



Observatório
Nacional

MINISTÉRIO DA
CIÊNCIA, TECNOLOGIA
E INOVAÇÃO



AST-B09

Observational Astronomy

Rogério Monteiro-Oliveira, Ph.D. (孟羅傑)

**Multi-Messenger Astronomy &
Large Projects in Modern Astronomy**

Learning Objectives

- **Understand** the fundamental physics governing the emission and propagation of Gravitational Waves, Neutrinos, and Cosmic Rays.
- **Analyze** the sophisticated detector technologies required to observe these elusive messengers (interferometry, Cherenkov radiation).
- **Review** the current state-of-the-art in multi-messenger observational campaigns.
- **Survey** the landscape of next-generation observatories (ELTs, JWST, SKA) and massive data-driven surveys (Rubin, J-PAS).

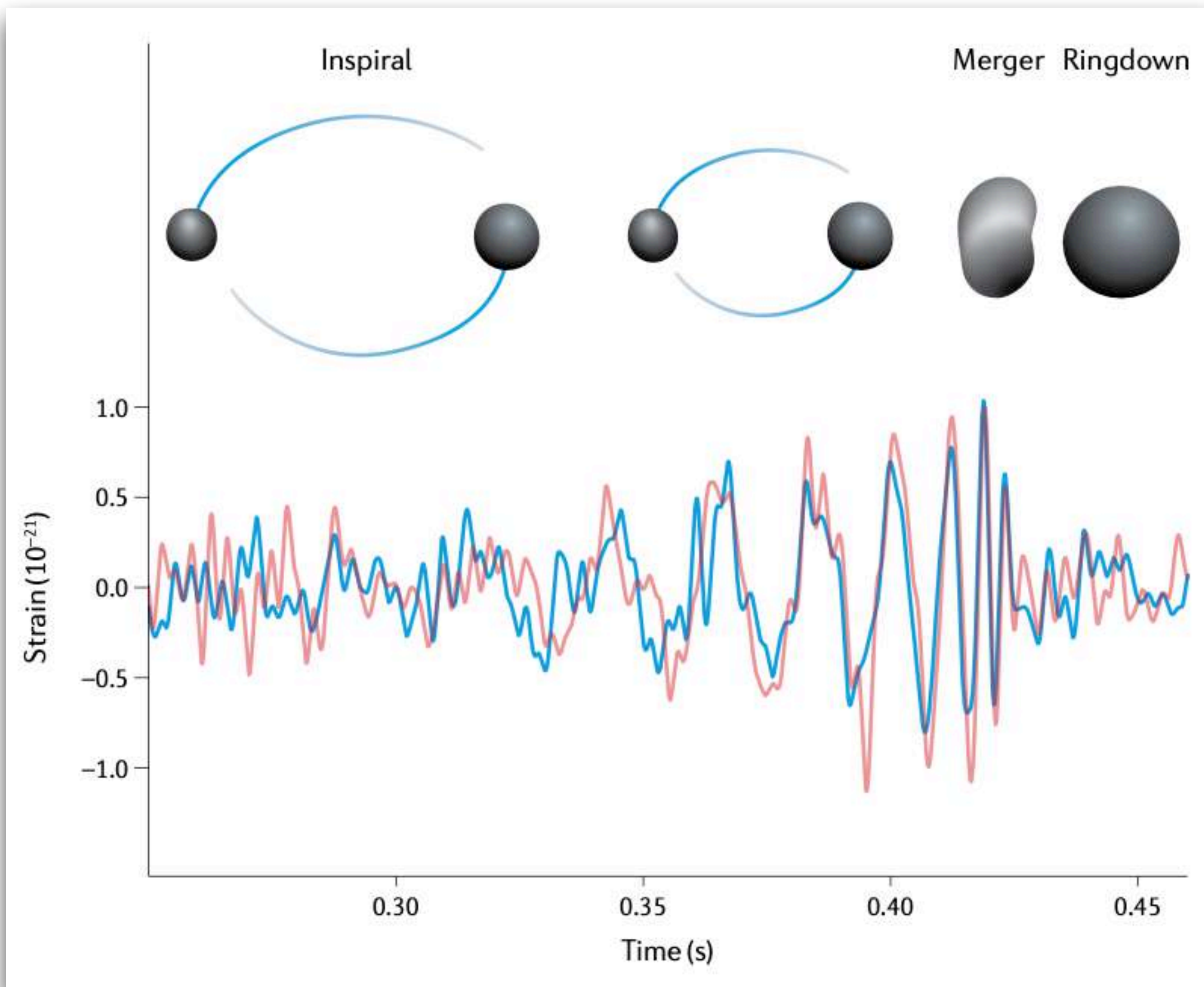
Multi-Messenger Astronomy

Introduction to the Multi-Messenger Era

- Coordinating observations of four distinct cosmic messengers:
 - ▶ **Photons (EM):** Atomic transitions, thermodynamics, surfaces.
 - ▶ **Gravitational Waves (GWs):** Macroscopic mass dynamics, spacetime curvature. Unattenuated by dust/matter.
 - ▶ **Neutrinos:** Weak interactions. Escape perfectly from the densest engines; point straight back to sources.
 - ▶ **Cosmic Rays (CRs):** High-energy charged particles tracing extreme magnetic fields and shocks.

Gravitational Waves: Ripples in Spacetime

- Predicted by Einstein in 1916. GWs are oscillations *of* spacetime itself, not *in* spacetime.
- If the EM spectrum provides “sight”, GWs represent the “hearing” of astronomy, allowing us to map the “dark” sectors (e.g., merging black holes).
- Generated by massive, asymmetric, rapidly accelerating objects. Governed by the *quadrupole formula*.

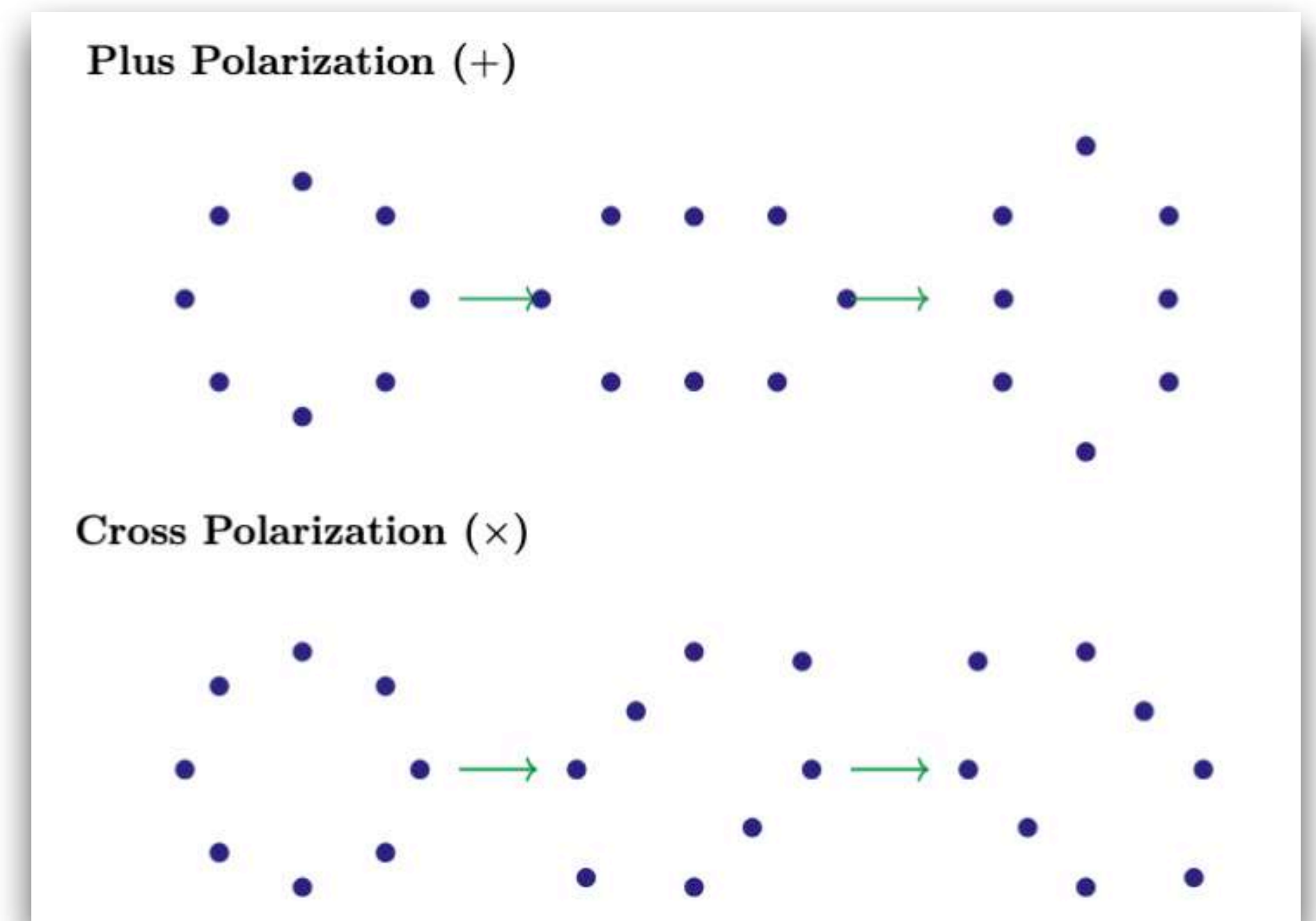


<https://doi.org/10.1038/s42254-021-00303-8>

The detected gravitational-wave strain amplitude as a function of time for GW150914, the first signal detected nearly simultaneously by the LIGO Hanford and Livingston observatories on September 14, 2015. The waveforms are shifted and inverted to compensate for the slightly different arrival times and different orientations of the detectors (red: LIGO Hanford, blue: LIGO Livingston). The upper inset is a simulation of the merger produced using numerical relativity to illustrate the evolution of the black hole event horizons as the system coalesces and merges.

GW Polarizations

- Travel at the speed of light (c). Manifest as a time-dependent strain: $h = \delta L/L$.
- Two Polarizations: **Plus (+)** and **Cross (×)**.
- Orthogonally stretch and squeeze space.

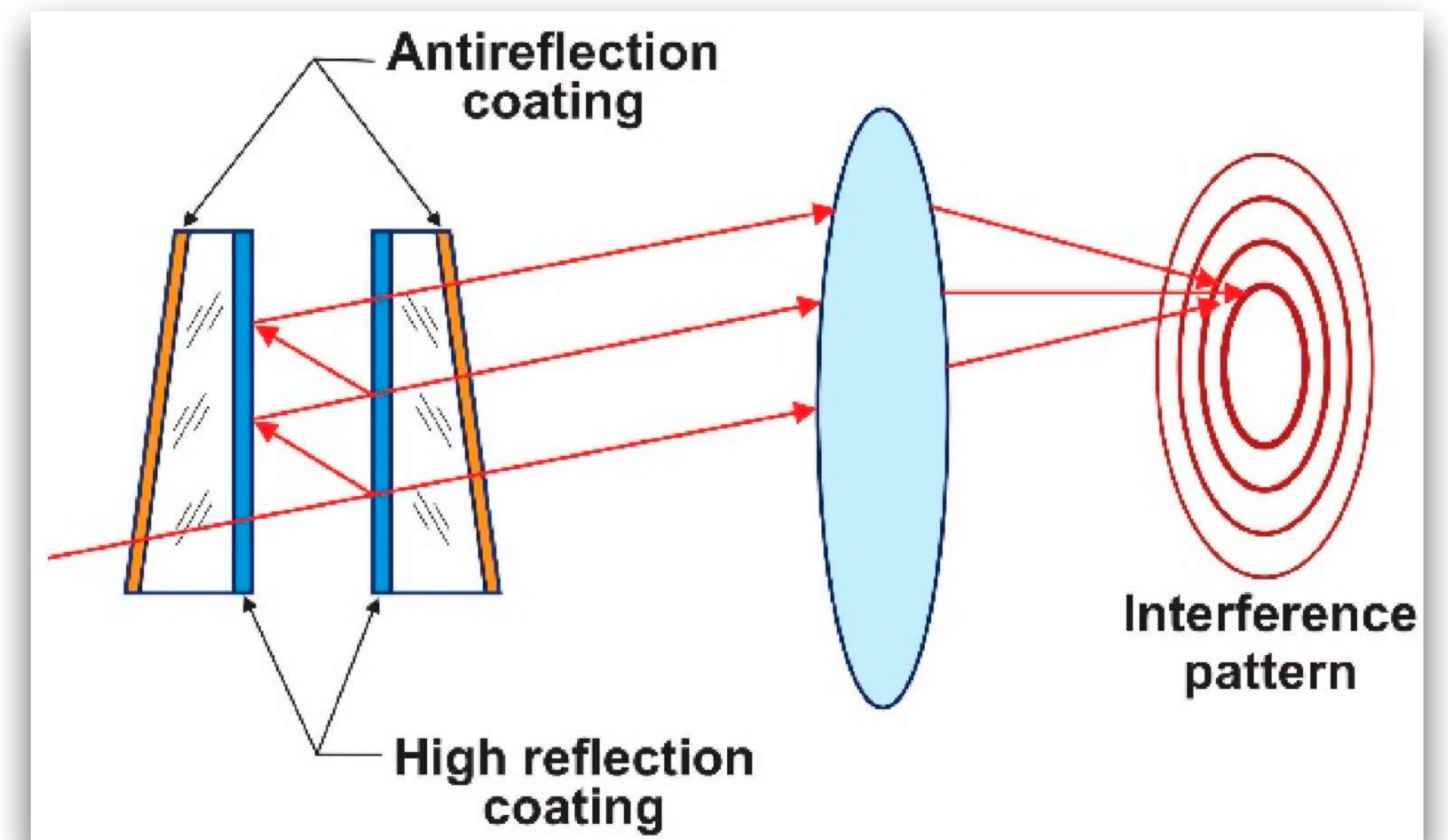


L09 Notes

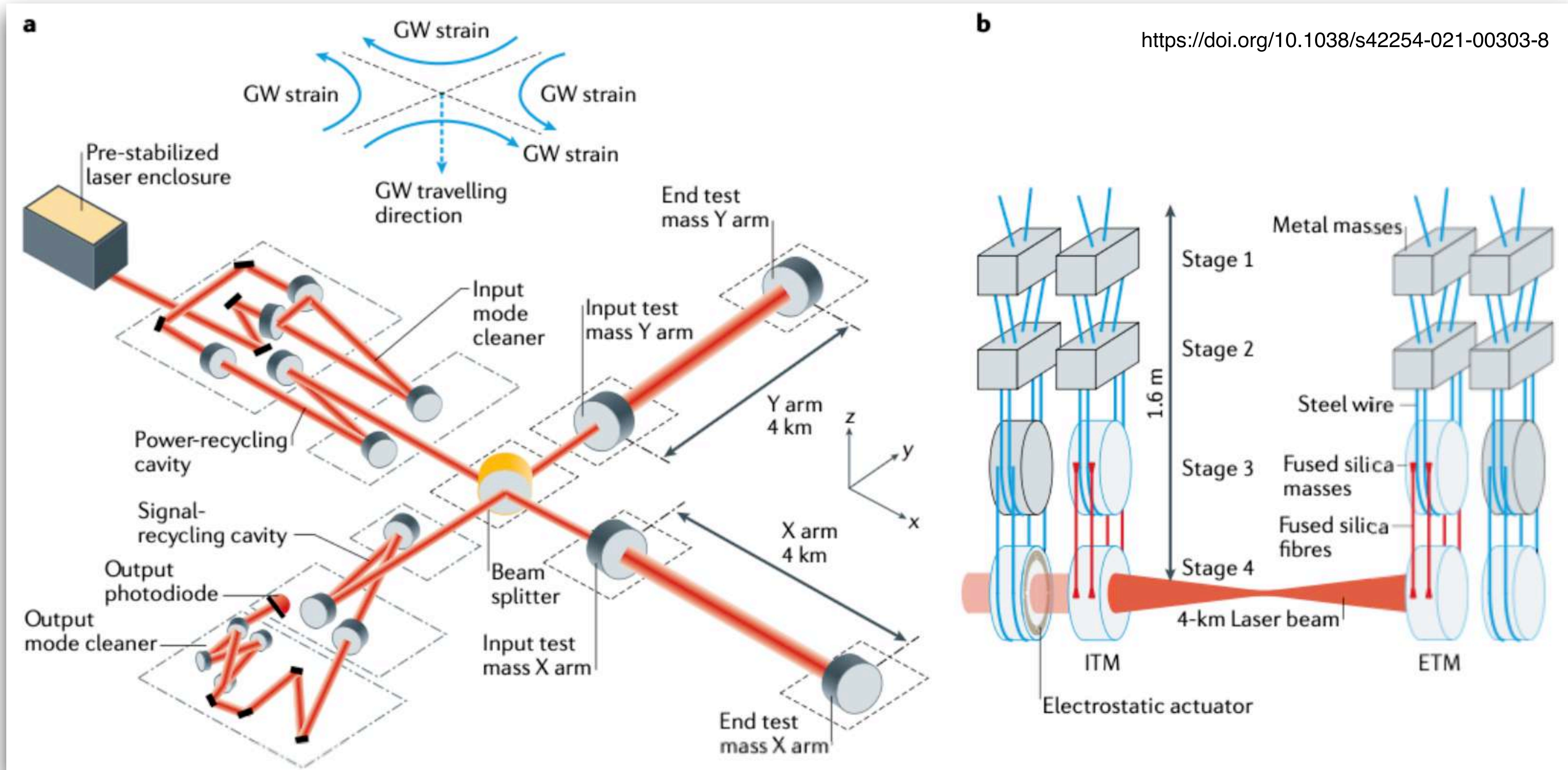
Detecting GWs: Advanced Interferometry

- Measuring a strain of $h \sim 10^{-21}$.
Equivalent to measuring $\delta L \sim 4 \times 10^{-18}$ m over a 4 km baseline.
- Modified Michelson interferometers with Fabry-Pérot cavities in the arms to trap light and increase the effective arm length to nearly 1,200 km.

Scheme of Fabry-Pérot cavity



<https://www.mdpi.com/1424-8220/23/14/6493>



A schematic of a working laser interferometer gravitational-wave detector. **a** | A simplified view of the Advanced LIGO interferometer, showing the optical configuration including the laser, input mode cleaner, power-recycling and signal-recycling cavities, the 4-km-long arm cavities and the output mode cleaner. The gravitational-wave (GW) signal is recorded on the output photodiode after the output mode cleaner. **b** | A schematic of one of the arm cavities. The input test mass (ITM) and end test mass (ETM) mirrors are held by quadruple suspensions to suppress ground motion disturbances.

The Global GW Network

- LVK Collaboration:
 - **LIGO (USA):** Two 4-km detectors (Hanford & Livingston).
 - **Virgo (Italy):** 3-km detector.
 - **KAGRA (Japan):** 3-km, underground (seismic noise reduction), cryogenic mirrors (thermal noise reduction).
- *Future:* **LIGO-India** under construction to drastically shrink localization error boxes on the sky.

LIGO



https://www.ligo.caltech.edu/system/media_files/ binaries/756/original/LHO_Aerial_2023_showing_arm_length.jpg?1694117252

<https://sj.jst.go.jp/stories/2023/s0711-01p.html>

VIRGO



<https://www.researchgate.net/profile/Chris-Van-Den-Broeck/publication/231019374/figure/fig1/AS:300623959478275@1448685745687/An-aerial-view-of-the-Virgo-gravitational-wave-detector-The-detector-Virgo-is-located-in.png>

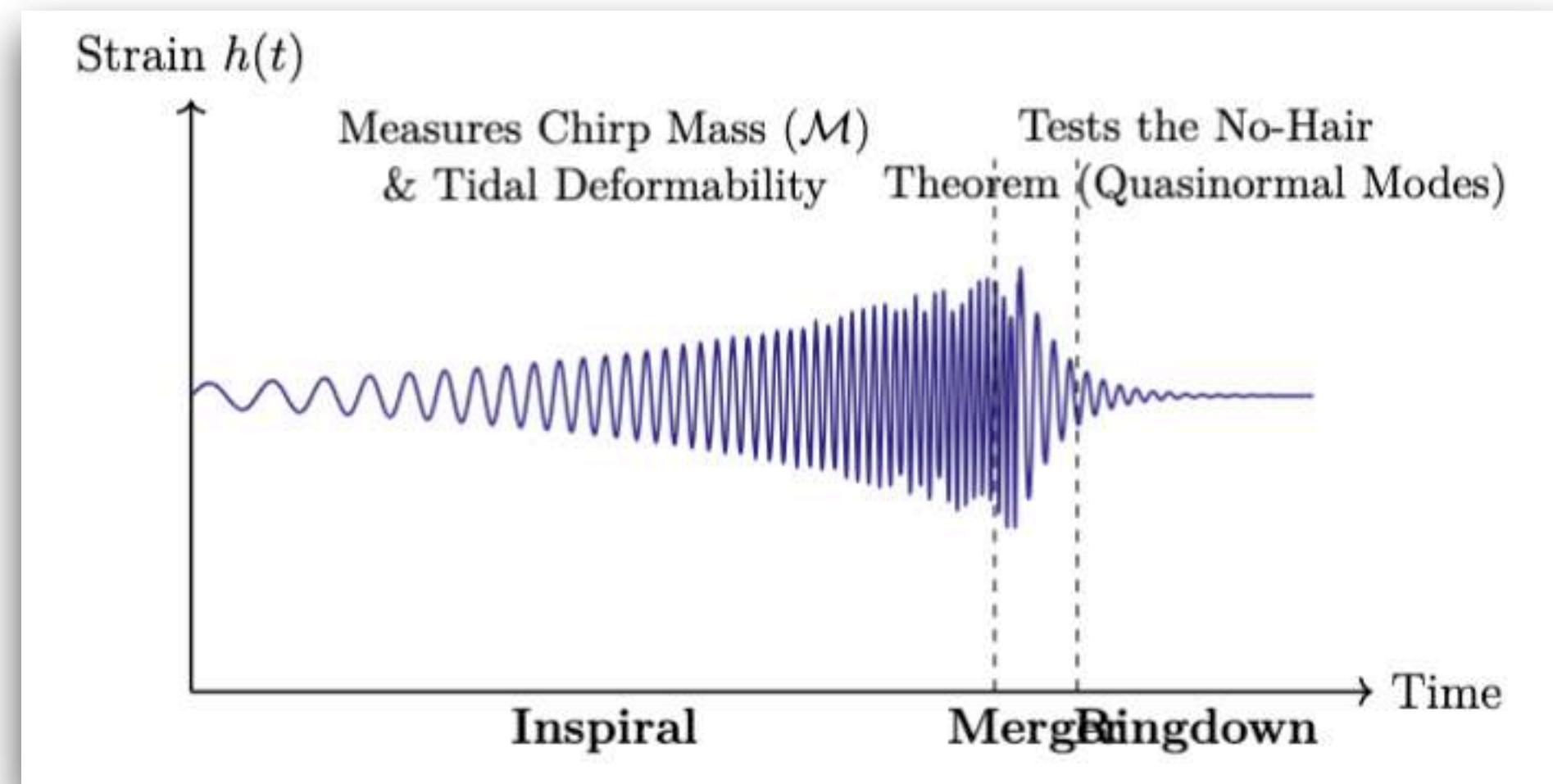
KAGRA



Noise Limits in GW Detectors

- *Low-Frequency Barrier (<10 Hz):* Newtonian/Seismic Noise. Unshieldable gravity gradient fluctuations from the Earth.
- *Mid-Frequency Sweet Spot (10-100 Hz):* Limited by Thermal Noise (Brownian motion of atoms in mirror coatings).
- *High-Frequency Limit (>100 Hz):* Standard Quantum Limit (SQL) - Quantum Shot Noise vs. Radiation Pressure Noise. Mitigated by “squeezed light”.

Decoding the GW Waveform



- **Inspiral (The Chirp):** Orbiting compact objects. Frequency/amplitude increase. Measures *chirp mass* and *tidal deformability*.
- **Merger:** Peak strain. Violent coalescence into a single remnant.
- **Ringdown:** Exponentially damped sinusoid. Tests the “no-hair theorem” of black holes via quasinormal modes.

GW Astrophysics: Major Breakthroughs

- *The Black Hole Mass Gap:* Detections like GW190521 ($85 M_{\odot}$ primary) forced theorists to rethink stellar collapse and invoke hierarchical mergers.
- *Neutron Star Equation of State:* GW170817 proved NS radii are highly compact (~ 11 - 12 km).
- *Testing General Relativity:* Confirming the no-hair theorem and measuring GW speed ($v_{GW} = c$).

Future Horizons for GWs

- The GW spectrum depends on source size/mass.
- *3G Ground (Audio Band)*: Einstein Telescope (Europe) & Cosmic Explorer (USA). Will see virtually every stellar-mass BBH merger in the universe.
- *Space-Based (mHz Band)*: **LISA** (late 2030s). Targeting supermassive black holes ($10^4 - 10^7 M_{\odot}$) at galactic centers.
- *Pulsar Timing Arrays (nHz Band)*: **NANOGrav**. Using the galaxy as a detector to find the stochastic GW background of ultramassive black holes.

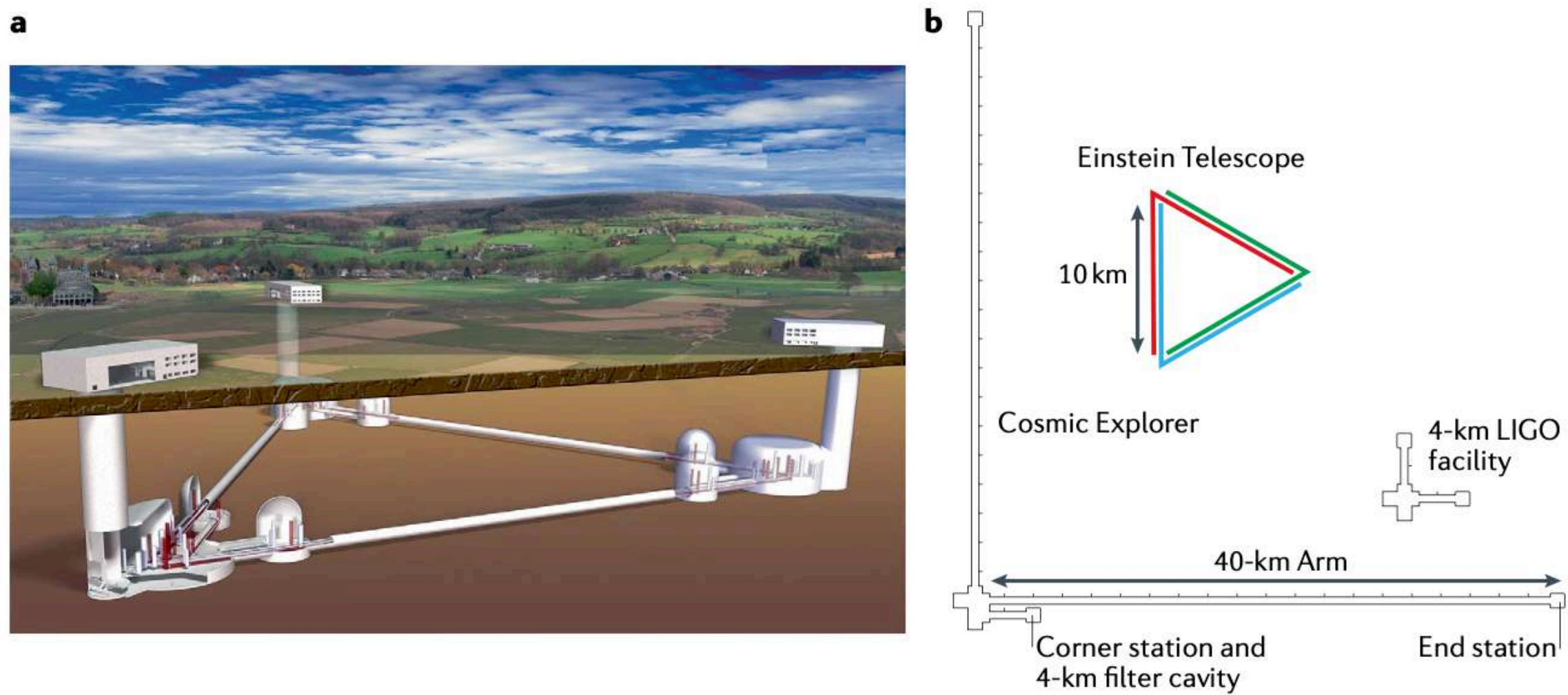


Fig. 10 | **Third-generation ground-based detectors.** **a** | Concept for the Einstein Telescope. A triangular underground installation with 10-km-long arms is planned. The influence of Newtonian noise is reduced with the underground location, and the multiple detectors in the triangular arrangement give a wide sensing bandwidth and polarization resolution. **b** | A comparison of the Einstein Telescope and Cosmic Explorer detector configurations. For comparison, the current Advanced LIGO detector is also shown. Panel **a** courtesy of the ET design study team.

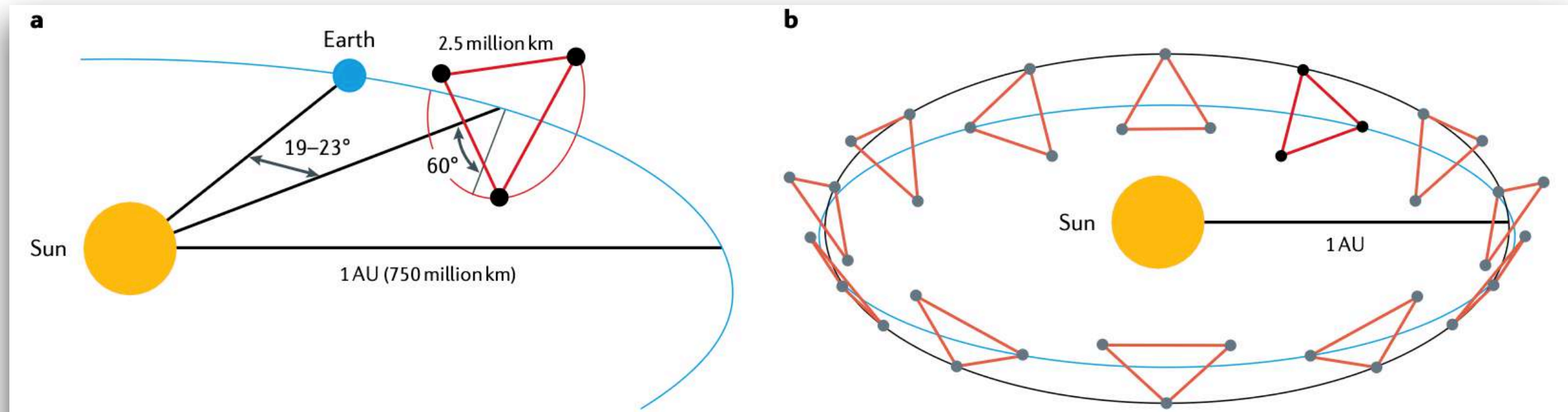


Fig. 11 | **The LISA mission.** **a** | Three spacecraft, in a triangular stable orbit, are separated by 2.5×10^6 km. Laser beams measure between each spacecraft in both directions; from these six legs, distortions due to passing gravitational waves in both polarizations can be resolved. **b** | A 1-AU orbit is chosen, and the constellation scans the sky once per year. Figure courtesy of the LISA Consortium.

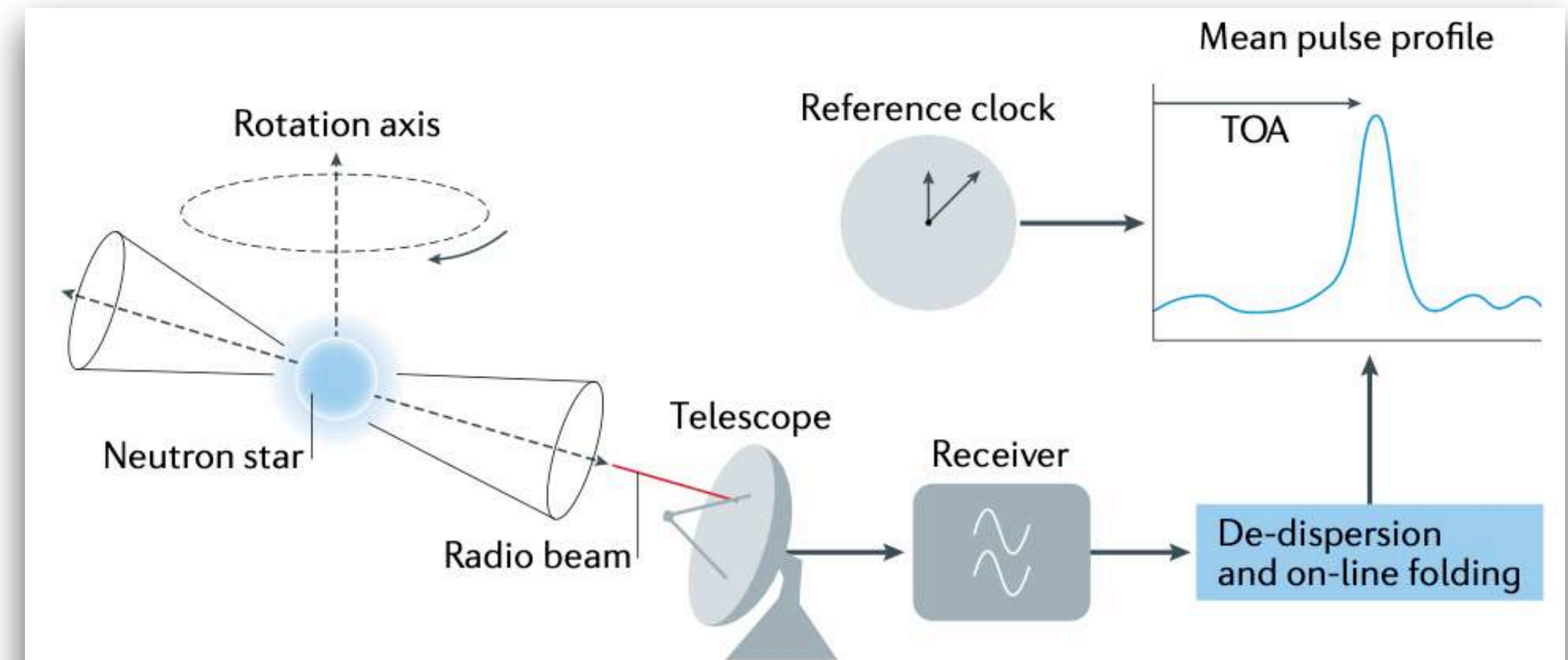
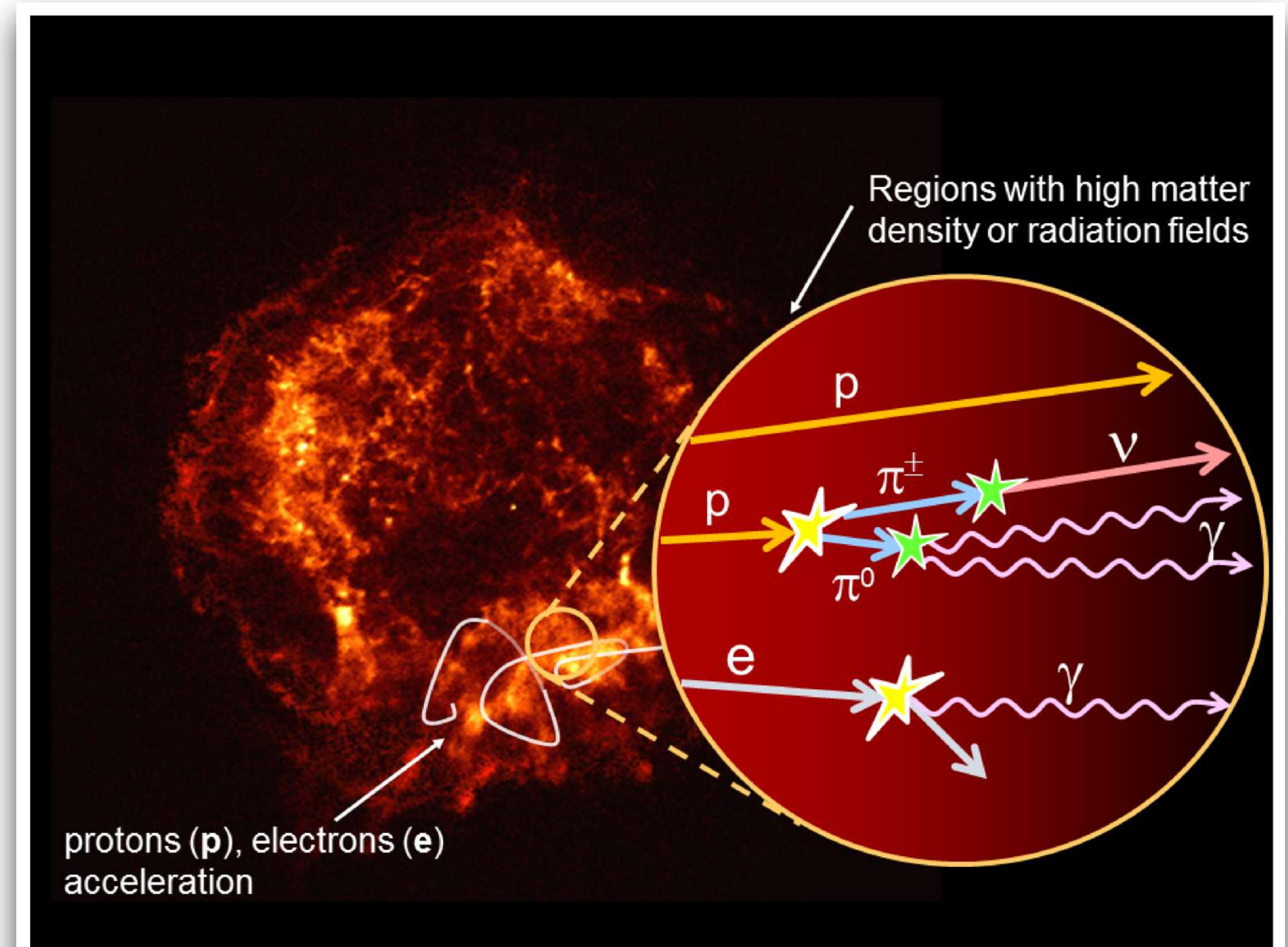


Fig. 6 | **Illustration of the radio pulsar timing process.** The pulsar beams sweep across the radio antenna and are detected using a radio receiver at \sim GHz frequencies. The data are corrected for delays due to the interstellar medium ('de-dispersion') and then folded at the period of the pulsar to create an integrated profile. This profile is then cross-correlated with a noise-free template profile to calculate a time of arrival (TOA), using a high-precision reference clock at the observatory.

Neutrinos: The Ghostly Messengers

- Elementary, nearly massless leptons. Interact only via weak force and gravity.
- They escape the densest environments (stellar cores, AGN accretion disks) unimpeded and travel in perfectly straight lines, unaffected by magnetic fields.
- Neutrino detection definitively proves the presence of ultra-relativistic proton acceleration.



https://www.mdpi.com/universe/universe-06-00030/article_deploy/html/images/universe-06-00030-g001.png

Neutrino Production & Flavor Oscillation

- *Production:* Protons collide with ambient gas or photons \rightarrow pions \rightarrow muons \rightarrow neutrinos. Initial flavor ratio at source is (1 : 2 : 0) for $(\nu_e : \nu_\mu : \nu_\tau)$.
- “Flavor” eigenstates are superpositions of “mass” eigenstates. As they travel, different mass states evolve at different rates.
- Mixing (PMNS matrix) averages out over extragalactic distances, resulting in a democratic (1 : 1 : 1) observed ratio.

Catching Ghosts: Cherenkov Detectors

- *The Challenge:* Tiny interaction cross-section ($\sigma \sim 10^{-38} \text{ cm}^2$). Requires cubic-kilometer target volumes.
- *The Mechanism:* Neutrino interacts with ice/water \rightarrow produces charged lepton \rightarrow lepton travels faster than light in the medium \rightarrow emits blue **Cherenkov radiation** in a forward cone ($\theta_c \approx 41^\circ$).
- **IceCube** (South Pole) uses thousands of deeply buried PMTs.



50 m

Ice Top

86 strings of DOMs,
set 125 meters apart

Amundsen–Scott South
Pole Station, Antarctica
A National Science Foundation-
managed research facility

1450 m

60 DOMs
on each
string

DOMs
are 17
meters
apart

2450 m

IceCube
detector

DeepCore

Antarctic
bedrock

IceCube Laboratory
Data is collected here and
sent by satellite to the data
warehouse at UW–Madison

Digital Optical
Module (DOM)
5,160 DOMs
deployed in the ice

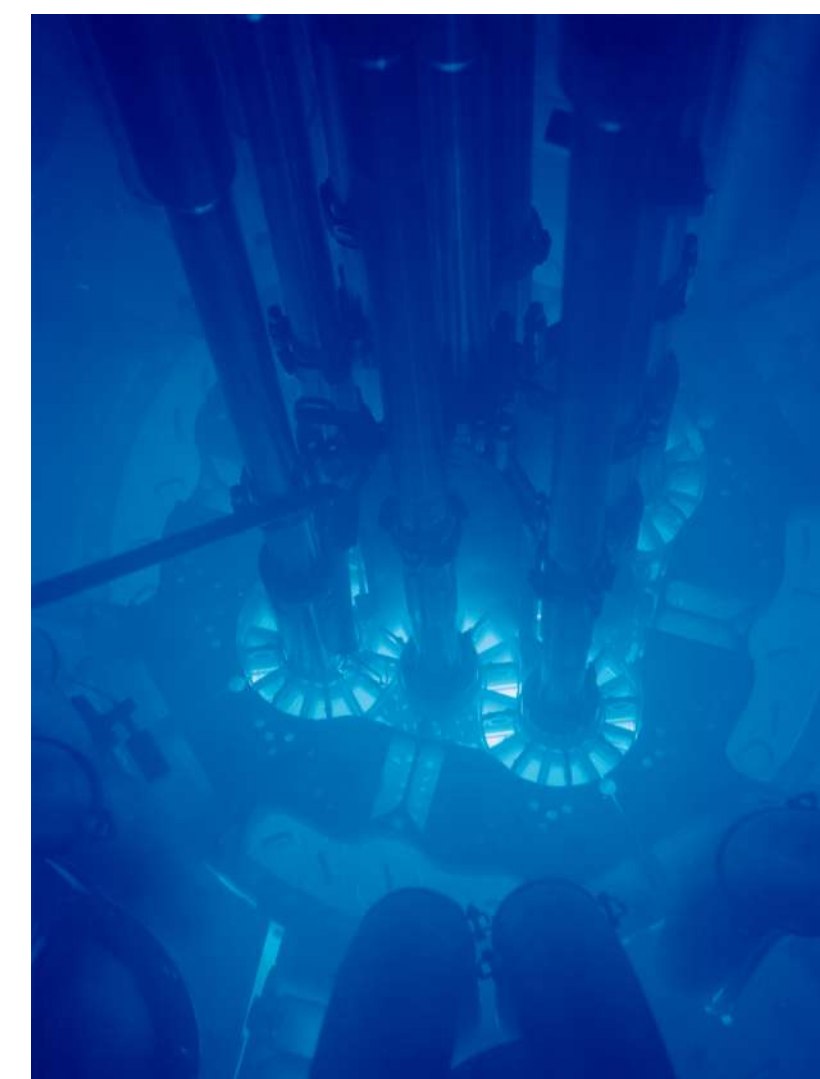
Cherenkov light

Neutrino

Charged
particle
in water

Photosensors

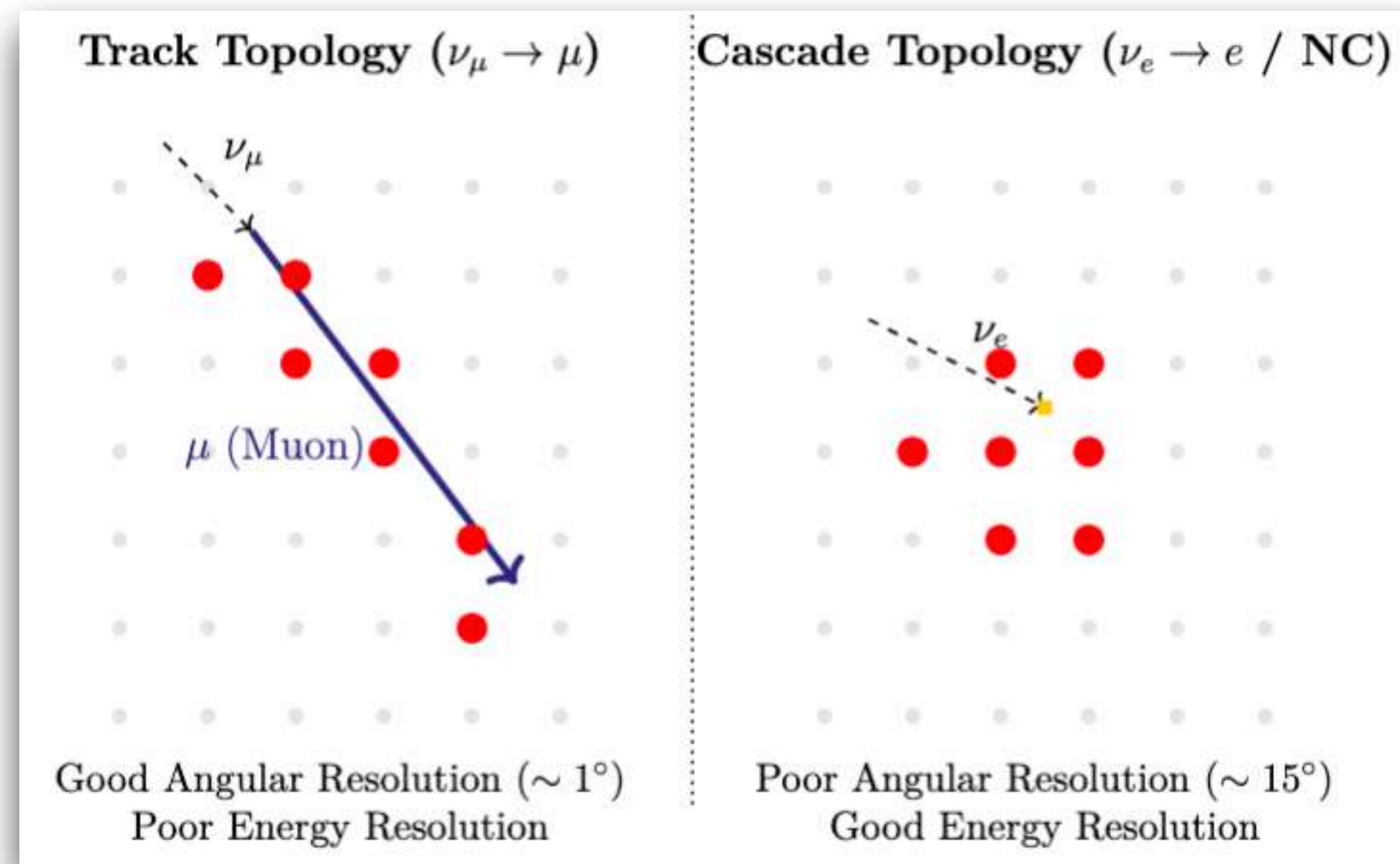
<https://physicsopenlab.org/wp-content/uploads/2016/04/cherenkov.jpg>



https://upload.wikimedia.org/wikipedia/commons/f/f2/Advanced_Test_Reactor.jpg

<https://icecube.wisc.edu/science/icecube/>

Event Topologies in IceCube



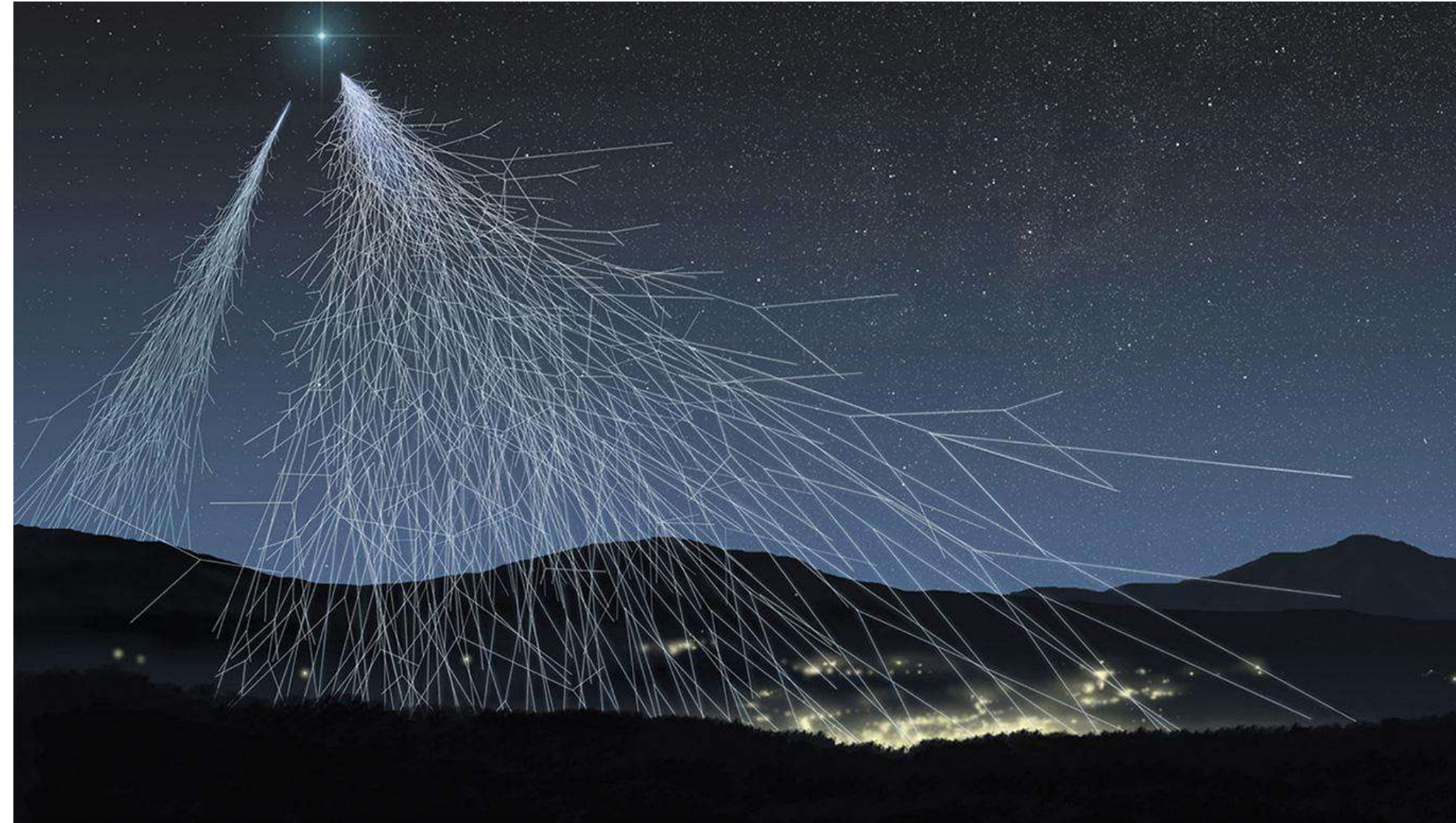
L09 Notes

- **Tracks ($\nu_\mu \rightarrow \mu$):** Muons travel kilometers through ice. Leaves a straight line of light. *Good angular resolution ($< 1^\circ$), poor energy resolution.* Best for pointing.
- **Cascades ($\nu_e \rightarrow e$ or **NC**):** Electrons shower immediately. Leaves a spherical blob of light. Poor angular resolution ($\sim 15^\circ$), good energy resolution.

High-Energy Neutrino Breakthroughs & Future

- 2013 discovery of a diffuse, isotropic extragalactic high-energy flux.
- TXS 0506+056 (2017) – First association of a neutrino with a flaring blazar.
- NGC 1068: 10-year analysis reveals steady flux from this Seyfert II galaxy's corona.
- *Future: IceCube-Gen2* (8x volume + radio array for Askaryan effect) and **KM3NeT** (Mediterranean, pointing at the Galactic Center).

Cosmic Rays: The Most Energetic Particles

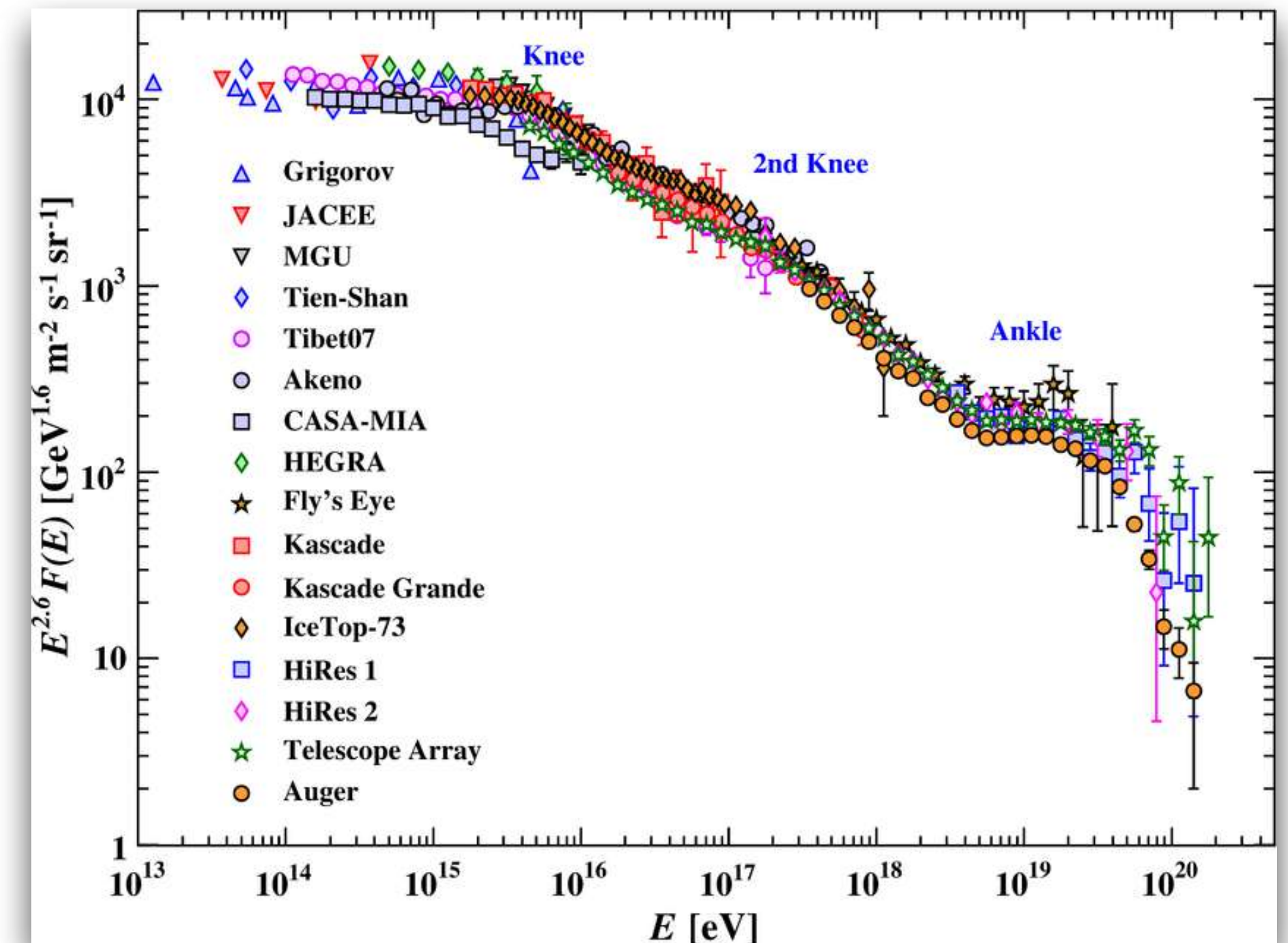


<https://news.uchicago.edu/sites/default/files/styles/gallery/public/images/2023-12/cosmic-rays.jpg?h=944f5cba&itok=6SqVxWoM>

- Non-thermal population of charged particles (89% protons, 10% alpha, 1% heavier nuclei).
- Because they are charged, they are deflected by magnetic fields, scrambling their directional origins.
- Millions of times more energetic than LHC collisions.

The CR Spectrum & The GZK Cutoff

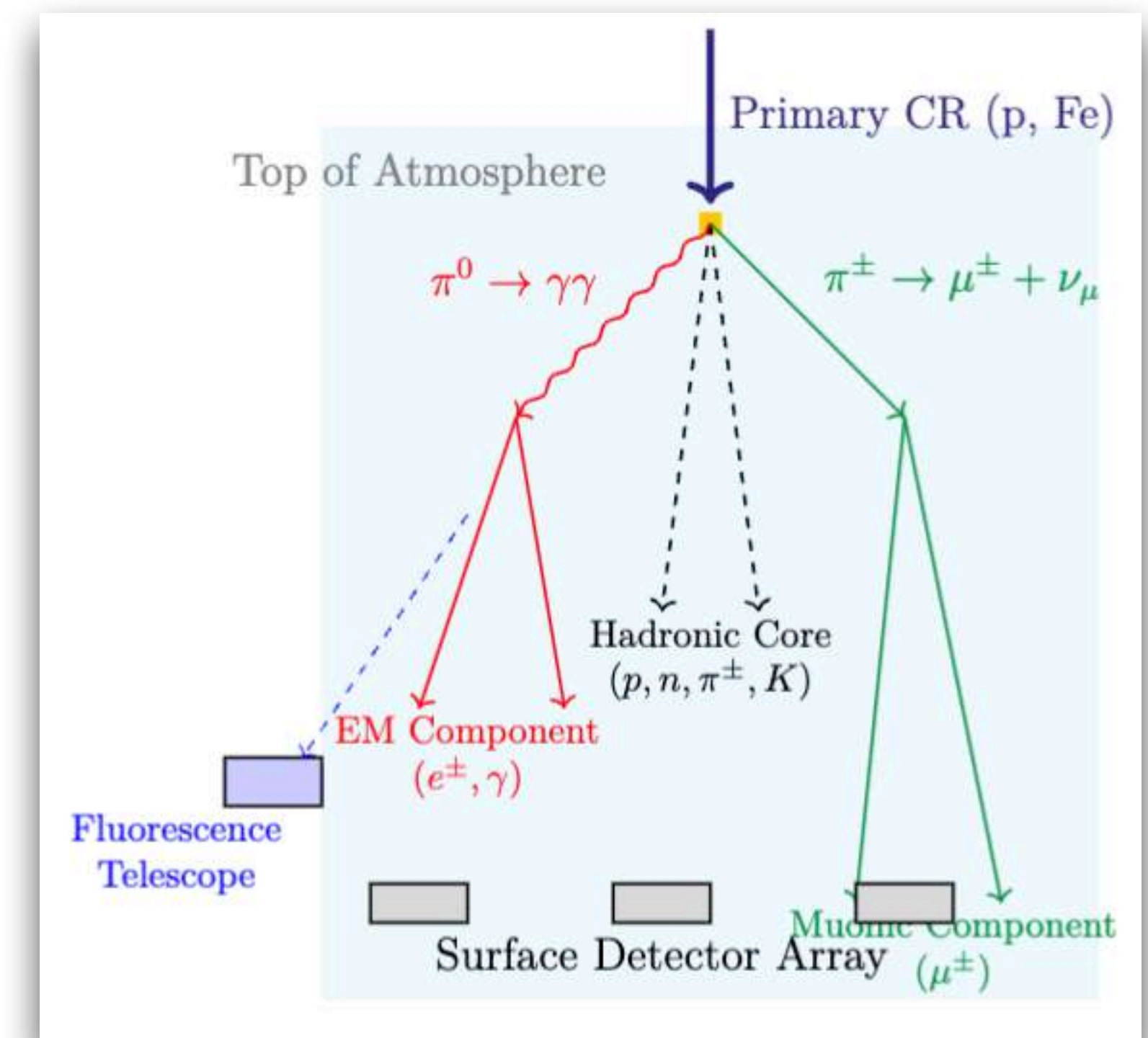
- *Spectrum breaks:* "The Knee" (~ 3 PeV, max galactic proton energy), "Second Knee" (~ 100 PeV, galactic iron limit), "The Ankle" (~ 3 EeV, transition to extragalactic dominance).
- *The GZK Cutoff* (5×10^{19} eV): The Universe becomes opaque to UHECRs. They interact with CMB photons (photopion production). Mean free path is limited to ~ 50 Mpc.



<https://www.researchgate.net/publication/349538532/figure/fig1/AS:1008795039838209@1617526888386/The-all-particle-energy-spectrum-of-cosmic-rays-Figure-extracted-from-reference-2.ppm>

Detecting CRs: Extensive Air Showers

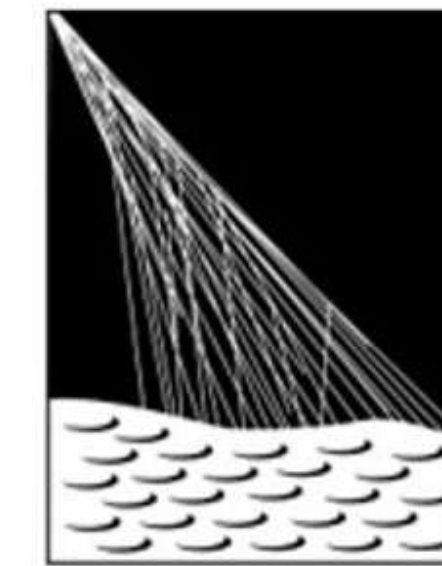
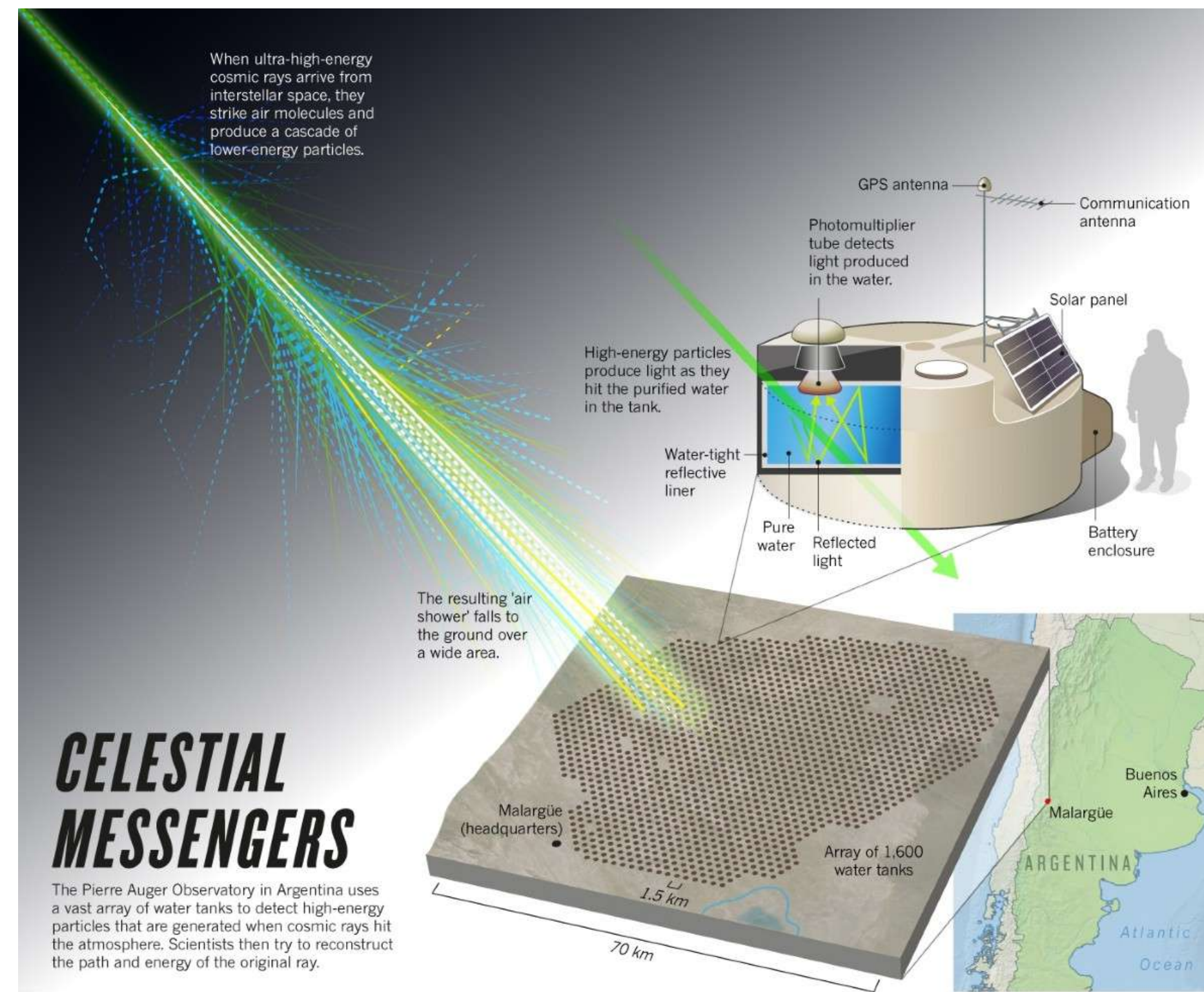
- Earth's atmosphere is used as a giant calorimeter. CR strikes an atmospheric nucleus, initiating an avalanche of secondary particles.
- *Three Components:* Hadronic Core, Electromagnetic Component, Muonic Component.
- *Hybrid Detection:* Surface Detector (SD) Arrays (Cherenkov/scintillator tanks) + Fluorescence Detectors (FD) (telescopes observing UV glow of nitrogen).



L09 Notes

Major CR Observatories

- *Facilities:* Pierre Auger Observatory (Argentina), Telescope Array (USA), LHAASO (China).



PIERRE
AUGER
OBSERVATORY

https://media.springernature.com/lw1200/springer-static/image/art%3A10.1038%2F514020a/MediaObjects/41586_2014_Article_BF514020a_Figb_HTML.jpg

Large Projects in Modern Astronomy

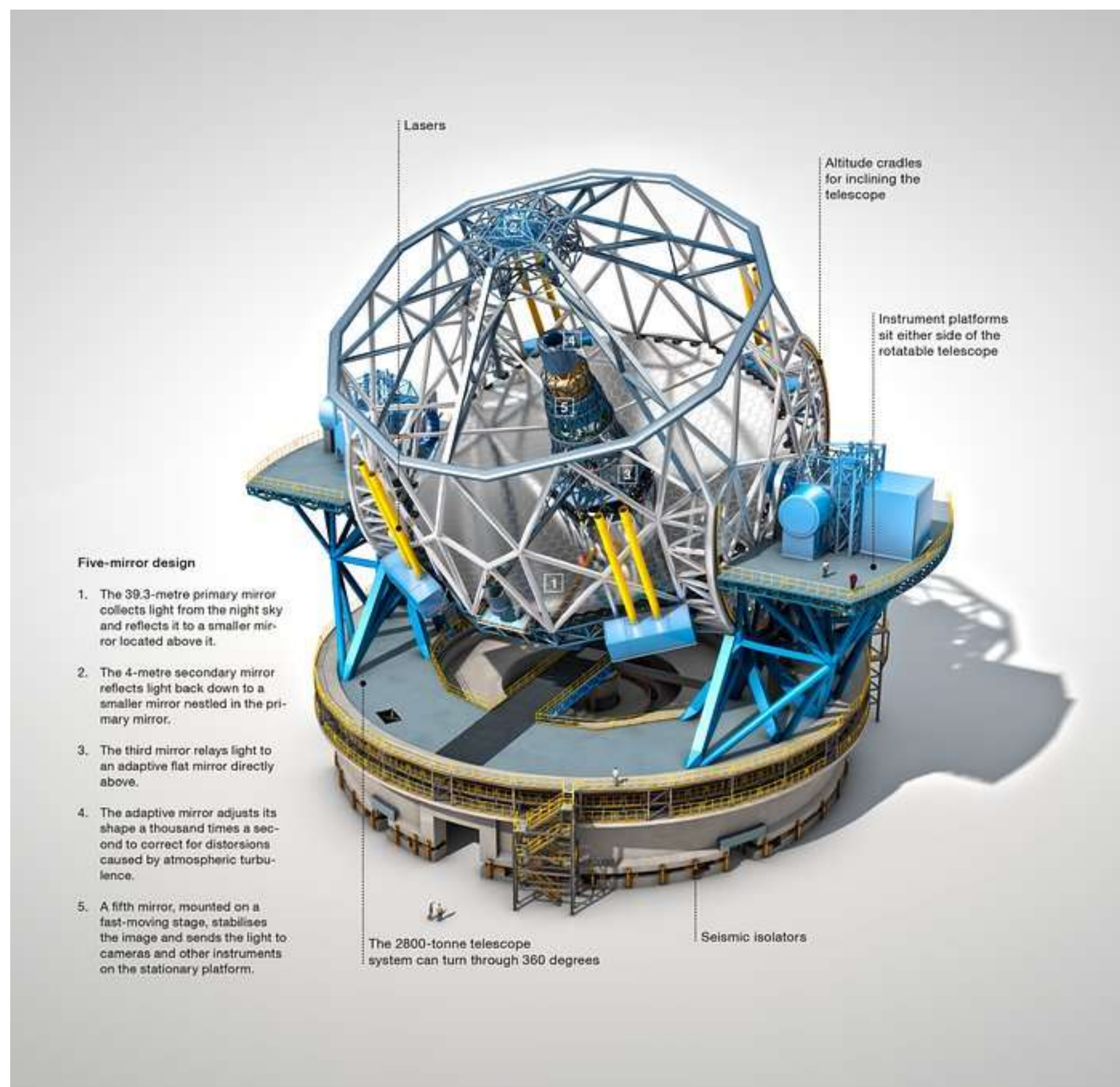
The Mega-Facility Era: Breaking Optical Limits

- *The Need:* Photon starvation at $z > 10$, source confusion in dense fields, and the Rayleigh diffraction limit ($\theta = 1.22\lambda/D$).
- *The Solution:* Mega-facilities relying on massively segmented mirror architectures, Extreme Adaptive Optics (XAO), and exascale computing.

Extremely Large Telescopes & Space Facilities

- *ELTs (Ground)*: Signal-to-noise scales as D^4 .
 - **ELT (39.3m)**: 798 segments, Atacama.
 - **TMT (30m)**: Northern hemisphere synergy.
 - **GMT (24.5m)**: Seven massive 8.4m circular mirrors. Excellent for exoplanet high-contrast imaging.
- *Space-Based*: Stable PSFs, no atmosphere.
 - **JWST (6.5m)**: Redefining high-z galaxies and exoplanet transmission spectroscopy.
 - **Roman Space Telescope (2.4m)**: Wide-field (100x Hubble) for Dark Energy and weak lensing.

The Extremely Large Telescope

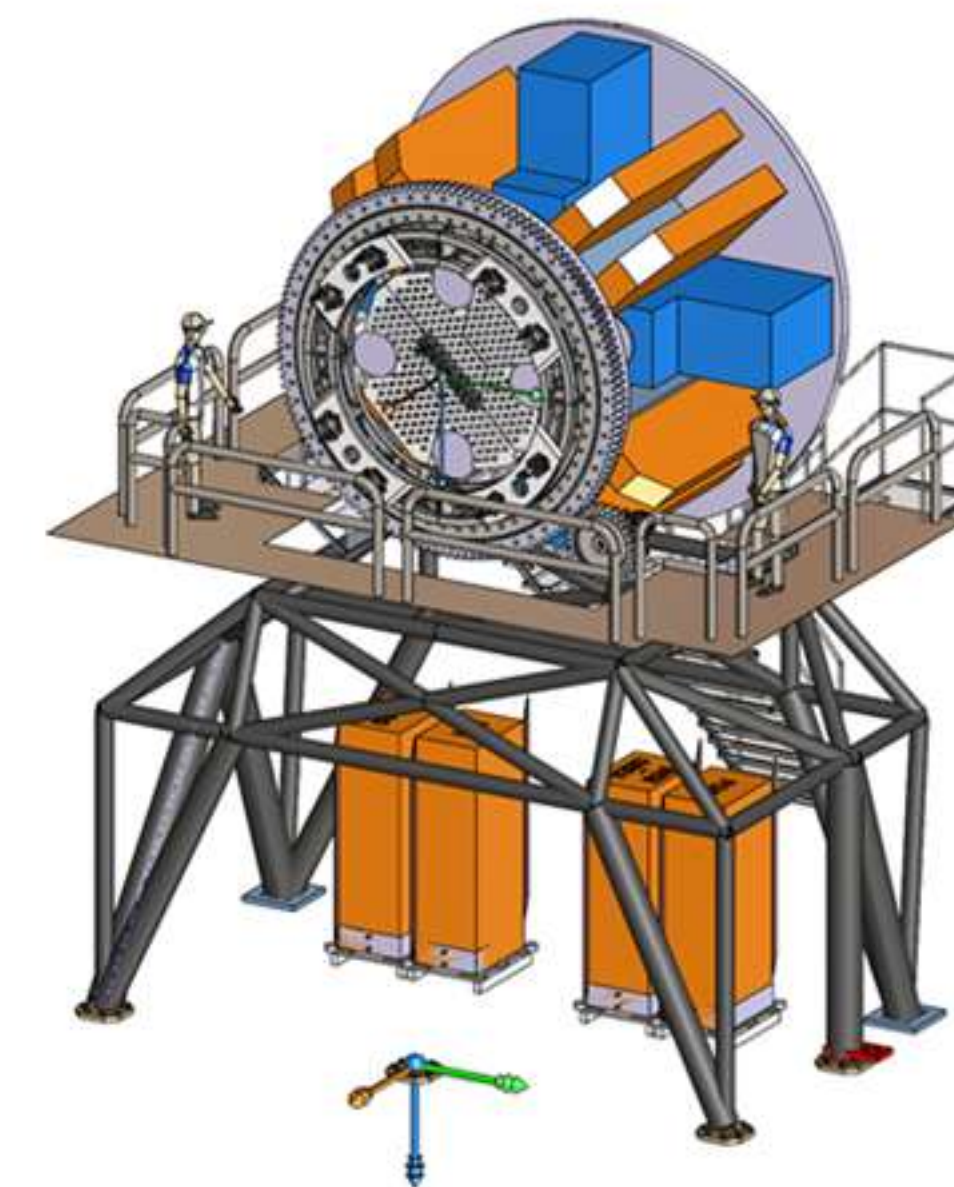


https://www.eso.org/public/images/E-ELT_labels_5000/



MOSAIC

<https://www.iag.usp.br/pesquisa/projeto/mosaic>

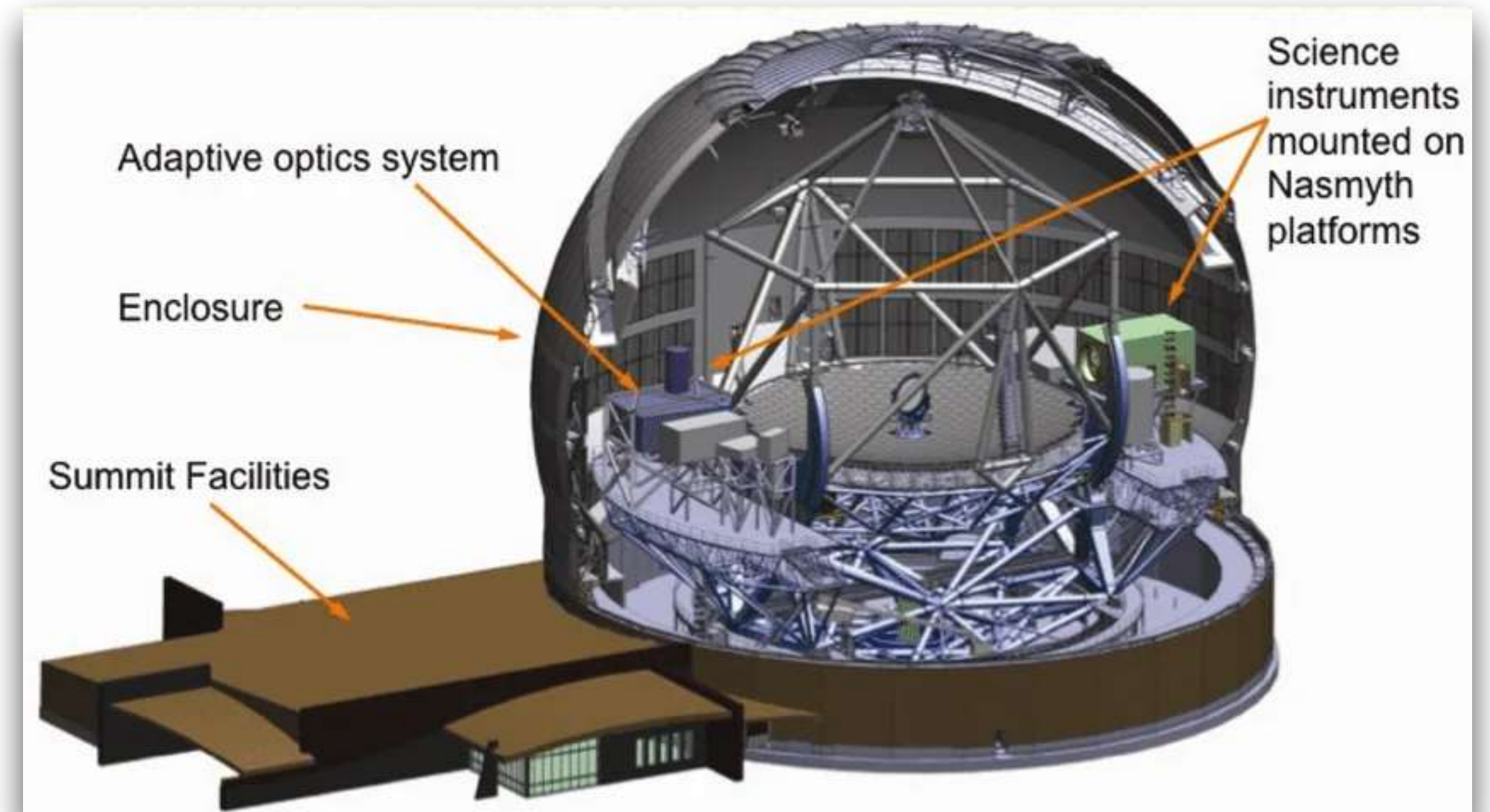


Brazil participates in the MOSAIC (multi-object spectrograph) consortium

The Thirty Meter Telescope

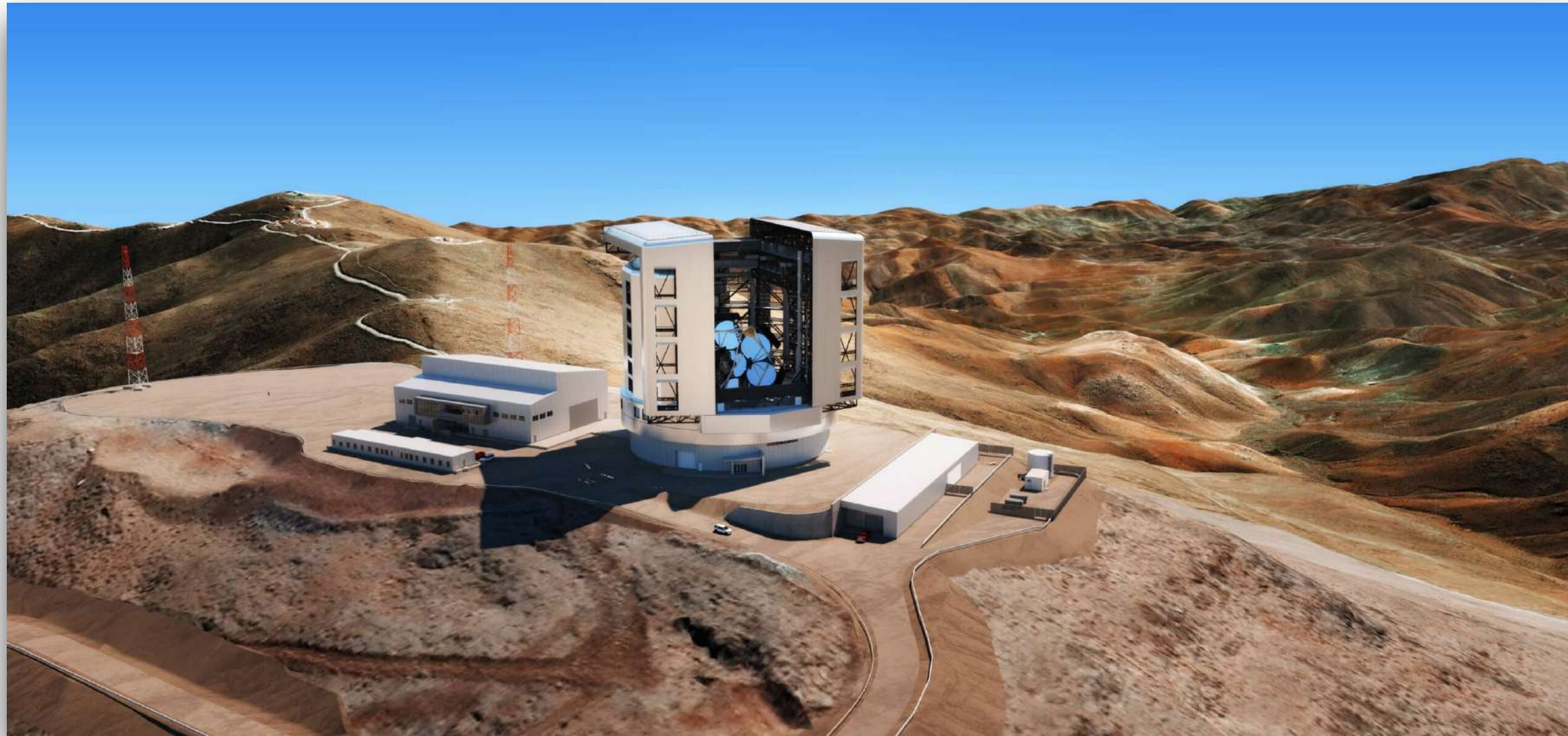


https://pt.wikipedia.org/wiki/Telesc%C3%B3pio_de_Trinta_Metros

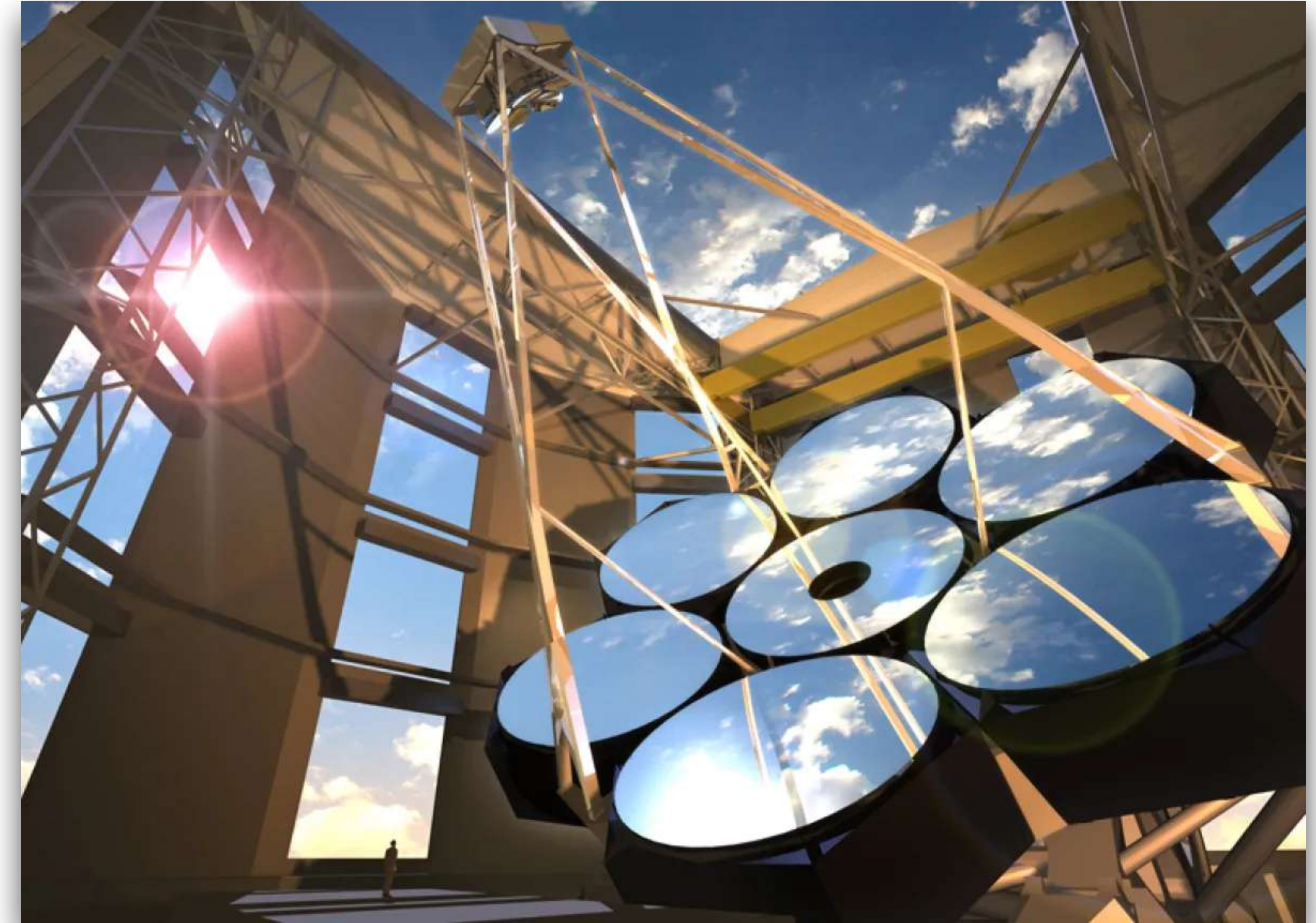


<https://www.researchgate.net/publication/325444860/figure/fig1/AS:631961328553985@1527682730778/An-overview-of-the-design-for-the-Thirty-Meter-Telescope-Observatory-The.png>

Giant Magellan Telescope



<https://giantmagellan.org/wp-content/uploads/2012/08/M3-Image-0919-1-scaled.jpg>



<https://rsaa.anu.edu.au/news-events/news/worlds-most-advanced-mirror-giant-telescope-completed>

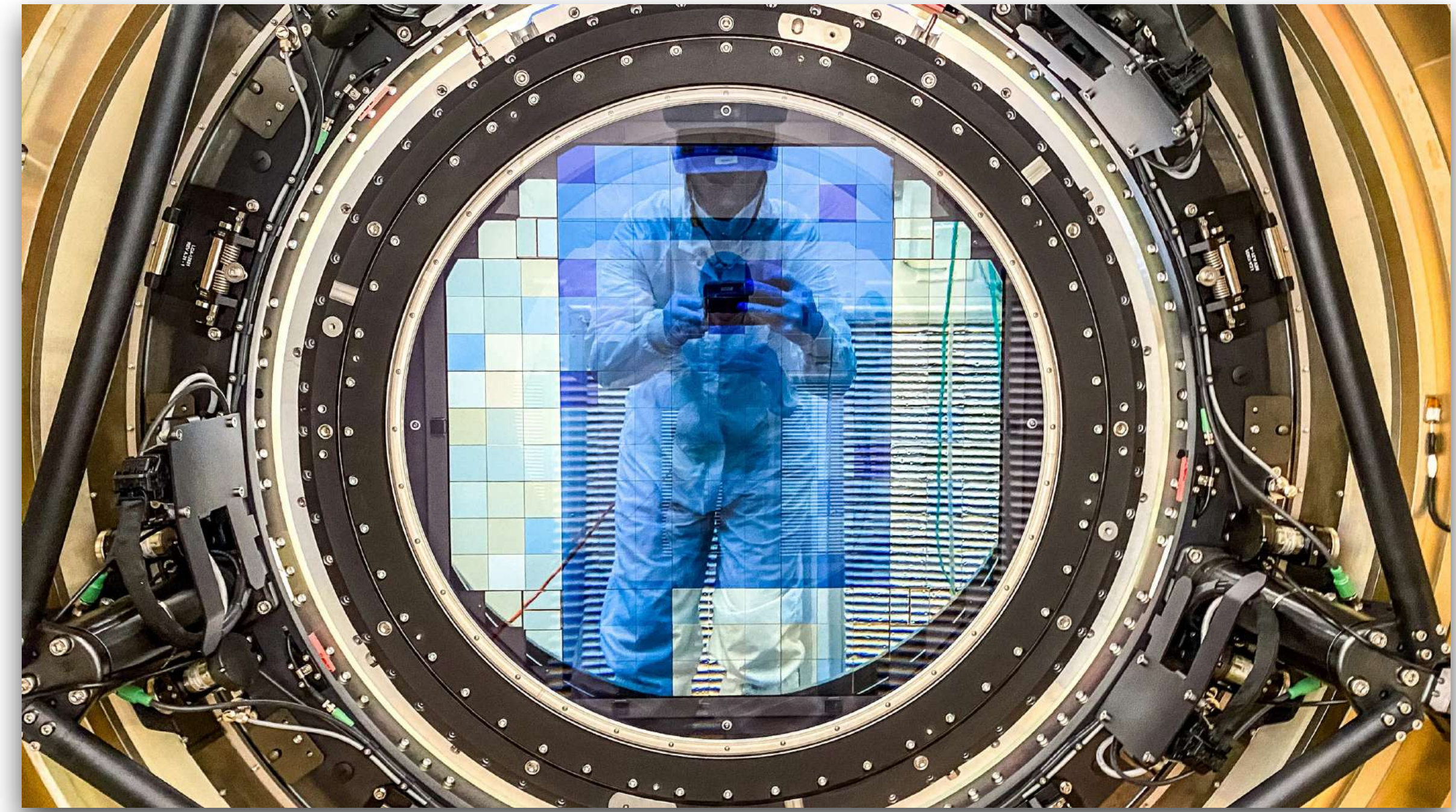
The Survey Paradigm & Time-Domain Era

- *The Shift*: Moving from “pointed observations” to continuous, wide-sky “surveys” (Era of Big Data and Etendue $A\Omega$).
- *Vera C. Rubin Observatory (LSST)*: 8.4m mirror, 3.2 Gigapixel camera. Will map the southern sky every 3-4 nights. Generating 10 million alerts/night with <60 sec latency.
- *Square Kilometre Array (SKA)*: Ultimate radio interferometer (South Africa + Australia). Probing the Epoch of Reionization via 21cm hydrogen lines. Requires exascale computing.

Vera C. Rubin Observatory



<https://news.ucsc.edu/wp-content/uploads/2025/06/Rubin-observatory-main-scaled.jpg>

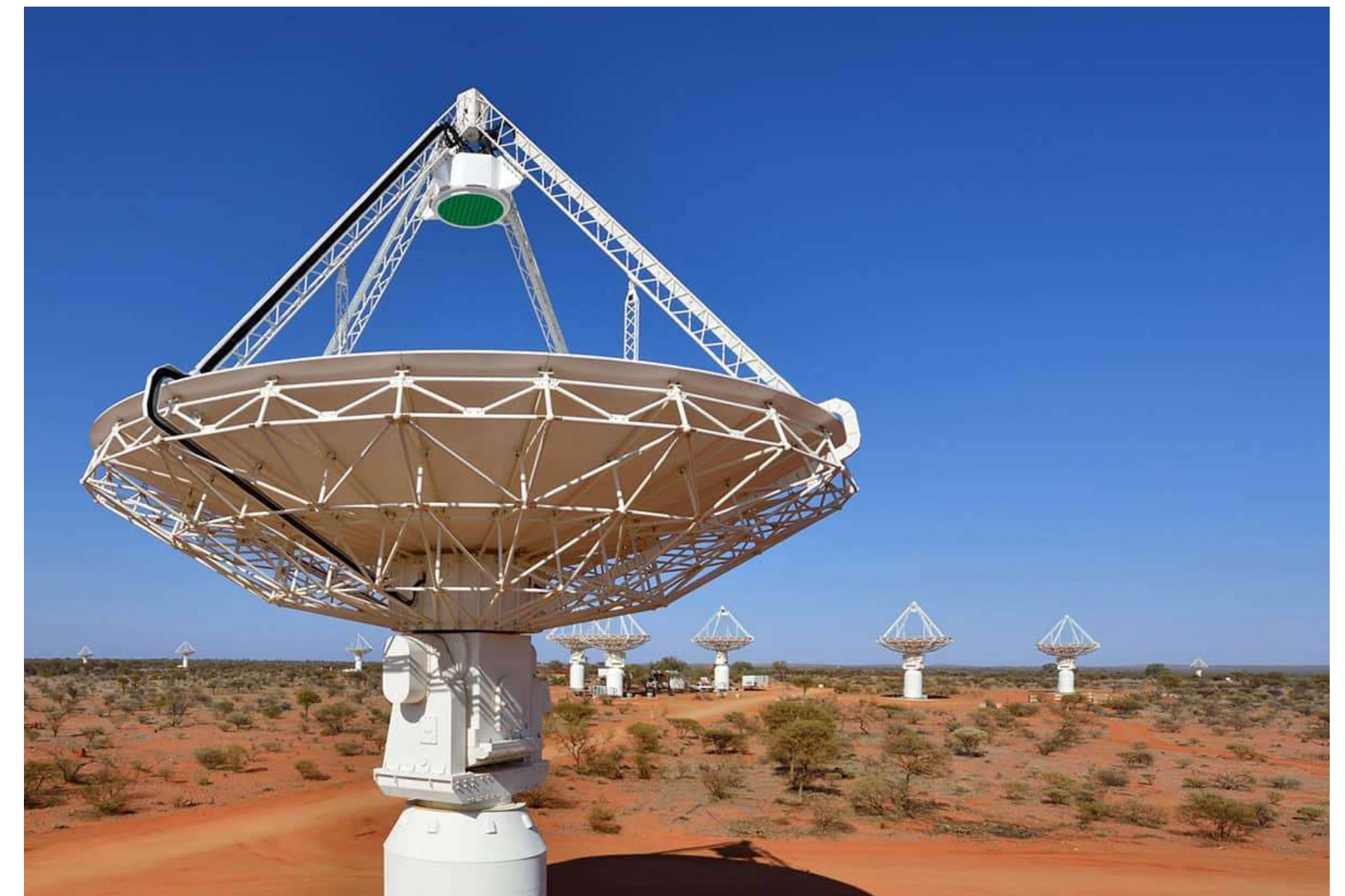


https://wp.technologyreview.com/wp-content/uploads/2024/12/53604630588_5cc7fff217_o.jpg

Square Kilometre Array



https://www.physics.ox.ac.uk/sites/default/files/styles/meta_open_graph/public/header_images_group/SKA%20at%20daytime.jpg?itok=cFXUcwJ1



<https://physicsworld.com/wp-content/uploads/2025/03/2025-02-Wild-SKA-CSIRO.jpg>

Brazilian Leadership in Mega-Surveys

- **J-PAS:** 54 narrow-band optical filters. Low-res integral field spectrograph for precise photo-z's.
- **S-PLUS:** 12-band southern sky survey. Identifying metal-poor stars via chemical tagging.
- **PFS:** Massively multiplexed spectroscopy (Subaru).
- **BINGO:** 21cm intensity mapping for BAO signals (Paraíba, Brazil).
- **CTA & LLAMA:** Next-gen gamma-ray and submillimeter observatories.
- **LineA:** The central computational/Big Data hub for Brazilian astronomers.

Summary & Synthesis

- Astronomy has transitioned from an EM-only discipline to a fully integrated **Multi-Messenger** science.
- GWs and Neutrinos allow us to pierce the opaque barriers of the universe, revealing the dark, dense, and hadronic engines of the cosmos.
- Cosmic Rays trace the most extreme acceleration mechanisms, bounded by physical limits like the GZK cutoff.
- Next-generation optical/radio observatories and mega-surveys are driving astrophysics into an era of Big Data, requiring massive international cooperation and computational innovation

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