

# SINGLE DISH RADIO TELESCOPES

## BEAM:

- The **beam** is the angular response of the antenna to a point source (radio analogue of the optical PSF)
- Exact shape of the primary beam depends on the structure of the antenna as seen by the incoming radiation.
- The primary beam defines the PSF. For circular dish with uniform illumination:
  - Airy pattern: Main lobe + side lobes;  $\vartheta_{\text{FWHM}} \approx 1.2 \lambda / D$
  - Beam solid angle:  $\Omega_{\text{beam}} \approx 1.13 \vartheta_{\text{FWHM}}^2$

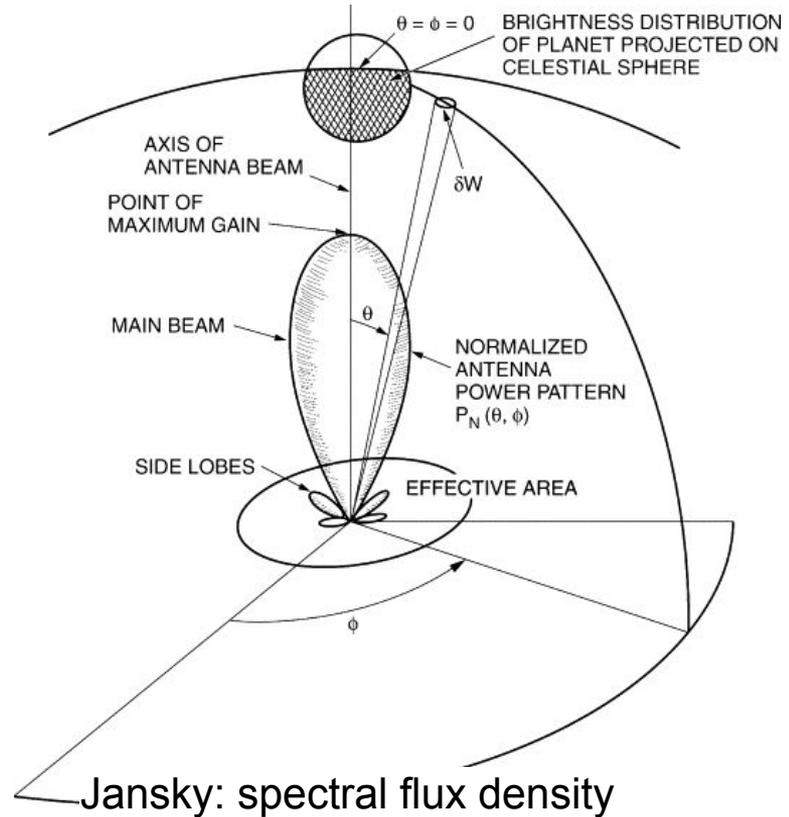
## SENSITIVITY:

- Peaks in the direction of telescope pointing, and it falls off with off-axis angle
- Improves with larger bandwidth and longer integration

$$\Delta S = \frac{2k_B \Delta T}{A_{\text{eff}}}$$

Noise on measured antenna temperature

Effective collecting area  $\propto D^2$



$$1 \text{ Jy} = 10^{-26} \text{ W} \cdot \text{m}^{-2} \cdot \text{Hz}^{-1}$$

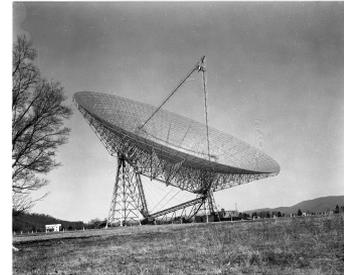
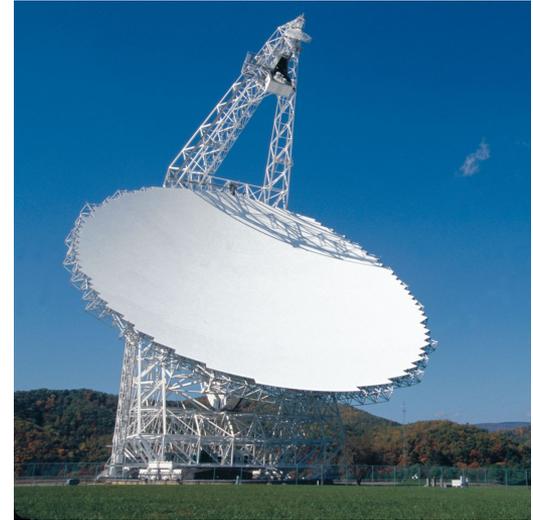
# SINGLE DISH RADIO FACILITIES: GBT

## Green Bank Telescope:

- West Virginia, first light 2000
- Largest steerable radio telescope: 110m x 90m
  - Replaced previous 90m (1962) telescope that just collapsed one day
- Frequency range: 290 MHz to 115 GHz
- Good mapping sensitivity thanks to new multiplex detectors
- Active Surface: The main dish surface is equipped with 2,209 robotic motors that actively adjust the shape of the surface panels to maintain parabolic shape despite changes in wind and temperature, ensuring optimal performance at high frequencies.
- Site is suboptimal for mm-wave because of water vapor in these very green area

## Main science:

- Pulsar Research
- Astrochemistry
- Galaxy and Star Formation



# SINGLE DISH RADIO FACILITIES: ARECIBO

## Arecibo (1963-2020):

- Arecibo. Puerto Rico
- Fixed spherical reflector: 305m
  - Pointing achieved by movable feed platform suspended by cables (sky coverage ~40%)
- Frequency range: 50 MHz to 10 GHz
- Angular resolution @1.4 GHz:  $\theta \sim 3'$
- Very large collecting area ( $3 \times 10^4 \text{ m}^2$ ) → extremely low flux limits

## Main science:

- Pulsar timing (PSR B1913+16)
- Weak spectral lines
- HI galaxy surveys
- SETI program



# SINGLE DISH RADIO FACILITIES: FAST

## Five-hundred Aperture Spherical Telescope (2016-):

- Guizhou, China
- Fixed spherical reflector: 500m
  - Active surface with  $\sim 4400$  panels (surface dynamically deformed into a paraboloid)
  - Movable feed cabin
- Frequency range: 70 MHz to 3 GHz
- Angular resolution @1.4 GHz:  $\theta \sim 2.9'$
- Very large collecting area ( $7 \times 10^4 \text{ m}^2$ )  $\rightarrow$  extremely low flux limits
- System temperature as low as  $T_{\text{sys}} \sim 20 \text{ K}$

## Main science:

- Pulsar timing (PSR B1913+16)
- Fast Radio Burst
- Galactic and extragalactic HI surveys and intensity mapping
- Molecular lines
- SETI program



# SINGLE DISH RADIO FACILITIES: SRT

## Sardinia Radio Telescope (2013-):

- Sardinia, Italy
- Fully steerable 64m parabolic reflector
- Optimized for multi-frequency flexibility
- Frequency range: 300 MHz to 116 GHz
  - MISTRAL: wide-field mm-wave camera:
    - Multi-pixel configuration with KIDs operating at  $\sim 0.2\text{K}$
    - $\nu \sim 90\text{ GHz}$  FoV:  $4'$
- Angular resolution
  - @1.4 GHz:  $\vartheta \sim 14'$
  - @22 GHz:  $\vartheta \sim 0.9'$
  - @90 GHz:  $\vartheta \sim 12''$  (complement both CMB telescope and interferometer)
- Collecting area ( $2 \times 10^3\text{ m}^2$ )
- Cryogenic receivers

## Main science:

- Pulsar and FRBs
- Galactic and extragalactic HI
- Molecular lines
- Part of VLBI

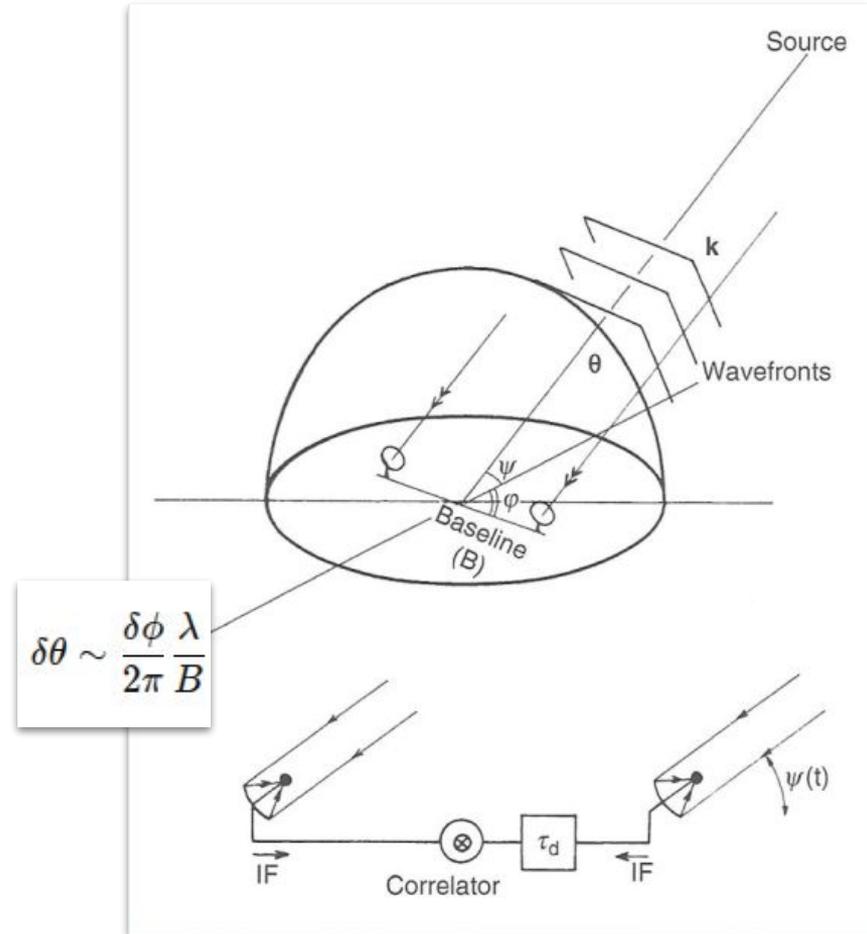


# RADIO INTERFEROMETERS

- Interferometer consist of collections of antennas separated by the baseline B
- Correlators combine information from the antennas into *visibilities*, which are related to the Fourier transform of the brightness distribution of the source

$$V(u, v) = \int I(l, m) e^{-2\pi i(ul+vm)} dl dm$$

- $(u, v) = b / \lambda$  are the spatial frequencies
- Angular resolution set by the maximum baseline:
  - $\vartheta \sim \lambda / B_{\text{MAX}}$
- Measurement of the interference (fringe) phase allows extremely accurate determination of source direction because phase directly encodes geometric delay, which depends on sky position.
- Finite number of antennas imply an incomplete sampling of the Fourier modes
- Earth rotation helps to fill the  $(u, v)$  plane



# RADIO INTERFEROMETERS: VLA

## Very Large Array:

- New Mexico, first light 2000
- 27 parabolic antennas, each 25 m
  - 351 simultaneous visibility measurements
- Y-shaped configuration with baseline up to 36 km (reconfigurable array)
- Frequency range: 1-50 GHz
- Angular resolution @1.4GHz  $\vartheta \sim 1.3''$
- $\mu\text{Jy}$ -level sensitivity

## Main science:

- HI 21 cm emission in galaxies and intensity mapping
- AGN jets and radio galaxies
- FRB and transient





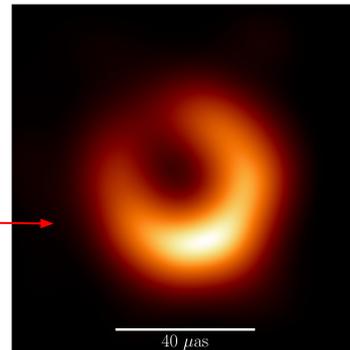
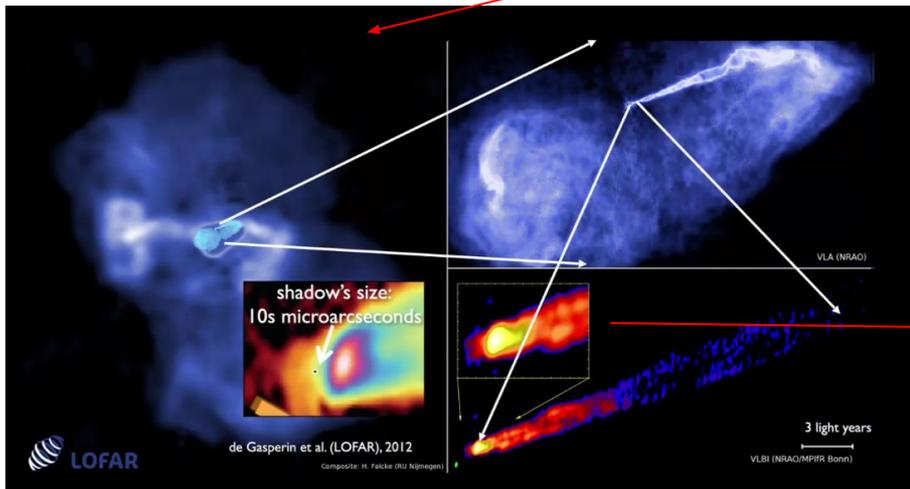
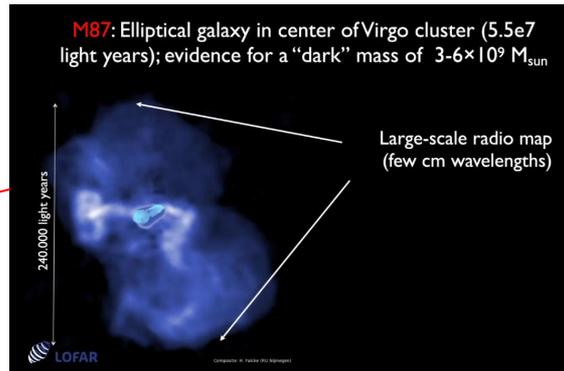
# BH IMAGING

## A very basic problem

- Black holes (BHs) are most compact objects known
- BHs are at astronomical distances
- BH must be resolvable on the sky
- Best resolution ( $\sim 10 \mu\text{as}$ ) is finite

Coin on the surface of the moon

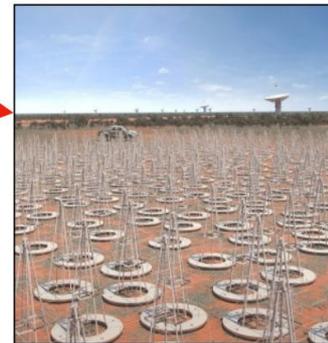
Need **very massive BHs** and **sufficiently close** to us: M87\*, Sgr A\*, ... IC 1459, NGC 4594



# RADIO INTERFEROMETERS: SKA

## Square Kilometre Array:

- Order-of-magnitude leap in sensitivity
- Combines deep + wide surveys



- Full members
- SKA Headquarters host country
- SKA Phase 1 and Phase 2 host countries



- African partner countries (non-member SKA Phase 2 host countries)

This map is intended for reference only and is not meant to represent legal borders.

### SKA1-mid

the SKA's mid-frequency instrument

$0 < z < 3$



Location:  
South Africa



Frequency range:  
**350 MHz**  
to  
**15.3 GHz**

with a goal of 24 GHz



**197 dishes**  
(including 64 MeerKAT dishes)



Maximum baseline:  
**150km**

### SKA1-low

the SKA's low-frequency instrument

$3 < z < 27$



Location: Australia



Frequency range:  
**50 MHz**  
to  
**350 MHz**



**~131,000**  
antennas spread between  
**512 stations**



Maximum baseline:  
**~65km**

# RADIO INTERFEROMETERS: SKA

Prime motivation:  
Study the history of  
the Universe in  
Hydrogen

## SKA— Key Science Drivers: The history of the Universe

Testing General Relativity  
(Strong Regime, Gravitational Waves)

Cosmic Dawn  
(First Stars and Galaxies)

Cradle of Life  
(Planets, Molecules, SETI)

Galaxy Evolution  
(Normal Galaxies  $z \sim 2-3$ )

Cosmology  
(Dark Matter, Large Scale Structure)

Cosmic Magnetism  
(Origin, Evolution)

Exploration of the Unknown

Extremely broad range of science!

# RADIO INTERFEROMETERS: ALMA

## Atacama Large mm/submm Array:

- Chajnantor Plateaus, Chile → 5000m, dry stable atmosphere
- 66 antennas: 50 x 12 m (main array), 12 x 7m (compact array), 4 x 12 m total power antennas (single dishes)
- Reconfigurable array: baselines 15m to 16 km
- Frequency range: 35 - 950 GHz ( $\lambda = 0.3 - 3$  mm)
- Angular resolution @1mm  $\vartheta \sim 10$  mas

## Main science:

- Molecular gas in high-z galaxies
- ISM physics in early Universe
- Clusters SZ effect



# MM TELESCOPES: SPT

## South Pole Telescope:

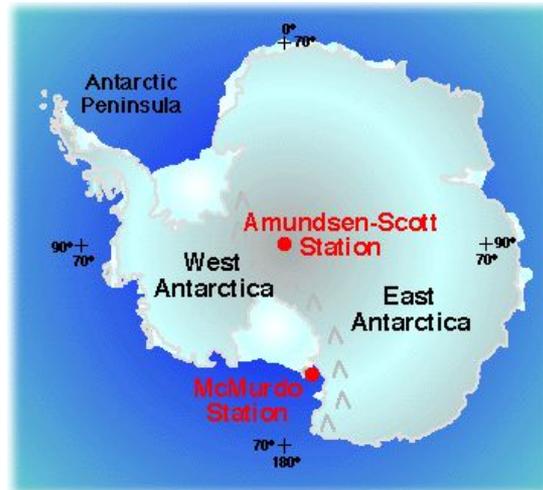
- South Pole → driest site in the world, stable weather and oscillating periods of darkness and light
- 10m off-axis parabolic primary. Surface accuracy allows for sub-mm observation.
- Large FoV:  $\sim 1$  deg (half of the sky observable)
- Frequency range: 90 - 220 GHz
- Angular resolution @ 150GHz (2mm)  $\vartheta \sim 1$  arcmin

## Main science:

- High-resolution CMB measurements (lensing and polarization)
- Galaxy Clusters surveys via SZ effect



Photo Credit: Daniel Luong-Van



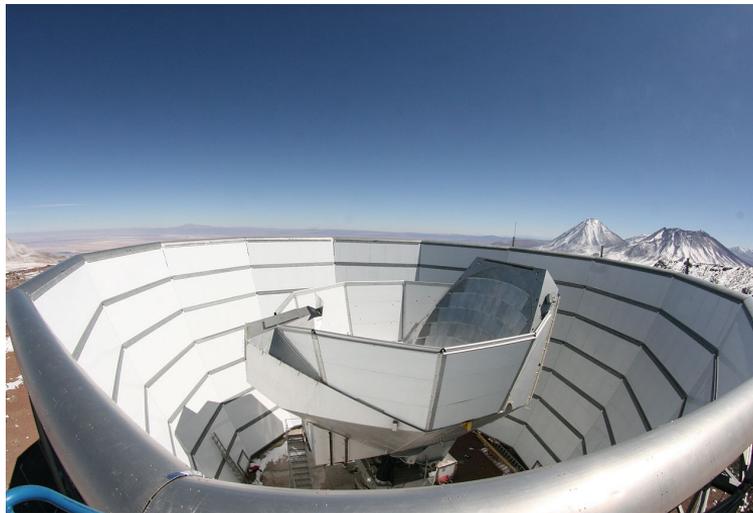
# MM TELESCOPES: ACT

## Atacama Cosmology Telescope:

- Atacama desert, Chile → 5200m, dry stable atmosphere
- 6m off-axis telescope
- Large FoV: ~1-2 deg (large fraction of the southern sky. Strong overlap with DES, DESI)
- Frequency range: 90 - 280 GHz
- Angular resolution @ 150GHz (2mm)  $\theta \sim 1.4$  arcmin

## Main science:

- High-resolution CMB mapping (lensing and polarization)
- SZ cluster surveys



# MM TELESCOPES: SPO / SO / CMB-S4?

## South Pole Observatory:

- 1 LAT: SPT 3G
- 4 SATs: BICEP Array



## CMB-S4

On July 9, 2025, the U.S. Department of Energy (DOE), Office of Science, Office of High Energy Physics and the U.S. National Science Foundation (NSF) issued a statement informing the CMB-S4 Project that "DOE and NSF have jointly decided that they can no longer support the CMB-S4 Project."

## POLARBEAR → Simons Array → Simons Observatory:

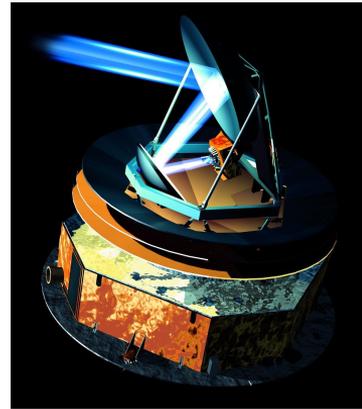
- 1 LAT:
- 3 SATs:



# MM TELESCOPES: PLANCK

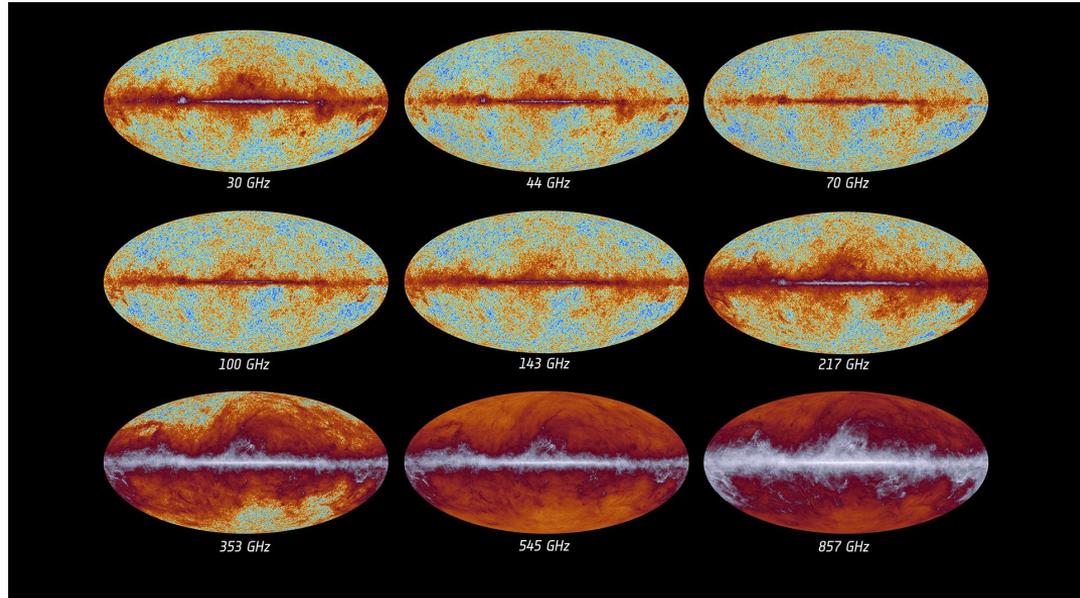
## Planck (2009 - 2013):

- Space mission operated from L2
- 1.5m primary telescope
- Two detectors (intensity and polarization):
  - LFI: 30, 44, 70 GHz
  - HFI: 100, 143, 217, 353, 545, 857 GHz
- Angular resolution:  $\vartheta \sim 5 - 1$  arcmin



## Main science:

- CMB cosmology
- Milky way studies



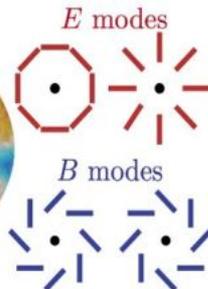
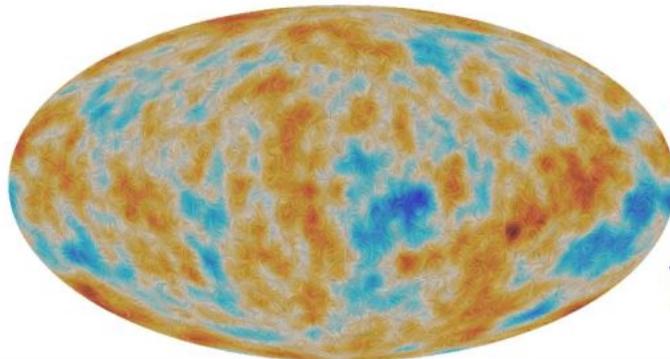
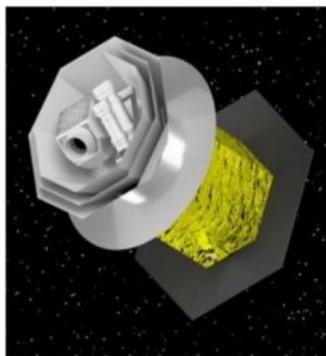
## LiteBIRD Overview

Scheduled for 2032



- Lite (Light) satellite for the study of B-mode polarization and Inflation from cosmic background Radiation Detection
- JAXA's Strategic Large-class mission selected in May 2019
- Expected launch in **late 20s** with JAXA's H3 rocket
- **All-sky 3-year survey**, from Sun-Earth Lagrangian point L2
- Large frequency coverage (**40–402 GHz**, 15 bands) at **70–18 arcmin** angular resolution for precision measurements of the CMB B-modes
- Final combined sensitivity: **2.2  $\mu\text{K}\cdot\text{arcmin}$**

LiteBIRD Collaboration PTEP 2022



# Multi-Messenger Astronomy

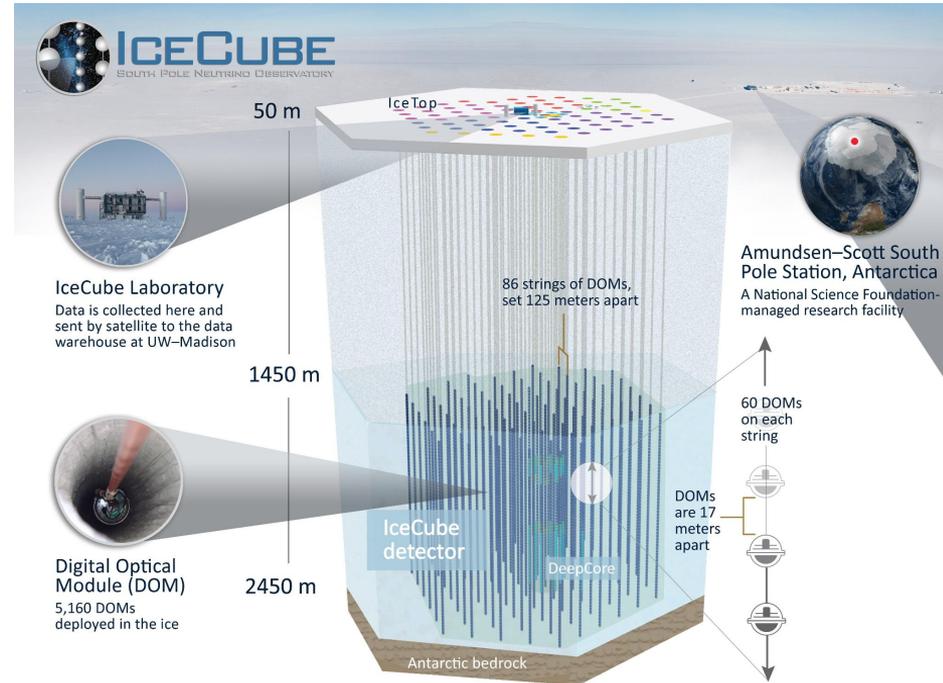
# COSMIC NEUTRINO DETECTOR: ICECUBE

## Detector characteristics:

- 1km<sup>3</sup> of ice (~0.5 Gton detector)
  - Sensitive to 100 TeV to EeV
- 5160 Digital Optical Modules
- IceTop is for veto and calibration

## Main science:

- Ultra high-energy neutrinos ( $E > \text{PeV}$ )





# GRAVITATIONAL WAVE DETECTORS: LIGO / VIRGO

## Gravitational wave detectors:

- Long-base (~km) interferometers able to detect spacetime strain of the order  $h = \Delta L/L \sim 10^{-21}$
- Major Detectors:
  - LIGO (USA, 4 km arms)
  - Virgo (Italy, 3 km)
  - KAGRA (Japan, 3 km)

## Main science:

- Astrophysics and cosmology from compact binarie GWs

