Geant4 Usage at JPL

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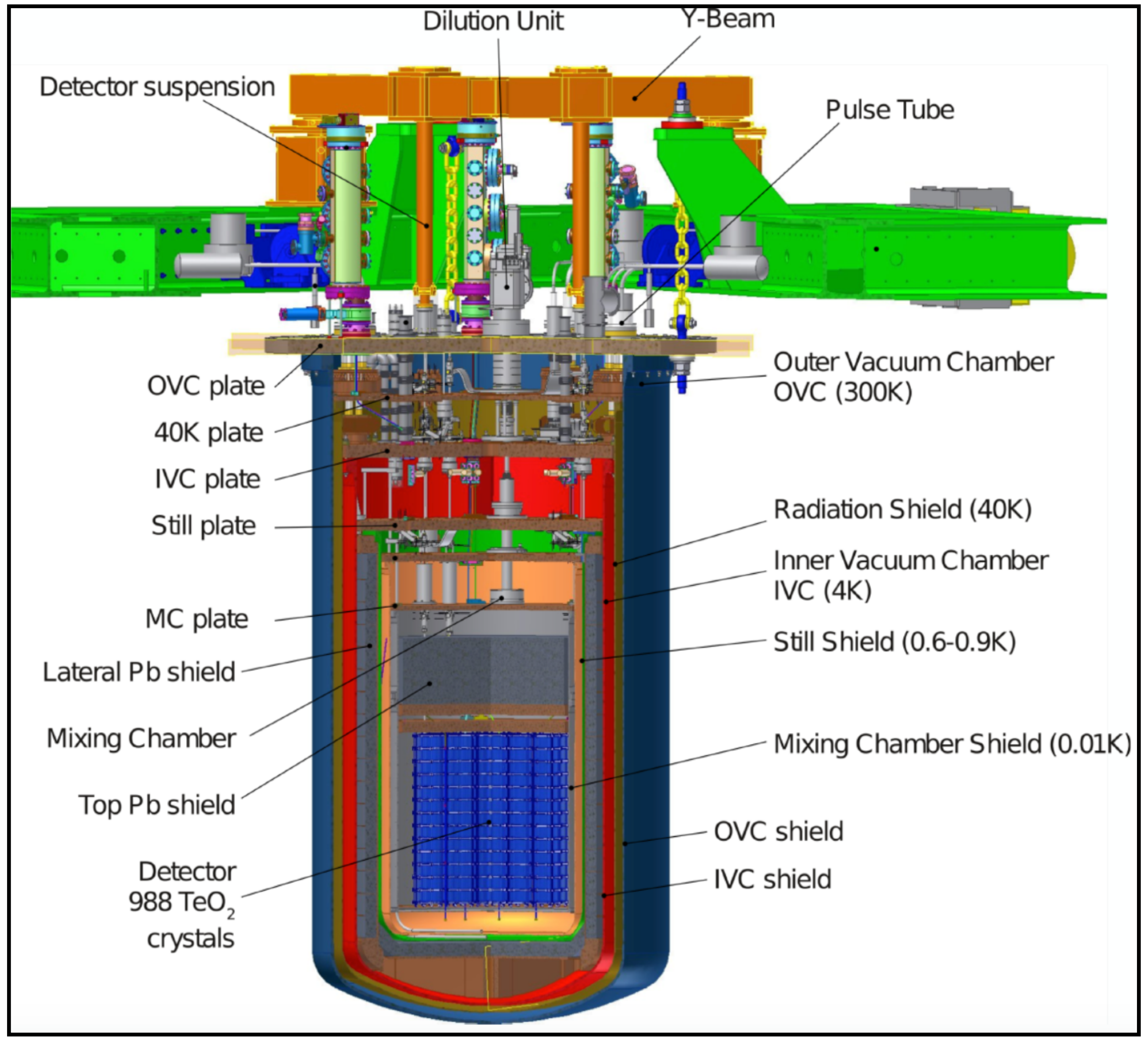
Before JPL

My previous experience: particle physics, underground rare event searches looking for neutrinoless double-beta decay

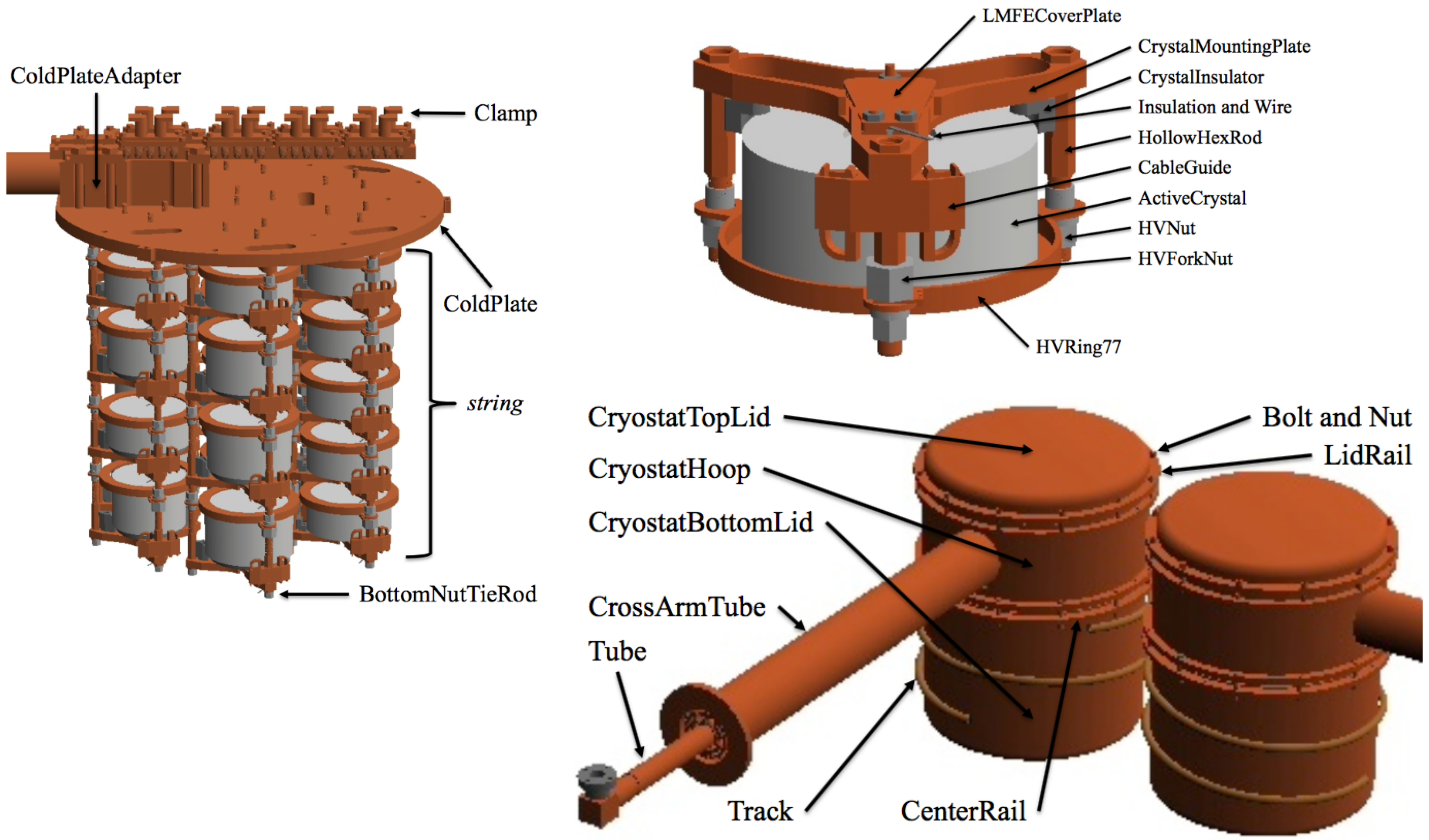
Heavily relied on Geant4 simulations for characterizing/understanding radioactivity in all detector materials

Reducing background radioactivity is key when searching for a decay with $t_{1/2} > 10^{26}$ years!

CUORE experiment



Majorana/LEGEND experiments



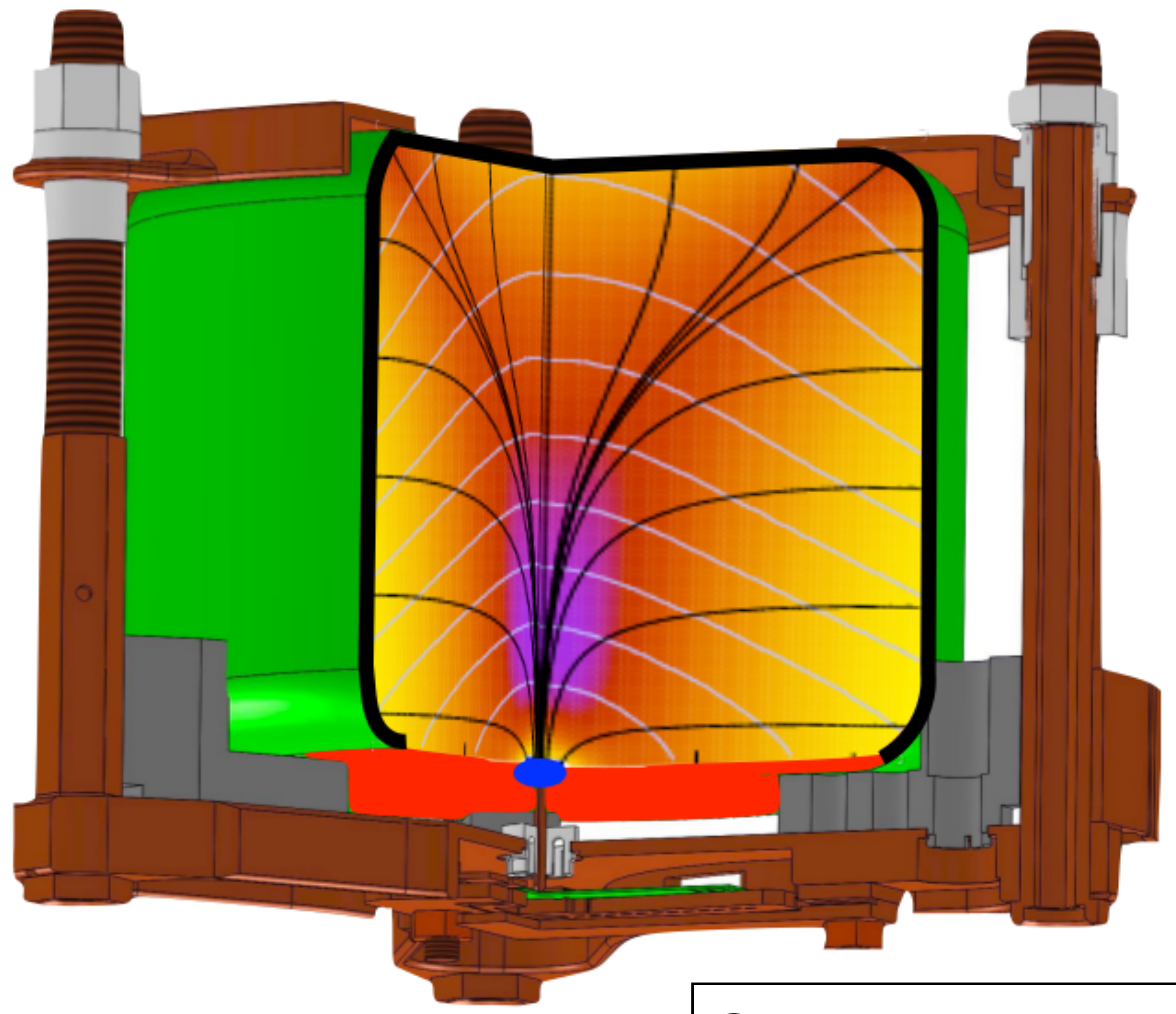
Comparison of Geant4 Usage

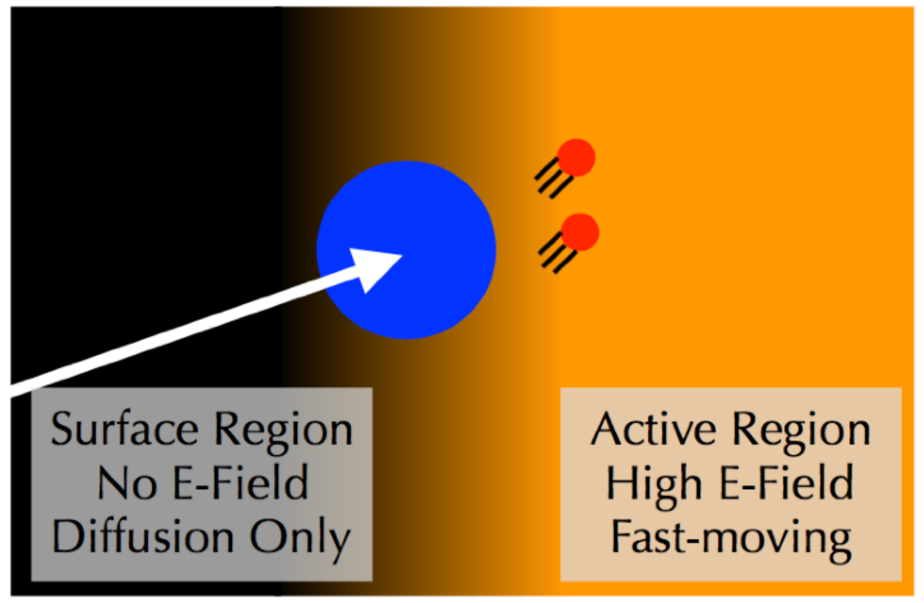
Majorana/LEGEND

- Geometries are simplified and defined using **native Geant4 classes** (a lot of work for a graduate student)
- **Radioactive decay** sources internal to/on surface of volumes
- Significant effort post-processing simulation output to mimic detector response (eg: dead-layer response of germanium detectors)

At JPL

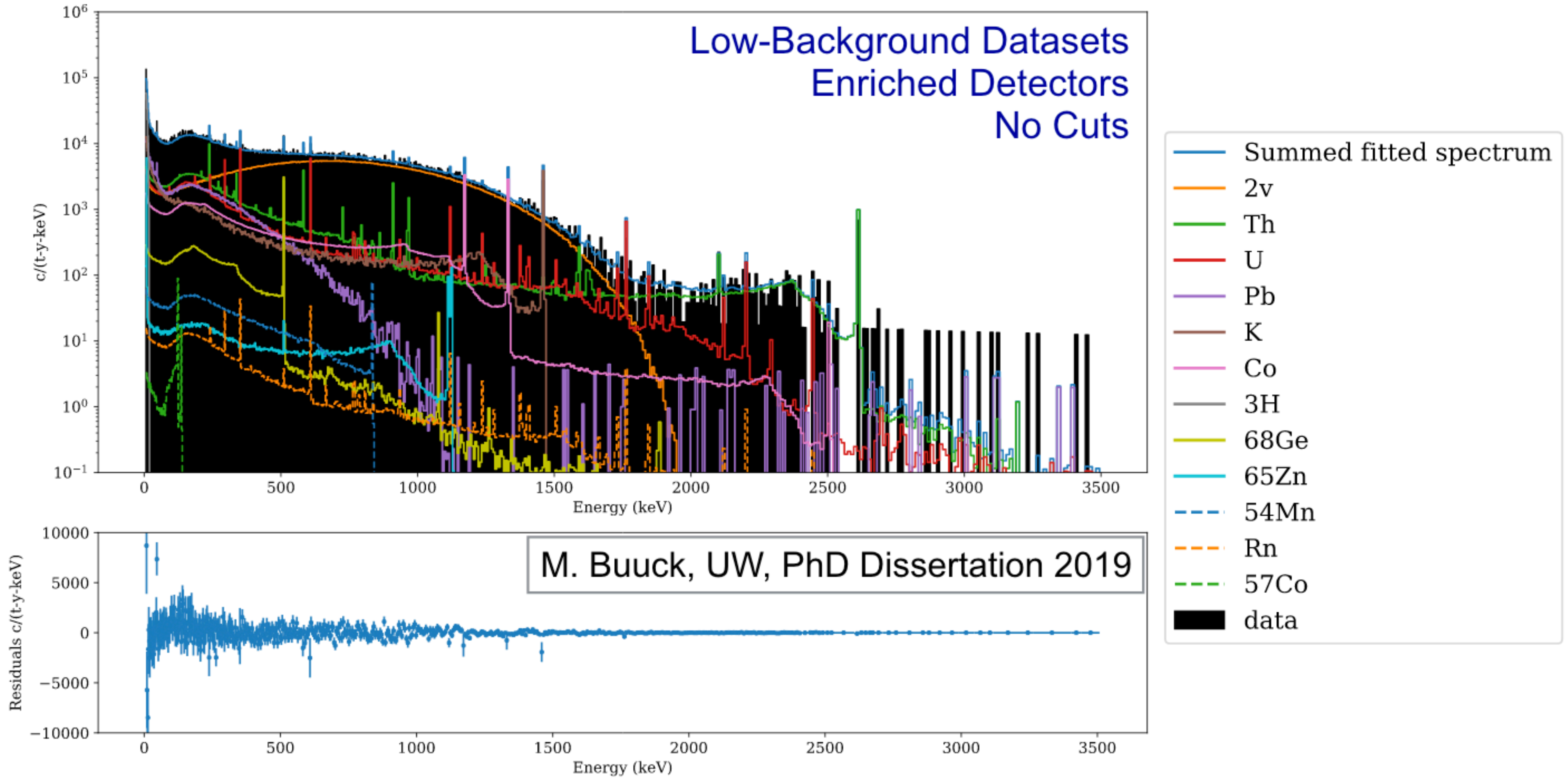
- Complex geometries converted from **CAD to GDML**. Transport analyses are heavily utilized during instrument design and parts selection phase of a mission
- **External/omnidirectional** radiation environment of electrons and protons
- Limited post-processing of simulation output





- p^+ Point Contact (Ge)
- n^+ Outer Contact (Li)
- Active (Intrinsic) Volume
- Passivated Surface
- Transition Layer (~1mm)

C. Wiseman, USC



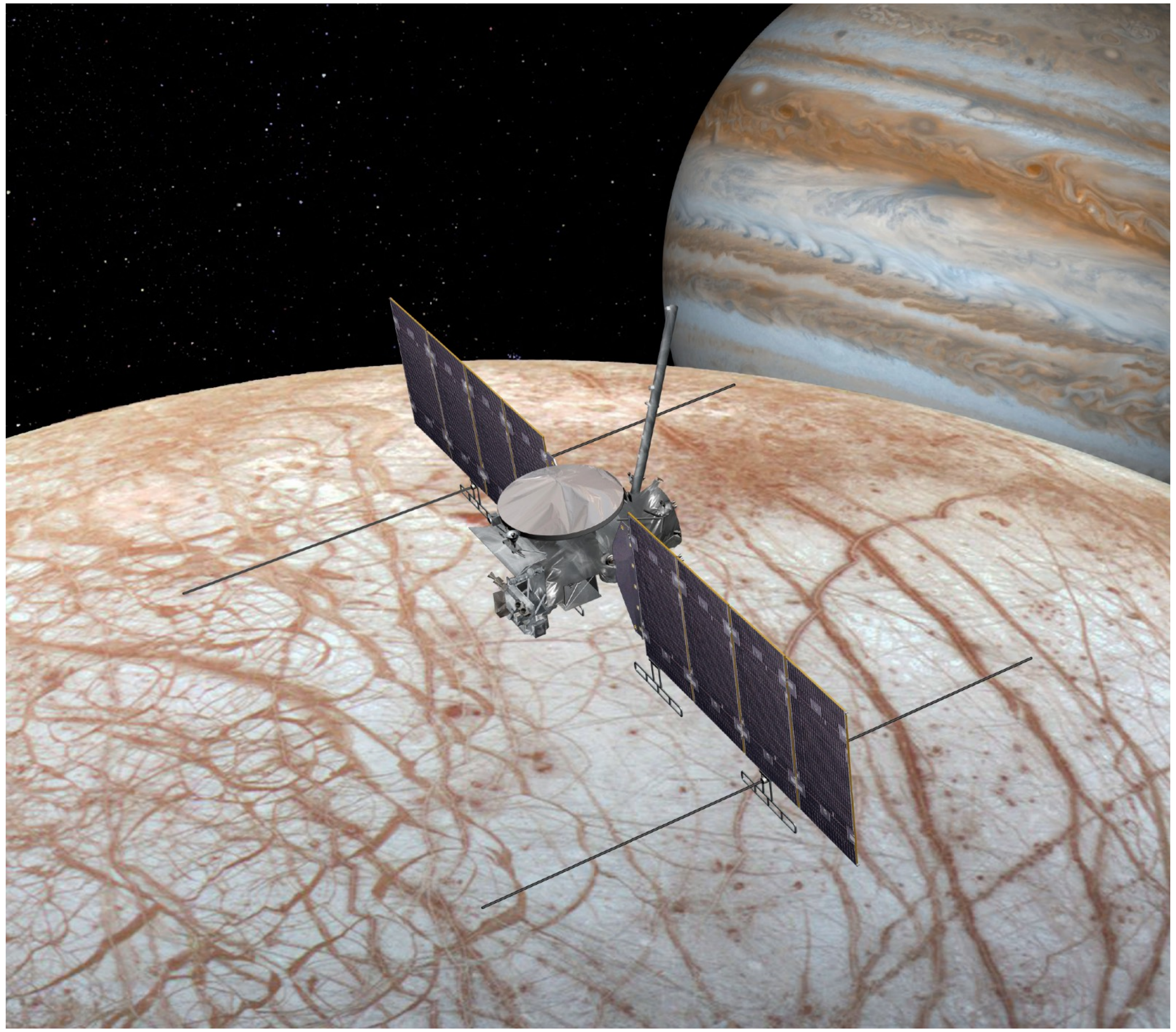
M. Buuck, UW, PhD Dissertation 2019

Summary of Geant4 Activities at JPL

- Support for flagship missions: Europa Clipper
- Support for smaller missions: SPARCS
- Miscellaneous Activities:
  - Juno detector response analysis
  - CAD conversion tools

Europa Clipper

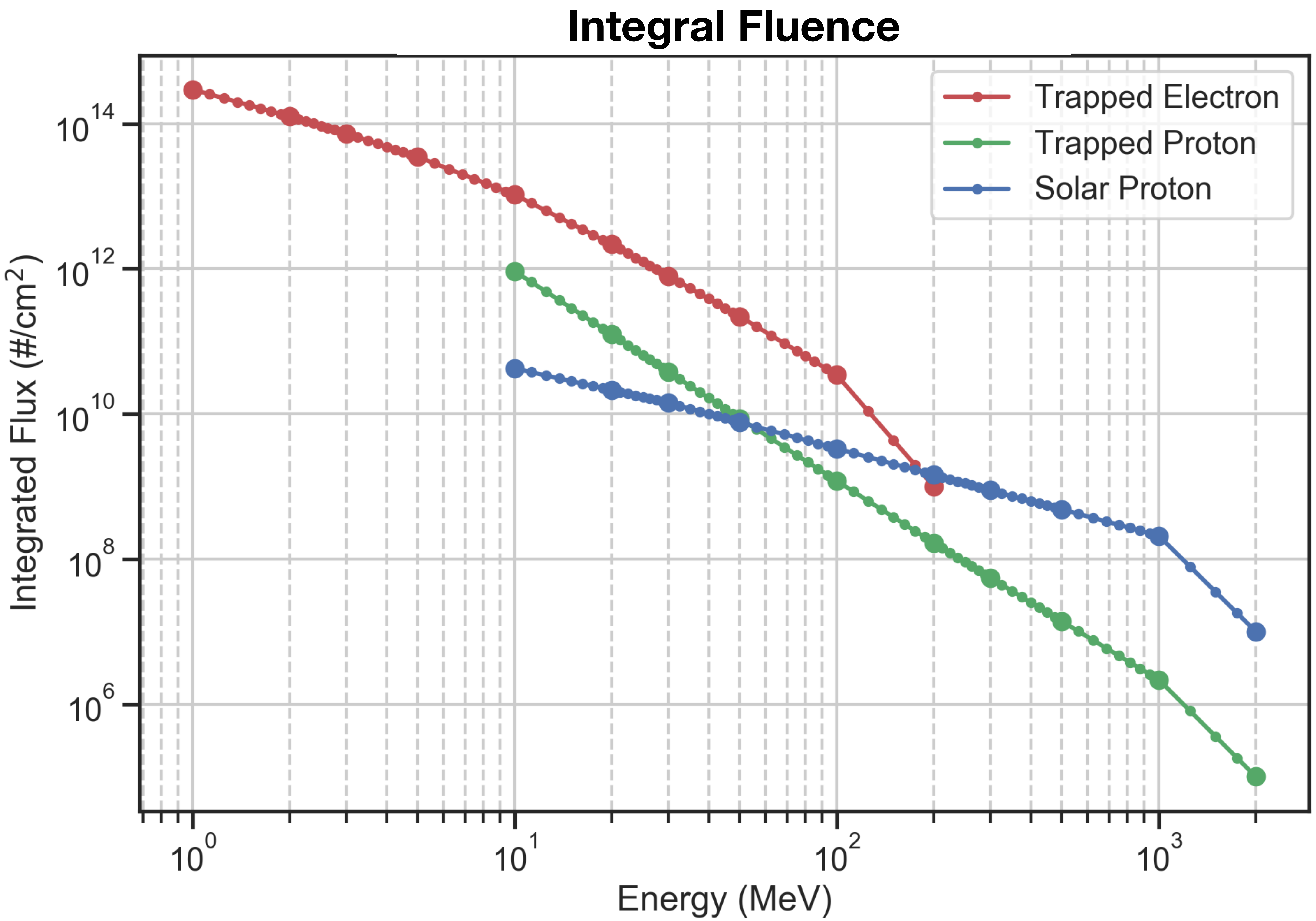
- Europa Clipper will conduct a detailed reconnaissance of Jupiter's moon Europa
    - 45 flybys of Europa with 25 km closest approach
    - Investigate how the ingredients for life might interact to produce habitable environments on Europa
- Complement ESA's JUICE mission
- **Intense radiation environment** sets heavy design constraints on instruments
    - Transient noise analyses performed using FMC (Geant4 and MCNP)
    - Other tools (RMC) used for TID, DDD, SEE, charging analyses



Code Comparison Studies

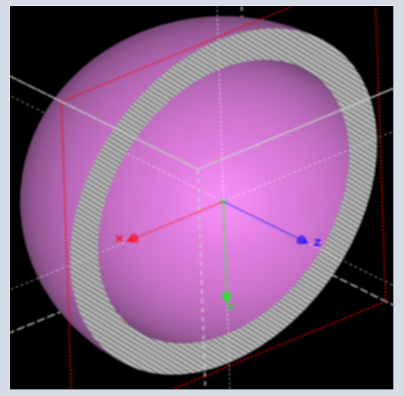
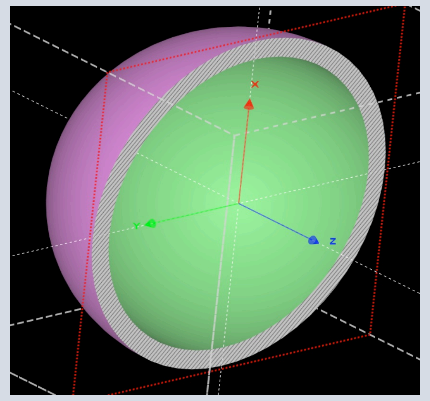
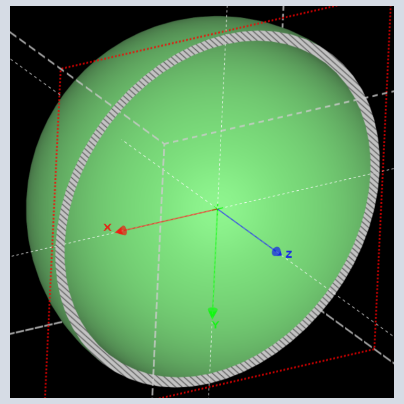
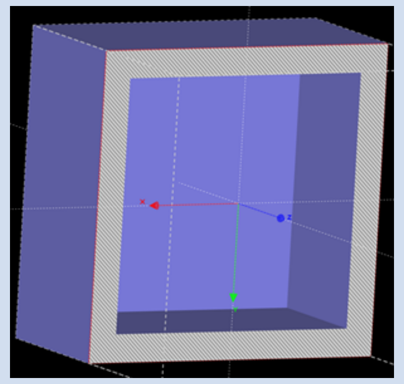
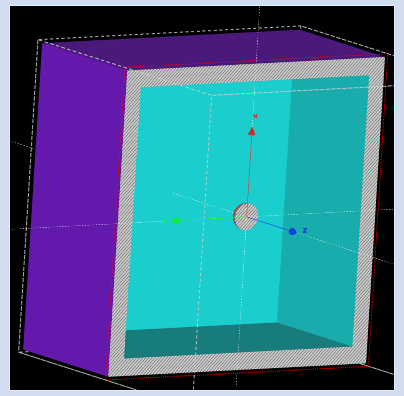
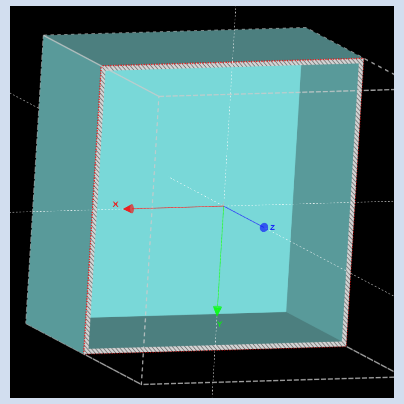
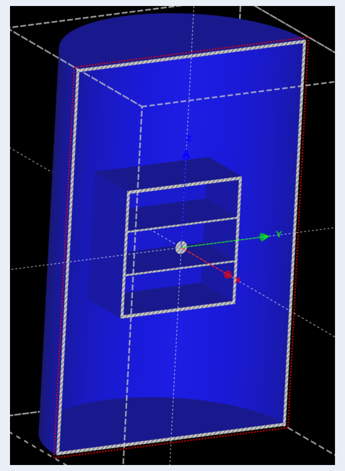
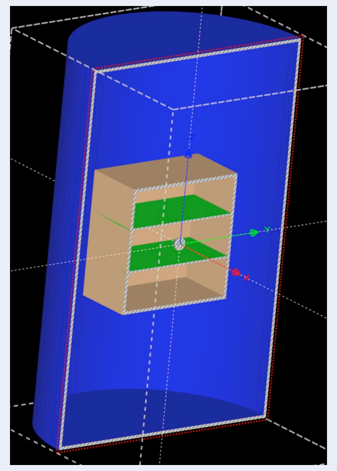
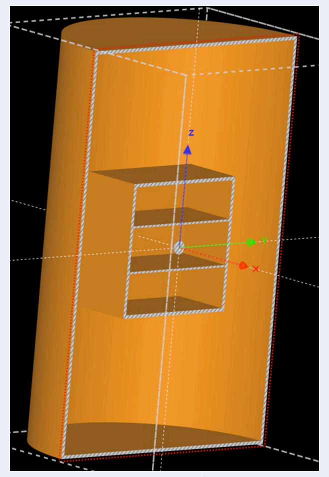
- Europa Clipper has many instruments developed by many institutions using a **wide range of transport tools**
- Tools may produce differing results beyond statistical uncertainties
- Good understanding of dose predictability of transport tools is critical for shielding design optimization
- Tools compared: Geant4.10.5, MCNP6.1, FASTRAD 3.8.10, NOVICE2017
  - Simple geometries used to compare all tools
  - JPL’s heritage transport tools are MCNP and NOVICE

Jovian Radiation Environment



- Intense radiation environment, dominated by trapped electrons
- Trapped particle fluences derived using Divine-Garrett and GIRE3 models
- Solar proton fluences from JPL-SPE model

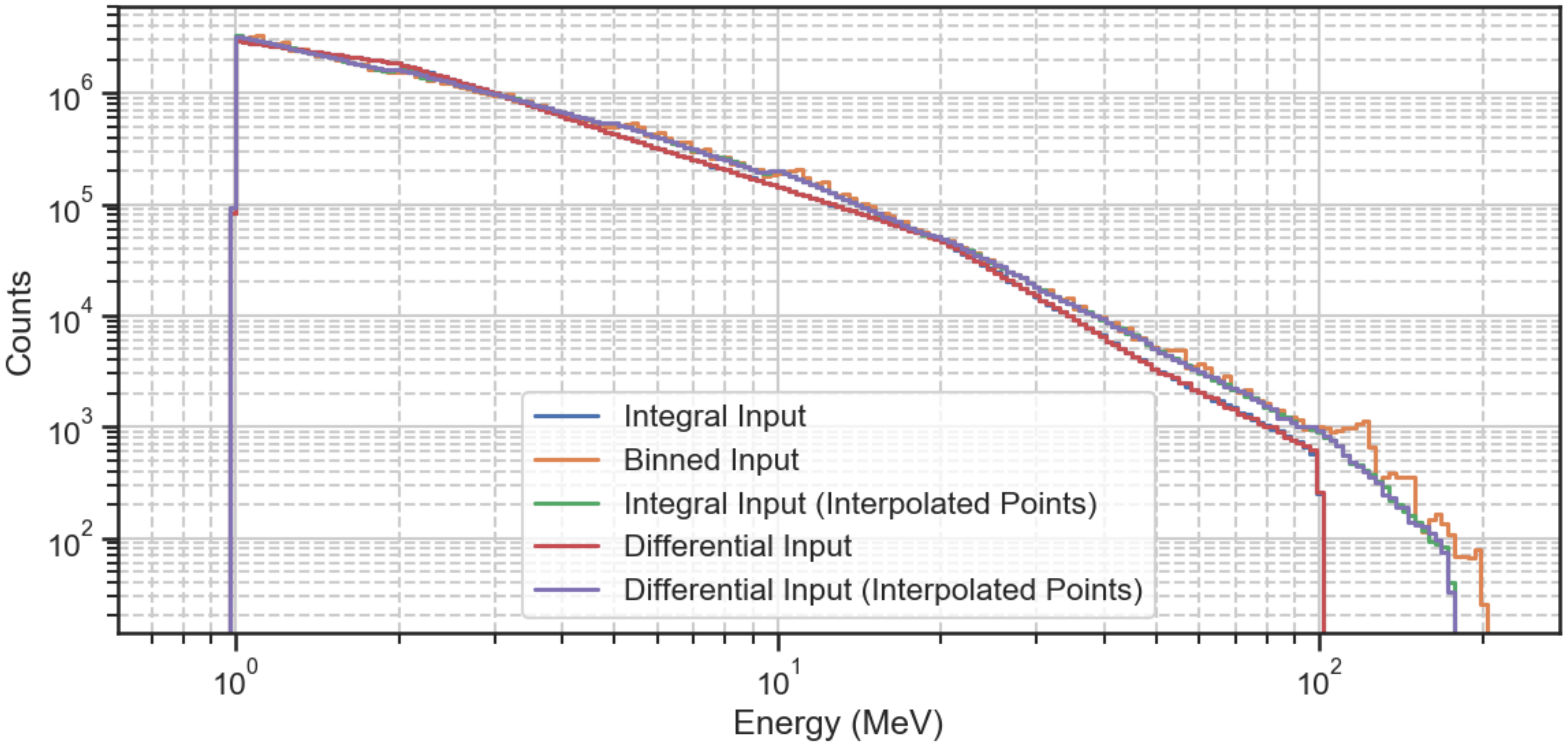
Shielding Geometries Used

 S-1	 S-2	 S-3	Spherical Shell 1. Material S-1: Aluminum S-2: Tantalum/Al S-3: Ta 2. Dimension Radius: 5 cm Thickness: 0.05 ~ 30 g/cm^2
 B-1	 B-2	 B-3	Cubic Box 1. Material B-1: Aluminum B-2: Tantalum/Al B-3: Ta 2. Dimension Length: 10 cm Thickness: 0.05 ~ 30 g/cm^2
 C-1	 C-2	 C-3	Cylindrical vault 1. Material C-1: Aluminum C-2: PCB/Ta/Aluminum C-3: Ta 2. Dimension Cylinder (RxH)=10cm x30cm Box/slab length= 10cm Thickness: 0.25 cm

- Shielding Materials
  - Aluminum (2.7 g/cm^3)
  - Tantalum (16.6 g/cm^3)
- Scanned a wide range of shielding thicknesses (0.05 to 30 g/cm^2)
- Point detector used for RMC studies
- Volume detector (spherical shell r=5mm) used for FMC studies

Lessons Learned: Input Spectrum Format

Input Spectrum to Geant4 using different formats

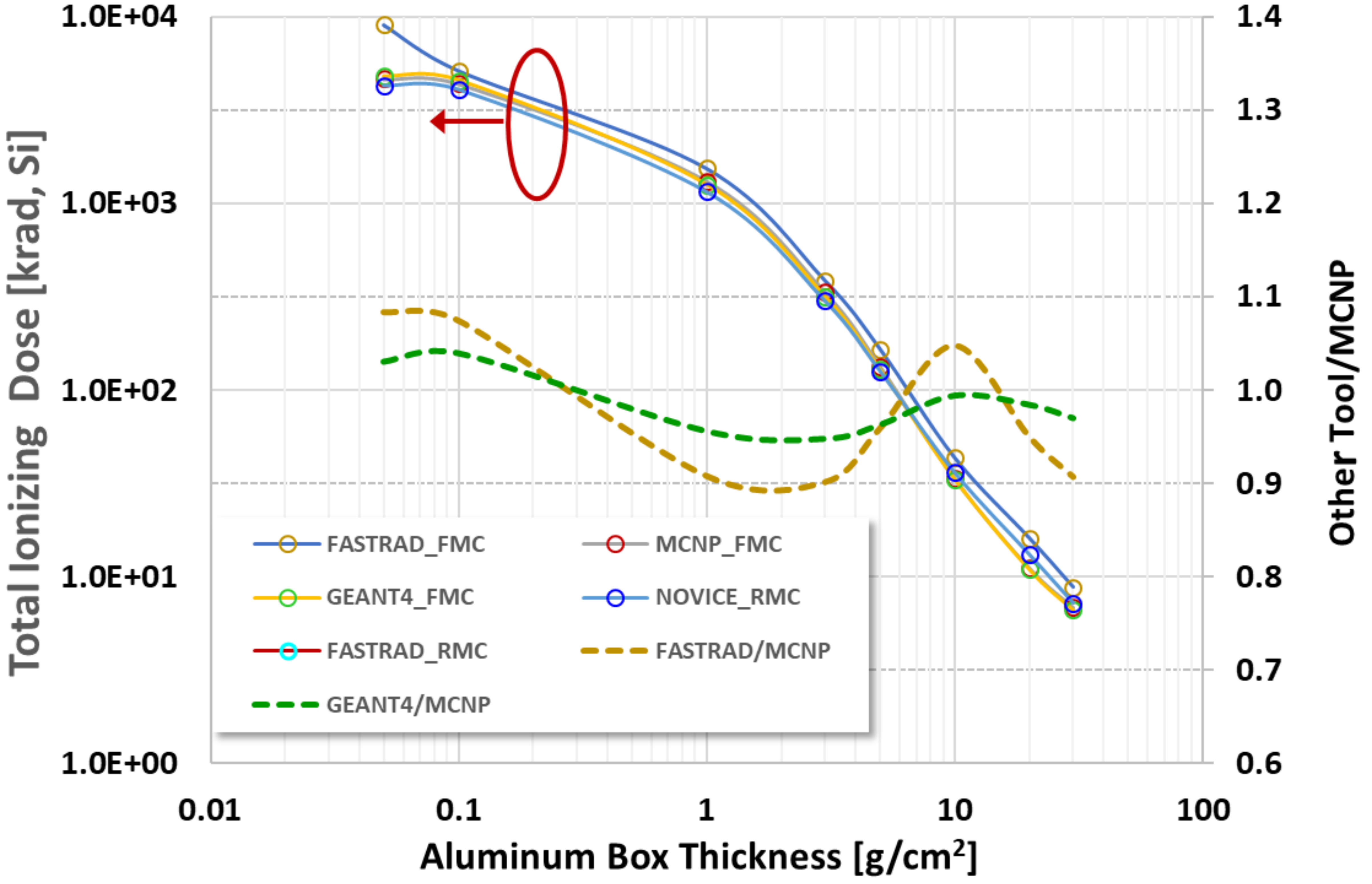


Same environment, but with additional interpolated points using log-log interpolation

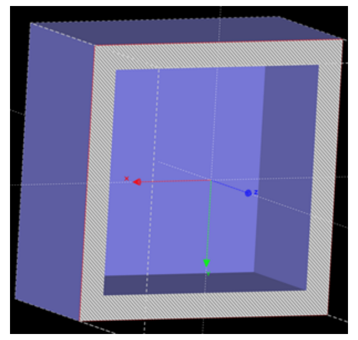
- Initial comparisons with MCNP showed up to 30% difference in TID values at large shielding thicknesses, discovered it was due to differences in input spectrum
- When comparing tools, **consistent input spectra** format is very important
  - GPS internally converts integral fluence to differential before sampling
  - Adding additional interpolation points to environment spectrum with few energy points provides more consistent results
- Decided to use the binned input format, to stay consistent with MCNP input format

TID Comparison Results [1/2]

- Good TID agreement between Geant4 and MCNP
  - Discrepancy increases with high-Z and shielding thickness
- FASTRAD (FMC) comparable to Geant4, but with larger uncertainty
- RMC results are comparable to with ±20%, neither FASTRAD nor NOVICE are always conservative compared to FMC

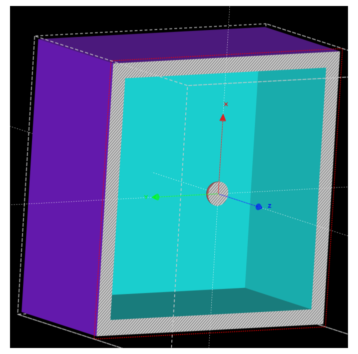


TID Comparison Results [2/2]



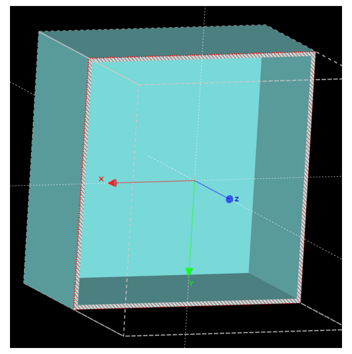
Aluminum only

Al Thickness [g/cm^2]	TID_MCNP [krad, Si]	Geant4 /MCNP	FASTRAD FMC /MCNP	FASTRAD RMC/ MCNP	NOVICE/ MCNP
0.05	4.62E+03	3.1%	8.4%	10.7%	-7.9%
0.1	4.37E+03	4.0%	7.5%	12.1%	-7.2%
1	1.32E+03	-4.4%	-9.2%	2.8%	-12.6%
3	3.33E+02	-5.2%	-9.8%	0.0%	-10.3%
5	1.34E+02	-3.7%	-4.0%	-3.1%	-5.8%
10	3.34E+01	-0.6%	4.8%	-13.7%	7.9%
20	1.11E+01	-1.6%	-5.0%	-18.1%	18.3%
30	6.82E+00	-3.0%	-9.3%	-22.9%	5.9%



Aluminum + Tantalum

Al/Ta Thickness [g/cm^2]	TID_MCNP [krad, Si]	Geant4 /MCNP	FASTRAD FMC /MCNP	FASTRAD RMC/ MCNP	NOVICE/ MCNP
0.025/0.025	4.62E+03	2.4%	6.6%	10.9%	-7.4%
0.05/0.05	4.36E+03	2.4%	5.4%	11.3%	-6.8%
0.5/0.5	1.08E+03	14.1%	-13.3%	1.8%	5.0%
1.5/1.5	2.25E+02	-4.2%	-14.5%	-5.4%	29.3%
2.5/2.5	8.56E+01	-6.4%	-21.0%	-14.7%	43.7%
5/5	2.05E+01	8.5%	-4.5%	-21.0%	72.3%
10/10	9.56E+00	-10.1%	-17.7%	-33.7%	27.6%
15/15	4.97E+00	2.8%	-2.8%	-12.4%	40.6%



Tantalum only

Ta Thickness [g/cm^2]	TID_MCNP [krad, Si]	Geant4 /MCNP	FASTRAD FMC /MCNP	FASTRAD RMC/ MCNP	NOVICE/ MCNP
0.05	4.46E+03	4.9%	-0.4%	16.1%	-4.6%
0.1	4.26E+03	2.9%	2.3%	12.0%	-4.6%
1	9.72E+02	12.3%	-21.3%	-4.5%	17.2%
3	1.91E+02	-9.7%	-24.6%	-17.2%	51.7%
5	7.93E+01	-9.6%	-22.7%	-29.5%	52.6%
10	3.17E+01	-6.4%	-11.9%	-33.6%	9.4%
20	1.67E+01	-6.1%	-12.8%	-20.7%	-28.2%
30	9.72E+00	3.5%	-10.5%	-5.8%	-29.5%

MCNP

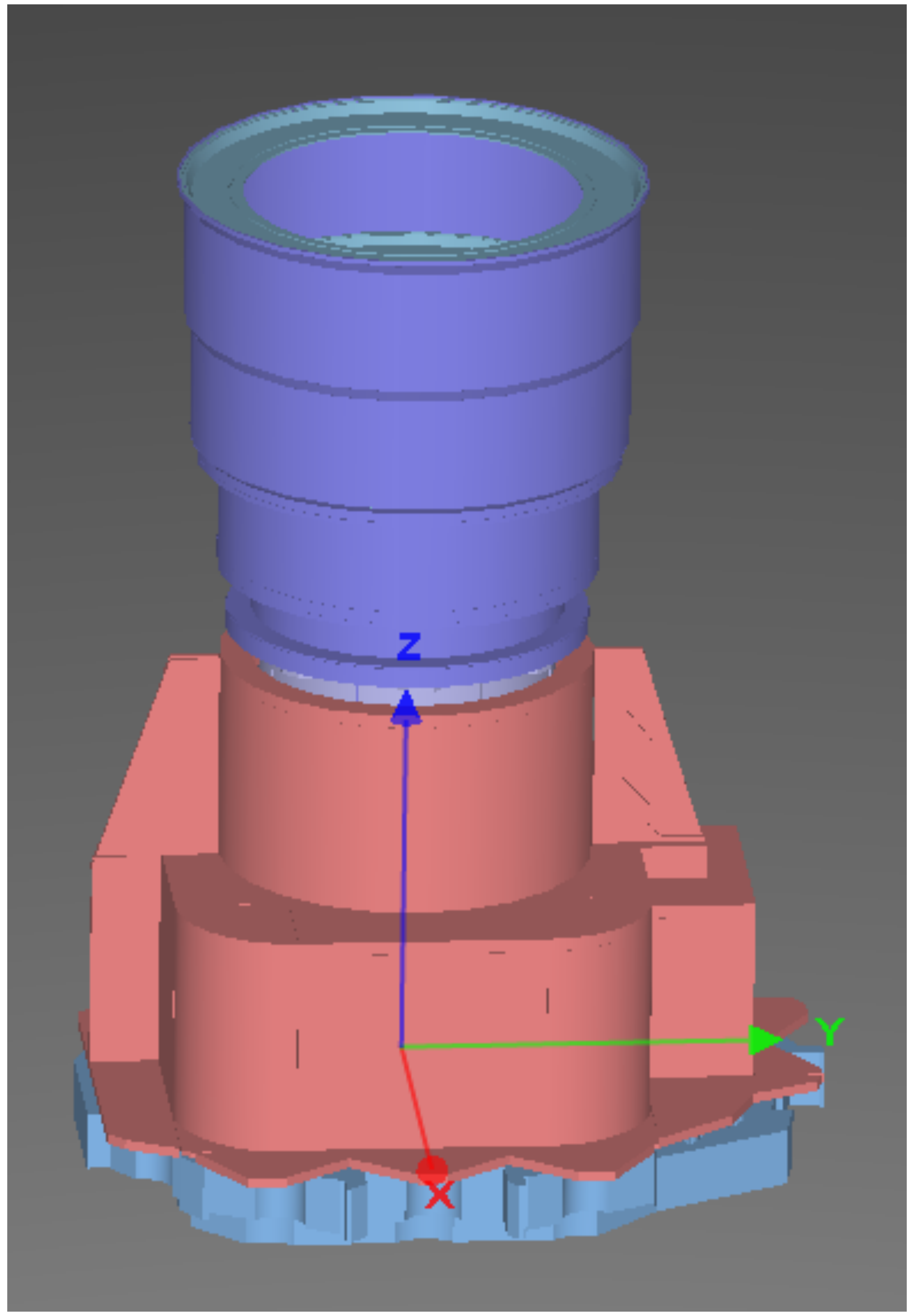
-34%	-30%	-20%	-10%	0%	10%	20%	30%	40%	50%	60%	70%	73%

Not Conservative (Under Predict) ← → *Conservative (Over Predict)*

Transient Noise Analyses

- Detecting stars among high rate of transient ionizing events presents a unique challenge for SRU algorithms
- Geant4 used to estimate transient noise:
  - Used mono-energetic electron/proton to scan over energy range of environment
  - Modeled signal deposition and noise contributions along different spacecraft trajectories with different fluxes
  - Provided insight on directionality of penetrating events

SRU Optical Head

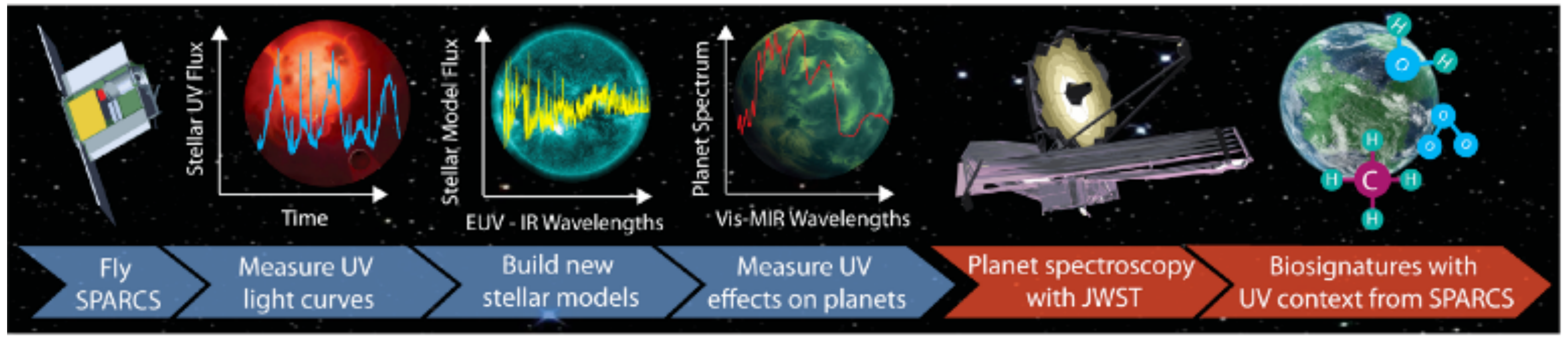


CAD conversion to GDML via FASTRAD

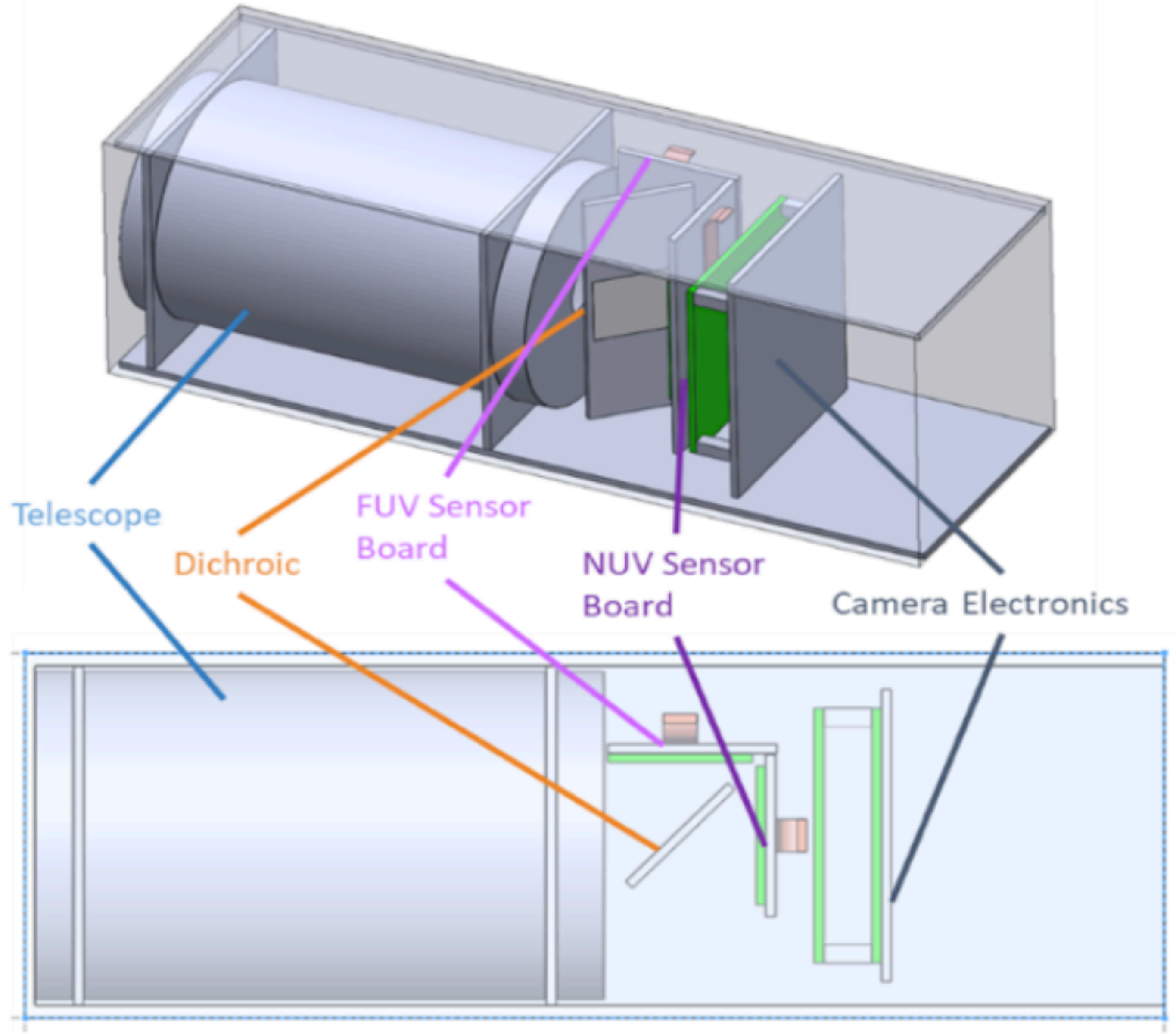
SPARCS

- Star-Planet Activity Research CubeSat (SPARCS)
  - UV radiation from M-type stars (red dwarfs) affects atmospheric loss of exoplanets, impacting habitability zone
  - Monitor NUV (260-300 nm) and FUV (153-171 nm) emissions to assess the habitability of exoplanets orbiting these stars
  - 6U CubeSat, sun-synchronous orbit at ~500 km altitude
- First mission dedicated to monitoring the high-energy radiation environments of exoplanets
  - One of the few CubeSats with science mission requirements

SPARCS Mission Science Goals



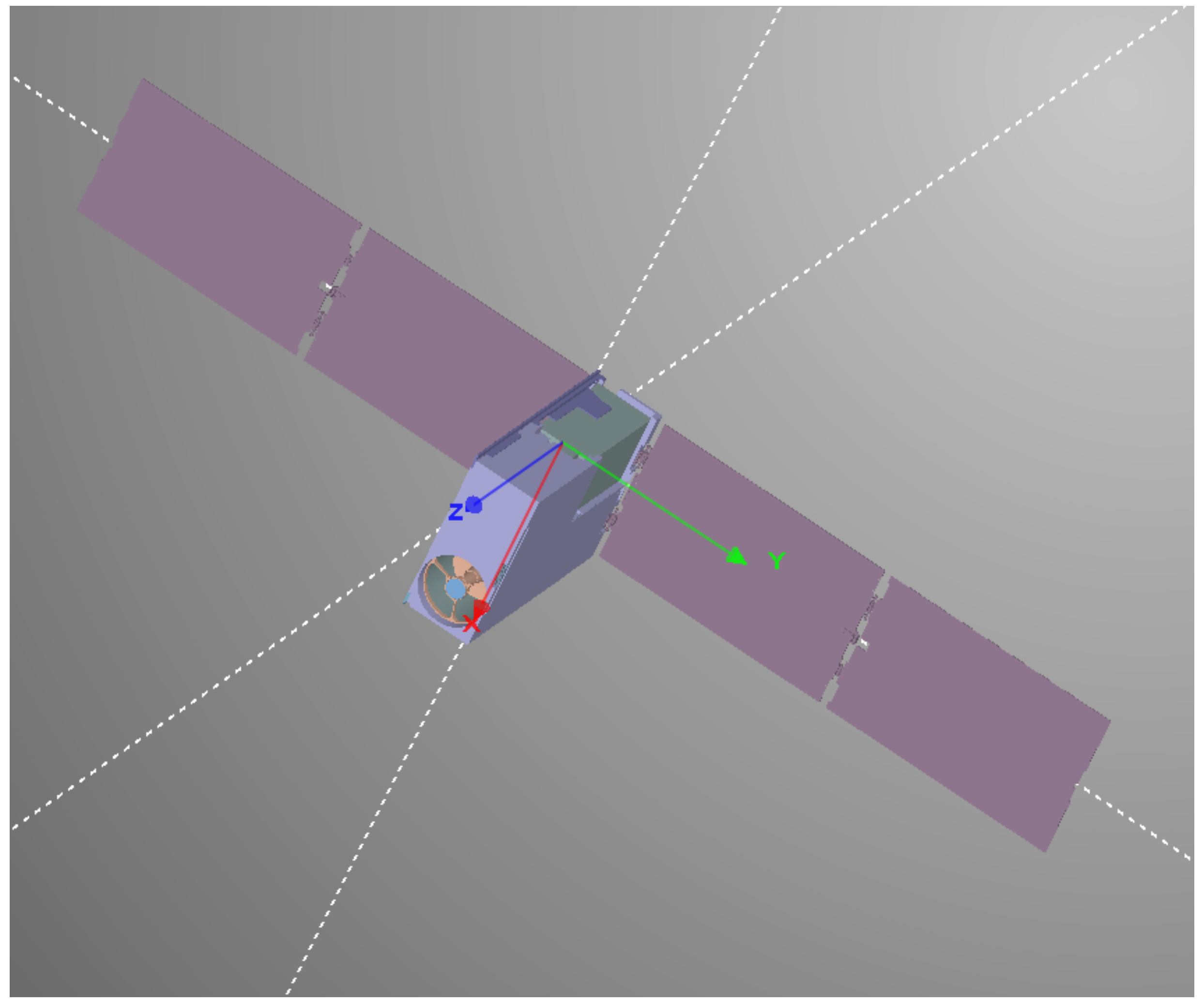
Notional Payload Configuration



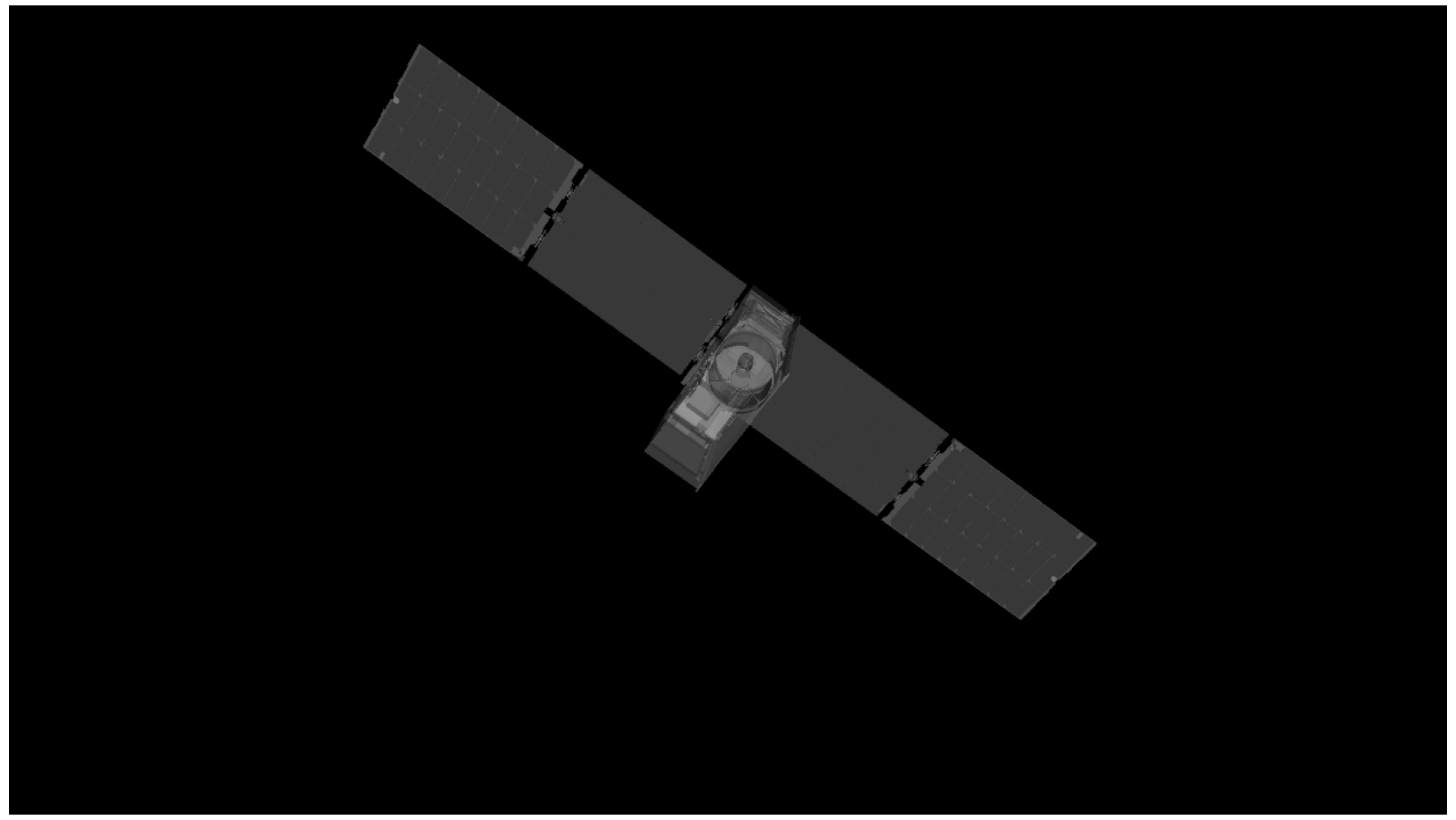
SPARCS: Geant4 Analyses

- JPL team provides the camera for the spacecraft
- Geant4 analyses:
  - TID analysis over full mission trajectory
  - Transient noise analysis over operational periods
  - Experimenting with Geant4 optical photon simulations (and comparing with analytic calculations) to estimate Cerenkov background

CAD conversion to GDML via FASTRAD



Geant4 visualization using VRML



Miscellaneous Activities

- Geant4 simulations on Juno instruments to characterize response to high energy radiation
- Exploring other CAD conversion tools: DAGMC
  - Can potentially integrate geometry models for Geant4, MCNP, FLUKA, etc

UNIVERSITY OF WISCONSIN–MADISON
DAGMC
Direct Accelerated Geometry Monte Carlo Toolkit

Summary

- Ramping up Geant4 usage at JPL to support space missions
- Many lessons learned from transport code comparison studies with simple geometries
- Ongoing efforts to better understand Geant4 as well as exploring new tools to improve our analysis capabilities

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