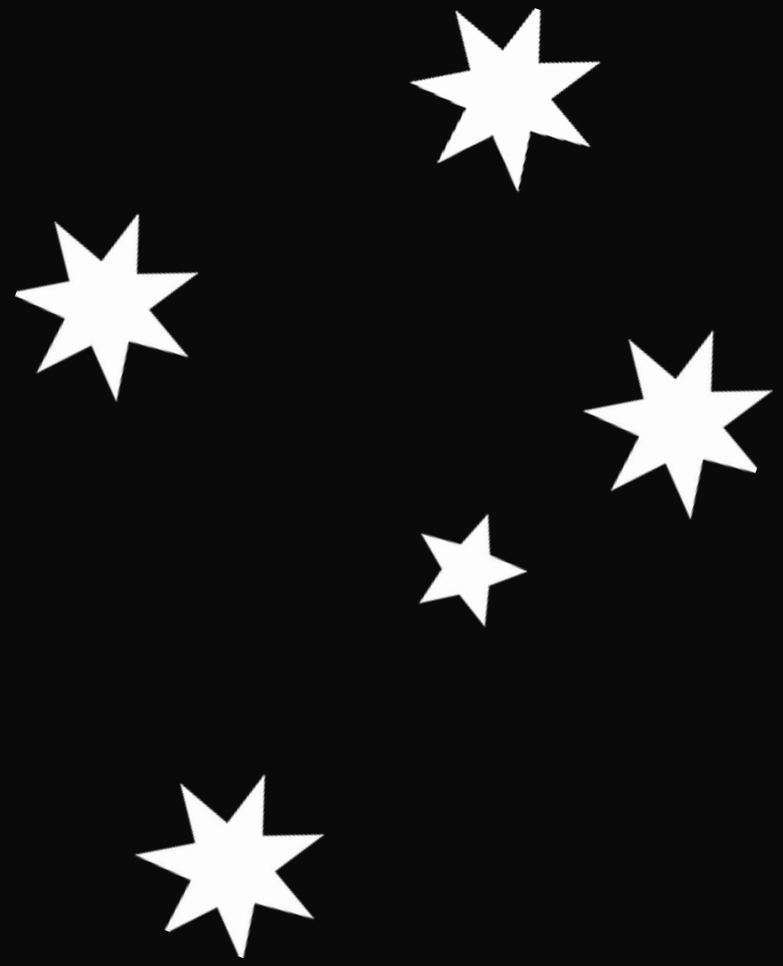


Seven Sisters painting by Christine Jugarnu Collard and the Pleiades star cluster. Christine Collard, Yamaji Art

PLANTS FOR SPACE

ARC CENTRE OF EXCELLENCE

MATTHEW GILLIHAM

MELiSSA Conference

Toulouse – November 2022

@plants4space

MISSON

To enable
human deep Space exploration
&
improve on-Earth sustainability
through
plant & food redesign

Plants for space

ARC CENTRE OF EXCELLENCE

ARTEMIS

IMPACT: NOW 2030 2040

3 year round trip

P4S: MULTIDISCIPLINARY TEAMS FOR COMPLEX SOLUTIONS

- Food scientists
- Plant scientists
- Process engineers
- Systems engineers
- Psychologists
- Nutritionists
- Educators
- Lawyers

PLANTS

PRODUCTS

PROCESSES

PEOPLE

ZERO-WASTE PLANT
growth & processing

PLANT-BASED SOLUTIONS
for health & well-being

Future-ready
people & products

GLOBAL CO-ORDINATION
& connectivity


RECYCLE
PLANTS
LAW
MEDICINE
FOODS
FLAVOUR
TEAMS
MATERIAL
05
SPINACH
DAYS TO YIELD: 6
06
SPINACH
DAYS TO YIELD: 6
07
TOMATO
DAYS TO YIELD: 2
08
TOMATO
DAYS TO YIELD: 2
09
CARROT
DAYS TO YIELD: 3
10
CARROT
PANTRY


P4S will deliver
fundamental learnings
& innovations
for Space
and Earth
PLANTS
MEDICINE
MATERIAL
LAW
FOODS
FLAVOUR
RECYCLE
TEAMS
PANTRY

INNOVATION FOR SPACE & EARTH

LEGAL, ETHICAL, REGULATORY & BIOSECURITY

- ☑ Protection for astronauts and planets
- ☑ Legal reforms to support ethical growth of biomanufacturing

P4S Cultural Charter

INNOVATION FOR SPACE & EARTH

PLANT SCIENCE

- ☑ Fast growth, zero-waste plants
- ☑ Plants as sensors

INNOVATION FOR SPACE & EARTH

PLANT-BASED NUTRITION

☑ A suite of complete nutrition plants

FOODS WITH VARIED TEXTURE & FLAVOUR

☑ New plant-based health and food products

INNOVATION FOR SPACE & EARTH

BIOMANUFACTURING

SUSTAINABILITY

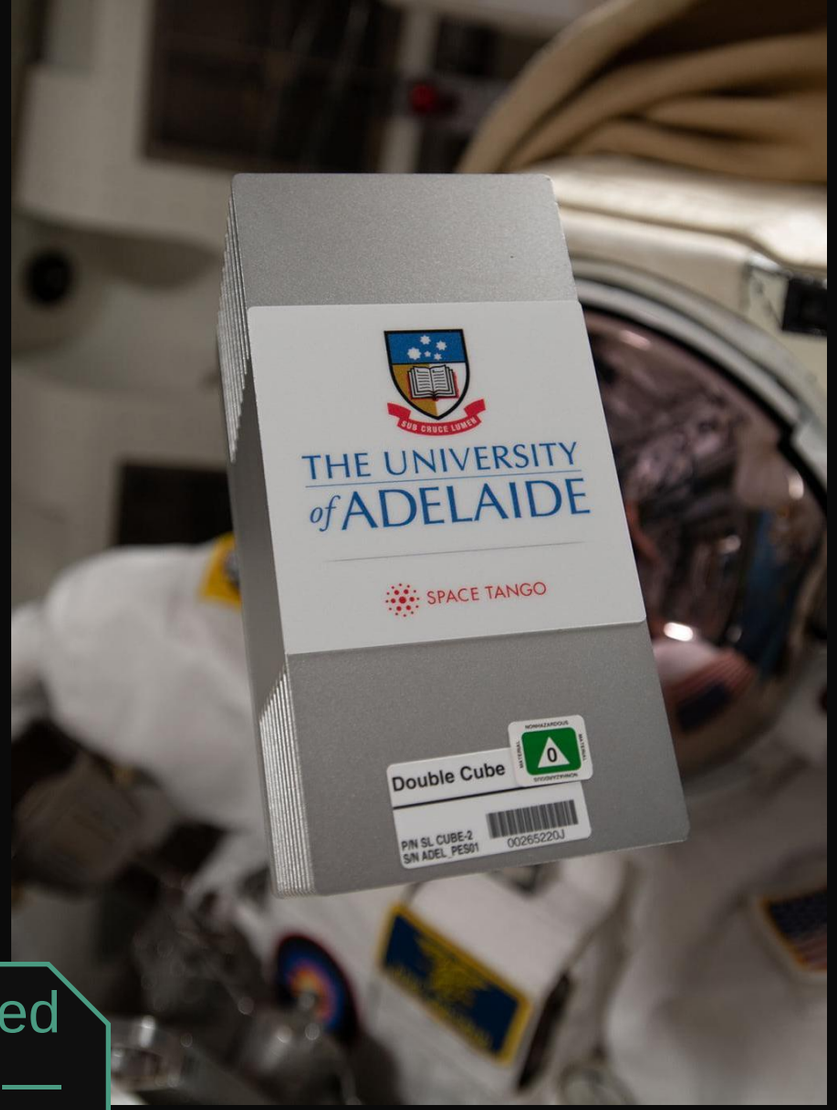
- ☑ On-demand plant production
- ☑ Low-input biomanufacturing

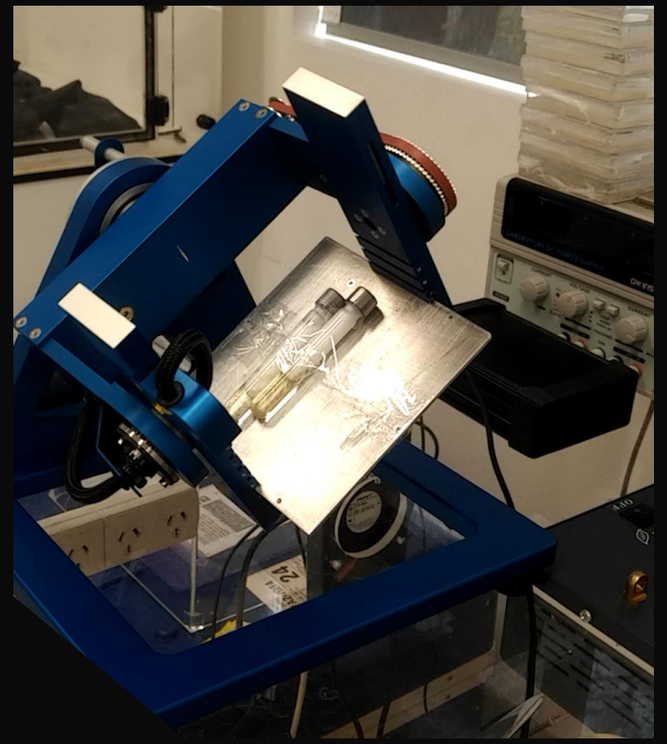
INNOVATION FOR SPACE & EARTH

TEAMWORK & CONNECTIVITY

- ☑ Foods and plants to support psychological well-being in isolation
- ☑ A global hub for international space plant research

P4S PILOT PROGRAMS HAVE BEGUN





First Australian-led mission to ISS — pharmaceutical stability

DUCKWEED

THE UNIVERSITY of ADELAIDE

LA TROBE UNIVERSITY

THE UNIVERSITY OF WESTERN AUSTRALIA

HAMILTON SECONDARY COLLEGE Space SCHOOL

The Andy Thomas Space Foundation

Botanic Gardens of SOUTH AUSTRALIA

Government of South Australia
Department of Primary Industries and Regions

SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE

NASA

DLR

AXIOM SPACE

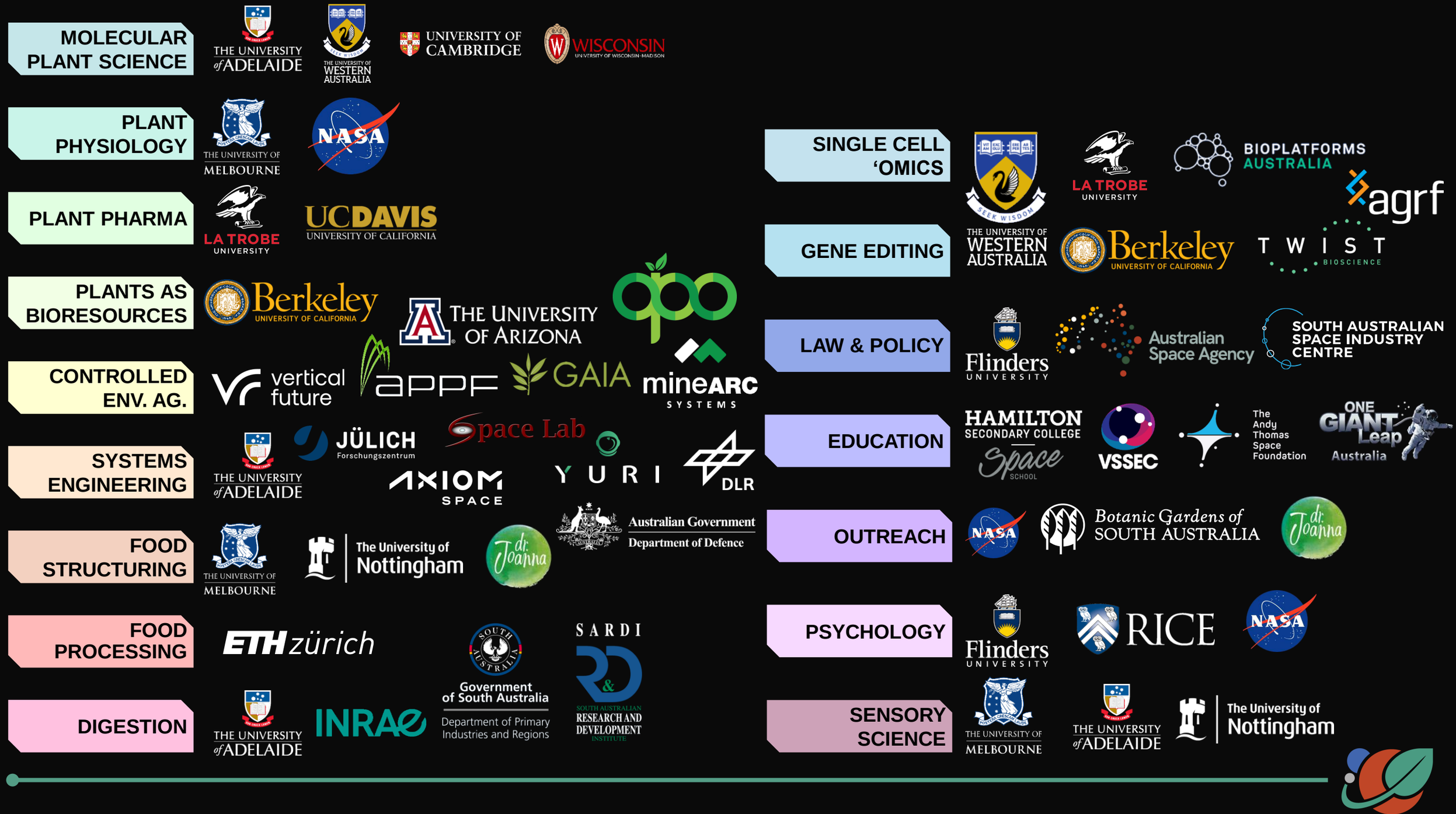
YURI

vertical future

Leaves expressing pigment marker

Space Lab

µG-LilyPond & harvester


MOLECULAR PLANT SCIENCE
THE UNIVERSITY of ADELAIDE
THE UNIVERSITY OF WESTERN AUSTRALIA
UNIVERSITY OF CAMBRIDGE
WISCONSIN
UNIVERSITY OF WISCONSIN-MADISON
PLANT PHYSIOLOGY
THE UNIVERSITY OF MELBOURNE
NASA
PLANT PHARMA
LA TROBE UNIVERSITY
UCDAVIS
UNIVERSITY OF CALIFORNIA
PLANTS AS BIORESOURCES
Berkeley
UNIVERSITY OF CALIFORNIA
THE UNIVERSITY OF ARIZONA
CONTROLLED ENV. AG.
vertical future
appf
GAIA
mineARC SYSTEMS
SYSTEMS ENGINEERING
THE UNIVERSITY of ADELAIDE
JÜLICH Forschungszentrum
Space Lab
AXIOM SPACE
YURI
DLR
FOOD STRUCTURING
THE UNIVERSITY OF MELBOURNE
The University of Nottingham
dr. Joanna
Australian Government Department of Defence
FOOD PROCESSING
ETH zürich
DIGESTION
THE UNIVERSITY of ADELAIDE
INRAE
Government of South Australia
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SARDI
SOUTH AUSTRALIAN RESEARCH AND DEVELOPMENT INSTITUTE
SINGLE CELL 'OMICS
THE UNIVERSITY OF WESTERN AUSTRALIA
LA TROBE UNIVERSITY
BIOPLATFORMS AUSTRALIA
agrf
GENE EDITING
Berkeley
UNIVERSITY OF CALIFORNIA
TWIST BIOSCIENCE
LAW & POLICY
Flinders UNIVERSITY
Australian Space Agency
SOUTH AUSTRALIAN SPACE INDUSTRY CENTRE
EDUCATION
HAMILTON SECONDARY COLLEGE
Space SCHOOL
VSSEC
The Andy Thomas Space Foundation
ONE GIANT Leap Australia
OUTREACH
NASA
Botanic Gardens of SOUTH AUSTRALIA
dr. Joanna
PSYCHOLOGY
Flinders UNIVERSITY
RICE
NASA
SENSORY SCIENCE
THE UNIVERSITY OF MELBOURNE
THE UNIVERSITY of ADELAIDE
The University of Nottingham

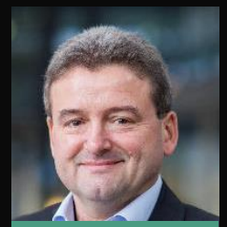
OUR INVESTIGATOR TEAM


CI


CI


CI


CI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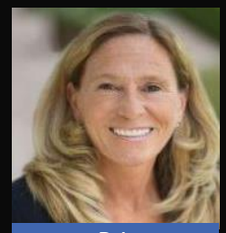
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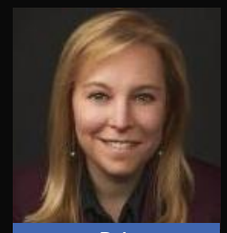
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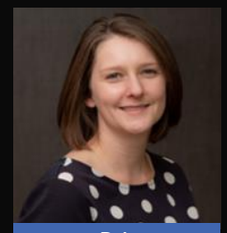
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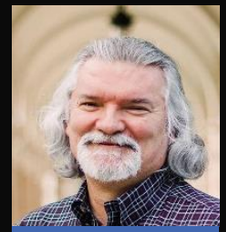
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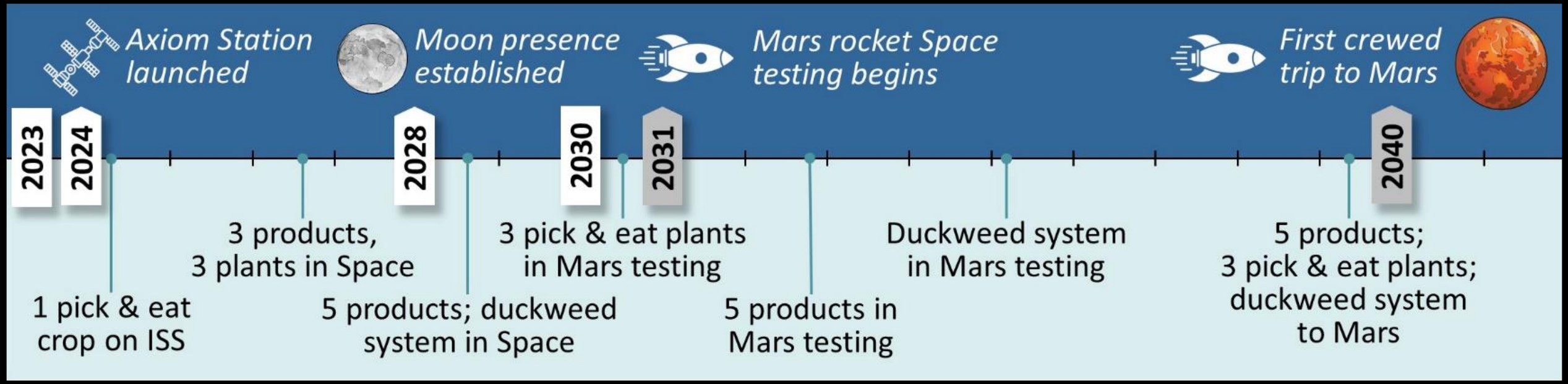
OUR EXPANDED TEAM

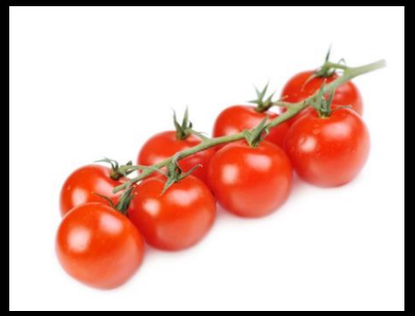
PLANTS



Water spinach

Vitamins

Tomatoes



Flavour, lycopene

Strawberries

Texture, Flavour

Carrots

Texture, vitamin A

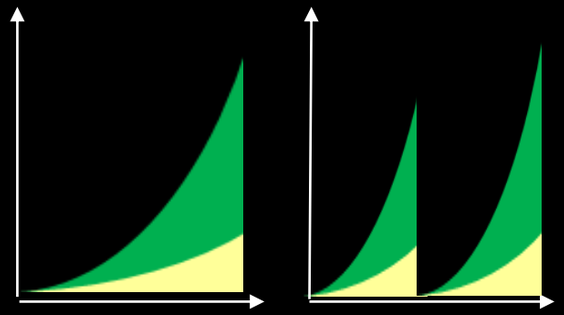
Duckweeds

Nutrients & Vitamins

CHALLENGES

DOUBLE RELATIVE GROWTH RATE PER DAY

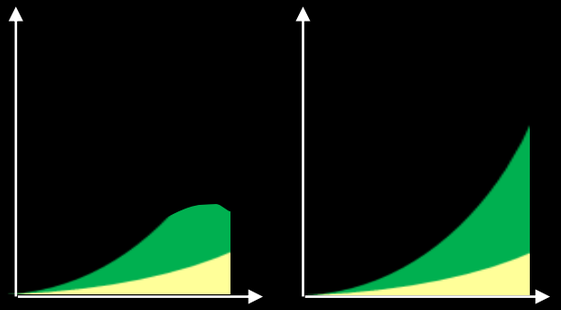
~0.3 TO >0.6



- Photorespiration
- Review stress responses (biotic & abiotic)

INCREASE NUTRIENT AND WATER USE-EFFICIENCY, AND SALT AND HYPOXIA TOLERANCE

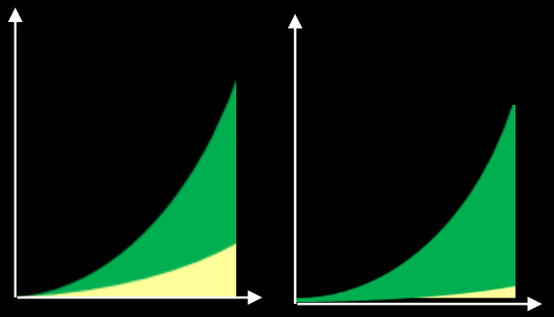
by 50%



- Transporters & metabolites – salt, nutrients
- Transpiration
- Hypoxia tolerance

RAISE HARVEST INDEX FROM 0.4–0.75

TO APPROACH 1.0

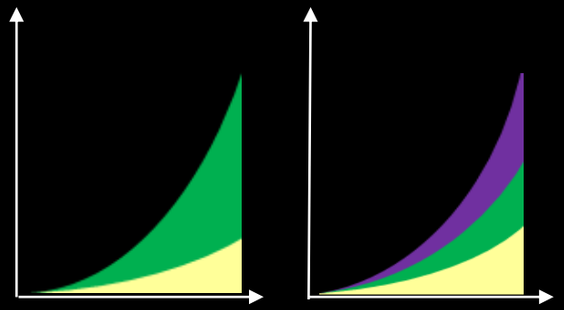


- Successive harvesting
- Redesign and reduce root systems
- Tissue composition

CHALLENGES

REFINE PROTEIN COMPOSITION

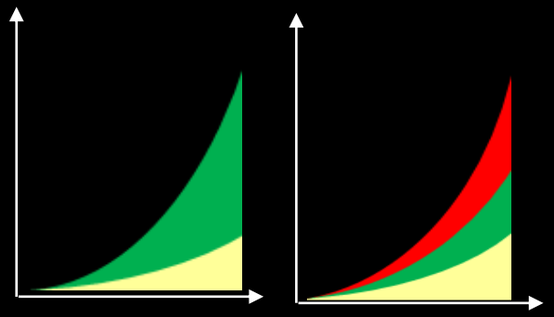
BETTER BALANCE OF ALL ESSENTIAL AMINO ACIDS FOR NUTRITION



- Amino acid profiles
- Protein turnover
- Storage proteins

MAXIMISE LEAF FAT CONTENT

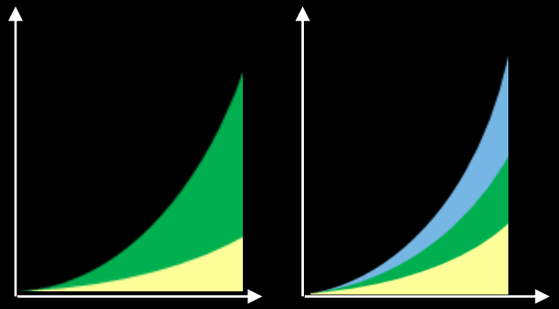
CALORIC, NUTRITIONAL, AND TASTE IMPACT



- Oleic acid formation.
- Increase fat sinks
- Decrease sugar export from leaves, inc.TAG

CHANGE LEAF CARBOHYDRATES

OPTIMISE STARCH & FIBRE CONTENT FOR HEALTH



- Pectin (cardiovascular, cancer, bone)
- Soluble fibre
- Alter starch

HELPING TO PREPARE THE NEXT GENERATION OF LEADERS

Outreach

Equity & diversity

Training & professional development

Entrepreneurship

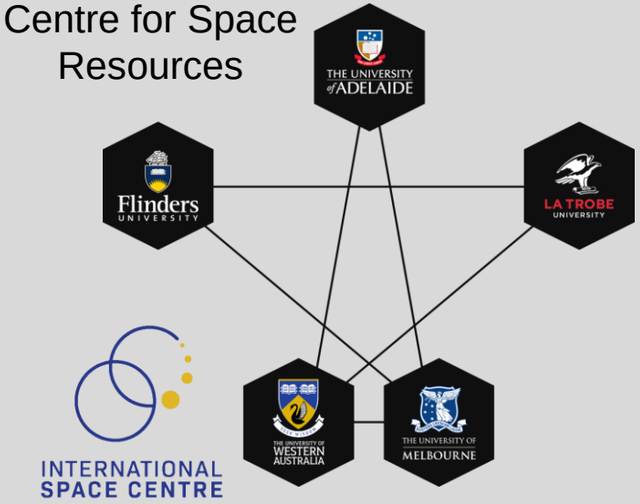
Industry experience

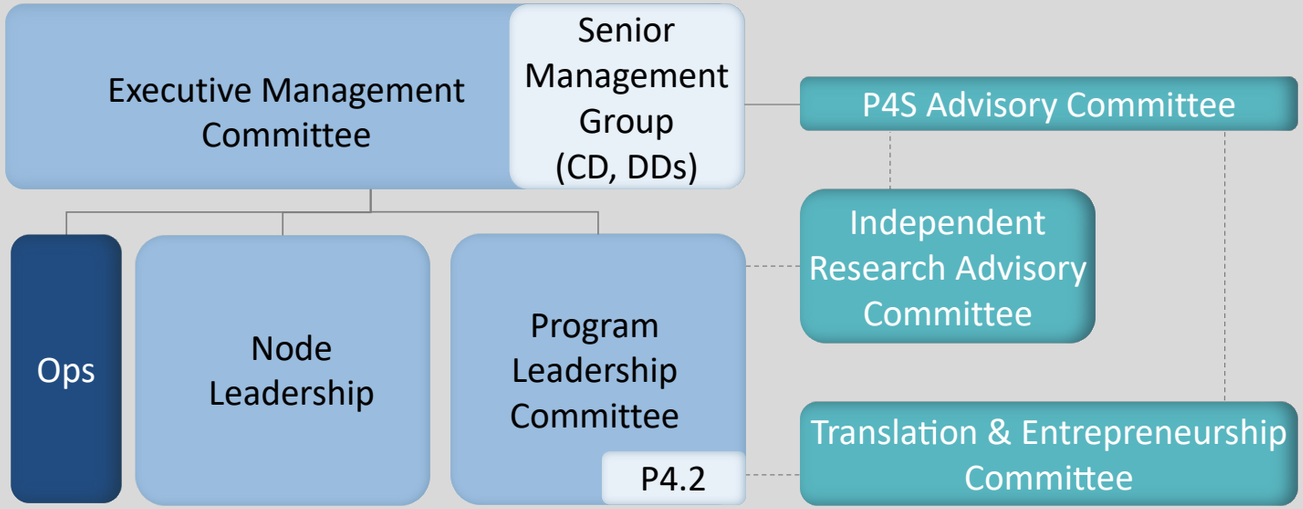
Mentorship

P4S NETWORKS & CO-ORDINATION BRING NEW OPPORTUNITIES

- *Molecular plant science*
- *Plant physiology*
- *Plant pharma*
- *Plants as bioresources*
- *Controlled Env. Ag.*
- *Systems engineering*
- *Food structuring*
- *Food processing*
- *Single cell 'omics*
- *Gene editing*
- *Law & policy*
- *Education*
- *Outreach*
- *Psychology*
- *Digestion*
- *Sensory science*

UoA Andy Thomas Centre for Space Resources





AXIOM SPACE
Nyx
esa
Lunaria One
Berkeley UNIVERSITY OF CALIFORNIA
UC DAVIS UNIVERSITY OF CALIFORNIA
WISCONSIN UNIVERSITY OF WISCONSIN-MADISON
RICE
THE UNIVERSITY OF ARIZONA
UNIVERSITY OF CAMBRIDGE
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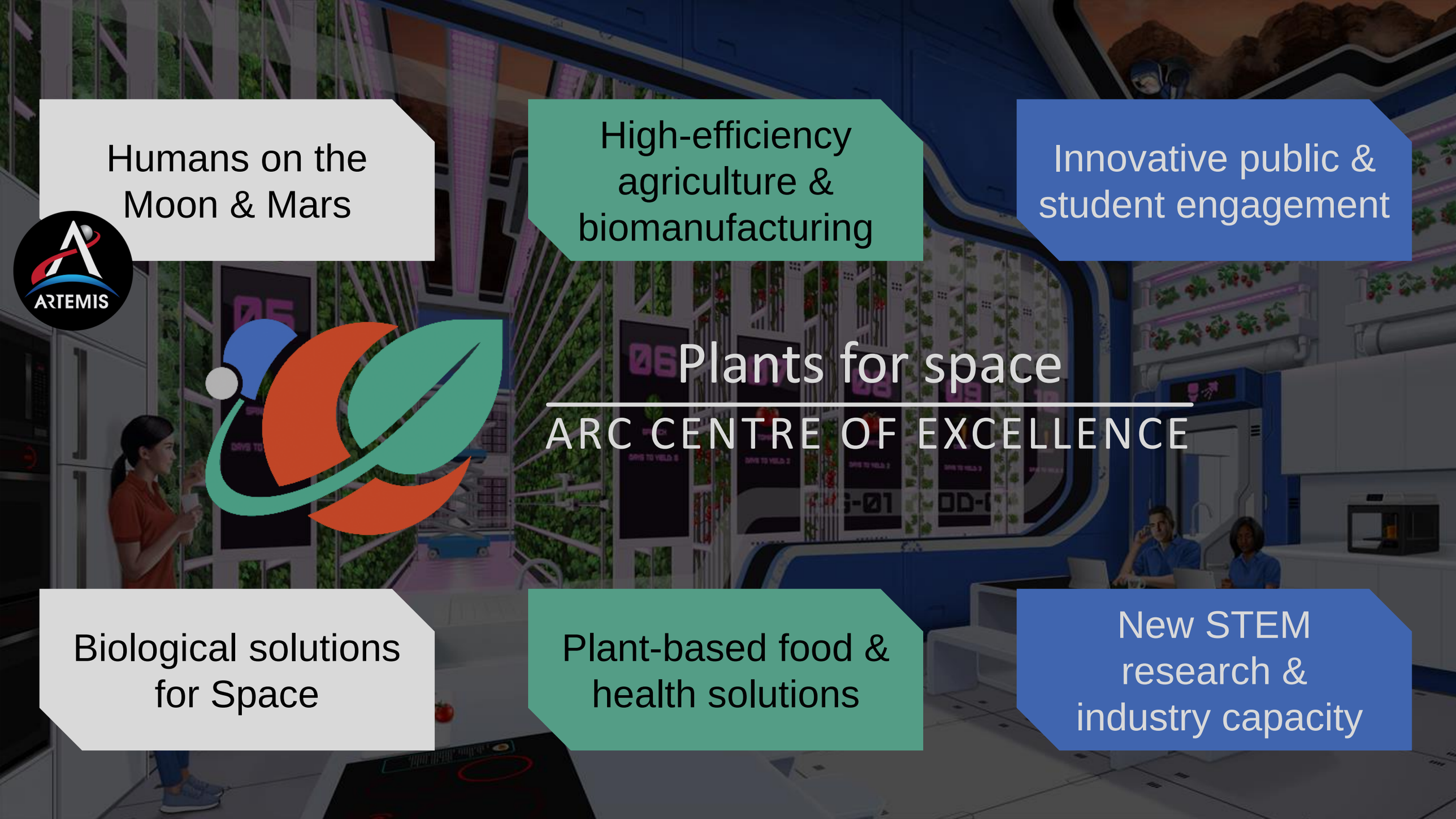
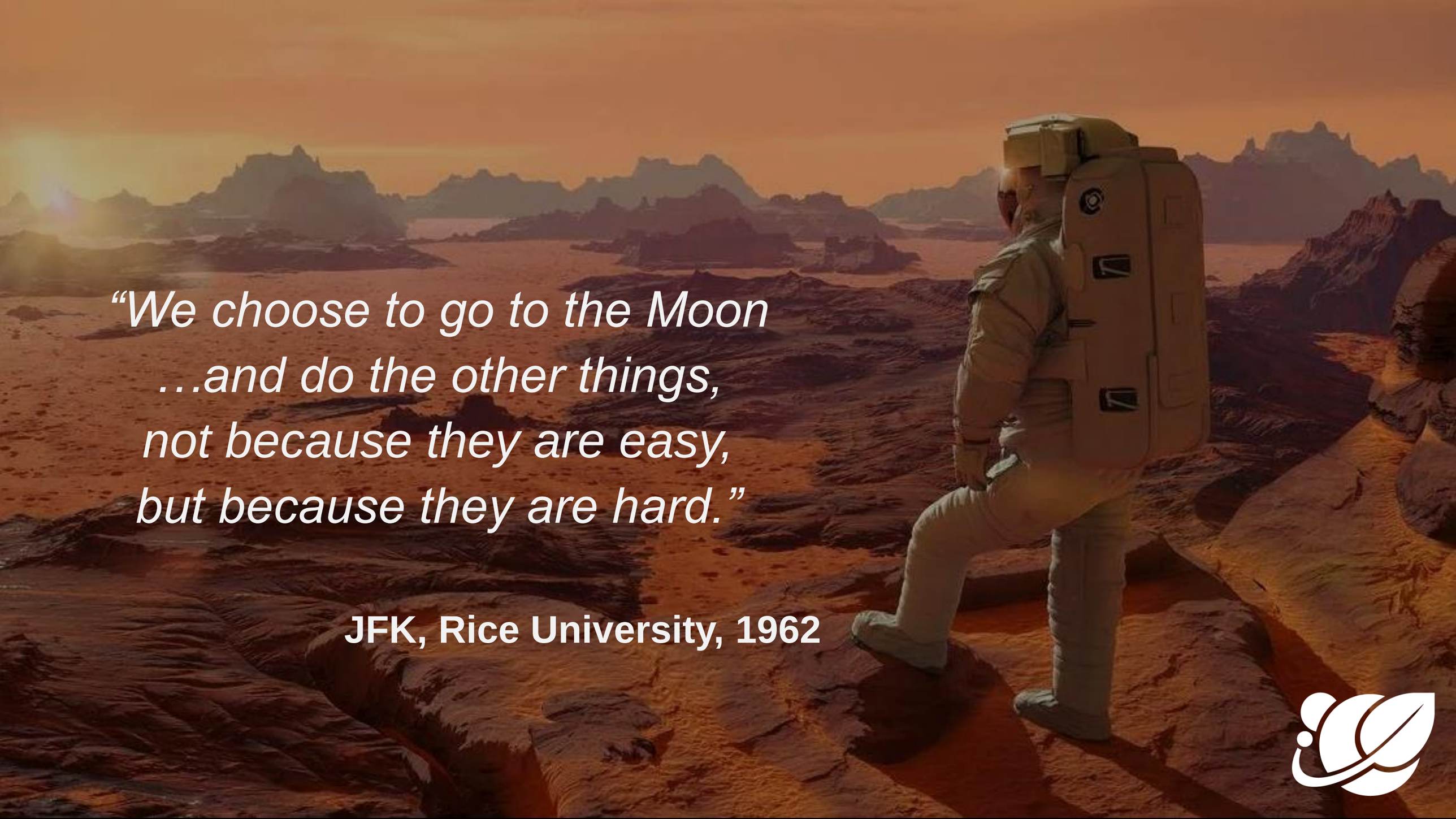

Humans on the Moon & Mars
High-efficiency agriculture & biomanufacturing
Innovative public & student engagement
ARTEMIS
Plants for space
ARC CENTRE OF EXCELLENCE
Biological solutions for Space
Plant-based food & health solutions
New STEM research & industry capacity

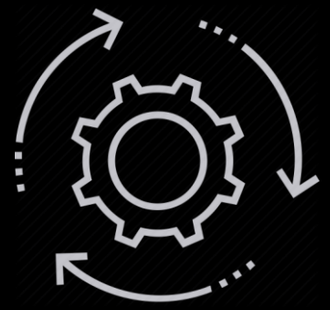

“We choose to go to the Moon
…and do the other things,
not because they are easy,
but because they are hard.”
JFK, Rice University, 1962

MULTIDISCIPLINARY P4S TEAMS FOR COMPLEX SOLUTIONS

PLANTS

- ☑ Plant attributes

PROCESSES

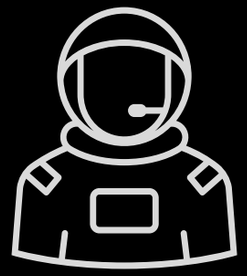


- ☑ Processing, structure & texture

PRODUCTS

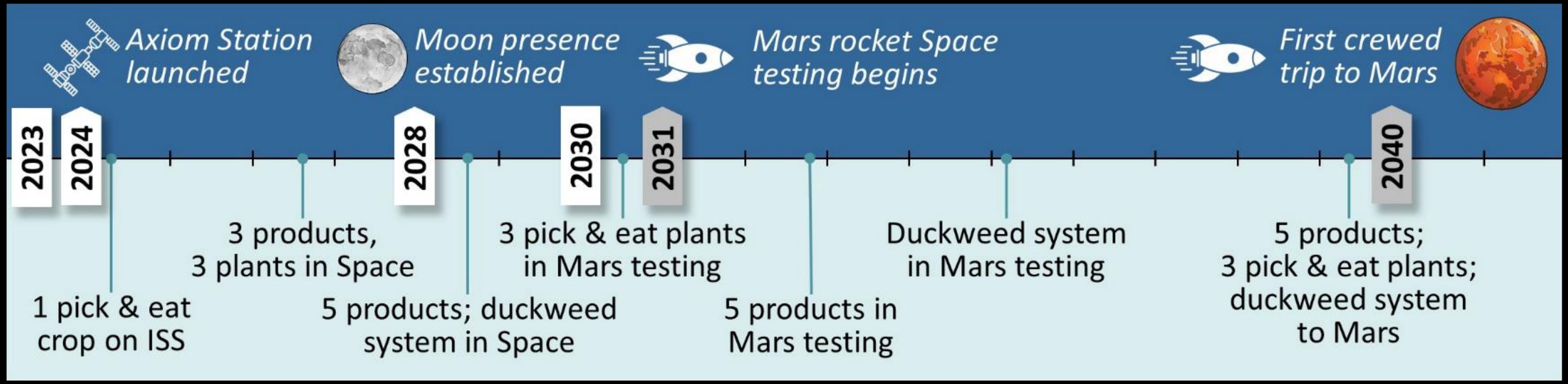
- ☑ Nutrition, flavour & storage
- ☑ Sensory attributes
- ☑ Digestibility

PEOPLE



- ☑ Psychological impact
- ☑ Market acceptance
- ☑ Legal frameworks

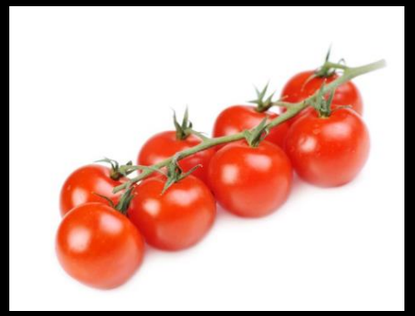
PLANTS



Water spinach

Vitamins

Tomatoes



Flavour, lycopene

Strawberries

Texture, Flavour

Carrots

Texture, vitamin A

Duckweeds

Nutrients & Vitamins

STATE OF PLAY

RADISH

NASA astronaut Kate Rubins with Plant Habitat-02 (PH-02) experiment aboard the International Space Station with radish seedlings.

LETTUCE

NASA astronaut Peggy Whitson shows off some leafy greens grown on the International Space Station.

CHILLIES

Crew poses with the chiles they harvested before eating them. This plant experiment was the longest in the history of the space station at 137 days.

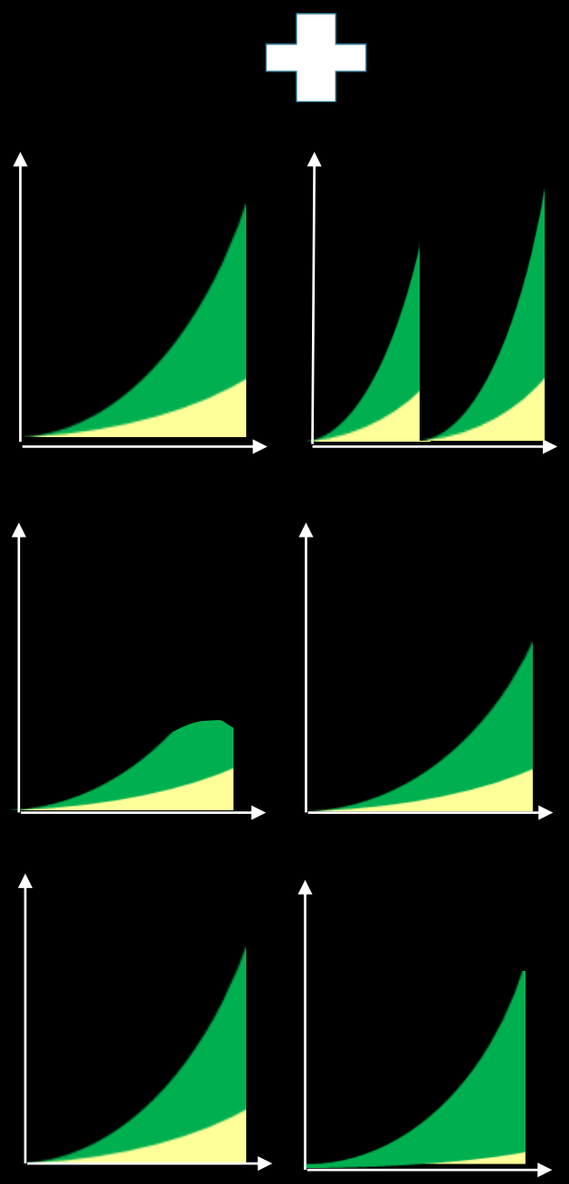
CHALLENGES

DOUBLE RELATIVE GROWTH RATE PER DAY
~0.3 TO >0.6

INCREASE NUTRIENT AND WATER USE-EFFICIENCY, AND SALT AND HYPOXIA TOLERANCE
by 50%

RAISE HARVEST INDEX FROM 0.4–0.75

TO APPROACH 1.0



P4S TARGETS

- Photorespiration
- Reactive Oxygen Species quenching
- Stress responses

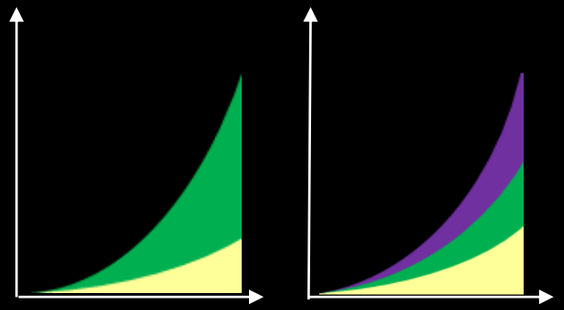
- Transporters & metabolites - salt
- Hypoxia tolerance

- Successive harvesting
- Redesign and reduce root systems

CHALLENGES

REFINE PROTEIN COMPOSITION

BETTER BALANCE OF ALL ESSENTIAL AMINO ACIDS FOR NUTRITION



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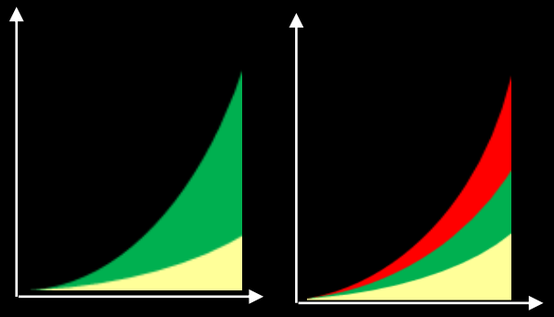

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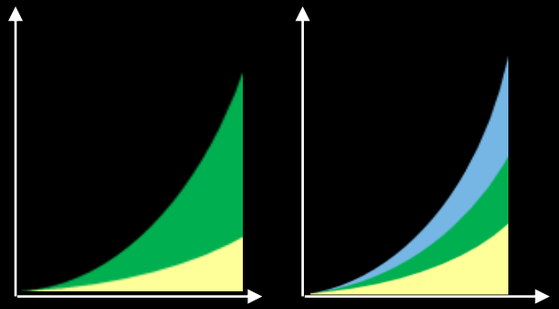


- Pectin (cardiovascular, cancer, bone)
- Soluble fibre
- Alter starch

Our team is READY

Matt Gilliham (UoA)	Melissa de Zwart (Flinders)	Sally Gras (UM)	Harvey Millar (UWA)	Volker Hessel (UoA)	Ryan Lister (UWA)	Michelle Watt (UM)	Jim Whelan (LTU)	Kim Johnson (LTU)	Ian Small (UWA)	Eva Kemps (Flinders)	Mat Lewsey (LTU)	Jenny Mortimer (UoA)	Matt Tucker (UoA)	Sigfredo Fuentes Jara (UM)	Christine Feinle-Bisset (UoA)
C I	C I	C I	C I	C I	C I	C I	C I	C I	C I	C I	C I	C I	C I	C I	C I
Gioia Massa (NASA)	Jens Hauslage (DLR)	Jana Stoudemire (Axiom)	Sumen Rai (SASIC)	Christine Escibar (SpaceLab)	Jen Bromley (VF)	Jake Eisenberg (OPO)	Nadun Hennayaka (GAIA)	Jennifer Doudna (UCB)	Jay Keasling (UCB)	Adam Arkin (UCB)	Karen McDonald (UCD)	Simon Gilroy (UWM)	Eduardo Salas (Rice)	Murat Kacira (UAz)	Alex Webb (UCam)
P I	P I	P I	P I	P I	P I	P I	P I	P I	P I	P I	P I	P I	P I	P I	P I
Ian Fisk (UoN)	Ulrich Schurr (Julich)	Didier Dupont (INRAE)	Raffaele Mezzenga (ETH)	Joanne McMillan (DrJo)	Sarah Baker (Hamilton)	Luca Bertolacci (VSSEC)	Jackie Carpenter (One Giant Leap)	Natalie Curach (BPA)	John Culton (UoA)	Ole Mouritsen (SfL)	Erik Murchie (UoN)	Sue Bastian (UoA)	Corinne Scown (UCB)	Bo Xu (UoA)	L Ong (UM)
P I	P I	P I	P I	P I	P I	P I	P I	P I	A i	A I	A I	A I	A I	Researcher	Researcher
Ni Yang (UoN)	Louise Hewson (UoN)	Jim Stevens (VF)	Katie Wilkins (VF)	John Stephen (AGRF)	Nick Beagley (DSTG)	Daniel Kaschubek (yuri)	Megan Hochenstrasse(IGI)	Olivia Menard (INRAE)	Sasi Nayar (SARDI)	Maria Saarela (SARDI)	Paul Petrie (SARDI)	Michelle Waycott (BGSH)	Siyuan Chen (Twist)	Bernd Willems (Twist)	Emily Hilder (DSTG)
Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Researcher	Staff
Christian Maender (Axiom)	Simon Jenner (Axiom)	Kirsten Whittingham (Axiom)	Daniela Bezdan (yuri)	Brad Ringeisen (IGI)	Zenka Mathys (DSTG)	Nicola Sasanelli (ATSF)	Michael Pakakis (VSSEC)	Mak Djukic (BGSH)	Holger Plange (MineARC)	Daragh Quinn (MineARC)	Mark Dupal (Twist)	Jeremy Dumsday (Twist)	Ryan Edwards	Melinda Nguyen	Jon Diab
Staff	Staff	Staff	Staff	Staff	Staff	Staff	Staff	Staff	Staff	Staff	Staff	Staff	HDR	HDR	HDR
Matt Morgan	Quy Don Tran	Svenja Schmidt	Changping Zhuang	Shu Liang	Manuel Alejandro Varon Hoyos	Sushant Bajpai	Thitima Sombuttan	George Warne	Robert Rintoul	Nigel Vermonden	Laura Beckett	Alex Thomas			
HDR	HDR	**HDR**	HDR	HDR	HDR	HDR	HDR	HDR	HDR	HDR	HDR	HDR			

Investigators

Water spinach
Ipomoea aquatica

Key advantages

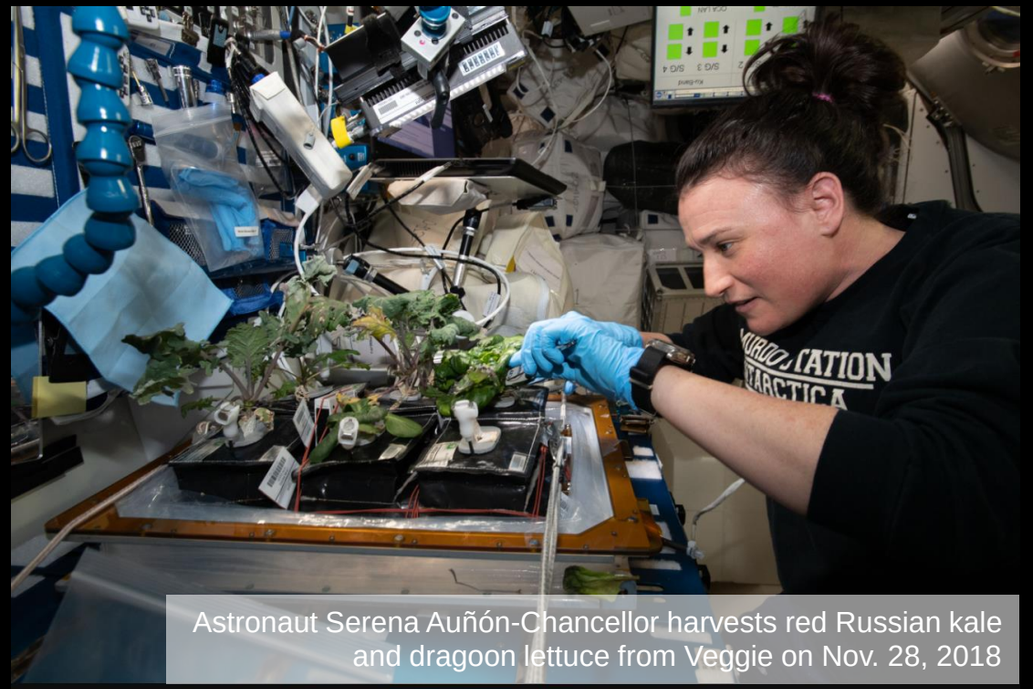
- strong visual and texture appeal
- fully edible shoot and regenerating rhizome
- grows in unstirred water based media and hydroponics
- high protein content in leaves (2.5-3g per 100g)

- genetic transformation available since 2005

DOI:10.5511/plantbiotechnology.20.335

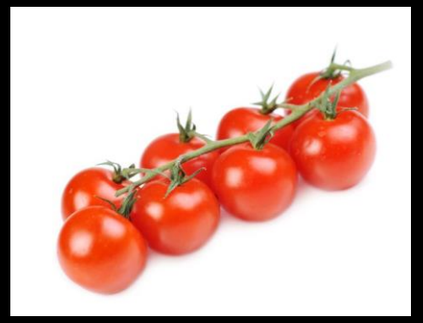
- fully sequenced genome in 2021 (550.03 Mb)
  includes 30,693 predicted protein-coding genes.

DOI:10.1016/j.scienta.2021.110501



Astronaut Serena Auñón-Chancellor harvests red Russian kale and dragoon lettuce from Veggie on Nov. 28, 2018

NASA's Matt Romeyn works in the Crop Food Production Research Area of the Space Station Processing Facility, Kennedy Space Center in Florida.
Credits: NASA/Cory Huston



Tomatoes
Solanum lycopersicum

Key advantages

- high, energy-rich yield
- strong appeal for flavour, texture
- extensive research community and bioengineering
- high in key vitamins

- high efficiency agrobacterium-mediated transformation

doi: 10.1007/978-1-4939-8778-8_16.

- fully sequenced genome in 2012

doi:10.1038/nature11119

Red Robin tomato variety bred for dwarf growth with NASA

Canadian astronaut Chris Hadfield with fresh tomatoes transported to ISS

CARROTS
Daucus carota

Key advantages

- strong appeal for flavour and crunch
- high in key vitamin A precursors
- edible leaves and a large tuber for nutrient manufacture and storage

- Genetic transformation of Daucus and other apiaceae species. Transgenic Plant J. 2008;2:18–38.

- High-quality genome assembly in 2016
  doi.org/10.1038/ng.3565

Hydroponic carrot trials for future deployment

Astronaut Steve Kelly with mini carrots transported to ISS on ISS

Strawberries
Fragaria spp.

Jeff Richards displays plants successfully growing in a specially developed solution of nutrients under spacecraft-like conditions. Image credit: NASA

Key advantages

- Extremely strong visual, flavour, texture appeal
- high in key vitamin precursors
- edible leaves and fruit

- Genetic transformation with low efficiency (5%) by agrobacterium 2014

doi.org/10.4161/gmcr.27229

- Challenging octoploid genome, assembly and gene prediction in 2019 for *Fragaria* × *ananassa*

doi: 10.1038/s41588-019-0356-4

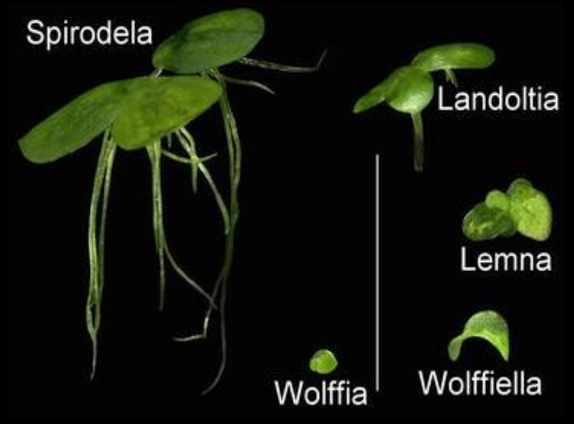
https://www.nasa.gov/mission_pages/science/f_strawberries.html

Duckweed

Lemna,Wolffia spp.

Key advantages

- Fastest growing plant on earth, doubles in a day
- Grows in stagnant water & scavenges nutrients
- Salt tolerant, radiation resistant
- Nutrient profile close to human requirements
- Highly adaptable metabolism
- Genome sequences and transformable



doi.org/10.1007/978-3-319-58538-3_67-1