NASA GeneLab space omics database: expanding from space to ionizing radiation data on the ground

National Aeronautics and
Space Administration

To enable scientific discovery and space exploration through multi-omics data-driven research

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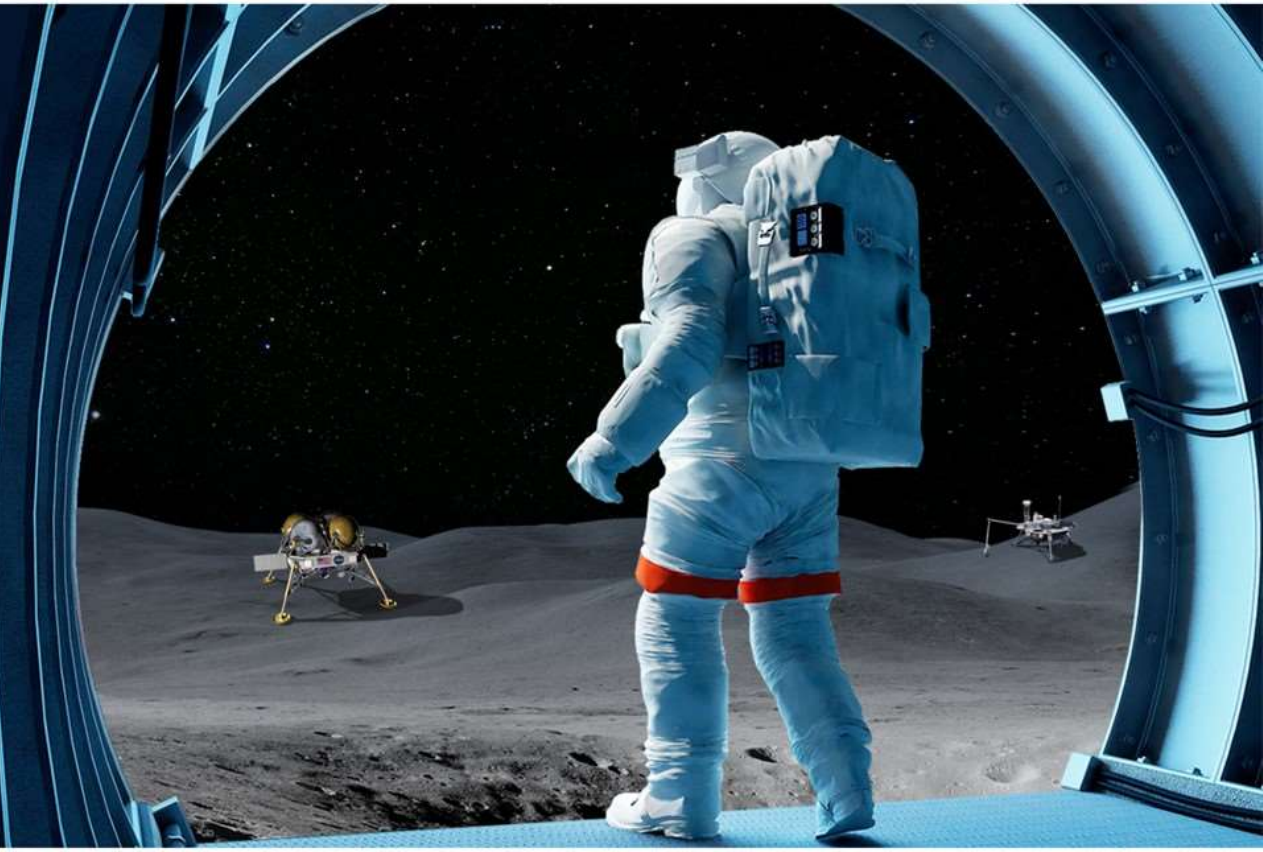
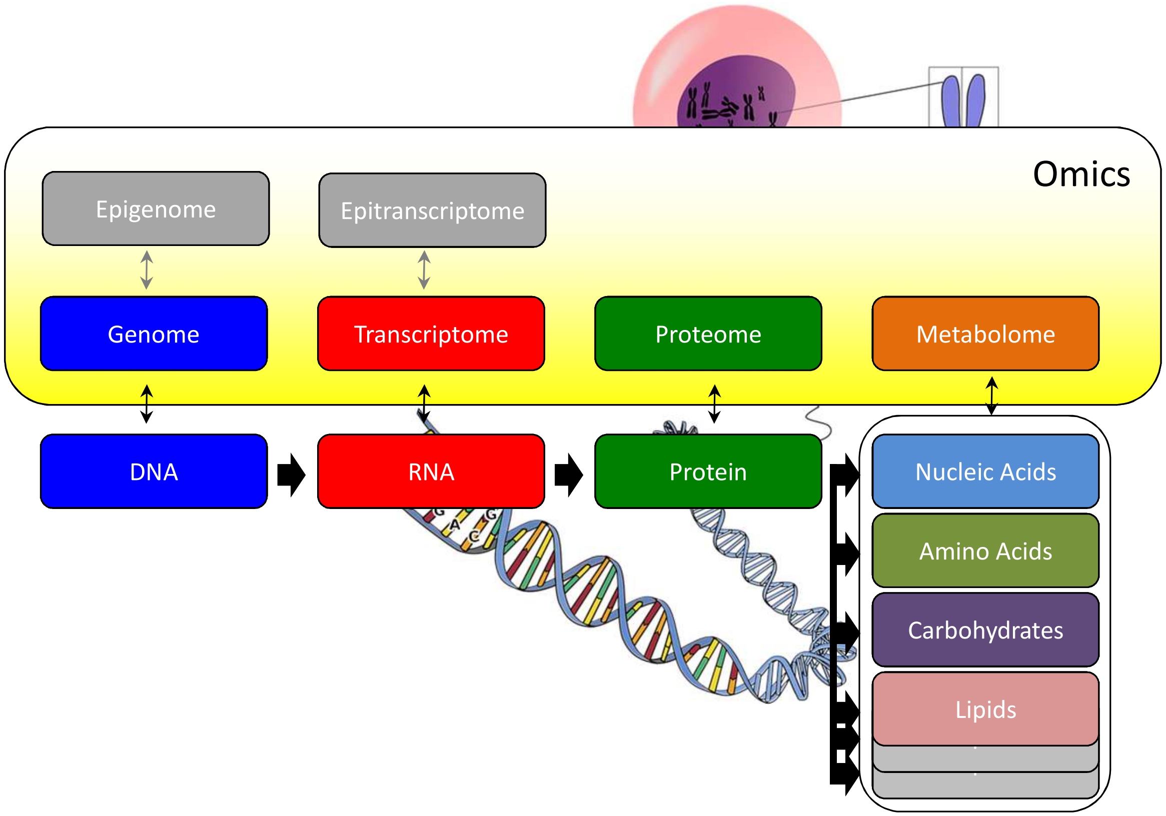
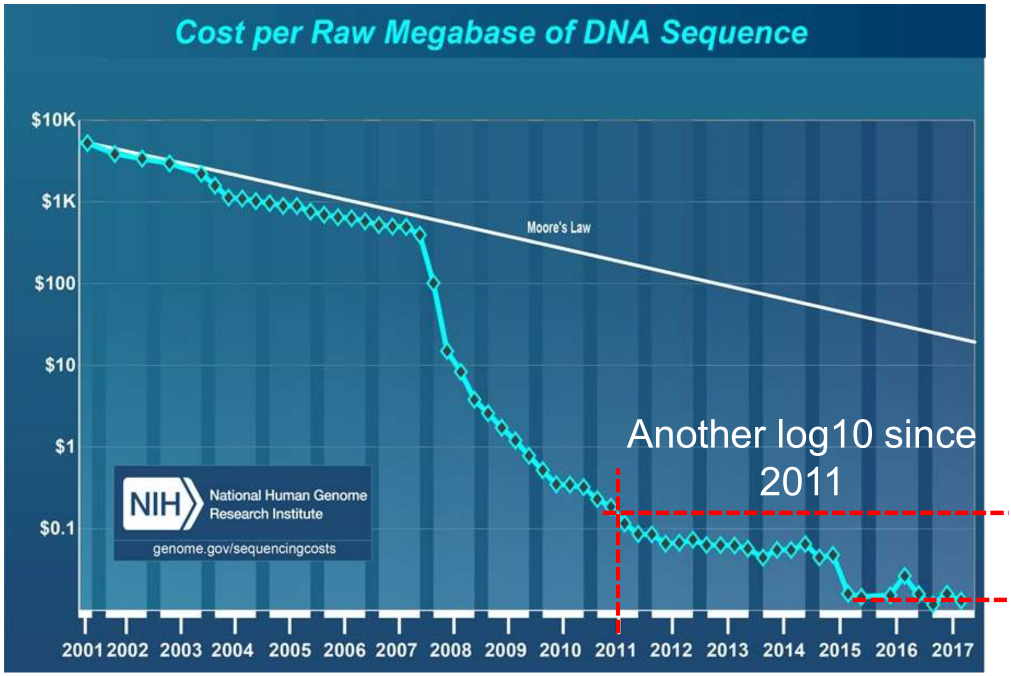
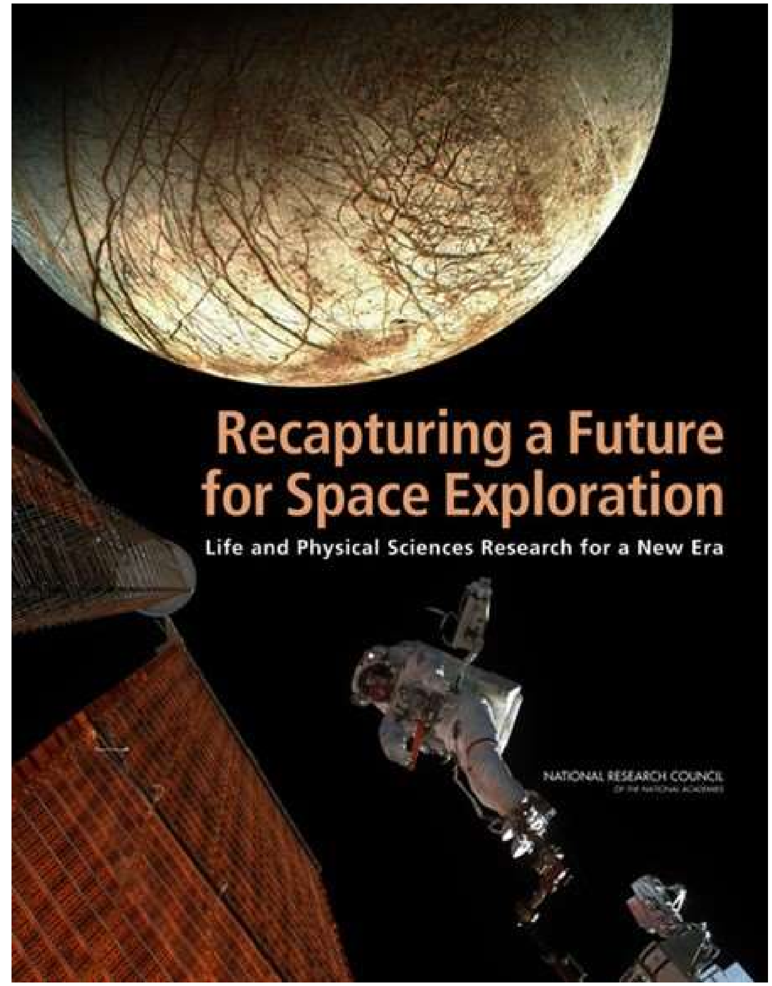


What is Omics?



2011 NRC Decadal Survey and the Sequencing Paradigm Shift



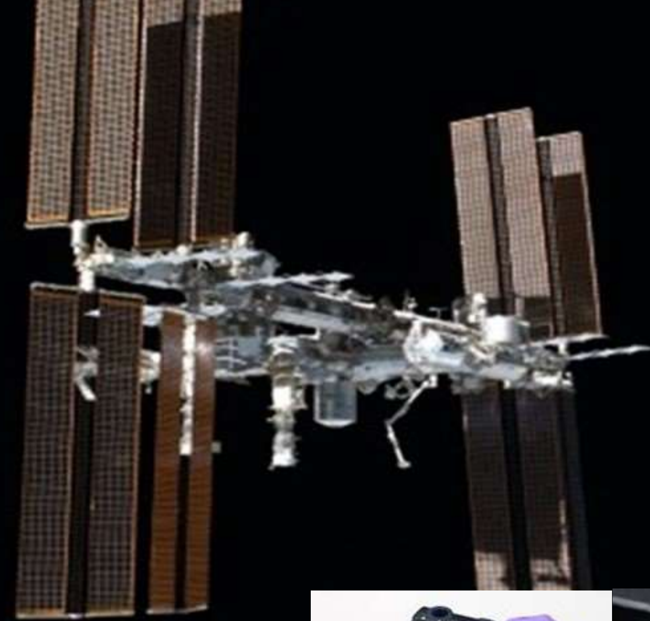


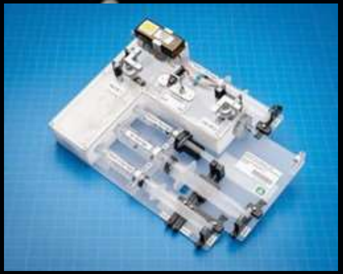
*"…**genomics, transcriptomics, proteomics, and metabolomics** offer an immense opportunity to understand the effects of spaceflight on biological systems…"*

*"…Such techniques generate considerable amounts of **data that can be mined and analyzed** for information by multiple researchers…"*

Omics Acquisition in Space is Now a Reality

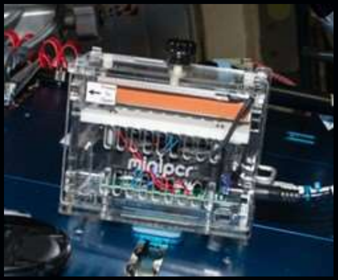
This is truly an exciting time for cellular and molecular biology, omics and biomedicine research on ISS with these amazing additions to the suite of ISS Laboratory capabilities.





Sample Preparation Module

Oxford Nanopore MinION Gene Sequencer



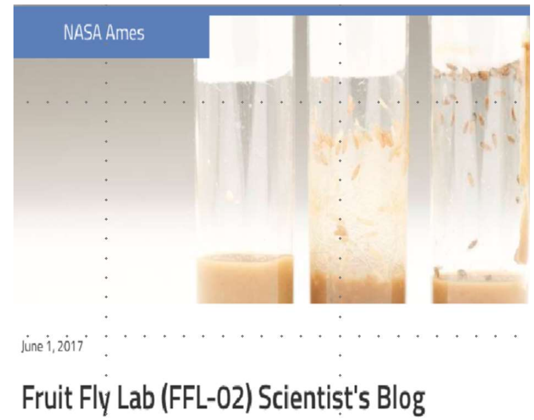
Mini-PCR

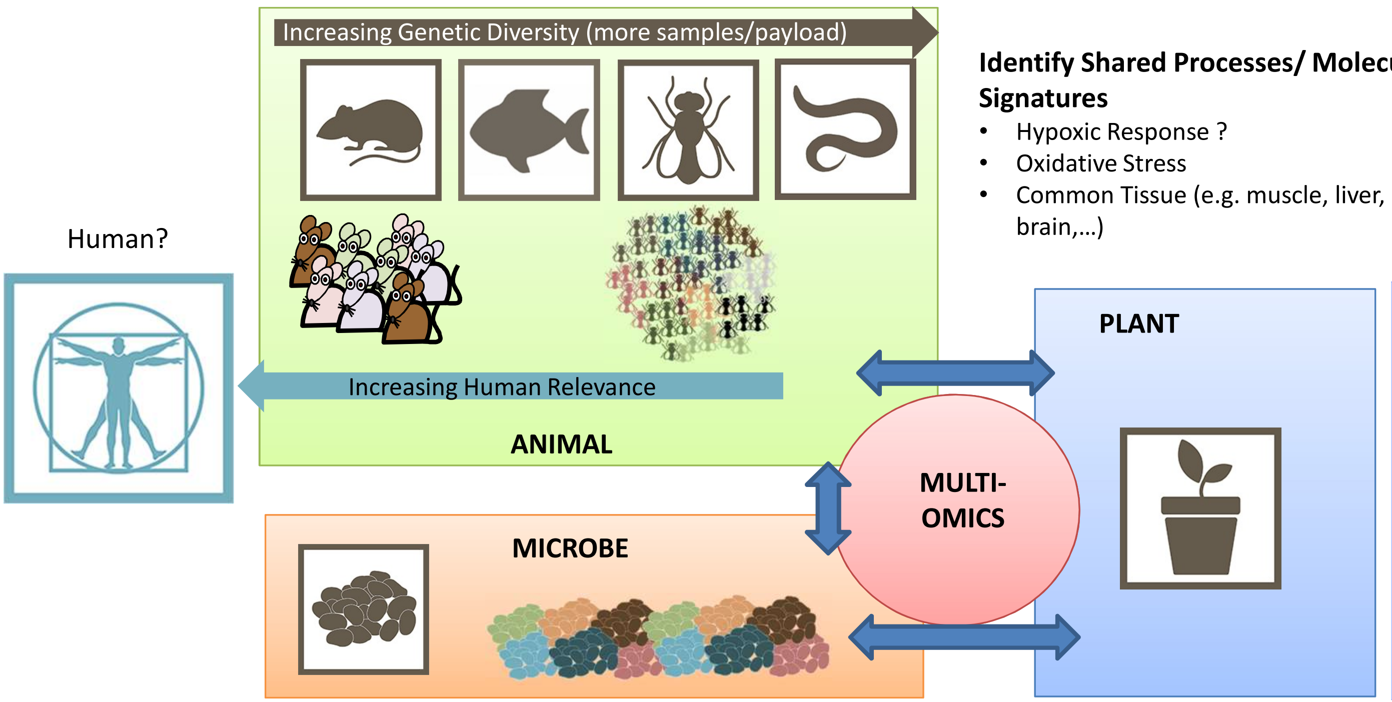
Cepheid Smart Cycler qRT-PCR

Reaction tube containing lyophilized chemical assay bead (proprietary)

GeneLab ecosystem: maximizing knowledge by bringing experiments together as a system

- **Sequencing on ISS is still limited in the amount of data generated**
  - Most of the work needs to happen on earth
- **Measurements on human cannot be too invasive and limited in numbers**
  - Usage of animals





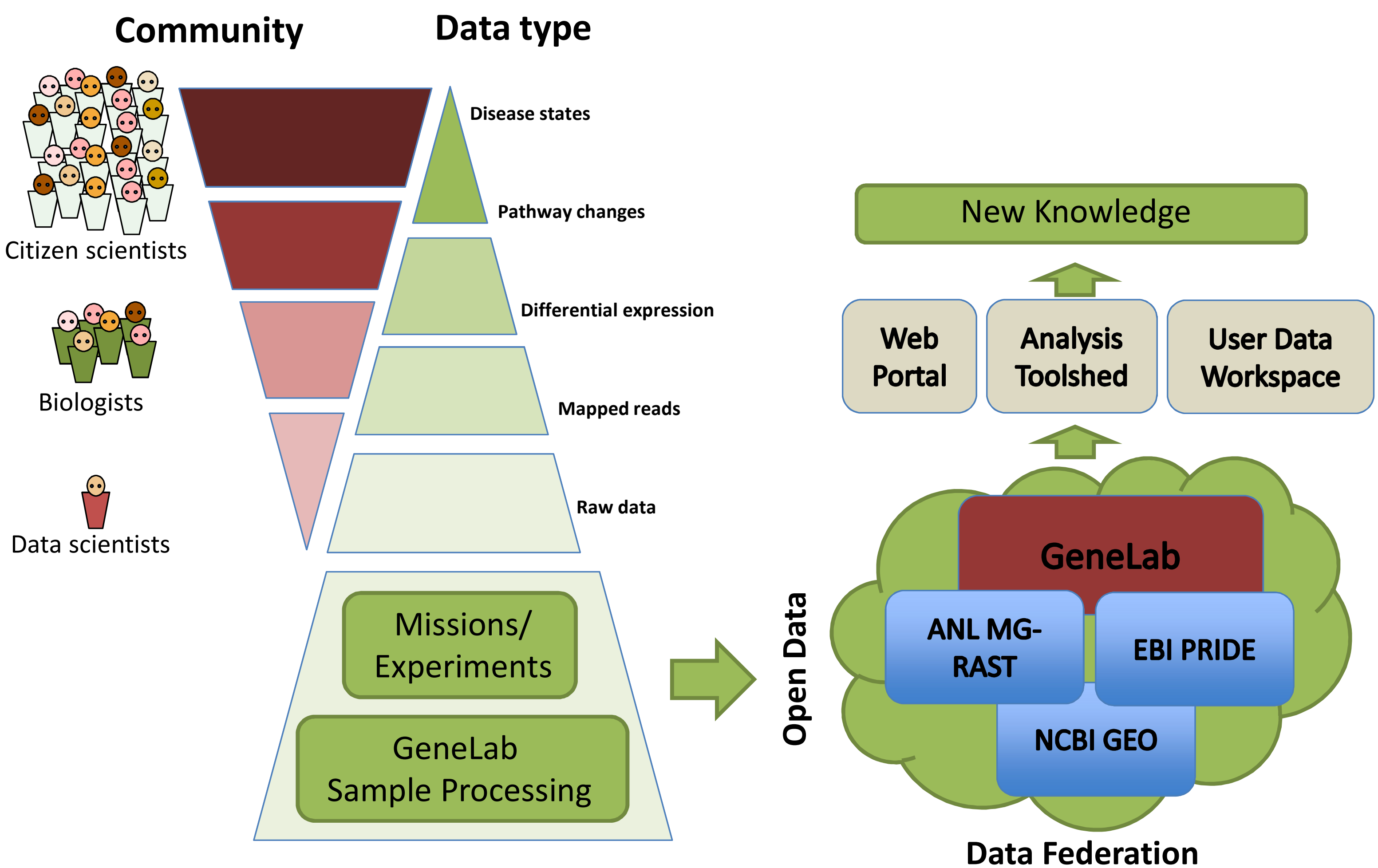
Identify Shared Processes/ Molecular Signatures

- Hypoxic Response ?
- Oxidative Stress
- Common Tissue (e.g. muscle, liver, heart, eyes, brain,…)

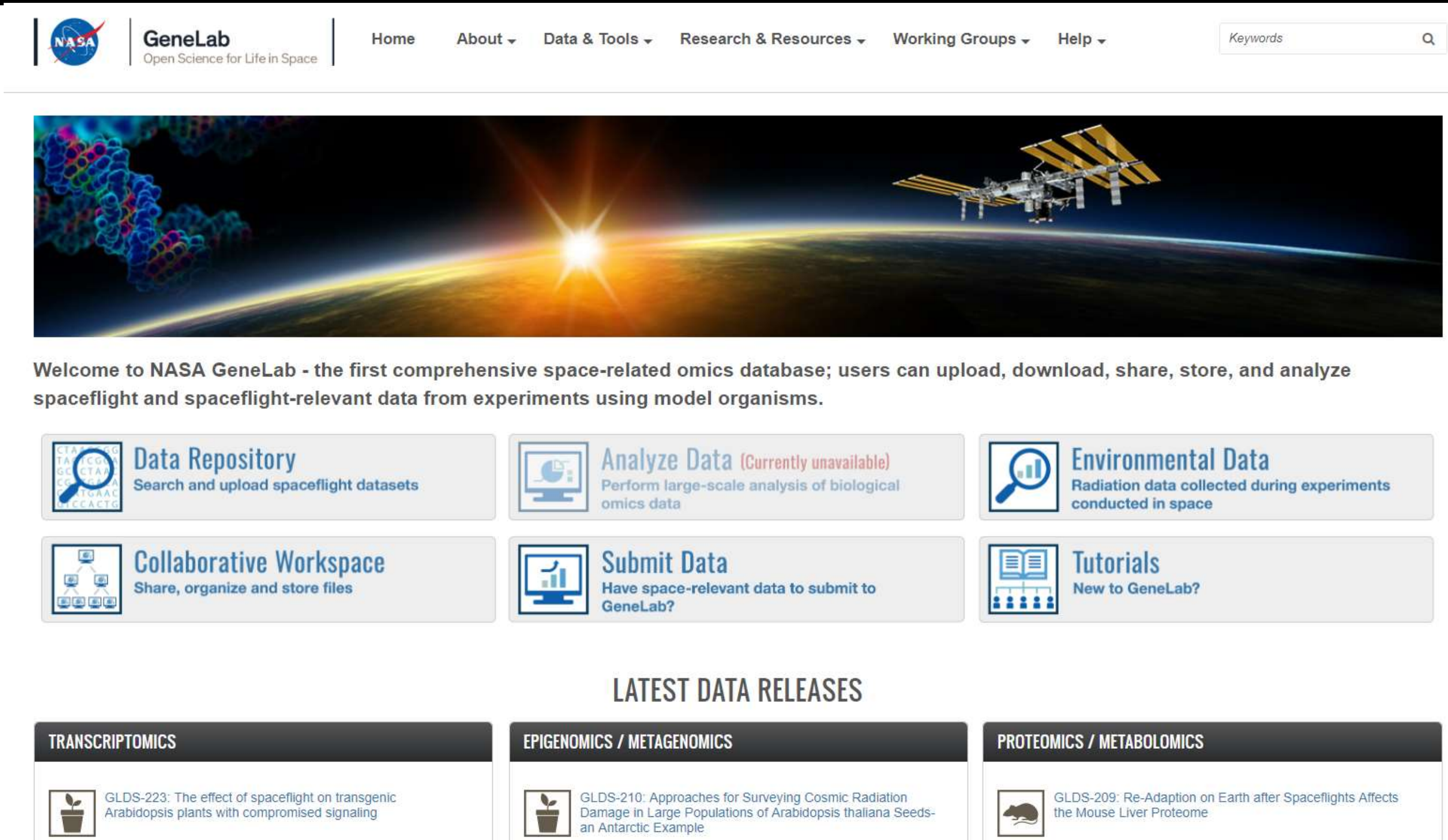
For Spaceflight

- High "n" number – statistically significant data
- Genetically identical animals
- Low resource requirements
- Short life cycle - multiple generations
- Measure response of a whole multicellular animal
- **Flies used as a model for humans for innate immunity, circadian rhythm, oxidative stress, neurobehavior, development, genetics, GWAS, "omics" studies etc.**

GeneLab Data Democratization

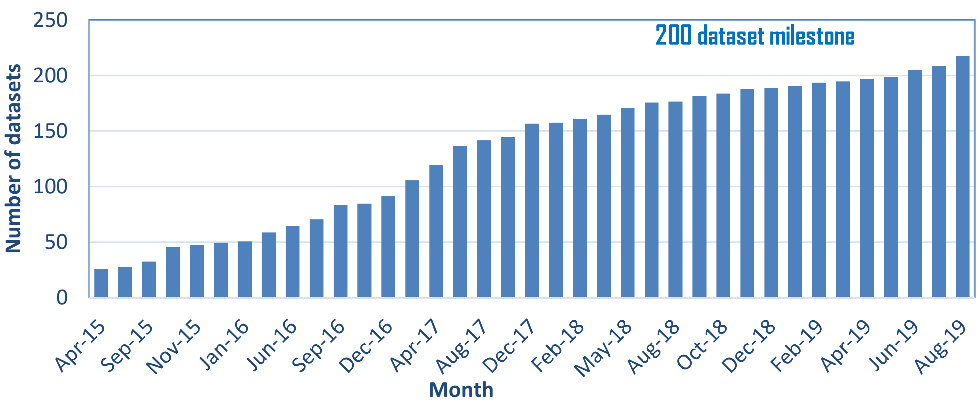


GeneLab Webpage: genelab.nasa.gov

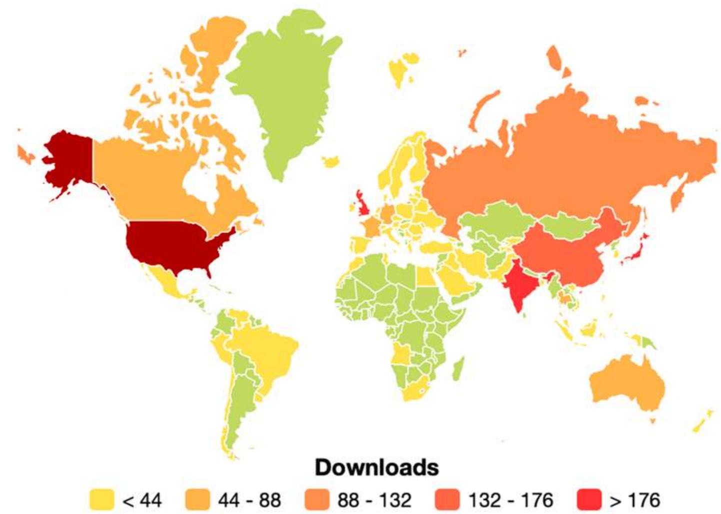


GLDS Metrics Highlights

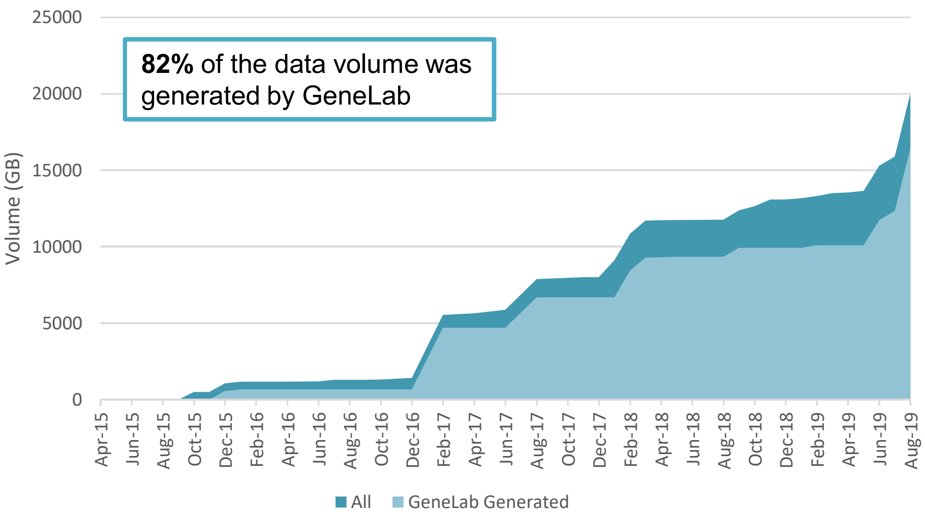
Total Number of Datasets



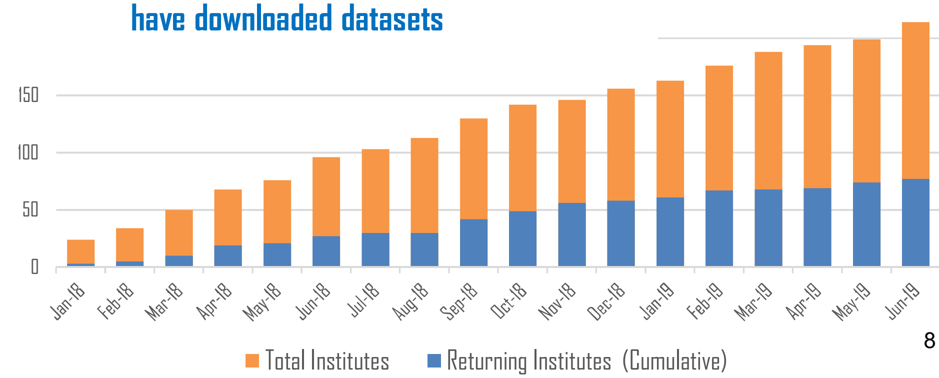
Users in 77 countries around the world have downloaded GLDS datasets



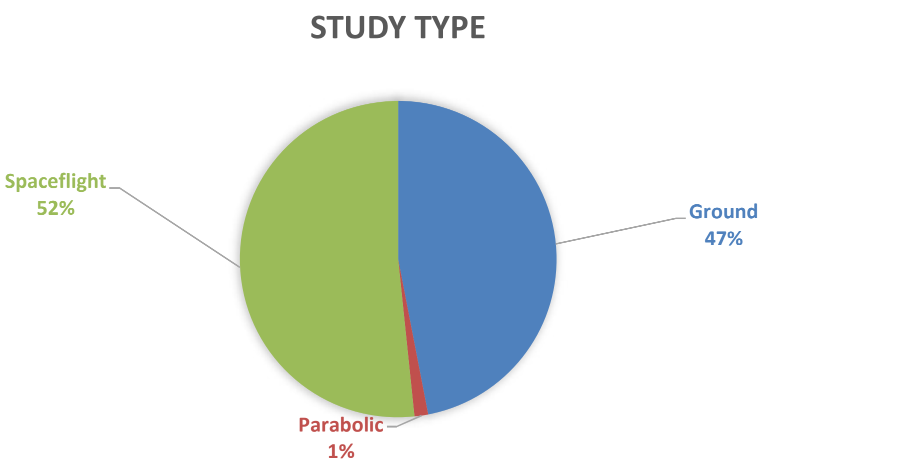
Cumulative Growth of Data in GL Repository

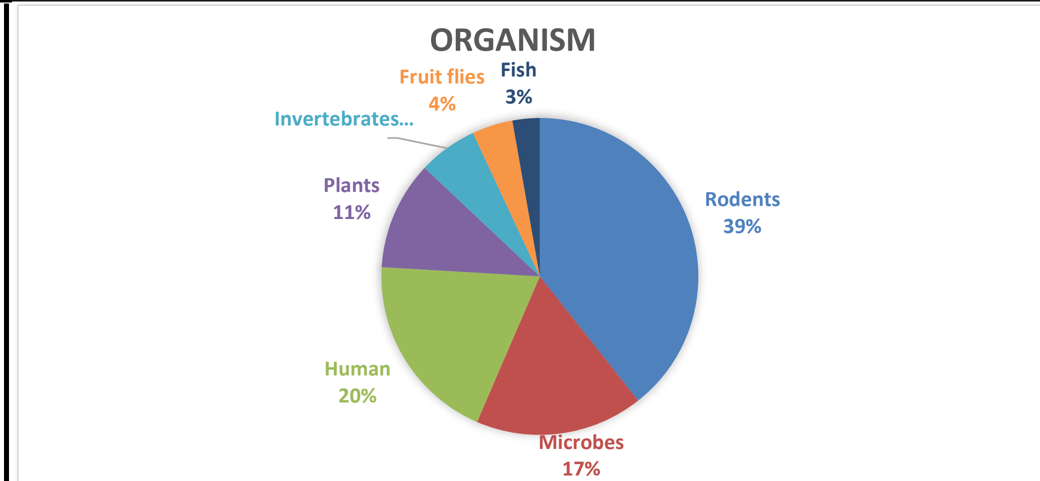


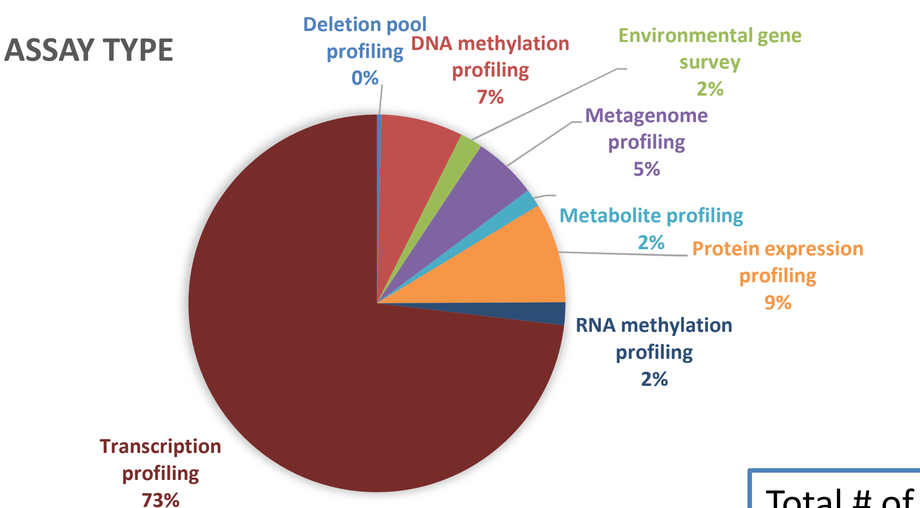
214 identifiable institutes in 34 countries have downloaded datasets

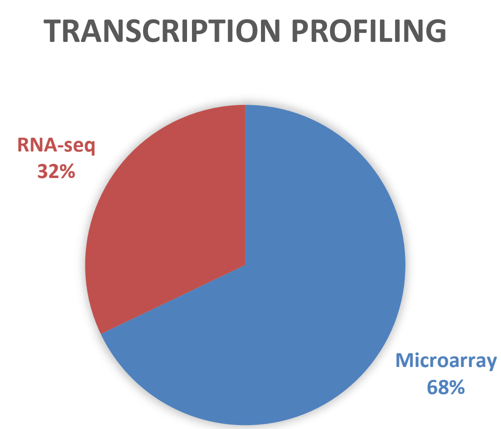


Overview: Database content



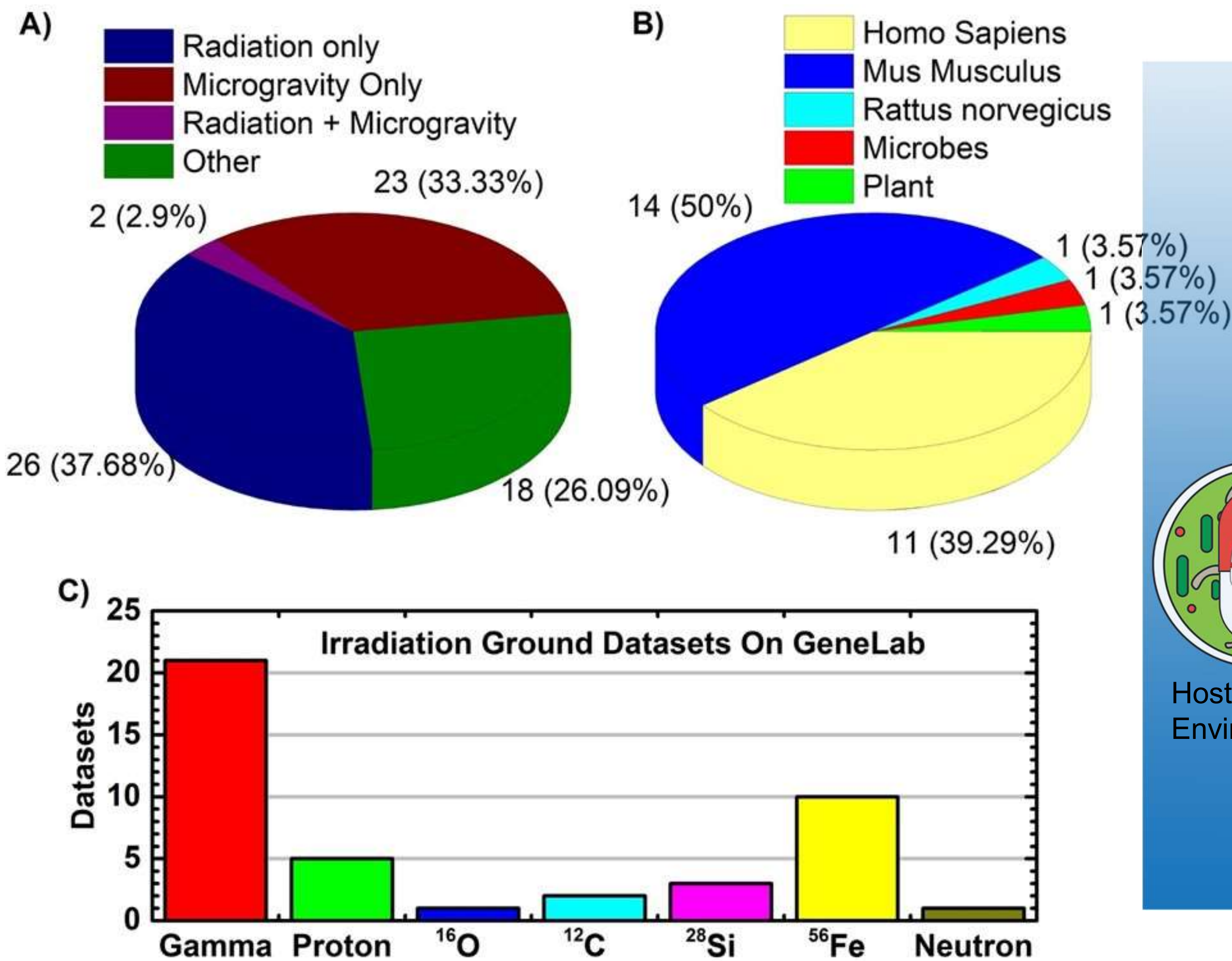




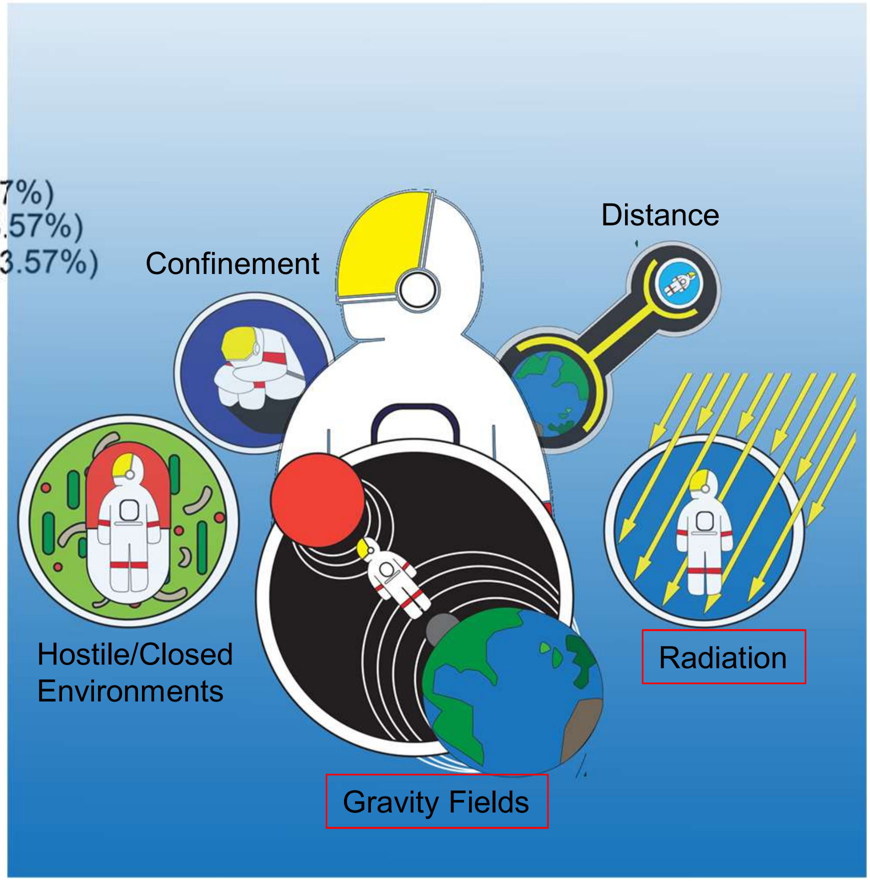


Total # of studies: 213

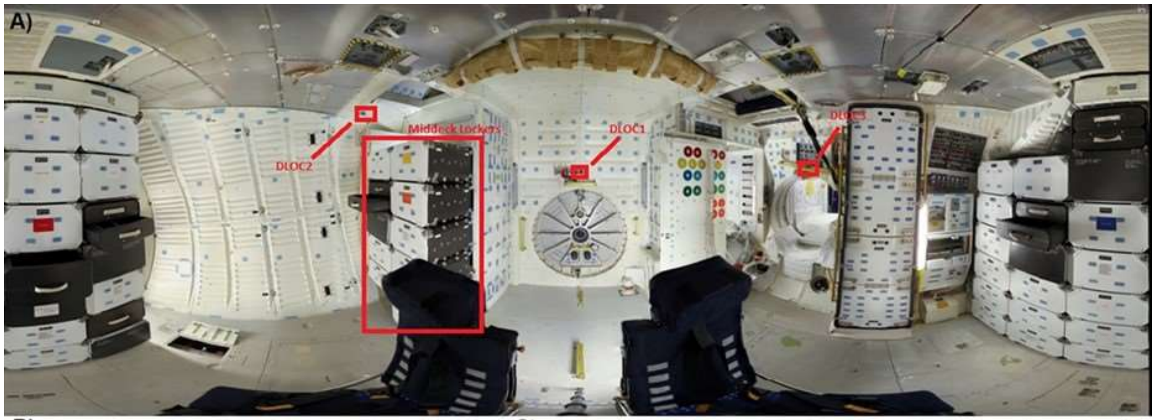
69 Ground Data Sets: Radiation and simulated microgravity

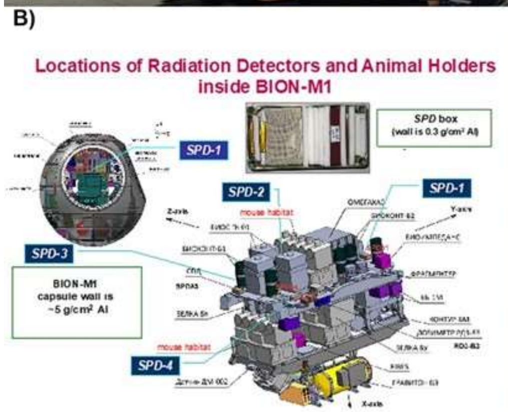


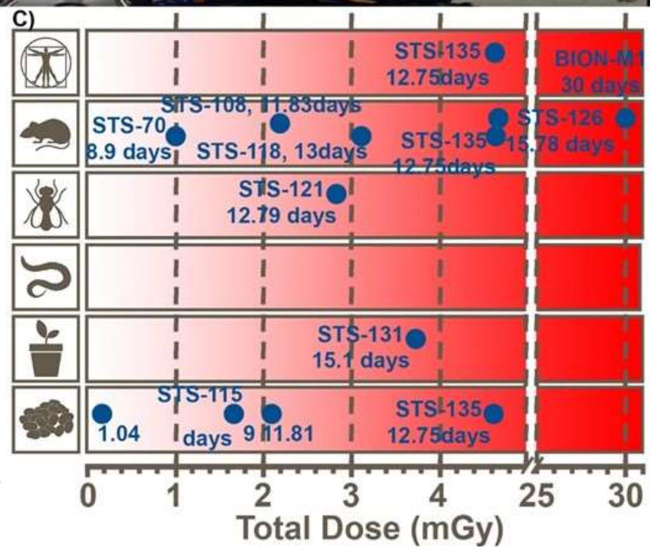
Beheshti et al., Radiation Research 2018



Large difference in radiation Dosimetry on the Space Shuttle





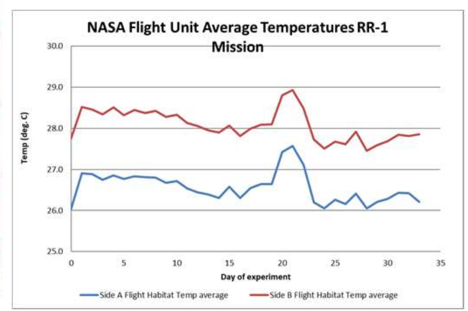


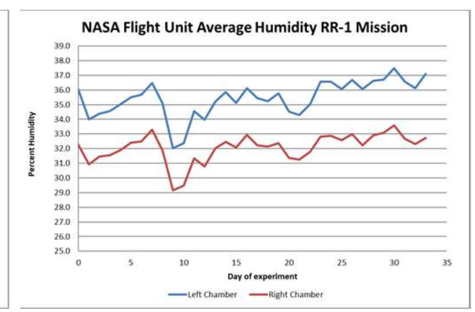
Beheshti et al., Radiation Research 2018

STS = Space Transportation System (Shuttle Program)

Abs Dose Rate
(mGy/day)

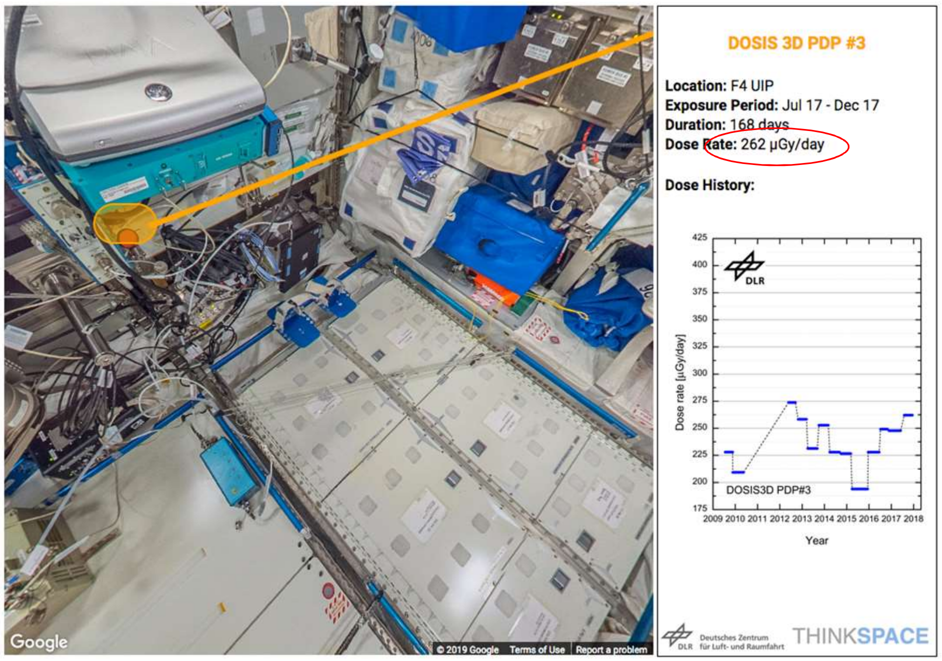
	DLOC1	DLOC2	DLOC3
STS-126	0.22	0.33	0.35
STS-131	0.20	0.20	0.34
STS-135	0.26	0.43	0.41





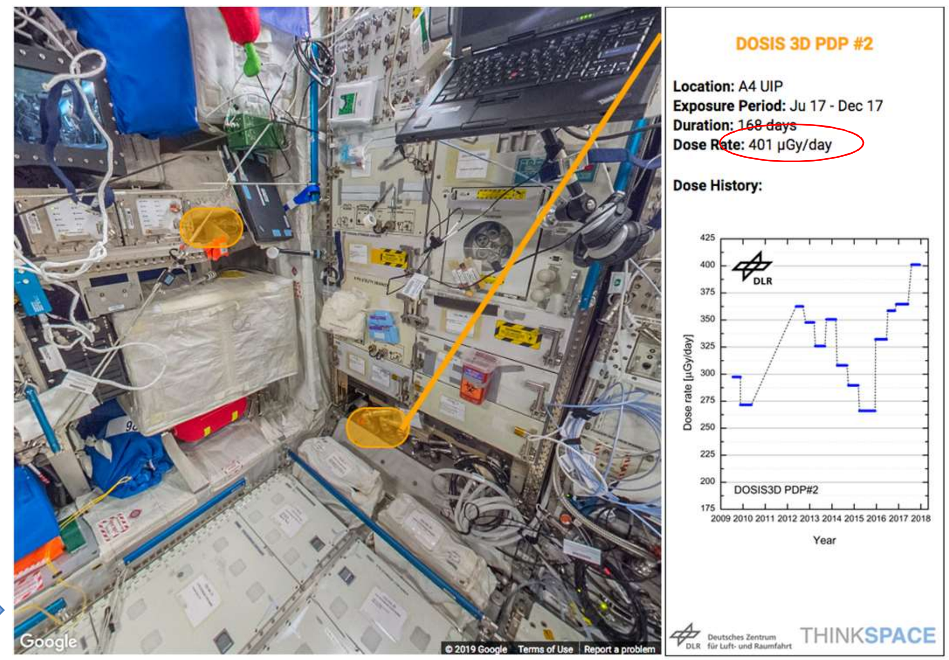
Large dose difference on the Columbus module
DOSIS 3D Radiation Sensor Interactive Overlay

Passive detector



1.5X higher

Passive detector



https://dosis-3d-data-viewer.thinkspaceconsulting.com/

J. Space Weather Space Clim., 6, A39 (2016) DOI: 10.1051/swsc/2016034

Experiments where no dosimetry was conducted at all – what to use? Nearest detector?

GLDS-95 (E. coli, US Lab)

- No dose data from US Lab.
- Data from Node2 REM (COL1A2) (avg. GCR=0.11/d, SAA=0.16/d) and TEPC (SMP327) (avg. GCR=0.10/d, SAA=0.22/d)
- Use Node 2 data (highest total dose).

GLDS 207 (Drosophila)

- Samples kept in Dragon capsule, sharing atmosphere with ISS.
- Berthed to Node 2 ("Harmony") Nadir Common Berthing Mechanism (CBM)
- Data from REMs in Kibo and Columbus; (Kibo is closest to Nadir CBM)

GeneLab number	Launch/ mission start	Landing/ mission end	Experiment start	Experiment end	Launch Vehicle	Return Vehicle	Spacecraft (ISS Module)	Habitat[1]	Dosimeter[2] (Module/Rack)[3]	Average Absorbed Dose[4] Rate (mGy/day)		Cumulative Absorbed Dose[4] (mGy)		
										GCR*	SAA*	GCR*	SAA*	Total
95	1/9/14	5/8/14 10/25/14	1/13/14	1/15/14 (49 hours)	Orbital CRS-1	SpaceX CRS-3 SpaceX CRS-4	ISS (US Lab)	CGBA-FPA	REM (NOD254)	0.11	0.24	0.21	0.48	0.69
207	4/18/14	5/18/14	4/18/14	5/18/14	SpaceX CRS-3	SpaceX CRS-3	ISS (Dragon Docked to Node 2 Nadir)	VFB	REM (JPM1F8OVHD)	0.10	0.23	3.13	7.18	10.31
									REM (COL1A2)	0.12	0.12	3.64	3.79	7.43

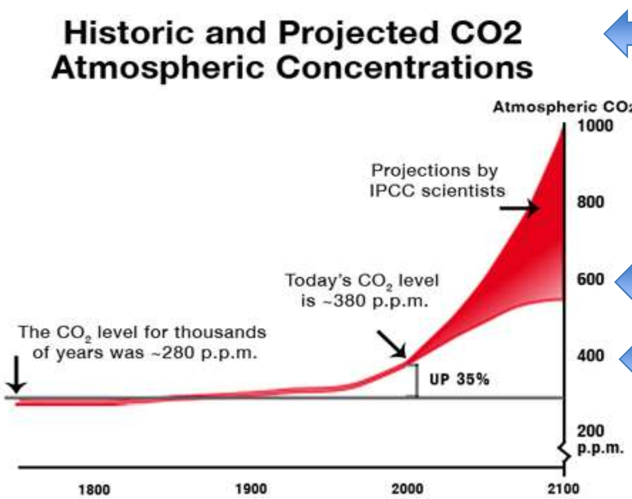
Sensitivity of OMICS: Ground Control (GC) Experiment

KSC ISS Environmental Simulator (ISSES; CO_2, O_2, Temp, RH)

AEM vs Vivarium Control

Animal Enclosure Module (AEM)

Sample vivarium cage



Source: IPCC
http://www.ipcc.ch/present/graphics.htm

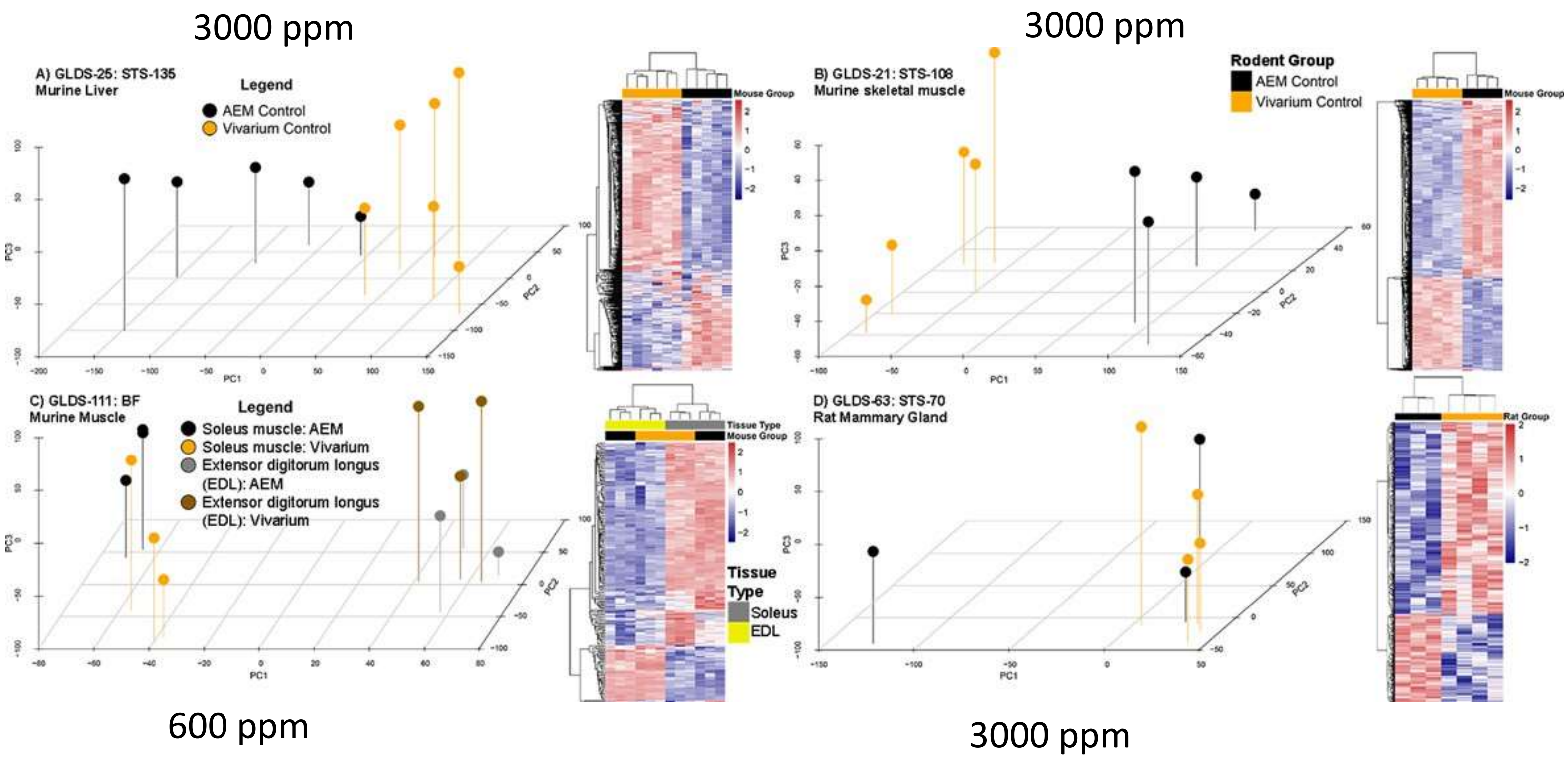
AEM (3000 ppm)

AEM (600 ppm)

Vivarium (380 ppm)

4 Datasets

Physiological levels of Carbon Dioxide as an Environmental Stressor in Spaceflight are detectable by OMICS



AEM = Animal Enclosure Modules (now referred to as Rodent Habitats)

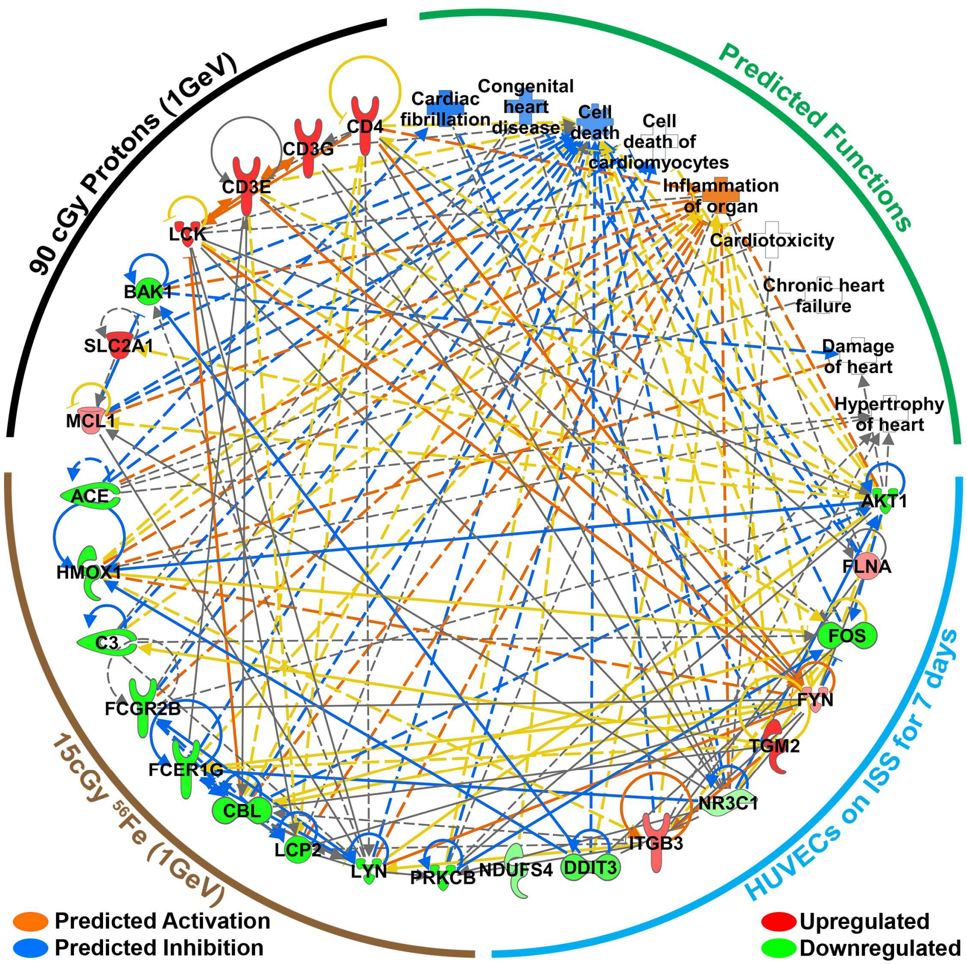
Vivarium = normal ground based rodent cages

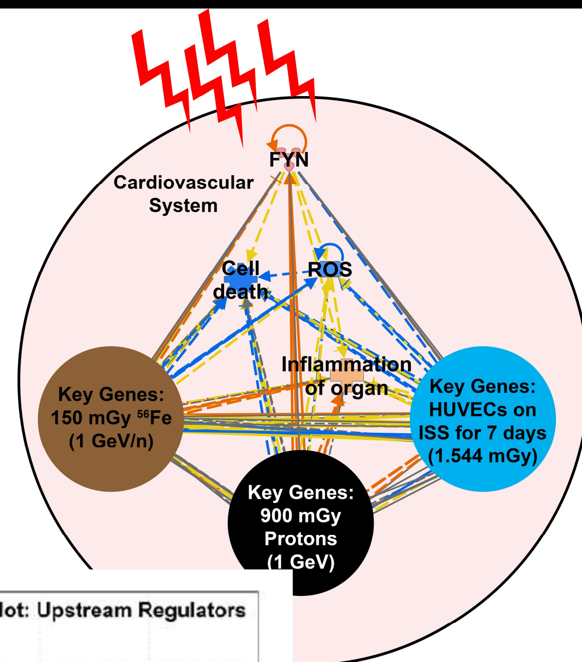
Even though simulated levels up to 3000 ppm CO2 are considered safe without detectable physiological impacts, hypoxic responses are detected from such exposure in mouse tissue

Beheshti, et al., Scientific Reports, 2018

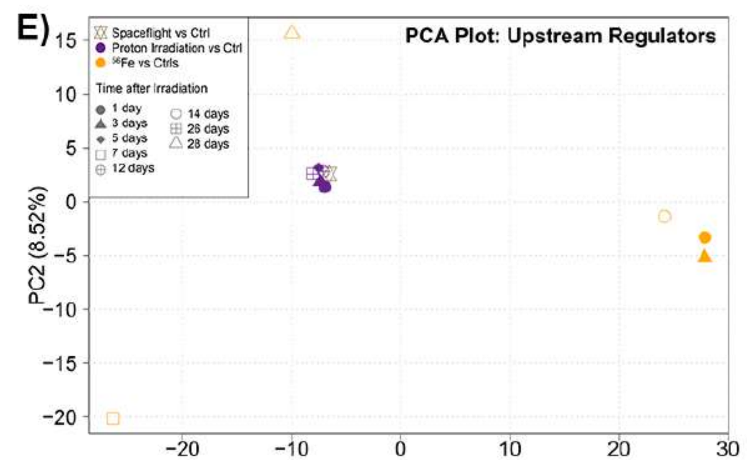
Statistical analysis reveals molecular changes in space most resemble ground simulation of Proton, not Fe-56

Key Driving Genes





Beheshti, et al. IJMS, 2019



Environmental Data for Spaceflight Experiments

Any and all data regarding the conditions under which an experiment is conducted may have bearing on how the data produced during the experiment are interpreted; these conditions, explicitly documented or not, are a part of the experiment design. Therefore, GeneLab is taking actions, where possible and policies and available resources permit, to collect and publish data on these conditions. We have grouped these conditions into the areas listed below.

Space Radiation Dosimetry

Dosimetry measuring techniques vary depending on the particular experiment environment. Through 2018, most flight experiments have not employed "dedicated" dosimeters (i.e. dosimeters integrated into experiment platform housing). Therefore, doses to which study samples are exposed frequently must be interpolated and/or extrapolated from close-by dosimeters. Two qualities of radiation were considered: low-LET (photons and electrons) and high-LET (charged nuclei). Both passive (thermoluminescent dosimeters: TLD, or plastic nuclear track detectors: PNTD) and active (solid state, tissue equivalent proportional counters) have been used. For passive dosimeters, TLD are sensitive to low-LET charged particles (< 10 keV/μm) and PNTD to high-LET (> 10 keV/μm). Active dosimeters are sensitive to a wider range in LET and, depending on the detector, can provide time resolution, LET spectra and some particle identification. By integrating the dose from the time-resolved data over the duration of the experiment, the total absorbed dose can be calculated. Depending on the configuration of dosimeters in the vicinity of the samples, absorbed dose may be reported as averaged with other detectors, or individually.

Datasets in the GeneLab repository with samples flown in space have corresponding metadata which includes the exposure duration, and the average, minimum and maximum absorbed dose received, broken out into low LET and high LET charged particles (when LET resolution is available). The duration of the exposure is defined as the time a sample was in space and biologically active, i.e. when the sample has returned to Earth or when it is chemically fixed or frozen in space. It is important to note that the absorbed doses we provide in these metadata are an approximation, due to several limiting factors. First, there is known contribution of sensitivity in charge and LET for each detector being used. For example, even though TLDs detect low-LET radiation, the detected dose also includes some contribution from charged nuclei depending on the charge and speed of the nuclei traversing the detector. Similarly, active detectors even if tuned to specific energies and charges can still have traces dose from low-LET particles and neutrons. Second, reported dosimetry does not take into account the additional shielding provided by the sample enclosure. For low energy particles or low-LET this hardware could have significant attenuating effect and would be unique for each mission and experiment. Therefore, in addition to the radiation metadata for individual dataset, GeneLab also reports dosimetry measurements for all detectors available for the types of missions listed below.

Abbreviations: LET = Linear Energy Transfer, TLD = Thermoluminescent Dosimeters, PNTD = Plastic Nuclear Track Detectors.

STS (Space Shuttle) Radiation Dosimetry
For STS (Space Shuttle) experiments, three passive dosimeter packages were fixed in locations on the shuttle middeck, where biological samples were located. More details and dosimetry values...

BION-M1 Radiation Dosimetry
Both passive and active dosimeters were used. More details and dosimetry values...

Foton-M4 Radiation Dosimetry
Passive dosimeters were used. More details and dosimetry values...

ISS Radiation Dosimetry

ENVIRONMENTAL DATA

+ Environmental Data for Spaceflight Experiments
  - STS (Space Shuttle) Radiation Dosimetry
  - BION-M1 Radiation Dosimetry
  - Foton-M4 Radiation Dosimetry
  - ISS Radiation Dosimetry Data
    - Rodent Research Radiation Dosimetry
    - US Lab Radiation Dosimetry
    - International Labs Radiation Dosimetry

Radiation Metadata for GLDS Studies

Table 1 contains information used to calculate the absorbed dose of radiation for STS ("space shuttle") experiments. The absorbed dose from ionizing radiation received by the specimens (animals, plants, cells) was estimated from data recorded by three passive radiation dosimeter (PRD) packages, designated DLOC1, DLOC2, and DLOC3, in the middeck of the space shuttle, where biological payloads were located. Each package contains a number of TLD-100 thermoluminescent detectors. The TLDs are passive detectors: they integrate dose and must be processed--in the case of TLDs, by heating. (As opposed to active detectors which are powered and can be read out continuously, in real-time.) The detectors are returned post-flight and the data analysed by the Space Radiation Analysis Group at NASA-Johnson Space Center. The reported dose for each PRD is the average over all the TLDs +/- the standard deviation, with appropriate background subtraction and error propagation. Correction for dose accumulated on the ground pre- and post-flight is done by subtracting the dose in identical detectors that remain on the ground, and a calibration factor is applied to convert dose in the TLDs to dose in water.

Radiation Metadata Table 1

GLDS Accession Number	GLDS-63	GLDS-21	GLDS-11 GLDS-15 GLDS-20	GLDS-4	GLDS-1 GLDS-3	GLDS-50	GLDS-17 GLDS-44 GLDS-121	GLDS-25 GLDS-54 GLDS-72 GLDS-87 GLDS-108 GLDS-116 GLDS-173 GLDS-222
Mission	STS-70	STS-108	STS-115	STS-118	STS-121	STS-126	STS-131	STS-135
Inclination	28.45	51.60	51.60	51.60	51.60	51.60	51.60	51.60
Launch/mission start	07-13-95	12-05-01	09-09-06	08-08-07	07-04-06	11-14-08	04-05-10	07-08-11
Landing/mission end	07-22-95	12-17-01	09-21-06	08-08-07	07-17-06	11-30-08	04-20-10	07-21-11
Mission duration (days)	8.93	11.83	11.81	12.76	12.79	15.87	15.10	12.76
Experiment duration (days)	8.93	11.83	1.00	12.76	12.79	14.00	12.88	12.76
Sample location	Middeck (AEM)	Middeck (CBTM)	Middeck (GAPS)	Middeck (AEM)	Middeck	Middeck (CGBA/FPA)	Middeck (BRIC)	Middeck (AEM)
Detector types	Passive	Passive	Passive	Passive	Passive	Passive	Passive	Passive
DLOC1: Absorbed Radiation Dose (mission) (mGy)	0.80	1.74	1.86	2.32	2.39	3.53	3.07	3.26
DLOC1: Absorbed Radiation Dose Uncertainty (mGy)	0.09	0.02	0.02	0.04	0.03	0.04	0.05	0.06
DLOC1: Absorbed Radiation Dose Rate (mGy/day)	0.09	0.15	0.16	0.18	0.19	0.22	0.20	0.26
DLOC2: Absorbed Radiation Dose	1.23	2.58	2.05	3.61	3.07	5.22	3.02	5.46

ENVIRONMENTAL DATA

GLDS Studies from BION-M1 experiments

Accession Number	Study Title
GLDS-111	Global gene expression analysis highlights microgravity sensitive key genes in soleus and EDL of 30 days space-flown mice
GLDS-135	Global gene expression analysis highlights microgravity sensitive key genes in longissimus dorsi and tongue of 30 days space-flown mice
GLDS-139	Mouse muscle LC-MSMS upon weightlessness
GLDS-209	Re-adaptation on Earth after spaceflight affects the mouse liver proteome
GLDS-232	The response of murine cartilages to 30 days of microgravity

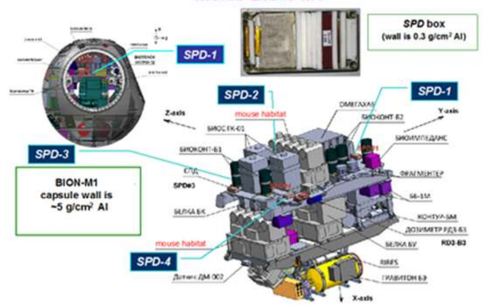
BION-M1 Radiation Dosimetry

Launch: 1000 UT 4/19/2013 (Baikonur, Kazakhstan)
Landing: 0312 UT 5/19/2013 (Orenburg region, Russia)
Orbit: apogee 585 km; perigee 555 km; inclination 65 deg

Detectors:
SPD1-4[1] Passive (thermoluminescent dosimeters, plastic nuclear track detectors) — charged particles
RD3-B3[2] Active (solid state, Liulin-type) — charged particles
(Operated 4/19-5/13)

Note: Tissues were obtained from surviving mice from the three animal habitats. Advise that data be used as averages and upper and lower bounds for radiation exposure.

Locations of Radiation Detectors and Animal Holders inside BION-M1



SPD data[1]

	Avg. Abs. Dose D (μGy/day)			Abs. Dose (mGy)[2]		
SPD	Low LET	High LET	Total	Low LET	High LET	Total
1	1267	151	1418	37.82	4.507	42.33
2	546	84	630	16.30	2.507	18.81
3	713	112	825	21.28	3.343	24.63
4	1008	141	1149	30.09	4.209	34.30

[1] From I. Ambrožová *et al.*, Radiat. Meas. 106 (2017) 262-266.
[2] Exposure duration was 29.85 days.

Notes:
- Low LET D measured with TLD
- High LET D and H measured with PNTD

RD3-B3 data[3]

Avg. Abs. Dose D (μGy/day)			
Total	GCR	IRB (SAA)	ORB
985	102.8	908	4.2

[3] From T. Dachev *et al.*, J. Atmos. Solar Terr. Phys. 123 (2015) 82-91.

Notes:
- GCR = galactic cosmic ray charged nuclei
- IRB (SAA) = inner radiation belt (South Atlantic Anomaly)
- ORB = outer radiation belt
- Total (GCR+IRB+ORB) is somewhat greater than total, due to overlap in selection criteria (as defined in Dachev *et al.*)

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TS (Space Shuttle) Radiation
osimetry

ION-M1 Radiation Dosimetry

oton-M4 Radiation Dosimetry

S Radiation Dosimetry Data

Rodent Research Radiation
Dosimetry

US Lab Radiation Dosimetry

International Labs Radiation
Dosimetry

US Lab Radiation Dosimetry

GLDS #	Launch/ mission start	Landing/ mission end	Experiment start	Experiment end	Launch Vehicle	Return Vehicle	S
GLDS-7	Launch		Germination	Harvest			
7(1B)	11/16/09	2/22/10	12/3/09	12/15/09	STS-129	STS-130	
7(3A)	2/8/10	In review	2/21/10	3/7/10	STS-130	?	
7(2A)	4/5/10	5/26/10	4/9/10	4/21/10	STS-131	STS-132	
7(2B)	4/5/10	5/26/10	4/21/10	5/3/10	STS-131	STS-132	
GLDS-16	11/16/09	2/22/10	2/22/10	2/22/10	STS-129	STS-130	
GLDS-37	9/21/14	10/25/14	Germinated in orbit; grown for 8 days	In review	SpaceX CRS-4	SpaceX CRS-4	
GLDS-38	1/10/15	2/11/15	Germinated in orbit; grown for 3 days	In review	SpaceX CRS-5	SpaceX CRS-5	

Habitat[1]	Dosimeter[2] (Module/Rack)[3]	Average Absorbed Dose Rate[4] (mGy/day)		Cumulative Absorbed Dose[4] (mGy)			Notes
		GCR*	SAA*	GCR*	SAA*	Total	
ABRS (EXPRESS Rack)	TEPC (NOD2PD3)	0.16	0.11	2.02	1.46	3.48	Data from several replicates. Seeds were launched, held on ISS for periods ranging from 3-25 days, germinated and grown for 12-14 days, then harvested and fixed: doses reported are for germination+growth; 2; dose data from multiple detectors in several modules; for 2B, data for 4/21-22 are from SMP
	TEPC (JPM1FD3,NOD2P05)	0.14	0.13	2.16	2.00	4.16	
	TEPC (SMP327)	0.12	0.15	1.58	1.93	3.51	
	TEPC (NOD3F3,SMP327)	0.15	0.11	1.69	1.23	2.92	
ABRS (EXPRESS Rack 2)	TEPC (NOD2PD3)	0.16	0.11	2.02	1.46	3.48	Run 1B: 12/3/2009–12/15/2009 2009. Paper DOI: 10.1089/ast.2014.1210 (Note: pub says return was on 2/8/10; actually 2/22/10. 2/8 was launch date of STS-130; return was 2/22)
BRIC-PDFU	REM (LAB103)	0.13	0.07	1.06	0.58	1.63	Expt. start/end dates uncertain. Total dose = avg. x 8 days
BRIC-PDFU	REM (LAB103)	0.13	0.06	0.38	0.17	0.56	Expt. start/end dates uncertain. Total dose = avg. x 3 days
CHab in CGBA EXPRESS Rack 1)	TEPC (US Lab)	0.15	0.07	38.1	17.8	55.9	SRAG database has data for 6/15-8/21 only; comparing dose from TEPC in US Lab (6/16-8 /21/07) to doses measured w/ TLD100 (2000-2006) and in Russian segment (2001-2008), doses are consistent; therefore use avg. value form US Lab TEPC x 254 days
CGBA-FPA	REM (NOD254)	0.11	0.24	0.21	0.48	0.69	No data from US Lab. Data from Node2, REM (COL1A2) (avg. GCR=0.11/d, SAA=0.16/d) and TEPC (SMP327) (0.10, 0.22). Use Node 2 data (highest total dose).

SLPSRA

NASA

ENVIRONMENTAL DATA

International Labs Radiation Dosimetry

GLDS #	Launch/ mission start	Landing/ mission end	Experiment start	Experiment end	Launch Vehicle	Return Vehicle	Spacecraft
GLDS-13	9/18/06	9/29/06	9/18/06	9/22/06	Soyuz TMA-9 (ISS 13S)	Soyuz TMA-8	ISS (Zvezda)
GLDS-29	3/30/06	9/29/06	3/30/06	4/8/06	Soyuz TMA-8 (ISS 12S)	In review	ISS (Zvezda)
GLDS-31	10/18/03	10/28/03	10/18/03	10/28/03	Soyuz TMA-3 (ISS 7S)	Soyuz TMA-2	ISS (Zvezda)
GLDS-33	8/29/09	11/27/09	8/29/09	11/27/09	STS-128	STS-129	ISS (Kibo)
GLDS-35	4/19/04	4/30/04	4/19/04	4/30/04	Soyuz TMA-4 (ISS 8S)	Soyuz TMA-3	ISS (Zvezda)
GLDS-36	10/18/03	10/28/03	10/18/03	10/21/2003 (54 hrs)	Soyuz TMA-3 (ISS 7S)	Soyuz TMA-2	ISS (Zvezda)
GLDS-39	9/18/06	9/29/06	9/18/06	9/29/06	Soyuz TMA-9 (ISS 13S)	Soyuz TMA-8	ISS (Zvezda)

International Labs Radiation Dosimetry

Habitat Location[1]	Dosimeter (Location)[2]	high-LET threshold	Average Absorbed Dose Rate[3] (mGy/day)		Cumulative Absorbed Dose[3]	
			low-LET (or SAA)	high-LET (or GCR)	low-LET (or SAA)	high-LET (or GCR)
Kubik	TLD-100 (Zvezda)		—	—	—	—
Kubik	TLD-100 (Zvezda)		—	—	—	—
Zvezda	track etch (CR-39), OSLD (TLD-500), TLD-700 (Zvezda)		0.175	0.005*	1.75	0.05*
MDS (JPM EXPRESS Rack 4)	PADLES (TLD, track-etch (CR-39)) (JPM)	≥ 10 keV/um	0.286(0.033)	0.031(0.011)*	26.026(3.003)	2.821(0.325)*
Kubik, Aquarius	R-16 Radiometer, TLD		—	—	—	—
Aquarius	R-16 Radiometer, TLD		—	—	—	—
Zvezda	track-etch (PADC), OSL, TLD* (Zvezda)		0.19	0.021	2.28	0.25
CBEF	PADLES (TLD, track-etch (CR-39)) (JPM)	≥ 10 keV/um	0.286(0.033)	0.031(0.011)*	2.288(0.26)	0.248(0.088)*

The needs and challenges for more accurate payload dosimetry

Sensitivity of OMICS data are getting more and more sensitive

- Sequencing is getting more and more affordable, allowing deeper analysis
- OMICS are getting more and more precise
- Database is growing, increasing the statistical power for correlating doses to biological endpoints
- Biological precision on radiation response is ~20% - Current uncertainties on payload dose estimates on the ISS: ~<50%

Recorded doses to bio payloads depend on:

- location on ISS (not always known)
- dosimeter type
- relative locations of dosimeter(s) and sample

Proposals to Space Biology

- Dosimetry integrated with payload
  - Active vs Passive is being debated
  - Standard approach across agencies is a better strategy
- Dose modeling – Extrapolation from standard cabin dosimeters may be sufficient

Publications using GeneLab – 12 derived publications – 2 pending

Year	Title	Journal	Authors	Status	GLDS #	Utilizing GeneLab
2017	Validation of methods to assess the immunoglobulin gene repertoire in tissues obtained from mice on the international space station	Gravitational and Space Research	Rettig TA, Ward C, Pecaut MJ, Chapes SK	Published		GLDS-48
2018	A microRNA signature and TGF-β1 response were identified as the key master regulators for spaceflight response	PLoS One	Beheshti A, Ray S, Fogle H, Berrios D, Costes SV	Published		GLDS-25, 21, 63, 111, 4, 61, 48
2018	Nasa GeneLab project: Bridging space radiation omics with ground studies	Radiation Research	Beheshti A, Miller J, Kidane Y, Berrios D, Gebre SG, Costes SV	Published		Database paper- radiation datasets
2018	Global transcriptomic analysis suggests carbon dioxide as an environmental stressor in spaceflight: A systems biology GeneLab case study	Scientific Reports	Beheshti A, Cekanaviciute E, Smith DJ, Costes SV	Published		GLDS-21,111,25,63
2018	Meta-analysis of data from spaceflight transcriptome experiments does not support the idea of a common bacterial "spaceflight response"	Scientific Reports	Michael D. Morrison & Wayne L. Nicholson	Published	GLDS-185	GLDS-31,39,15,11,185,138,145
2018	GeneLab: Omics database for spaceflight experiments	Bioinformatics	S Ray, S Gebre, H Fogle, D Berrios, PB Tran , JM Galazka, SV Costes	Published		Database paper
2018	FAIRness and Usability for Open-access Omics Data Systems	AMIA Annual Symposium Proceedings Archive	Daniel C. Berrios, Afshin Beheshti, and Sylvain V. Costes	Published		Database paper
2019	Exploring the Effects of Spaceflight on Mouse Physiology using the Open Access NASA GeneLab Platform	JoVE	A Beheshti, Y Shirazi-Fard, S Choi, D Berrios, SG Gebre, JM Galazka, SV Costes	Published		Database paper
2019	GeneLab database analyses suggest a long term impact of Space Radiation on the Cardiovascular System by the activation of FYN through Reactive Oxygen Species	International Journal of Molecular Sciences	A Beheshti, J. T. McDonald, J. Miller, P. Grabham, SV Costes	Published		GLDS-52,109,117
2019	Comparison of Bacillus subtilis transcriptome profiles from two separate missions to the International Space Station	NPJ Microgravity	Michael D. Morrison, Patricia Fajardo-Cavazos & Wayne L. Nicholson	Published	GLDS-185	GLDS-185, 138
2019	Mice exposed to combined chronic low-dose irradiation and modeled microgravity develop long-term neurological sequelae	International Journal of Molecular Biology	Eliah G. Overbey, Amber M. Paul, Willian da Silveira, Candice G.T. Tahimic, Sigrid S. Reinsch, Nathaniel Szewczyk, Seta Stanbouly, Charles Wang, Jonathan M. Galazka and Xiao Wen Mao	Published		GLDS-202
2019	Reproducible changes in the gut microbiome suggest a shift in microbial and host metabolism during spaceflight	BMC Microbiome	Peng Jiang, Stefan J. Green, George E. Chlipala, Fred W. Turek, and Martha Hotz Vitaterna	Published		GLDS-48, 168
2019	A Multi-Omics Approach Demonstrates that Spaceflight Leads to Lipid Accumulation in Mouse Livers	Scientific Reports	Afshin Beheshti, Kaushik Chakravarty, Homer Fogle, Hossein Fazelinia, Willian A. da Silveira , Valery Boyko, San-Huei Lai, Amanda M. Saravia-Butler, Deanne Taylor, Jonathan M. Galazka, and Sylvain V. Costes	Submitted		GLDS-48, GLDS-47, GLDS-137
2019	Multi-Omics Analysis using GeneLab database recognizes Mitochondrial Dysfunction as a mediator of spaceflight health risks.	New England Journal of Medicine	Willian A. da Silveira, Hossein Fazelinia, Sara Brin Rosenthal, Evagelia C. Laiakis, Cem Meydan, Jonathan Foox, Yared Kidane, Komal S. Rathi, Susana Zanello , Scott M. Smith, Brian Crucian, Dong Wang, Adrienne Nugent, Sara R. Zwart, Sonja Schrepfer, Larry N. Singh, Douglas Wallace, Jeffrey S. Willey, J. Tyson McDonald, Sylvain V. Costes, Helio A. Costa , Christopher E. Mason, Kathleen Fisch, Deanne Taylor, Gary Hardiman, Afshin Beheshti			Multiple

Scientific Outreach Highlights
Letting the scientific community take the lead

AWG Members represent:

- 48 US Universities
- 4 NASA Centers
- 4 Other Government-funded Organizations
- 3 Institutes or Private Industry
- 3 International Universities

Total AWG Members: ~100

Members are now the leads

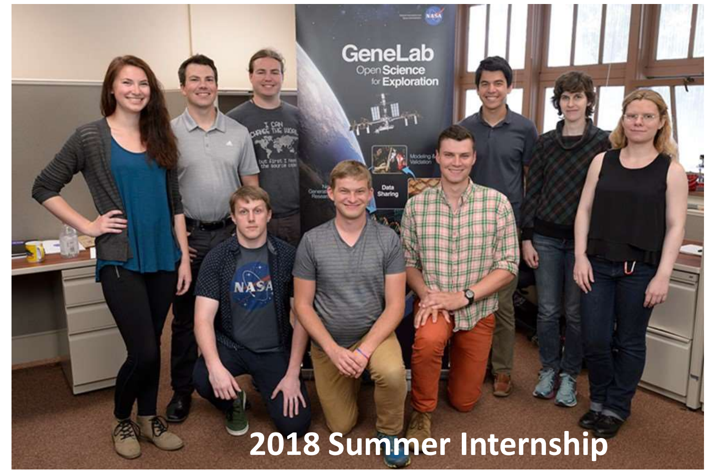
AWG Members Per Group:

Animal	30
Multi-Omics/System Biology	45
Plants	15
Microbes	17

**Some members are in multiple groups*


Pre-ASGSR AWG Workshop (Nov 2019)

GeneLab included in Bioinformatics curriculum of degree granting university


2018 Summer Internship

One intern became a new GeneLab member


GeneLab for High School (Tutorial + Tools)

2019 Summer Internship

GeneLab 1st NASA project approved for technical social media audience (vs general public @ 6th grade level)!

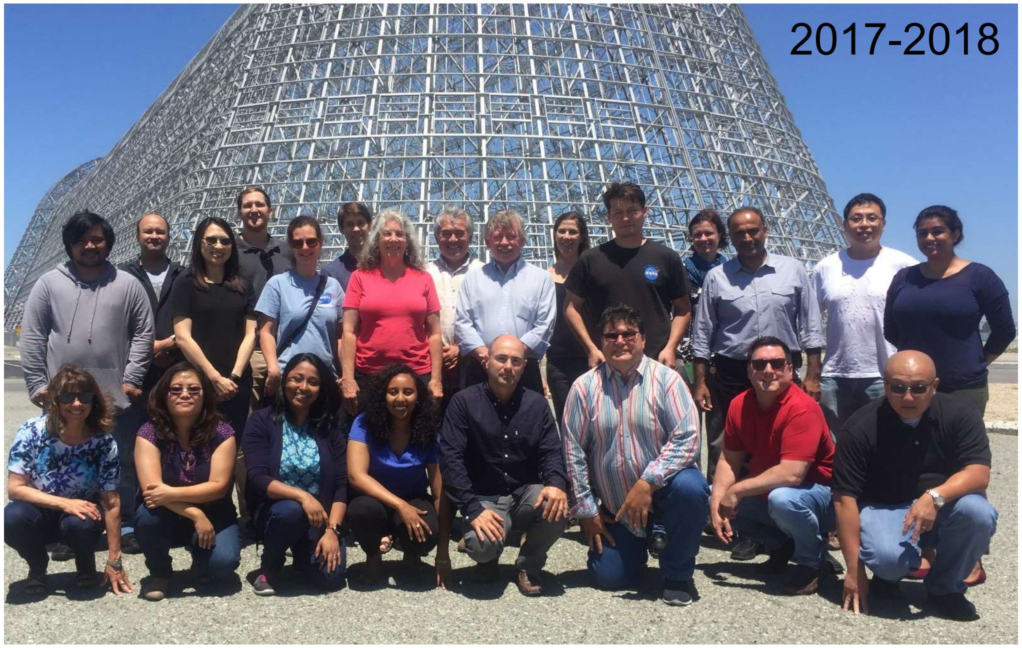

UK bedrest study

Spatial RNAseq

Visiting Scientists 2018-2019

NASA GeneLab AstroBotany COSE TOAST experience

GeneLab Team



Special thanks to Organizers and the following colleagues:

Data Gathering

Eddie Semones, Kerry Lee, Ramona Gaza, Ryan Rios (JSC-SRAG)
Thomas Berger (DLR)
Tsvetan Dachev (STIL-BAS)
Vyacheslav Shurshakov (IBMP)

Dedicated dosimetry proposal

Eric Benton (OSU)