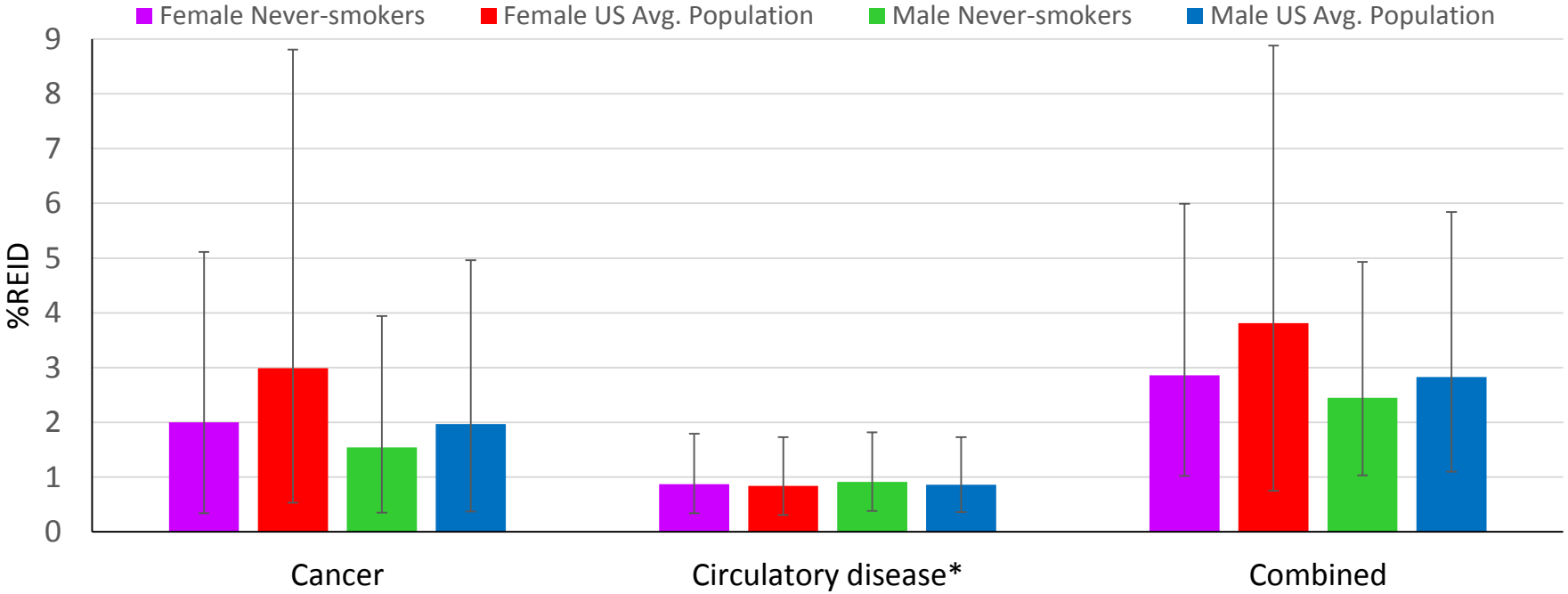
    (Circulatory disease risks: cardiovascular disease and Ischemic heart disease risks)

*Little et al. (2012) Environmental Health Perspectives 120: 1503-1511

Lifetime risks for cancer and circulatory disease

1-y interplanetary transfer at average solar minimum

Lifetime Fatal Risks for 45-y M/F from 1-y Interplanetary Transfer at Avg. Solar Minimum

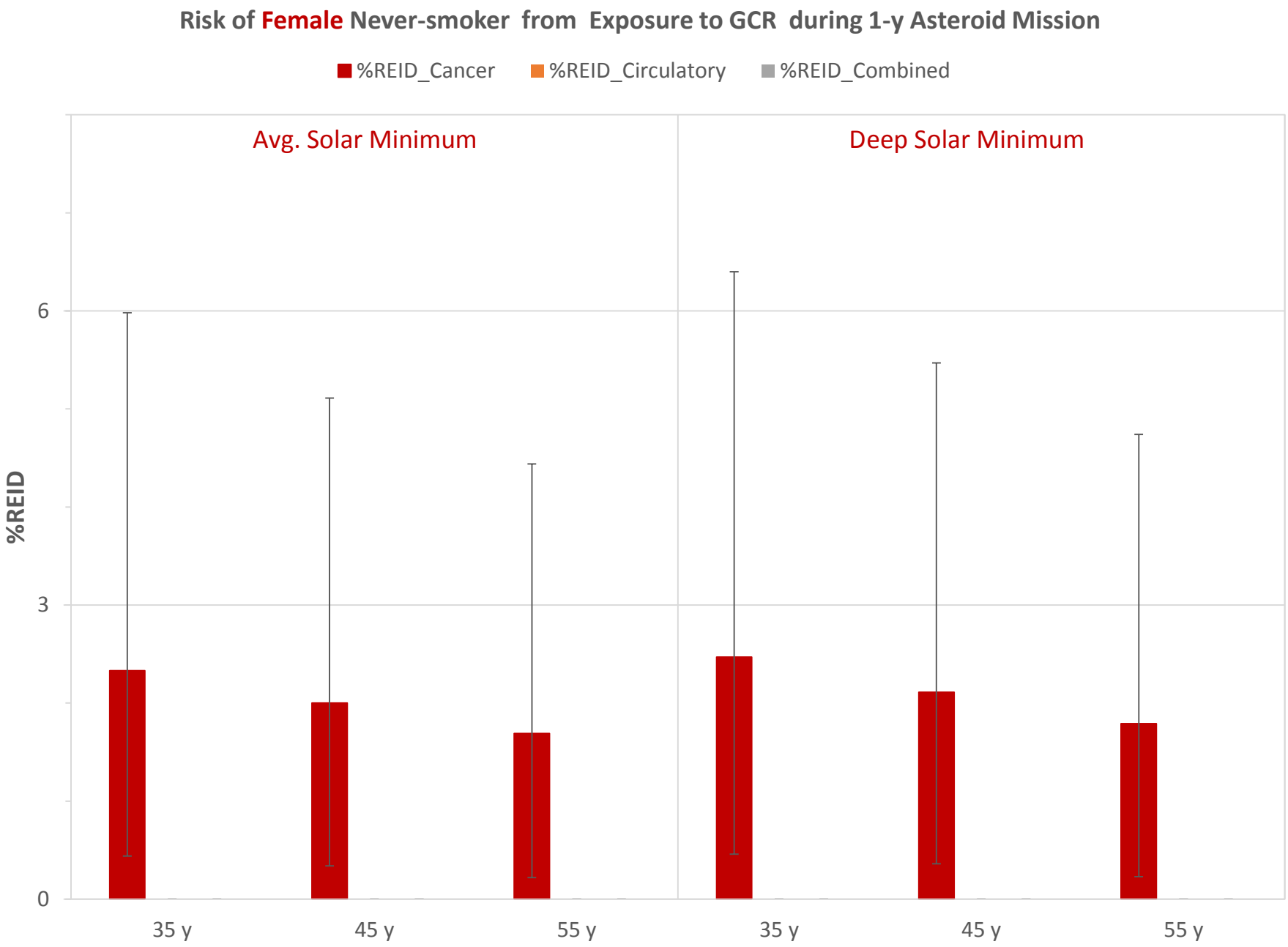


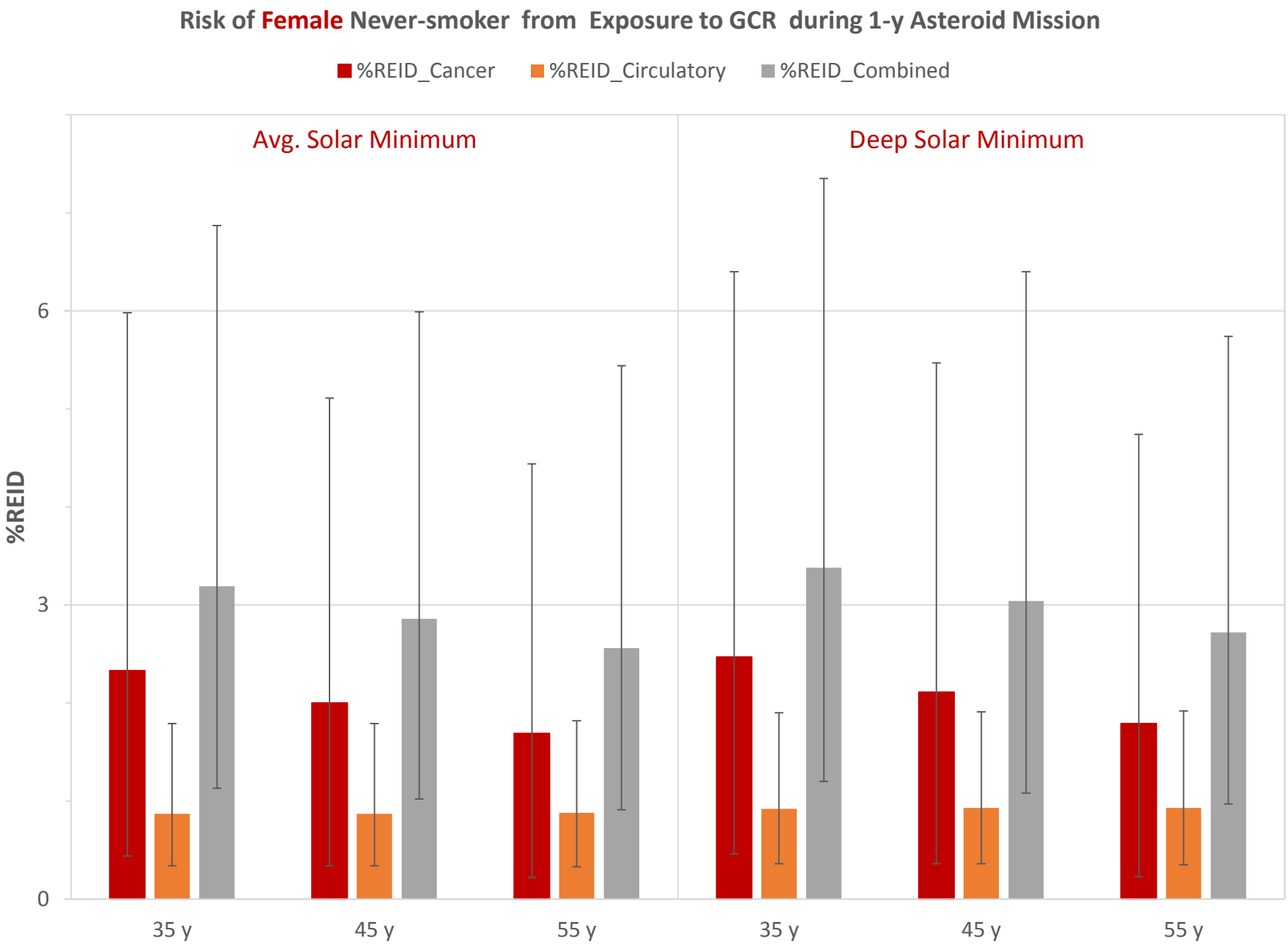
- Fatal cancer risk: 25% higher for females compared to males
- Circulatory disease* risks: cardiovascular disease and ischemic heart disease
- Similar risks of circulatory disease between NS and U.S. average populations
  → Cancellation of the combined effects of lower background rates and longer lifespan for NS: Leads to additional risks
- The combined fatal risk: 15% higher for females compared to males
- Added circulatory disease: $\%REID_{combined}$ increased by ~40%, but less dependent on age-at-exposure compared to cancer risks alone

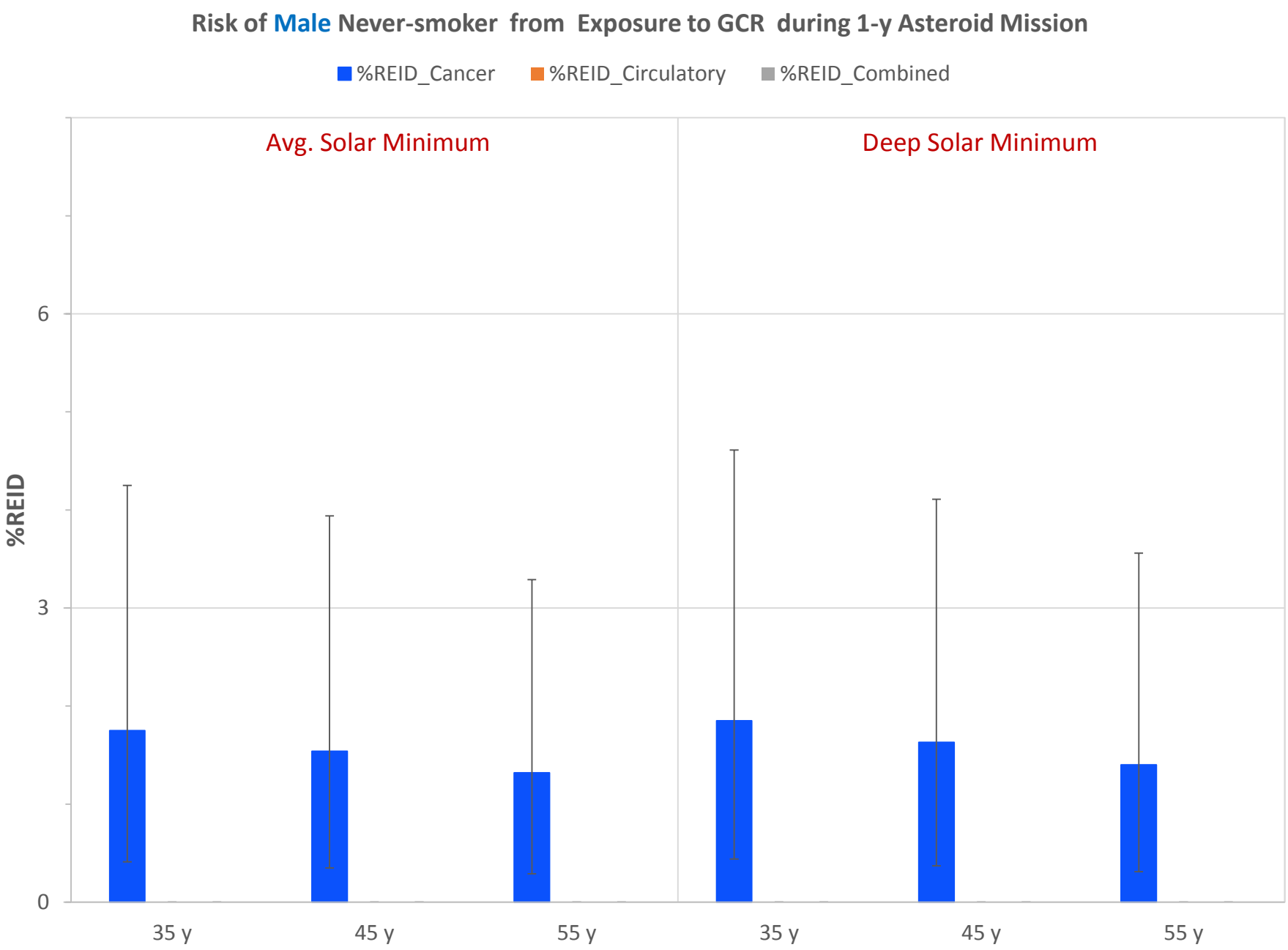
Risk Assessments

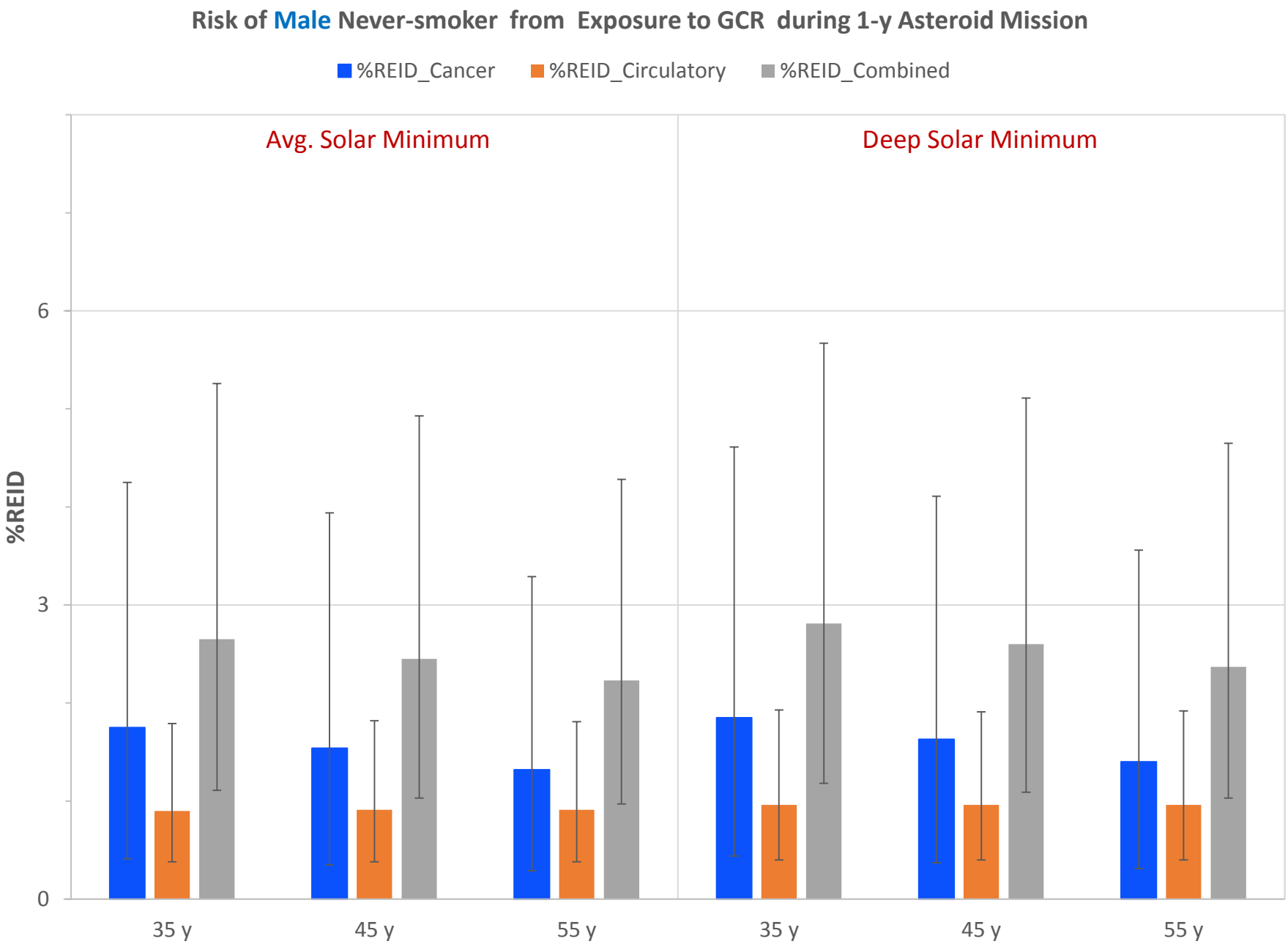
Comparison of Heliospheric Condition for 1-y Asteroid Mission

- Age-dependent Female/Male Never-smokers


Risk of Female Never-smoker from Exposure to GCR during 1-y Asteroid Mission
%REID_Cancer
%REID_Circulatory
%REID_Combined
Avg. Solar Minimum
Deep Solar Minimum
%REID
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

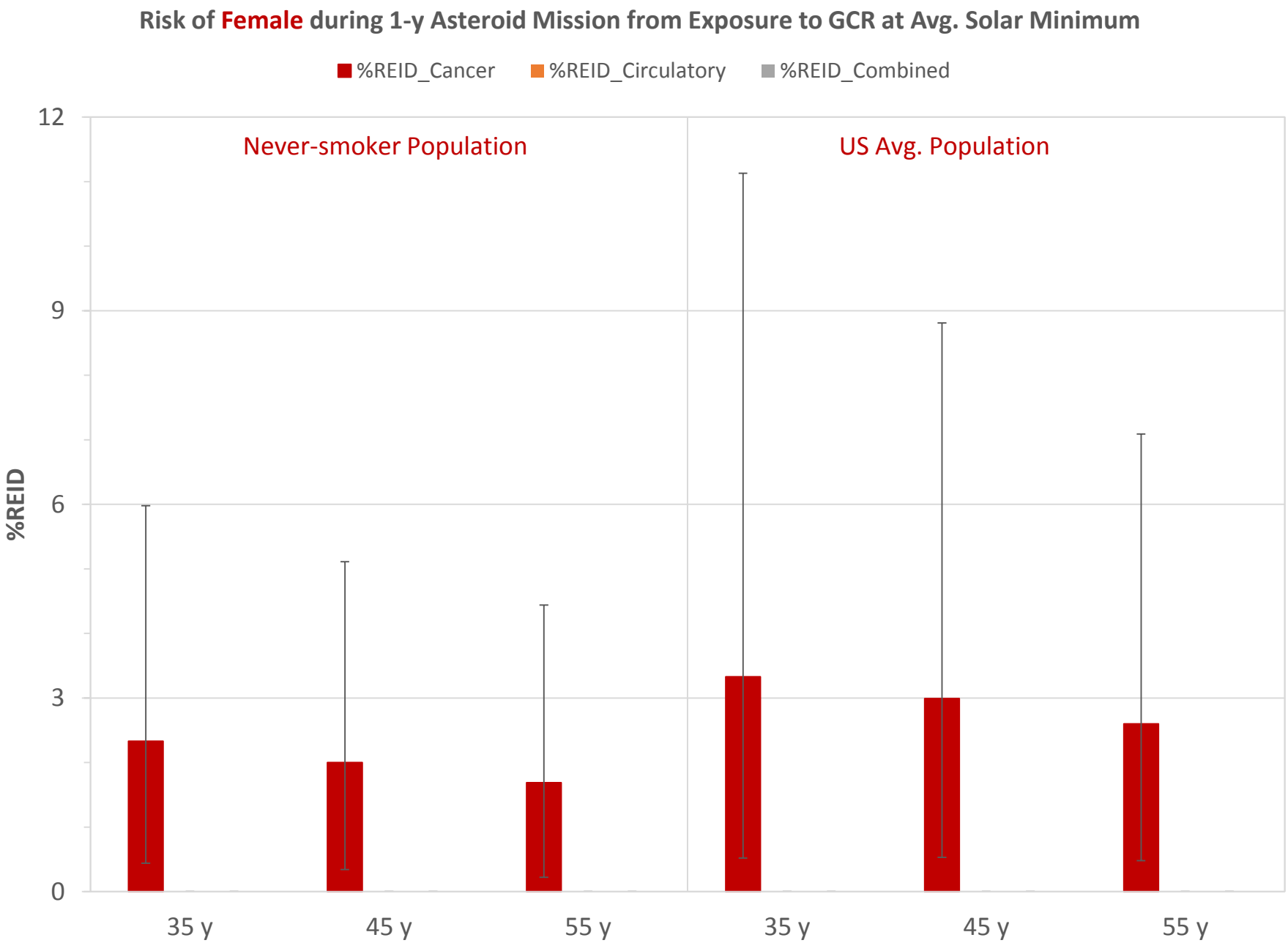

Risk of Female Never-smoker from Exposure to GCR during 1-y Asteroid Mission
%REID_Cancer
%REID_Circulatory
%REID_Combined
Avg. Solar Minimum
Deep Solar Minimum
%REID
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

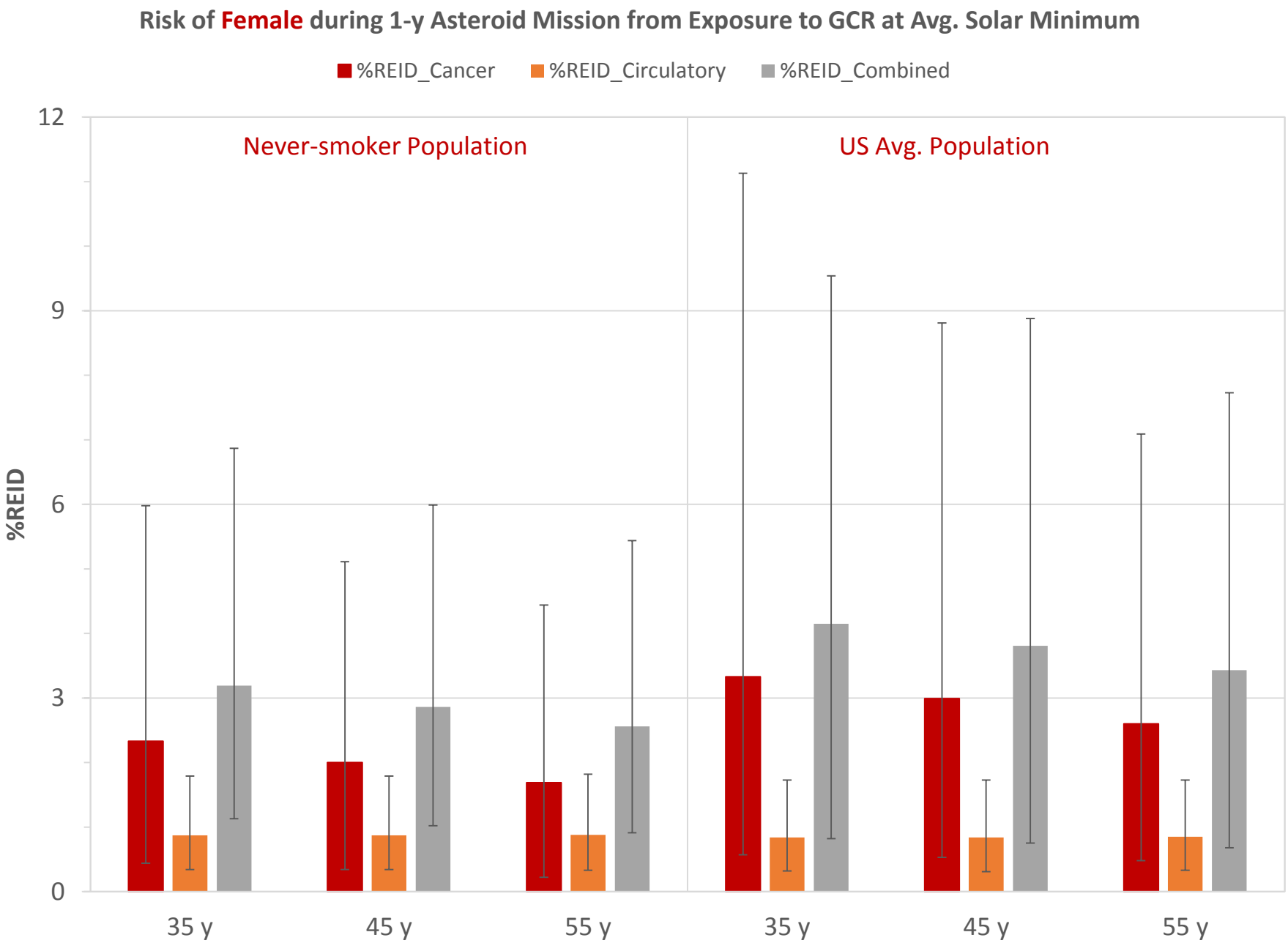

Risk of Male Never-smoker from Exposure to GCR during 1-y Asteroid Mission
%REID_Cancer
%REID_Circulatory
%REID_Combined
Avg. Solar Minimum
Deep Solar Minimum
%REID
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

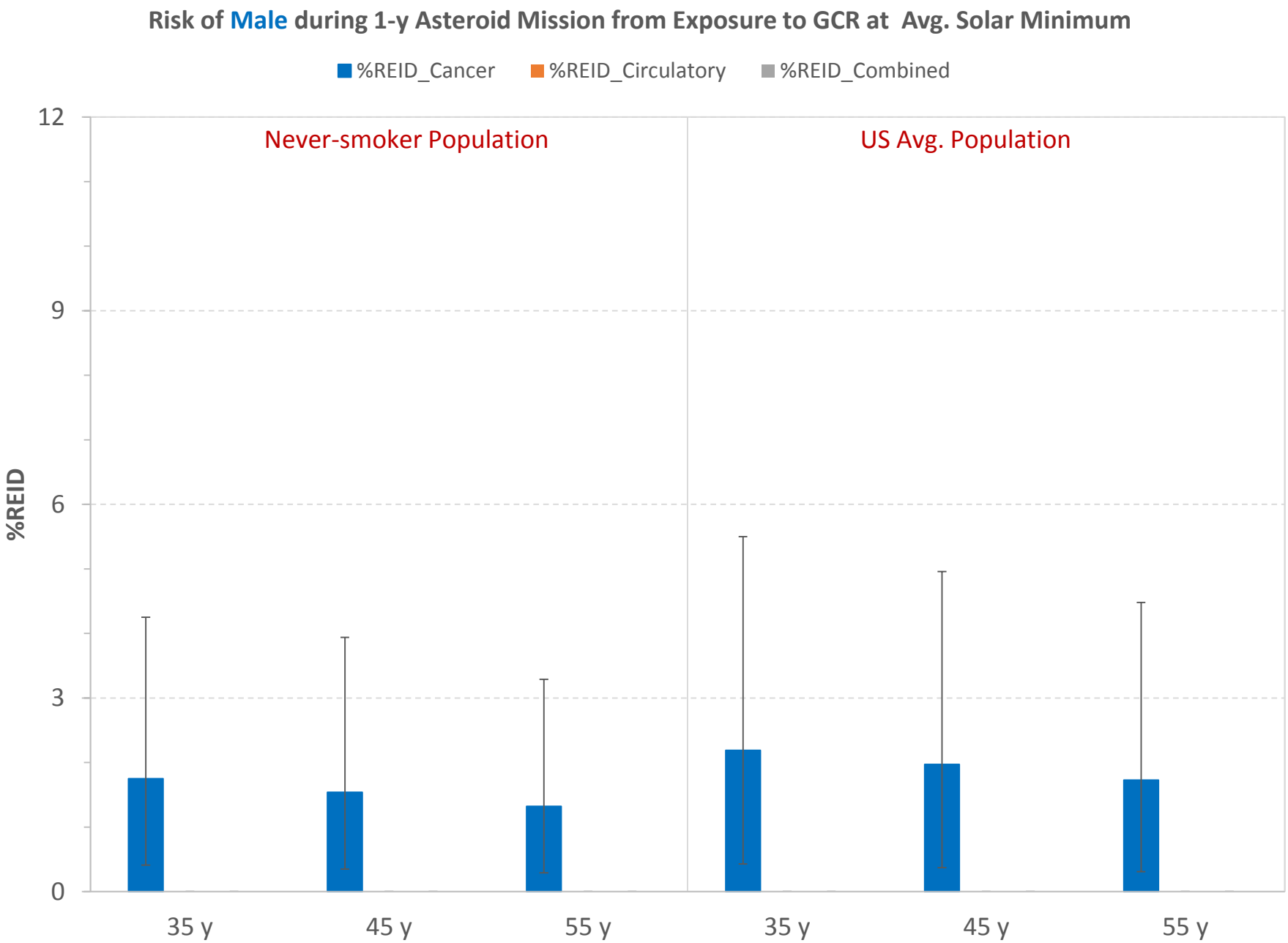

Risk of Male Never-smoker from Exposure to GCR during 1-y Asteroid Mission
%REID_Cancer
%REID_Circulatory
%REID_Combined
Avg. Solar Minimum
Deep Solar Minimum
%REID
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

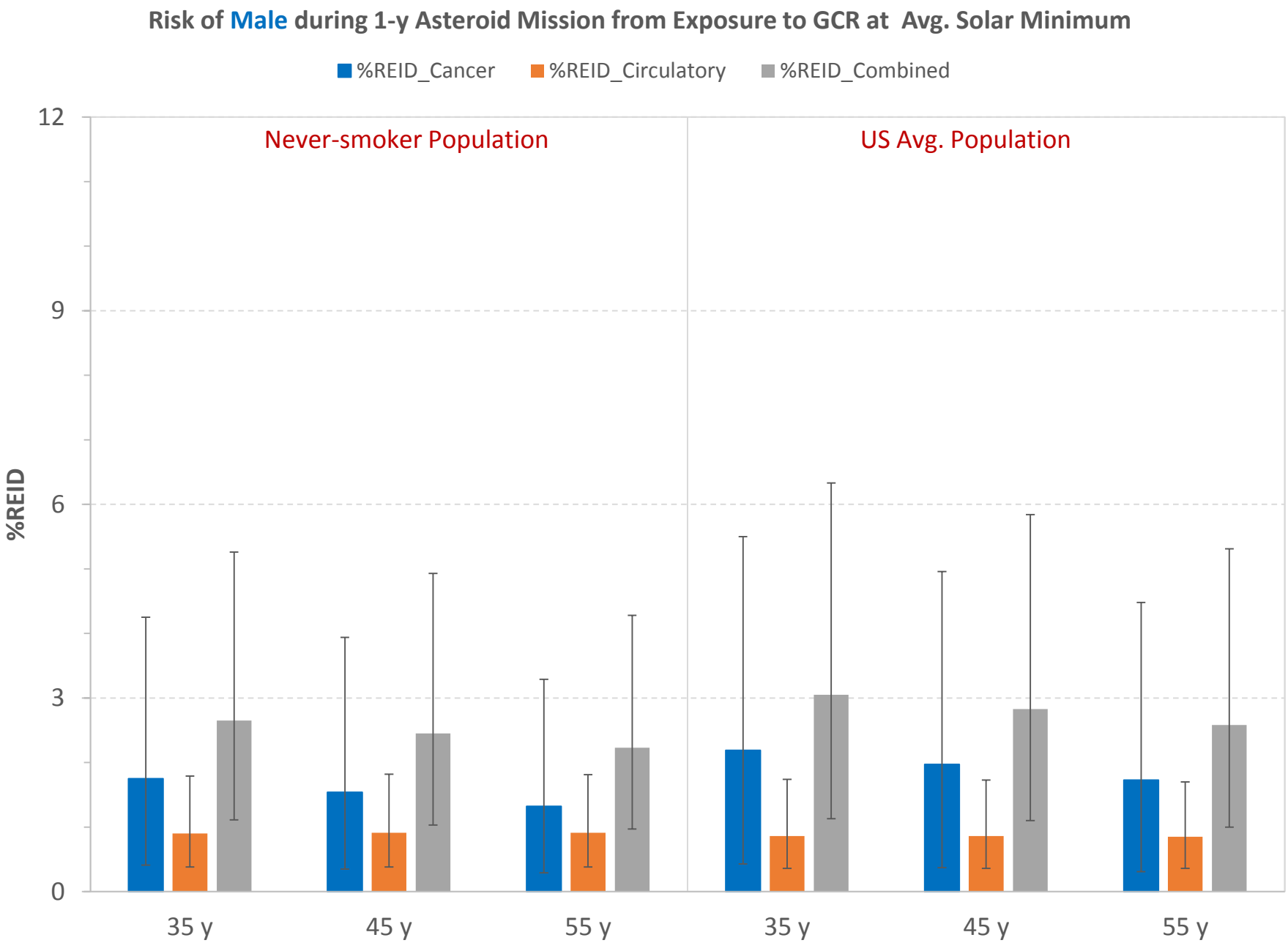
Risk Assessments

Demographic-specific Analysis for 1-y Asteroid Mission at Avg. Solar Minimum


Risk of Female during 1-y Asteroid Mission from Exposure to GCR at Avg. Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
Never-smoker Population
US Avg. Population
%REID
12
9
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y


Risk of Female during 1-y Asteroid Mission from Exposure to GCR at Avg. Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
Never-smoker Population
US Avg. Population
%REID
12
9
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

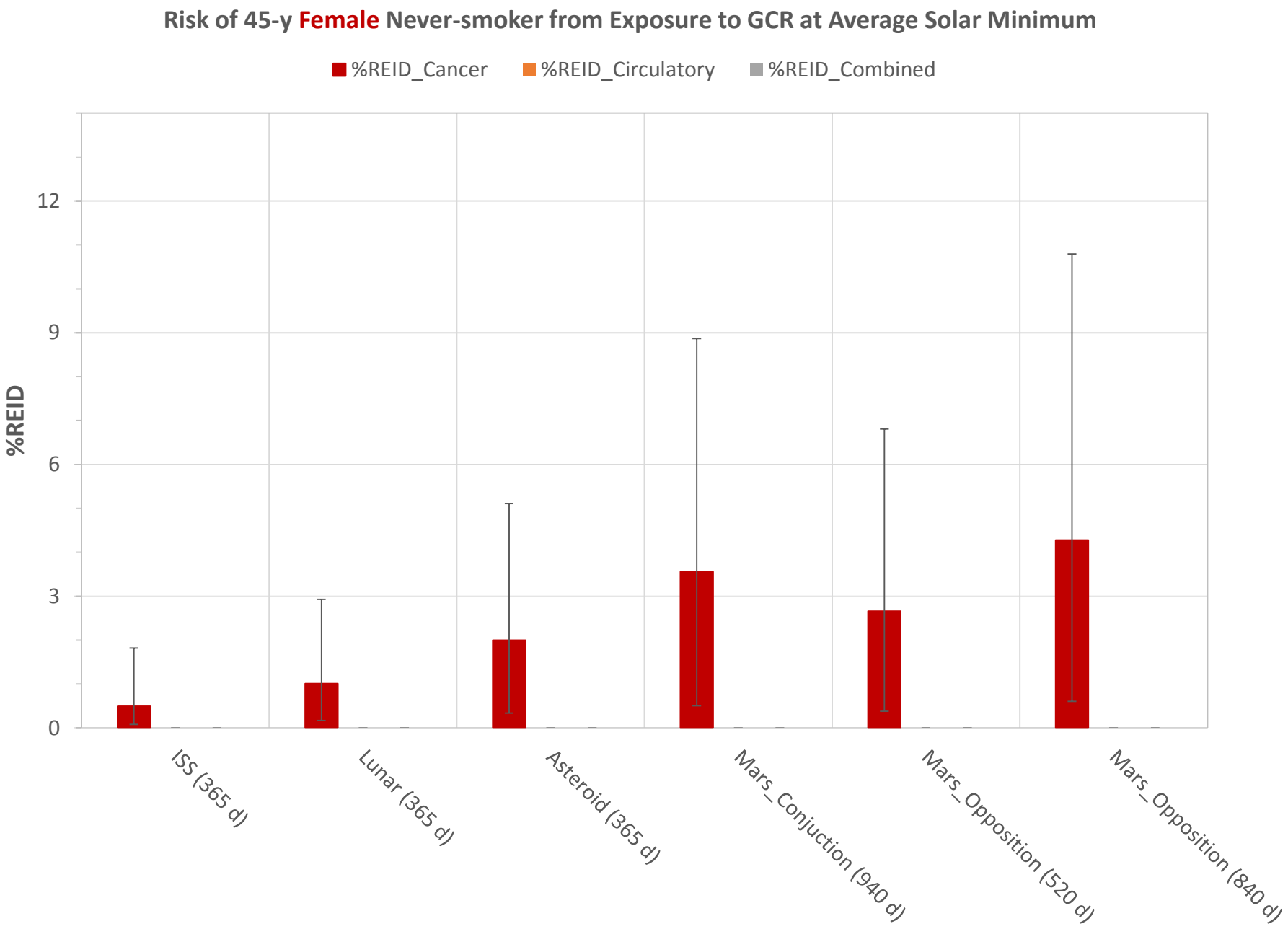

Risk of Male during 1-y Asteroid Mission from Exposure to GCR at Avg. Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
Never-smoker Population
US Avg. Population
%REID
12
9
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

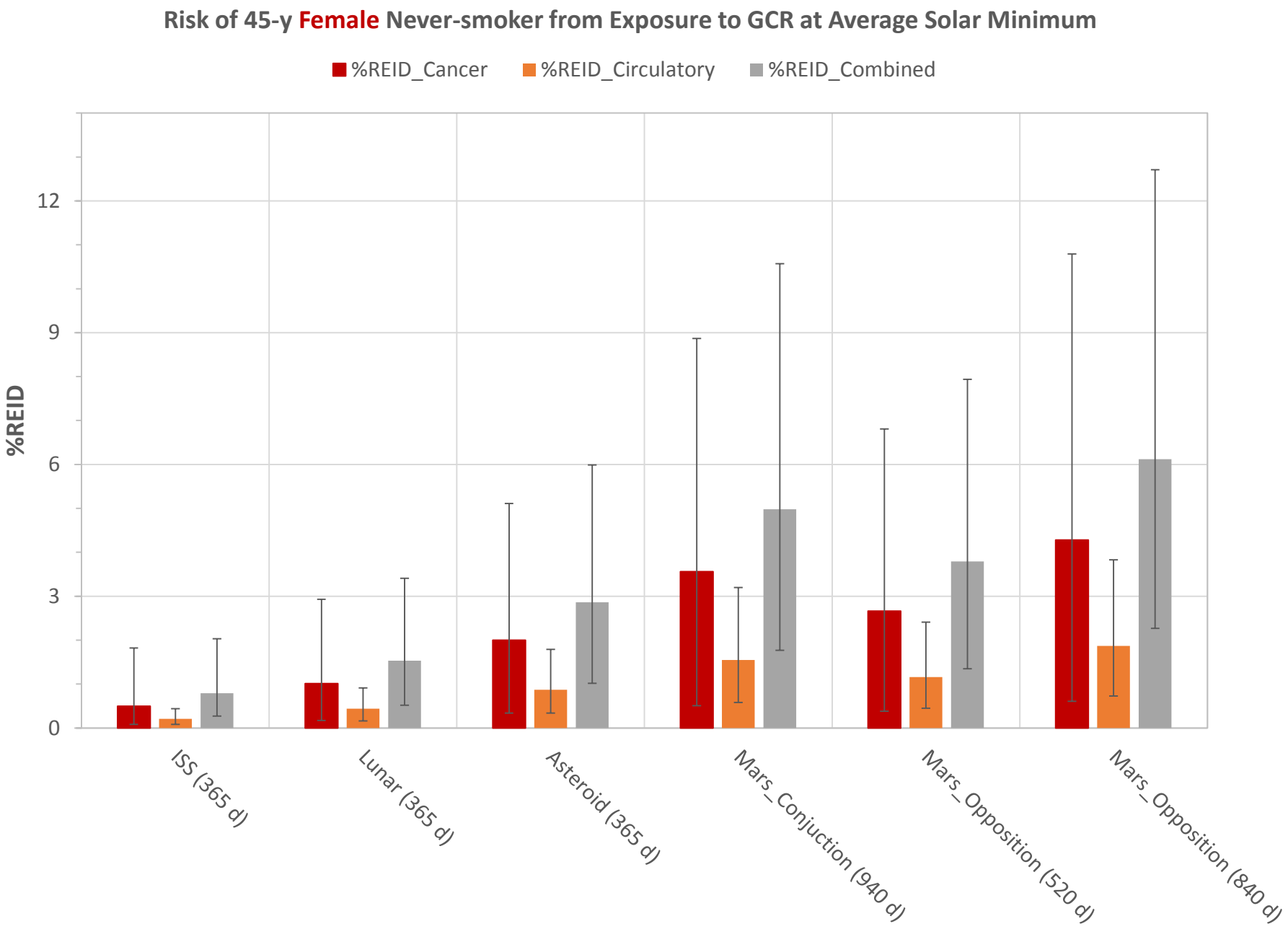

Risk of Male during 1-y Asteroid Mission from Exposure to GCR at Avg. Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
Never-smoker Population
US Avg. Population
%REID
12
9
6
3
0
35 y
45 y
55 y
35 y
45 y
55 y

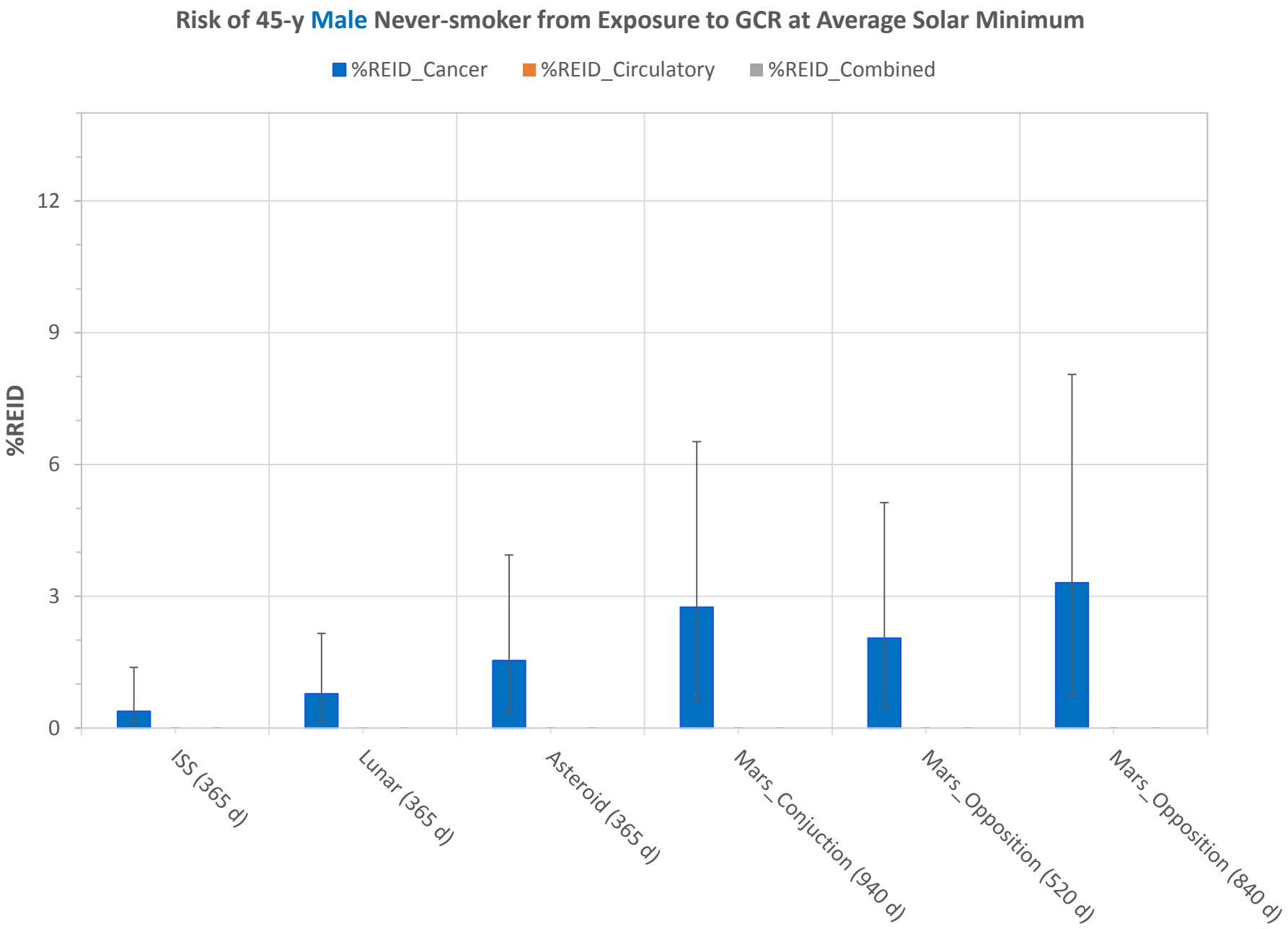
Comparison for Design Reference Missions

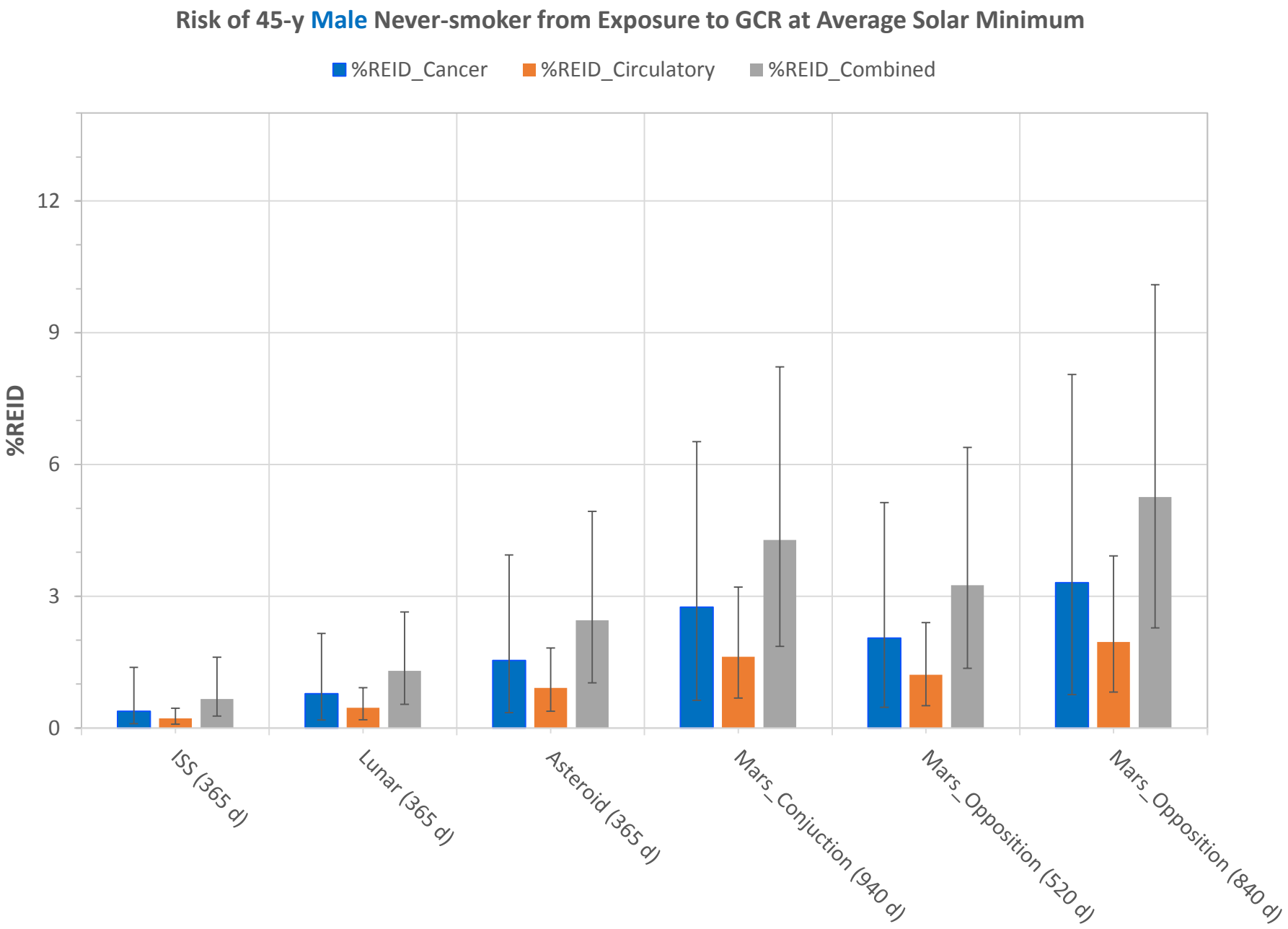
%REID from Cancer & Circulatory Diseases Combined

- Female/Male Never-smokers
- GCR at Average Solar Minimum


Risk of 45-y Female Never-smoker from Exposure to GCR at Average Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
%REID
0
3
6
9
12
ISS (365 d)
Lunar (365 d)
Asteroid (365 d)
Mars_Conjuction (940 d)
Mars_Opposition (520 d)
Mars_Opposition (840 d)


Risk of 45-y Female Never-smoker from Exposure to GCR at Average Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
%REID
0
3
6
9
12
ISS (365 d)
Lunar (365 d)
Asteroid (365 d)
Mars_Conjuction (940 d)
Mars_Opposition (520 d)
Mars_Opposition (840 d)


Risk of 45-y Male Never-smoker from Exposure to GCR at Average Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
%REID
0
3
6
9
12
ISS (365 d)
Lunar (365 d)
Asteroid (365 d)
Mars_Conjuction (940 d)
Mars_Opposition (520 d)
Mars_Opposition (840 d)


Risk of 45-y Male Never-smoker from Exposure to GCR at Average Solar Minimum
%REID_Cancer
%REID_Circulatory
%REID_Combined
%REID
0
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9
12
ISS (365 d)
Lunar (365 d)
Asteroid (365 d)
Mars_Conjuction (940 d)
Mars_Opposition (520 d)
Mars_Opposition (840 d)

Conclusions

- Predictions of fatal risks from cancer and circulatory diseases
  - REID was much less on ISS compared to deep space missions
  - Missions of 1-year on the ISS at solar minimum: within the acceptable risk level for astronauts
  - Mars missions:
    - Combined REID increased by ~40% from the cancer risk alone
    - An increased REID to the crew of 8-11% (Avg. cancer risk w/o space flight is 14% for normal weight/non-smoking US average)
- Exploration missions exceeded NASA's radiation limit by a large amount
  - Exposure to all GCR energies
  - The longer mission duration
- Large uncertainties in the risk estimates
  - A 3-fold ratio of the upper 95% CI to the central estimates
  - Reduced uncertainties to be obtained from significant knowledge and data (risk coefficients for cancer/non-cancer mortality, QFs, DDREF etc.)
- Need to continue to track advances and understanding of cancer, cardio and CNS effects