The future of cosmology

Joseph Silk

IAP, JHU, Oxford

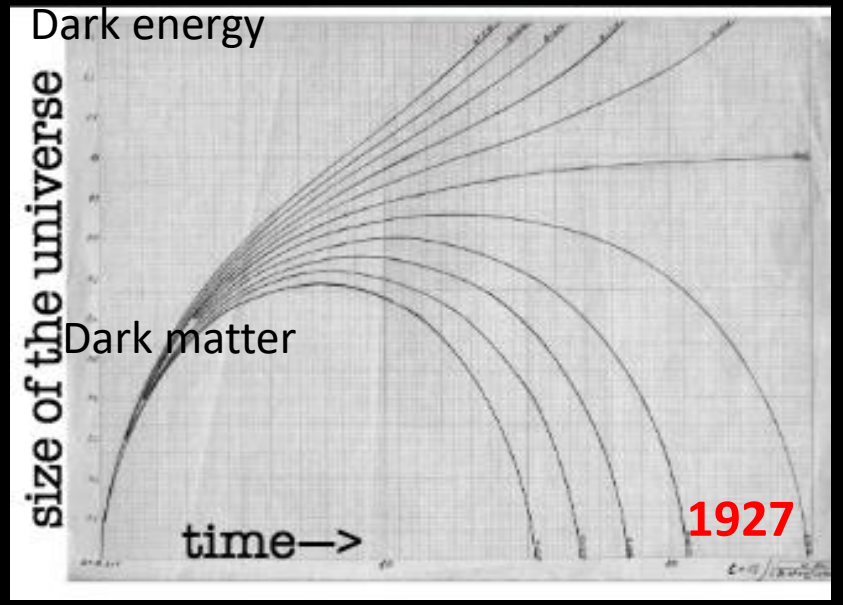
15 June 2024

The birth of modern cosmology

Georges Lemaitre

the energy *in vacuo* would be different from zero. In order that absolute motion, i.e., motion relative to vacuum, may not be detected, we must associate a pressure $p = -\rho c^2$ to the density of energy ρc^2 of vacuum. This is essentially the meaning of the cosmical constant λ which corresponds to a negative density of vacuum ρ_0 according to

1933



Inflation was a great success, c. 1980!


Alexei Starobinsky


Alan Guth


Andrei Linde


Andreas Albrecht


Paul Steinhardt

Our biggest questions

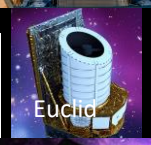
Beginning?

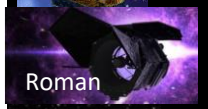
Dark ages?

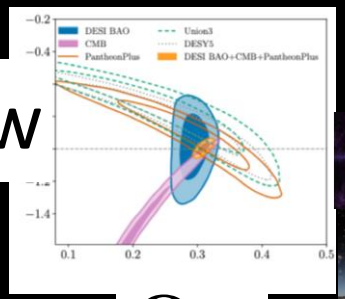
Are we alone?

current progress in cosmology

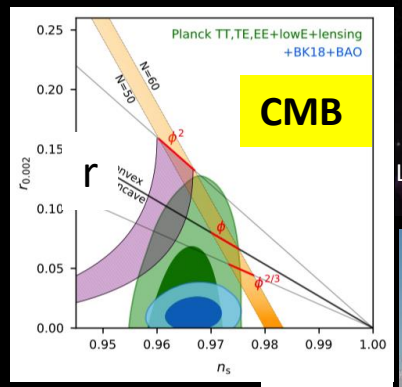
dark energy

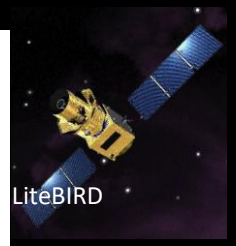


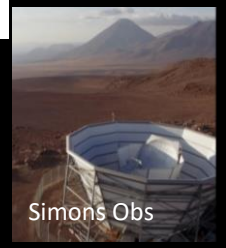




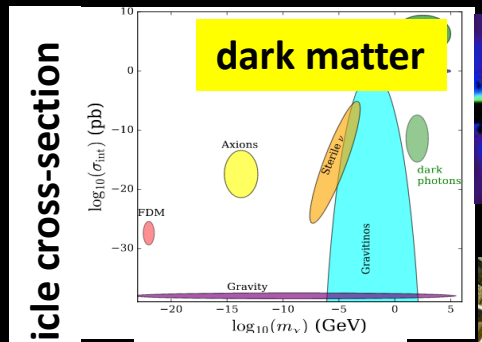
CMB

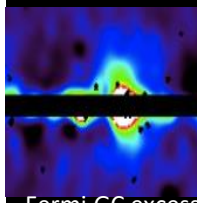






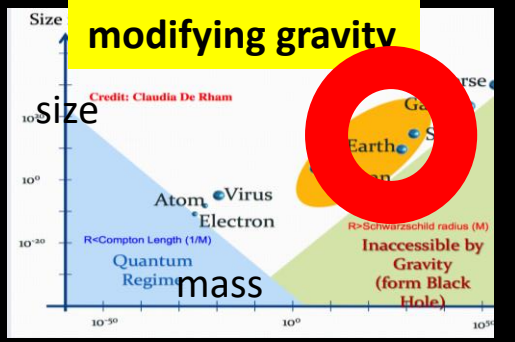
dark matter





seeking SUSY

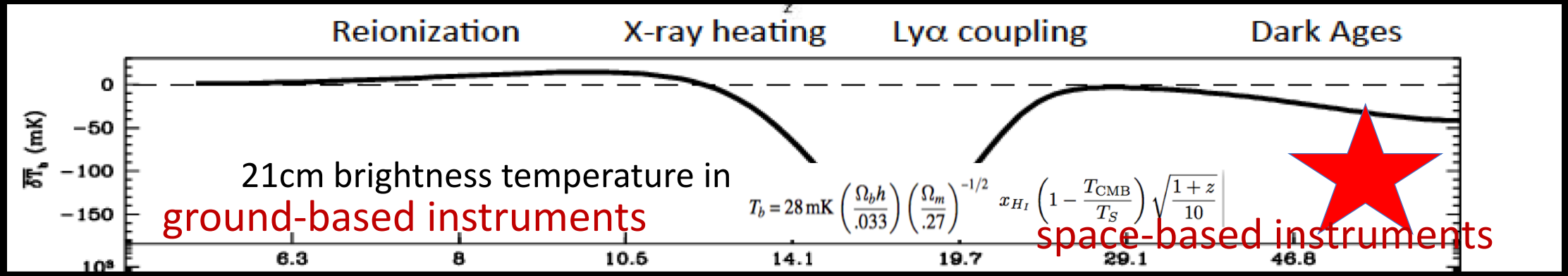
modifying gravity



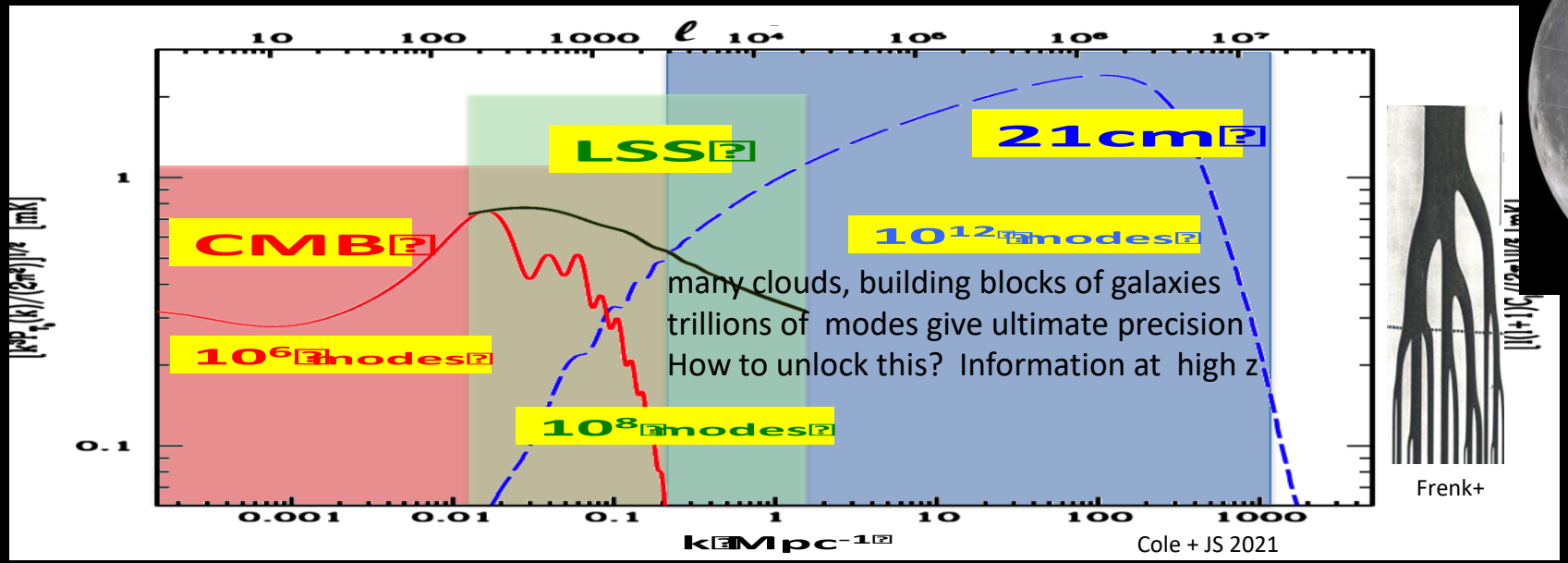
in common for all current or planned experiments:

no guaranteed return!

1 Dark ages are new frontier



Where? there's only one place to go: the far side of the Moon

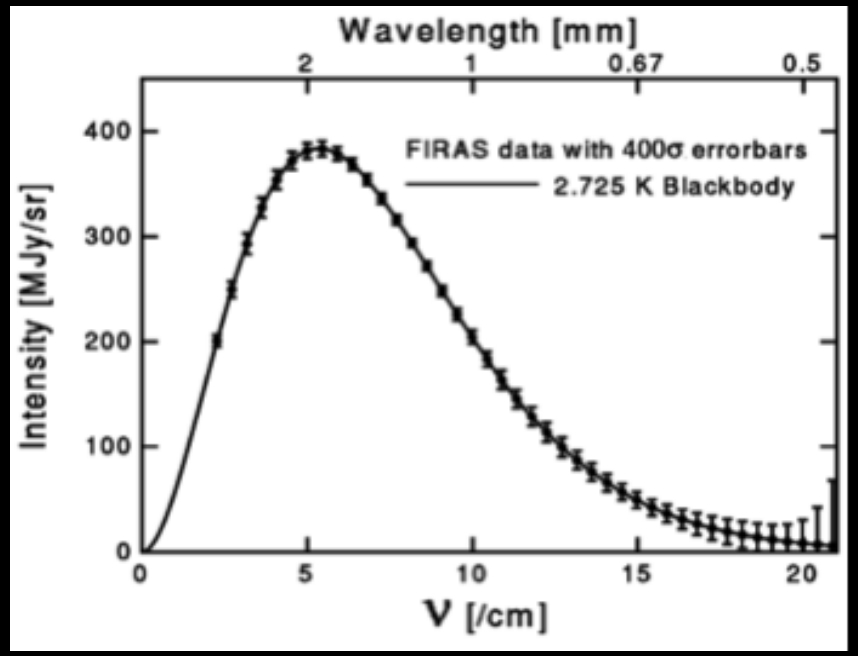


Frenk+

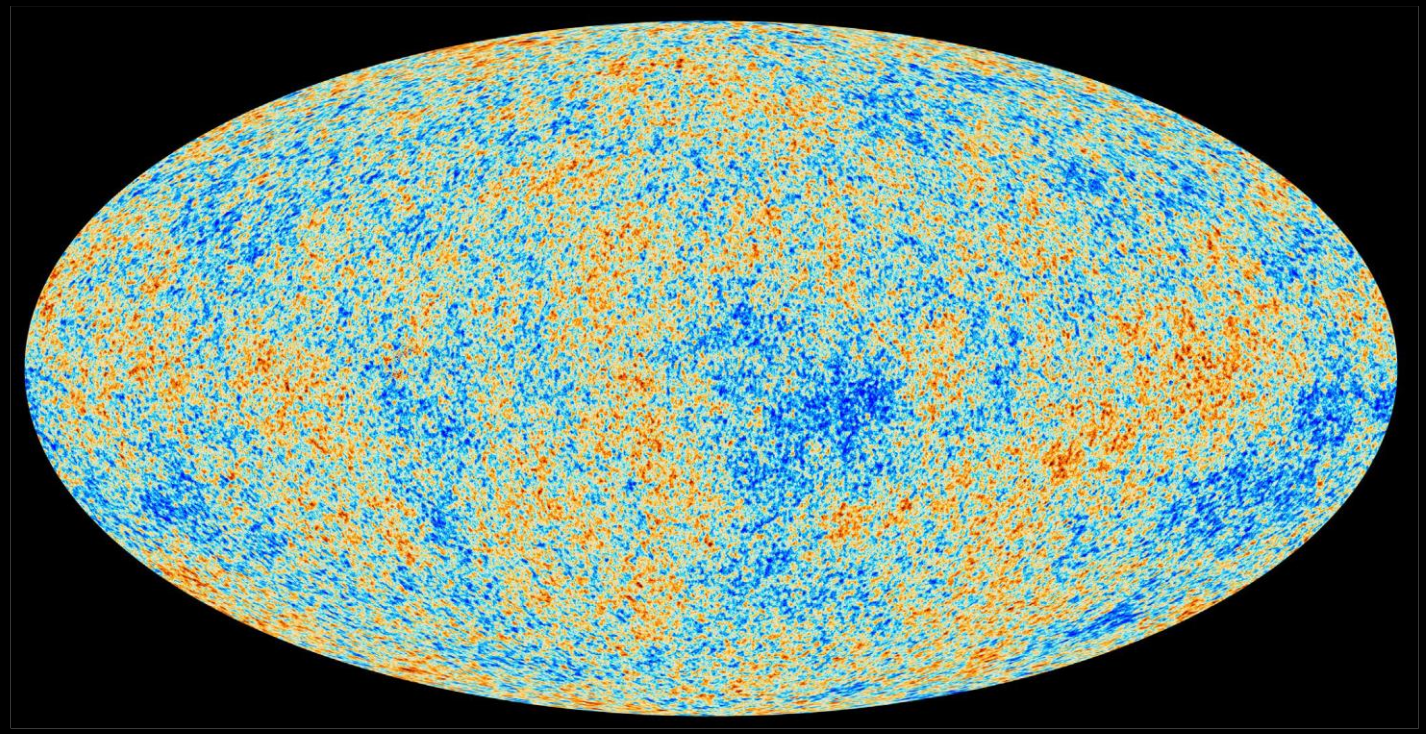
- no ionosphere
- no terrestrial radio interference
- most radio quiet environment in inner solar system

Analogy with the CMB

1990. COBE



2018. PLANCK



First: detection of the dark ages shadow

Next: the fluctuations

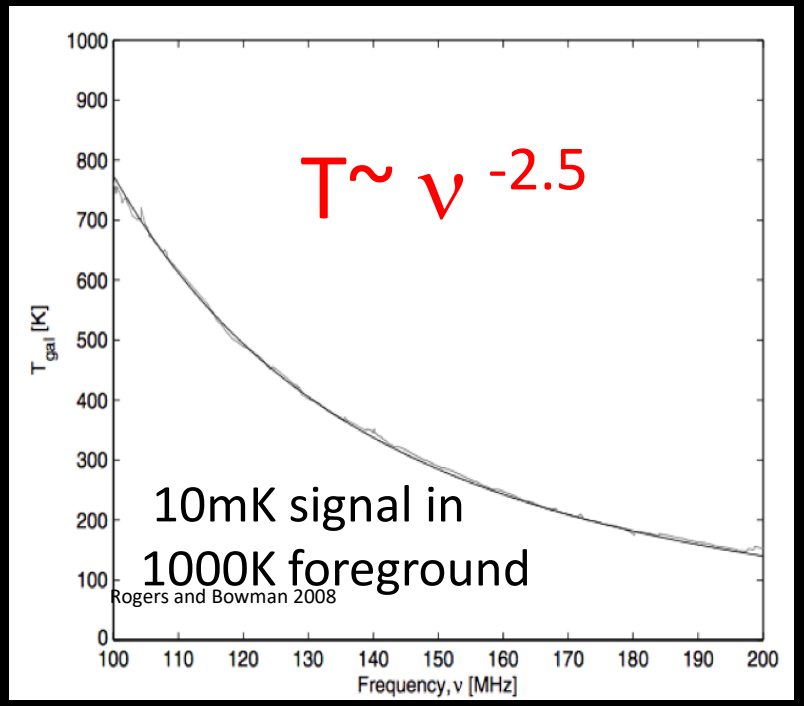
Lunar far side interferometer

21cm: probe z=50 at λ~ 10 m or 30MHz
100 x CMB resolution ℓ ~ 10^5 or k~ 10Mpc^{-1}
Optimal array ℓ $\lambda/2\pi$ or D~100 km
Sensitivity: millions of dipoles: $\frac{D^2}{4\lambda^2}$ ~10^6

$\delta T/T\ (1+ f_{NL}\ \delta T/T)$

f_{NL} ~ -5/12 (n_s-1) ~ 0.01 n_s=0.96 (9 σ)

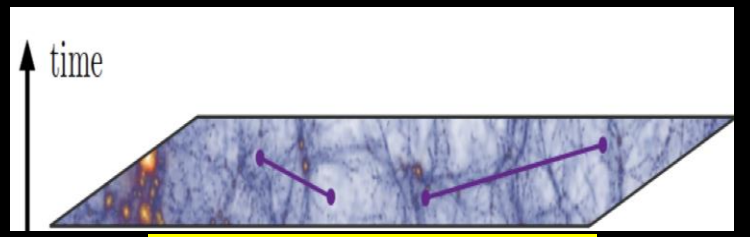
Maldacena 2003, Cabass + 2017; Mattarese + 2021



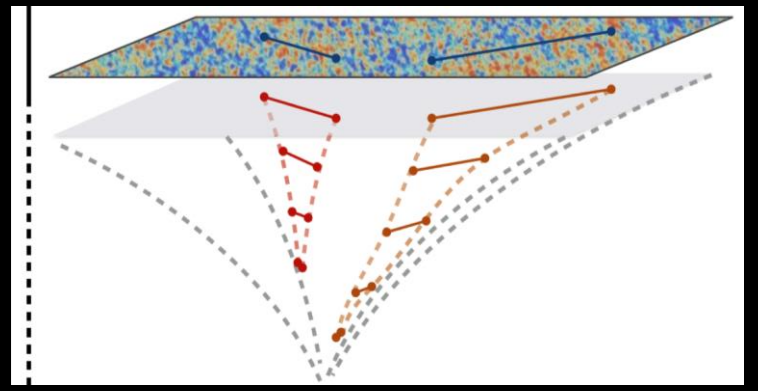
N ~ 10^6
CMB pixels f_{nl}~10

N~ 10^8
galaxies f_{nl}~1

N~ 10^{12}
hydrogen clouds f_{nl}~0.01

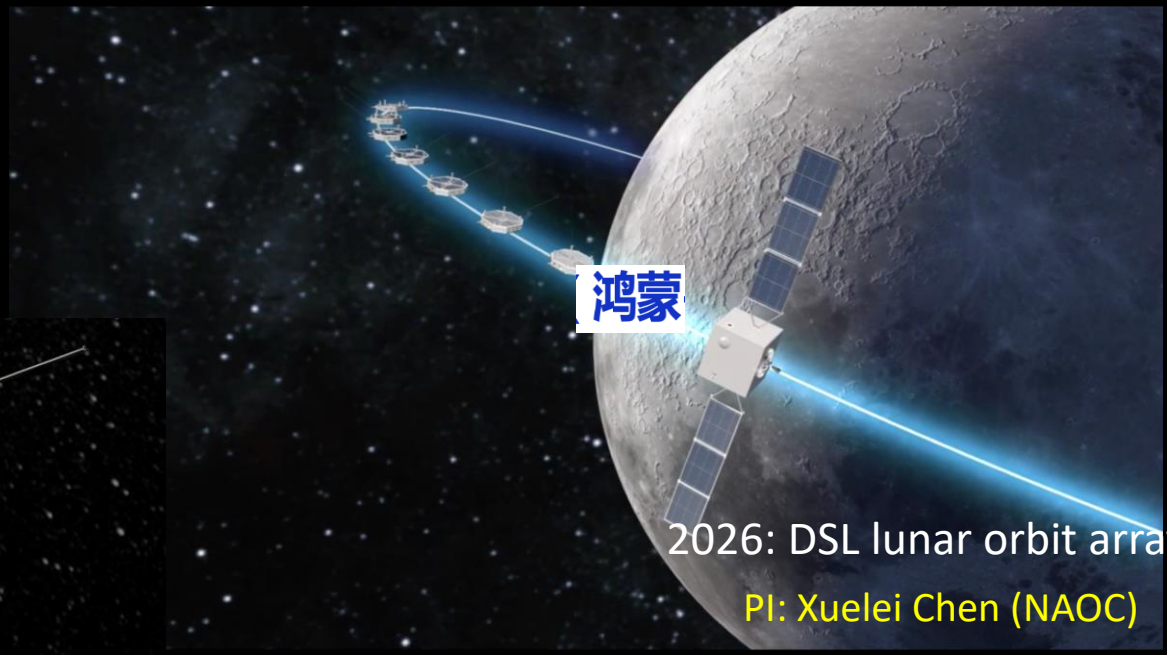


dark ages 21cm



Test inflation via primordial nongaussianity: ultimate precision cosmology

Its happening soon: 2026!



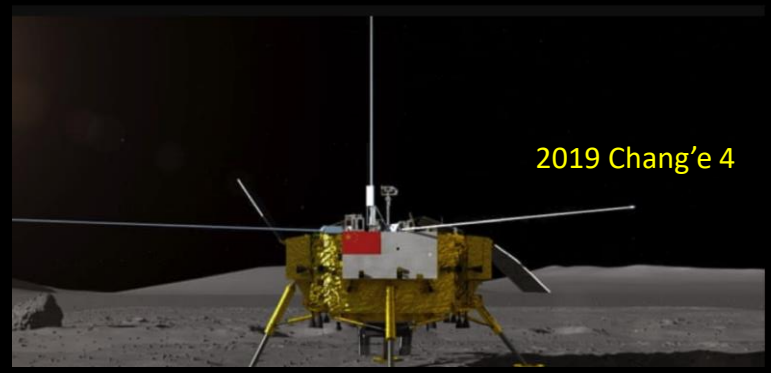
2026: DSL lunar orbit array 8 +1

PI: Xuelei Chen (NAOC)

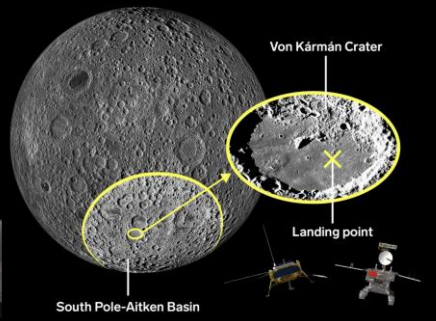
NASA CLPS LUSEE-Night **PI: Stuart Bale (UCB)**

Launch – December 2025 on Falcon 9. Land: January 2026

Firefly Aerospace 'Blue Ghost' lunar lander



2019 Chang'e 4



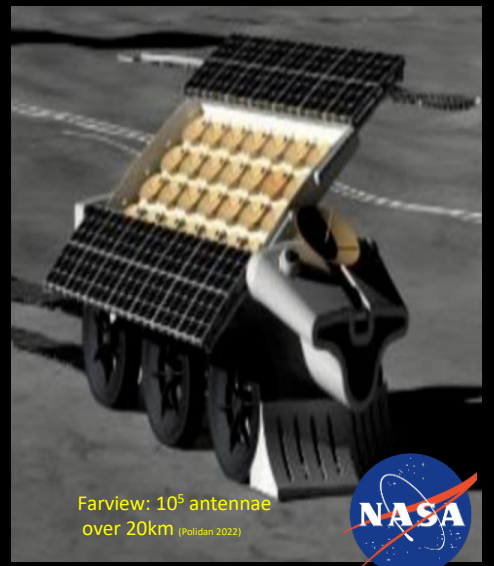
2030-2050: lunar radio telescopes

SKA-Low: an array of 100000+ 50-350 MHz antennae in Western Australia: 2028

We can do this!

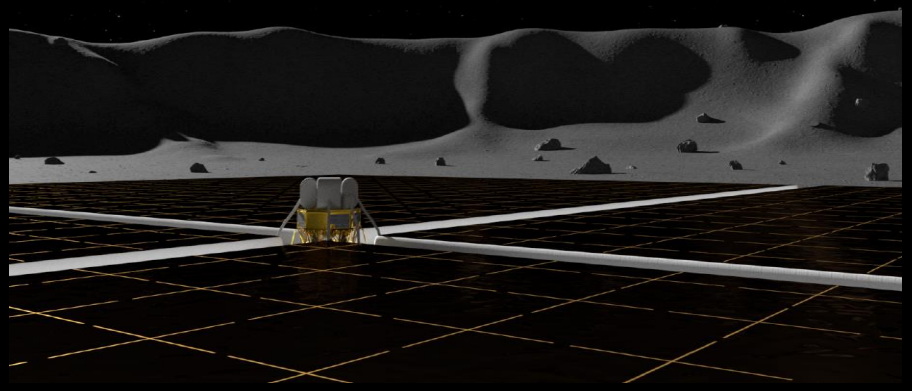
FAST 500m Guizhou China

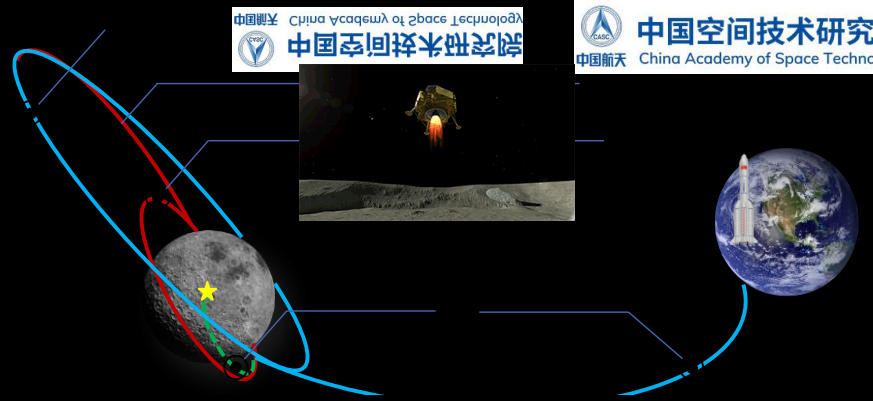
FARSIDE 128 antennae PI: Jack Burns



ESA. Astronomical Lunar Observatory

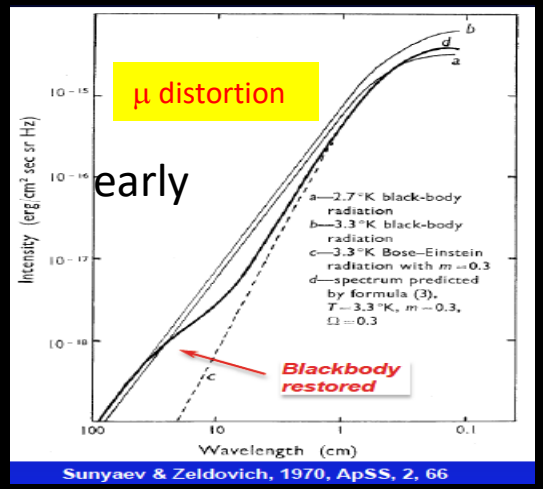
- One single EL3 lander as central unit
- Minimal: 32*32 elements

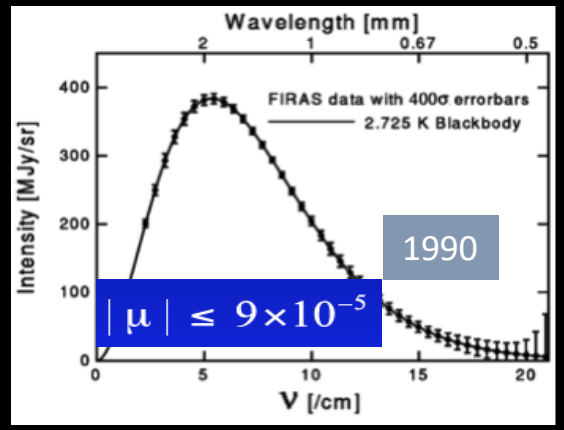




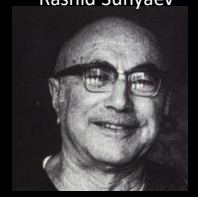
LARAF: 270 dipoles, 10 km

2. Cosmic microwave background radiation





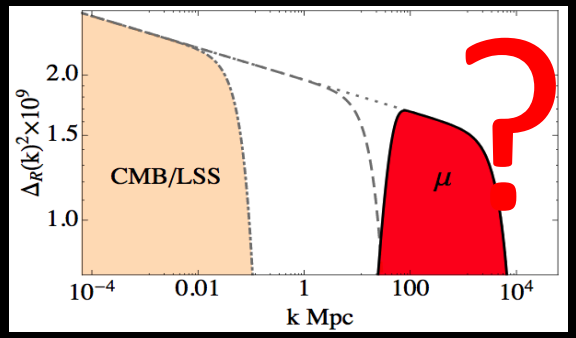

Rashid Sunyaev


Yaakov Zeldovich

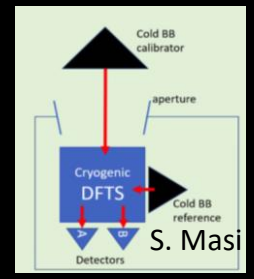
bottom-up formation is fundamental prediction of cold dark matter cosmology

the most perfect blackbody is in the sky.
Trillions of modes from dwarf galaxy precursors inject early energy --> spectral distortions

Fourier transform interferometer in space
PIXIE rejected (2011, 2017) by NASA MIDEX: 55cm telescope $\mu < 10^{-8}$

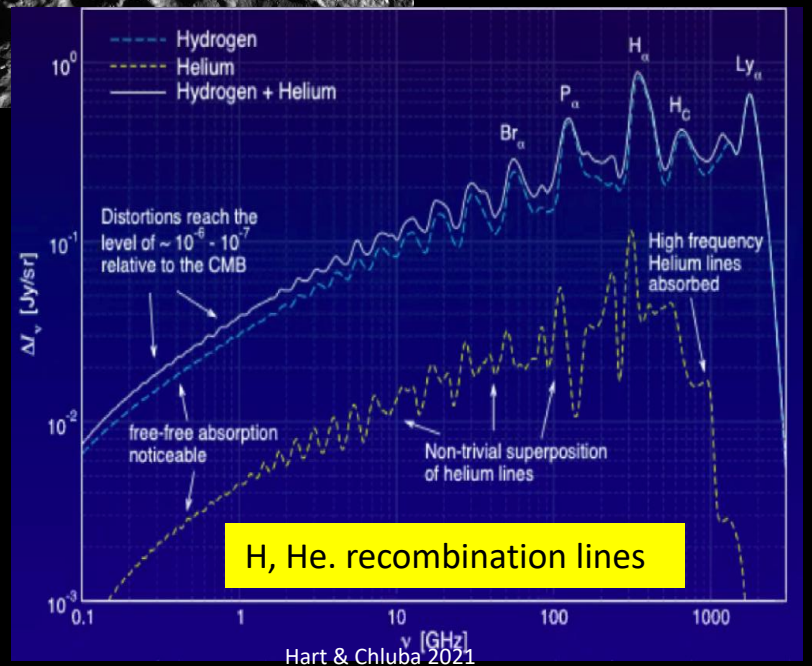


ESA Voyage2050: CMB spectral distortion
L class mission. 1m telescope + FTS $\mu < 10^{-9}$

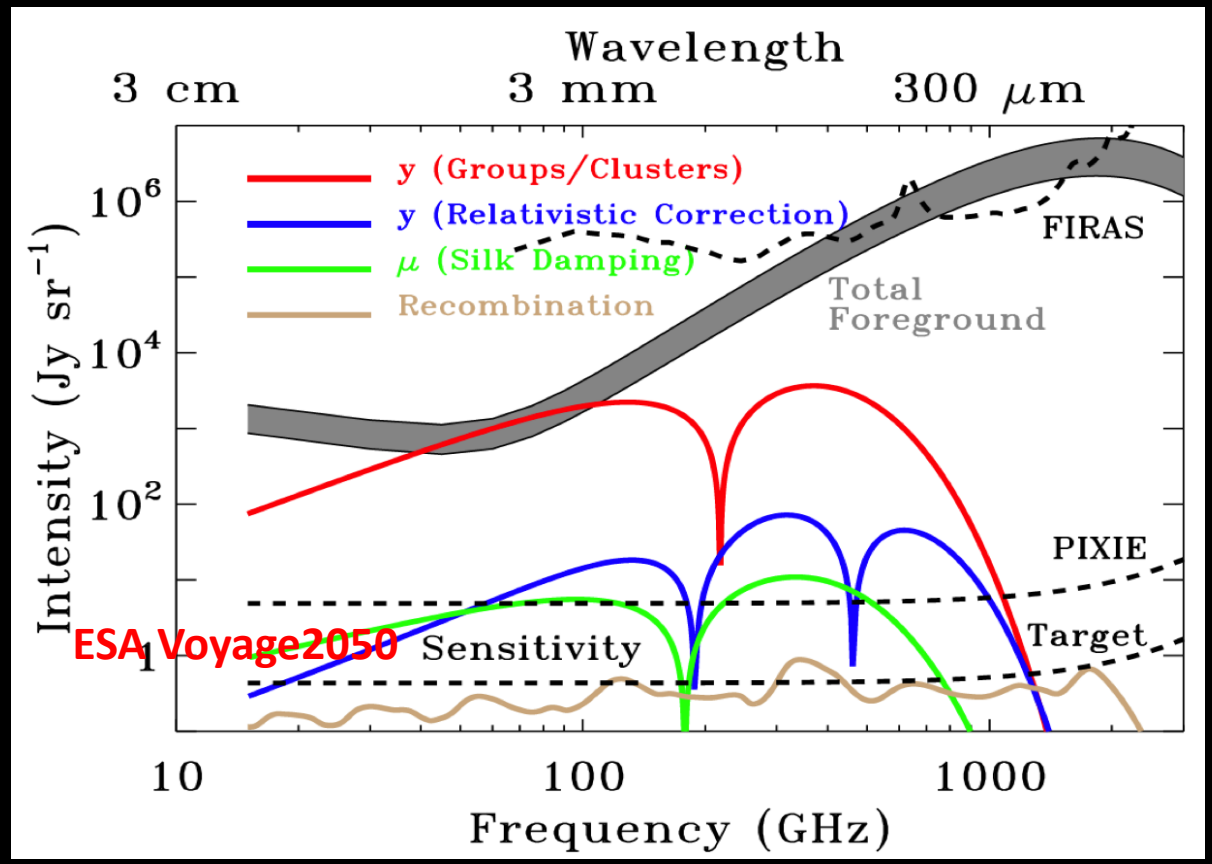


Why not on the moon?

90--2000 GHz bolometer array in a ~30K permanently dark crater
1 m telescope cooled to 2.5 K.
Scan sky by lunar rotation. Sunlit rims for perpetual solar power
Probe $\mu \sim 10^{-9}$ COBE FIRAS 1990 $\mu > 5.10^{-5}$

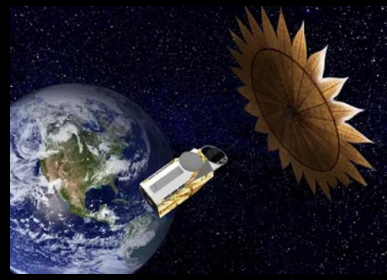


Hart & Chluba 2021



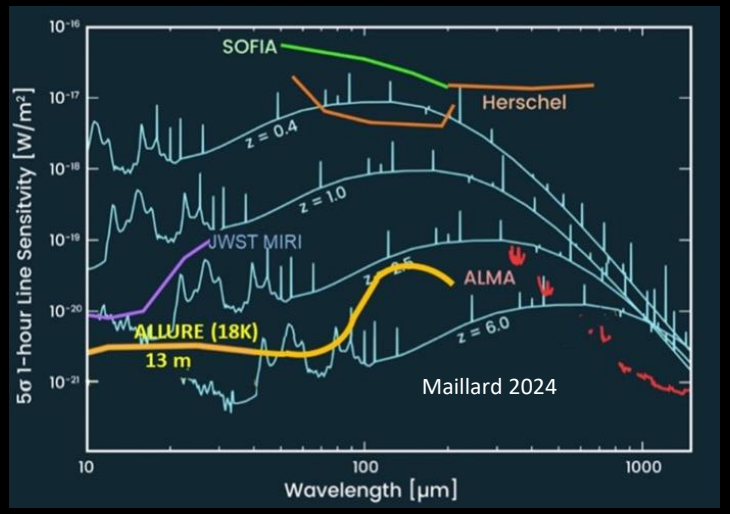
3. Lunar optical/IR telescopes

6.5m HWO
Habitable Worlds Observatory

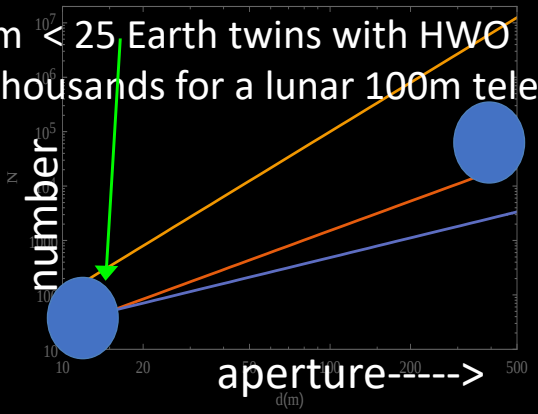


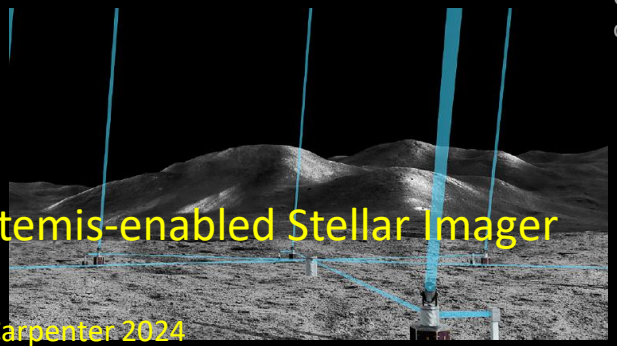
no atmosphere: FIR spectroscopy
larger apertures: exoplanet numbers and resolution

Chinese 15cm telescope
observing since 2014



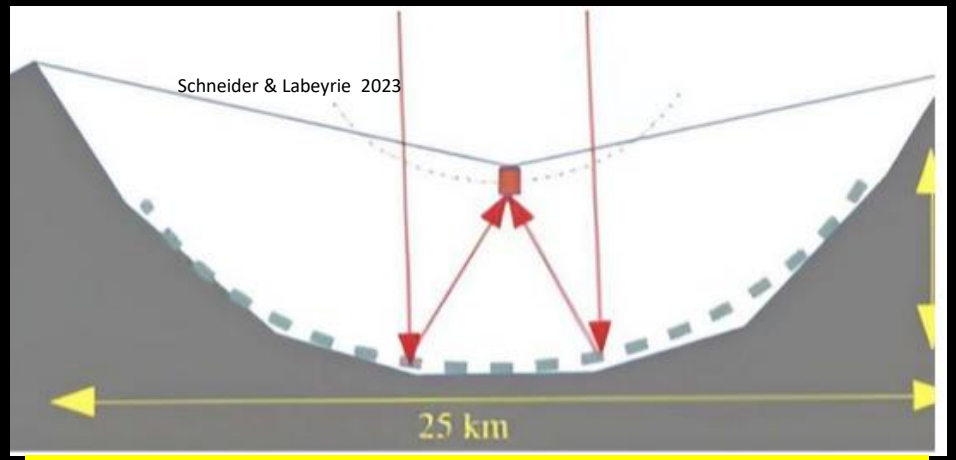
from < 25 Earth twins with HWO
to thousands for a lunar 100m telescope!





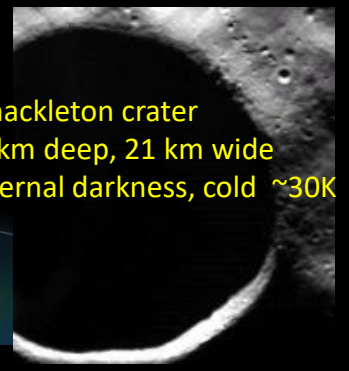
Artemis-enabled Stellar Imager

K. Carpenter 2024



Optical/IR interferometer in lunar polar crater

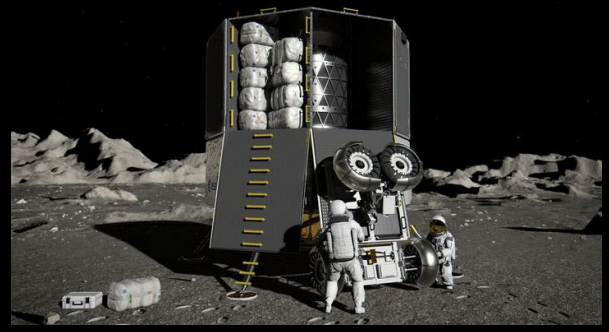
Integrate combining beams for hours vs msec on Earth
10μsec resolution at Trappist-1 system at 12.5 pc



Shackleton crater
4 km deep, 21 km wide
eternal darkness, cold ~30K

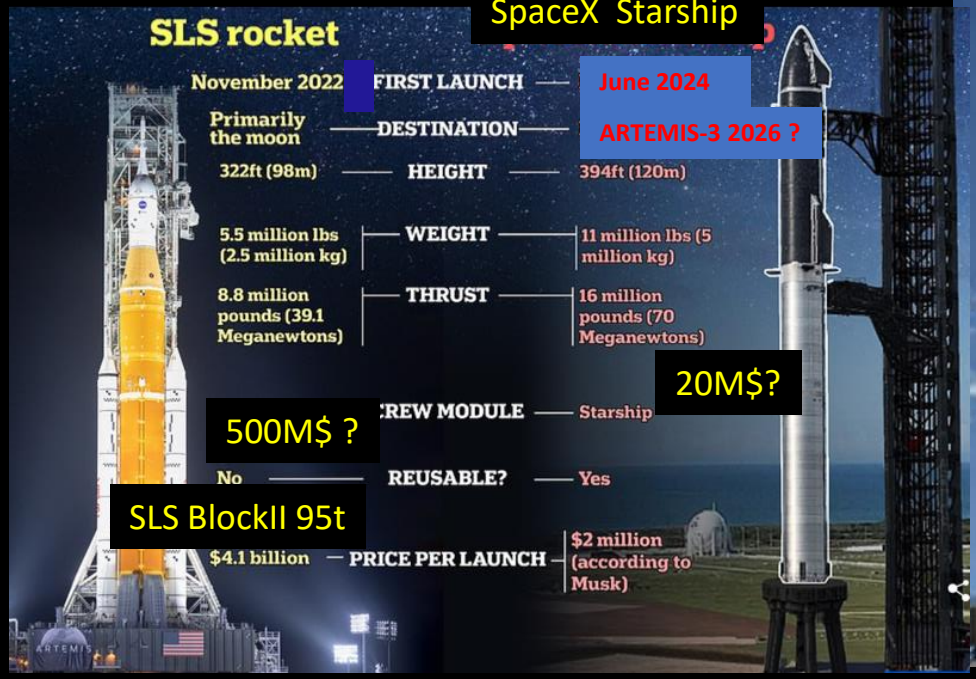
Is it too expensive?

- NASA commercial launch providers
- ESA's Argonaut lander 1.5 ton payload
- Larger lunar payloads are feasible
- Telescopes will piggyback on lunar exploration: cf HST
- Chinese astronauts on Moon by 2030
- Launch costs/ton are plummeting



Elon Musk

Jeff Bezos

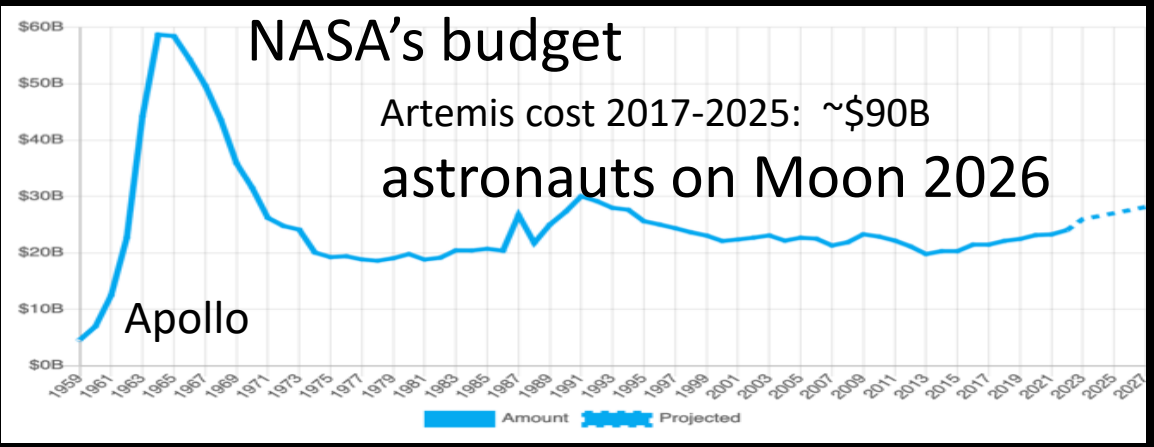


SpaceX Starship

20M$?

500M$?

SLS BlockII 95t



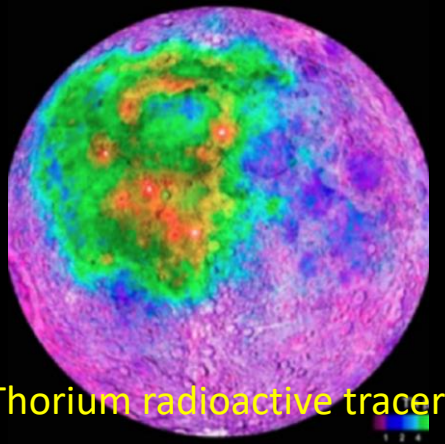
Competition

rare earth mining

Earth: 140 megatonnes (China 55 Mt, US 14 Mt)

Terrestrial reserves are limited

The Moon has huge reserves: a trillion tons



Thorium radioactive tracer

ice mining

Icy polar craters

India's Chandrayaan-1

tourism

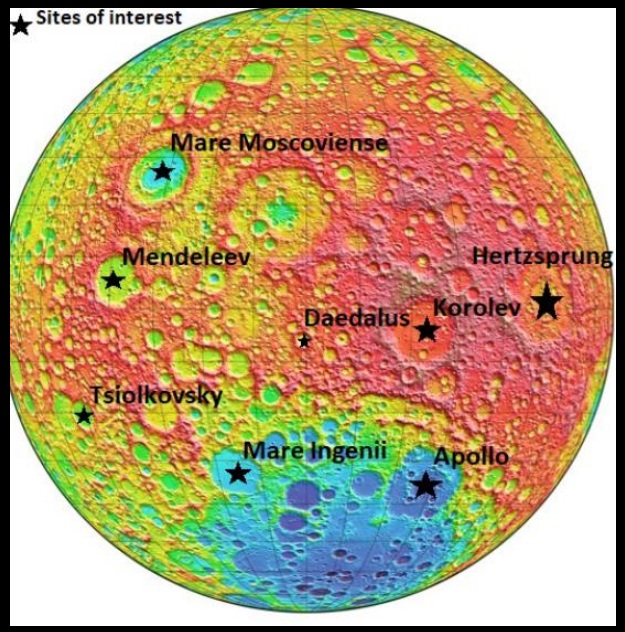
ESA's Moon village concept

Issues for the future of lunar exploration

Property law/Mineral rights/Criminal law/Pollution Enforcement?

Number of suitable sites is limited

5-50 km scale craters with smooth/mild slopes
far side for low terrestrial interference
permanently shadowed cold polar craters
High rims for solar power



United Nations Outer Space Treaty of 1967
provides basic framework on international space law,


1969


2024

Lets avoid the wild west scenario!

There is a space race

for commercial reasons and inspiration

Apollo 8 (1968)

Compelling science is relatively **inexpensive** and **humanity** will benefit

The future of cosmology: what were our cosmic origins?

The future of astronomy: are we alone?

Low frequency radio astronomy
Far infrared
Optical/IR at high resolution
Gravity waves at decihertz
X-rays at keV

Now's the time to plan

There are no limits but the sky

Miguel de Cervantes