ESA Perspective on Cold Atoms in Space

Community Workshop on Cold Atoms in Space

23 September 2021

→ THE EUROPEAN SPACE AGENCY

European Leadership in Space and Economy Connections

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Maintaining European leadership in space

Best Space Earth Climate System; Scientific excellence; Technological break-throughs; Prepares Europe for ambitious international human spaceflight and robotic missions; System Architect role, able to invite international partners

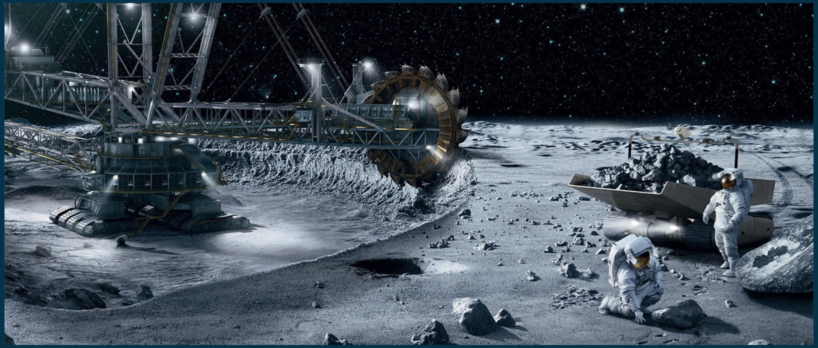
Promoting space business & commercial initiatives

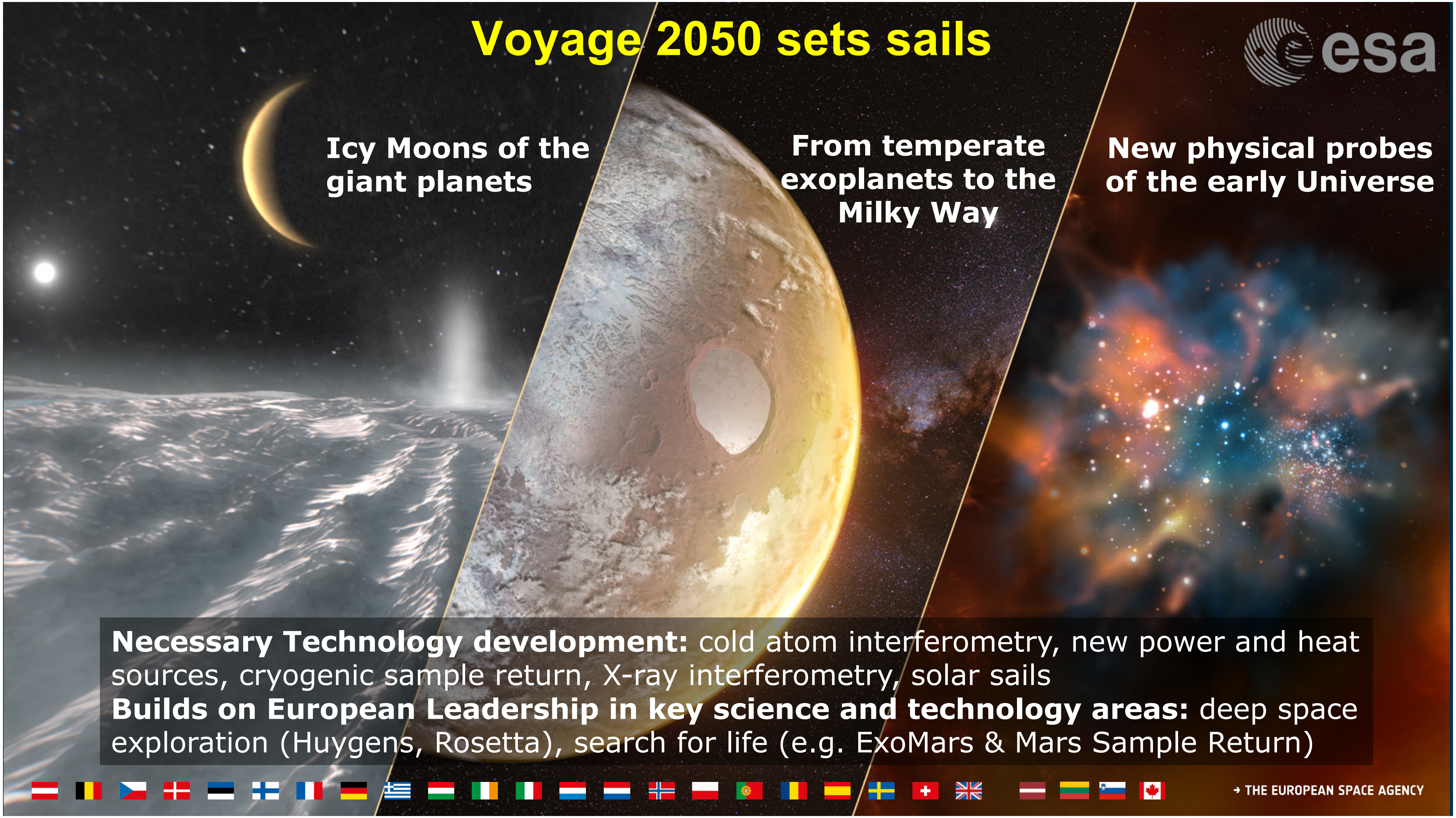
- Refuelling and in-orbit assembly => COMS market, constellations, robotic exploration
- Space mining: Earth moon, asteroids

Pushing our technological boundaries

Quantum sensors; power systems; in-orbit assembly and fuelling; autonomous operations; deep-space quantum-optical communications; cryogenic sampling and preservation; autonomous operations; safe Earth atmosphere re-entry;

Asteroid mining




Voyage 2050 sets sails
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Icy Moons of the giant planets
From temperate exoplanets to the Milky Way
New physical probes of the early Universe
Necessary Technology development: cold atom interferometry, new power and heat sources, cryogenic sample return, X-ray interferometry, solar sails
Builds on European Leadership in key science and technology areas: deep space exploration (Huygens, Rosetta), search for life (e.g. ExoMars & Mars Sample Return)
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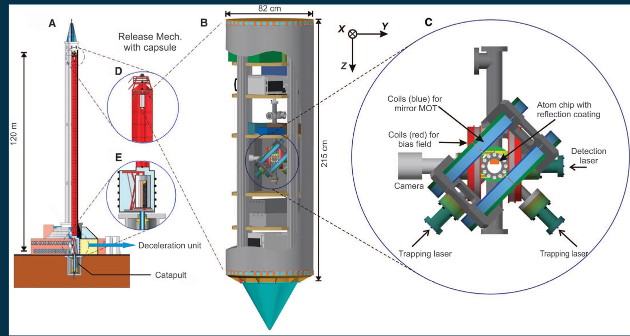
Quantum Technology Leadership

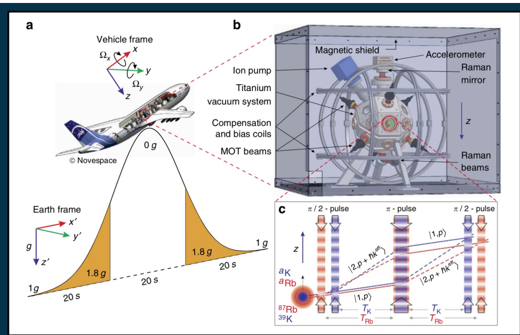
- Quantum Accelerometer
  - Enables the Quantum mission for climate to provide measurements of new climate variables of unprecedented quality
  - Possible use in Icy moon mission
  - Enables fundamental physics missions
  - To be demonstrated on a pathfinder mission
- Space Atomic/Optical Clocks
  - To test Fundamental Physics in space (Gravitational red-shift, time variation of fundamental constants, tests of SME)
  - Differential geopotential measurements to cm level resolution over the geoid
  - Clock comparisons over intercontinental distances
  - Universal time scales: UTC, TAI…
  - Technology towards future GNSS systems.
- Deep space optical/quantum communication
  - Develop a deep space optical link with connectivity to HydRON with future extension
    - Enables high data rate deep space quantum enabled optical communications
    - Enables synergies with quantum key developments

Road to Space (Microgravity Environment on Ground since 2007)

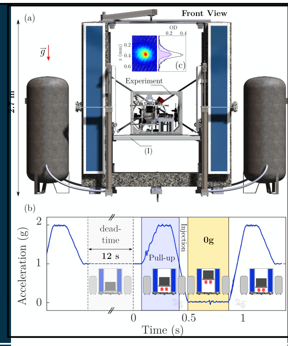
- Drop tower (Bremen)
  - up to 9s free falling
  - 2-3 drops per day



- Airbus 0-g (Novespace)
  - 20s free falling
  - 30 parabolas per flight

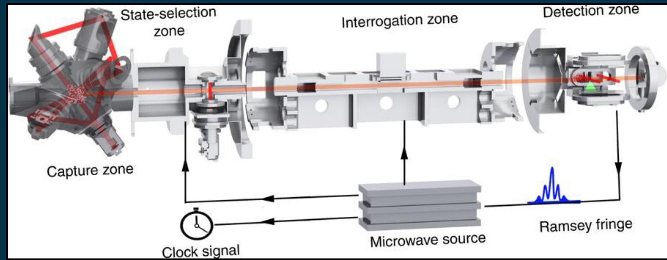


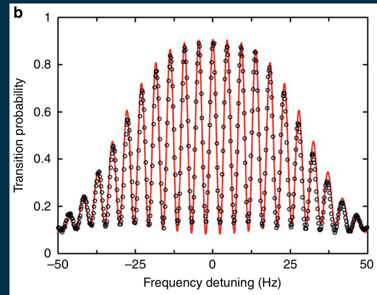
- Einstein Elevator (LP2N)
  - 0.4s free falling
  - Launch every tens seconds



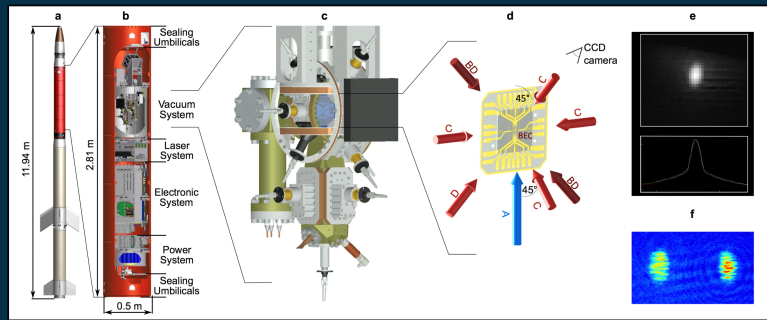
Road to Space

- In-Orbit Laser cooled 87-Rb Atomic Clock (Chinese Academy of Sciences), 2016

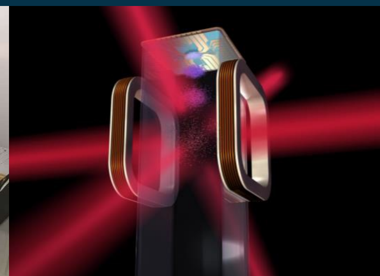




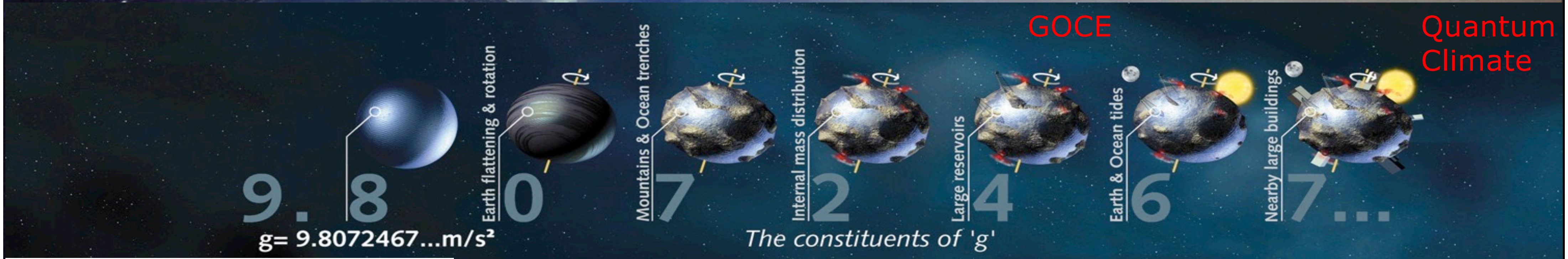
- MAIUS (DLR / Hannover), 2017: Sounding Rockets: First BEC in space

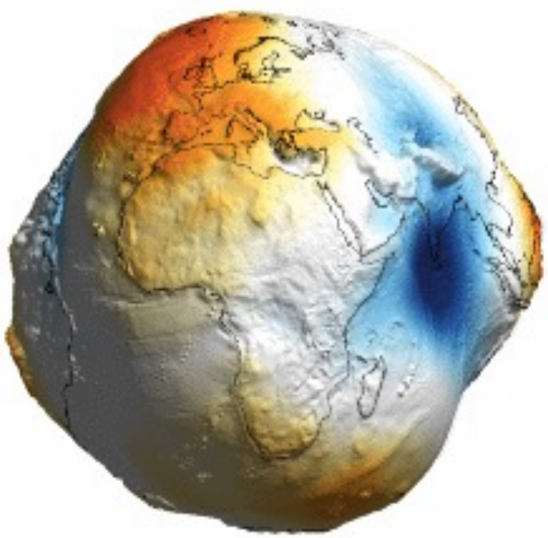


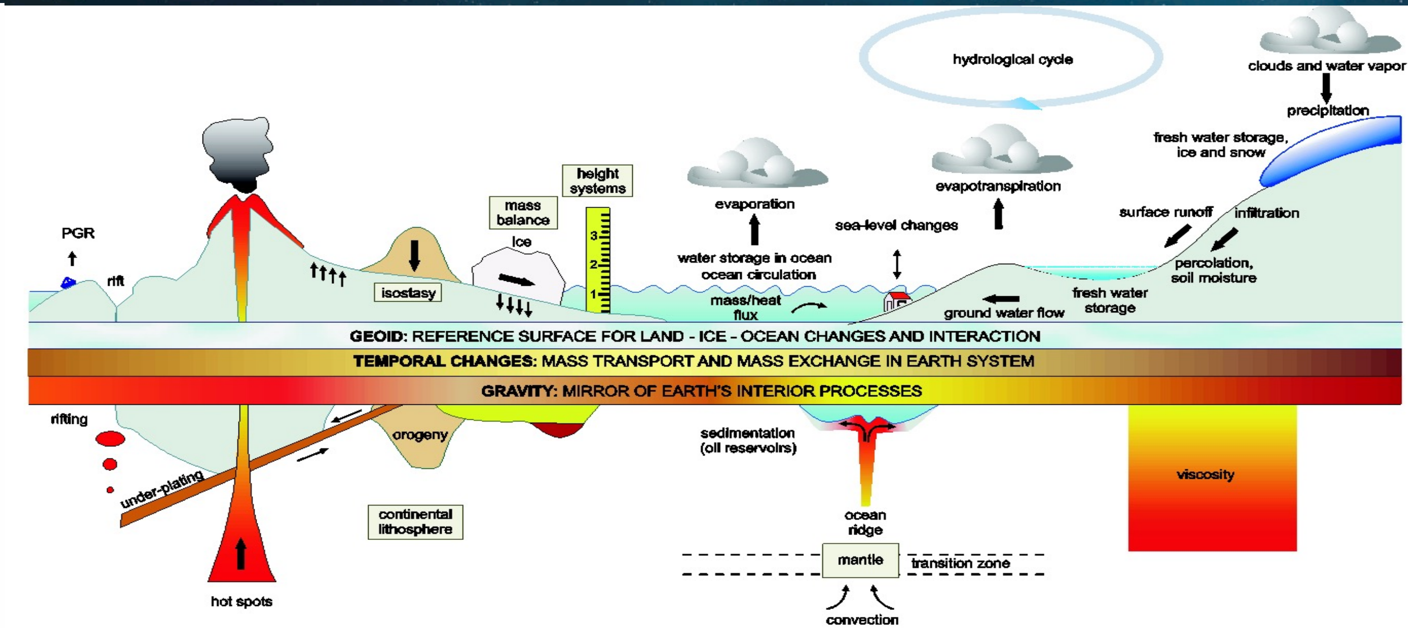
- Cold Atom Lab (NASA-JPL), 05/2018: Aboard the ISS



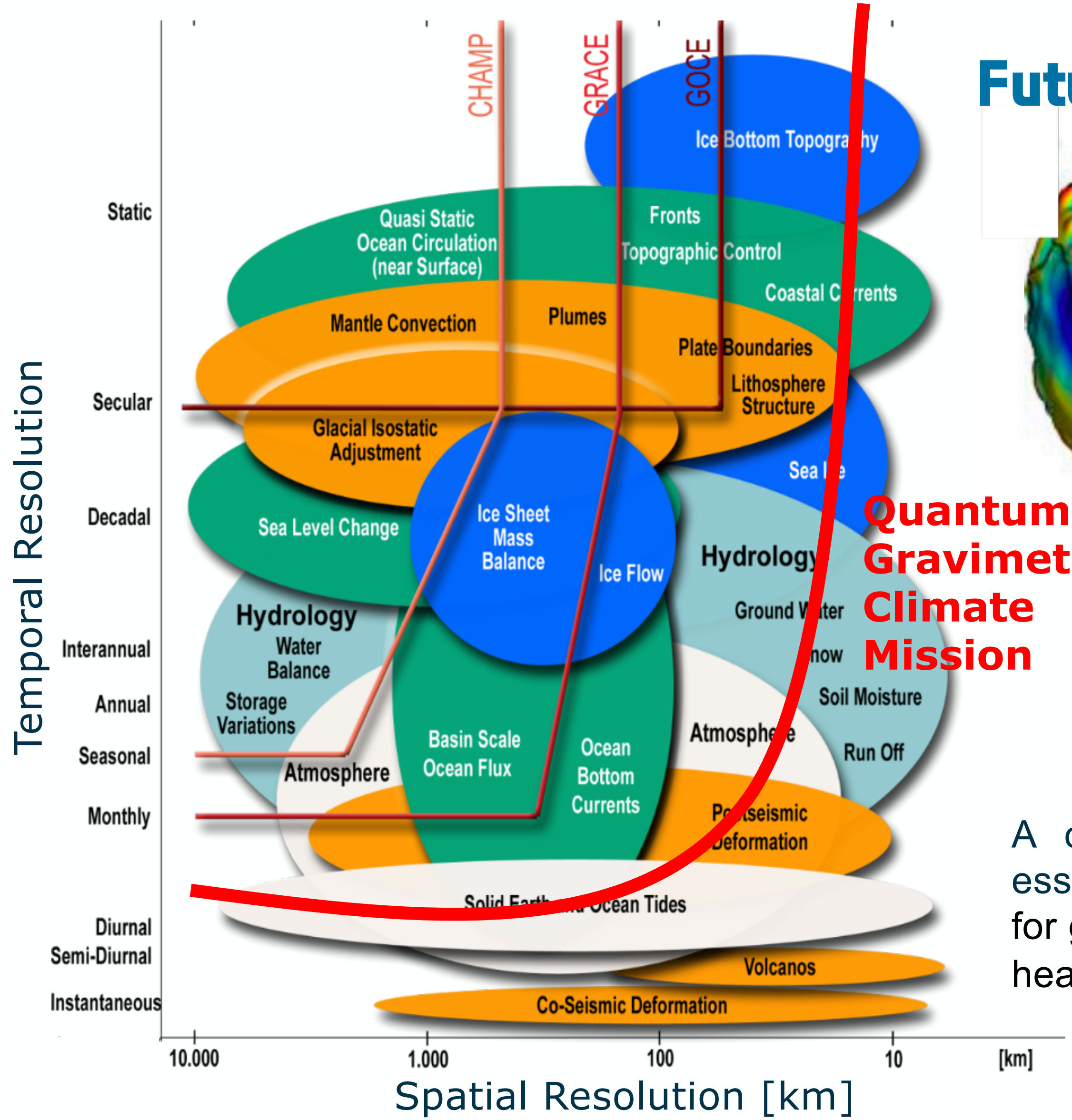
Higher resolution on Earth Gravity with Quantum Climate Mission



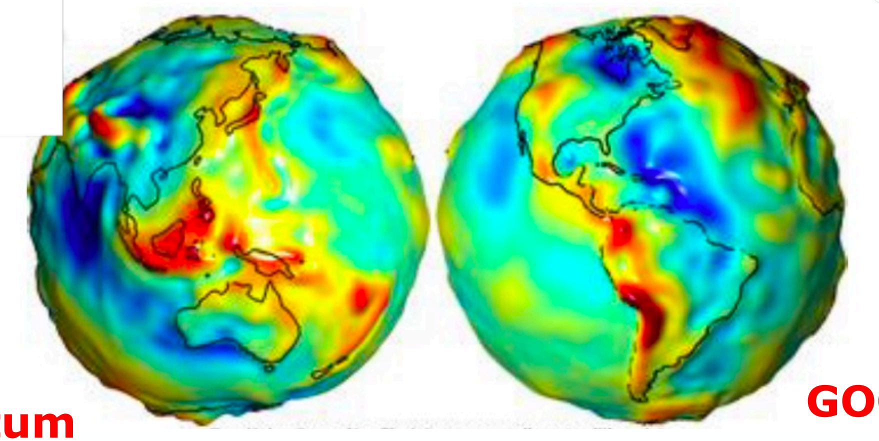




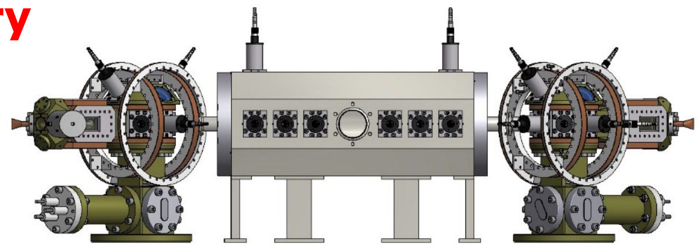
Future needs for Climate Monitoring



Quantum Gravimetry Climate Mission



GOCE

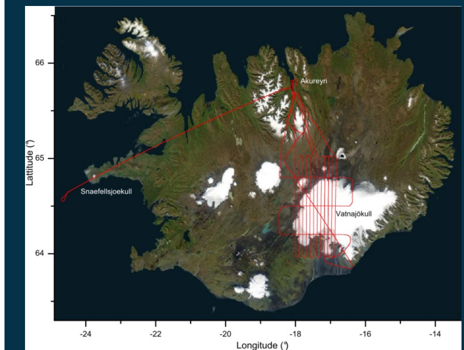


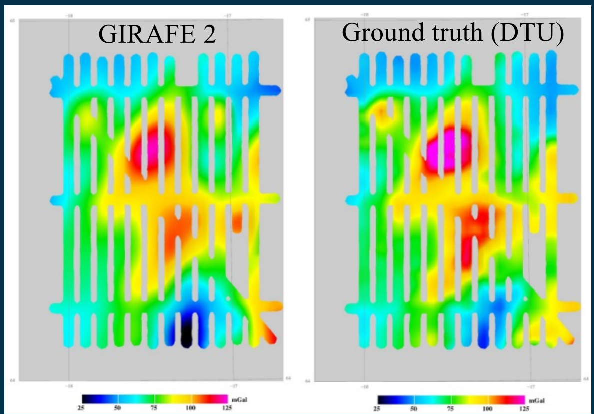
A cold atom Climate gravimetry mission will provide essential new climate variables of unprecedented quality for ground water, mass balance of ice sheets and glaciers, heat and mass transport, with huge benefits for humanity.

EOP Campaigns

1. CryoVex/KAREN 2017 Campaign:

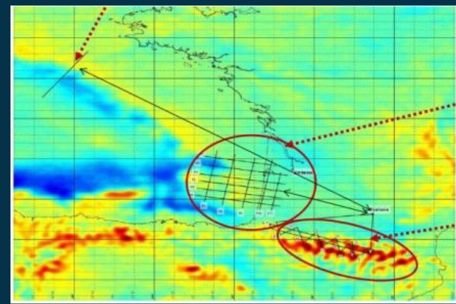
First successful airborne survey of a matter wave gravimeter

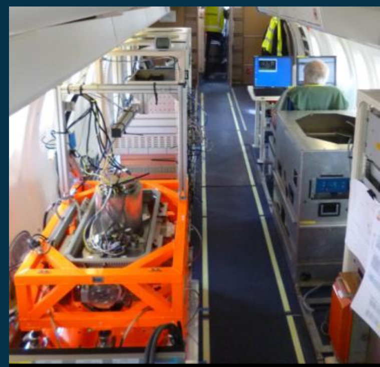


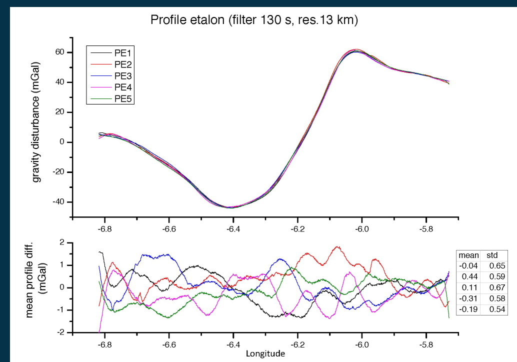


2. Airgravi Campaign (CNES-ESA):

Reaching state of the Art of standard campaign

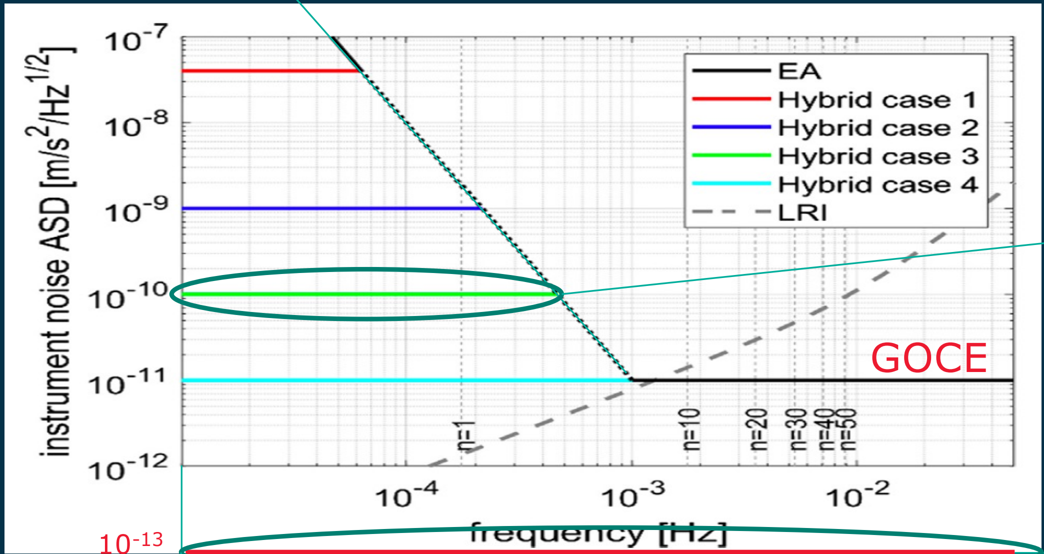






Precision Challenges for Cold Atom Sensors for EOP & fundamental physics community

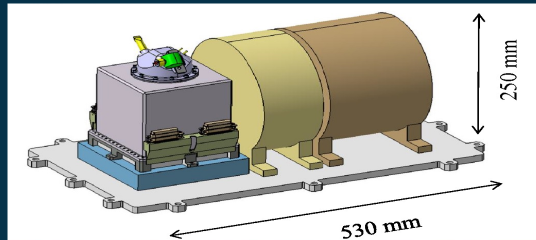
airborne



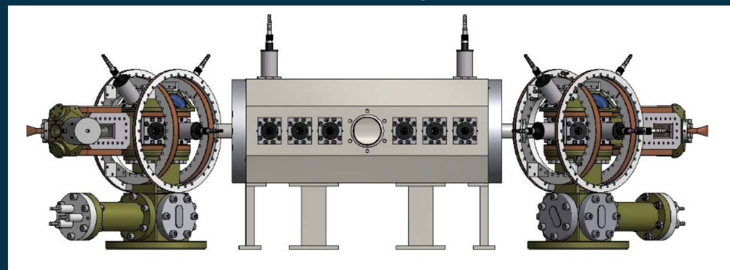
10^{-13}

10^{-20}

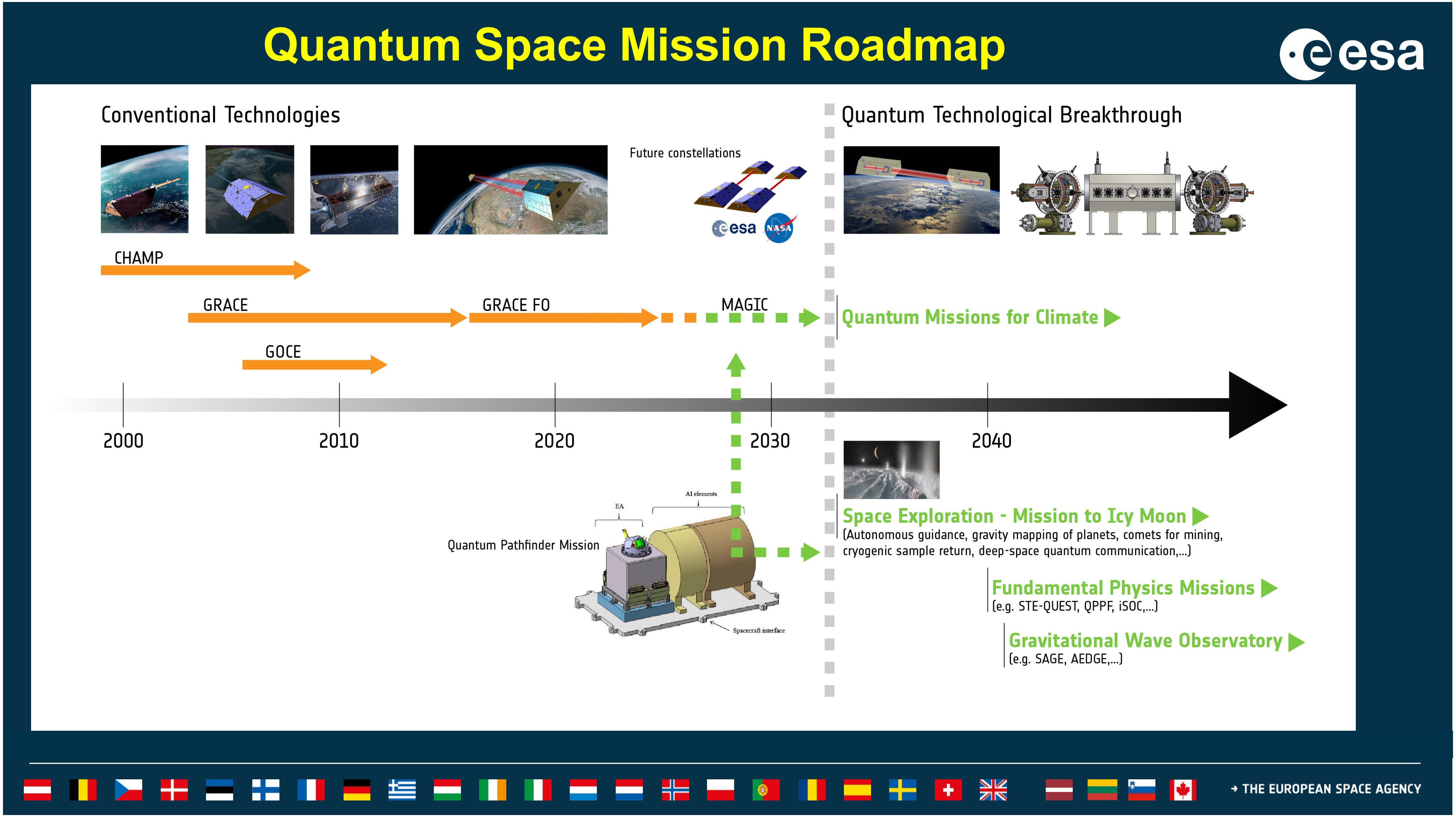
Quantum Pathfinder Mission



Quantum Climate & Icy Moon Mission



Fundamental Physics and Quantum Gravity Wave Mission



Quantum Space Mission Roadmap
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Conventional Technologies
Future constellations
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CHAMP
GRACE
GRACE FO
MAGIC
GOCE
2000
2010
2020
2030
2040
Quantum Pathfinder Mission
AI elements
EA
Spacecraft interface
Quantum Technological Breakthrough
Quantum Missions for Climate
Space Exploration - Mission to Icy Moon
(Autonomous guidance, gravity mapping of planets, comets for mining, cryogenic sample return, deep-space quantum communication,...)
Fundamental Physics Missions
(e.g. STE-QUEST, QPPF, iSOC,...)
Gravitational Wave Observatory
(e.g. SAGE, AEDGE,...)
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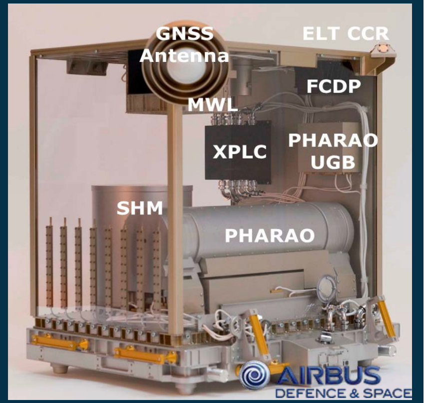
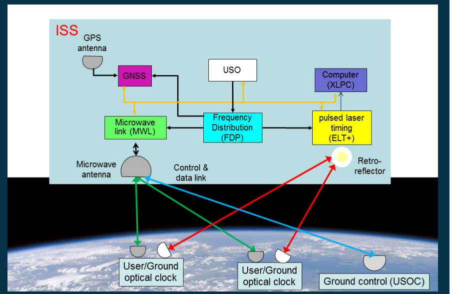
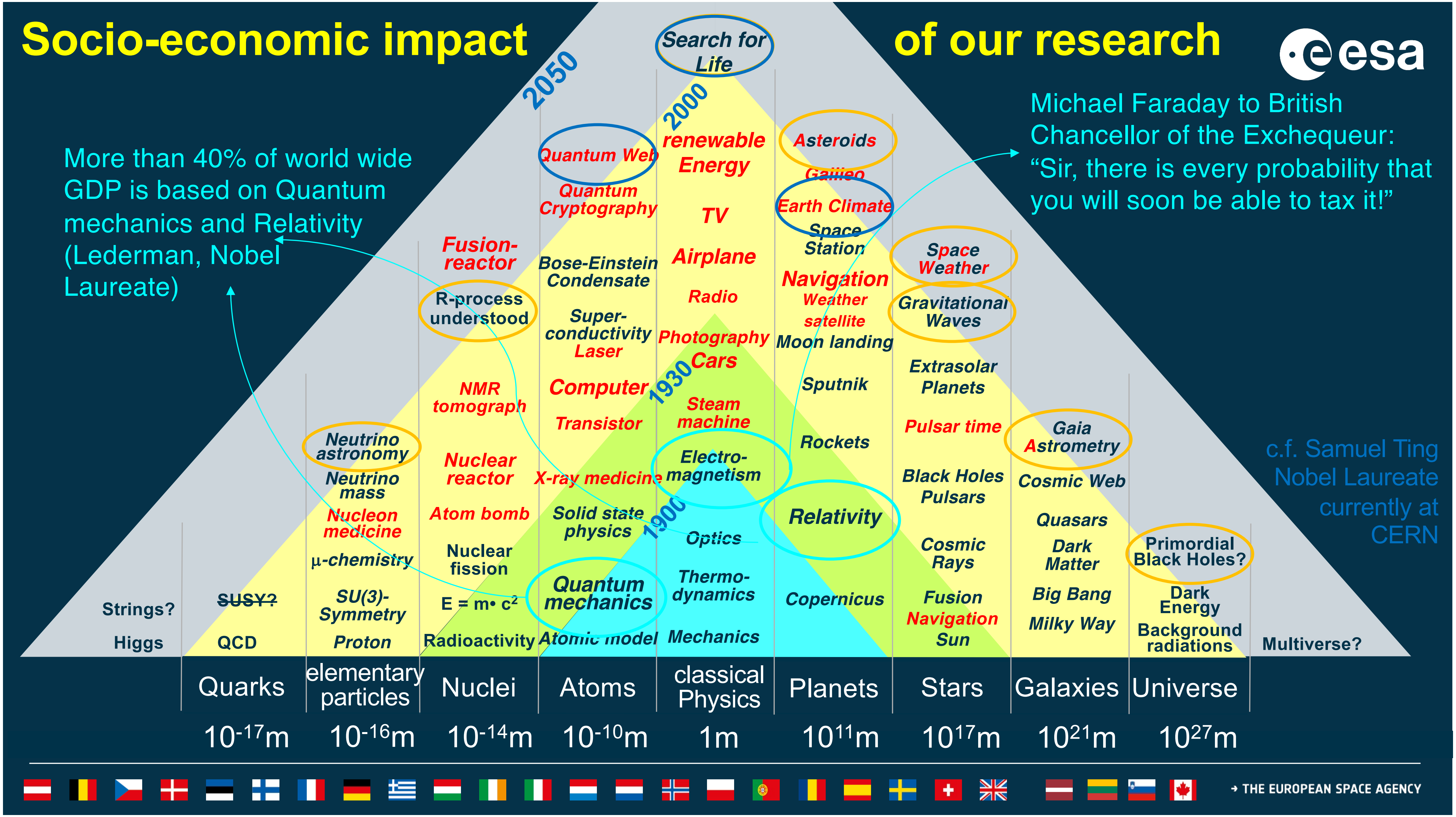
Space Clock Roadmap

- ACES
  - Absolute measurement of the gravitational red-shift at a precision < $50 \cdot 10^{-6}$ after 300 s and < $2 \cdot 10^{-6}$ after 10 days of integration time.
  - Time variations of the fine structure constant α at a precision level of $\alpha^{-1} \cdot d\alpha/dt < 1\cdot 10^{-17} yr^{-1}$ down to $3\cdot 10^{-18} yr^{-1}$ in case of a mission duration of 3 years.
  - Search for anisotropies of the speed of light at the level $\delta c / c < 10^{-10}$.
  - Launch to ISS in 2022 (TBC)
- ISOC Pathfinder
  - Measurement of the Sun gravitational time dilation (red-shift) effect to a fractional uncertainty of $2.5\cdot 10^{-5}$.
  - Measurement of the Moon gravitational time dilation (red-shift) effect to a fractional uncertainty of $4\cdot 10^{-3}$.
  - Enabling world-wide searches for time variation of fundamental constants and tests of the Standard Model Extension.
  - Contribution to the realization of atomic time scales to fractional frequency inaccuracy lower than $1\cdot 10^{-18}$ and synchronized to the few ps level.
  - Enable mapping of the geopotential on the land masses of North America, South America, Africa, Europe, Asia, Australia, with approximately 300 km×300 km grid size using transportable $1\cdot 10^{-18}$ clocks, with a resolution of 0.15 m^2/s^2 (1.5 cm on the differential geoid height).
  - Inter-and intracontinental differential geopotential measurements with resolution in the gravitational potential U at the level down to 0.05 m^2/s^2 (0.5 cm on the differential geoid height).
- Future Space Optical Clock
  - Optical frequency reference (Sr clock laser) and femto-second frequency comb generator
  - Sr optical lattice clock physics package







Socio-economic impact of our research
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Michael Faraday to British Chancellor of the Exchequeur: “Sir, there is every probability that you will soon be able to tax it!”
More than 40% of world wide GDP is based on Quantum mechanics and Relativity (Lederman, Nobel Laureate)
c.f. Samuel Ting Nobel Laureate currently at CERN
2050
2000
1930
1900
Search for Life
Quantum Web
Quantum Cryptography
renewable Energy
TV
Airplane
Radio
Photography
Cars
Asteroids
Galileo
Earth Climate
Space Station
Navigation
Weather satellite
Moon landing
Sputnik
Rockets
Space Weather
Gravitational Waves
Extrasolar Planets
Pulsar time
Black Holes Pulsars
Cosmic Rays
Fusion
Navigation
Sun
Fusion-reactor
R-process understood
NMR tomograph
Nuclear reactor
Atom bomb
Nuclear fission
E = m• c²
Radioactivity
Bose-Einstein Condensate
Super-conductivity
Laser
Computer
Transistor
X-ray medicine
Solid state physics
Quantum mechanics
Atomic model
Steam machine
Electro-magnetism
Optics
Thermo-dynamics
Mechanics
Relativity
Copernicus
Neutrino astronomy
Neutrino mass
Nucleon medicine
μ-chemistry
SU(3)-Symmetry
Proton
Strings?
Higgs
SUSY?
QCD
Gaia Astrometry
Cosmic Web
Quasars
Dark Matter
Big Bang
Milky Way
Primordial Black Holes?
Dark Energy
Background radiations
Multiverse?
Quarks
elementary particles
Nuclei
Atoms
classical Physics
Planets
Stars
Galaxies
Universe
10-17m
10-16m
10-14m
10-10m
1m
1011m
1017m
1021m
1027m
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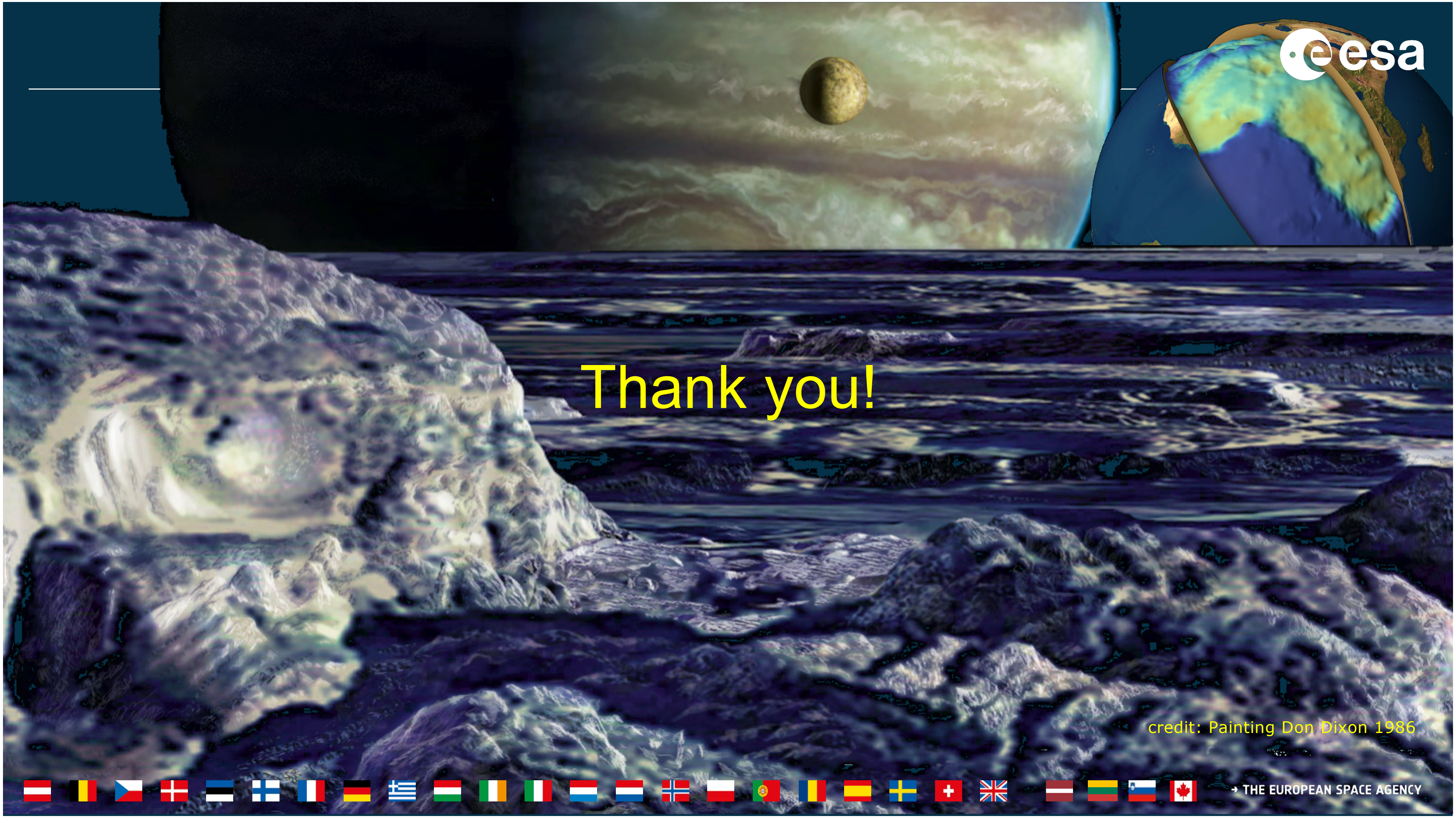
Examples of long-term economic benefits from basic science

- Electromagnetism (Faraday)
- Quantum Mechanics (Fraunhofer Lines, Ultraviolet Catastrophe, Planck/Heisenberg/Einstein et al., electronics …)
- Relativity (Mercury perihelium, Einstein, GNSS)
- The Maser/Laser (Astrophysical Molecules, fabrication …)
- The World-Wide Web (ARPA, CERN, Internet of Things …)
- The iPhone (WIFI, CCDs, Navigation, Lidar …)
- Glass (Pyrex, Zerodur, ceramic induction stoves, multifocal lenses from X-ray astronomy…)
- Medical applications from astronomy (adaptive optics for eye surgery, cancer detection algorithms, cold plasma healing, …)
- Dutch company ASML with global SMD market dominance spun out from TNO astronomy group …
- COSINE company spun out of ESTEC: world leader in X-ray optics and high-tech applications
- Many technologies developed for science/EOP in European Industry used on multitude of spacecraft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Thank you!
credit: Painting Don Dixon 1986
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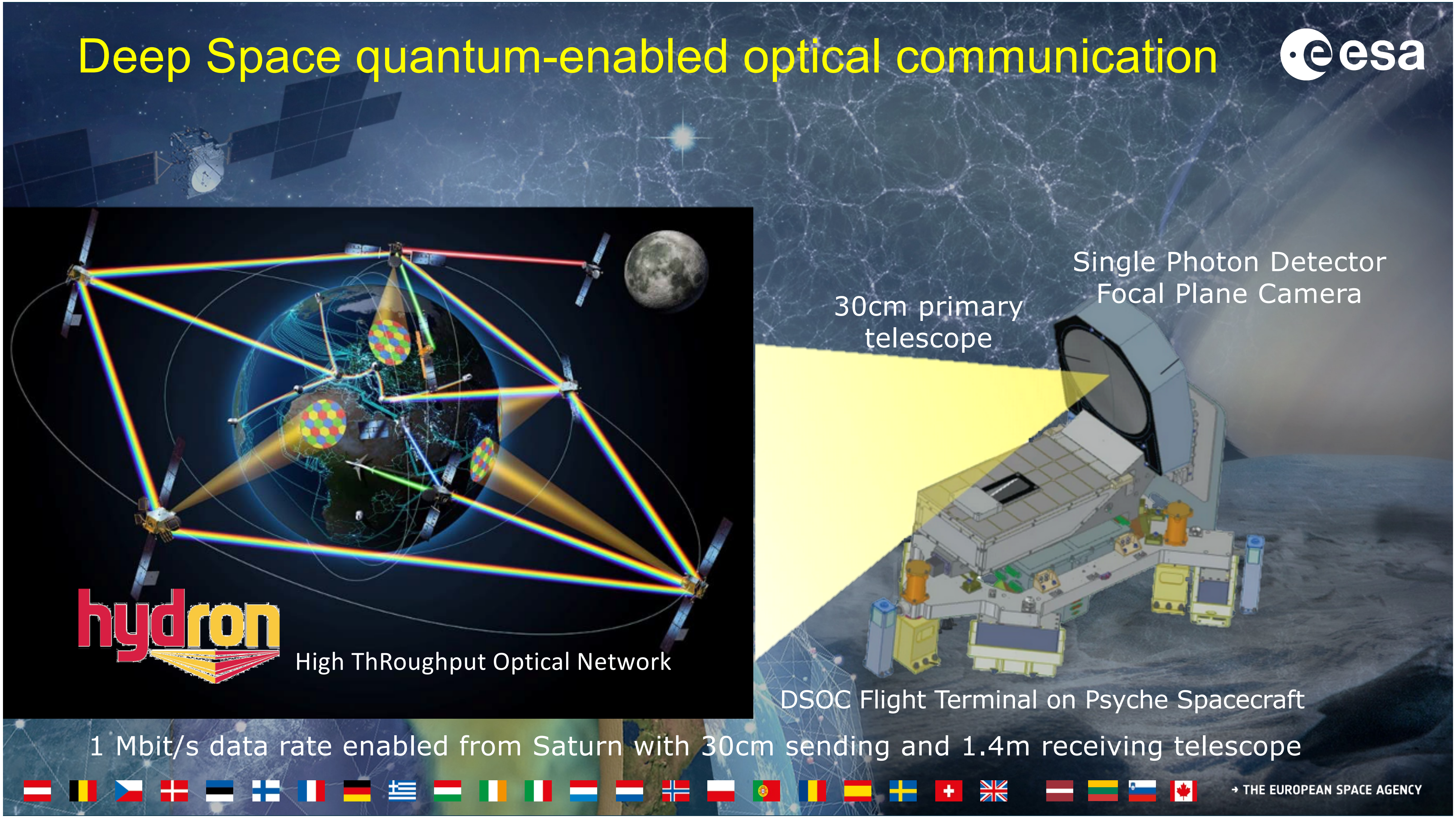
Deep Space quantum-enabled optical communication
esa
hydron
High ThRoughput Optical Network
30cm primary telescope
Single Photon Detector Focal Plane Camera
DSOC Flight Terminal on Psyche Spacecraft
1 Mbit/s data rate enabled from Saturn with 30cm sending and 1.4m receiving telescope
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