ESTIMATION OF EXPOSURE LEVELS FOR CONSEQUENCES OF SOLAR PARTICLE EVENTS

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INTRODUCTION

- Exposure to intense solar particle events (SPEs):
  - Possible acute radiation risk during interplanetary transfer and EVAs on the lunar and Martian surfaces
  - Posing increased cancer risk/degenerative disease from multiple exposures to large SPEs with high energies
- NASA's operational strategies for protection:
  - Real-time estimation of exposure levels of SPEs
  - Applying proper shielding solutions in a timely manner
  - Improved forecasting capability
  - Developing early-warning systems
- Problem: Making a realistic temporal estimation in a timely manner has not been readily available because the exposure analysis relies on required components
- Objective: To estimate realistic temporal exposures using predictor fluences

APPROACH

- Band fit parameters of 59 ground-level enhanced events (GLEs) observed since 1956: as an accurate functional representation of complete energy spectrum of major SPEs
- NASA BRYNTRN code system: for transport properties with detailed shielding and body geometry models
- Response quantities: BFO dose and NASA effective dose
- Solar energetic proton measurements below 500 MeV from NASA's IMP-8 GME experiment from 1973 to 2001: primary database of Φ_{200} and updated database of Φ_{30}, Φ_{60}, Φ_{100}
- Prediction models for BFO dose and NASA effective dose: as a function of the predictor fluence of Φ_{30}, Φ_{60}, Φ_{100}, or Φ_{200}
- Unconditional probability of a BFO dose exceeding the limit (BFO dose risk): by taking into account the distribution of BFO dose as a function of the predictor

BAND FUNCTION FIT IN RIGIDITY

- Based on Band et al., *Astrophysical Journal,* 413, 281-292, 1993 — A double power law in proton rigidity smoothly joins satellite & neutron-monitor spectra from ~10 MeV to ~10 GeV
- Functional forms:

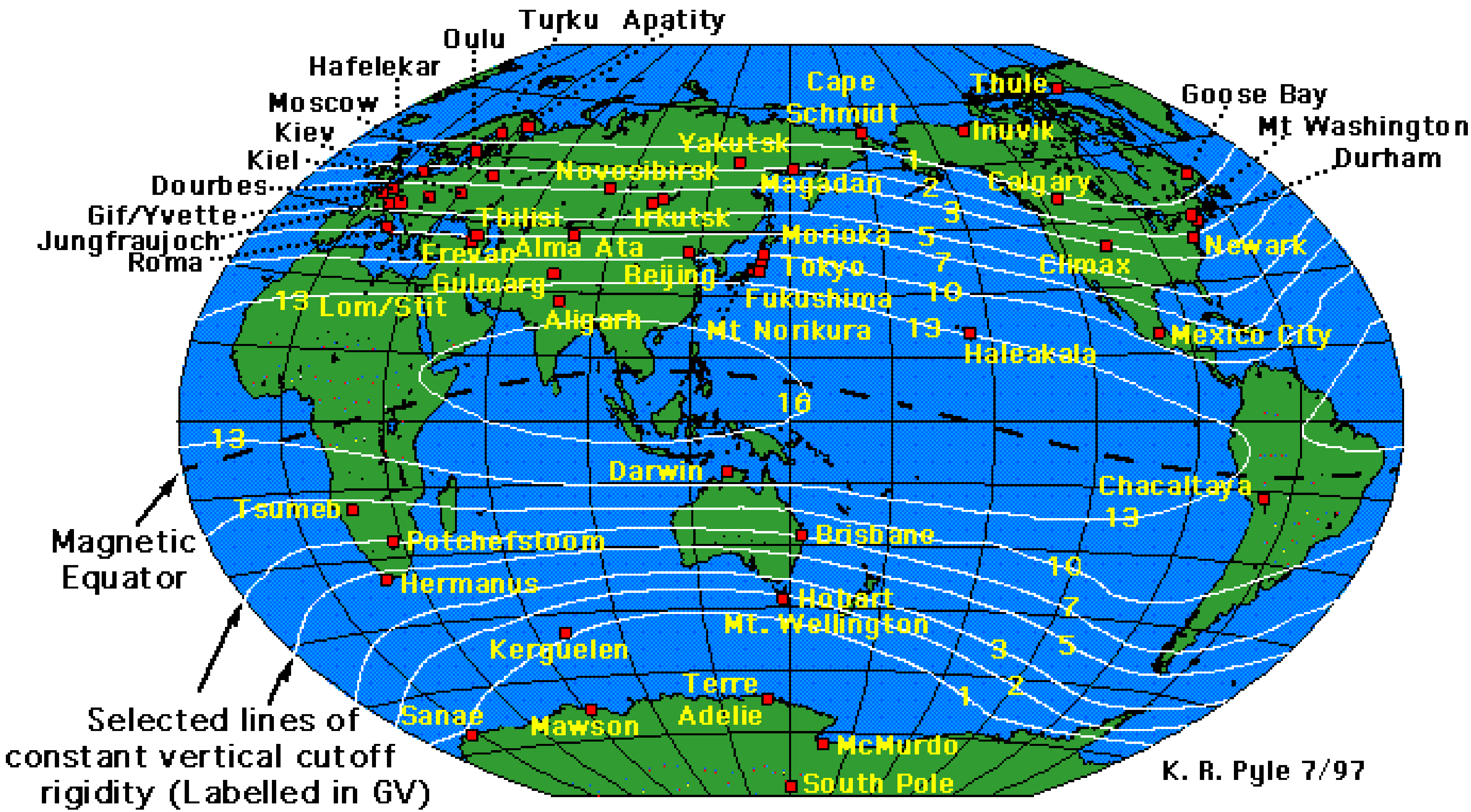
$$\Phi(>R) = J_0 R^{-\gamma_1} e^{-R/R_0} \qquad \text{for } R \leq (\gamma_2 - \gamma_1) R_0$$

$$\Phi(>R) = J_0 R^{-\gamma_2} \left\{ \left[(\gamma_2 - \gamma_1) R_0 \right]^{(\gamma_2 - \gamma_1)} e^{(\gamma_1 - \gamma_2)} \right\} \qquad \text{for } R \geq (\gamma_2 - \gamma_1) R_0$$

GLE-specific 4 Parameters: J_0 (p/cm^2), γ_1, γ_2, R_0 (GV)

- Catalogues of proton spectra for 59 GLEs observed since 1956:
  - Allan Tylka and William Dietrich, "Proton Spectra in Ground-Level Enhanced (GLE) Solar Particle Events," 37th Committee on Space Research (COSPAR) Scientific Assembly, Session D23-0003-08, Montreal, Canada, 2008.
  - Tylka and Dietrich, the 31st International Cosmic Ray Conference, Lodz, Poland, July 7-15, 2009.

WORLD-WIDE NEUTRON MONITOR (NM) NETWORK MAP



Source: Neutron Monitor Program, Bartol Research Institute, U. of Delaware

WORLD-WIDE NEUTRON MONITOR (NM)

Converting NM Data to Absolutely Normalized Fluence Measurements:

- Each stations at different geographical position → Characterization of the flux of charged particles arriving at the magnetosphere (arrival direction and rigidity/energy)
- The combination of NMs with the Earth's atmosphere and magnetosphere → Be a unique instrument with directional and energy resolution
- Advantage of the use of all stations as a unified multidirectional detector → Substantially higher (< 0.1% for hourly data) accuracy than for a single instrument

New Technique (Tylka and Dietrich, 2009)[1] for Analyzing GLE NM Data:

- Pressure-corrected data from the world-wide NM network
- Yield functions (Clem and Dorman, 2000)[2]
- Cutoff code "RcUT3" (Smart et al., 2006)[3]
- Altitude correction (McCracken, 1962)[4]

→Absolute Normalization and Spectral Index

[1]Tylka AJ and Dietrich WF, Proceedings of the 31st International Cosmic Ray Conference, Lodz, Poland, July 7-15, 2009.

[2]Clem JM and Dorman LI, *Space Sci. Rev.,* 93, pp. *335*-359, 2000.

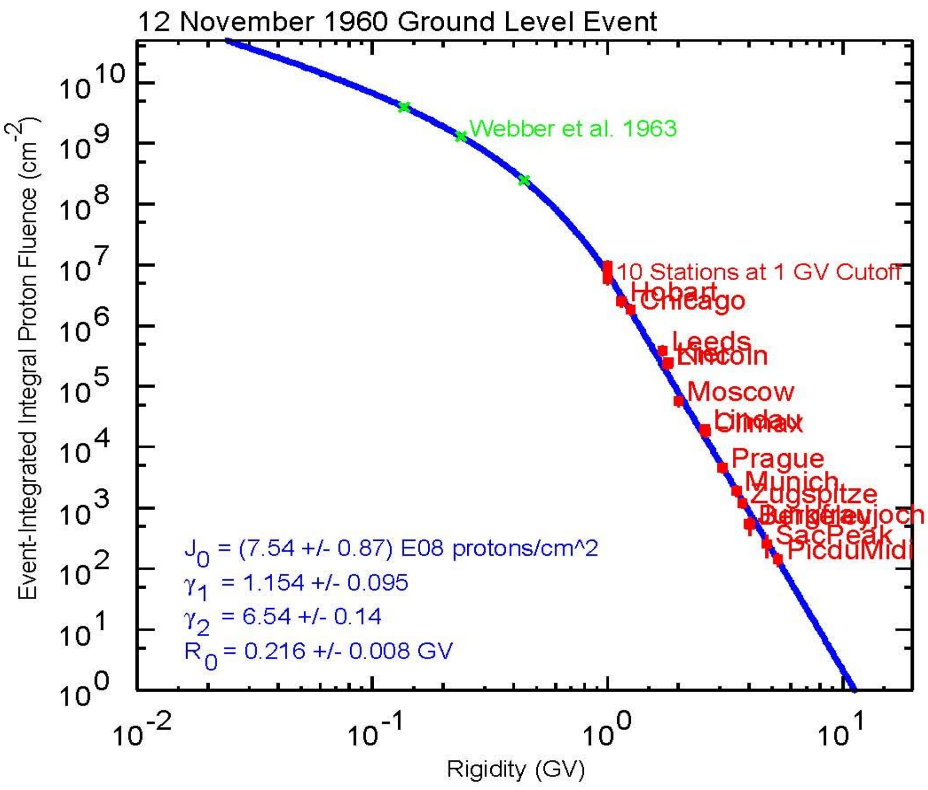
[3]Smart DF, et al., *ASR,* 37, pp. 1206-1217, 2006.

[4]McCracken KG, *JGR,* 67, pp. 423-458, 1962.

BAND FUNCTION FIT IN RIGIDITY
- Example -

- **Fitting of two data sets for 12 Nov 1960 GLE:**
  - **satellite data**
  - **neutron monitor data at the neutron monitor ground stations each having a different geomagnetic rigidity cutoff**
- **Fitting parameters in light blue:** Tylka AJ and Dietrich WF, 31st ICRC, 2009

12 Nov 60 GLE



1 GV proton ~ 430 MeV

SOURCE DATA OF IMP-8 GME EXPERIMENT 1973 - 2001

IMP-8 GME for 28 SPEs					Corresponding 33 GLEs		
						Φ_{200} (p/cm^2)	
Event Start Date / Time	Event End Date / Time	Solar Cycle	Event Duration (days)	GME index	Official GLE No.	GME data	Band Fit
4/30/76 17:15	5/3/76 23:45	20Min	3.29	36	27	$5.37\text{x}10^5$	$7.01\text{x}10^5$
9/19/77 9:15	9/24/77 4:45	21Max	4.83	47	28	$4.81\text{x}10^5$	$6.75\text{x}10^5$
9/24/77 5:15	10/6/77 0:15	21Max	11.81	48	29	$8.46\text{x}10^5$	$1.38\text{x}10^6$
11/22/77 8:15	12/3/77 0:15	21Max	10.69	52	30	$9.73\text{x}10^5$	$2.01\text{x}10^6$
5/7/78 0:45	5/21/78 12:15	21Max	14.50	66	31	$5.08\text{x}10^5$	$4.59\text{x}10^5$
9/23/78 6:15	10/1/78 0:15	21Max	7.77	75	32	No GME data	$2.58\text{x}10^6$
4/24/81 11:45	5/28/81 10:15	21Max	33.96	141	35	$4.84\text{x}10^5$	$2.75\text{x}10^5$
10/8/81 0:15	10/27/81 0:15	21Max	19.02	153	36	$1.26\text{x}10^6$	$1.39\text{x}10^6$
11/21/82 6:15	11/26/82 1:45	21Max	4.83	180	37a	$1.03\text{x}10^4$	$4.61\text{x}10^5$
11/26/82 2:15	12/7/82 17:45	21Max	11.67	181	37b	$2.70\text{x}10^5$	
12/7/82 18:15	12/13/82 13:45	21Max	5.83	182	38	$6.35\text{x}10^5$	$1.28\text{x}10^6$
2/16/84 0:15	3/5/84 0:15	21Max	18.02	200	39	$1.20\text{x}10^6$	$6.94\text{x}10^5$
7/25/89 3:15	7/28/89 10:15	22Max	3.31	266	40	$1.14\text{x}10^5$	$4.77\text{x}10^5$
8/12/89 10:45	9/8/89 20:15	22Max	27.42	268	41	$9.57\text{x}10^6$	$5.13\text{x}10^6$
9/29/89 10:15	10/19/89 0:15	22Max	19.60	271	42	$4.38\text{x}10^7$	$3.11\text{x}10^7$
10/19/89 8:15	11/14/89 0:15	22Max	25.69	272	[43+44+45]	$9.91\text{x}10^7$	$9.26\text{x}10^{7\$}$
					43	$5.65\text{x}10^7$	$5.51\text{x}10^7$
					44	$2.12\text{x}10^7$	$1.59\ \text{x}10^7$
					45	$2.15\text{x}10^7$	$2.16\ \text{x}10^7$
11/15/89 4:15	11/25/89 0:15	22Max	9.85	273	46	$1.84\text{x}10^5$	$3.15\text{x}10^5$

32: Φ_{200} not observed by IMP-8 GME

37a+37b:Sum of 2 separate SPEs by GME 180 and 181 for GLE 37 observation.

$Sum of Band fit for GLEs 43, 44, and 45.

SOURCE DATA OF IMP-8 GME EXPERIMENT 1973 - 2001

IMP-8 GME for 28 SPEs					Corresponding 33 GLEs		
						Φ_{200} (p/cm^2)	
Event Start Date / Time	Event End Date / Time	Solar Cycle	Event Duration (days)	GME index	Official GLE No.	GME data	Band Fit
5/21/90 22:45	6/9/90 10:15	22Max	18.50	286	[47+48+49+50]	$5.83x10^6$	$6.41x10^{6\%}$
					47	$8.88x10^5$	$1.43x10^6$
					48	$1.45x10^6$	$2.35x10^6$
					49	$1.01x10^6$	$1.60x10^6$
					50	$2.48x10^6$	$1.03x10^6$
5/29/91 14:15	6/26/91 15:45	22Max	28.08	306	[51+52]	$9.05x10^6$	$8.29x10^{6\&}$
					51	$5.10x10^6$	$3.99x10^6$
					52	$3.95x10^6$	$4.30x10^6$
6/24/92 0:15	7/2/92 17:15	22Max	8.73	334	53	$2.85x10^5$	$5.37x10^5$
10/30/92 16:15	11/12/92 0:15	22Max	12.35	337	54	$6.49x10^6$	$2.77x10^6$
11/3/97 8:15	11/13/97 19:15	23Max	10.48	377	55	$2.16x10^6$	$3.62x10^6$
5/2/98 13:15	5/6/98 4:15	23Max	3.65	384	56	$3.39x10^5$	$5.97x10^5$
5/6/98 4:45	5/8/98 12:15	23Max	2.33	385	57	$7.45x10^4$	$1.57x10^5$
8/19/98 8:15	9/4/98 0:15	23Max	15.69	395	58	$3.61x10^5$	$3.86x10^5$
7/9/00 0:15	8/10/00 0:15	23Max	32.02	445	59	$2.77x10^7$	$3.39x10^7$
4/9/01 12:45	4/15/01 12:15	23Max	6.00	465	60	$1.27x10^{5*}$	$8.09x10^6$
4/15/01 12:45	4/26/01 8:15	23Max	10.83	466	61	$4.22x10^{6**}$	$1.24x10^6$
				28 SPEs	33 GLEs	32 GME data	33 Band fit

% Sum of Band fit for GLEs 47, 48, 49, and 50.

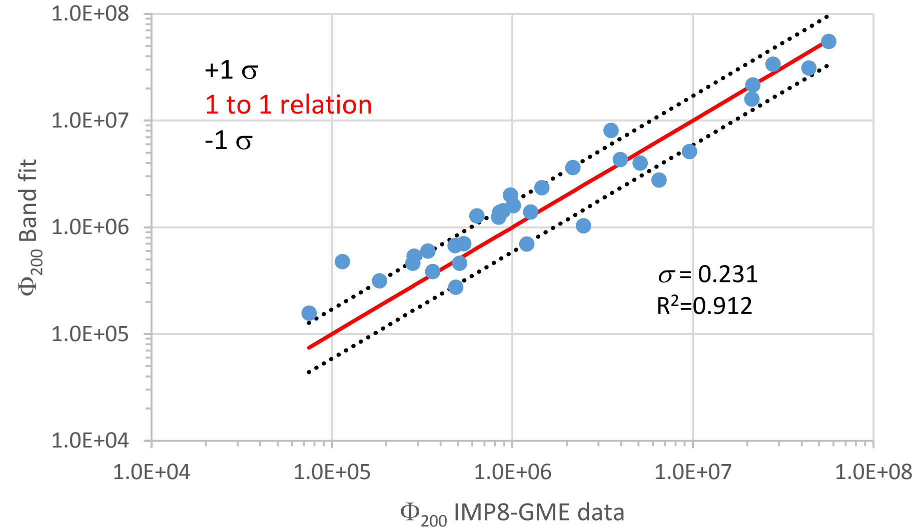
& Sum of Band fit for GLEs 51 and 52.

* GLE 60, $\Phi_{200}=3.51x10^6$ (data taken from GMEs 465 and 466 until April 17, 2001, 23:45).

** GLE 61, $\Phi_{200}=8.36x10^5$ (data taken from GME 466 starting April 18, 2001, 0:15).

SOURCE DATA OF IMP-8 GME EXPERIMENT 1973 - 2001

- A long-time series database of 479 SPEs for optimal solar proton fluxes of background interplanetary particles subtracted
- Φ_{200} GME data for 32 official GLEs comparable to Band fit
  - ➢ Good correlation (R=0.955)
  - ➢ Dispersion of data with $\pm 1\ \sigma$ error



- Φ_{200} database compiled with 32 GME data
- $\Phi_{30,60,100}$ databases updated with GME data
  → More observables of historical SPEs
- The more available historical data, the better estimation of the distribution of historical predictor (Φ_E)
  - ➢ Prediction model improved with better correlation and increased accuracy of linear approximation by taking into account of variability of spectral shape of predictor (Φ_E).
  - ➢ Estimation of unconditional probability improved for "BFO dose risk" exceeding the NASA limit

DATABASE OF Φ_E

GLEs		Φ_{30}	Φ_{60}	Φ_{100}	Φ_{200}
N	59	54	48	51	32
Data source		a-f	a-f	a-f	f

[a] King, J. H., Solar proton fluences for 1977-1983 space missions, J. Spacecraft, **11**, No. 6, pp. 401-408, June 1974.

[b] Goswami JN, McGuire RE, Reedy RC, Lal D, Jha R., J Geophys Res **93**:7195–7205; 1988.

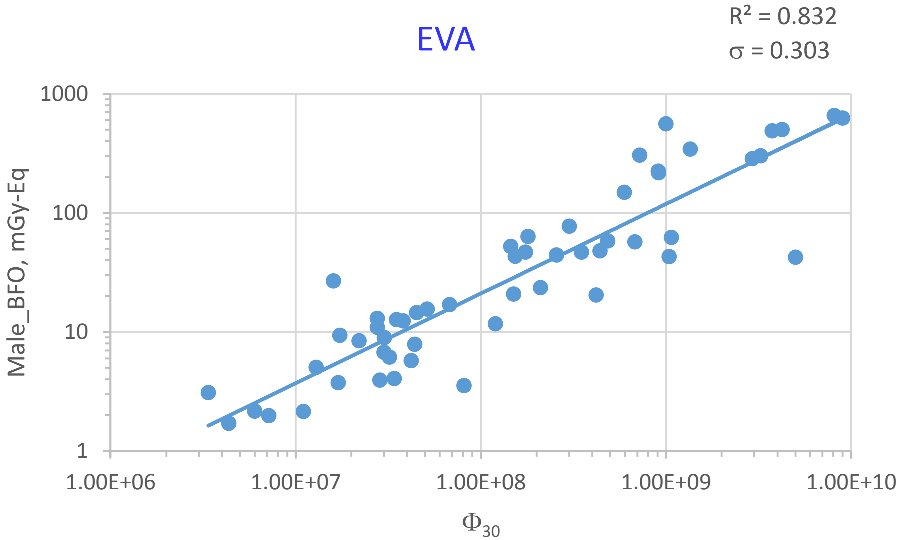
[c] Shea, M. and Smart, D., Solar Physics, **127**, pp. 297-320, 1990.

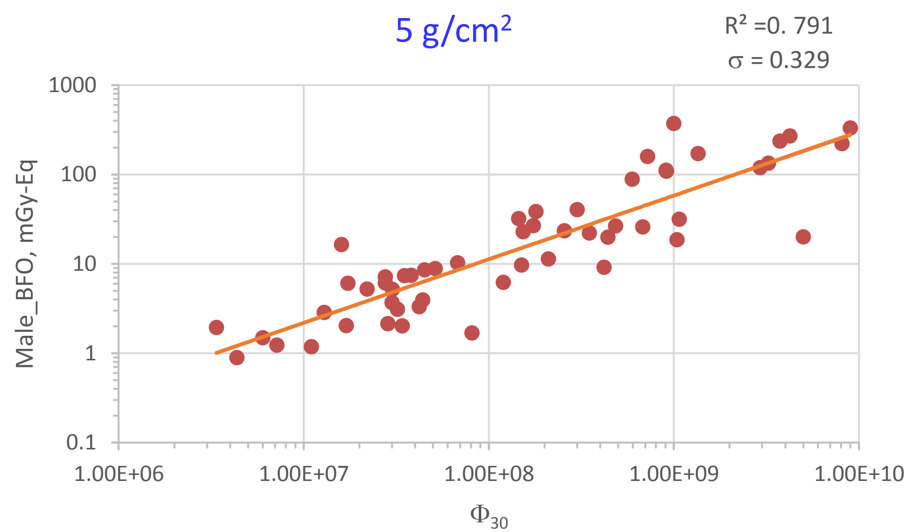
[d] Feynman, Armstrong, Dao-Gibner, and Silverman, J. Spacecraft, **27**, No. 4, pp. 403-410, July-August, 1990.

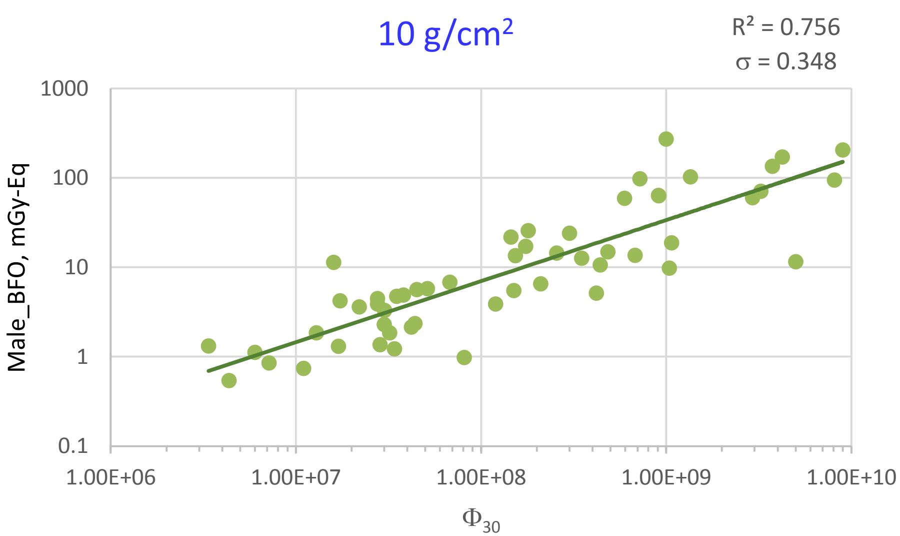
[e] GOES SEM archive: http://satdat.ngdc.noaa.gov/sem/goes/data/

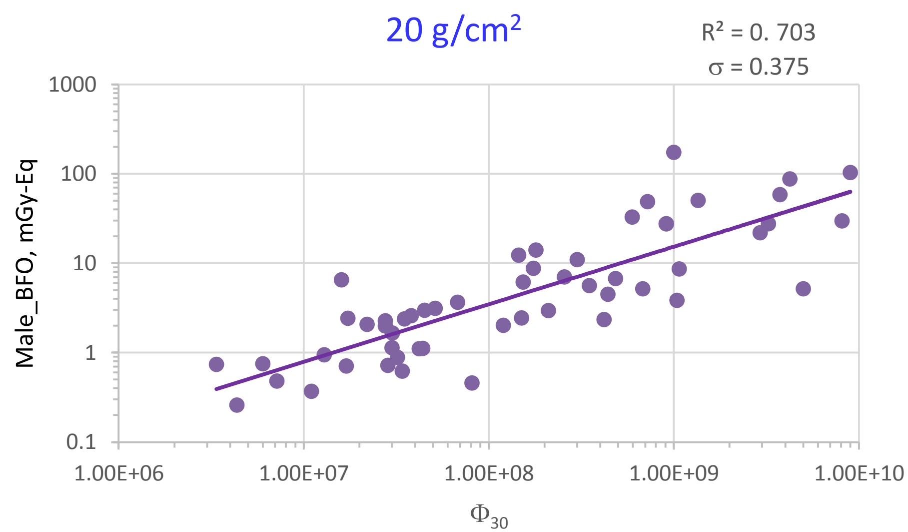
[f] Interplanetary Monitoring Platform (IMP-8) Goddard Medium Energy (GME) Experiment

DISTRIBUTION OF BFO DOSE$_{MALE}$(Φ_{30}), N=54

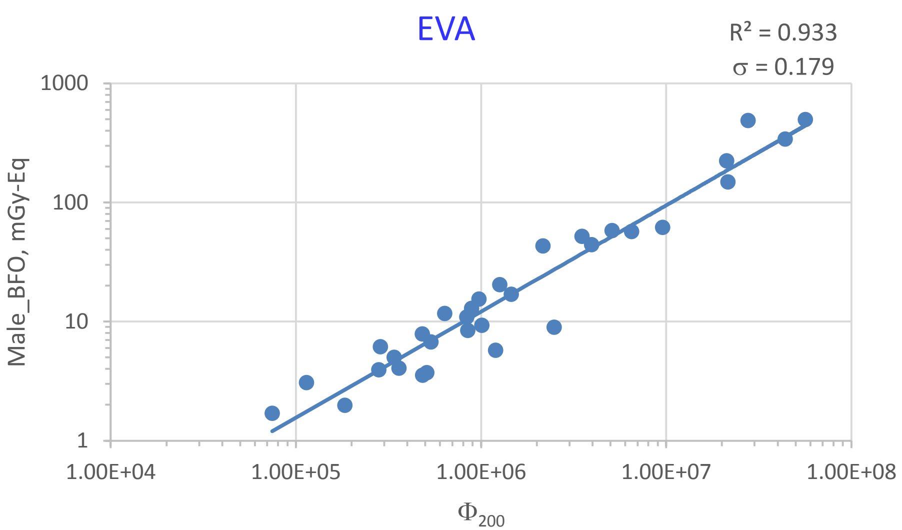


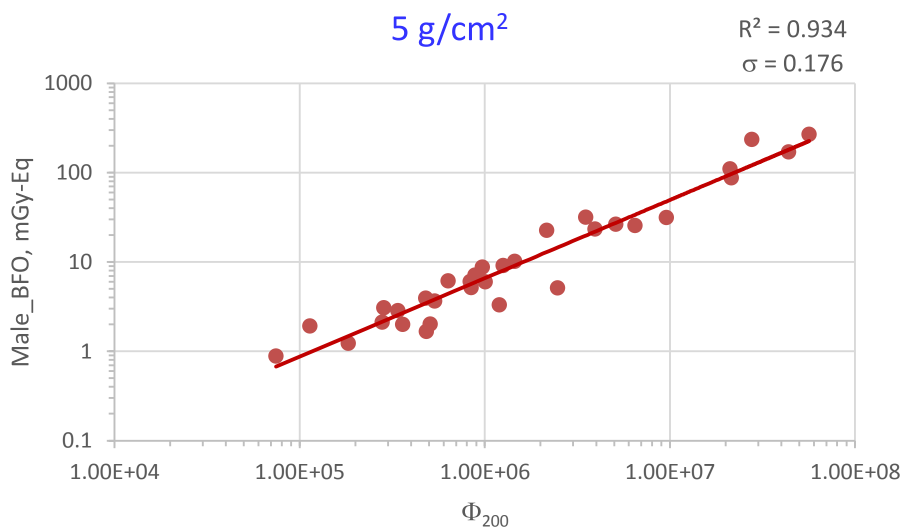


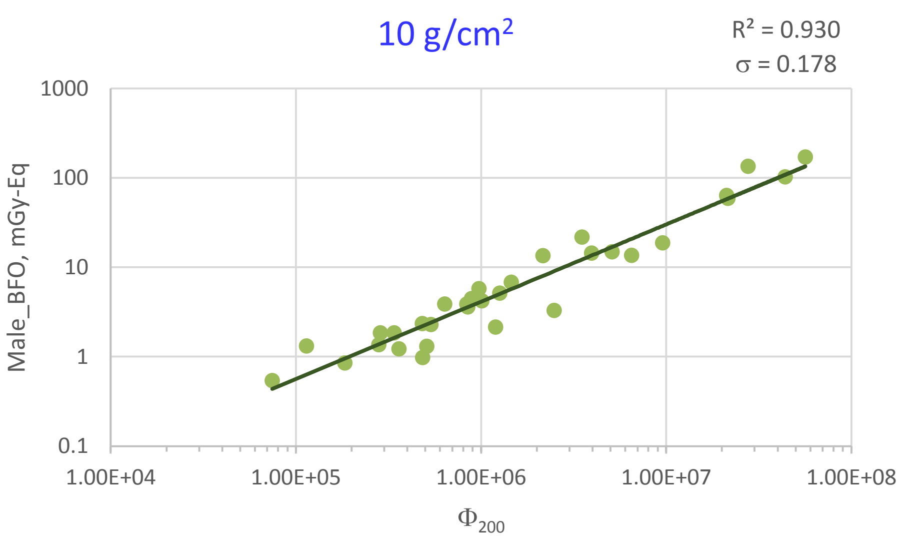


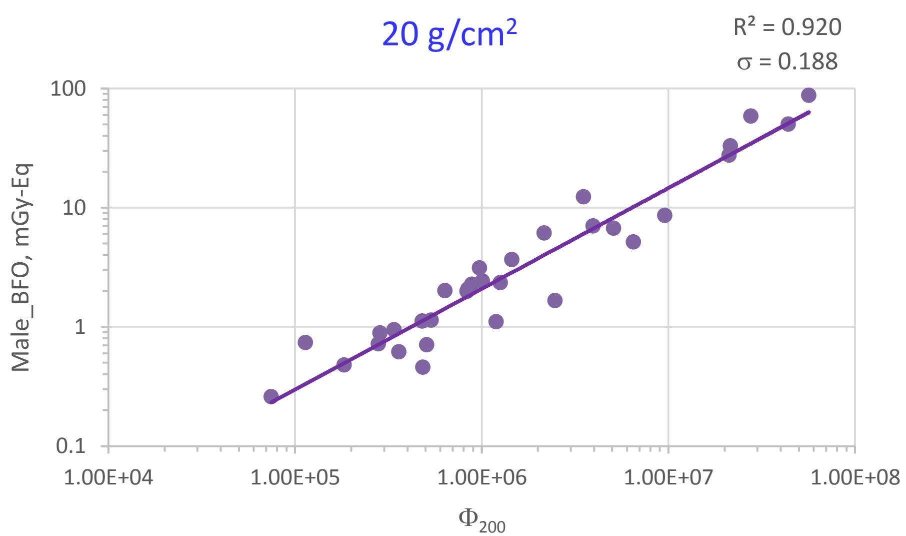


DISTRIBUTION OF BFO DOSE$_{MALE}$(Φ_{200}), N=32



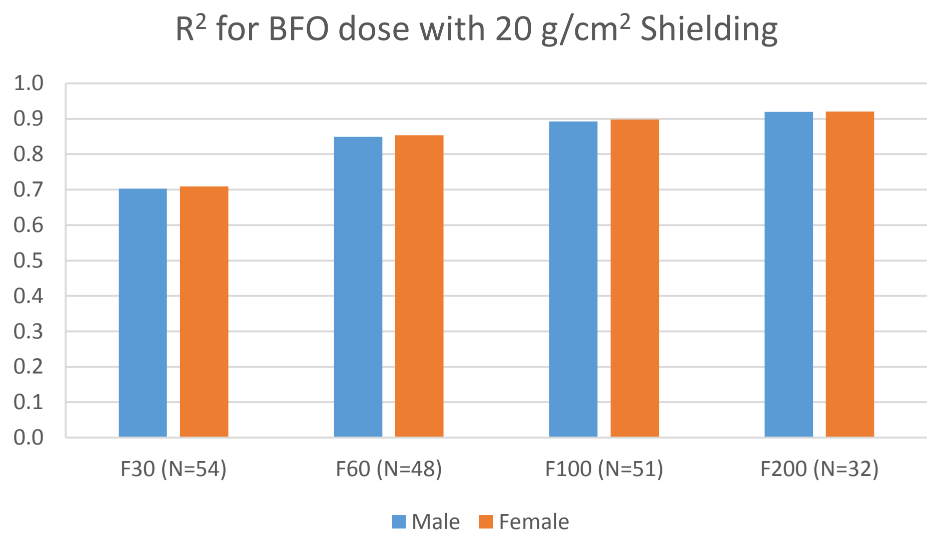


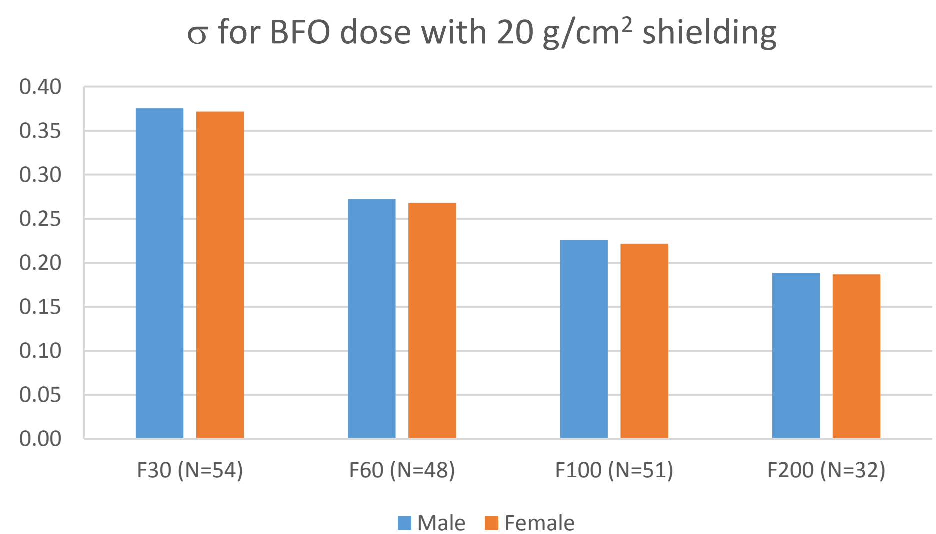




REGRESSION MODELS

- Regression model improved by higher proton energy threshold (Φ_{30} to Φ_{60} to Φ_{100} to Φ_{200} regardless of size, N:
  As *E* increased,
  - ❖ R^2 increased → Better correlation through data points
  - ❖ σ decreased → Increased accuracy of linear approximation (taking into account the probability distribution of energy spectrum $\Phi_{0<E<\infty}$)
- Overall prediction improved as the energy threshold increases:
  BFO dose determined more by protons with higher energies than lower energies
- Exposure to extreme SPEs (GLE or sub-GLE):
  BFO dose determined by far the most weight by protons above 200 MeV





RISK ASSESSMENT FOR FUTURE SPEs

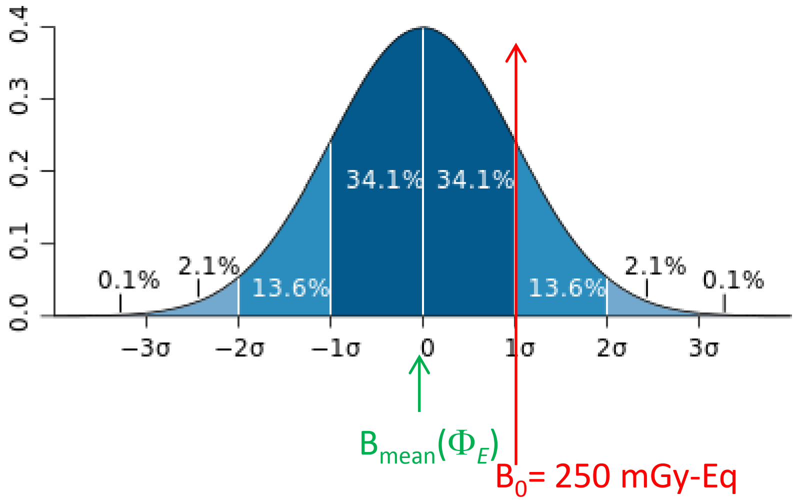
- Not feasible to model the probability distribution of complete energy spectra $\Phi(E)$ $(0 < E < \infty)$ for future SPEs
- Practical alternate to accurate assessment of radiation risk from SPEs:
  Risk approximation based on measurements at high energies of protons having the most weight in the dose calculation for deep-seated organs (Φ_{30}, Φ_{60}, Φ_{100}, Φ_{200}) for an unspecified future SPE with spectral shape variability of historical SPEs

$$\log_{10} R(\Phi_E) = \beta_{0E} + \beta_{1E} \log_{10} \Phi_E + u_E$$

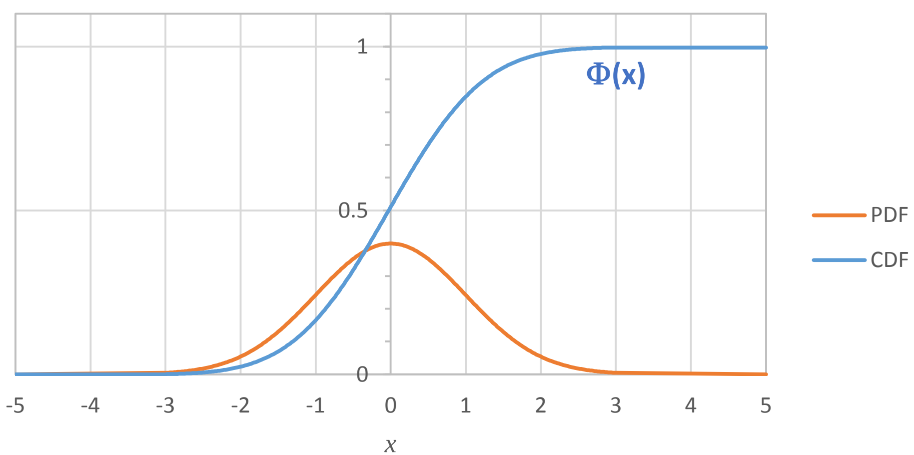
where $u_E = N(0, \sigma^2)$

normally distributed random error term with zero mean and variance σ^2

PARTIAL INFORMATION OF Φ_E AND RANDOM VARIATION OF THE REST ENERGY SPECTRUM OF FUTURE SPE



$u_E \sim N(0,\sigma_E{}^2)$



- Normally distributed error term around the BFO dose approximation based on the predictor (Φ_E), attributable to variability of spectra of SPEs:

  $u_E \sim N(0,\sigma_E{}^2)$

- Error function is related to the CDF:

  $\Phi(x)=\frac{1}{2}\left[1+\mathrm{erf}\left(\frac{x-\mu}{\sigma\sqrt{2}}\right)\right]$

- Evaluation of error function at $z=\frac{x}{\sigma\sqrt{2}}$

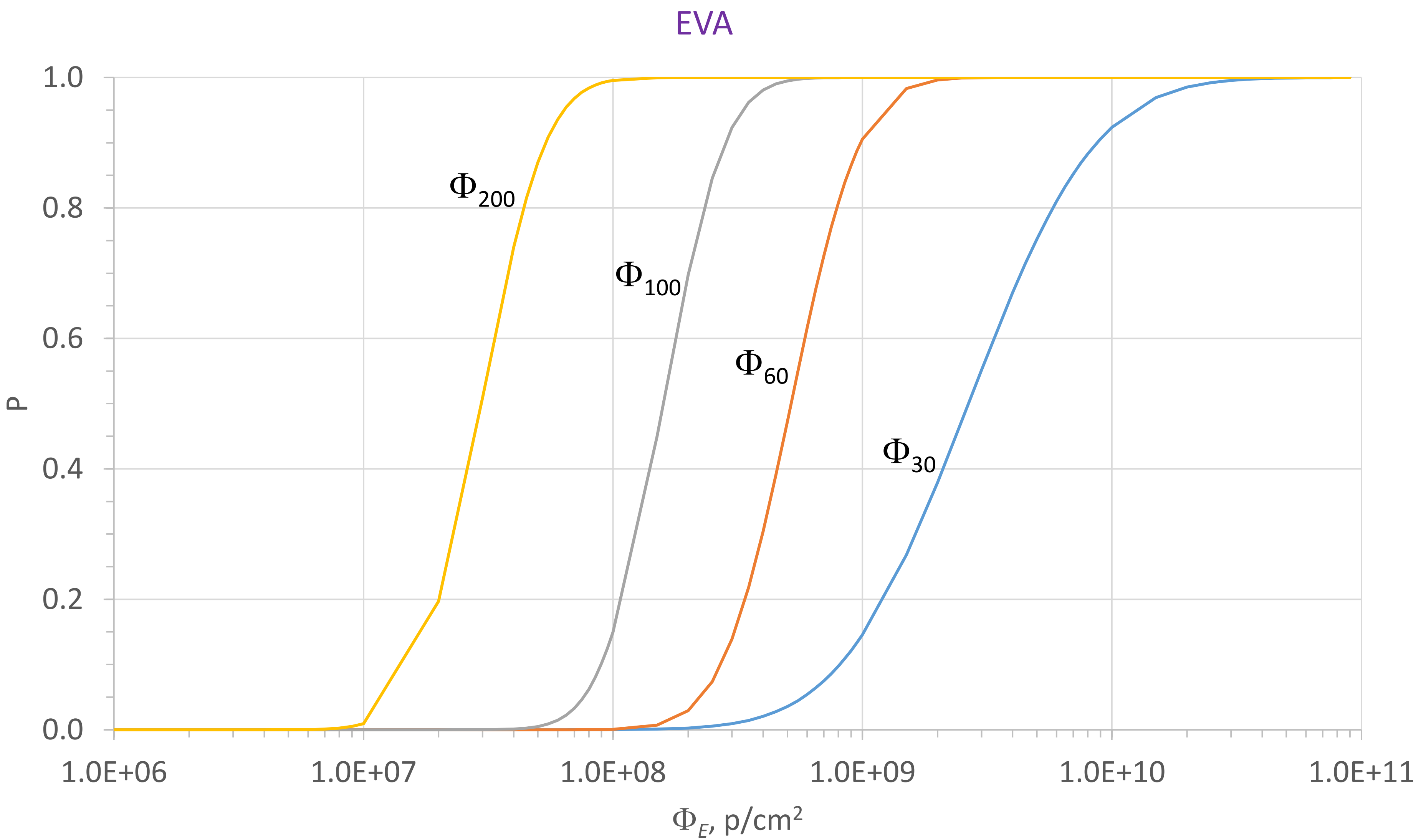
  $\mathrm{erf}(z)=\frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$

  → the probability having a distance less than the number of standard deviation , x

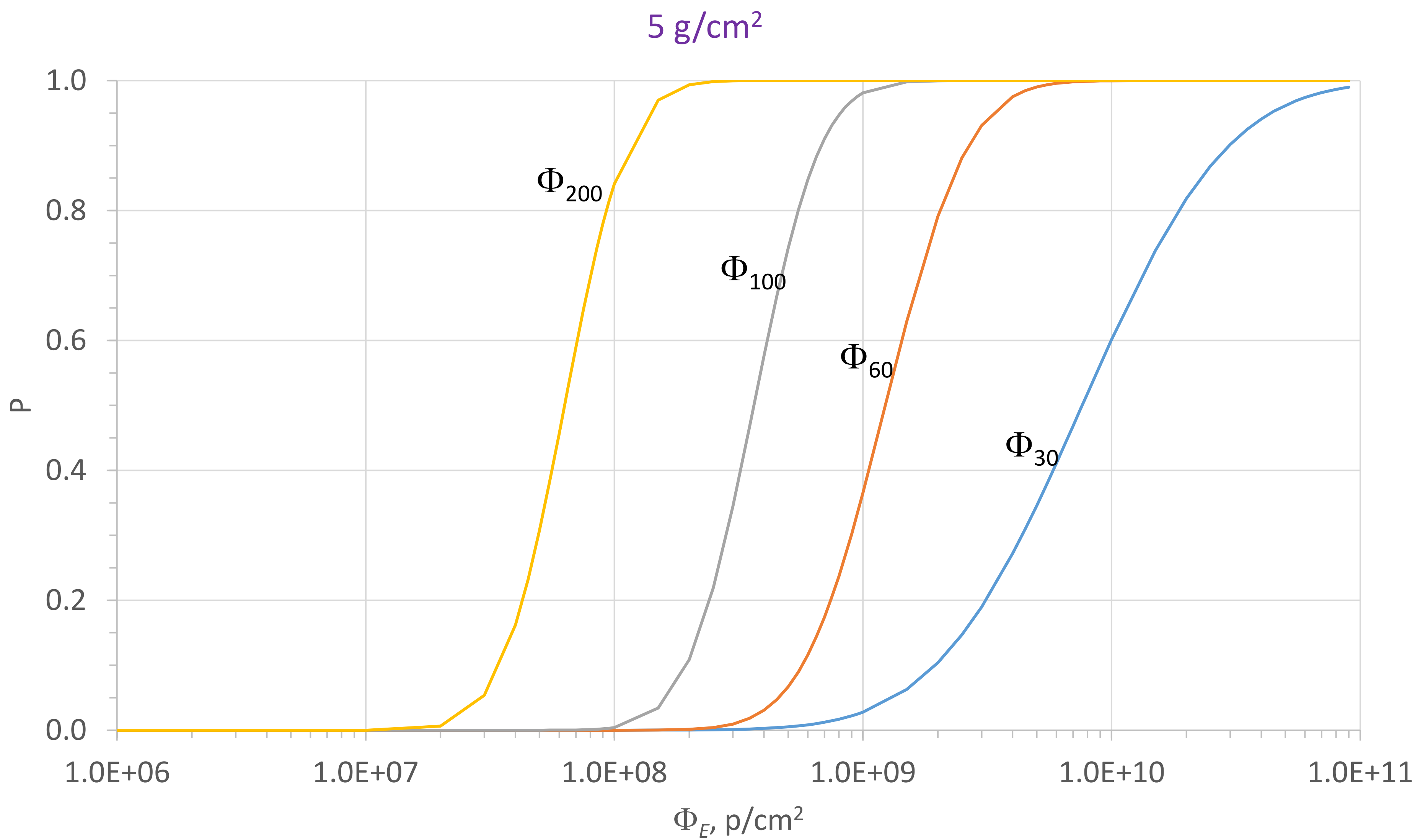
- Unconditional probability of "BFO dose risk":

  $P(BFO\ dose > B_0)=\frac{1.0-\mathrm{erf}(z)}{2}$

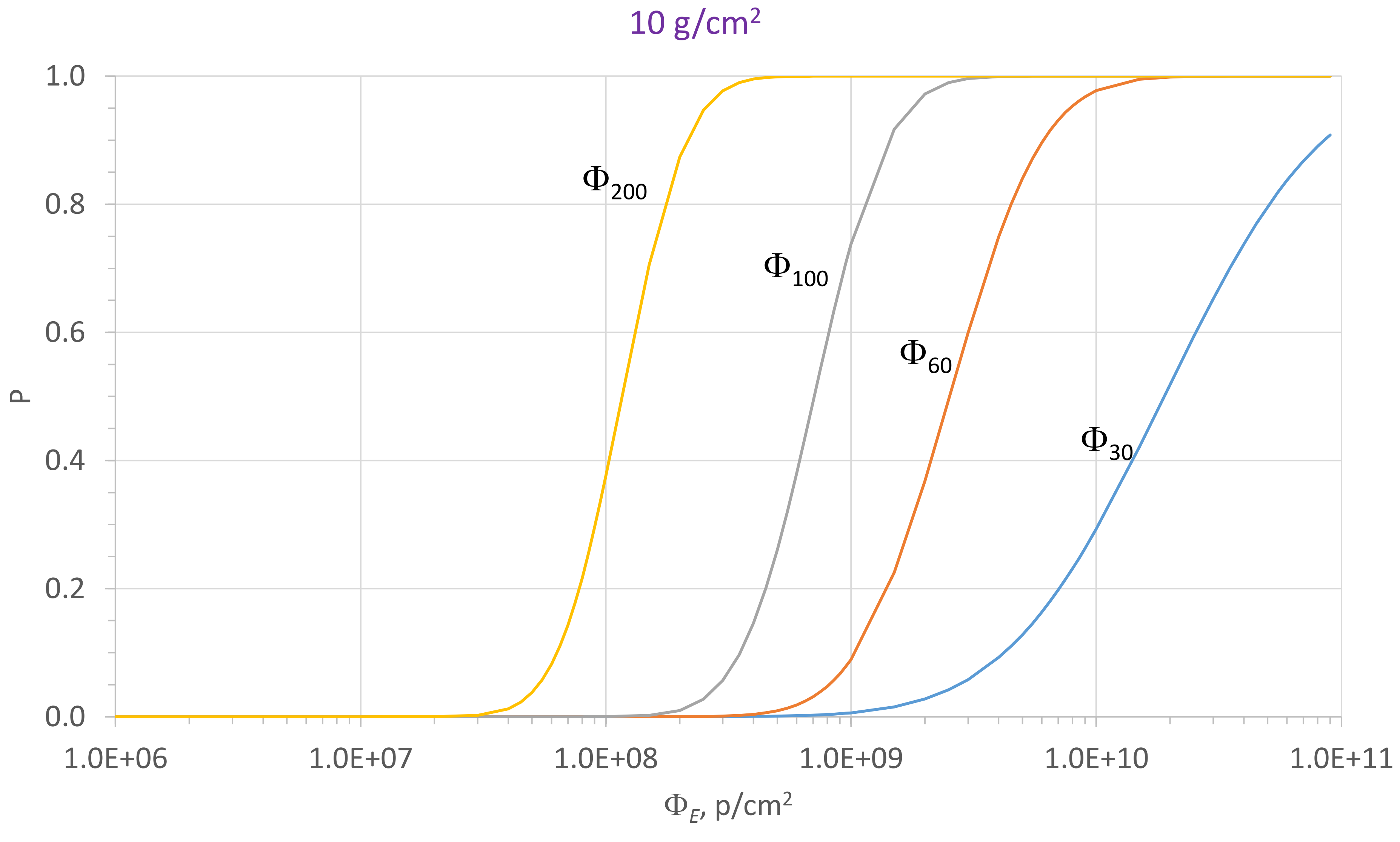
UNCONDITIONAL PROBABILITY OF BFO DOSE RISK FOR MALE



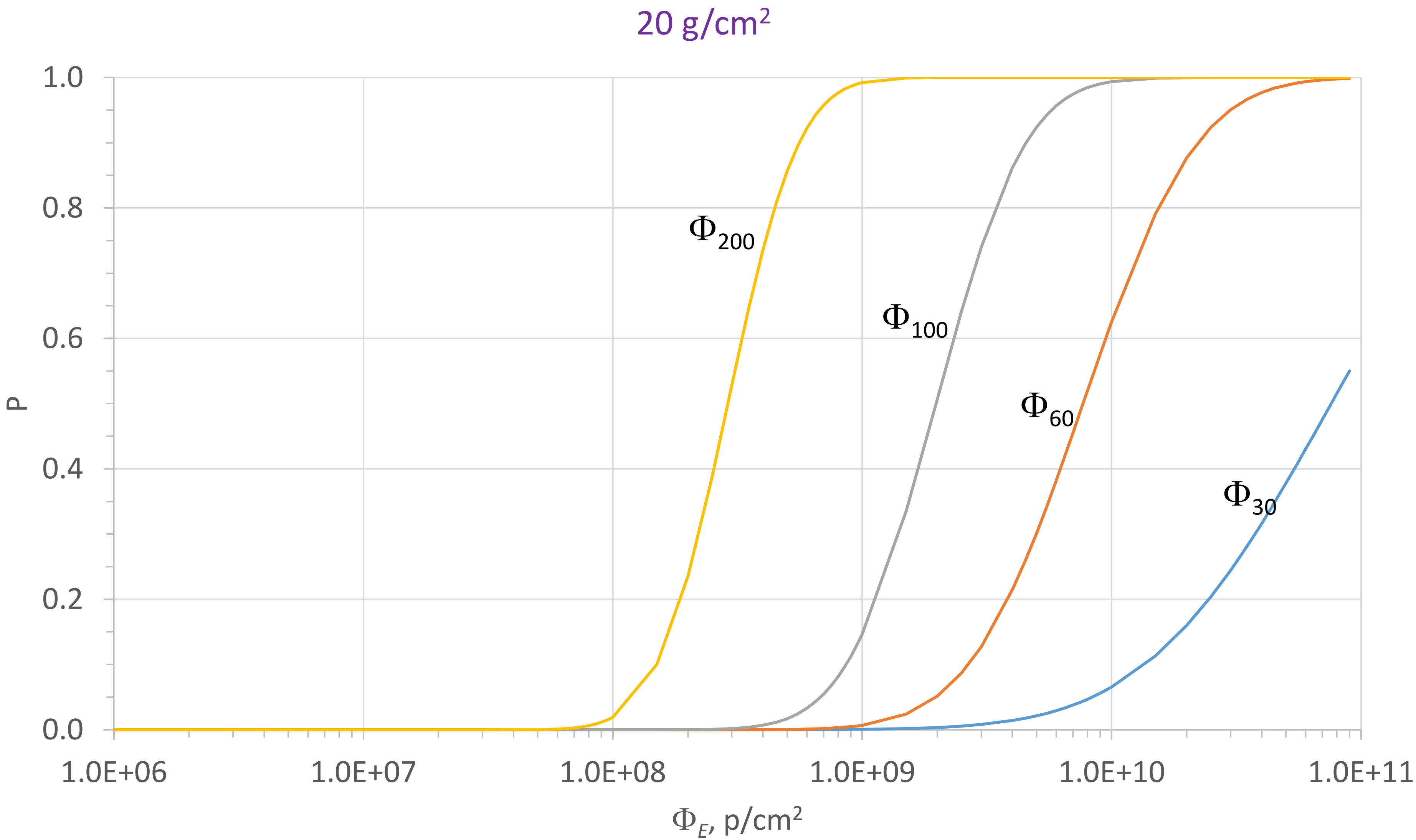
UNCONDITIONAL PROBABILITY OF BFO DOSE RISK FOR MALE



UNCONDITIONAL PROBABILITY OF BFO DOSE RISK FOR MALE

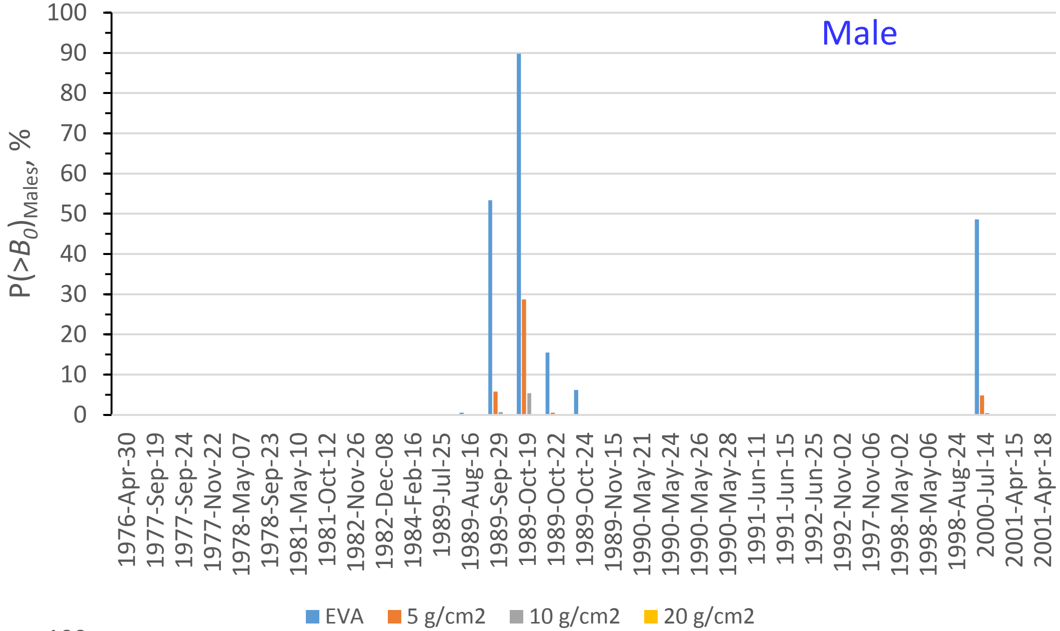


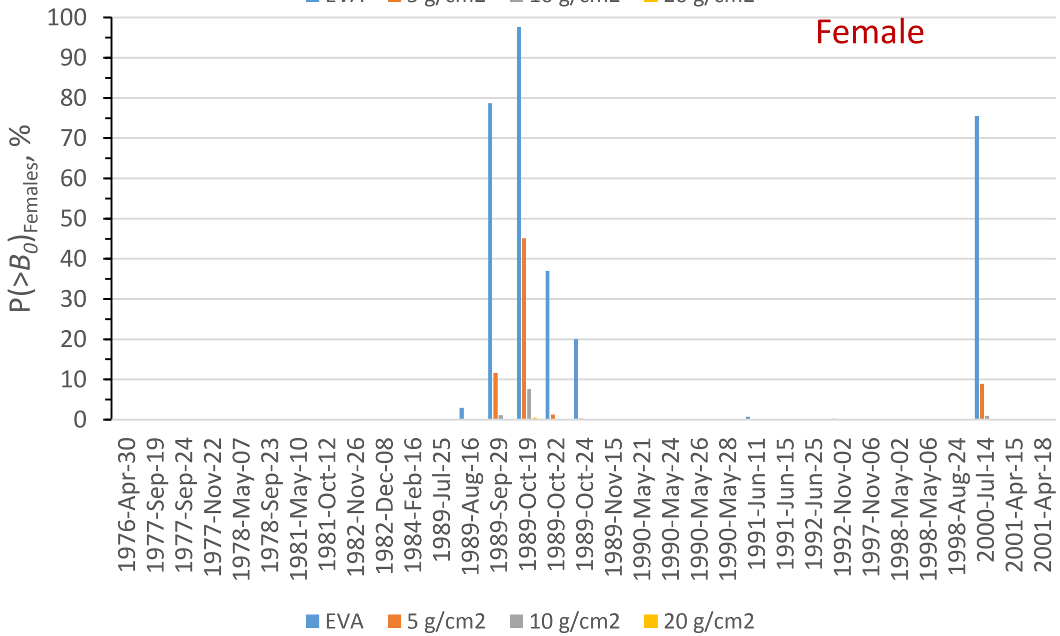
UNCONDITIONAL PROBABILITY OF BFO DOSE RISK FOR MALE



EVALUATION OF EXPOSURE LEVELS USING IMP-8 GME DATA

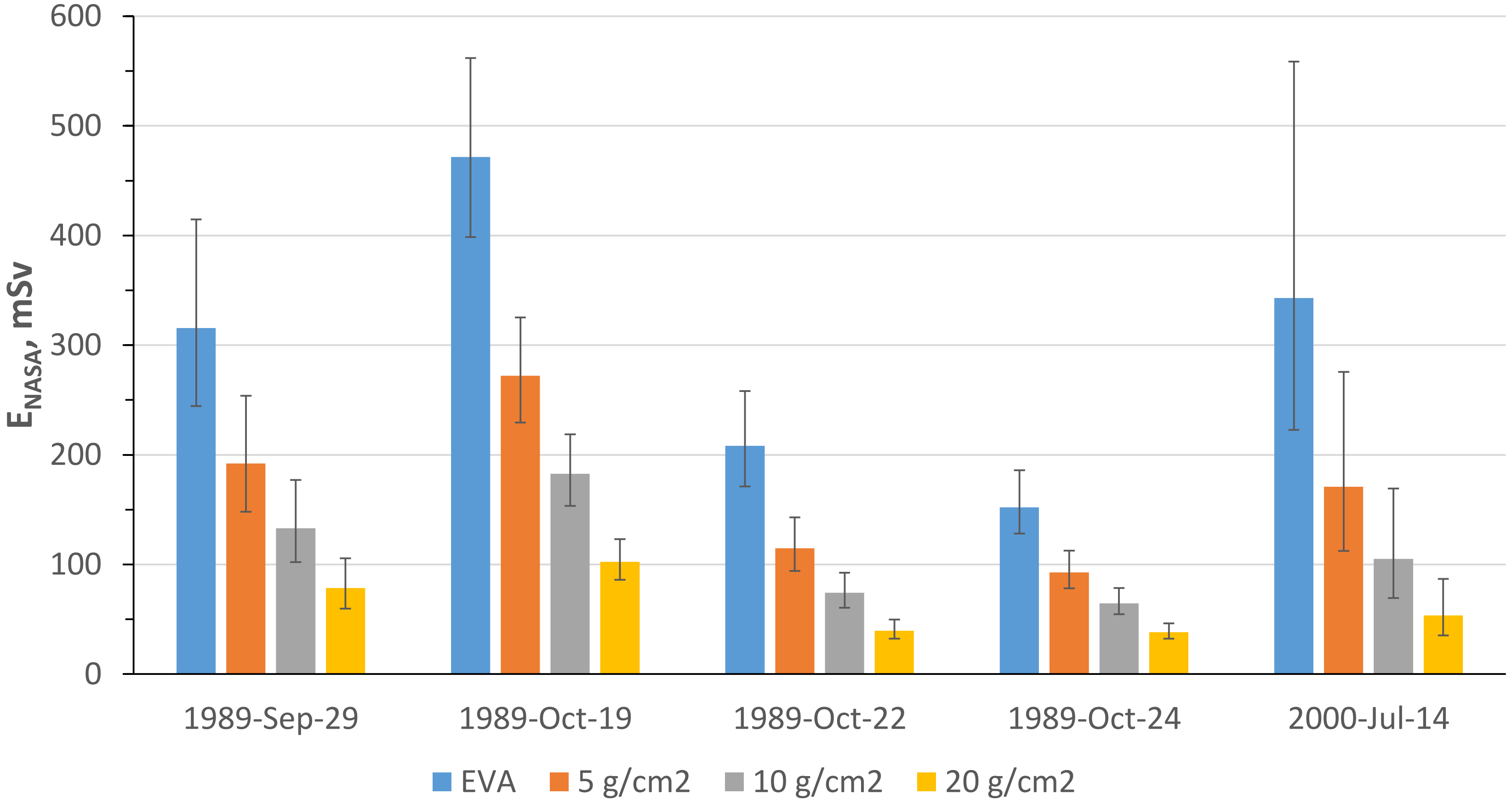
$P(> B_0)$ OF 33 GLEs BASED ON IMP-8 GME Φ_{100}



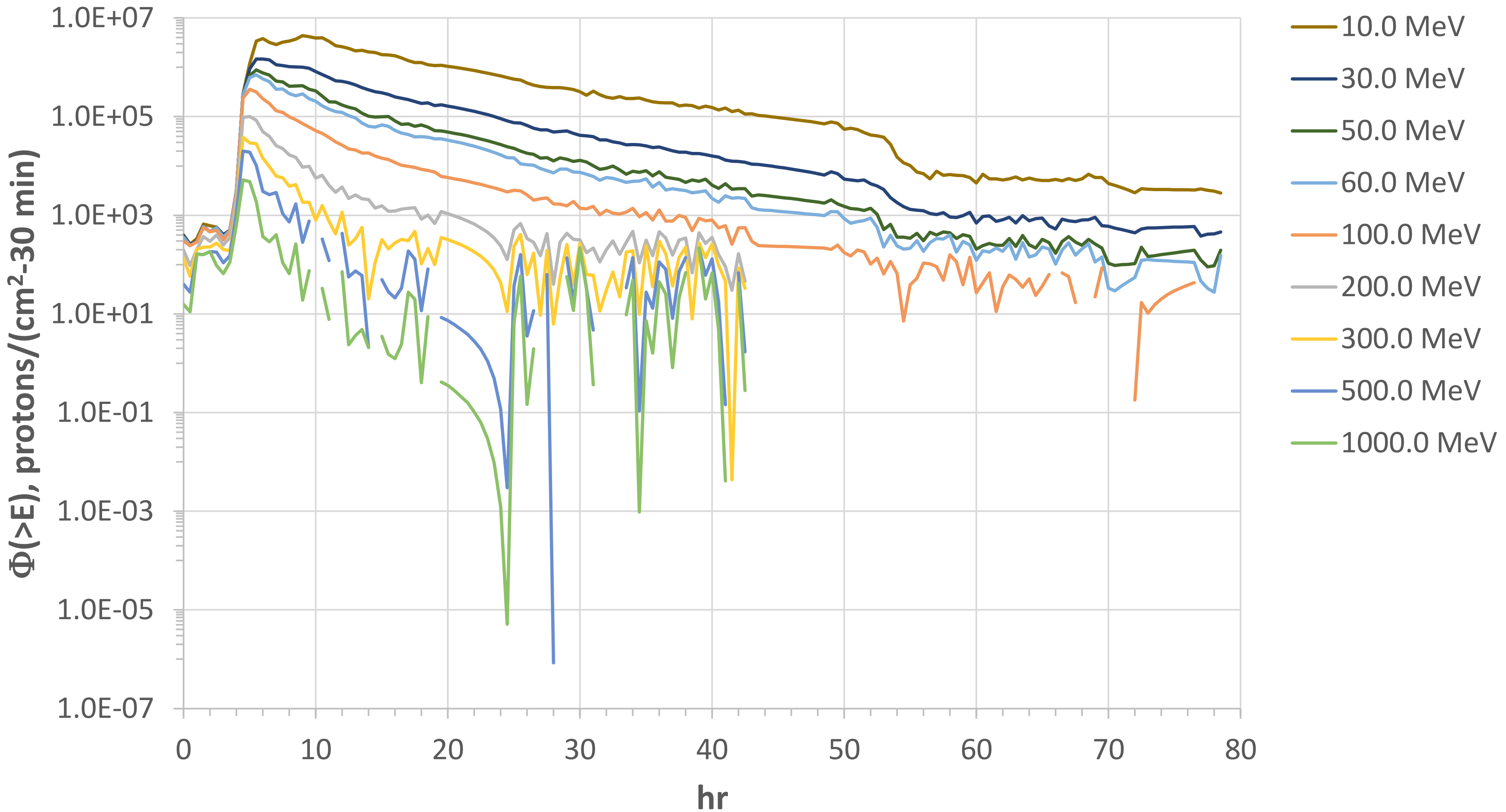


- Most GLEs to small crew doses with near-zero probability of exceeding the NASA 30-d limit
- SPEs concerned to fulfill ALARA and career limit
- 5 outstanding GLEs would lead to significant health risks without proper shielding
  1989-Sep-29
  1989-Oct-19
  1989-Oct-22
  1989-Oct-24
  2000-Jul-14
- Once per 10 years occurrence probability for the fluence to the magnitude of these individual GLE assessed by cumulative occurrence probability density function for space era (Usoskin *et al*. 2012; Kovaltsov *et al*. 2014)

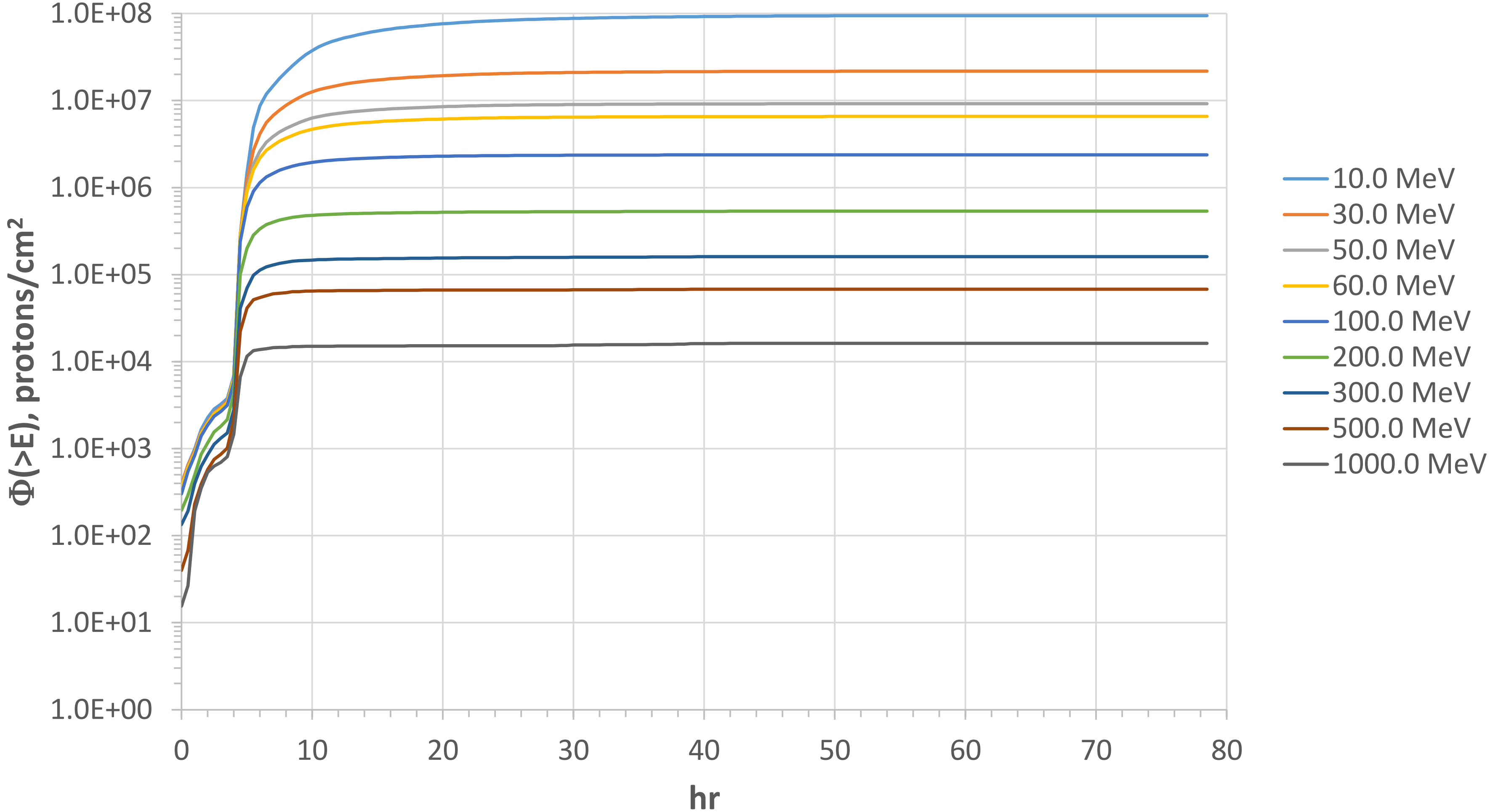
NASA EFFECTIVE DOSE FOR MALE MEDIAN WITH 90% TOLERANCE LIMITS



SOLAR PROTON FLUENCE AT 30-MIN RESOLUTION OF IMP-8 GME DATA
FROM THE ONSET OF 4/30/1976 17:15

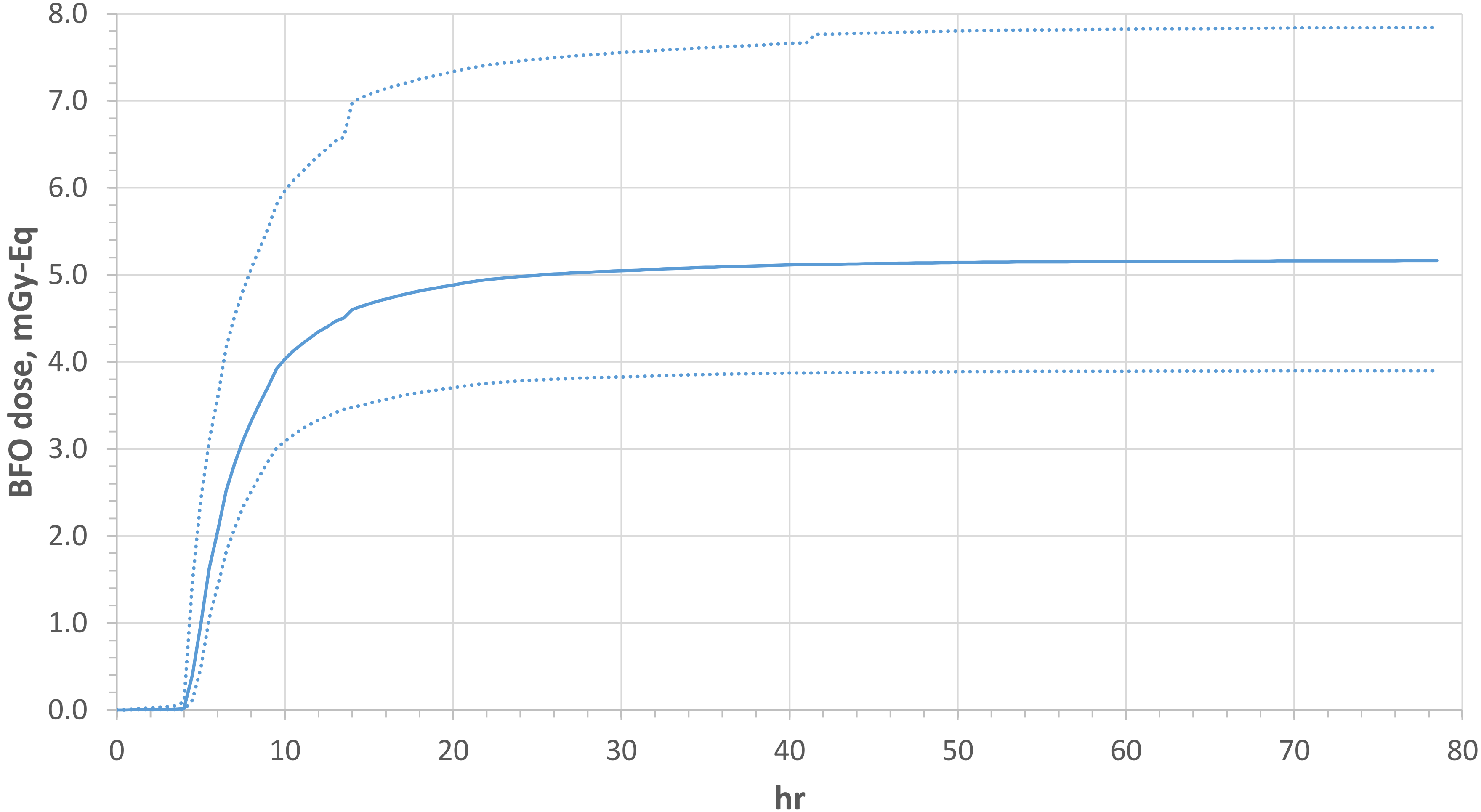


ACCUMULATED SOLAR PROTON FLUENCE
IMP-8 GME DATA
FROM THE ONSET OF 4/30/1976 17:15

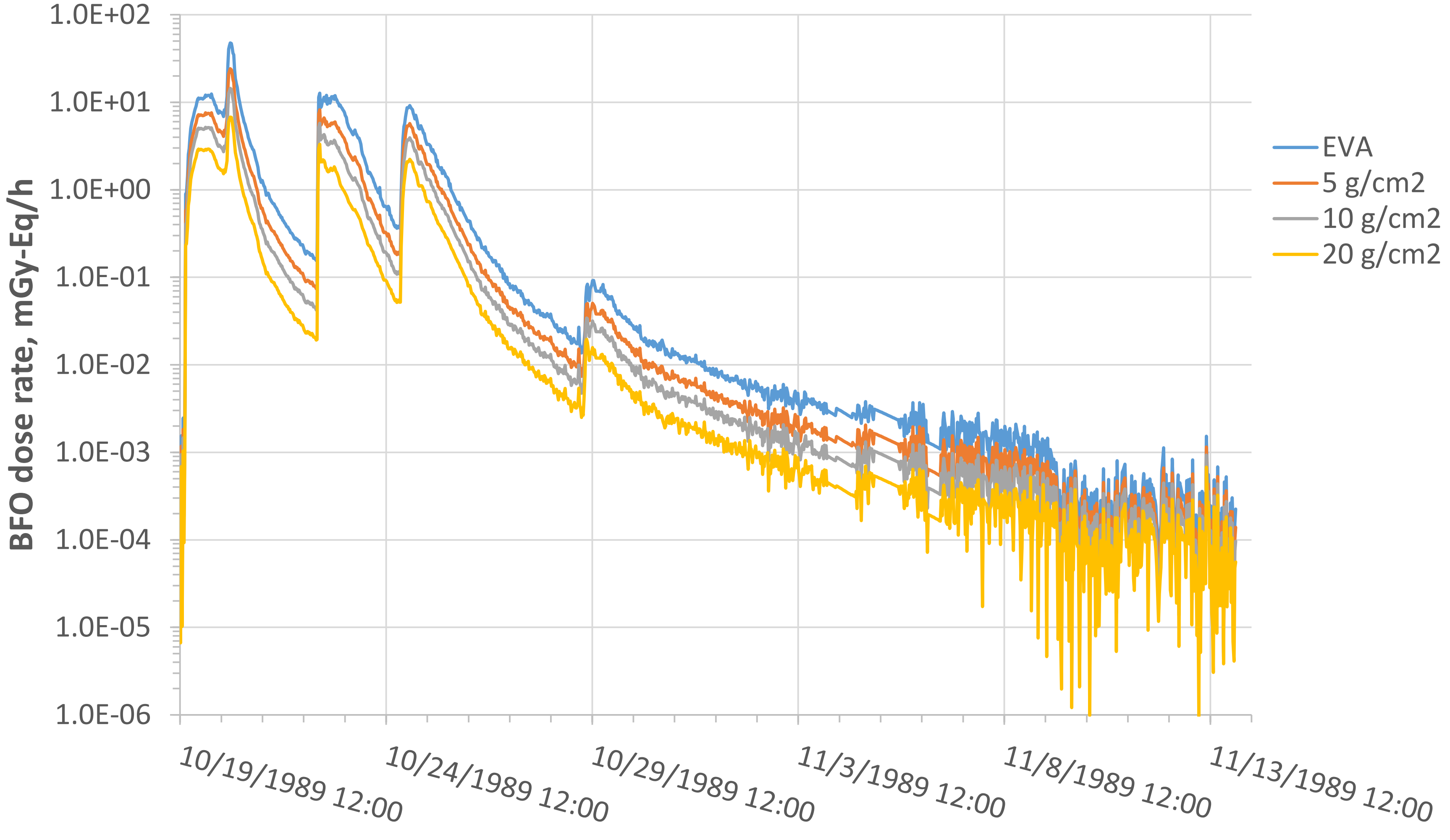


ACCUMULATED BFO DOSE FROM THE ONSET OF 4/30/1976 17:15

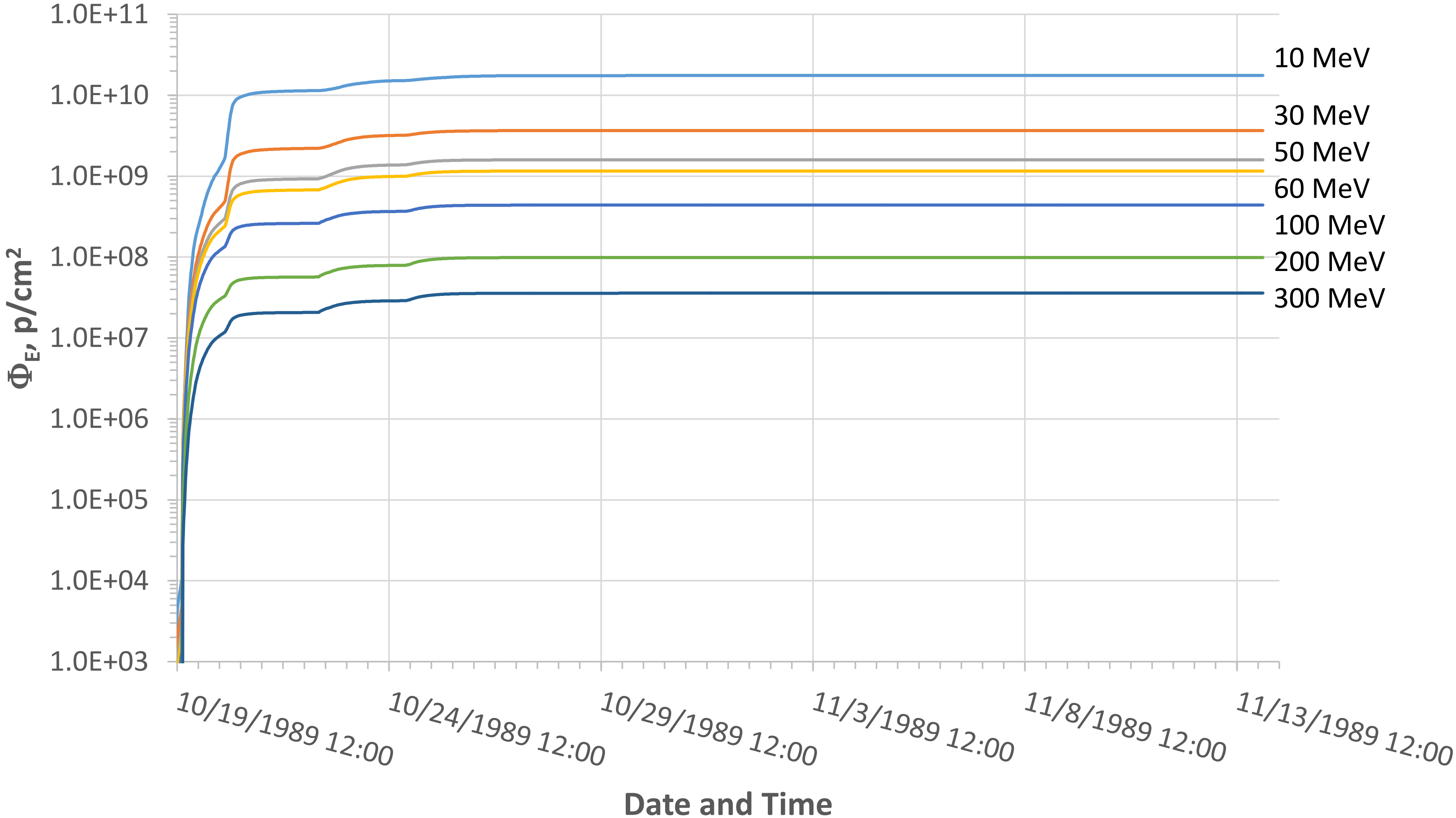
MEDIAN WITH 90% TOLERANCE LIMITS FOR MALE DURING EVA



BFO DOSE RATE FOR MALE IMP-8 GME DATA 10/19/1989 10:15 – 11/14/1989 0:15



ACCUMULATED SOLAR PROTON FLUENCE IMP-8 GME DATA 10/19/1989 10:15 – 11/14/1989 0:15



P(> B_0) BASED ON Φ_{100} IMP-8 GME DATA FOR 26 DAYS FROM THE ONSET OF OCT 19, 1989 10:15