a **Multi-Stressor Space: Exploration Baseline vs. Lunar Reality**

Terrestrial Baseline (1 g)

Atmospheric Pressure:
101.3 kPa (14.7 psia)

Oxygen Fraction (O2):
21% (21.3 kPa pO2)

Carbon Dioxide (CO2):
420 ppm (0.04 kPa pCO2)

Magnetic Field (|B|):
25–65 μT (Dipolar GMF)

Ionizing Radiation:
~1–2 mGy/year (Shielded)

Exploration Enclosure & Lunar Surface

Exploration Pressure:
56.5 kPa (8.2 psia) / 34 kPa

Elevated Oxygen (O2):
34% (19.2 kPa pO2)

Elevated CO2:
1200–3000 ppm (0.12–0.30 kPa)

Lunar Magnetic Field:
0.40–0.82 nT (Deep Void)

Chronic GCR / SPE:
GCR: 60–100 mGy/yr | SPE: 0.5–2 Gy

STRESSOR CONVERGENCE: Combined physical stressors converge on mitochondrial terminal oxidases and reactive oxygen species generation

b **The Organellar CO2 <-> O2 <-> ROS Nexus**

Exploration Atmosphere Gas Balance (CO2 <-> O2 Nexus)

Phase II: 72–120 h (Greening)
RuBisCO active in plastids
Elevated CO2 (1200–3000 ppm)
suppresses glycolate H2O2

Phase I: 0–72 h (Heterotrophic)
Peroxisomal lipid β-oxidation (H2O2)
Mitochondrial restart: O2•- leak
Anaplerotic CO2 carboxylation

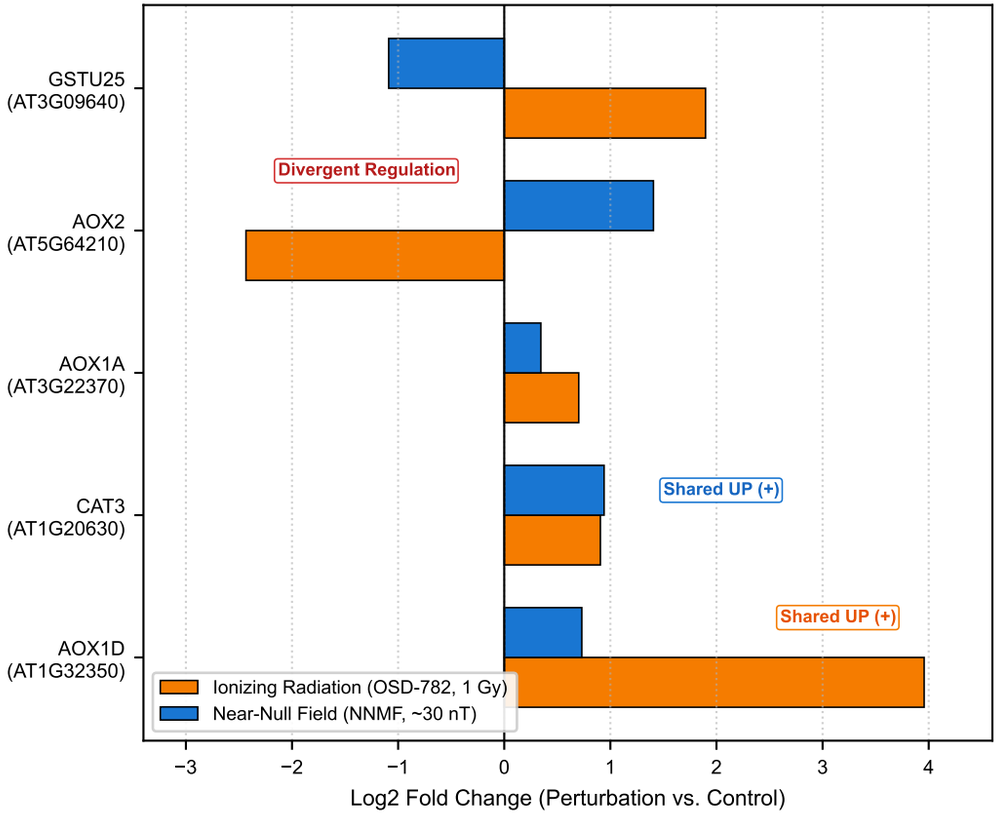
CENTRAL ROS & MITOCHONDRIAL-RETROGRADE HUB

Complex I & III electron leak ⟶ Superoxide (O2•-) ⟶ H2O2
Coupled to Fe-S cluster turnover & GCR radiolytic radicals (OH•)

Alternative Oxidase (AOX1D) vents excess redox pressure directly to O2
Catalase (CAT3) scavenges peroxisomal & mitochondrial H2O2

Core Concept 5: Hypomagnetic fields, ionizing radiation, and exploration atmospheres converge on the exact same mitochondrial bioenergetic and antioxidant loci

c **Empirical Multi-Omics Overlap: Peak Window Across 0–120 h**



d **Cross-Kingdom Convergence: Plant BLSS & Human Health**

Conserved Spaceflight Mitochondrial Vulnerability

Plant Space Biology (BLSS)

- Mitochondrial ETC electron leak
- Alternative Oxidase (AOX) bypass
- Fe-S biogenesis (AtNFS1) stress
- 10–30% germination & yield loss
- Early pigment & chlorosis defect

Human Astronaut Health

- Mitochondrial dysregulation #1 hub (NASA Twins Study; Da Silveira 2020)
- Complex I & III ROS runaway
- Endothelial oxidative damage
- Musculoskeletal & immune decay

THE SHARED MITOCHONDRIAL PARADIGM

In both plants and humans, removal of the geomagnetic field coupled with ionizing radiation and altered atmospheres impairs respiratory electron coupling and triggers ROS overflow. Plant bioenergetic resilience directly protects astronaut life support and fresh food supply.