

Nuclear Data Measurements in Support of NASA Planetary Science Missions

NSRL as a tool for fundamental science research

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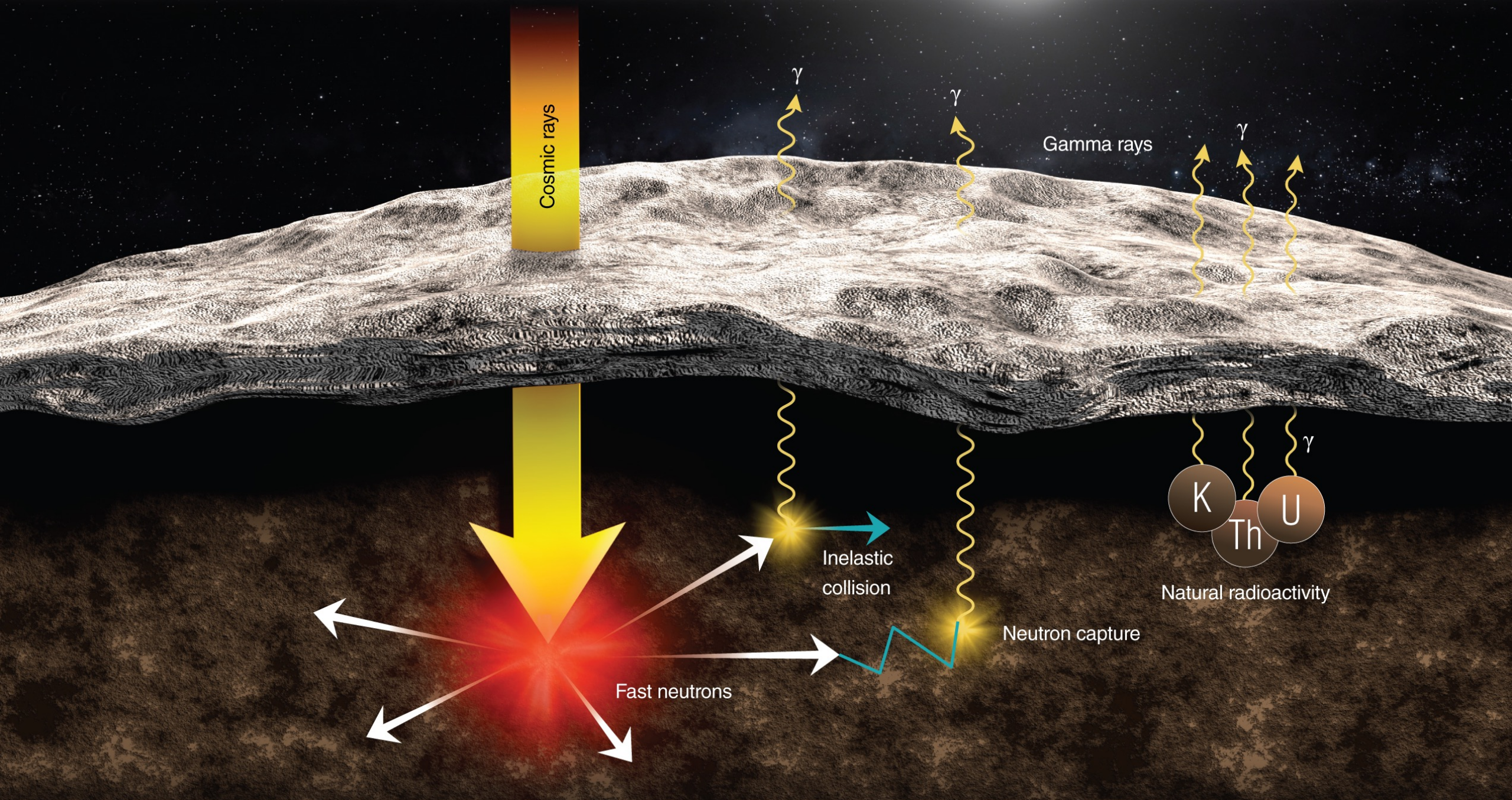
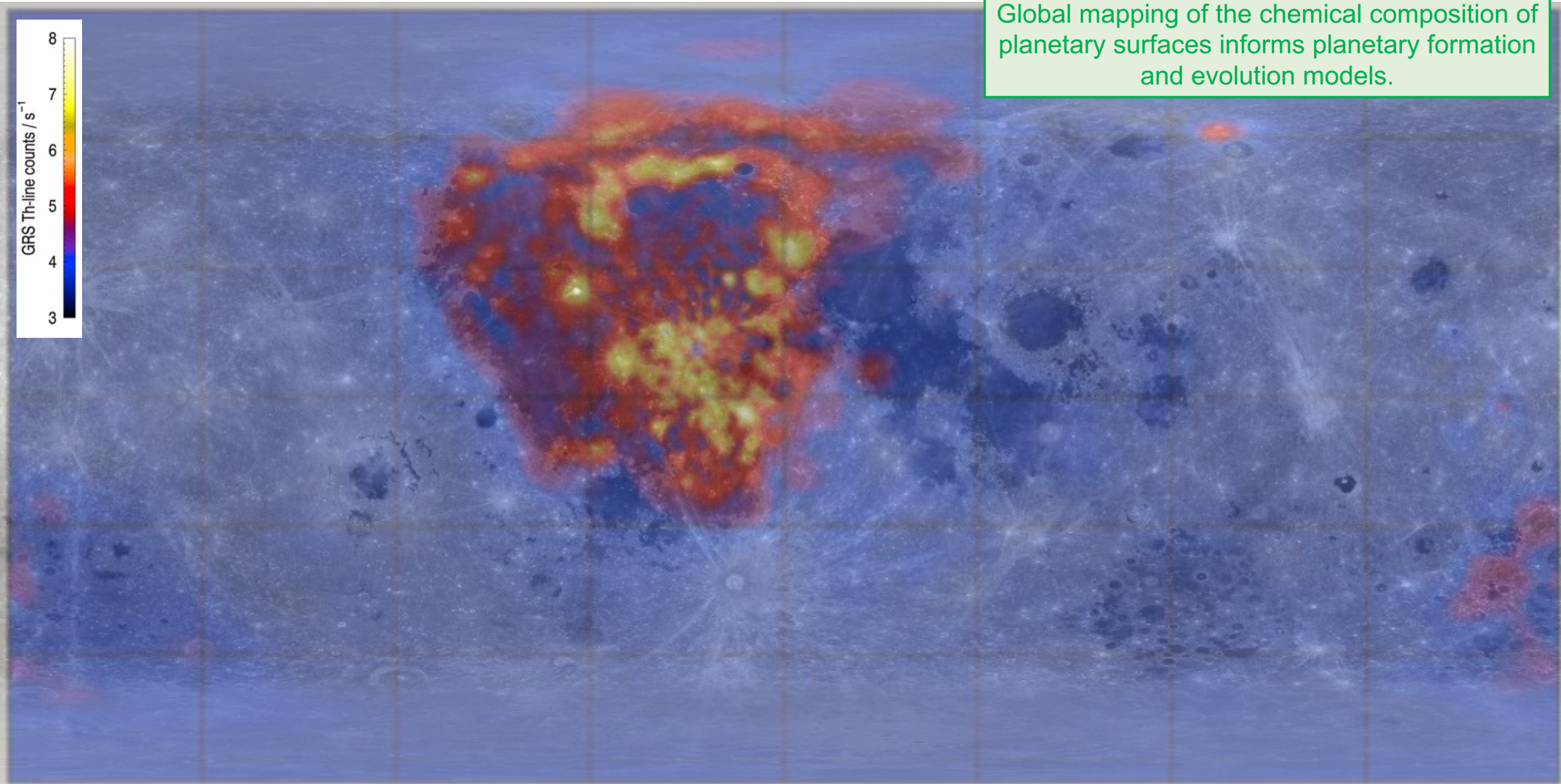
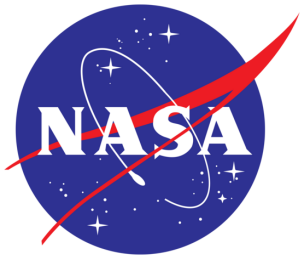




IMAGE CREDIT: NASA

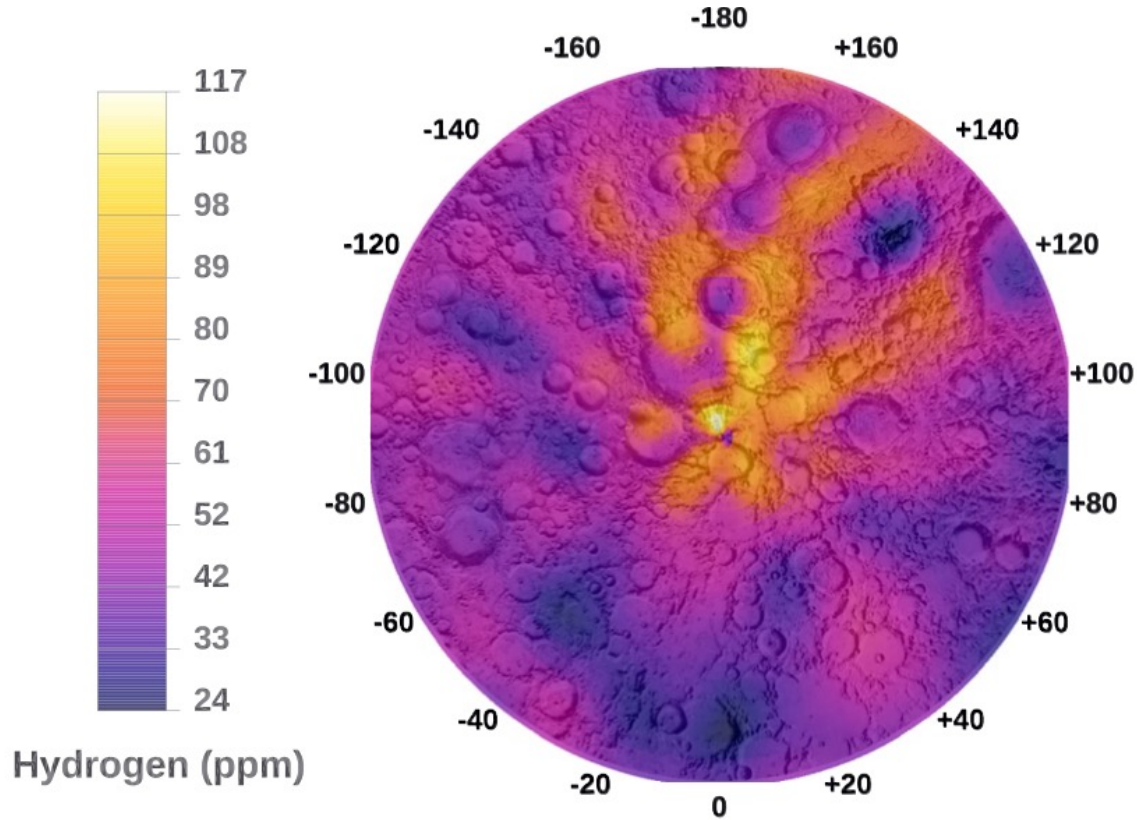
Global mapping of the chemical composition of planetary surfaces informs planetary formation and evolution models.



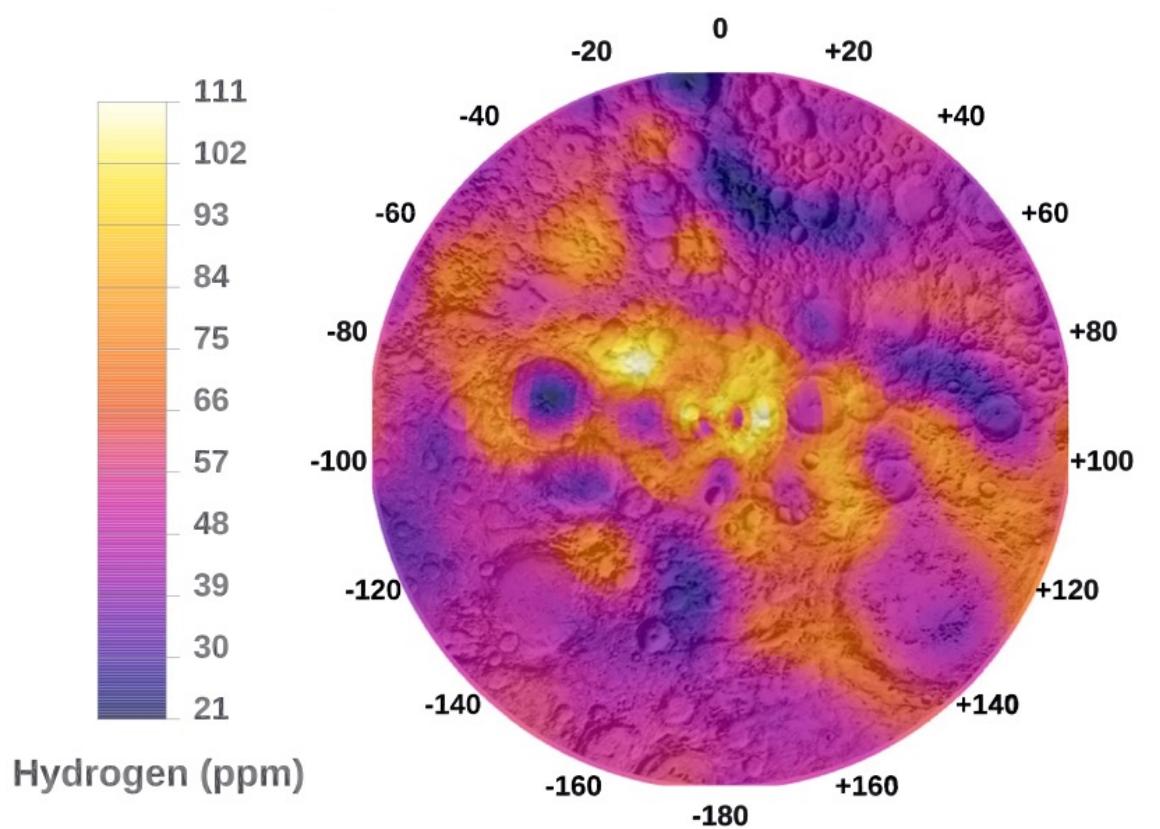


Global mapping of hydrogen (and other resources) supports long-term human exploration.

North Pole



South Pole



Lunar Prospector Neutron Spectrometer Measurements

Gamma-ray and neutron spectrometers are included on many current and upcoming planetary science missions.

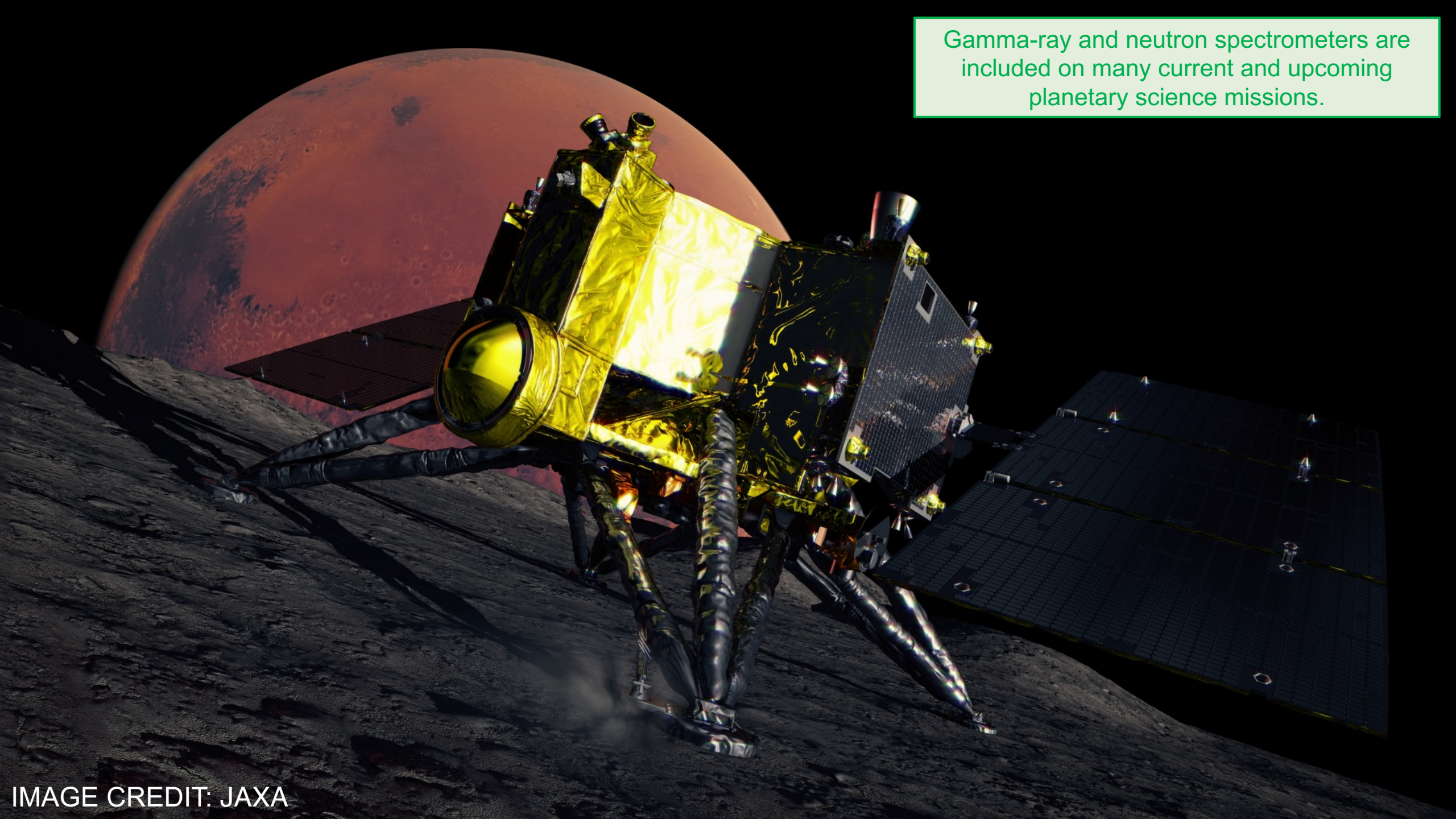
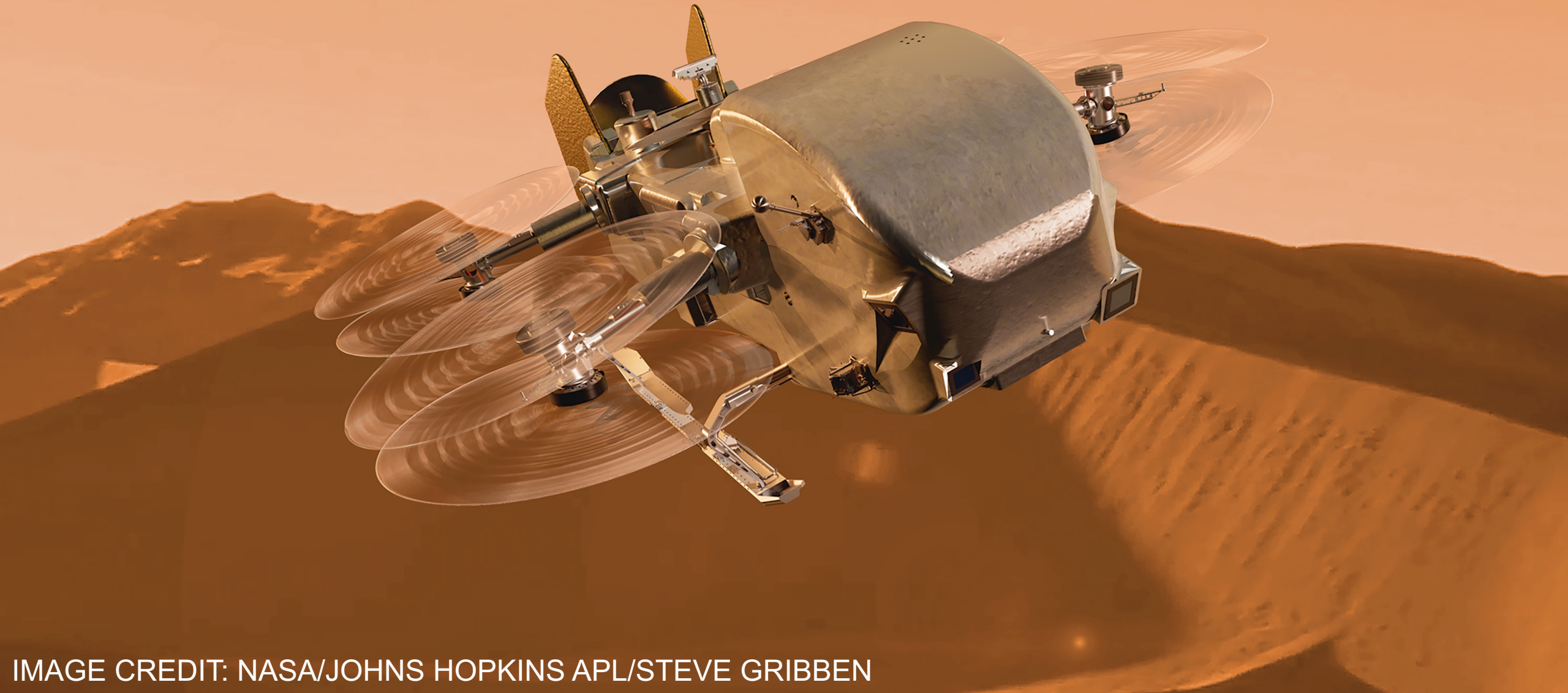
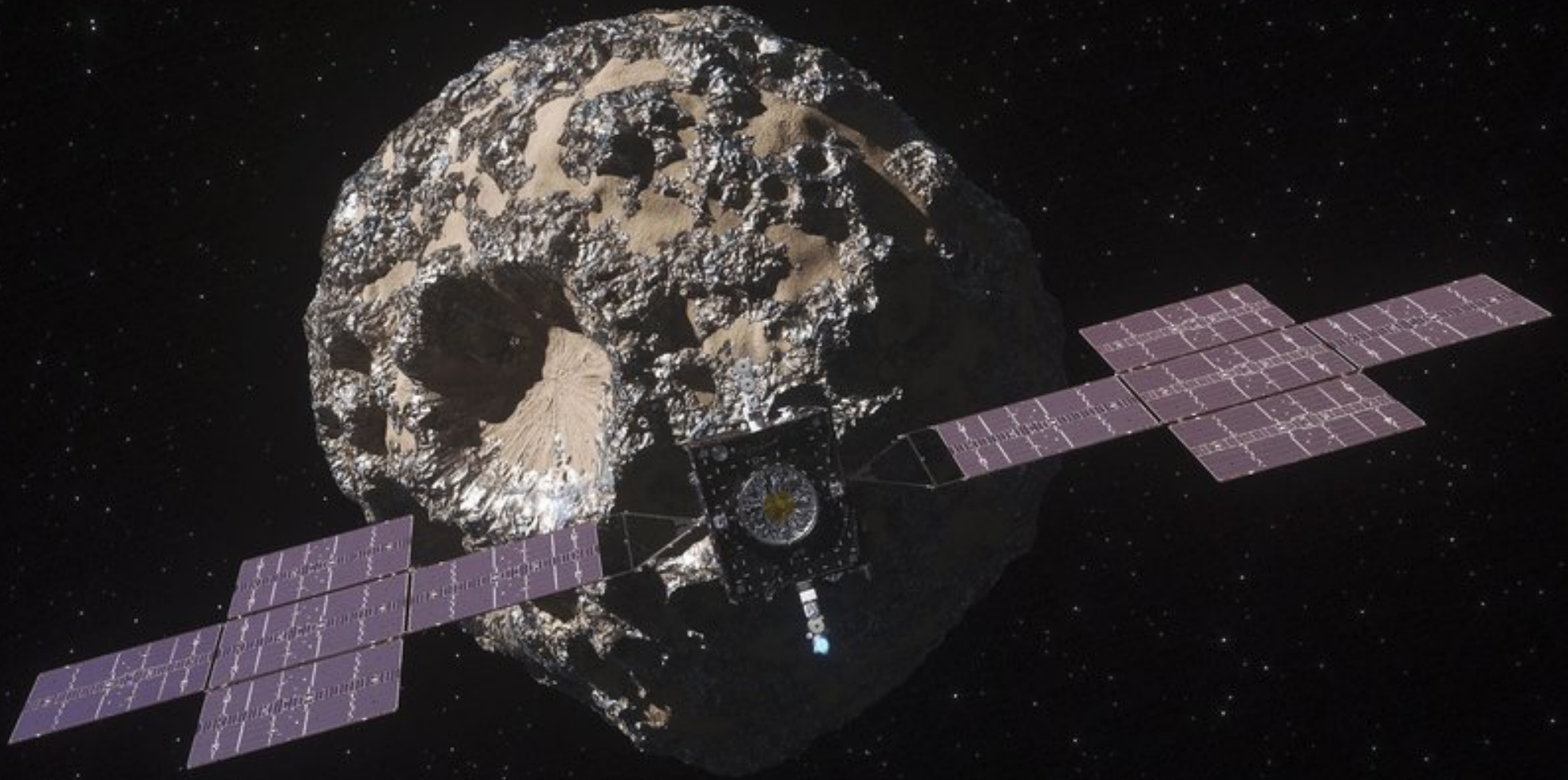


IMAGE CREDIT: JAXA

Gamma-ray and neutron spectrometers are included on many current and upcoming planetary science missions.



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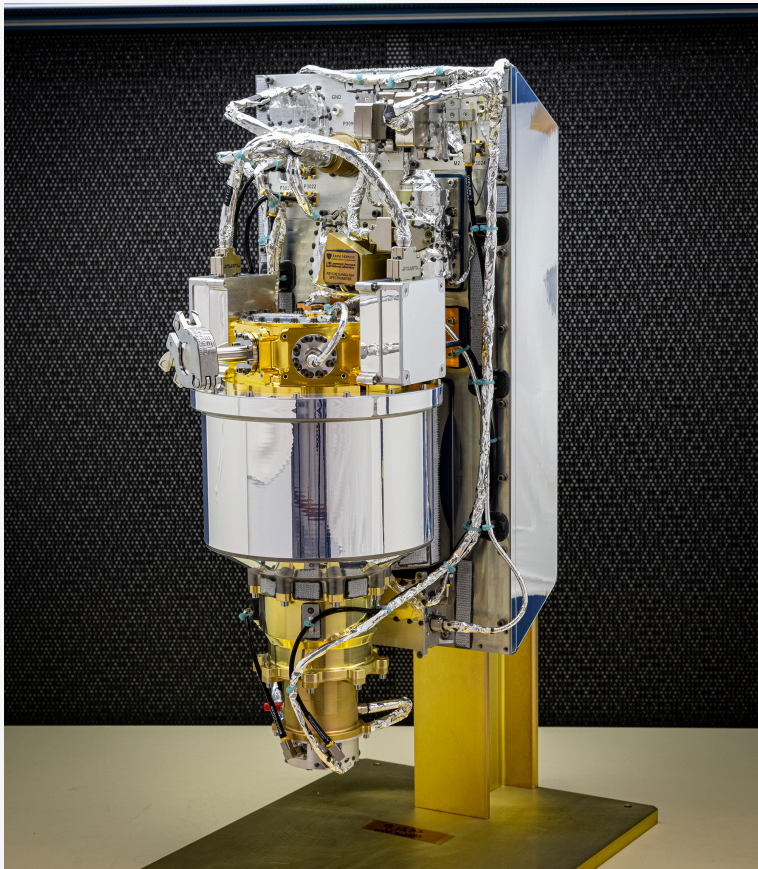
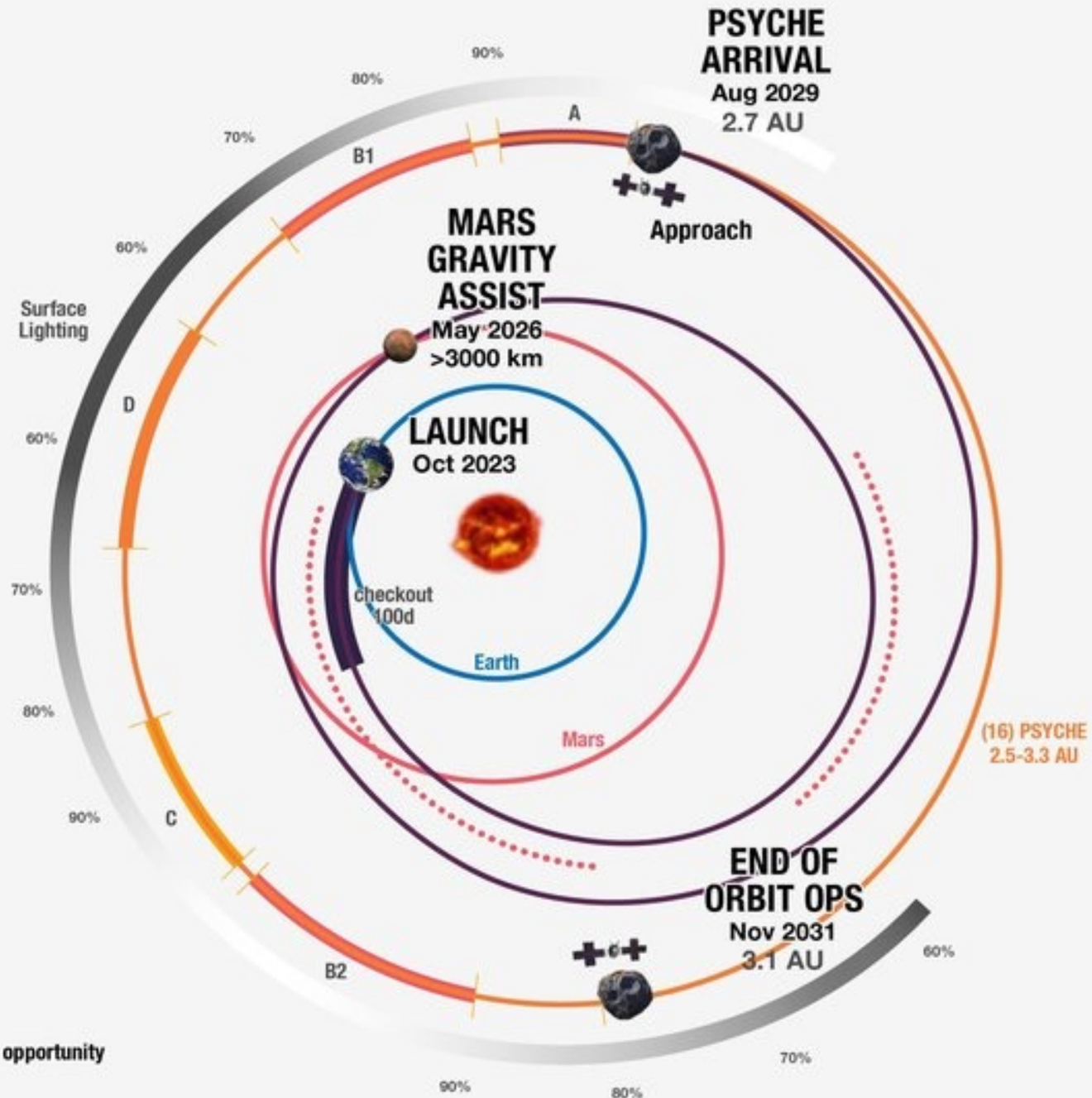


Image Credit: Johns Hopkins APL



- (16) PSYCHE orbit
- Cruise trajectory
- ⋯ Deep Space Optical Comm. opportunity

Image Credit: NASA/JPL-Caltech

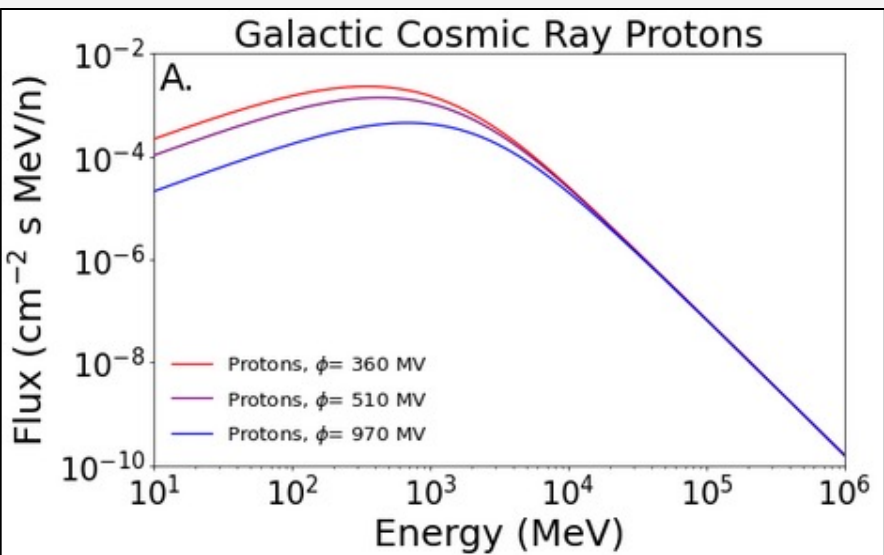


Image Credit: P. Peplowski, Johns Hopkins APL

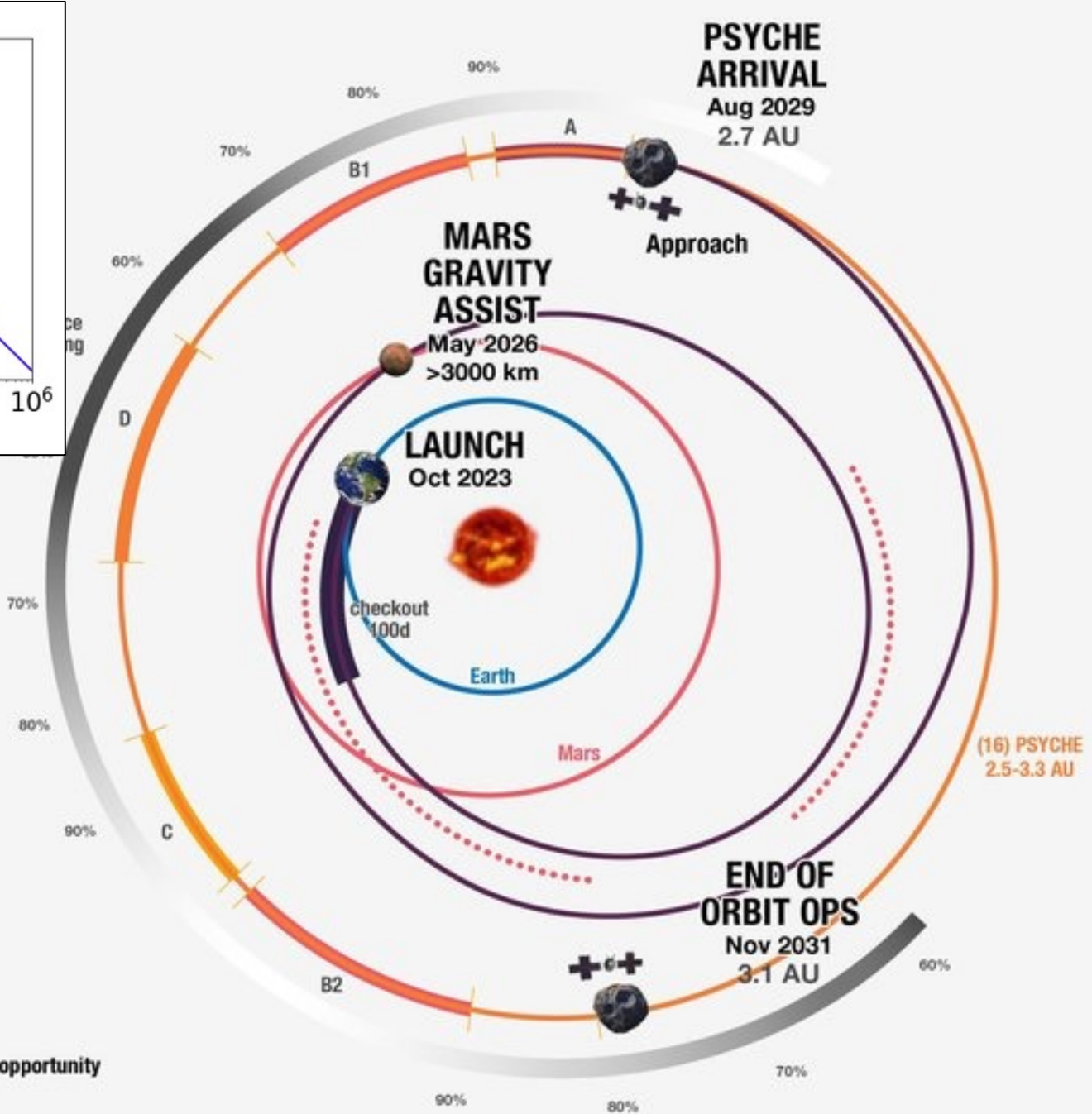
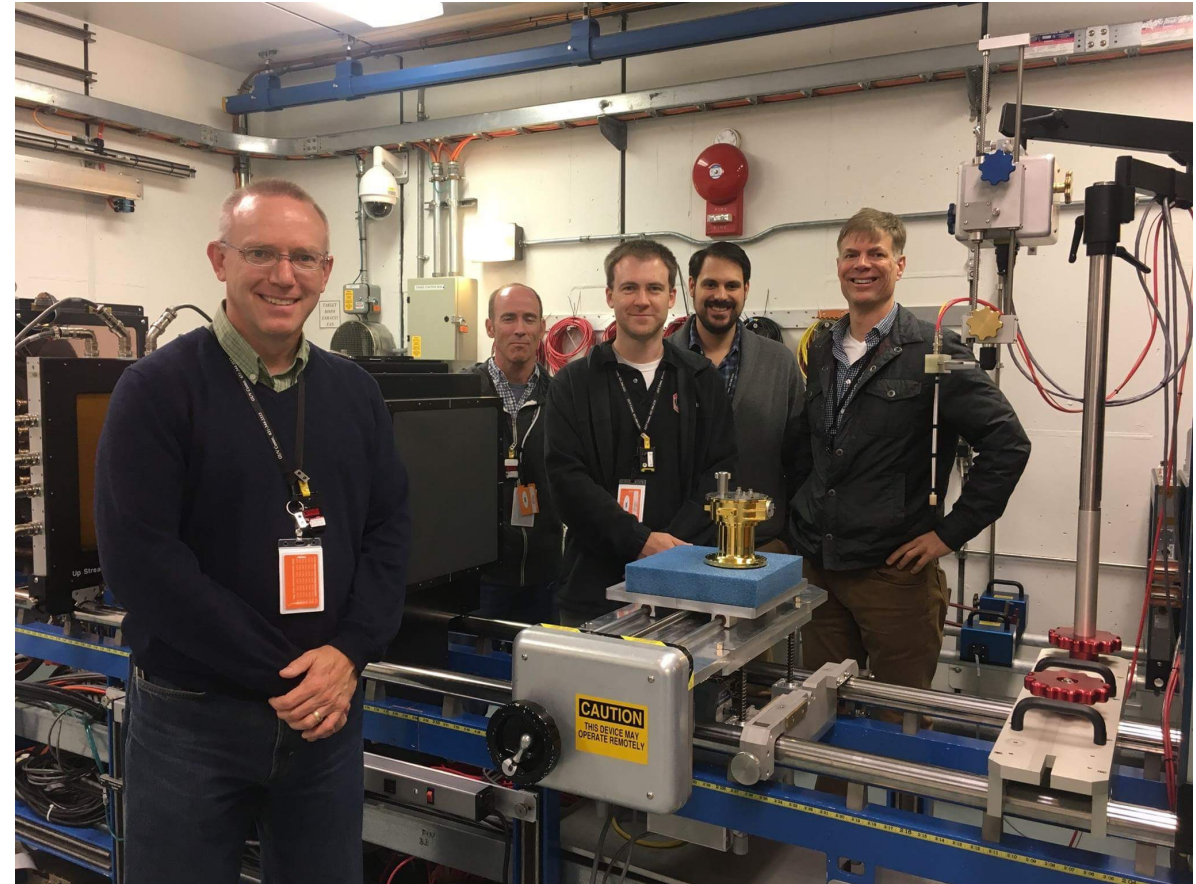


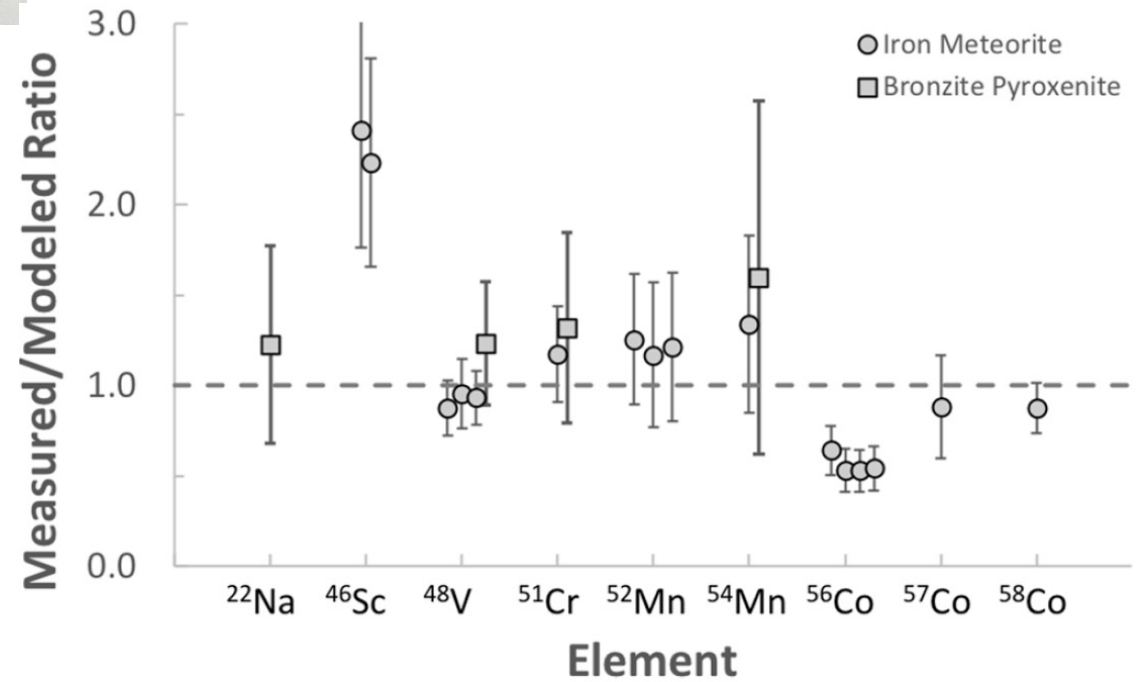
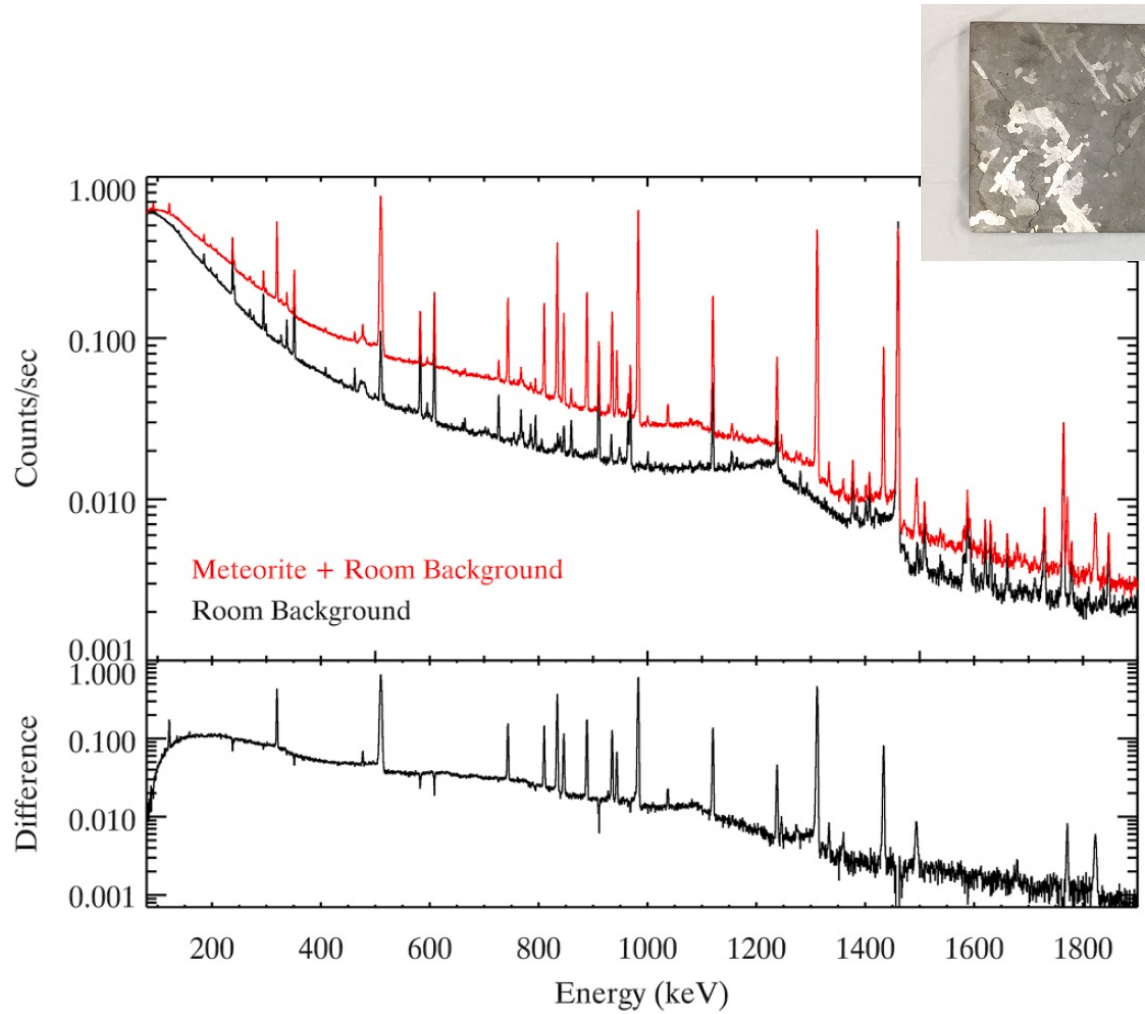
Image Credit: NASA/JPL-Caltech

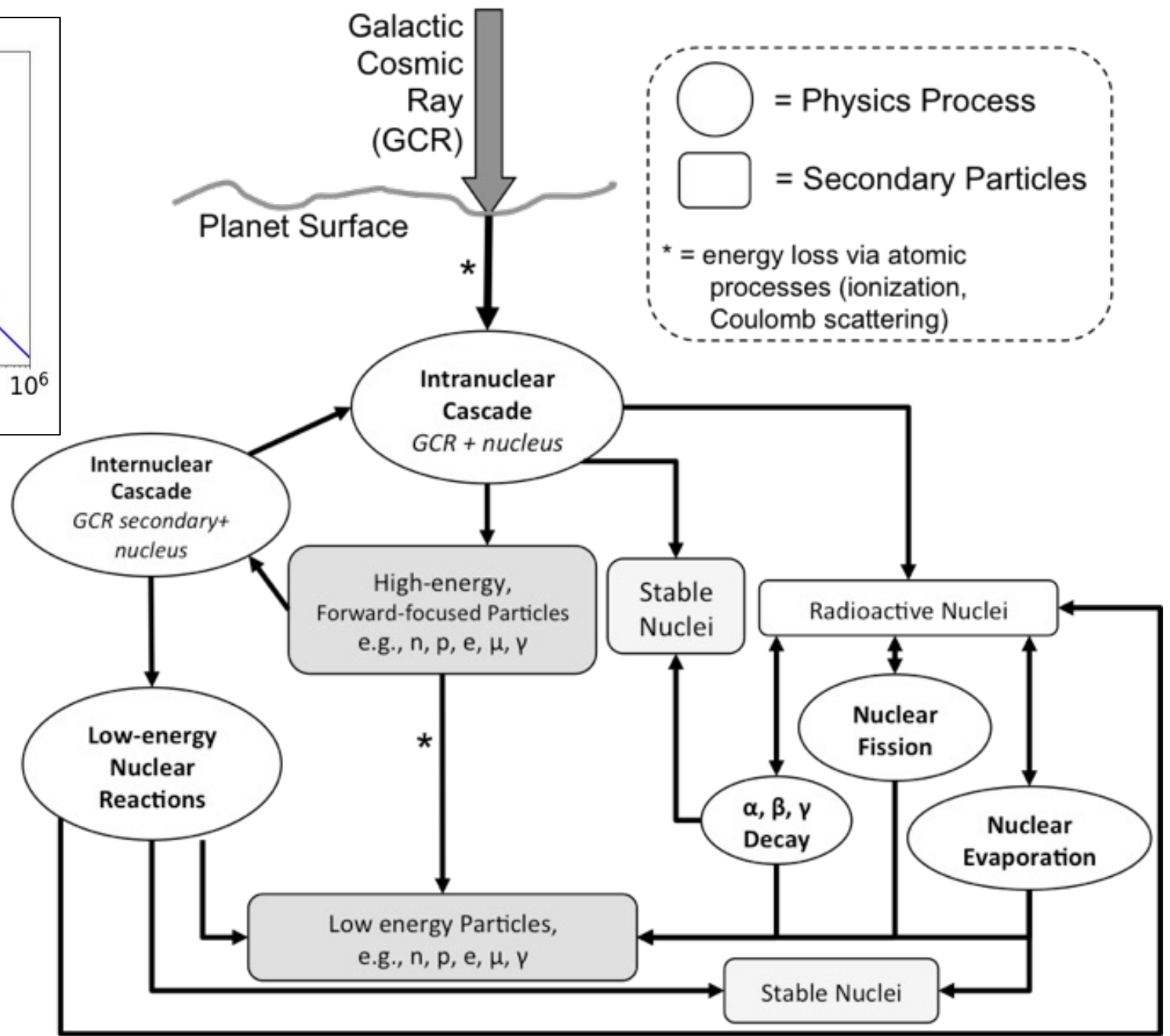
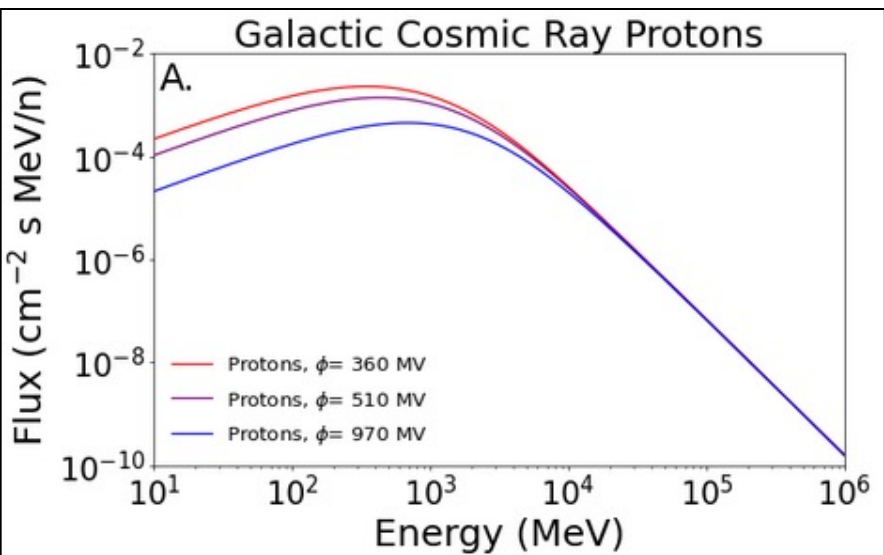
Radiation Damage Studies

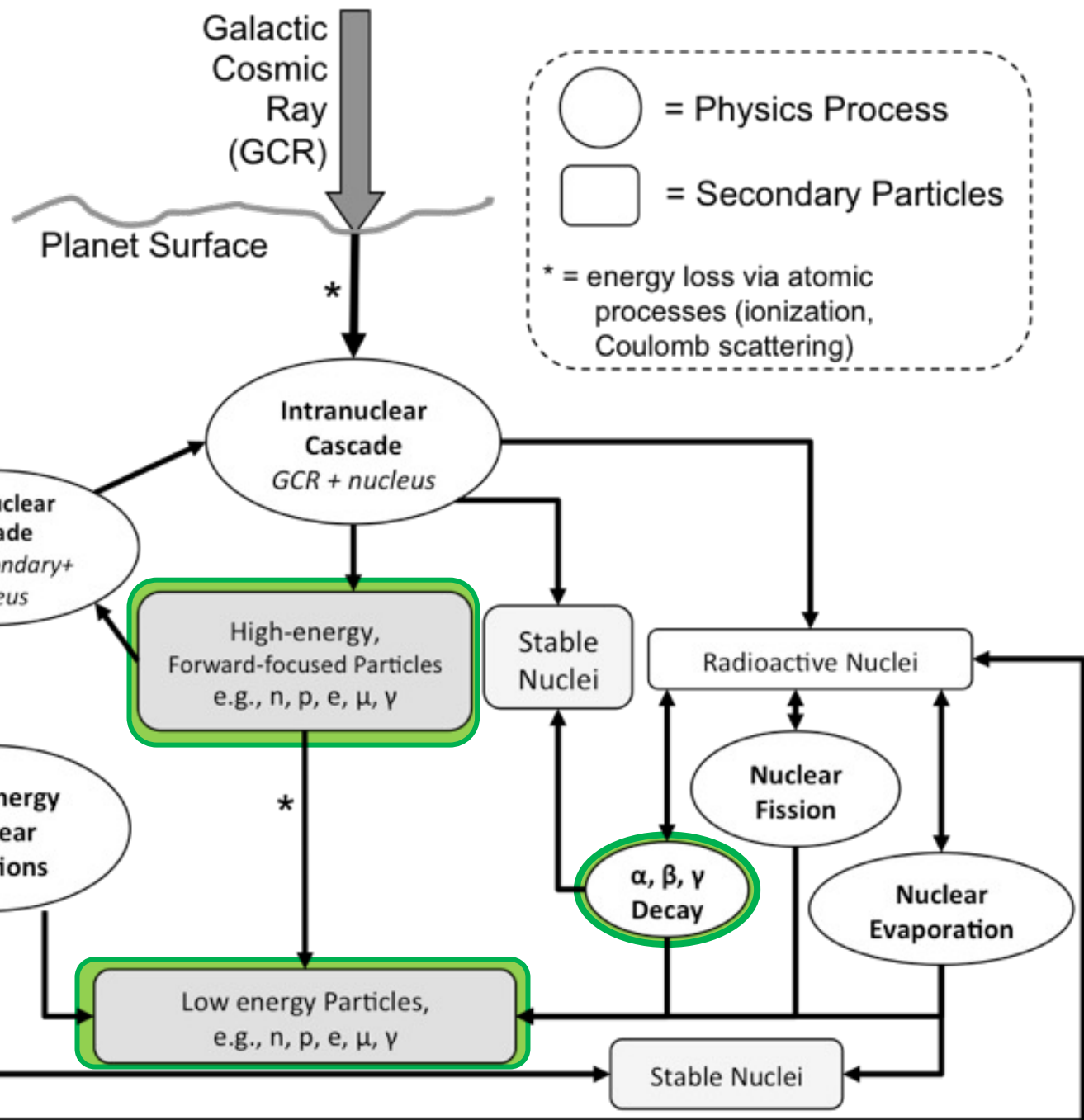
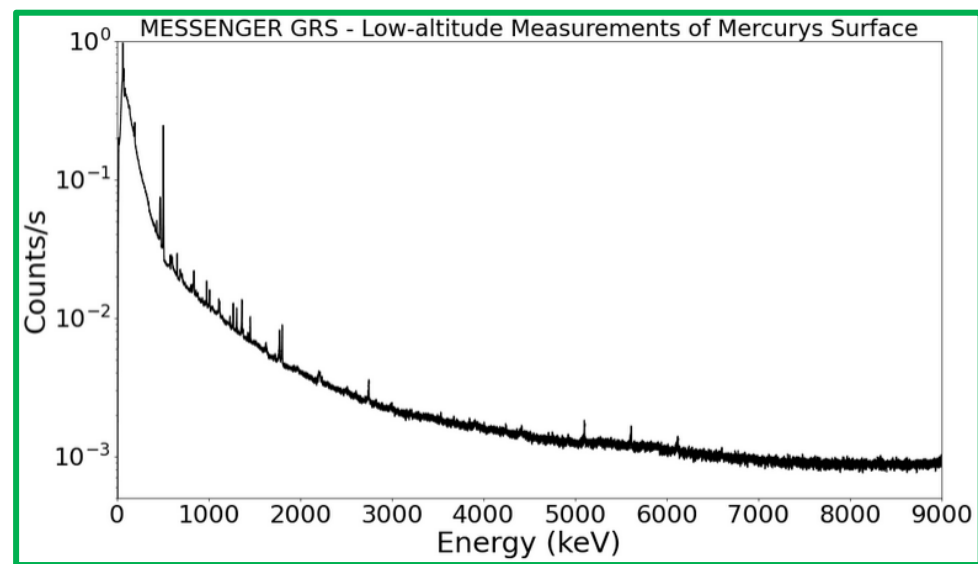


October 2017 – The first of many trips to NSRL

Meteorite Irradiation







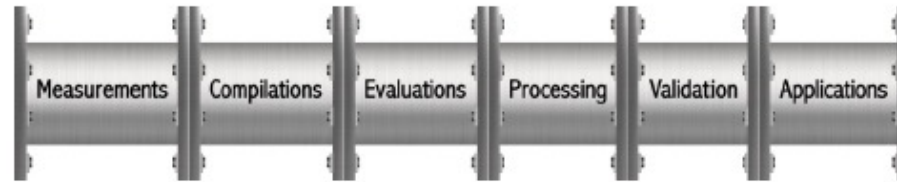
γ -ray and neutron production on planetary surfaces results from dozens of nuclear processes, caused by a variety of particles with energies spanning ~10s of MeV to >GeV.

Models are required to interpret nuclear spectroscopy measurements.

Data is required to validate those models.

Nuclear Data at NSRL

The Nuclear Data Pipeline



“Nuclear spectroscopic investigations also require knowledge of spallation cross sections from energies of a few tens of MeV to hundreds of GeV in typical rock-forming elements. The number of neutrons released in a spallation reaction is particularly important. Because of the wide variety of elements and energies in question, benchmarking experiments are particularly valuable [230] for guiding the decision of physics simulations for GEANT4 and MCNP6. These data needs overlap with the needs of the radiation shielding and isotope production communities.”

References NSRL cross section measurements

Current nuclear data needs for applications

Karolina Kolos,¹ Vladimir Sobes,² Ramona Vogt,^{1,3} Catherine E. Romano,⁴ Michael S. Smith,⁵ Lee A. Bernstein,^{6,7} David A. Brown,⁸ Mary T. Burkey,⁹ Yaron Danon,¹⁰ Mohamed A. ElSawi,^{11,12} Bethany L. Goldblum,^{6,7} Lawrence H. Heilbronn,² Susan L. Hogle,¹³ Jesson Hutchinson,¹⁴ Ben Loer,¹¹ Elizabeth A. McCutchan,⁷ Matthew R. Mumpower,¹⁵ Ellen M. O’Brien,¹⁶ Catherine Percher,¹⁷ Patrick N. Peplowski,¹⁸ Jennifer J. Ressler,⁹ Nicolas Schunck,¹ Nicholas W. Thompson,¹⁴ Andrew S. Voyles,^{6,7} William Wieselquist,¹⁹ and Michael Zerkle²⁰

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¹⁹Nuclear Energy and Fuel Cycle Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA

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Accurate nuclear data provide an essential foundation for advances in a wide range of fields, including nuclear energy, nuclear safety and security, safeguards, nuclear medicine, and planetary and space exploration. In these and other critical domains, outdated, imprecise, and incomplete nuclear data can hinder progress, limit precision, and compromise safety. Similar nuclear data needs are shared by many applications, thus prioritizing these needs is especially important and urgently needed. Many levels of analysis are required to prepare nuclear measurements for employment in end-user applications. Because research expertise is typically limited to one level, collaboration across organizations and international borders is essential. This perspective piece provides the latest advances in nuclear data for applications and describes an outlook for both near- and long-term progress in the field.

DOI: [10.1103/PhysRevResearch.4.021001](https://doi.org/10.1103/PhysRevResearch.4.021001)

I. INTRODUCTION

Nuclear data provide the empirical foundation for studies

touch many aspects of everyday life. In homes, food is served that has been irradiated by ⁶⁰Co and ¹³⁷Cs to kill bacteria, making it safe for long-term storage and distribution. ⁶³Ni is

Nuclear Data Needs – NASA's Psyche Mission



IMAGE CREDIT: NASA/JPL-Caltech/ASU

- Asteroid 16 Psyche
 - Location: Asteroid Belt, ~3.5 AU
 - Density: 3.4 – 4.1 g cm³
 - Spectral Class: M-type, similar to iron meteorites
- Is Psyche the exposed Fe+Ni core of a now-disrupted protoplanet?

Nuclear Data Needs – NASA's Psyche Mission

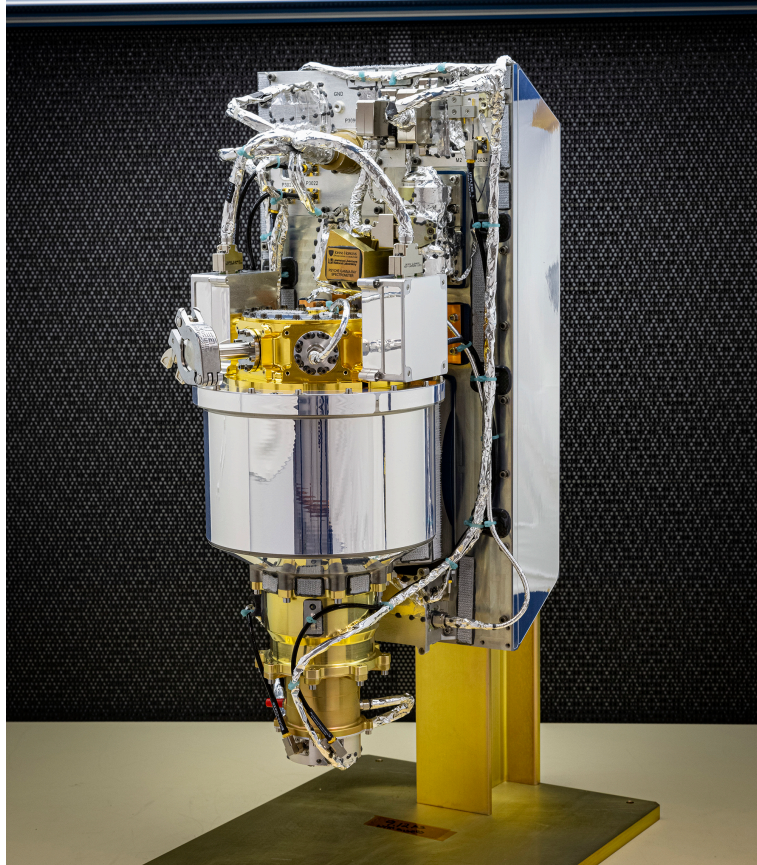


Image Credit: Johns Hopkins APL

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- Is Psyche the exposed Fe+Ni core of a now-disrupted protoplanet?
 - Use γ -ray and neutron spectroscopy to measure the elemental composition of Psyche.

Nuclear Data Needs – NASA’s Psyche Mission

Could spallation reaction products in the Psyche Gamma-Ray and Neutron Spectrometer (GRNS) be mistaken for Fe and Ni γ -ray signatures from the asteroid?

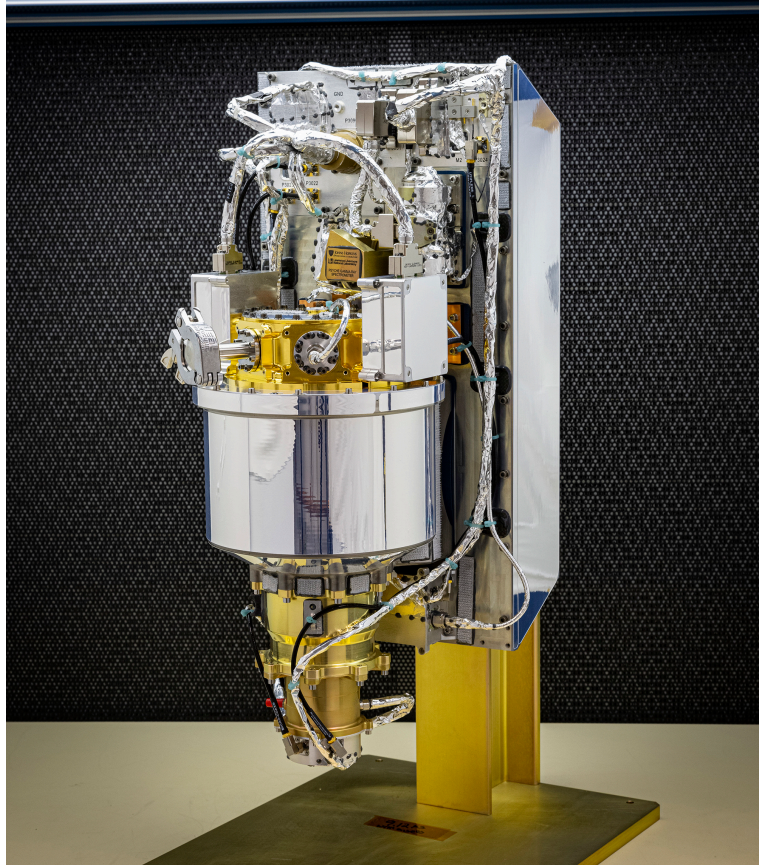


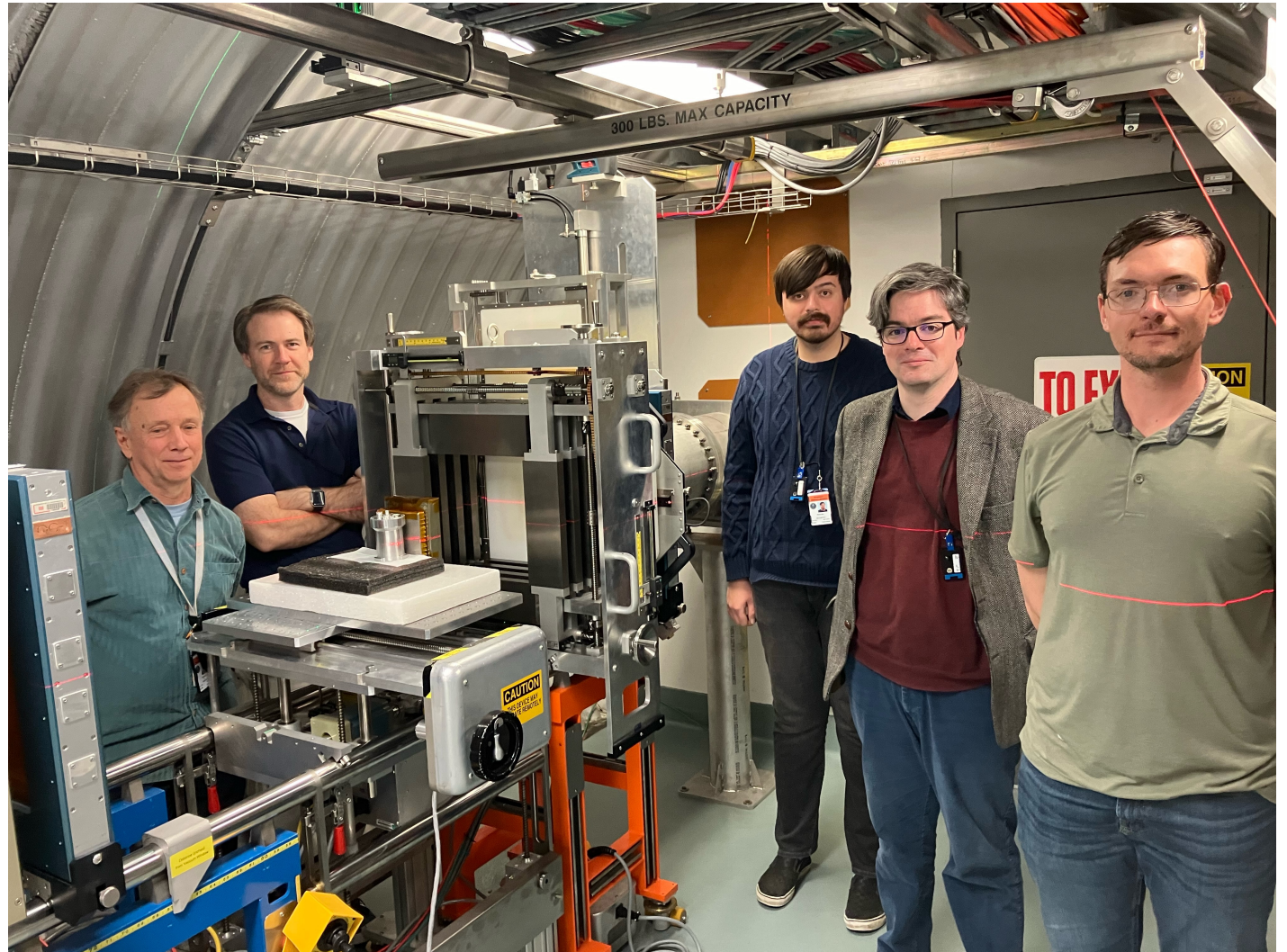
Image Credit: Johns Hopkins APL

Proton Number	28	56Ni 6.081 d $\epsilon+\beta+=100\%$	57Ni 35.6 h $\epsilon+\beta+=100\%$	58Ni STABLE 68.0769%	59Ni 8.10e+4 y $\epsilon+\beta+=100\%$	60Ni STABLE 26.2231%	61Ni STABLE 1.1399%	62Ni STABLE 3.6345%	63Ni 100.8 y $\beta^-=100\%$	64Ni STABLE 0.9256%
		55Co 17.53 h $\epsilon+\beta+=100\%$	56Co 77.236 d $\epsilon+\beta+=100\%$	57Co 271.8 d $\epsilon=100\%$	58Co 70.883 d $\epsilon+\beta+=100\%$	59Co STABLE 100%	60Co 5.271 y $\beta^-=100\%$	61Co 1.65 h $\beta^-=100\%$	62Co 1.51 min $\beta^-=100\%$	63Co 26.9 s $\beta^-=100\%$
	26	54Fe STABLE 5.845%	55Fe 2.756 y $\epsilon=100\%$	56Fe STABLE 91.754%	57Fe STABLE 2.119%	58Fe STABLE 0.282%	59Fe 44.495 d $\beta^-=100\%$	60Fe 2.61e+6 y $\beta^-=100\%$	61Fe 6.03 min $\beta^-=100\%$	62Fe 68 s $\beta^-=100\%$
		28	29	30	31	32	33	34	35	36
		Neutron Number								

NSRL is uniquely suited to explore spallation reactions in the energy range of interest (10s of MeV to many GeV) for interplanetary exploration.

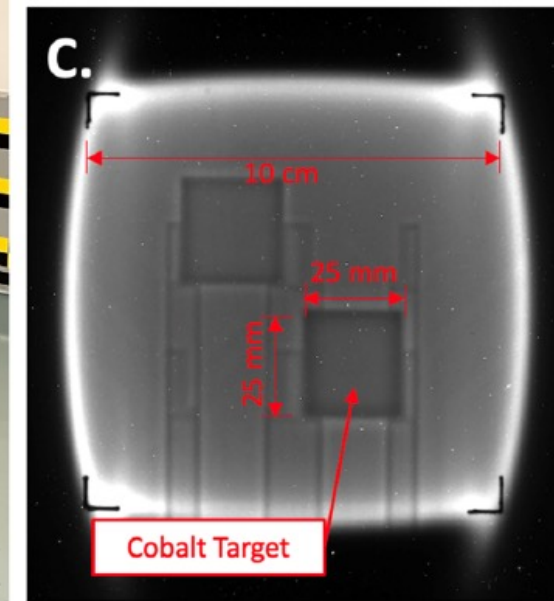
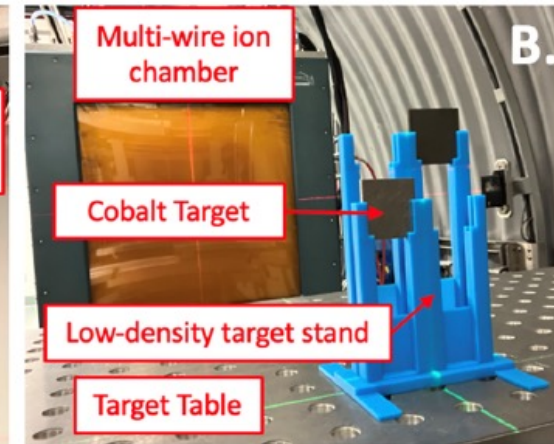
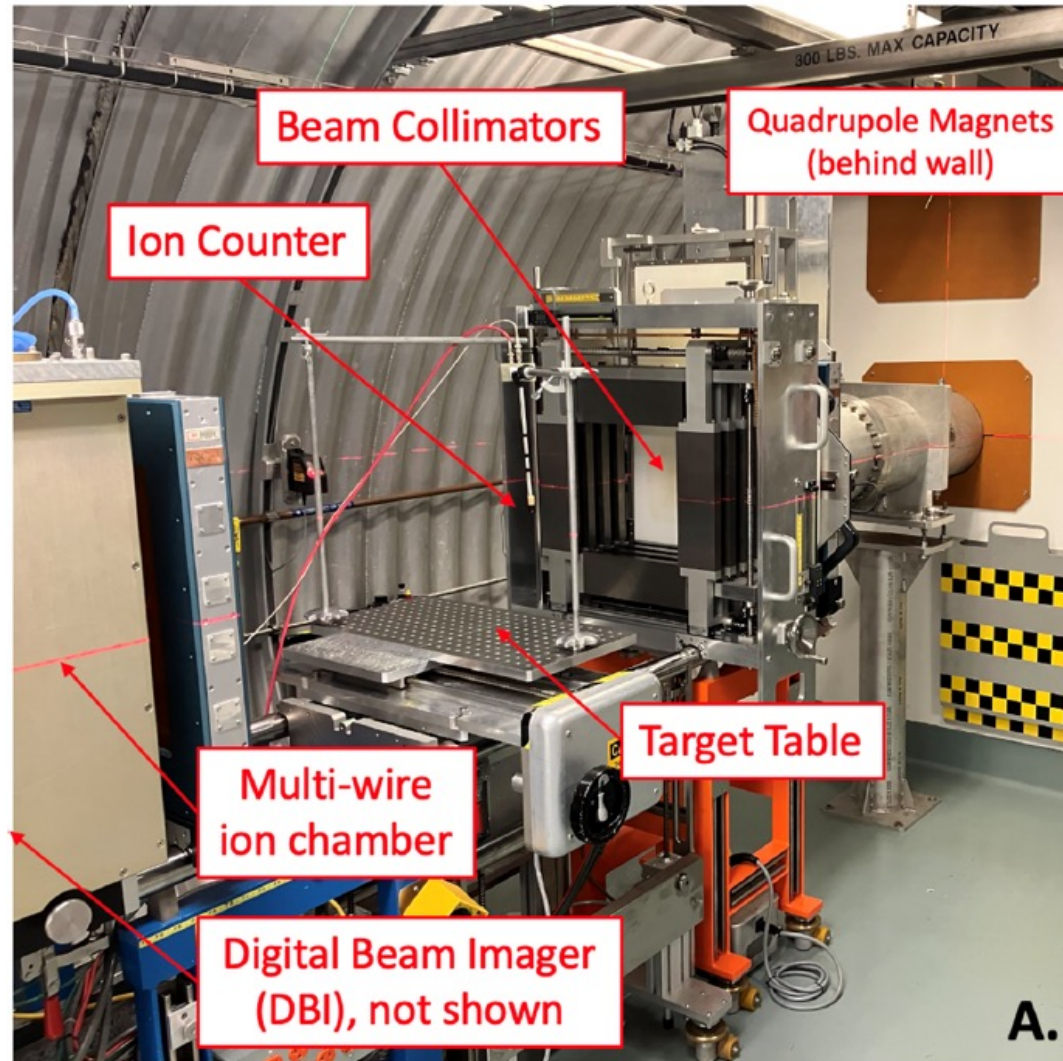
Cobalt Spallation Experiment

- Five cobalt targets
 - 2.5 x 2.5 cm
 - 2-mm thick
 - Five incident proton energies (from 250 MeV to 2 GeV)
- On-site (same day) and off-site (irradiation + months) monitoring of activated targets.
- NSRL provides:
 - Uniform, tunable beam profiles
 - High precision and accuracy measurements of incident proton fluence
 - Excellent service
 - Morning coffee



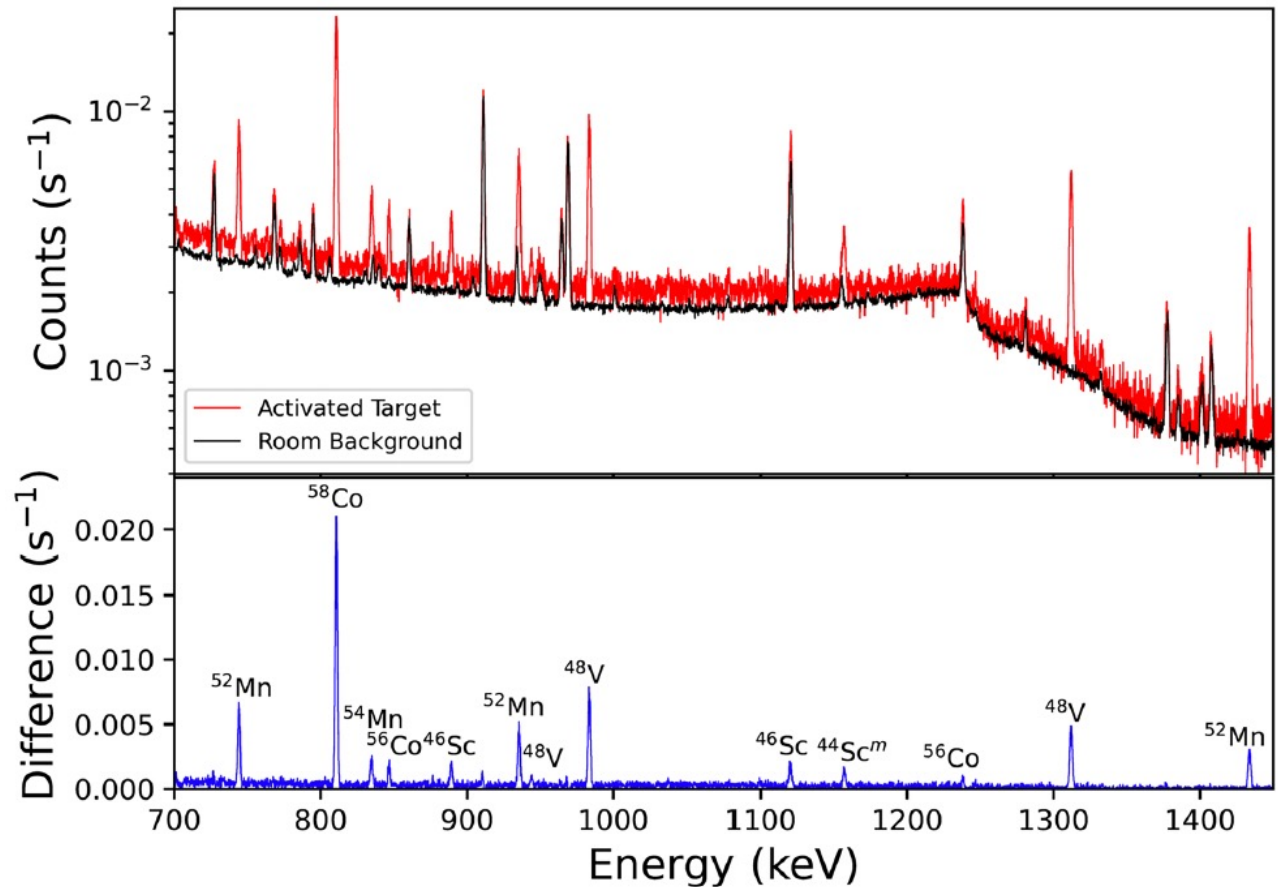
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Cross Section Measurements at NSRL

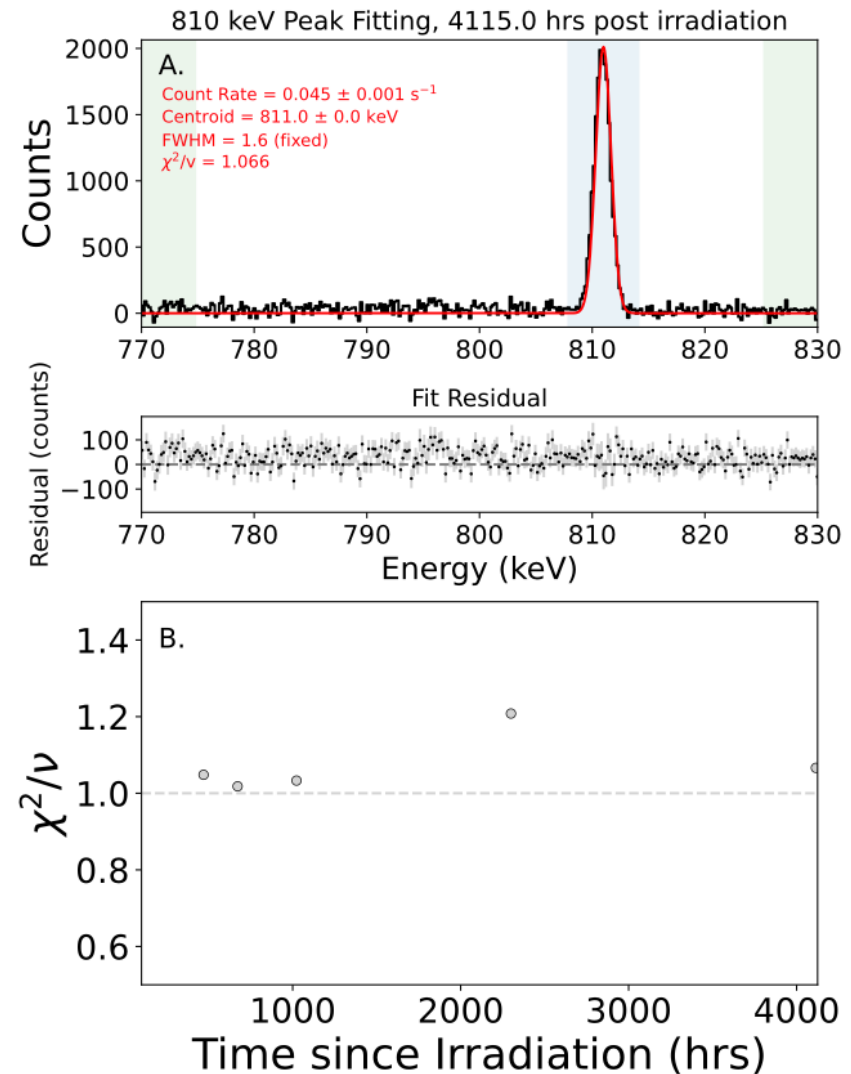
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 - Short, intense irradiation
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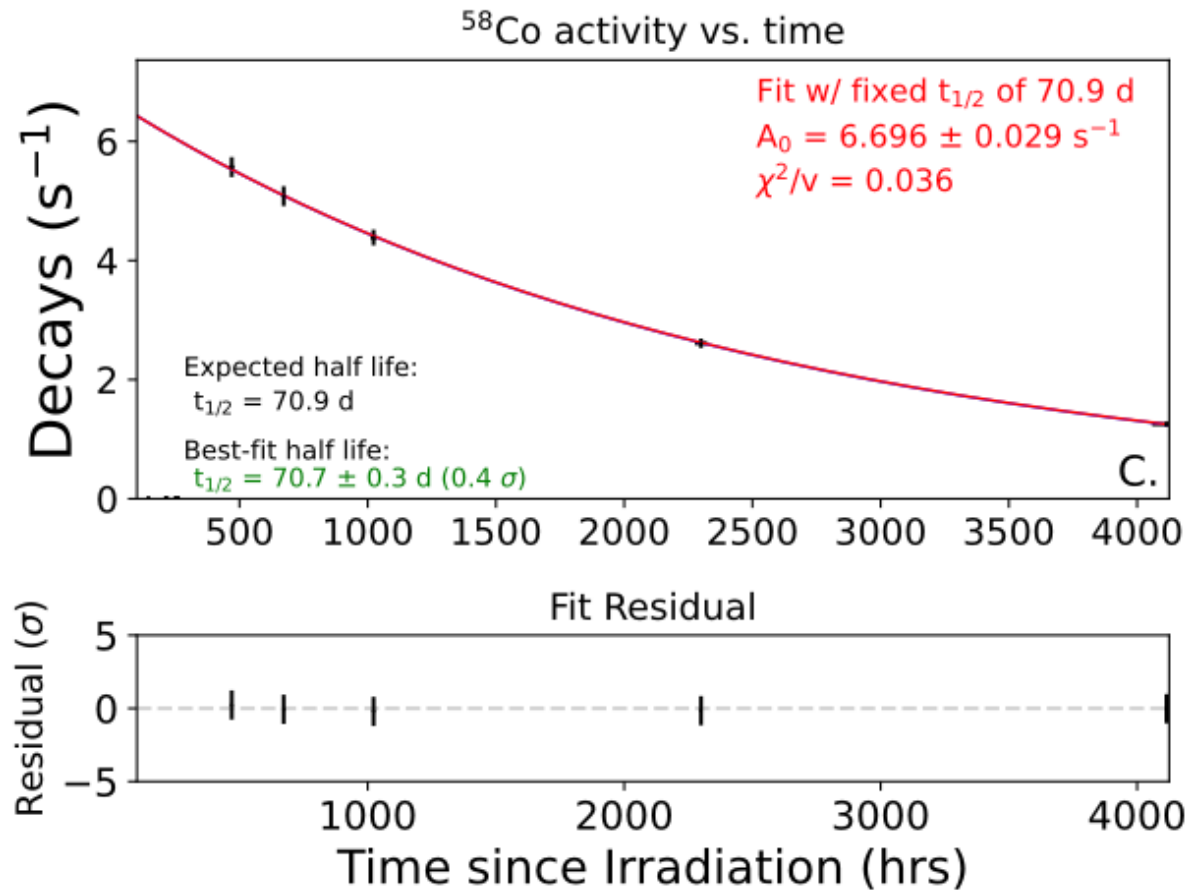
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$^{59}\text{Co}(p,X)^{58}\text{Co}$; Energy = 250 MeV



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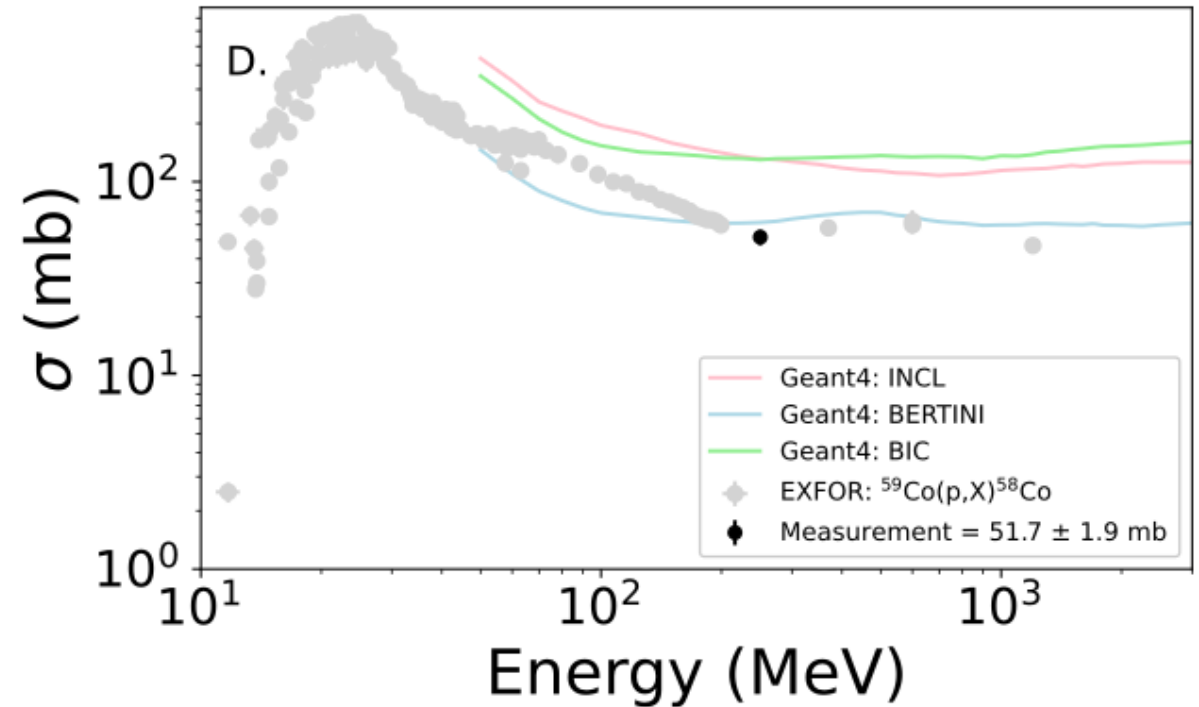
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Gamma-rays observed in activated targets.

Isotope	Reaction	Gamma Ray		Half Life	
		Energy (keV)	Intensity (%)	ENSDF	Measured *
⁵⁸ Co	⁵⁹ Co(p,pn) ⁵⁸ Co	810.8	99.45%	70.86 d	71.1 ± 0.9 d
⁵⁷ Co	⁵⁹ Co(p,p2n) ⁵⁷ Co	122.0	85.6 ± 0.2%	271.74 d	279 ± 65 d
⁵⁷ Mn	⁵⁹ Co(p,3p) ⁵⁷ Mn	122.0	14 ± 5%	85.4 s	85.2 min ^c
⁵⁶ Co	⁵⁹ Co(p,p3n) ⁵⁶ Co	846.8	99.94%	77.236 d	98 ± 19 d
⁵⁶ Cr	⁵⁹ Co(p,X) ⁵⁶ Cr	83	95.3%	5.94 m	5.96 m ^c
⁵⁶ Mn	⁵⁹ Co(p,X) ⁵⁶ Mn	846.8	98.85%	2.58 h	2.58 h ^c
⁵⁵ Co	⁵⁹ Co(p,p4n) ⁵⁵ Co	931	75%	17.53 h	4.6 ± 5.3 h
⁵⁴ Mn	⁵⁹ Co(p,3p3n) ⁵⁴ Mn	834.8	99.998%	312.2 d	286 ± 57 d
⁵³ Fe	⁵⁹ Co(p,X) ⁵³ Fe	377.9	42%	8.51 m	8.4 ± 0.6 m
⁵² Mn	⁵⁹ Co(p,X) ⁵² Mn	744.2	90.0%	5.591 d	6.7 ± 0.8 d
⁵¹ Cr	⁵⁹ Co(p,X) ⁵¹ Cr	320.1	9.91%	27.7 d	35 ± 6 d
⁴⁹ Cr	⁵⁹ Co(p,X) ⁴⁹ Cr	152.9	30.3%	42.3 m	69 ± 34 m
⁴⁸ V	⁵⁹ Co(p,X) ⁴⁸ V	983.5	99.98%	15.974 d	14.8 ± 0.9 d
⁴⁷ Sc	⁵⁹ Co(p,X) ⁴⁷ Sc	159.4	68.3%	3.3491 d	3.7 ± 0.2 d
⁴⁶ Sc	⁵⁹ Co(p,X) ⁴⁶ Sc	889.3	99.98%	83.79 d	89.4 ± 12.3 d
⁴⁴ Sc	⁵⁹ Co(p,X) ⁴⁴ Sc	1157.0	99.89%	4.04 h	2.4 ± 0.9 h
⁴⁴ Sc ^m	⁵⁹ Co(p,X) ⁴⁴ Sc ^m	271	86.72%	58.62 h	60 ± 3 h

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80 separate cross section measurements were produced from just ~10 minutes of NSRL beam time

Table 3. Reaction cross sections derived from the activated target measurements

Reaction	Type [∇]	Cross Section (mb) and statistical uncertainty				
		250 MeV	500 MeV	750 MeV	1200 MeV	2000 MeV
⁵⁹ Co(p,n) ⁵⁸ Co	I	51.7±4.8	45.9±4.2	44.5±4.2	44.6±4.2	46.4±4.3
⁵⁹ Co(p,p2n) ⁵⁷ Co	I	38.2±4.1	26.2±2.7	24.5±2.8	24.0±2.4	24.2±2.9
⁵⁹ Co(p,3p) ⁵⁷ Mn	I	0.4±0.2	1.0±0.4	1.6±0.2	0.6±0.7	0.8±0.5
⁵⁹ Co(p,p3n) ⁵⁶ Co	I	9.4±1.2	6.9±0.9	5.3±0.8	5.3±0.9	3.6±0.6
⁵⁹ Co(p,4p) ⁵⁶ Cr	I	0.10±0.03	0.14±0.03	0.14±0.02	0.14±0.02	0.15±0.01
⁵⁹ Co(p,X) ⁵⁶ Mn	C	4.5±0.3	5.6±0.4	6.9±0.5	8.5±1.2	9.1±2.9
⁵⁹ Co(p,5p) ⁵⁵ Co	I	3.5±0.3	2.3±0.2	2.5±0.4	2.2±0.5	2.9±0.3
⁵⁹ Co(p,3p3n) ⁵⁴ Mn	I	37.7±3.8	34.8±3.5	32.6±3.6	28.9±3.4	27.2±2.9
⁵⁹ Co(p,X) ⁵³ Fe	C	1.9±0.1	1.4±0.1	1.3±0.1	0.9±0.1	0.8±0.1
⁵⁹ Co(p,X) ⁵² Mn	C	8.9±1.7	6.6±1.5	6.0±1.7	6.2±1.8	3.3±0.6
⁵⁹ Co(p,X) ⁵¹ Cr	C	28.2±3.5	31.1±3.8	23.7±5.1	23.2±3.7	17.6±3.7
⁵⁹ Co(p,X) ⁴⁹ Cr	C	--	--	--	3.1±0.2	2.7±0.1
⁵⁹ Co(p,X) ⁴⁸ V	C	6.8±0.8	9.5±1.0	9.9±1.2	8.8±1.0	7.3±0.8
⁵⁹ Co(p,X) ⁴⁷ Sc	C	2.8±2.7	2.6±1.2	4.9±2.2	4.4±1.4	3.3±0.5
⁵⁹ Co(p,X) ⁴⁶ Sc	C	3.0±0.6	5.3±0.8	6.2±1.3	5.7±0.8	4.0±0.6
⁵⁹ Co(p,X) ⁴⁴ Sc	C	--	--	7.3±0.6	7.0±0.6	5.6±0.4
⁵⁹ Co(p,X) ⁴⁴ Sc ^m	C	2.0±1.1	5.1±1.4	9.2±2.1	6.7±1.9	6.4±1.2

[∇] "I" denotes an individual cross section measurement, "C" denotes a cumulative cross section measurement

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Cross sections are accompanied by well-characterized systematic uncertainties – a critical aspect of nuclear data work

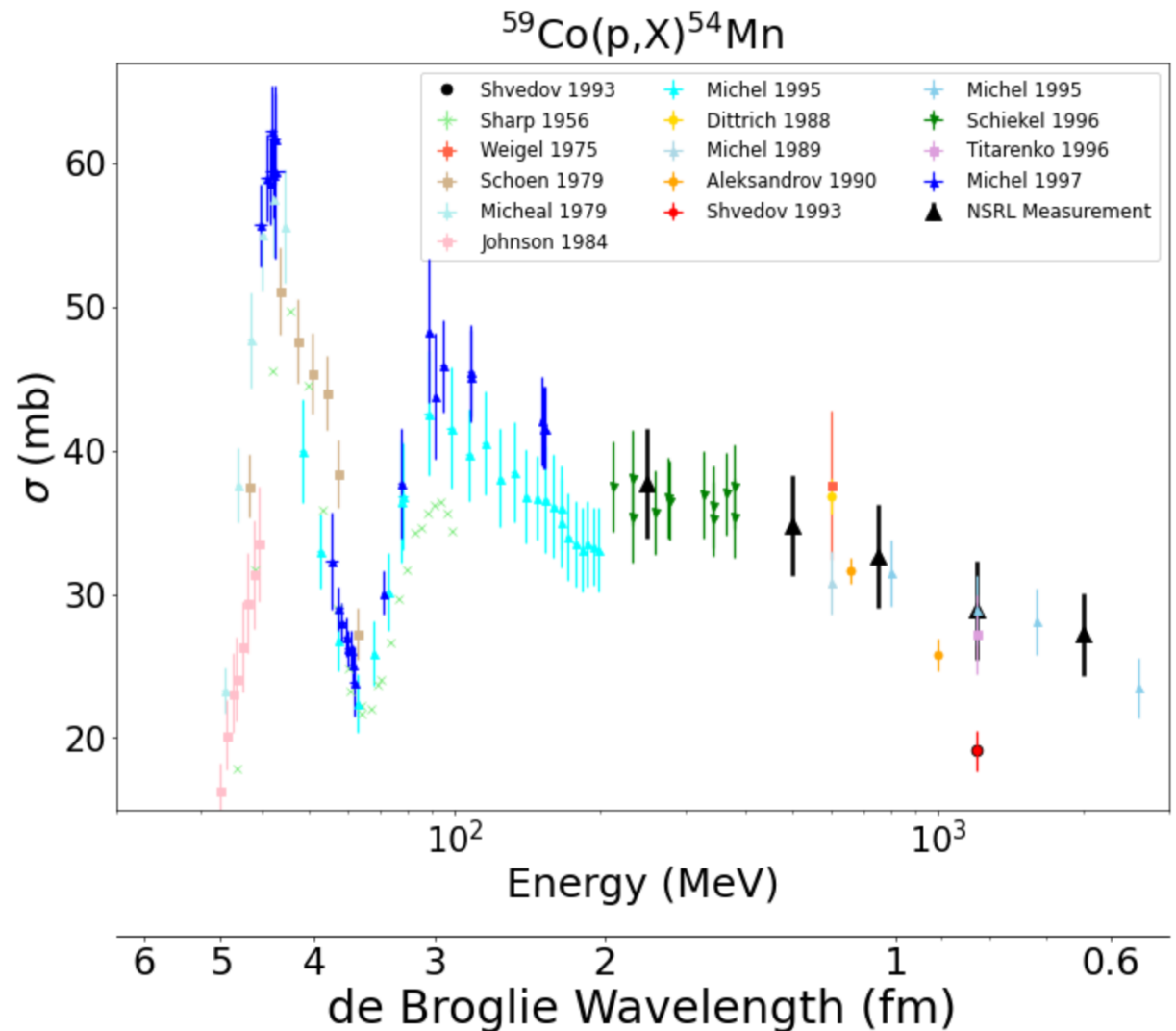
Parameter	Details	Solution	Value	
			HPGe	CeBr ₃
t	Time since irradiation	Measured (clock)	±10 s	
I_γ	Decay Branching Ratio	Adopted from ENSDF	Varies*	
λ	Mean lifetime	Adopted from ENSDF	Varies	
ϵ	Photopeak Efficiency	GEANT4 model with NIST-traceable source benchmark (±3%)	3.0%	3.5%
Ω	Solid Angle	GEANT4 model with measured position knowledge (±0.5 mm)	0.6%	
L_γ	Self-attenuation	GEANT4 model	0%	
N_p	Proton fluence	Measured (by NRSL)	3.6%	
N_t	Target Atom Density	Measured (from target weight, density)	1%	
A	Target Area	Measured (physical measurement of targets)	0.1%	
Total Systematic Uncertainty			4.8%	5.2%

* Ignored for all isotopes except ⁵⁷Mn, where ENSDF reports an 30% uncertainty on the γ -ray intensity that we incorporated into the ⁵⁹Co(p,X)⁵⁷Mn cross section

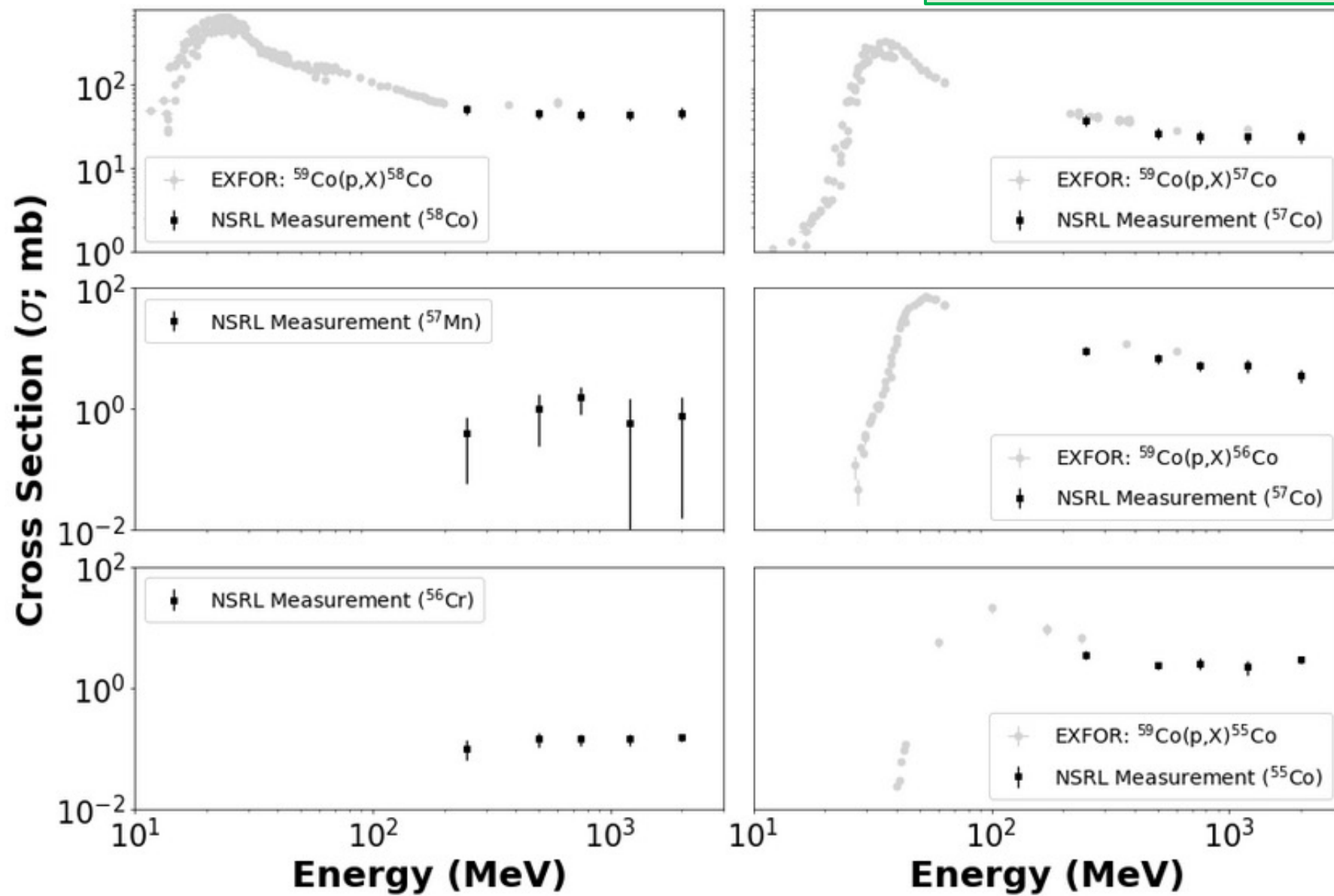
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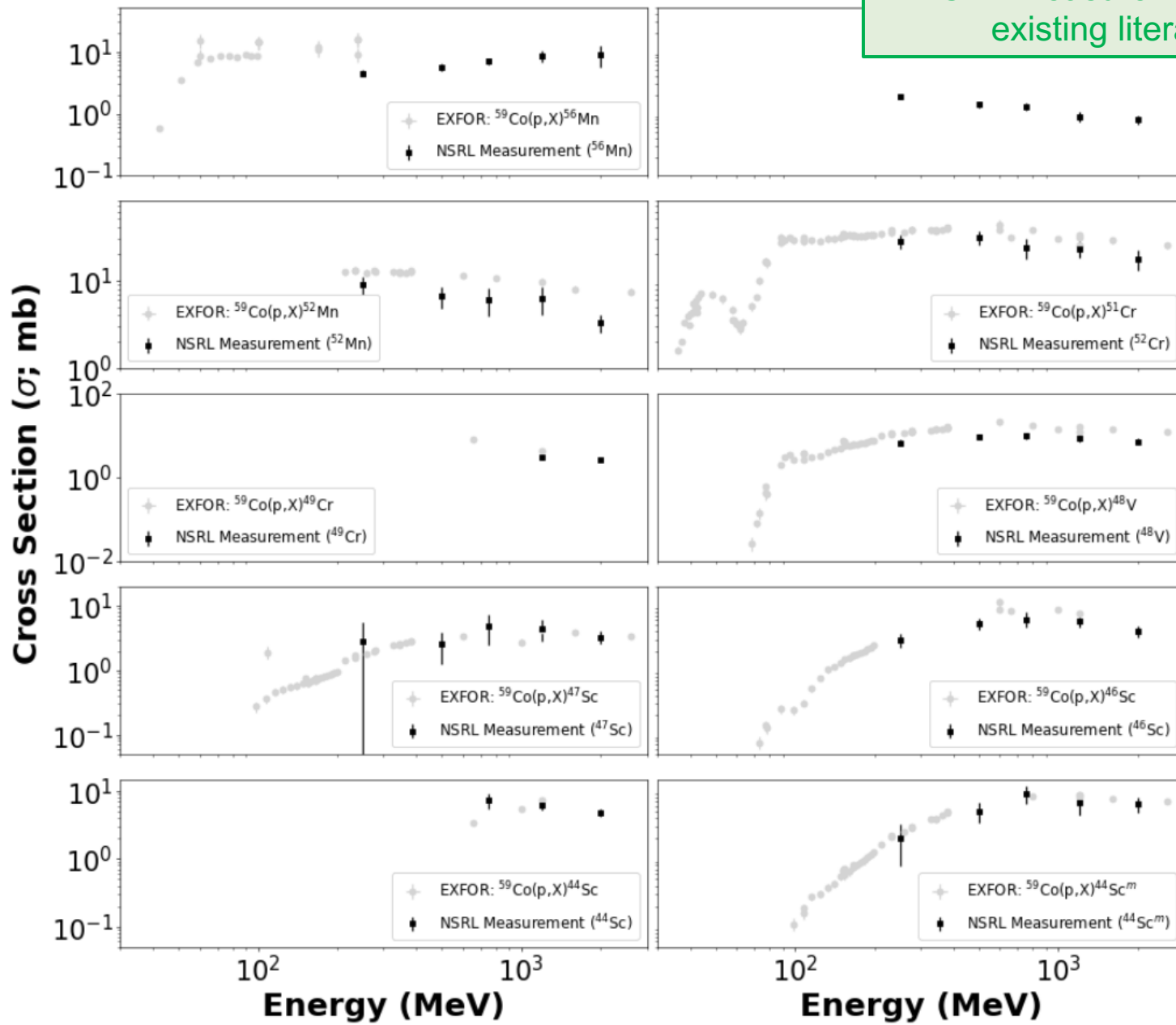
NSRL measurements were validated against published results from dedicated cross section measurements.

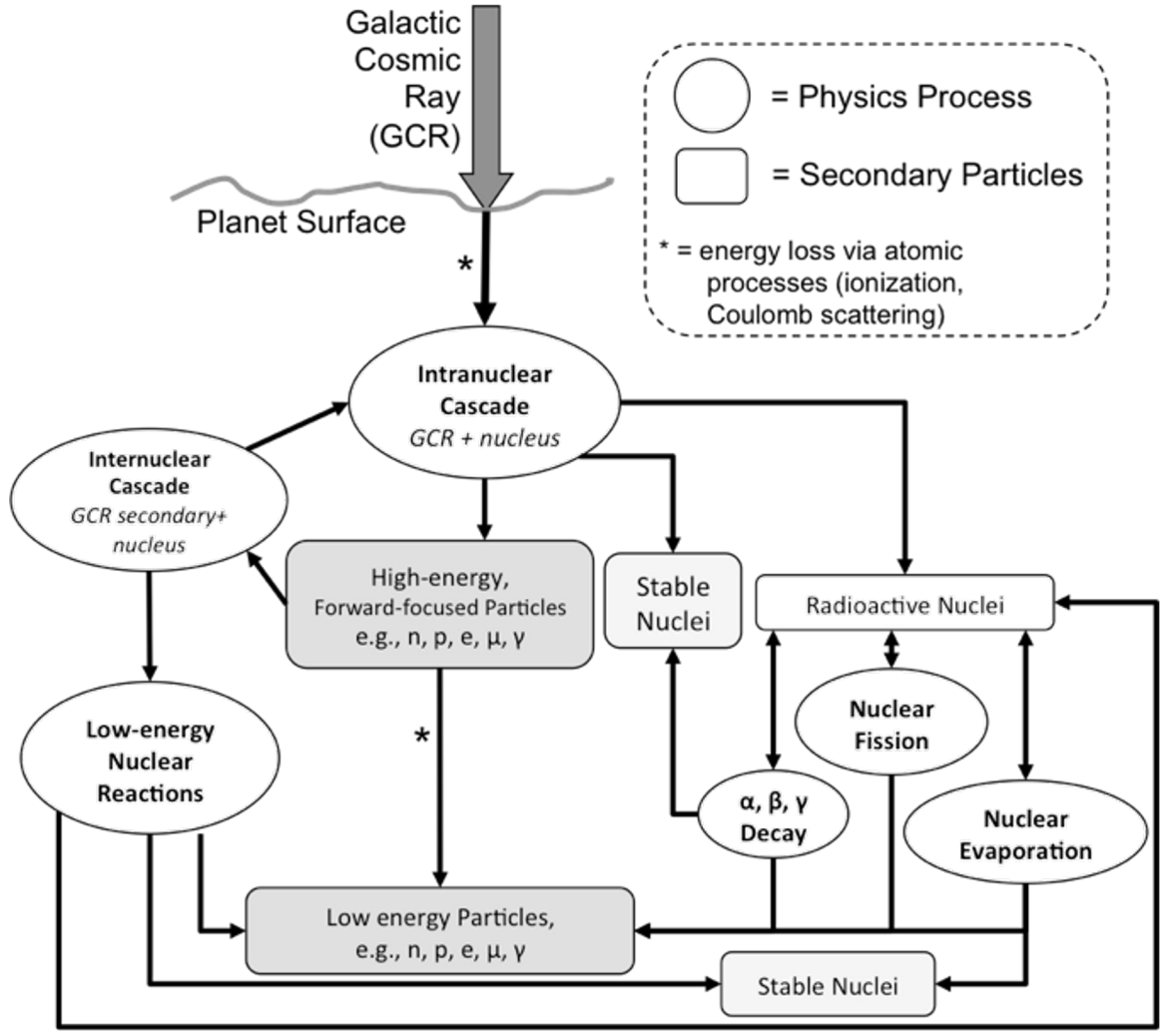


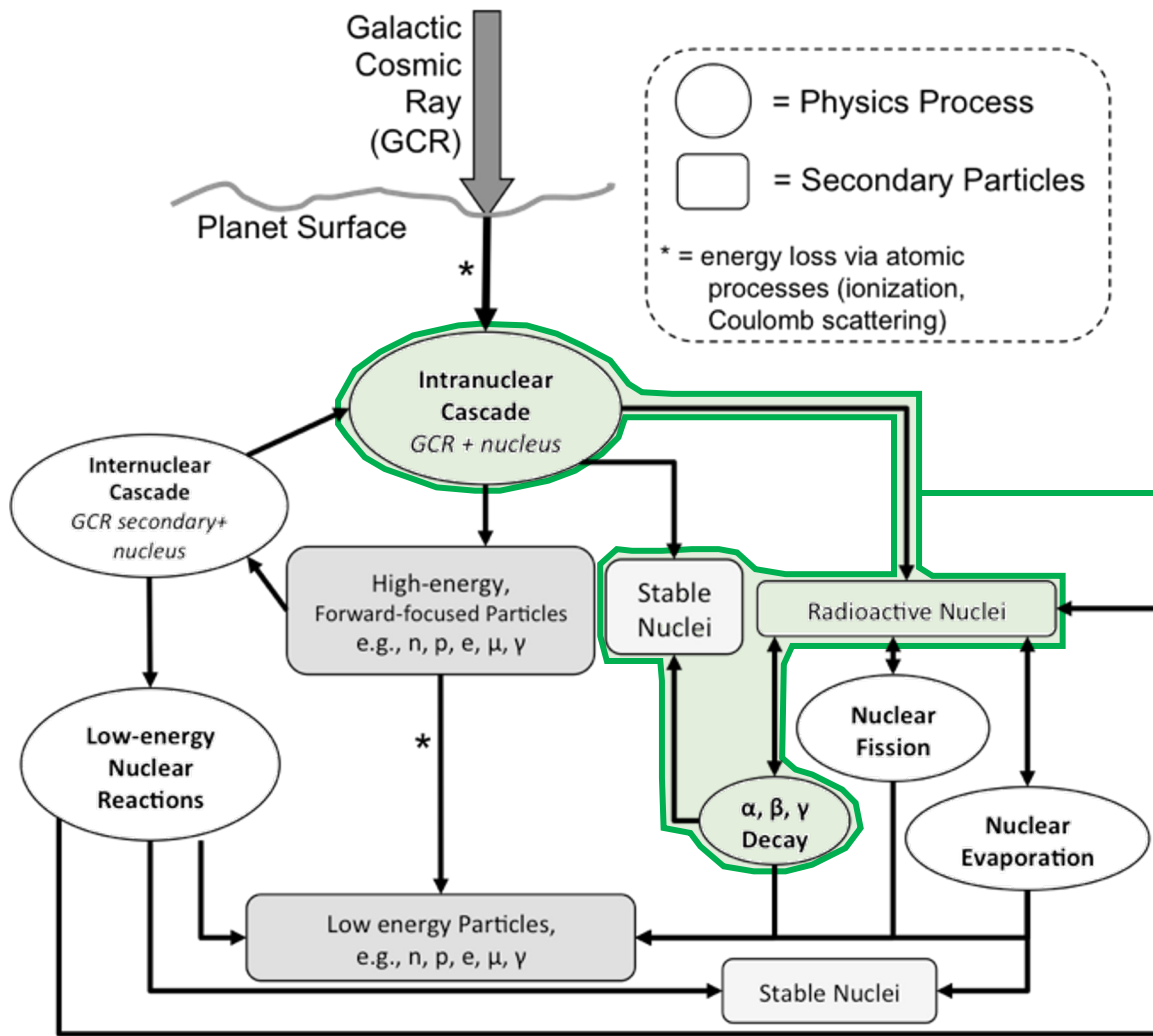
NSRL measurements fill many gaps in the existing literature (from EXFOR)



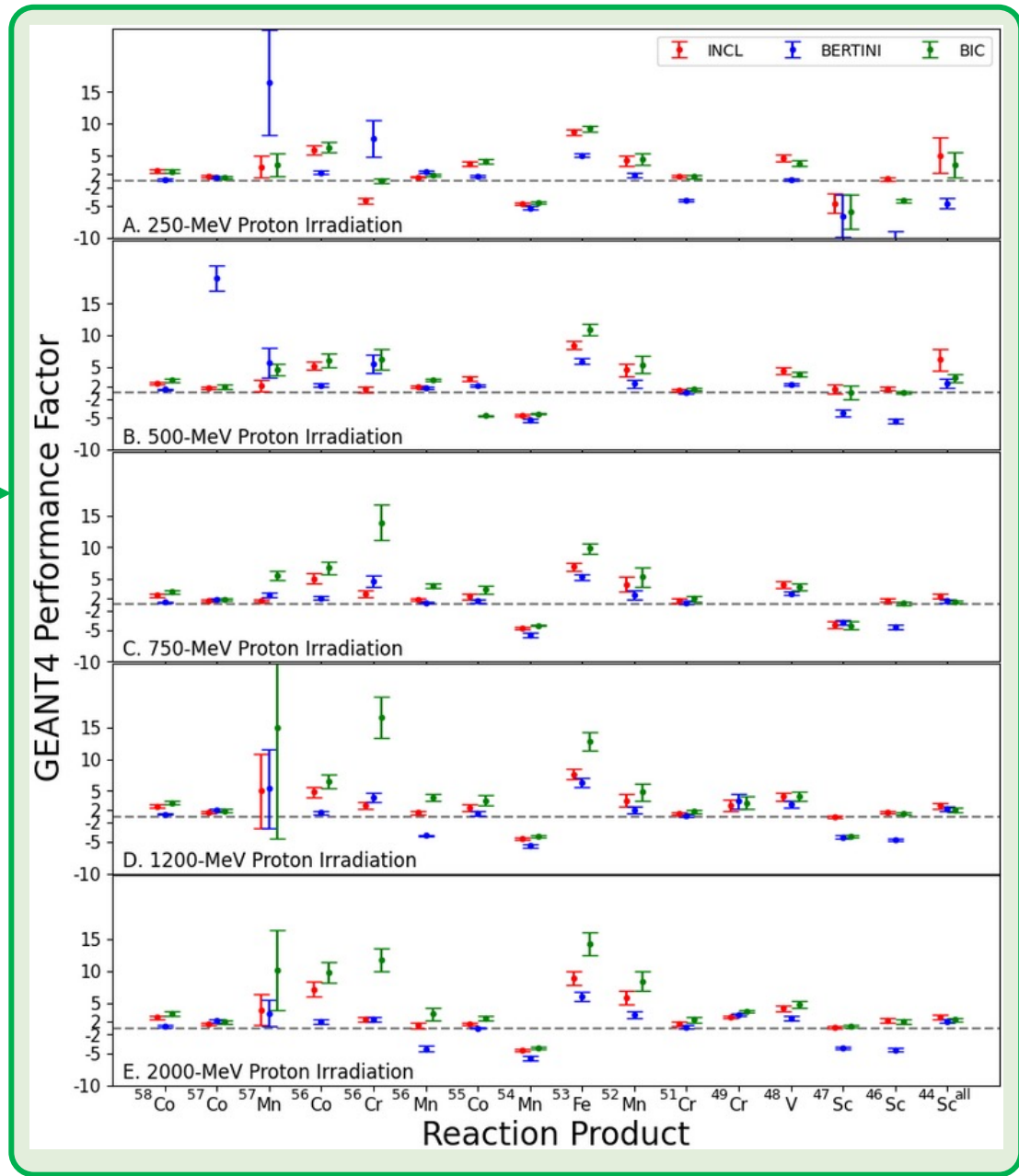
NSRL measurements fill many gaps in the existing literature (from EXFOR)

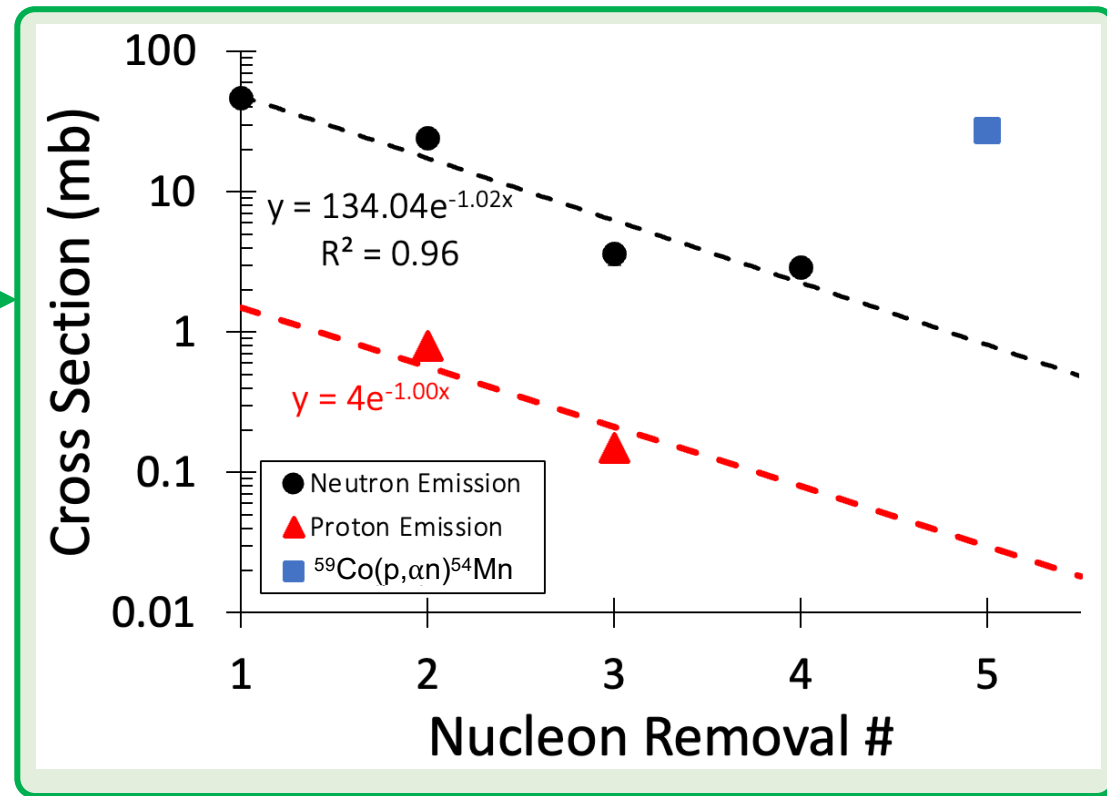
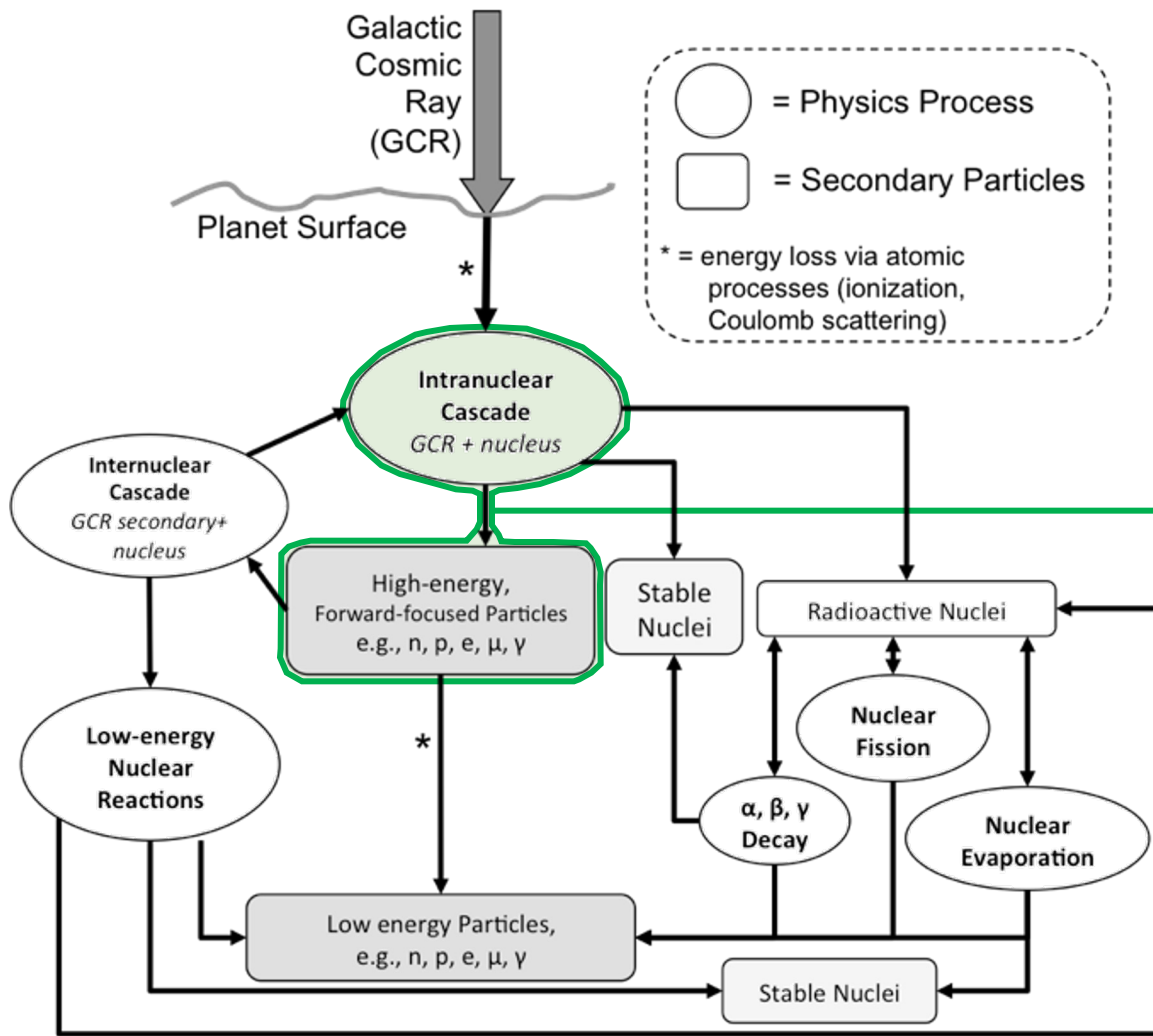






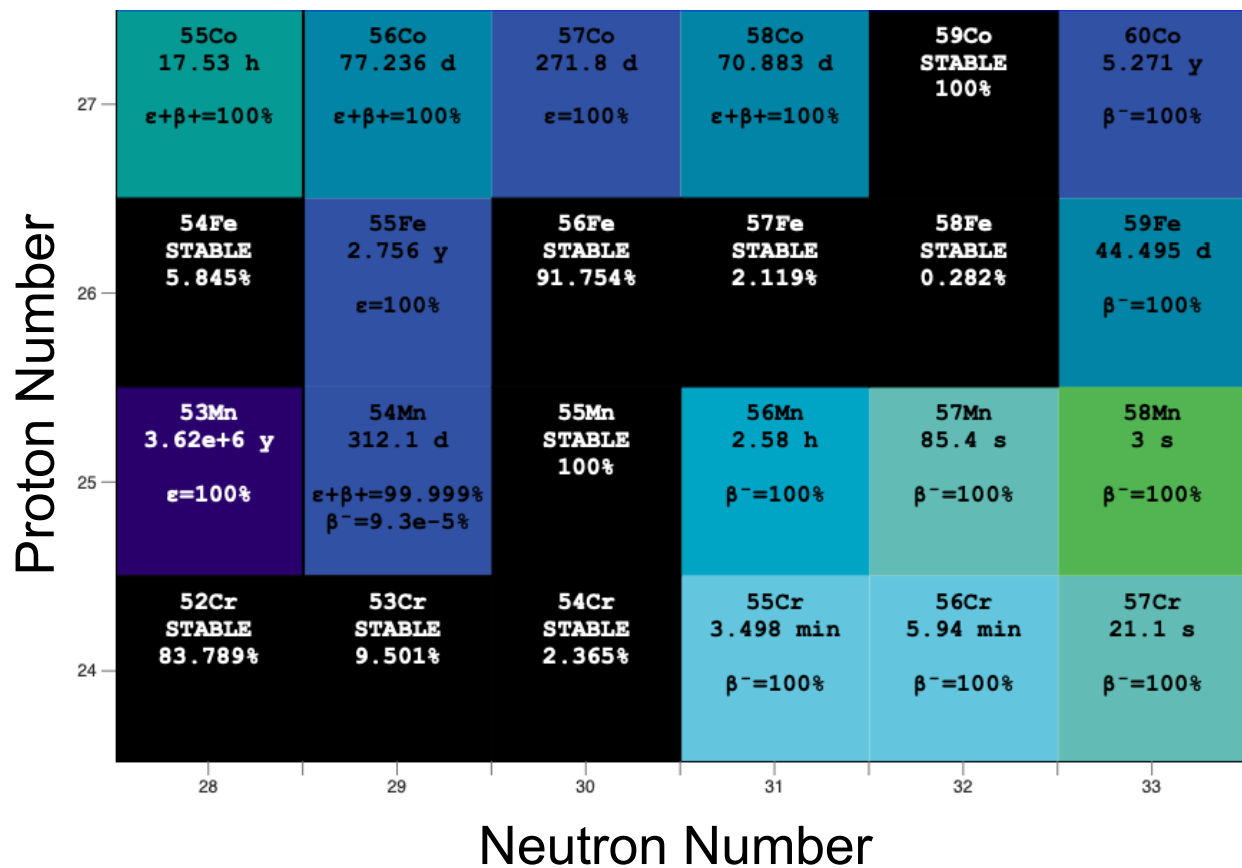
NSRL-measured cross sections provide validation of the radiation transport models used for Psyche data analysis



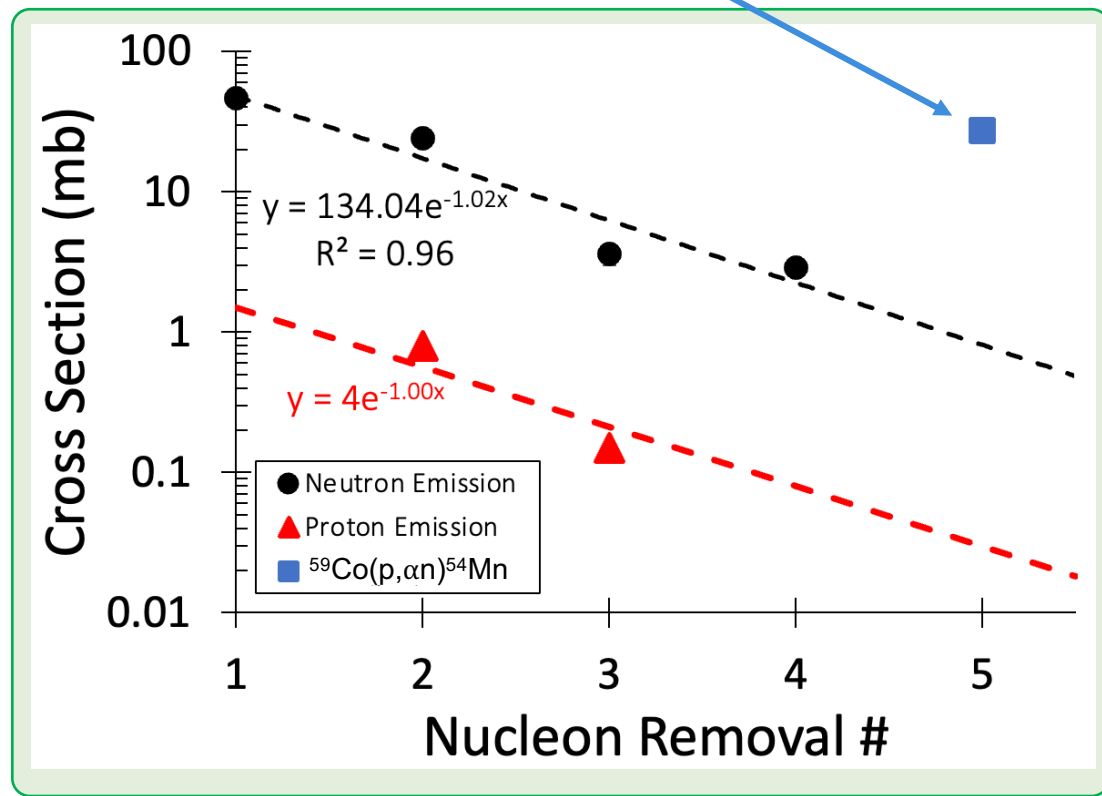


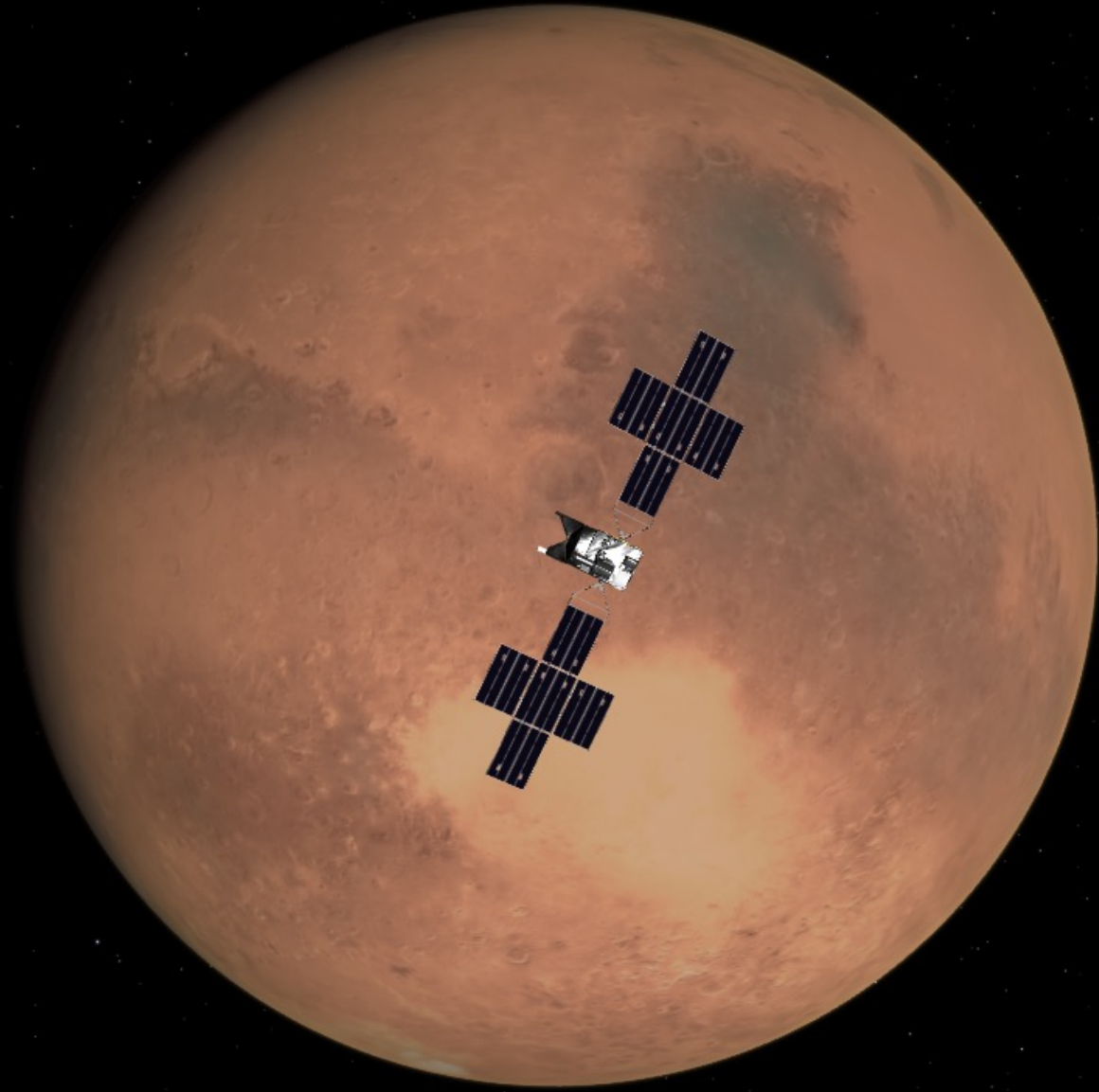
NSRL-measured cross sections provide validation of the radiation transport models used for Psyche data analysis

NSRL-measured cross sections hint at unexpected phenomena in nuclear structure



Evidence for α -clustering in ^{59}Co ?





May 15, 2026 (This Friday!)



IMAGE CREDIT: NASA/JPL (Eyes on the Solar System)

Conclusions

- NSRL is uniquely suited to support NASA planetary science missions.
 - Applications span the range of basic science (spallation cross section) to application (electronics and detector testing).
 - NSRL measurements have led to peer-reviewed science in multiple journals.
 - Radiation damage and annealing of HPGe detectors
 - *Peplowski et al.*, 2019, Nuc. Inst. and Methods A
 - Cosmogenic radionuclide production in metallic meteorites
 - *Peplowski et al.* 2019, Nuc. Inst. And Methods B
 - $^{nat}\text{Cu}(p,X)$ spallation cross sections
 - *Peplowski*, 2022, Nuc. Physics A
 - $^{59}\text{Co}(p,X)$ spallation cross sections
 - *Peplowski et al.* 2026, Nuc. Physics A
- Future partnerships can expand on the work to date and expand the role of NSRL in the nuclear data community.



Backup

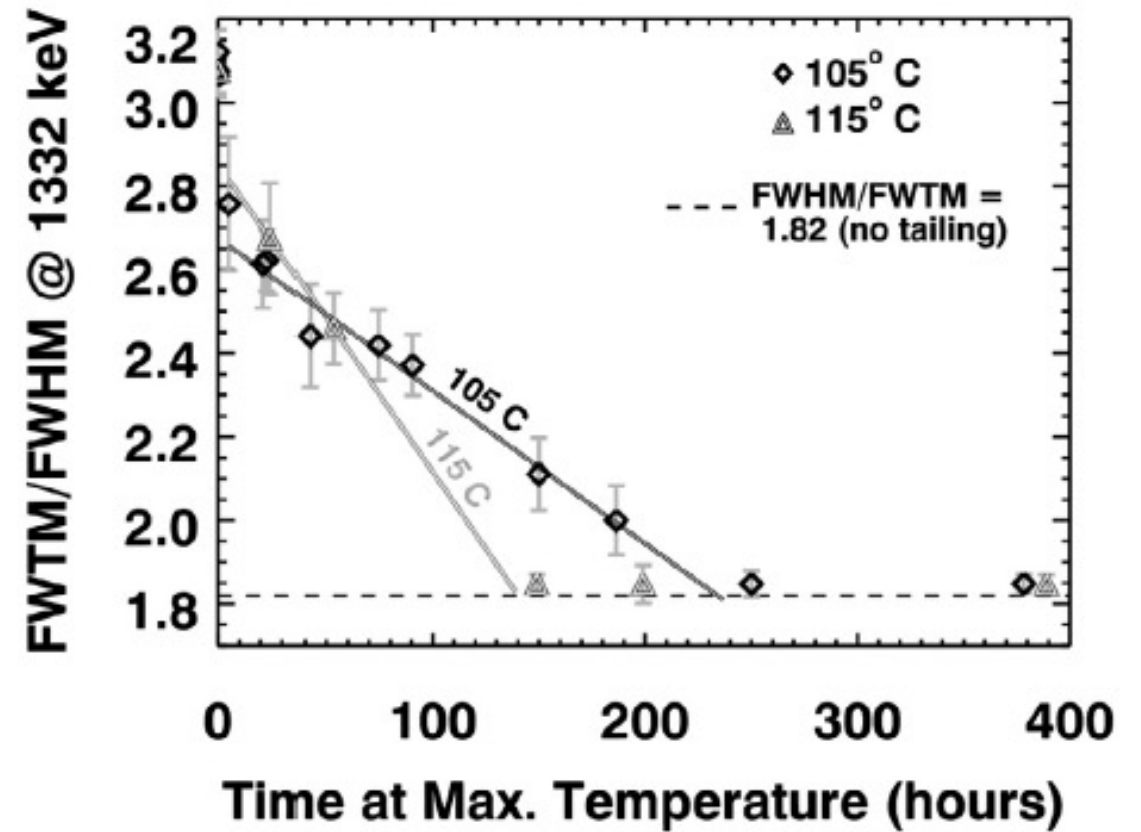
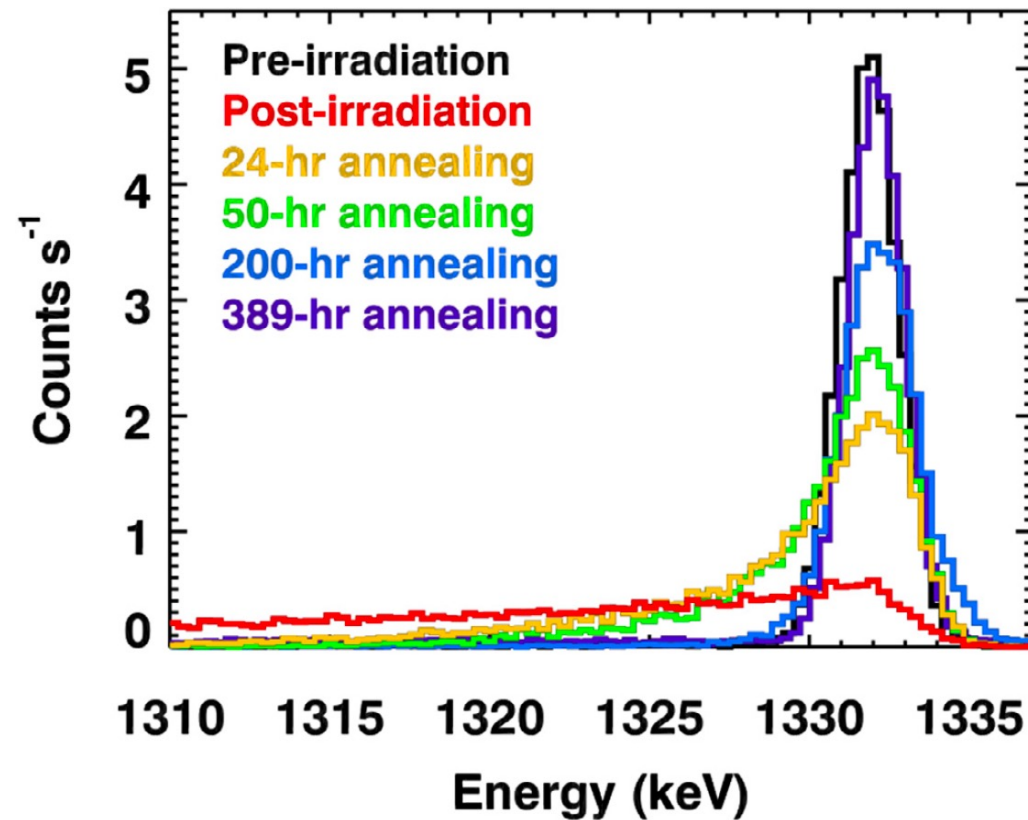
Radiation Damage Studies



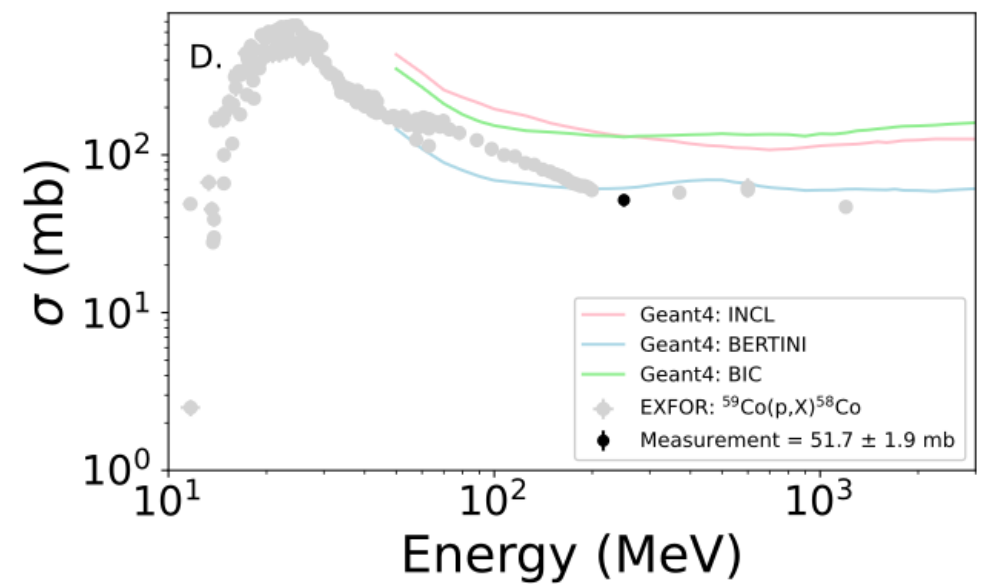
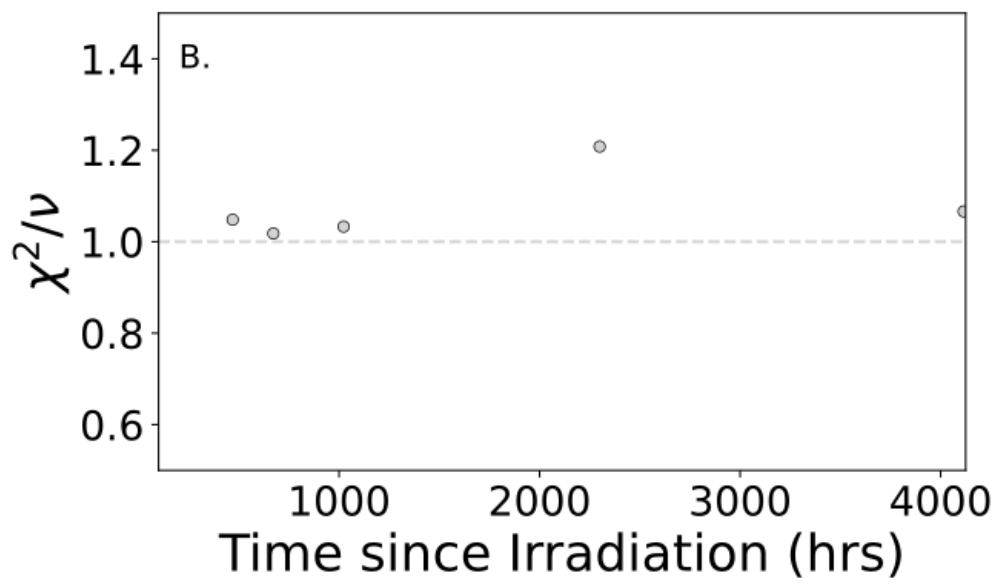
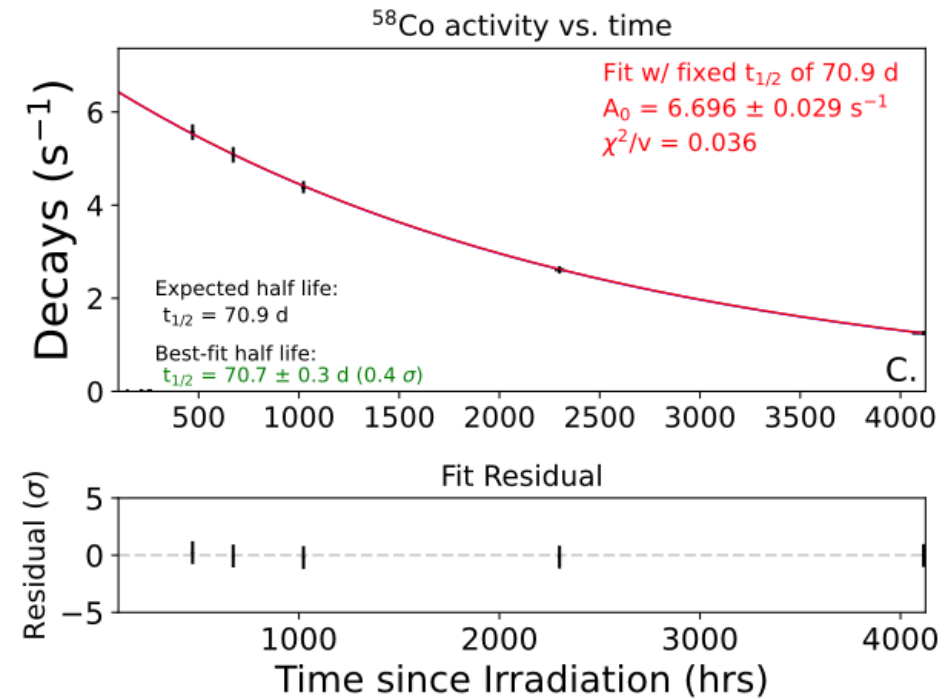
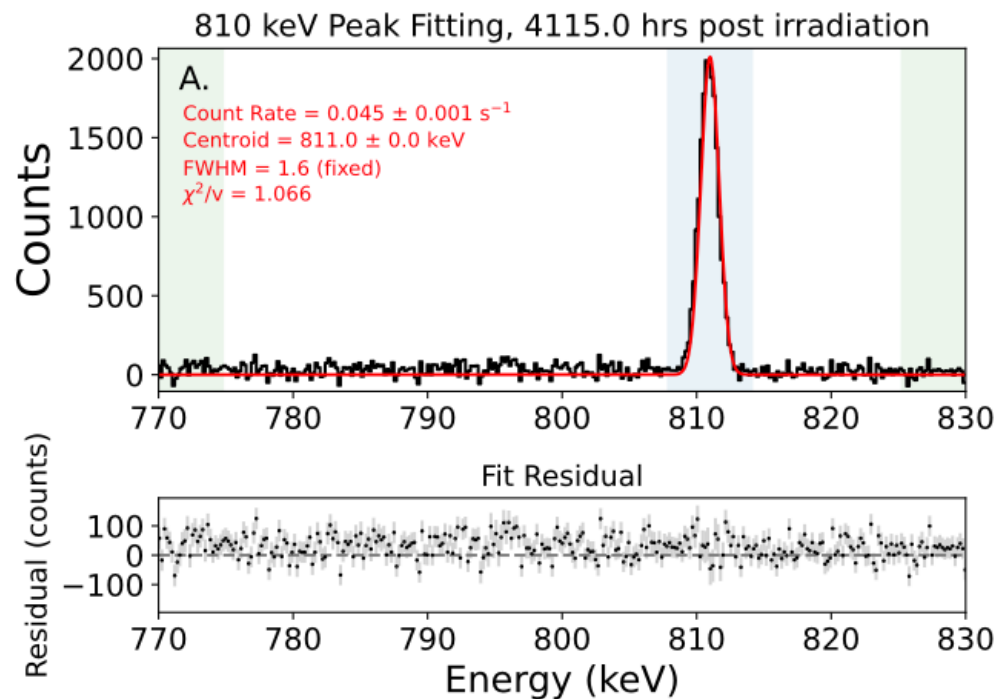
Radiation damage and annealing of three coaxial n-type germanium detectors: Preparation for spaceflight missions to asteroid 16 Psyche and Mars' moon Phobos

Patrick N. Peplowski^{a,*}, Morgan Burks^b, John O. Goldsten^a, Samuel Fix^a, Lena E. Heffern^{b,1}, David J. Lawrence^a, Zachary W. Yokley^a

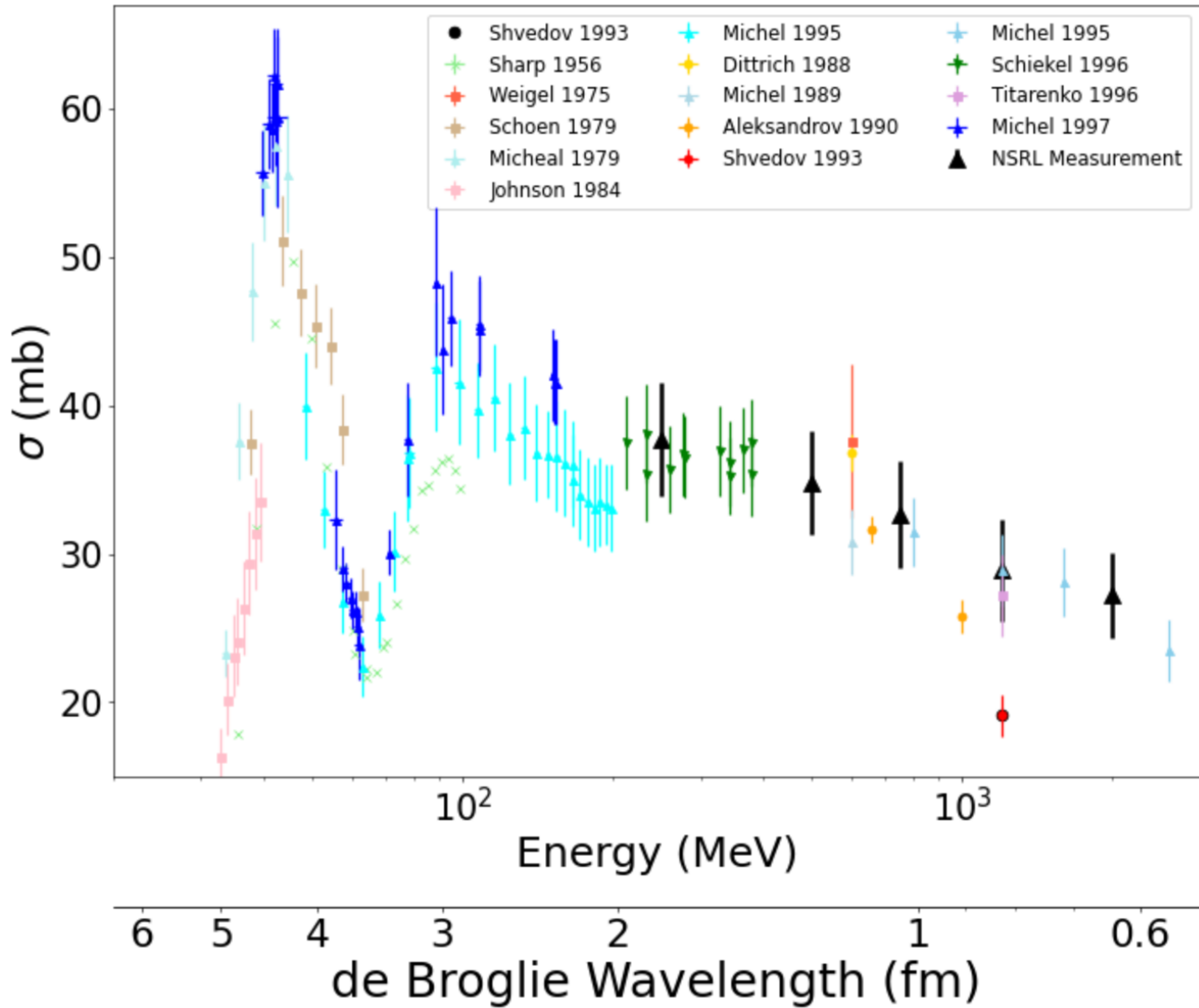
^a Johns Hopkins Applied Physics Laboratory, 11100 Johns Hopkins Road, Laurel MD 20723, USA
^b Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore CA 94550, USA



$^{59}\text{Co}(p,X)^{58}\text{Co}$; Energy = 250 MeV



$^{59}\text{Co}(p,X)^{54}\text{Mn}$



27	^{55}Co 17.53 h $\epsilon+\beta^+=100\%$	^{56}Co 77.236 d $\epsilon+\beta^+=100\%$	^{57}Co 271.8 d $\epsilon=100\%$	^{58}Co 70.883 d $\epsilon+\beta^+=100\%$	^{59}Co STABLE 100%	^{60}Co 5.271 y $\beta^-=100\%$
26	^{54}Fe STABLE 5.845%	^{55}Fe 2.756 y $\epsilon=100\%$	^{56}Fe STABLE 91.754%	^{57}Fe STABLE 2.119%	^{58}Fe STABLE 0.282%	^{59}Fe 44.495 d $\beta^-=100\%$
25	^{53}Mn 3.62e+6 y $\epsilon=100\%$	^{54}Mn 312.1 d $\epsilon+\beta^+=99.999\%$ $\beta^-=9.3e-5\%$	^{55}Mn STABLE 100%	^{56}Mn 2.58 h $\beta^-=100\%$	^{57}Mn 85.4 s $\beta^-=100\%$	^{58}Mn 3 s $\beta^-=100\%$
24	^{52}Cr STABLE 83.789%	^{53}Cr STABLE 9.501%	^{54}Cr STABLE 2.365%	^{55}Cr 3.498 min $\beta^-=100\%$	^{56}Cr 5.94 min $\beta^-=100\%$	^{57}Cr 21.1 s $\beta^-=100\%$
	28	29	30	31	32	33

Proton Number vs Neutron Number

NSRL measurements were validated against published results from dedicated cross section measurements.