

A photograph of an astronaut in a blue flight suit floating in a space station corridor. The astronaut is blowing a large, clear bubble. The background shows the complex structure of the space station with various equipment and panels.

Key Non-Polar Destinations Across the Moon to Address Decadal-
level Science Objectives with Human Explorers

Panel on Human and Biological Science

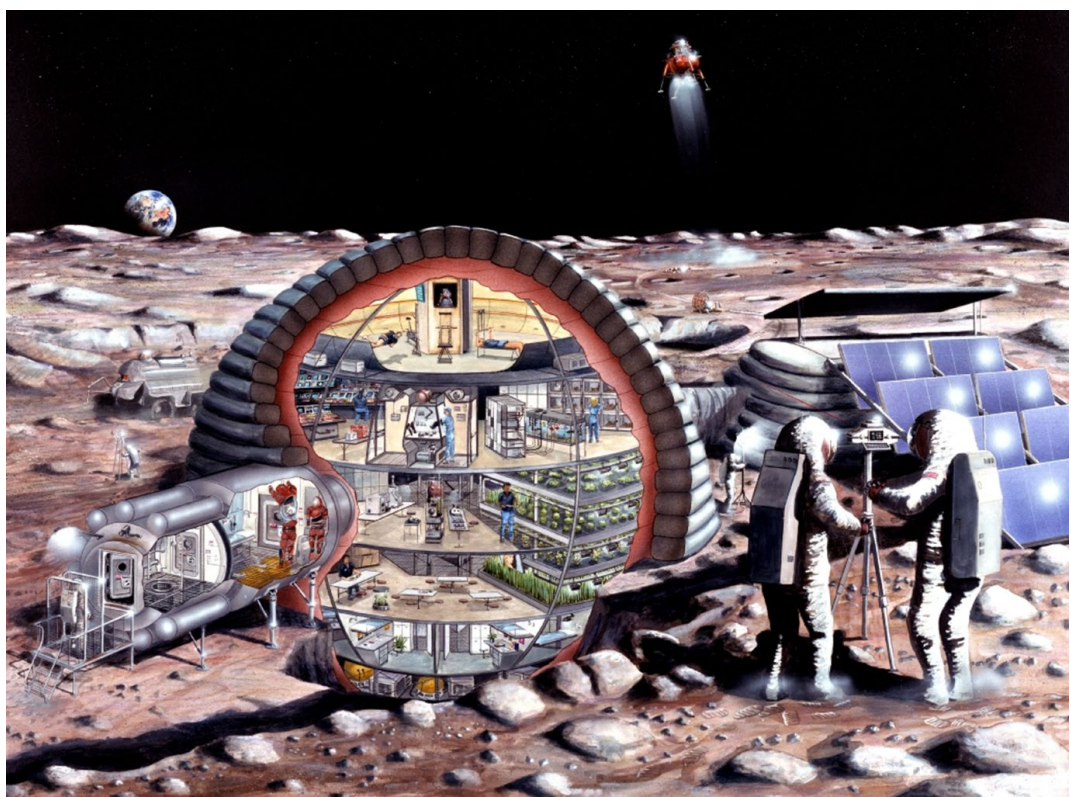
Biophysical limitations in microgravity

MARSHALL PORTERFIELD, PURDUE UNIVERSITY

PRESENTED TO:
NATIONAL ACADEMIES OF SCIENCE, ENGINEERING AND MEDICINE
SPACE STUDIES BOARD
BOARD ON PHYSICS AND ASTRONOMY
AERONAUTICS AND SPACE ENGINEERING BOARD
October 6, 2025, Irvine, CA



BioAstronautics Redox Exchange Countermeasure Systems
Professor D. Marshall Porterfield



SPACE BIOPHYSICS & MEDICINE
BIOREGENERATIVE LIFE SUPPORT



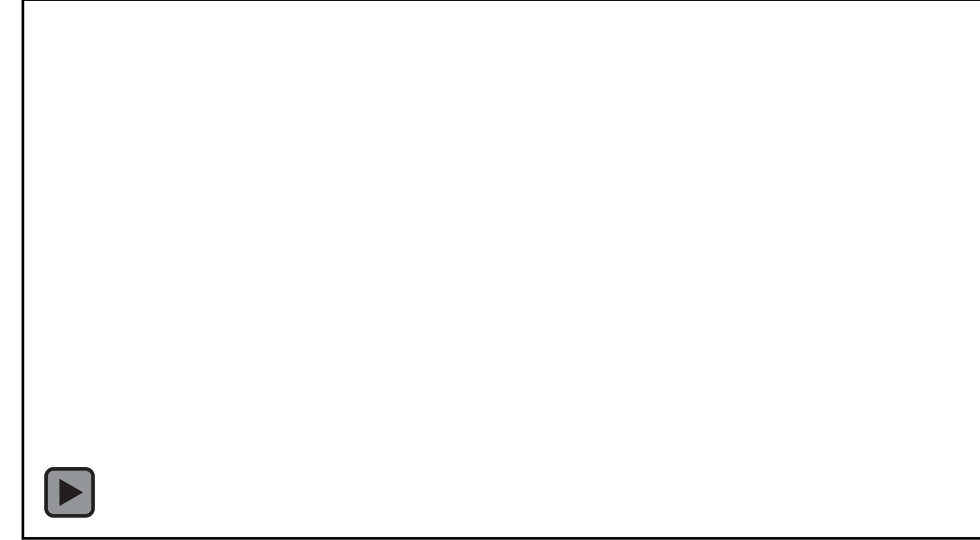
BIOSENSORS



BIOSYSTEMICS AND GENOMIC
SYSTEMS

Two Main Hazards

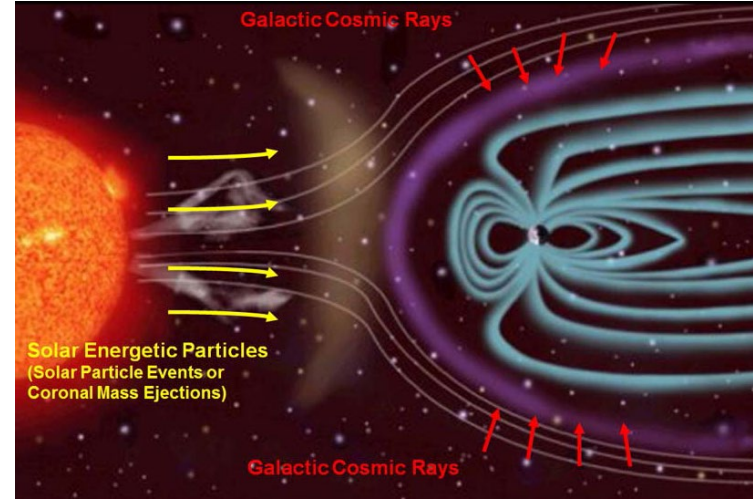
Mars



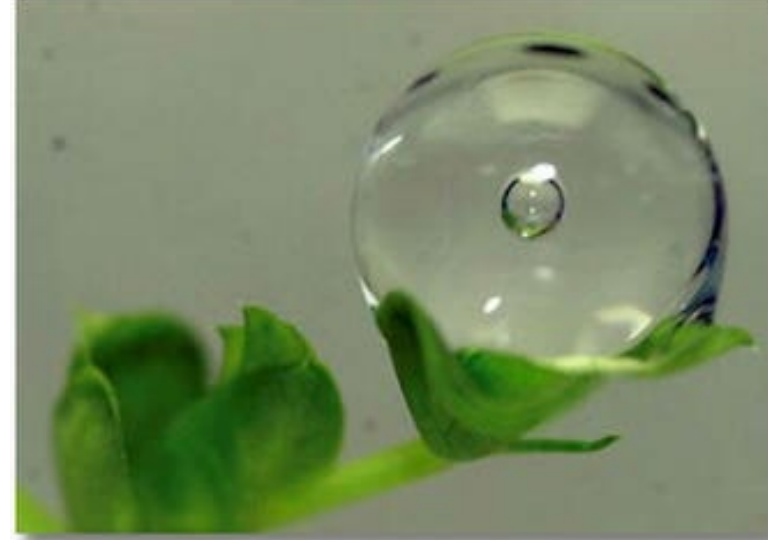
Moon



Radiation



Microgravity

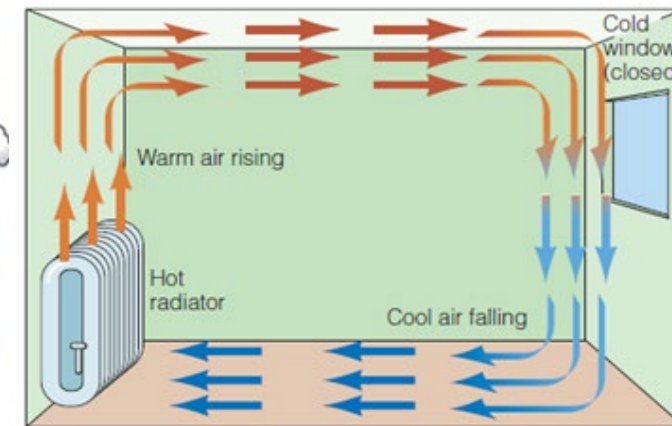
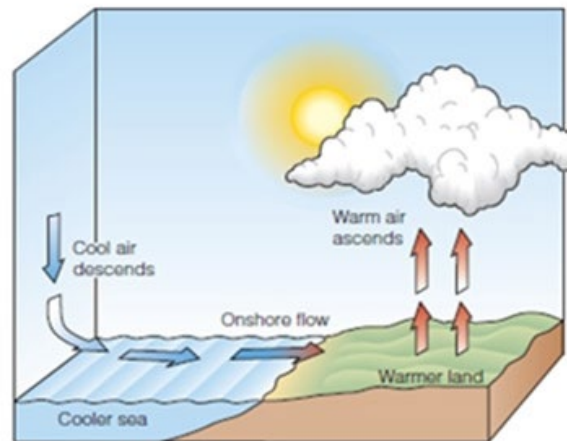
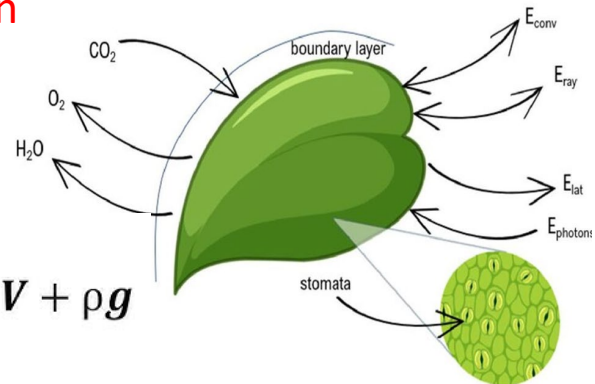


Biophysical Mass Transport >>><<< Convection + Diffusion

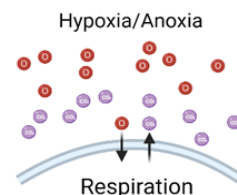
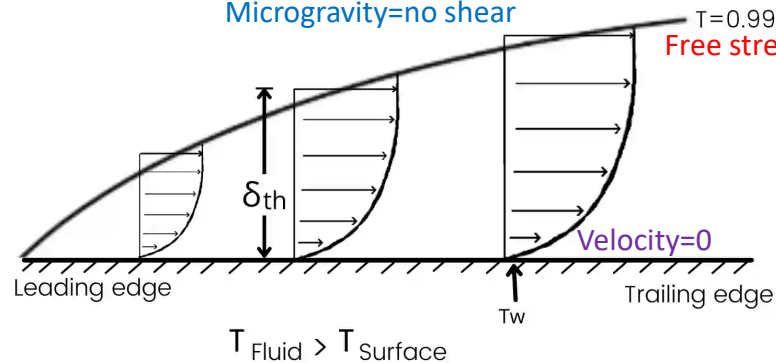
Gravitational Convection

bulk flow
thermal/gravity
buoyant density

$$\rho \left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V} \cdot \nabla \mathbf{V} \right) = -\nabla p + \mu \nabla^2 \mathbf{V} + \rho \mathbf{g}$$

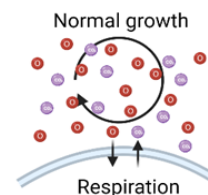


High Shear → Low Shear
Microgravity=no shear
Free stream $T = 0.99T_\infty$



Transient Hypoxia

Normoxia



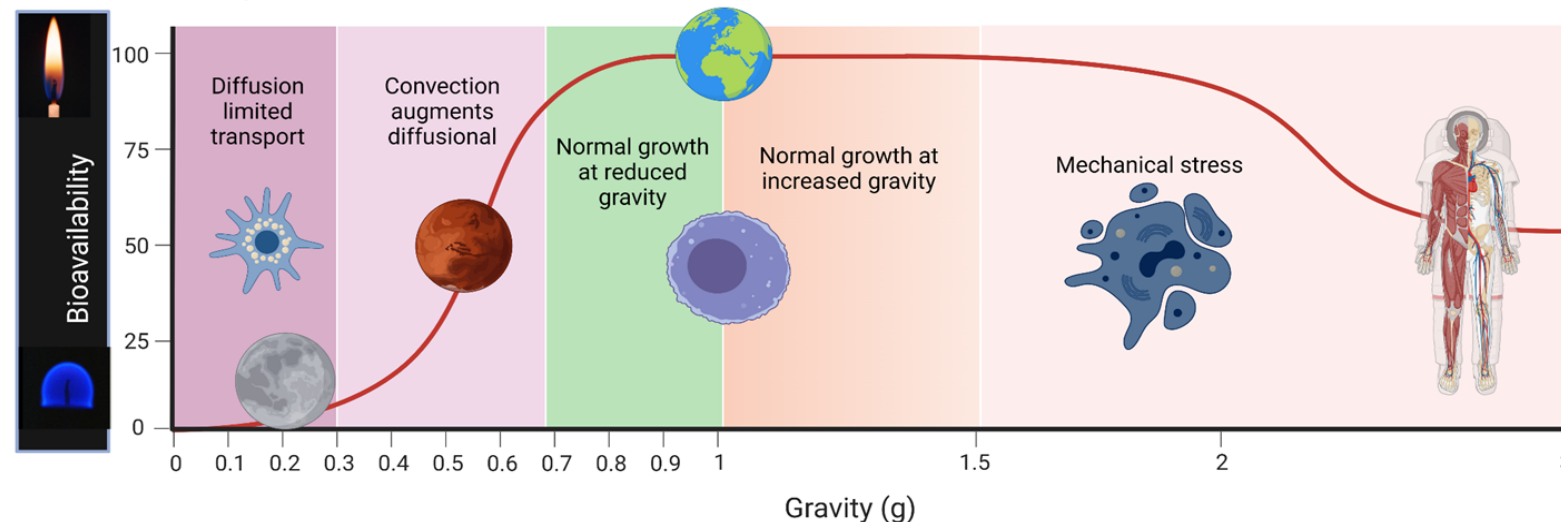
Normoxia



Molecular Diffusion

molecular walk
Brownian motion
concentration driven

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2}$$



M. Faraday
1791-1867



COURSE OF SIX LECTURES
ON THE
CHEMICAL HISTORY OF A CANDLE;

TO WHICH IS ADDED

A LECTURE ON PLATINUM.

BY

MICHAEL FARADAY, D.C.L., F.R.S.,

FULLERIAN PROFESSOR OF CHEMISTRY, ROYAL INSTITUTION; FOREIGN ASSOCIATE
OF THE ACADEMY OF SCIENCES, ETC.

*Delivered before a JUVENILE AUDITORY at the ROYAL INSTITUTION of GREAT
BRITAIN during the Christmas Holidays of 1860-1.*

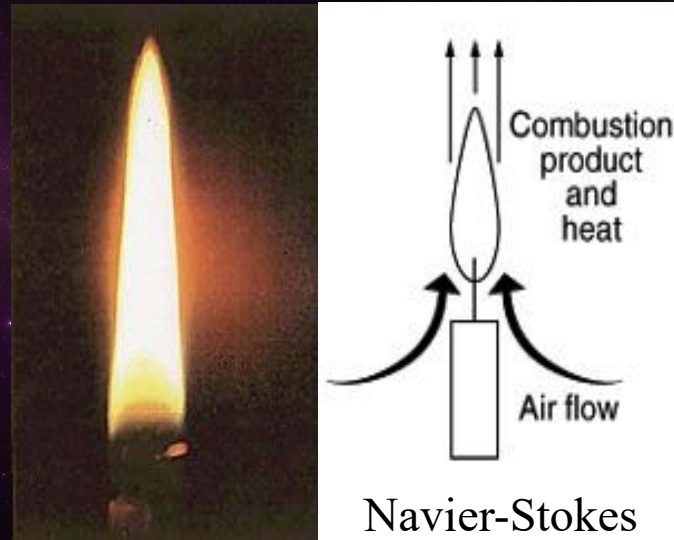
EDITED BY WILLIAM CROOKES, F.C.S.

WITH NUMEROUS ILLUSTRATIONS.

LONDON:
GRIFFIN, BOHN, AND COMPANY,
STATIONERS' HALL COURT.
MDCCCLXI.

Buoyancy-Driven Convection and Diffusion

"There is no better, there is no more open door by which you can enter into the study of natural philosophy (science) than by considering the phenomena of a candle ... Faraday."



Image/Schematic of a Candle Flame in 1g



Image of USML-1 Candle Flame in Microgravity. (Ross et al., 1991, Microgravity. Combust. Sci. Technol. 75:155-160)

μg = a diffusion limited environment!

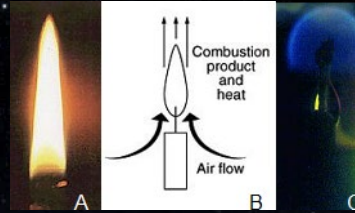
FICK'S LAW

- This facilitates crystallization, combustion, and metallurgical research

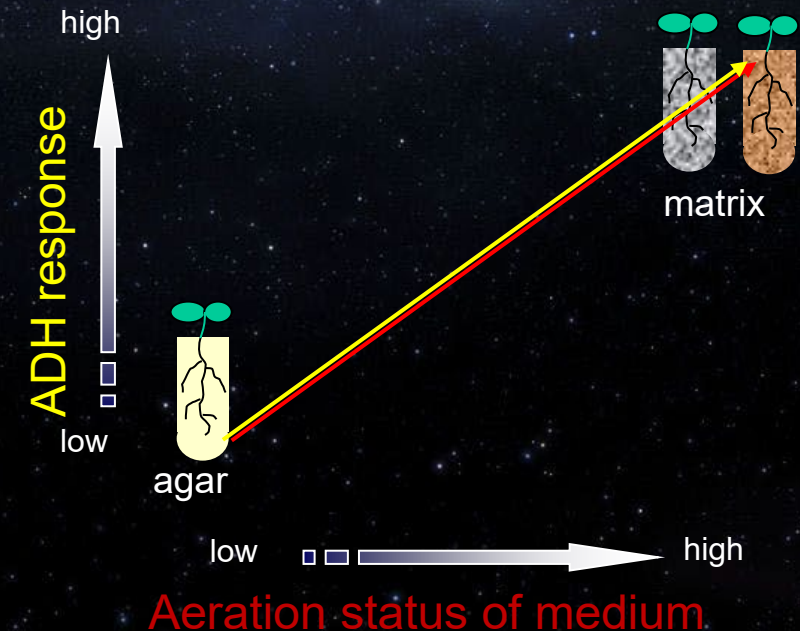
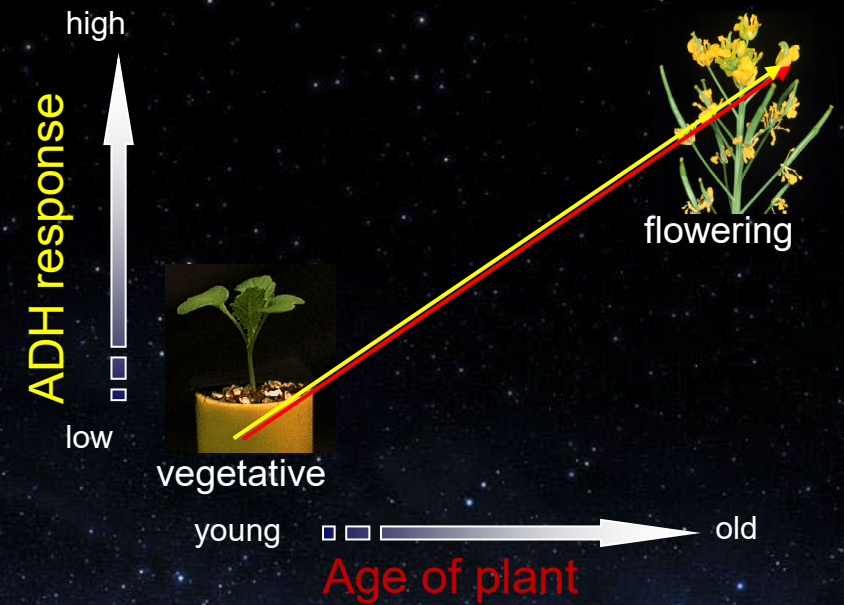
Porterfield DM. 2002. The biophysical limitations in physiological transport and exchange in plants grown in microgravity. J Plant Growth Regul. 21(2):177-90

Mitochondrial Stress in Spaceflight

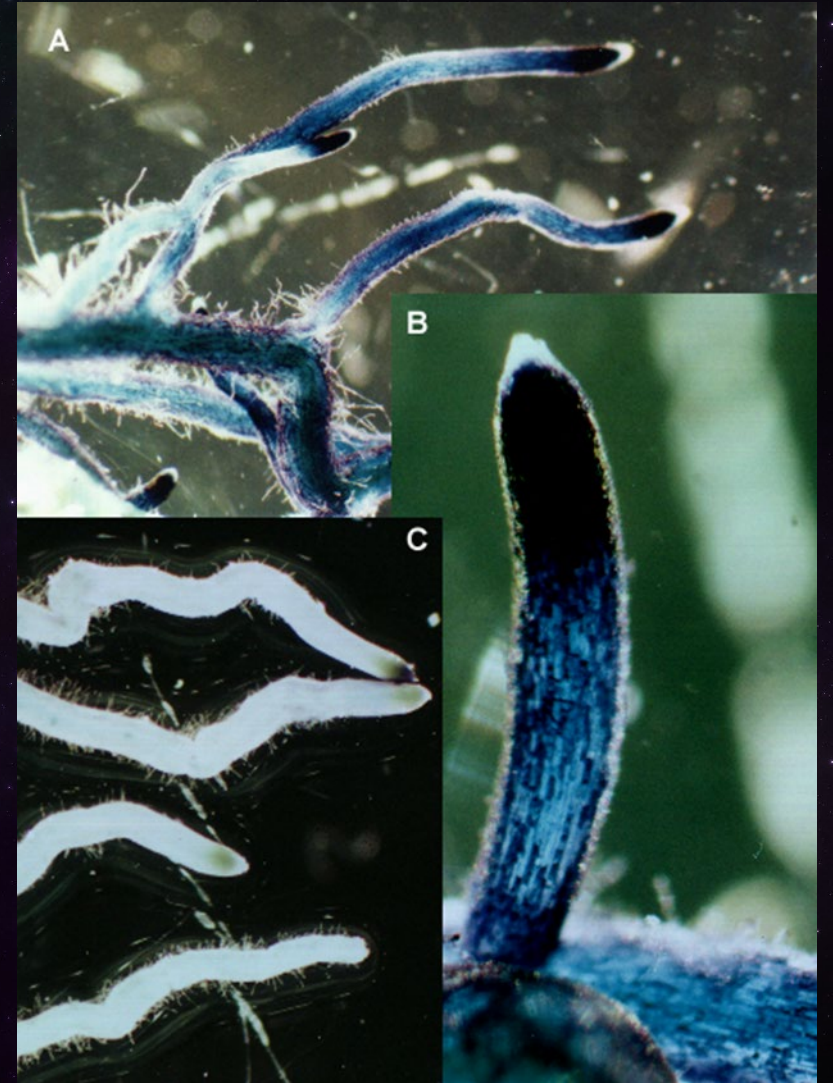
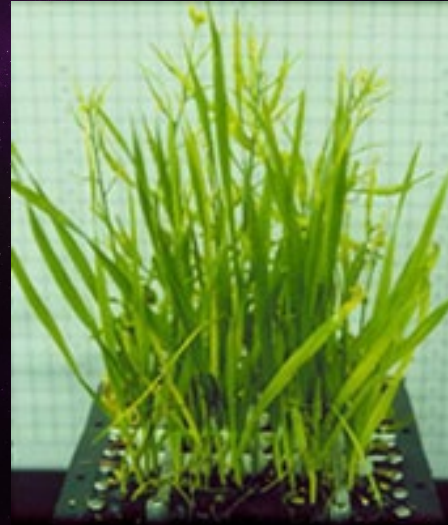
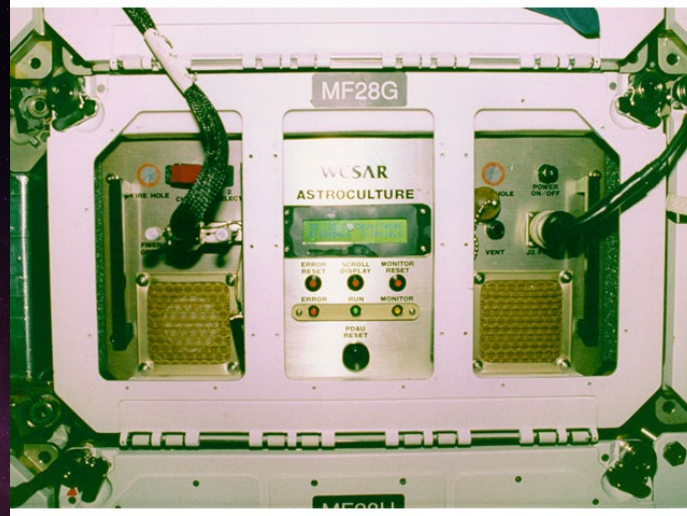
Spaceflight Exposure Induces Changes Increases in ADH Activity in Plant roots



- Chromex-03 (1993 10 Days)
 - 89% increase (flowering *Arabidopsis thaliana*)
- Chromex-05 (1994 14 Days)
 - 89% increase (flowering *Arabidopsis thaliana*)
- Astroculture-04 (1995 11 Days)
 - 248% increase (Dwarf Wheat vegetative)
 - 324% increase (flowering *Brassica rapa*)
- Collaborative Ukrainian Experiment (1998 15 Days)
 - 54% increase (vegetative *Brassica rapa*)
 - 478% increase (flowering *Brassica rapa*)



Astroculture Experiment



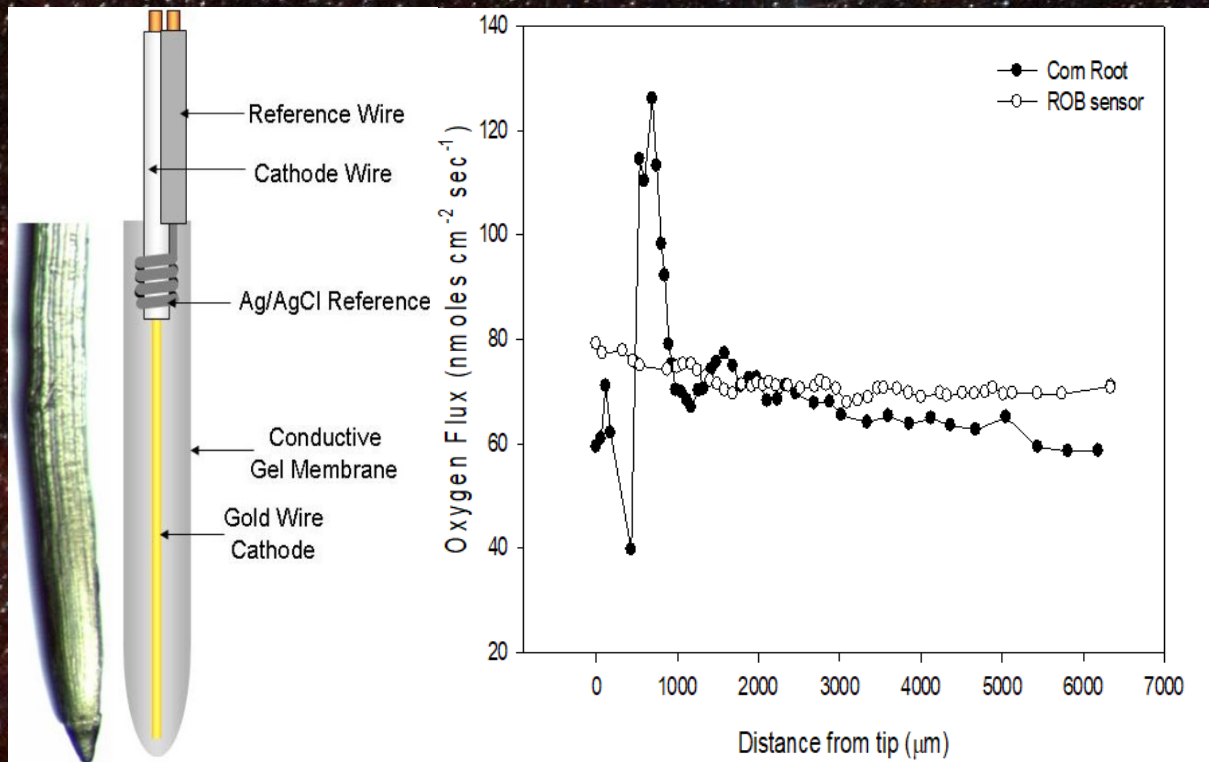
Light microscopy of cytochemical ADH localization in dwarf wheat spaceflight exposed (A) and spaceflight control (B) roots. Blue color denotes ADH activity. A control for the cytochemical stain (C) shows blue color reaction is inhibited by reversing the kinetics of the enzyme reaction

Root Oxygen Bioavailability (ROB) Sensor

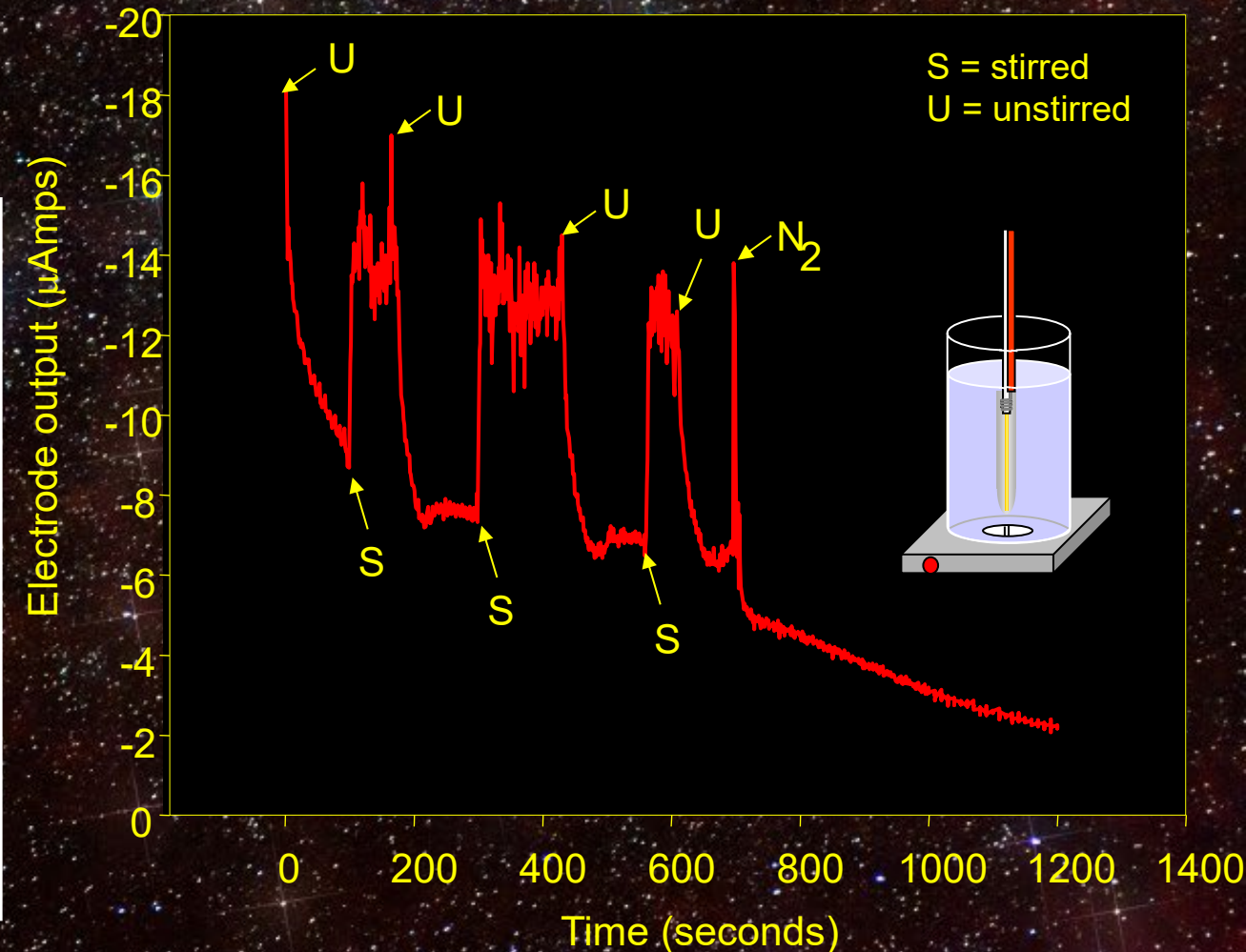
Biophysical mimetics as a design approach in engineering!

Biomimetic Design

- Stir-sensitive (Buoyant density driven convection dependent)
- Same size, shape and O₂ consumption rate of a root tip
- Amperometric output = Sensor O₂ consumption/availability
- Function as a root oxygen consumption simulator



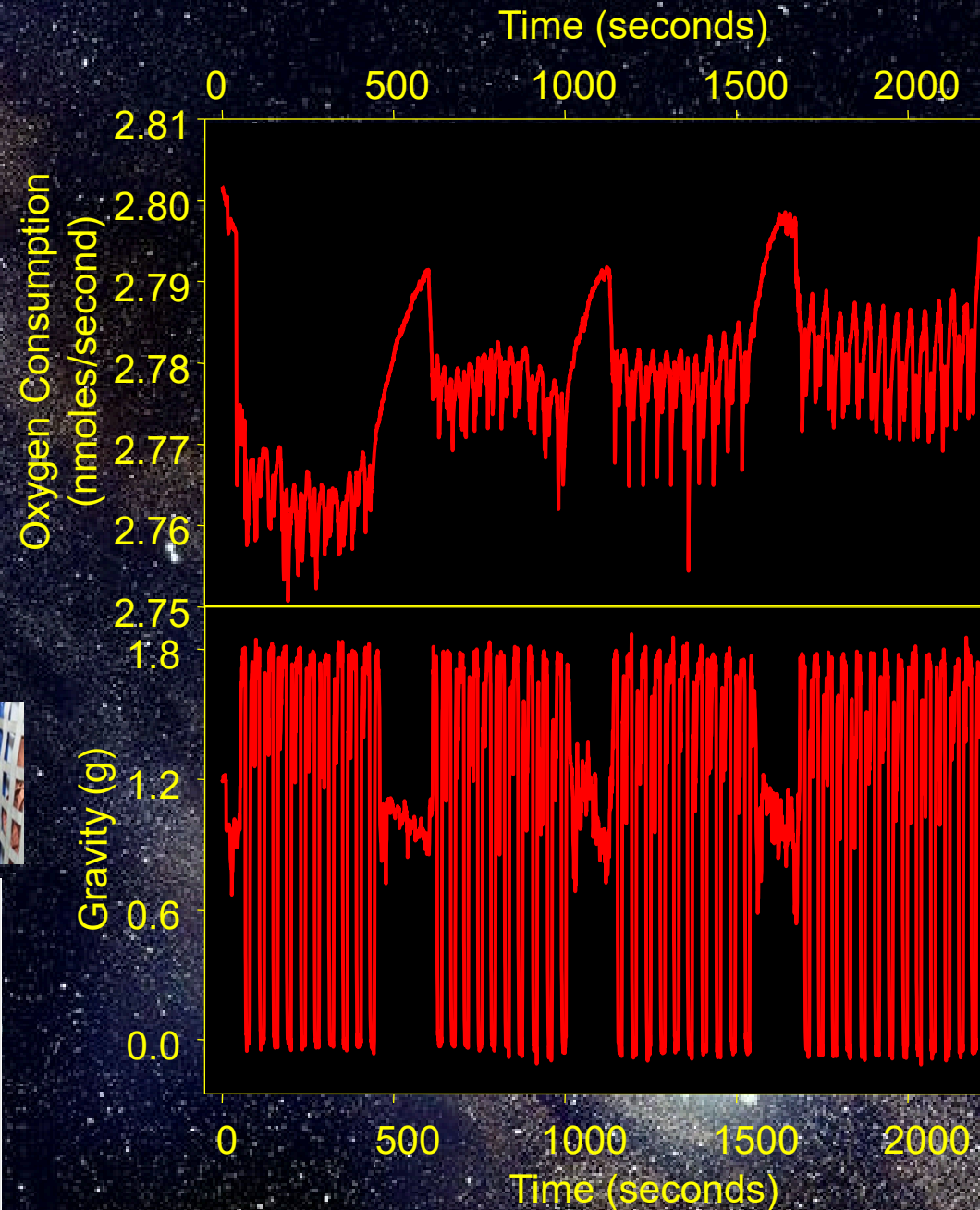
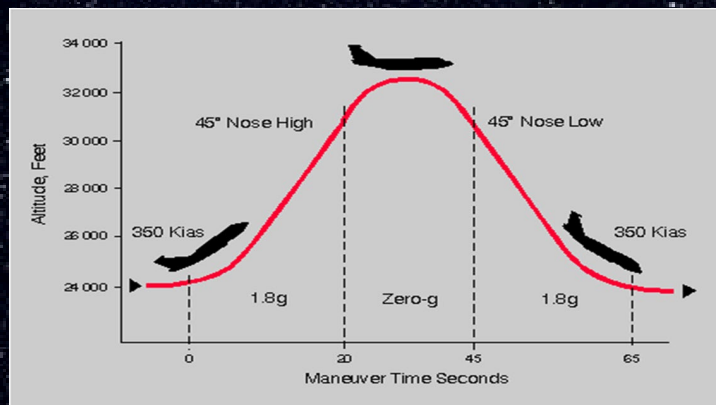
ROB Sensor Performance Characterization

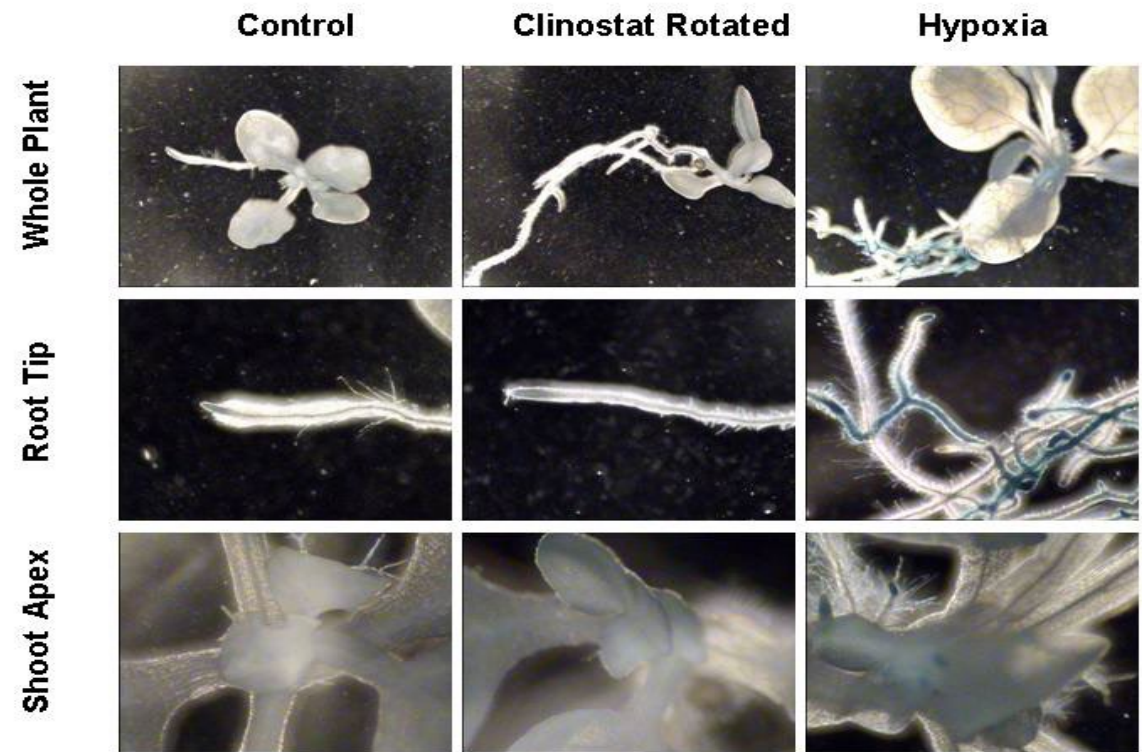
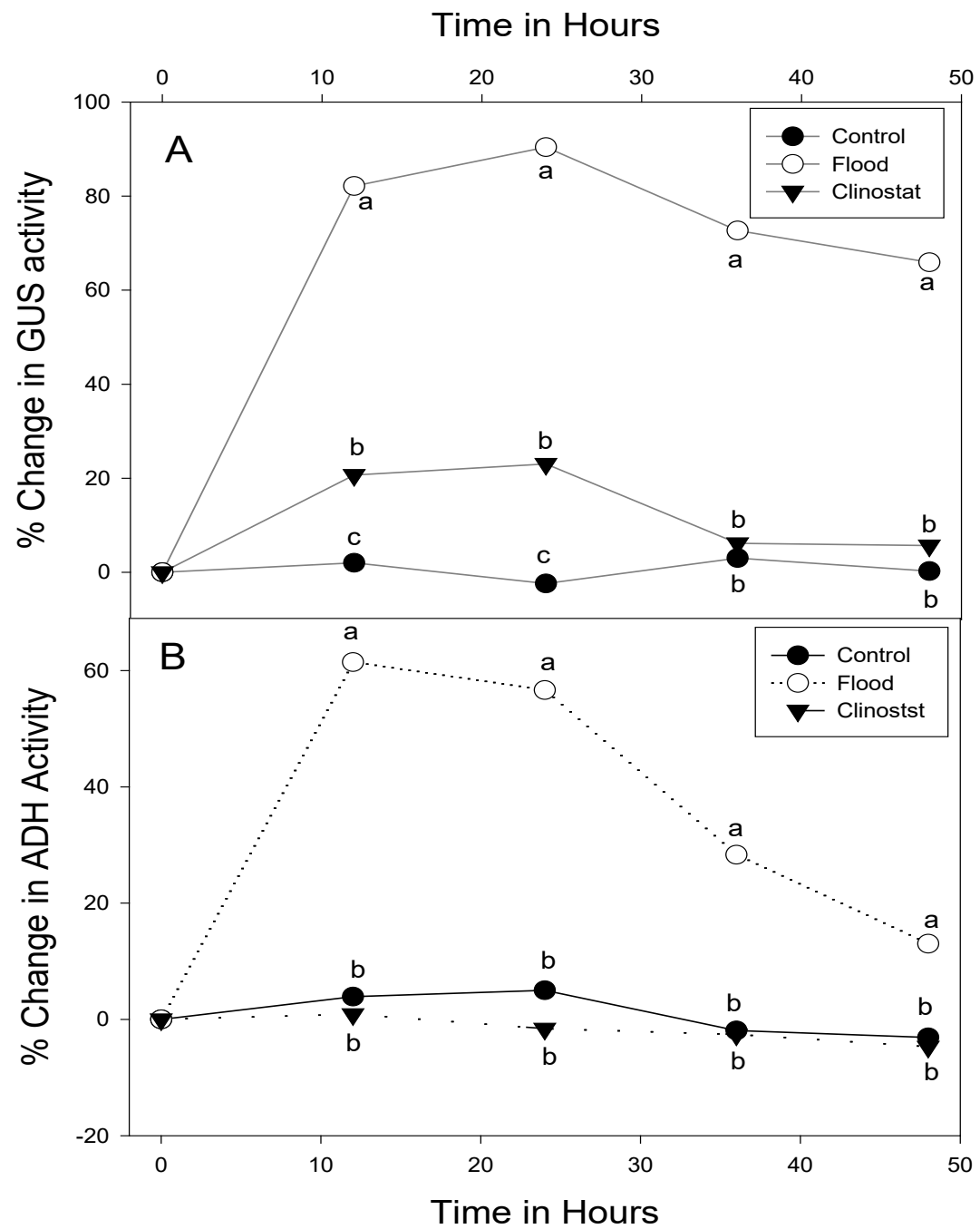


ROB Sensor KC-135 Flight Experiment



- Sealed root module
- Clay media (1mm)
- 50% volumetric H₂O
- KC-135 flight
- 40 parabolas (4x10)

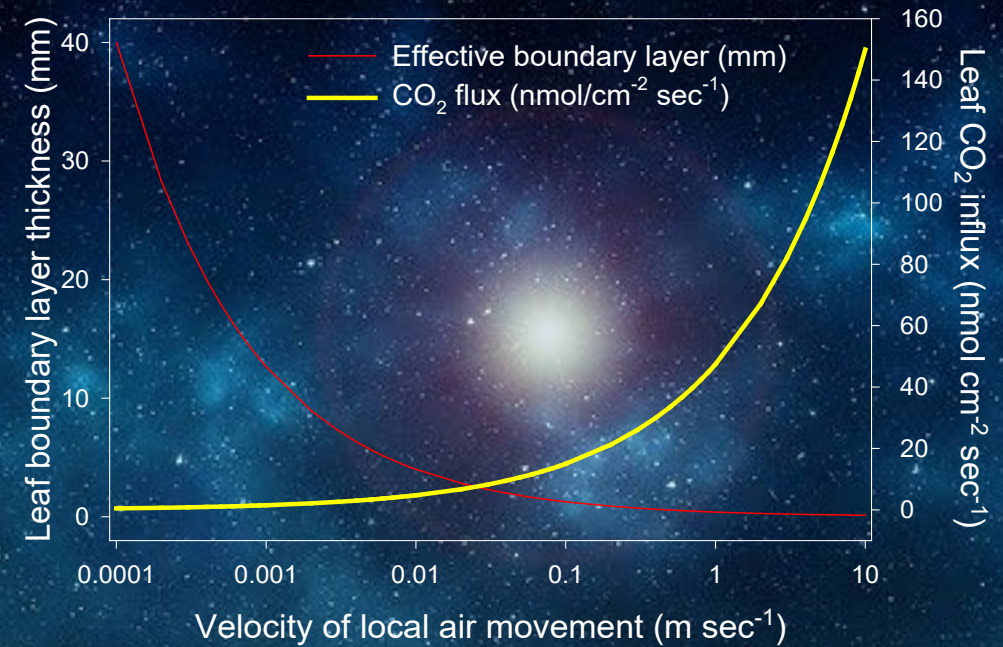




Indirect Biophysical Diffusion Stress

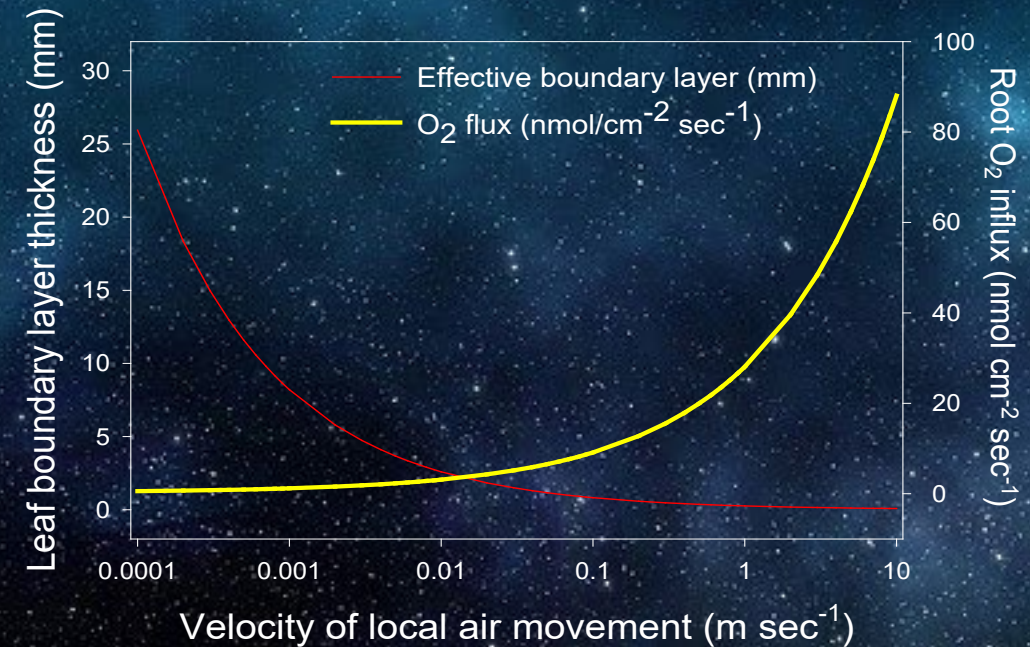
Leaf or Planar Structure

$$J = \frac{2\pi D\Delta C}{\ln(R_1/R_2)}$$



Cylindrical Plant Tissue

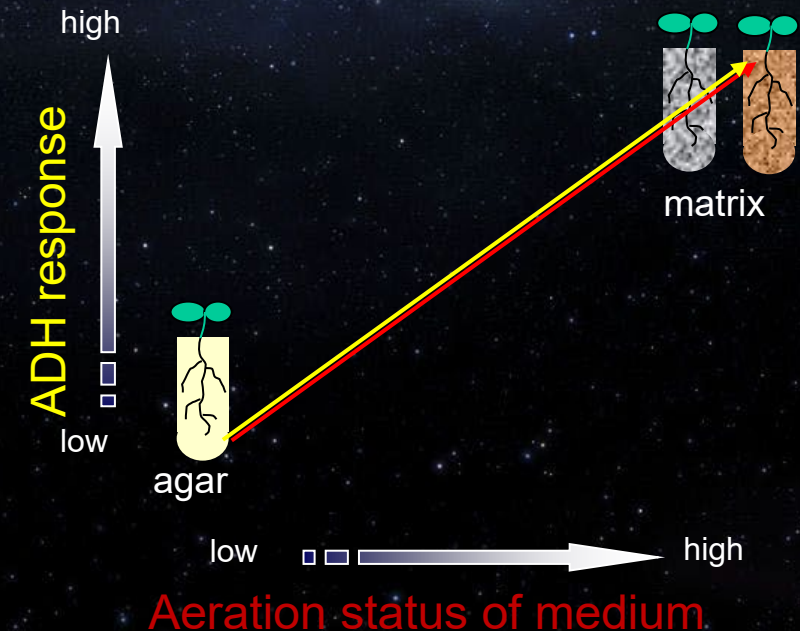
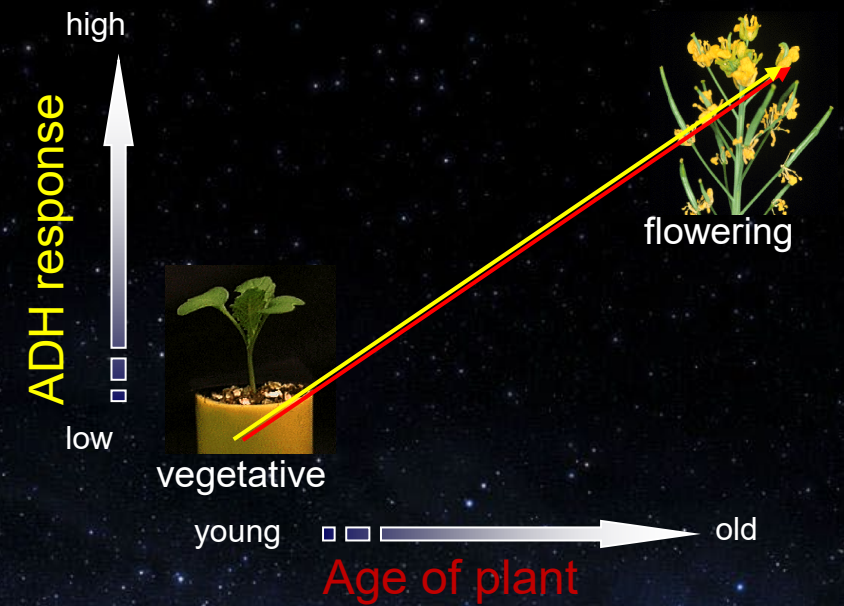
$$J = \frac{2\pi D\Delta C}{\ln(r/(r + 5.8\sqrt{d/v}))}$$



Mitochondrial Stress in Spaceflight

Spaceflight Exposure Induces Changes Increases in ADH Activity in Plant roots

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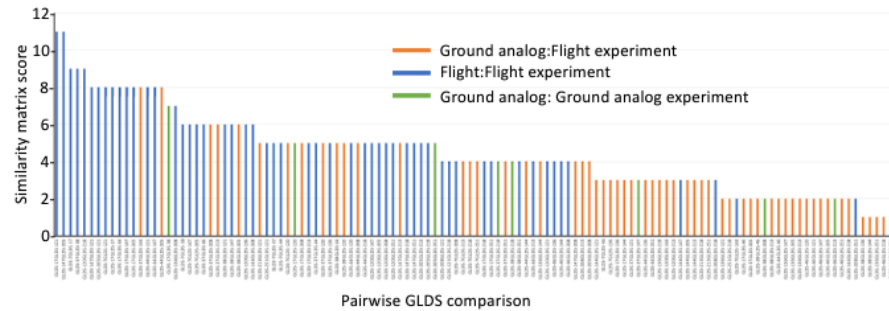
ARTICLE OPEN

Meta-analysis of the space flight and microgravity response of the *Arabidopsis* plant transcriptome

Richard Barker¹, Colin P. S. Kruse², Christina Johnson³, Amanda Saravia-Butler^{4,5}, Homer Fogle^{4,6}, Hyun-Seok Chang¹, Ralph Møller Trane⁷, Noah Kinscherf¹⁰, Alicia Villacampa¹¹, Aránzazu Manzano⁸, Raúl Herranz¹², Laurence B. Davin¹³, Norman G. Lewis¹⁴, Imara Perera¹⁵, Chris Wolverton¹⁶, Parul Gupta¹², Pankaj Jaiswal¹², Sigrid S. Reinsch¹⁷, Sarah Wyatt¹³ and Simon Gilroy¹⁸✉

Spaceflight presents a multifaceted environment for plants, combining the effects on growth of many stressors and factors including altered gravity, the influence of experiment hardware, and increased radiation exposure. To help understand the plant response to this complex suite of factors this study compared transcriptomic analysis of 15 *Arabidopsis thaliana* spaceflight experiments deposited in the National Aeronautics and Space Administration's GeneLab data repository. These data were reanalyzed for genes showing significant differential expression in spaceflight versus ground controls using a single common computational pipeline for either the microarray or the RNA-seq datasets. Such a standardized approach to analysis should greatly increase the robustness of comparisons made between datasets. This analysis was coupled with extensive cross-referencing to a curated matrix of metadata associated with these experiments. Our study reveals that factors such as analysis type (i.e., microarray versus RNA-seq) or environmental and hardware conditions have important confounding effects on comparisons seeking to define plant reactions to spaceflight. The metadata matrix allows selection of studies with high similarity scores, i.e., that share multiple elements of experimental design, such as plant age or flight hardware. Comparisons between these studies then helps reduce the complexity in drawing conclusions arising from comparisons made between experiments with very different designs.

npj Microgravity (2023)9:21 | <https://doi.org/10.1038/s41526-023-00247-6>



Supplementary Figure 1. Pairwise similarity scores of spaceflight-to-spaceflight, spaceflight-to-ground analog and ground analog-to-ground analog studies. Similarity scores were drawn from the similarity matrix in Supplementary Data Table 2. Orange, Flight mission study vs ground analog study; Blue, flight mission vs flight mission; Green, ground analog study vs ground analog study. Note, in this analysis, spaceflight studies are most similar to other spaceflight studies and least similar to ground analog experiments, which in turn are most similar to each other.



Biophysical stress in the Genelab era

R. Barker et al.

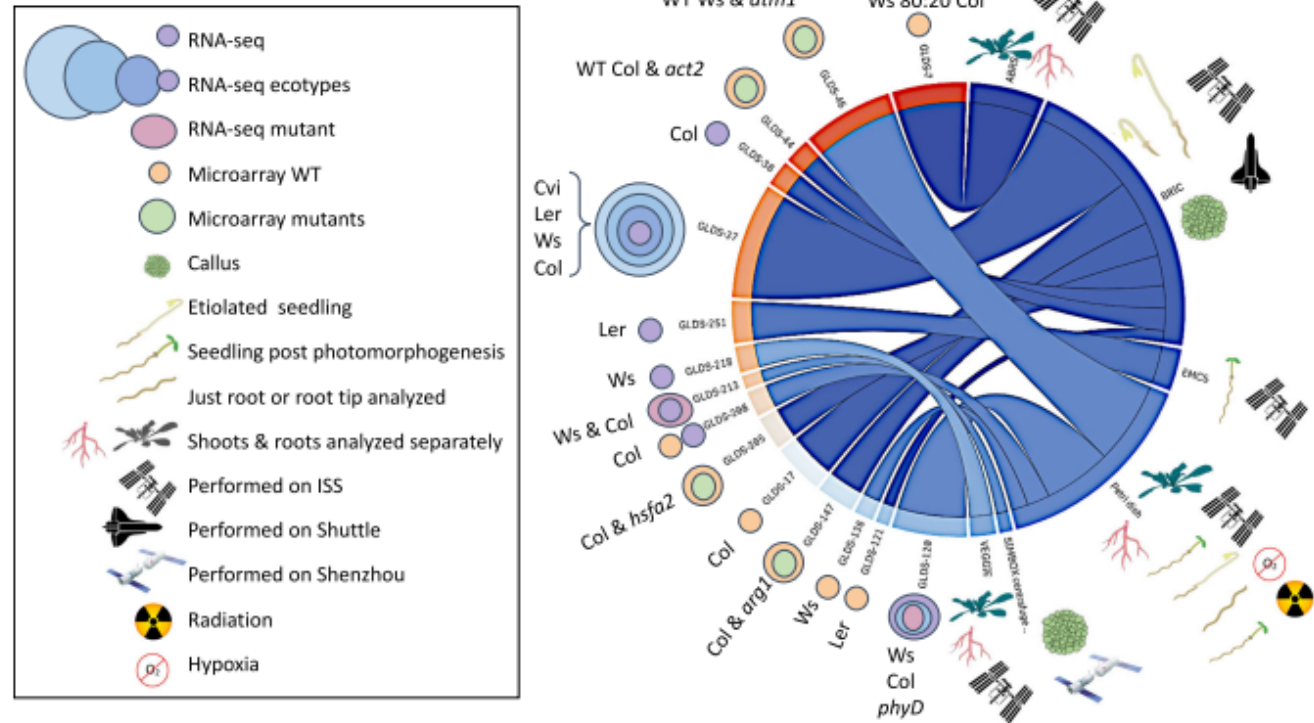
npj
5

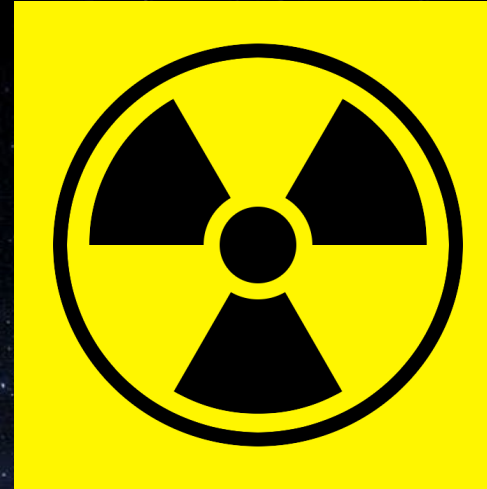
Fig. 4 Graphical representation of metadata related to tissues, assay type and flight vehicle. The specific assay and tissue types for each dataset are indicated with network clustering based on hardware. See Supplementary Data 1 and 2 for the Matrix driving this visualization. Note the hardware used to analyze plant response to spaceflight often defines the types of tissue that are available and so these two variables are often linked. Purple color circles represent RNAseq analysis of wild-type Col-0 plants, shades of blue represent other WT ecotypes, the pink circle represents RNA-seq analysis performed on mutants. The size of circles is a qualitative representation of the amount of differentially expressed loci relative to other genetic varieties used during that study. Ecotypes: Col Columbia, Cvi Cape Verde Island, Ws Wassilewskija, Ler Landsberg, Col-0 + Ws mixed sample 80% Ws and 20% Col ecotypes. Genotypes: WT wild-type, *arg1* altered response to gravity 1, *hsfa2* heat shock transcription factor A2, *atm1* ataxia-telangiectasia mutated 1, *phyD* phytochrome D, Hardware: BRIC Biological Research in Canister, EMCS European Modular Cultivation System, VEGGIE Vegetable production system, SIMBOX SIMBOX incubator system, ABRS Advanced Biological Research System. An interactive version of this visualization is available at: <https://gilroy-qlik.botany.wisc.edu/a/sense/app/20aa802b-6915-4b1a-87bd-c029a1812e2b/sheet/6241e71a-a3c5-4c63-9210-e05c743699d7/state/analysis>.

2 Sources of Mitochondrial Stress in Spaceflight

Direct Radiation Induced Biochemical Damage

Hydrolysis > ROS O_2^- H_2O_2

Direct lipid peroxidation of Mitochondrial
Mitochondrial DNA Damage



Indirect Biophysical Diffusion Stress

Thermal and Redox Stress

Biophysical CO_2 Rebreathing

Hypercapnic and Hypoxic

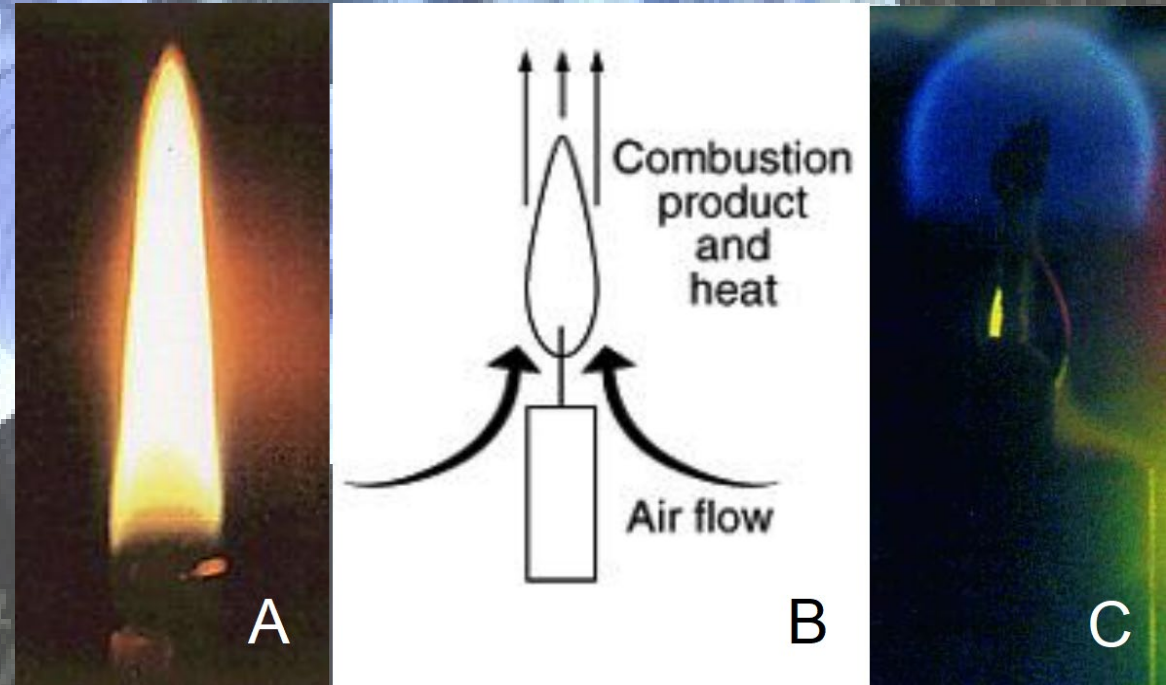


Hypothesis: Microgravity Effects on Human Metabolism

Buoyancy-Driven Convection and Diffusion Indirect Biophysical Diffusion Stress

Image/schematic of a candle flame in 1g and μ g

- Direct Effects
 - Disruption of gravity sensing
 - Intracranial pressure
 - Bone/Muscle wasting
- Indirect Effects
 - Biophysical diffusion of fluids and gases
 - Hypercapnia
 - Hypoxia



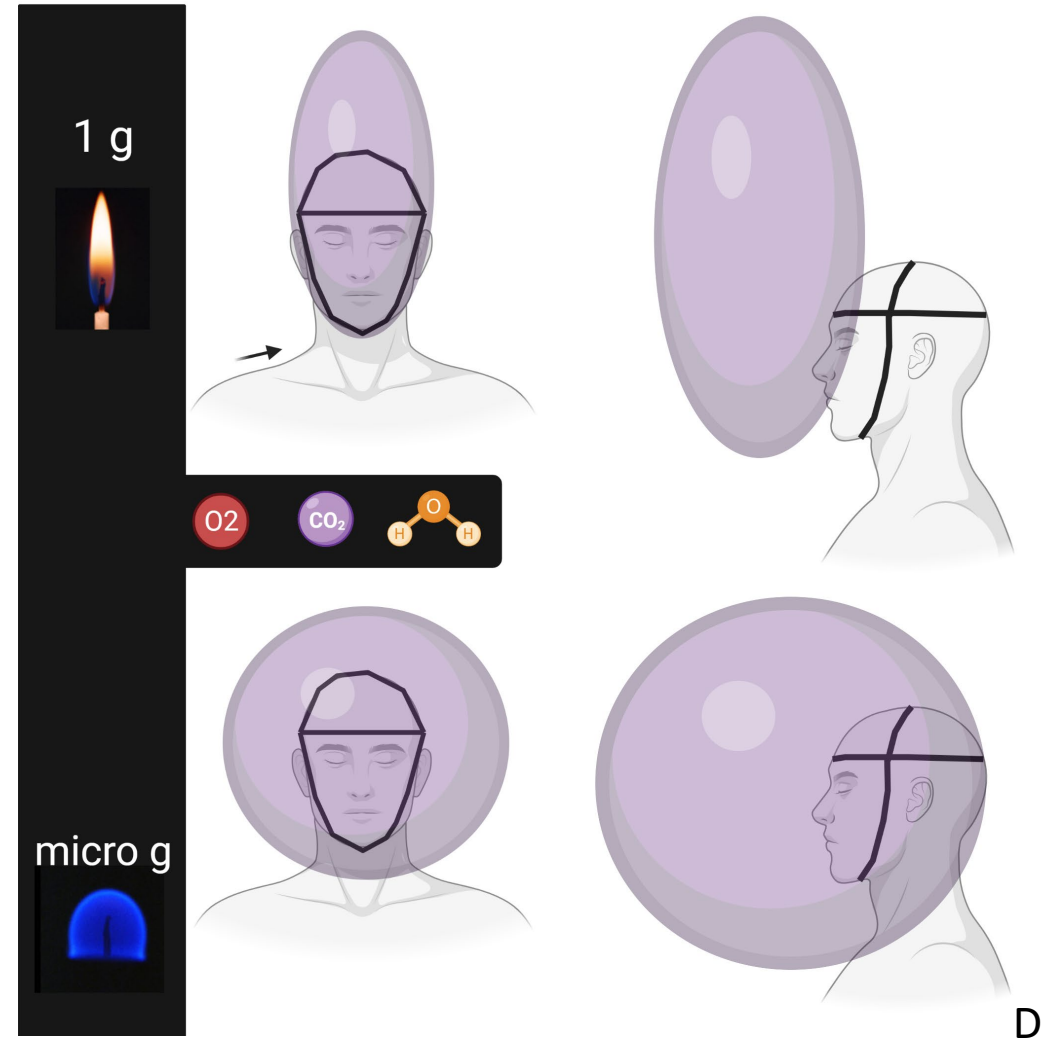
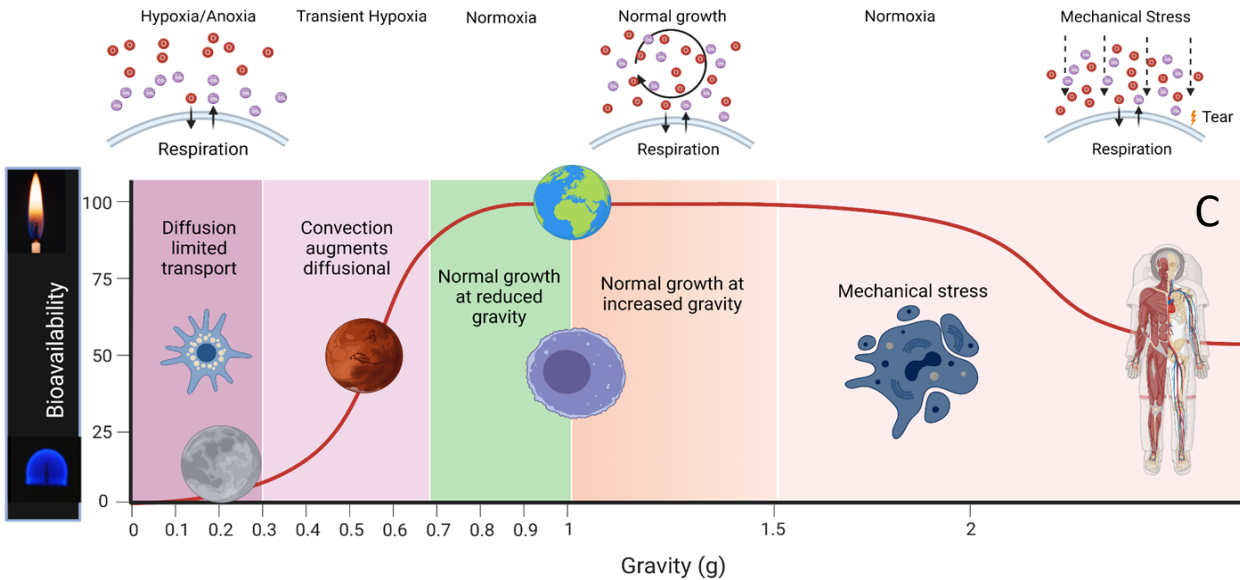
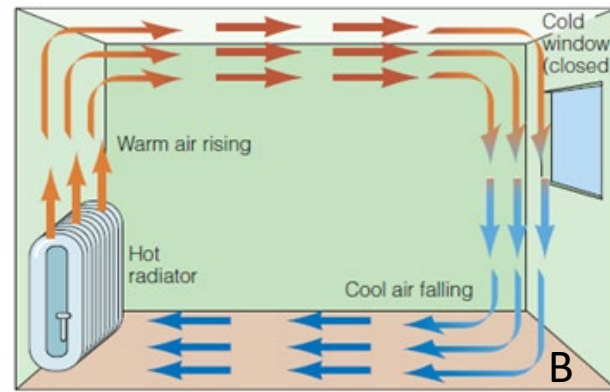
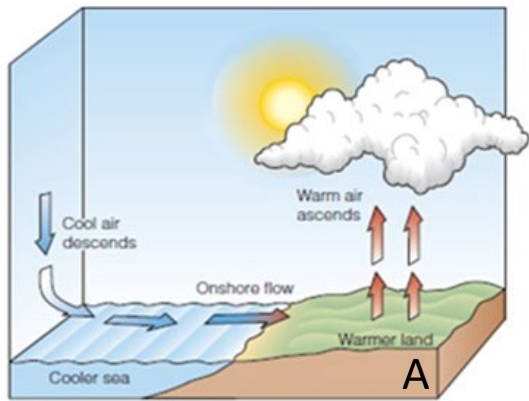
(Ross et al., 1991, Microgravity. Combust. Sci. Technol. 75:155-160)

μ g = a diffusion limited environment!

- This facilitates crystallization, combustion, and metallurgical research

Buoyancy-Driven Convection and Diffusion

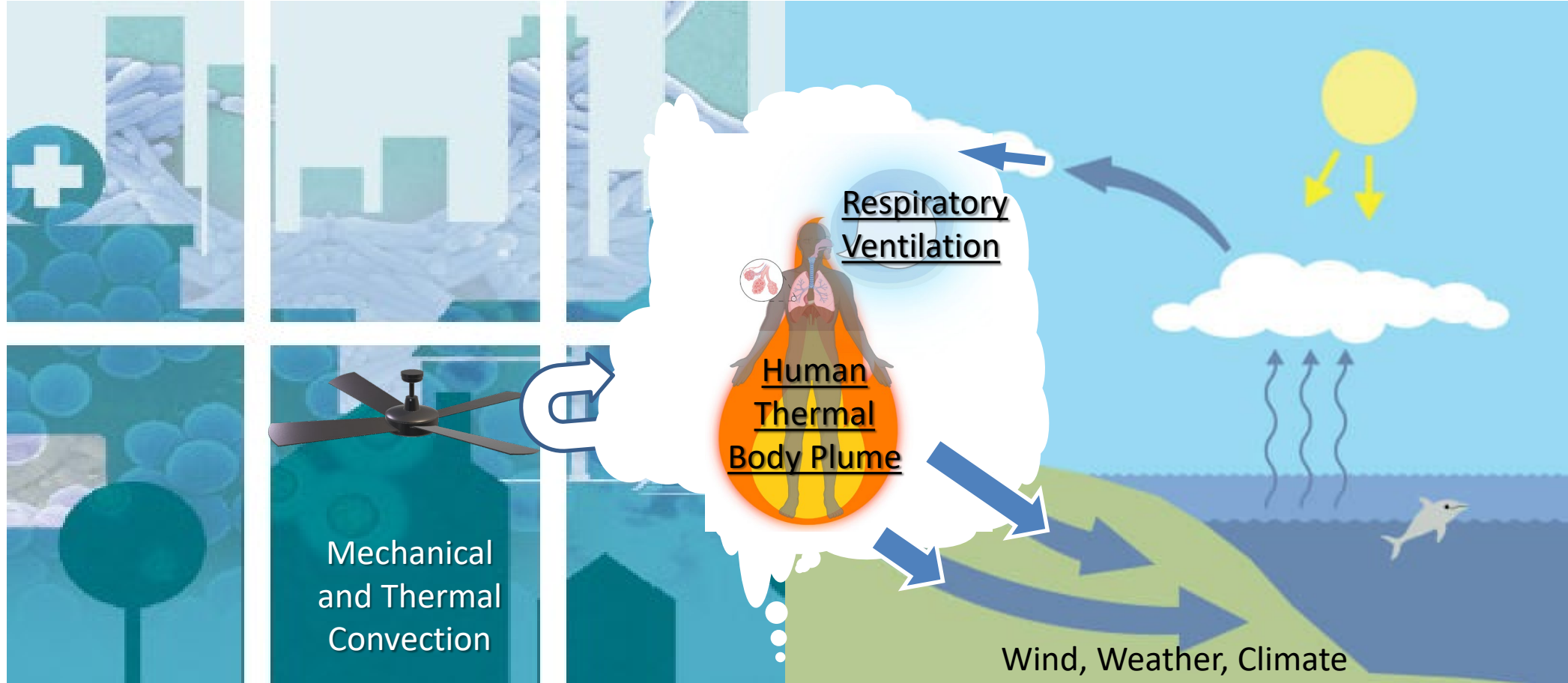
Indirect Biophysical Diffusion Stress



System Convection

Built Environment

Natural Environment



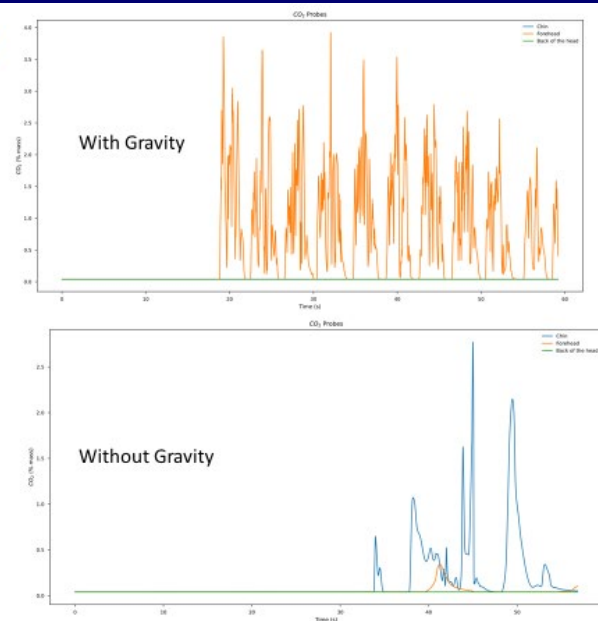
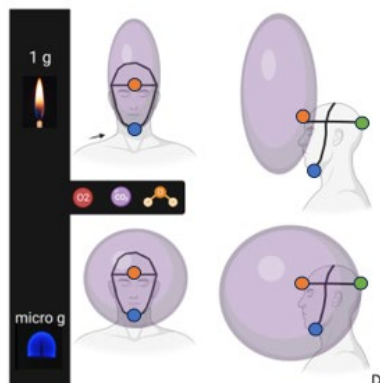
Biophysical limitations in human redox exchange in microgravity

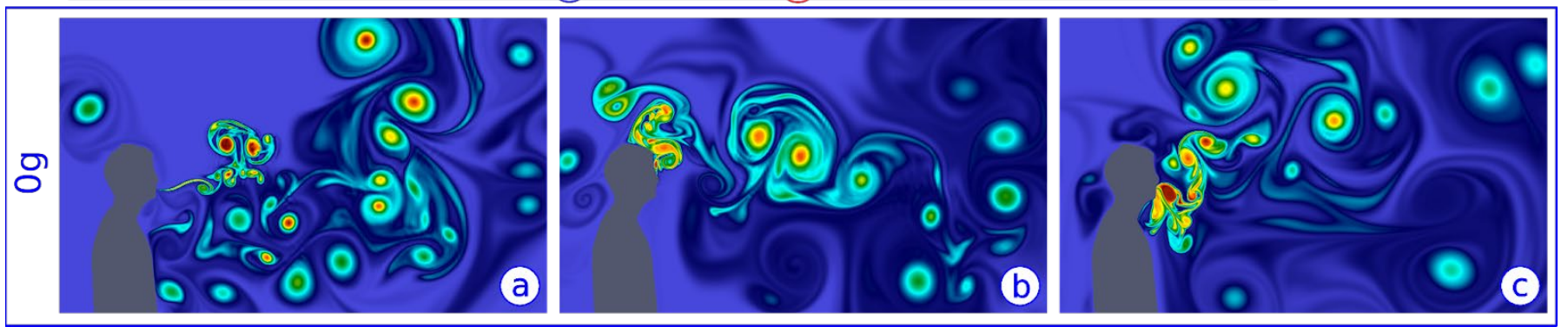
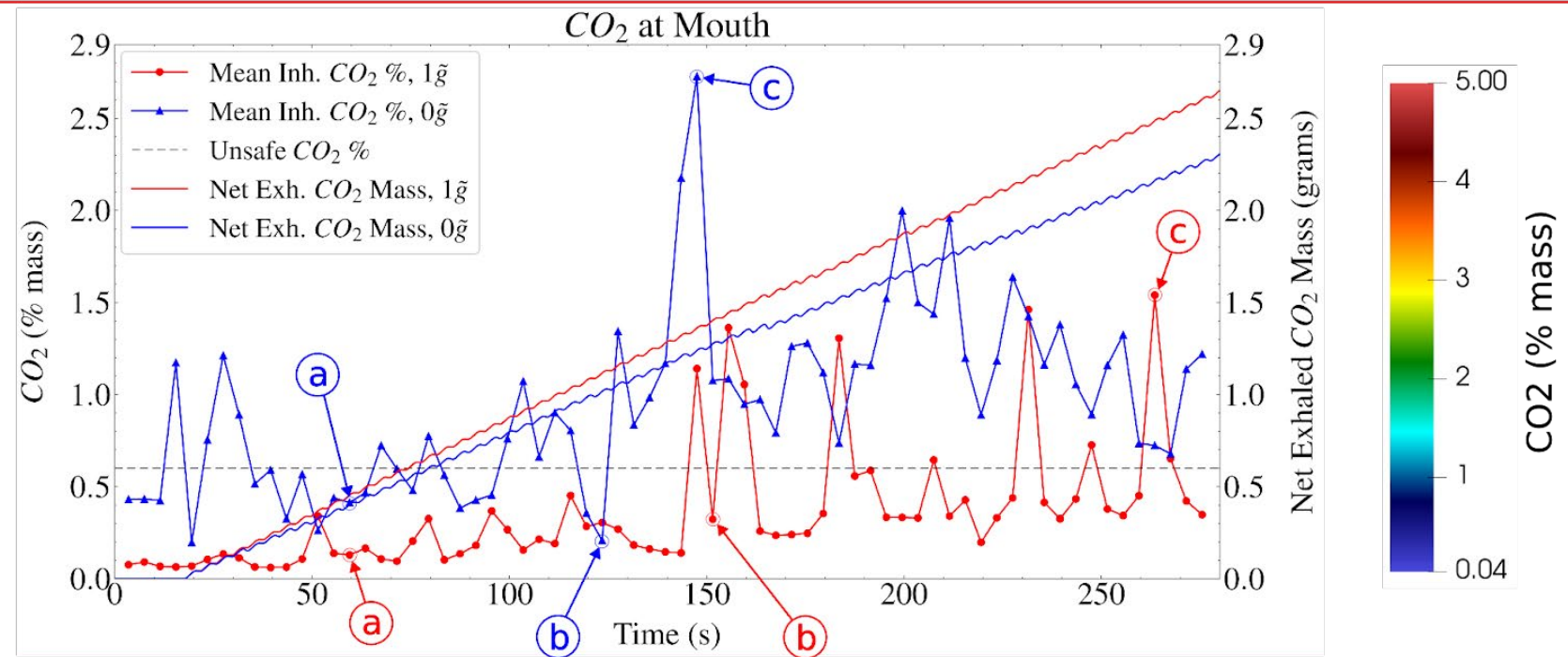
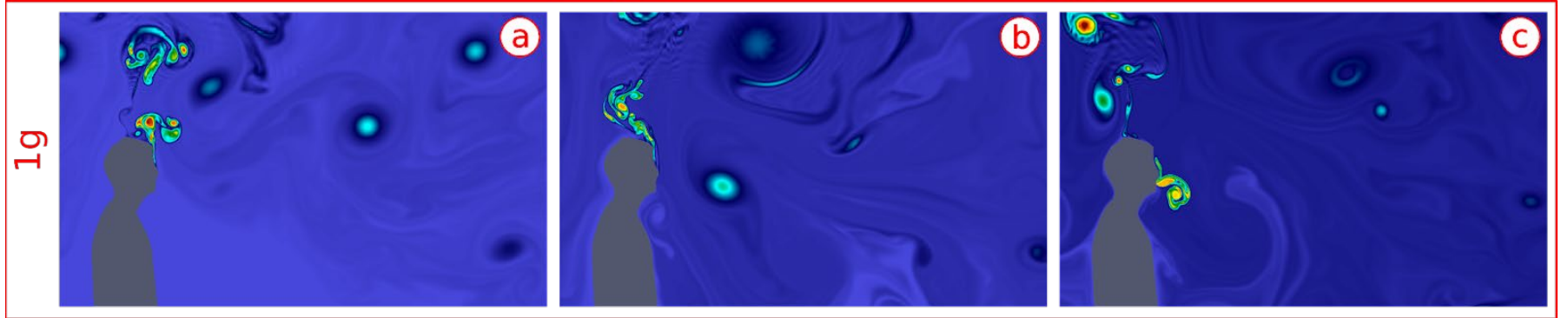
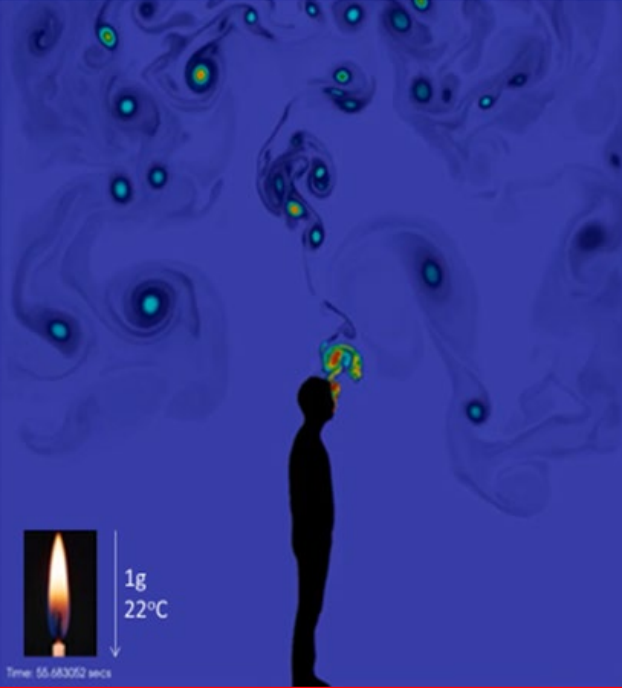
MARSHALL PORTERFIELD, PURDUE UNIVERSITY

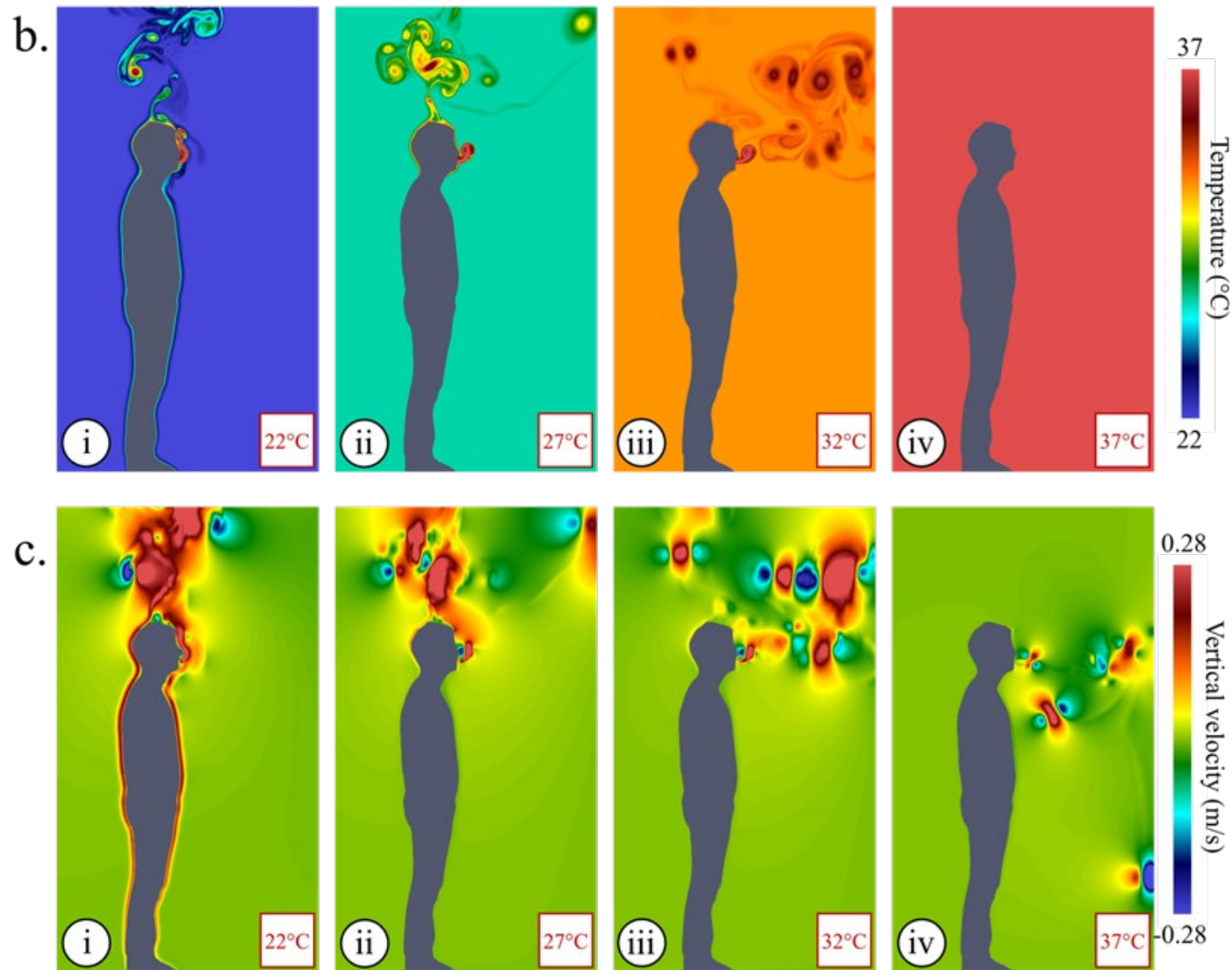
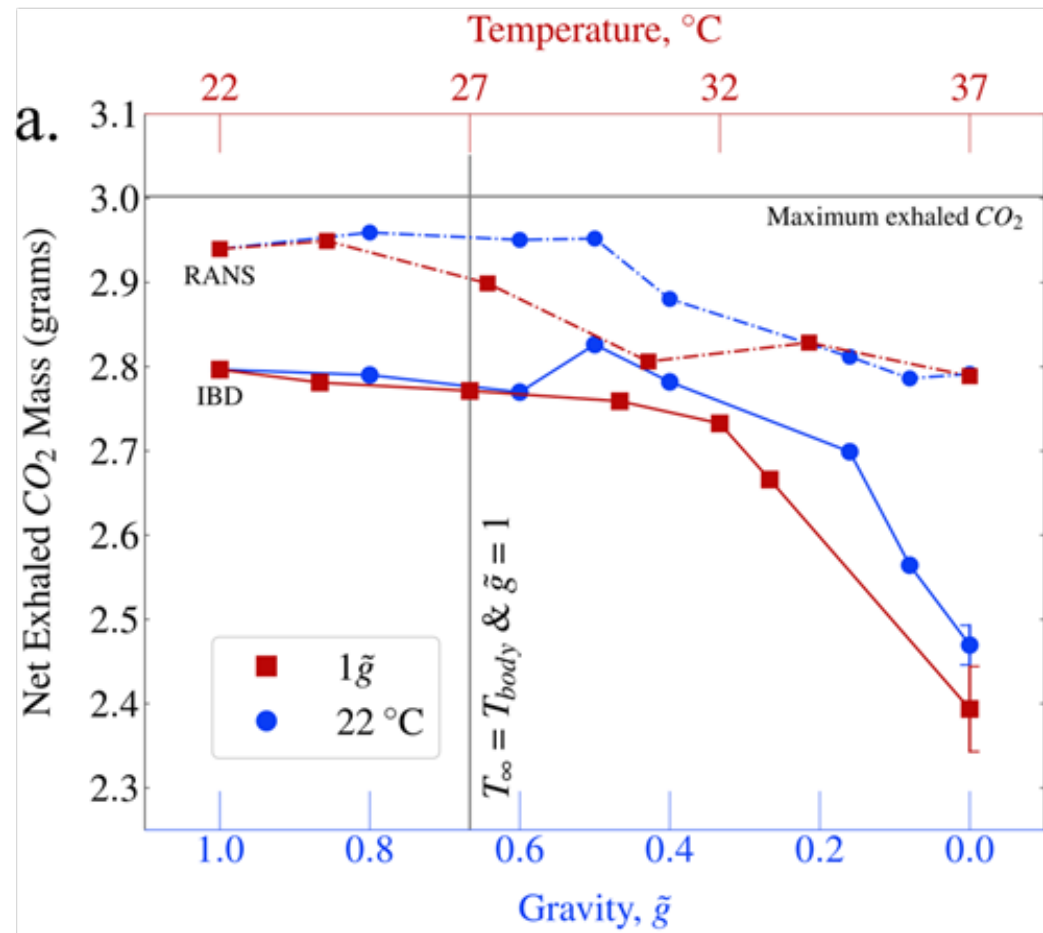
CHIEF OF SCIENCE, ART, AND ENGINEERING, ELEVATED BIOASTRONAUTICS

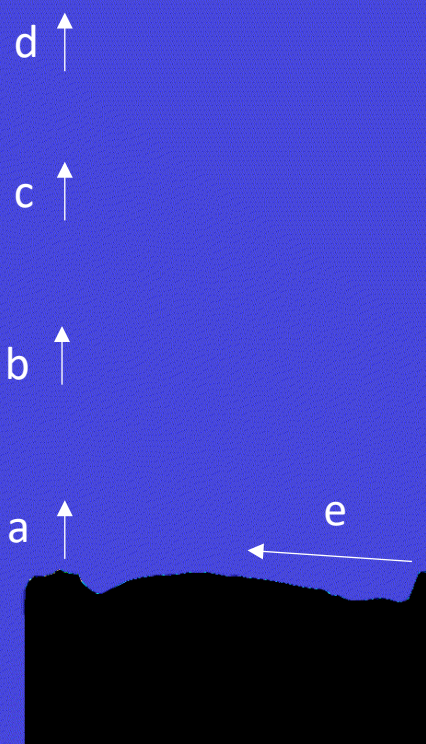


ARES Atmospheric REDOX Exchange Sensor NASA HERO ECLSS

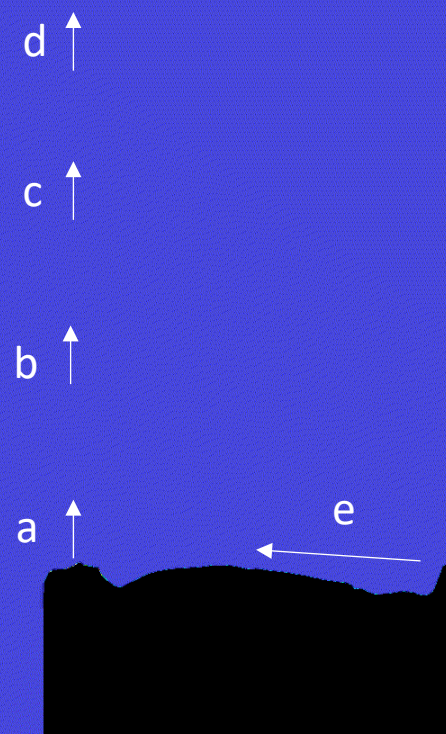








Earth Gravity: 9.8 (m/s²)
Time: 0.059190 sec

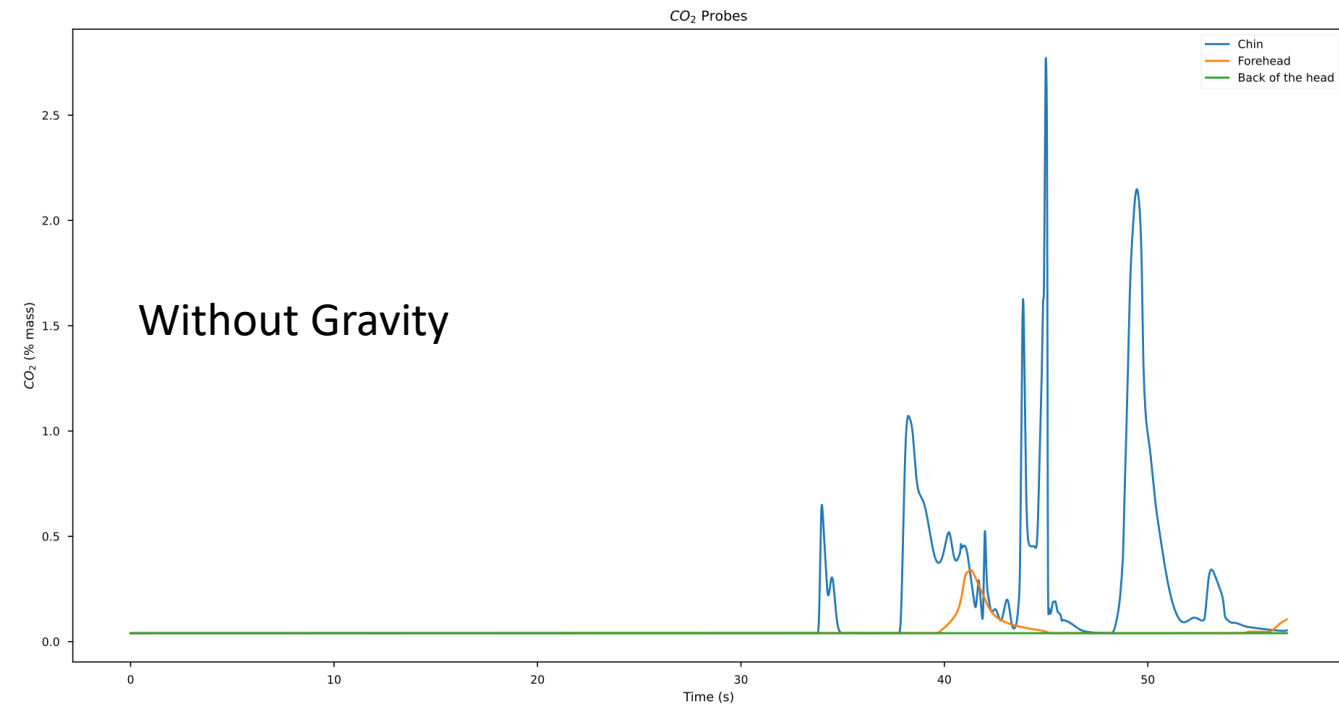
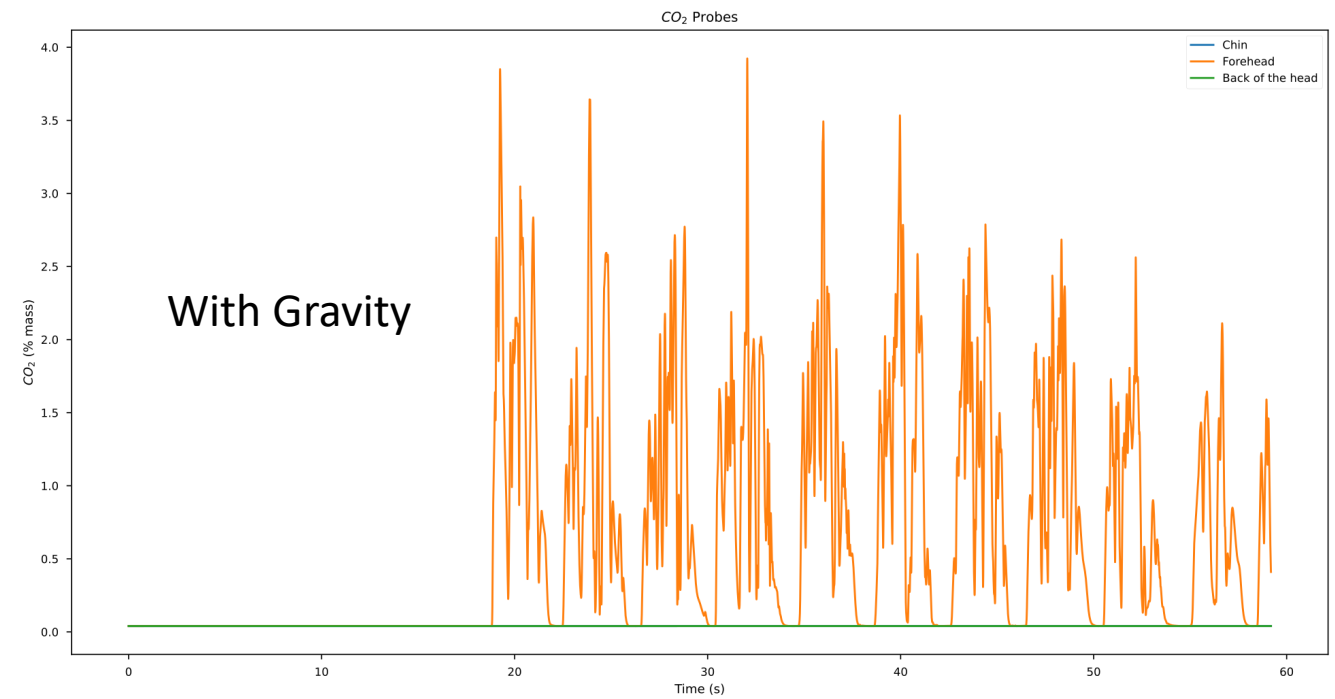
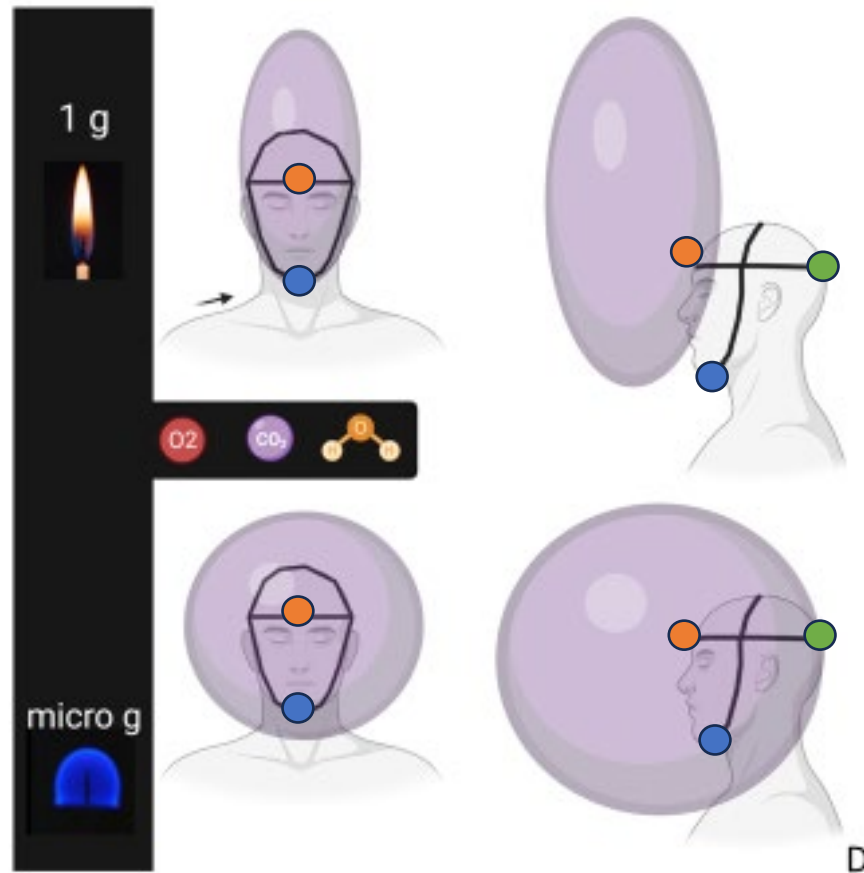


Spaceflight Gravity: 0.0 (m/s²)
Time: 0.059190 sec

NEXT GENERATION ECLSS

AI/ML Air Exchanger

Faraday Earthling-Biophysical REDOX Sensor



MOLECULAR BIOLOGY & GENETICS

Development of mouse preimplantation embryos in space

Xiaohua Lei^{1,*}, Yujing Cao^{1,†}, Baohua Ma^{2,†}, Yunfang Zhang¹, Lina Ning¹, Jingjing Qian^{1,3}, Liwen Zhang^{1,3}, Yongcun Qu^{1,3}, Tao Zhang⁴, Dehong Li⁵, Qi Chen¹, Junchao Shi¹, Xudong Zhang¹, Chiyuan Ma¹, Ying Zhang^{1,*} and Enkui Duan^{1,*}

¹State Key Laboratory of Stem Cell and Reproductive Biology, Institute of Zoology, Chinese Academy of Sciences, Beijing 100101, China;
²College of Veterinary Medicine, Northwest A&F University/Key Laboratory of Animal

ABSTRACT

The development of life beyond planet Earth is a long-standing quest of the human race, but whether normal mammalian embryonic development can occur in space is still unclear. Here, we show unequivocally that preimplantation mouse embryos can develop in space, but the rate of blastocyst formation and blastocyst quality are compromised. Additionally, the cells in the embryo contain severe DNA damage, while the genome of the blastocysts developed in space is globally hypomethylated with a unique set of differentially methylated regions. The developmental defects, DNA damage and epigenetic abnormalities can be largely mimicked by the treatment with ground-based low-dose radiation. However, the exposure to simulated microgravity alone does not cause major disruptions of embryonic development,

Spaceflight Impact on the Mitochondria



Cell

Log in

ARTICLE | VOLUME 183, ISSUE 5, P1185–1201.E20, NOVEMBER 25, 2020

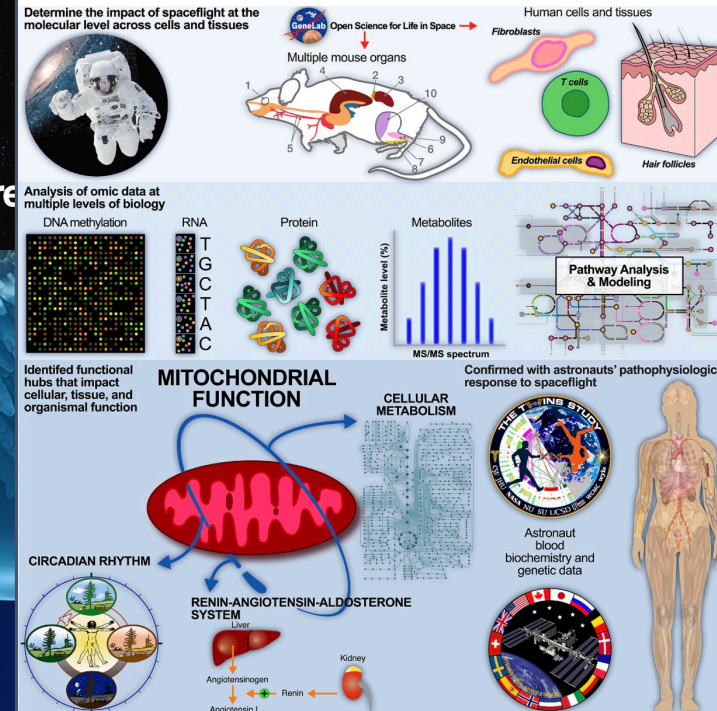
Comprehensive Multi-omics Analysis Reveals Mitochondrial Stress as a Central Biological Hub for Spaceflight Impact

William A. da Silva²³ • Hossein Fazelinia²³ • Sara Brin Rosenthal²³ • ...Christopher E. Mason²⁴ • Sylvain V. Costes²⁴ • Afshin Beheshti^{24, 25} • Show all authorsShow footnotes/DOI: <https://doi.org/10.1016/j.cell.2020.11.002> Check for updates

PlumX Metrics

Highlights

- Multi-omics analysis and techniques with NASA's GeneLab platform
- The largest cohort of astronaut data to date utilized for analysis
- Mitochondrial dysregulation driving spaceflight health risks
- NASA Twin Study data validates mitochondrial dysfunction during space missions



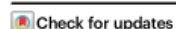


Space radiation damage rescued by inhibition of key spaceflight associated miRNAs

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J. Tyson McDonald^{1,32}, JangKeun Kim^{2,32}, Lily Farmerie^{3,4,32}, Meghan L. Johnson^{3,32}, Nidia S. Trovao⁵, Shehbeel Arif^{6,7}, Keith Siew⁸, Sergey Tsoy⁹, Yaron Bram⁹, Jiwoon Park², Eliah Overbey², Krista Ryon², Jeffrey Haltom¹⁰, Urminder Singh¹¹, Francisco J. Enguita¹², Victoria Zaksas^{13,14}, Joseph W. Guarnieri¹⁰, Michael Topper¹⁵, Douglas C. Wallace^{10,16}, Cem Meydan², Stephen Baylin¹⁵, Robert Meller¹⁷, Masafumi Muratani^{18,19}, D. Marshall Porterfield²⁰, Brett Kaufman^{3,4}, Marcelo A. Mori^{21,22}, Stephen B. Walsh⁸, Dominique Sigaud-Roussel²³, Saida Mebarek²⁴, Massimo Bottini²⁵, Christophe A. Marquette²⁶, Eve Syrkin Wurtele^{11,27}, Robert E. Schwartz⁹, Diego Galeano²⁸, Christopher E. Mason², Peter Grabham^{29,33} & Afshin Beheshti^{30,31,33}✉

Our previous research revealed a key microRNA signature that is associated with spaceflight that can be used as a biomarker and to develop countermeasure treatments to mitigate the damage caused by space radiation. Here,

scientific reports

OPEN

Aging and putative frailty biomarkers are altered by spaceflight

Andrea Camera^{1,39}, Marshall Tabetah^{2,39}, Veronica Castañeda^{3,39}, JangKeun Kim^{4,39}, Aman Singh Galsinh⁵, Alissen Haro-Vinueza⁶, Ivonne Salinas⁷, Allen Seylani⁸, Shehbeel Arif^{9,10}, Saswati Das¹¹, Marcelo A. Mori^{12,13}, Anthony Carano¹⁴, Lorraine Christine de Oliveira^{15,16}, Masafumi Muratani^{17,18}, Richard Barker¹⁹, Victoria Zaksas^{20,21}, Chirag Goel²², Eleni Dimokidis²³, Deanne M. Taylor^{24,25}, Jisu Jeong²⁶, Eliah Overbey⁴, Cem Meydan⁴, D. Marshall Porterfield², Juan Esteban Díaz²⁷

Identification and validation of multi-omics frailty biomarkers in human spaceflight

Leading the project

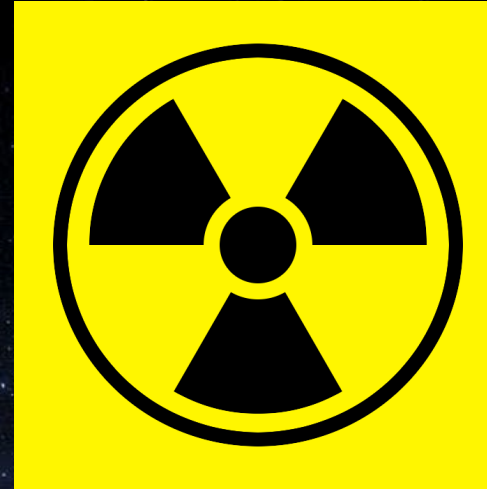


2 Sources of Mitochondrial Stress in Spaceflight

Direct Radiation Induced Biochemical Damage

Hydrolysis > ROS O_2^- H_2O_2

Direct lipid peroxidation of Mitochondrial
Mitochondrial DNA Damage



Indirect Biophysical Diffusion Stress

Thermal and Redox Stress

Biophysical CO_2 Rebreathing

Hypercapnic and Hypoxic



Blueskies research

Goal: Investigate the short-term effects of the Lunar surface environment on model space crops.

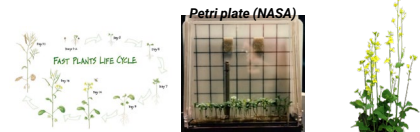
Objectives: We will grow model crops in Earth and on the lunar surface and use remote monitoring technology to identify **phenotypic** differences and will analyze returned samples to identify any **biomolecular differences**.

Meet the model pyhtonauts



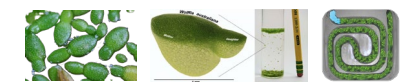
Arabidopsis thaliana (Wild type Col-0 variety):

- Is well-studied to this mission due to its well characterized genome.
- This has and it a useful tool to help us understand the genetic response of plants to the space environment.
- Small size and short growth cycle allow for compact experimental design which is often essential requirement for bioastronautics missions.
- As a plant model organism, Arabidopsis can help study the effects of microgravity on plant development, growth, and stress response.



Brassica rapa (Wisconsin Fast Plant AstroPlant variety):

- Specifically bred for space research, with a fast growth rate and compact size.
- Easy to grow and maintain in controlled environments, such as those found on the moon.
- As a relative of Arabidopsis, Brassica rapa can provide complementary insights into plant biology in space.
- While also being more robust and adaptable to K12 education programs.

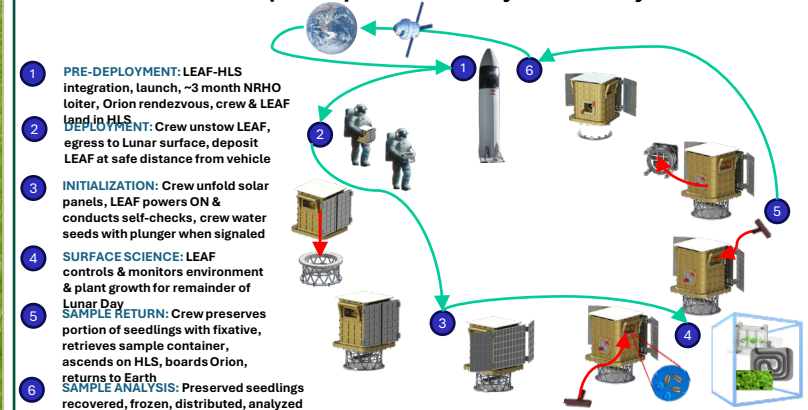


Wolffia australis:

- Small size and simple growth habits, making it easy to cultivate in space.
- Ability to thrive in a variety of environments, including microgravity.
- Potential to serve as a bioindicator for environmental stressors and radiation effects.

Mission Summary

LEAF Concept of Operations – Payload Life Cycle



Open Questions

- What are the major stressors that may influence plant health, gene expression and biomass yields on the lunar surface?
- What questions might we want to ask of the data that is created by the sensors?
- What questions might we want to ask of the data that is created by the returned samples?
- What parallel ground control experiments could be used to provide additional insights into the samples returned during the mission?
- What data is needed to help you model the yields of future astro-agroecosystems?
- How might radiation effect the organisms?
- How might the exploration atmosphere effect crop yields?
- What methods can be used to identify and quotate phenotypes?

Global Collaboration

Systems Biology guiding the design of new exploration environments

Upon splashdown to Earth, the Space-Exposed Reaction Unit (SRU) will be retrieved and transferred to a boat, where it will be immediately frozen to preserve the samples. The frozen plant samples from both flight and ground units will then be shipped to NASA's GeneLab for further analysis.

Multi-Omics Analysis

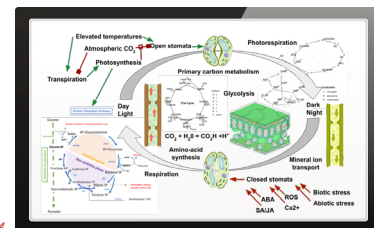
- Bulk Transcriptomics:** GeneLab will conduct bulk RNA sequencing to identify differentially expressed genes and pathways.
- Microbiomics:** Kennedy Space Center (KSC) will perform microbiome analysis to investigate changes in microbial communities associated with the plants.
- Single Cell Transcriptomics and Proteomics:** La Trobe University will conduct single cell RNA sequencing and proteomic analysis to reveal cellular heterogeneity and molecular responses at the individual cell level.

Specialized Analysis

- Cell Wall Analysis:** University of Adelaide will investigate changes in plant cell wall composition and structure.
- Regulatory Network Modeling:** University of Colorado and La Trobe University will jointly develop regulatory network models to predict key transcriptional regulators and their targets.

Data Integration and Systems Biology

- Identify key nodes and edges in the regulatory networks
- Reconstruct molecular pathways and networks
- Predict functional outcomes and phenotypic responses



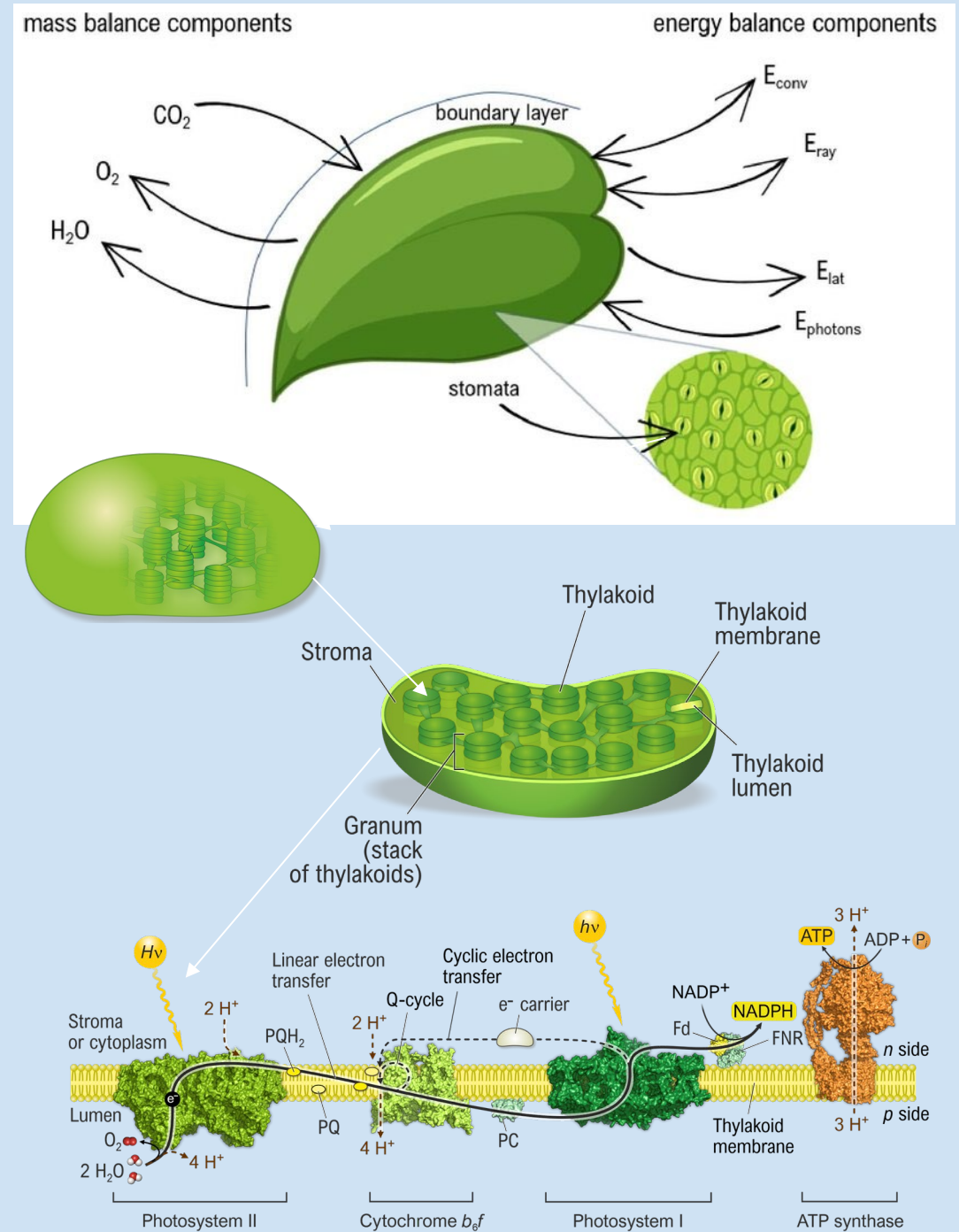
The Challenge of Spaceflight for Plants.

- Biophysical systems on Earth are dependent on gravity for growth and development.
- Spaceflight introduces unique biophysical factors like altered gravity and radiation.
- In Low Earth Orbit (LEO), the ISS is partially shielded, allowing focus on microgravity effects.



Microgravity and lunar gravity can have direct and indirect effects.

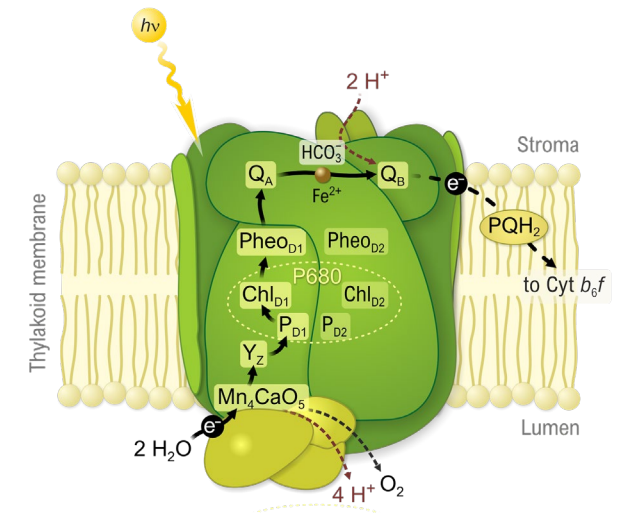
- Indirect effects include biophysical diffusion stress at the membrane boundary layers, limiting transport of metabolites/by-products. This can lead to thermal and redox limitations.
- Hardware and nutrient delivery configuration can alter the homeostatic end point equilibrium.



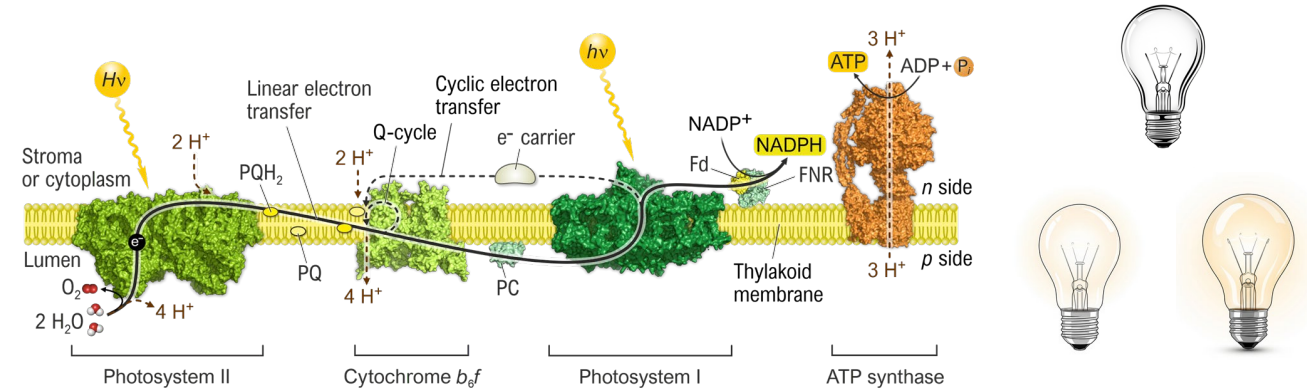
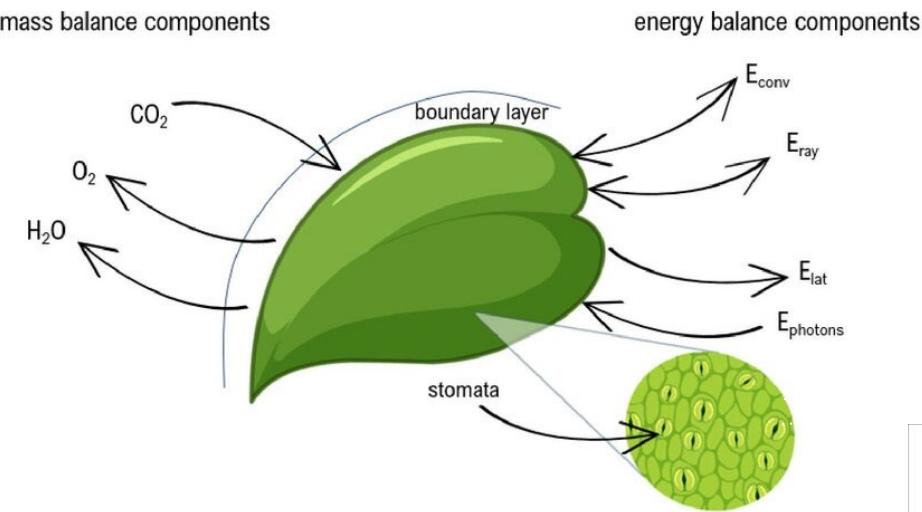
A diagram illustrating the stages of plant growth. It shows a sequence of five illustrations: 1. A seedling with a small green shoot and a yellow root. 2. A seedling with a green shoot and a brown root. 3. A seedling with a green shoot and a brown root. 4. A seedling with a green shoot and a brown root. 5. A seedling with a green shoot and a brown root.



RNA-seq

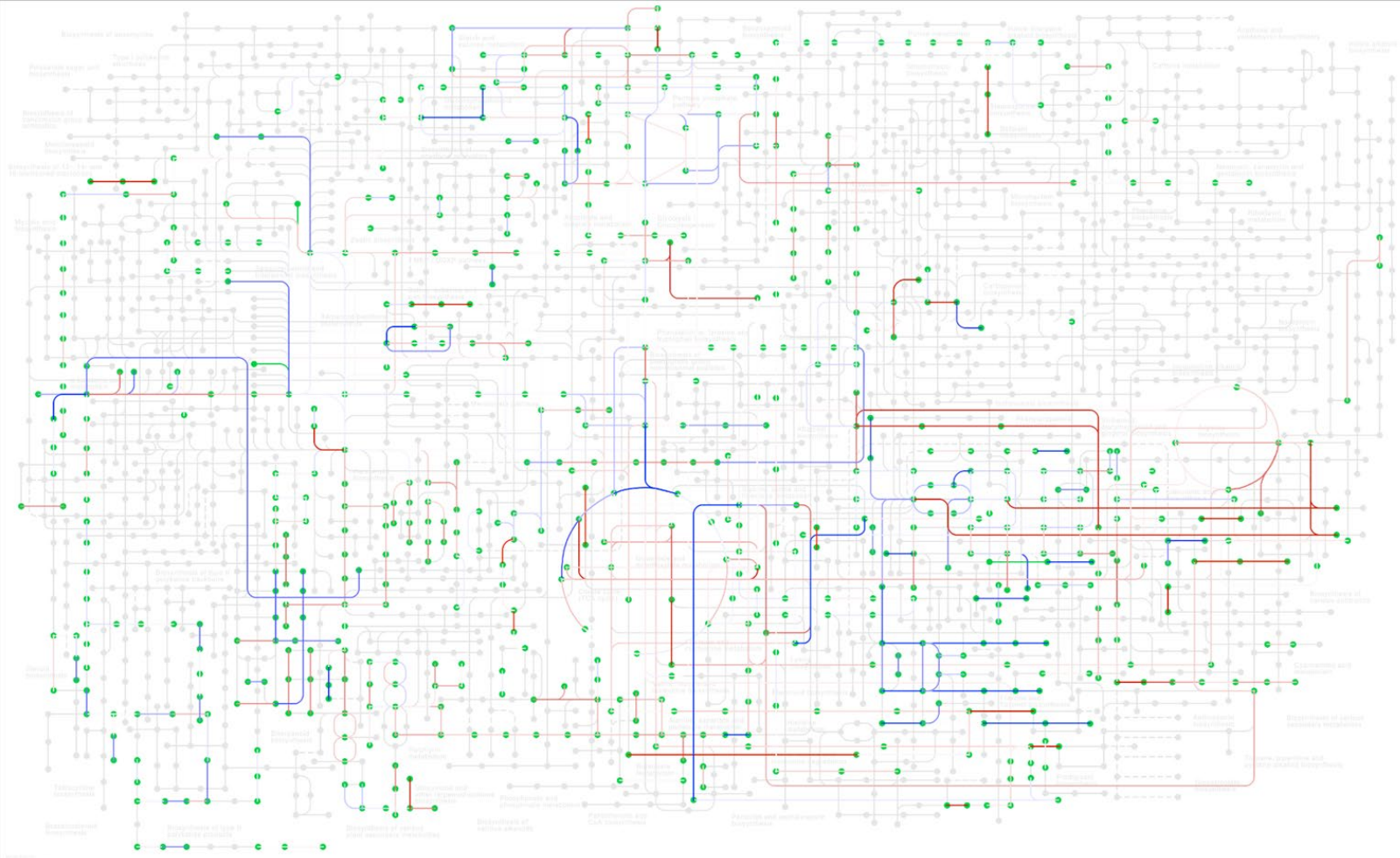


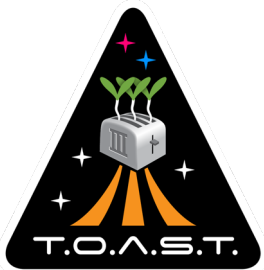
- *Arabidopsis thaliana* is a model organism for spaceflight studies due to its small size, rapid life cycle, and characterized genome.
- The NASA Open Science Data (OSD) repository provides valuable datasets for investigating *Arabidopsis Molecular* responses.
- This study performs a meta-analysis of RNA-seq data from seven *Arabidopsis* spaceflight studies from the OSDR.



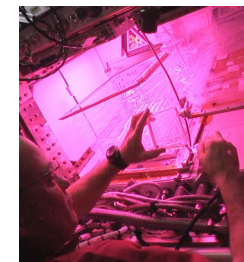
All samples.
Visualize of true log2fc
FLT contrasting GC.

Red denotes +1 (upregulation)
Blue denotes -1 (downregulation).





Multilayer Stress Pattern Recognition

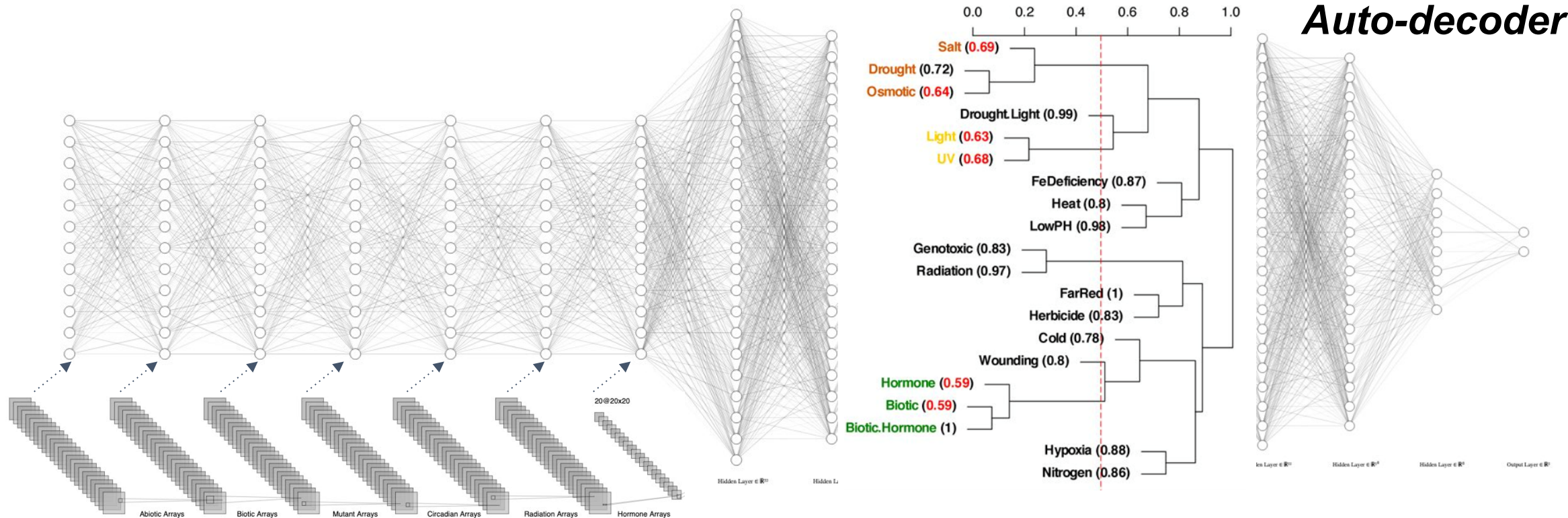


Auto-encoder input: 85 stress response assays from GEO

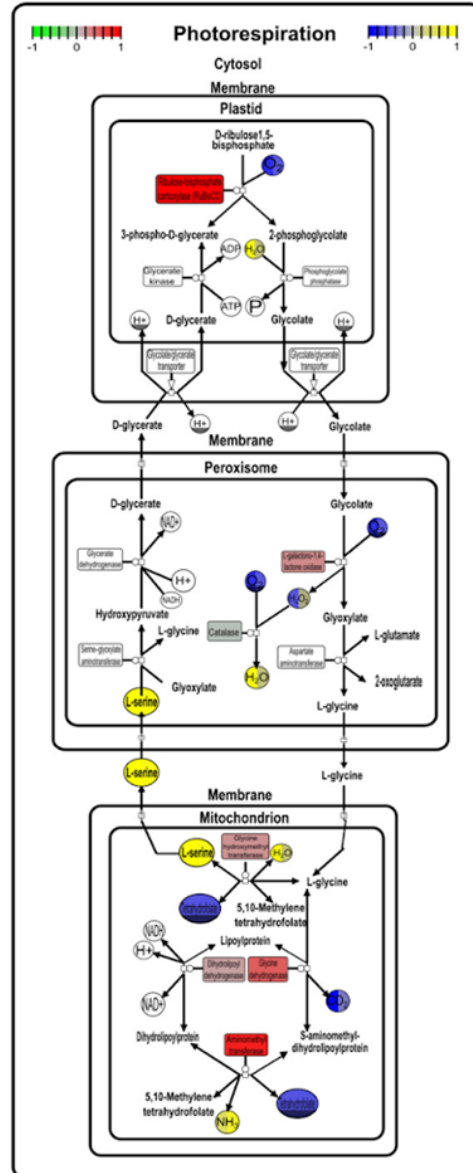
Hidden processing layer: “Physiospace” as described by Esfahani *et al.*, (2022)

Auto-decoder output: 20 dimensional stress space model

Application: Identification system for 20 distinct stress groups

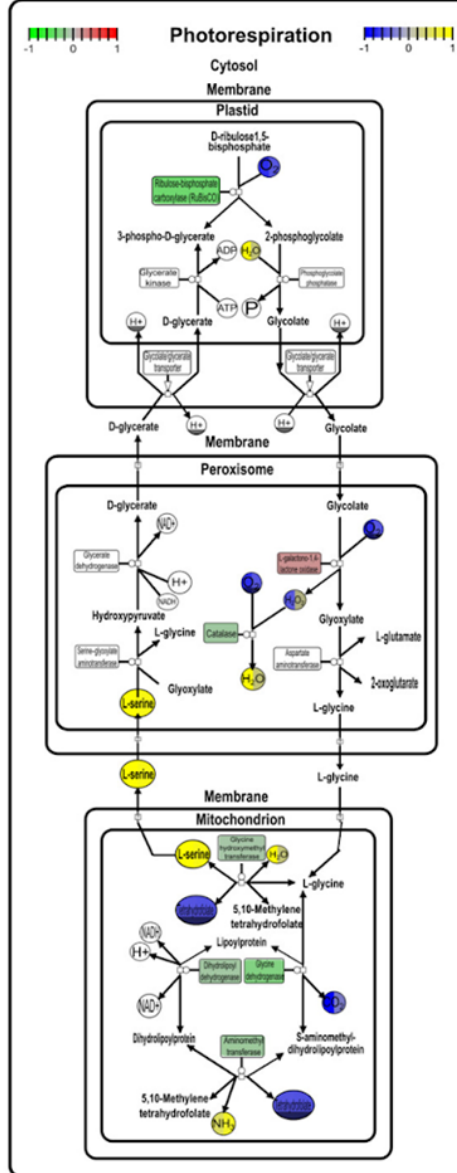


BRIC, Dark



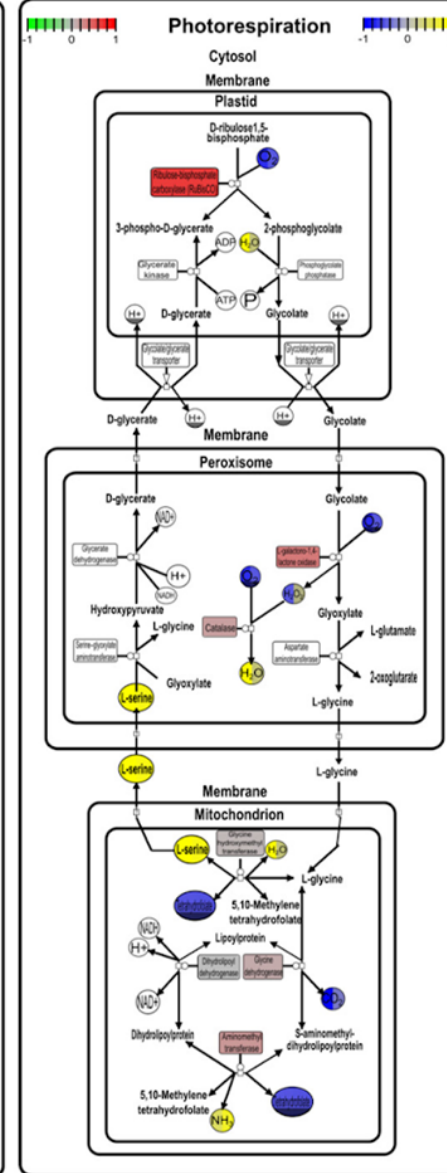
(OSD-37, -38, -321)

BRIC LED, Light: Dark, 16Hrs: 8Hrs



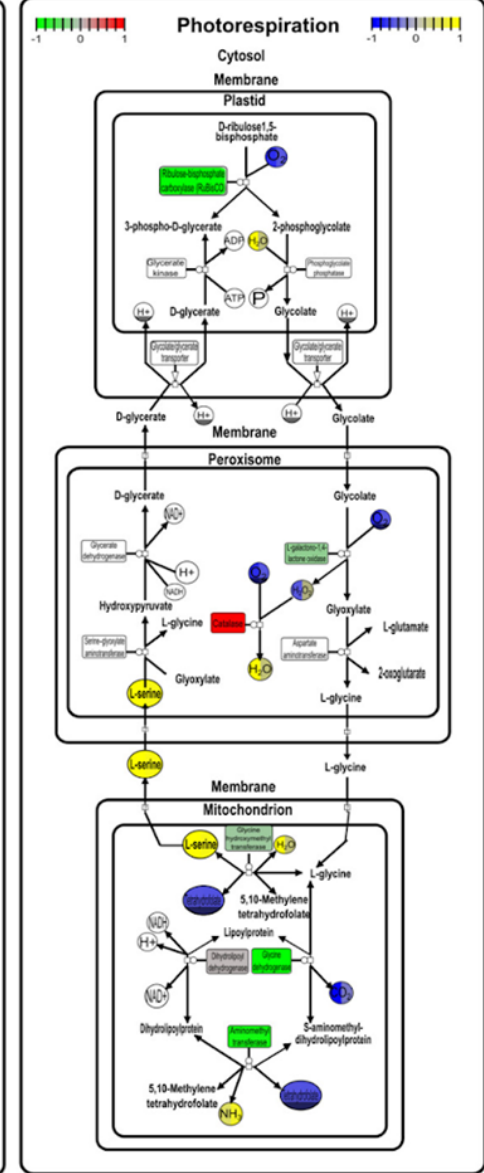
(OSD-552)

ISS, Dark

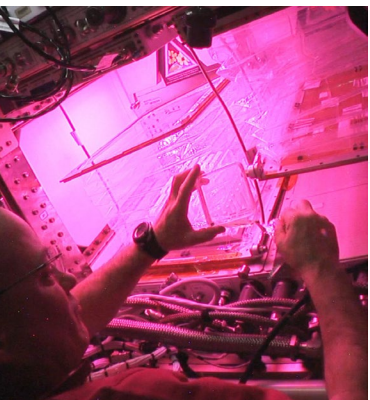


(OSD-120, OSD-678)

ISS, Light

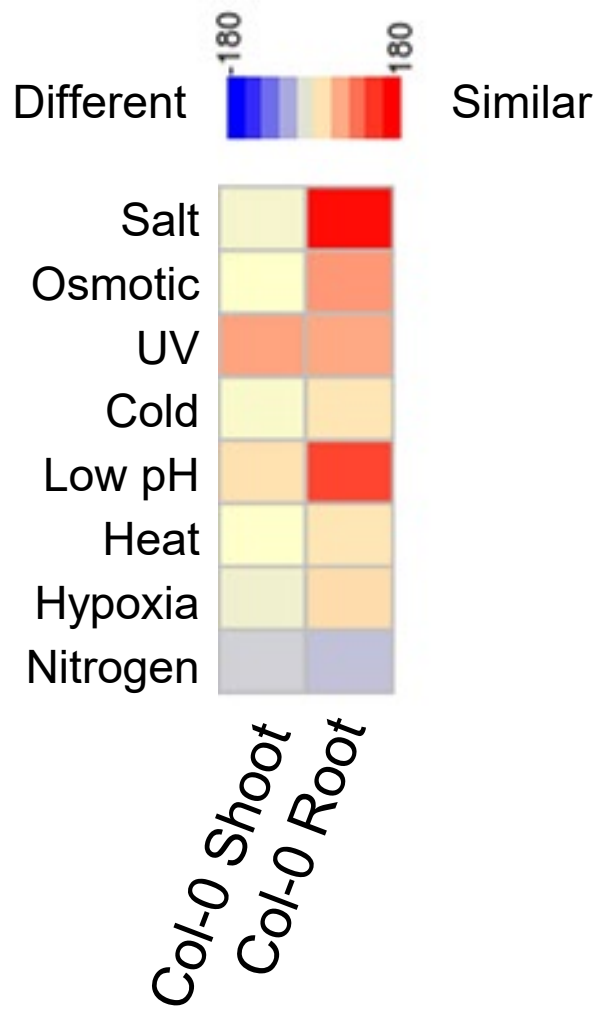
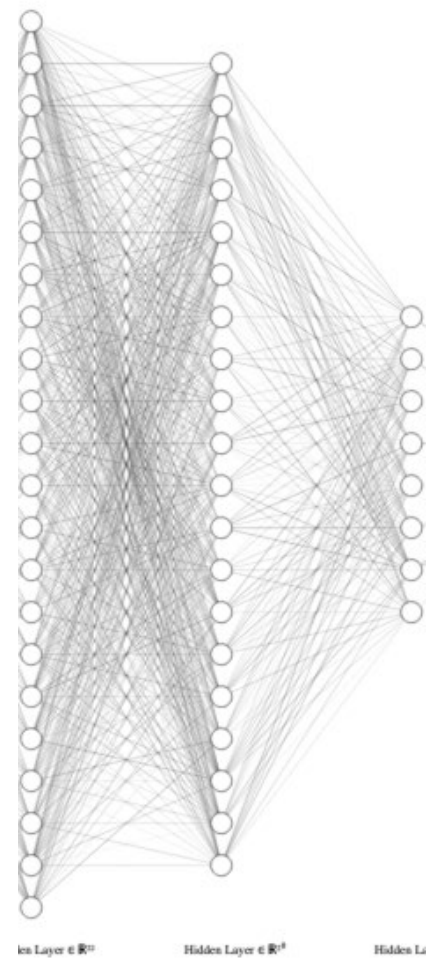
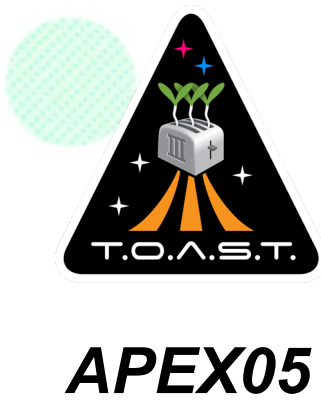


(OSD-120, OSD-678)



Wild type Col-0 Flight vs Ground control

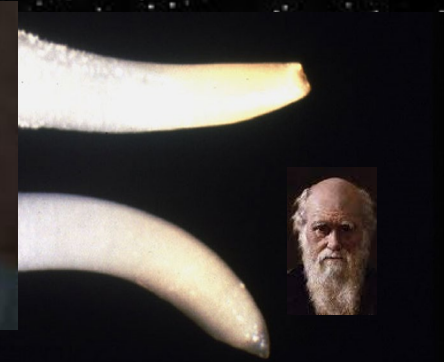
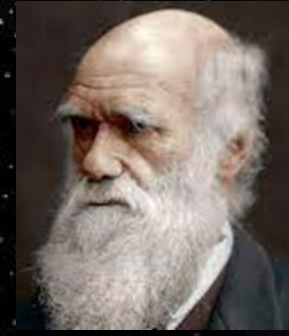
Plants
In physiospace





Newton
1642-1727

Darwin
1809-1882



BioPhysics 101: Direct vs Indirect Effects of Microgravity

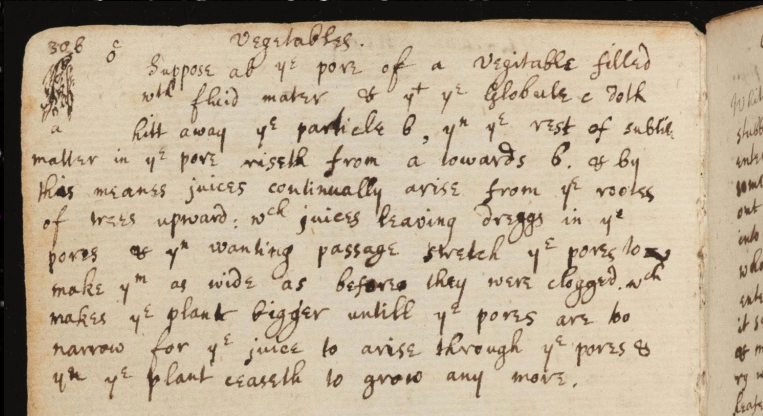
How does gravity effect growth and reproduction?

- **Direct gravity effect – on biological mass**
 - *Gravitropism/sensing, bone/muscle, intercranial pressure*
- **Indirect effect – microenvironmental stress – air and water**
 - *Biophysical fluids and gases*

What aspects of physiology
depend upon gravity
through an indirect
biophysical mechanism?



Newton's lost notebooks



BIOASTRONAUTICS

Next generation transistion from transportation to human habitation.

ENDURANCE AND RESILIANCY: Human health, agriculture, and environmental systems.

CHALLENGE 1. RADIATION (low earth orbit<DEEP SPACE)

CHALLENGE 2. DISTANCE

Human Spaceflight Health Countermeasures

- Food and nutrition
 - Radiation
 - Altered gravity
 - Isolation
- Spacecraft environment
- Human psychology and performance

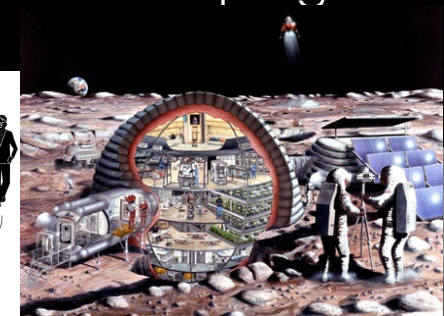
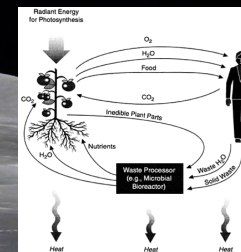


Sustainable Life Support for Exploration & Habitation

- Food and nutrition
- Space habitation agriculture
- Bioregenerative tech for life support
- Plant and crop production in space
- Science and spaceflight hardware
 - Materials science program



**Deep space
biologistics**



"Our planet is a lonely speck in the great enveloping cosmic dark. In our obscurity, in all this vastness, there is no hint that help will come from elsewhere to save us from ourselves."

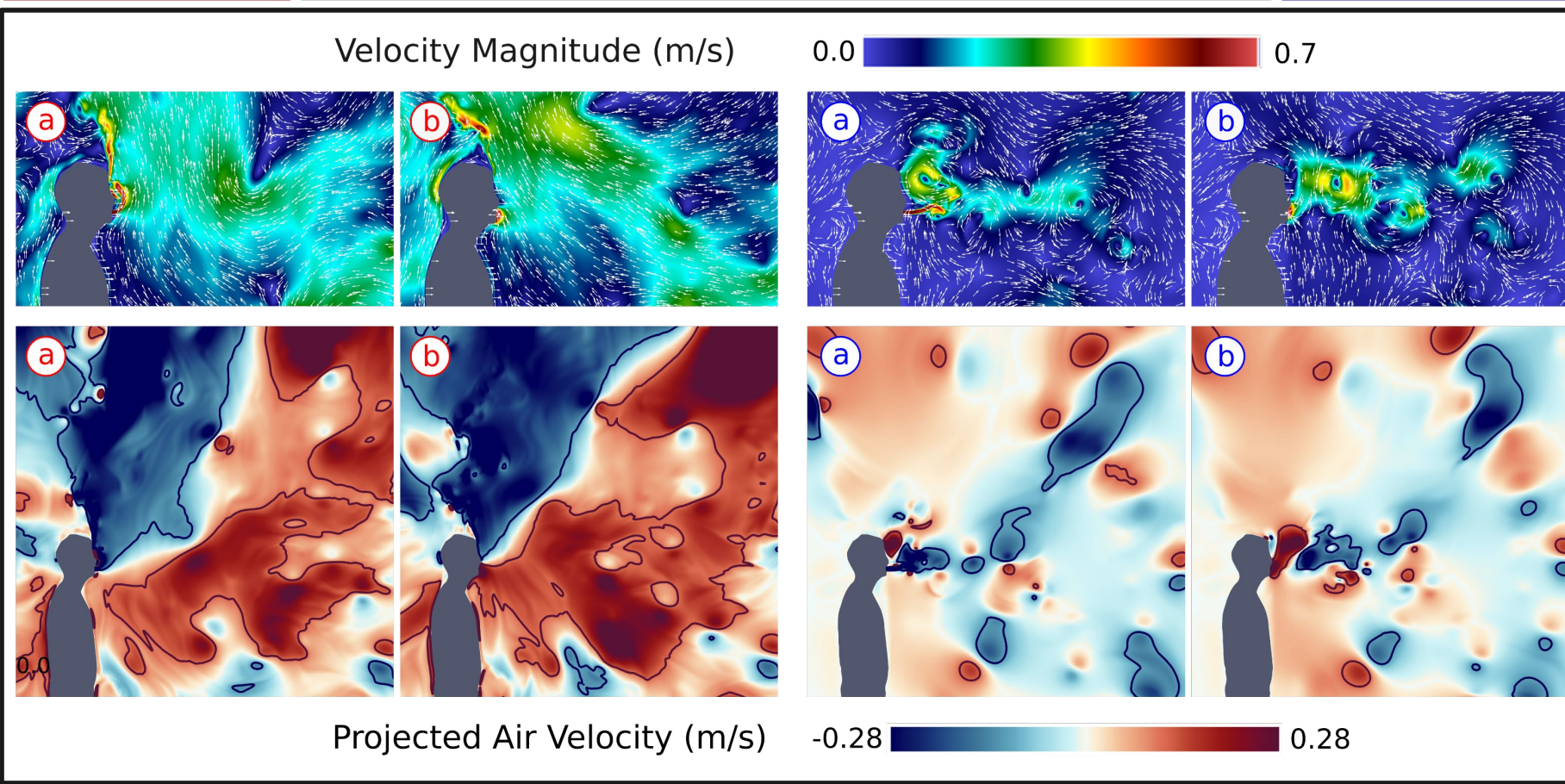
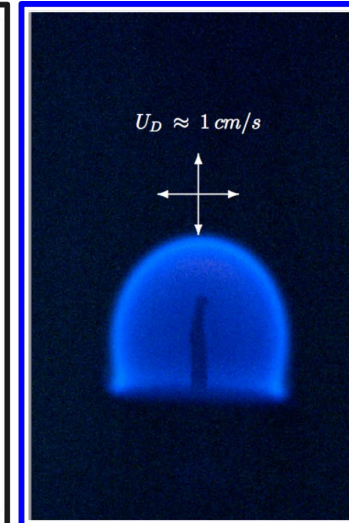
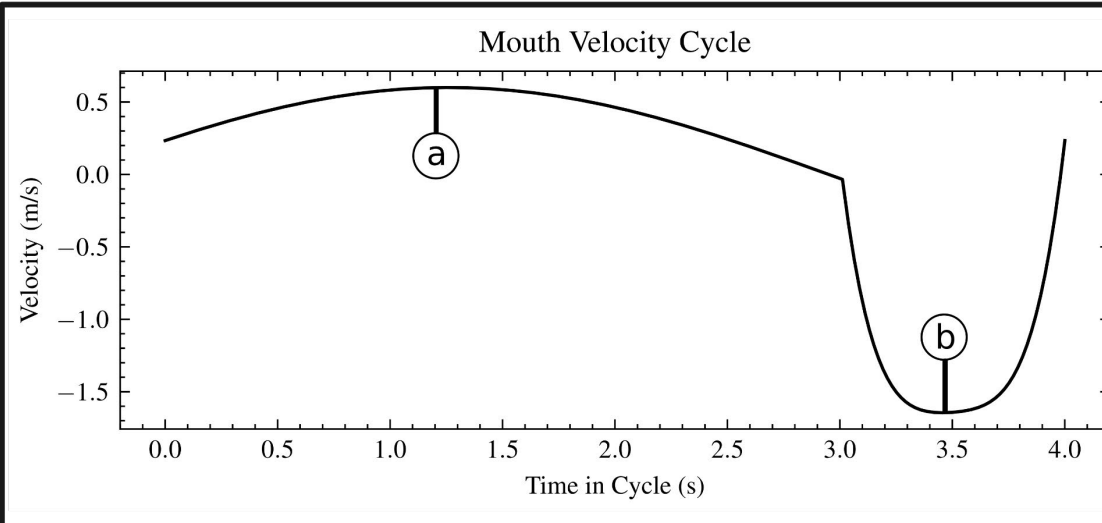


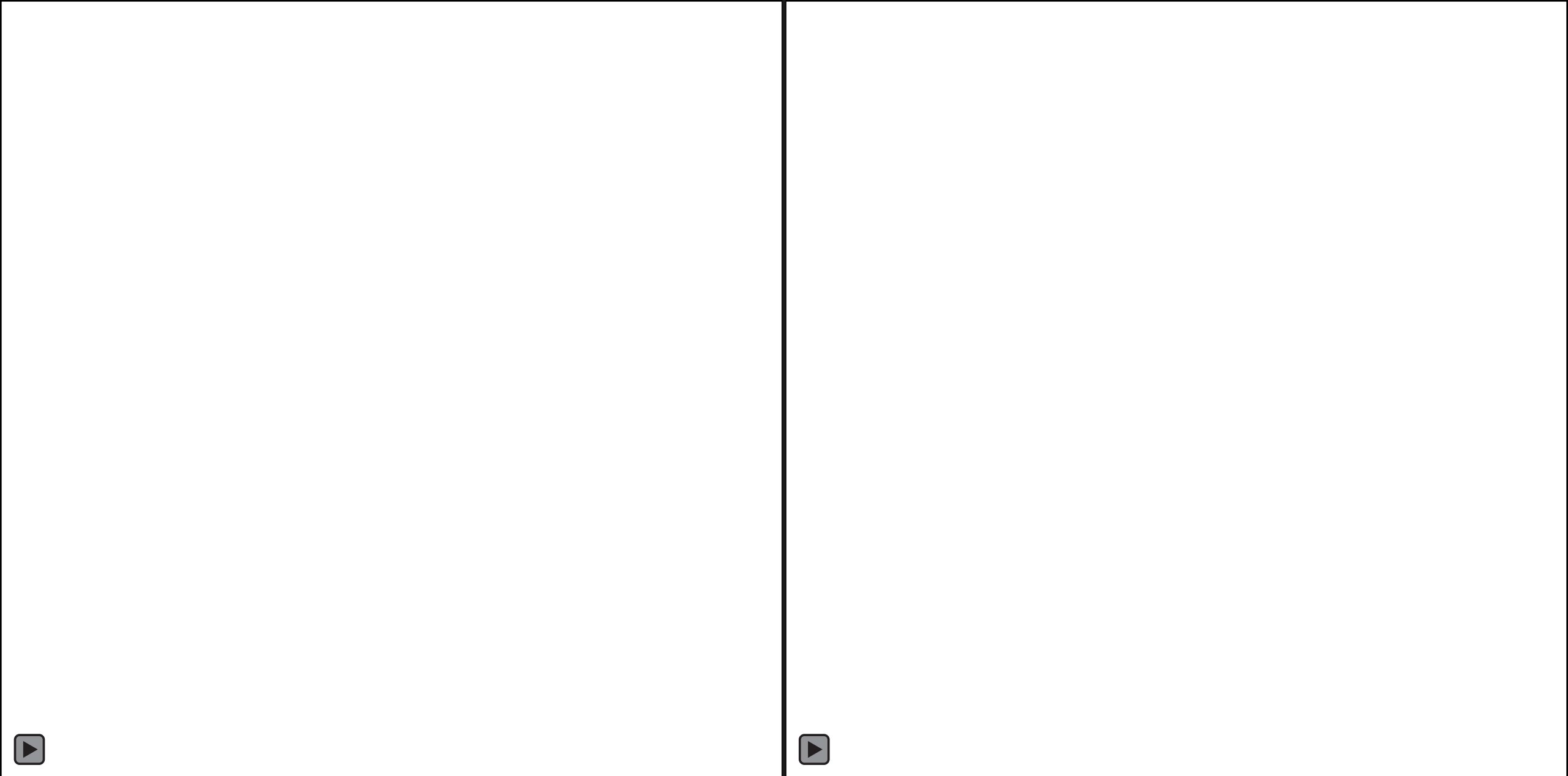
CARL SAGAN

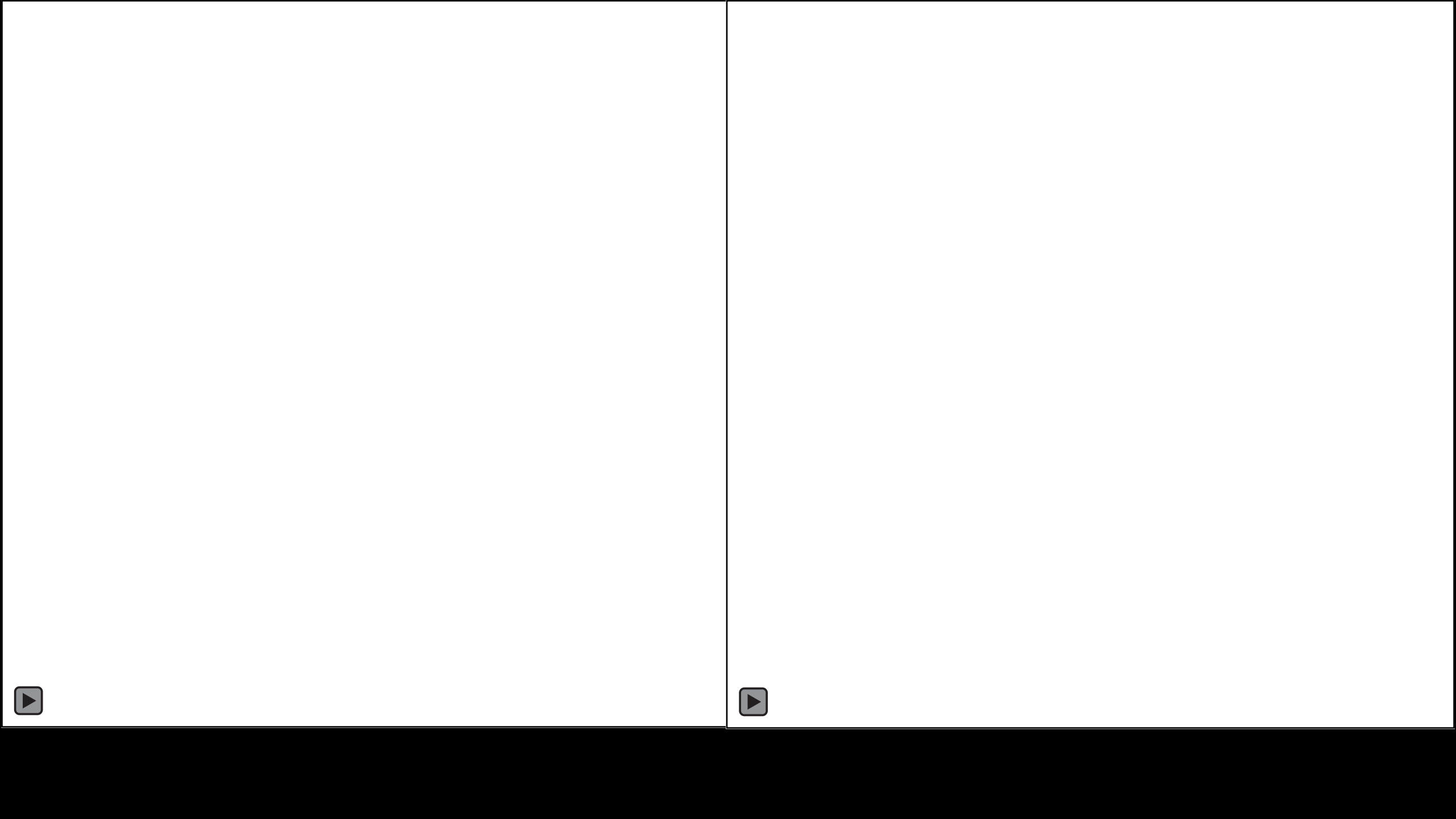
BACKUP

Lessons Learned from NASA CEA Research

- Recirculating hydroponics (NFT) works for a wide range of crops, including rootzone crops. Trees and shrubs?
- Yields for many species essentially limited by lighting; 2-4 X record yields obtained with wheat and potato.
- 1 g dry mass / mol PAR close to upper limit for light conversion
- Some crops can be affected by ethylene as low as 40 ppb
- Approximately 20 m² plants can provide O₂ for one human
- Approximately 50 m² of plants (crops) can provide food for one human







Gravity and Human Respiration: Biophysical Limitations in Physiological Transport and Exchange in Spaceflight

Dutta¹, S., Kadomtsev¹, A., Parik¹, A., Chen¹, Y.C., D'Agostino^{2,3}, DP., Schwertz, H.^{5,6,7}, Tabetah⁴, M., Tulodziecki⁸, D., and D.M. Porterfield^{4,9}

¹Department of Mechanical and Aerospace Engineering, Utah State University, Logan, UT,

²Department of Molecular Pharmacology and Physiology, University of South Florida, Tampa, FL, United States.

³Human Healthspan, Resilience, and Performance, Institute for Human and Machine Cognition, Pensacola, FL, United States.

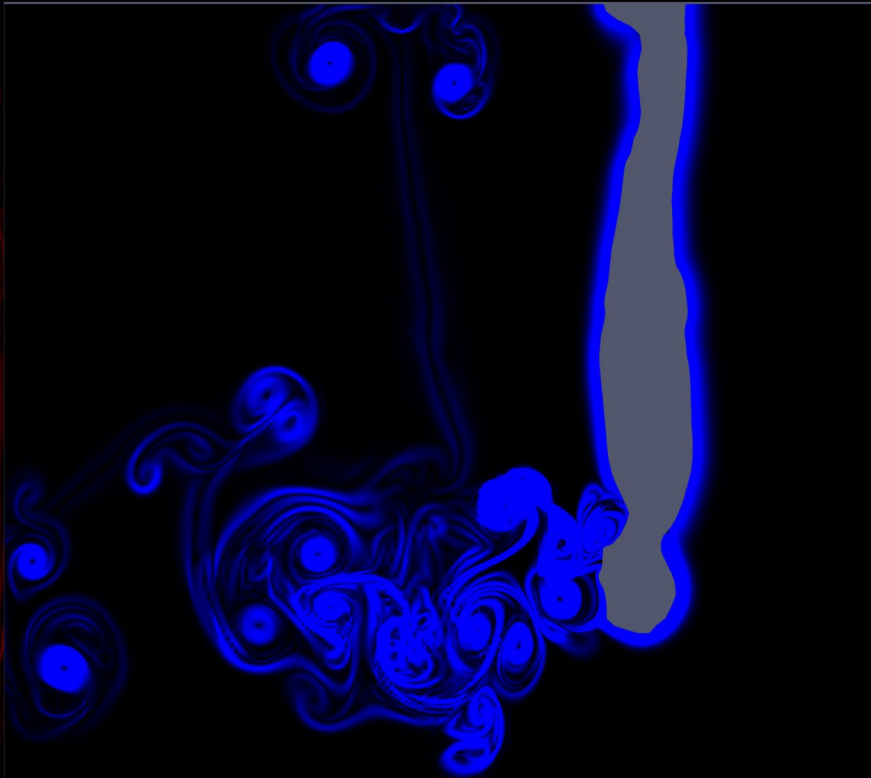
⁴Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907

⁵Molecular Medicine Program, Division of Occupational Medicine⁶, The University of Utah, Salt Lake City, UT 84112

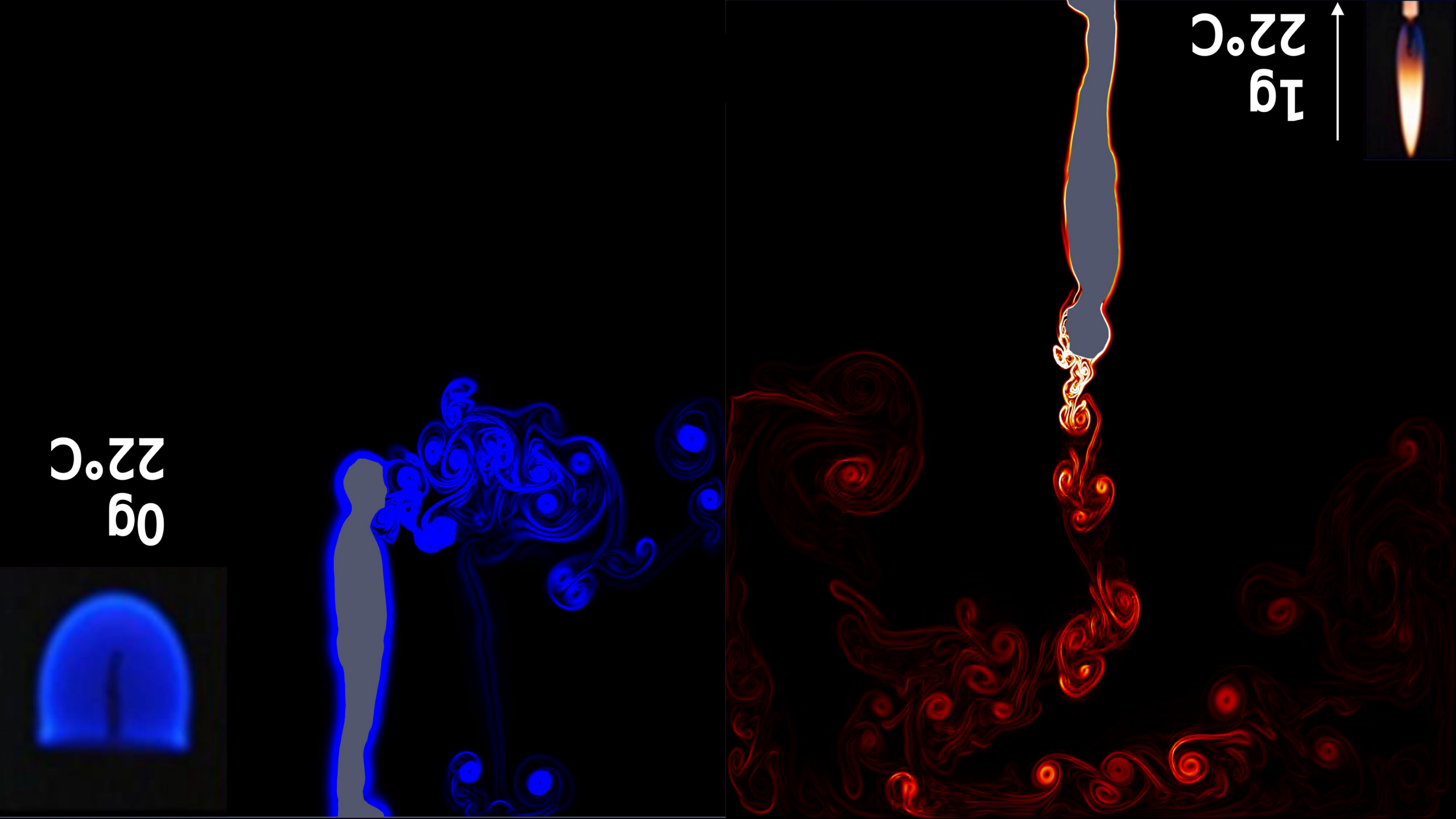
⁷Department of Occupational Medicine, Billings Clinic Bozeman, Bozeman, MT 59718

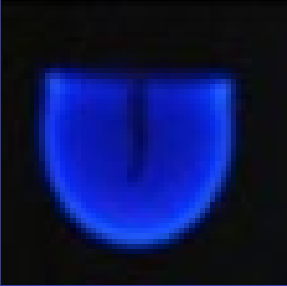
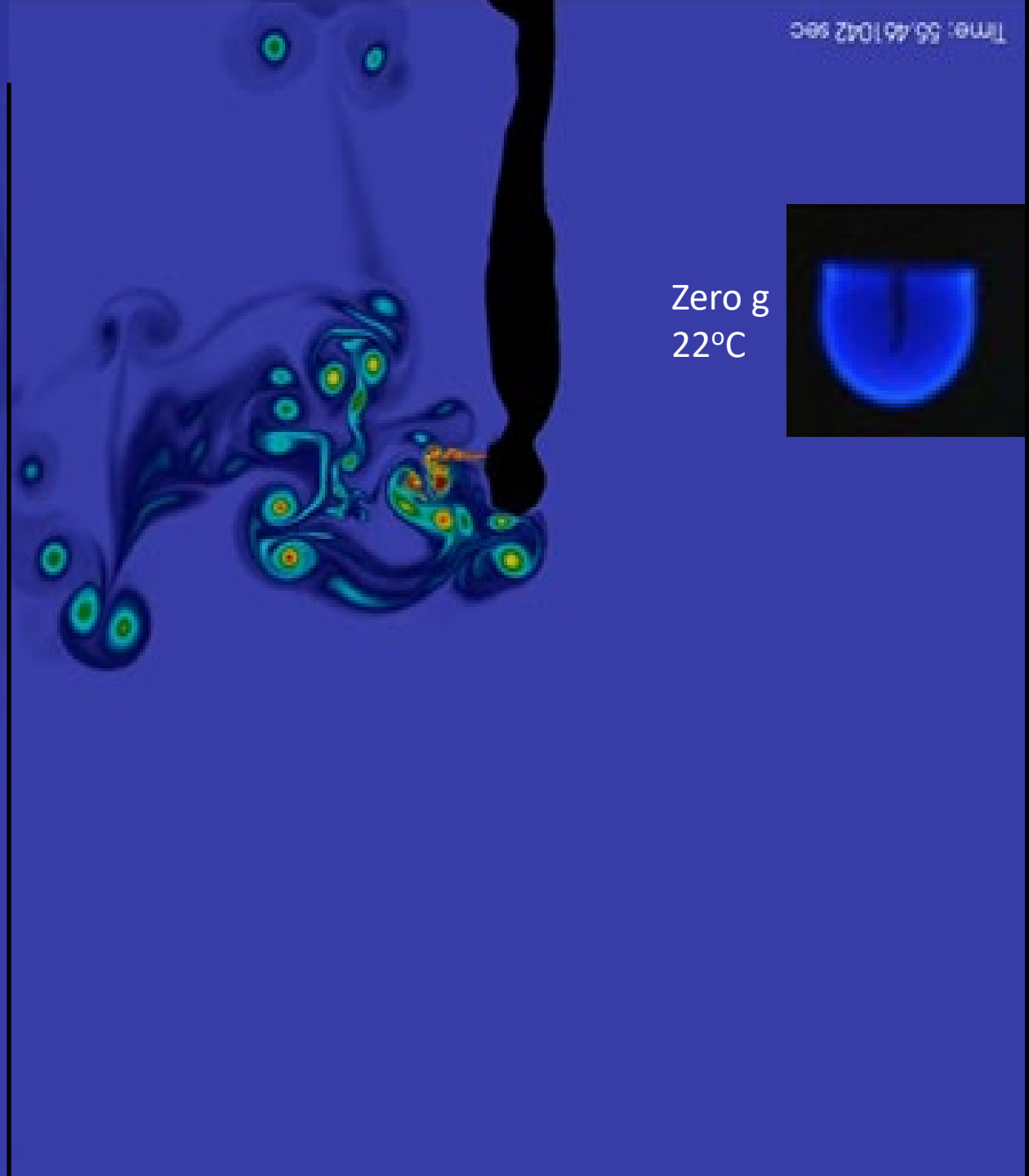
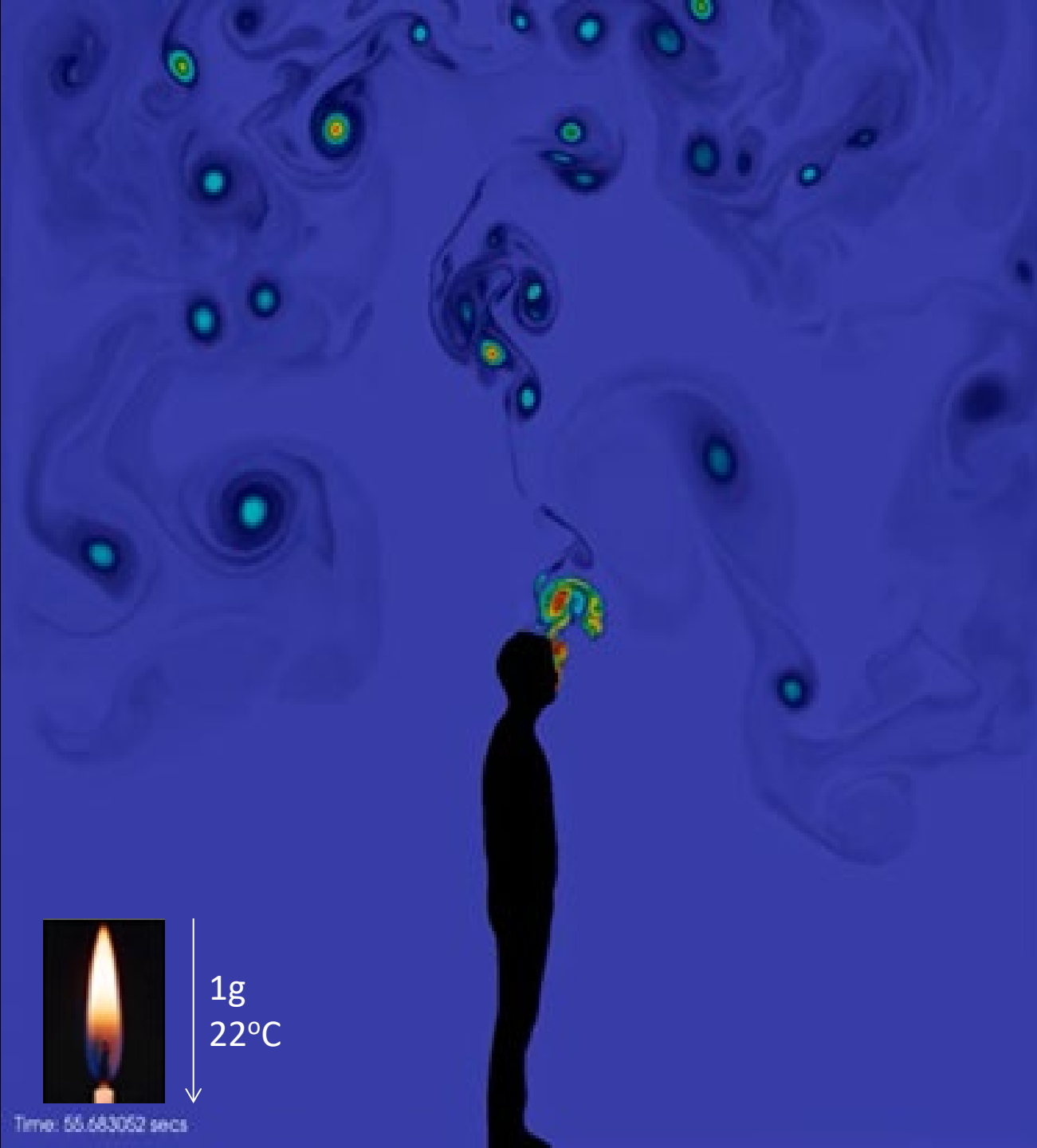
⁸Department of Philosophy, Purdue University, West Lafayette, IN 47907





0g
22°C







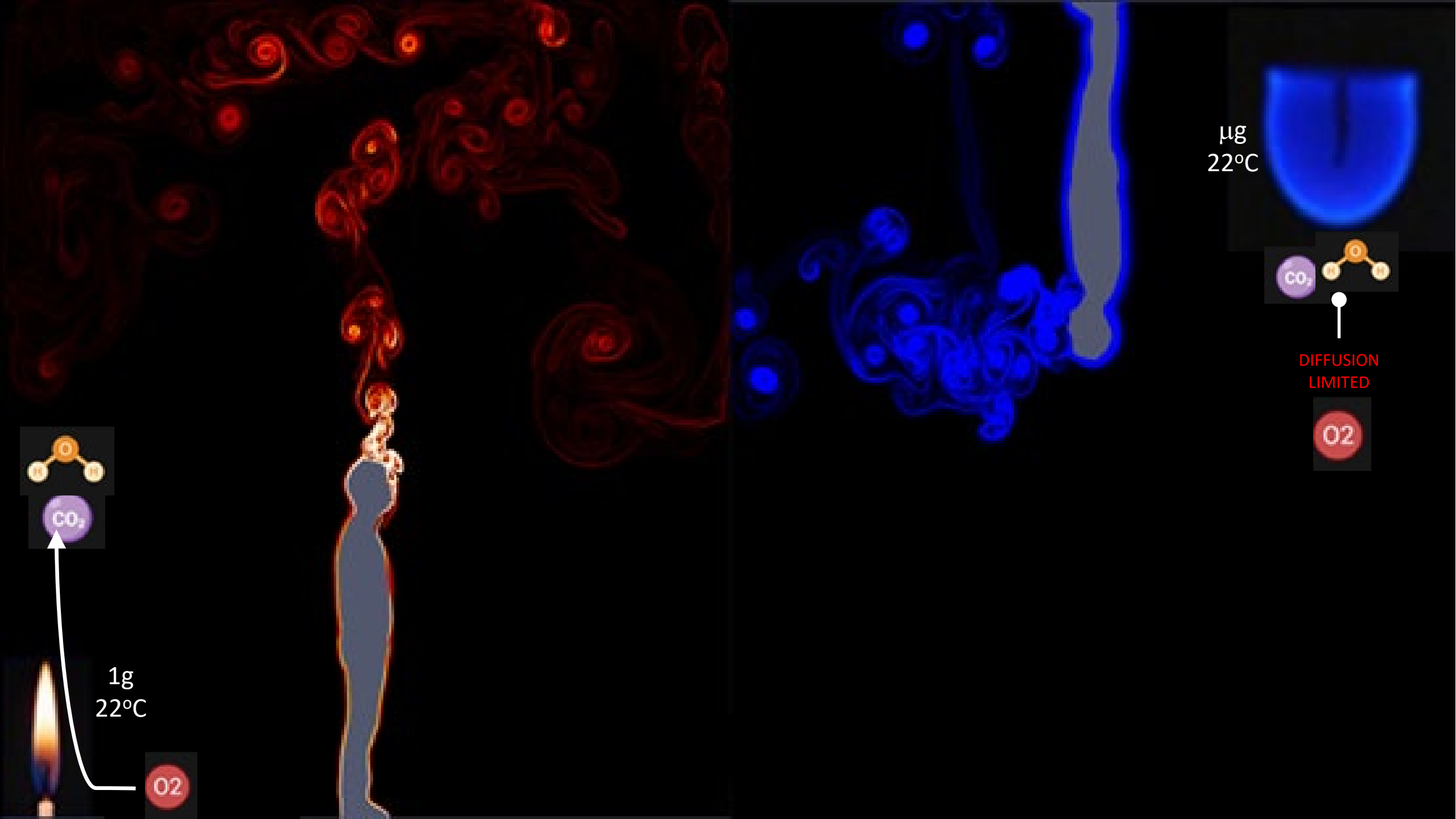
Zero g
22°C

Time: 55.461042 sec

22°C
1g



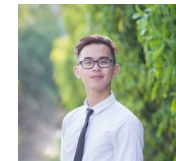
Time: 55.663052 sec



Mitochondria Dysregulation Across All Species During Space Flight: Ongoing work



Zeynab Maghsoudi



Hung Nguyen



Tin C Nguyen



University of Nevada, Reno



Army, Navy, Air Force, and the foundations of BioAstronautics



- Royal Navy. Captain James Cooke. Endeavor Voyage (1768-1771)
 - Countermeasures for scurvy: Sanitation/ventilation in crew's quarters. Nutritional countermeasures: diet that included cress, sauerkraut, and a kind of orange extract.
 - Shelf life of Vitamin C in the ISS is months not years.



- US NAVY. 1958, submarine development, working on different cabin-ecology designs. Biologist Jack Myers, University of Texas, “the use of plants to regenerate air in a closed ecological system, such as that of a space cabin.”
- This research was used by submarine engineers to improve the “space flight under sea.” The use of “ecological systems for underwater vehicles” later became the norm in spaceship engineering.



- US Army. 1959, Project Horizon. Study for a scientific/military base on the Moon produced by Army Ballistic Missile Agency (ABMA later become NASA Marshall Space Flight Center). Included farming and controlled ecological life support.



- US Air Force. May 1961, The Lumex Project. Just as Kennedy had decided that NASA should put an American on the moon, the US Air Force released a secret report, summarizing the result of years of planning to place a military base on the moon by 1967.

1959 study for a scientific/military base on the Moon produced by Army Ballistic Missile Agency (ABMA later become NASA Marshall Space Flight Center).

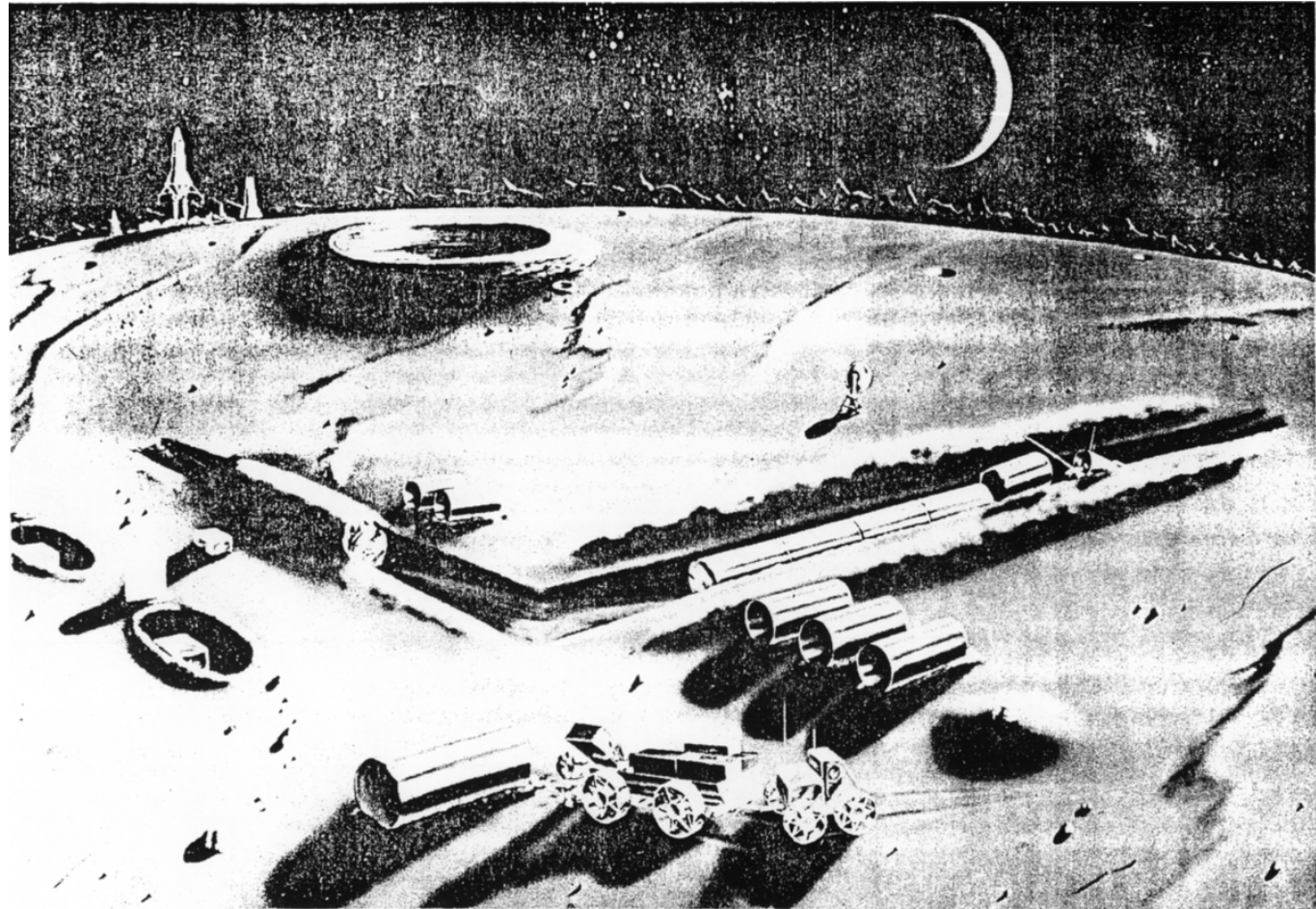
Dr. Wernher von Braun appointed Heinz-Hermann Koelle to head the project, "all Technical Services of the Army participated in the investigation."

The report begins by emphasizing what the Pentagon saw as the immediate and overwhelming need to beat the Soviets to the Moon: "The political implications of our failure to be first in space are a matter of public record... From the viewpoint of national security, the primary implications of the feasibility of establishing a lunar outpost is the importance of being first."

Includes plans for "space farming" and "closed ecological life support."

US Army Quartermaster Hydroponics Farming for USAAC (USAF). Wake Island, Pacific Theater

Project Horizon



USAF-Bioastronautics and Aerospace Medicine

June 14, 1949, The first mammal in space was Albert II, a rhesus monkey.

1951. Physics and Medicine of the Upper Atmosphere. USAF School of Aviation Medicine, Randolph Air Force Base

October 4, 1957 – Sputnik Event!

November 3, 1957 - Liaka

1958: Physics and Medicine of the Upper Atmosphere and Space. USAF, Aviation Medicine, Randolph Air Force Base

May 28, 1959, Able & Baker

April 12, 1961 – THE FIRST MAN! Yuri Gagarin

May 5, 1961 – First American, Alan Sheppard (Apollo 14)

1964: “3rd” International Symposium on Bioastronautics and the Exploration of Space. Medical Division of the USAF Systems Command, Brooks Air Force Base, Texas.

Controlled Ecological Life Support

1968: Forth International Symposium on Bioastronautics and the Exploration of Space. Aerospace Medical Division (AFSC), Brooks Air Force Base, Texas

1st BLiSS Habitat

July 16, - July 24, 1969 – Apollo 11 Armstrong goes for a walk!

April 19, 1971, the Soviet Union first space station, Salyut.

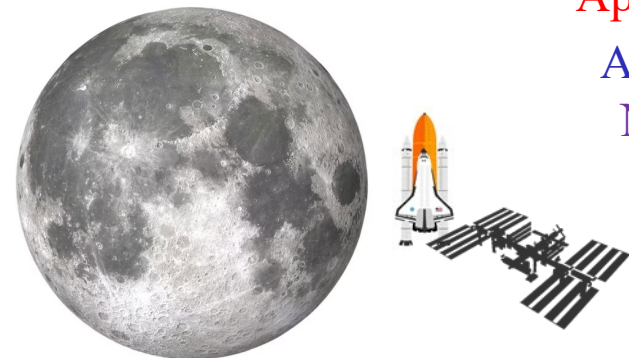
April 12, – April 14, 1981. STS-1 first orbital spaceflight.

November 2, 2000. ISS First Crew to Reside on Station

October 15, 2003, First Chinese Man, Yang Liwei

May 10, 2017. Beijing Lunar Palace 1

April 29, 2021 TianGon Station



April 6, 2016. 1st Mouse embryology
January 3, 2019. 1st plant growth on the moon

Lunar Palace 1: China's One-Year Mock Moon Mission in Pictures

By Space.com Staff published May 17, 2018



Taking the Oath



Xinhua/Ju Huanzong/Getty

In May 2018, China wrapped up a yearlong mission inside "Lunar Palace 1," a Beijing facility designed to help the nation prepare to put boots on the moon. See images of the experiment here. ([Read our full story here.](#)) Here: Four volunteers take the oath in front of Lunar Palace 1, a facility for conducting bioregenerative life-support systems experiments key to setting up a lunar base, at the Beijing University for Aeronautics and Astronautics (BUAA) on May 10, 2017. A ceremony was held in the BUAA that day as eight volunteers in two groups started a 365-day experiment in Lunar Palace 1.

Setting Records



Xinhua/Luo Xiangguang/Getty

Volunteers work in the cabin at Beihang University in Beijing on Jan. 26, 2018. Two male and two female students from Beihang University, the second group of volunteers staying in Lunar Palace 1, completed the second phase of its 365-day on-ground experiment that day, setting a world record for the longest stay in a self-contained "cabin." The first group of volunteers, who had previously stayed in the cabin for 60 days, re-entered the cabin to replace the second group, starting the third and final phase, which lasted 105 days. The experiment was designed to see how the Bioregenerative Life Support System, in which animals, plants and microorganisms co-exist, works in a lunar environment, as well as the physical and mental conditions of humans in such an environment.



China builds Mars simulation in similar desert landscape to prepare for exploration

By Reuters

June 15, 2021 | 11:54am | Updated

MORE ON:

CHINA

Chinese hackers infiltrated US Ambassador to China's emails: report

Henry Kissinger, 100, meets Xi Jinping amid tense US-China relations

Elite IRS whistleblowers are bravely standing up to the Bidens, DOJ

Democrat asks 'who cares' if Hunter Biden and Gal Luft got money from Chinese firm

China has built a "Mars Camp" in Lenghu Town of northwest China's Qinghai Province to simulate the environmental conditions on Mars, as part of China's Mars exploration preparation.

The town is known as China's "Mars Camp" due to its eerily eroded desert landscape that resembles the surface of the red planet. The red rock area of the Qaidam basin in western Qinghai has been dubbed "the most Martian place on Earth" as experts claimed that the landscape, rocks, sand, and even the temperatures are similar to those on the Red Planet.

The simulation camp was launched in the town in 2019 with a base designed as a place for space enthusiasts and professionals to get a better understanding of Mars with immersive experiences in the simulation environment. Covering 1,734 acres, the "Mars Camp" consists of a tourism center, a Mars community, a simulation base and other

facilities.

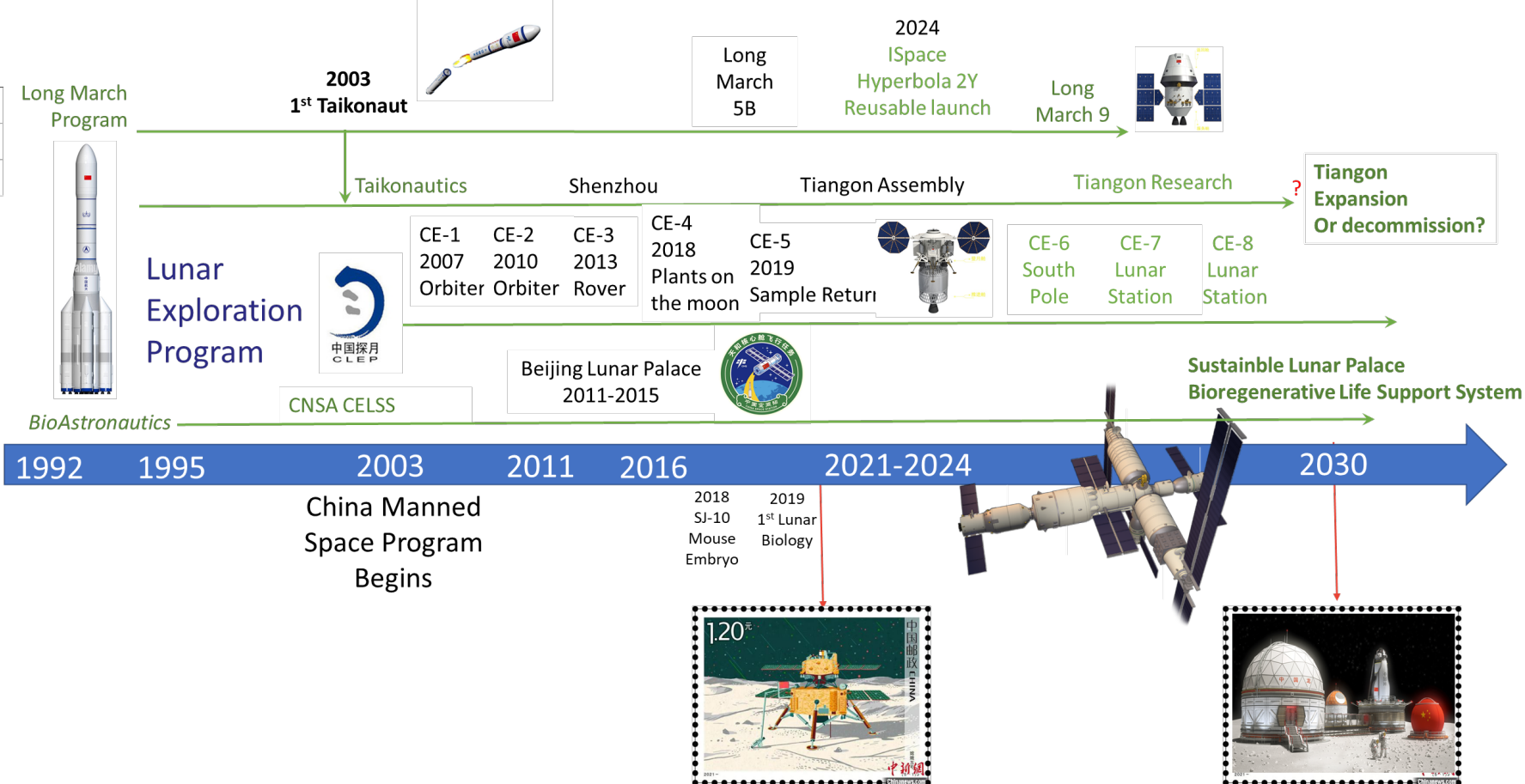
Relying on characteristic resources, the local authorities are developing the service industry and moving towards a new pattern of integrating scientific research, popularization of science, scientific education and cultural tourism.

<https://youtu.be/6WGRtKXRQzk>



Covering 1,734 acres, the "Mars Camp" consists of a tourism center, a Mars community, a simulation base and other facilities.

Country
China, Russia
China



International Lunar Space Research Station	2021	2030
Tiangong	2021	2037
Long March 9	2018	2030
ISpace Hyperbola 2Y Reusable Launch	2016	2030
China Manned Space Program (Project 921)	1992	2030
Long March Program	1970	2030
Taikonautics	2003	2030
BLISS	2003	2030
China's 1st Crewed Lunar Mission	2029	2029
Chang'e 8 Lunar Station	2028	2028
Chang'e 7 Lunar Exploration	2026	2026
Chang'e 6 South Pole	2024	2024
Chang'e 5	2019	2019
Chang'e 4	2019	2019
Long March 5B	2007	2019
Chang'e 3	2018	2018
Yuegong-1	2017	2017
Shi Jian 10	2016	2016
Chang'e 2	2013	2013
Chang'e 1	2010	2010
Chinese Lunar Exploration Program (Chang'e)	2007	2007
Shenzhou	2003	2024
Tiangong	2003	2037



Country	
USA, Russia, ESA, JAXA, CSA	
USA	
USA cut 2004	

LUNAR Exploration program



Space Launch System Orion



Heavy Launch System Starship

ART-1 2022
Orbiter

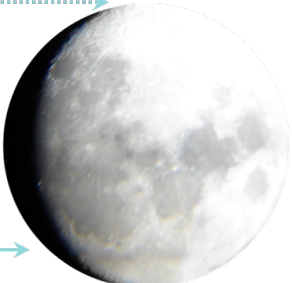
ART-2 2025
Crewed
Orbiter

ART-3 2026
Crewed Lander

Lunar Gateway

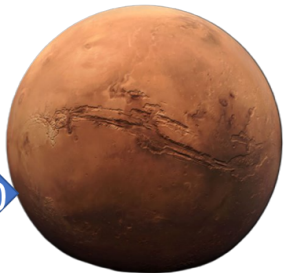
ART-4 2028
Crewed Lander

ART-5 2029
Crewed Lander



ISS
Expansion
Or decommission?

CLD Program



NASA

July 21, 1969



STS



ISS Construction

ISS Operations

ISS National Lab /Center Advance Science In Space?

NASA SLPS/BPS-Human Research Program

NASA BioPLEX

NASA Code U/OBPR

NASA CHAPEA

BioAstronautics

NASA CELSS

1990

2004

2011

2020

2026

2030

NASEM Decadal
2011

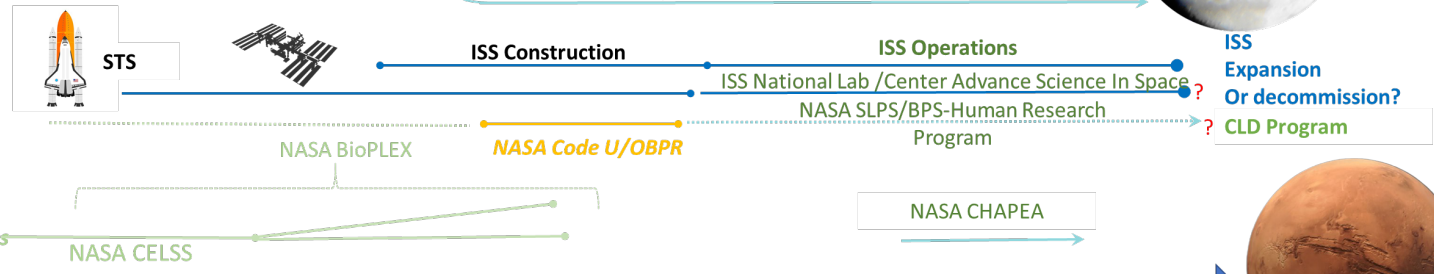
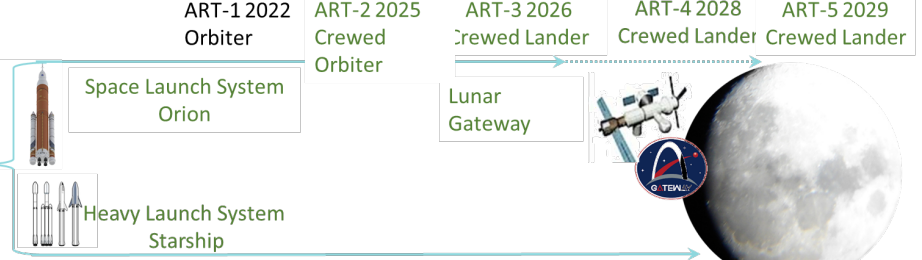
NASEM Decadal
2023

Program	Start year	1990	1995	2000	2005	2010	2015	2020	2025	2030	2035	End Year
ISS - Life extension before decommissioning	2011											2031
ISS - In constant habitation	2000											2015
ISS - Construction	1998											2000
Commercial LEO Destinations	2021											2030
Biological and Physical Sciences	2019											2030
ISS National Lab	2011											2030
Human Research Program	1992											2030
Artemis Program	2021											2029
Artemis 5	2029											2029
Artemis 4	2028											2028
Artemis 3	2026											2026
Gateway	2019											2027
Artemis 2	2025											2025
Artemis 1	2022											2022
Chapea	2023											2026
SLS (Constellation) Orion	2005											2022
Space Life and Physical Sciences	2011											2019
NASEM NRC Decadal	2010											2019
STS	1981											2011
NASA Code U/OBPR	2001											2004
BIOPLex	1998											2004
Office of Life and Microgravity Sciences and Applications (OLMSA)	1993											2004
Controlled Ecological Life Support System (CELSS)	1984											2004





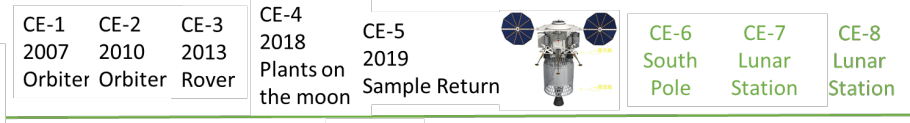
LUNAR Exploration program



1990 2004 2011 2020 2026 2030

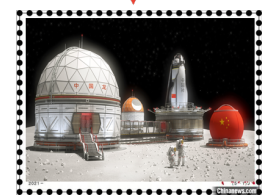


Lunar Exploration Program



1992 1995 2003 2011 2016 2021 - 2024 2030

China Manned Space Program Begins



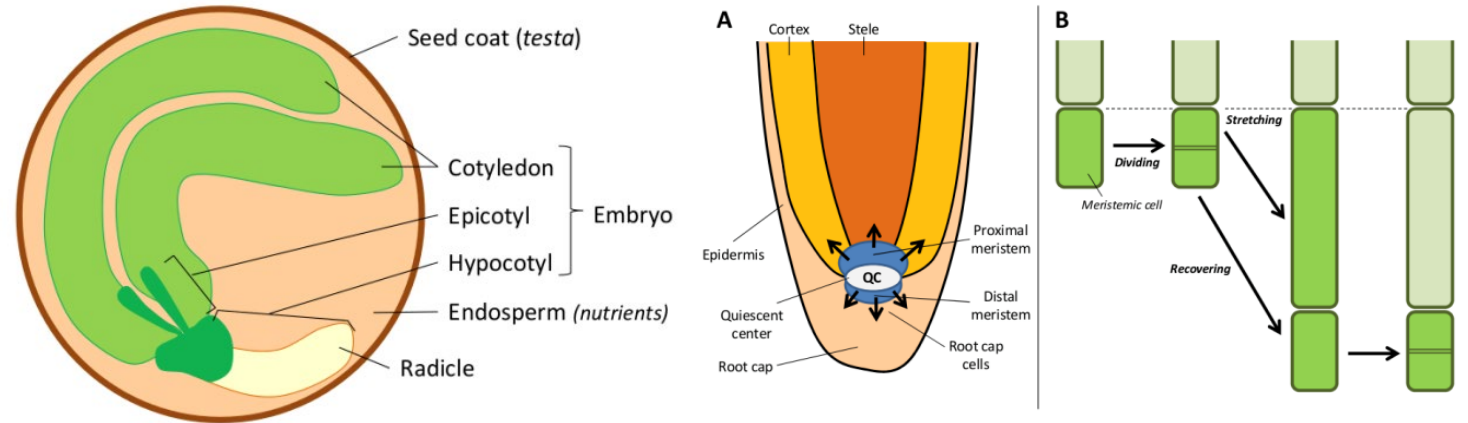


Country
USA, Russia, ESA, JAXA, CSA
USA
China, Russia
China

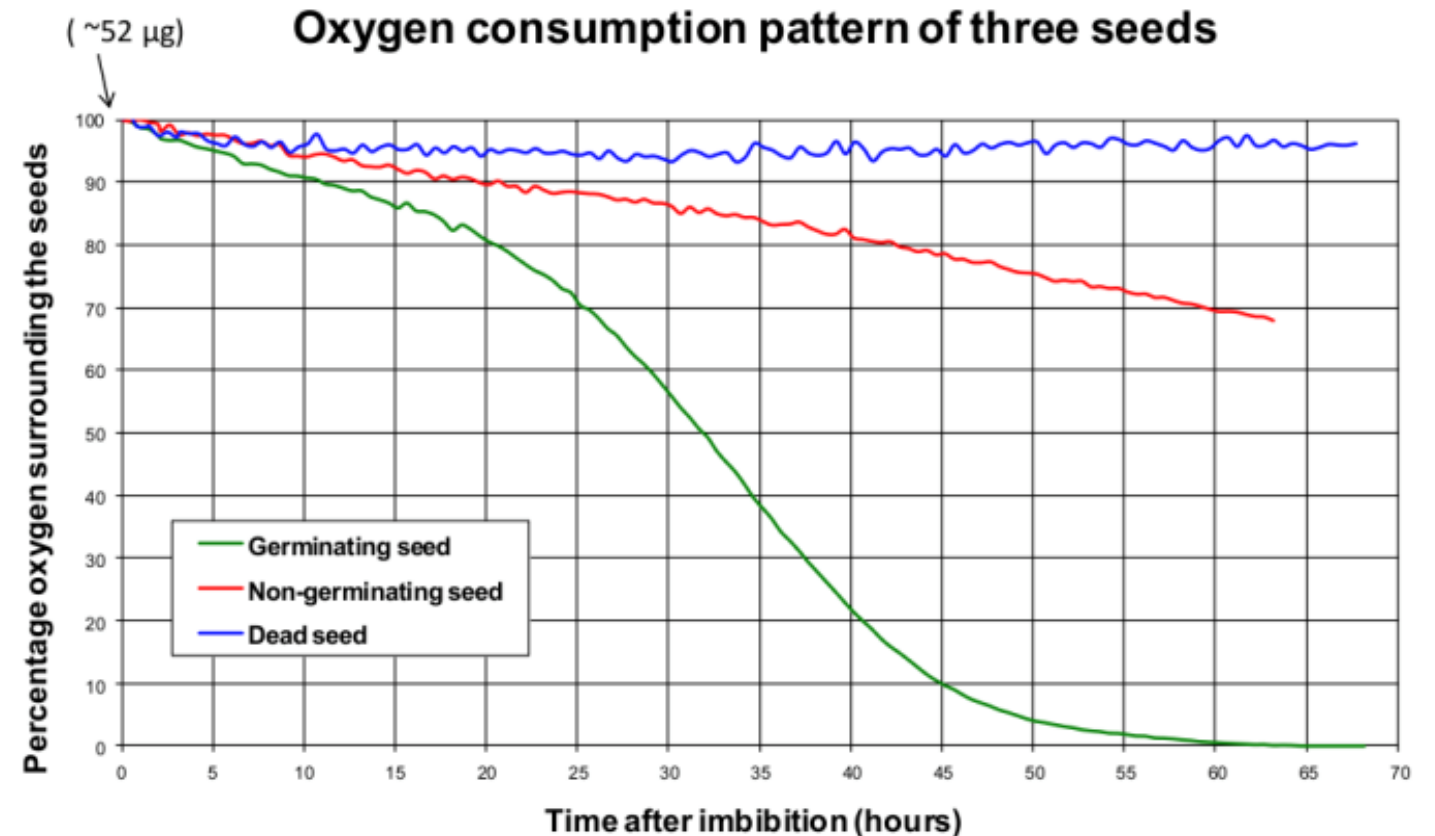


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BIOplex	1998											2004
Office of Life and Microgravity Sciences and Applications (OLMSA)	1993											2004
Controlled Ecological Life Support System (CELSS)	1984											2004
International Lunar Space Research Station	2021											2030
Tiangong	2021											2037
Long March 9	2018											2030
ISpace Hyperbola 2Y Reusable Launch	2016											2030
China Manned Space Program (Project 921)	1992											2030
Long March Program	1970											2030
Taikonautics	2003											2030
BLISS	2003											2030
China's 1st Crewed Lunar Mission	2029											2029
Chang'e 8 Lunar Station	2028											2028
Chang'e 7 Lunar Exploration	2026											2026
Chang'e 6 South Pole	2024											2024
Chang'e 4	2019											2019
Chang'e 5	2019											2019
Long March 5B	2007											2019
Chang'e 3	2018											2018
Yuegong-1	2017											2017
Shi Jian 10	2016											2016
Chang'e 2	2013											2013
Chang'e 1	2010											2010
Chinese Lunar Exploration Program (Chang'e)	2007											2007
Shenzhou	2003											2024
Tiangong	2003											2037

Validated and compared using background from:
Measuring and modelling respiration... Budko et al., (2013)

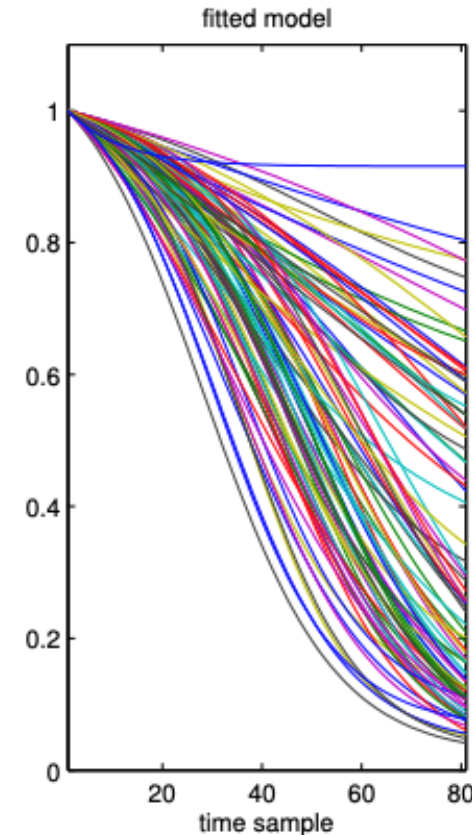
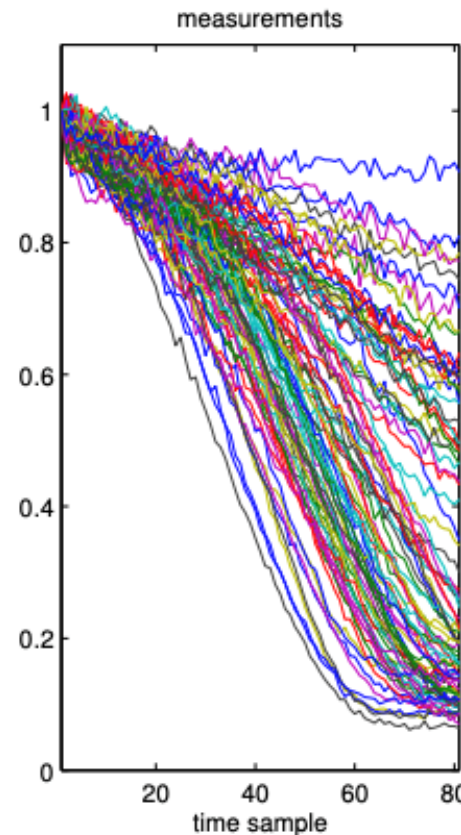
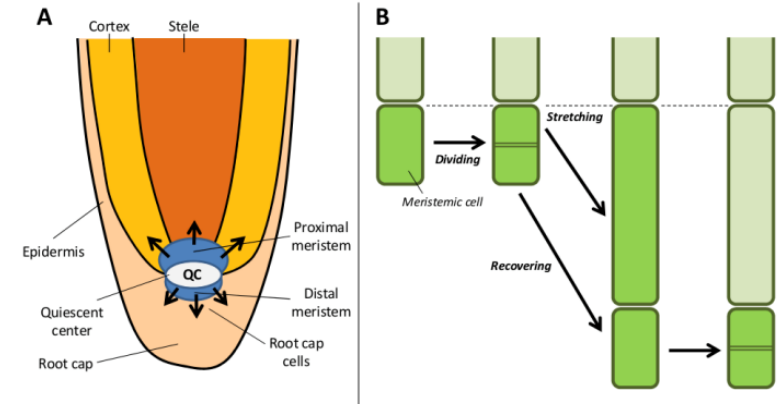
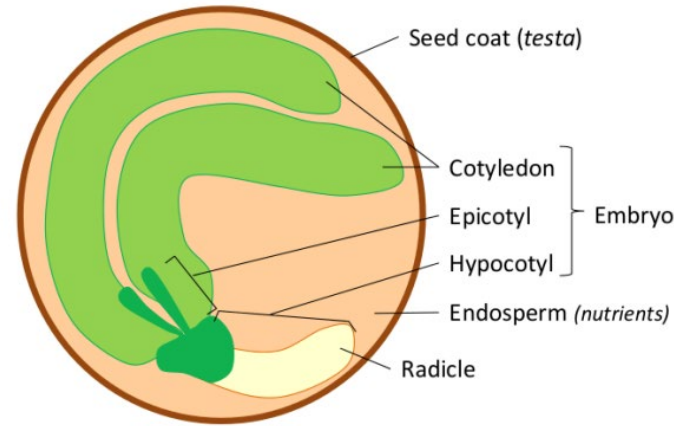


Xin et al. (2013) A real-time, non-invasive, micro-optrode technique for detecting seed viability by using oxygen influx. Real-time monitoring capability with 1-minute resolution, Detection limit: $5 \text{ pmol O}_2 \text{ min}^{-1}$
Enables correlation of OCR with specific developmental events. Early seed germination rates for *Brassica rapa* only, validate/confirm *B. rapa* model using Budko et al.



Measuring and modelling respiration using Budko et al., (2013)

Seed OCR model was integrated into an environmental simulation based on the LEAF payload volume and the performance of the earth normal (EN) and exploration atmospheres (EX). Simulation integrates the physiological seed OCR as physical drivers of the atmosphere. The resulting LEAF Chamber Seed Germination Redox (LCSGR) Model was developed to integrate a gravity dependent diffusion model based on humidity and changes in water bioavailability in microgravity that can be toggled to simulate chamber convection. This suggests that the microgravity diffusion model can be tested in real-time in reduced gravity environments. We call this the “fan test.”



Seed Germination O₂ Consumption Model

Interactive biophysics simulation for closed-environment life support systems

Chamber Parameters

Atmosphere Type
Earth (101.3 kPa, 21% O₂)

Chamber Volume: 20 L

Temperature: 22°C

Duration: 72 hours

Seed Load

Arabidopsis: 50,000

Brassica rapa: 10,000

☒ Mixed Culture (Both Species)

Seed mass ratio ~5:1 (Arab:Brass)

Model Features

Physiological Models:

- Multi-phase OCR (imbibition, activation, growth)
- Temperature-dependent respiration (Q₁₀ model)
- Species-specific allometric scaling
- O₂-limitation feedback on OCR
- Time-varying respiratory quotient (RQ)

Transport Physics:

- Boundary layer O₂ depletion
- Water film diffusion resistance
- Ideal gas law for chamber dynamics
- Mars vs Earth atmospheric pressure

Diffusion Model

☐ Apply Diffusion Limitations

Final Bulk O₂

17.61%

O₂ Depletion

16.1%

Final Seed O₂

17.61%

Final CO₂

3.06%

Diffusion Model

☒ Apply Diffusion Limitations

- Boundary layer: 30% reduction
- Water film: 35-45% reduction
- Effective O₂ at seed: ~45-55% of bulk

⚠ Critical O₂ Threshold Reached
B. rapa germination compromised at t = 0.0 hours (pO₂ < 10%)

Final Bulk O₂

18.72%

O₂ Depletion

10.9%

Final Seed O₂

8.52%

Final CO₂

2.05%

Seed Germination O₂ Consumption Model

Interactive biophysics simulation for closed-environment life support systems

Chamber Parameters

Atmosphere Type

Exploration (56.5 kPa, 16.5% O₂)

Chamber Volume: 20 L

Temperature: 22°C

Duration: 72 hours

Seed Load

Arabidopsis: 50,000

Brassica rapa: 10,000

☒ Mixed Culture (Both Species)

Seed mass ratio ~5:1 (Arab:Brass)

Diffusion Model

☐ Apply Diffusion Limitations

Final Bulk O₂

10.96%

O₂ Depletion

33.6%

Final Seed O₂

10.96%

Final CO₂

4.95%

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- Effective O₂ at seed: ~45-55% of bulk

Critical O₂ Threshold Reached
B. rapa germination compromised at t = 0.0 hours (pO₂ < 10%)

Final Bulk O₂

13.34%

O₂ Depletion

19.1%

Final Seed O₂

5.14%

Final CO₂

2.81%

Model Features

Physiological Models:

- Multi-phase OCR (imbibition, activation, growth)
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Modelling respiration using Budko et al., (2013)

Seed Germination O₂ Consumption Model

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Seed mass ratio ~5:1 (Arab:Brass)

Diffusion Model

☐ Apply Diffusion Limitations

Fan On

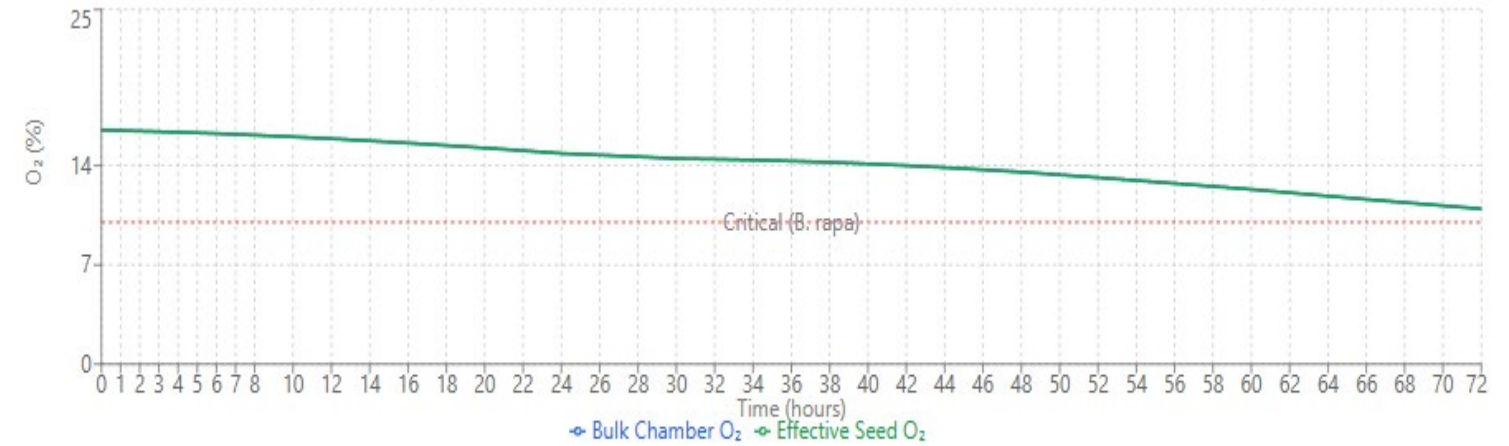
Final Bulk O₂
10.96%

Final Seed O₂
10.96%

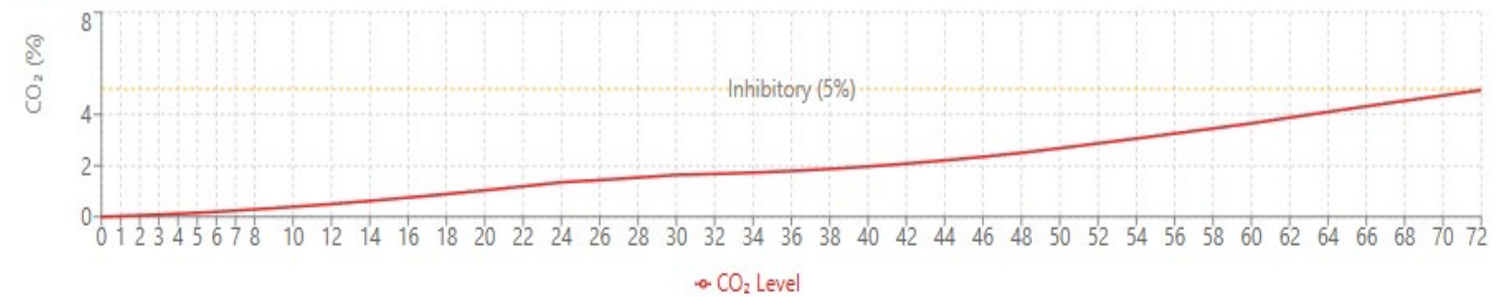
O₂ Depletion
33.6%

Final CO₂
4.95%

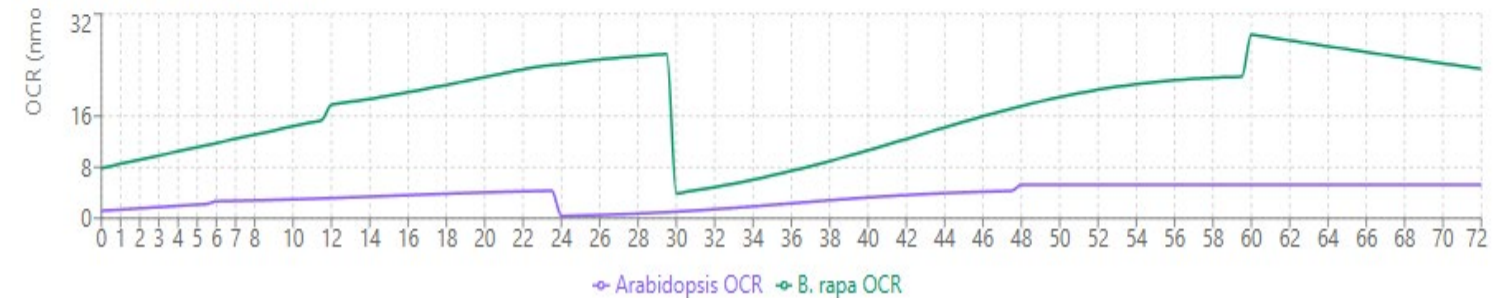
O₂ Partial Pressure Over Time



CO₂ Accumulation



Oxygen Consumption Rate Profile



Modelling respiration using Budko et al., (2013)

Seed Germination O₂ Consumption Model

Interactive biophysics simulation for closed-environment life support systems

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Final Bulk O₂

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Final Seed O₂

8.52%

O₂ Depletion

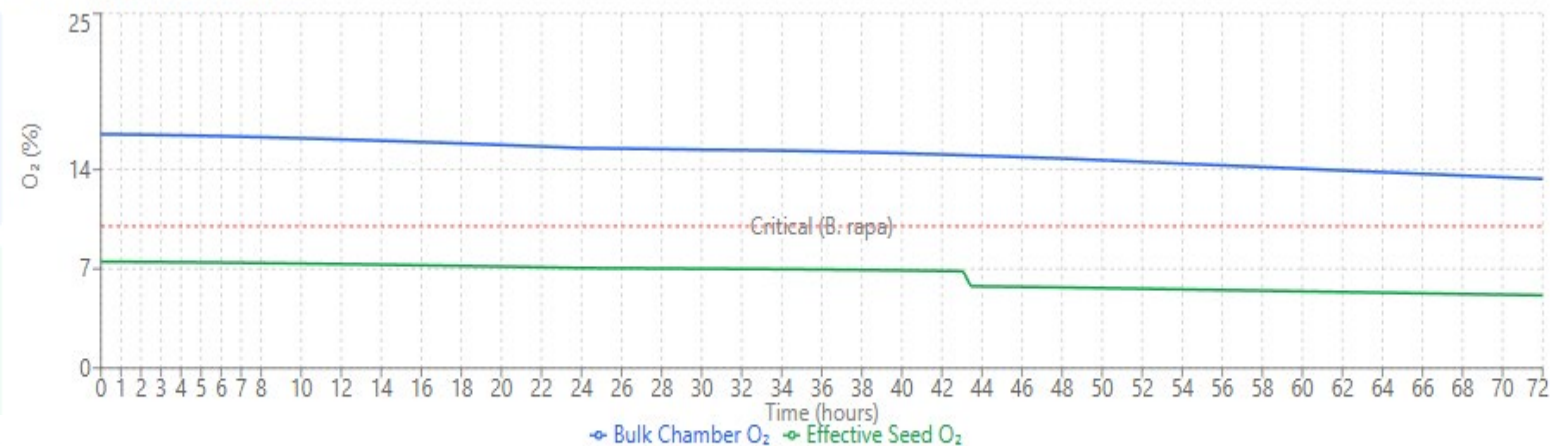
10.9%

Final CO₂

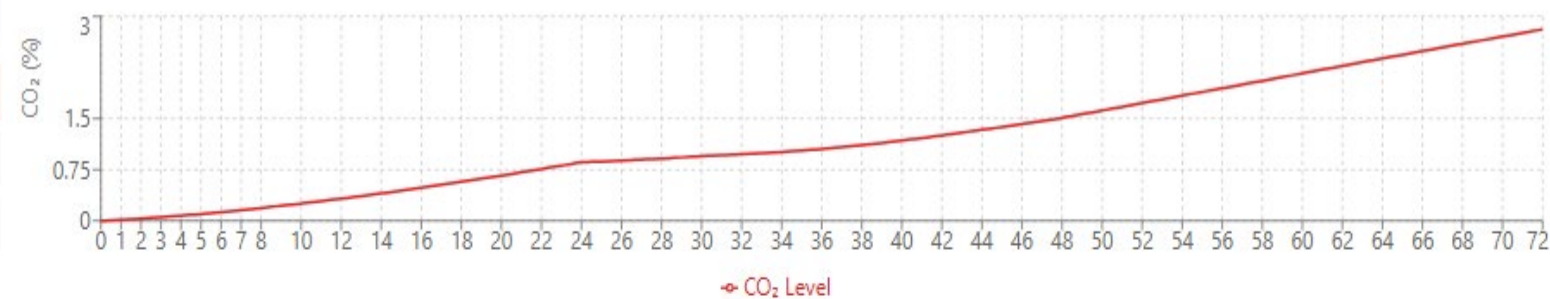
2.05%

Fan Off

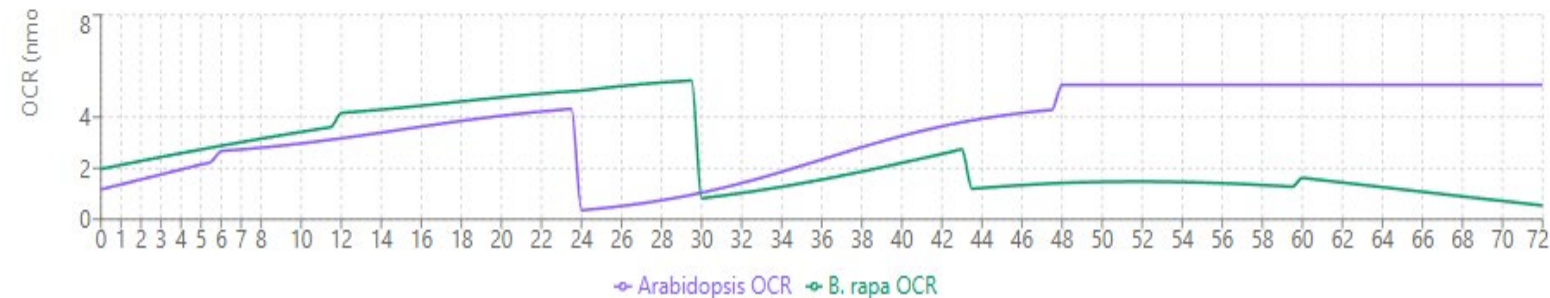
O₂ Partial Pressure Over Time



CO₂ Accumulation

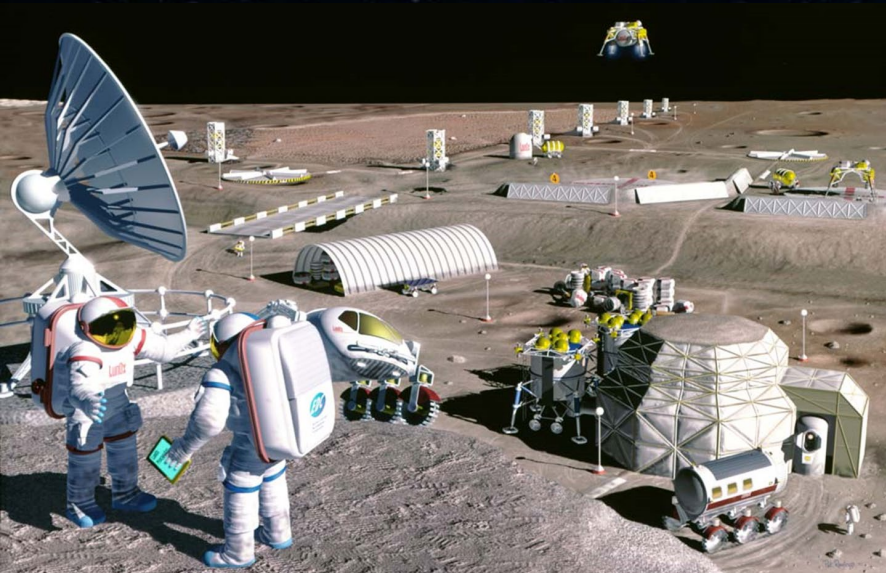


Oxygen Consumption Rate Profile

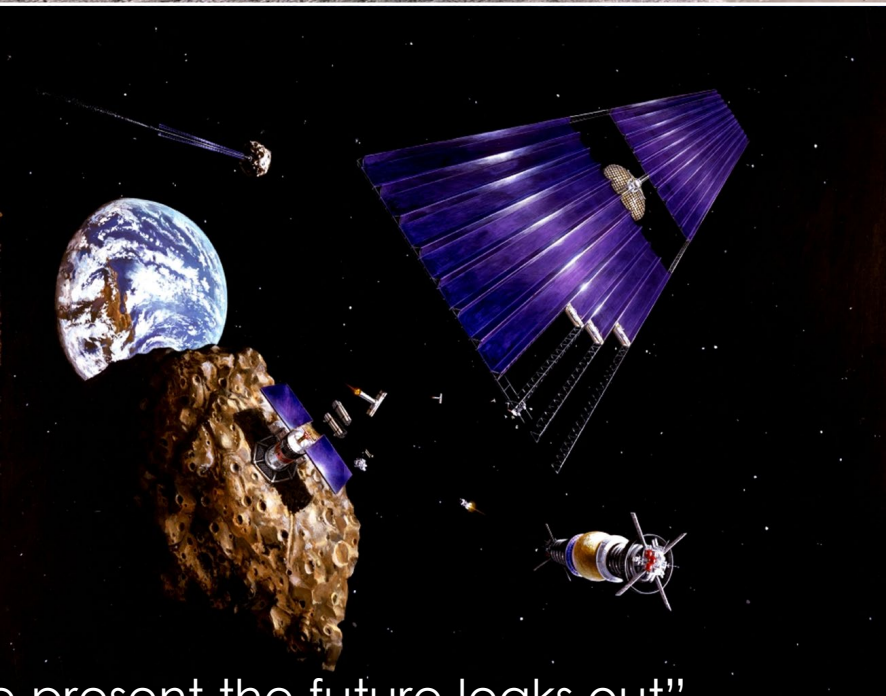




present



future



“when you cut into the present the future leaks out”
Jack White



Dr. Porterfield Professor of Ag & Biological Engineering at Purdue University
Chief of Science, Art and Engineering with Elevated BioAstronautics



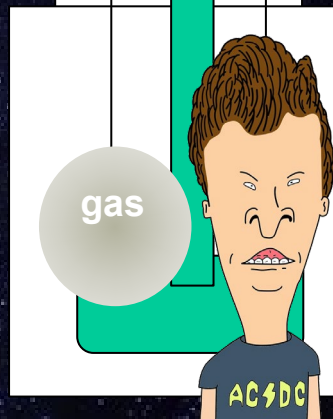
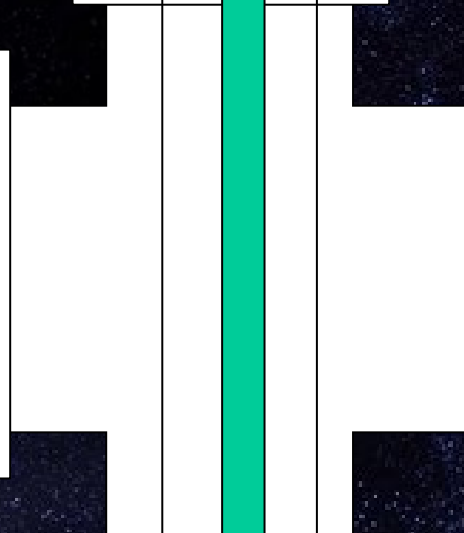
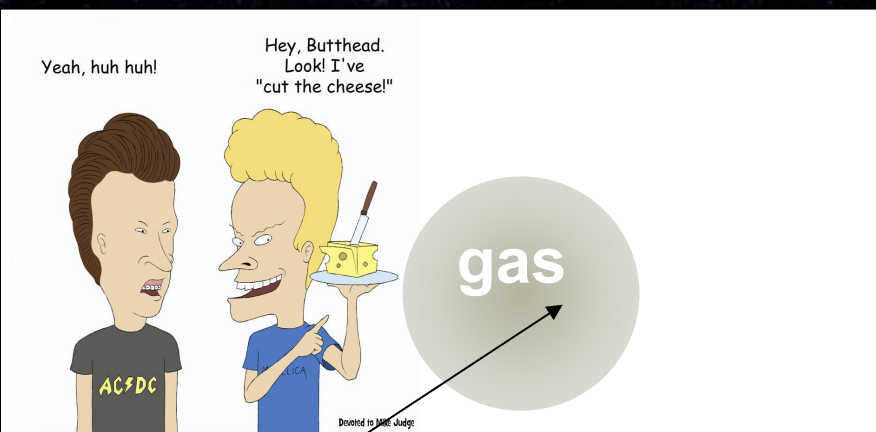
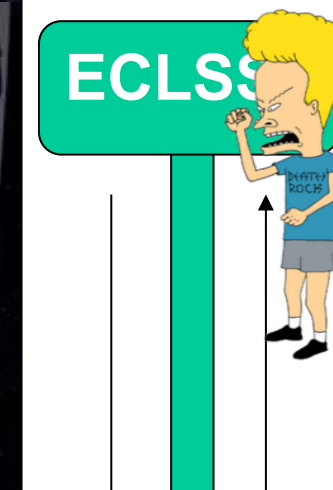
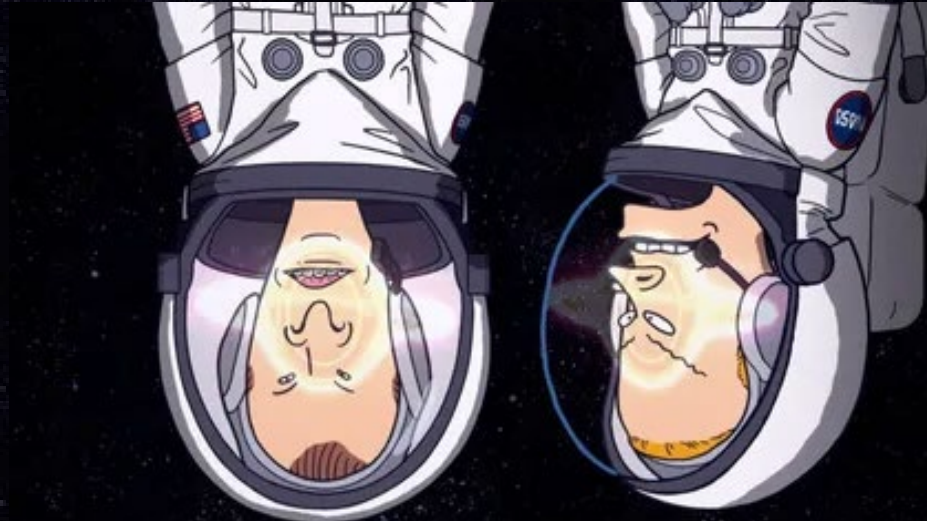
He has been doing space biology research for 30+ years. His primary focus is on understanding the biophysical microgravity environment at the cellular and whole organism levels, including: (1) biomedical countermeasures, (2) bioregenerative life support technology, and (3) controlled environment agriculture for long-duration human habitation. His work in gravitational and space biology includes cell signaling, biophysical limitations in microgravity, plant nutrient delivery technology, and biomimetic sensors.

His spaceflight work has focused on plant root system performance in microgravity. His work was first to show mitochondrial stress in spaceflight environments in a series of microgravity plant growth experiments. He also worked on hydroponic technologies, and early spaceflight experiments with LED lighting systems at the Controlled Ecological Life Support System program at Hanger L (Kennedy Space Center, Florida). He has led in the area of computational biophysics and the application of nanotechnology and microbiosensors in space research satellite systems.



Marshall served as Division Director for Space Life and Physical Sciences at NASA headquarters (2011-2016, Washington, D.C.), overseeing the Human Research, Physical Sciences, and Space Biology Programs. These programs focused on science for future exploration by leveraging advancements in the new systems informatics omics era, including establishing the GeneLAB Open Science program; the original Twins Study; 1YM; Cold Atom Lab; MaterialsLab & SporeSat MicroSatellite.

His work includes 100s of peer reviewed manuscripts and publications, and invited talks worldwide. He has received numerous awards in his career and was recently recognized as one of the top 2% of influential researchers in his field by the Stanford survey. He has served his peers as the President of the American Society for Gravitational and Space Biology, and as the President for the Institute for Biological Engineering.



The total pressurized volume of the ISS is approximately $1,000 \text{ m}^3$. An average gas release CO_2 concentration (0.0022 m^3) would lead to an increase in the gas fraction across the total volume of the ISS of about $(0.0022 \text{ m}^3 \text{ CO}_2 / 1000 \text{ m}^3 \text{ total}) = 0.0000022$, or 0.00022% .

We can now recalculate the diffusion speed and time using the revised concentration differential.

Substituting the new concentration difference (0.0000022) over the length of the module (8.5 m), the diffusion speed would be approximately $0.0000000041 \text{ m}^3/\text{s}$.

Calculating the time it would take for all of the CO_2 to diffuse out of the module: $0.0022 \text{ m}^3 / 0.0000000041 \text{ m}^3/\text{s}$ gives us about 187 days.

This revised calculation underscores the importance of ventilation and active air circulation within the ISS to maintain a safe and comfortable environment for the astronauts. Without it, even a small amount of CO_2 could linger for a considerable time, causing potentially hazardous conditions over the long term.



<https://www.facebook.com/eitanbernath/videos/hydrophobic-science-experiment-with-food/533822198499881/>