Pillars of Creation
http://hubblesite.org/newscenter/archive/releases/2015/01/image/c/warn/

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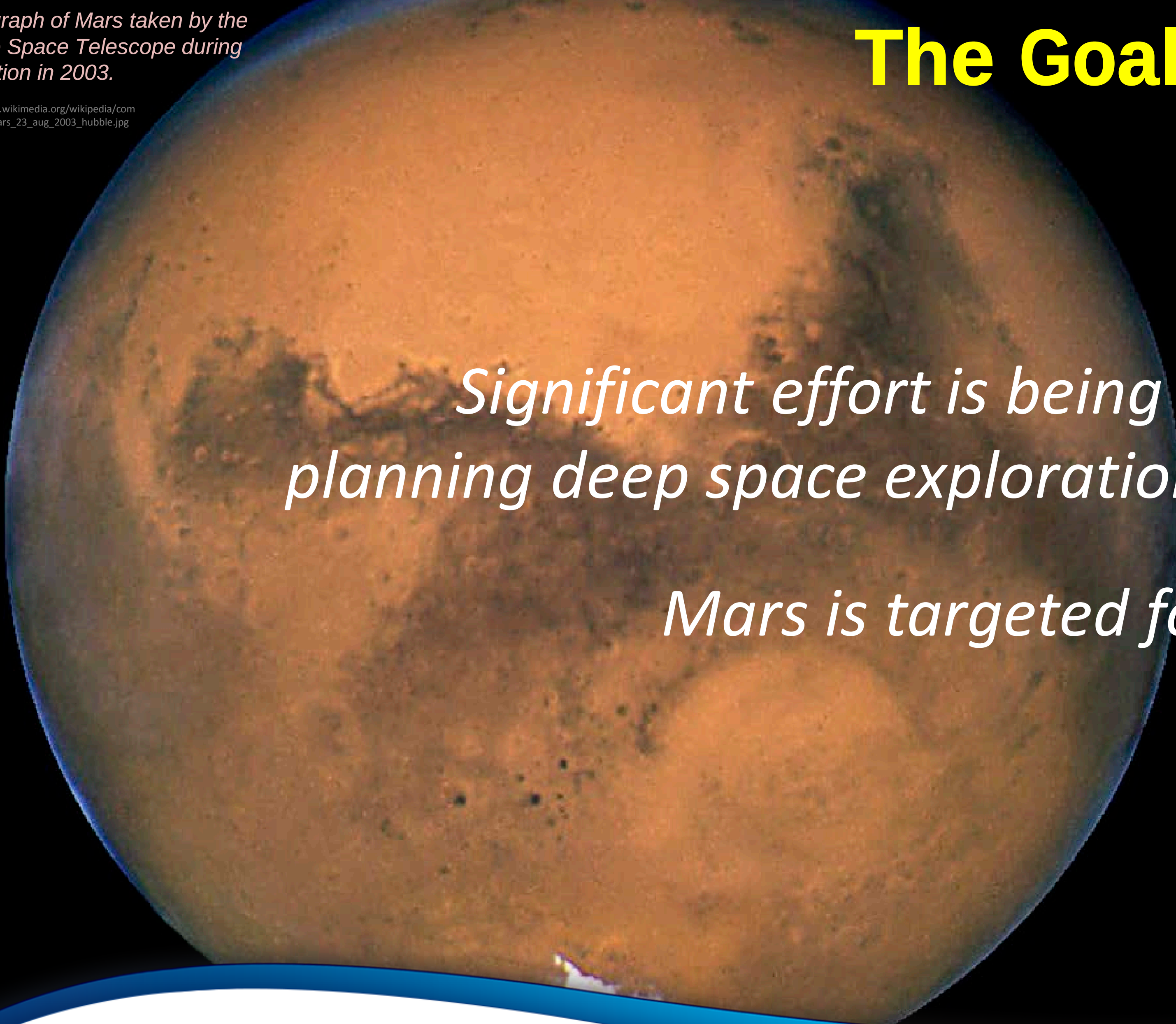
A generalized approach for modelling deep space radiation exposures

21st Workshop on Monitoring for the International Space Station
ESTEC, Noordwijk, Netherlands
September 6 - 8th, 2016

Canadian Nuclear Laboratories | Laboratoires Nucléaires Canadiens

The Goal is Mars!



Photograph of Mars taken by the Hubble Space Telescope during opposition in 2003.

https://upload.wikimedia.org/wikipedia/commons/5/58/Mars_23_aug_2003_hubble.jpg

Significant effort is being devoted to planning deep space exploration missions.

Mars is targeted for ~2030's!

First, the Moon!

To get to Mars, we must return to the Moon…

Mars is 6 months away, the Moon is less than 3 days!

The Moon is easier to plan for (no atmosphere, no magnetic field, and we've already been there)

The Moon will act as a proving ground for technologies needed to make it to Mars.

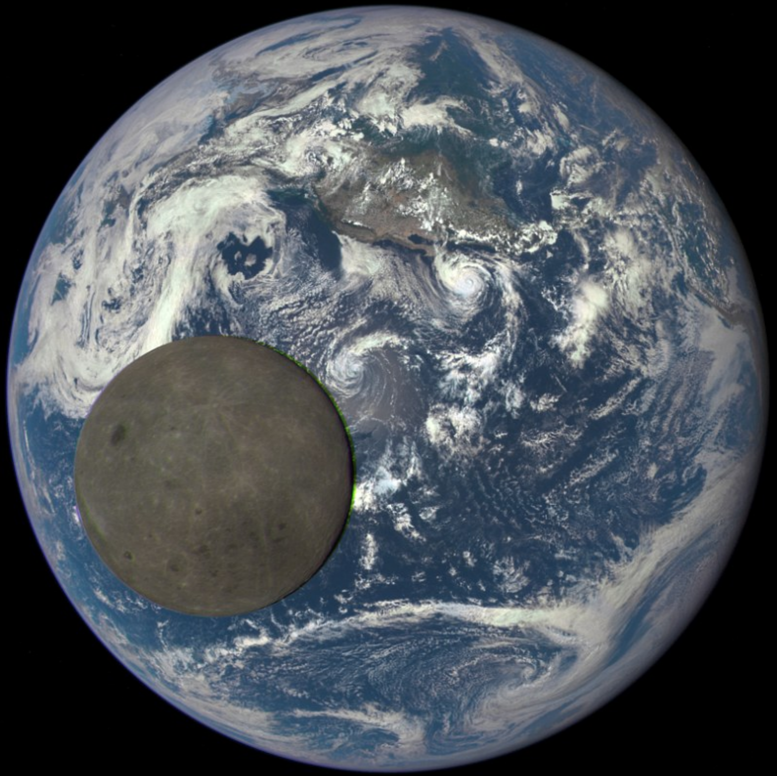


Image captured by NASA's Earth Polychromatic Imaging Camera (EPIC) on the DSCOVR satellite orbiting 1 million miles from Earth.

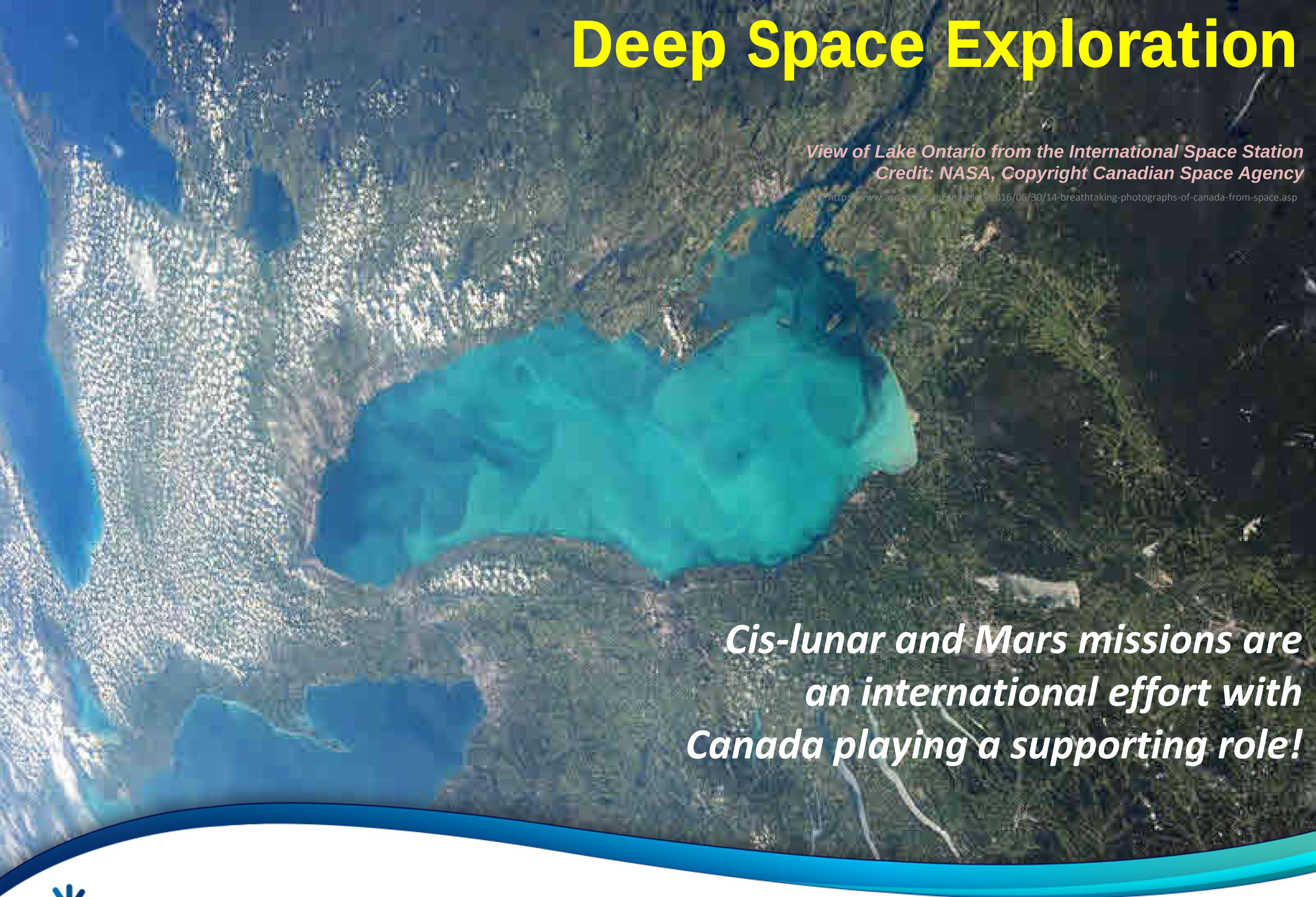
When do we go?

The Moon is targeted for the 2020's. Not too far away!

Saturn V boosters lift the Apollo 11 astronauts toward the moon, July 16, 1969.

http://time.com/3880305/apollo-11-photos-of-what-liftoff-looked-like/

Deep Space Exploration



View of Lake Ontario from the International Space Station
Credit: NASA, Copyright Canadian Space Agency
http://www.asc-csa.gc.ca/eng/blog/2016/06/30/14-breathtaking-photographs-of-canada-from-space.asp

Cis-lunar and Mars missions are an international effort with Canada playing a supporting role!

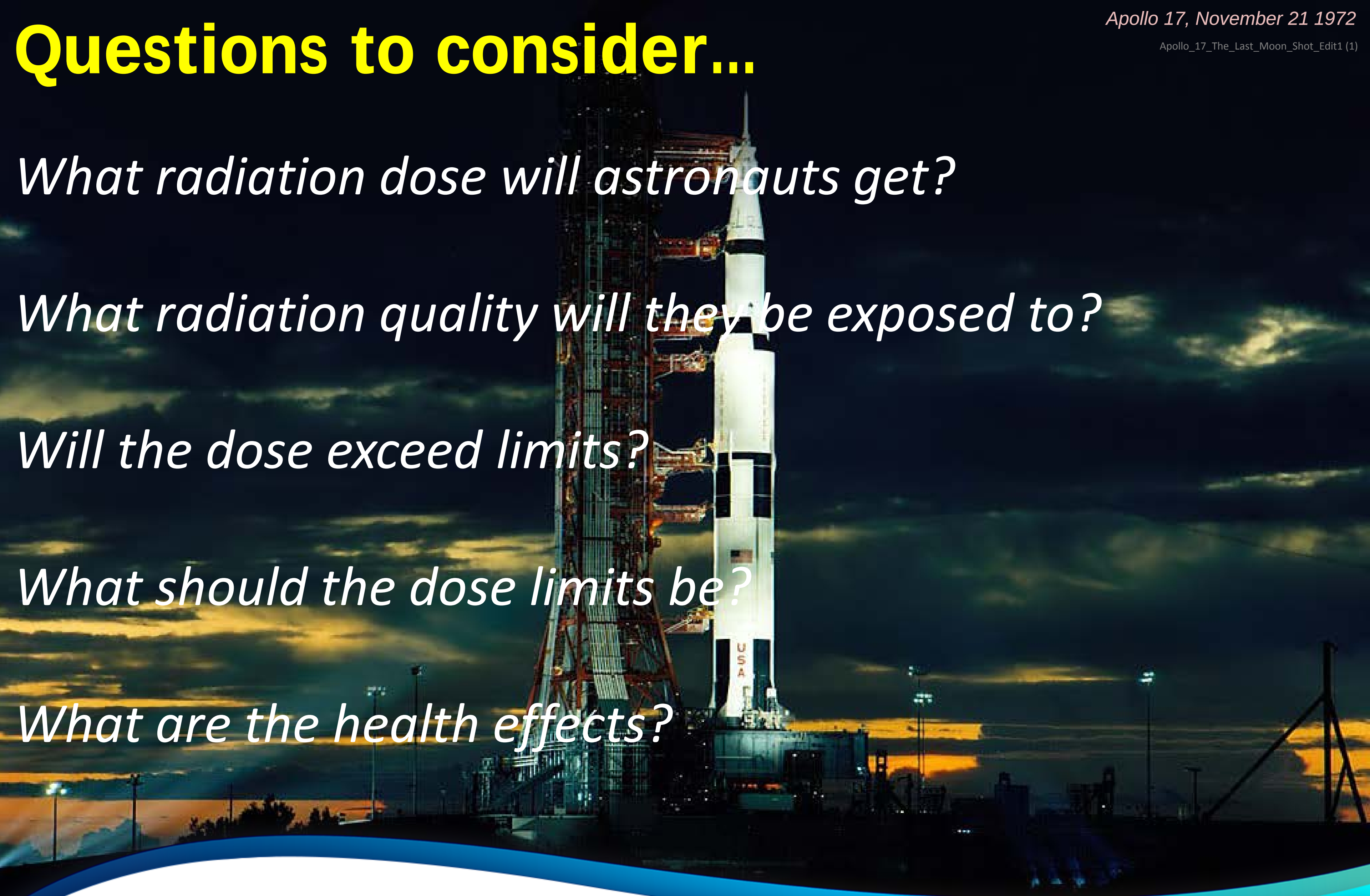
But... can we go?!?!

Canadian Space Agency astronaut Chris Hadfield making one of the first spacewalks by a Canadian during the STS-100 mission in 2001

http://spaceflight.nasa.gov/gallery/images/shuttle/sts-100/html/sts100-395-032.html

Health effects from space radiation are a serious concern.

Questions to consider...



Apollo 17, November 21 1972

Apollo_17_The_Last_Moon_Shot_Edit1 (1)

What radiation dose will astronauts get?

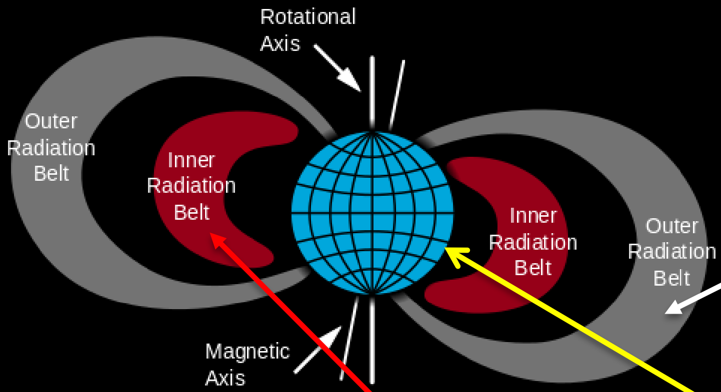
What radiation quality will they be exposed to?

Will the dose exceed limits?

What should the dose limits be?

What are the health effects?

Shoot for the Moon!



High energy electrons from 2.8 to 12R_E

High energy protons from 200 km up to 2.4 Earth radii (R_E = 6371 km)

~60R_E

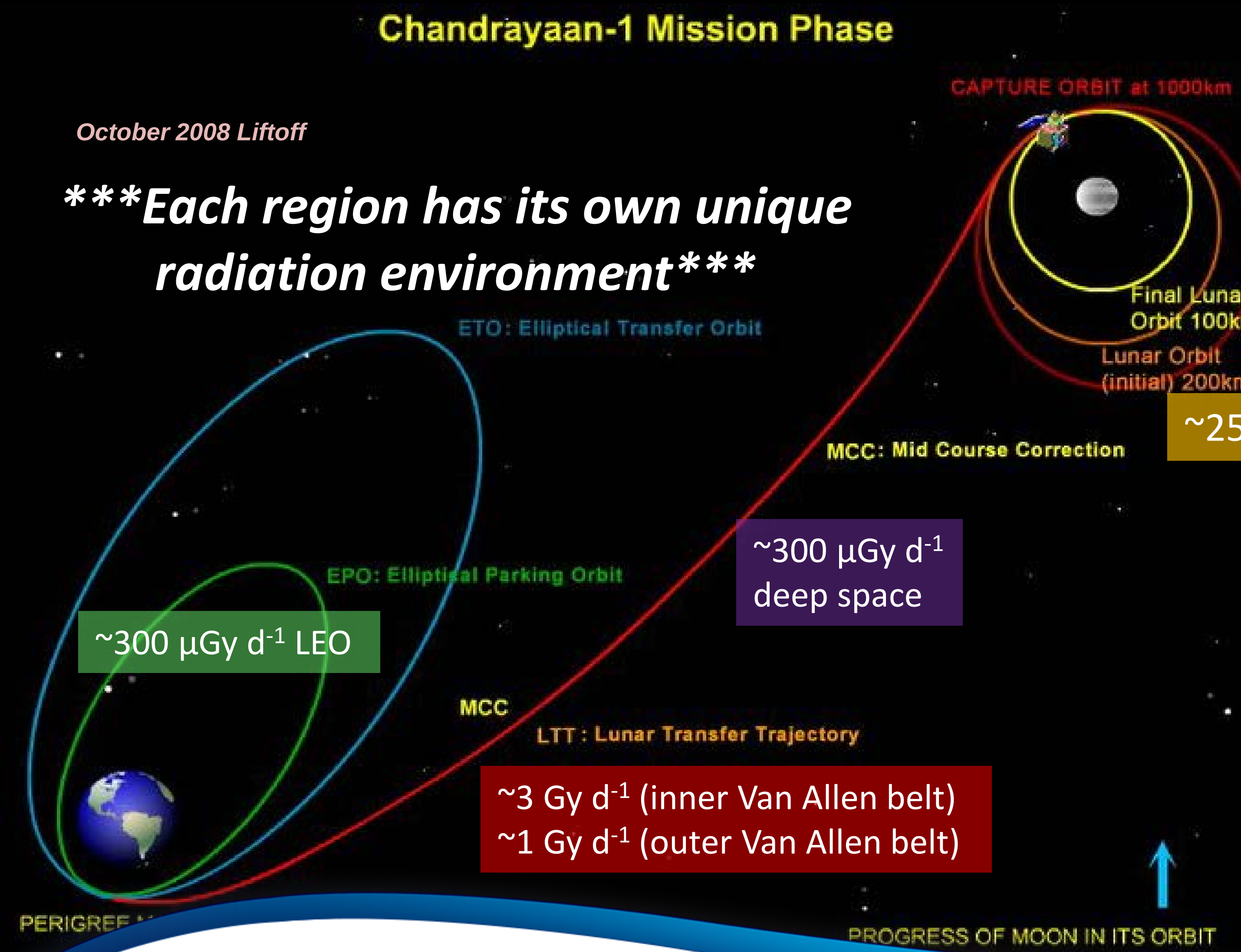
The region between Earth and the Moon dominated by galactic cosmic radiation and solar particle events (if they occur).

T. Dachev, B. T. Tomov, Y. N. Matviichuk, P. S. Dimitrov, S. V. Vadawale, J. N. Goswami, G. De Angelis and V. Girish, "An overview of RADOM results for earth and moon radiation enevironment on Chandrayaan-1 satellite," *Advances in Space Research,* vol. 48, no. 5, pp. 779-791, 2011.

What can we expect?

October 2008 Liftoff

******Each region has its own unique radiation environment******



~228 µGy d^{-1}

~257 µGy d^{-1}

~300 µGy d^{-1} deep space

~300 µGy d^{-1} LEO

~3 Gy d^{-1} (inner Van Allen belt)
~1 Gy d^{-1} (outer Van Allen belt)

The Spider Nebula

T. Dachev, B. T. Tomov, Y. N. Matviichuk, P. S. Dimitrov, S. V. Vadawale, J. N. Goswami, G. De Angelis and V. Girish, "An overview of RADOM results for earth and moon radiation eneviroment on Chandrayaan-1 satellite," *Advances in Space Research*, vol. 48, no. 5, pp. 779-791, 2011.

http://m.esa.int/var/esa/storage/images/esa_multimedia/images/2007/12/chandrayaan-1_mission_profile/10241667-2-eng-GB/Chandrayaan-1_mission_profile_highlight_mob.jpg

http://photojournal.jpl.nasa.gov/jpegMod/PIA20357_modest.jpg

Omega Nebula

https://www.nasa.gov/sites/default/files/thumbnails/image/p1613a1r.jpg

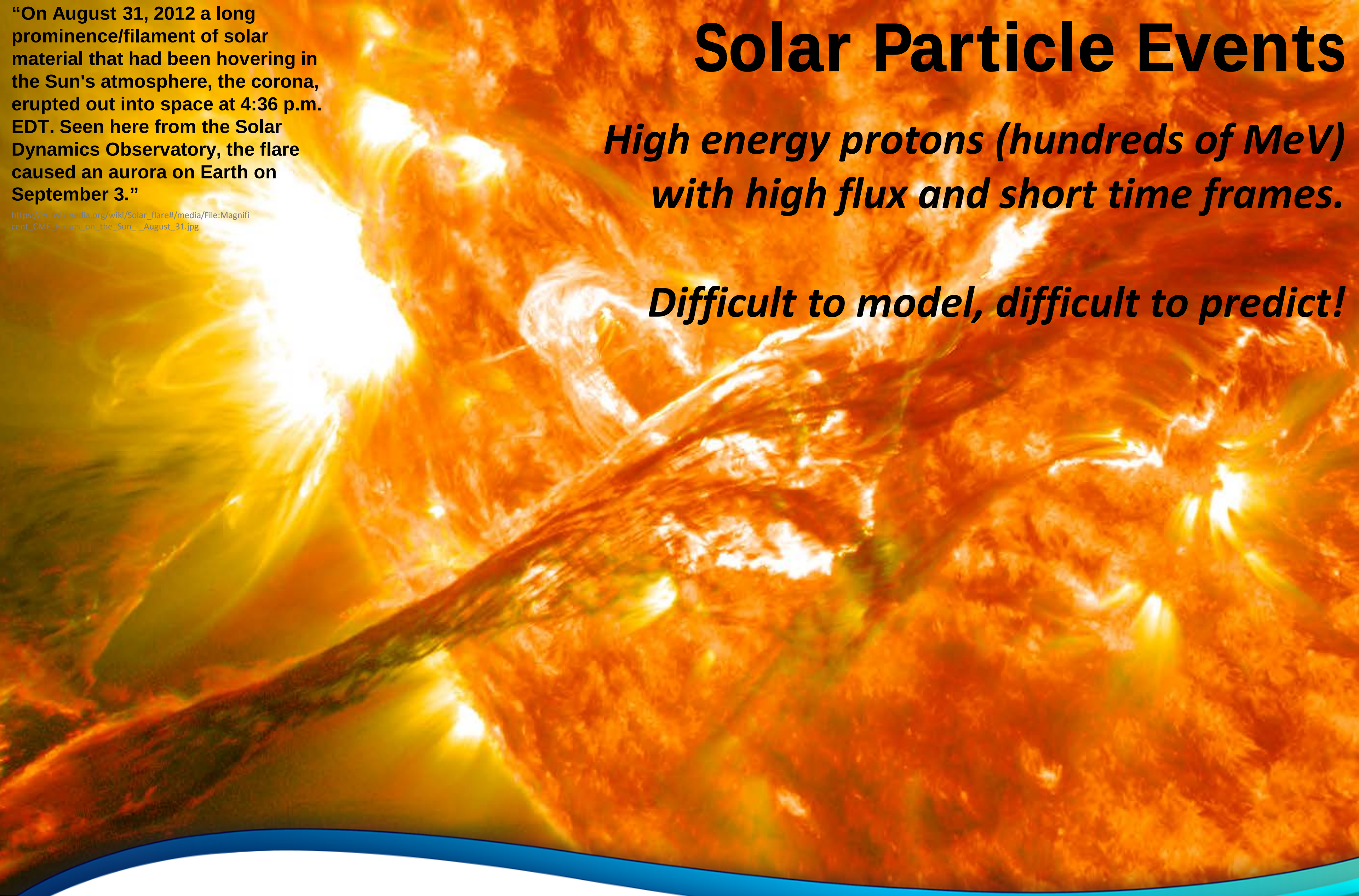
Galactic Cosmic Radiation

98% of GCR is made up of protons (~87 %), alpha particles (~12 %), and heavy nuclei (~1 %).

Remaining 2 % is populated by electrons and positrons.

GeV energies!!

Solar Particle Events



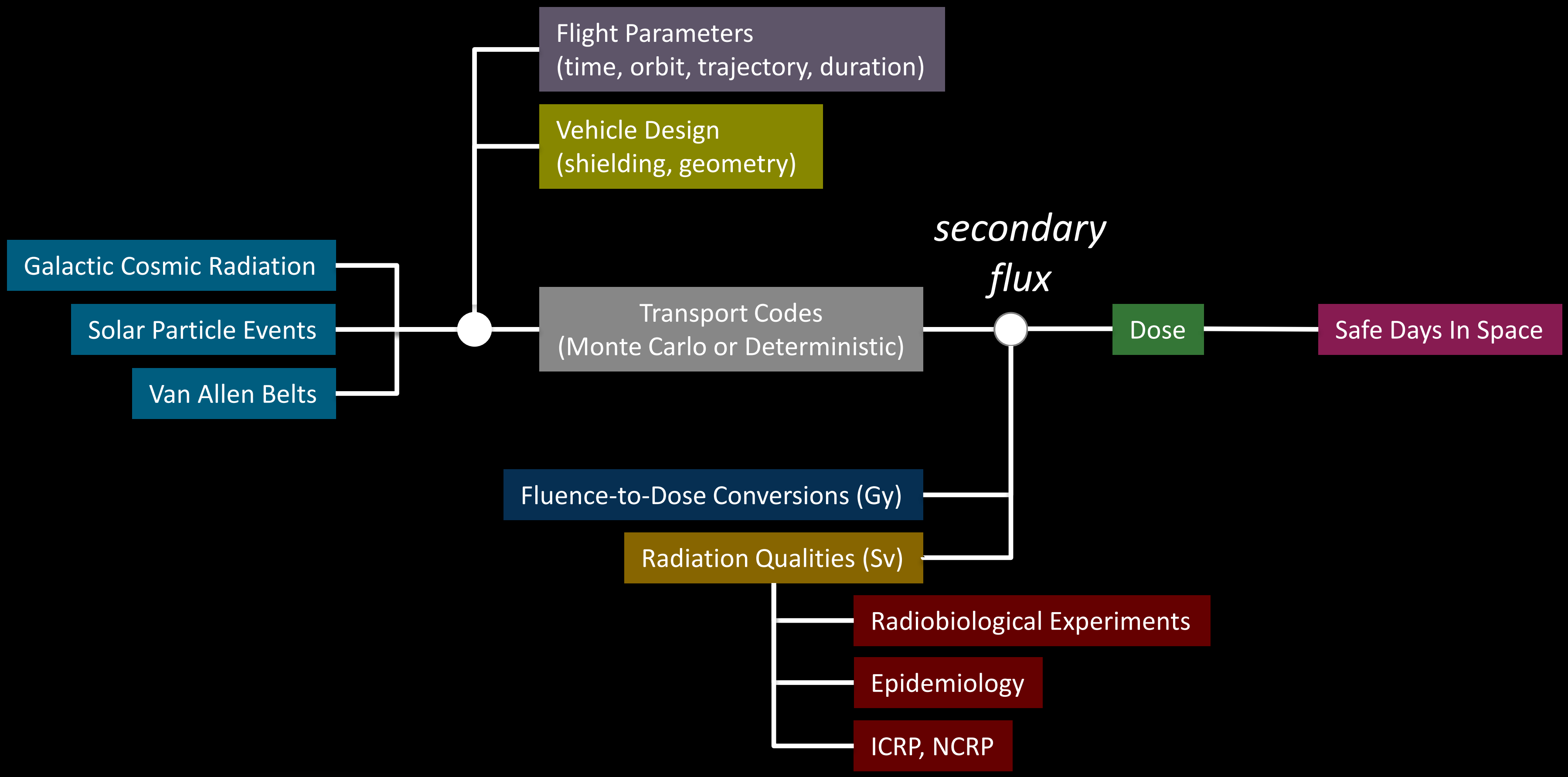
“On August 31, 2012 a long prominence/filament of solar material that had been hovering in the Sun's atmosphere, the corona, erupted out into space at 4:36 p.m. EDT. Seen here from the Solar Dynamics Observatory, the flare caused an aurora on Earth on September 3.”

https://en.wikipedia.org/wiki/Solar_flare#/media/File:Magnificent_CME_Erupts_on_the_Sun_-_August_31.jpg

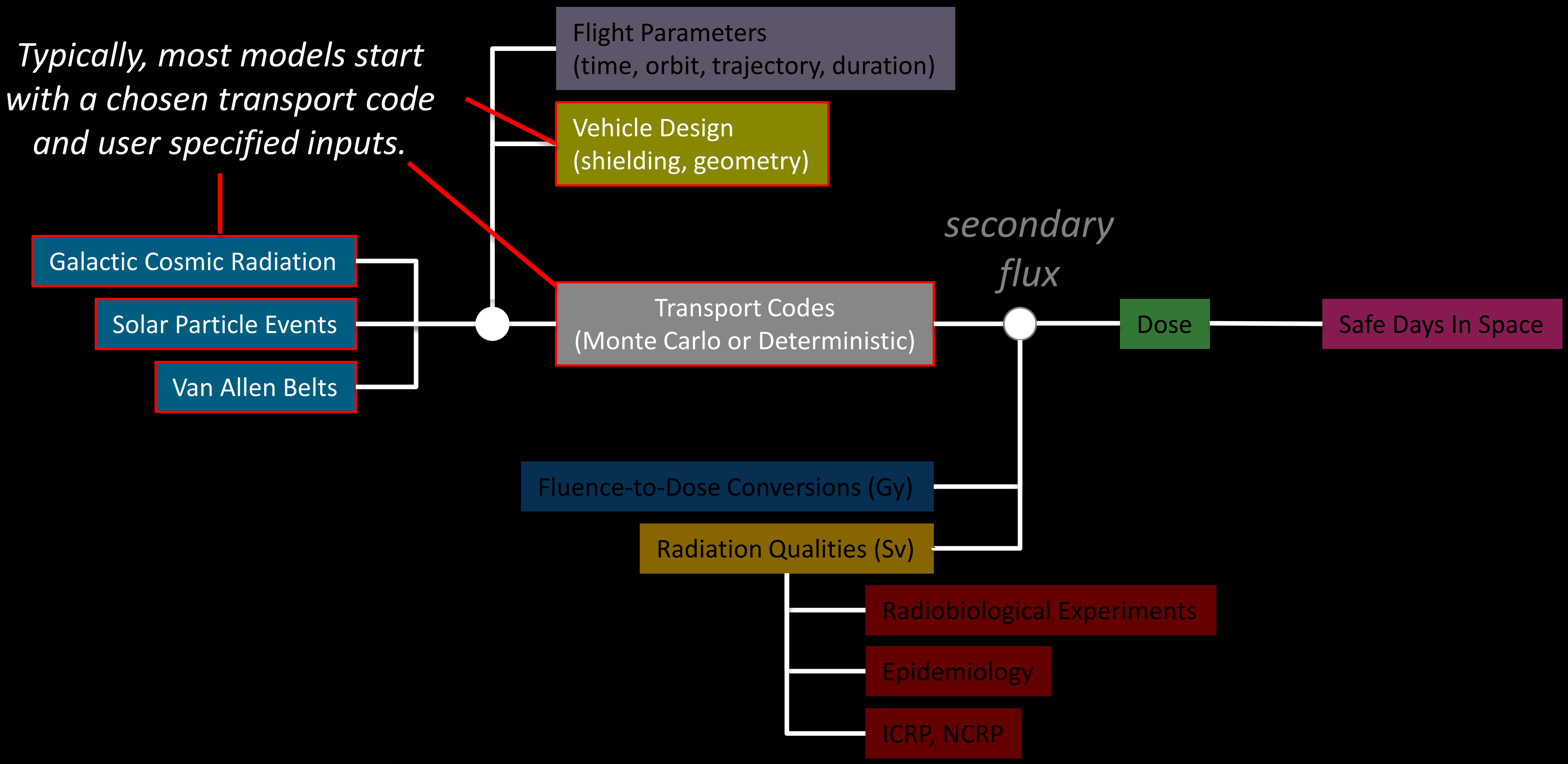
High energy protons (hundreds of MeV) with high flux and short time frames.

Difficult to model, difficult to predict!

Models Play a Significant Role!



Models Play a Significant Role!



Modelling worst case SPEs using MCNPX

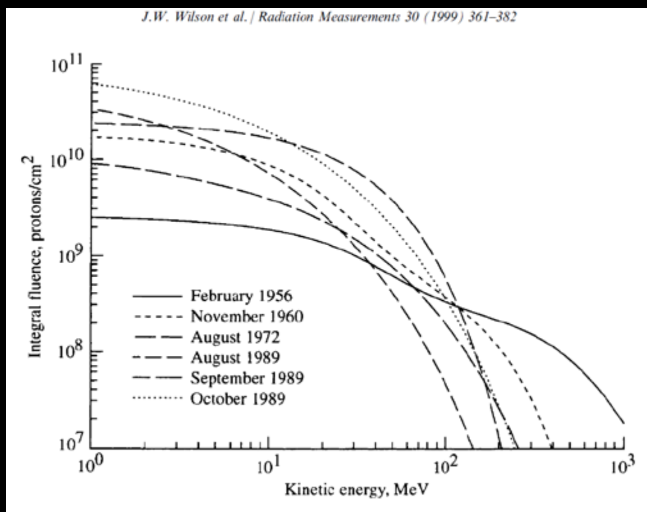
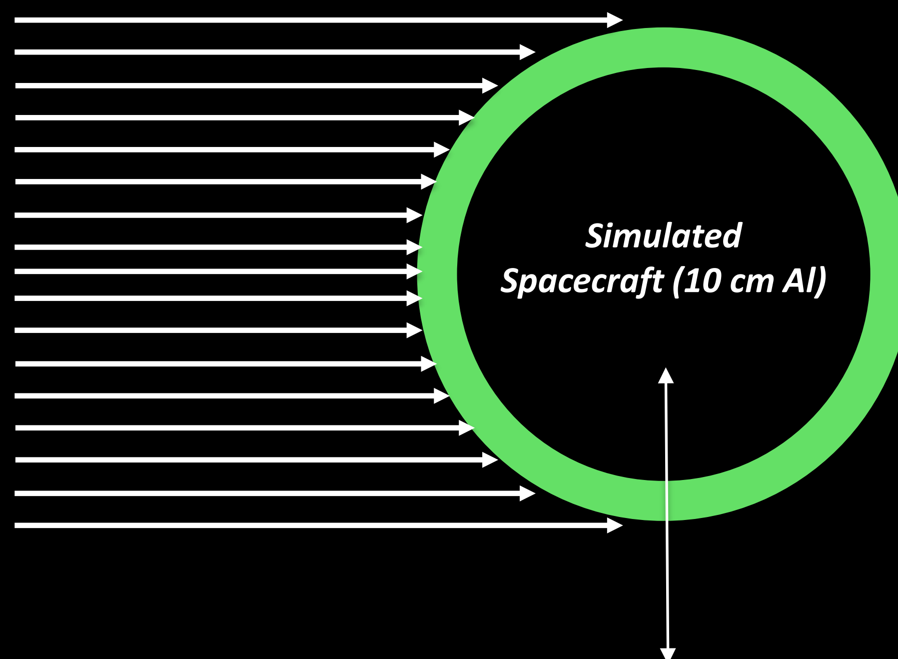


Fig. 3. Large solar proton event integral fluence spectra at 1 AU.

Worst case SPE spectra

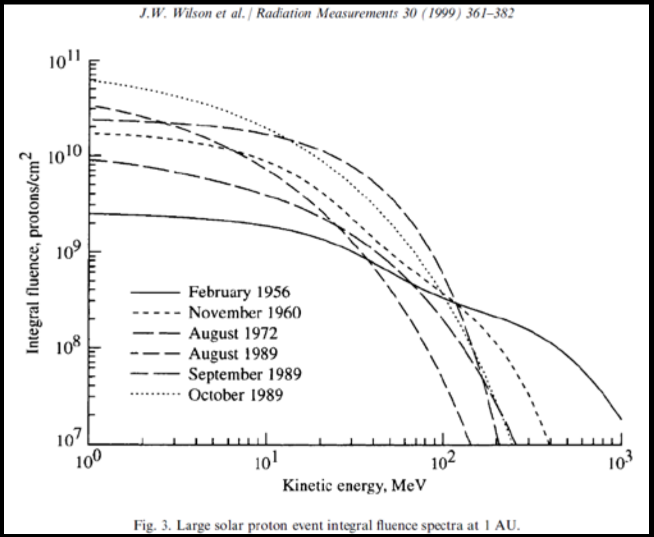


Secondary Particle Flux
(n, γ, p, α, heavy ion Z = 3 -28)

Modelling worst case SPEs using MCNPX

Need variance reduction techniques to get reasonable statistics.

Simulations are time consuming given relatively limited resources (CPU power).



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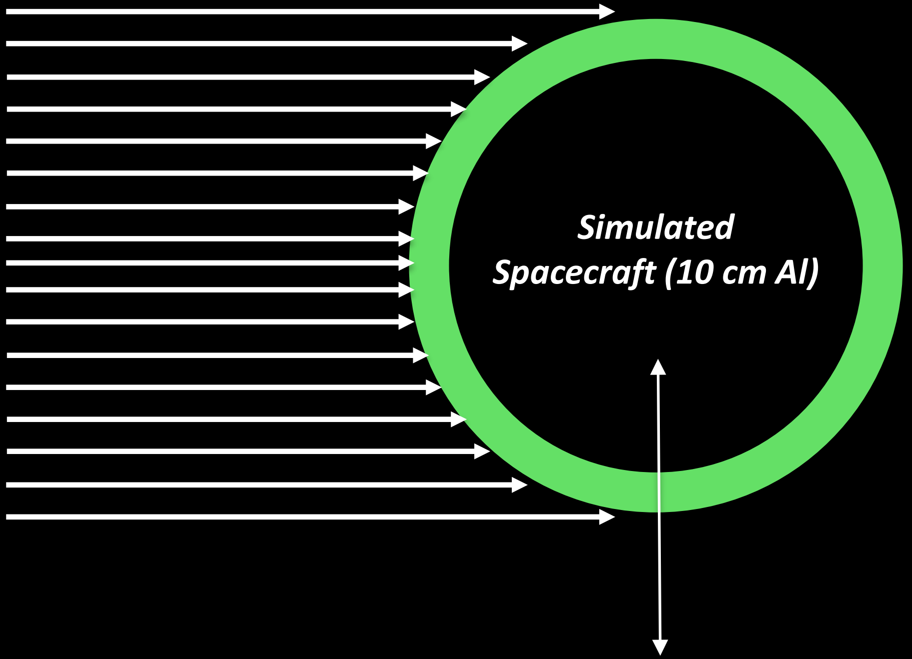
Worst case SPE spectra

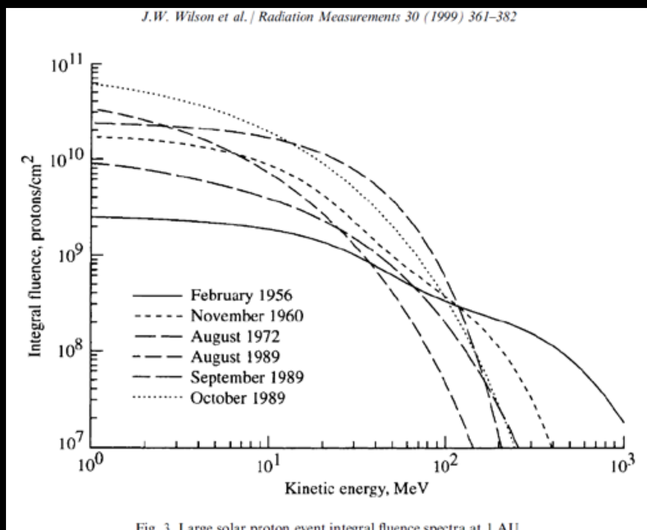


Secondary Particle Flux
(n, γ, p, α, heavy ion Z = 3 -28)

Modelling worst case SPEs using MCNPX

More importantly, will the next SPE look like these?

If not, how will that modify dose?



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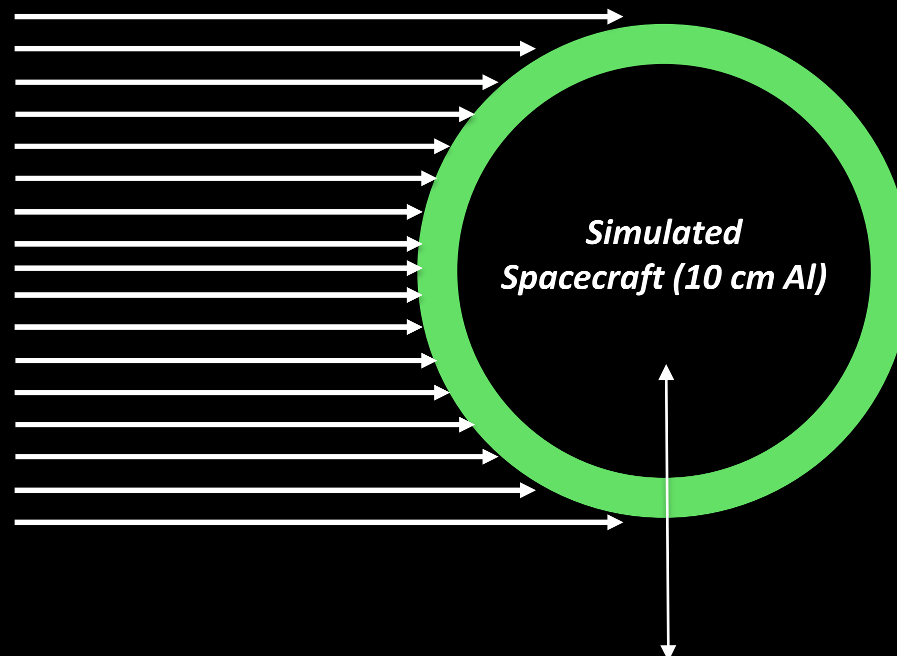
Worst case SPE spectra



Secondary Particle Flux
(n, γ, p, α, heavy ion Z = 3 -28)

Modelling worst case SPEs using MCNPX

Instead of transporting spectra, why not transport monoenergetic protons?
Better convergence of answers, quicker solutions of future SPE events, more flexible!

J.W. Wilson et al. / Radiation Measurements 30 (1999) 361–382

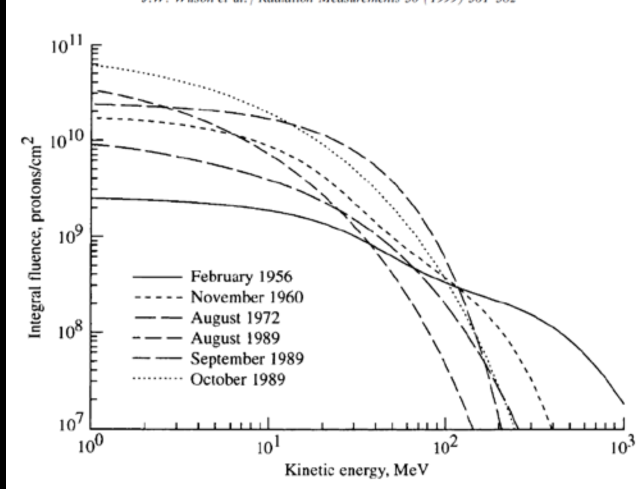
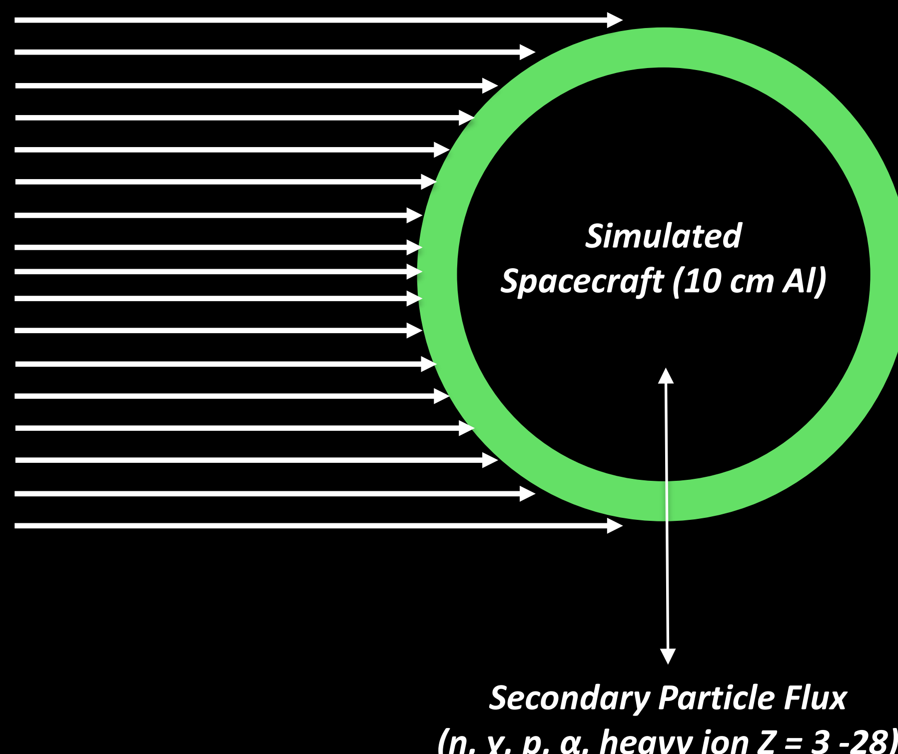
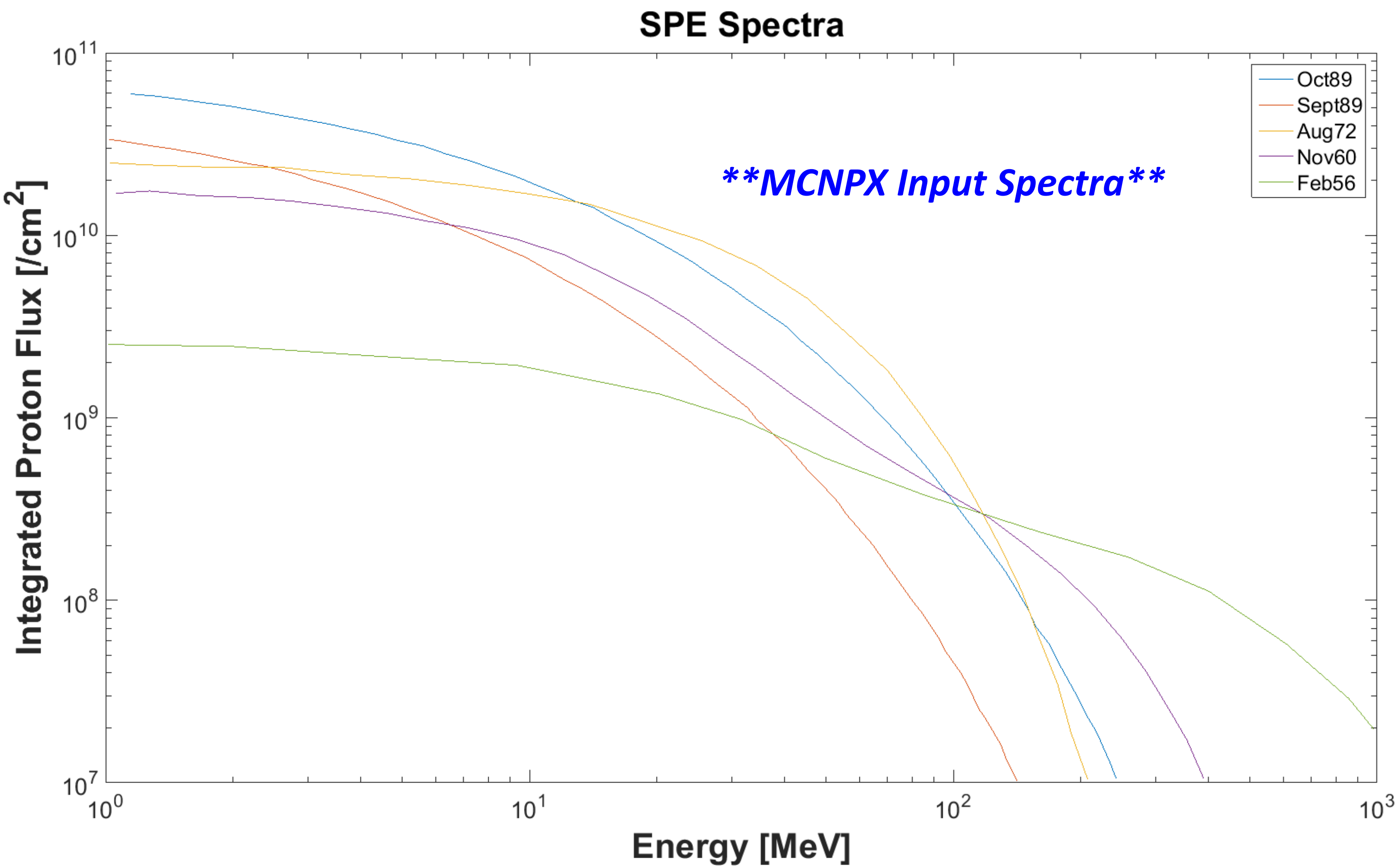


Fig. 3. Large solar proton event integral fluence spectra at 1 AU.

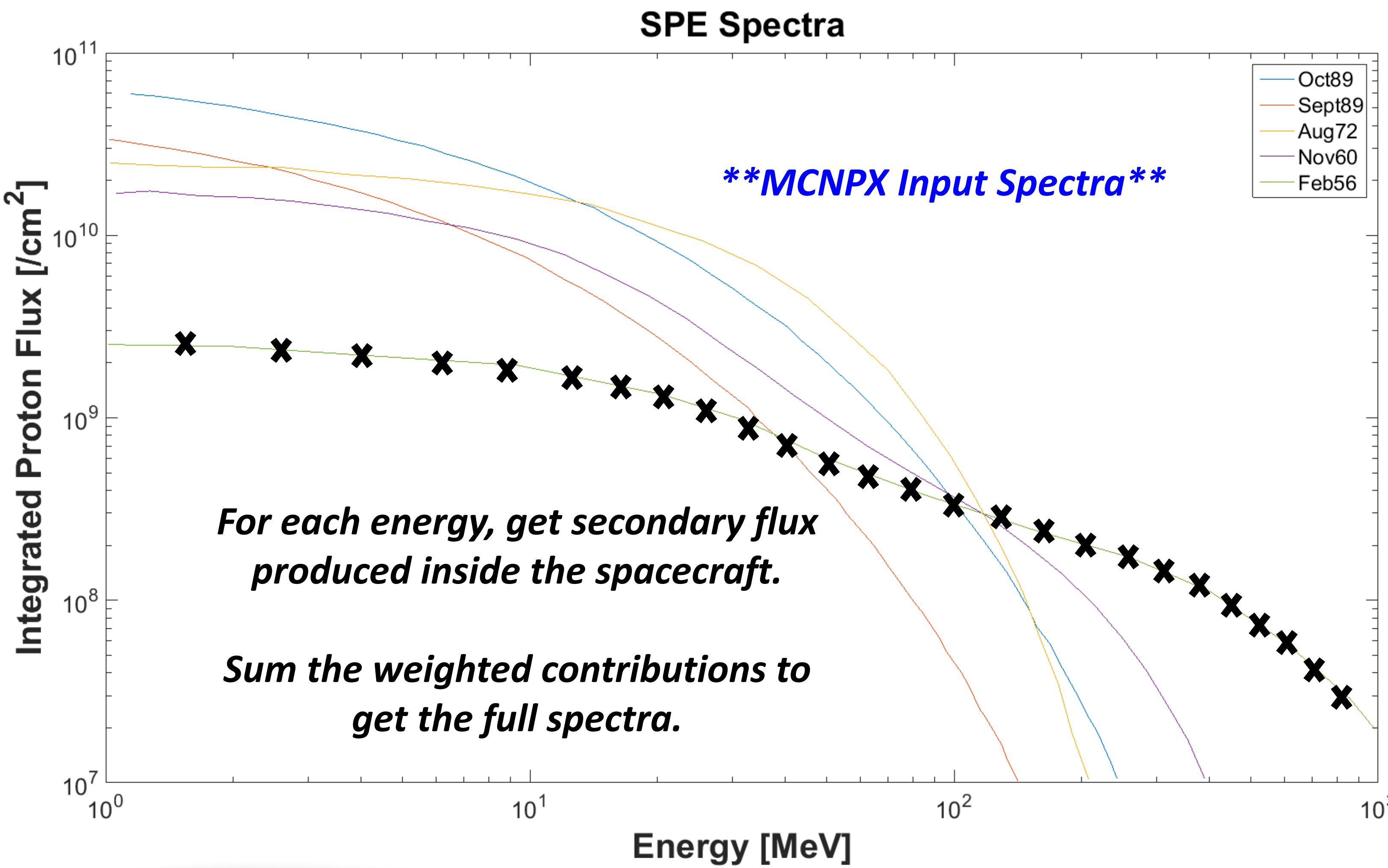
Worst case SPE spectra



Modelling Worst Case SPEs Using MCNPX



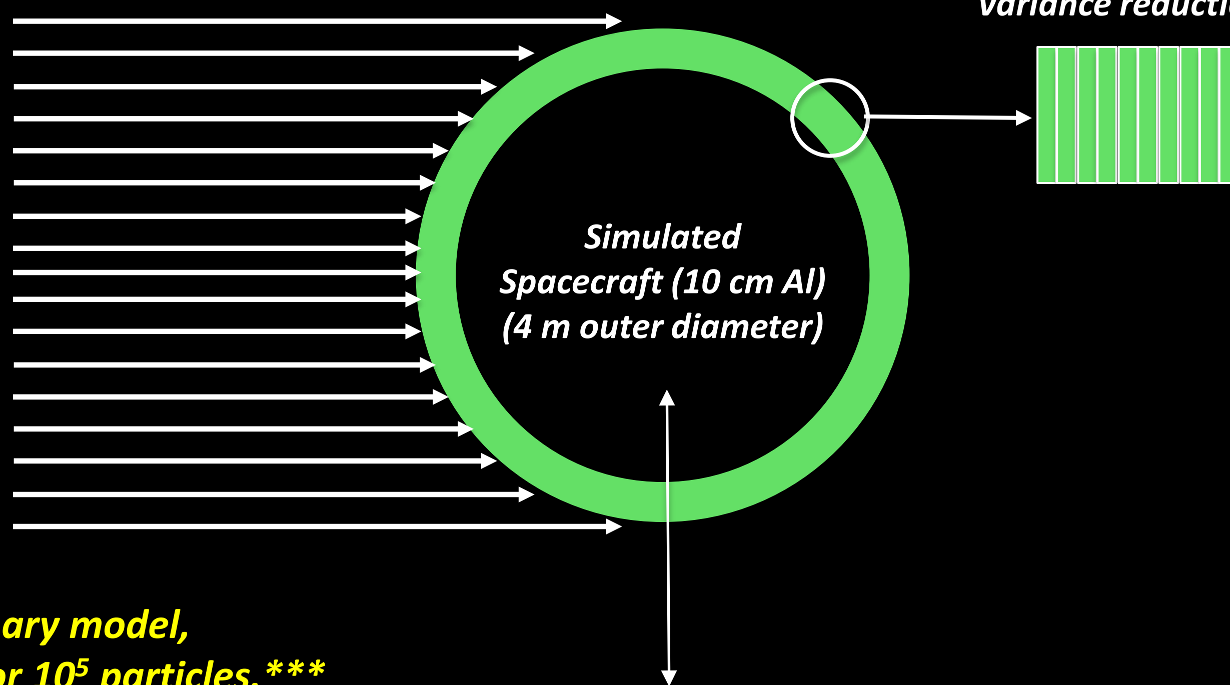
Modelling Worst Case SPEs Using MCNPX



General Details of the Model

Planar, uniform, spherical source.

Ten 1 cm thick aluminum layers using cell-based variance reduction.



Monoenergetic Protons

10^0 – 10^1 MeV in Steps of 1 MeV

10^1 – 10^2 MeV in steps of 10 MeV

10^2 to 10^3 in steps of 100 MeV

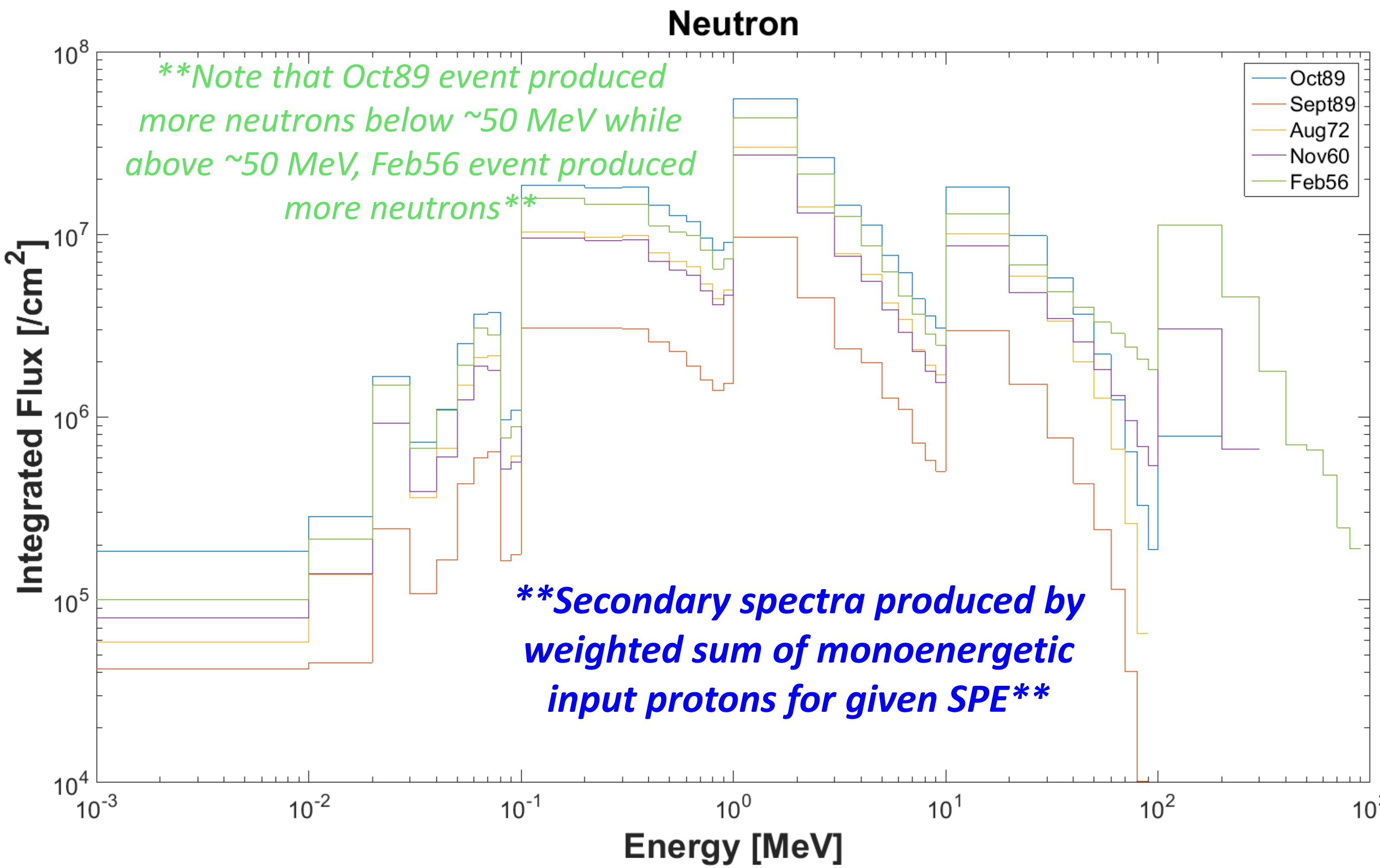
10^3 to 10^4 in steps of 1000 MeV

Secondary Particle Flux
(n, ɣ, p, α, heavy ion Z = 3 -28)

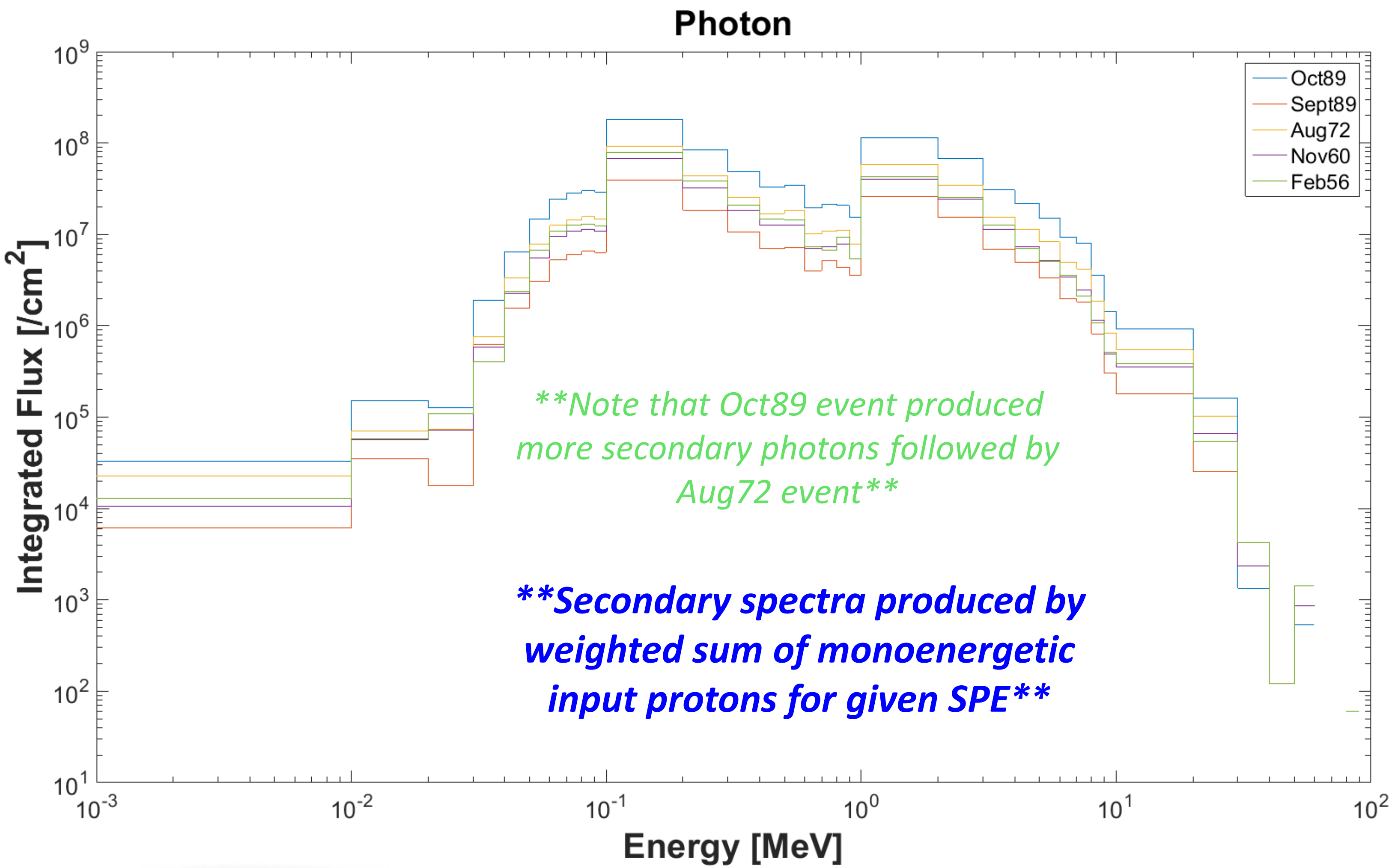
****In this preliminary model, most iterations ran only for 10^5 particles.****

****Results are automated via MATLAB.****

Preliminary Results: Secondary Neutrons



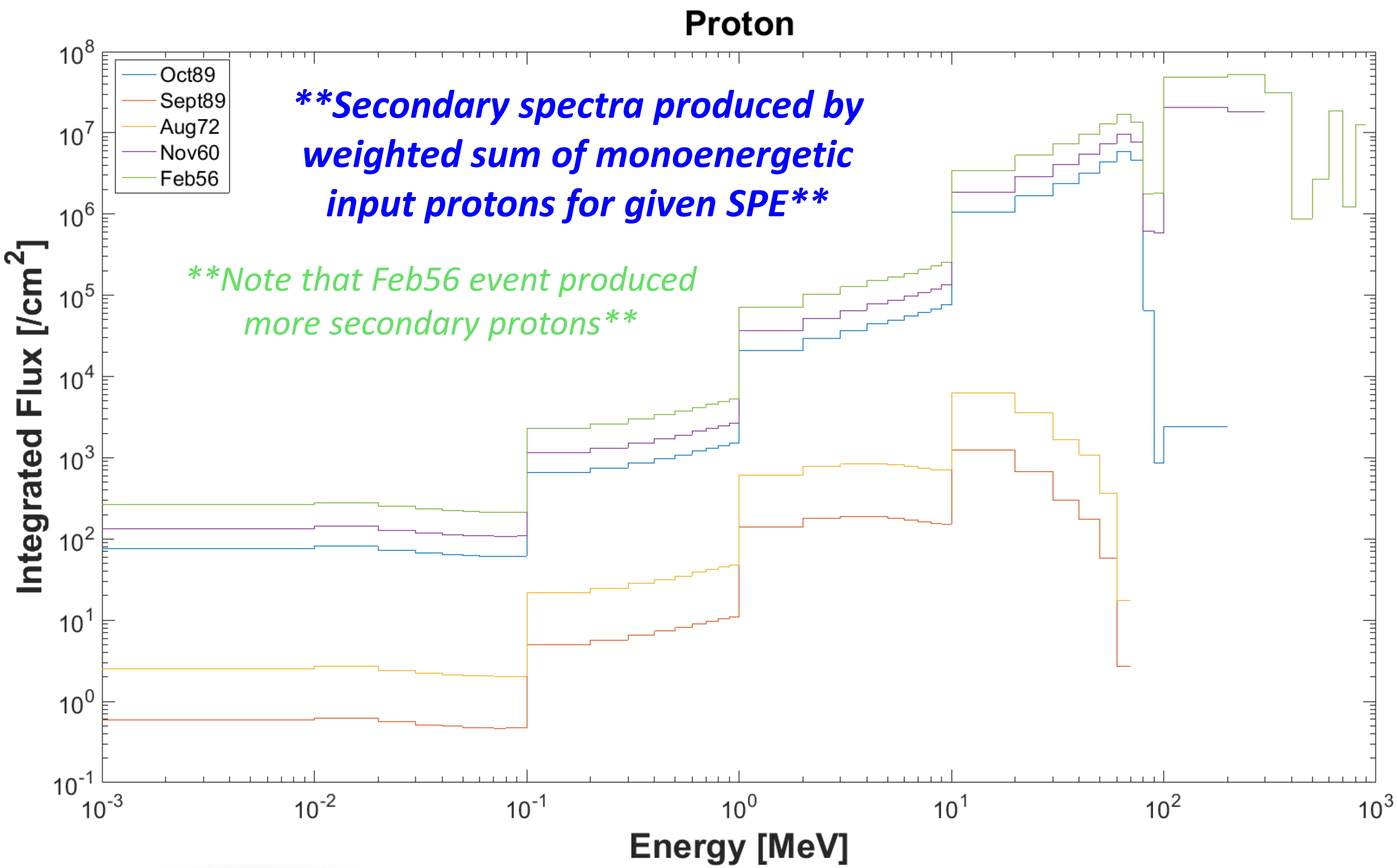
Preliminary Results: Secondary Photons



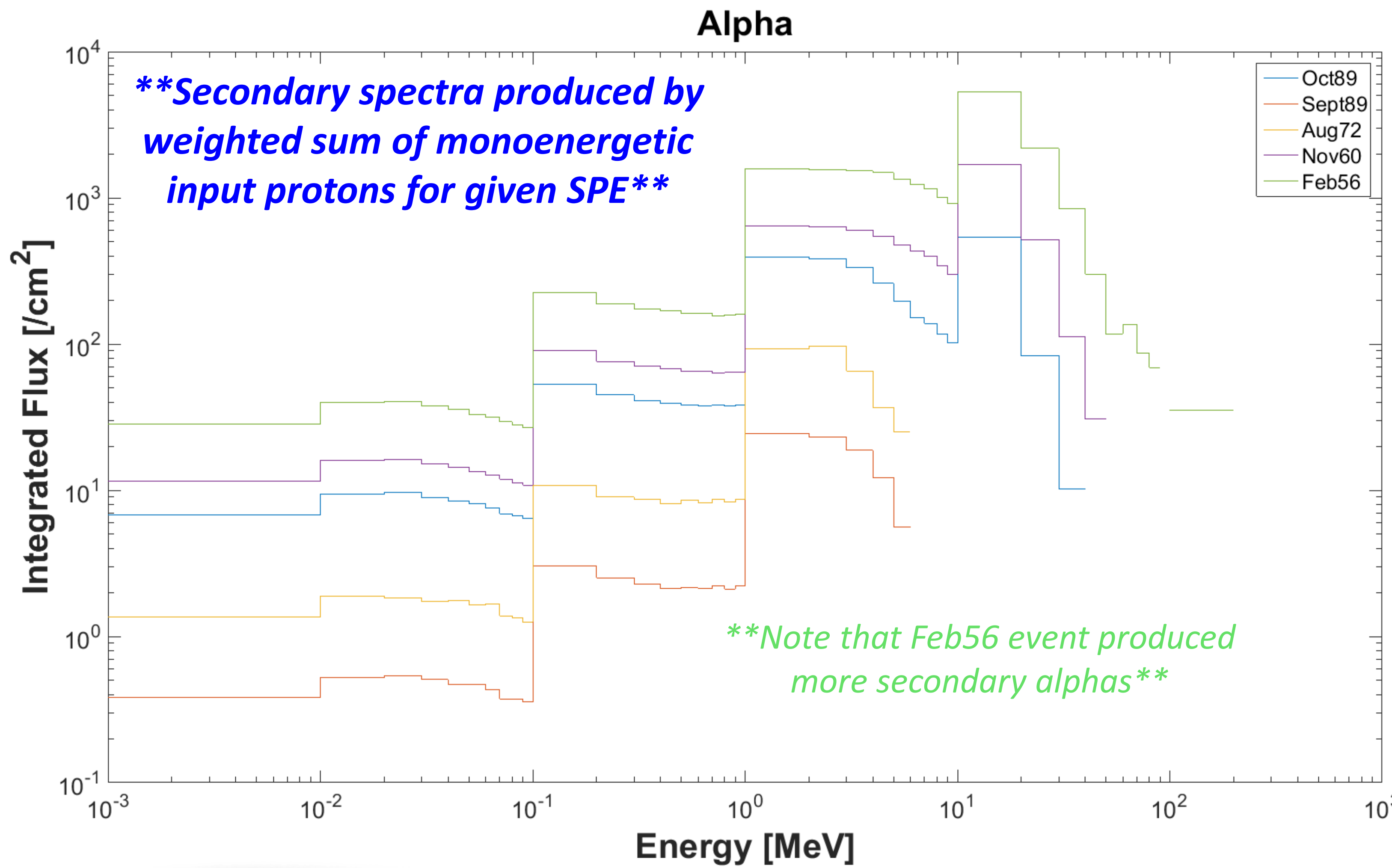
Note that Oct89 event produced more secondary photons followed by Aug72 event

*****Secondary spectra produced by weighted sum of monoenergetic input protons for given SPE*****

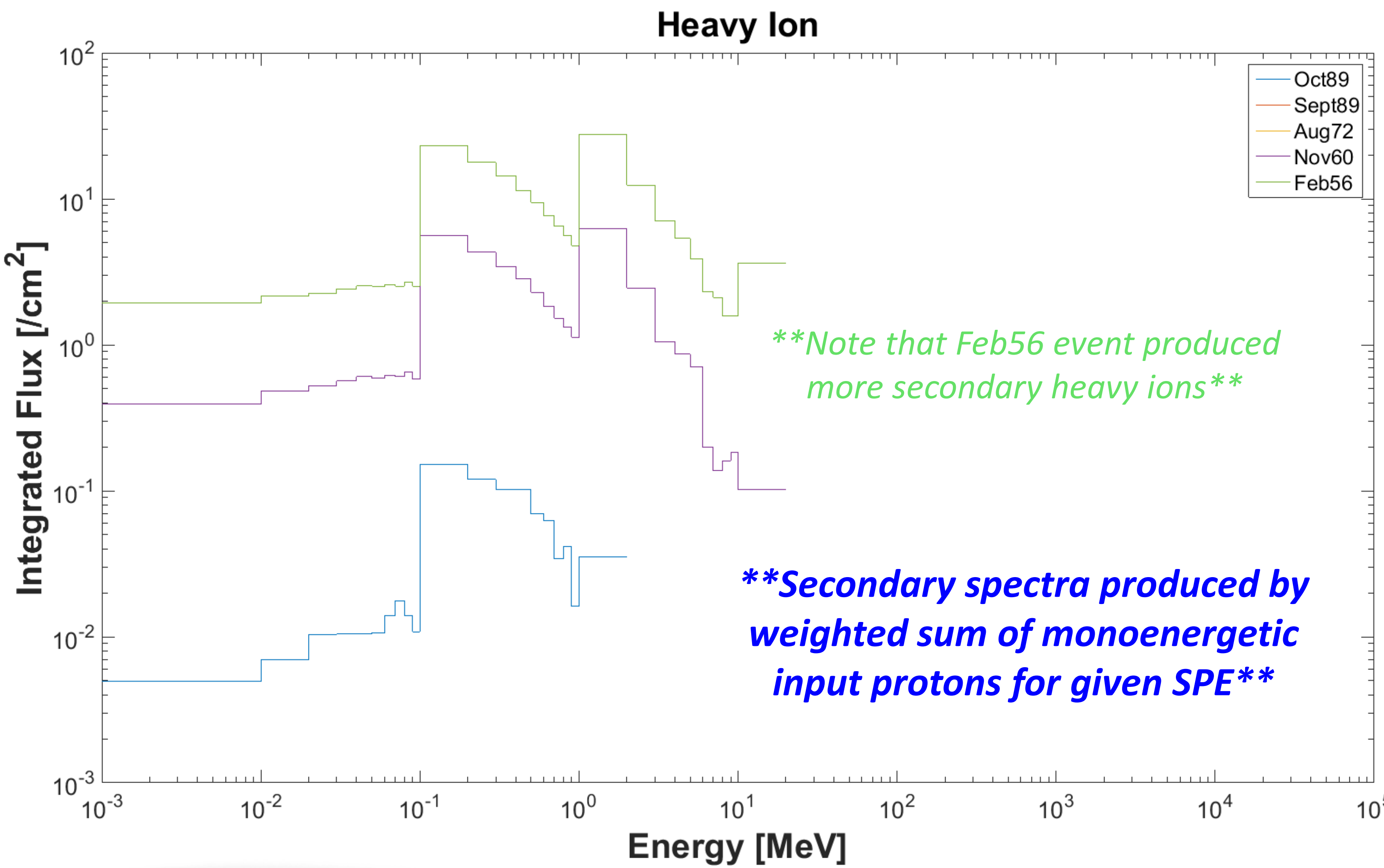
Preliminary Results: Secondary Protons



Preliminary Results: Secondary Alphas



Preliminary Results: Secondary Heavy Ions



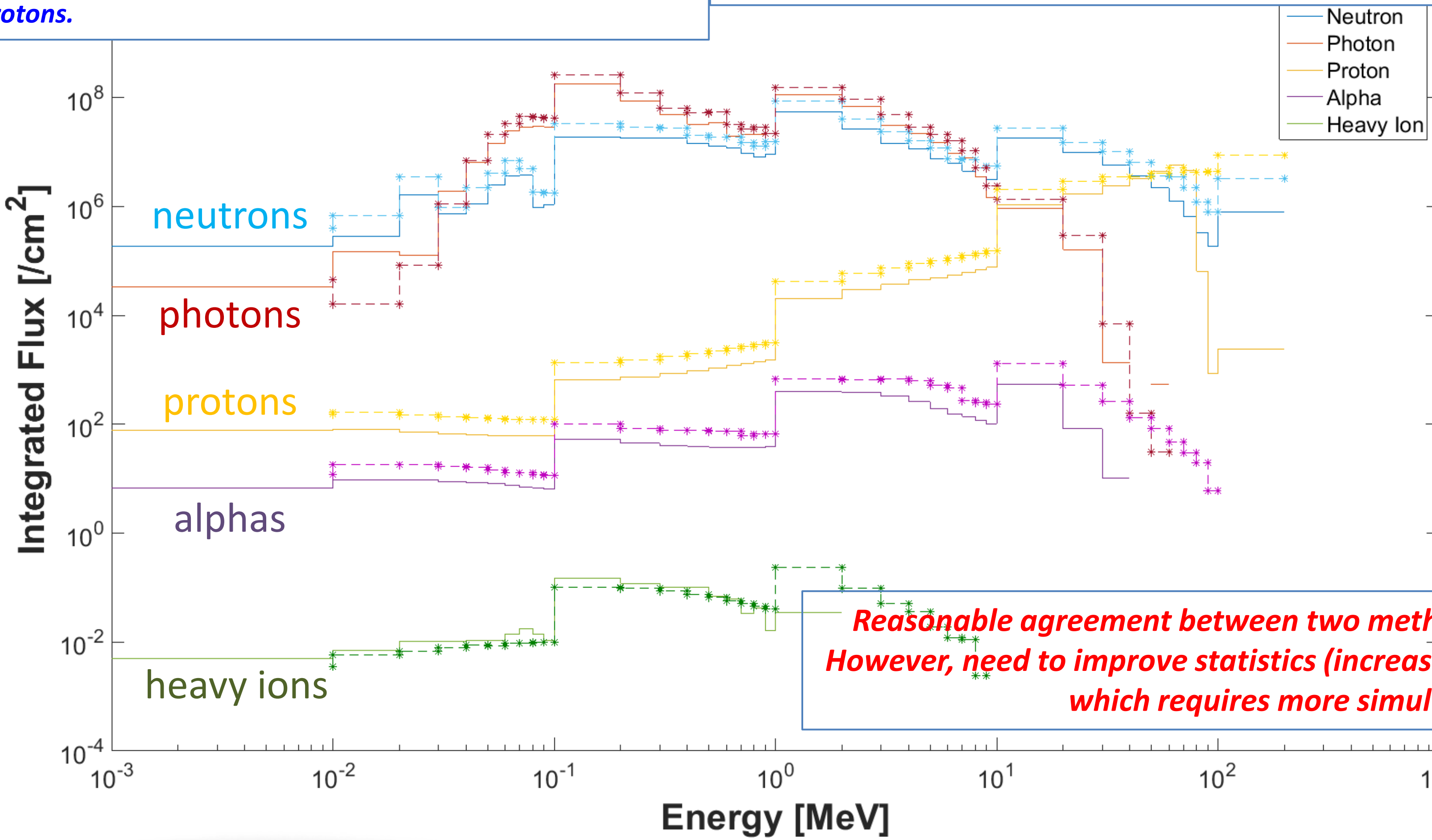
Note that Feb56 event produced more secondary heavy ions

Secondary spectra produced by weighted sum of monoenergetic input protons for given SPE*

Preliminary Results: Secondary Spectra Oct89

***SOLID LINE* - Secondary spectra produced by weighted sum of secondary particles from MCNPX transport of monoenergetic input protons.**

***DASH LINE* - Secondary spectra produced by transporting full SPE spectra at once in MCNPX and tallying secondary particles.**



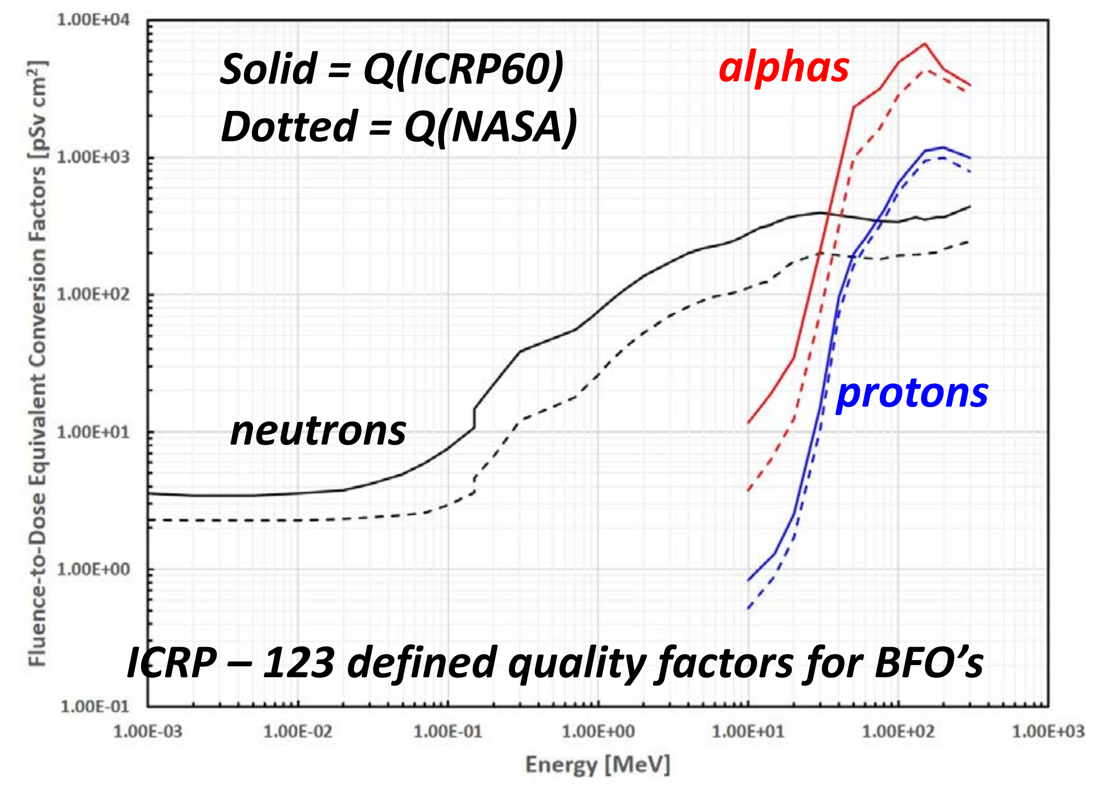
Reasonable agreement between two methodologies. However, need to improve statistics (increase histories) which requires more simulation time.

Preliminary Results: BFO Dose Equivalent

Organ dose equivalent to Blood Forming Organs (BFO)) calculated using ICRP-123 defined fluence-to-dose equivalent conversion factors (based on ICRP-60 Q(L) and NASA Q(Z,E)) calculaated for each SPE.

******Only considers secondary neutrons, protons, and alphas for 10 cm aluminum sphere******

	BFO Dose Equivalent (Sv)	
SPE	Q(ICRP60)	Q(NASA)
Oct-89	0.046	0.021
Sep-89	0.007	0.003
Aug-72	0.022	0.009
Nov-60	0.073	0.052
Feb-56	0.117	0.081



Results based on the weighted sum of secondary spectra produced by MCNPX transport of monoenergetic protons.

Preliminary Results: BFO Dose Eq. Aug-1972

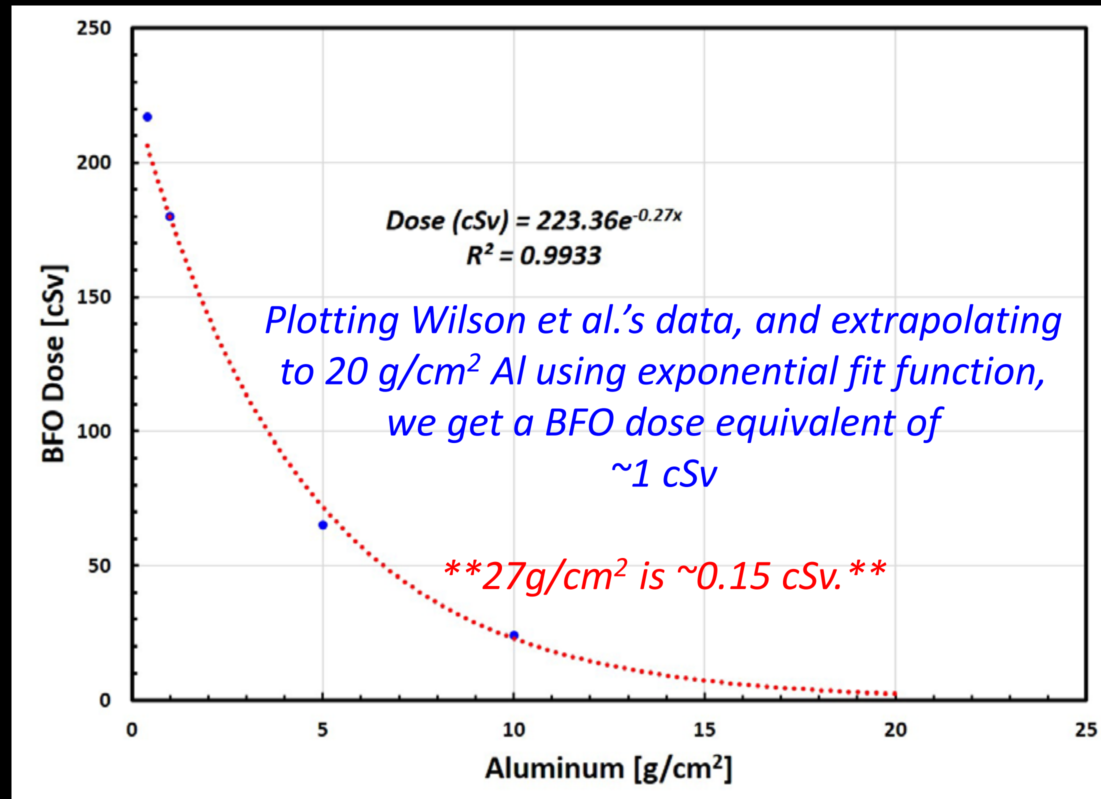
Table 5
Dose equivalent and dose in critical body organs within an aluminum structure during the August 1972 solar event, cSv (cGy)

Organ	Space suit	Pressure vessel	Equipment room	Shelter
Skin	9350 (4830)	3560 (2120)	427 (294)	110 (76)
Lens	3830 (2400)	2140 (1420)	367 (263)	101 (71)
BFO	217 (157)	180 (130)	65 (47)	24 (17)

J.W. Wilson et al. / Radiation Measurements 30 (1999) 361–382

Space suit = 0.4 g/cm^2 ; pressure vessel = 1 g/cm^2 ; Equipment room = 5 g/cm^2 ; shelter = 10 g/cm^2

Previous estimate of BFO organ dose equivalent, by Wilson et al., for Aug 1972 for various thicknesses of Al (0.4 – 10 g/cm^2)

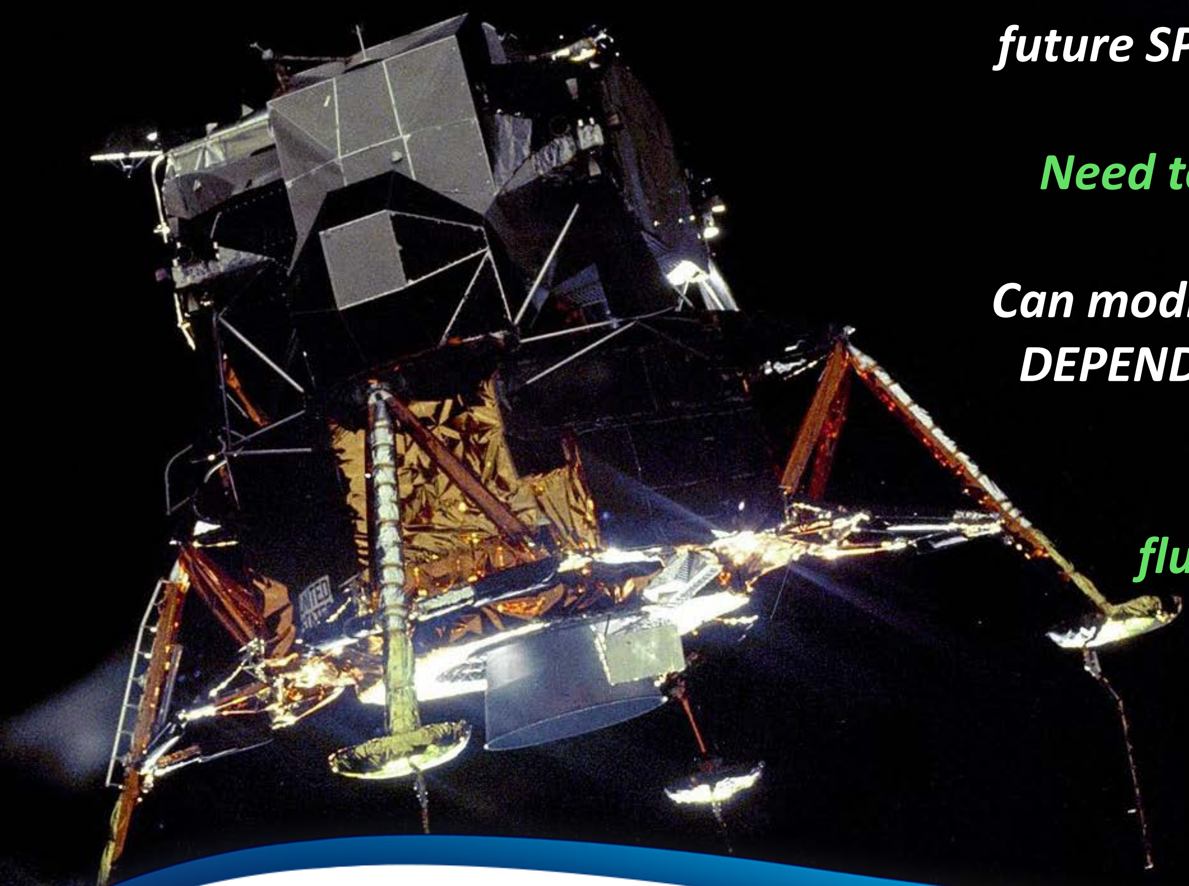


MCNPX simulations estimate a ~ 0.9 (Q_{NASA}) – 2.2 cSv (Q_{ICRP60}) BFO dose compared to Wilson et al.'s extrapolated value of 1 cSv at 20 g/cm^2
Values are not within the same range, requires investigation.

Summary

Apollo 11 Lunar Module Eagle, July 20 1969,

1280px-Apollo_11_Lunar_Module_Eagle_in_landing_configuration_in_lunar_orbit_from_the_Command_and_Service_Module_Columbia



Preliminary results show promise.

Demonstrated ability to model any and future SPE spectra quickly and efficiently!

Need to improve stats for low-energies.

Can modify the code to automate a TIME-DEPENDENT SPE dose quickly efficiently!

Need to calculate dose (Sv) via fluence-to-dose conversion factors!

Future (Ongoing) Work @ CNL!

Isotropic, uniform source

Monoenergetic Protons, Alphas, heavy ions Z= 1 - 28

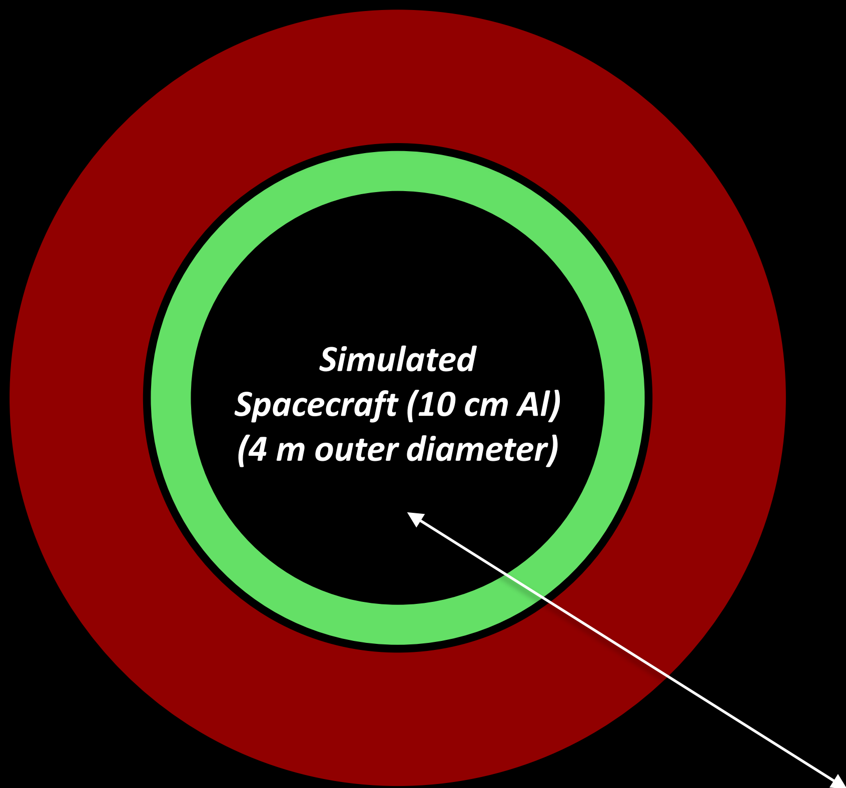
$10^0 – 10^1$ MeV in Steps of 1 MeV

$10^1 – 10^2$ MeV in steps of 10 MeV

10^2 to 10^3 in steps of 100 MeV

10^3 to 10^4 in steps of 1000 MeV

10^4 to 10^5 in steps of 10^4 MeV



Secondary Particle Flux (n, ɣ, p, α, heavy ion Z = 3 -28)

Future Considerations!

Monte Carlo models typically ignore mechanical and physical properties and focus only on shielding.

Realistically, models may not capture shielding distributions necessary for proper dose assessment.

Example of a Typical Monte Carlo Model

It would be better to first start off with realistic geometry and then add additional shielding as necessary to try and reduce dose.

Simulations can be repeated with new geometries and/or shielding.

Orion crew module

http://www.universetoday.com/114064/heat-protecting-back-shell-tiles-installed-on-nasas-orion-eft-1-spacecraft-set-for-dec-2014-launch/

http://www.nasa.gov/centers/dryden/multimedia/imagegallery/Orion/ED08-0230-362.html

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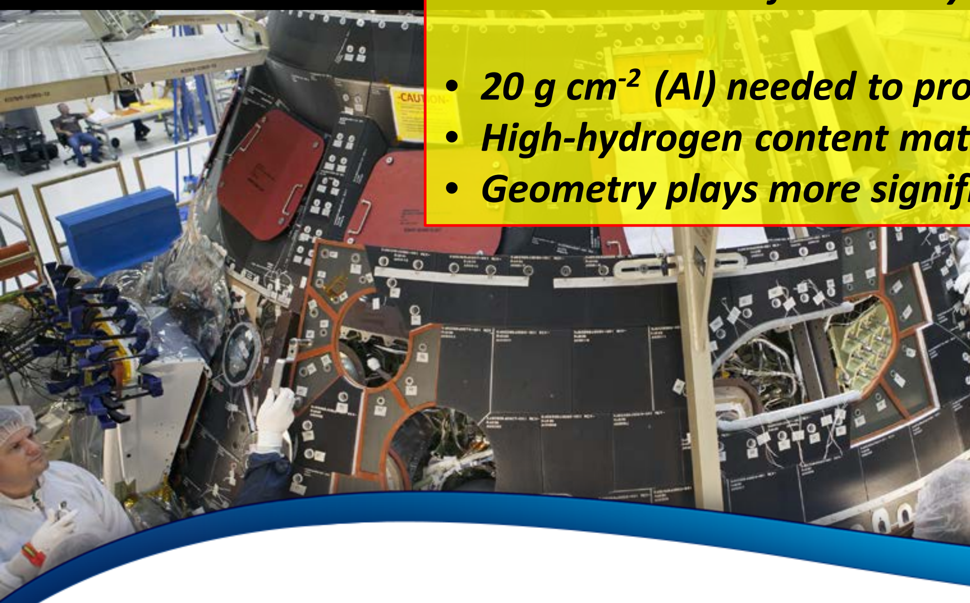


We have a sense of necessary shielding:

- ***20 g cm^{-2} (Al) needed to protect against effects of SPEs.***
- ***High-hydrogen content material is optimal.***
- ***Geometry plays more significant role for SPEs vs. GCR.***

Thank You!

This work is supported by AECL administered Federal S&T funding.

I would like to acknowledge the project team: Fawaz Ali, Shayne O'Brien, Sheila Kramer-Tremblay, Eugene Masala, Ankur Chaudhuri.

I'd also like to acknowledge the support of Amanda Barr, Chental Kuehl, Kristina Archer, Nick Priest, Joanne Ball, and Fred Beranek!

Thank you to the WRMISS-21 organization committee!

Earthrise viewed by Apollo 8, Christmas Eve, Dec. 24, 1968.
http://www.hq.nasa.gov/office/pao/History/alsj/a410/AS8-14-2383HR.jpg

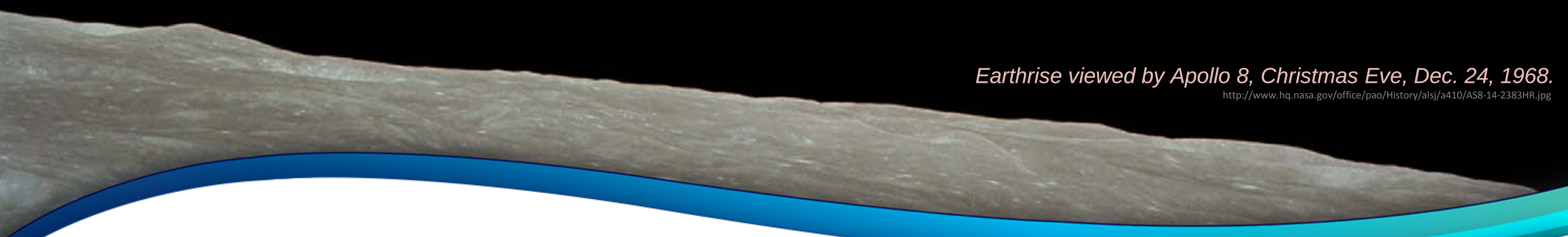
Thank You!

"We came all this way to explore the Moon, and the most important thing is that we discovered the Earth."

William Alison "Bill" Anders

Maj Gen, USAFR, Ret., Nuclear Engineer, & NASA Astronaut

Lunar Module Pilot for Apollo 8 Mission



Earthrise viewed by Apollo 8, Christmas Eve, Dec. 24, 1968.

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