NASA SPACE RADIATION LABORATORY GALACTIC COSMIC RAY SIMULATOR

EXPLORE MOON to MARS



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NASA Headquarters
Human Exploration and Operations Mission

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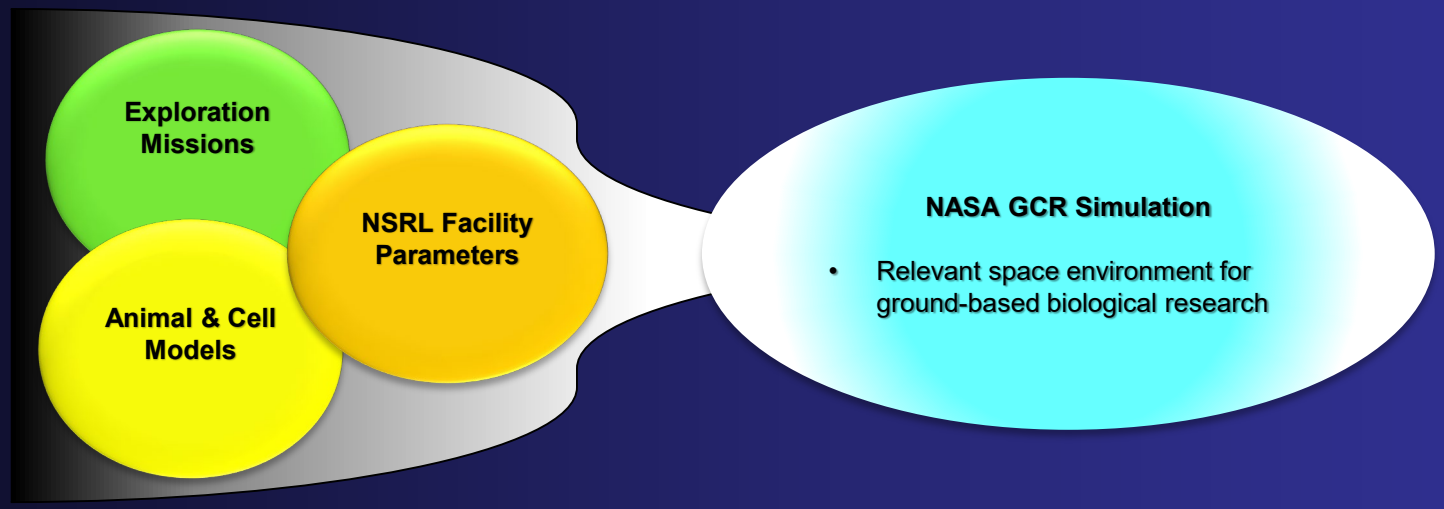
GOALS: NSRL GCR Simulator Development

- Inform and validate space permissible exposure limits
  - Characterization of cancer, cardiovascular disease, central nervous system decrements in mixed-field environment
  - Improve our understanding of dose rate effects
  - Understand the synergistic modifiers of risk from other spaceflight stressors
- Define relevant environment for countermeasure testing and verification



"YEAR" Chris Malbon

Design, Implementation, and Operations



- Defining a single reference field representative of NASA's missions
- Identifying an implementation strategy that accelerator facility/operations can achieve: *energy constraints, number of particles, order, and dosimetry systems*
- *Particle selection: Traceability to large body of historical single particle data, range in species*
- Balancing field complexity across stochastic and deterministic endpoints
- *Delivering the simulation in a reasonable amount of time: animal housing, throughput, beam hour costs*
- *Reliability and repeatability: software, hardware, available personnel , contingency*
- *Open challenges: Neutrons and dose rate*

Moon to Mars
NASA Exploration Mission Exposures

International Space Station



Mission	Mission Duration	Dose (mGy)	Effective Dose (mSv)
ISS in LEO	6 months	30 – 60	50 – 100
ISS in LEO	12 months	60 – 120	100 - 200
Sortie to Gateway	30 days	20	55
Sustained Lunar Operations	1 yr.	100 - 120	300 – 400
Deep-Space Habitat	1 yr.	175 - 220	500 - 650
Mars Mission	650 to 920 days	300 - 450	850 - 1200

Relevant doses for radiobiology: 125 , 250, 500, and 750 mGy
GCR Simulator normalized to 500 mGy

Gateway



Images courtesy of NASA

Artemis lunar surface

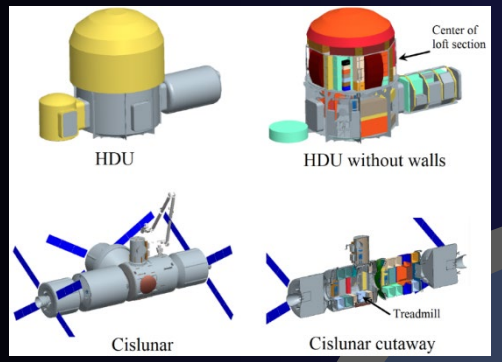


Mars mission

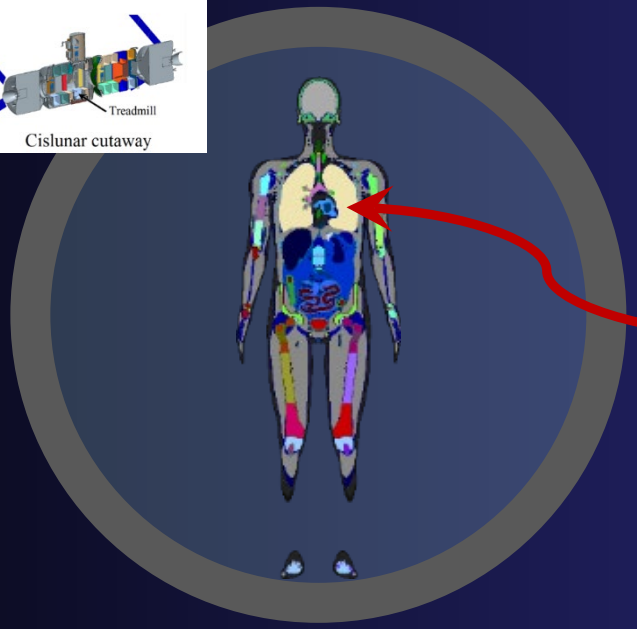


Image Credit: NASA/Pat Rawlings, SAIC

Galactic Cosmic Radiation External and Internal Fields



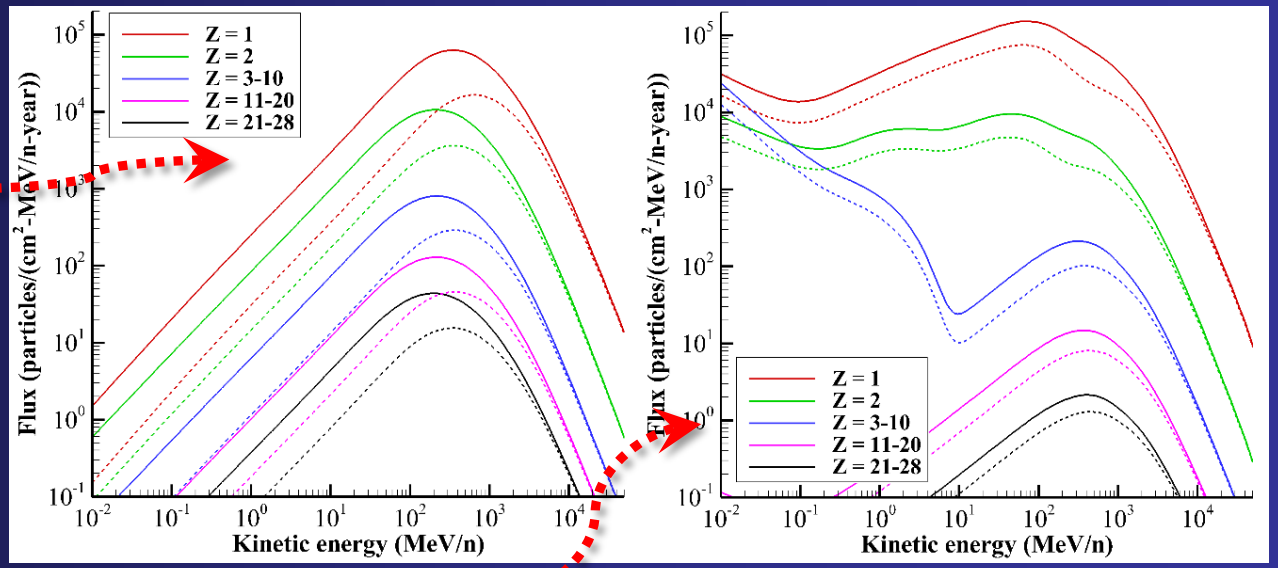
External Field



Local Tissue Field

Free Space
GCR spectrum solar min and max

Shielded spectrum: 20 g/cm2 aluminum to female BFO



GCR free space environment of primary importance to human spaceflight:

- Ions from H to Nickel (Z=28)
- Energy range extending from ~ 10 MeV/n to ~50 GeV/n

NSRL Capability:

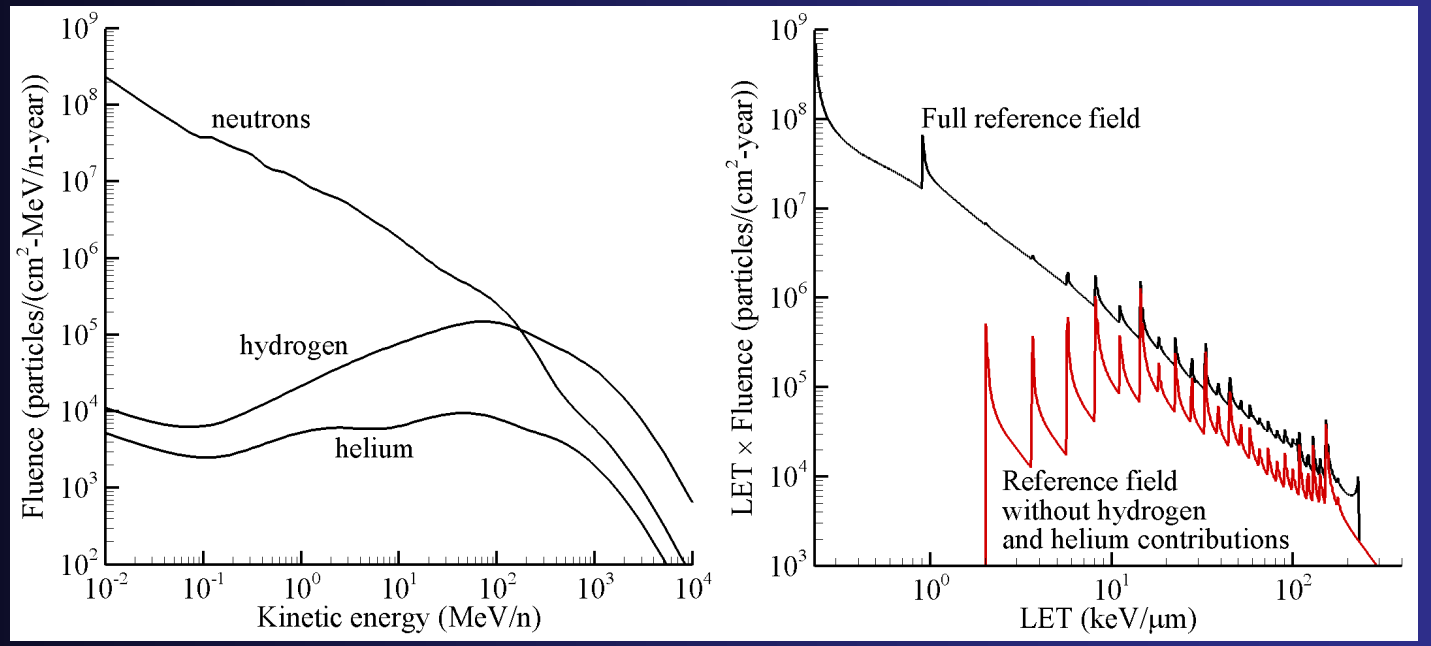
- Protons up to 2.5 GeV
- He and heavier ions up to 1.5 GeV/n

GCR Reference Field Specification

Female BFO (blood forming organ) behind 20 g/cm² spherical aluminum shielding during solar minimum conditions

Annual reference and normalized field quantities

	Average hits per cell	Dose (mGy/Year) 134 mGy/yr	Percent Contribution	Dose Distrimution normalized to 500 mGy	% contribution of Normalized dose to 500 mGy
Pi/EM	0.1	15.5	11.6	0	0
Neutron	N/A	1.1	0.8	0	0
hydrogen	126	86	64.2	366.3	73.3
helium	7	22.5	16.8	95.8	19.2
HZE	0.5	8.9	6.6	37.9	7.6



Variation across all tissues and geometries was found to be +3% for dose and +16% for dose equivalent.

Slaba et al 2015

GCR Simulator Beam Definition

Normalized to 500 mGy

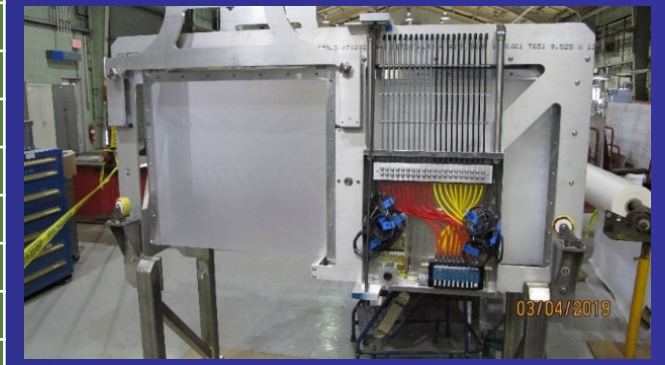
GCR Simulation Beam consists of 33 beams

- *4 H energies plus degrader (65-75% dose)*
- *4 He energies plus degrader (10-20% dose)*
- *5 Heavy ions: C, O, Si, Ti, Fe (6-8% dose)*

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	100	***Polyethylene degrader to***		
^{1}H	150	15.9	0.54	35.0
^{1}H	250	38.1	0.39	68.9
^{1}H	1000	326.6	0.22	123.6
^{4}He	100	***Polyethylene degrader to***		
^{4}He	150	16.0	2.17	7.5
^{4}He	250	38.3	1.56	16.4
^{4}He	1000	327.8	0.88	24.9
^{12}C	1000	110.1	7.95	11.7
^{16}O	350	17.0	20.8	15.4
^{28}Si	600	22.7	50.2	8.1
^{48}Ti	1000	32.5	109.5	4.5
^{56}Fe	600	13.1	175.1	4.1
Total				***500.0***

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{1}H	20.0	0.43	2.59	30.4
^{1}H	23.3	0.56	2.29	6.7
^{1}H	27.2	0.75	2.02	7.4
^{1}H	31.7	0.98	1.79	8.0
^{1}H	37.0	1.30	1.58	8.7
^{1}H	43.2	1.72	1.39	9.3
^{1}H	50.3	2.26	1.23	10.0
^{1}H	58.7	2.99	1.09	10.6
^{1}H	68.5	3.95	0.97	11.1
^{1}H	79.9	5.20	0.86	11.2
^{1}H	100.0	7.76	0.73	**27.2**

Ion	Energy (MeV/n)	Range (cm)	LET (keV/µm)	Dose (mGy)
^{4}He	20.0	0.43	10.34	**11.0**
^{4}He	23.3	0.57	9.14	**2.1**
^{4}He	27.2	0.75	8.06	**2.2**
^{4}He	31.7	0.99	7.12	**2.3**
^{4}He	37.0	1.31	6.29	**2.5**
^{4}He	43.2	1.73	5.56	**2.6**
^{4}He	50.3	2.28	4.92	**2.7**
^{4}He	58.7	3.01	4.36	**2.7**
^{4}He	68.5	3.97	3.86	**2.7**
^{4}He	79.9	5.23	3.43	**2.7**
^{4}He	100.0	7.81	2.90	**6.1**



Large binary filter system used to deliver lower energy H and He beams – installed 2019

NSRL: Animal Handling
60 by 60 cm^2 Beam



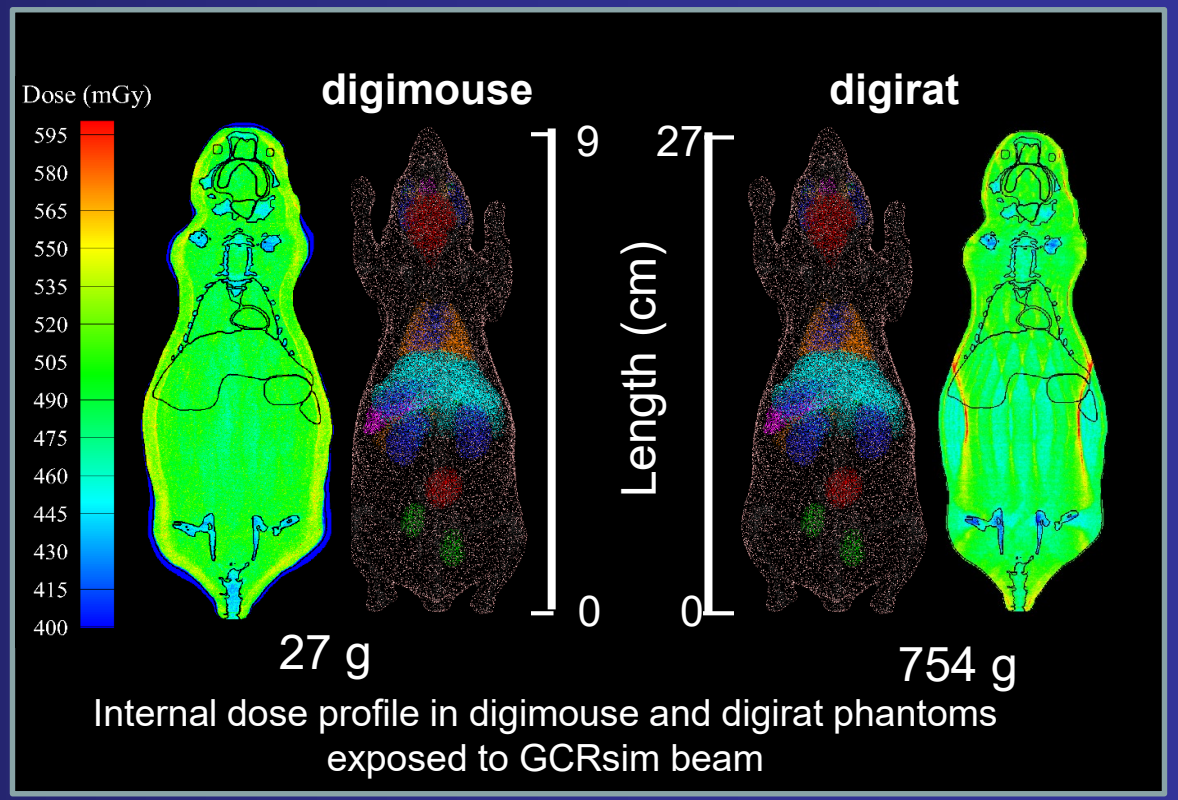


- Mouse boxes: 9 by 6 array; 10 x 10 x 4.5 cm; 2-3 mice each; Capacity 108-162.



- Rat boxes: 3 by 5 array; 10 x 10 x 20 cm; 1 rat each (perhaps 2); Capacity 15.
- External fans circulate air through vents
- Nestlet provided in cage
- Animals can remain cage for upto 8 to 10 hours

GCRsim delivers a homogeneous dose distribution (3-10% var.)



Internal dose profile in digimouse and digirat phantoms exposed to GCRsim beam

- Dose and fluence matched over full range of LET
- Acute irradiations: Limit 2 mice per cage or 1 rat per cage to avoid ion range (Bragg peak) issues associated with body shielding from cage mates.

Advanced ion source technology & control system enables GCR Simulator operations

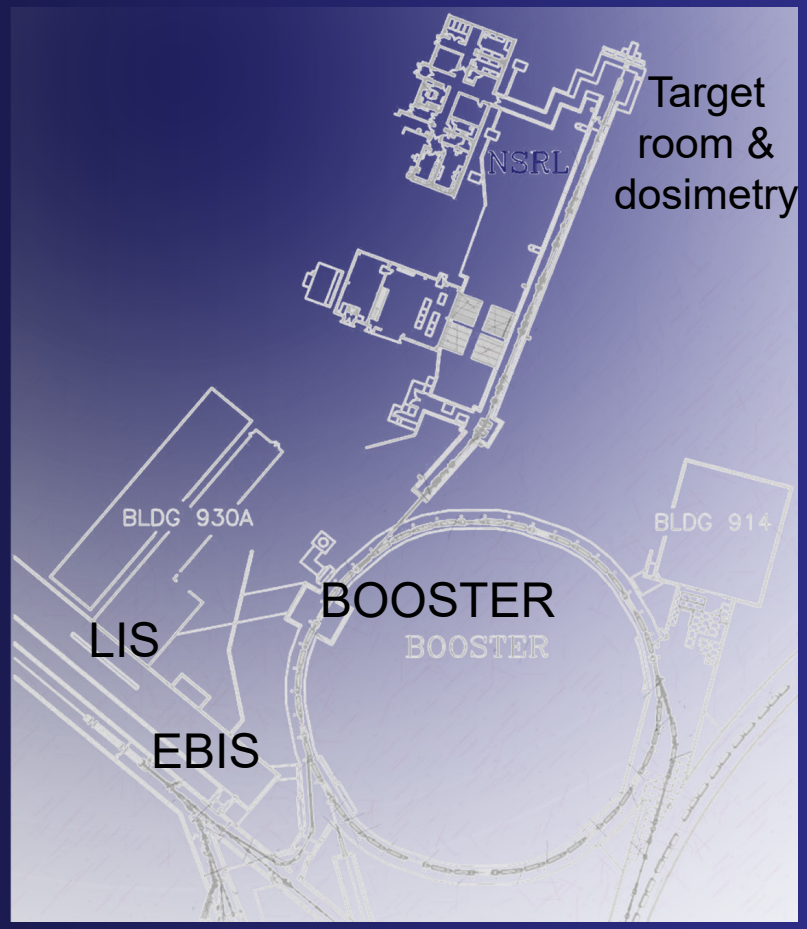
Operationally, the GCR Simulator is the ability to rapidly and reliably change between multiple ion-energy beam combinations and sequentially deliver to the target at predetermined doses.

Laser ion source (LIS):

Produces ions from many different solid targets and can rapidly switch between species generated.



Enables EBIS to supply several ions in rapid succession.



Controls System:

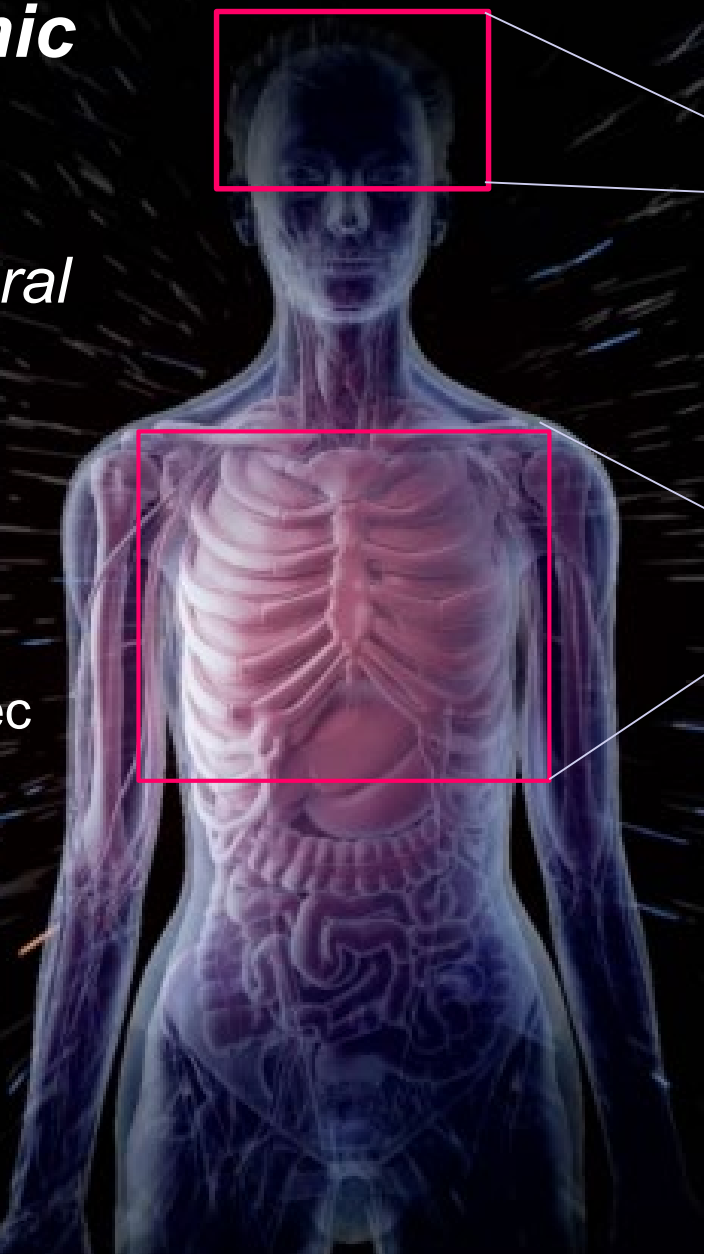
Requires software to control system hardware settings, from ion production by the LIS through booster injection, acceleration, extraction and delivery to the NSRL target room – dosimetry & binary filter.



Controls software run as single application controlling order of ion/energy combinations and dose delivered to the target [ion, energy, dose]

Galactic Cosmic Rays:

The physics of spatial and temporal scales



Brain tracks/sec

669 proton
36 He
2 HZE

Targets within the CNS may be larger - ~500 μm^2

Lung tracks/sec

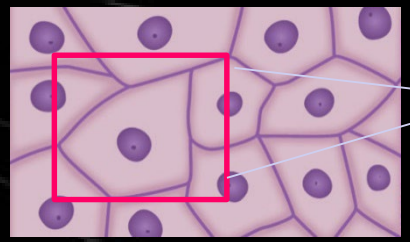
1,833 proton
99 He
5 HZE

Larger areas may be reflective of non-target effects/tissue microenvironments

Whole body hits

- 13,456 protons/sec
- 728 He/sec
- 38 HZE/sec

Cell nucleus hits/yr



126 proton hits/yr
7 He hits/year
0.5 HZE hits/yr

"…every cell nucleus in an astronaut's body would be hit by a proton every few days and by an HZE ion about once a month" Cucinotta, F.A., Durante, M., *Lancet Oncol* **7**: 431-435; 2006; Curtis and Letaw, *Adv. Space Res.* **9**: 293-298; 1989. → Similar findings.

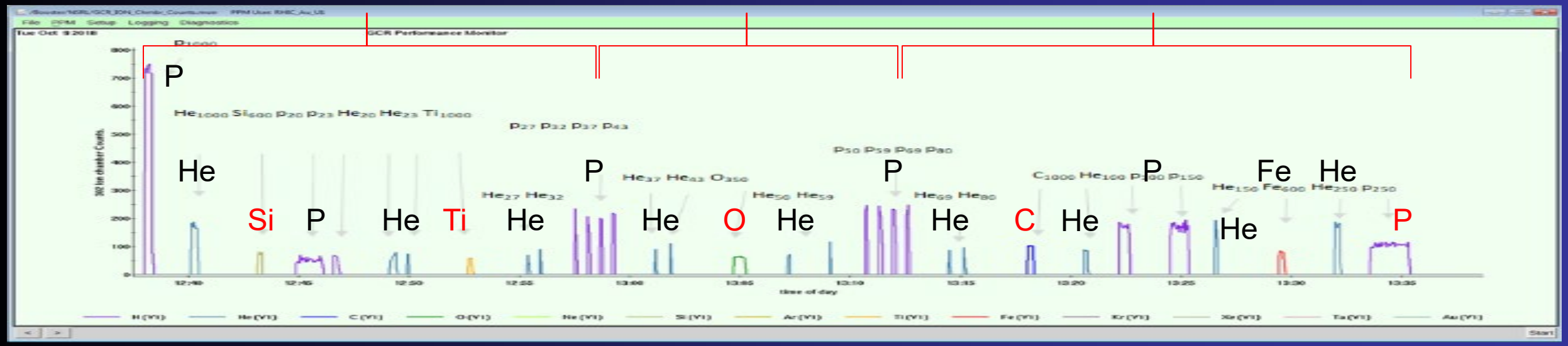
GCR Simulator Beam Definition & NSRL Operations

Ion Delivery Order

- GCR is comprised of a continuous shower of protons with interspersed helium and sporadic heavy ions
- Order selected to approach space conditions and minimize beam energy switching

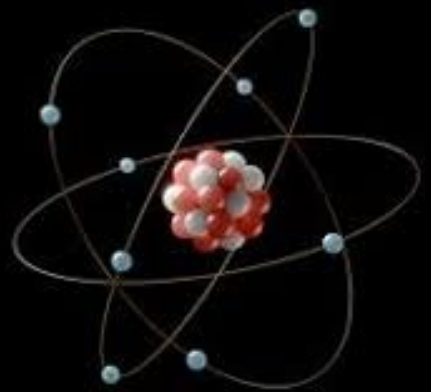
Distinct Ions selected to represent GCR reference environment (MeV/n)

- *(p 1000), (He 1000), (Si 600), (p 20), (p 23), (He 20), (He 23), (Ti 1000), (He 27), (He 32), (p 27), (p32),*
- *(p 37), (p 43), (He 37), (He 43), (O 350), (He 50), (He 58), (p 50), (p 58),*
- *(p 68), (p 80), (He 68), (He 80), (C 1000), (He 100), (p 100), (p 150), (He 150), (Fe 600), (He 250), (p 250)*



21 unique switches with ~ 75 min delivery time (50 minutes devoted to switching) for 500 mGy

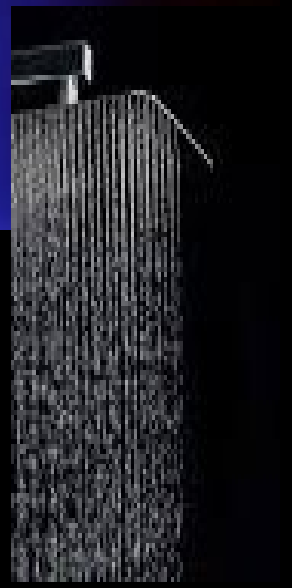
NEUTRONS





& DOSE RATE





Main components of "neutron dose" *are* included in GCRsim

Slaba et. al; An overview of the GCR simulator at the NASA Space Radiation Laboratory. 43rd COSPAR Scientific Assembly. 2021

Included in proton reference field spectrum and GCRsim

Elastic

- Mainly low energy neutrons
- Neutron collides with target and transfers energy but no new particles are produced
- Produces recoil protons and recoil heavy nuclei depending on target composition

Neglected in GCRsim / local field approach: Particles contribute <1% dose and ~10 % to dose equivalent

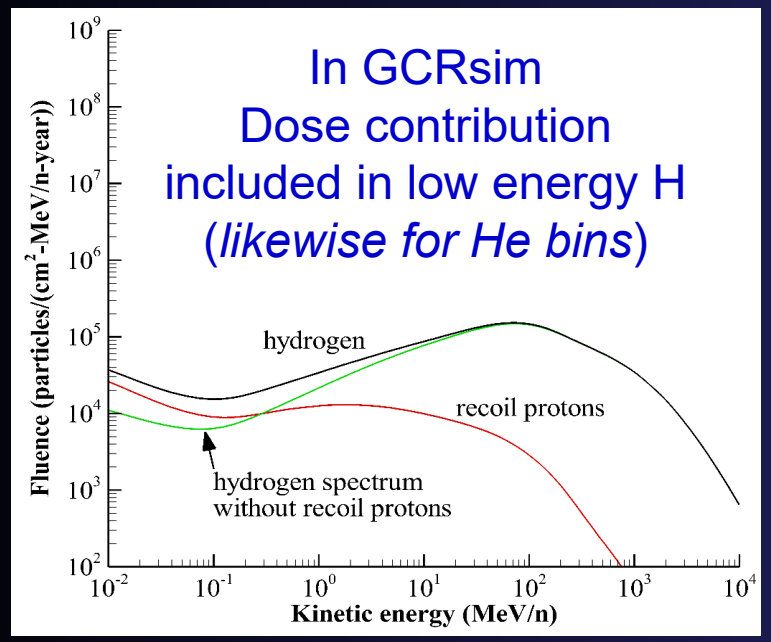
Recoil protons ← Elastic → Recoil heavy ions (Z > 2)

&

Neutron, proton & light-ion target fragments ← Inelastic → Heavy ion target fragments (Z > 2)

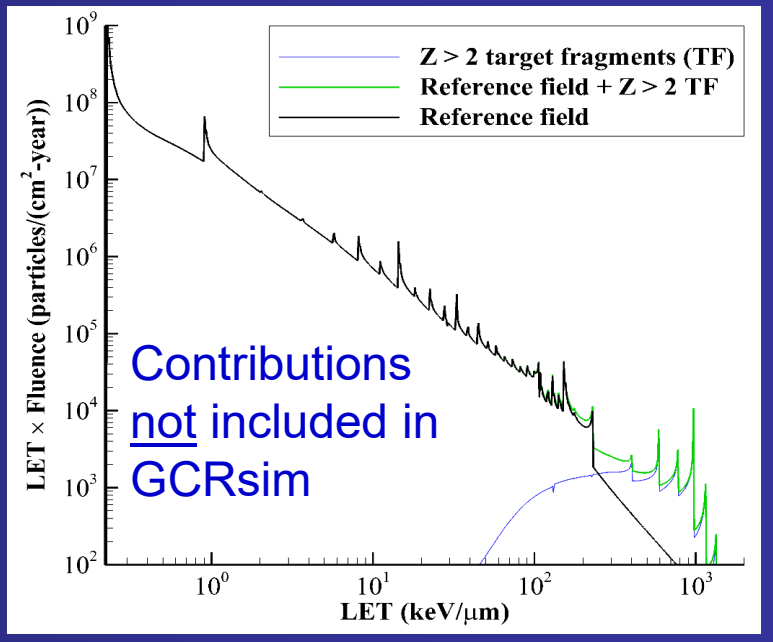
Inelastic

- Mainly high energy neutrons
- Neutron collides with target and causes target nuclei to break-up
- Produces energetic neutrons and light ions and low-energy (<10MeV/n) heavy target fragments (> 300 keV/μm)

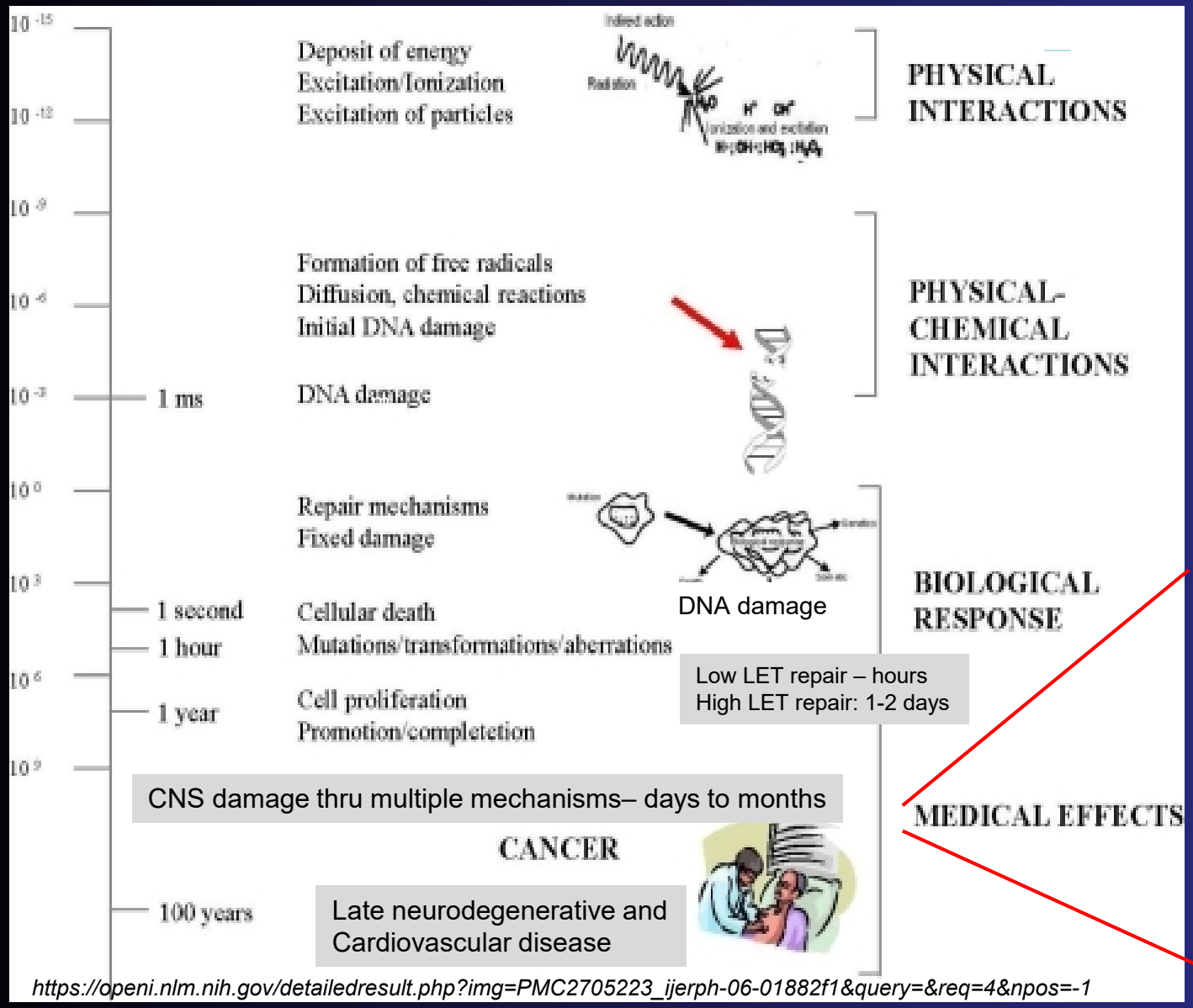


Challenge for accelerator-based simulators

- Generating & measuring a broad neutron energy spectrum that will deposit desired dose within a small mass/volume at target
- Verification with dosimetry



Ground-based dose rate studies:
Consideration of relevant biological time scales in experimental design



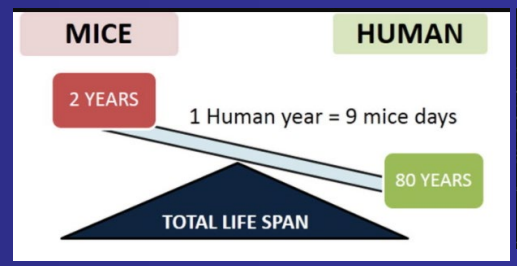
https://openi.nlm.nih.gov/detailedresult.php?img=PMC2705223_ijerph-06-01882f1&query=&req=4&npos=-1

Simulating dose rate requires an understanding of underlying mechanisms and biological timescales relevant to risks in the selected model system

- Biophysical models of HZE hit probabilities suggest irradiations approaching 30 days to avoid high dose-rate artifacts (Kim et al. 2015)
- Balance with IACUC animal care

LATE EFFECTS







- *Lifespan in astronauts ~80 yrs*
- *Lifespan in mice ~2 years*
- *Mars mission 3 years*
- *Mouse Mars Mission 27 days*

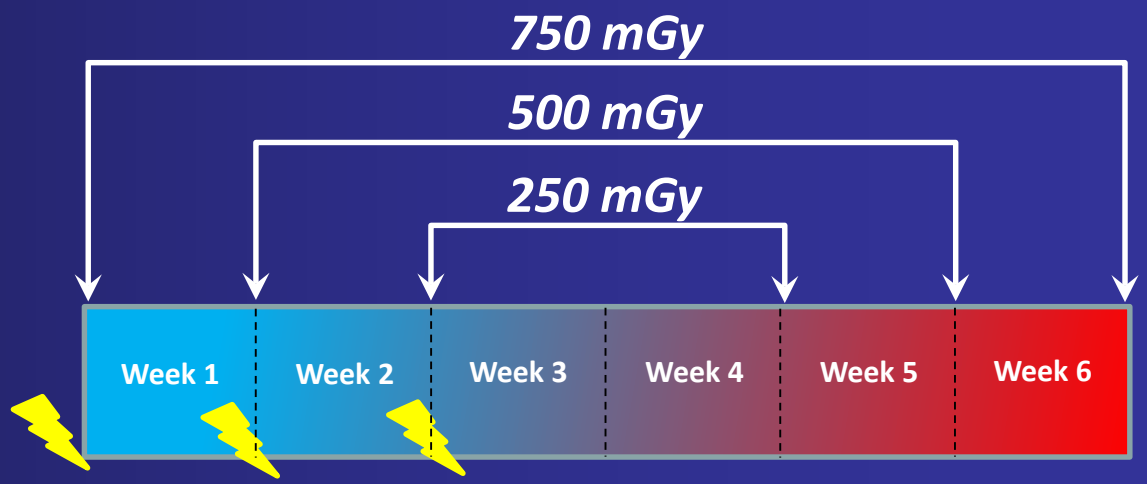
Concept of Operations: Initial Dose Rate Studies "NSRL GCR Simulator"

GOAL: Operate at low dose-rate limit such that hits are independent (avoid track interactions) on relevant biological timescales (allow for repair) to best simulate the space environment

***Protracted GCR exposures over 2-6 weeks*:**

- 33 ion beams delivered daily
- Daily dose fixed - duration allows for 3 dose points (250, 500, 750 mGy)
- Dose rate of delivery ~10 mGy/min for most species in in 60 x 60 cm^2 beam
- Beam delivered 6 days per week
- All chronic studies include acute exposures to improve our understanding of DDREF

Exposure Scheme: 20.8 mGy per day



- *Min operational time 1 - 2 hrs*
- *Max time 8 to 10/15 hrs. per day*

Three parameters: Dose fraction (mGy); Dose rate of delivery (mGy/min); Time between particle doses (hrs - days)

p – He – Z_1 - p - He – p – He – Z_2 – p – He – p – He – Z_3 – p – He – p- He – Z_4 – p – He – p – He –Z_5 – p – He – p – He

P= 1.2 to 4.2 mGy fractions; He = 0.25 to 0.8 mGy fractions; Z= 0.15 to 0.35 mGy fractions

- *New cut-off chamber at NSRL can reliably measure dose as low as .01 mGy; Previous limiting dose was 0.1 mGy*

Comparison of Acute vs Fractionated/Chronic Exposures Dose Rate Studies

Dose rate studies: Combination of experimental & biophysical modeling

- 10 PI teams looking at dose rate
- Multiple cell, animal models, and endpoints

Fractionated Single Ion
Multiple dose rates,
Multiple times between fractions, order

Acute GCR	Acute Neutron
Fractionated GCR High-, Low- LET, Mixed field	Chronic Neutron

Biophysical Modeling

- 1 to 100 mGy/min (still order's of mag > space)
- 24, 48, 72 hrs between fractions

- Over 2, 4, 6, weeks
- Over 1, 10, and 15 hrs

- Over 200-400 days

Dose rate simulation requires experimental and biophysical models to verify understanding of risk and countermeasure efficacy

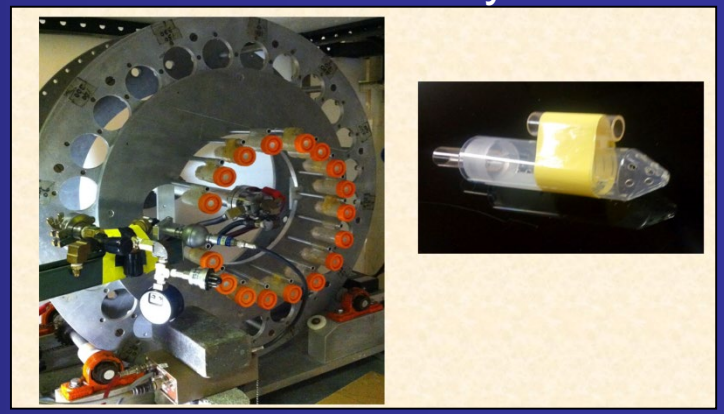
Understanding High LET dose rate effects



Chronic: Neutron Irradiator @CSU 1mGy/day

(20 times higher than space HZE component)

Acute: Columbia RARAF fast neutron facility



GCR Simulator – Answering Major Scientific Questions

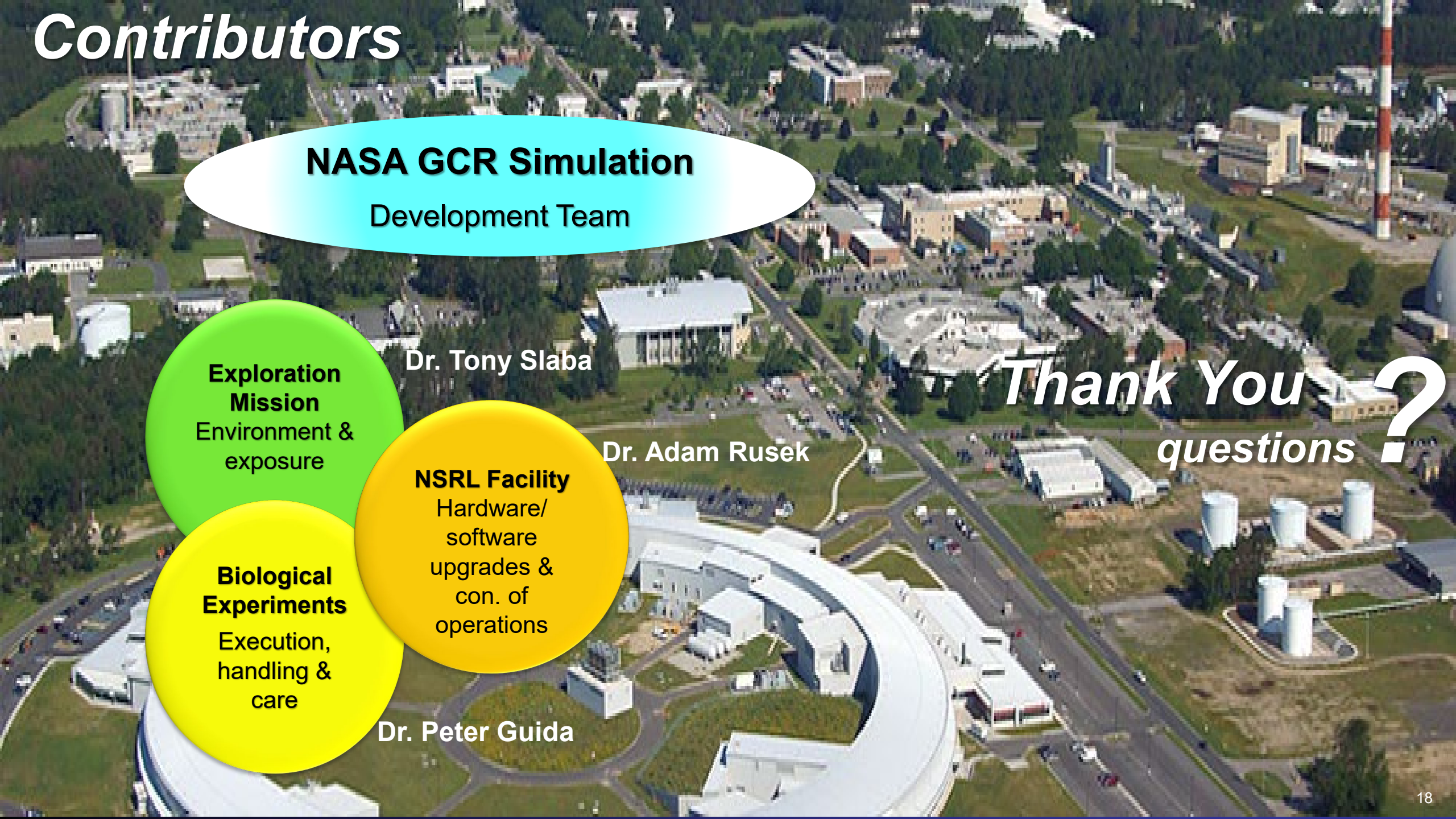
…….on the additivity of biological responses from single-ion data and the effect of dose rate

- Is there synergy, antagonism, or neither in space radiation-induced tumorigenesis, cardiovascular disease, or CNS decrements after mixed GCR-like exposures compared to that predicted from results with individual ion beams?
- How should dose-rate modifiers be implemented in models of risk to scale from acutely exposed human terrestrial cohorts (low LET gamma/neutron) to astronauts who are chronically exposed to a mixed field of low- and high-LET ions?
- Will dose-rate scale risk inversely, conventionally, or have no effect?
- Can a ground-based analog operate in a low dose and dose-rate regime that sufficiently mimics the space environment to verify countermeasure efficacy?

Status –

- Currently, 80 - 90% of biology PI teams utilizing the GCR Simulator
- Extensive tissue sharing across risks
- 75% of NSRL hours are now GCR Simulations
- NSR has delivered ~715 hours of GCR simulator
- Research results are forthcoming!

Contributors



Thank You

questions ?